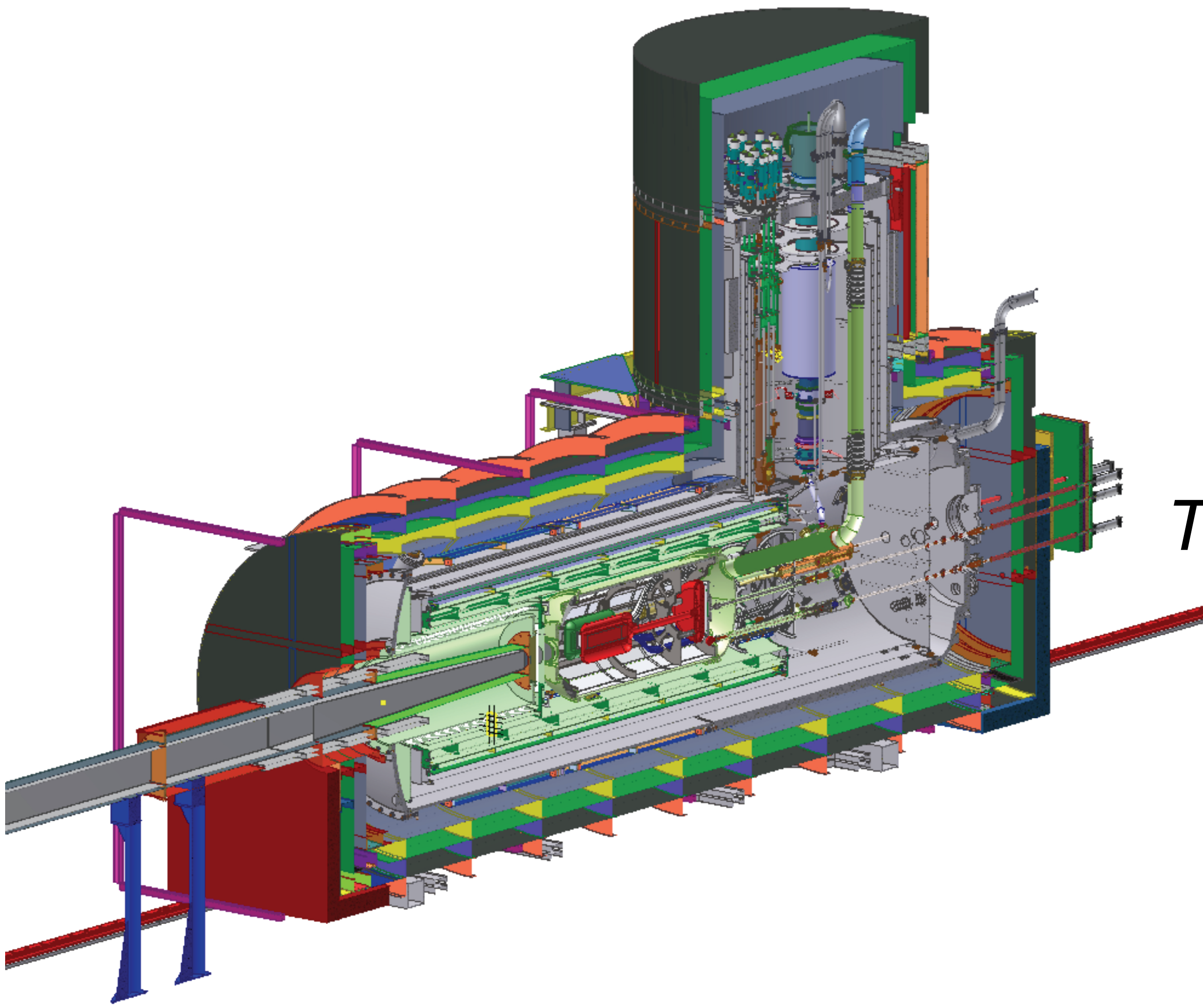
Search for the Electric Dipole Moment of the Neutron



Paul Huffman

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Oak Ridge National Laboratory
Triangle Universities Nuclear Laboratory

Overview

- Our goal is to measure the neutron electric dipole moment with a sensitivity of $\boldsymbol{d_n < 5 \times 10^{-28}}$ **e•cm** (90%)
  – *the current experimental limit is* $\boldsymbol{d_n < 3 \times 10^{-26}}$ **e•cm** *(Institut Laue Langevin)*

- Collaborative effort based at Oak Ridge National Laboratory (ORNL), that includes 21 institutions and more than 67 individuals.

Physics Motivation

Significant discovery potential in search for EDMs

- If particle EDMs are observed in the next round of experiments, a new source of CP violation will have been discovered.

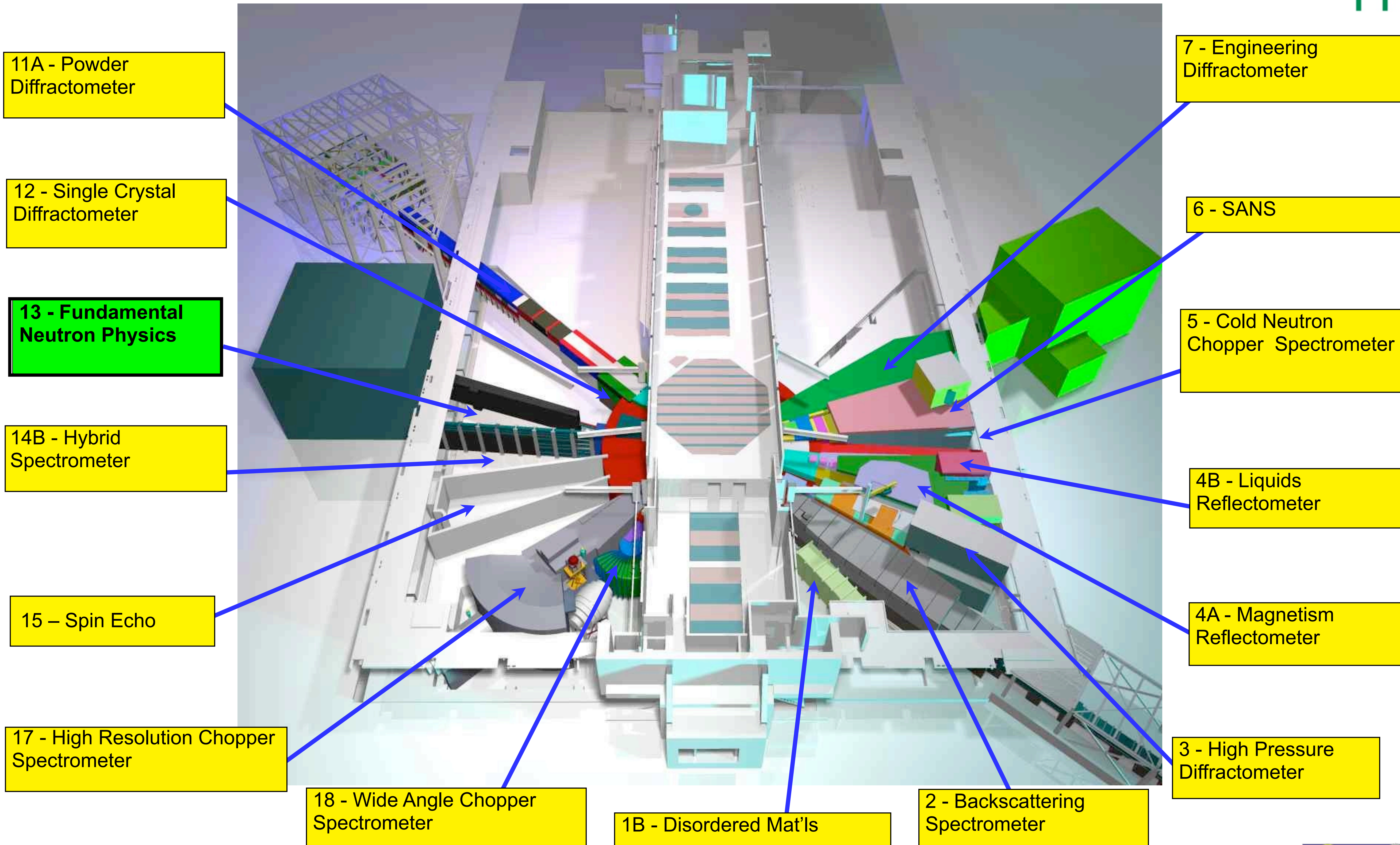
- Such CP violation could play a role in explaining the observed excess of matter over anti-matter in the Universe.

- The neutron is a key component of understanding new CP violation should it be observed in any EDM.

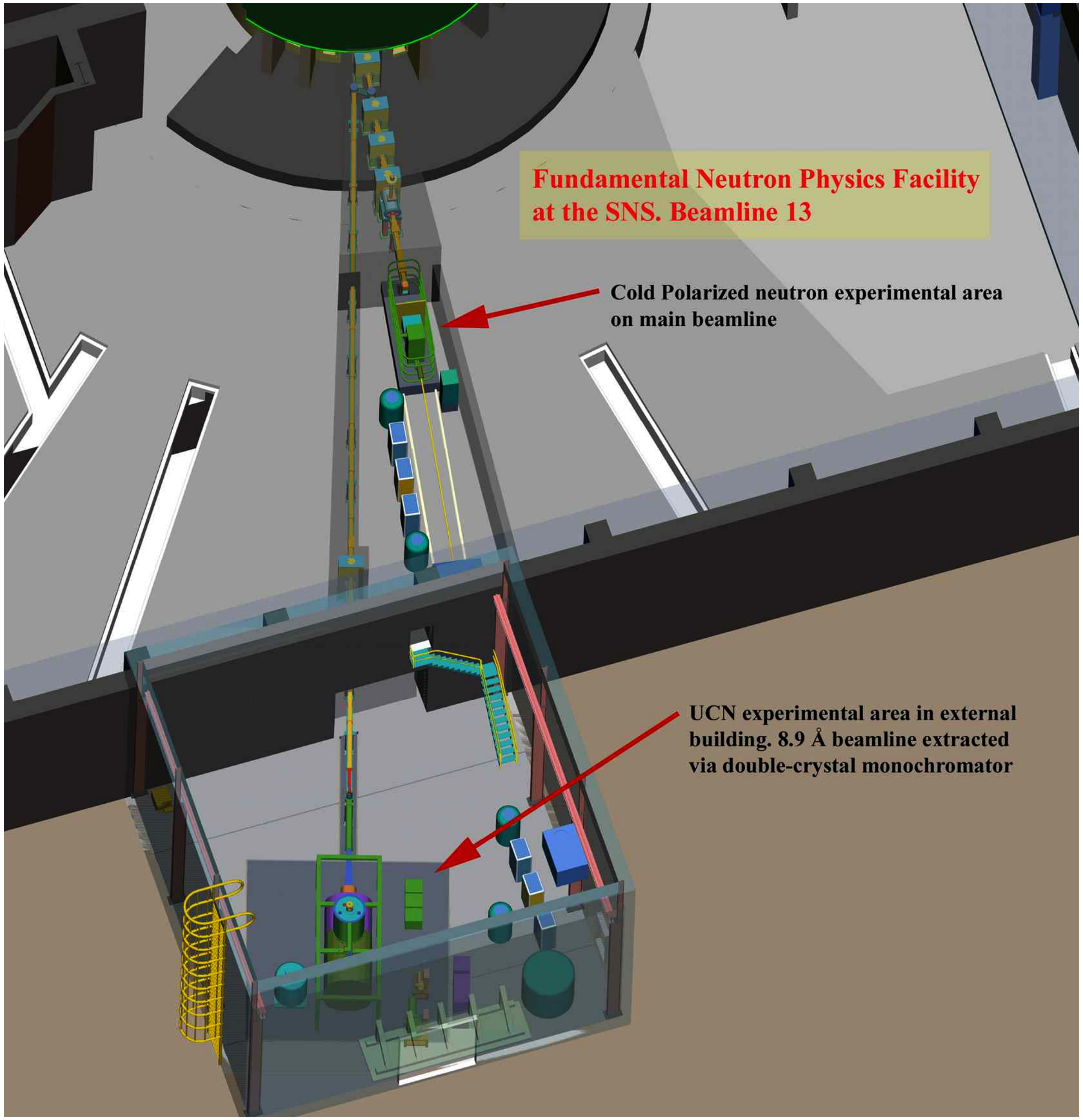
- EDM searches continue to be compelling even as the LHC produces new physics results.

SNS Facility, Oak Ridge, TN

SNS Instrument Suite



FNPB Facility



Unique Features of Our Experiment

- Production of ultracold neutrons (UCN) within the apparatus
  – *higher UCN density and longer storage times*
- Use of liquid as a high voltage insulator
  – *higher electric fields*
- Use of a ^{3}He co-magnetometer and superconducting shield
  – *better control of magnetic field systematics*
- Employ two different measurement techniques
  – *oscillation of scintillation rate and dressed spin techniques*

Tackling unknown systematic effects requires unique handles in the experiment that can be varied.

Figure of Merit for EDM Experiments

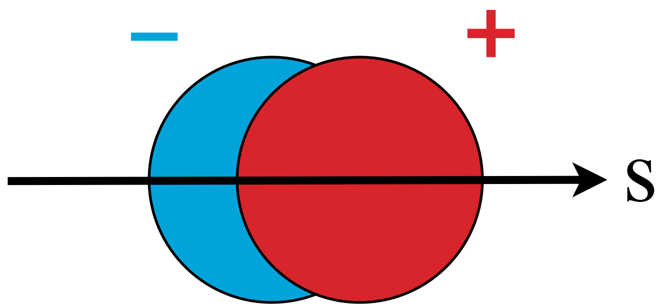
$$E\sqrt{N\tau}$$

By performing the experiment directly in superfluid helium-4 (dielectric properties + superthermal neutron production) that is doped with polarized helium-3 that serves as a co-magnetometer and spin precession analyzer:

$\tau \rightarrow 4\ \tau$
$N \rightarrow 100\ N$
$E \rightarrow 5E$

× ~100 when operated at the SNS

Basic Experimental Technique



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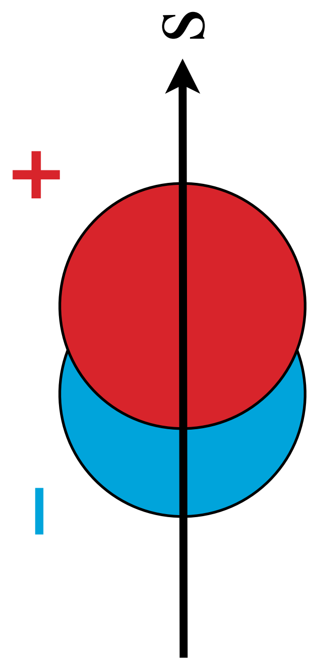

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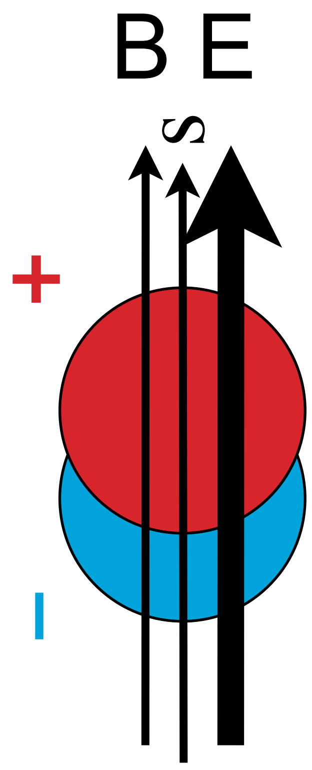

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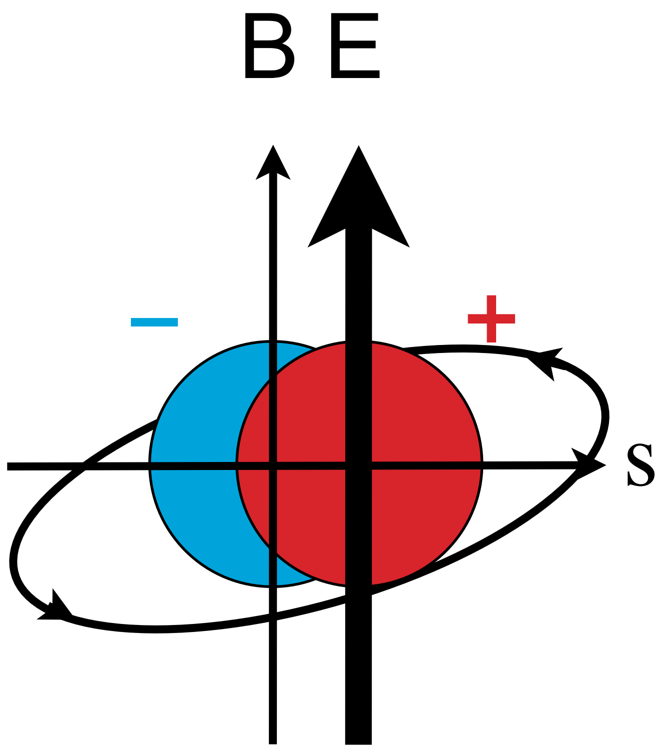
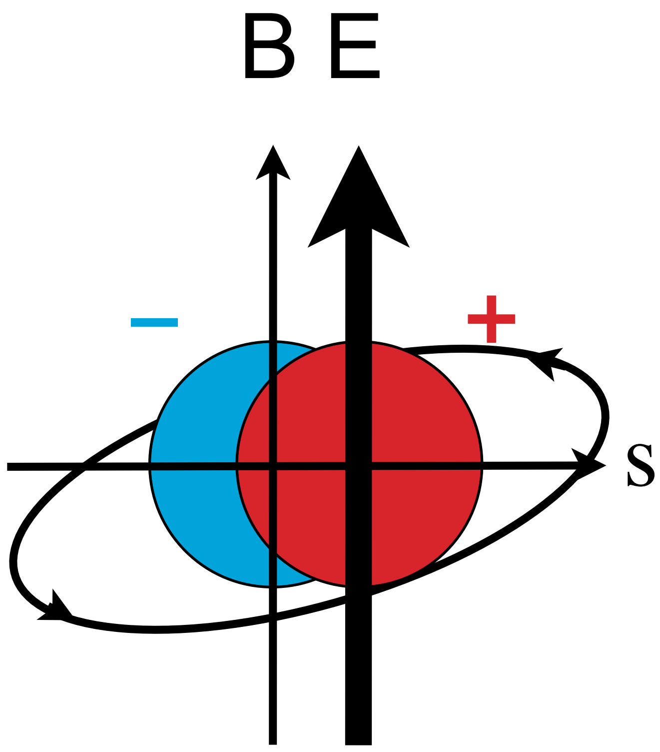


Look for a precession frequency $f_n = \gamma_n B \pm 2 d_n E$

Basic Experimental Technique



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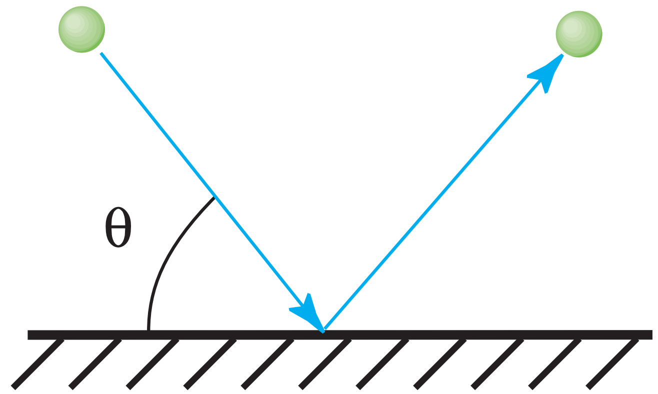
Key Experimental Concepts

- Ultracold Neutrons/Superthermal Production
- ^{3}He Co-Magnetometry
- Charge Particle Detection in Liquid Helium

Ultracold Neutrons

- Strong Interaction



$$\sin\theta \le \sin\theta_c = (V/E)^{1/2}$$

$$V = \frac{2\pi\hbar^2}{m} Na$$

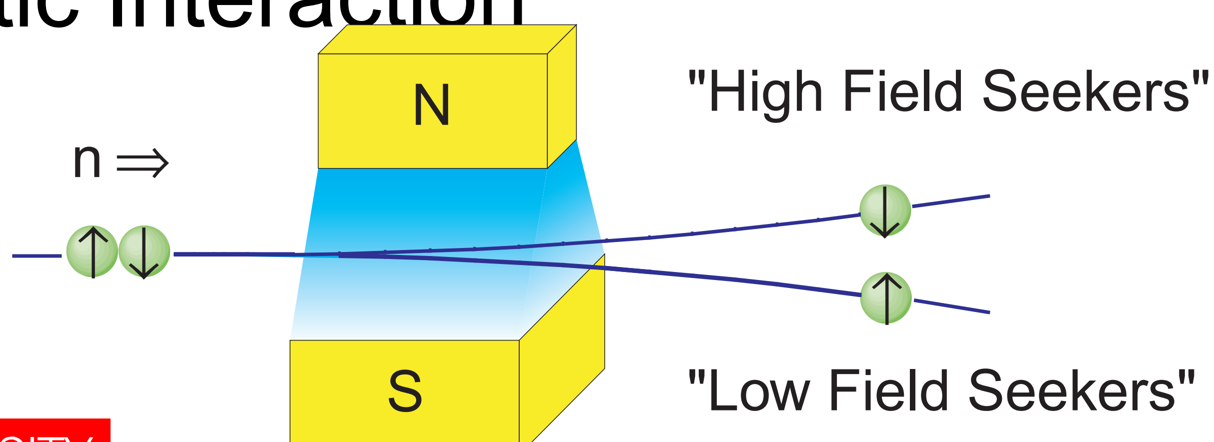
$$V \sim 10^{-7}\text{eV}$$

- Gravitational Interaction

$$V_g = mgh$$

$$10^{-7}\text{eV/m}$$

- Magnetic Interaction

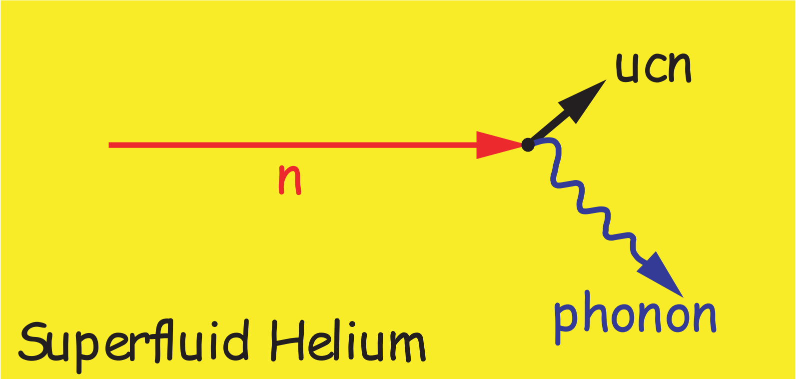


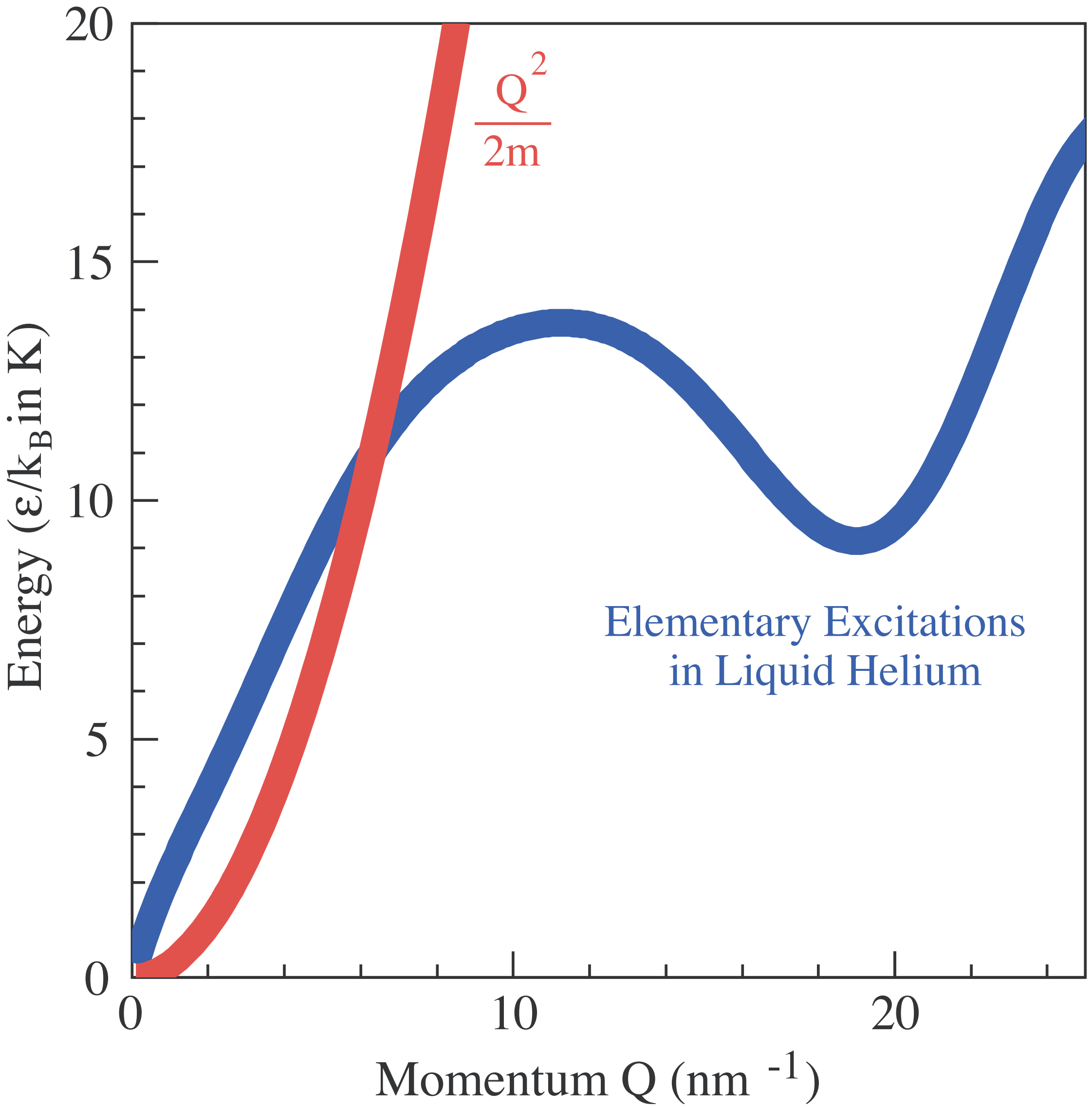
$$V_m = -\vec{\mu} \cdot \vec{B}$$

$$10^{-7}\text{eV/T}$$

Superthermal Production of UCN

- 8.9 Å (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.



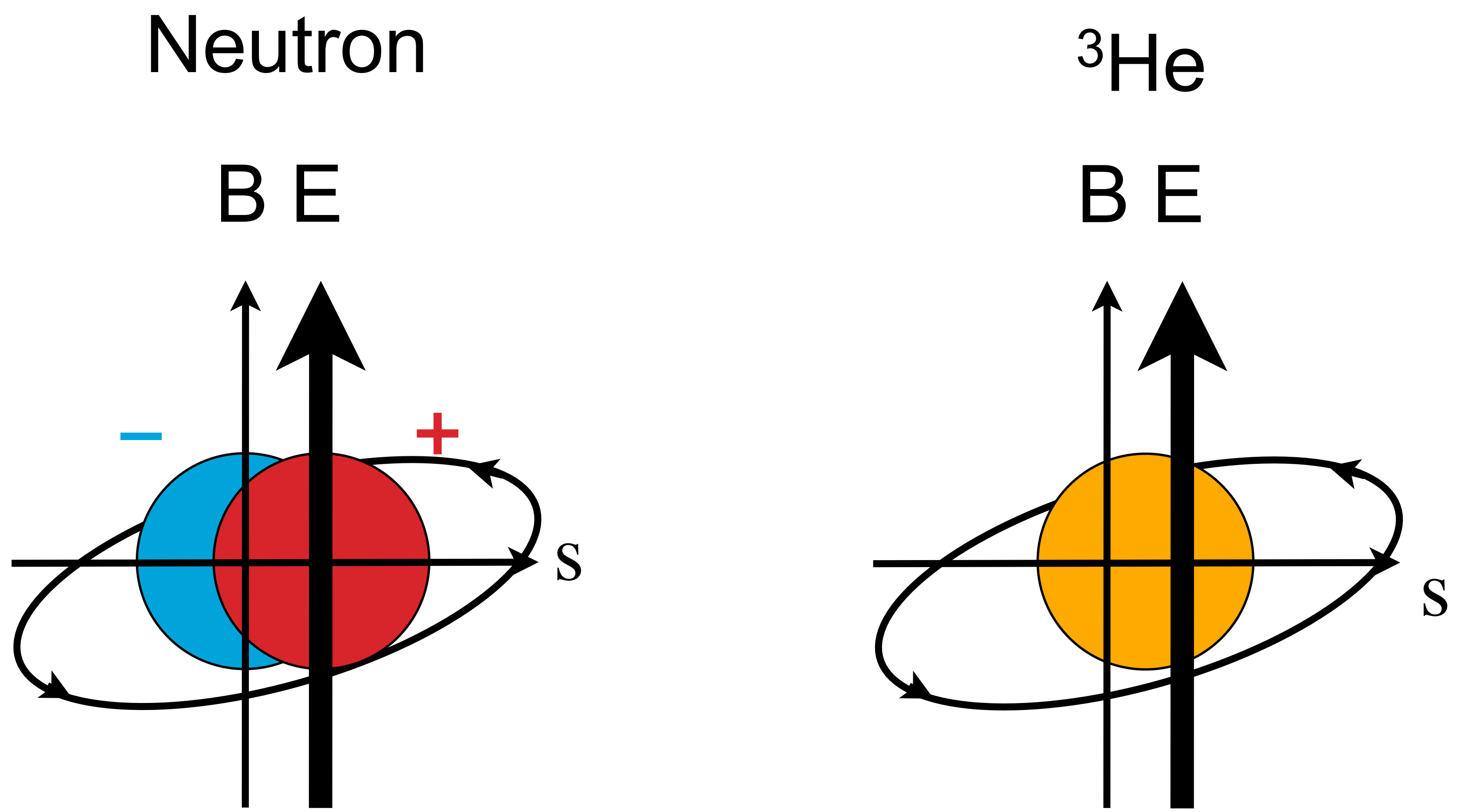


- Upscattering (by 12 K phonon absorption)

  ~ Population of 12 K phonons

  ~ $e^{-12\ K/T_{bath}}$

Co-Magnetometry



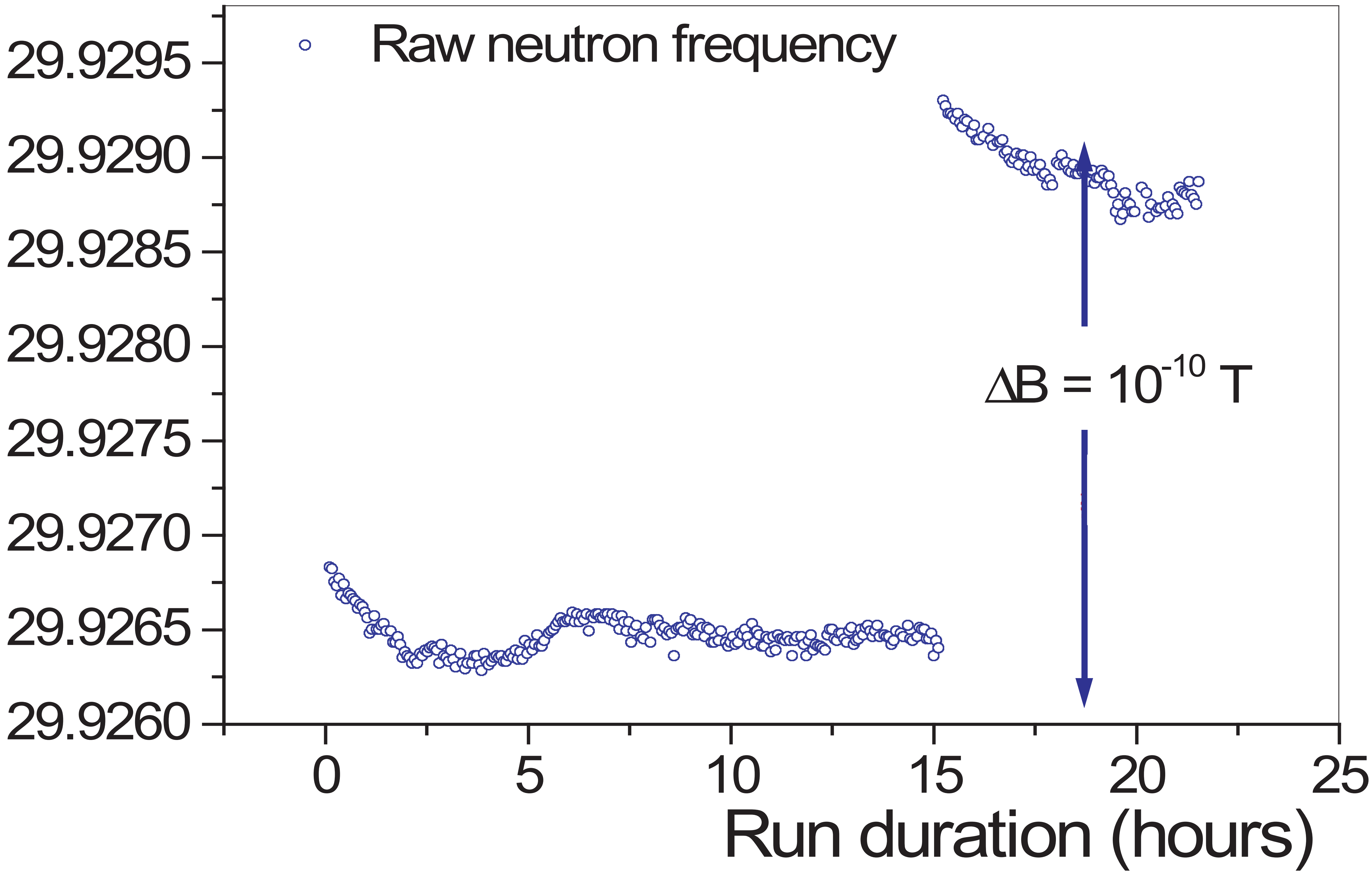
$f_n = \gamma_n B \pm 2\, d_n E$

$f_3 = \gamma_3 B$

$\gamma_3 = 1.1\ \gamma_n$

- Look for a difference in precession frequency
  $f_n\text{-}f_3 = (\gamma_n\text{-}\gamma_3)\, B \pm 2\, d_n E = (0.1\ \gamma_n)\ \mathrm{B} \pm 2\, d_n E$
- Detect precession of ^{3}He magnetization by SQUIDS which serves as a direct magnetometer ($d_{3He} << d_n$)

^{199}Hg Co-Magnetometer (ILL Experiment)



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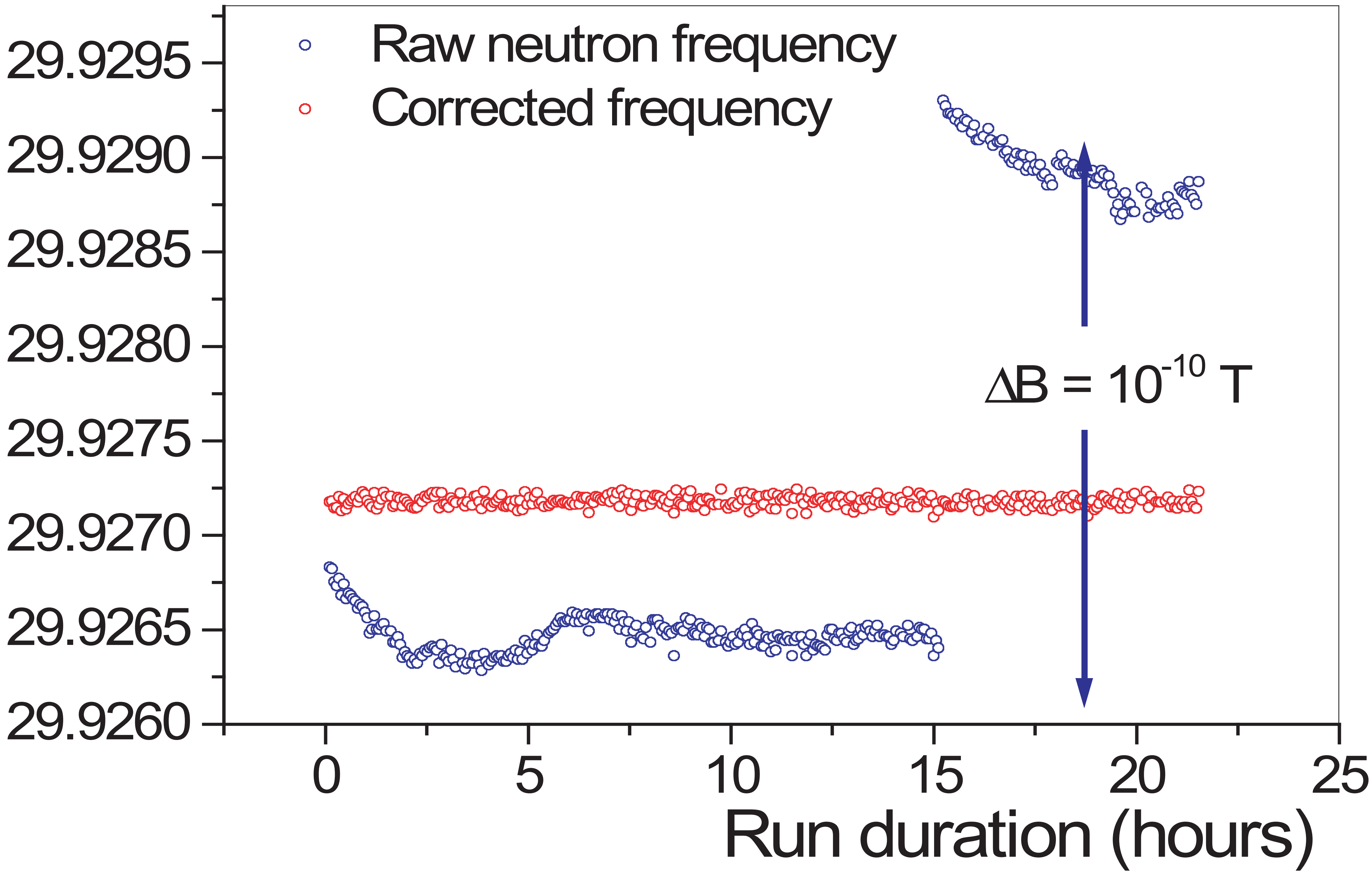
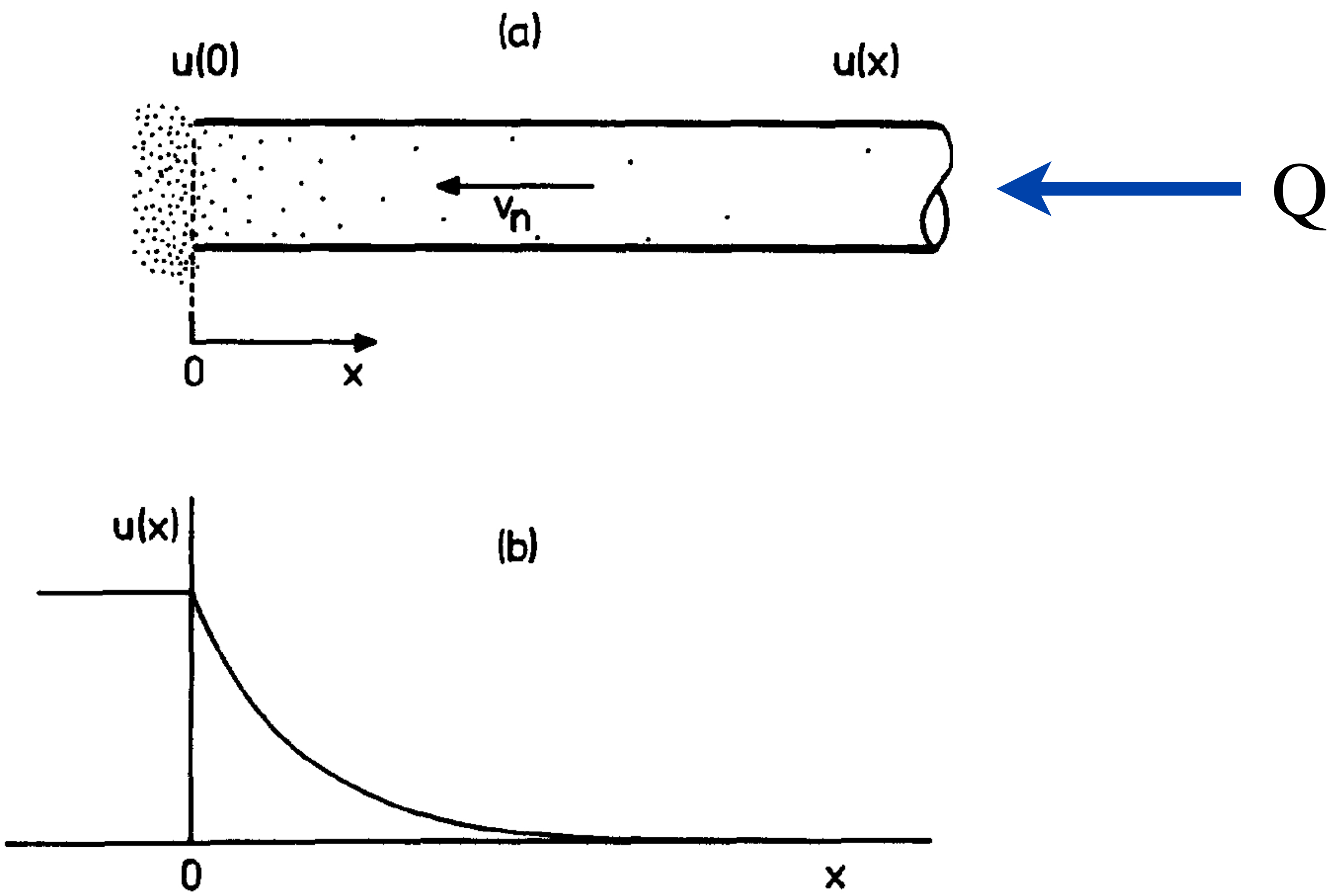


^{3}He Transport - Heat Flush Technique

- Used to move ^{3}He around in the apparatus
- Source of our isotopically pure ^{4}He



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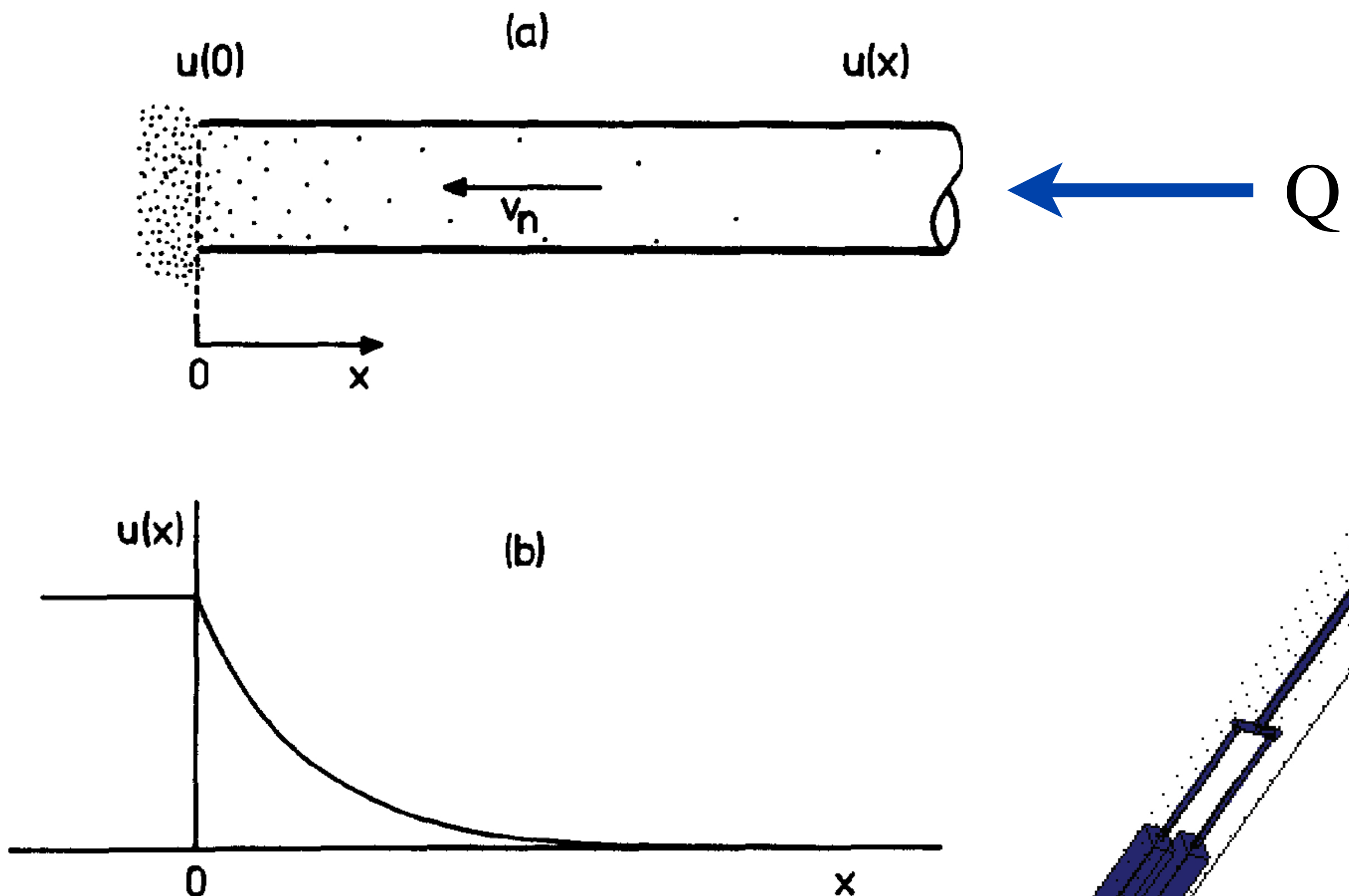

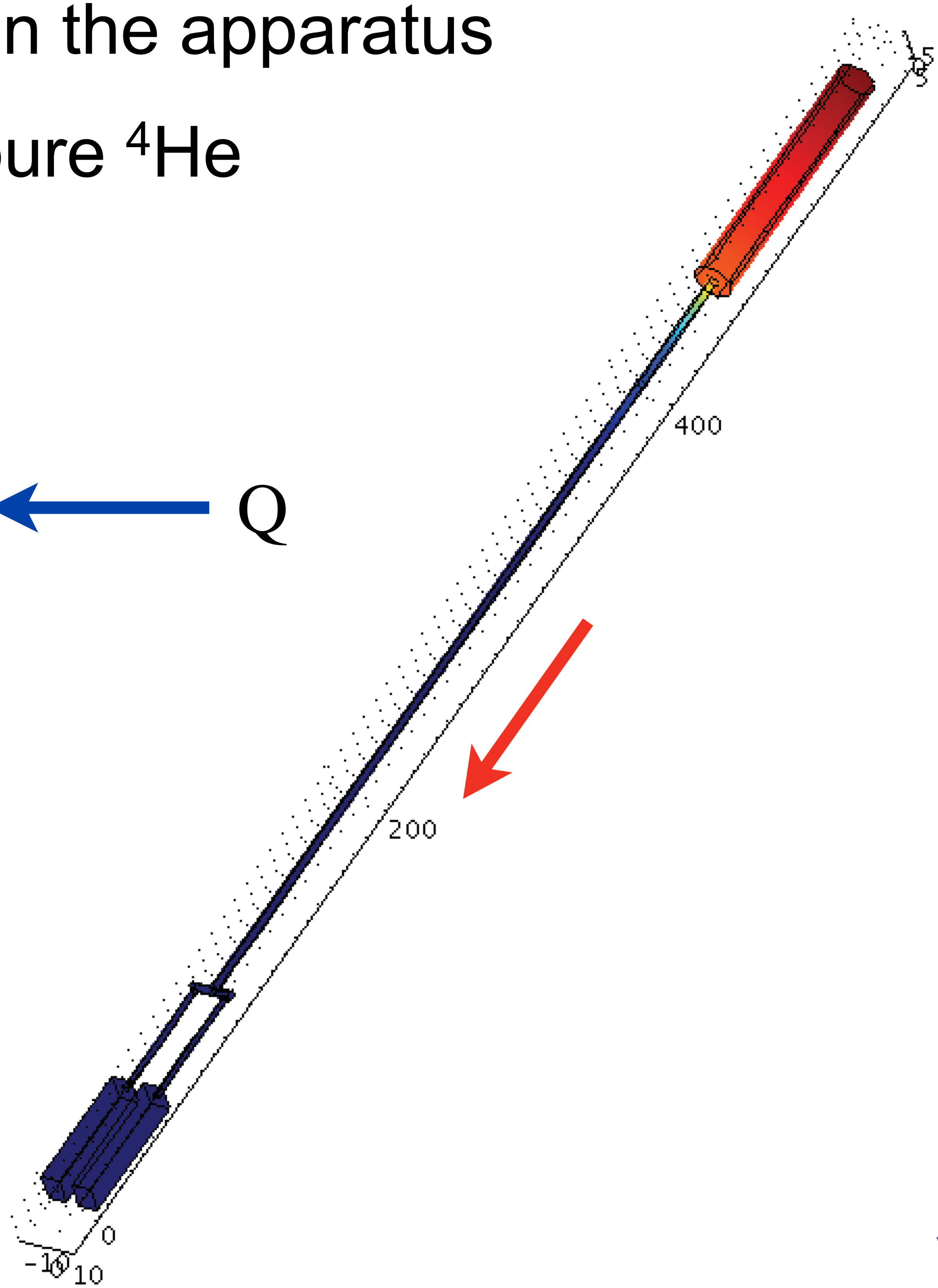

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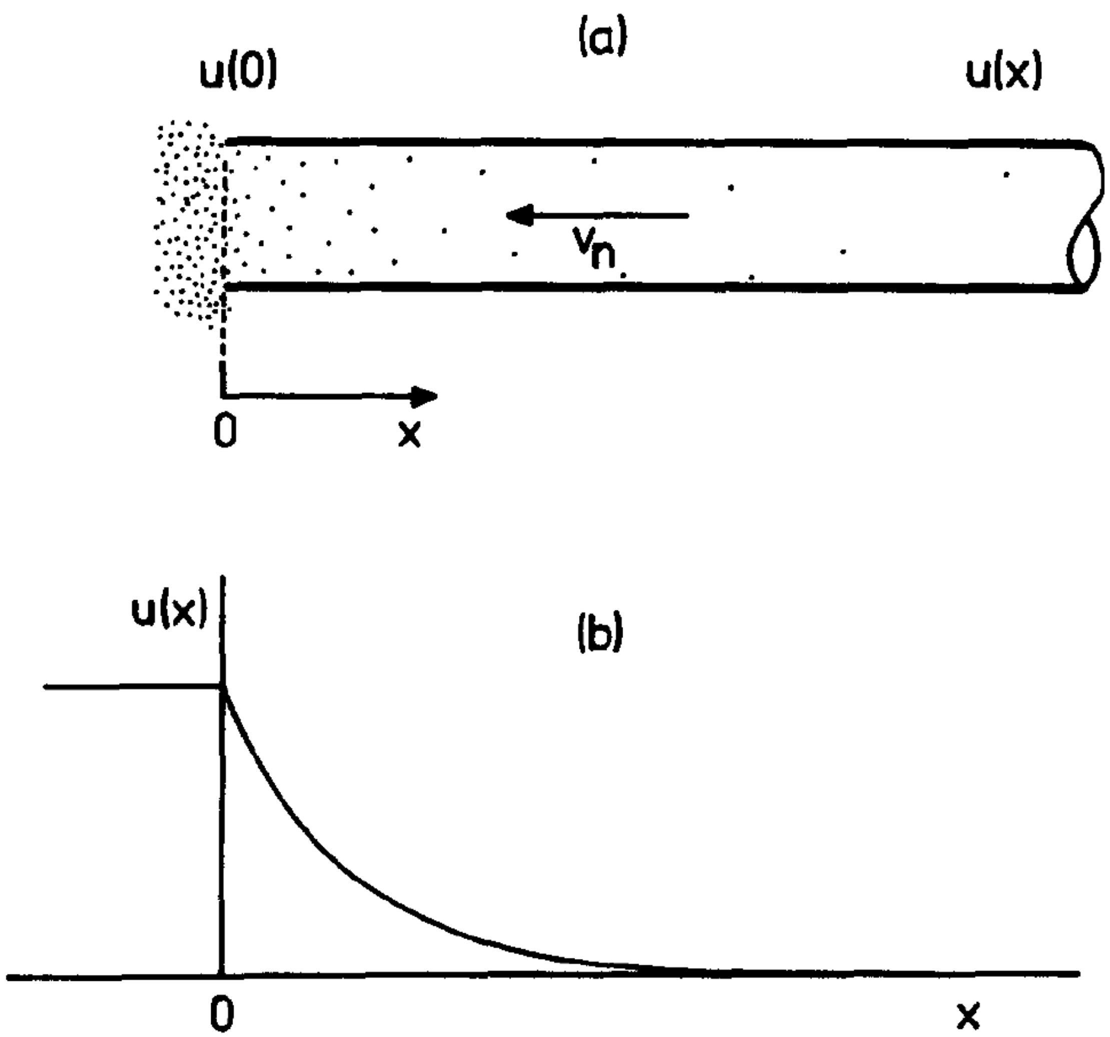
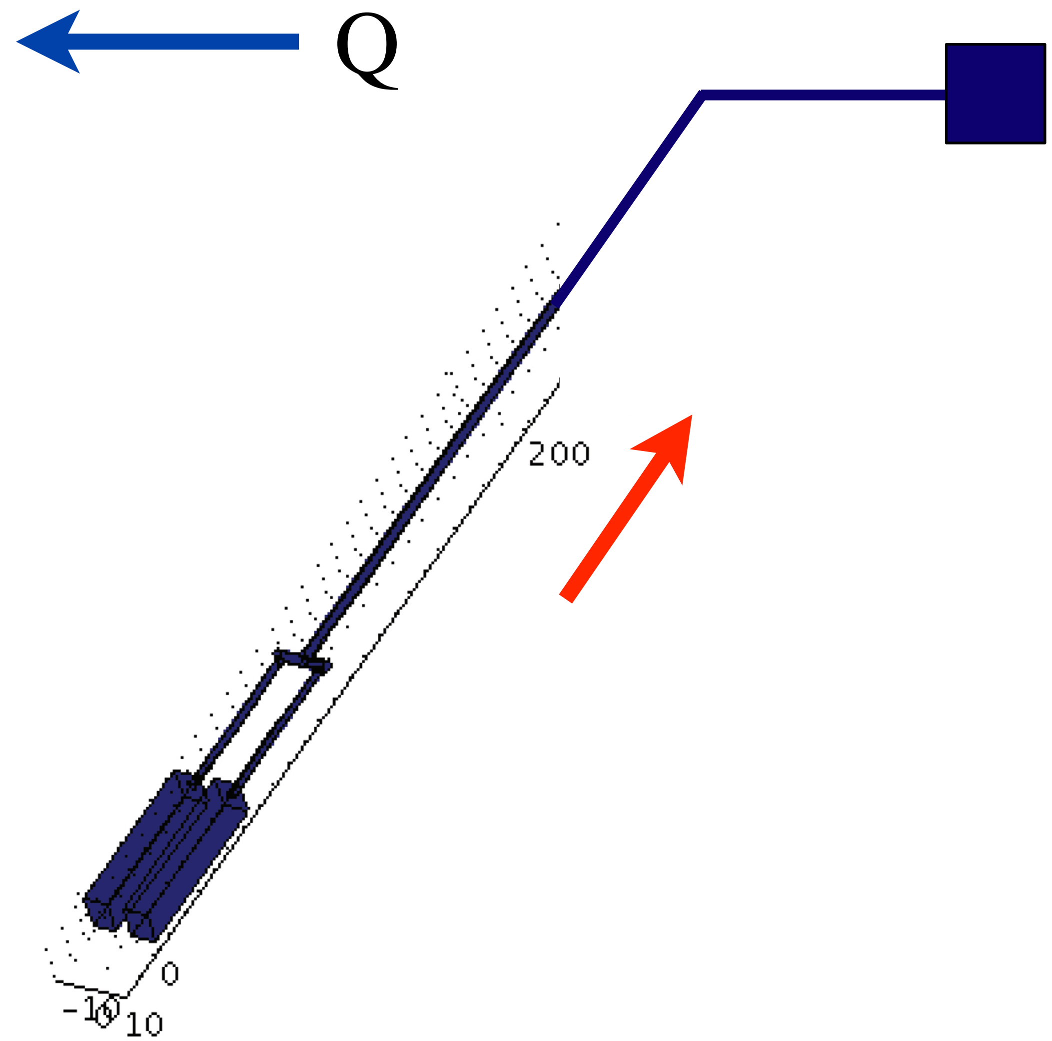




Scintillations in Liquid Helium

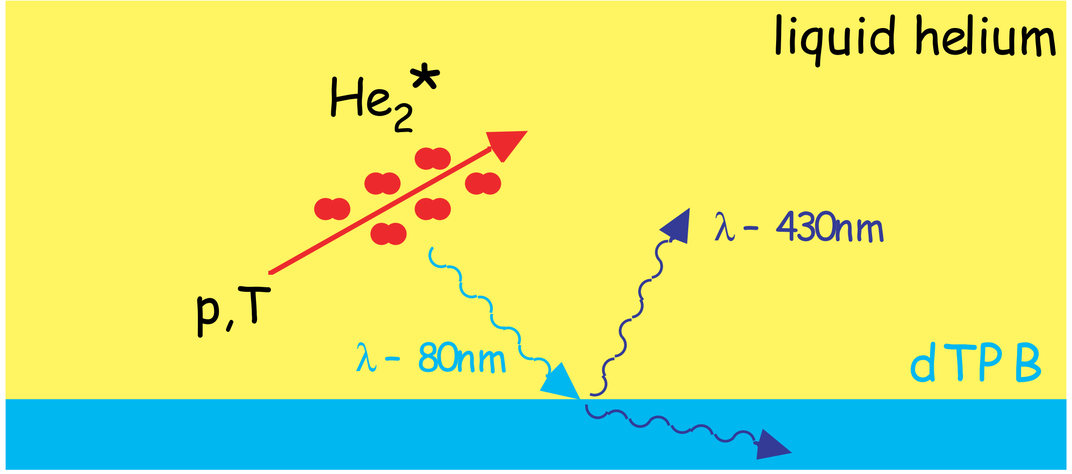
- Recoiling charged particle creates an ionization track in the helium.
- Helium ions form excited He2* molecules (ns time scale) in both singlet and triplet states.
- He2* singlet molecules decay, producing a large prompt

  (< 20 ns) emission of extreme ultraviolet (EUV) light.
- EUV light (80 nm) converted to blue using the deuterated organic fluor dTPB (tetraphenyl butadiene).

σ(parallel) < 10^2 b

σ(opposite) ~ 10^4 b

$$n + {}^3He \rightarrow p + T$$



Measurement Overview

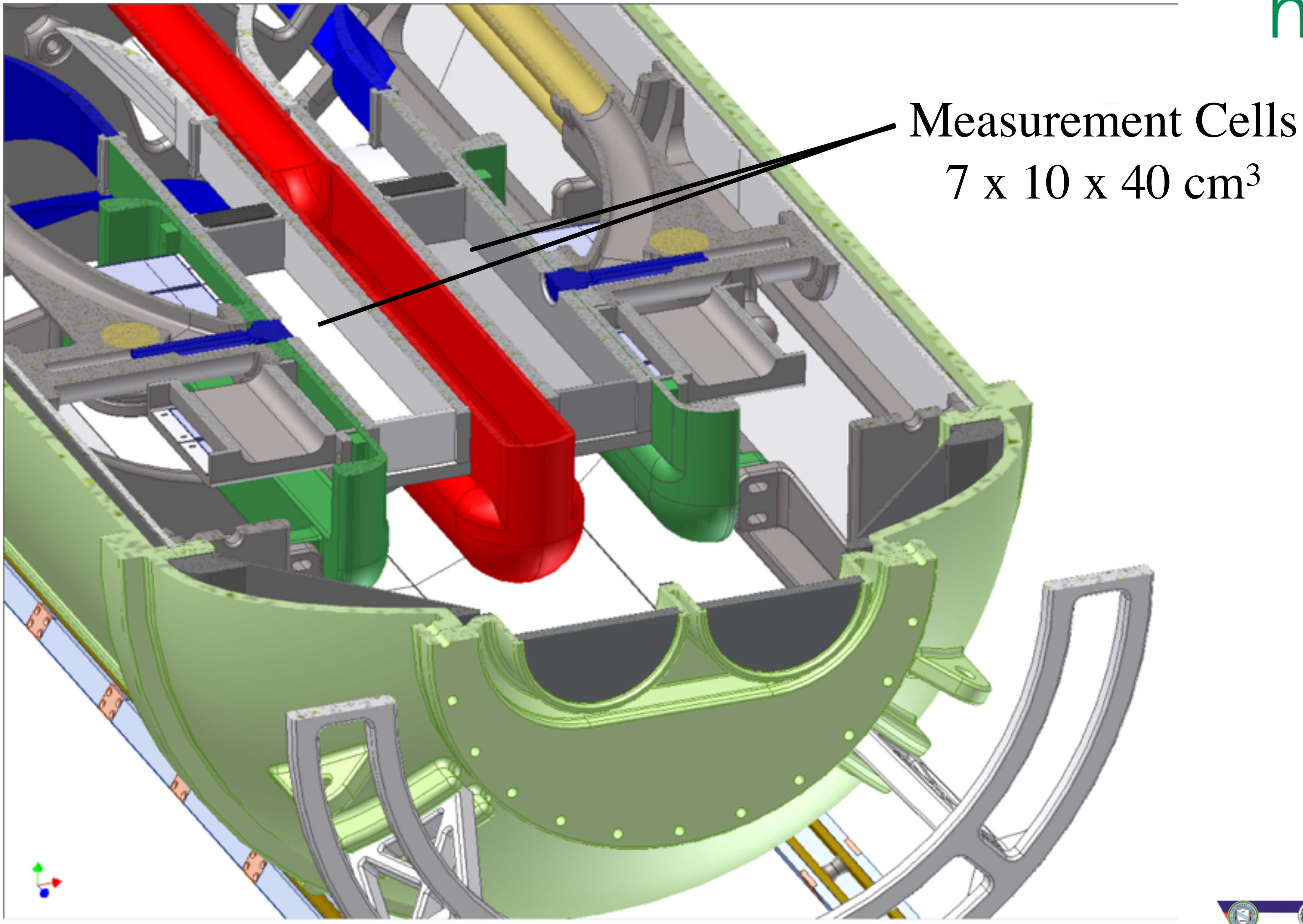
- Two measurement techniques
  - Oscillation of the scintillation rate (baseline)
  - Spin Dressing
- Capabilities for performing both techniques are being built into the apparatus.
- Oscillation of scintillation rate
  - Look for a difference in precession frequency

    $f_n - f_3 = (\gamma_n - \gamma_3)\, B \pm 2\, d_n E = (0.1\, \gamma_n)\, B \pm 2\, d_n E$
  - Detect precession of ^{3}He magnetization by SQUIDS which serves as a direct magnetometer
- Spin Dressing
  - seeks to make the magnetic moments equal to minimize sensitivity to background fields

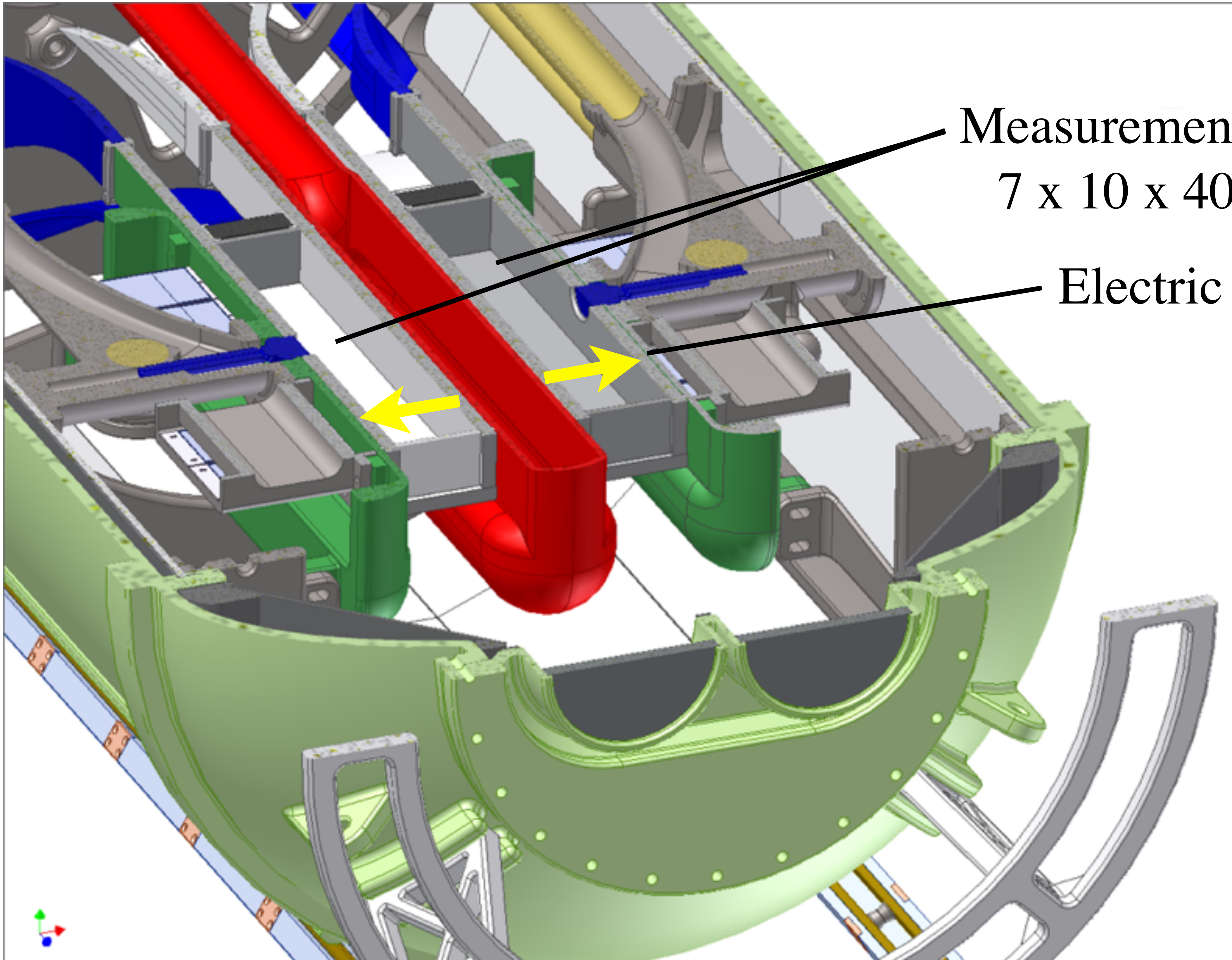
Systematics

Error Source	Systematic error (e-cm)	Comments	Key parameters
Geometric phase (linear E×v)	$< 1 \times 10^{-28}$	Uniformity of B0 field	B field gradient, temperature
Quadratic E×v	$< 0.5 \times 10^{-28}$	E-field reversal to <1%	
Pseudomagnetic Field Effects	$< 1 \times 10^{-28}$	π/2 pulse, comparing 2 cells	^{3}He density, π/2 pulse
Gravitational offset	$< 0.2 \times 10^{-28}$	With 1 nA leakage currents	
Heat from leakage currents	$< 1.5 \times 10^{-28}$	< 1 pA	temperature
E×v rotational n flow	$< 1 \times 10^{-28}$	E-field uniformity < 0.5%	
E-field stability	$< 1 \times 10^{-28}$	ΔE/E < 0.1%	
Miscellaneous	$< 1 \times 10^{-28}$	Other E×v, wall losses	

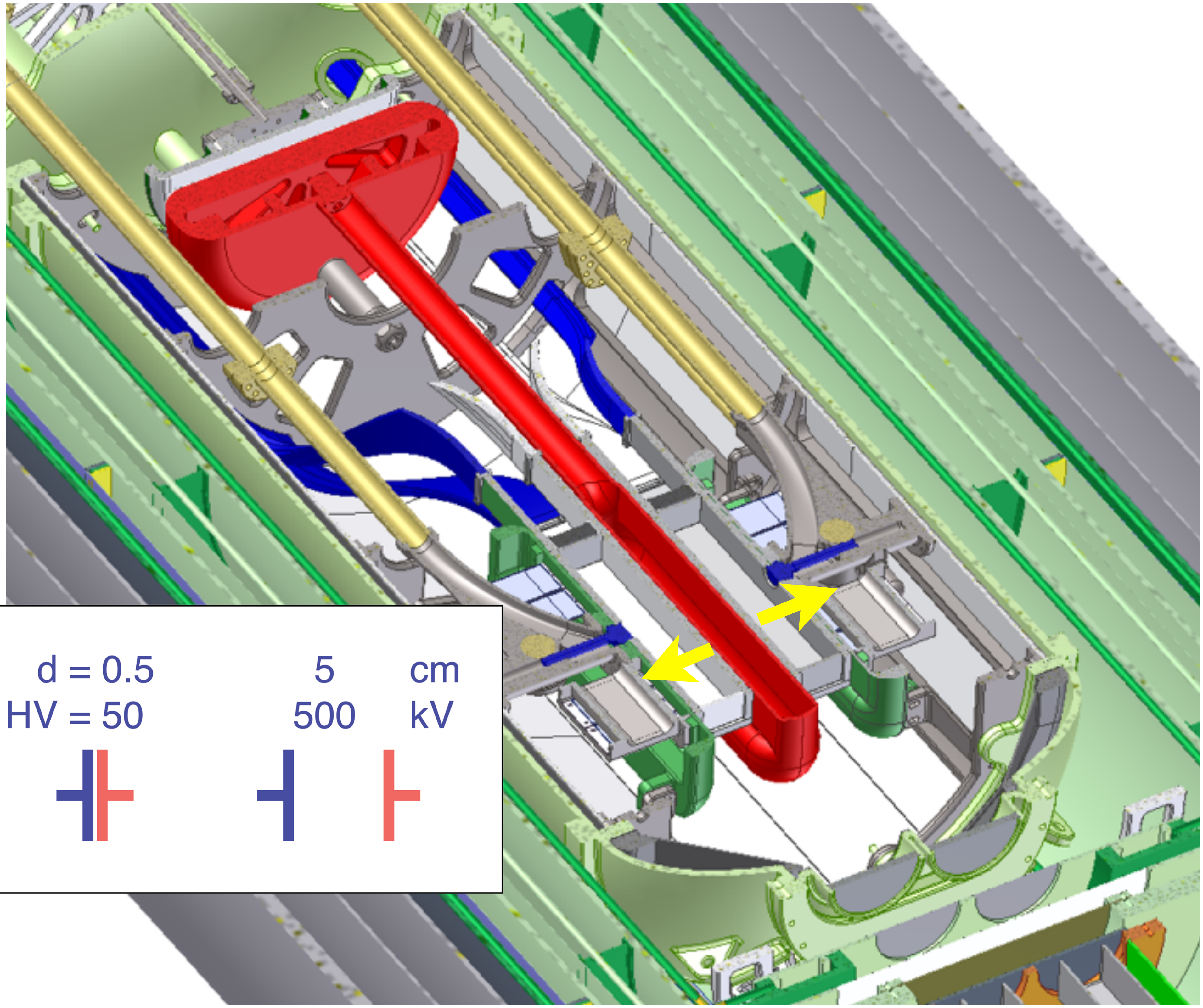
Measurement Cells



Measurement Cells



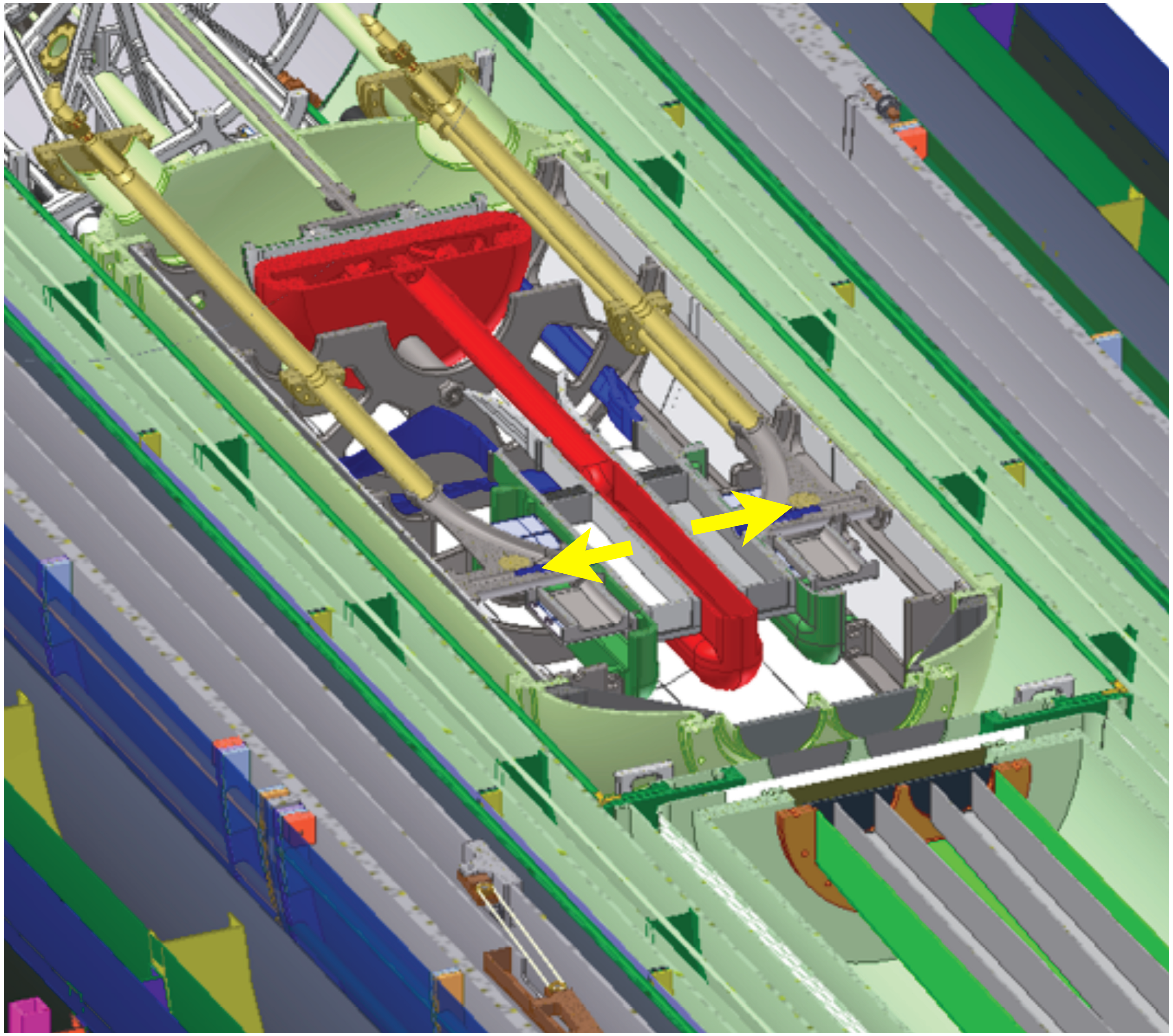
HV Capacitor



d =	0.5	5	cm
HV =	50	500	kV

$q = CV$

Magnets and Cryogenic Magnetic Shields



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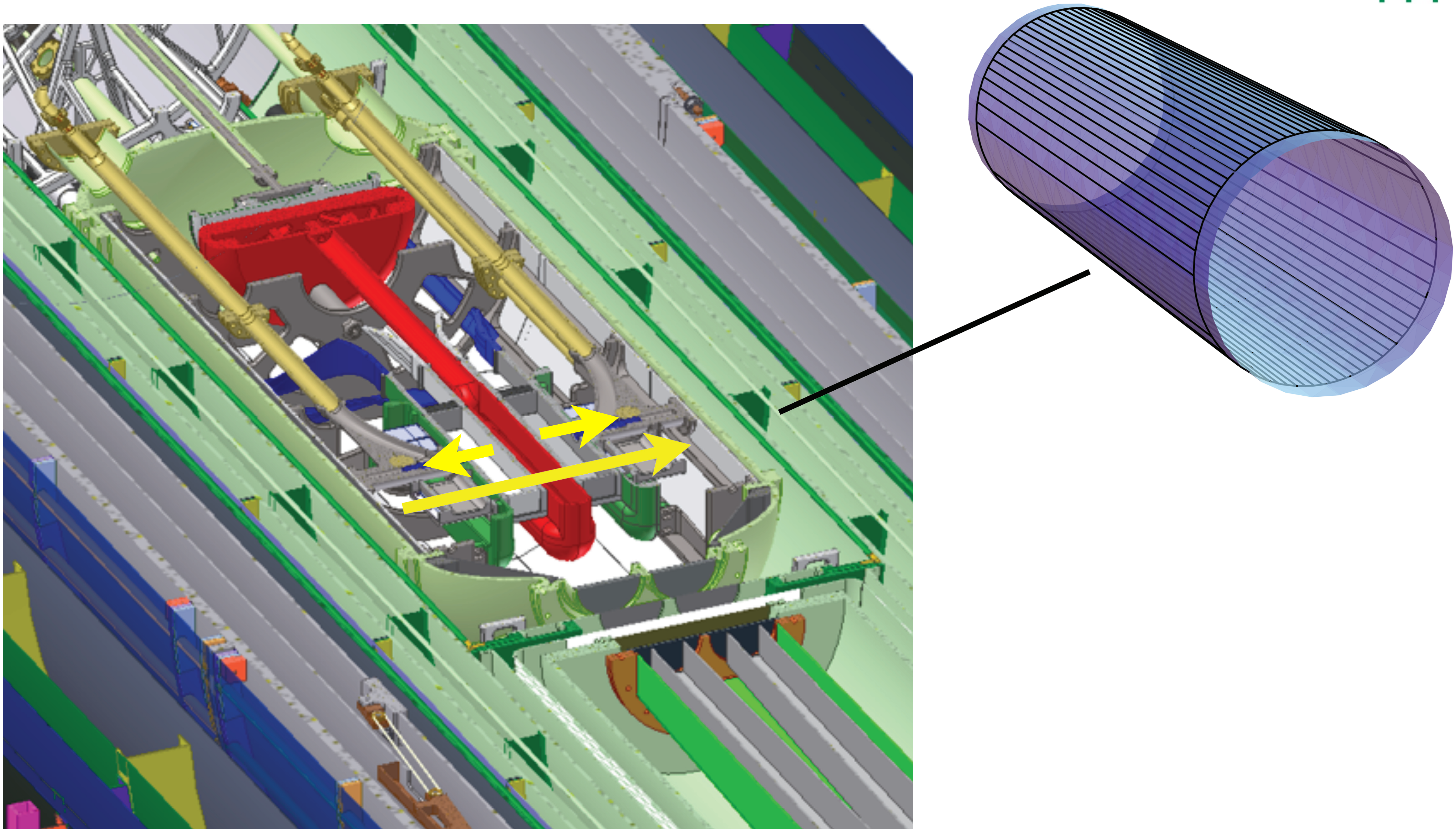

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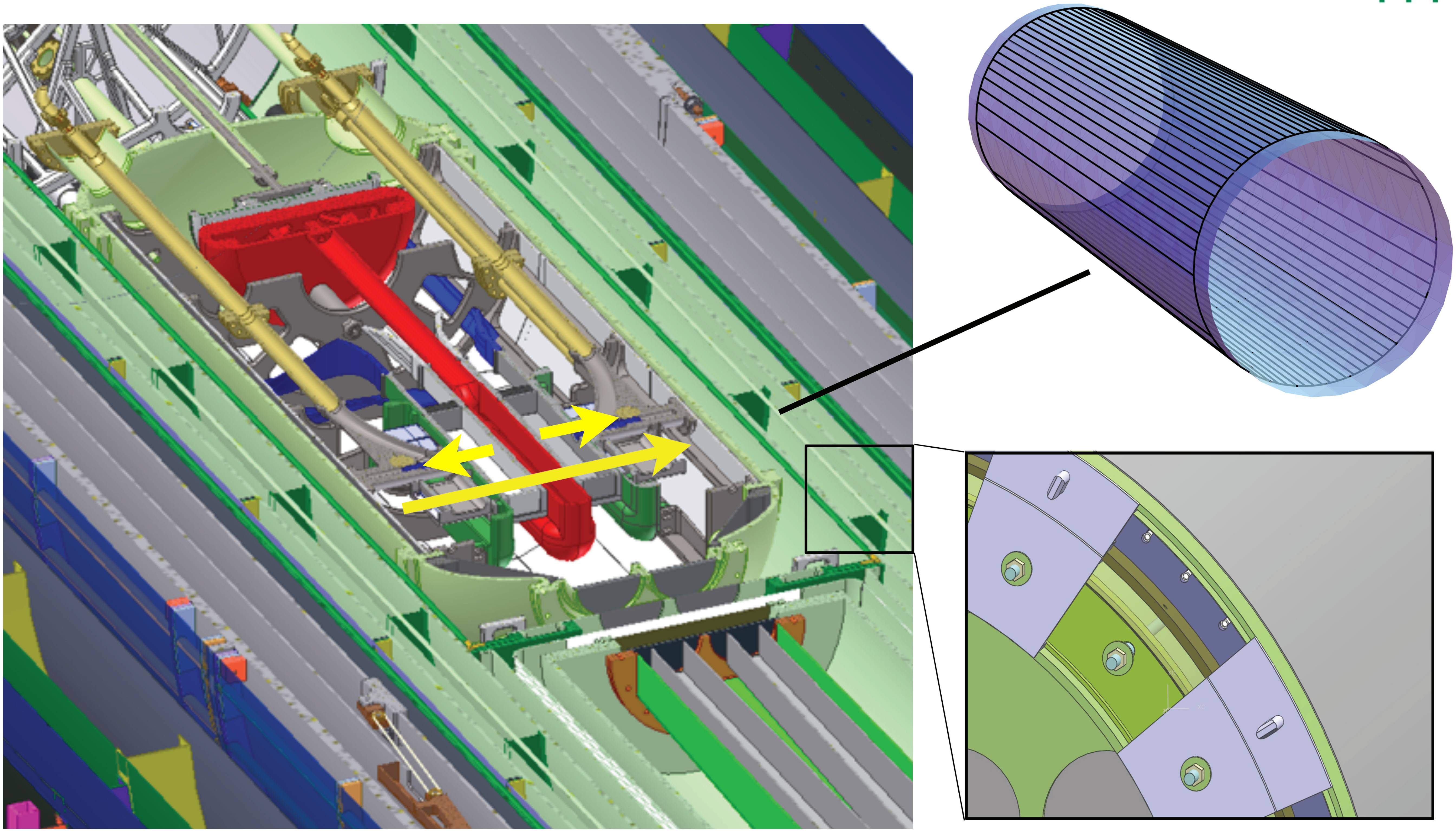

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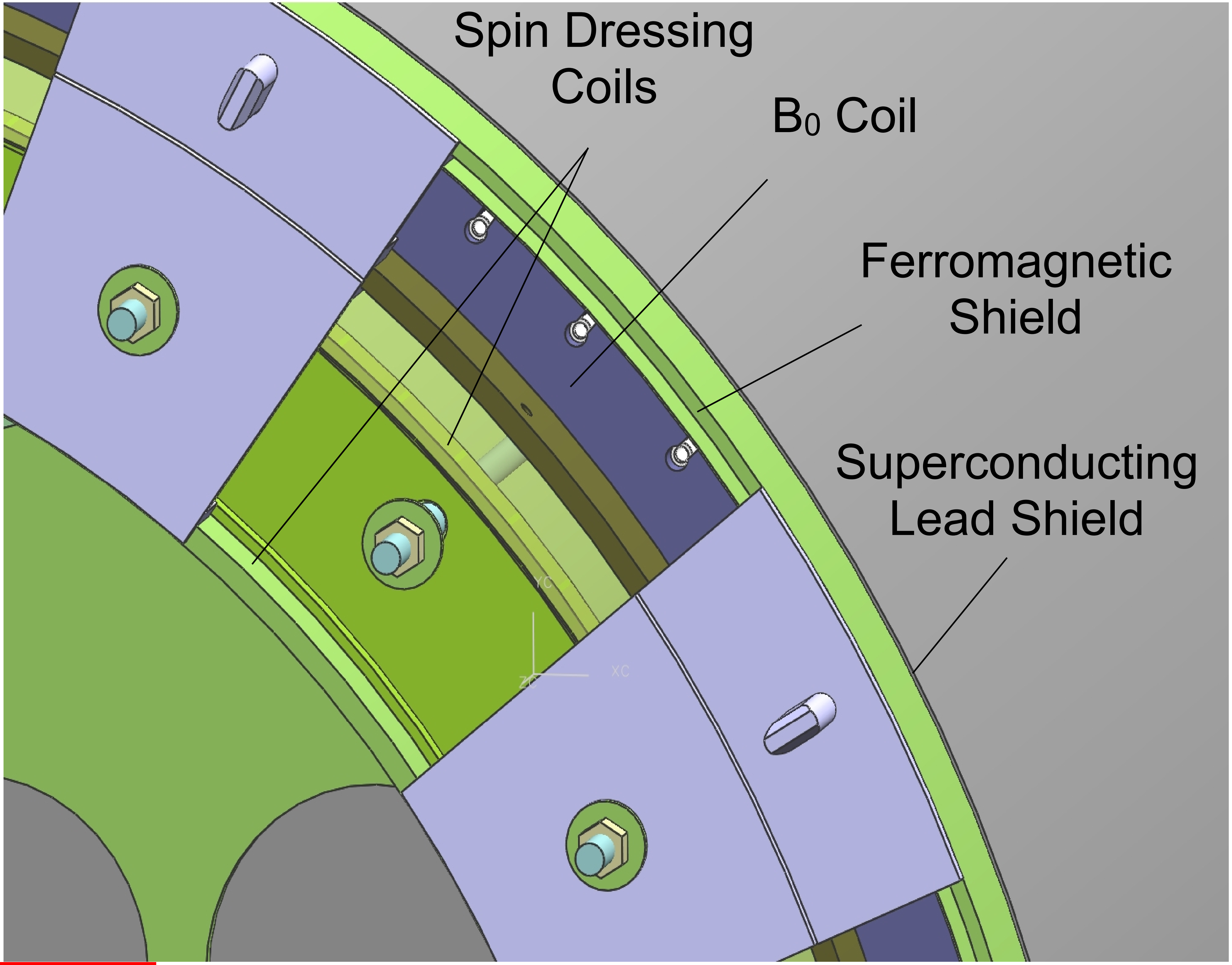
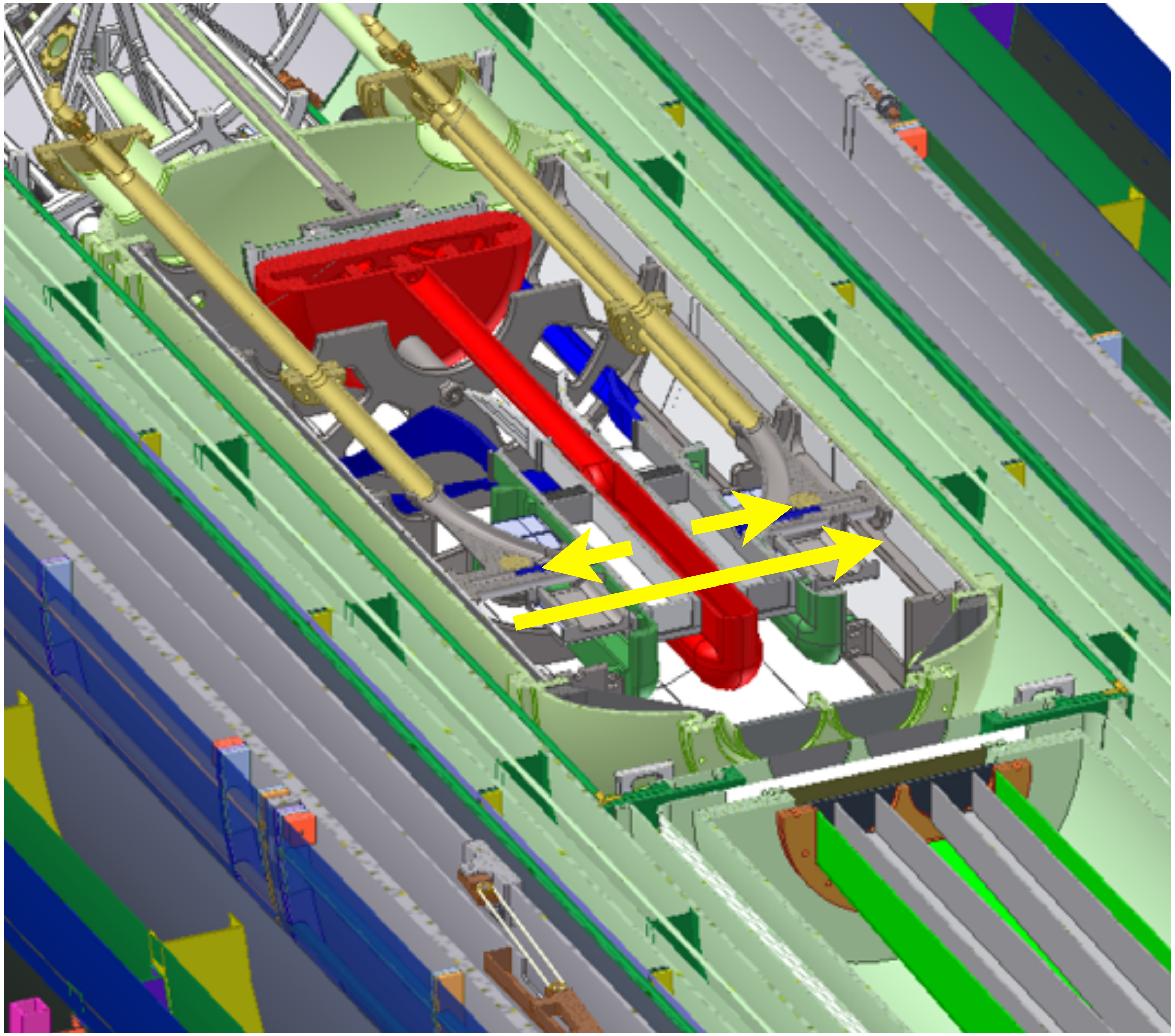


Cryovessel



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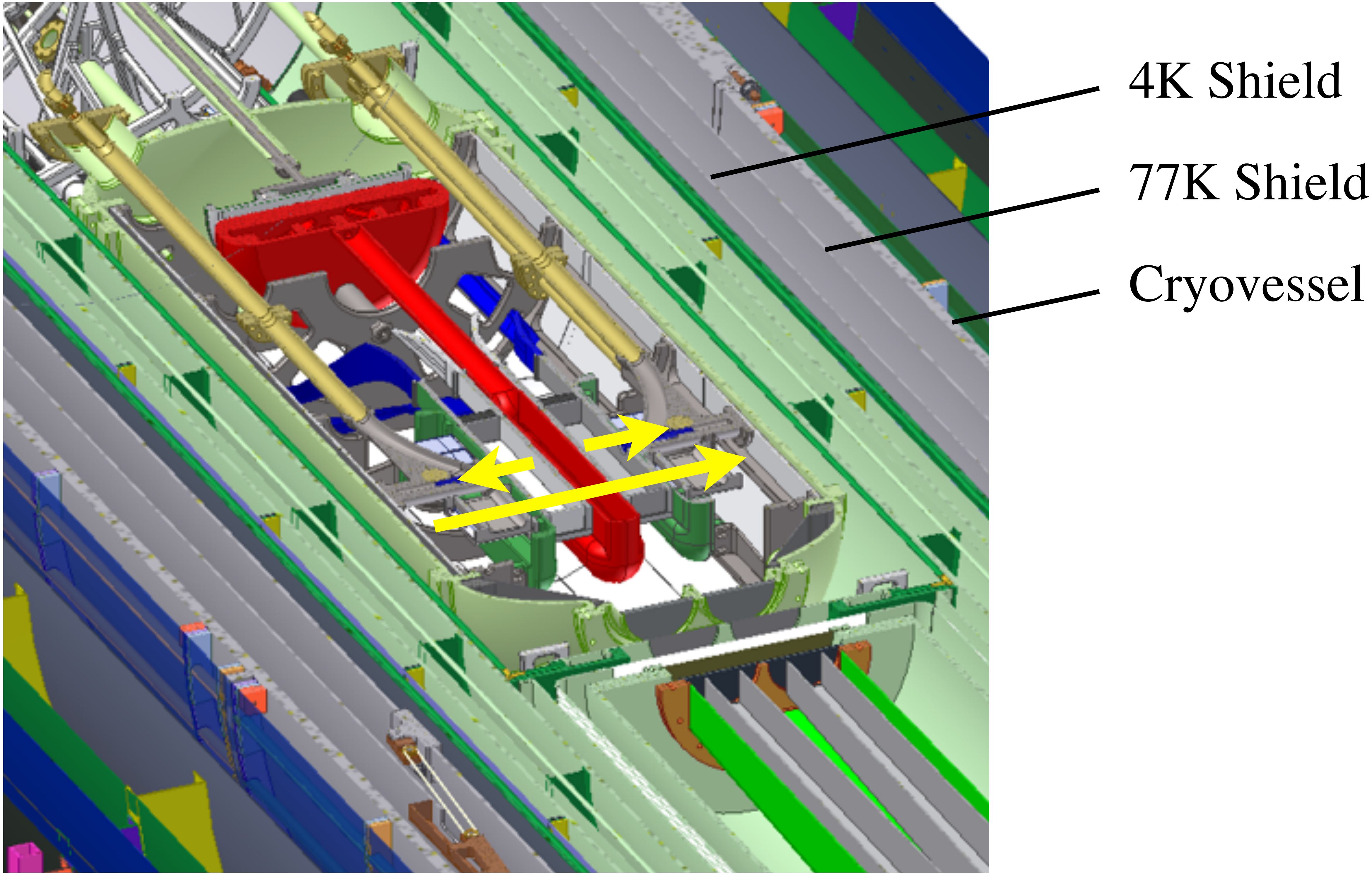
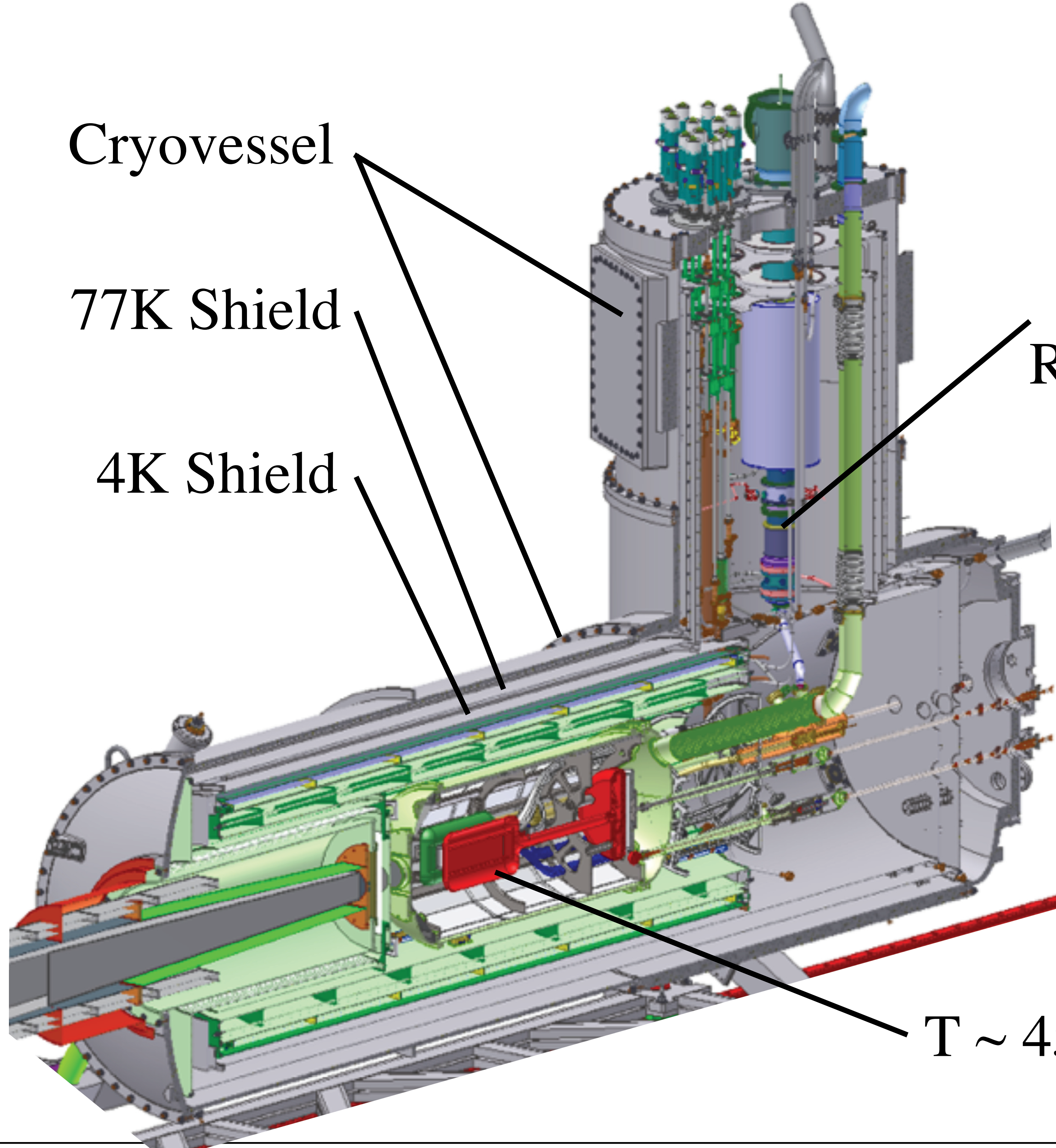


Cryogenics

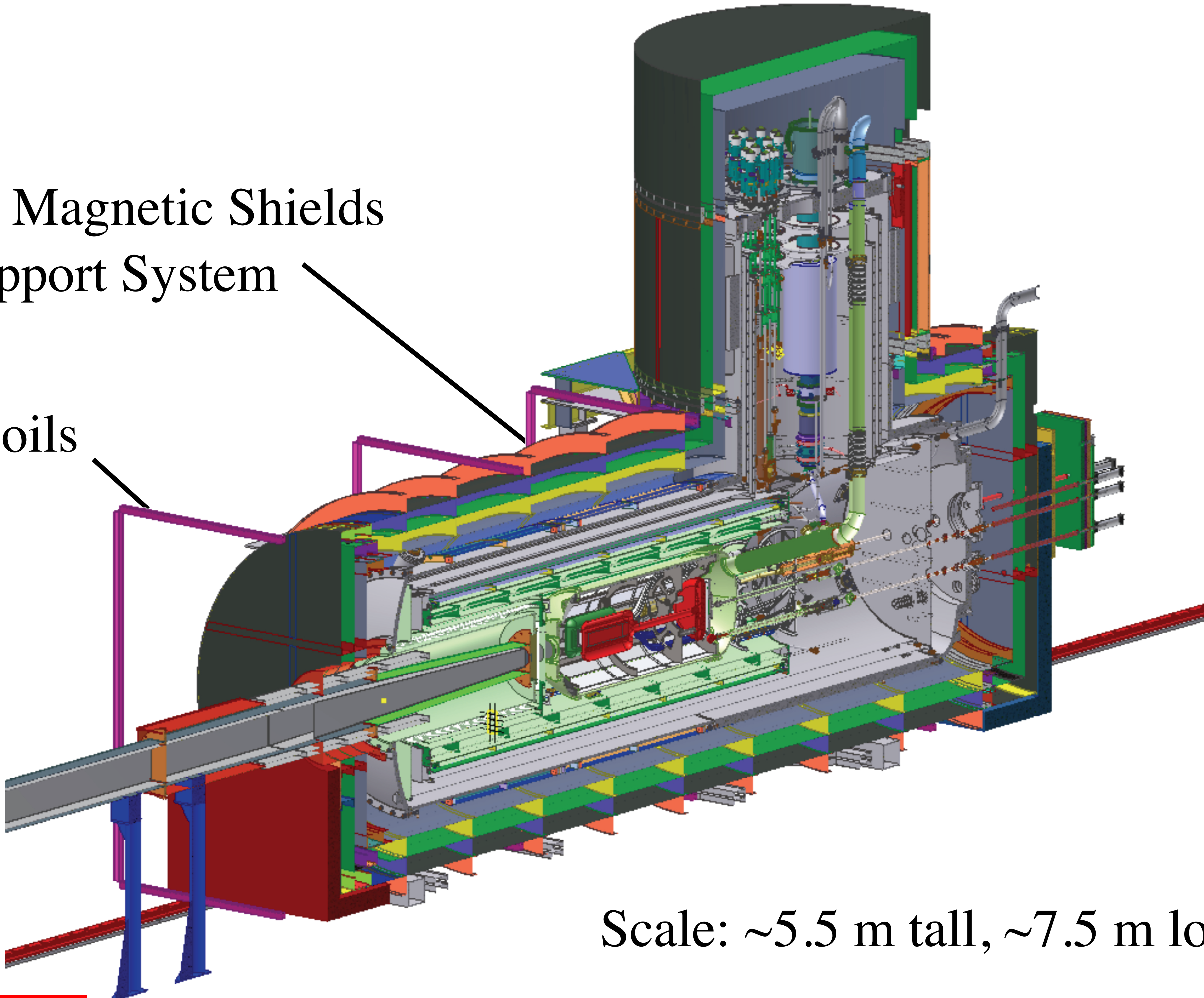


Helium Liquefier and Gas Handling System (not shown)

External Magnetic Shielding

4-layer Magnetic Shields
and Support System

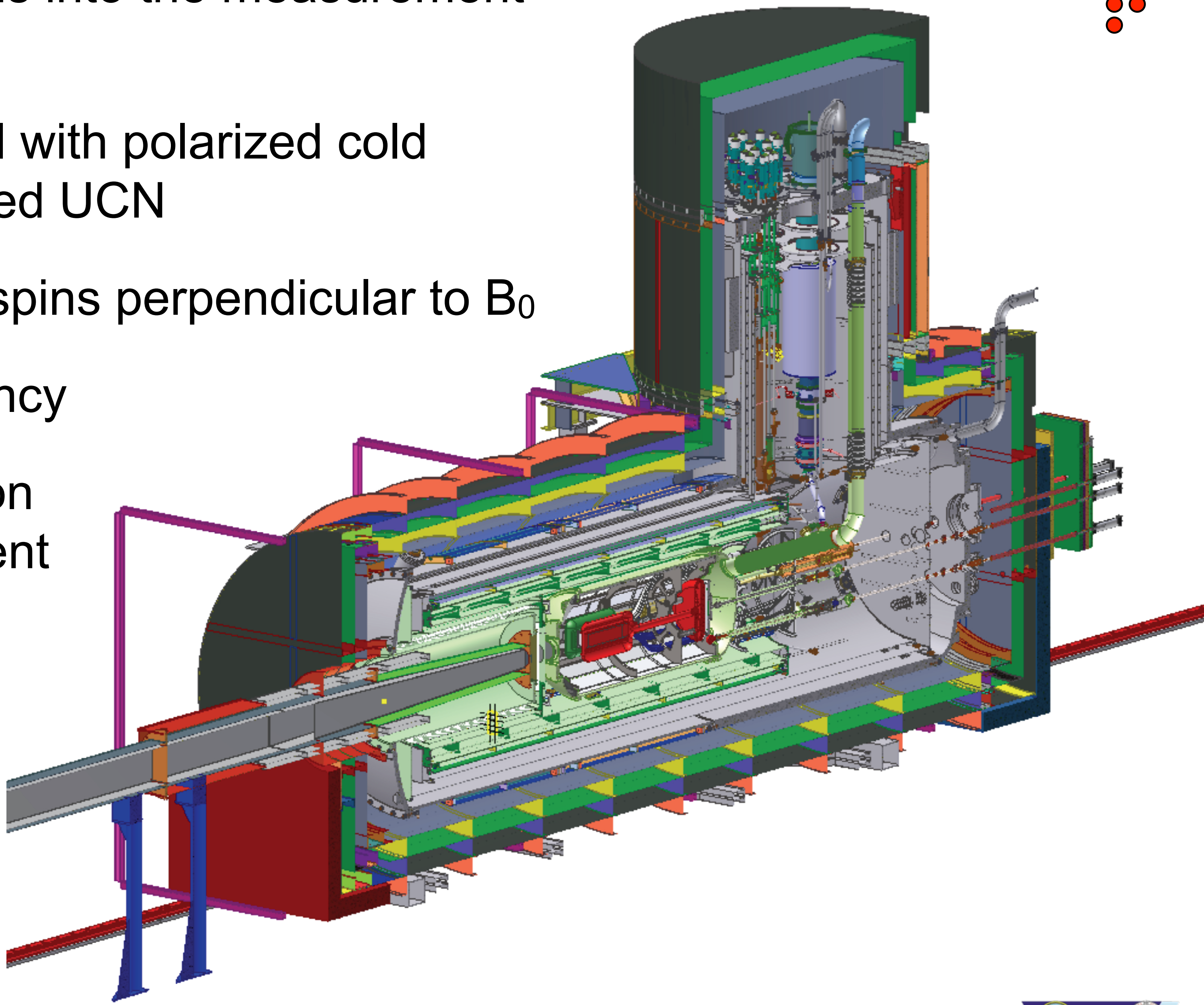
Trim Coils



Scale: ~5.5 m tall, ~7.5 m long

Measurement Cycle

- Load collection volume with polarized ^{3}He atoms
- Transfer polarized ^{3}He atoms into the measurement cell
- Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
- Apply a π/2 pulse to rotate spins perpendicular to B_0
- Measure precession frequency
- Remove reduced polarization ^{3}He atoms from measurement cell
- Repeat (periodically reversing B and/or E)



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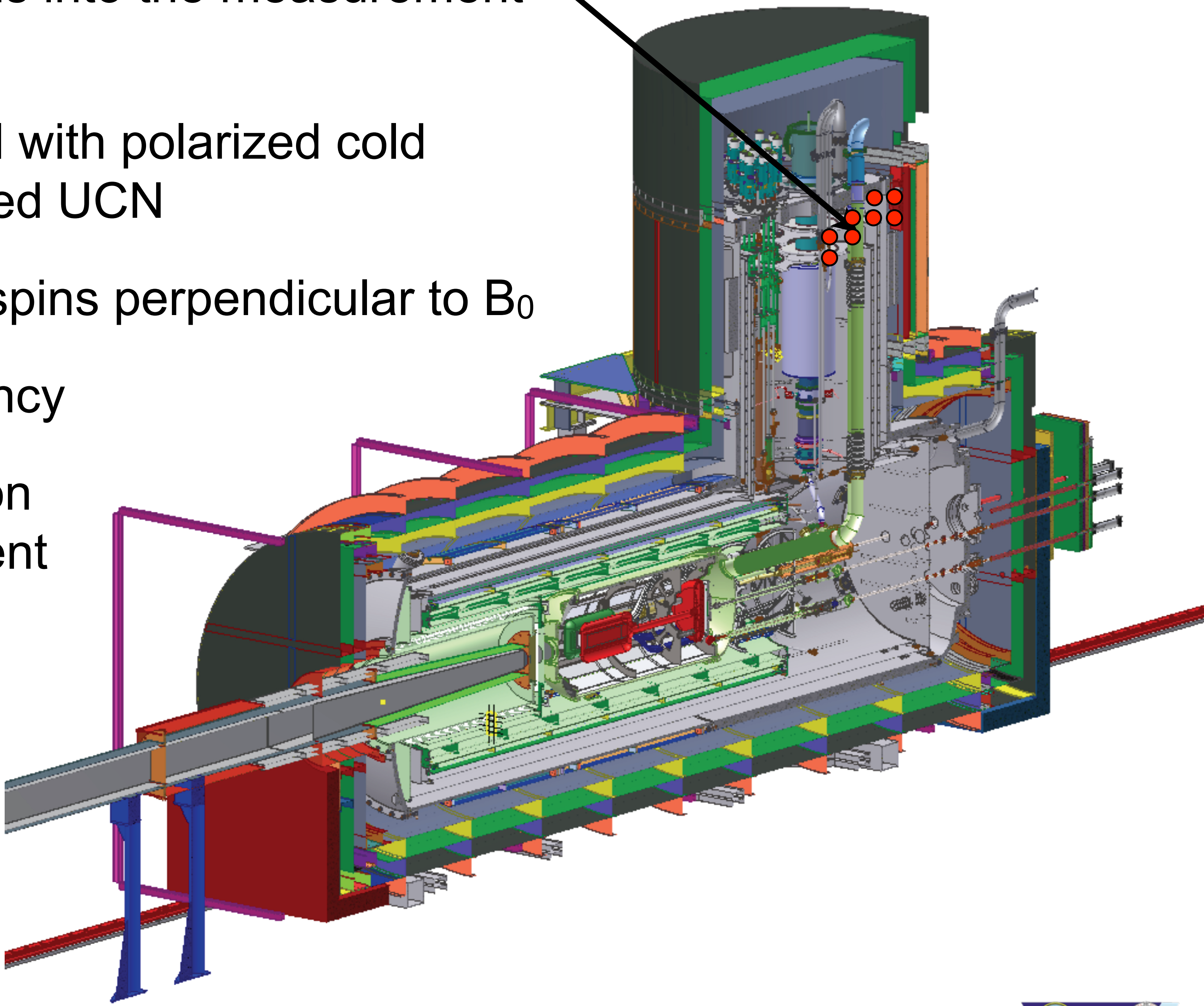

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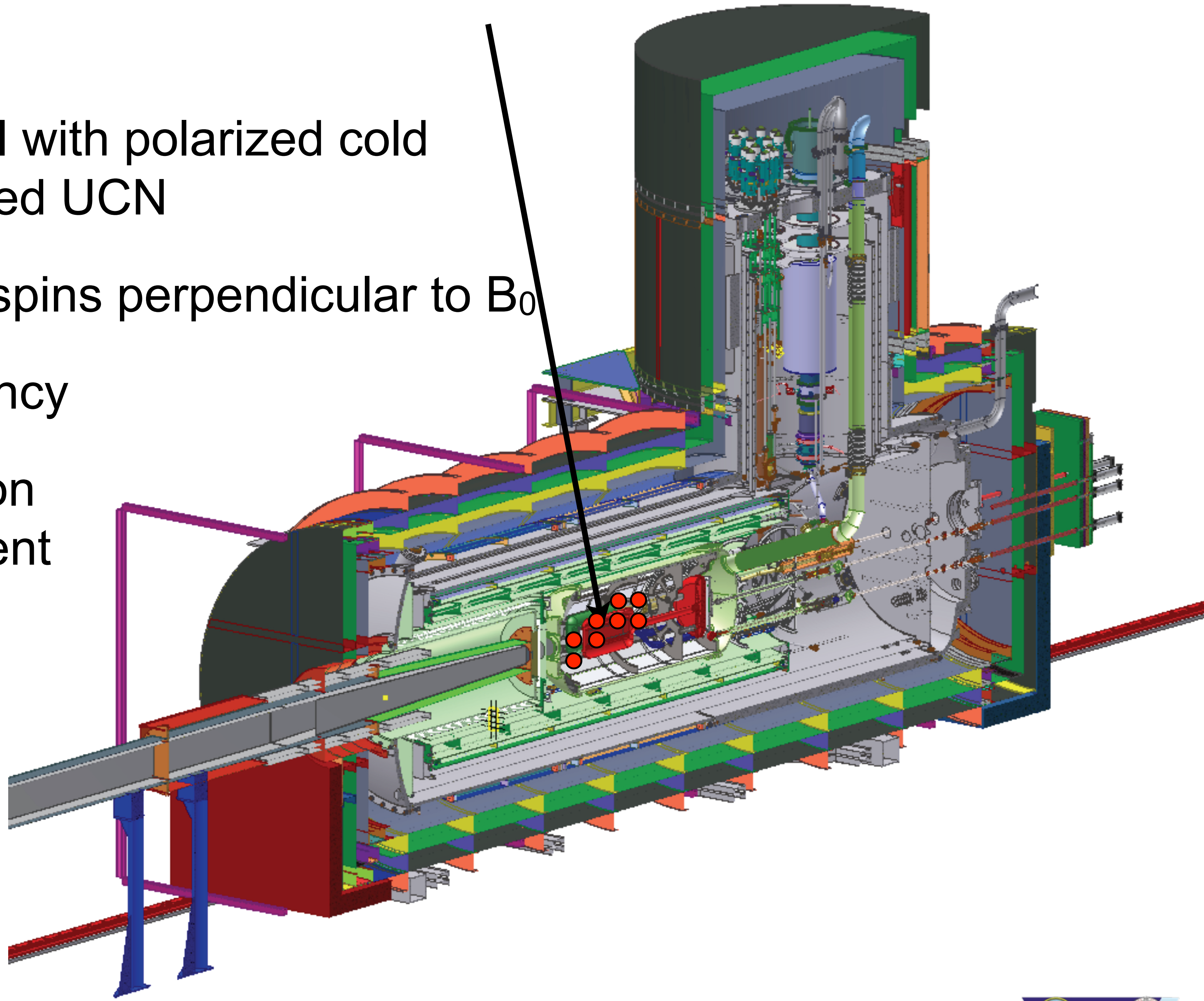

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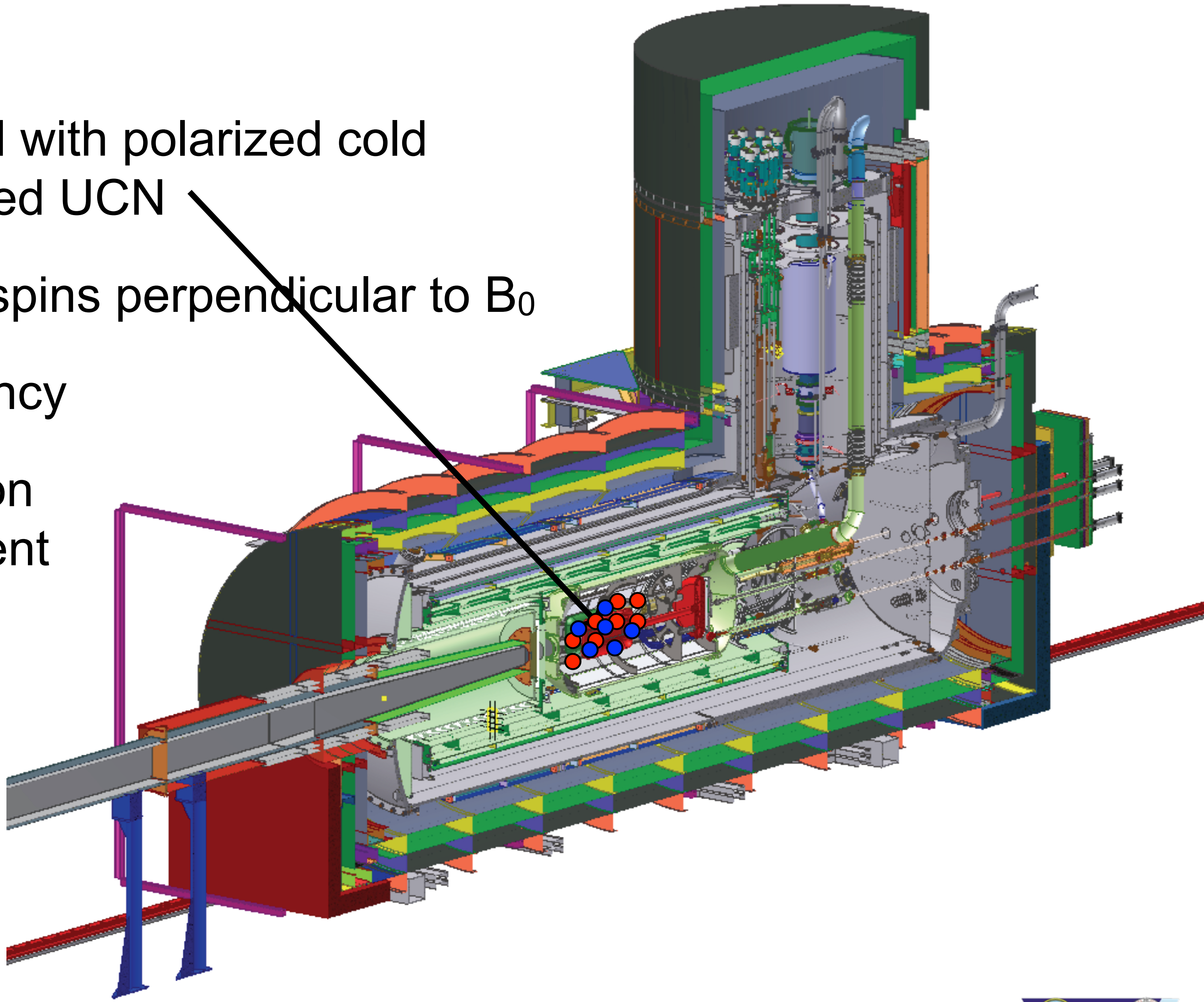

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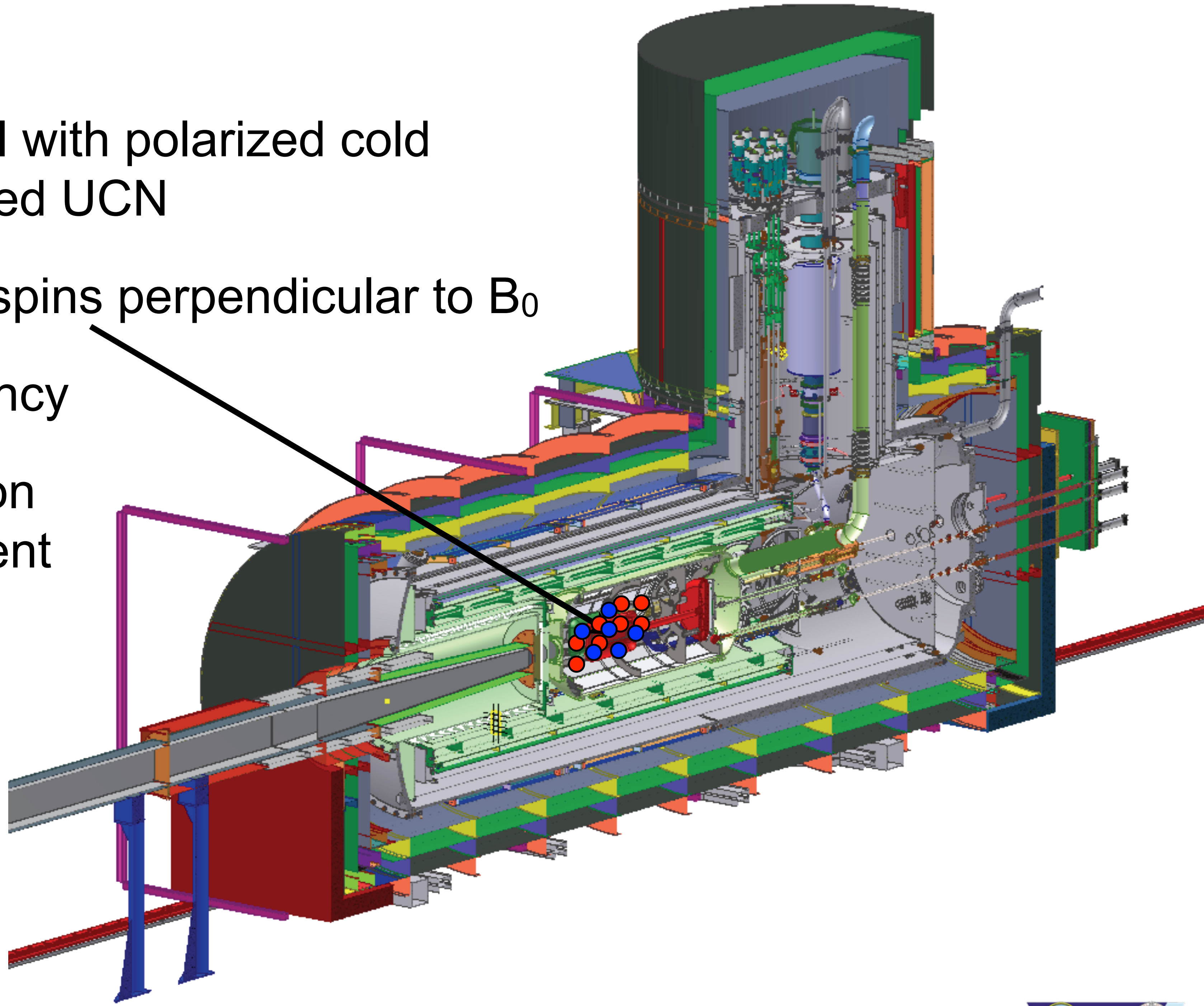

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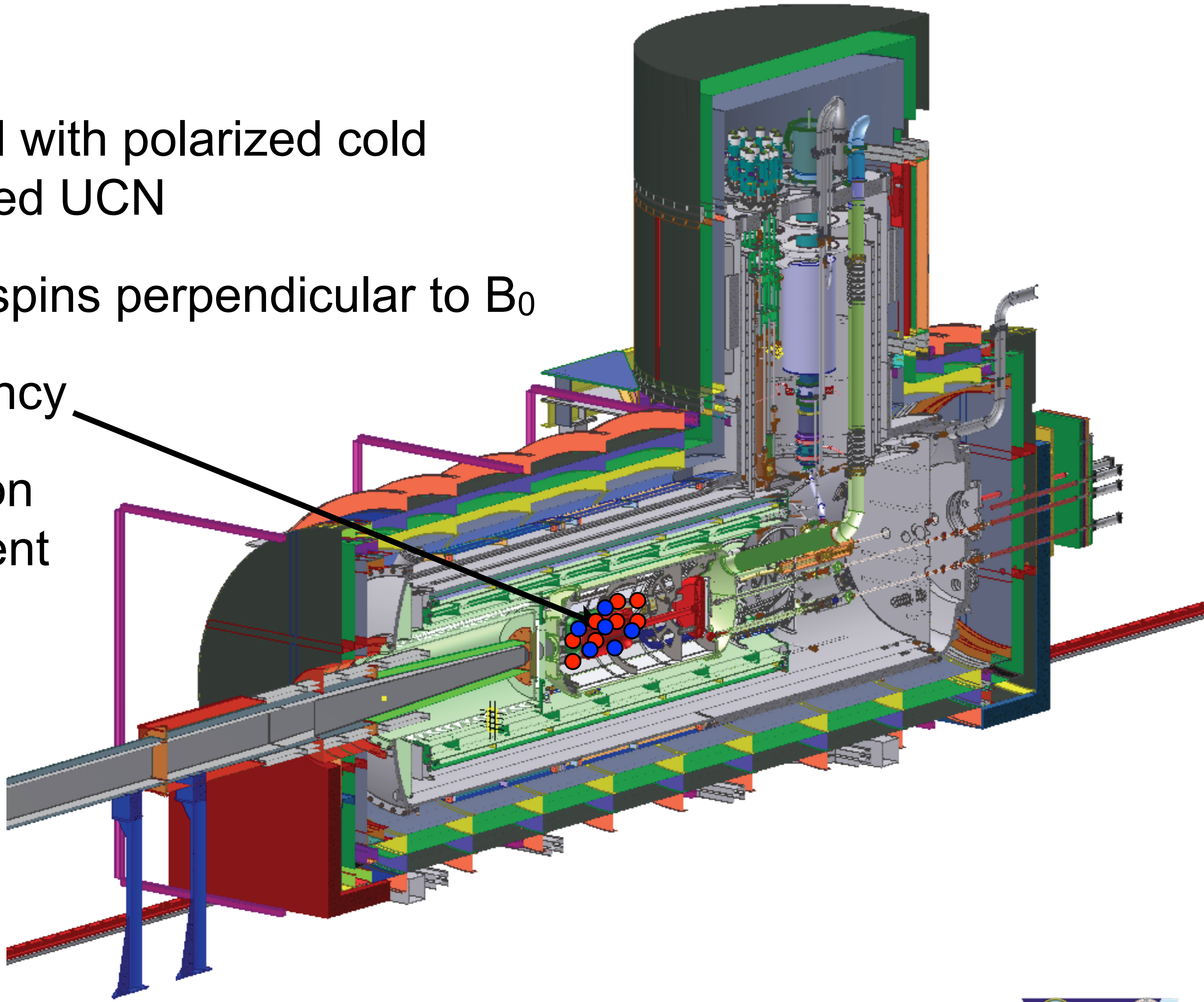

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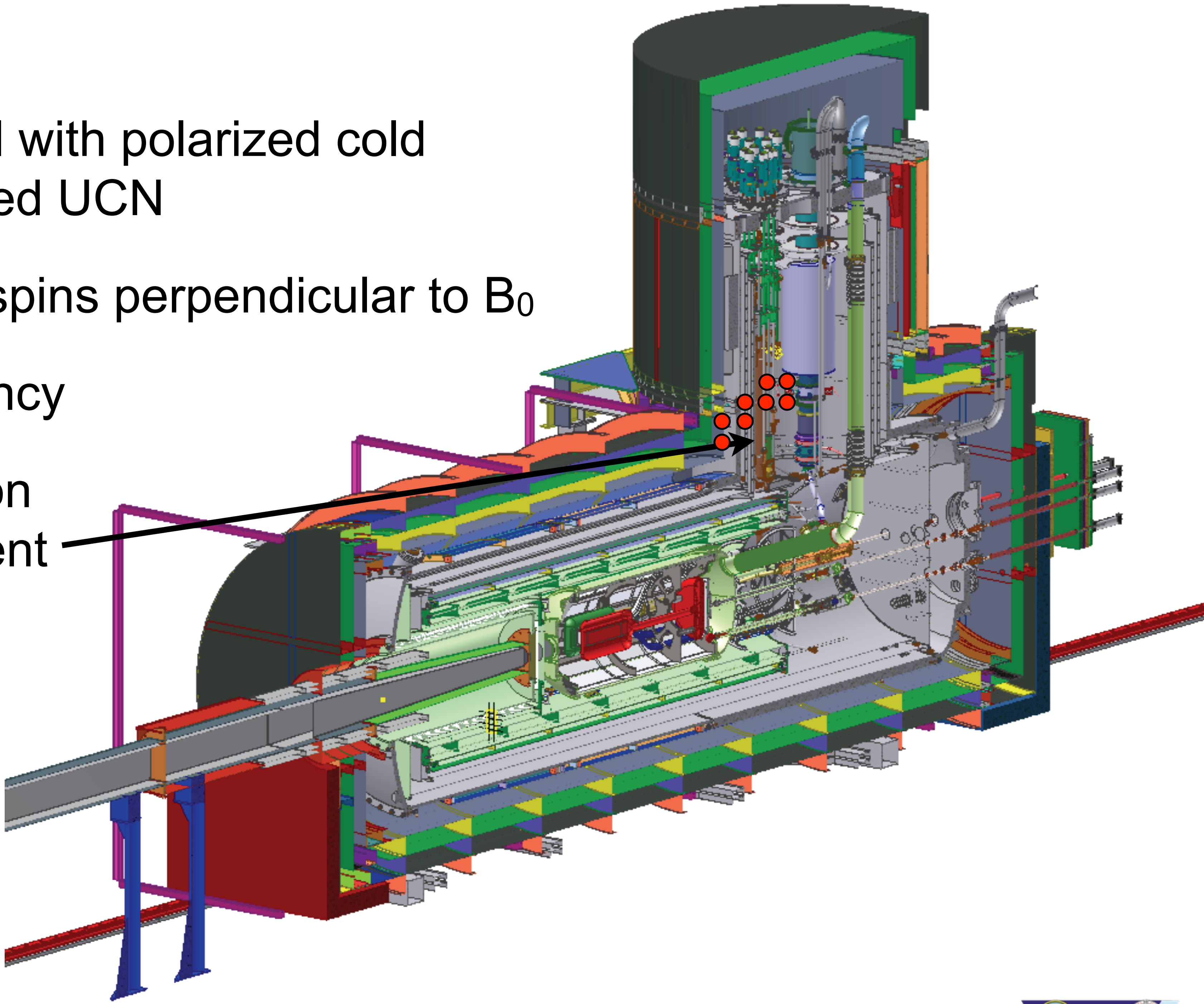

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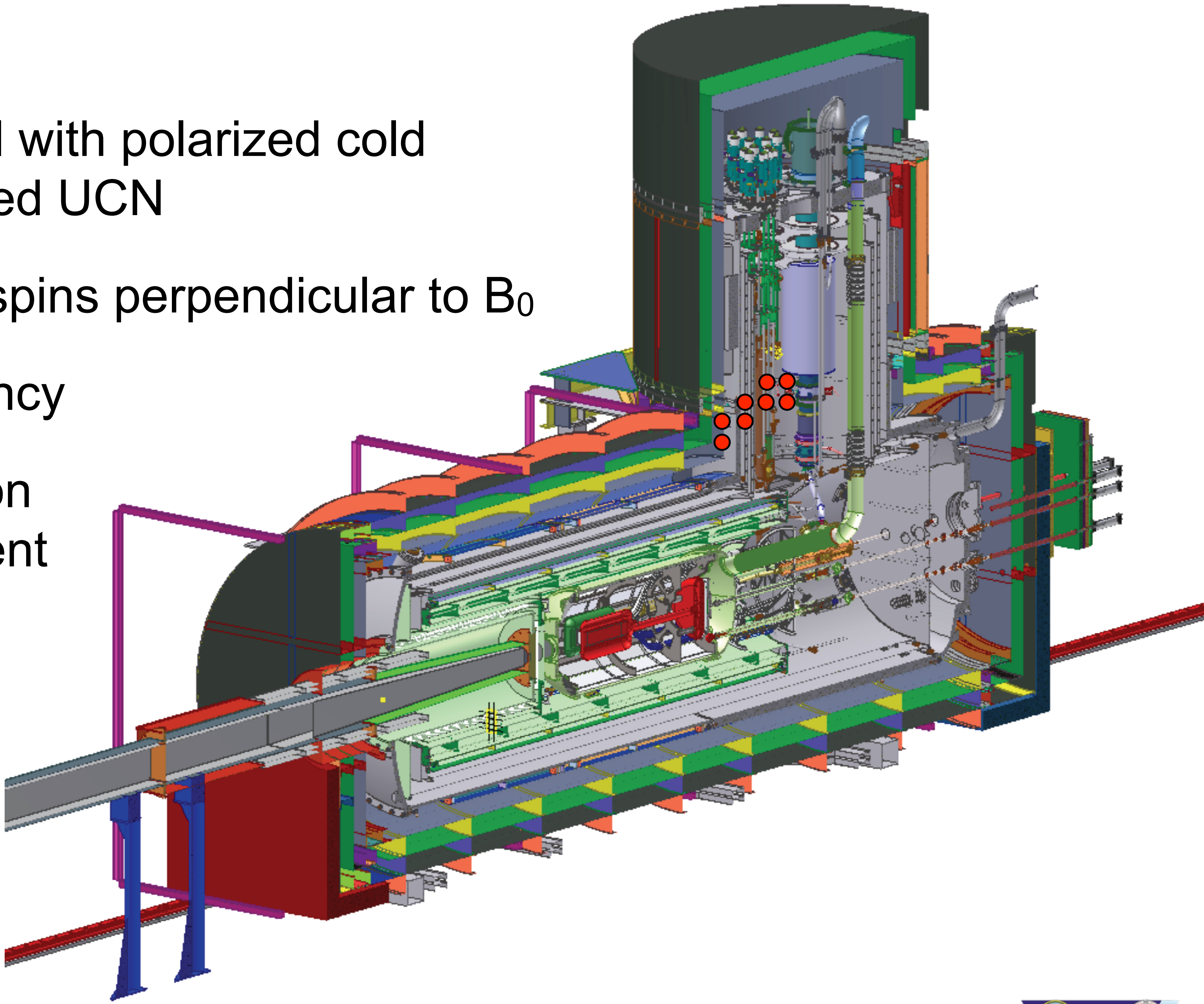
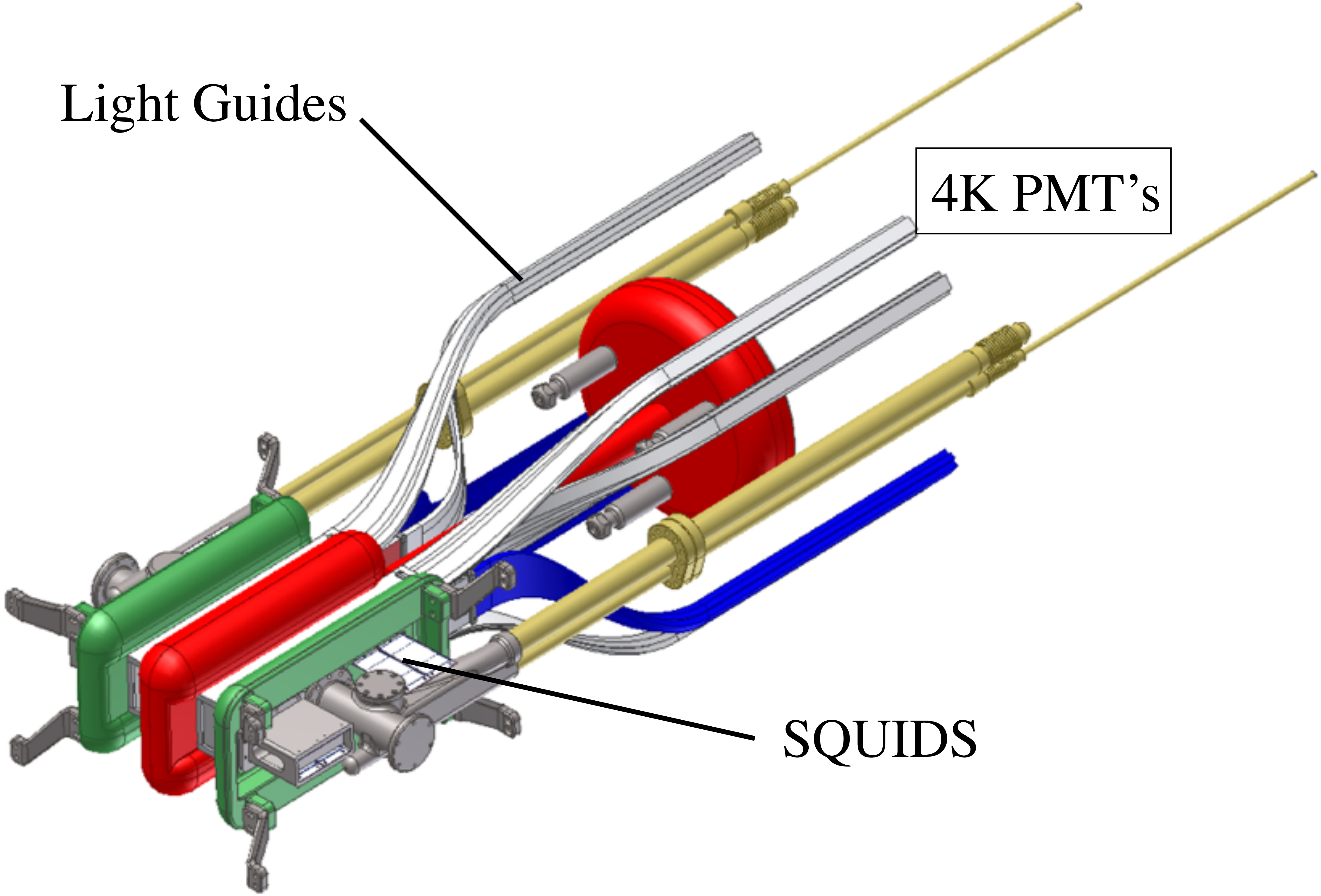
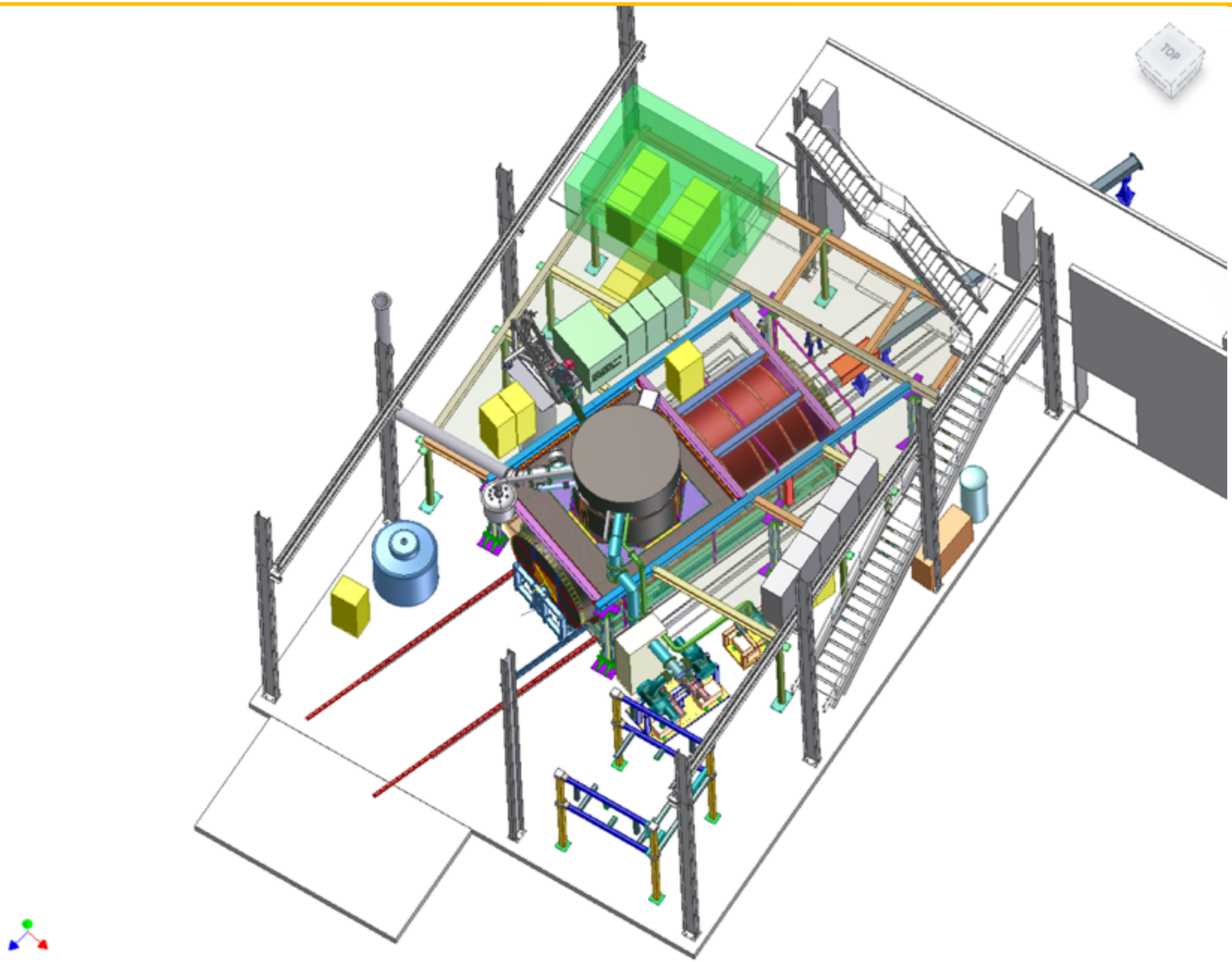


Signal Detection



Global View



Summary

- The neutron EDM remains an important parameter in understanding the origin of the universe and testing for physics beyond the Standard Model.
- Both the free precession and dressed spin techniques give an ultimate sensitivity of $\boldsymbol{d_n < 3\text{–}5 \times 10^{-28}}$ **e•cm** (90%) using the cold beamline at the FnPB.
- The experimental design has many features that will allow us to explore possible unknown systematic effects.
- We expect to begin putting neutrons into the apparatus in approximately 6-7 years.