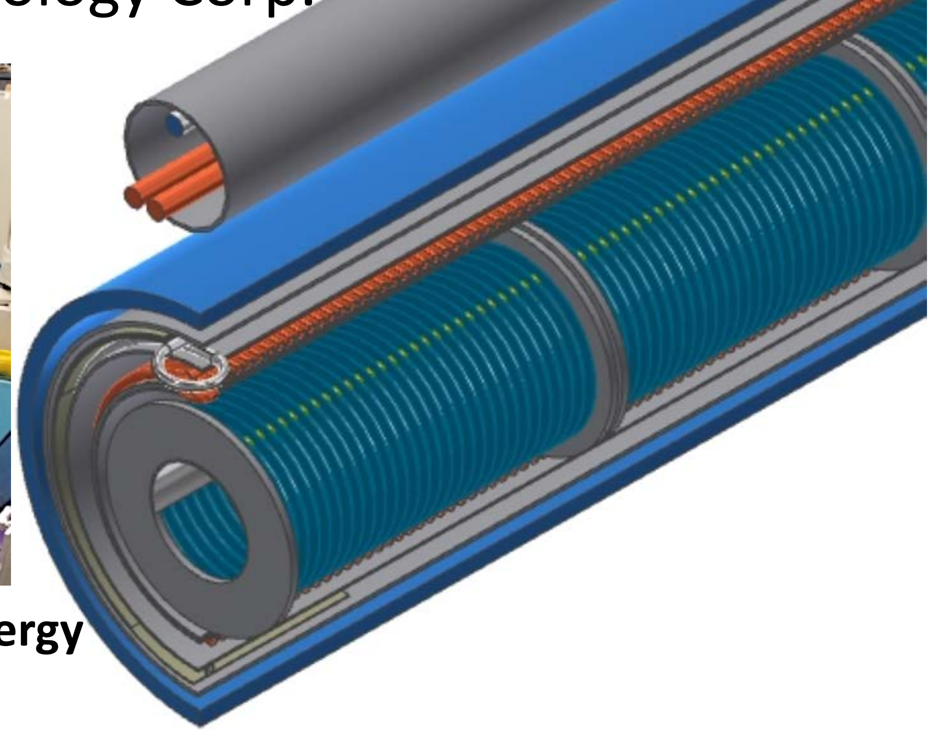
Micro-aligned Solenoid for Magnetized Electron Cooling in the Ion Ring

Peter McIntyre[1,2], Jeff Breitschopf[1], James Gerity[1], Joshua Kellams[2] , and Akhdiyor Sattarov[1,2]

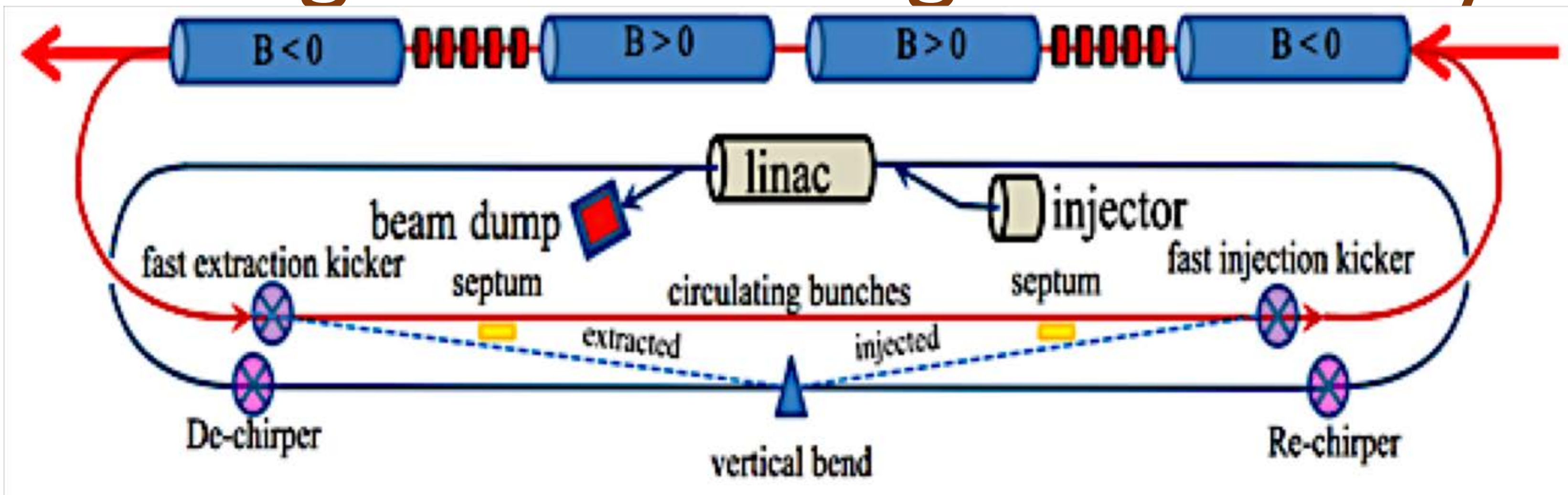
[1]Texas A&M University

[2]Accelerator Technology Corp.



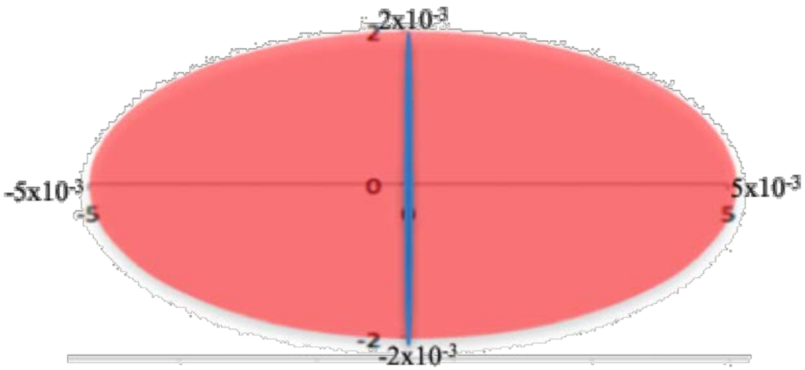
Funded by a Phase 1 SBIR grant from US Dept. of Energy DE-SC0018468. Phase 2 proposed for FY2019.

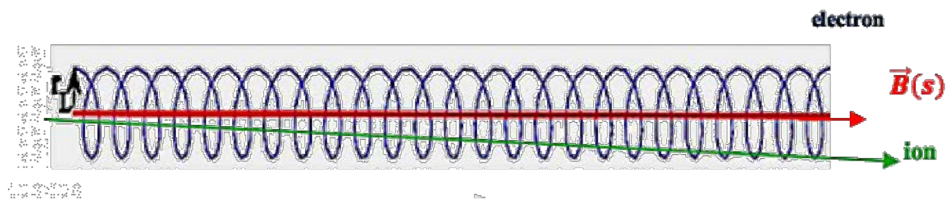
JLEIC needs magnetized bunch-beam e-cooling to sustain high luminosity



- Sustaining high luminosity requires the use of bunched-beam electron cooling to control emittance growth in the circulating ion beam.
- Electron cooling of ion beams requires precise alignment of the electron beam with the equilibrium trajectory of the ion bunch.

Magnetized electron cooling

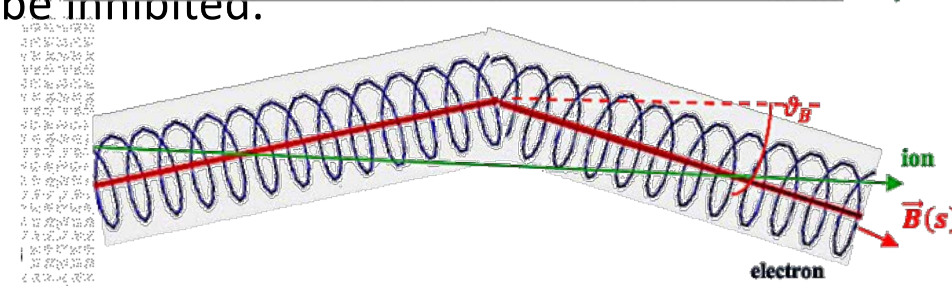




Rest-frame velocity distributions of electrons (blue) and ions (red) in JLEIC

- In magnetized cooling, the electrons are immersed in a strong solenoidal magnetic field.
- Each electron is trapped on a line of force, and spirals with tiny Larmor radius (3 μm for 1 T).
- An electron that scatters from an ion cannot recoil transversely, and so cooling is enhanced by a factor $N_s = 1 + \frac{v_{e\perp}}{2\pi v_{\parallel}} \sim 10$
- But the magnetic lines of force must be precisely aligned with the ion bunch trajectory.
- If the lines of force are misaligned in part of the solenoid, the electrons and ions will not superpose in velocity space and cooling will be inhibited.
- The required alignment is

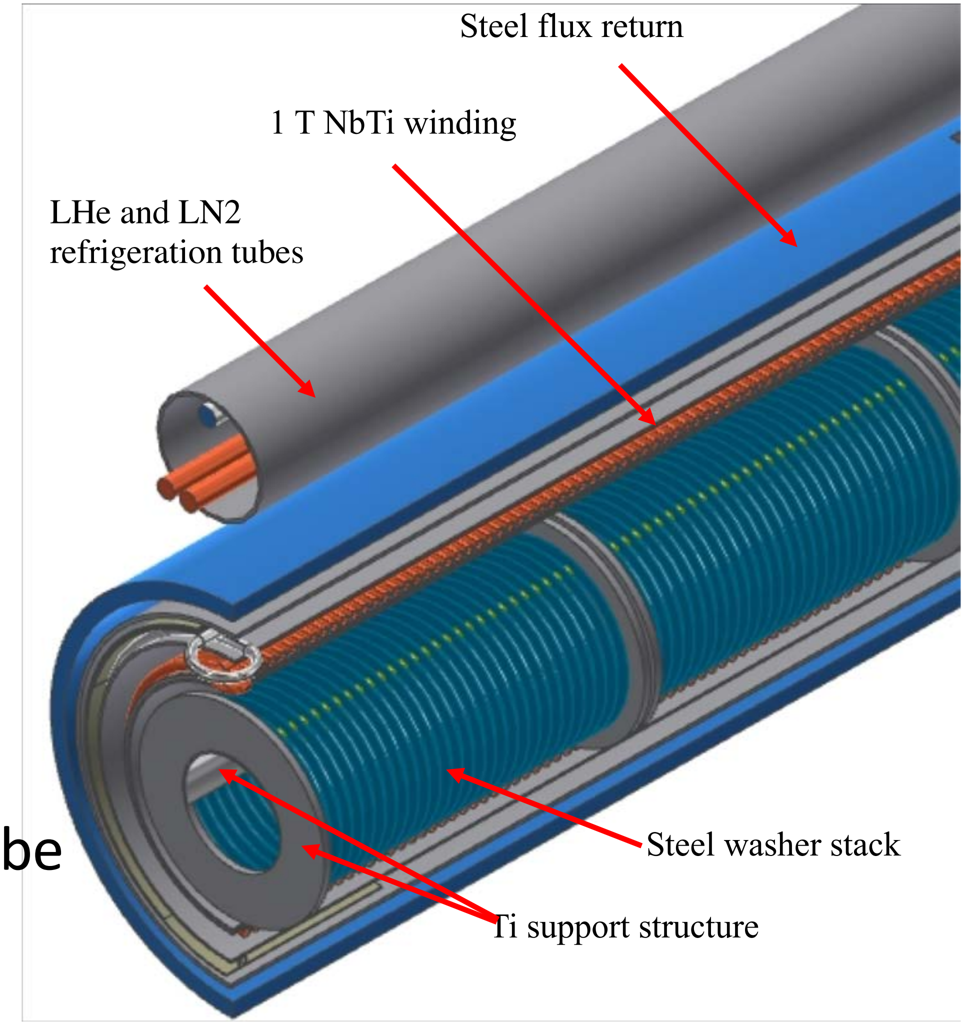
$$\vartheta_{rms} = \sqrt{\frac{\varepsilon_N}{\gamma\beta}} = 10^{-5} rad.$$



Suppress transverse magnetic fields using a stack of steel washers.

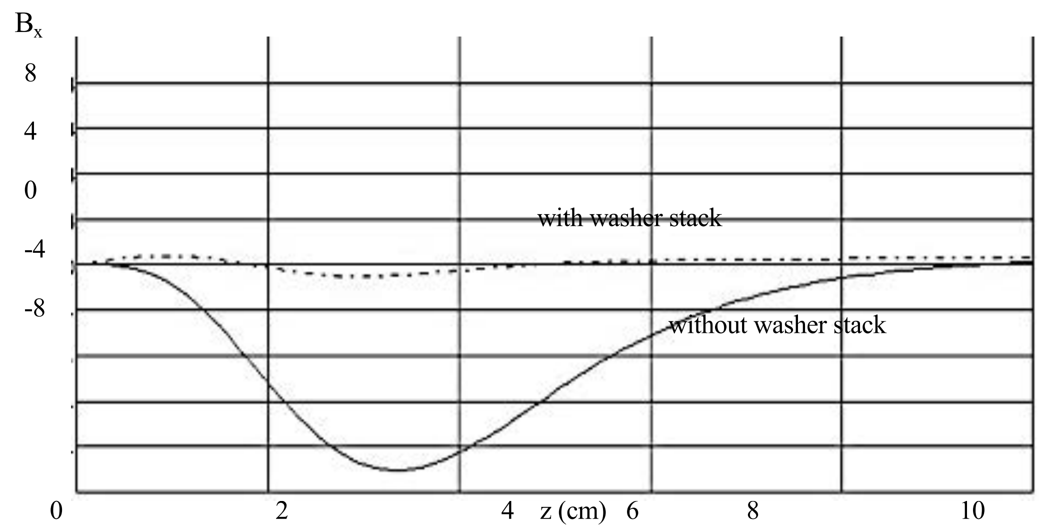
- Steel is unsaturated at 1 Tesla.
- A washer acts as a shunt to shield the region inside from transverse fields.
- The washer stack is ~invisible to axial field of the solenoid.

- ***Challenge:*** how to align all washers to be oriented precisely parallel.



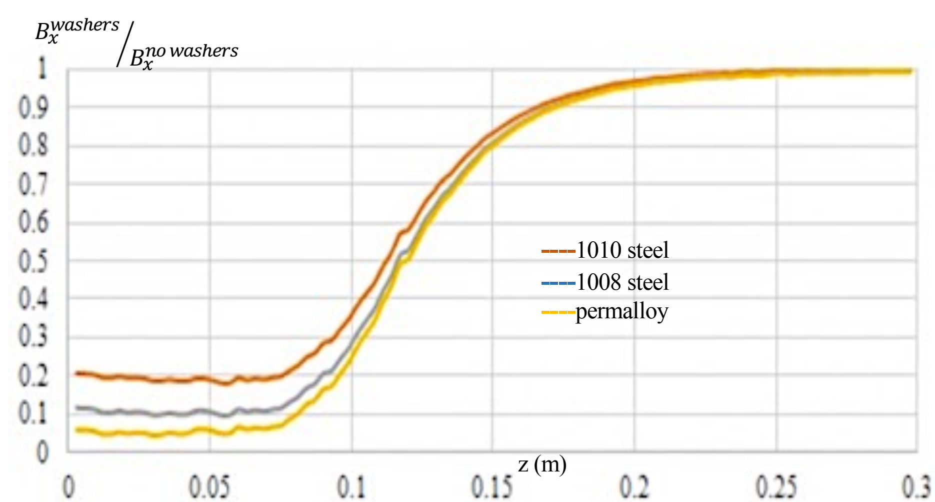
Simulation of transverse field shielding

- Displace one turn of solenoid in x direction.



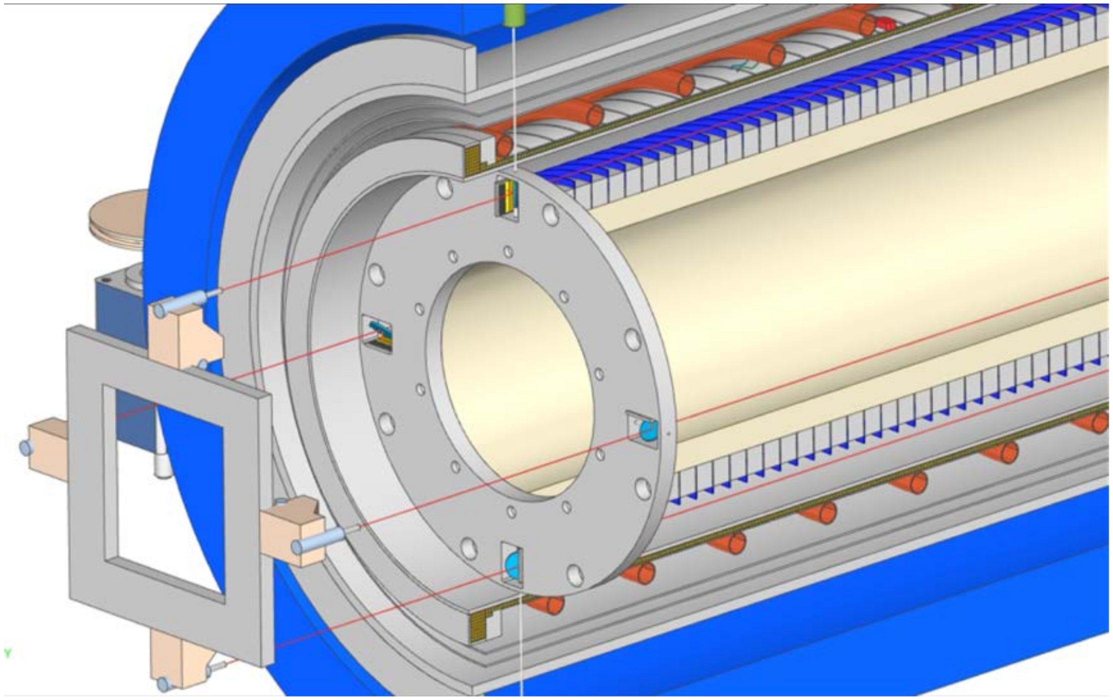
Transverse field $B_x(z)$ along the solenoid axis when one error turn of the solenoid is displaced in the x direction.

- Simulate $B_x(z)$ with and without the washer stack.
- 10:1 suppression of B_x



Shielding ratio for 3 choices of magnetic material.

How to micro-align a washer stack



Aluminum spacer ring mounted on a steel base plate and locked to the magnetic chuck of the surface grinder.

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

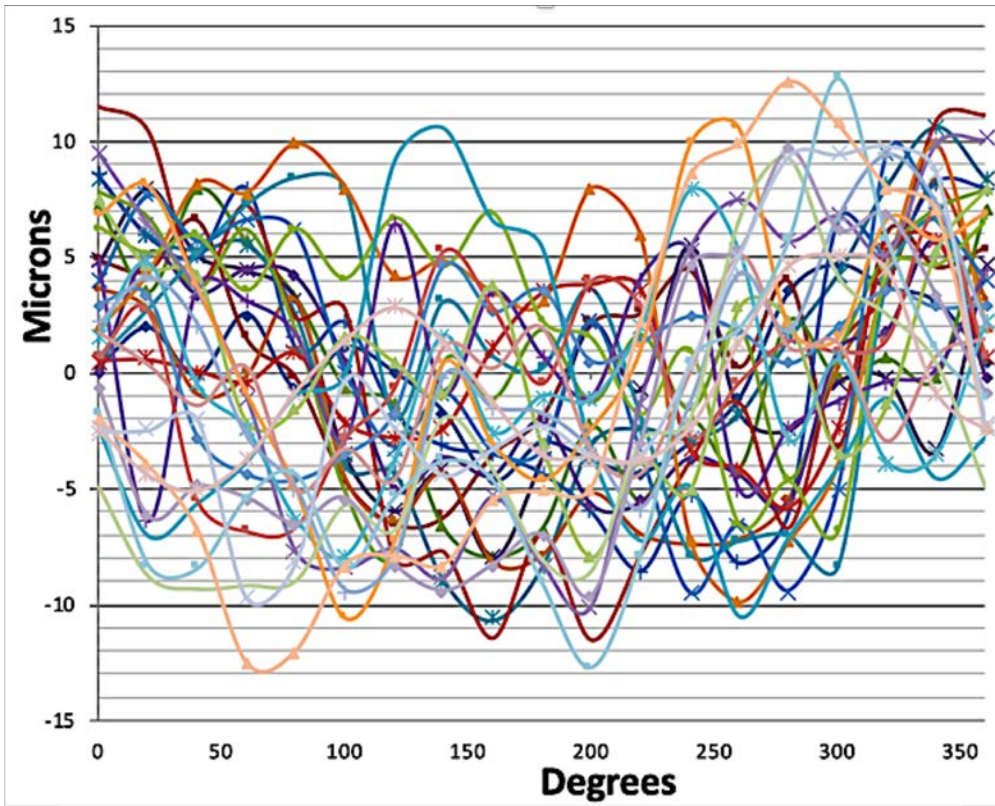
Metrology to measure micro-alignment

Microsense model 6530-LR-06 capacitive probe.

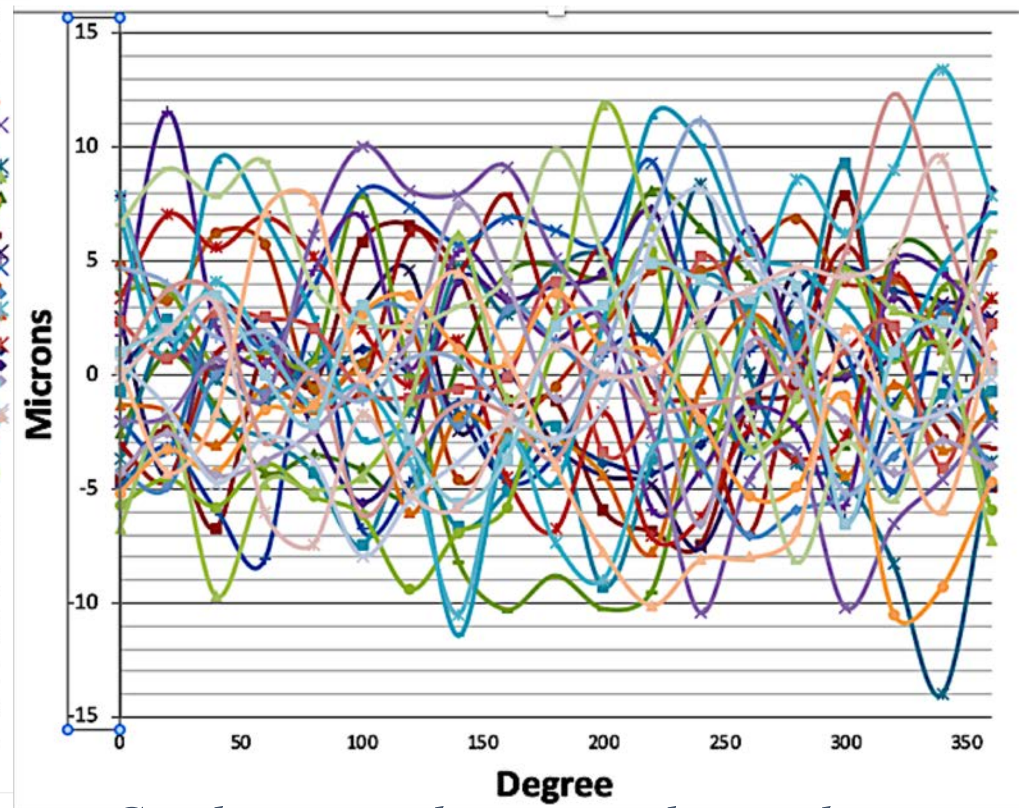
Measurement of alignment in a 30-washer stack.

- 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 obtain washer spacing.
- Rotate washer stack through 360^o to measure alignment on short and long baseline.

Metrology of a sequence of 30 washers in the compressed washer stack



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



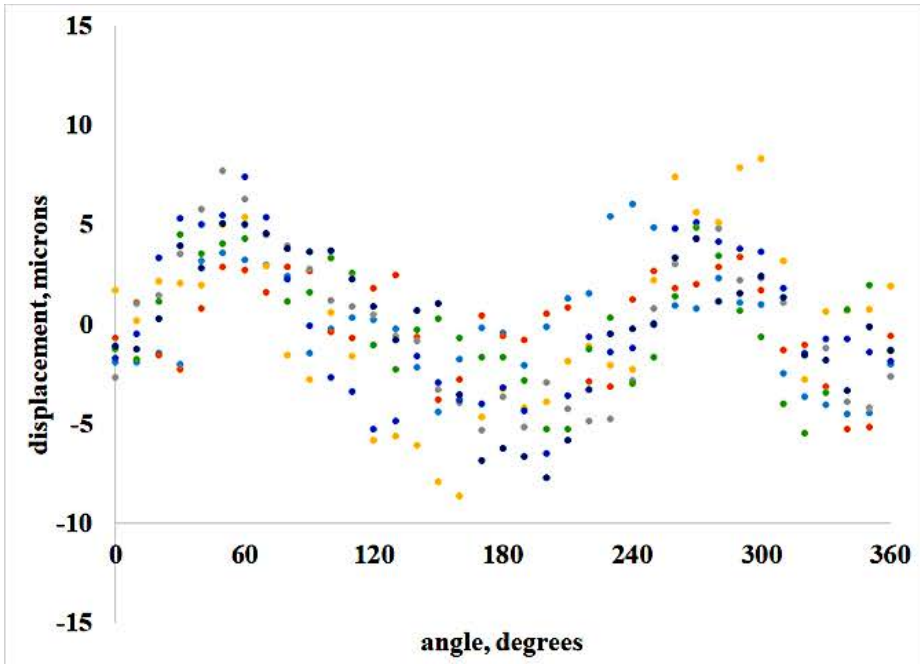
Gap between adjacent washers, taken in sequence up the stack.

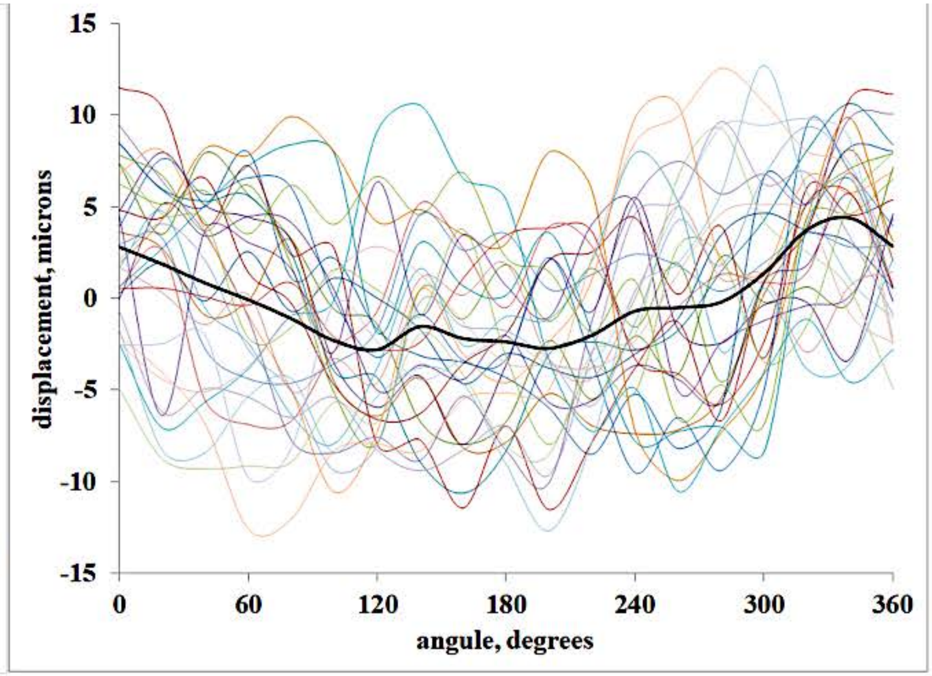
The overall experimentally measured global and local co-planarity of the washers is $\sigma_z = 5\ \mu m$.

The big picture: aligning $\overrightarrow{\boldsymbol{B}} \parallel \overrightarrow{\boldsymbol{p_i}}$ over 30 m

- We measured $\sigma_x \sim \sigma_y \sim$ 5 μm coplanarity within stack. What is corresponding σ_θ for magnetic lines of force?
- The manageable length of a single washer stack is ~m. How do we mount a sequence of washer stacks with no gap between, and align their axes to 10^{-5} rad?
- The sequence of washer stacks must be mounted within the aperture of a cold-bore superconducting solenoid. How do we align the washer stack sequence parallel to the solenoid axis?
- How do we align the whole system to the actual axis of the ion beam as it traverses the straight section?

Flatness and gaps for a 30-washer stack





There is a <5 μm quadrupole deviation from flatness on the nearest 8 washers to each end – due to deformation of end flanges.

There is a smaller ~3 μm dipole deviation in the global alignment, which propagates from a tiny granular body on the surface of one washer.

As will be seen below, the micro-alignment of the prototype washer stack is sufficient for the required micro-alignment of $\vec{B}$ for magnetized cooling.

We have identified the origins of the two dominant limiting mis-alignments, and we can eliminate both to further reduce alignment to ~2 μm.

Now simulate the effect of micro-alignment of washer planarity on the micro-alignment of solenoidal field

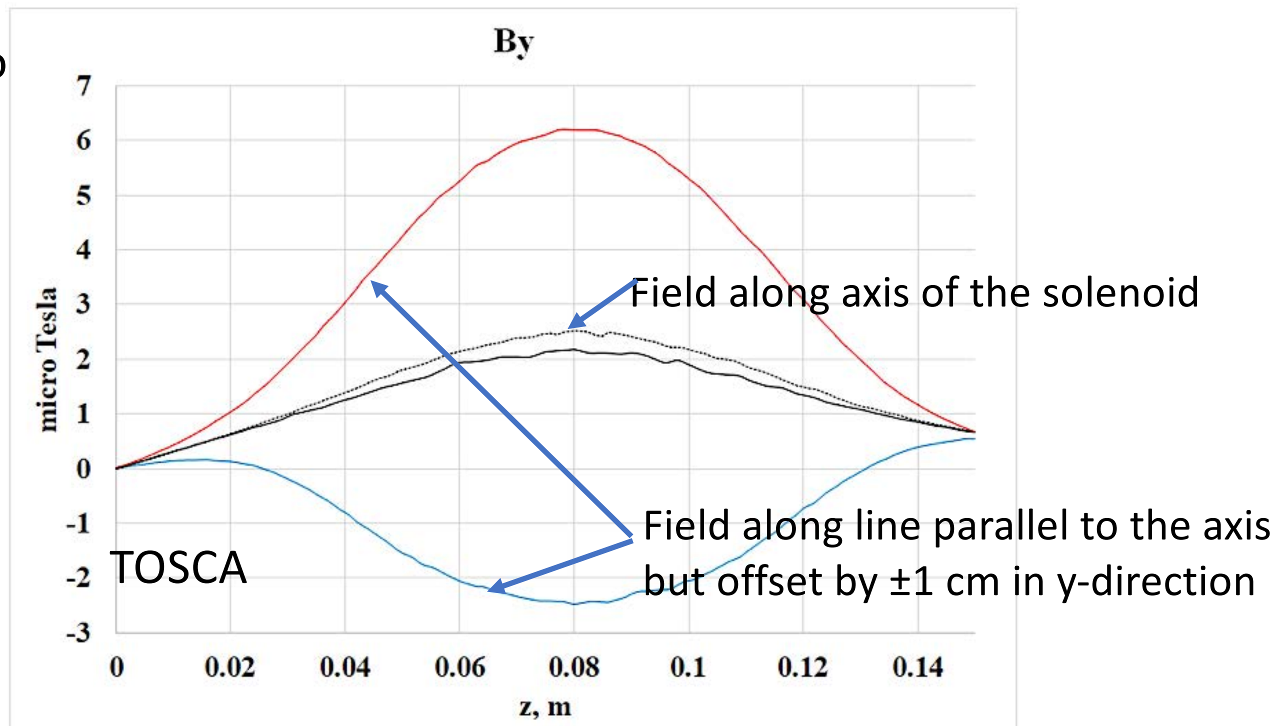
Simple estimates of distortion:

$$\Delta p_x \approx \int_{z_1}^{z_2} B_y dz$$

$\theta < 10\mu$rad requirement leads to

$$\left| \int_{z_1}^{z_2} B_y dz \right| \leq 2\mu T \cdot m$$

Start with the pattern of mis-alignments in the 8 end washers of the washer stack in an insertion segment of the solenoid:

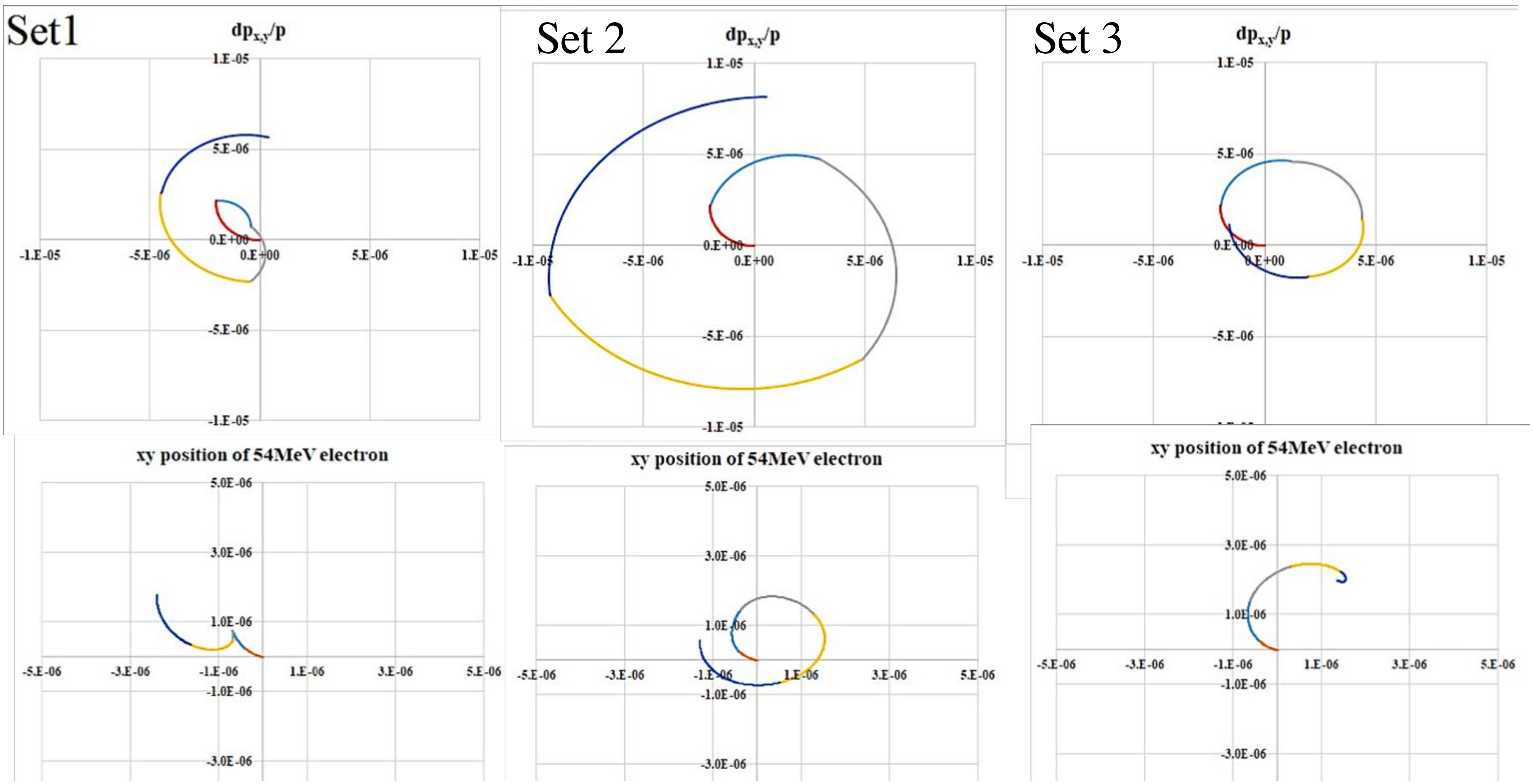


Then concatenate a sequence of those field distortions, each with random rotation, along a long 1 T solenoid. Transport a 52 MeV electron along that field distribution.

Track a 52 MeV electron in the mis-aligned solenoid

$$\frac{d}{dt}(\vec{p}+\delta\vec{p}) = \frac{1}{m_0\gamma}(\vec{p}+\delta\vec{p})\times\{\vec{B}+\delta\vec{B}\} \qquad \frac{d}{dt}\delta\vec{p} = \frac{1}{m_0\gamma}\left(\vec{p}\times\delta\vec{B}+\delta\vec{p}\times\vec{B}\right)$$

Generate 3 different field maps from measured data, transport electron through each map.
Pitch length of gyro-spiral is ~1.1 m, each map provides a sample of micro-alignment over 1.5 m.



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

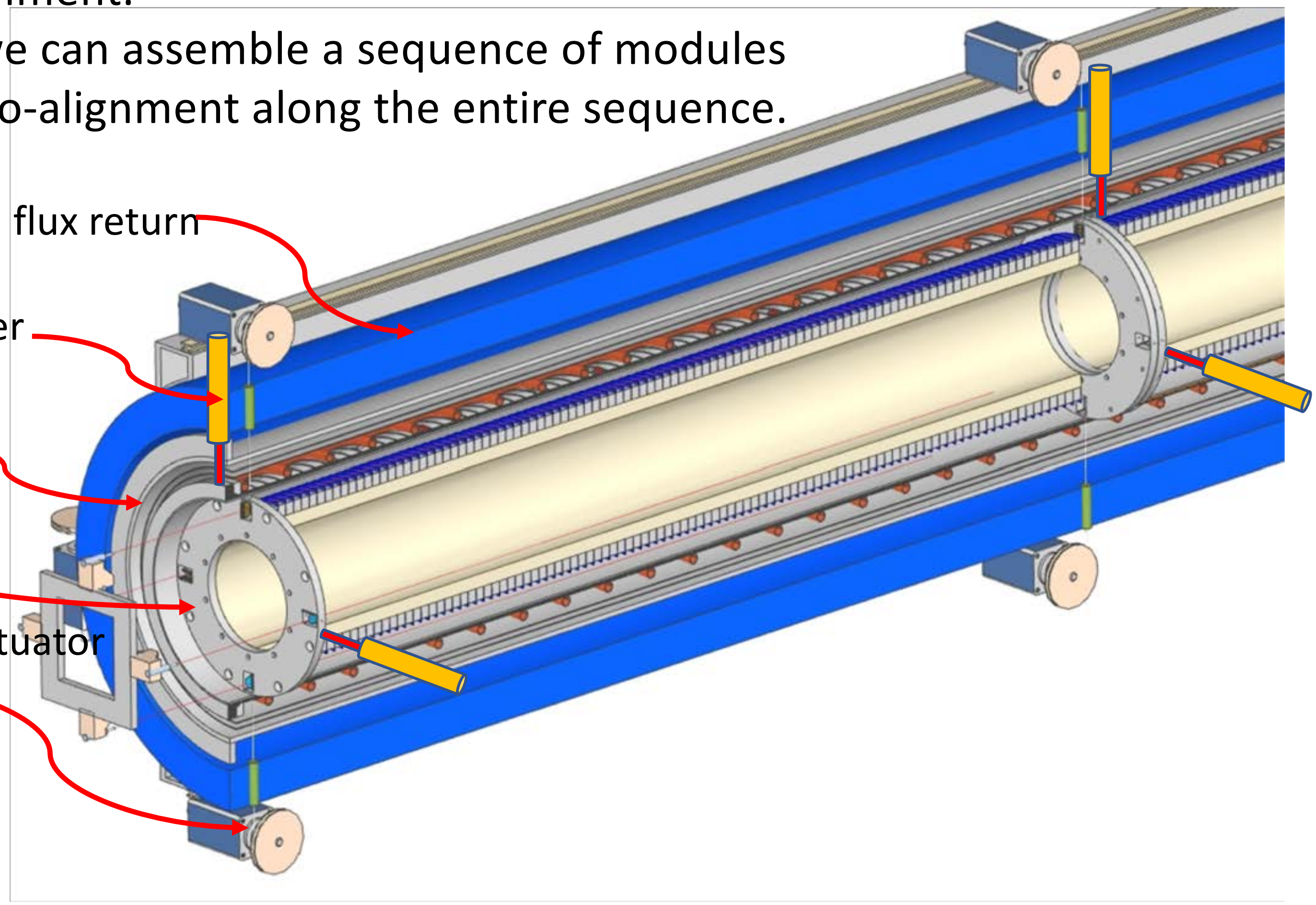
ATC has built and measured a 1-m model of the micro-aligned washer stack.

- Phase 1 SBIR:
  - We built the stack.
  - We built the metrology setup.
  - We measured the alignment within the washer stack.
  - ***Result: washer stack preserves magnetized e-cooling.***
- Phase 2 SBIR proposal:
  - Build a 5 m NbTi 1 T superconducting solenoid.
  - Install a 5 m sequence of washer stacks.
  - Mount the washer stacks and beam tube in solenoid with provisions to preserve micro-alignment over 5 m.
  - Use a micro-electron beam, phosphor screen, and alignment telescope to measure micro-aligned field lines through the 5 m length.

Aligning a sequence of washer stacks within a superconducting solenoid

We have shown that we know how to make a ~ m-long washer stack module with internal micro-alignment.

In Phase 2 we must show that we can assemble a sequence of modules with no gaps and the same micro-alignment along the entire sequence.

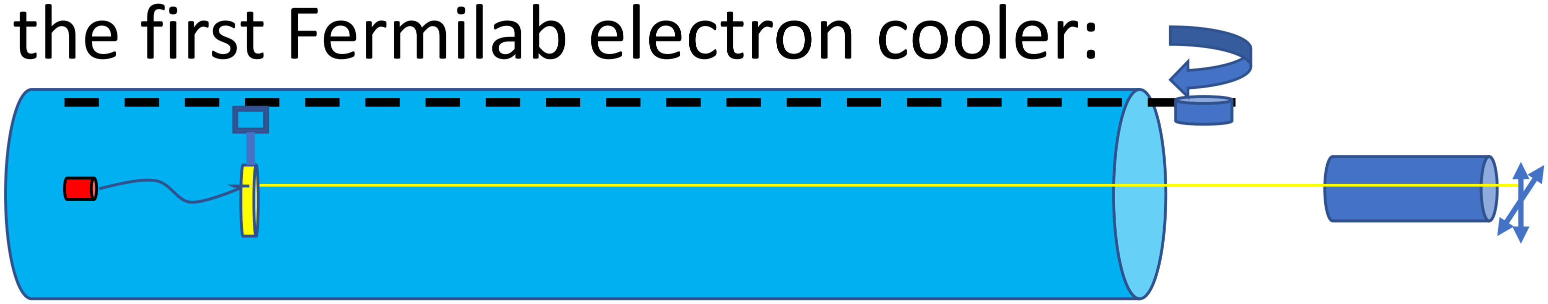


Strategy:

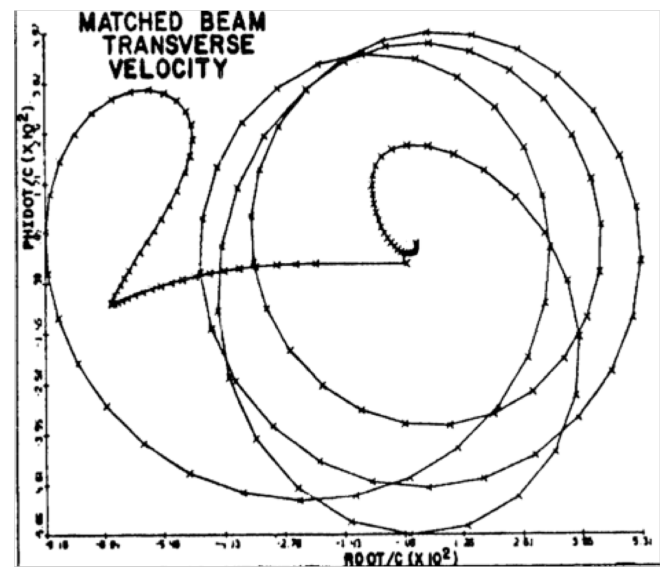
1. Survey monuments = fiducials along the outside of the warm-iron flux return
2. Wire tension supports, each actuated by a stepper motor
3. Capacitive transducers to correlate x/y monuments on washer stack, solenoid, warm iron

Measuring micro-alignment of magnetic field lines using an electron microprobe

- In 1979 PM used an electron micro-probe to follow an actual magnetic line of force along the solenoid of the first Fermilab electron cooler:



- A ~kV e-gun with micro-probe collimator is mounted inside the beam tube of the solenoid near one end.
- A phosphor screen is moved along the solenoid so that the e-beam hits the screen.
- An alignment telescope with digital camera measures the x-y position of the beam spot.



S.B. Herrmannsfeldt *et al.*, ‘The electron beam for the Fermilab electron cooling experiment, IEEE Trans. Nucl. Sci. NS-26, 3, 3236 (1989).

Conclusions

- We have devised a method to micro-align the lines of force in a long solenoid for magnetized cooling.
- We have built a first model of the washer stack.
- We have devised and used a method to measure the micro-alignment of the washers to the precision required for magnetized cooling in JLEIC.
- In Phase 2 we propose to build a 5 m long 1 T model solenoid, equip it with a sequence of washer stacks, and align the stacks to 5 μm co-planarity.
- We will use an electron micro-probe to directly measure the micro-alignment of the lines of force.
- ***Outcome: eliminate technical risk of micro-alignment for high-energy magnetized cooling.***