A Multi-Cubic-Meter Ioffe Trap for Project 8

Alec Lindman for the Project 8 Collaboration PRISMA+ Cluster of Excellence | Johannes-Gutenberg Universität Mainz, Mainz, Germany | lindman.alec@gmail.com

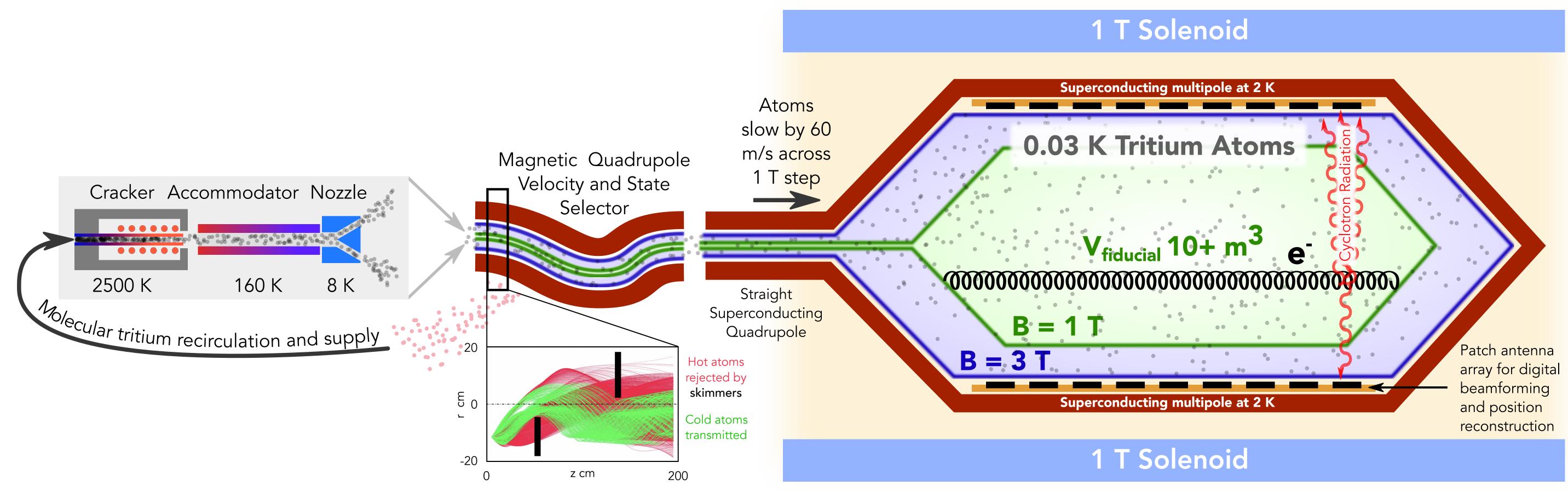




CRES

Cyclotron Radiation Emission Spectroscopy is a new method, invented by Project 8, for measuring individual electron energies. We use it to record the energy spectrum of tritium beta decay, which is sensitive to the mass of the neutrino.

CRES converts the emission frequency of electrons in a uniform field back into the original electrons' energies. The signals are small, about 1 fW, but we regularly measure them and have achieved ~2 eV resolution at 17.8 keV.



Atomic Tritium

The energies of electrons from beta decays of molecular tritium are smeared by about 1 eV, thanks to rovibrational excitations of the molecular system. Atomic tritium has no such smearing, making it a compelling tool for precision spectroscopy.

We have designed a production, cooling, and injection chain to supply tritium atoms cooled to about 30-50 mK for storage in the main trap.

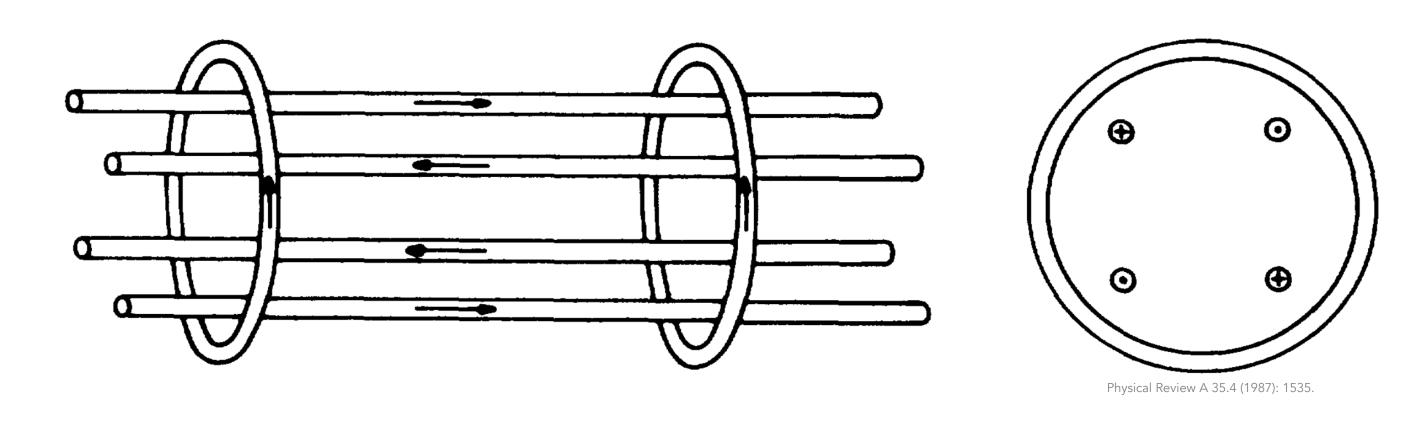
Using atomic tritium, Project 8 will have a sensitivity of 0.04 eV (90% CL) to the neutrino mass.

Requirements

The final Phase IV of Project 8 will require:

- A background 1-T solenoid
- A closed magnetic bottle within the solenoid
- At least 10 m³ of fiducial volume
- Better than 10⁻⁷ nonuniformity in the fiducial volume
- An opening for loading the trap with atoms
- Separate coil (~4 K) and wall (2-90 K) temperatures
- Space for a tritium isolation container
- Space for the CRES antennae

The design proposed here achieves or accommodates each of these requirements.



Proposed Trap Design

The design shown here is composed of a loading

quadrupole, a new transition/closure topology, and a

high-order main trap multipole. Simulations and

calculations show it provides appropriate field

Unlike classic loffe traps, the diameter of the main trap

is completely independent of the loading opening, if

any, and there are no pinch coils. This permits a low-

field region of unprecedented scale and uniformity.

uniformity over a large fiducial volume.

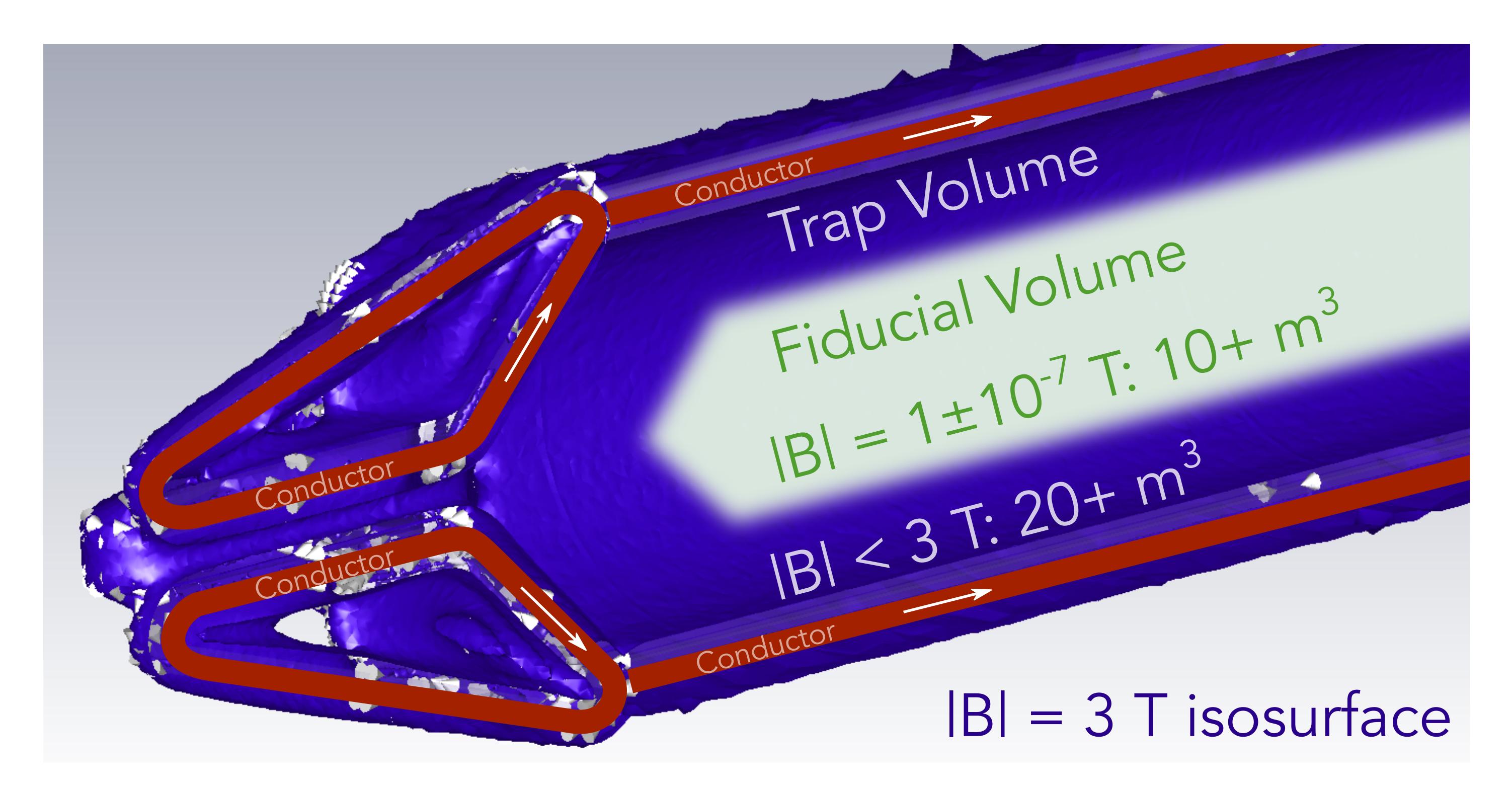
The Classic Ioffe Trap

Atomic tritium recombines to molecules on contact with physical surfaces. Therefore, a magnetic bottle is required to store tritium atoms for a useful length of

Four axial conductors and two pinch coils form the traditional loffe trap. However, this configuration fails two important requirements of Project 8.

Field uniformity: any inhomogeniety in the magnetic field in the fiducial volume directly worsens our energy resolution; the quadrupole-pinch loffe trap has a strongly-varying field everywhere.

Trap volume: if the quadrupole bars are moved apart for more volume, low-field gaps will appear and atoms will escape the trap. Even loffe traps that are large by atom- or neutron-trapping standards are measured in millimeters or centimeters; Project 8 requires a meterscale trap.



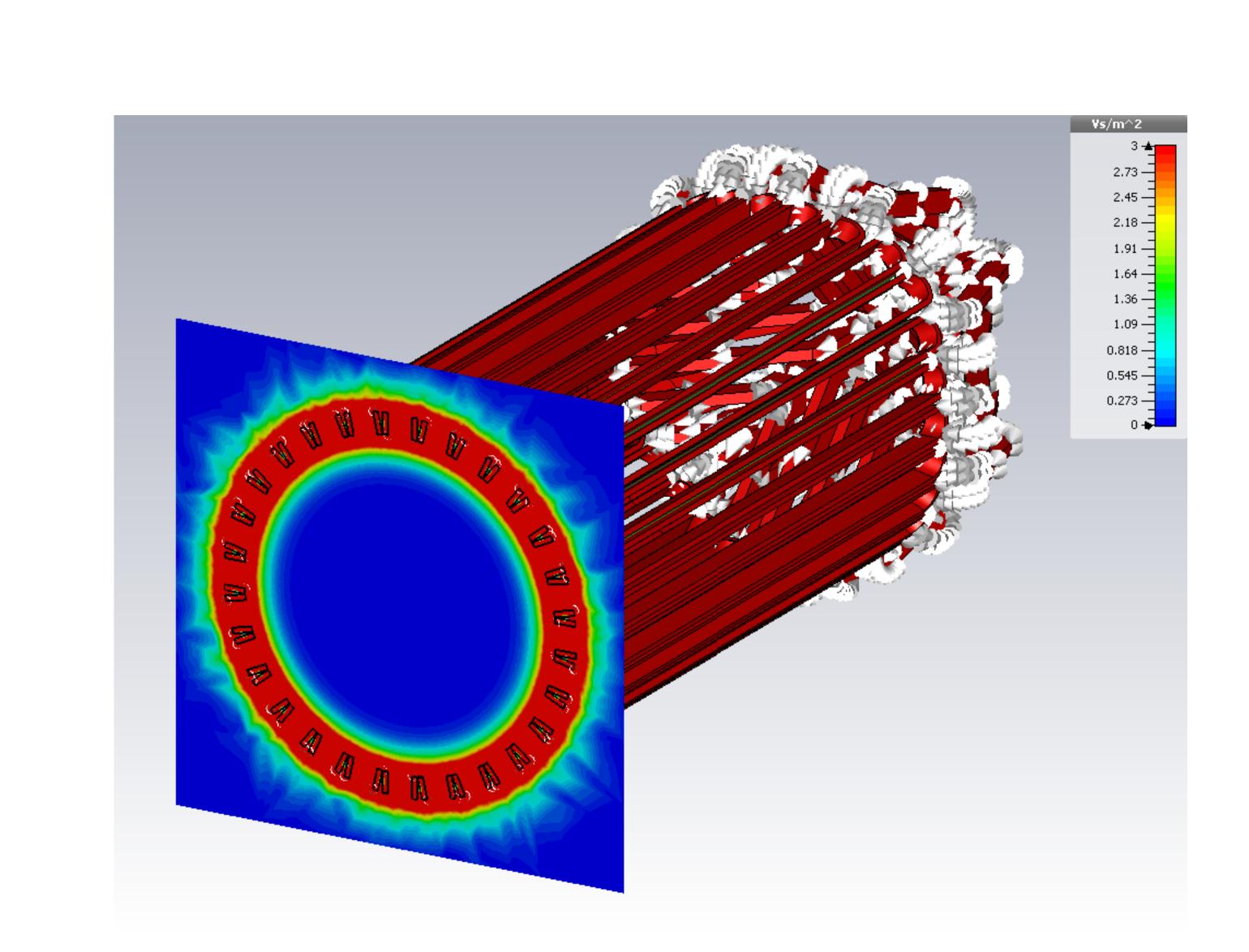
High Multipole Orders

As the four bars of a traditional loffe trap are moved outwards, they eventually develop gaps in the trapping isosurface. For larger trap radii, then, we must add additional conductors in the gaps.

Preserving the four original conductors to form the loading opening, the allowed conductors numbers are:

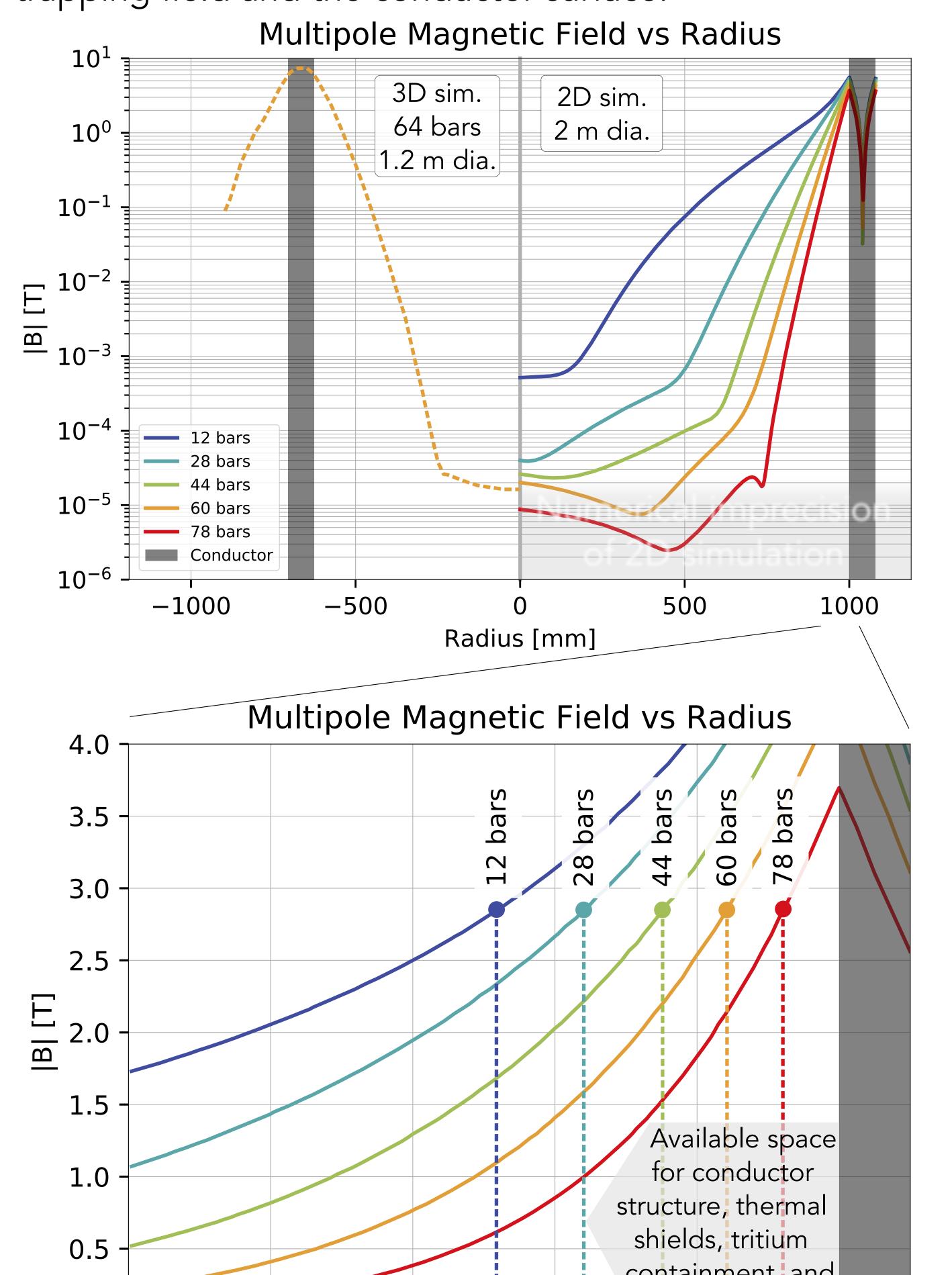
$$N_{\text{bars}} = 4 + 8n \ \forall \ n \in \mathbb{Z}$$

Below is an example of a high-order, large-volume trap with a 1.2-m diameter. The shape of the field near the walls is nearly independent of the overall diameter; see the section on Radial Trapping for field profiles.



Radial Trapping

High multipole orders produce large low-field regions, but leave limited space for structure between the trapping field and the conductor surface.



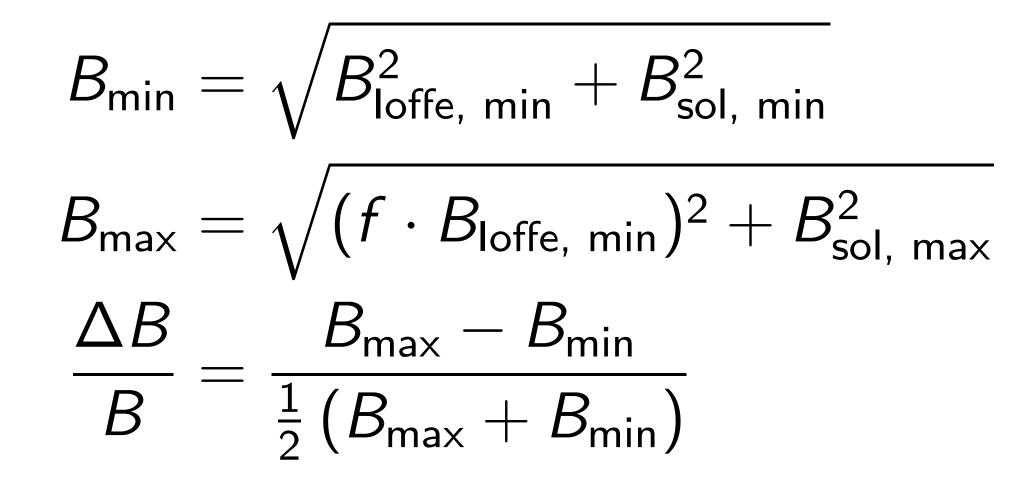
Radius [mm]

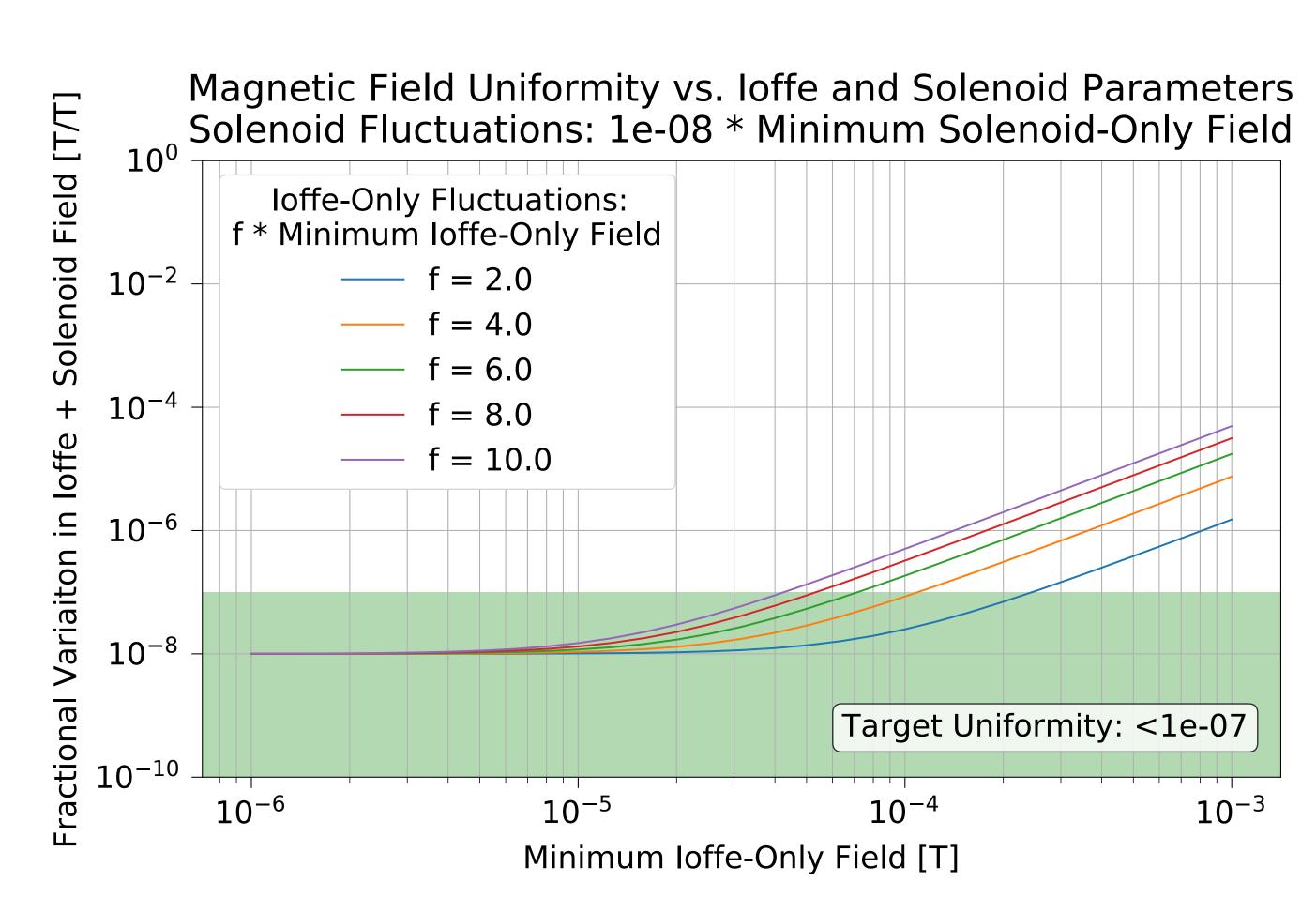
Flat Racetracks

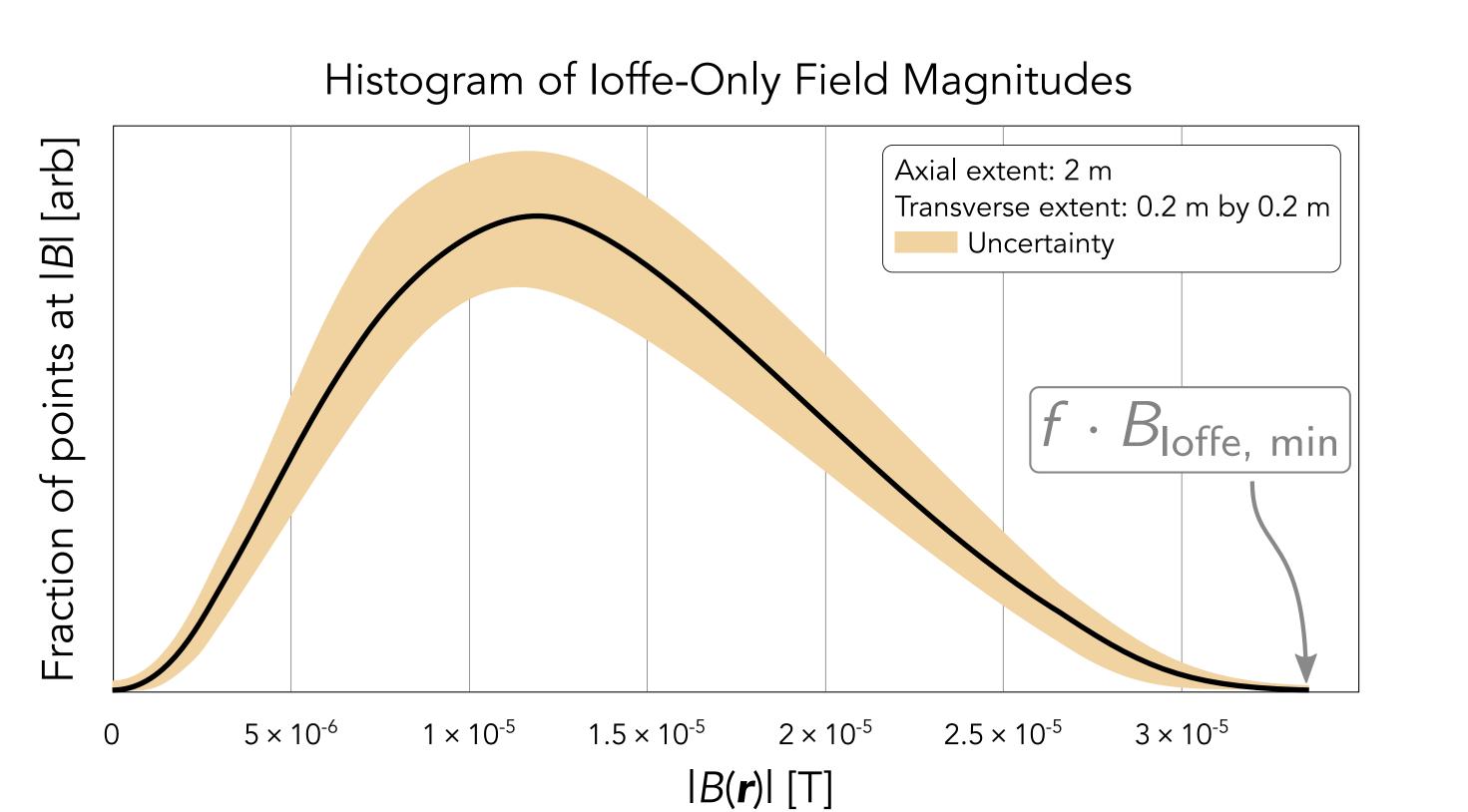
The original Blue Whale is elegant but difficult to manufacture. It is possible to replicate its function with only planar racetrack coils, which simplifies manufacturing. The proposed magnet uses NbTi coils of 40 mm by 80 mm cross-section at 200 A/mm².

Field Uniformity

The proposed Blue Whale loffe magnet meets the Project 8 target of 10⁻⁷ fractional variation when summed in quadrature with a sufficiently uniform



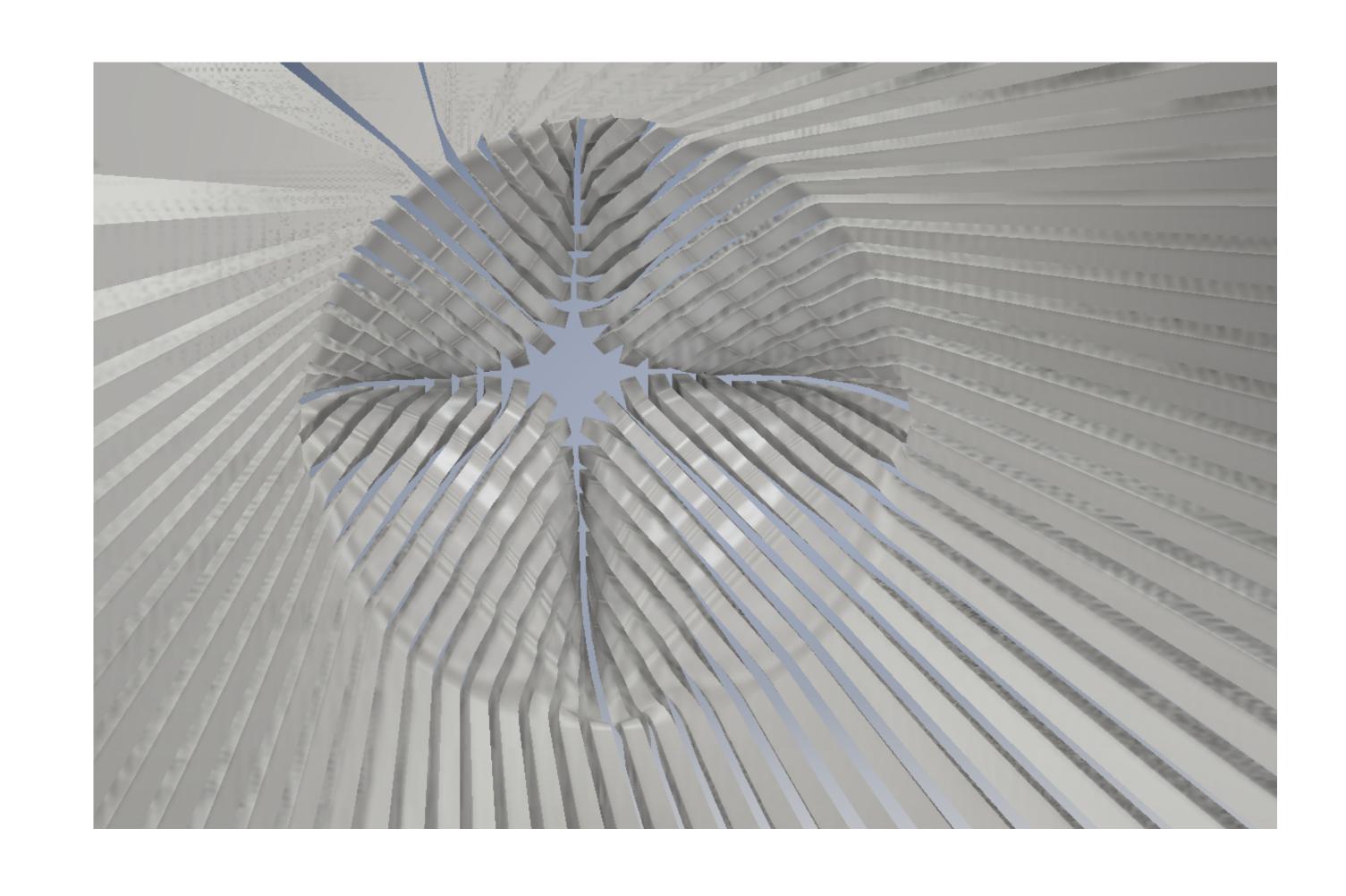




The "Blue Whale"

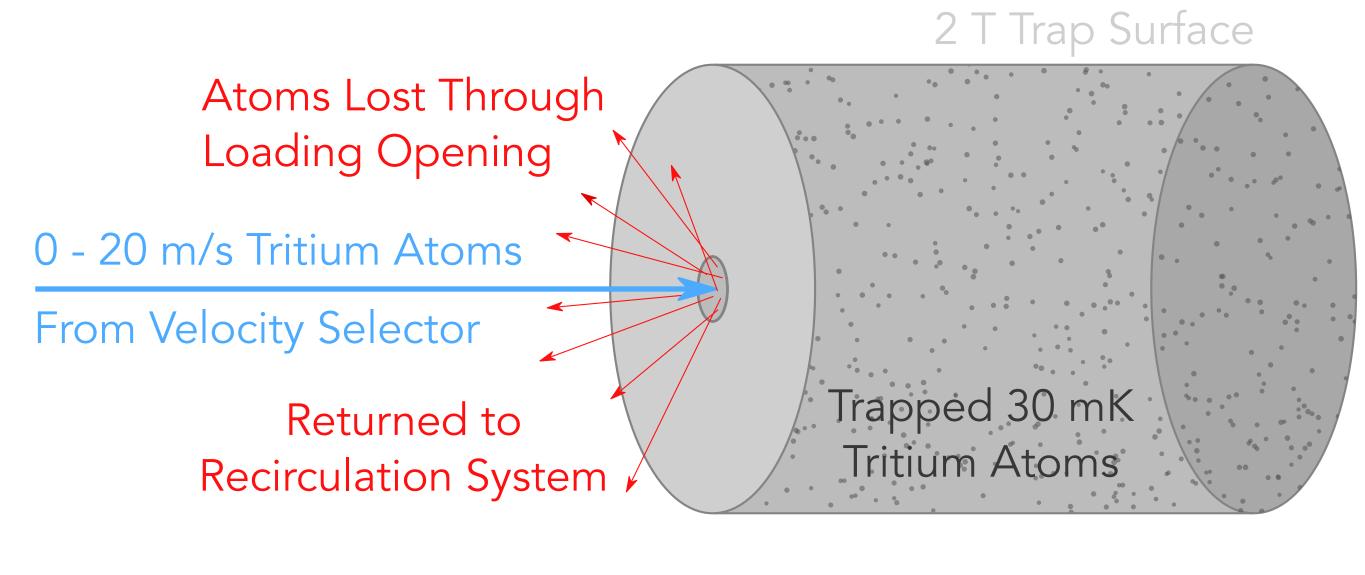
Two circular pinch coils close the ends of the traditional loffe trap. The axial extent of these coils' fields is substantial: for a 1-m diameter coil with a 2-T peak field, the field on axis does not drop below 10⁻⁷ until 135 m from the coil plane.

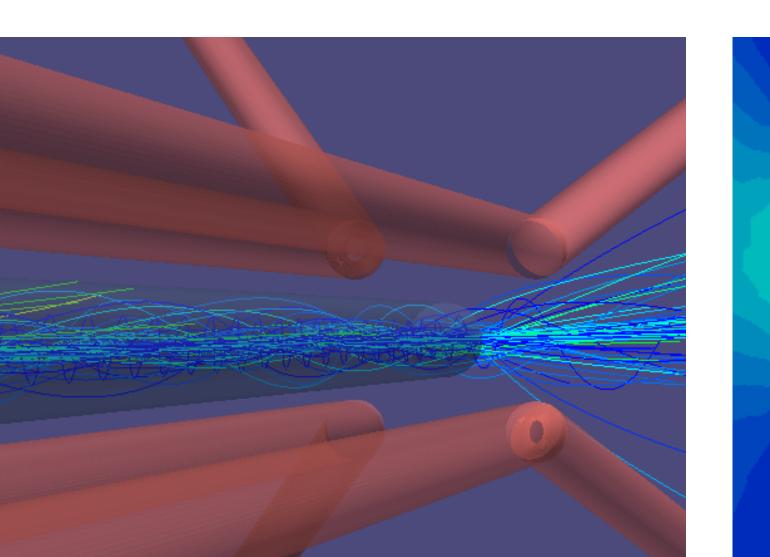
Instead, consider the trap surface as a flexible cylinder. By pinching four points at one end together, the cylinder closes down without pinch coils.

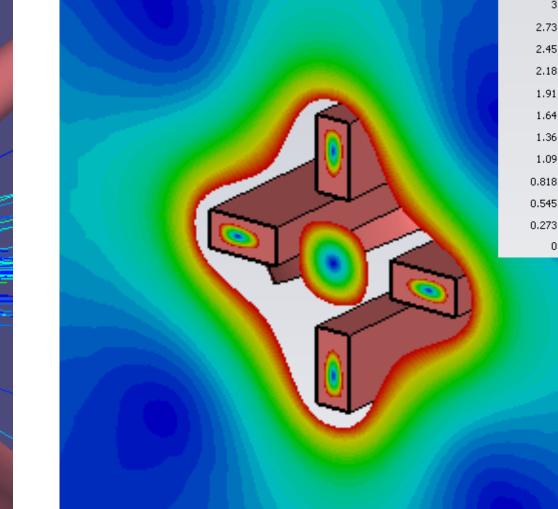


Loading the Trap

To fill our magnetic bottle, we take perhaps the simplest approach: leaving it uncapped. A beam of atoms is directed at a hole in the trapping potential, first filling the trap and then balancing the flux of lost atoms to maintain a steady trapped population at intended density.







Next Steps

We are proceeding with engineering design of a scaled-down Atom Trapping Demonstrator, which will include all the mechanical and thermal engineering required to translate this proposed design into a fullscale apparatus for Project 8.

