Micro-aligned Solenoid for Magnetized Bunched-beam Electron Cooling of 100 GeV/u Ions

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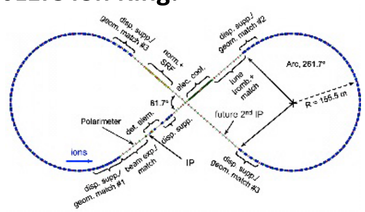
Abstract: Magnetized electron cooling of ion beams requires precise alignment of the electron beam with the equilibrium trajectory of the ion bunch. For the parameters required for JLEIC, a solenoid with bore field ~1 T, length ~30 m, and alignment of ~ 5 μrad r.m.s. is required. Such precise alignment 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.

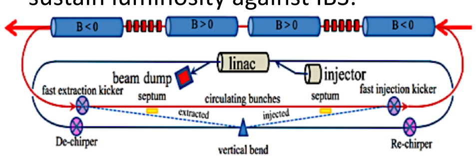
High-Energy Bunched-Beam Electron Cooling

JLEIC Ion Ring:



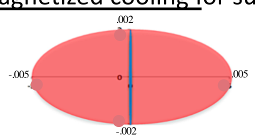
Electron-Ion collisions:
100 GeV polarized p,
50 GeV polarized d
12 GeV polarized e
High Luminosity

Bunched-beam electron cooling during collisions to sustain luminosity against IBS:



50 MeV Recirculating Linac

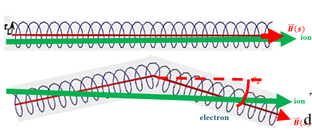
Magnetized cooling for sufficient damping rate:



The electrons are confined in a 1 T solenoid. Each electron travels in a tight spiral along the line of force of magnetic field.

Rest-frame velocity distributions (v/c) of the electrons (blue) and ions (red) in JLEIC.

The magnetic field lines must align tightly with the ion beam direction so that electrons cool.



An electron that scatters from an ion cannot recoil transversely, and so cooling is enhanced by a factor

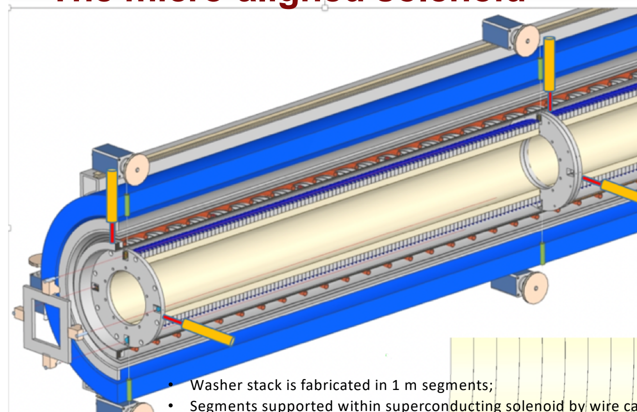
$$N_s = 1 + \frac{v_{e\perp}}{2\pi v_\parallel} \sim 10$$

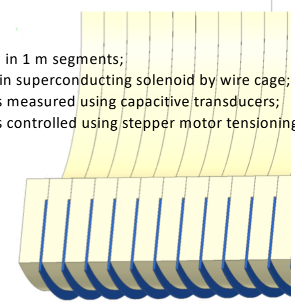
The proton beam has $T = 100$ GeV, invariant emittance during collision is ε_{Nx} =1.2 10^{-6} m, ε_{Ny} = 0.6 10^{-6}m. The r.m.s. angular spread in the ion beam is

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

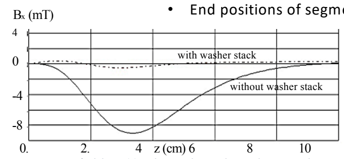
The 1 T solenoid must be aligned within 10 μrad to sustain magnetized cooling! That has never been accomplished…

The micro-aligned solenoid





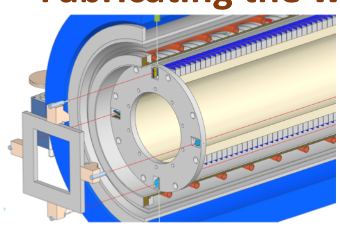
- Washer stack is fabricated in 1 m segments;
- Segments supported within superconducting solenoid by wire cage;
- End positions of segments measured using capacitive transducers;
- End positions of segments controlled using stepper motor tensioning.



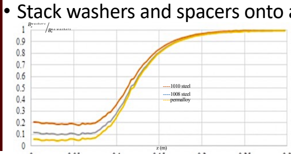
Transverse field $B_x(z)$ along the solenoid axis when one error turn of the solenoid is displaced in the x direction.

Arrange a stack of thin steel washers with axis parallel to the solenoid axis. The flat face of the washers imposes a perpendicular boundary condition, and shields transverse fields from the interior of the washer stack.

Fabricating the washer stack



- Use surface grinding to prepare a set of spacer washers.
- Use wire EDM to cut 1008 steel shim stock into washers.
- Stack washers and spacers onto a center tube, compress between end flanges.

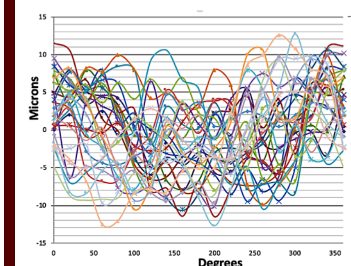


Shielding ratio for 3 choices of magnetic material.

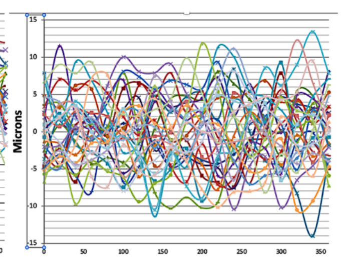
Measuring washer microalignment

Microsense model 6530-LR-06 capacitive probe.

- Mount washer stack on a precision rotary table.
- Mount 2 non-contact capacitive probes on a CMM arm.
- Each capacitive probe gives reproducible precision ~3 nm.
- Measure separation of 2 washers simultaneously, subtract to get washer spacing.
- Rotate washer stack through 360° to measure alignment on short & long baseline.



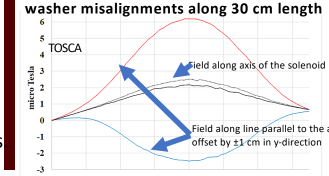
Absolute offset of each location on each washer with respect to the lowest washer of the stack.



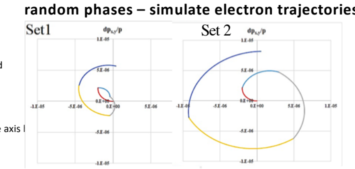
Gap between adjacent washers, taken in sequence up the stack.

The overall experimentally measured global and local co-planarity of the washers is $\sigma_z = 5$ μm.

Calculate transverse fields from measured washer misalignments along 30 cm length



Concatenate field map along 5 m trajectory with random phases – simulate electron trajectories



5 μm co-planarity of washers produces micro-alignment of ~5 μrad in electron trajectories.

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