Bailey Tool & Mfg. Co.

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New PCT Technology for the Navy Rail Gun Project

Volume 1. Technical Proposal

Technology Sub-Objective: WPN-17-75

Pulsed Current Transport and Pulse Conditioning for a Multi-MA RailGun

This proposal is submitted pursuant to Request for Ordinance Initiatives DOTC-17-01

Reference #: DOTC-17-01-INIT0690.

Offeror certifies that, if selected for award, the Offeror will abide by the terms and conditions of the DOTC Ordnance Technology Base Agreement.

John Buttles (President) _______________ Date: July/25/2016

Proprietary data disclosure statement:

NAC MEMBER INFORMATION SHEET FORMAT

NAC MEMBER NAME AND ADDRESS: (LIST ALL LOCATIONS WHERE WILL WORK WILL BE PERFORMED)	Bailey Tool & Mfg. Co. 600 West Beltline Road, Lancaster, TX 75146 906 Mercury Avenue, Duncanville, TX 75137
PROTOTYPE ORDNANCE TECHNOLOGY OBJECTIVE AND SUB-OBJECTIVE AREA FROM ANNUAL TECHNOLOGY PLAN:	Weapon System/WPN-17-75
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EXECUTIVE SUMMARY

Bailey Tools & Mfg, the Accelerator Research Lab at Texas A&M University, the Pulsed Power & Energy Lab at the Univ. of Texas at Arlington, and Accelerator Technology Corp formed the BATS Consortium to develop and test prototypes of technical components with the ability to enhance performance and reduce risk in a pulsed current transport (PCT) system, as defined in topic WPN-17-75 of the DOTC solicitation:

The Government is seeking proposals for the development of a prototype articulating high current transfer mechanism that meets RailGun requirements. A reliable, safe method of transferring high currents from the consolidation point to the RailGun breech is needed that allows for a large range of articulation in at least one axis of rotation, while passing current. A new method of moving several mega-amperes of current while allowing a large range of articulation is discussed in this proposal

The Navy RailGun Program has achieved an important milestone by successfully launching 10 kg projectiles with a velocity greater than Mach 8, corresponding to a range greater than 100 km. The RailGun delivers a 2 MA current pulse to a pair of copper-alloy rails. The current pulse is generated by an array of identical pulsed power modules (PPMs) that each produce a ~50 kA pulse with up to ~4 kV potential. The PPM outputs are added to develop the 2 MA pulse, and the pulse is transported to the rail terminals using an array of approximately 56 semi-flexible coaxial cables.

Objective of the Proposal: The BATS Consortium has developed a comprehensive design for an articulated PCT (APCT) system that can deliver up to 5 MA through a single rigid coax transmission line that is coupled through two rotary joints. Figure 1 shows the APCT system as it would be installed with a ship-board 32 MJ RailGun. The APCT system provides complete freedom to aim the RailGun in any desired direction.

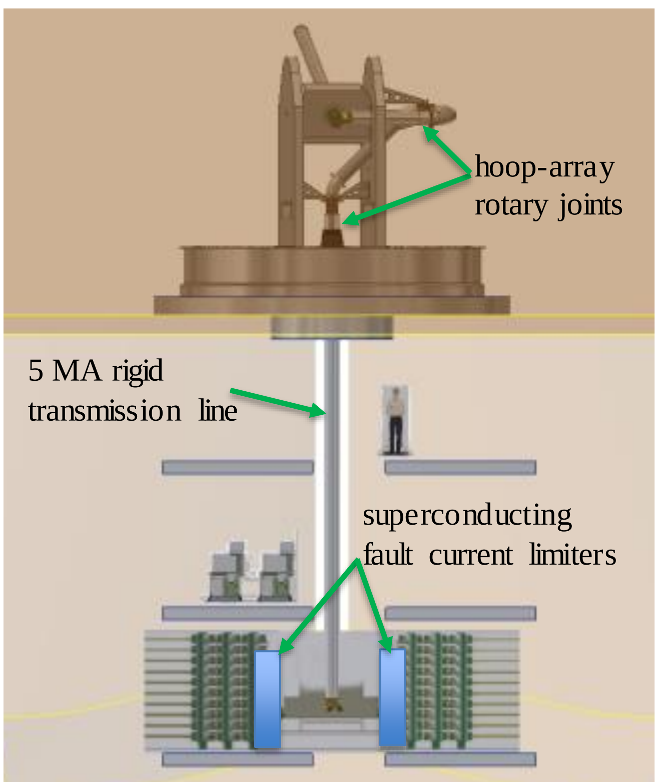
BATS proposes to build a 500 kA scale-model prototype of the APCT system and test it using the 500 kA PPM network at the UT Arlington facility. The proposed prototype development is structured into five tasks that specifically address all key aspects of the APCT system from the PPM outputs to the breech:

- Develop rigid coaxial transmission line using Litz-cable technology.
- Build, install, and test a 500 kA rigid transmission line connecting the PPN to a water load.
- Build a 500 kA rotary joint, integrate onto the transmission line, and test in operation.
- Build and test a 100 kA Superconducting Fault Current Limiter (SFCL) for a PPM protection.
- Operate the entire APCT system with cold nitrogen gas coolant flow, test 10 pulses/minute.
- Develop a system integration of a 5 MA APCT system, designed to meet all requirements for integration with a 32 MJ RailGun capable of aiming in any direction.

The proposed development of the APCT addresses the stated goals of the DOTC program:

- **APCT is a reliable, safe method of transferring high currents from consolidation point to the RailGun breech.** One mode of failure of the PCT system is the failure to short the capacitor and/or the switch of any PPM in the pulse-forming network. In present systems such a failure can result in delivering a significant part of the total pulse energy into the failed PPM and can cause that capacitor to explode and destroy the network. The superconducting FCL (Task 3) limits the reverse surge current in such a failure to ~twice the design pulse current from that module, which protects the failed module so that it can be disconnected from the PFN and replaced during a maintenance period.

- **APCT moves several mega-amperes of current while allowing for a large range of articulation in at least one axis of rotation while passing current.** The only way to provide free motion of the RailGun in both axes of rotation is to mimic the human arm: provide two rigid segments connected by two rotary joints. The rigid segments (Task 1) carry the mega-ampere current with low resistive loss without permitting the conductors to flex under the large Lorentz forces during each pulse. The hoop-array rotary joints (Task 2) convey the mega-ampere current while permitting free rotation about the axis of the rigid segment. Two successive rotary joints permit complete freedom to aim the RailGun to 360° in azimuth and 90° in elevation.
- **APCT accommodates high repetition rate with modest resistive loss in current transport.** The inner and outer conductors are fabricated using clusters of Litz cables, which permit full penetration of a fast current pulse through the thickness of the wires. The spaces between inner and outer conductors and inside the inner conductor carry the flow of coolant, so that the resistive heat that is deposited from each pulse can be removed to accommodate sustained fast repetition rate. The coolant can utilize the boil-off liquid nitrogen (Task 4) from the SFCL network, which reduces the resistance of copper by a factor 5 and further improves the energy efficiency and rep rate capability.



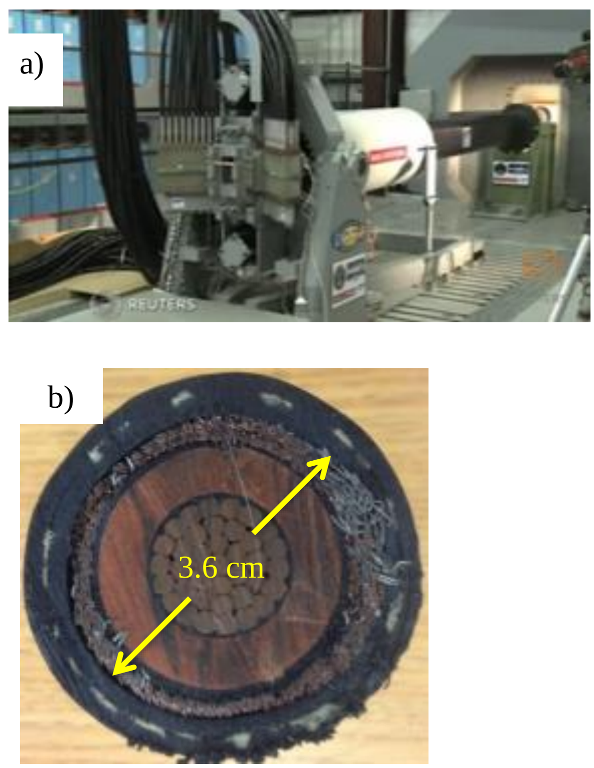


Figure 1. Articulated PCT system and superconducting FCL installed on ship-board railgun.

Figure 2. Conventional 5 MA railgun PCT, with 56 cables connected to the breech.

TECHNOLOGICAL APPROACH

TECHNOLOGY GAP OBJECTIVES

Problems with present PCT technology

The present RailGun PCT system is based upon a cluster of semi-flexible coaxial cables, shown in Figure 2. Each cable carries approximately 50 kA, and the PCT dissipates about 400-kJ/m resistive losses in transporting a 5 MA pulse. The inner and outer conductors are each cabled using un-insulated copper wires. The overall size of the cable, about 3 cm, is a practical limit for there to be even a modicum of flexibility to the cable. The wire size and cable thickness are also at a limit beyond which current sharing would be limited by skin depth and proximity effect.

BATS' articulated PCT with superconducting FCL addresses all of the above problems

BATS has designed a single rigid coaxial transmission line which contains the same copper cross-section as the cluster of 56 coax cables in the present RailGun PCT. The rigid coax offers three significant improvements over present systems and for future higher-current systems:

- The single rigid coax transmission line can be fitted with rotary joints so that the gun can be rotated through 360° of azimuth and 90° of elevation without constraint (Task 2).
- The transmission line utilizes a cylindrical array of rectangular-geometry Litz cables that maintain uniform current sharing within any thickness of cable, so that the design has less than half the AC resistance and is scalable for 5 MA PCT requirements.
- The coax transmission line has high-capacity cooling channels integrated within the coax structure, and can accommodate high pulse repetition rates greater than 10 pulses per minute.

BATS proposes to develop a prototype APCT to demonstrate articulated rotation, efficient current transport, and protection of the PPMs within the pulse-forming network

UT Arlington has installed three 11 kV, 200 kA pulse-forming network modules, which can be added to deliver a 500 kA pulse through a PCT and absorb the pulse energy in a water load. BATS proposes to develop a 500 kA scale-model of its APCT system and test the above features in practice. In a succession of tasks, which can be approached in series or parallel according to available funding, BATS will build and test:

- A segment of rigid transmission line containing Litz-cable conductors to measure its resistive losses during fast pulses;
- A pair of hoop-array rotary joints to validate that they can carry 500 kA pulses without degradation in the hoop-array connection at the joint;
- A 100 kA superconducting FCL to evaluate its ability to handle failure-to-short conditions on a source point;
- Cooling the rigid transmission line and rotary joint using boil-off nitrogen gas to evaluate its benefit in reduced heat load from current pulses.

BATS proposes to use the results of those four tasks to prepare a construction-ready design for a full-scale 5 MA APCT that would meet operational RailGun requirements, and a system integration study of how it could best integrate with PFN and RailGun systems to meet Navy requirements.

Deliverables of the proposed effort

Task 1 will deliver a design and test performance report on a 500kA rigid coax transmission line.

Task 2 will deliver a design and test performance report on a 500 kA hoop-array rotary joint.

Task 3 will deliver a design and test performance report on a 100 kA superconducting FCL.

Task 4 will deliver a design and test performance report on operation of the rigid coax and rotary joint when cooled using boil-off nitrogen gas.

Task 5 will deliver a design report for a 5 MA full-scale APCT system and a system integration study for its implementation with a current-generation PFN and RailGun.

Scope of the proposed effort

The proposed effort will address four issues that limit the performance of current PCT systems for navy RailGuns:

- Sustained rapid-fire sequences of 5 MA pulse current through a reliable transmission line.
- Enhanced aiming of a RailGun by eliminating current system constraints.
- Protection of the PFN network against failure of component PMMs.
- Optimization of the energy efficiency and rapid-rate capability of a PCT system.

Initial Objectives

The proposed effort will develop and test the core technical components of an articulated pulsed current transport (APCT) system at a 500 kA scale. The system will use a rigid Litz-cable-based coax transmission line; a hoop-array rotary joint; a 100 kA superconducting FCL; and internal cooling flow within the transmission line to operate it at 80 K temperature to reduce resistive losses.

The technical solutions embodied in the APCT system are a Litz-based rigid transmission line; a hoop-array MA-capable rotary joint; a 100 kA SFCL, and integrated cryogenic gas flow within a high-current coaxial cable network. The hoop-array MA-capable rotary joint uniquely makes it possible to connect a multi-MA PCT to a RailGun and yet articulate the RailGun to fire in any direction. It is a patent-pending breakthrough innovation by the Texas A&M group.

The coaxial configuration of REBCO tape-conductors in the SFCL uniquely enables packaging a 100 kA current limiter in a compact module that can be integrated with each PPM. It is a patent-pending breakthrough innovation by the Texas A&M group.

The coaxial flow of boil-off nitrogen gas through the transmission line reduces ohmic losses by a factor 4 and makes it possible to sustainably fire a 32 MJ RailGun at high rep rate. It is a patent-pending breakthrough innovation by the Texas A&M group.

Core of the proposed approach

At the core, the proposed approach uses, biomimetics, in which an attribute of a living creature is incorporated in a technical system to improve its performance. It is a challenge to transport 5 MA of electric current without constraining the motion of a RailGun. The solution discussed in this proposal imitates the human arm by using a single rigid coaxial transmission line to transport the current incorporated with two rotary joints to provide enhanced aiming. It imitates the human arm, in which the rigid upper and lower segments are connected by the shoulder and elbow so that a baseball player can pitch in any direction he chooses.

A second core of the proposed approach is to simplify the current transport in the rotary joint by means of an array of ~10^4 sliding hoop contacts. Each contact slides in only one orientation as the joint rotates, each contact carries only ~100 A, and neighboring contacts provide local bypass for current transport in event that any contact momentarily fails.

A third core of the proposed approach is to protect the PPM components of the pulse-forming network by integrating a compact superconducting FCL in series with each PPM. The FCLs for all the PPMs of one PFN chassis are housed in a single liquid nitrogen cryostat that mounts to each side of the chassis.

A fourth core of the proposed approach is to integrate the flow of boil-off nitrogen gas through the coax transmission line to dramatically reduce the resistive heat produced by each current pulse, and use to full advantage the enthalpy of the liquid nitrogen.

Technical Details of the Proposed Approach

Task 1: Rigid coaxial transmission line using Litz cable

A Litz cable dramatically reduces the AC losses for transporting fast current pulses in a cable. When a fast current pulse is driven in a cable, there are four considerations that can increase the AC losses of a cable of given copper cross-section:

1. The diameter of the wire is comparable to or greater than the skin depth causing AC losses.
2. The neighboring wires are in electrical contact with one another so that current can bridge locally and cause AC losses.
3. A wire does not transpose from inside to outside within the cable geometry.
4. Neighboring cables magnetically couple causing AC losses.

All four of these effects are addressed by constructing a coaxial cable where each current shell is a cylindrical array of Litz cables. In a Litz cable all strands are coated with insulating enamel so that neighboring strands cannot bridge current locally, thus minimizing the AC losses associated with local current bridging. In addition, all strands fully transpose from locations on the inside of the cable geometry to locations on the outside and there is no suppression of current flow in some strands in favor of others from the presence of the Lorentz forces being produced by the magnetic fields within the cable exerting force upon the current-carrying electrons.

With those constraints satisfied, and with a choice of strand size ~1 mm (skin depth at 1 kHz in copper is 2 mm), current flow will be nearly uniform over the entire cross-section of each conductor layer in the transmission line and the AC losses will be minimized.

Two geometries of Litz cables are routinely produced: a round-profile cable-of-cables (

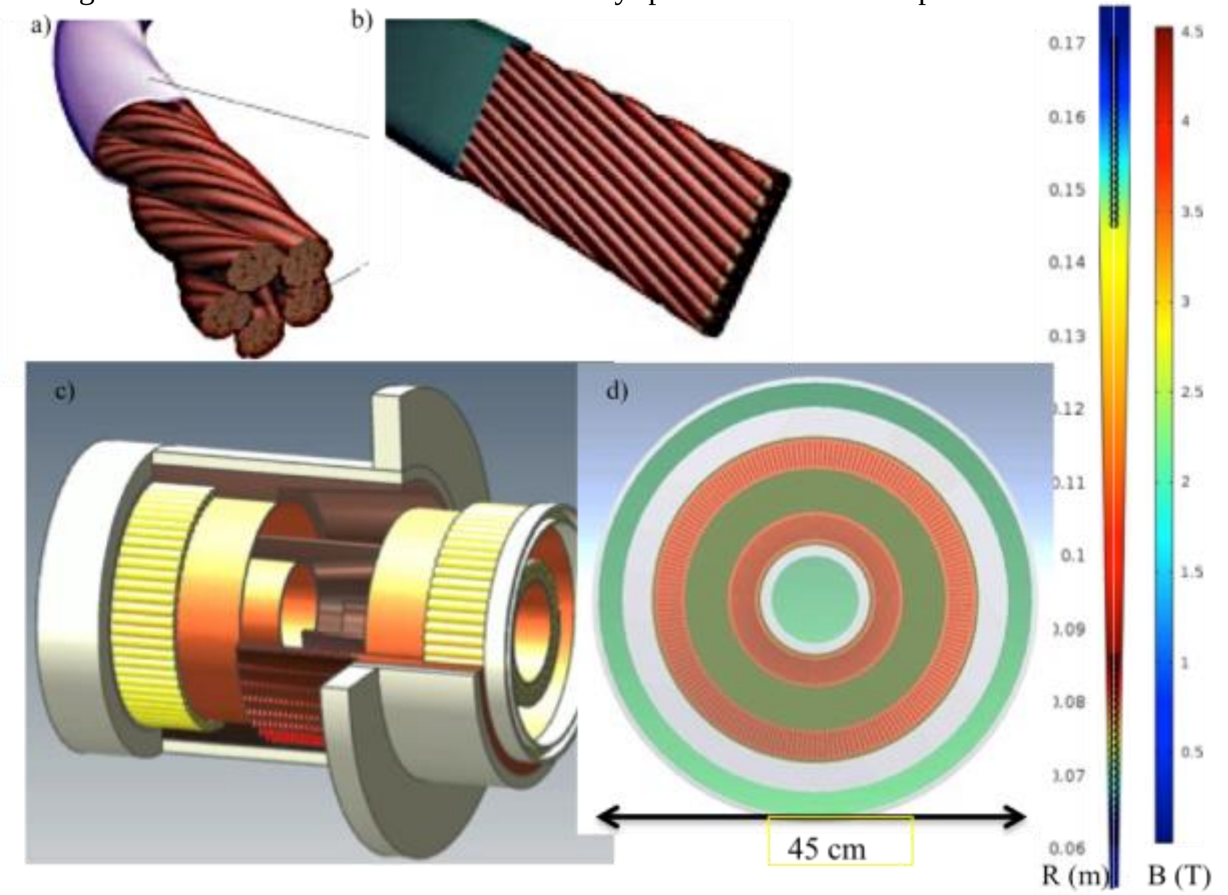


Figure 3a) and a rectangular Rutherford cable (

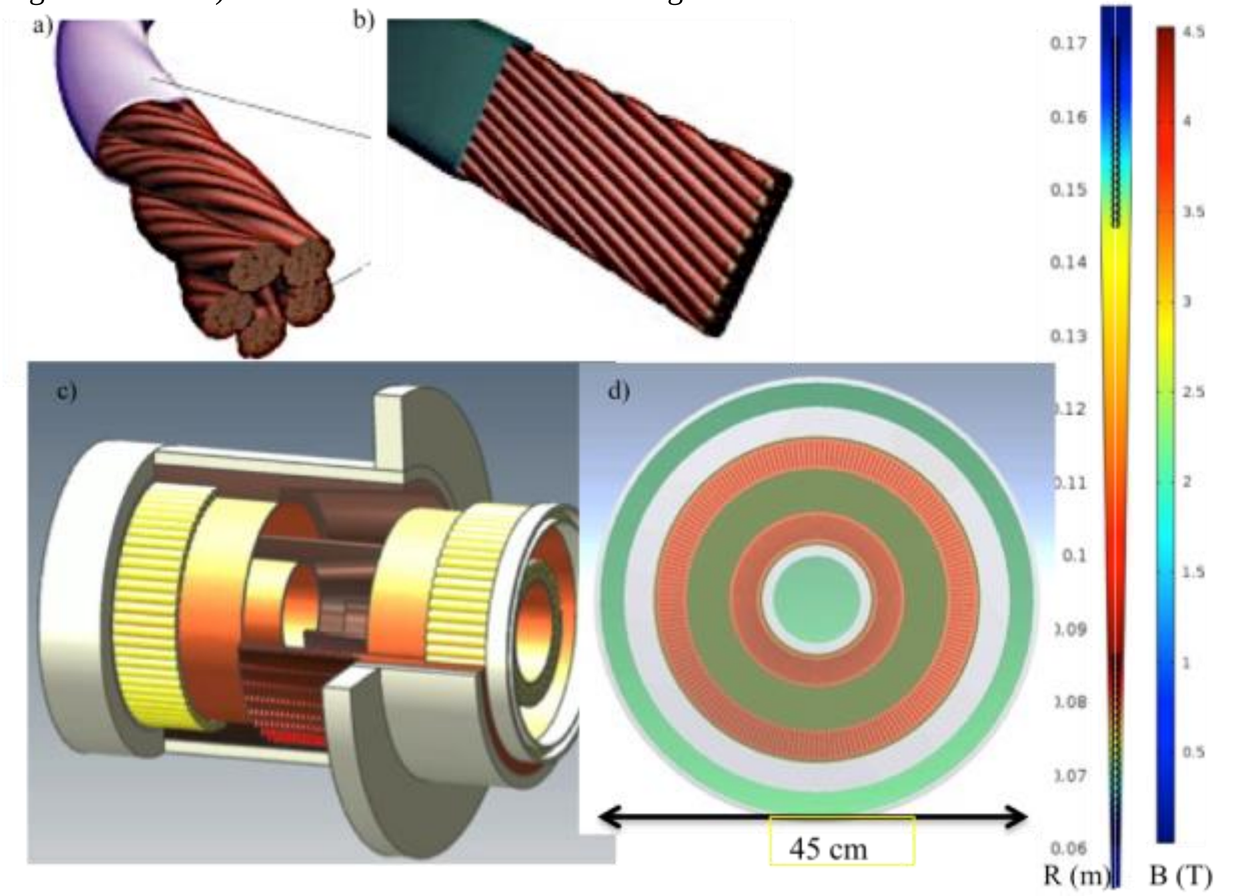


Figure 3b). In both cases all strands are coated with a thin layer of electrically insulating enamel (*e.g.* Formvar, polyimide) so that currents cannot re-distribute among strands along the length of the transmission line. Also in both cases all strands fully transpose: each strand spans as much of the cable length located on the inside of the transmission line geometry as it does on the outside, so there is no net inhibition of current flow in one strand *vs*. another.

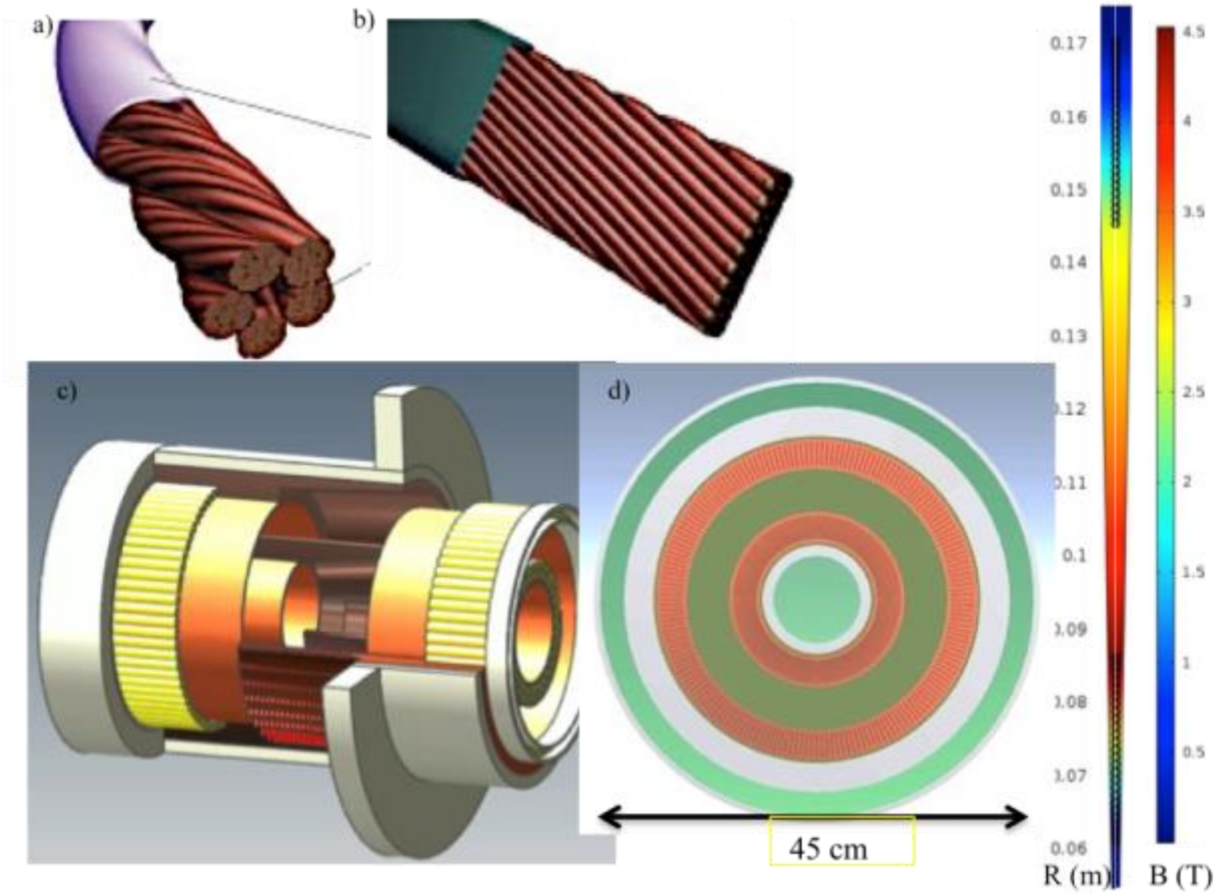


Figure 3. a) Litz cable geometries: round cable-of-cables and Rutherford rectangular geometry; b) cutaway showing rotary joint in water-cooled rigid transmission line for 2 MA service; c) cross-section of 2 MA transmission line using Rutherford cables; d) magnetic field distribution in the Rutherford Litz cables during a 2 MA pulse in the transmission line.

Figure 3d shows the calculated magnetic field distribution in an azimuthal slice of the transmission line. We have modeled the distribution of current within the cables using the AC transmission simulations of COMSOL MultiPhysics. The cable maintains its d.c. resistance R_{dc} = 2.3 μΩ/m for frequency components up to 100 Hz (the flat-top of the 10 ms PFN pulse), increasing to 3.6 μΩ/m for 1 kHz frequency components (the leading and tailing edges of the PFN pulse).

Litz transmission line design

The transmission line can be fabricated both in straight segments (for which the cables run parallel to the transmission line axis) and in bending segments of 45° or 180° that are required for the dual-rotary-joint configuration for Task 2. For the bending segments each layer of cable is wound onto its forming mandrel with a spiral twist pitch so that it naturally conforms to the bend radius – an important benefit of the Rutherford-Litz cable geometry.

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The transmission line shown in Figure 3b has about the same a.c. resistance per meter, as does the 56-cable cluster of non-Litz cables presently used by Navy. The Litz cable makes it possible to maintain parity in the efficient use of copper in a single coaxial transmission line compared to a multiple-cable cluster. Carrying current in a single coax structure is absolutely necessary to make a rotary joint feasible. If one were to make a 5 MA joint by clustering non-Litz copper cables equivalent to the copper in the inner and outer shells of 56 coax cables, the combination of skin depth and proximity effect would drastically limit the fraction of the copper actually carrying current. By using Litz cables one preserves the full utilization of copper and the 5 MA target can be achieved without penalty.

A preliminary design for a 5 MA version of the transmission line and its rotary joints has been prepared and is shown in Figure 3. We have also prepared a scale-model design for a 500 kA rigid transmission line suitable to be driven by a parallel network of the three 200 kA PFN modules that are installed and operational at UT Arlington. The UTA facility provides an opportunity to install and test each element of the APCT system, work out bugs, and optimizing the parameters of the system. Figure 4 shows two versions of that design, using Litz sub-cables that are round and rectangular, respectively. In Task 1 we will evaluate the two designs and select one for fabrication and testing of a 3 m long sample transmission line.

Task 2: Develop/test a hoop-array rotary joint for the coaxial transmission line

A primary motivation in developing the single rigid coaxial transmission line for the 5 MA pulse is to make it possible to deliver the pulse from the PFN below deck to the RailGun on its turret with *complete freedom of rotation of the turret and inclination of the barrel*. This requires a pair of rotary joints, one that pivots on a vertical axis to connect the vertical transmission line from the PFN to a penetration in the turret, and the other that pivots about a horizontal axis mounted to the turret and delivers the pattern of Litz cables to a pair of bus plates connected to the rails at the RailGun breech.

The rotary joint must reliably connect the 5 MA current from each cable layer of the transmission line, through a sliding rotary joint, to the same cable layer in the next transmission line, and yet permit free rotation. The challenge in doing so is to provide reliable connection of 5 MA

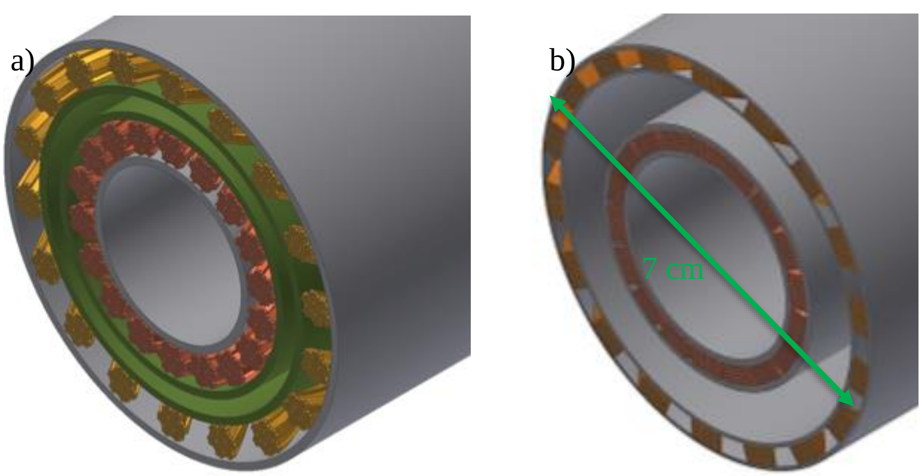

Figure 4. Two example designs for 500 kA Litz-based coax transmission lines that will be investigated: a) based upon round sub-cables; b) based upon Rutherford sub-cables.

through a sliding conical surface. A variety of methods have been used for such purposes: brush contacts [1], button-contacts on spring-foil fingers, and sliding wire contacts. None has the reliability required for such a large contact current in an inductive circuit.

We propose a new approach to make such a reliable joint: a conical hoop-array that provides uniform spring-loaded contact of ~20,000 Be-Cu wire hoops to a conical surface. The rotary joint design is shown in Figure 5 and Figure 6.

The unique feature of the hoop-array approach is that all hoop contacts are oriented so that, as the joint rotates, each hoop slides on the contacting surface in a direction that is parallel to the plane of the hoop. Tribology teaches that wear, abrasion, and fracture are minimized when the contacting surfaces of a sliding joint are made to contact on a gradual, curved contour with a uniformly sustained compressive force. The radial space in which the hoops are compressed is controlled by the depth of insertion of the male conical member into the female conical member, so by shimming we can precisely pre-load the compression of all hoops to assure optimum electrical and wear performance.

Because all contacts are independently and uniformly spring-loaded against the mating surface, even if one instantaneously encounters a particle, or insulating micro-patch, or rough feature on the surface, its neighbors act independently and the only current that is instantaneously interrupted by one hoop is ~100 A.

The array design utilizes hoops of 0.7 mm diameter phosphor bronze wire, bent in a 180° hairpin with curvature 1.5 diameter. Each hairpin is welded into a pair of holes in the surface of a conical contact. Hoops are located on a 2 mm x 3 mm pattern over a 30 cm-long conical surface, so that ~20,000 hoops are contained in each rotary joint.

We will evaluate two fabrication geometries for making the hoop-array joint. In Method 1, illustrated in Figure 5(a), electron-beam drilling is used to drill the pattern of 40,000 holes in the conical cupro-nickel surface. While this may seem exotic, a partner company Acceleron [2] has expert facilities for electron beam welding and electron beam drilling, and they routinely drill arrays of ~40,000 through-holes of such diameter in a precise pattern in a ~5 mm thick cylinder of high-strength alloy. They estimate that for our application the operation will take about half a day to fabricate the entire array.

BTM will develop two custom machines for the forming and loading of the hairpins into the holes in the conical surface. A first machine will form the hairpin in a uniform geometry in a rapid-automation process. The formed hairpins will then be spring-tempered. A second machine will load the hairpins into the hole array.

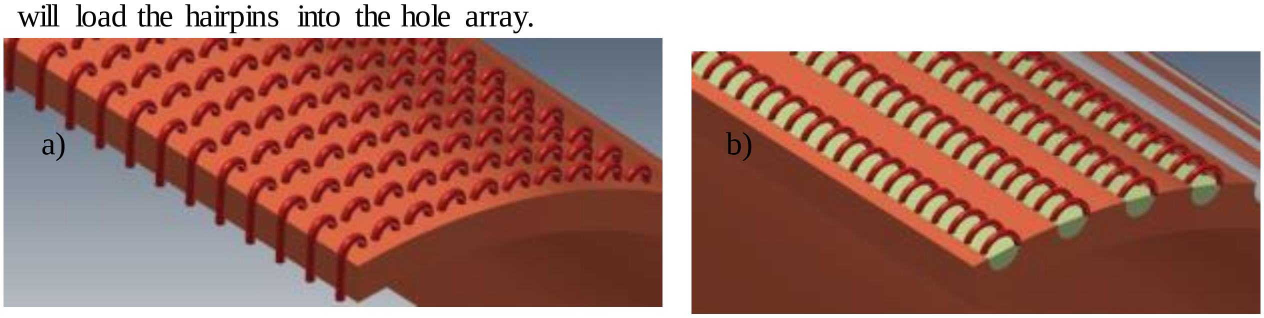

Figure 5. Methods for fabrication of the hoop arrays for the rotary joint: a) Method 1 in which wire hairpins are secured into holes in a conical mandrel; b) Method 2 in which coil springs are secured into grooves on the surface of the conical mandrel.

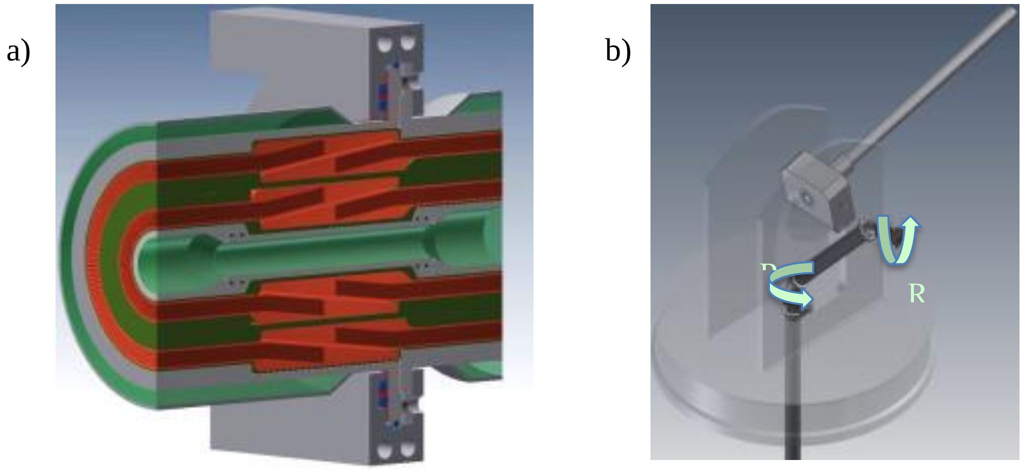

Figure 6. a) Cutaway section of rotary joint, showing the transmission line, the male and female conical joint elements, the provisions for water flow, and the rotary shell; b) configuration of rigid transmission line and 2 rotary joints to transport 5 MA current pulses from the consolidation point to the RailGun.

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The final step in the fabrication process is to load all hairpins so that the outermost contact surfaces of all hairpins are at a precisely equal distance from the cone surface, and then braze all of them into the cone. The hairpins are coated with a noble metal (Ag or Au) before insertion into the holes, and then all hairpins are loaded into the cone. Next a mating conical fixture is fitted to set all hairpins to the desired positions (a natural self-centering in this geometry). The assembly will then be oven-brazed to permanently braze all hairpins into their holes. The brazing operation will be done at Accurate Brazing [4]. Several choices for the material of the sizing cone will prevent it from bonding to the hairpins during brazing.

In Method 2 for making the hoop array we will embed segments of coil spring in channels in the conical surface of the rotary joint, as shown in Figure 5(b). The recessed portion of the spring is oven-brazed in its channel while the entire array is preloaded by a conical fixture, just as in Method 1.

Figure 8 shows a cutaway CAD design for a sub-scale learning-model rotary joint (1" diameter) that we fabricated to evaluate issues of forming and mounting hoops in an array and to evaluate the actual rotation of the joint. Figure 8 shows a short video clip in which Jeff assembles the hoop-array joint and rotates it. This test was gratifying: the joint rotated smoothly, all hoops contacted as it turned, and there was no indication of wear or galling along the contacting arcs.

For a 5 MA-sized PCT, the overall geometry of the assembled rotary joint is shown in Figure 6a. Figure 6b shows the assembly of two rotary joints with the transmission line in a PCT system. A first segment of transmission line connects from the PFN below-deck to the first rotary joint through a penetration on the rotation axis of the RailGun turret. A second segment makes two rigid 45° joints to a second rotary joint, aligned on a horizontal axis that passes through the inclination pivot axis of the RailGun. The current is then connected from the second rotary joint to the rails at the breech by an interconnection that does not have to be flexed as the RailGun is aimed in any desired direction.

a) b)

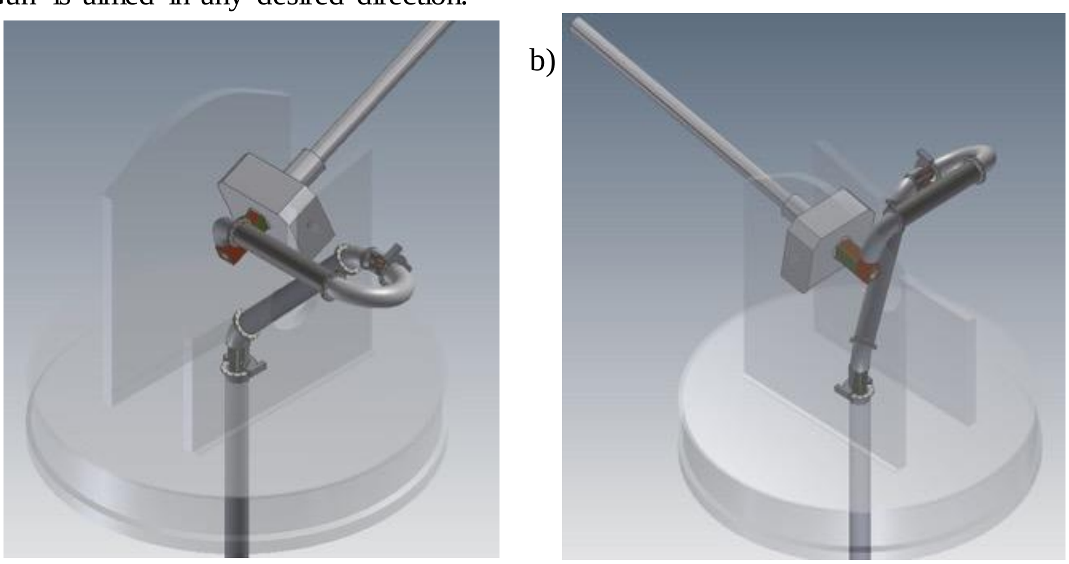


Figure 7. Two example orientations of a RailGun showing the interconnection of the second rotary joint R_h to the breech. The rotary joints accommodate free RailGun motion in any direction.

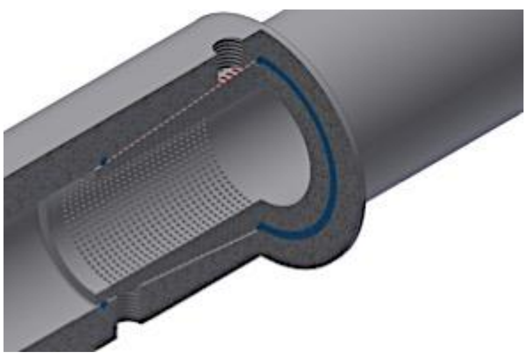


Figure 8. First learning model of hoop-array rotary joint: a) cutaway showing hole array with wire hoops installed; b) video clip showing assembly and rotation of the joint (double-click to view).

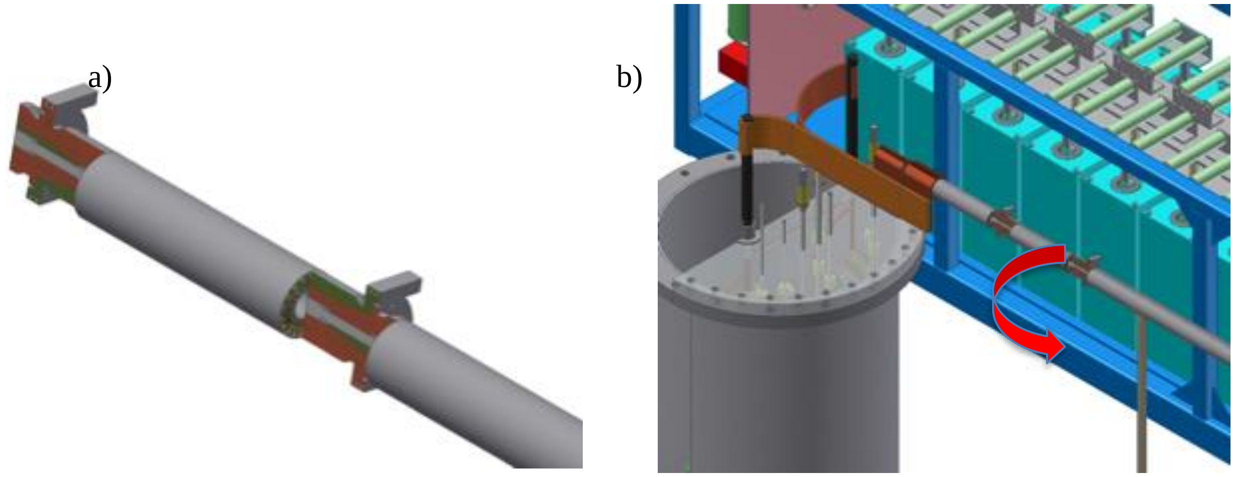


Figure 9. Test configuration of for testing rotary joints: detail showing two rotary joints connecting a 1 m rigid coax line and a 3 m coax line; b) test configuration connected from the parallel 3-PPM current source to a water load. Rotary joint can be rotated as shown.

The 500 kA rigid line and rotary joints will be tested as an assembly. 500 kA of pulse current will be generated by the parallel cluster of PFN modules at IT Arlington, and the far end of the line will be terminated in a water load as shown in Figure 9

Task 3: Develop/test a Superconducting Fault Current Limiter for PCT Network

A pulse-forming network (PFN) is used to generate the multi-MA current pulse to drive the RailGun. It consists of a network of identical pulsed power modules (PPMs) each consisting of a capacitor that is charged from a d.c. source and then discharged through a pulsed switch to deliver a low-impedance current I_{PPM}~50 kA with up to ~5 kV voltage. The outputs of the PPMs are added in an inductive network to deliver a pulsed current of ~5 MA to the rails.

The adding of currents in the present PFN network is done in two stages: a first stage gathers the outputs of ~12 PPMs to form a current pulse of ~600 kA, and a second stage adds the currents from multiple first stages to form the final multi-MA current pulse for the PFN output to the RailGun. It is desirable to provide fault current limiting (FCL) that can prevent damage in the event that a single PPM, or a single first stage, develops a short-circuit fault. Such a FCL must pass the current that normally flows during a pulse, but it must limit the (typically reverse polarity) current that would flow in a fault-short condition.

Superconducting FCLs have been developed over the past decade to serve this function in AC power distribution networks, typically with load parameters of up to ~30 kA and voltage ~150 kV. Estimating the maximum current that could be delivered to a fault-shorting PPM requires analysis of the detailed inductive network used in the PFN, and we are not presently privy to those details. For purposes of an example design we will examine a case when the maximum current is twice the normal PPM current $\sim 2I_{PPM} = 100$ kA.

We have designed a superconducting Fault Current Limiter to passively protect a PPM or consolidation point with little dissipation and no requirement for controls. Its circuit is shown in Figure 10. The FCL unit consists of a cylindrical array of N = 140 REBCO superconducting tapes, each 1.2 cm wide and 2 m long. Each tape is bonded to a copper supporting bar and formed into an elongated U. The U-shaped tapes are bonded to the inside surfaces of two nested

cylindrical shells, with 38 tapes on the smaller-radius shell and 100 tapes on the larger-radius shell, as shown in Figure 10. The source ends of all tapes on each shell are spliced to a common ring, likewise the load ends. The supply rings of the two shells are connected in parallel through a vapor-cooled lead to the source terminal of the FCL assembly, and the load rings of the two shells are connected through a vapor-cooled lead to the load terminal. Each of the cylindrical shells forms a magnetic toroid (so there is no mutual inductance between them), and the two shells have a parallel self-inductance $L_1 \approx 0.2\mu H$.

We propose to use SuperPower SF12-100 REBCO tape [5] in the FCL design. The tape is designed to operate at liquid nitrogen temperature (77 K). Its parameters are well optimized for the characteristics required for fast response and stable pulsed-mode operation. Each tape is rated to carry a current up to its critical current I_c=350 A with near-zero resistance (SuperPower now manufactures an improved version of the same tape with I_c = 450 A).

In normal operation the FCL does not limit the current pulse delivered from the PPM, and very little heat is dissipated in the tiny resistance of the superconducting tapes. But when the current is increased beyond I_c the tape develops a resistive voltage V_r that increases as a steep power law of the current: $V(I) = V_c\left(\frac{I}{I_c}\right)^n$, where n ~30 is the index characterizing the steepness of the resistive transition. This strongly nonlinear response is shown in Figure 10c, and is key to the remarkable performance that is possible with a superconducting fault currently limiter. The parallel network of tapes thus presents a resistance $R_1 = \frac{V(I)}{NI}$ across the terminals. The series circuit H_1-L_1 thus represents the equivalent circuit of the superconducting tape array.

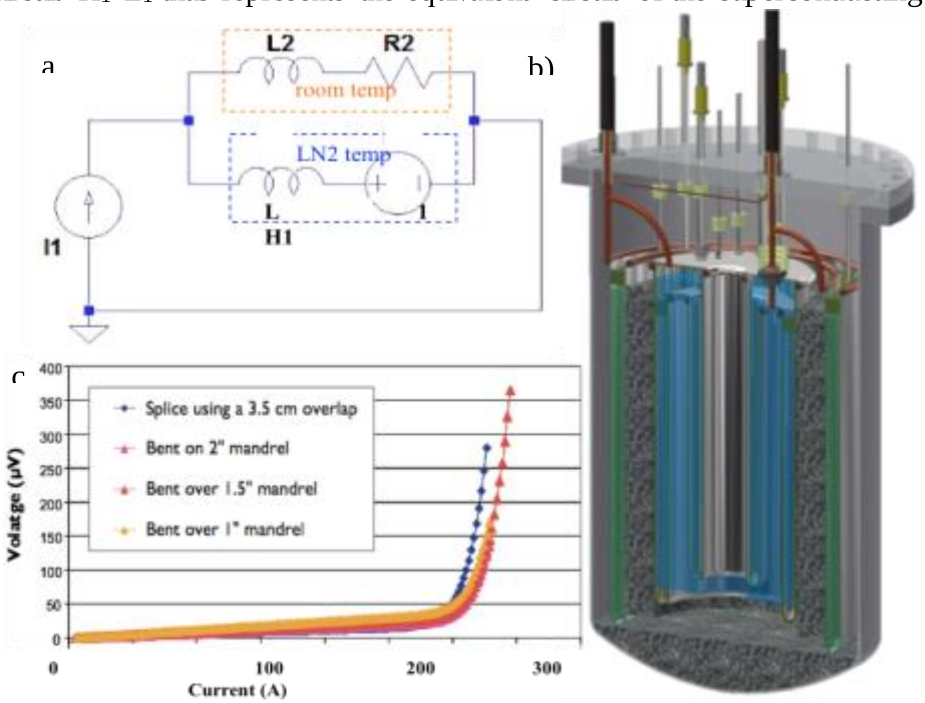


Figure 10. a) Equivalent circuit of a superconducting fault current limiter – the warm and cold circuit elements are indicated; b) isometric cutaway of an FCL capable of protecting a 100 kA source; c) measured I-V response of SuperPower SF12-100 REBCO tape.

Use or disclosure of data contained in this sheet is subject to the restriction on the title page of this proposal.

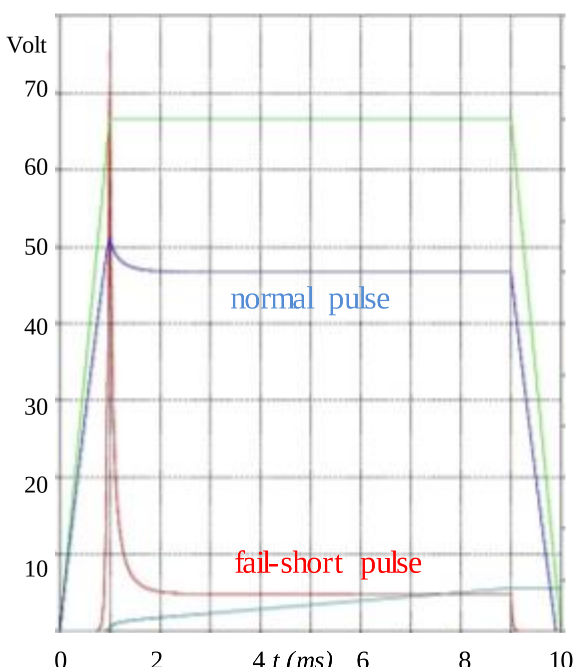
A room-temperature series L_2-R_2 circuit is connected in parallel with the superconducting loop, as shown in Figure 10a. So long as the superconductor has zero resistance, no voltage appears across the room-temperature terminals and so no current flows through L_2-R_2. But in the event that a fault causes a higher current to flow in either direction, the superconducting tapes become resistive, a voltage appears across L_2, and the current i_2 in R_2 increases. The dynamics of the parallel network of the cold H_1-L_1 circuit and the warm R_2-L_2 circuit has been modeled using PSPICE and its thermal response using COMSOL. The value of L_2 is chosen to provide a time constant of ~1 ms so that the FCL can track well with the rise and fall times of the current pulses

Figure 11 shows the response of the FCL circuit to a fault current pulse of 100 kA (assuming normal operation of a PPM gives a pulse current of 50 kA), under two example choices for the room-temperature resistor R_2. The circuit of Figure 10 does not model the time-changing inductive load of the RailGun, nor does it model the action of the spark gap that fires when the armature exits the RailGun.

Figure 12 shows a test configuration in which the 100 kA prototype SFCL will be connected as a load on a single PPM module (or on a parallel of all three modules) at the UT Arlington Pulse Power Lab. Studies will be done to develop a correspondence of the experimental performance and simulation of the SFCL under normal pulse conditions and under overload conditions.

We have simulated the non-linear response of the superconducting tapes, the total heat deposited in the SFCL, and the quantity of liquid nitrogen that is boiled off in two events in the testing:

- A normal 100 kA pulse from a single module dissipates 600 J in the SFCL, and boils 0.02 cc of liquid nitrogen.



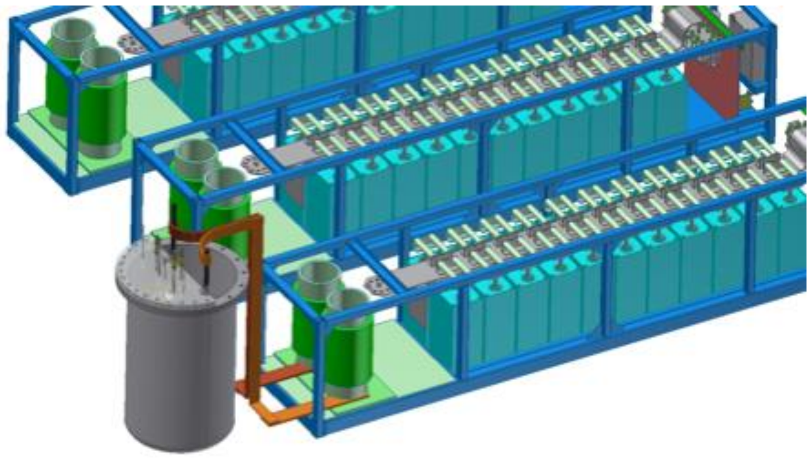
- An overcurrent pulse from the fully charged parallel network of all three modules that would produce 500 kA in an shorted load, would be current-limited to ~150 kA, it would dissipate the full 2.5 MJ stored in the three PPM modules by boiling ~11 liters of liquid nitrogen.

The normal-mode operation is thus a quiet non-event. The failure mode produces a sure flow of cold nitrogen gas that must be vented so that it does not create overpressure conditions. We have experience with such venting using a special Kautzky valve, and with that provision the worst-case situation of a short-failed PPM module would receive only its normal share of energy, and the PFN energy would be dissipated without incident by boiling liquid nitrogen in the SFCL of that module. In other words, our simulation shows that the SFCL would protect the PPMs safely in the PCT of a high-energy RailGun.

Figure 11. Simulations of the response of the fault current limiter to a normal 100 kA pulse, and to a fail-short pulse that would deliver 500 kA and 2.5 MJ into a shorted capacitor without the SCL.

Use or disclosure of data contained in this sheet is subject to the restriction on the title page of this proposal.

These examples illustrate that the FCL design is robust to enable optimization for protection against specific failure-mode scenarios. If our proposed task is funded we will need to obtain a detailed understanding of Navy's overall PFN, RailGun design, and firing dynamics. We will confer with Navy personnel to define failure mode scenarios that they wish to protect. Then we can optimize the FCL design for those requirements.



Error! Reference source not found.a shows an example integration of cryo-insulated tanks in a ship-board RailGun installation, each containing 20 compact 100 kA SFCLs, with each tank configured with each chassis of PMMs in the PFN region below-decks.

Figure 12. Test configuration in which the prototype superconducting FCL is connected as a load across one PPM at UT Arlington.

Task 4: Integrating cryogas coolant flow within the APCT to reduce ohmic losses

Copper has a resistivity that decreases with temperature [6], as shown in Figure 13. We can operate the inner and outer conductor shells of the rigid transmission line at ~80-90 K by flowing the boil-off vapor that is produced in the SFCL through the rigid transmission line. Averaged along the transmission line, the reduced temperature corresponds to a factor 4 reduction in resistance, hence a factor 4 reduction in ohmic heating during each current pulse. Put another way, a PCT can operate with up to 4 times greater rep rate that it could otherwise accommodate.

The liquid nitrogen must be produced in a liquefier that must be staged ship-board. To see how this works, follow the energy that is used to make liquid nitrogen, then to cool the SFCL by boiling it into vapor, then using the vapor to cool the APCT. The heat of vaporization for liquid nitrogen is H_v = 200 J/g – that is the heat that is absorbed from the SFCL in boiling liquid nitrogen into cold vapor at 80 K. As the vapor is transported within the hollow channels of the transmission line, it expands and warms. If the flow is managed to produce an exit temperature of ~120 K at the breech end of the line, the resistance per length r_e along the line varies from ~1/5 of its value r_{e0} at room temperature at the PFN end to ~1/3 r_{e0} at the breech end, corresponding to an average value r_e/r_{e0} = 1/4. The amount of heat that is that is absorbed in increasing the vapor temperature from 80 K to 120 K by the flowing nitrogen vapor.

The overall energetics must take into account the energy consumed by the refrigerator to liquify nitrogen from room-temperature air. The ideal Carnot efficiency is $\epsilon = \frac{80}{300-80} = 1/3$. A modern nitrogen refrigerator [7] can operate with overall efficiency ~1/4, so the 4x reduction of ohmic heating is roughly offset by the 4x increase in the energy to remove the heat.

The liquefier is a separate system that does not complicate the integration of current transport in the PCT. It is needed in any case to refrigerate the SFCL array, and to remove the modest amount of heat that is dissipated in its insertion loss during normal pulse operation. Operation with cooled APCT thus improves the rep rate capability with no energy/shot penalty. Indeed the cold gas can be routed into the barrel to reduce the resistance of the rails and to provide an inert atmosphere that suppresses oxidation of surfaces and of aluminum mist during each shot.

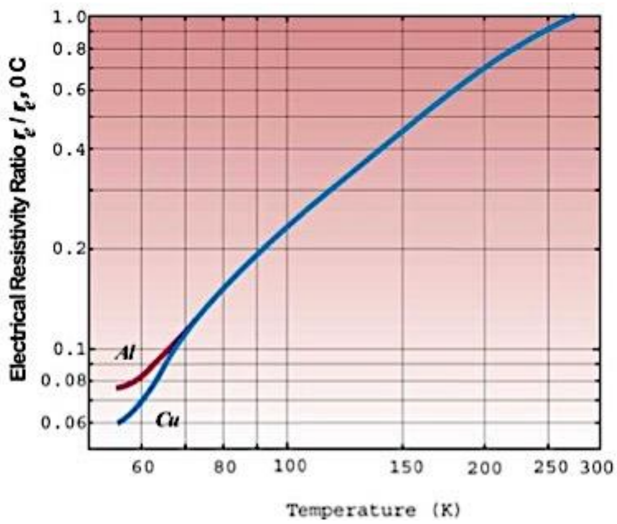


Figure 13. Resistance ratio of copper, compared to its value at room temperature.

Task 5: Integrated design and simulation of 5 MA APCT and SFCL on a RailGun system

The prototype APCT that will be developed in Tasks 1-4 is designed to operate with the 500 kA current pulse that can be generated at the UT Arlington Pulse Power Lab. When the APCT design is matured through Tasks 1-2, we will develop a design for a full-scale 5 MA APCT system, likely similar to the conceptual design shown in Figure 7.

The APCT is designed to be configured to accommodate 360° rotation of the turret and 0-90° elevation of the barrel, as shown in Figure 7. The configuration shown uses a vertical segment of rigid line, a rotary joint, a 45° bend and short rigid segment, a second bend, and a 180° bend to connect from the PFN below-deck to the RailGun breech. The vertical line must penetrate the deck through the rotation axis of the turret and the diagonal segment must pass through the turret truss as shown.

When the APCT design is matured through Tasks 1-4, we will develop a design for the above configuration that conforms to the current Navy design for the turret of the RailGun on which APCT is to be integrated.

The inner and outer conductor layers of the transmission line must be connected to the two rails of the RailGun in the breech assembly. We have developed conceptual designs for the interconnect using two approaches, a multi-cable interconnect to a pair of copper plates similar to present breech assemblies, and a conformal interconnect in which the array of Litz cables within the inner and outer conductors are gathered to a planar configuration that bonds to each breech plate. We will evaluate those options with Navy personnel and develop an optimal design for integration with the Navy RailGun.

The superconducting FCL provides best protection of the PPMs of the PFN if FCLs are integrated at the PPM level in the PFN configuration, as illustrated in **Error! Reference source not found.**. Each PPM connects to an FCL, the FCLs for all PPMs along one side of a chassis are housed in a common thermally insulated cryostat, the outputs are ganged on a copper bus that runs within the cryostat, and the pulse current busses are in turn ganged at a summing junction that connects to the single rigid transmission line that carries the pulse above-deck to the breech. We will confer with Navy to optimize the configuration of the FCL cryostat to integrate with the PFNs that will be used on the RailGun.

We will develop a simulation of current transport, heat transport, forces and energy delivered to barrel and projectile for the APCT – SFCL system integrated with a specified Navy RailGun. Simulate normal firing of a projectile and failure modes.

Comparison of the proposed approach to present approaches

Single rigid coax transmission line compared to cable clusters

No array of semi-flexible cables can support rotation of the RailGun to aim in any desired direction. By carrying the entire pulse current through a single rigid transmission line, and inserting two rotary joints connecting segments of the line to support *complete freedom of rotation of the turret and inclination of the barrel* as shown in Figure 7.

Rotary coax joint compared to flexing cable clusters

No PCT that does not have rotary joints can support rotation of the RailGun to aim in any desired direction. The two rotary joints and rigid transmission line provide the same benefits for a RailGun that a pitcher's arm does for a baseball player: the RailGun can be rotated in 3-D by appropriate rotation of the two rotary joints.

Superconducting fault current limiter compared to fuse protection of PFNs

The energy stored in the capacitors of each PPM is sufficient to explode a single capacitor in the event that a single capacitor develops a short-circuit failure. Present PCT systems use fuses to limit surge current in such failure modes. Some PCTs rely upon the open state of the fast switch on each PPM to prevent reverse current surge through a short-failed capacitor. Fuses require manual replacement before another pulse could be fired. Fast switches can fail short.

Cryo-cooling APCT compared to operation at ambient temperature

The ohmic heat deposited by each pulse in the APCT is ~half that deposited in a cluster of coax cables with the same copper cross-section (because of the improved conductance of its Litz-based design). The ohmic heat is further reduced by another factor of ~4 by flowing boil-off nitrogen gas through the channels of the transmission line. Both improvements translate directly into sustainable rep rate for firing the RailGun.

MANAGEMENT, SCHEDULE, AND RESOURCES

Technical baseline from which BATS will undertake the proposed effort

Bailey Tool & Manufacturing

BTM has 20 years experience in manufacturing components for the automobile industry, and has extensive experience in precision machining, metal stamping and forming operations, and complex assemblies. Over the past six years *John Buttles* has led BTM in undertaking a number of challenging jobs in very different applications: fabrication of cowlings and cooling assemblies for rocket engine cowlings for Space-X; fabrication of die-stamping components and complex support structures for advanced superconducting magnets for the TAMU group (DOE accelerator R&D); and development of an advanced bullet-manufacturing system that forms the casings for Army bullets to exacting specifications. In all of these tasks BTM has succeeded in providing quality parts and assemblies, on-time and on-budget, and also in working clients to find optimum designs to meet their challenges. This last task (the bullet-manufacturing system, under contract for ARDEC) met its performance tests in operation at BTM and has now been installed at ARDEC and commissioned for their operations.

Challenge (Task 1): How to compactify each of the inner-conductor and outer-conductor subassemblies of the rigid transmission line to immobilize the sub-cables?

BTM will develop the methods for compression-bonding the metal sheath tube of each of the inner- and outer-conductor subassemblies of the rigid transmission line. This is necessary to immobilize the sub-cables within each subassembly so that, during a current pulse, the Lorentz forces cannot cause fatigue or abrasion of sub-cables within the sheathed aperture, and also to provide good heat transport from each sub-cable to the cooling fluid flow in the flanking regions of the transmission line. BTM will evaluate two options for this purpose: hydroforming the metal sheath to compress it against the sub-cables, and drawing the metal sheath to preload it against the metal cables. In each case the deformation must expand the inner sheath within the inner-conductor subassembly, and compress the outer sheath of the outer-conductor subassembly.

BTM will also take lead in developing the manufacturing plan for extending what is learned in building and testing the 500 kA prototype APCT transmission line into a manufacturable 5 MA APCT transmission line.

Texas A&M University – Accelerator Research Lab

The Accelerator Research Lab (ARL) at TAMU has a 20-year track record of innovation and successful fabrication and testing of high-field superconducting magnets, superconducting rf cavities, and practical applications of superconductivity for MRI and MR spectroscopy in biomedicine, superconducting energy storage for the utility industry, and advanced materials for ultra-high-stress structures.

The ARL team pioneered stress management in high-field superconducting magnets, where the immense Lorentz stress in ~16 Tesla dipoles reaches stress levels of 200 MPa. The structure must support fragile superconducting windings and prevent deflections of the winding positions that would initiate a quench to the normal state in the superconductor. The ARL team pioneered the methods and showed they work, and they are now applying those for a new generation of magnets for ultimate-energy hadron colliders. Their skills with advanced materials and with stress management strategies will be on-target for the requirements of the tasks in the project.

Peter McIntyre leads the TAMU team and is an internationally respected leader in magnet technology and accelerator physics. He was the first to propose proton-antiproton colliding beams in Fermilab's Tevatron, which became the basis for two generations of high-energy physics discovery. He built the first whole-body 4 Tesla MRI system for brain imaging, and the first self-shielded MR spectroscopy system for resolving the structure of proteins.

Tim Elliott and *Ray Garrison* are senior technicians with 10 years experience in building complex magnetic systems and making them work. *Jeff Breitschopf* is a graduate student who plans to undertake aspects of RailGun technology development as his dissertation project.

Challenge (Task 2): How to fabricate a hoop-array rotary joint that intrinsically enforces equal distribution of MA pulse current among ~10^4 hoop contacts?

In a rotary joint containing an array of many hoop contacts, as one rotates the joint some contacts will likely make or break from one position to the next, or exhibit somewhat higher or lower contact resistance. We expect to be able to use to advantage the mutual inductance of each sub-circuit (through each hoop contact) to intrinsically re-inforce current sharing among the hoop contacts: if any one hoop contact had an anomalously large current share, that larger current would induce an inductive voltage that would tend to force part of the current through neighboring hoop contacts. The ARL team plan to develop both experiments and simulations to understand that mechanism and use it to advantage.

Challenge (Task 2): How to lubricate a hoop-array rotary joint to both minimize wear from sliding contact and uniformity of contact resistance?

The space between the inner tapered stem, on which the hoop array is anchored, and the mating outer tapered stem that forms the surface on which the array slides, must support that actual sliding boundary at which rotation occurs and the pulse current must pass through the hoop-surface contacts. We plan to fill that space with a conductive graphite powder that is heavily loaded with conductive nanopowder [8]. The graphite/copper compound will lubricate the sliding motion and also provide volumetric electrical conductivity that supports the hoop-surface contacts to assure low-resistance current transfer in the rotating joint.

UT Arlington – Pulsed Power and Energy Lab

The University of Texas at Arlington is a leading research institution located in Arlington, Texas. The PPEL was established in 2010 and since that time has executed a number of funded research grants from the US Office of Naval Research (ONR), Air Force Research Laboratories (AFRL) Kirtland, as well as other private industrial organizations. *David Wetz*, the PPEL PI, has over thirteen years of experience in the fields of pulsed power, electromagnetic launch, electrochemical energy storage, and microgrids. Since 2006, Dr. Wetz has been actively involved with the US ONR EMRG program and has performed research in the prime power, pulsed power, and launcher areas of the program. He the only member of the team with experience in all three areas. In 2015, NSWC Dahlgren donated three 1.1 MJ capacitor modules to UTA's PPEL. Those will be leveraged in the effort proposed here. Dr. Wetz and his students will provide consulting to the BATS team on the areas of high-pulsed current transfer (PCT) and will act as the facilitators of test and evaluation of the novel PCT technologies proposed here. With the funds proposed, UTA PPEL will hire a dedicated PhD level student to support the ongoing efforts and Dr. Wetz will take the lead on execution of all proposed tests of APCT components.

Accelerator Technology Corp.

ATC is a College Station-based company with expertise in the superconducting technology that will be used in Task 4. ATC plans to develop a product line of superconducting FCLs for Navy requirements and for applications in grid stabilization and security.

Akhdiyor Sattarov is an accomplished calculational physicist, who makes all forms of multi-physics design and simulation for all of the projects that the BATS collaboration undertakes. Recently he developed the magnetic design for a compact open-MRI system for breast imaging to support well-patient screening for breast cancer. He has performed the dynamics simulations for armature acceleration and sabot levitation scenarios for RailGuns, and will perform a host of design simulations for the APCT and the superconducting FCL.

Josh Kellams is a superconducting materials technologist, who has developed new wire fabrication for high-performance Bi-2212/Ag wire. He will lead the development of the REBCO tape subassembly for the superconducting FCL (Task 3). Josh will also develop the method for cabling the Litz cables around the center tube to fabricate the inner and outer conductor shells for the rigid transmission line (Task 1).

Challenge (Task 3): How to connect the rigid transmission line to the superconducting current leads of the SFCL?

The transition from the rigid transmission line to the superconducting FCL is a particularly challenging combination of heat transfer and current transfer. Dr. Sattarov has designed a proprietary transition section that can accomplishes that transition with acceptable nitrogen boil-off rate and supports both routine normal pulse operation with low insertion loss and high-insertion-loss operation during an over-current event in which the FCL limits current. The transition can operate with the rigid transmission line operating at room-temperature, or in a mode in which the boil-off nitrogen cryo-gas (80 K) is channeled to flow through the inner and outer channels within the rigid coax cable and rotating joints so that they operate in the temperature range 80-150 K and provide a x5 reduction in heat loss in the PCT system (Task 4).

Sensor Systems LLC

Sensor Systems was formed in 2000 to develop methods for indirect detection and characterization of fractures and voids in well pipe and fittings for the oil/gas industry. They are widely respected in the instrumentation that they have developed for that purpose, and they install and support that instrumentation in the operations of a number of major energy companies.

John Zeigler is an electrical engineer with 30 years experience in high-current systems, complex control systems, and experimental testing to measure properties of systems under extremes of conditions. He was the lead engineer in the successful development of a 200 kA superconducting transformer to test high-current cable for superconducting magnetic energy storage. He designed the test instrumentation for complex tests to failure of high-pressure cryogenic rupture disks for the superconducting magnet system of AMS, a large particle spectrometer that was flown to the International Space Station on the Shuttle. Sensor Systems has worked with the TAMU group on those and related projects. Mr. Zeigler will lead the design of the electrical system and controls for the superconducting FCL.

Summary of participants, roles, relative effort

Team Participant	Role and Key Contribution	PI	FTE Effort
Bailey Tool & Mfg.	Contractor, integration, program mgt	John Buttles	17%
Texas A&M Univ.	innovator of APCT technology	Peter McIntyre	39%
UT Arlington PPEL	testing prototype system	David Betz	17%
ATC	Superconducting system design FCL	Dior Sattarov	20%
Sensor Systems, LLC	high-current system design	John Zeigler	7%
			100%

Plans for implementation of results from the proposed effort

The ultimate implementation of the proposed effort is for a ship-board RailGun with the operational capabilities specified by Navy: 5 MA pulse current, 32 MJ pulse energy, 10 shots/minute sustained rep rate, free to train and elevate in any direction pulse-pulse.

Pending the results of the proposed effort, we would envision proposing a follow-on effort to develop a full-scale APCT system, with superconducting FCL integrated at the module level to protect the PFNs in the event of a fail-to-short failure of one PPM. Task 5 would indeed provide the foundation for that proposed follow-on effort.

Pending authorization to proceed with a scale-up to full operational specifications, we would envisage also proposing development of the elements of the PFN, the breech system, the fast loader, and the turret to develop a next-level integration of the APCT with those systems to maximum benefit for the performance, cost, and reliability of a Navy RailGun.

Potential end item applications for BATS' new technologies

Superconducting FCL

The 100 kA fault current limiter has been for 20 years a focus of development for protection of the ~50-100 MW switchyards in grid distribution. The design presented here, for which we have filed patent application, has the potential to become cost-effective for that use. The 'shot-in-the-arm' from development for protecting RailGun PFNs will enable us to design it so that it has best chance to meet the aggressive cost targets for the grid application.

Intellectual property assertions

The hoop-array MA-capable rotary joint is the subject of a patent application by Texas A&M University.

The toroidal configuration of REBCO tape-conductors in the SFCL is the subject of a patent application by Texas A&M University.

The coaxial flow of boil-off nitrogen gas through the transmission line is the subject of a patent application by Texas A&M University.

Performance Improvement Metrics

Metric	'As-Is' Baseline	Initiative Goal
Rotation of turret constrained by PCT configuration	0-10°	0-360°
Rotation of barrel elevation constrained by PCT	0-10°	0-90°
Heat dissipated in PCT by one 32 MJ shot	400 kJ	100 kJ
Maximum energy dissipated in 1 short-failed capacitor	32 MJ	200 kJ

RISK ANALYSIS

The risks in the project are technical risk (can we meet the technical goals of the major can we meet the schedules defined below for each task?); schedule risk (can we complete the tasks on the schedule stipulated in the following section?); and cost risk (is the budget for labor and materials sufficient to complete the tasks?).

Technical risk

Task 1: The capability of the prototype transmission line to carry 500 kA with a capability for 10 pulses/minute was determined by simulations that model the electromagnetics of the cylindrical assembly of Litz cables on each of the coax conducting shells. Current transfer at the ends of the transmission line requires that the outer edge of each Litz sub-cable be stripped of its insulation and soldered to the inner metal shell form over a transposition length at each end. We have practiced this on free Litz cables, but completing it in the actual cable will require development.

Task 2: We will be evaluating the two methods of fabricating the hoop arrays, and fabricating first small-scale learning models to measure the effective contact resistance and the limit on pulse current transfer per hoop. The results may require re-sizing the hoop array if the preliminary measurements are not confirmed in that study.

Task 3: It is tricky to fabricate a mechanically robust warm/cold transition that brings the 500 kA pulse from a room-temperature copper flag to the ring electrodes on which all 180 superconducting tapes are bonded. Also we will integrate a Kautzky vale and ~4' diameter relieve line to vent nitrogen vapor in the event of a fail-short fault current.

Schedule risk

The schedule of each task was estimated on the assumption that all tasks are funded. There are a number of predecessor links among the schedules, so that if some tasks were not funded there would be impact upon the cost and schedule of other tasks. Should Navy opt to fund some but not all tasks, we would need to re-examine cost and schedule for the funded tasks to determine whether there were impact from the absence of other tasks.

Cost risk

We have costed most of the materials and contract fabrication processes that are required. The cost uncertainties are primarily associated with the time required for project personnel to do the proposed tasks. We allowed a contingency that is based upon our prior experience.

SCHEDULE

The five tasks of the proposed effort can be undertaken in series, parallel, or isolation according to available funding and Navy interest.

Task 1. Develop/Test 500 kA Transmission Line	Q1	Q2	Q3	Q4	Q5	Q6
1.1 Develop cylindrical array of Litz cables.						
1.2 Fabricate 1 m segment of transmission line.						
1.3 Build 3 m prototype 500 kA transmission line.						
1.4 Test 3 m prototype 500 kA transmission line.						

Task 2. Develop/test a 500 kA rotary joint for the coaxial transmission line	Q1	Q2	Q3	Q4	Q5	Q6
2.1 Develop/test fabrication of planar hoop arrays.						
2.2 Fabricate conical joint assembly.						
2.3 Build prototype rotary joint, mechanical tests.						
2.4 Integrate joint on short transmission line						
2.5 Test rotary joints on transmission line.						

Task 3. 100 kA Superconducting FLC	Q1	Q2	Q3	Q4	Q5	Q6
3.1 Design subassemblies, simulate dynamics.						
3.2 Build FCL prototype assembly.						
3.3 Test prototype superconducting FCL.						
3.4 Modify FCL using results from tests, re-test.						
3.5 Test transmission line at Building 152						

Task 4. Operate APCT and SFCL with flow of boil-off nitrogen gas through the transmission line.	Q1	Q2	Q3	Q4	Q5	Q6
4.1 Connect cryo-gas flow through transmission line.						
4.2 Test transmission line with cryo-gas cooling.						

Task 5. Integrated design and simulation of 5 MA APCT and SFCL on a RailGun system	Q1	Q2	Q3	Q4	Q5	Q6
5.1 Develop suitably scaled design for 5 MA APCT.						
5.2 Integrate APCT with RailGun turret.						
5.3 Integrate APCT with RailGun breech.						
5.4 Integrate SFCL with the PFN network.						
5.5 Simulate PFN–SFCL–APCT – RailGun system						

Project Personnel and Facilities

The proposed effort requires a spectrum of skills, experience, and facilities that span from electrodynamics to superconductivity to advanced materials synthesis. The BTM team contains an excellent pool of talent and experience for those challenges. The facilities and key personnel are described in detail on pages 24-26.

COST REALISM

Cost Element	Total Proposed Cost	Description/Explanation
Labor	$1,502,324	Labor contains Contractor and Subcontractor labor hours, including University Grad & Undergrad students
Labor Hours	47,739	
Subcontractors	$3,394,531	Texas A&M - $1,597,316 Sensor Systems - $276,500 ATC - $819,200 UT Arlington - $701,515
Subcontractors Hours	36,197	
Consultants	$120,000	
Consultants Hours	480	
Material/Equipment	$463,500	
Other Direct Costs	$282,000	
Travel	$115,000	
Indirect costs	$1,178,522	approved by DCAA 30 Sept 15
Total Cost	$4,098,637	cable, superconductor, consumables, PFN hardware, water loads
Fee	$ 0.00	Contained in rates
Total Cost Plus Fee	$4,098,637	5 Tasks were costed separately – if Government were to proceed with multiple tasks, many cost categories would fall in value due to redundancy
Cost Share **(if cost share is proposed then fee is un allowable)**	0	
Total Initiative Cost	$4,098,637	

APPENDIX A: RESUMES OF KEY PERSONNEL

John Buttles Resume
4543 Fairway Ave.
Dallas, TX 75219
jbuttles@baileytool.com
214 686 8919 cell

Education

Graduated Rumson/Fair Haven Regional High School 1970

Graduated BFA Rochester Institute of Tech 1974

Graduated MS Illinois State University 1976 – degree completed in Dallas, TX at UT North Dallas in 1978

OBJECTIVE: Develop Bailey Tool's market opportunities to commercialize IP development and transition of legacy manufacturing skill sets into new industries where great value and benefit to Customers and Employees can be achieved.

Work Experience

Hunt Hinges, Dallas, TX
President February, 1989 - present

- Purchased failing small business and successfully grew and expanded into national supplier of technical hinges for a variety of commercial and industrial applications
- Grew companies production capabilities to match

Bailey Tool & Mfg. Co., Dallas, TX
President January 1993 to present

- Purchased failing small business and built company revenues from $700,000 in 1992 to $17 million before Global Financial Crisis affected company future prospects
- Introduced automotive industry stamping capabilities to Bailey Tool and grew stamping revenues with national and international accounts
- Participated in North American Deep Drawing Stamping Group executive committee; brought automotive industry stamping science to Bailey Tool
- Significantly innovated stamping and material processes to bring value to Customer products
- Grew internal Intellectual Property development capability and transitioned company from serial production business model to R&D and development model
- Pioneered Defense Dept. contracting and Dept. of Energy development work developing products of critical value to various Government customers
- Initiated partnering with University educational systems to broaden R&D and development potential for the business

3380 UNIVERSITY DR. EAST, MAGNET LAB, COLLEGE STATION, TX 77845
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PETER M. McINTYRE

PROFESSIONAL PREPARATION

University of Chicago	A.B. Honors	Physics	1967
University of Chicago	M.S	Physics	1968
University of Chicago	Ph.D.	Physics	1972

APPOINTMENTS

Professor	Texas A&M University	1981 – Present
President	Accelerator Technology Corporation	1988 – Present
Group Leader	Fermilab	1979 – 1980
Assistant Professor	Harvard University	1975 - 1979
Visiting Scientist	CERN	1974 -1975

SELECTED PEER-REVIEWED PUBLICATIONS (802 TO DATE)

Progress on the design of the polarized Medium-energy Electron Ion Collider at JLab. (with F. Lin *et al.*), IPAC2015, Richmond, May 5, 2015.

Status of the MEIC ion collider ring design. (with Y. Cai *et al.*), *ibid*.

Magnet design and synchrotron damping considerations for a 100 TeV hadron collider. (with S. Assadi *et al.*), *ibid*.

Textured-powder Bi-2212/Ag wire technology development. (with J.N. Kellams *et al.*), *ibid*.

High field open MRI for breast cancer screening. (with A. Sattarov and L. Motowidlo), Proc. Appl. Superconductivity Conf., Charleston, Aug. 5, 2014.

Superconducting sector dipole for a strong-focusing cyclotron. (J. Kellams *et al.*), *ibid*.

Large-circumference, low-field optimization of a Future Circular Collider. (with S. Assadi *et al.*), Workshop on a Future Circular Collider, Geneva, Feb. 12-15, 2014.

Construction challenges and solutions in TAMU3, a 14 T stress-managed Nb_3Sn dipole. (with E. Holik *et al.*), Proc. Int'l. Conf. on Cryogenic Mater. (CEC-ICMC), Anchorage, June 17-21, 2013.

Nonlinear beam dynamics studies of high-intensity, high-brightness proton drivers. (with S. Assadi and K. Melconian), Proc. NAPAC'13 Particle Accel. Conf., Pasadena, Sept. 2013.

Accelerator-driven subcritical fission to destroy transuranics in spent nuclear fuel and close the nuclear fuel cycle. (with S. Assadi *et al.), ibid*

SELECTED PATENTS (15 TO DATE)

2014:	Nano-Ag-enhanced textured-powder Bi-2212 superconducting wire technology
2014:	Quench protected structured superconducting cable
2014:	High field open MRI magnet: design methodology and method of construction
2013: 8,592,346 B2	Textured powder wires
2013:_WO0051508	Accelerator-driven transmutation fission, method for excitation and control

2006: 7,746,192: Polyhedral contoured microwave cavities

2002: 6,448,501: Armored spring-core superconducting cable and method of construction

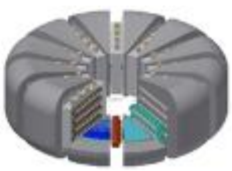
1999: 6,002,316: Superconducting coil, method of stress management in a superconducting coil

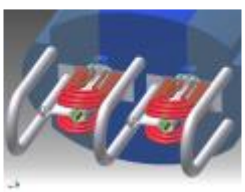
1999: 5,994,901: Magnetic resonance logging instrument

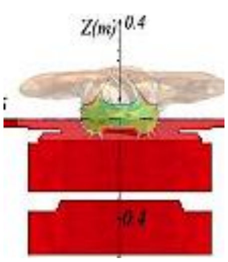
1997: 5,659,281: Structured coil electromagnets for magnetic resonance imaging

1994: 5,374,913: Twin-bore flux pipe dipole magnet

SYNERGISTIC ACTIVITES







- **ADS fission to destroy transuranics in spent nuclear fuel (ADAM) –** Utilizes the SFC to destroy the highly toxic, long-lived transuranic elements in spent nuclear fuel. Accelerator Driven Subcritical (ADS) fission can destroy the transuranics at the same rate that a conventional GW_e power plant produces them, and produces 350 MW of additional electric power.
- **MRI** – A new methodology for superconducting magnet design has been used to design a compact 1.5 T open-geometry MR breast imager, which will provide cost-effective MRI screening for early detection of breast cancer.
- **100 TeV hadron collider for the next generation of high energy physics** – A superconducting C-geometry superconducting dipole utilizing a superconducting cable-in-conduit is the heart of a minimum-cost method to make hadron collisions at 100 TeV collision energy to discover new gauge fields beyond the Higgs Boson.
- **Nano-Ag-enhanced textured-powder Bi-2212 superconducting wire** Bi-2212 is the only high-temperature superconductor that can be fabricated in round wire. A nano-Ag-enhanced textured powder process has been developed that provides greater current capacity and mechanical strength for use in high-field superconducting magnets.
- **Advisor** to 8 Ph.D. graduate students and 3 undergraduate Honors students, and mentor to 4 postdoctoral scientists.
- **Teaching and outreach -** Member of APS, AAAS, IEEE, and ANS. Reviewer for DOE, NSF, 3 journals and 4 conferences. Volunteer at the Physics Department's "Physics Day" twice a year where over 4000 children and adults come to see demonstrations. Lectures on recent physics discoveries for the public.

COLLABORATORS & OTHER AFFILIATIONS

Collaborators - My collaborators include Lesh Motowidlo (Supramagnetics) and Michael Tomsik (Hypertech) on superconducting wire technology; Charles Reese (JLab) on superconducting cavity technology; Pavel Tsvetkov (Texas A&M), Michael Simpson (Univ. of Utah), and Supathorn Phongikaroon (VCU) on ADS fission in a molten salt core; and Gijs de Rijk (CERN) on high-field dipole development.

Graduate Advisors and Postdoctoral Sponsors - Val Telegdi (graduate) and Carlo Rubbia (post doctoral)

Graduate Advisees and Postdoctoral Mentor- K Damborsky (Oxford Superconducting Technology), H Demroff (Lockheed Martin), E Holik (Angelo State Univ.), A Nassiri (JLab), P Noyes (NHMFL), N Pogue (PSI), D Raparia (BNL), R Soika (Nexans), E Sooby (Los Alamos), C Swenson (LBNL).

Akhdiyor Israilovich Sattarov

EDUCATION

1998 Ph.D. in Physics and Mathematics, Institute of Nuclear Physics, Tashkent, Uzbekistan
1987 M.S in Applied Mathematics and Computer Programming, St. Petersburg State University

PROFESSIONAL EXPERIENCE

8/2016-present Scientist, Accelerator Technology Corp., College Station, TX

2011-2016 **Senior** Research Scientist, Texas A&M University

2002 – May 2011 Associate Research Scientist, Texas A&M University

Spring 1999, Fall 2003, Spring/Summer 2004, Spring 2008, Spring 2010, Fall 2010

Visiting Associate Professor of Physics, Texas A&M University

1998 – 2002 Postdoctoral Research Associate, Texas A&M University

1993-1997 Research Scientist, Institute for Nuclear Physics, Academy of Science Uzbekistan

Fall 1992, March 1994, Spring 1996, Summer 1997

Visiting Research Scientist, Institut für Physik, Universitaat Mainz

RECENT PUBLICATIONS

1. S. Assadi *et al*., 'Nonlinear beam dynamics studies of the next-generation strong-focusing cyclotrons as compact high-brightness, low-emittance drivers', Proc. IPAC2015, Richmond, May 3, 2015.
2. S. Assadi *et al*., 'Fixed-energy cooling and stacking for an electron-ion collider', *ibid*.
3. K. Damborsky *et al*., 'Textured-powder Bi-2212/Ag wire technology development', *ibid*.
4. S. Assadi *et al*., 'Magnet design and synchrotron radiation considerations for a 100 TeV hadron collider', *ibid*.
5. Y. Cai *et al*., 'Status of the MEIC Ion Collider ring design', *ibid*.
6. A. Sattarov, L. Motowidlo, and P. McIntyre, 'High field open MRI for breast cancer screening', Proc. Appl. Superconductivity Conf., Charleston, Aug. 5, 2014.
7. N. Pogue *et al*., 'First results of the SRF wafer test cavity for the characterization of superconductors', *ibid*.
8. K. Melconian *et al*., 'Design of a MgB_2 beam transport channel for a strong-focusing cyclotron, IEEE Trans. Appl. Superconductivity **24**, 3, 4601404 (2014).
9. K. Melconian *et al*., 'Design and development of a MgB_2-based sector dipole and beam transport channel for a strong-focusing cyclotron', Adv. in Cryo. Eng. **1573**, 739 (2014).
10. S. Assadi *et al*., 'Large-circumference, low-field optimization of a Future Circular Collider', Workshop on a Future Circular Collider, Geneva, Feb. 12-15, 2014.
11. S. Assadi, P. McIntyre, and K. Melconian, 'Nonlinear beam dynamics studies of high-intensity, high-brightness proton drivers', Proc. NAPAC'13 Particle Accel. Conf., Pasadena, Sept. 2013.
12. S. Assadi *et al*., Accelerator-driven subcritical fission to destroy transuranics in spent nuclear fuel and close the nuclear fuel cycle, *ibid.*
13. E. Holik *et al*., Construction challenges and solutions in TAMU3, a 14 T stress-managed Nb_3Sn dipole', Proc. Int'l. Conf. on Cryogenic Mater. (CEC-ICMC), Anchorage, June 17-21, 2013.
14. S. Assadi *et al*., 'Strong-focusing cyclotron for high-current applications', AIP Conference Proc. 1525, 226-229 (2013).

SYNERGISTIC ACTIVITIES

Developed a new algorithmic method for optimization of the magnetics for compact open-MRI magnets.

Supervised ~2 graduate students/year for the past decade, instructing them in large-code computer simulations of magnetic fields, accelerator dynamics, heat transfer, stress/strain, and other properties important to ARL's research.

Detailed design and simulation of magnetic fields in many field geometries, including high-field dipoles and quadrupoles, solenoids for MR imaging and spectroscopy, and magnetic energy storage.

Finite-element simulation of mechanical stress in superconducting accelerator magnets.

Quench simulations for superconducting magnets.

Developed a particle-in-cell tracking code for nonsymmetrical magnetic fields in circular accelerators, used in the design and simulation of performance for the strong-focusing cyclotron.

Neutronics calculations for an accelerator driven subcritical system using MCNPX, MonteBurns, Origen2, and Scale codes

Electromagnetic design of a superconducting polyhedral cavity and a dielectric loaded superconducting test cavity for linac colliders.

Heat transfer modeling and design simulations for the heat exchanger in a molten salt subcritical fission core.

David Wetz

Associate Professor
Department of Electrical Engineering
University of Texas at Arlington, Arlington, TX
Ph: 817-272-1058; Email: wetz@uta.edu; Web: www.uta.edu/ee/powerlab

a. Professional Preparation

Texas Tech University, Lubbock, Texas	Electrical Engineering	B.Sc., 2003
Texas Tech University, Lubbock, Texas	Computer Science	B.Sc., 2003
Texas Tech University, Lubbock, Texas	Electrical Engineering	M.Sc., 2004
Texas Tech University, Lubbock, Texas	Electrical Engineering	Ph.D., 2006
University of Texas at Austin, Austin, Texas	EM Launchers	Postdoctoral, 2006-20

b. Appointments

Sept 2015 - Present	Associate Professor, Electrical Engineering Department, University of Texas at Arlington, Arlington, Texas
May 2012 – Present	Research Physicist, Sotera Defense Solutions, Virginia Beach, Virginia (Consultant for the Plasma Physics Division of the US Naval Research Laboratories (NRL)).
February 2016 – Present	Pulsed Power and Energy Storage Consultant, McKean Defense, Philadelphia, PA.
Aug 2010 – Sept 2015	Assistant Professor, Electrical Engineering Department, University of Texas at Arlington, Arlington, Texas
June 2015 – Aug 2015	Office of Naval Research (ONR) Senior Faculty Summer Fellow, Naval Surface Warfare Center, Carderock Division-Ship Systems Engineering Station in (NSWC CD-SSES), Philadelphia, Pennsylvania
May 2014 – Aug 2014	Office of Naval Research (ONR) Faculty Summer Fellow, Naval Surface Warfare Center, Carderock Division-Ship Systems Engineering Station in (NSWC CD-SSES), Philadelphia, Pennsylvania
May 2007 - Aug 2010	Research Associate, Institute for Advanced Technology at the University of Texas at Austin, Austin, Texas

c. Selected Publications:

(i) Closely Related Papers

1. D.A. Wetz, F. Stefani, J.V. Parker and I.R. McNab, 'Advancements in the Development of a Plasma-Driven Electromagnetic Launcher,' IEEE Transactions on Magnetics, Vol. 45, No. 1, Part 2, pp. 495-500, January, 2009.
2. D.A. Wetz, I.R. McNab, F. Stefani, and J.V. Parker, 'Electromagnetic Launch to Space,' Acta Physica Polonica A, Vol. 115 No. 6, June, 2009.
3. D.A. Wetz, T. Watt, D. Surls, and M.T. Crawford, 'Investigation into the Behavior of Armature Ejecta in Electromagnetic Launchers,' *IEEE Transactions on Plasma Science*, Vol. 39, No. 3, pp. 947 – 952, March 2011.
4. D. Motes, M. Crawford, J. Ellzey, F. Stefani, and D.A. Wetz, 'An Investigation of Internal Gas Dynamics for an Electrothermal Launcher,' *IEEE Transactions on Plasma Science*, Vol. 39, No. 2, Pages: 802 – 808, February, 2011.
5. R.W. Karhi, D.A. Wetz, J.J. Mankowski, and M. Giesselmann, 'Theoretical and Experimental Analysis of Breech Fed and 40 – Distributed Energy Stage Plasma Arc Railguns,' *IEEE Transactions on Plasma Science*, Vol. 40, No. 10, Part: 1, pp. 2637 – 2645, October 2012.

(ii) Other Papers

1. D.A. Wetz, P.M. Novak, B. Shrestha, J.M. Heinzel, and S.T. Donahue, ‘Electrochemical Energy Storage Devices in Pulsed Power,’ *IEEE Transactions on Plasma Science*, Vol. 42, No. 10, Part 2, pp. 3034 – 3042, October, 2014.
2. B.M. Huhman, J.M. Neri, and D.A. Wetz, ‘Application of a Compact Electrochemical Energy Storage to Pulsed Power Systems,’ IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 20, No. 4, pp. 1299 – 1303, August 2013.
3. D.A. Wetz, J.J. Mankowski, J.C. Dickens, and M. Kristiansen, “The Impact of Field Enhancements and Charge Injection on the Pulsed Breakdown Strength of Water,” *IEEE Transactions on Plasma Science*, Vol. 32 No. 5, October, 2006.
4. B.M. Huhman, J.M. Neri, and D.A. Wetz, ‘Development of a Rep-Rated Capacitor Bank Utilizing Electrochemical Energy Storage,’ *Proceedings of the 17th IEEE International Electromagnetic Launch Symposium*, La Jolla, California, July 7 – 11, 2014.
5. B.M. Huhman and D.A. Wetz, ‘Progress in the Development of a Battery-Based Pulsed Power System,’ *Proceedings of the 2015 IEEE Electric Ship Technologies Symposium (ESTS),* pp. 441 – 445, Alexandria, Virginia, June 21 – 24, 2015.

a. Synergistic Activities:

- Served in session chair positions at IEEE sponsored conferences and on IEEE conference technical committees
- Elected member of the IEEE Pulsed Power Science and Technology Committee since January of 2012
- Guest editor of the 2013 special issue of the IEEE Transactions on Dielectrics and Electrical Insulation (TDEI) on Power Modulators and Repetitive Pulsed Power as well as both the 2014 and 2016 special issues of the IEEE Transactions on Plasma Science on Pulsed Power
- Awarded the 2006 Pulsed Power Student of the Year award at the 16th IEEE International Pulsed Power Conference in June, 2007 and Outstanding Young Researcher award at the 2nd Euro Asian Pulsed Power Conference in Vilnius, Lithuania, September 2008
- Dr. Wetz has authored/co-authored over 70 papers in journals, magazines and proceedings of archival IEEE sponsored conferences.

b. Collaborators and Other Affiliations:

Dr. John Mankowski	Texas Tech University
Dr. Ankur Jain	University of Texas at Arlington
Mr. Brett Huhman	Naval Research Laboratories
Dr. John Heinzel	Naval Surface Warfare Center – Philadelphia
Dr. Qing Dong	Naval Surface Warfare Center – Philadelphia
Mr. Ryan Hoffman	Office of Naval Research

Laboratory Affiliations:

Center for Pulsed Power and Power Electronics at Texas Tech University, Lubbock, Texas
Naval Research Laboratory, Washington D.C.
Naval Surface Warfare Center at Philadelphia, Philadelphia, Pennsylvania
Naval Surface Warfare Center at Dahlgren, Dahlgren Virginia

Current Students under Supervision:

Mr. Clint Gnegy-Davidson (Doctoral Candidate in Electrical Engineering), Mr. Matthew Martin (Masters Candidate in Electrical Engineering),Mr. Derek Wong (Doctoral Candidate in Materials Science and Engineering), Ms. Caroline Storm (Direct PhD Student in Electrical Engineering), Mr. Charles Nybeck (Direct PhD Student in Electrical Engineering),Mr. Jacob Sanchez (Direct PhD Student in Electrical Engineering),Mr. David Dodson (Masters Candidate in Electrical Engineering),Mr. Calvin Howard (Undergraduate Student in Electrical Engineering)

P.O. Box 62428
Houston,TX 77205

936-494-8631
John.Zeigler@SensorDesignGroup.com

John C. Zeigler

Career Summary

Mr. Zeigler has extensive experience in applying new technologies to real-world problems in diverse industry segments including remote sensing, electric utilities, medical instrumentation, and high-energy physics. He has managed multi-disciplinary R&D programs and directed multiple concurrent development projects in commercial, non-profit, and academic environments.

Experience

2006 – Present	Sensor Design Group, LLC., Houston, TX **Managing Director, Senior Design Engineer**
2001 – 2006	Terrapoint USA, Inc., The Woodlands, TX **Manager of Sensor Development**
1984 – 2001	Houston Advanced Research Center, The Woodlands, TX **Program Manager**
1978 – 1984	Electric Power Institute, Texas A&M University, College Station, TX **Research Associate**

Key Skills

Development of multi-disciplinary systems incorporating computer-based data acquisition, control, and monitoring functions. Project management, including scheduling, budgeting, and manpower allocation. Report, proposal, and technical paper writing. Experimental test planning, instrumentation, execution, and data analysis. Data acquisition and control system design, development, and operation. Circuit design, simulation, construction, and testing. Computer programming in Unix, Linux, and PC environments.

Education

1984	Master of Science in Electrical Engineering Texas A&M University, College Station, TX
1979	Bachelor of Science in Electrical Engineering Texas A&M University, College Station, TX

Major Projects

Electromagnetic Inspection
Project Manager, Design/Test Engineer

Ongoing development of advanced techniques and systems for electromagnetic inspection (EMI) of pipe. Hardware improvements include replacement of conventional coil pickup sensors with discrete Hall-element sensors to provide superior detection of off-axis flaws. Software developments include a proprietary adaptive digital signal processing algorithm that increases signal to noise ratio and permits automated detection of smaller flaws in the presence of high background noise levels.

AMS-2 Superconducting Magnet
Design/Test Engineer

Participated in the cool down and testing of a 1-meter bore superfluid magnet for the AMS-2 project at CERN in Geneva, Switzerland. Performed component and subsystem tests of quench protection system, analyzed and repaired existing magnet current leads, and performed data acquisition and analysis for burst disc tests. The $1.5 billion AMS-2 spectrometer system has been installed on the International Space Station to study charged particles from cosmic rays and to investigate shielding techniques suitable for interplanetary manned space missions.

Virtual Zero Detection System
Software Engineer

Developing adaptive system to track and identify a 0° index point on a rotating pipe. Detection system uses Infrared (IR) and ultraviolet (UV) light sources and photodiodes

John C. Zeigler

P.O. Box 62428 936-494-8631, Houston, TX 77205
John.Zeigler@SensorDesignGroup.com

CAREER SUMMARY

Mr. Zeigler has extensive experience in applying new technologies to real-world problems in diverse industry segments including remote sensing, electric utilities, medical instrumentation, and high-energy physics. He has managed multi-disciplinary R&D programs and directed multiple concurrent development projects in commercial, non-profit, and academic environments.

WORK EXPERIENCE

2006 – Present: Sensor Design Group, LLC., Houston, TX
Managing Director, Senior Design Engineer
2001 – 2006: Terrapoint USA, Inc., The Woodlands, TX
Manager of Sensor Development
1984 – 2001: Houston Advanced Research Center, The Woodlands, TX
Program Manager
1978 – 1984: Electric Power Institute, Texas A&M University, College Station, TX
Research Associate

KEY SKILLS

Development of multi-disciplinary systems incorporating computer-based data acquisition, control, and monitoring functions. Project management, including scheduling, budgeting, and manpower allocation. Report, proposal, and technical paper writing. Experimental test planning, instrumentation, execution, and data analysis. Data acquisition and control system design, development, and operation. Circuit design, simulation, construction, and testing. Computer programming in Unix, Linux, and PC environments.

EDUCATION

1984	Master of Science in Electrical Engineering	Texas A&M University, College Station, TX
1979	Bachelor of Science in Electrical Engineering	Texas A&M University, College Station, TX

MAJOR PROJECTS

Electromagnetic testing
Project Manager, Design/Test Engineer

Ongoing development of advanced techniques and systems for electromagnetic inspection (EMI) of pipe. Hardware improvements include replacement of conventional coil pickup sensors with discrete Hall element sensors to provide superior detection of off-axis flaws. Software developments include a proprietary adaptive digital signal processing algorithm that increases signal to noise ratio and permits automated detection of smaller flaws in the presence of high background noise levels.

AMS-2 Superconducting Magnet

Participated in the cool down and testing of a 1-meter bore superfluid magnet for the AMS-2 project at CERN in Geneva, Switzerland. Performed component and subsystem tests of quench protection system, analyzed and repaired existing magnet current leads, and performed data acquisition and analysis for burst disc tests. The $1.5 billion AMS-2 spectrometer system has been installed on the International Space Station to study charged particles from cosmic rays and to investigate shielding techniques suitable for interplanetary manned space missions.

Virtual Zero Detection System - Software engineer

Developing adaptive system to track and identify a 0° index point on a rotating pipe.
Detection system uses Infrared (IR) and ultraviolet (UV) light sources and photodiodes to generate raw timing pulses. These hardware pulses are then processed on a National Instruments Compact-RIO

Programmable Automation Controller (PAC) using LabVIEW Real-Time software to produce a precision, low-jitter timing output.

High Temperature Superconducting Devices - Magnetic Designer, Test Engineer
Ongoing collaboration with developer of advanced high-temperature superconducting (HTS) materials to demonstrate advantages of second generation (2G) wire in real-world devices. Performed magnetic design and testing of a hybrid warm-bore HTS magnet with a central YBCO coil flanked by Helmholtz coils made from BSCCO wire.

LiDAR Topographic Mapping Systems - Program Manager
Developed Light Detection and Ranging (LiDAR) systems to conduct 3-dimensional topographic mapping surveys from small twin-engine aircraft. Developed airborne sensors integrating high-power lasers, scanning and receiving optics, detectors with time-dependent gain control, GPS positioning, inertial navigation, and custom data acquisition and control electronics. Managed development of advanced post-processing and calibration techniques to correct first- and second-order errors in sensor alignment and produce highly accurate point clouds. Provided field installation, support, and maintenance for worldwide sensor deployments. The company's successful commercialization of this technology for both the public and private sectors earned the first-ever achievement award given by NASA Goddard Space Flight Center in the National Resources category.
Fiber Optic Sensor - Design Engineer
Developed detector, signal conditioning, and processing electronics for fiber optic sensors used in remote and distributed measurement of temperature, pressure, strain, and acceleration. The sensors were based on Fabry-Perot cavities and white light interferometry.

Electric Power Transmission System Studies - Program Manager
Analyzed the ability of regional electric transmission systems to support new generation capacity. Used traditional ac load flow and advanced probabilistic load flow (PLF) analysis techniques to determine what modifications, if any, would be required to support the desired capacity at a proposed site. Used PLF to evaluate the impact of new generation and/or transmission modifications on overall transmission system reliability.

Transmission Enhancement SMES - Program Manager
Performed site-specific analysis of the feasibility for large-scale Superconducting Magnetic Energy Storage (SMES) units to increase utility transmission system stability and capacity and to provide ancillary services such as voltage and frequency control, load following, short-term spinning reserve, and sub synchronous resonance damping.
Typical power ratings ranged from 50-500 MVA with stored energies of 0.5-5 MWh. The project was one component of a 3-year, $3.75 M SMES Technology Development
High Temperature Superconductor Flux Pump - Design Engineer
Developed conceptual design for a high temperature superconductor (HTS) flux pump to power a high-energy physics detector magnet at 8.33 kA. Designed scale model prototype tested at 200 A.

Superconducting Magnetic Energy Storage (SMES) Project Leader, Design/Test Engineer
Developed components for a dual-use defense and civilian technology program designing a 400 MW, 20 MWh pulse power SMES system. Developed a 300 kA superconducting transformer, a 300 kA superconducting current sensor, and a distributed data acquisition and control system. Integrated these subsystems with a 1.8 K superfluid helium liquefier and a 5 T background field magnet to produce a complete test facility. Tested 200 kA cable-in-conduit (CIC) superconducting cables and splices under simulated operating conditions. The facility set the world record of 303 kA for the highest current in a superconducting cable.

APPENDIX B. STATEMENT OF WORK

Task 1: 500 kA rigid coaxial transmission line using Litz technology

1.1 Develop cylindrical array of Litz Cables.

The TAMU group has experience in fabrication of windings using Rutherford cables, and a variety of fixtures that are used in the process. Tooling will be developed to form cylindrical arrays of Litz cables, and to edge-solder them to a cylindrical mandrel. The mandrel is made of high-strength bronze; it forms the mechanical boundary of the cable assembly and also the high-voltage boundary surface for the coaxial region between inner and outer conductor shells, as shown in Figure 3a. Fixturing will be developed to form a cylindrical array of Litz cables onto the mandrel. The insulating coating on each cable will be ground off one edge to expose copper, so that the array can be soldered to the mandrel.

1.2 Build short segment of 500 kA rigid coax transmission line.

A 1 m long coaxial assembly shown in Figure 4 will be fabricated to validate the mechanical design of the cable and test electrical isolation in the coax structure. A mechanical model of the structure will be assembled with a water space in the region between inner and outer conductors and hydrotested to the pressure $P = B^2/2\mu_0 = 0.8MPa = 120\ psi$. The mechanical design will be validated to assure that the structure does not deflect or delaminate under impulse loading.

1.3 Design/Build 3 m prototype of 500 kA rigid coax transmission line.

A 3 m length of the validated transmission line design will be built. One end of the transmission line will be configured to connect to the current buses that interconnet the three PFNs at UT Arlington. The other end will be configured to connect to a water load for stand-along testing, and to adapt to one end of a hoop-array rotary joint for Task 2.

1.4 Test 3 m prototype of 500 kA transmission line.

The 3 m prototype transmission line will be tested by connecting it to the 500 kA PFN at UT Arlington, and delivering the pulse energy into a water load. The transmission line will be instrumented to measure the pulse transmission and line heating along the line length. Repeated pulses will be applied, within the limits of the UT Arlington facility.

Task 2. Develop/test a 500 kA rotary joint for the coaxial transmission line

2.1 Develop/test fabrication of hoop arrays

Test segments of planar hoop arrays will be fabricated using the two alternative methods shown in Figure 5a,b. Each will be evaluated under sliding friction that simulates the action in the conical contact arrays of a rotary joint.

A further consideration is the requirement that the joint be able to provide pulsed current flow even when it is moving, since the aiming strategy for the RailGun will likely require that it be continuously tracking a target even while the current pulse is being delivered to the rails. Such sliding-during-current-pulse operation will be simulated with the pulse current per contact equal to that for the RailGun but with ~1% of contact count and area.

A method will be selected that produces the most robust, uniform hoop arrays and provides stability under sliding contact.

2.2 Fabricate conical joint assembly

The selected array technology will be used to fabricate conical hoop arrays of the dimensions required for the 500 kA rotary joint.

2.3 Build prototype joint, mechanical tests

A complete rotary joint will be assembled and the sliding contact performance will be evaulated in rotary motion of the joint: micro-imaging of individual contacts during rotary motion, correlation of axial loading force of the pair of conical joints and the local contact force on the array of hoops, overall a.c. resistance when static and during rotation.

2.4 Integrate joint on short transmission line

The rotary joint will be integrated with the segment of rigid transmission line developed under Task 1.2. Issues of transition from the alignment of cables in the transmission line and in the rotary joint will be evaluated.

2.5 Test joint on short transmission line

The short transmission line with rotary joint will be tested under high-current transmission to evaluate contact life, E.M noise from rotation of the joint, and degradation of contact performance when the joint is rotated between pulse firings.

Task 3. Superconducting Fault Current Limiter for PCT Network

3.1 Design subassemblies, simulate dynamics.

Detailed design sessions will be held with the Navy RailGun team to define the specific modes of fault currents for which protection is to be provided. Protection could be provided at the individual PPM (protecting ~100 kA sources), at the consolidation point for each PPM cluster (protecting ~MA clusters), or at the final consolidation table (protecting the entire 5MA). If the FCL is to protect against extreme energy deposition in a failed-short PPM, the FCL must be located in series with each PPM as illustrated in Figure 1.

3.2 Build FCL prototype assembly.

An FCL unit similar to Figure 10b will be built. The cryogenic systems will be built by the TAMU group, the structural elements will be built by BTM, and the instrumentation and pulse-power interconnect will be designed by Sensor Systems and built at TAMU. The unit will be tested for stability of mechanical support for tapes under pulsed impulse, the electrical isolation among the three R-L elementsand to chassis ground, and the heat loads under quiescent operation and under simulations of pulsed load. The unit will be upgraded as necessary to address issues that arise in those evaluations.

3.3 Test prototype at UT Arlington.

The FCL unit will be installed at the UT Arlington PPM cluster. Failure modes can be simulated by connecting one terminal of the FCL to one PPM chassis and its other terminal to the water load.

3.4 Modify FCL using results from tests.

Following analysis of test results by Navy and revision if necessary of the choice of target applications, the FCL unit will be modified to test performance closely aligned to the required performance. This may entail building a larger-capacity embodiment depending upon the selected applications.

3.5 Test improved model FCL.

The revised FCL unit will be tested under conditions that simulate the actual failure modes of interest.

Task 4. Integrate cryogas coolant flow within the APCT to reduce ohmic losses

4.1 Connect cryo-gas flow through transmission line.

Provisions are integrated with the end design of the transmission line and rotary joint to accommodate flow of cooling fluid, flowing away from the PFN connection through the center hole within the inner conductor subassembly and the annular space between inner- and outer-conductor subassemblies, then venting at breech. Indeed the coolant flow could be channeled to the barrel itself and provide both barrel cooling and exclusion of air from the aperture within the rails so that there is no oxygen there during Railgun firing.

4.2 Test transmission line with cryo-gas cooling.

The rigid transmission line and rotary joint assemblies will be thermally insulated from ambient air by a standard foam jacket. The line will be operated to carry 500 kA pulses to a water load. The temperature T(t) along the inner and outer conductors will be logged as in Tasks 1 and 2.

Task 5. Integrated design and simulation of 5 MA APCT and SFCL on a RailGun system

5.1 Develop a suitably scaled design for a 5 MA APCT.

The prototype APCT that will be developed in Tasks 1-4 is designed to operate with the 500 kA current pulse that can be generated at the UT Arlington Pulse Power Lab. When the APCT design is matured through Tasks 1-2, we will develop a design for a full-scale 5 MA APCT system, likely similar to the conceptual design shown in Figure 10.

5.2 *Integrate APCT with RailGun turret.*

The APCT is designed to be configured to accommodate 360° rotation of the turret and 0-90° elevation of the barrel, as shown in Figure 7. The configuration shown uses a vertical segment of rigid line, a rotary joint, a 45° bend and short rigid segment, a second bend, and a 180° bend to connect from the PFN below-deck to the RailGun breech. The vertical line must penetrate the deck through the rotation axis of the turret and the diagonal segment must pass through the turret truss as shown.

When the APCT design is matured through Tasks 1-2, we will develop a design for the above configuration that conforms to the current Navy design for the turret of the RailGun on which APCT is to be integrated.

5.3 Integrate APCT with RailGun breech.

The inner and outer conductor layers of the transmission line must be connected to the two rails of the RailGun in the breech assembly. We have developed conceptual designs for the interconnect using two approaches, a multi-cable interconnect to a pair of copper plates similar to present breech assemblies, and a conformal interconnect in which the array of Litz cables within the inner and outer conductors are gathered to a planar configuration that bonds to each breech plate. We will evaluate those options with Navy personnel and develop an optimal design for integration with the Navy RailGun.

5.4 Integrate SFCL with the PFN network.

The superconducting FCL provides best protection of the PPMs of the PFN if FCLs are integrated at the PPM level in the PFN configuration, as illustrated in Figure 10. Each PPM connects to an FCL, the FCLs for all PPMs along one side of a chassis are housed in a common thermally insulated cryostat, the outputs are ganged on a copper bus that runs within the cryostat, and the pulse current busses are in turn ganged at a summing junction that connects to the single rigid transmission line that carries the pulse above-deck to the breech. We will confer with Navy to optimize the configuration of the FCL cryostat to integrate with the PFNs that will be used on the RailGun.

5.5 Develop simulation of integrated PFN – SFCL – APCT- RailGun system.

Simulate current transport, heat transport, forces and energy delivered to barrel and projectile for the APCT – SFCL system integrated with a specified Navy RailGun. Simulate normal firing of a projectile and failure modes.

COST-DRIVER MATERIALS AND SUBSYSTEMS

Whenever one undertakes development of a complex system that involves unusual materials, it is important to establish solid tech specs, price structure, and delivery availability from manufacturers who are capable of making the materials that are needed. In that spirit we have identified lead vendors for the unusual materials that are used in the proposed tasks, we have worked up with them specifications that meet our requirements that they can build, and we have obtained price/delivery quotations:

Rutherford/Litz cable: New England Electric Wire manufactures Litz cable for a variety of applications. They have quoted us for a Rutherford cable of insulated strands, containing 50 1 mm diameter strands that are formed into a rectangular package:

Quantity needed for 5 m length of 2 MA transmission line:

360 cables x $12/m = $4,320/m

REBCO tape: SuperPower manufactures REBCO superconducting tape for AC transmission line and superconducting magnet applications. Their conductor SX12-100 has optimum parameters for FCL requirements. They have a modest quantity currently in stock, with a critical current performance of 350 A:

120 m x $84/m = $10,080

They have just improved their manufacturing process and are offering a higher performance version of the same tape. One FCL sized to protect one PPM would require 140 tapes with I_c = 350 A, or 110 tapes with I_c = 450 A. The higher-performance tapes will soon become the standard that they manufacture, so we assume that for pricing:

110 tapes x 2 m x $101/m = $22,000

Stainless steel or Inconel pipes: The transmission line design uses heavy-wall pipe, of either 304 stainless steel or Inconel 718. 304SS is less expensive but has less strength and so must be specified in heavier wall to control the large Lorentz forces. We have priced the necessary pipe assuming 304 SS, but will revisit the choices with our Navy client, since other considerations arise besides material cost. Price/m for 304SS from Tork Systems:

4" schedule 120	$150/ft	=	$500/m
16" schedule 120	$1,570/ft	=	$4,710/m
			$5,210/m

E-beam drilling of hole pattern for rotary joint, armature: Acceleron has given us a budgetary quote for e-beam drilling of the hole pattern for each 30-cm long male contact array (~20,000 holes)

Non-recoverable one-time cost	$25,000
Cost per unit	$5,000

Brazing of rotary joint components, armature:

Accurate Brazing has given us a budgetary quote for brazing of the hoop-array assemblies:

Non-recoverable cost	$5,000
Cost per unit	$1,200

We have not undertaken more detailed cost analysis for materials and fabricated parts for the components to be developed in the several tasks, since specifications will evolve as designs converge. The budgets for materials, shop services, and fabrication services are based upon our experience with closely similar projects.

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