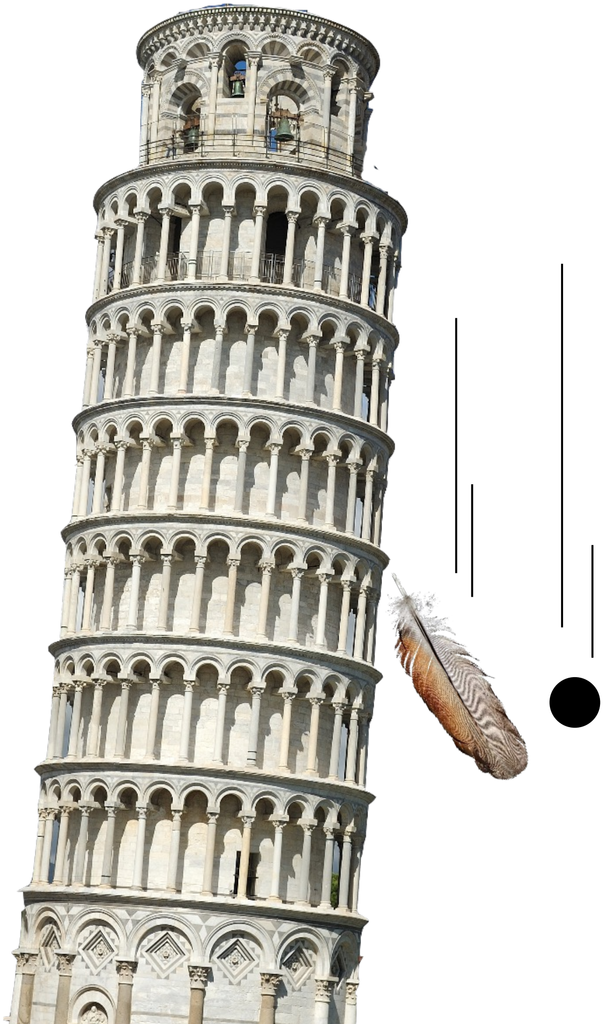
ALPHA-g & HAICU
Antimatter science at TRIUMF

Science Week 2023

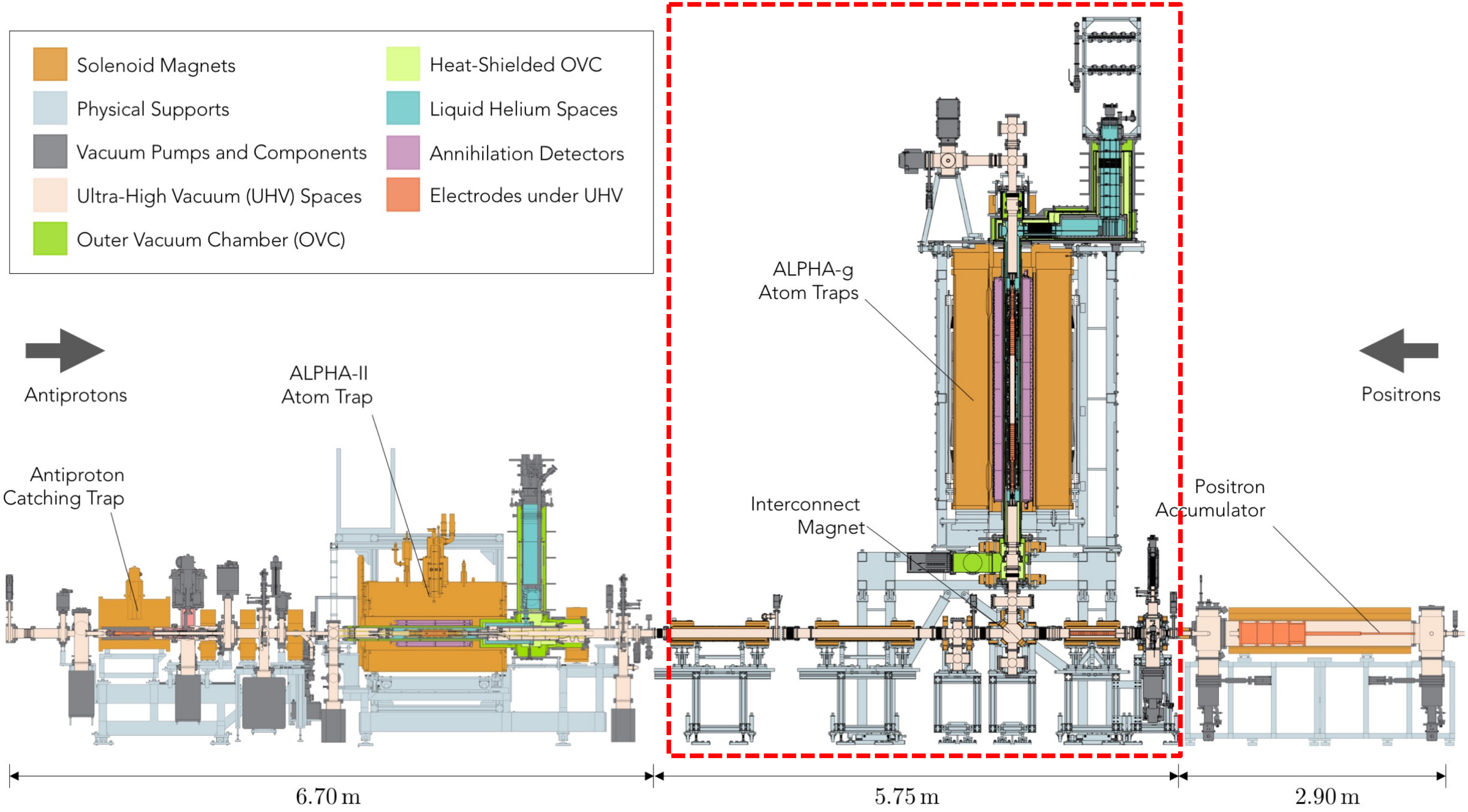
Chukman So

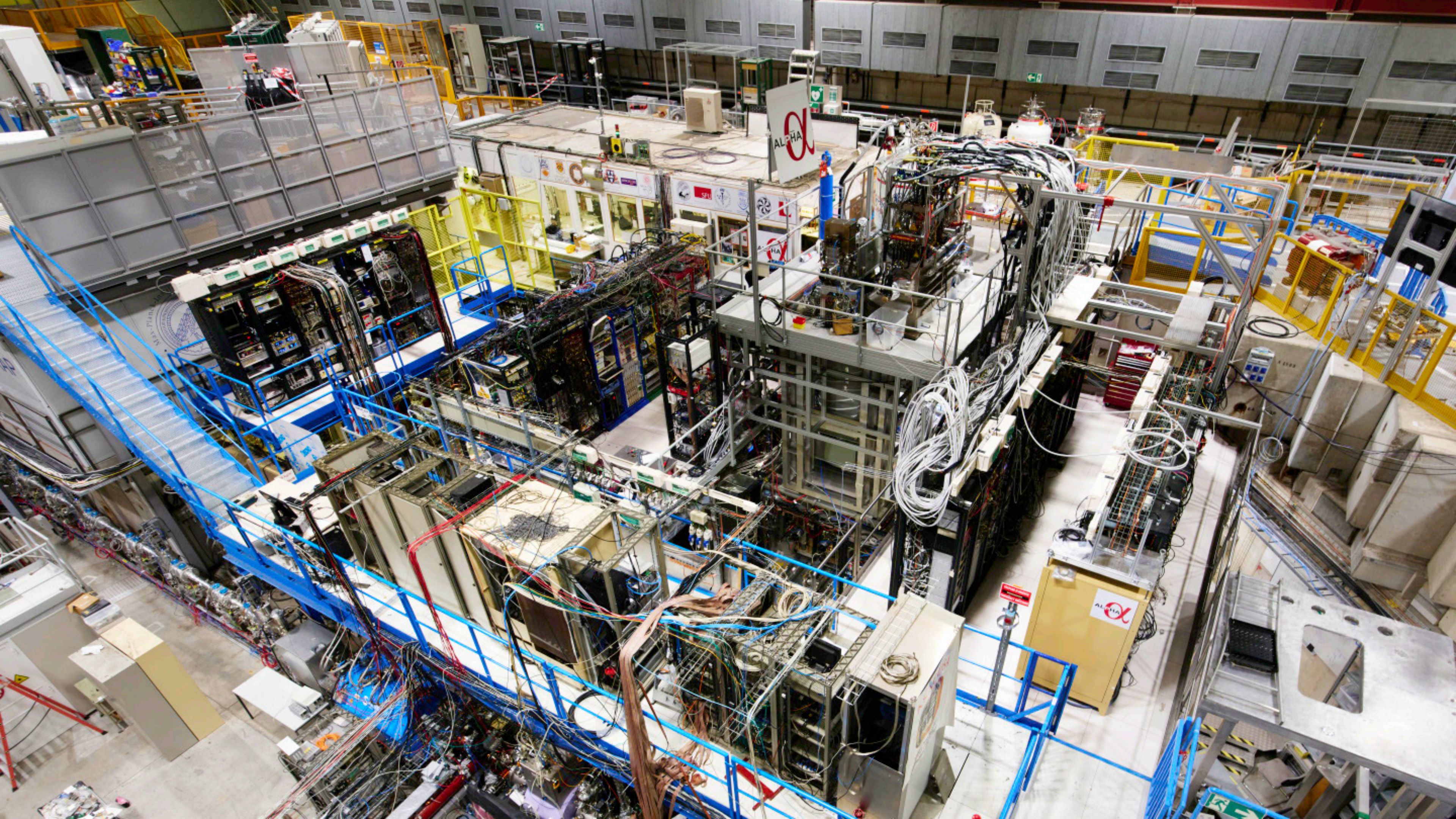
Antimatter science

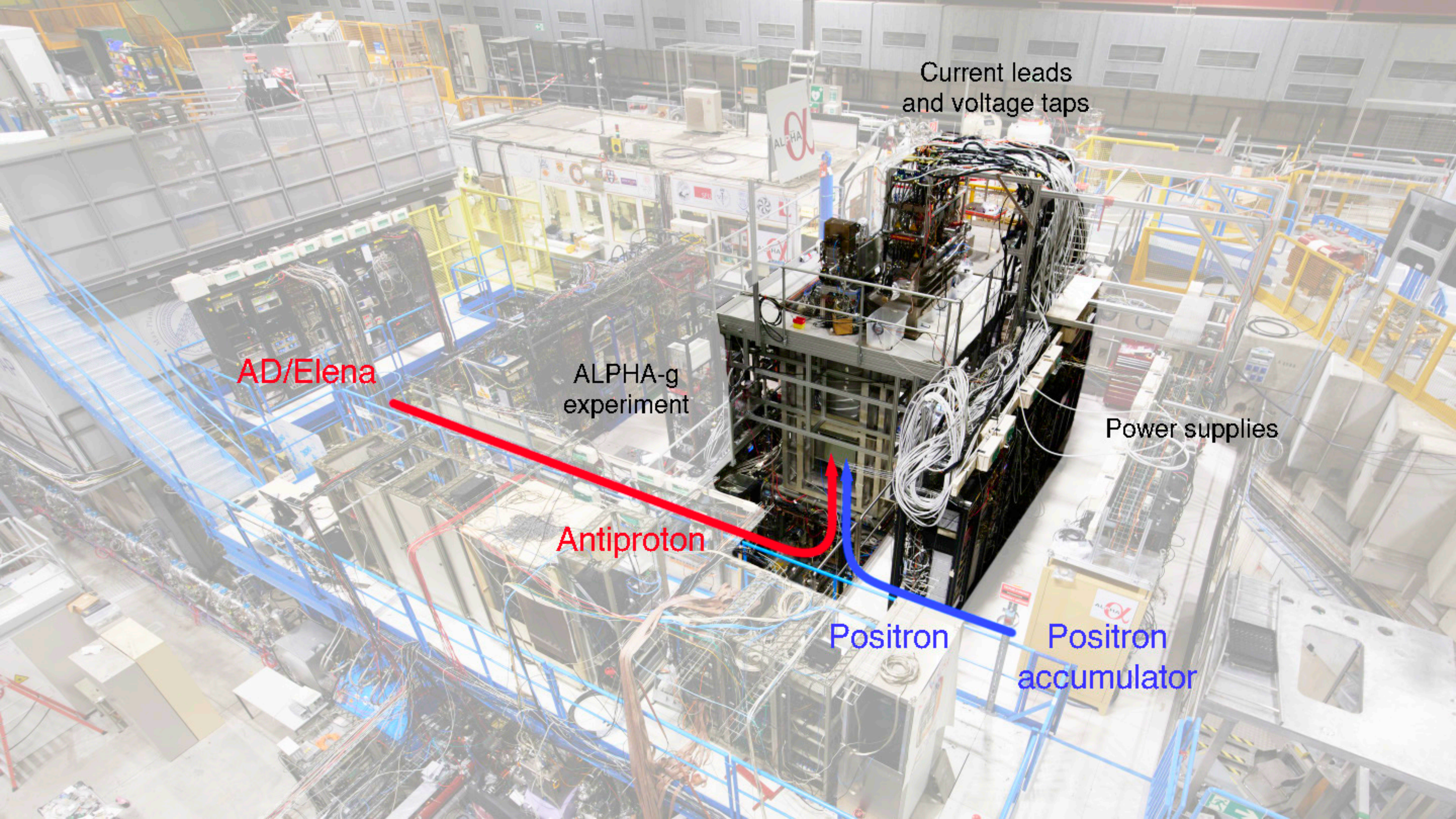
- Fundamental symmetries
- ALPHA at Cern's AD
  - First trapping in 2010 - *Nature* **468**, 673 (2010)
  - 1S-2S - Nature **557**, 71–75 (2018)
  - 1S-2P - Nature **561**, 211-215 (2018)
  - Hyperfine - Nature **548**, 66–69 (2017)
  - Lamb shift - Nature **578**, 375–380 (2020)
  - Charge neutrality - Nature Communications **5**, 3955 (2014)
- Next: gravity
  - More exotic than a feather!

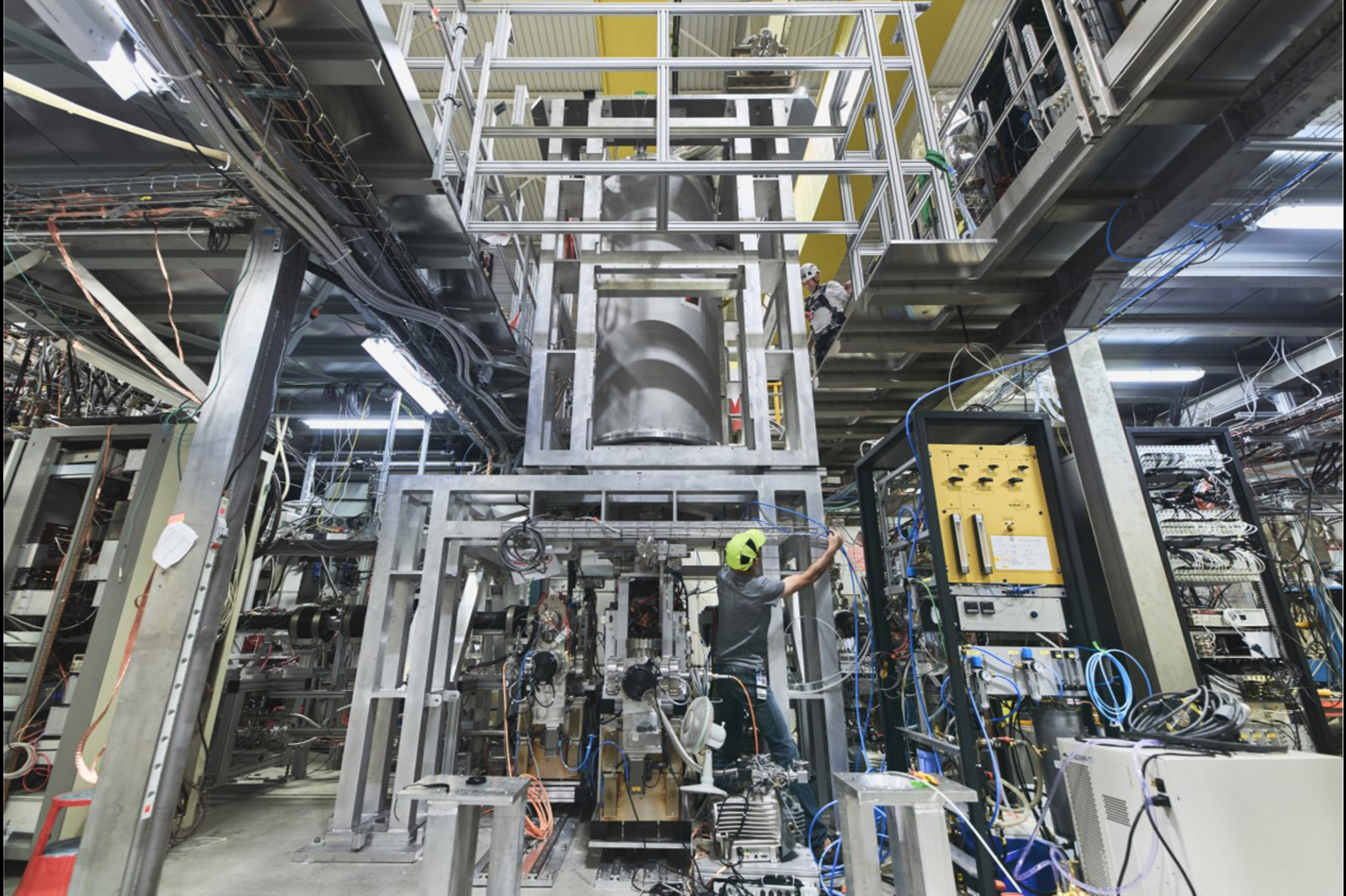


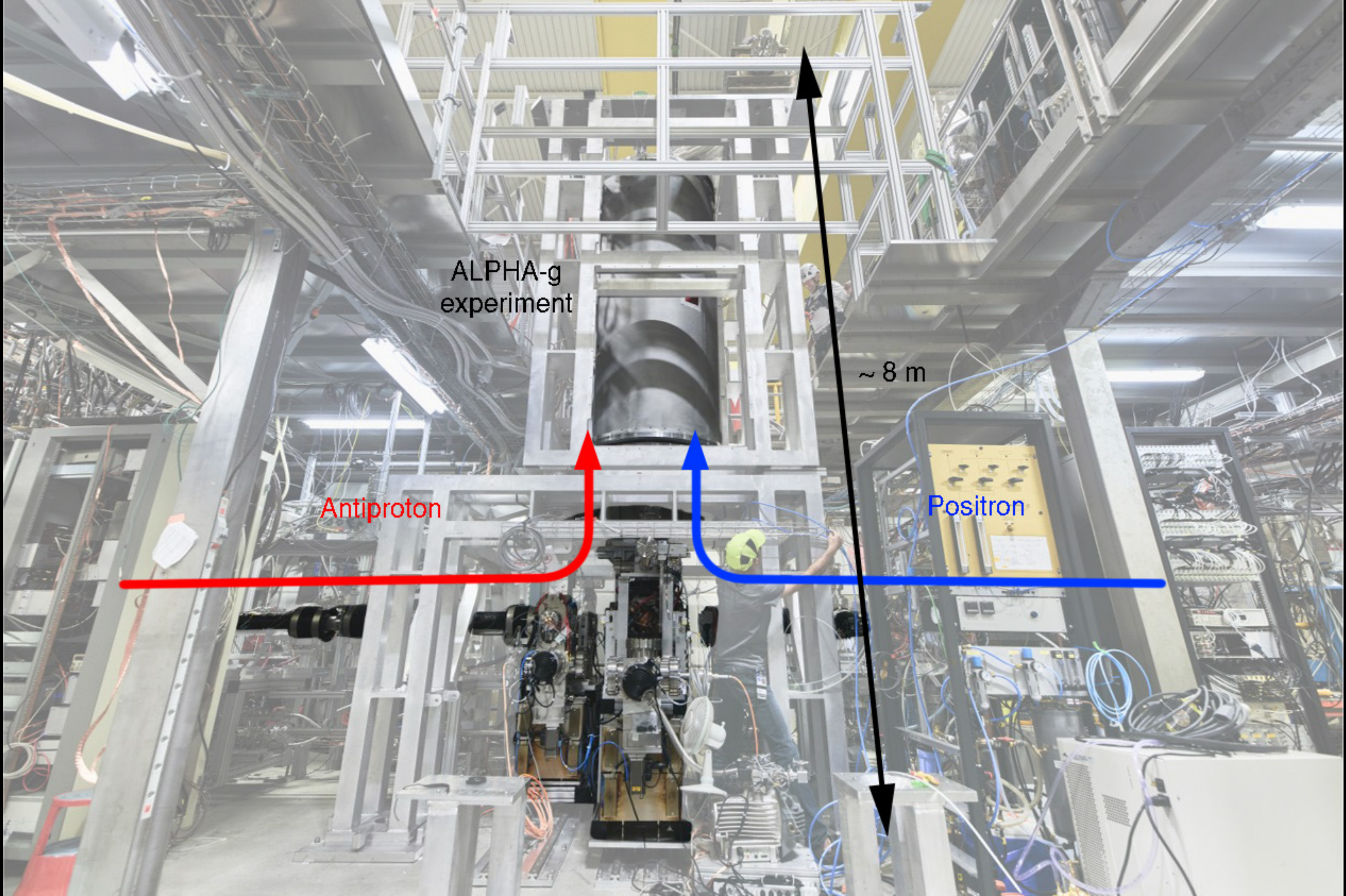
The ALPHA-g experiment





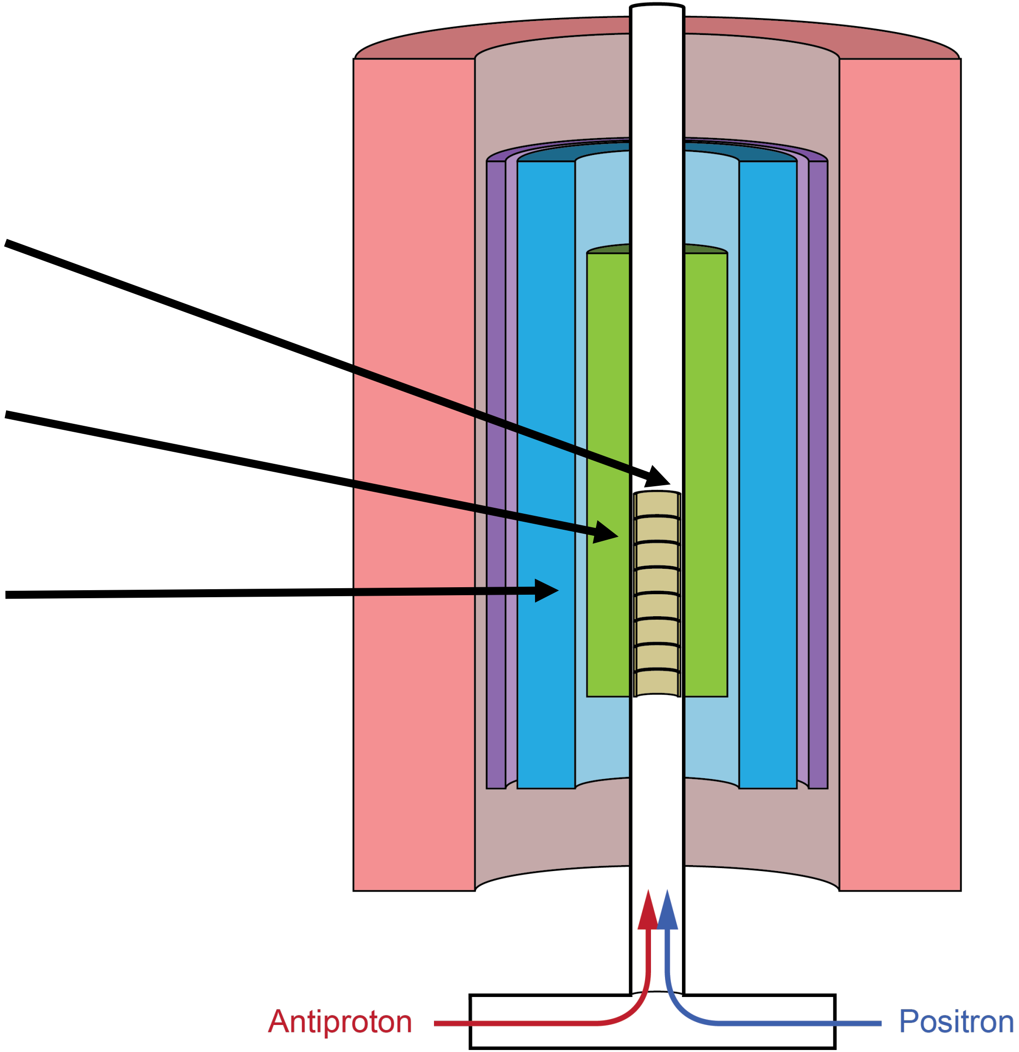

Current leads
and voltage taps
AD/Elena
ALPHA-g
experiment
Power supplies
Antiproton
Positron
Positron
accumulator




ALPHA-g
experiment
~ 8 m
Antiproton
Positron

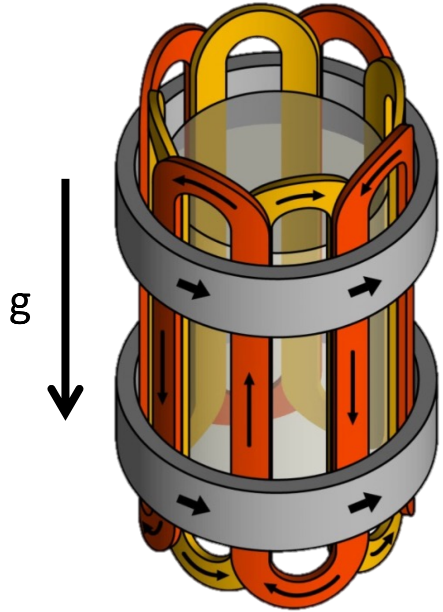
The ALPHA-g experiment

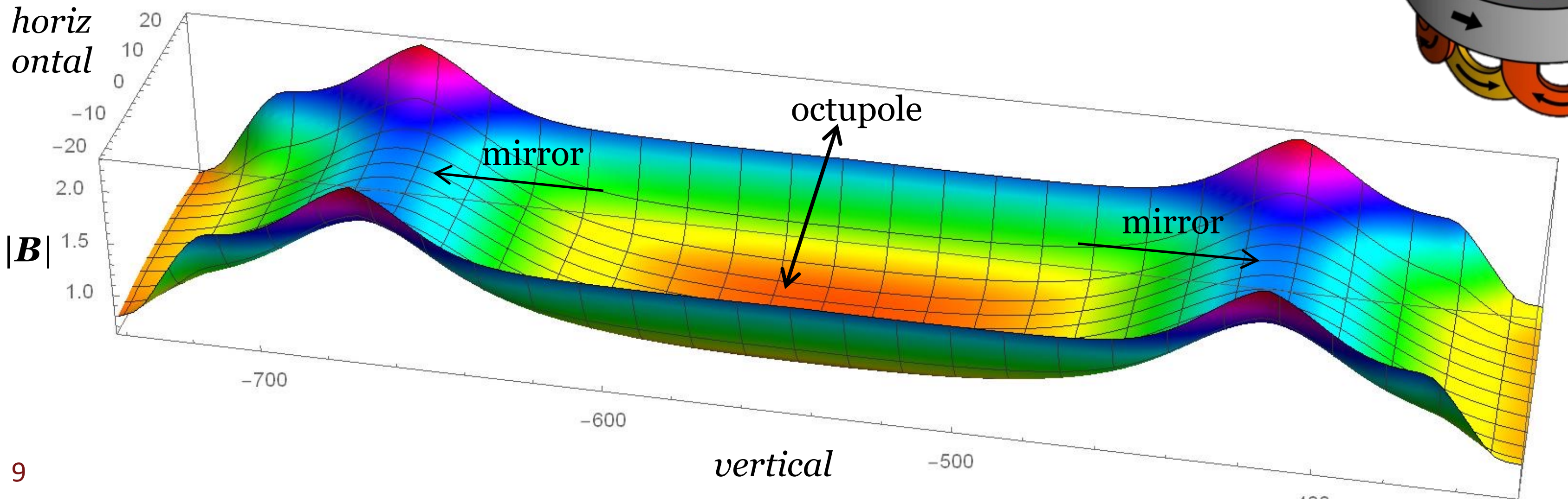
- Penning trap
  - Catching and cooling plasmas
  - Mixing to create antihydrogen
- Magnetic trap
  - Trapping anti-atoms
  - Release for gravity
- Detector
  - Determine the behaviour of antihydrogen
  - Rejecting anything else



Magnetic minimum trap

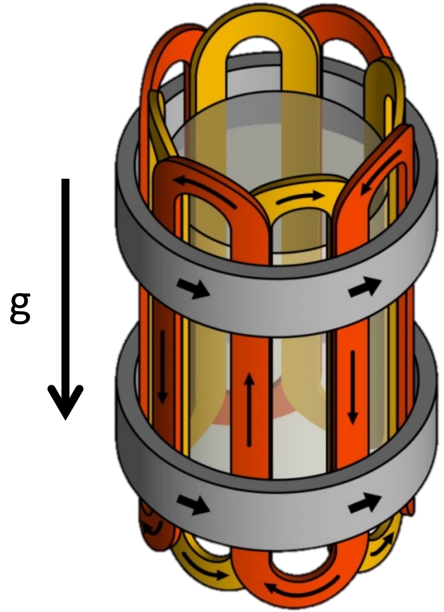
- Anti-atoms attracted to minimum in |***B***|
- Radial confinement: octupole
- Vertical confinement: mirror coils

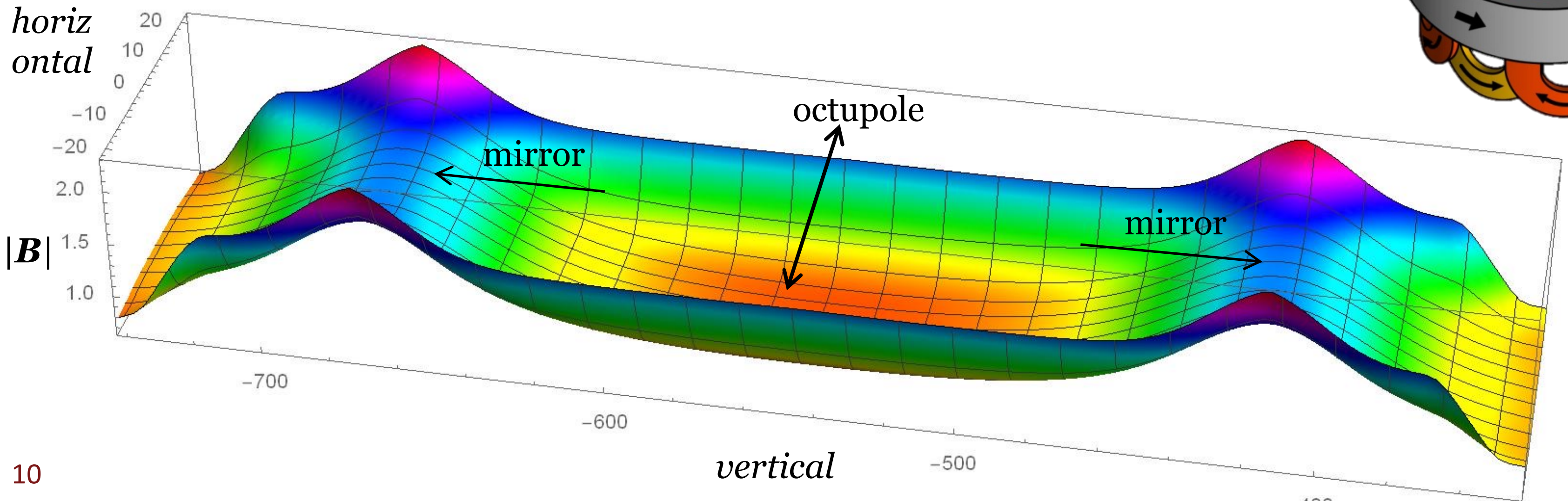




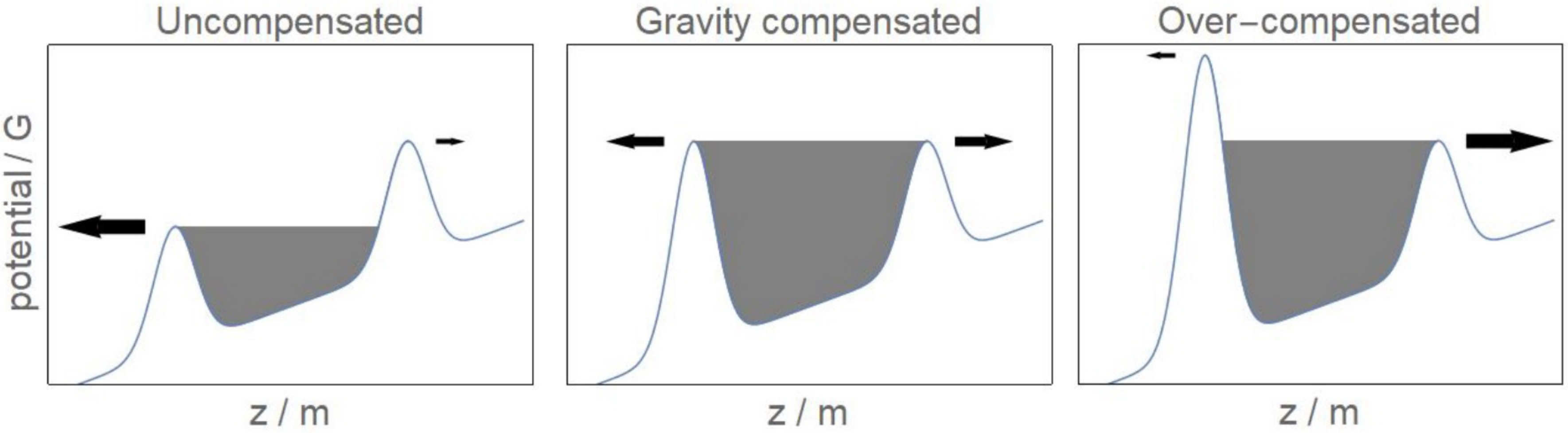
Gravity measurement

- Mirror coils slowly turned off
- Observe antiatom escape, up or down



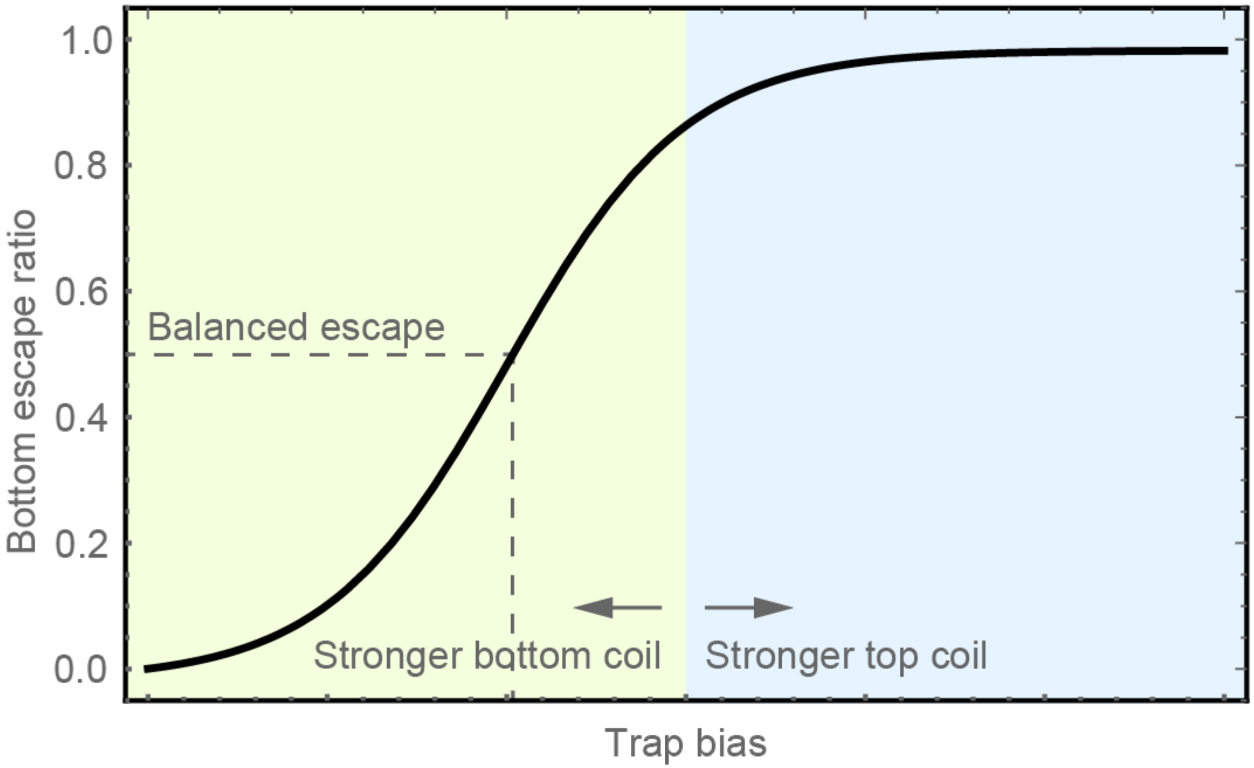


Gravity measurement



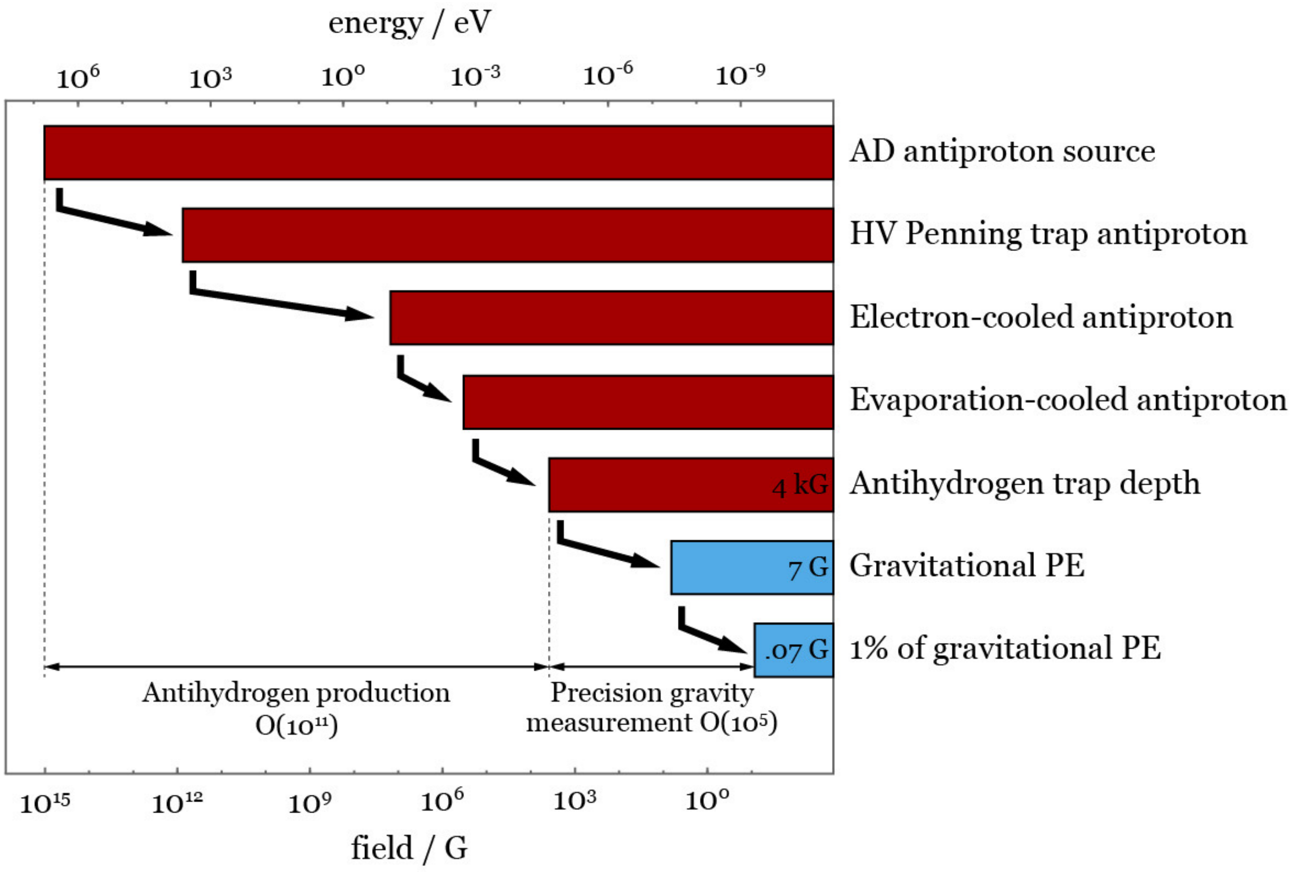
Gravity measurement

- Uncompensated trap favours “down”
- Balanced escape require stronger bottom coil
- Determine gravity by horizontal offset of the curve

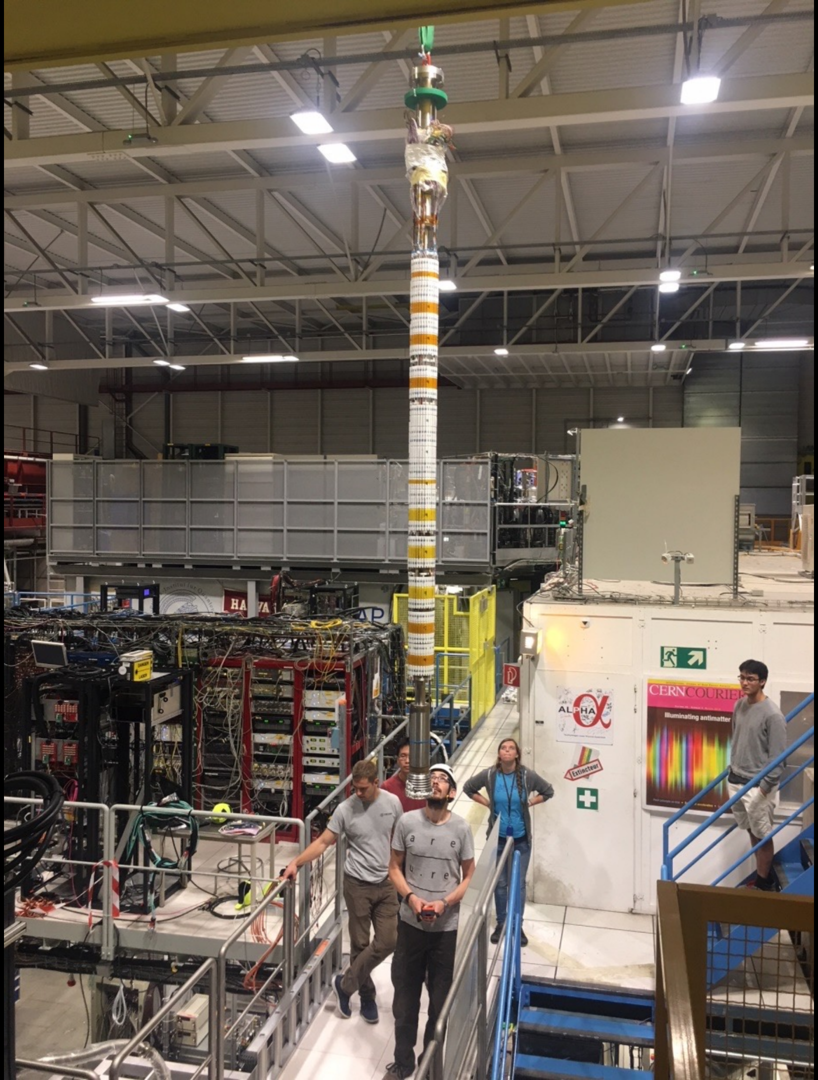


Challenges

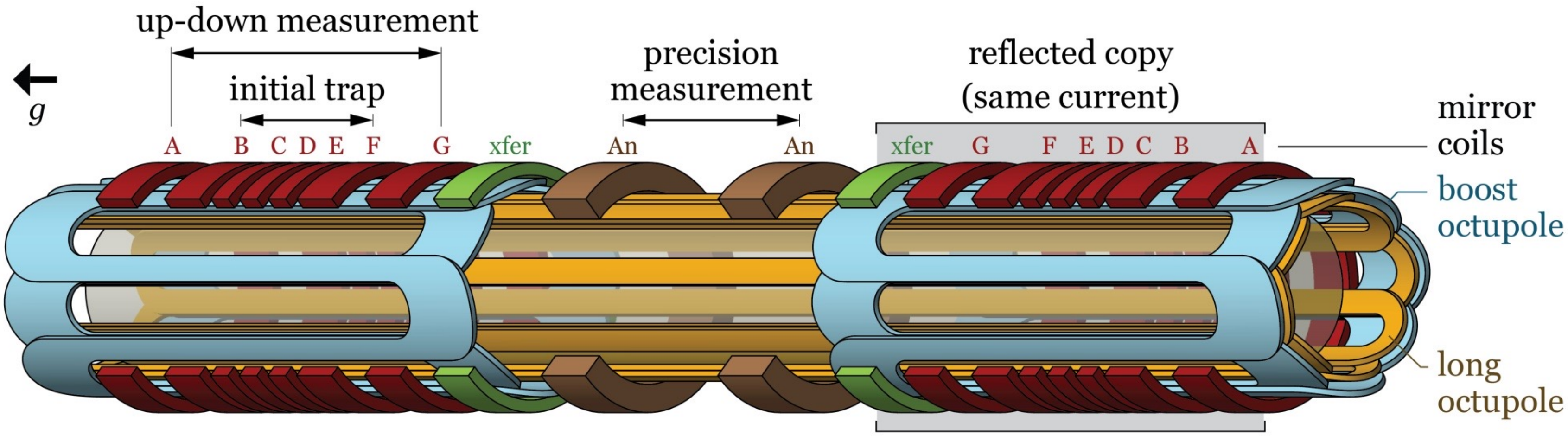
- Trapping antihydrogen
  - O(10^{11}) decrease in energy
  - Method developed and refined in ALPHA and ALPHA-2
- Precise field control
  - O(10^{-5}) control in trap field



Inner
magnets
3 m



Inner magnet geometry

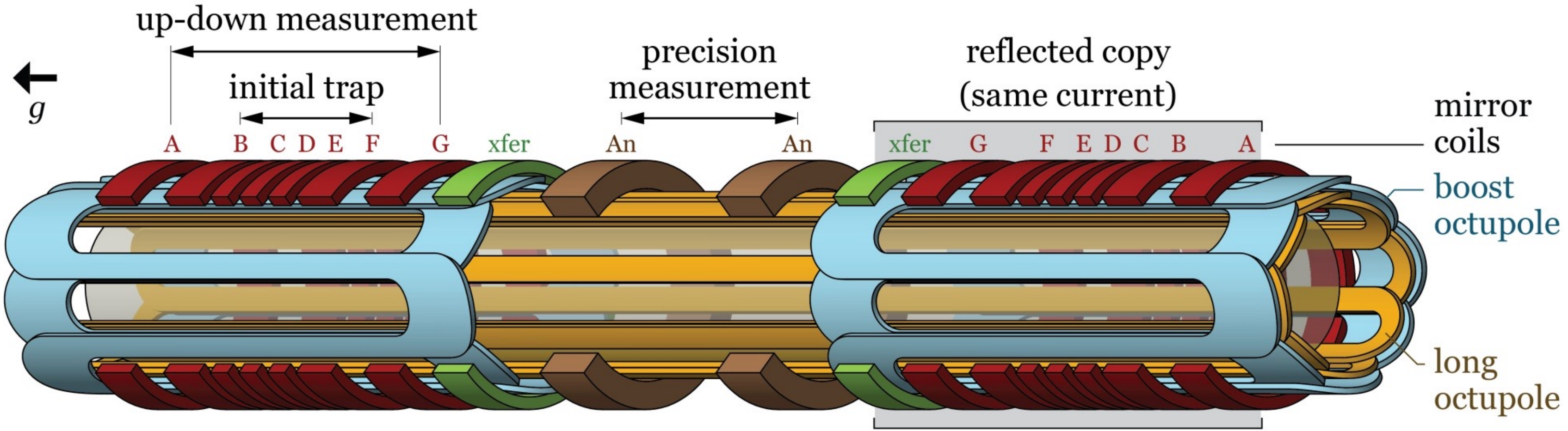


- Centre: Precision measurement
- Bottom: Stronger trap
- Top: reflected copy
- Why the complicated trap?

1. Persistent field

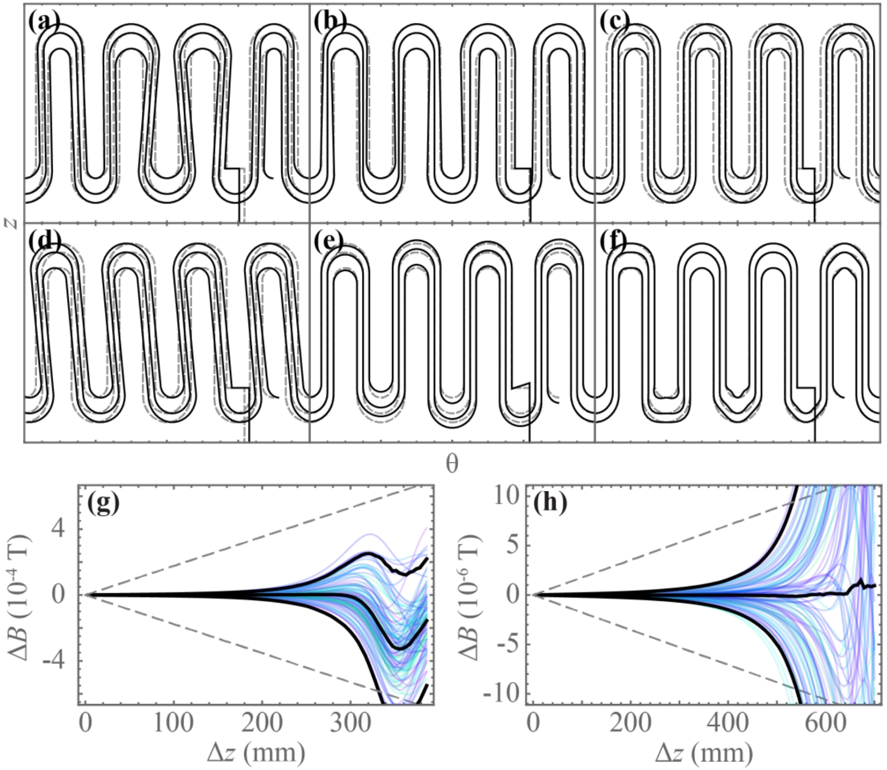
- Induced field in superconductor
  - Current loops induced in response to field changes
  - History-dependent

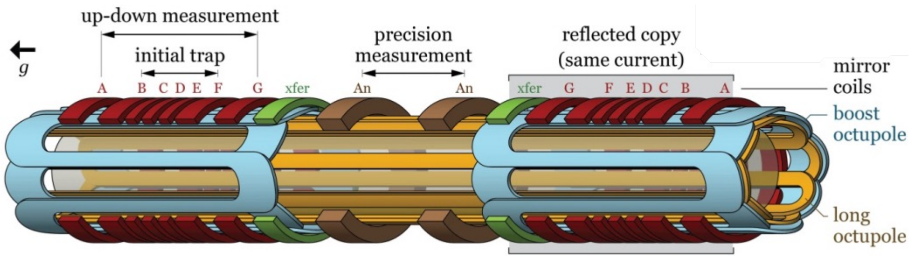
- Mitigation:
  - Weak magnets
  - Thin, numerous NbTi filaments
  - Symmetrise magnetic history
  - Neighbouring strong trap for initial trapping



2. Wire placement

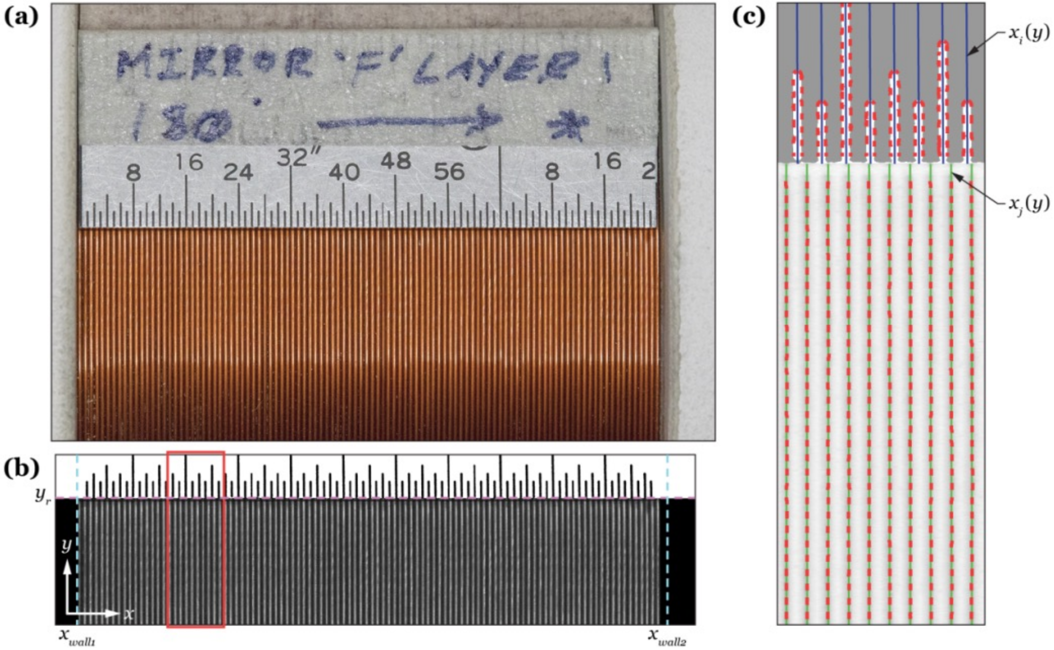
- Octupole winding
  - Wire-laying precisely controlled, but nothing is perfect
  - Field error most severe near end turns
  - Measurement regions avoid these regions
  - Long + short octupole minimises number of end turns near the precision region



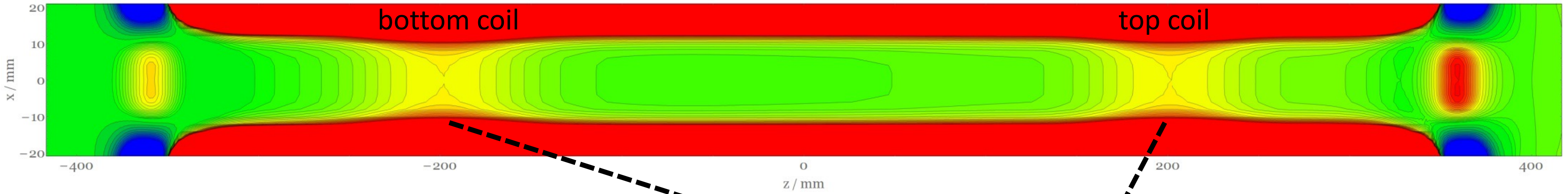


2. Wire placement

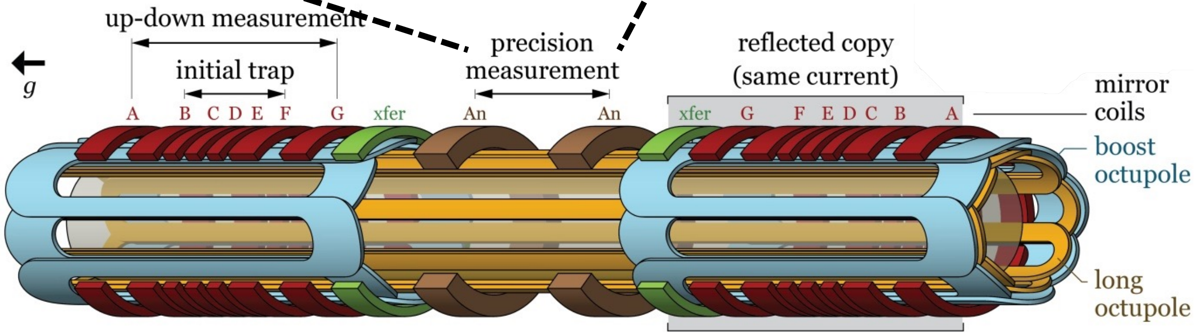
- Coil winding
  - Each layer is macro-photographed and analysed to locate turns



3. Separated DoF

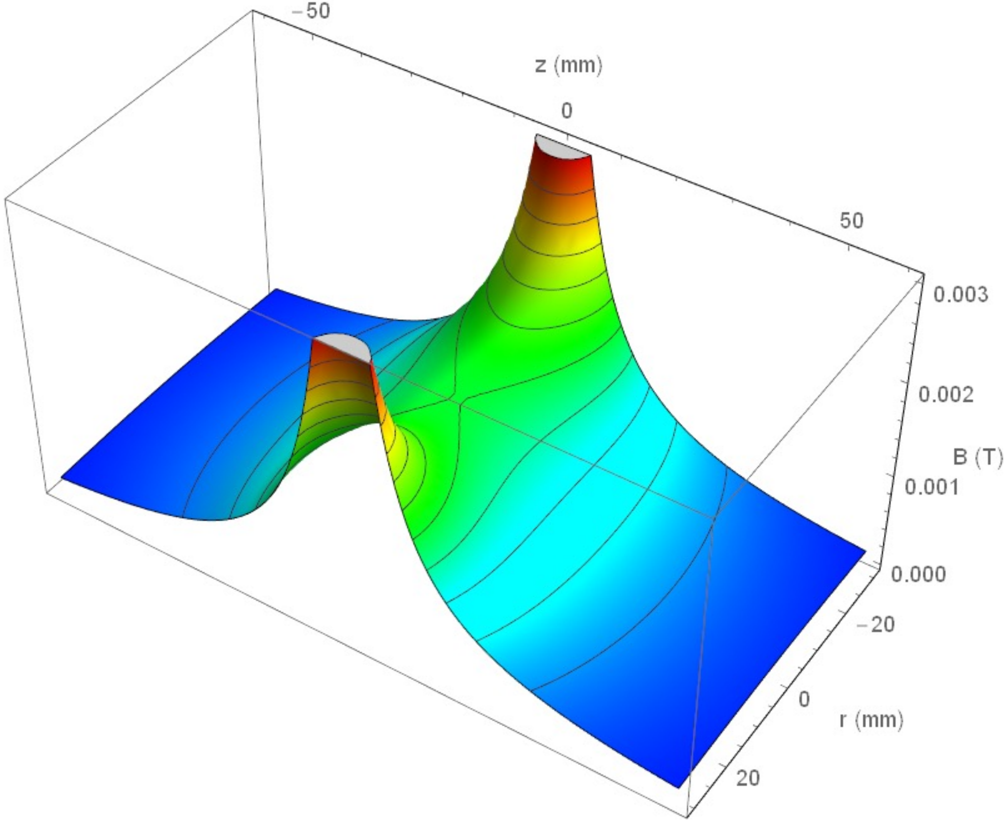


- Energetic escape requires hitting pin hole with all energy allocated to *z*
- Slow (*x*,*y*) and *z* energies mixing
- Anti-atoms mostly escape off-axis, at much later time
- Must tailor on- and off-axis fields



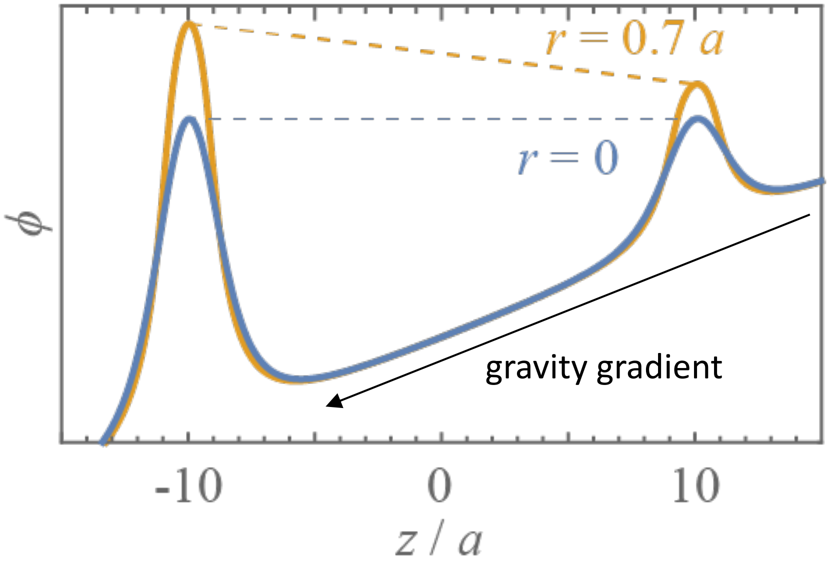
3. Separated DoF

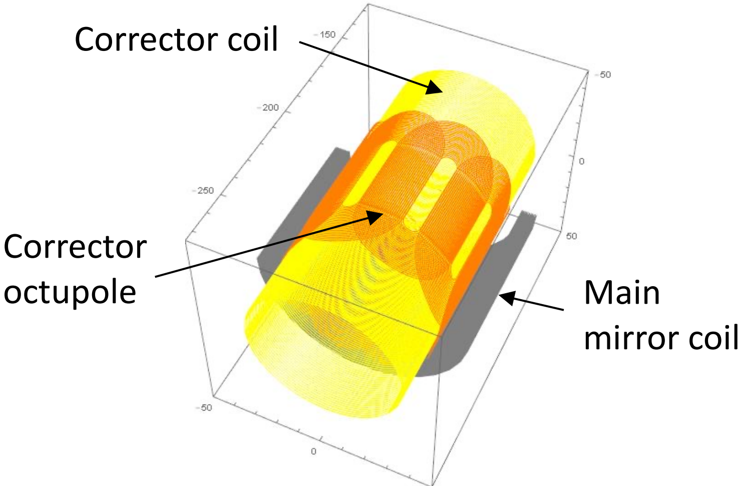
- A coil's field is saddle-shaped



3. Separated DoF

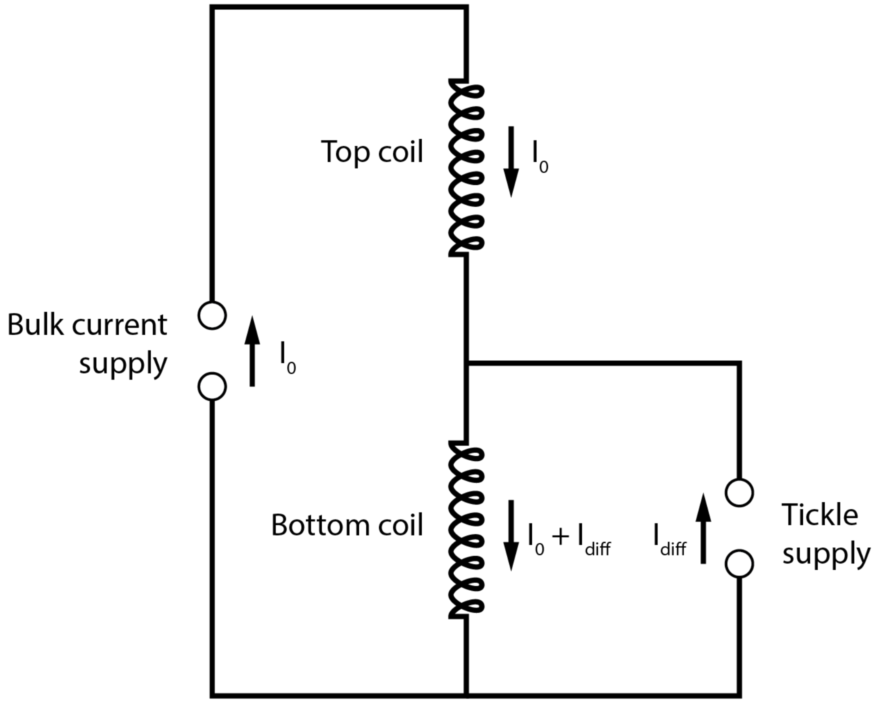
- Two coils at different currents cannot form equal barriers for all r
- Even messier picture with octupole contribution
- Correctors implemented to improve trap bias uniformity across r





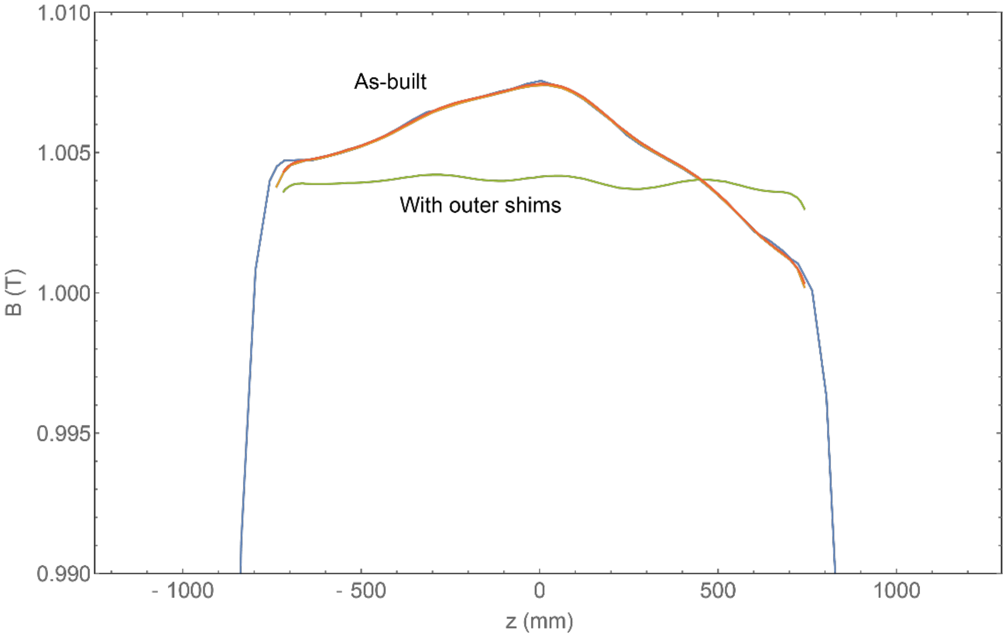
4. Current supply

- Extremely fine current control on barrier coils
  - Common mode: 70 A to ~0 A, no specific precision requirement
  - Difference: ~ 0.1 A, precise to ~1 mA
- Two completely separate PS: 10 ppm
- One bulk current supply and one “tickle” supply: 10000 ppm
- Two currents measured by DCCT and fed back to power supplies PID control



5. Background solenoid uniformity

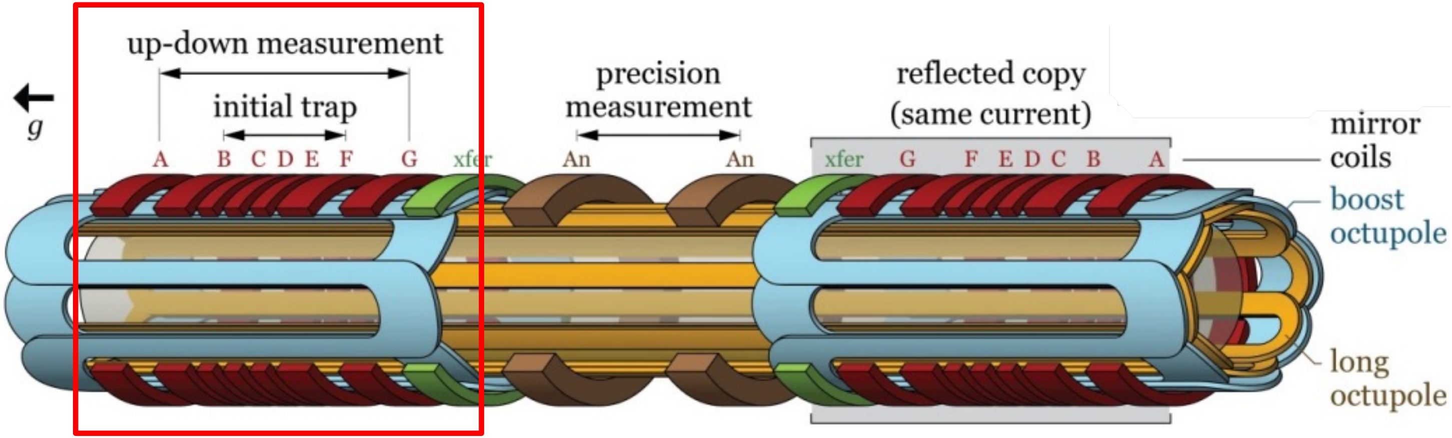
- Affects gravity measurement due to field gradient
- As-built
  - ~20 G non-uniformity
- With outer shims
  - ~4 G non-uniformity
  - Compensate by adjusting mirror coil currents
- Possible future inner shims
  - ~0.02 G non-uniformity
  - Reduced coil adjustment



Performing a first measurement

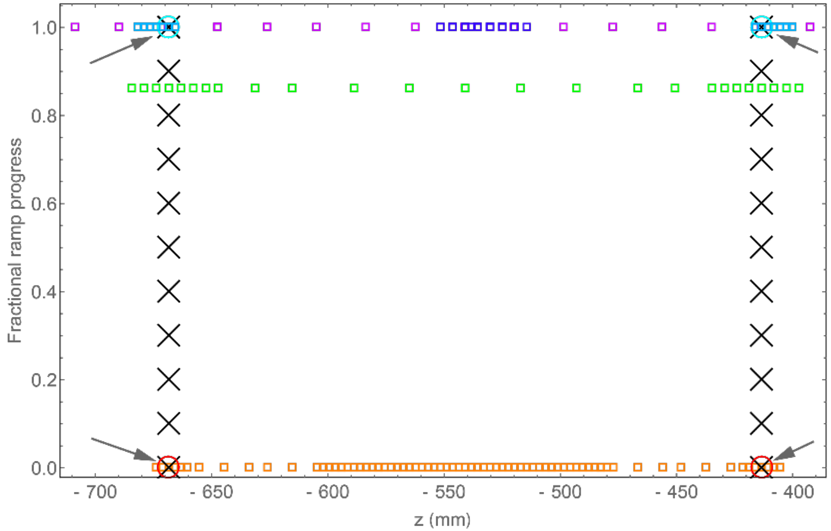
An “up-down” measurement

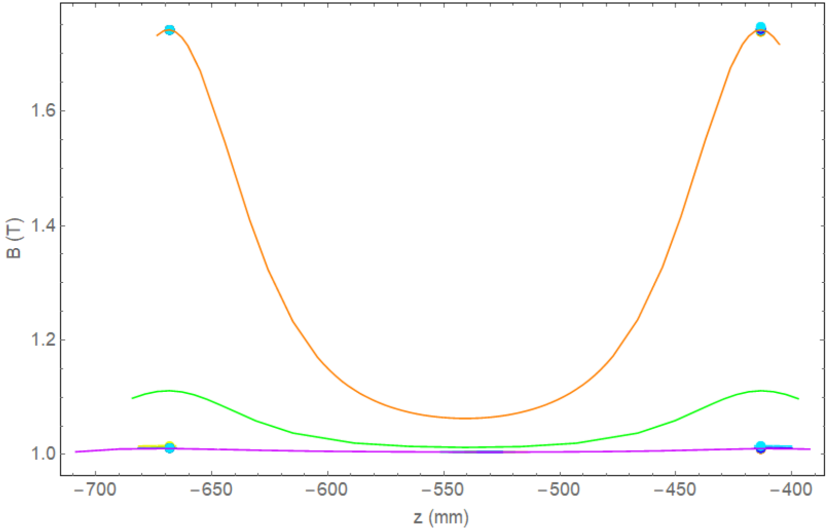
- Using only the bottom set of magnets
- Pro
  - Deeper trap, more statistics
  - Fewer magnet elements needed
- Con
  - Less accurate field – more persistence effect, no correctors
  - Cannot use the long octupole
- Aiming to resolve the direction of gravity on antihydrogen



Magnetometry

- Persistence effect is inevitable
- Measure field and adjust current, to maintain trap bias throughout release ramp
- ECR
  - Measures cyclotron frequency in Penning trap
  - Slow measurement process
- Magnetron counting
  - Measures the phase of ExB drift of Penning trap plasmas
  - Fast measurement
  - Less accurate than ECR
- Able to control relative trap bias to ~0.1 Gauss





Field model

- Magnetometry results are integrated into a 3D field model

$$
\begin{aligned}
B(z,p) = {} & B_{\text{babcock}}(z) + B_{\text{SOct}}(z) \\
& + B_{\text{MAB}}(z) I_{\text{MAB}}(p) + B_{\text{MGB}}(z) I_{\text{MGB}}(p) \\
& + A(z)(1 - \exp(-p/0.1346)) \\
& + B_{\text{res0}}(z)(1 - p) + B_{\text{res1}}(z) p
\end{aligned}
$$

Wire model field, from currents we provide

Exponentially saturating component from magnetron results

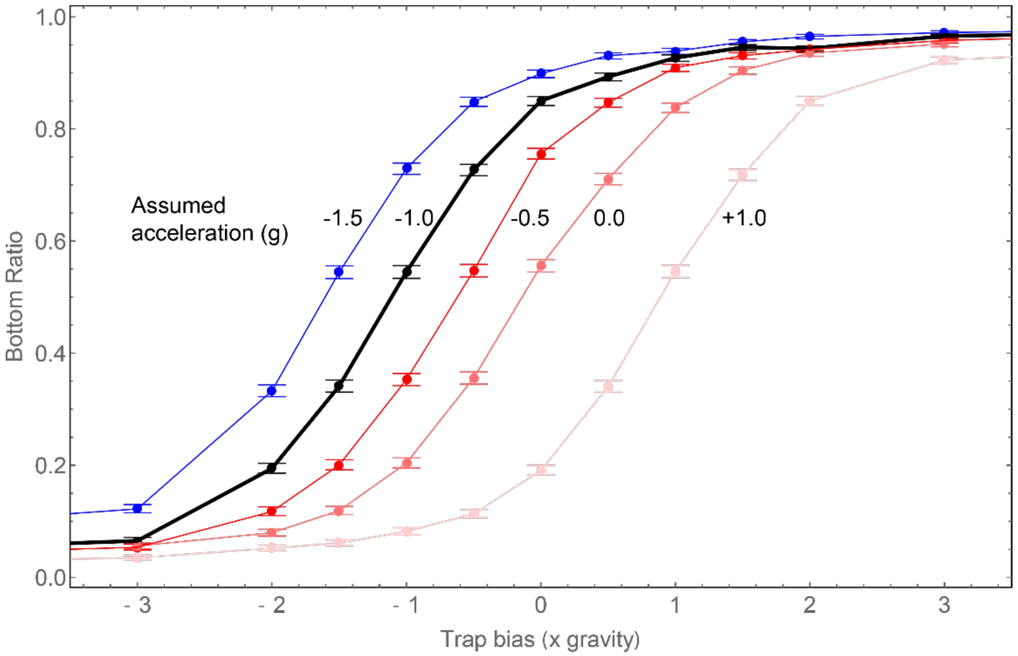
Residual to account for ECR

Field we don't control

- O(1 Gauss) precision, much better around the saddle points
- Particle pusher uses field to evolve anti-atoms through the entire experimental sequence
  - Obtain the expected escape bias as a function of gravitational acceleration
  - Field model is critical as antiatoms escape off-axis

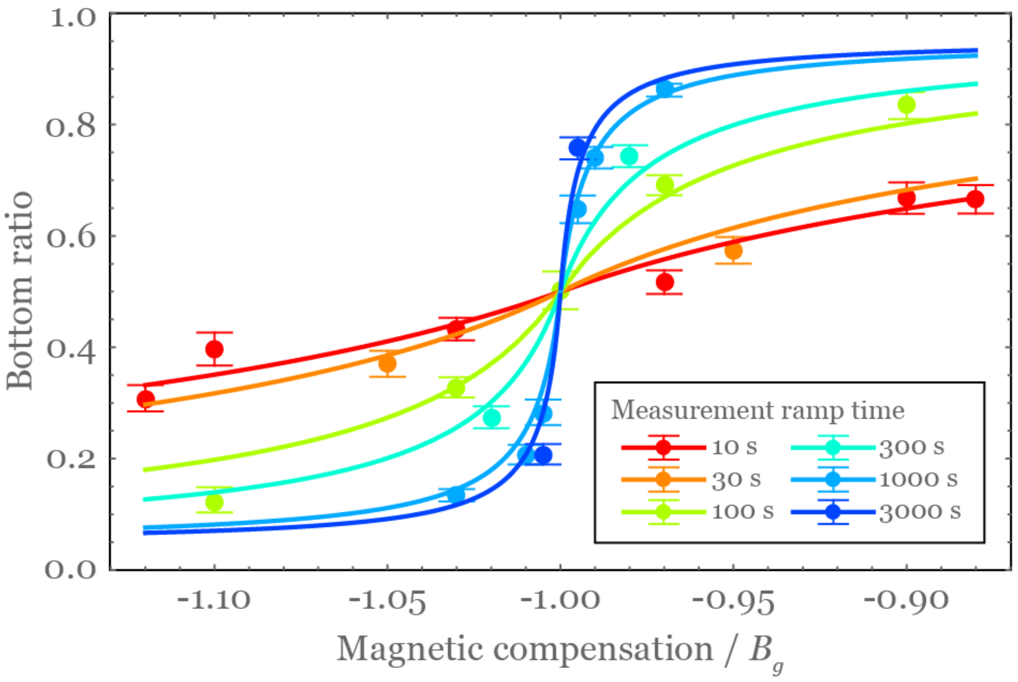
Experiment progress

- In 2022: performed experimental release at 13 trap biases
- Results being analysed and compared to simulation



Future precision

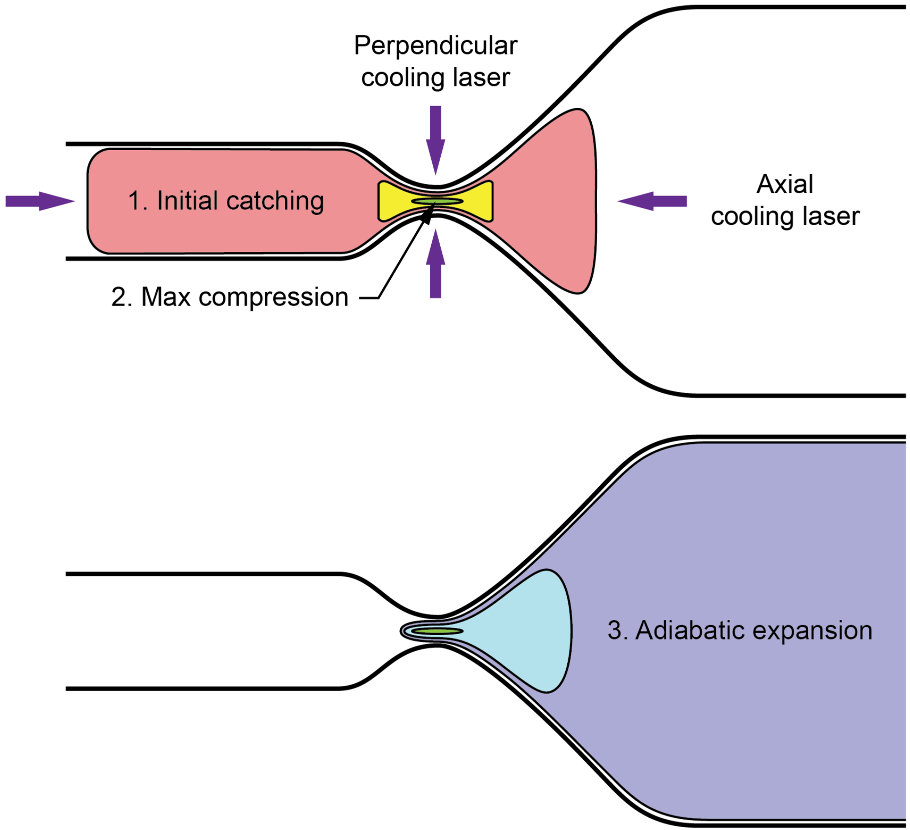
- Using the proper precision region
- Steepness of escape balance curve closely affects sensitivity
- Long ramp = more chance anti-atoms can escape on-time, higher sensitivity
- Down side:
  - Long window = more cosmics
  - Depends on our ability to reject cosmics
- Other factors like current noise and anti-atom temperature

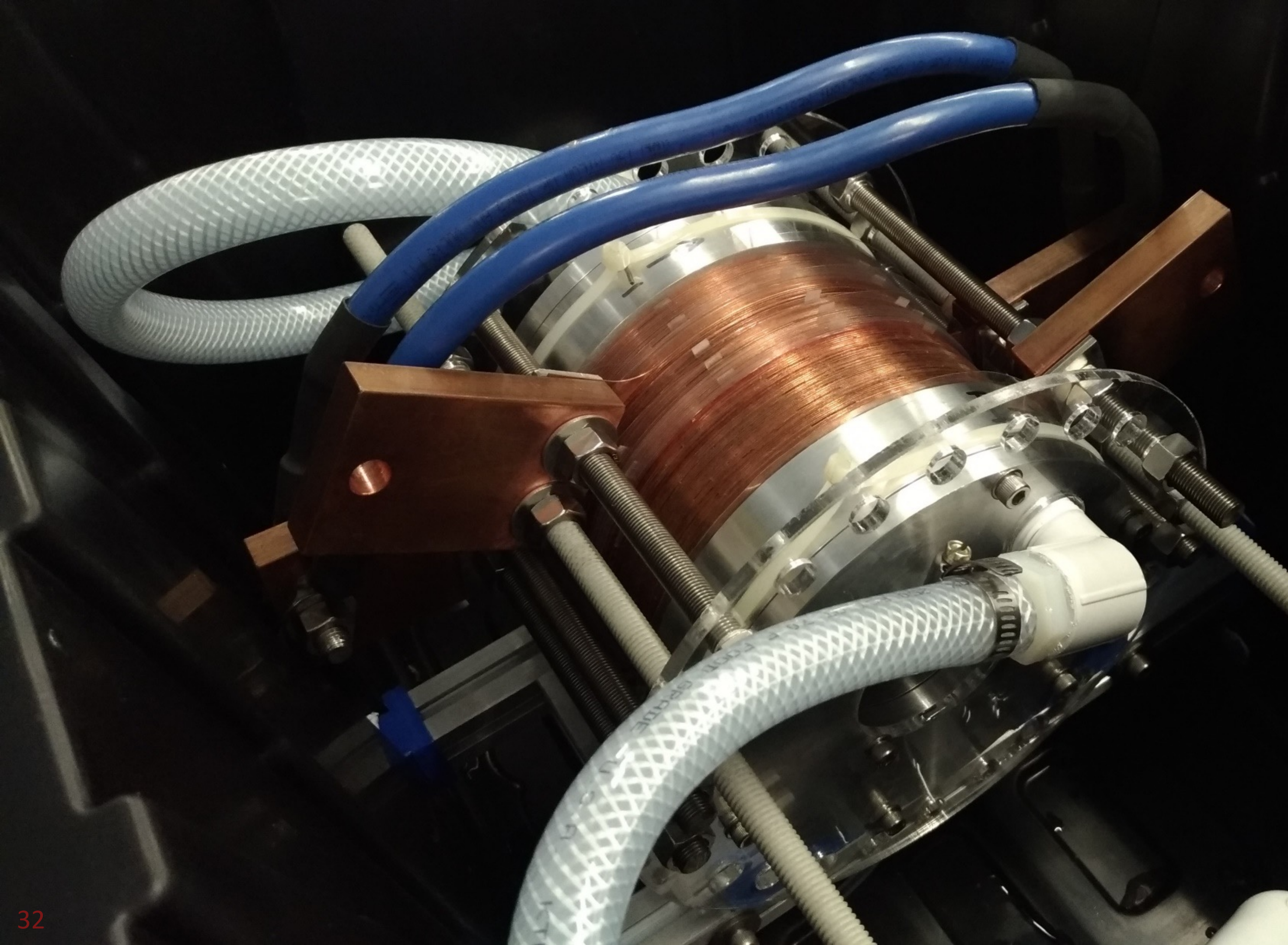


HAICU

Interferometer

- Raman interferometer:
  - Weighing atoms without field
  - Coherent interrogation during free-fall
  - 10^{-2} vs 10^{-14} precision
- Requires extremely slow atoms
  - Beyond Doppler laser cooling with magnetic compression
- Special magnetic trap with a “neck”
  1. Bitter magnet trap
  2. Bitter magnet trap with a neck
  3. Superconducting trap with a much stronger neck



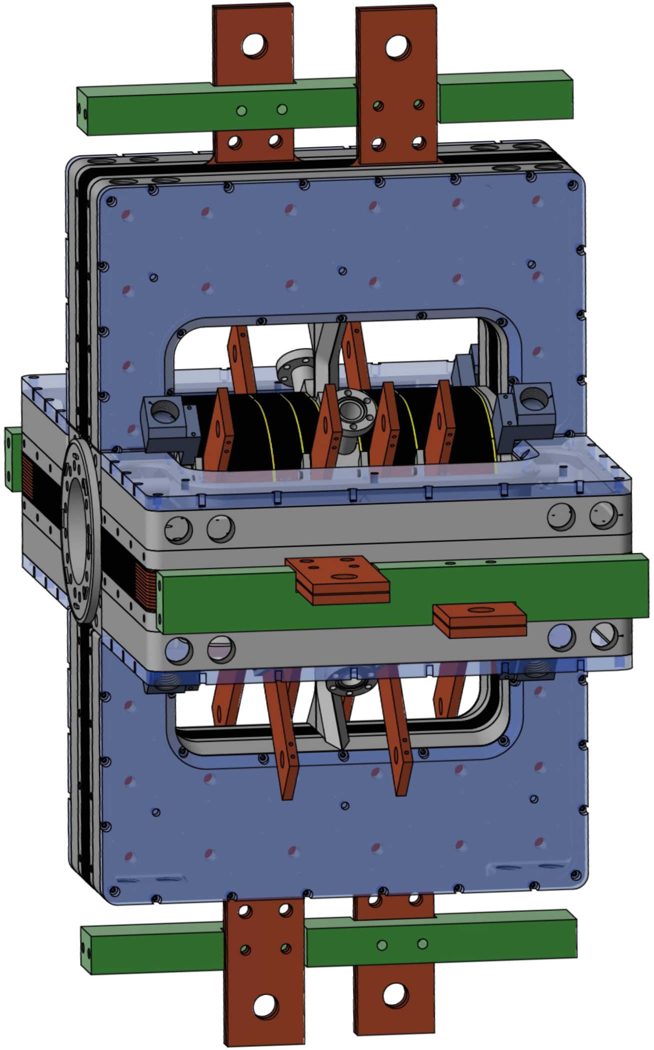


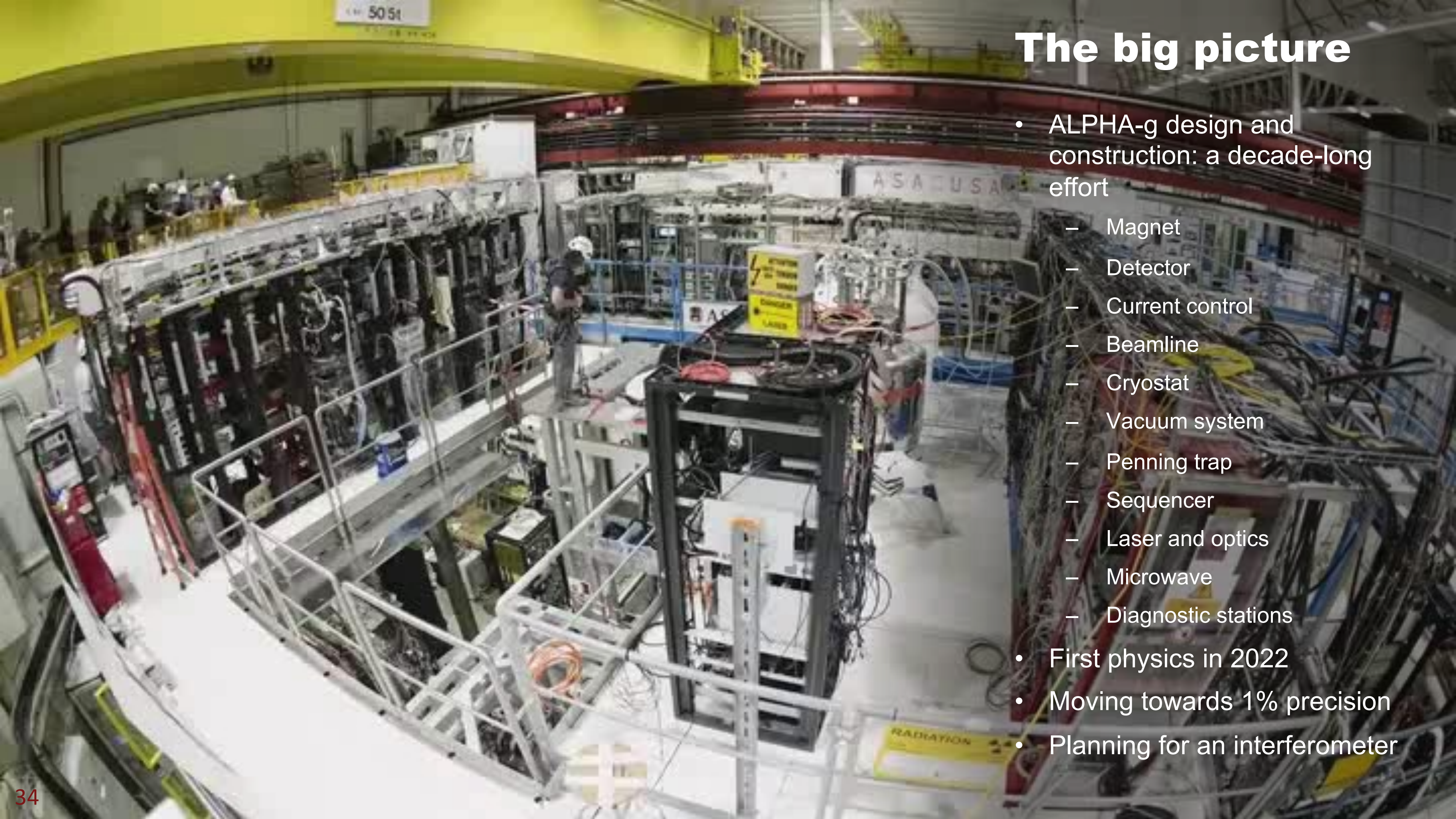
Bitter magnet development

- Water-cooled, normally conducting
- 350 A, 5 kW test coil
- Test of fabrication and assembly technique

Magnetic trap prototype

- High power density winding
  - 1800 A, 80 kW quadrupole
  - 350 A, 10 kW mirror coils
  - 0.2 T trap depth on a 0.3 T background
  - 10 L/s cooling water
- Axial and perpendicular optical access for laser cooling
- In final design stage
- Experiment located in meson hall extension
- Uses hydrogen atom as proxy
- Aiming for commissioning by end of 2023





The big picture

- ALPHA-g design and construction: a decade-long effort
  - Magnet
  - Detector
  - Current control
  - Beamline
  - Cryostat
  - Vacuum system
  - Penning trap
  - Sequencer
  - Laser and optics
  - Microwave
  - Diagnostic stations
- First physics in 2022
- Moving towards 1% precision
- Planning for an interferometer