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MICRO-ALIGNED SOLENOID FOR MAGNETIZED BUNCHED-BEAM ELECTRON COOLING OF 100 GeV/u IONS*

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Abstract

Magnetized electron cooling of ion beams requires precise alignment of the electron beam with the equilibrium trajectory of the ion bunch. For the parameters required for JLEIC, a solenoid with bore field ~1 T, length ~30 m, and rms alignment of ~µrad is required. Such precise alignment has never been accomplished in a 1 T solenoid.

The design of a micro-aligned solenoid is presented. A gap-separated stack of thin steel washers is located inside the solenoid. The washer stack shields transverse magnetic fields from its interior by a factor of ~10. A 30-washer module of the structure was built and measured using ultra-sensitive capacitive probes using a coordinate measuring machine. The r.m.s. coplanarity of the washer gaps was measured to be <5 µm, consistent with the required micro-alignment.

INTRODUCTION

Electron cooling of ion beams is used to reduce the emittance of an ion bunch and even to stack multiple bunches into a single volume of phase space [1]. It has been used to dramatically enhance the accumulation of antiproton bunches for $\bar{p}p$ colliding beams and to prepare ions for deceleration and capture in ion traps. The highest ion energy at which electron cooling has been accomplished to date was its use at Fermilab to cool a d.c. beam of $\bar{p}$s at 8 GeV energy in the Recycler Ring [2].

The JLab Electron-Ion Collider (JLEIC) is proposed to collide spin-polarized beams of electrons and ions at high energy (100-200 GeV/u) and high luminosity [3]. Sustaining high luminosity requires the use of bunched-beam electron cooling to control emittance growth in the circulating ion beam. The electron cooling requires that a bunched electron beam be coalesced with the ion bunches so that they travel with the same vector velocity through a long straight section in the collider ring. The electron beam must be confined by a ~1 T solenoidal magnetic field, so that each electron of the cooling beam is confined to move on a tiny-radius spiral around a field line (Figure 1a) and cannot recoil transversely when it scatters from an ion.

The design of the bunched-beam electron cooling is summarized in Ref. 4 and illustrated in Figure 2. It requires four 15 m long solenoid cooling channels, each with guide field ~1 T. The cooling process requires extremely tight alignment of the magnetic field lines with the ion beam axis, with a tolerance that is less than the angular spread within the ion beam. The target invariant emittance in the ion bunches with bunched-beam e-cooling in JLEIC [4] is

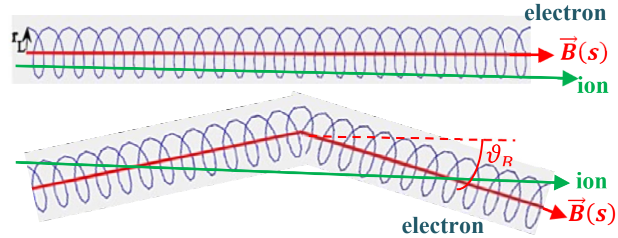

Figure 1: Schematic effect of magnetic field alignment on magnetized cooling: a) close alignment of $\vec{B}$ with ion beam; b) $\vec{B}$ misaligned so the spiraling electrons heat rather than cool the ion beam.

ε_{Nx} =1.2 µm, ε_{Ny} = 0.6 µm. The focal optics for the ions entering each solenoid channel has a betatron function β ~ 100 m. At the design proton energy T = 100 GeV of the collider, the protons have a relativistic $\gamma = {}^{T}/_{m} = 106$. The r.m.s. angular spread in the ion beam is

$$\vartheta_{rms} = \sqrt{\frac{\varepsilon_N}{\gamma\beta}} = 10^{-5} rad. \quad (1)$$

As an ion passes close to a particular electron, it Coulomb-scatters from the electron, imparts a small fraction of its momentum, and incrementally cools. The electron is constrained to spiral around a field line with a tiny Larmor radius

$$\rho = \frac{m_e v_{e\perp}}{eB} \sim 3\ \mu m \quad (2)$$

and so it cannot recoil freely in the transverse direction. It thus scatters repeatedly from the ion on successive spirals and longitudinal cooling is coherently enhanced. If the solenoidal field were perfectly aligned to the ion beam direction $\vec{B}(s) = B_0\hat{z}$, then the coherent enhancement N_s is the number of spirals for which the impact parameter remains within the Larmor radius:

$$N_s = 1 + \frac{v_{e\perp}}{2\pi v_{\parallel}} \sim 10 \quad (3)$$

The enhancement thus arises because the intrinsically flat rest-frame velocity distribution of the electron beam, which for parameters appropriate for one example application in JLEIC [5] is shown in Figure 3. Note that the rest-frame transverse velocities of the electrons and ions are

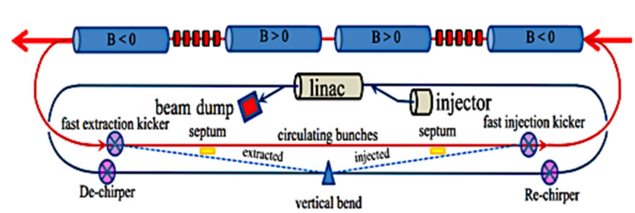

Figure 2: Configuration for bunched-beam electron cooling of ion bunches in JLEIC.

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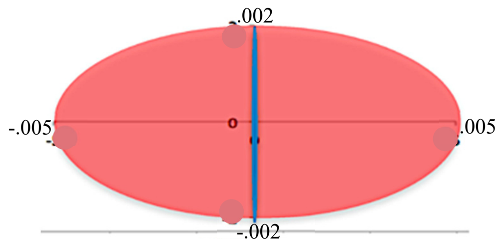

Figure 3: Rest-frame velocity distributions of the electrons (blue) and ions (red) in JLEIC. (from Ref. 5).

comparable, so that the cooling force on any ion is directed to collapse the red ellipse onto the blue disc.

For the same reason, any misalignment ϑ_B of the magnetic field that guides the electron beam will tilt the spiraling electron trajectories (Figure 1b) so that they do not align with the ion trajectories. If the tilt angle exceeds the spread ϑ_{rms} due to the ion bunch emittance, it would be equivalent to moving the blue disk vertically so that it no longer co-penetrates the red ellipse - the electrons would heat the ions rather than cool them.

Aligning the magnetic field lines within a solenoid to micro-radians over long length is a challenge for magnetic design. Forty years ago McIntyre *et al.* [6] achieved ~10^{-4} rad alignment in the solenoids for the Fermilab electron cooling experiment; the solenoids for present-day electron coolers achieve comparable alignment. No system to date has achieved the 10^{-5} alignment required for JLEIC.

THE MICRO-ALIGNED SOLENOID

A micro-aligned solenoid is being developed for this purpose, in which boundary conditions in a steel structure are used to transform the extreme requirement on alignment of magnetic lines of force into an extreme requirement on mechanical alignment of a stack of steel washers, as shown in Figure 4. A linear array of annular steel washers is assembled as a stack interleaved with precision-ground aluminum spacer washers. The array is supported within the superconducting solenoid using a macro-alignment support spider discussed below. When the solenoid is operated at ~1 T field, the steel in each washer is unsaturated and its flat face presents a strong boundary condition to shunt field components parallel to the face. Any transverse magnetic field is thereby shunted through the washers and shielded from affecting the beams traversing within the beam tube.

The shielding effect has been simulated using FEA field calculations of a solenoid containing a micro-aligned washer stack. A segment of the washer-stack structure was modeled in 3D using TOSCA [7]. The problem required fine-mesh divisions around the inner and outer lips of each washer, where local field concentration must be appropriately modeled. An example geometry that proved effective uses a stack of 1008 (low-carbon) steel washers with thickness 0.5 mm, inner radius 7.3 cm, outer radius 8.3 cm, and spacing 9 mm. The overall solenoid was modeled as a thick cylindrical current sheet, and a single pair of perturbing turns were superposed such that one turn canceled a

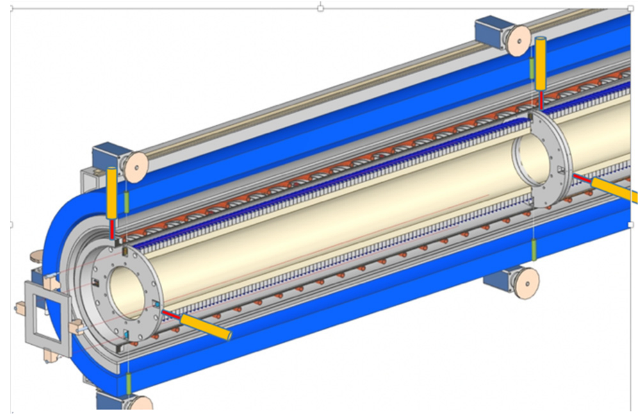
Figure 4: Isometric view of washer stack installed within bore of a 1 T superconducting solenoid.

symmetric hoop of current from the cylindrical sheet and the other turn was displaced in the (transverse) x direction. This locally displaced turn simulates the field distribution that would result from any of the several potential origins of local field misalignments.

The fields produced in the interior region of the solenoid were calculated in two cases for exactly the same meshed geometry. In both cases the current in the thick current sheet was chosen to produce 1 T on the axis of the solenoid. In one case, the B-H data appropriate for 1008 steel was used for the steel washers; in the other case the B-H data for the steel washers was set to that of vacuum ($\mu = \mu_0$). The two cases are shown in Figure 5. The spaced steel washers shunt transverse fields produced in misalignments in the solenoid winding, the flux return, or any external source and suppress the transverse fields seen by the beams by a factor 10.

Next we investigated several choices of material for the washers, including 1010 steel, 1008 steel, and permalloy. The shield ratio is ~0.2 with 1010 steel, 0.1 with 1008 steel, and 0.05 with permalloy.

MICRO-ALIGNED WASHER STACK

Several models of the washer stack were built and tested for co-planarity of the washers. A great deal was learned about what is required to achieve a co-planarity of 1 μm in a spaced stack of washers. The successful method uses a stack of .08 mm thick steel washers cut from 1008 shim stock and 1 cm thick spacers cut from MIC6 cast aluminum jig plate. The thickness of the shim stock was measured to be uniform to <4 μm over the dimension of a washer the

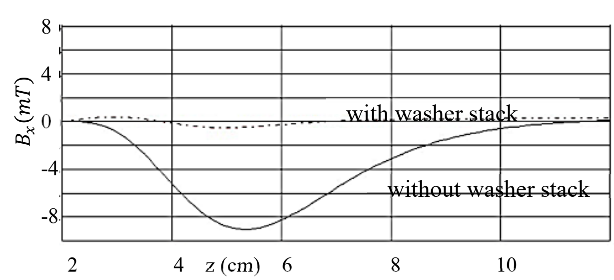

Figure 5: Transverse field $B_x(z)$ along the solenoid axis when one turn of the solenoid is displaced in $\hat{x}$ direction.

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Figure 6: a) Measurement of alignment in a 30-washer stack; b) Microsense model 6530-LR-06 capacitive probe.

surface finish was <1 µm. Each spacer washer is precision-ground on both faces to a thickness uniformity of <1 µm.

The washer stack is compressed using a center tube located just inside the washer ID to tension a pair of end support rings as shown in Figure 4.

METROLOGY OF MICRO-ALIGNMENT

Figure 6a shows the method by which micro-alignment was measued in a prototype 30-washer module. A rotary table was positioned on a granite reference table. The washer stack module was placed on the rotary table. A Mitutoyo coordinate measuring machine (CMM) was positioned on the granite table beside the rotary table. Two capacitive measurement probes (Figure 6b) were attached to the CMM arm and used to simultaneously measure the top surface positions on each of two steel washers, as shown in the left of Figure 6a.

The capacitive probe [8] is specially designed to measure the distance between the probe tip surface and an adjacent metal surface. The measurement is non-contact, so there is no potential for deflection of either probe or sample, and no risk of friction wear. The probe is shielded to isolate the measurement from other nearby objects – only the metal surface facing the probe tip produces capacitance. The manufacturer specified a measurement precision of 120 nm; we verified that sensitivity by a set of calibration measurements in the lab.

First the height of the rotary table surface was measured as it was rotated through 360°. The variation of the table surface height is <0.1 µm (nearly at the limit of measurement precision).

Next measurements were taken for the vertical position of the top of each washer surface at positions located every 20 degrees around azimuth. The data were analyzed to produce two plots that show the global and local alignment of each washer within the 30-washer stack. Figure 7 shows plots of the vertical position of the top surface for each washer as a function of azimuth. The zero of the vertical scale is taken by averaging the highest and lowest elevations for that washer. By that method all of the plots share a common zero. That approach shows the micro-alignment

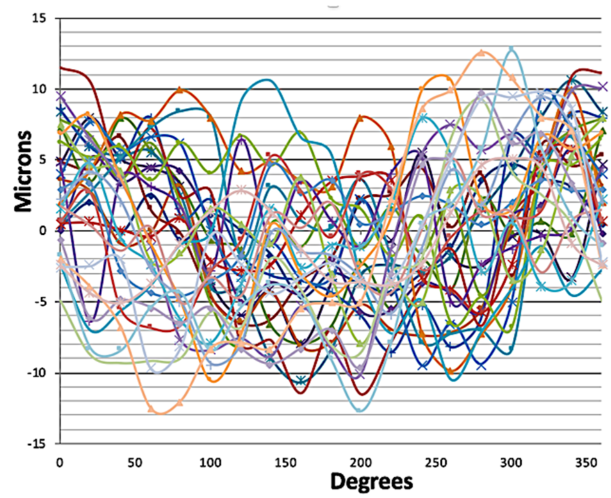

Figure 7: Metrology of the sequence of 30 washers in the compressed washer stack.

with full sensitivity – the alignment of the electron beam in the micro-aligned solenoid is not affected by slight variations in the washer-washer gap, only by angular misalignments between their surfaces. The overall measured global and local co-planarity of the washers is $\sigma_z = 5$ µm.

MACRO-ALIGNMENT OF WASHER-STACK MODULES WITHIN SOLENOID

The above procedure is now validated to fabricate and micro-align each washer stack module. It is then necessary to install a linear array of modules inside a long solenoid and support them with macro-alignment module-module of <5 µrad. For this purpose it is necessary to measure the end support ring of each module in a reference frame that can be transferred to global geodesy, and to adjust each such position so that the entire assembly is macro-aligned.

Figure 4 shows the spider of 4 wire supports that positions each end support ring of each module in the correct position for macro-alignment. Each wire is affixed to a coupling on the support ring, and is threaded through a 1 mm ID radial guide tube that passes through a hole in the actual solenoid mandrel. The wire then passes through 2 roller guides and out through a bellows seal to a spool mounted on the outside wall of the flux return. Opposite pairs of wires are tensioned using a stepper motors, so the x/y positions of each end of each washer stack can be precisely aligned to a global reference frame.

Capacitive transducers are mounted so that each sensing head (red shafts in Figure 4) is positioned close to a fiducial flat. The socket holding the transducer is fixed to a reference block on the outside of the (room temperature) steel flux return of the solenoid.

CONCLUSIONS

A method for achieving micro-alignment of 10 µrad in a long 1 T solenoid has been developed. The magnetic design and the method of fabrication have been demonstrated. 10 µrad micro-alignment has been measured. A method for sustaining that alignment along a long solenoid assembly has been devised.

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