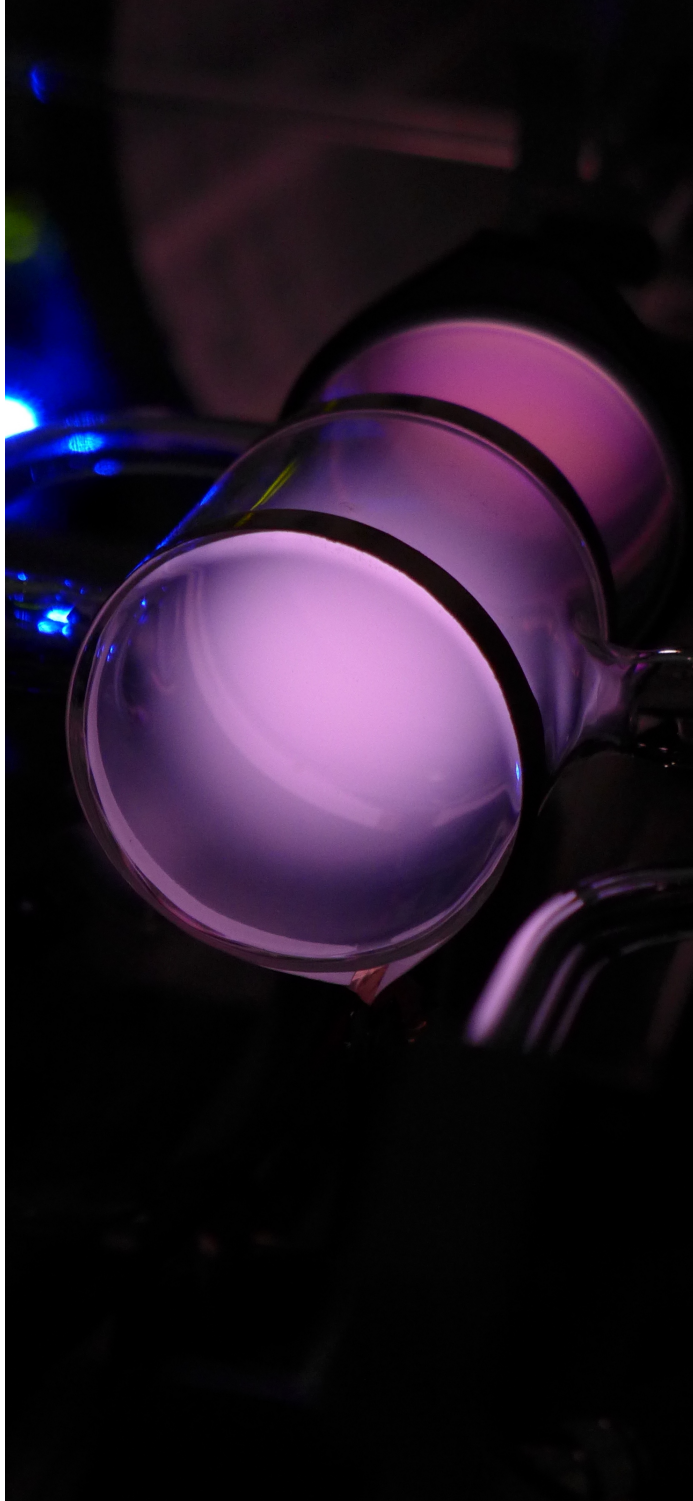
Development of a Polarized ^{3}He Beam Source

And Applications in Ghostbusting

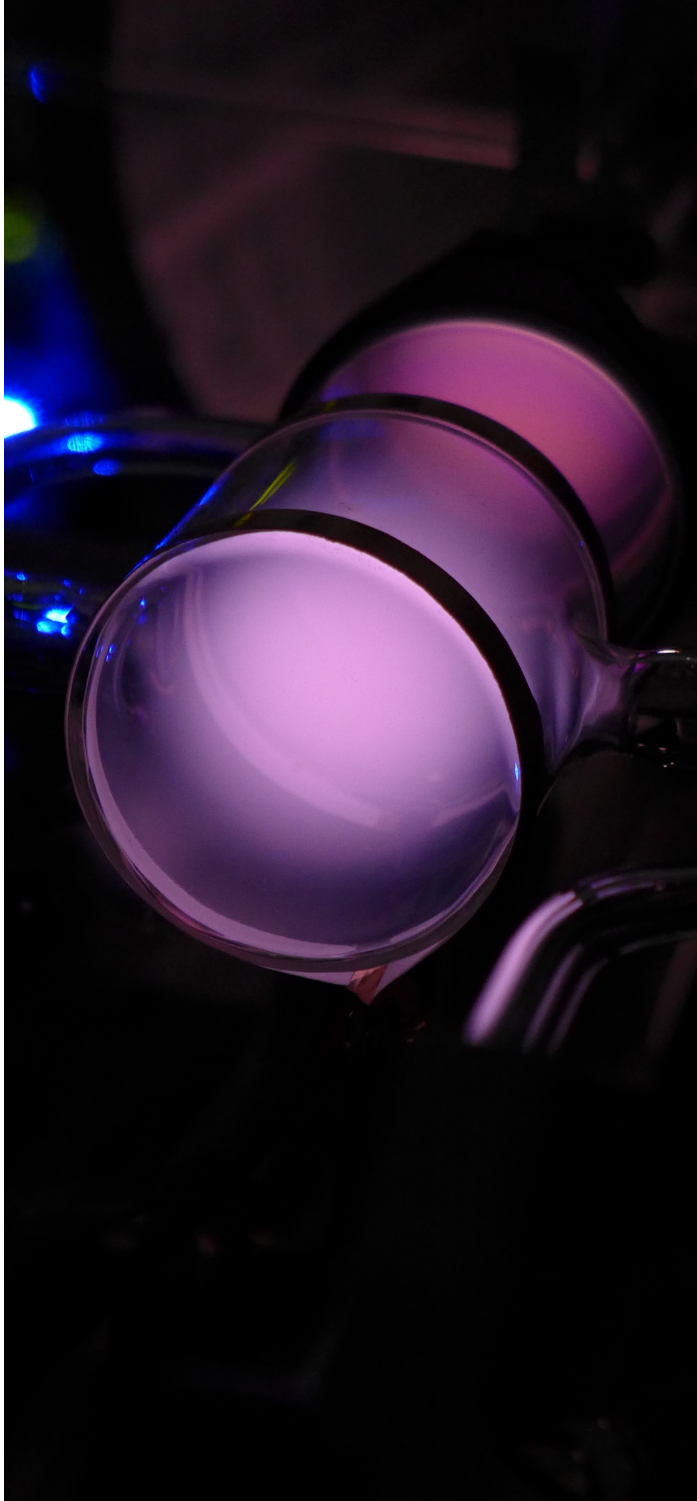
J. Maxwell

Jefferson Lab Pizza Seminar
June 8th, 2016



Outline

1. Polarized ^{3}He Source
   - Source Design
   - Polarization and Relaxation Tests
   - High Field Tests
   - Next Steps
2. Ghostbusters (2016)
   - He3 Polarizer on Film
   - Proton Pack Design
   - Other Fun Stuff



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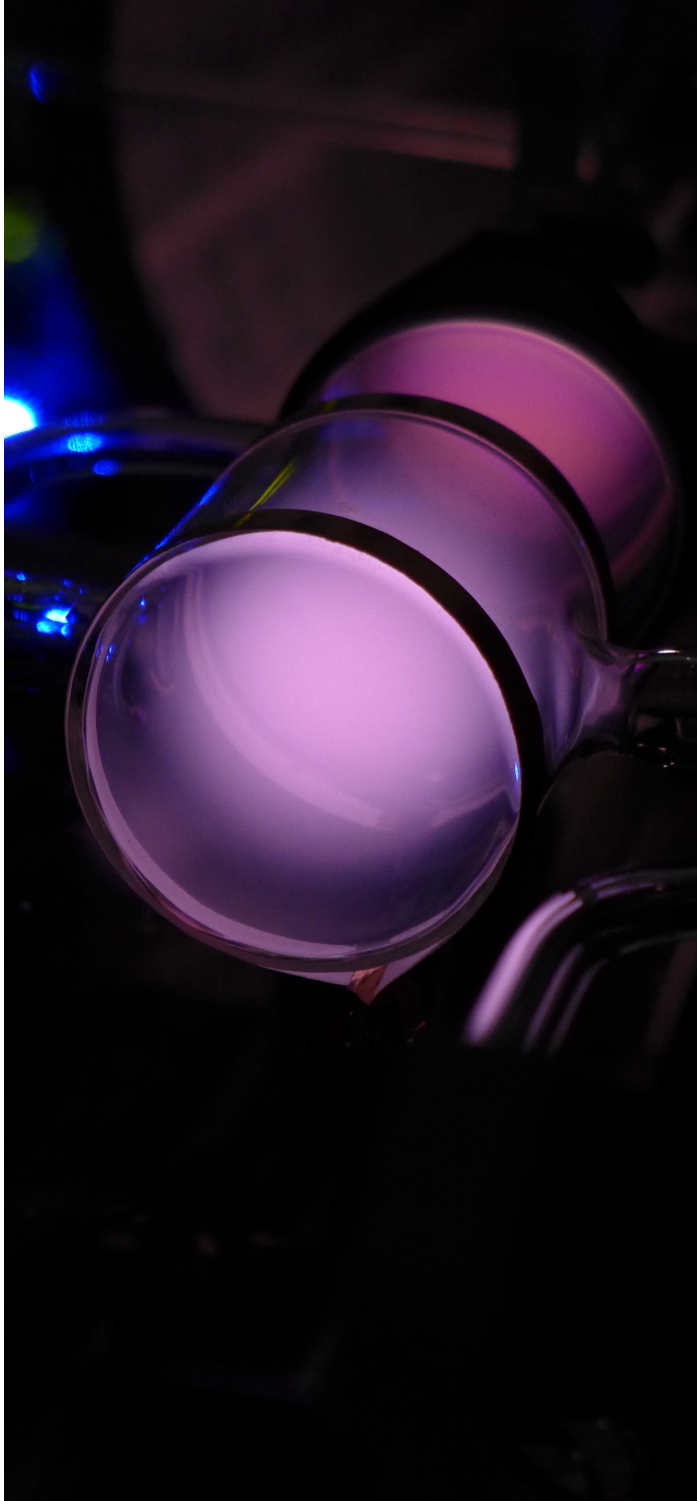
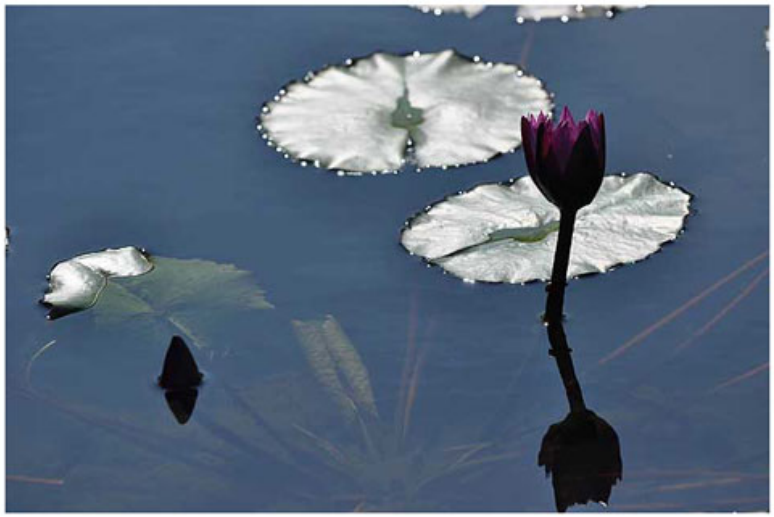
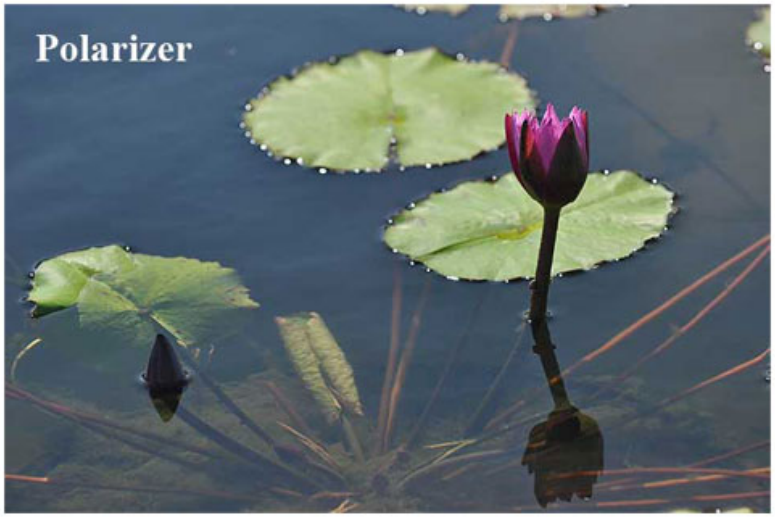


Polarized Scattering Experiments

- Polarized targets and sources are analogous to polarized lenses in sunglasses
  - Light from the sun is unpolarized
  - Reflected glare from the water or the road is more likely horizontally polarized
  - By selecting only vertically polarized light, we see a different picture

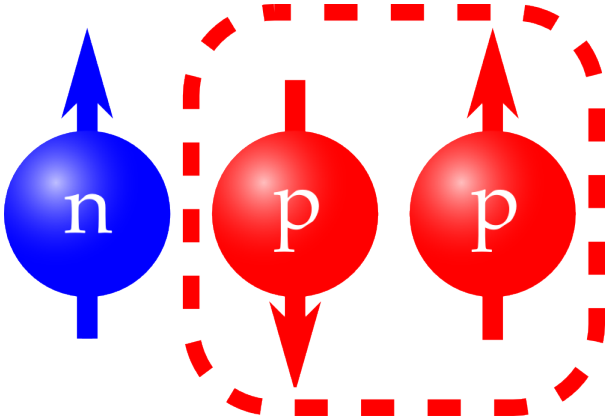




Nikon USA

Why a Polarized Helium 3 Source?

- Polarized DIS crucial for study of neutron spin structure
  - PPDFs; tests of QCD, Bjorken sum rule; higher energies



State	Probability
S	88.6%
S'	1.5%
D	8.4%

- S-state ^{3}He: nuclear spin carried by the neutron
- ^{3}He's magnetic moment close to n, compatible with RHIC spin manipulation
- Polarized ^{3}He ions offer a "polarized neutron beam" for RHIC and a future EIC

History of ^{3}He Ion Sources

- Rice University, 1969: MEOP for $^3He^+$
  - 16 keV, 8 particle μA at 11% polarization
- Univ. of Birmingham, 1973: Lamb Shift for $^3He^{++}$
  - 29 keV, 50 particle μA at 65% polarization
- Laval University, 1980: Stern-Gerlach for $^3He^+$
  - 12 keV, 100 particle nA at 95% polarization

Our Proposal[1]

- RHIC's **Electron Beam Ion Source** Preinjector
  - Proven in recent RHIC runs, NASA Space Radiation Lab
- Metastability Exchange Optical Pumping
- Doubly ionize $^3He^{++}$ for injection

[1] A. Zelenski, J. Alessi, ICFA Newsletter (2003).

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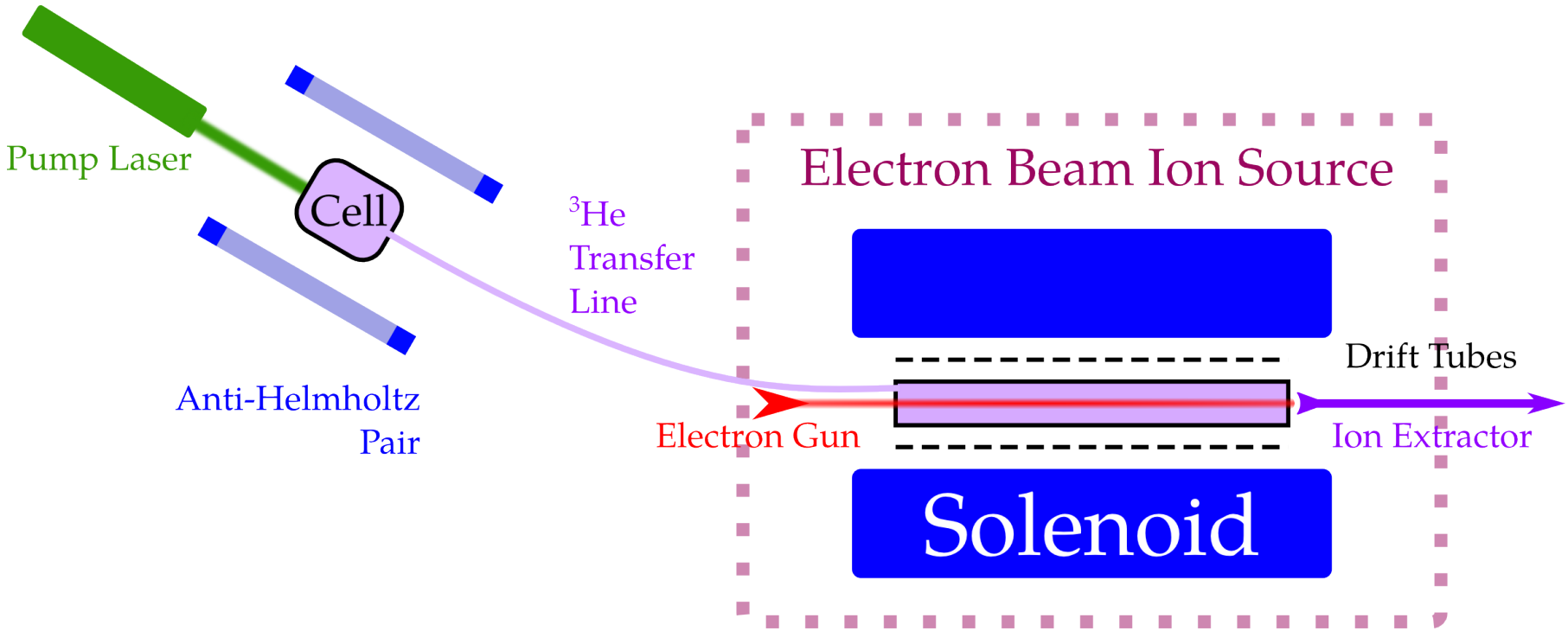
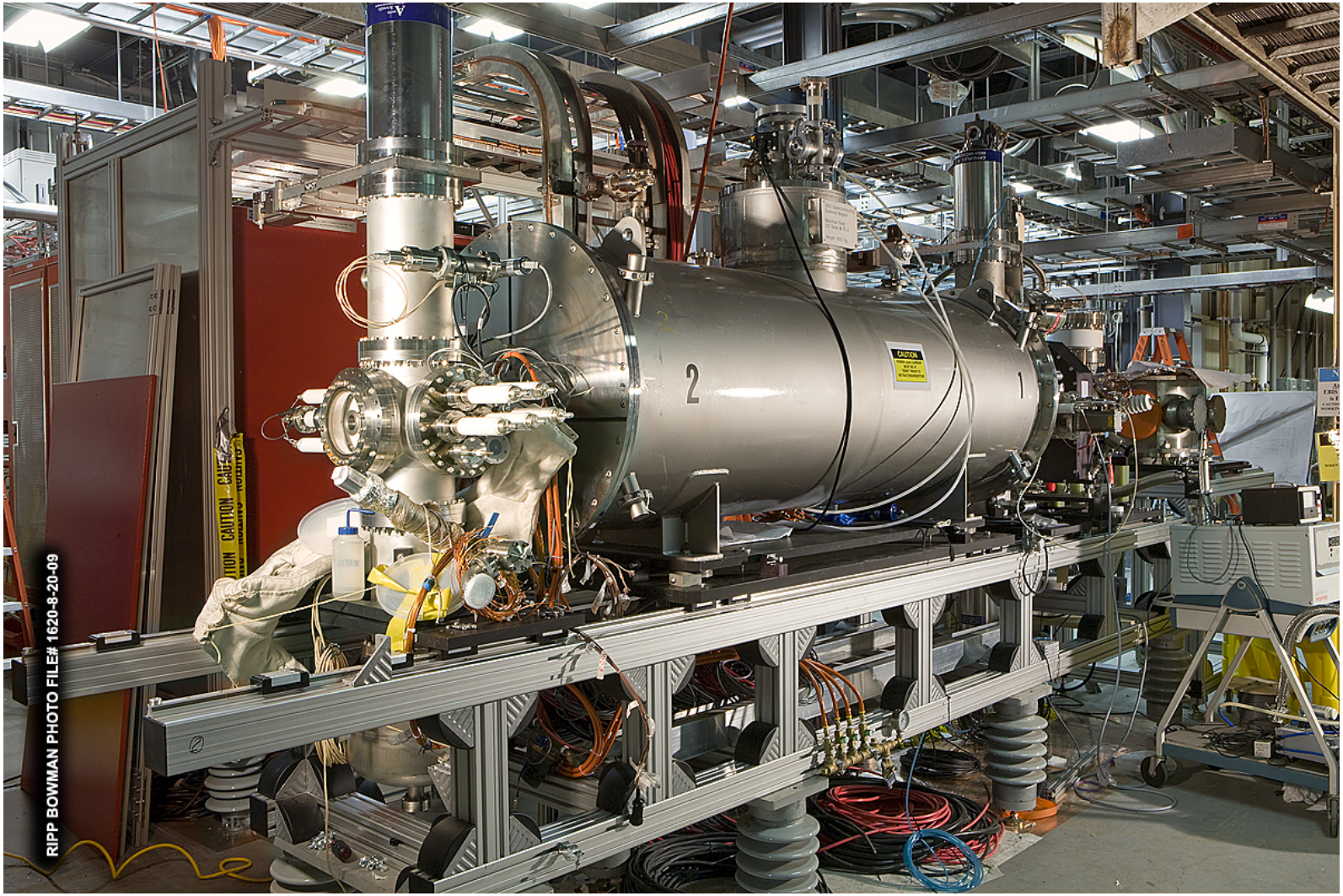
Source Design Goals

- Polarize to ~70% at 1 torr with 10 W laser
- Transfer ~10^{14} ^{3}He/s to EBIS at 5 T & 10^{-7} torr
- Deliver 1.5×10^{11} $^3He^{++}$ ions per 20 μsec pulse

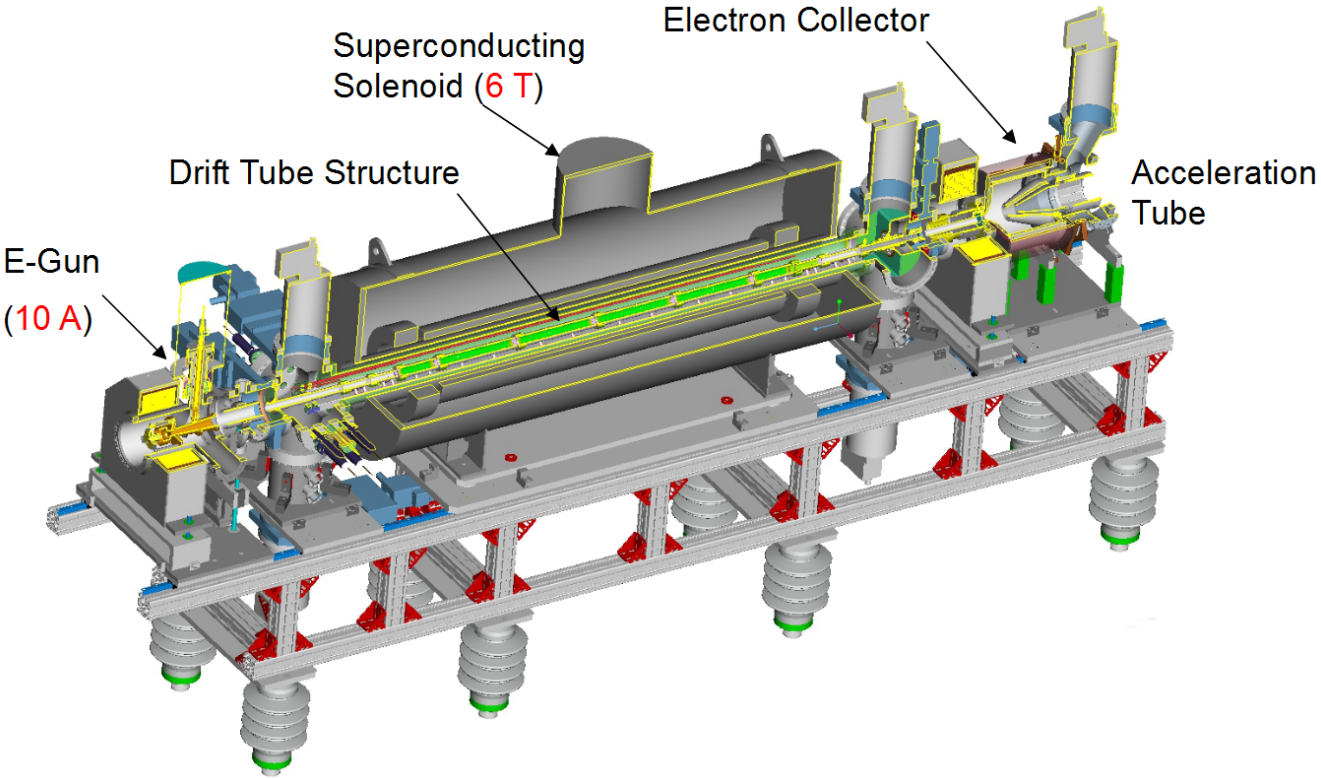


RHIC's Electron Beam Ion Source



RHIC's Electron Beam Ion Source

- 5 T Solenoid B Field; 1.5 m Ion Trap
- 20 keV electrons up to 10 A, 575 A/cm^2 Current Density
- **Any** species, switch between species in 1 sec



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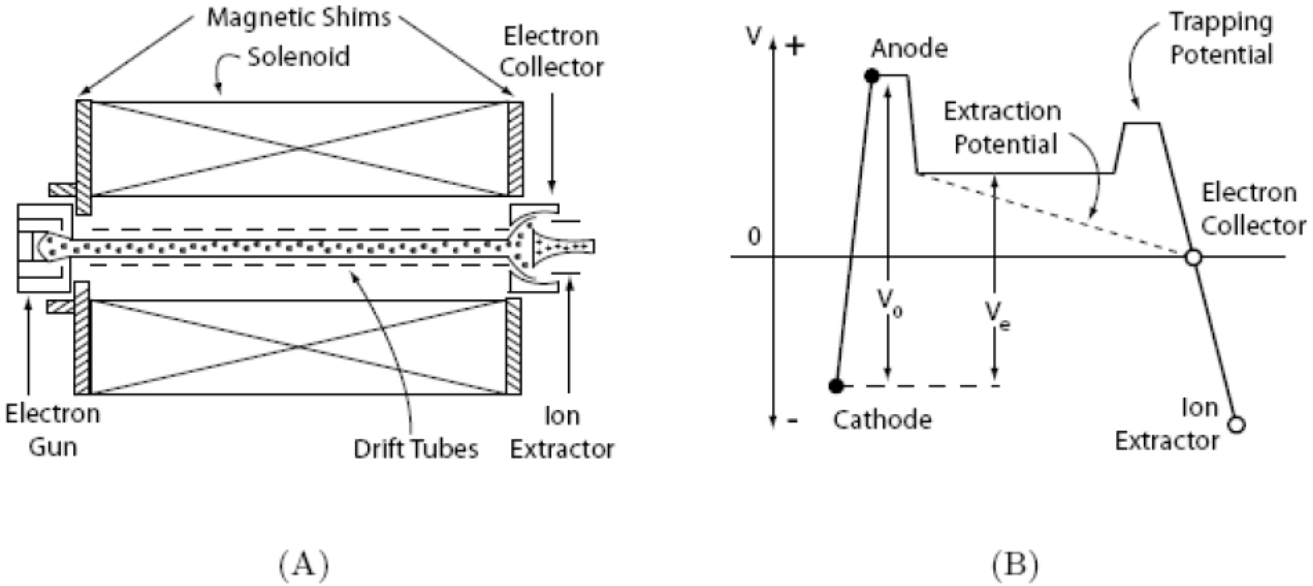
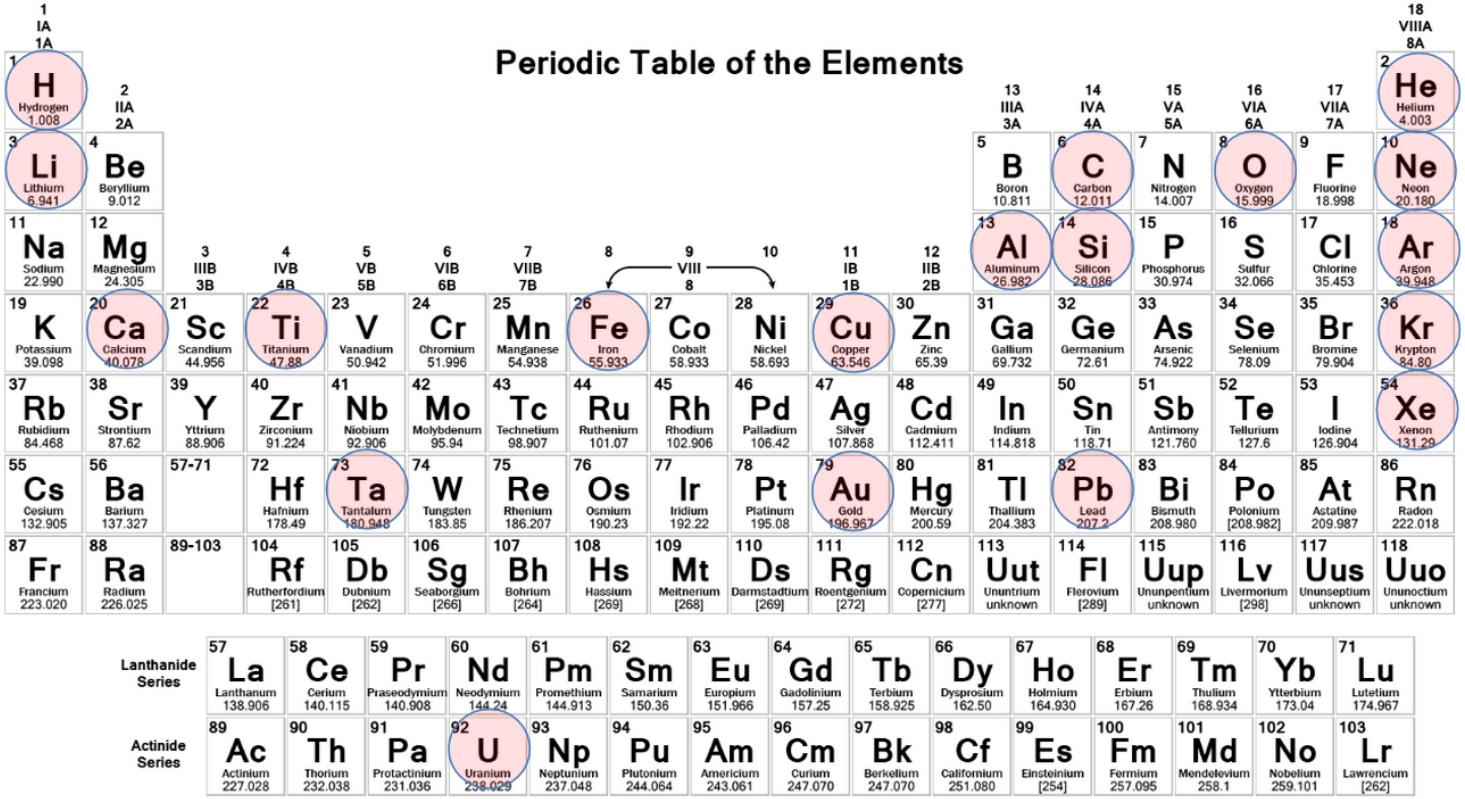


Figure 4. (A) A schematic of the EBIS course. (B) The electric potential along the axis of the source.

EBIS Beams Run to Date



D, $^3He^{2+}$, $^4He1^{+,2+}$, Li^{3+}, C^{5+}, O^{7+}, Ne^{5+}, Al^{5+}, Si^{11+}, Ar^{11+}, Ca^{14+}, Ti^{18+}, Fe^{20+}, Cu^{1+}, Kr^{18+}, Xe^{27+}, Ta^{38+}, Au^{32+}, Pb^{34+}, U^{39+}. Capable of $^3He \Rightarrow {}^3He^{++}$ at nearly 100%

^{3}He Polarization

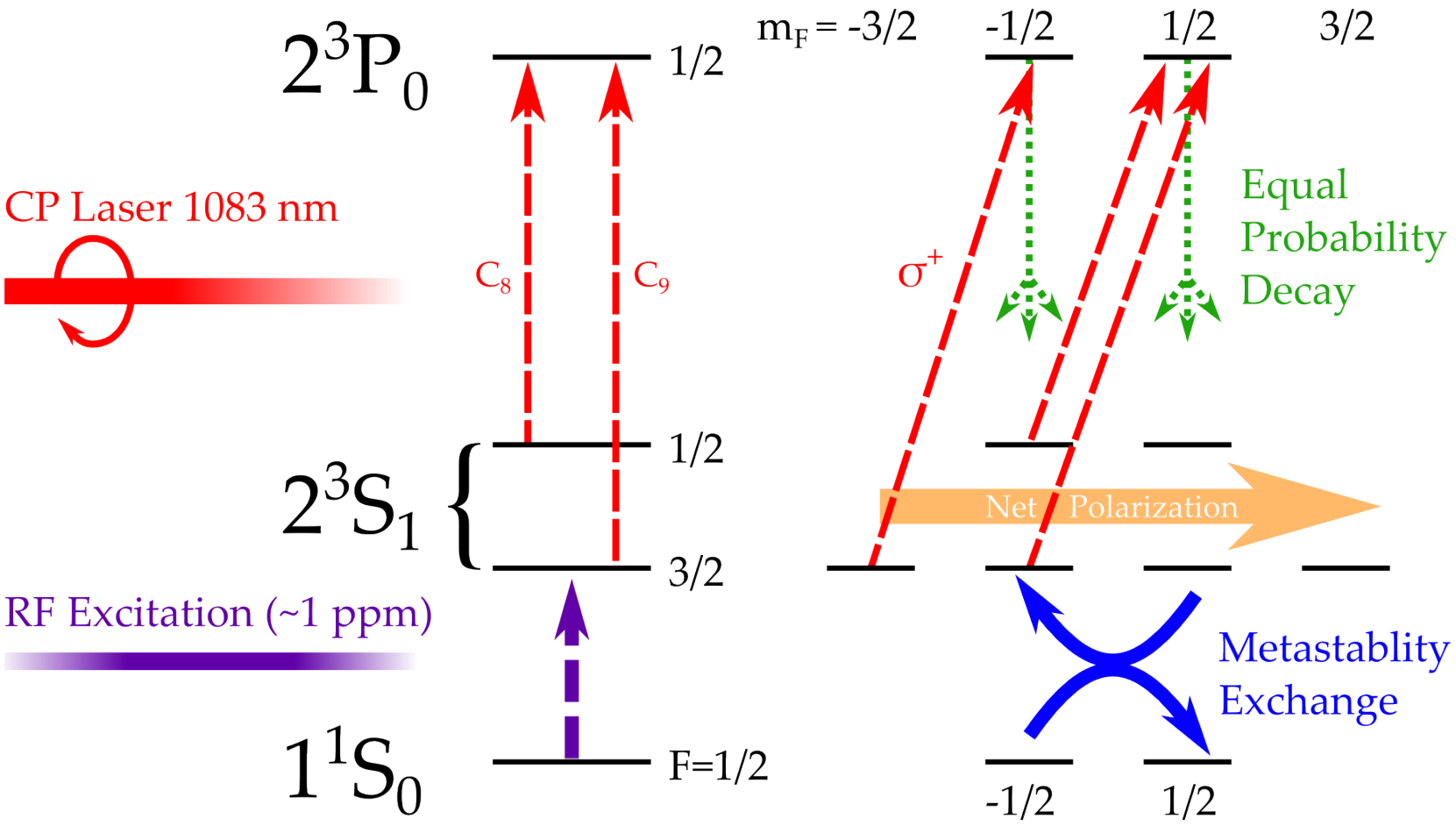
- EBIS has done much of the work for us!
- Need polarized ^{3}He; pure sample for injection
- Revisit MEOP technique[2] with modern lasers

Metastability Exchange Optical Pumping

- Mature technique: polarized targets, medical imaging[3]
- Laser technological advances give 10 W @ 1083 nm easily
- Polarize at $\approx$ 1 torr, $\approx$ 30 G or higher
- Pure ^{3}He sample, faster than SEOP

[2] Colegrove *et al*, Phys. Rev. 132 (1963).
[3] Kauczor *et al*, JMRI, 7 (1997).

MEOP Mechanism



Depolarization Contributions

- Wall Bounces
  - 3 mm long, 0.1mm diameter leak: 1 torr to 10^{-7} torr
  - 1m long, 2mm diameter tube: $\approx 10^6$ bounces, ≈ 1 msec
  - Negligible depolarization with glass walls
- Magnetic field gradients from EBIS stray field
  - Hinder Polarization
  - Depolarization During Transport to EBIS
- Small Contributions During Ionization:
  - Charge Exchange: $^3\text{He}^+ + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^{++} + {}^3\text{He}^+$
  - Recombination: $e^- + {}^3\text{He}^{++} \rightarrow {}^3\text{He}^+$
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Depolarization from Field Gradients

From Schearer[4], we have:

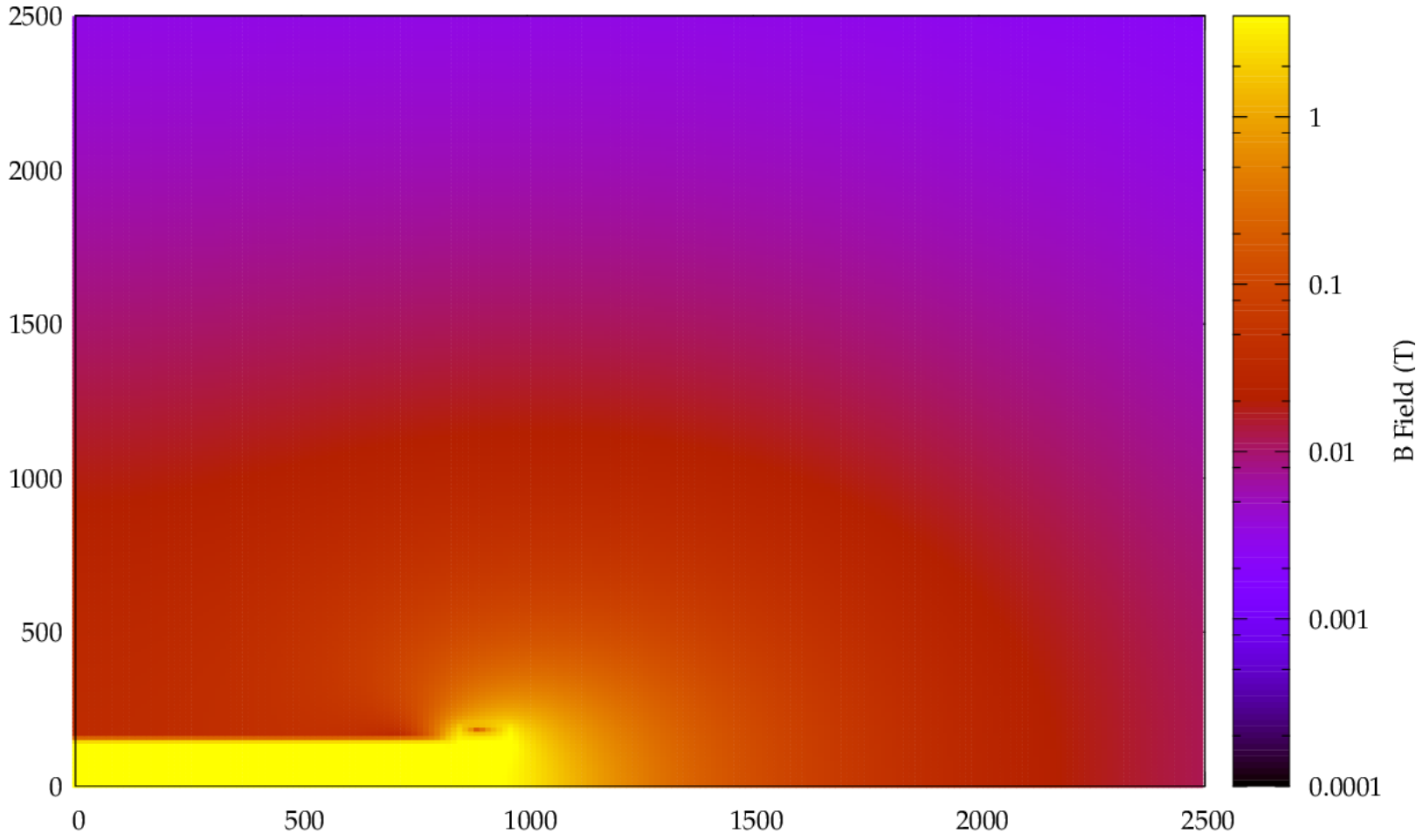
$$\frac{1}{\tau} = \frac{2}{3}\frac{|\Delta B_t|^2}{|B_l|^2}\langle v^2\rangle\frac{\tau_c}{\omega_0^2\tau_c^2+1}$$

- Transverse gradient ΔB_t
- Holding field B_l
- Velocity v
- Average time between collisions τ_c
- Resonant frequency ω_0

We can map regions of stray field which should be problematic.

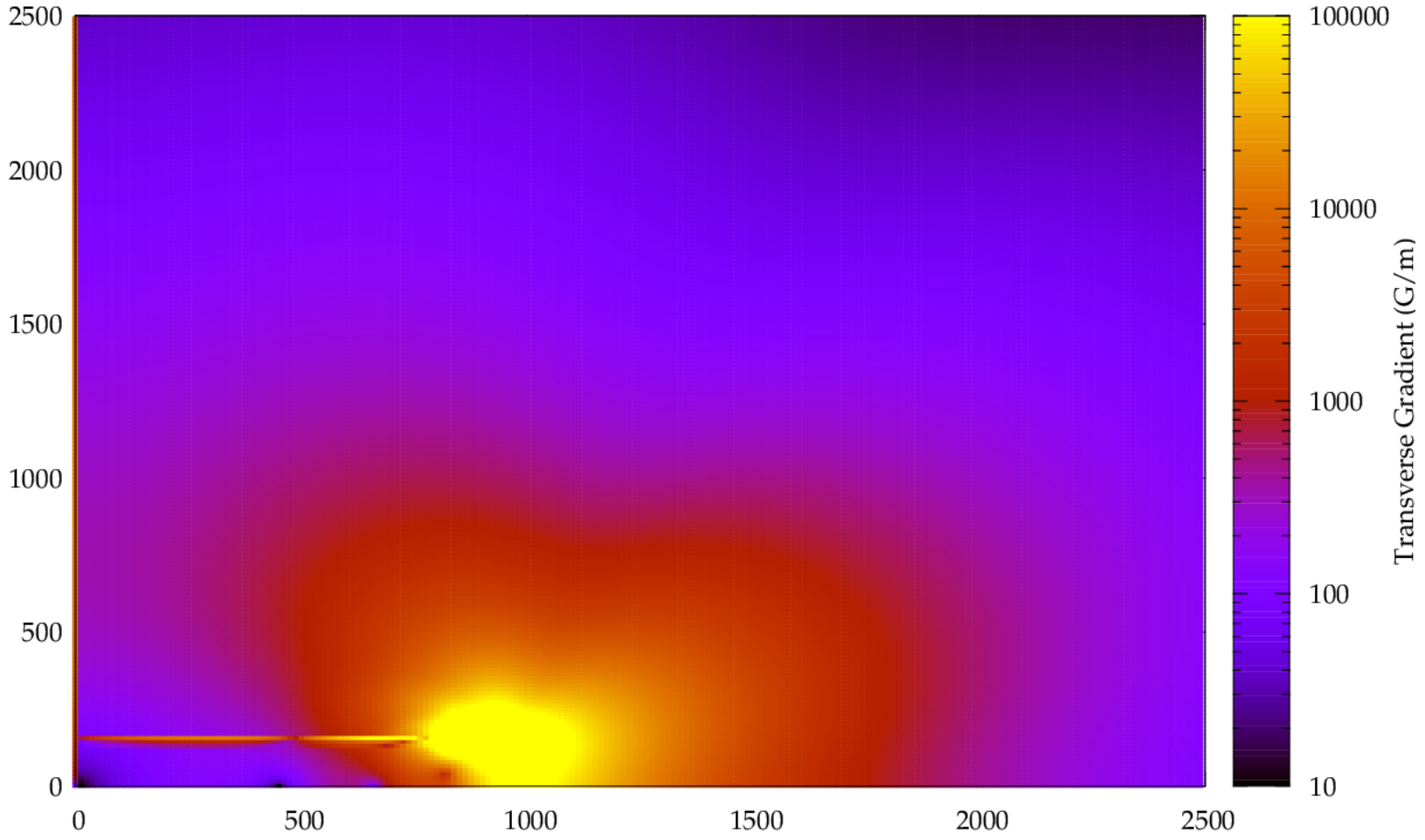
[4] Schearer, Walters, Phys. Rev. 139(5A) (1965).

Calculating Relaxation Time in EBIS B field



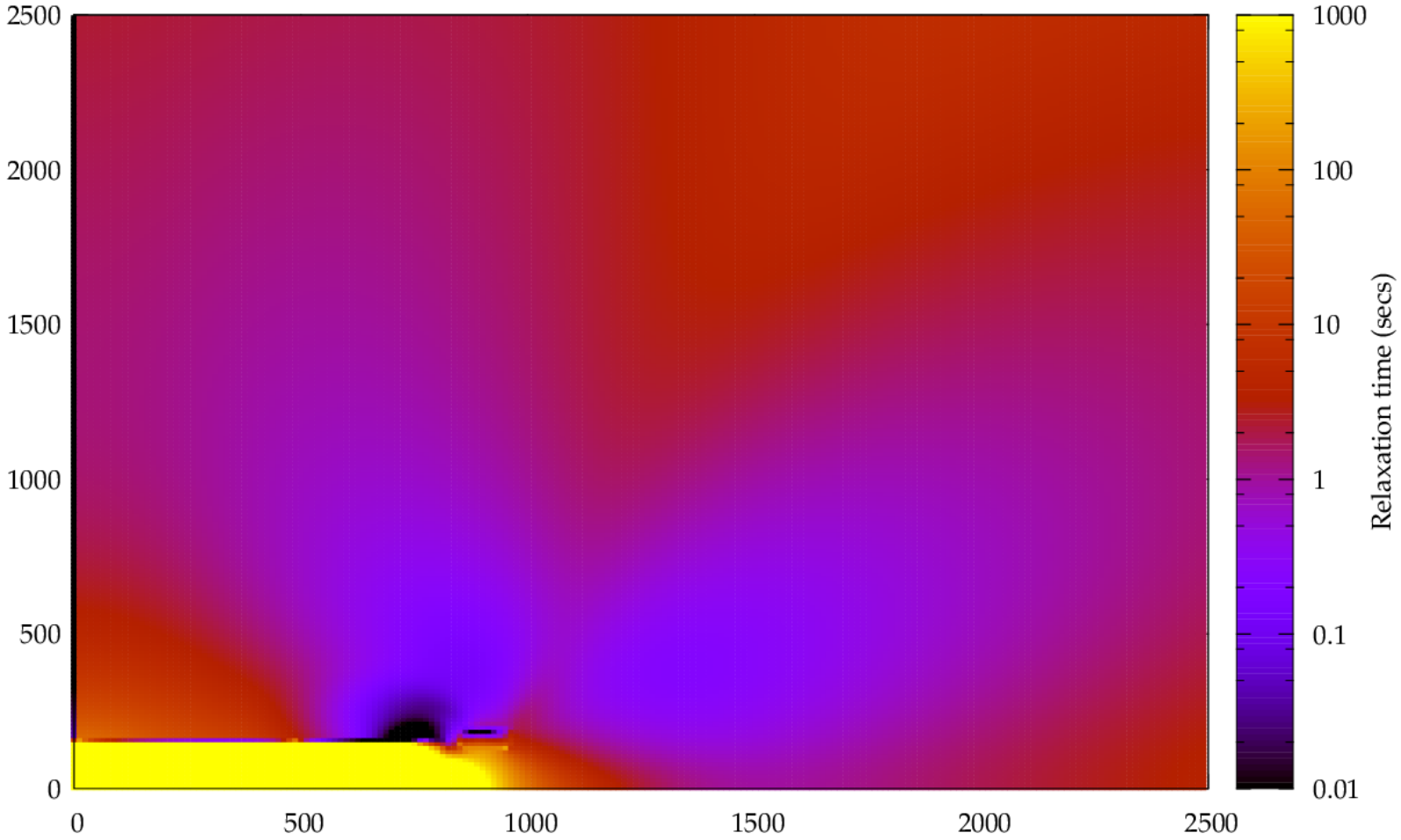
Map in mm of Field Magnitude

Calculating Relaxation Time in EBIS B field



Map in mm of Transverse Field Gradient

Calculating Relaxation Time in EBIS B field



Map in mm Relaxation Time (1 torr)

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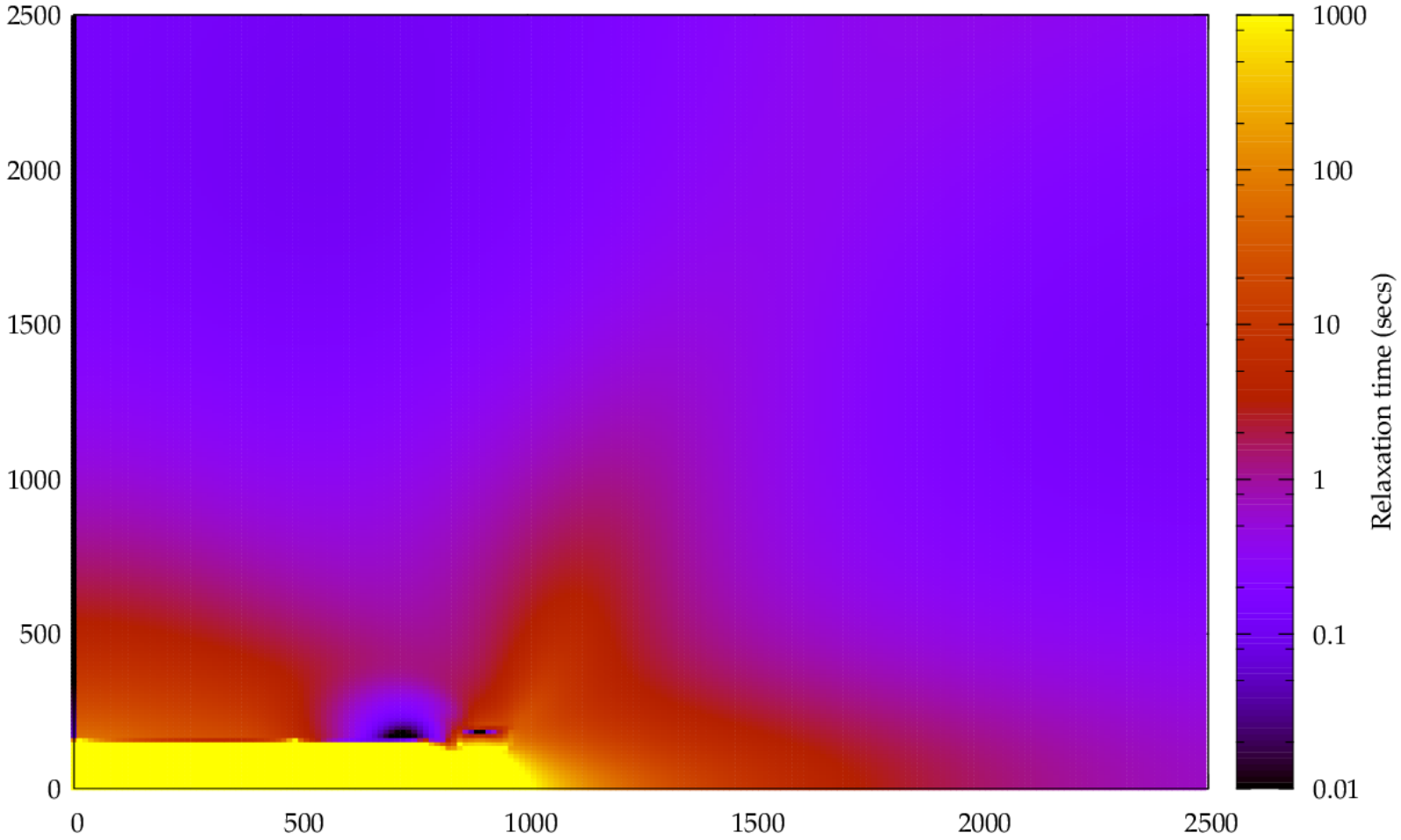
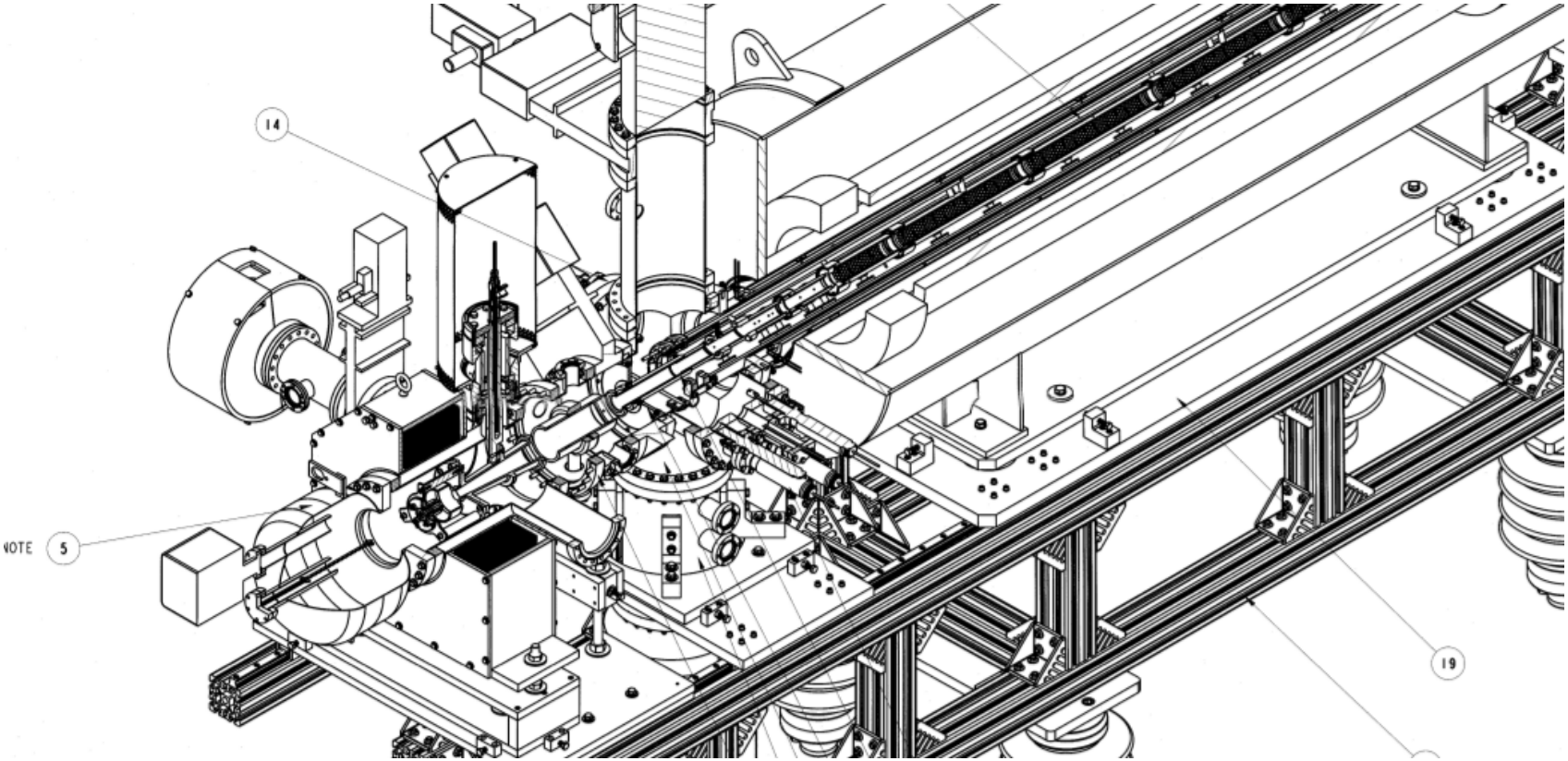


Map in mm Relaxation Time ($< 10^{-2}$ torr)

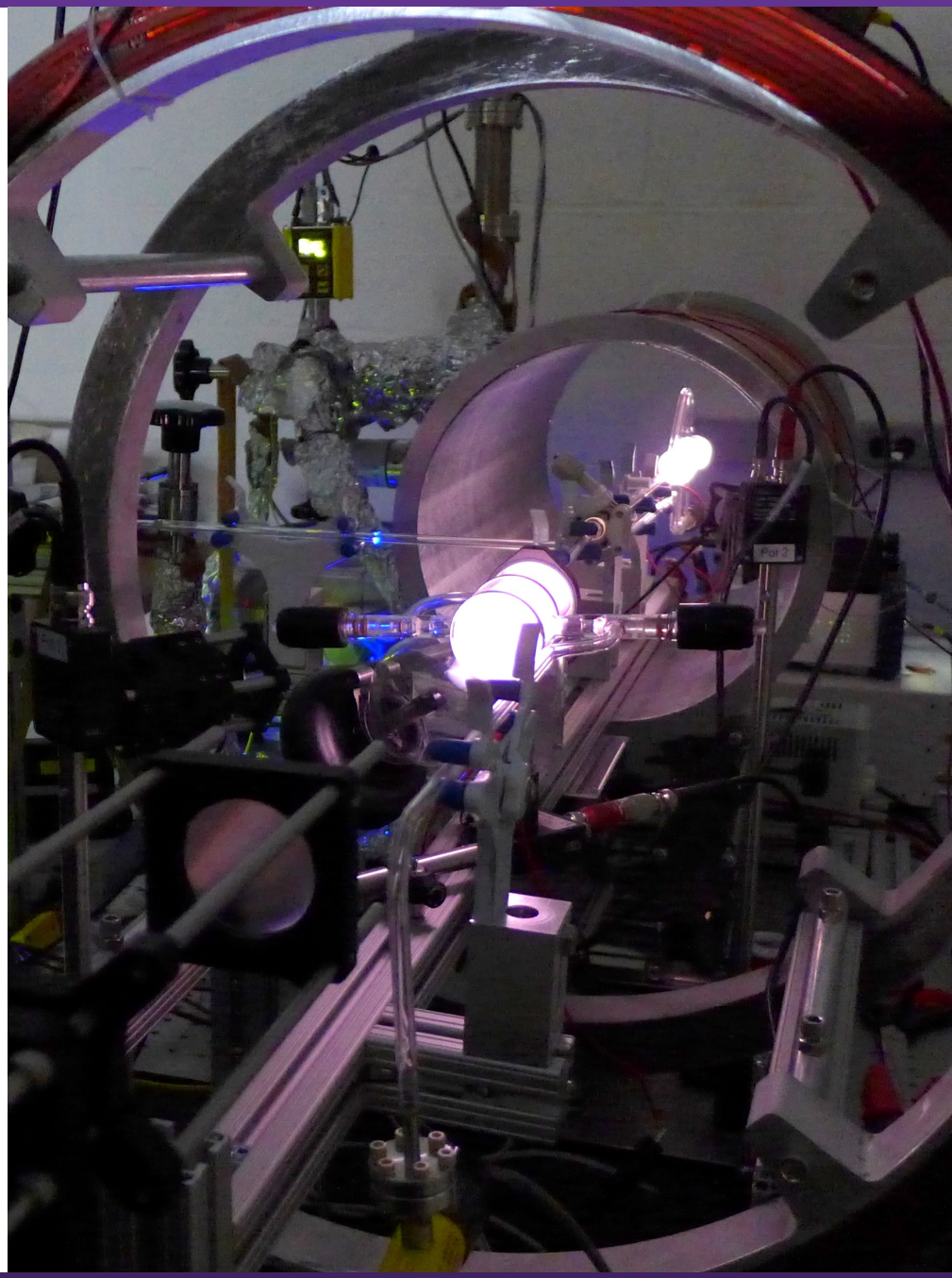
Two Source Design Options: Low or High Field?

- Two design possibilities present themselves:
  - Polarize at 30 G in EBIS stray field using field correction, then transfer into EBIS
  - Polarize in EBIS, or nearby, extending field region



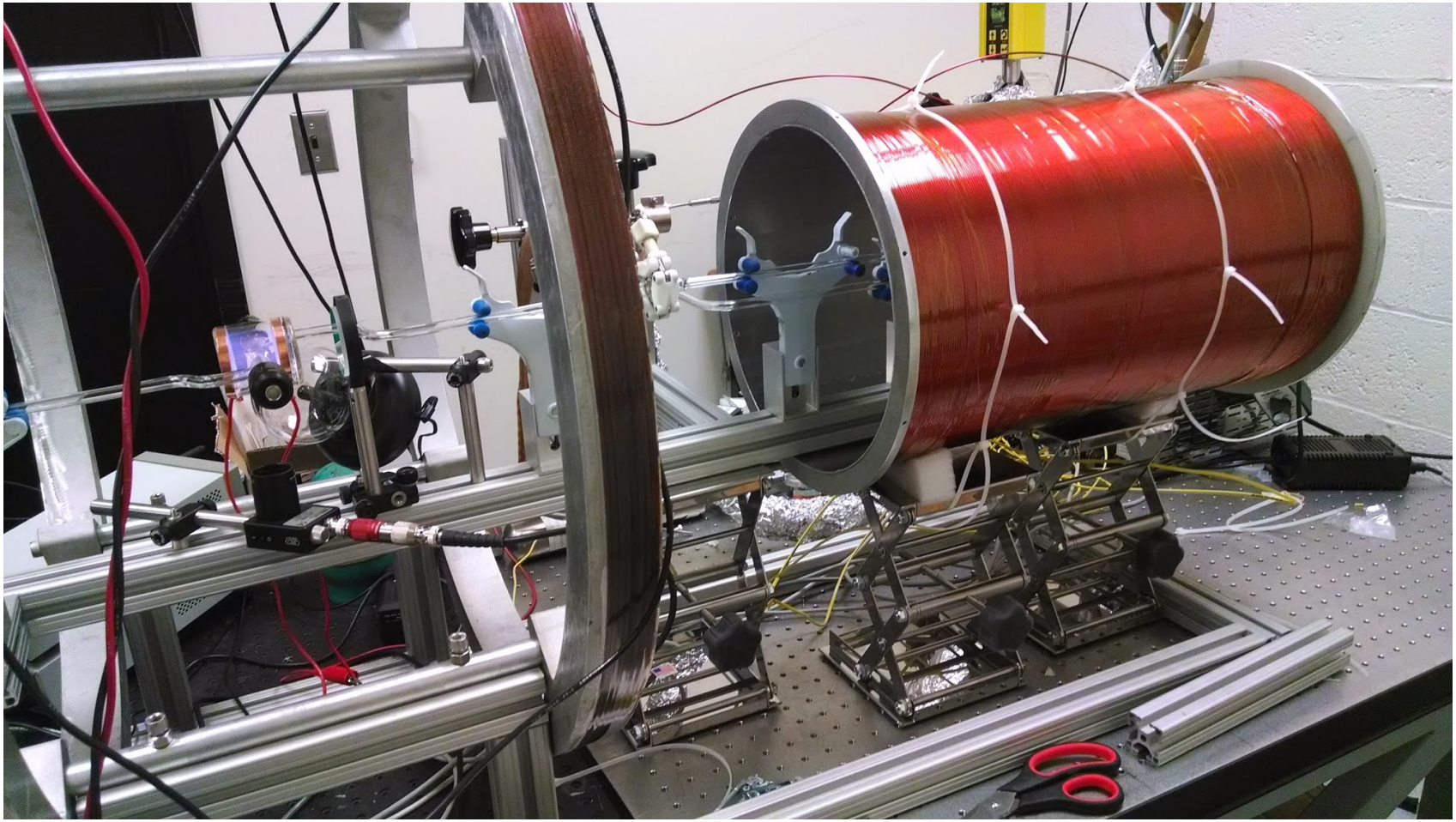
MIT Test Lab

- Magnet, vacuum, laser setup
- 70% polarization achieved
- Allows flow of polarized gas between cells
- Observe polarization diffusion through region of depolarizing gradients[5]
- Test bed for polarization, transfer and data acquisition
- Discharge and optical probe polarimeter development[6]

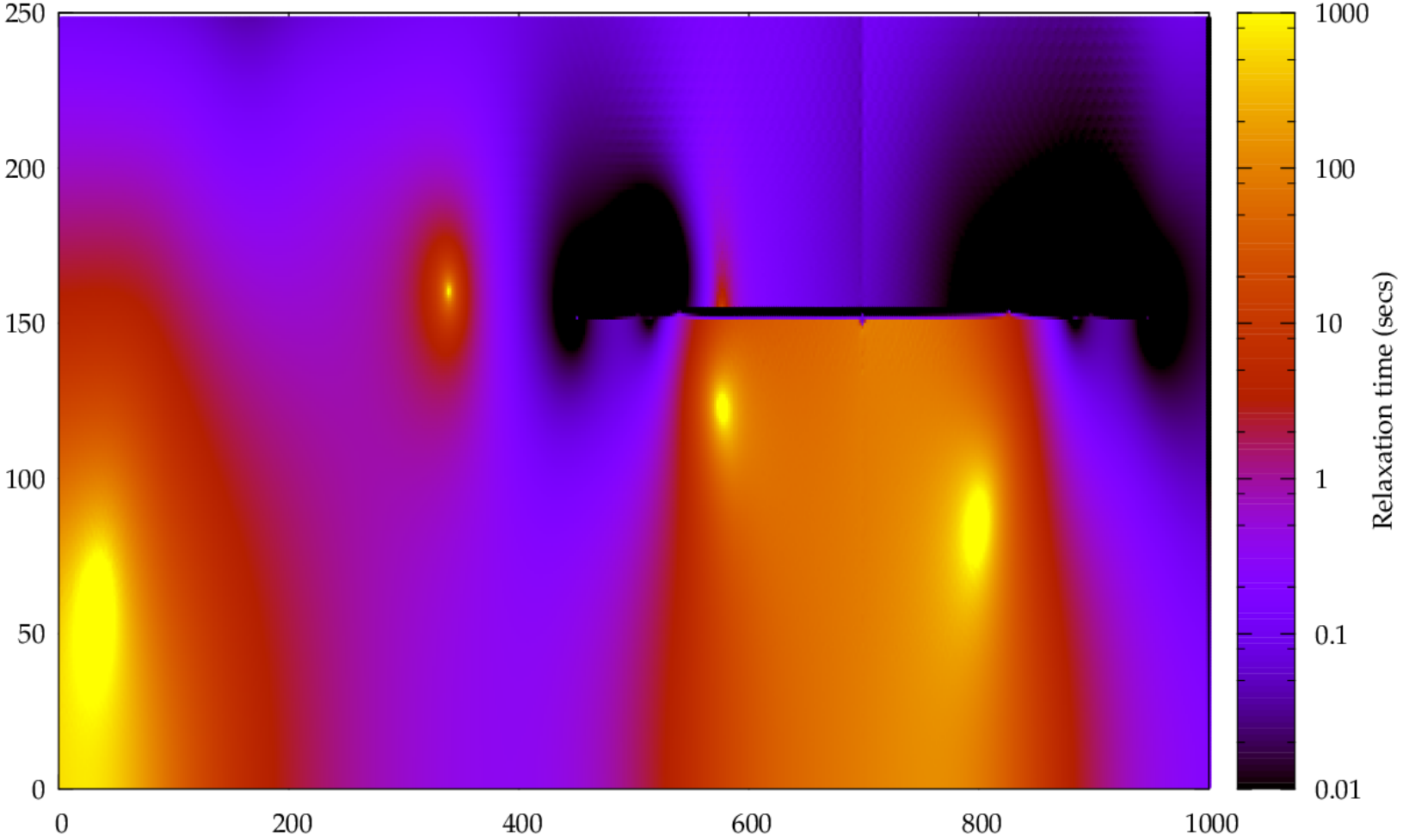


[5] Maxwell, Epstein, Milner, NIM A (777), 2015.
[6] Maxwell, Epstein, Milner, NIM A (764), 2014.

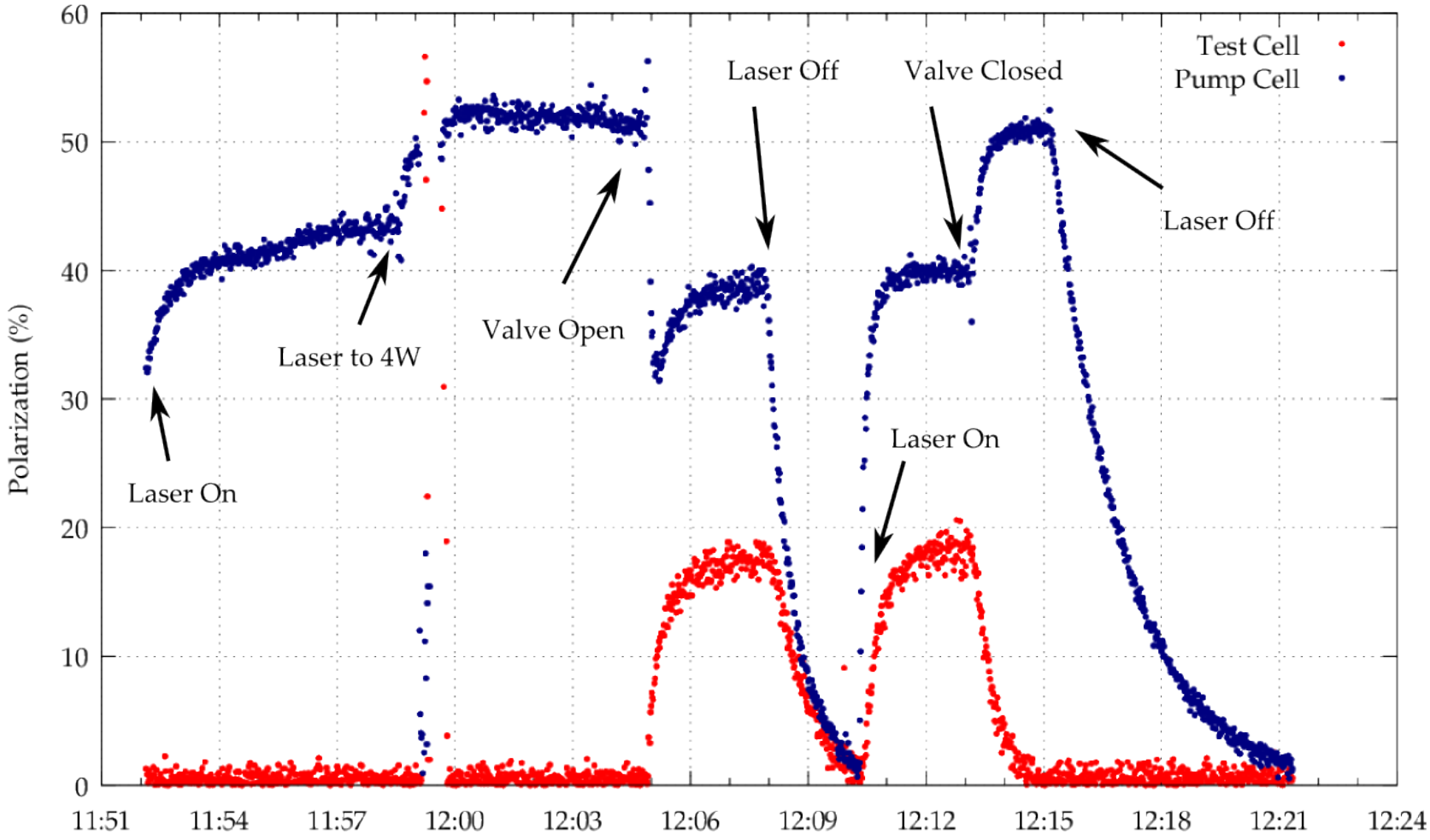
Transferring between B Fields via Diffusion



Relaxation Time Map, Helmholtz and Solenoid

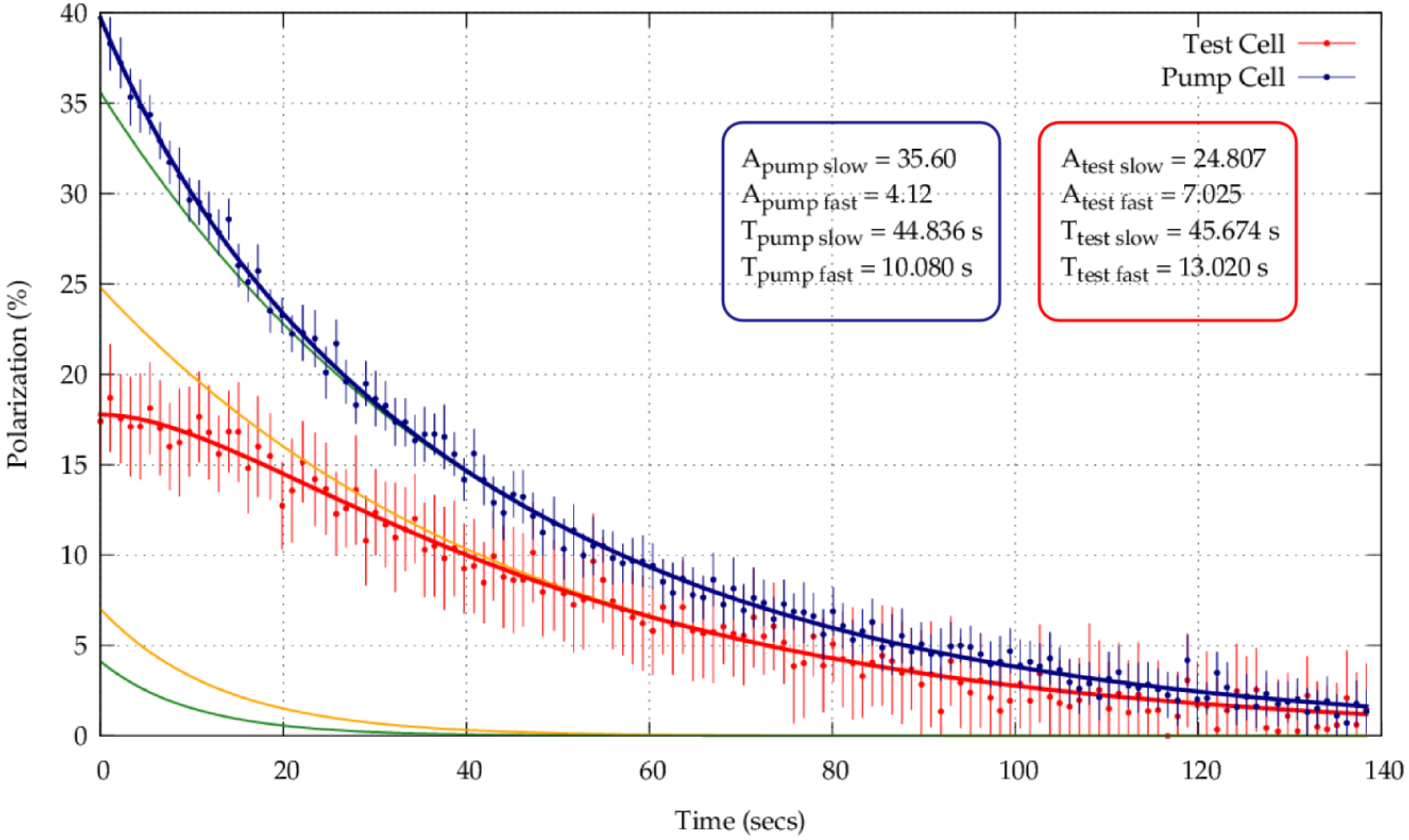


Polarization Transfer via Diffusion



Polarization measured via discharge light in each cell

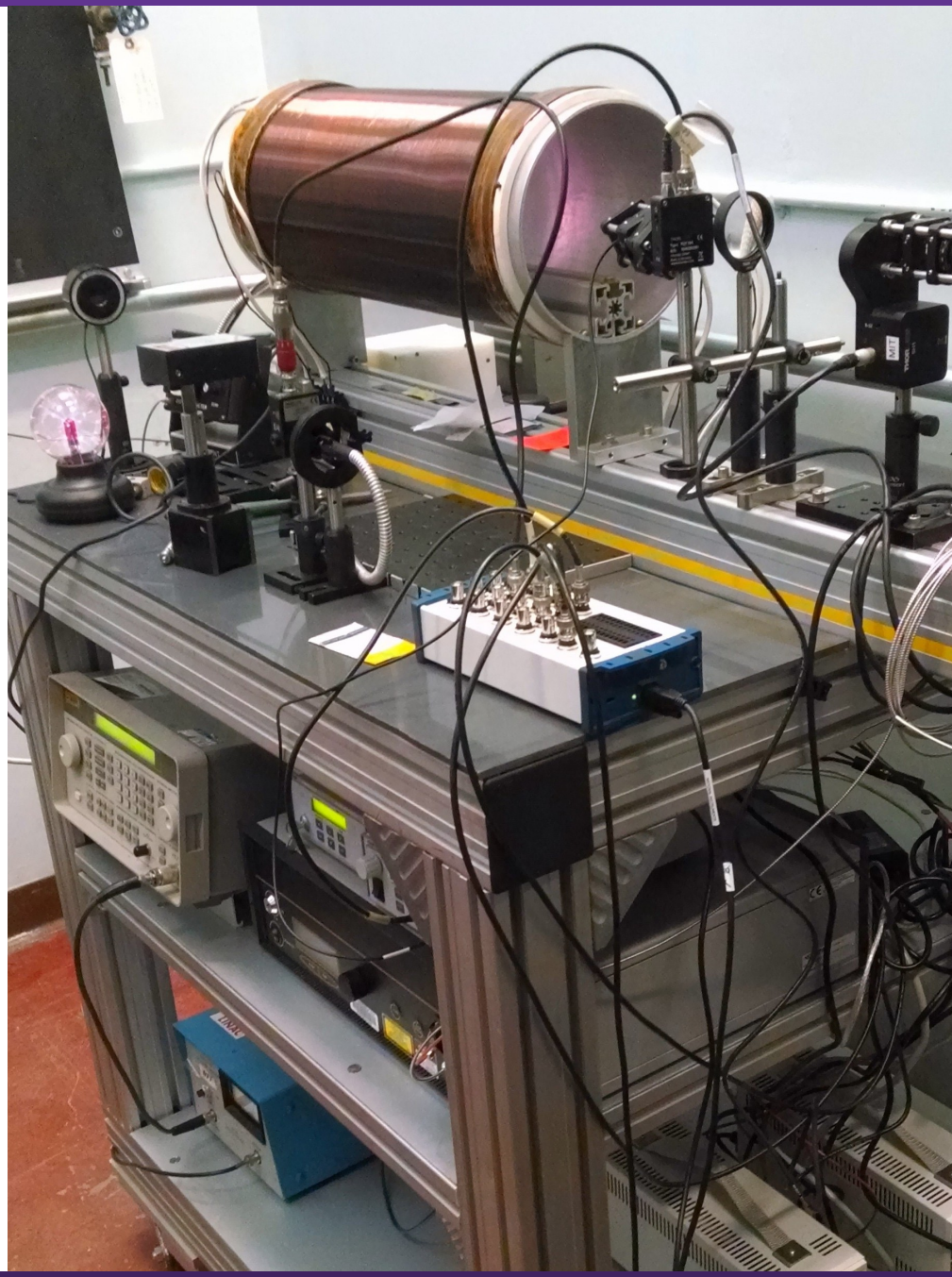
Relaxation in Both Cells



Fits roughly match relaxation & diffusion model of 2 cells, line

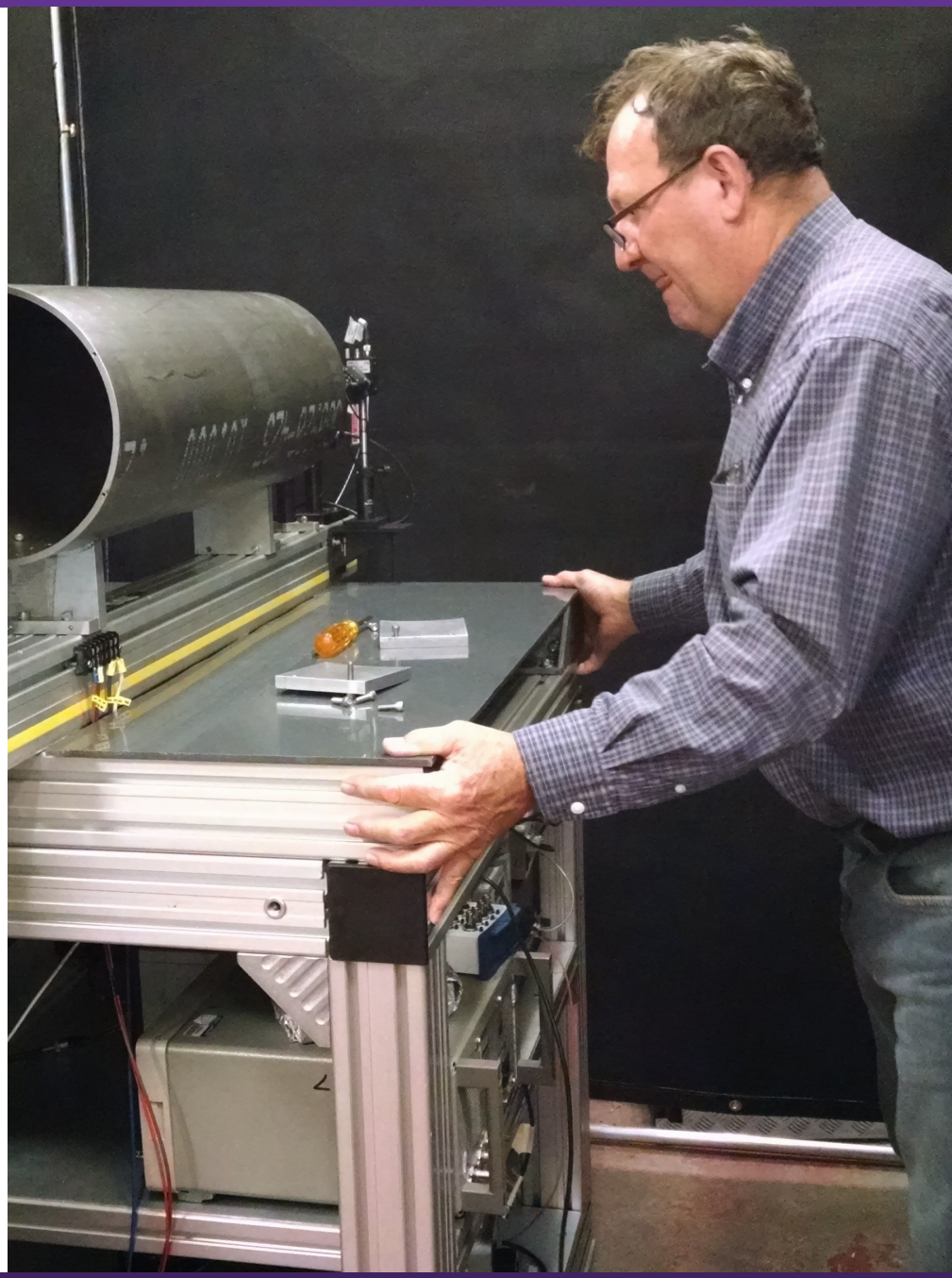
BNL Test Polarizer

- Polarizer on movable stand
- EBIS 5 T spare solenoid
- Allows polarization at any location in the stray field
- Initial polarization tests with NO field correction
- 30 G solenoid allows small increase of B_l
- Tested at two locations on axis of solenoid, one off axis



Stray Field Results

- Spare solenoid at 1 T
- Polarizing sealed cell, which attained 50% in 30 G solenoid
- At location of interest in stray field:
  - Only stray field, 17% with ∼0.5 A pump
  - Only stray field, 28% with ∼10 A pump
  - 6 second relaxation, matches calculation nicely
  - Adding 30 G holding field improves as expected



Low Field Conclusions Thus Far

- Transfer of polarized gas at 1 torr matches calculations
- Polarization and relaxation in the EBIS stray field with no magnetic shielding also agree
- Trusting these calculations, a path into EBIS through the stray field exists in which the path averaged relaxation time is around 0.7 sec (0.01 torr)

Low Field Source with MEOP and EBIS is feasible

- But not necessarily easy or optimal
- Battle must be fought with the stray field both to polarize and to transfer, compromising the achieved polarization, however little

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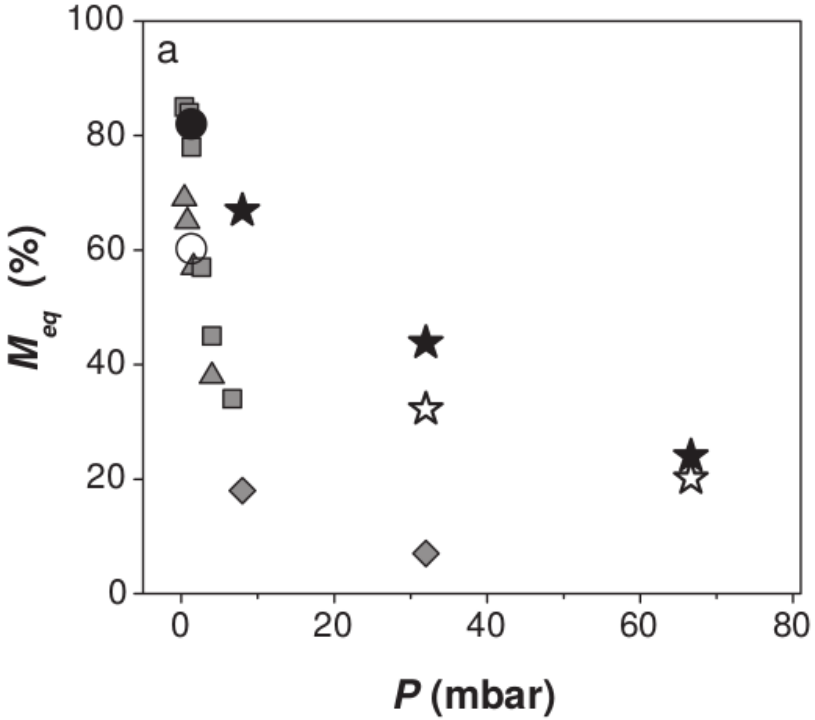
MEOP at High Magnetic Field

- European group (Paris, Krakow) researching high pressure MEOP, medical applications
- Pioneering achievements in pumping efficiency at high pressures leveraging fields above 1 T in last ten years

- M. Abboud, Europhys. Lett. 68, 2004
  - 1.5 T; 0.5, 2 W OP laser
  - 1.3, 8, 32, 67 mbar
  - Circles and stars are at 1.5 T, others at low field



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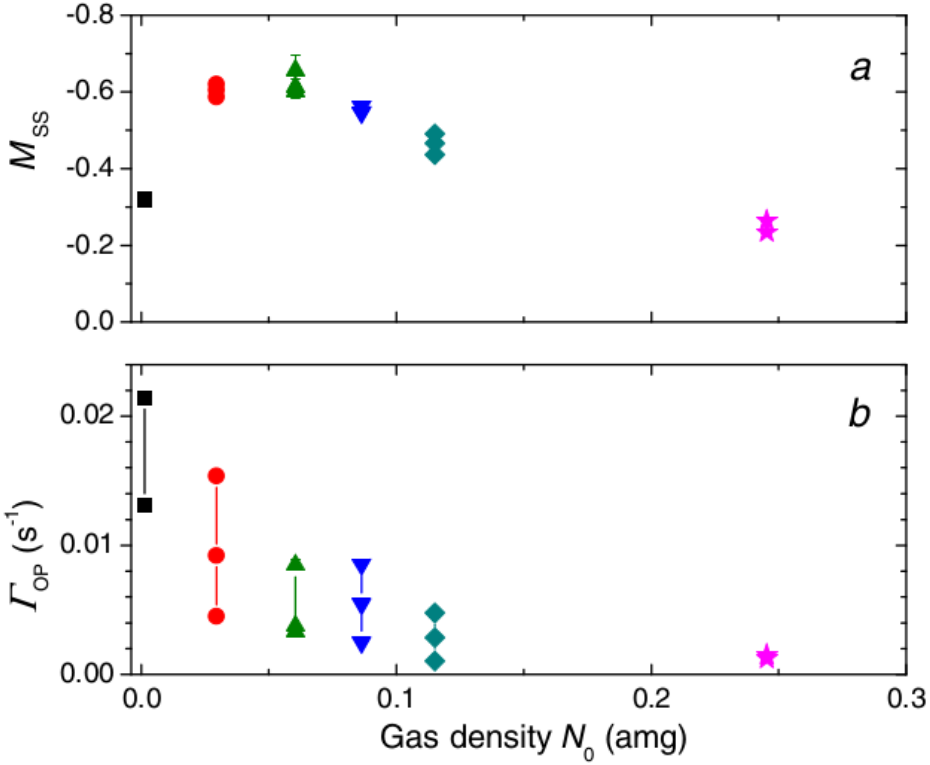
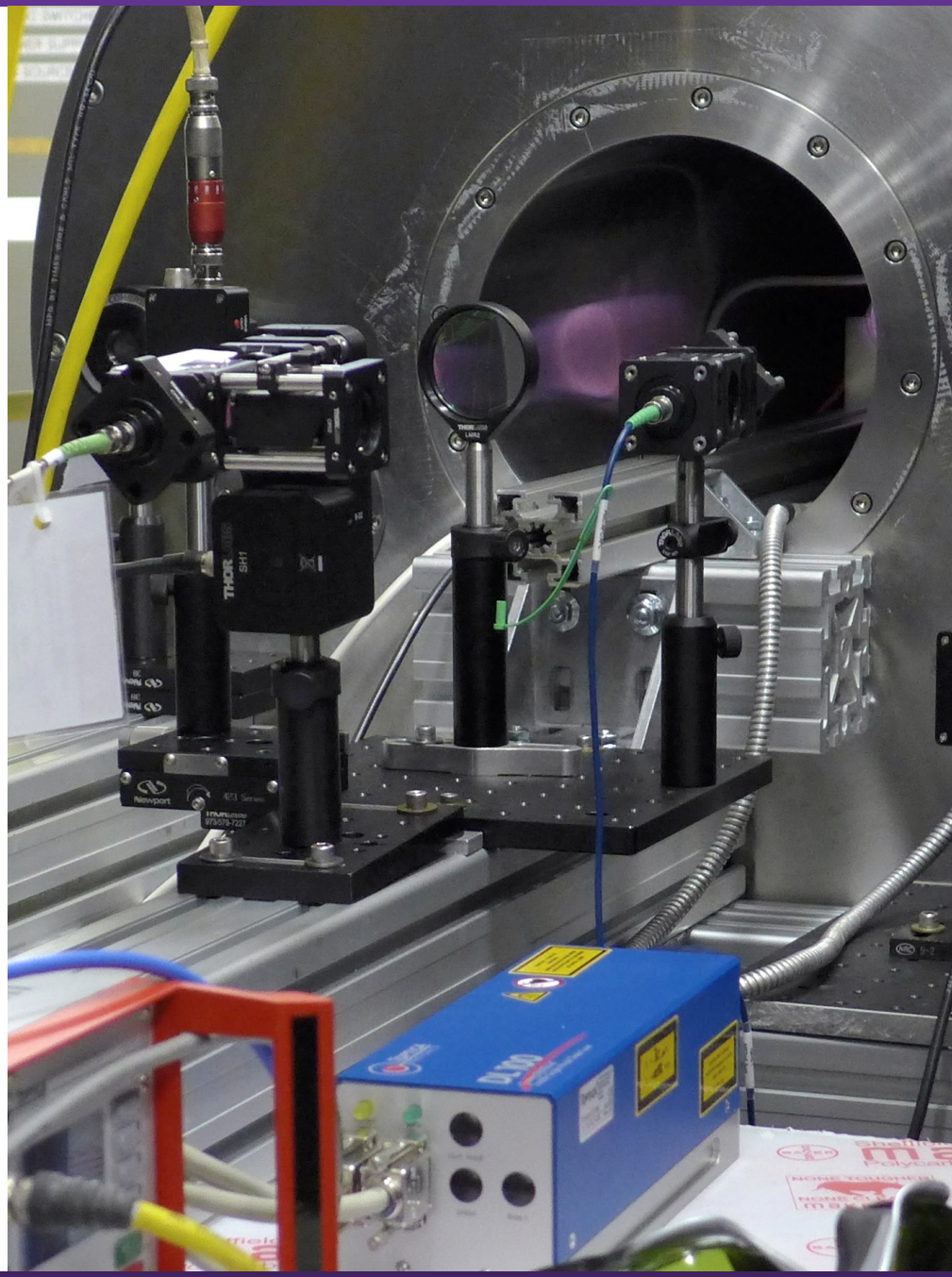
- A. Nikiel *et al*, Eur. Phys. J. D. 67, 2013
  - 4.7 T, 0.5 W OP laser
  - 1.3, 32, 67, 96, 128, 267 mbar
  - Noted trouble with RF for 1 torr cell



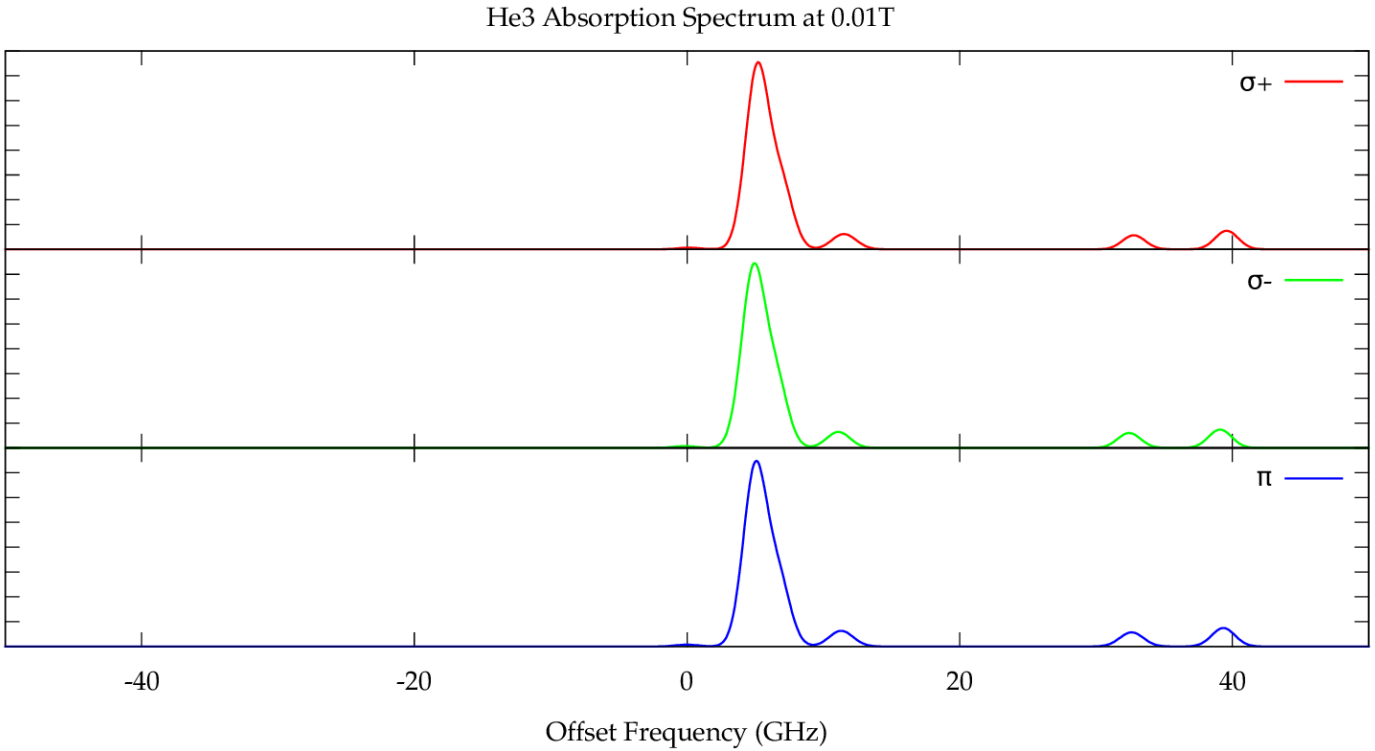
BNL High Field Tests

- EBIS spare solenoid at 1, 2, 3, and 4 T
- Low field polarimetry technique not effective above 10 mT
- High-field polarimetry with low power probe laser
  - AM on discharge for lock-in detection
- Sealed cells at 1 torr with two cell geometries
  - 5 cm OD, 5 cm long
  - 3 cm OD, 10 cm long



Optical Probe Polarimetry

- High or low field, no calibration required
  - Sweep low power probe laser through two 2^3S-2^3P transitions to directly probe states[7,8]



[7] Courtade *et al*, Eur. Phys. J. D 21 (2002).
[8] Suchanek *et al*, Eur. Phys. Special Topics 144 (2007).

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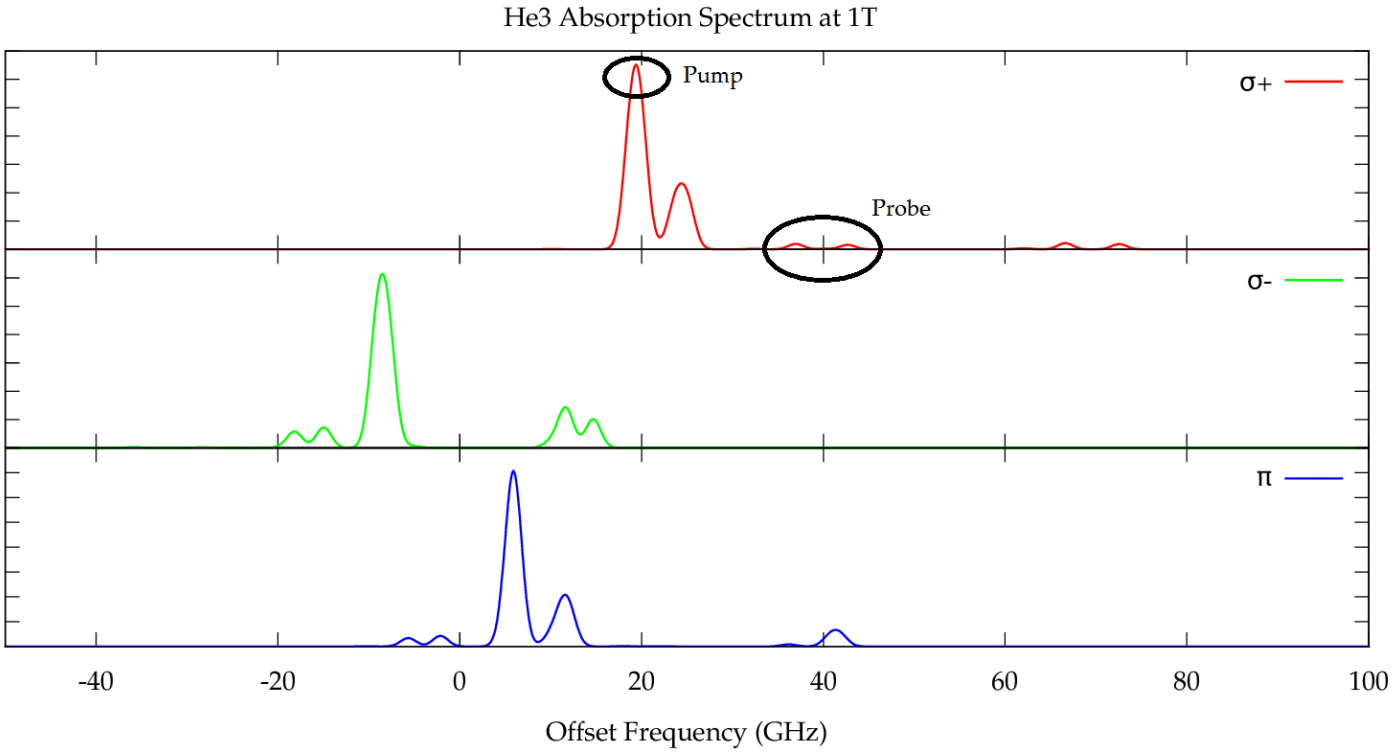

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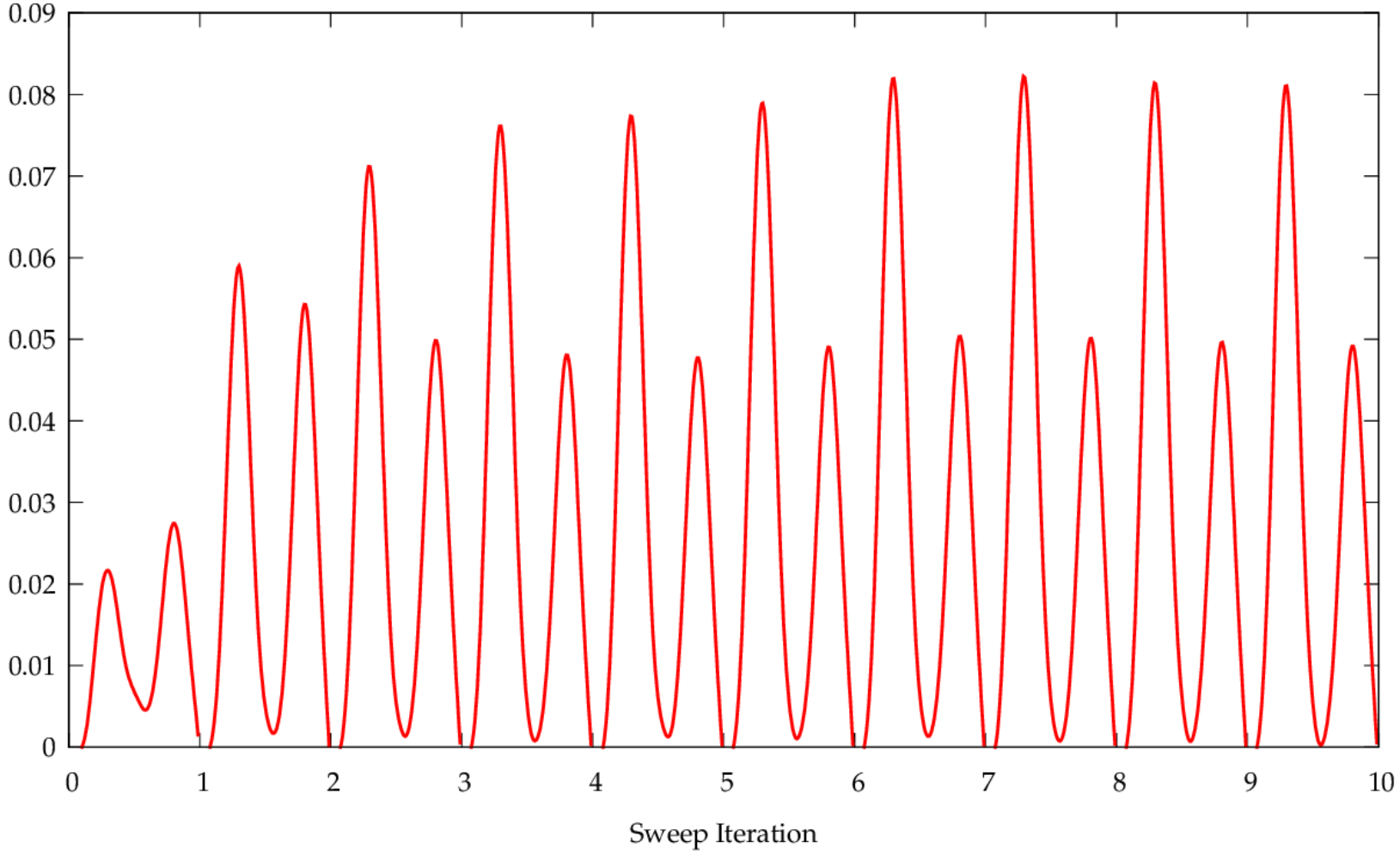
Measuring Optical Pumping



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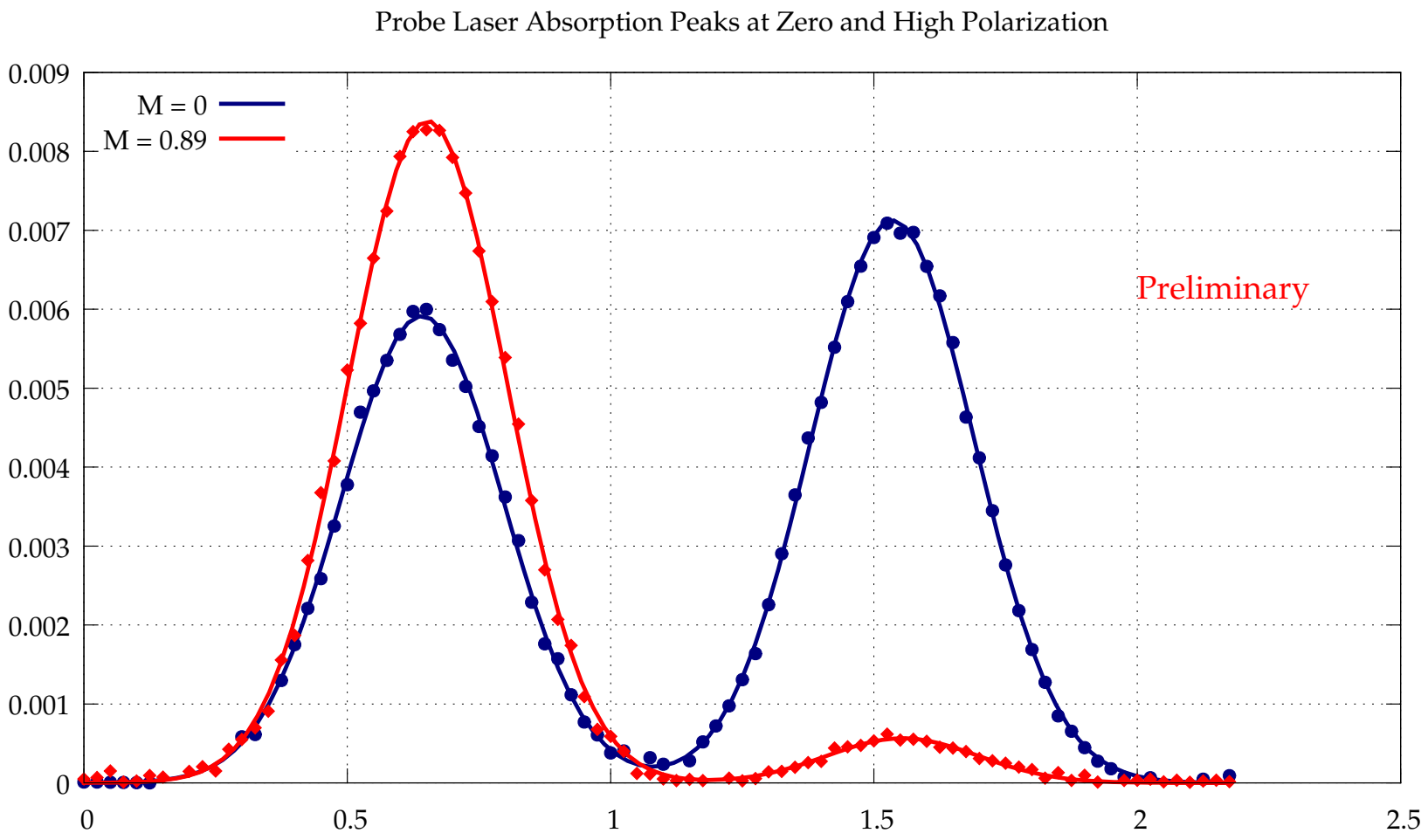
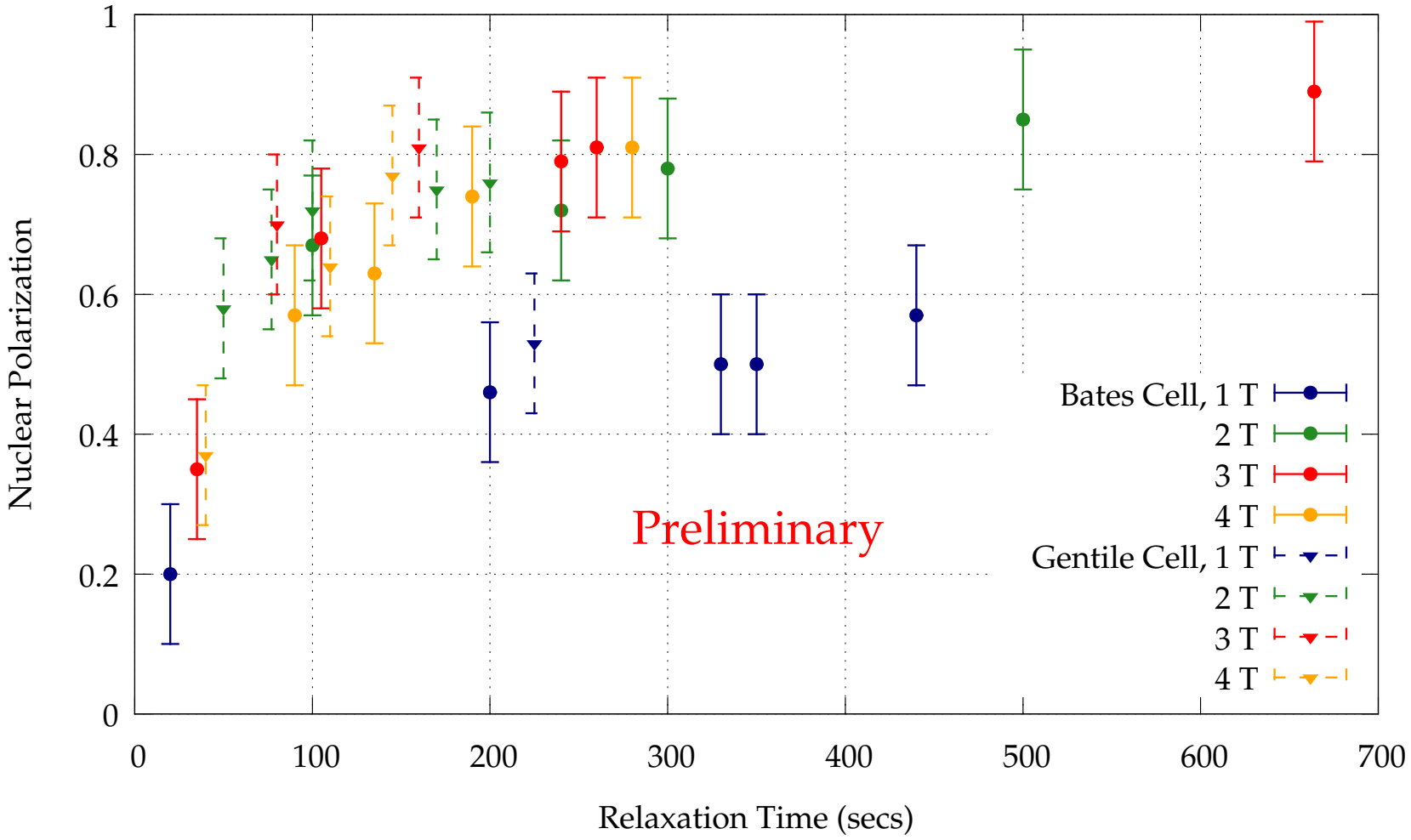


High Field Polarization Results



- Error set at 10% while measurement is investigated

High Field Conclusions Thus Far

- First results for MEOP at 3, 4 T and 1 torr, to near 90%
  - With discharge off, $T_1 = 2.7$ hours
- Not only is this possible but it's easy!
  - Cell which we struggled to get to 70% at 30 G reach over 80% at high field
  - Field uniformity a given at high field

High polarizations from MEOP over 1 T

- At high field, OP and ME both still work
- Zeeman splitting reduces electron-nucleus spin coupling for polarization, but also inhibits relaxation channels (such as 668 nm line used for low field measurement)
- Transition split allows pumping just one state with laser

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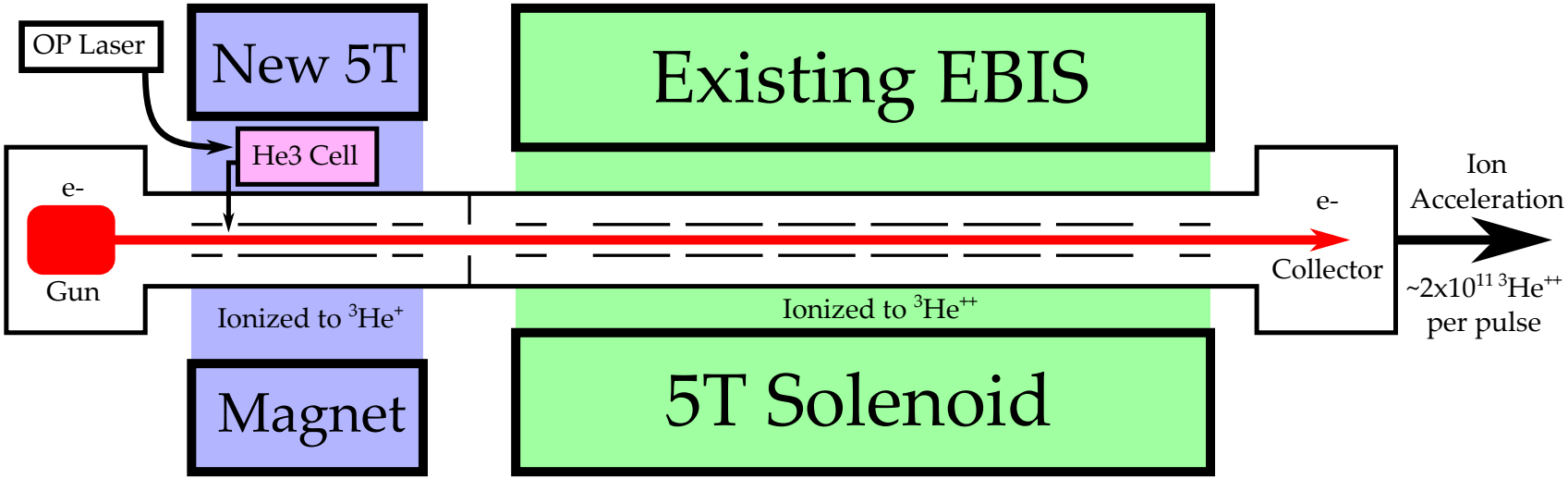
High Field Source Design: EBIS Upgrade

- New solenoid-injector section will improve EBIS operation with all gases, allow polarized $^3He^{++}$
- Lengthened ion trap brings increased heavy ion yield
- Test can be built and tested without affecting EBIS operation: goal $> 80\%$ polarization $^3He^{++}$ beam



BNL–MIT Pol He3 Source Collaboration:

- Brookhaven National Laboratory
  - J. Alessi, E. Beebe, J. Farrell, A. Pikin, J. Ritter, A. Zelenski
- MIT Laboratory for Nuclear Science
  - C. Epstein, J. Maxwell, R. Milner
  - Bates technical support

We gratefully acknowledge the advice of

- P.J. Nacher, G. Collier

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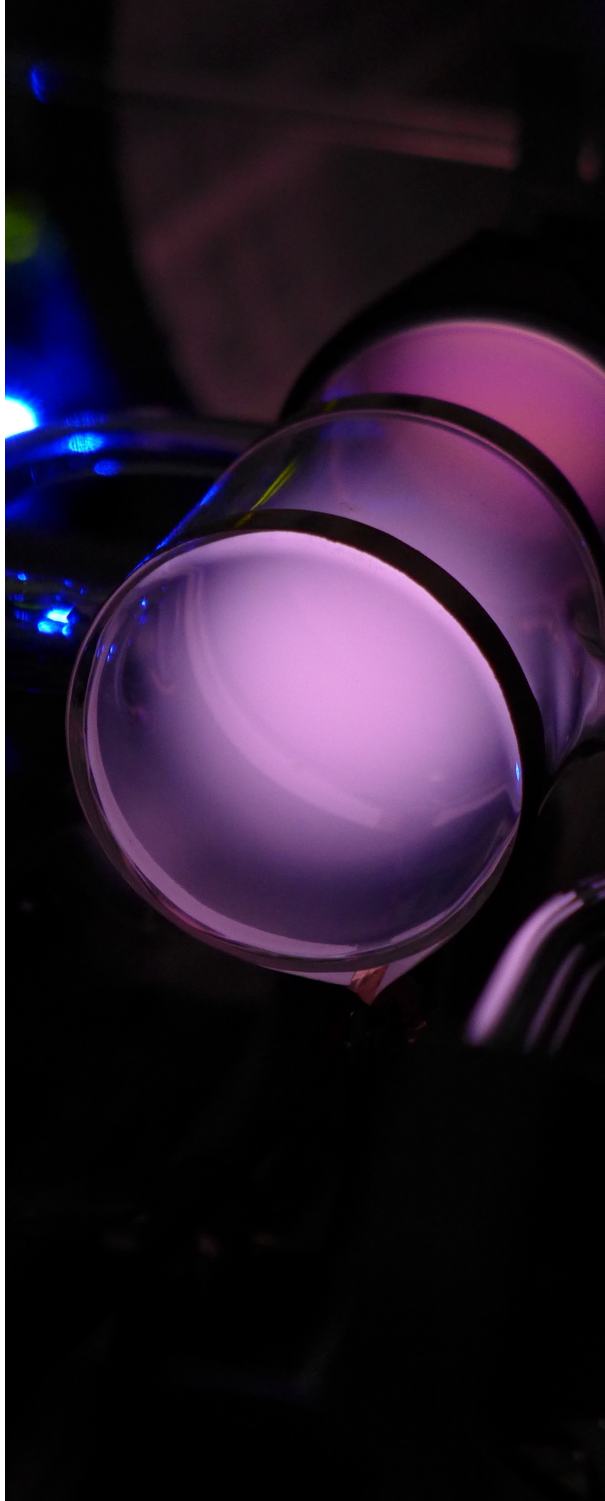
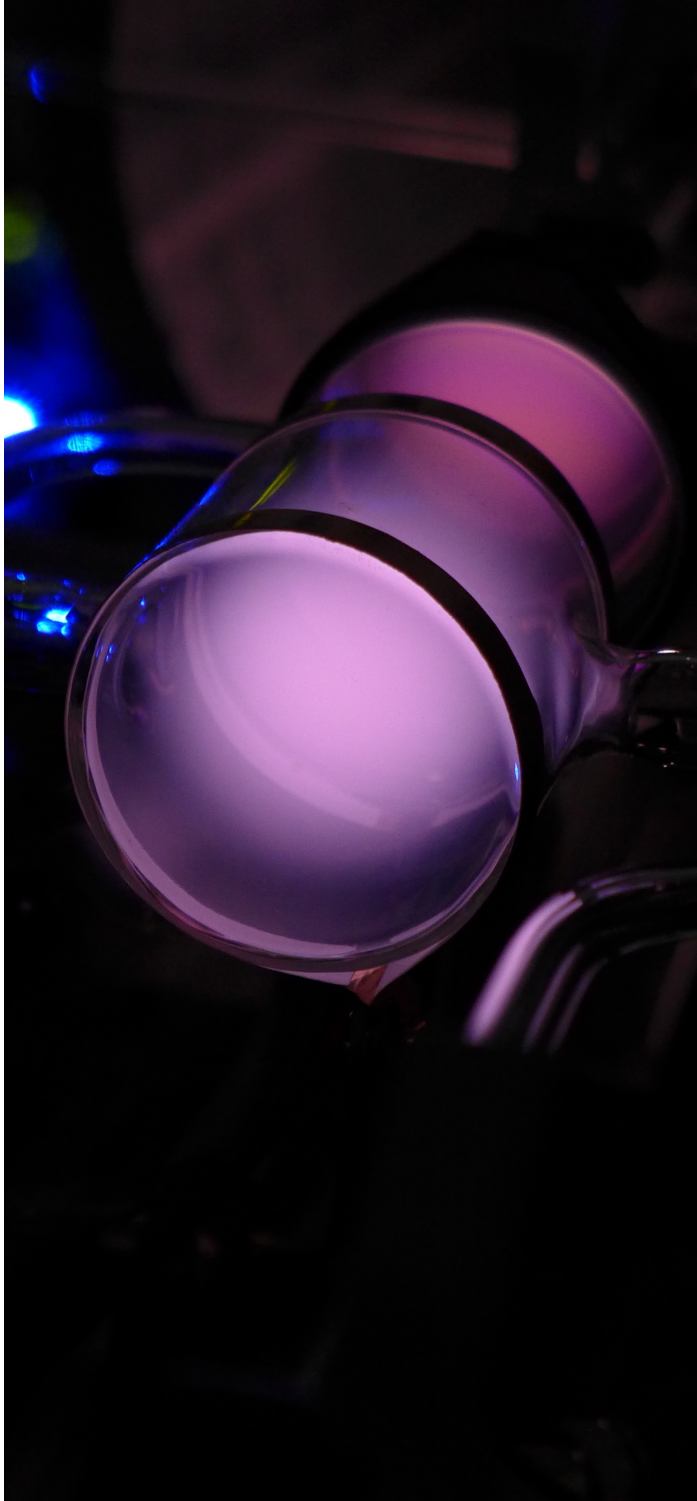
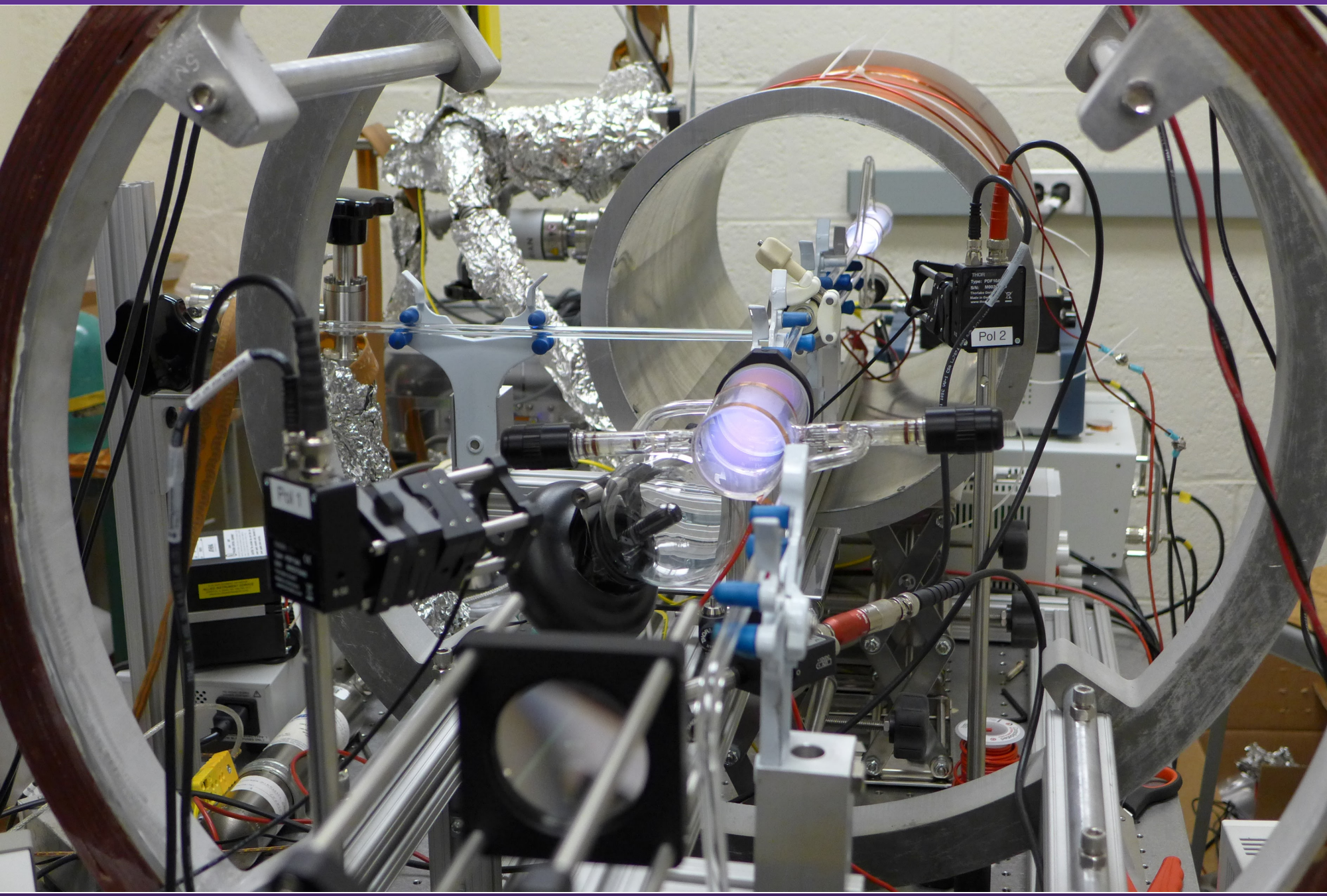
- DOE Office of Nuclear Physics, R&D for Next Generation Nuclear Physics Accelerator Facilities
- MIT Department of Physics



Outline



He3 Polarizer on Film



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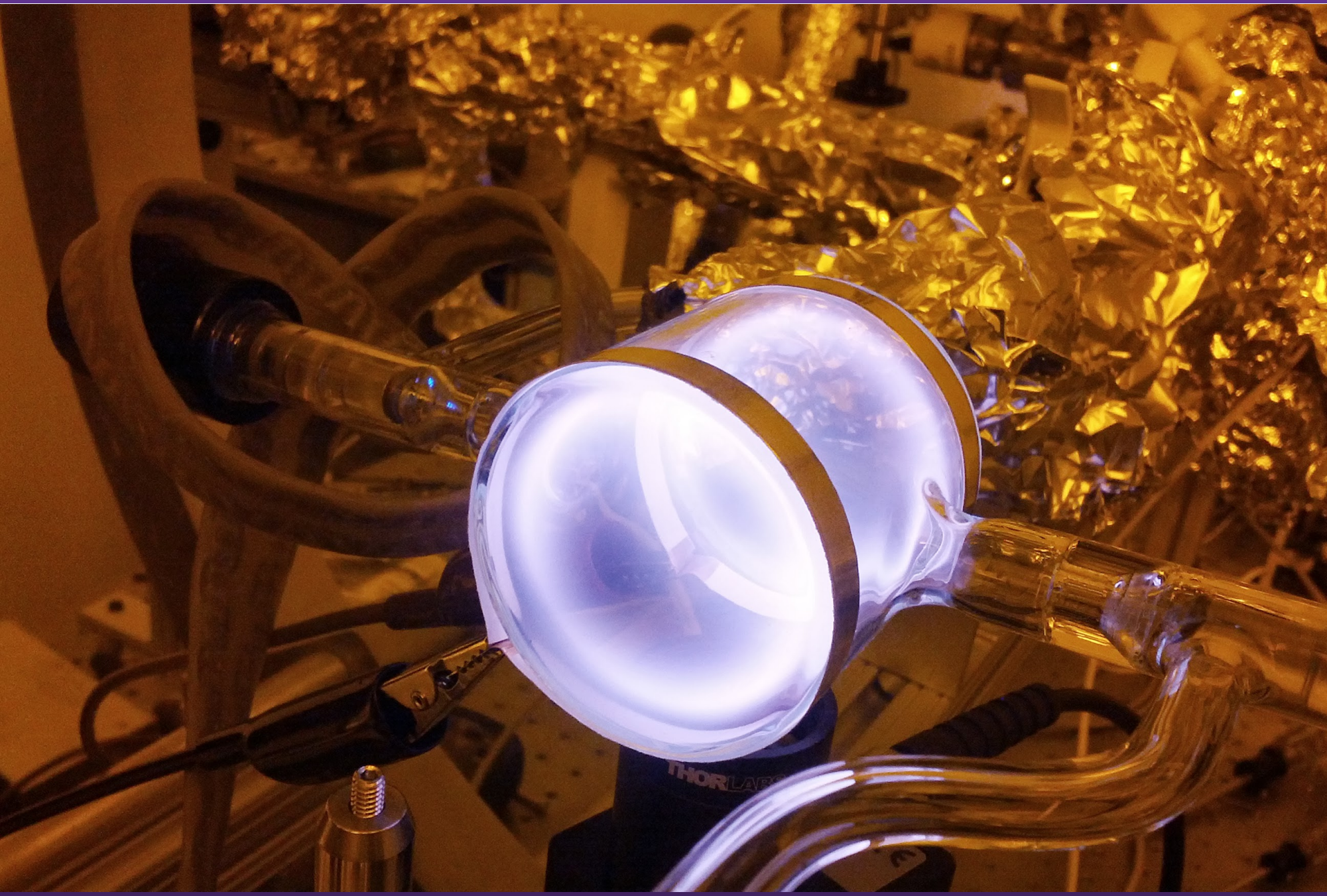

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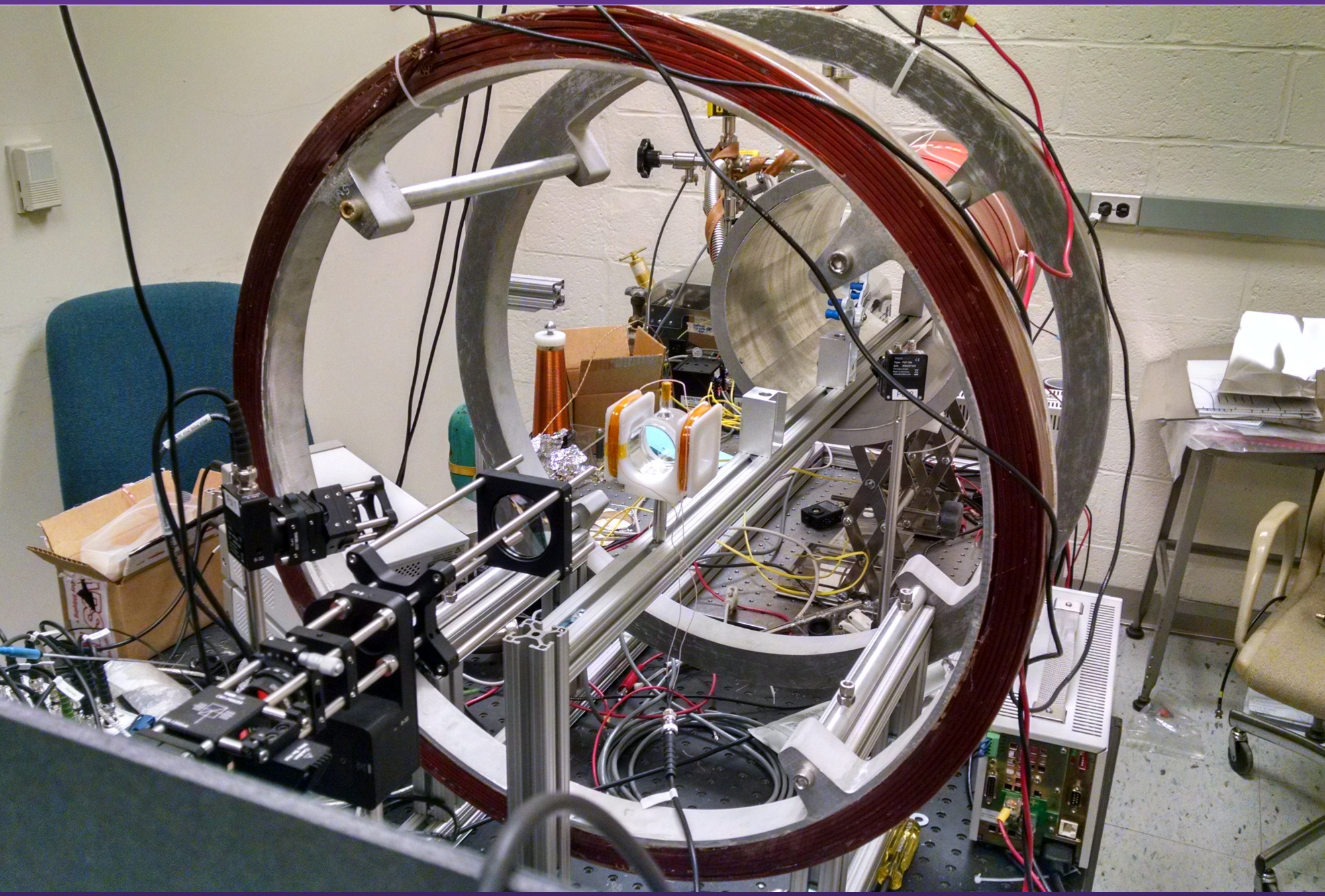

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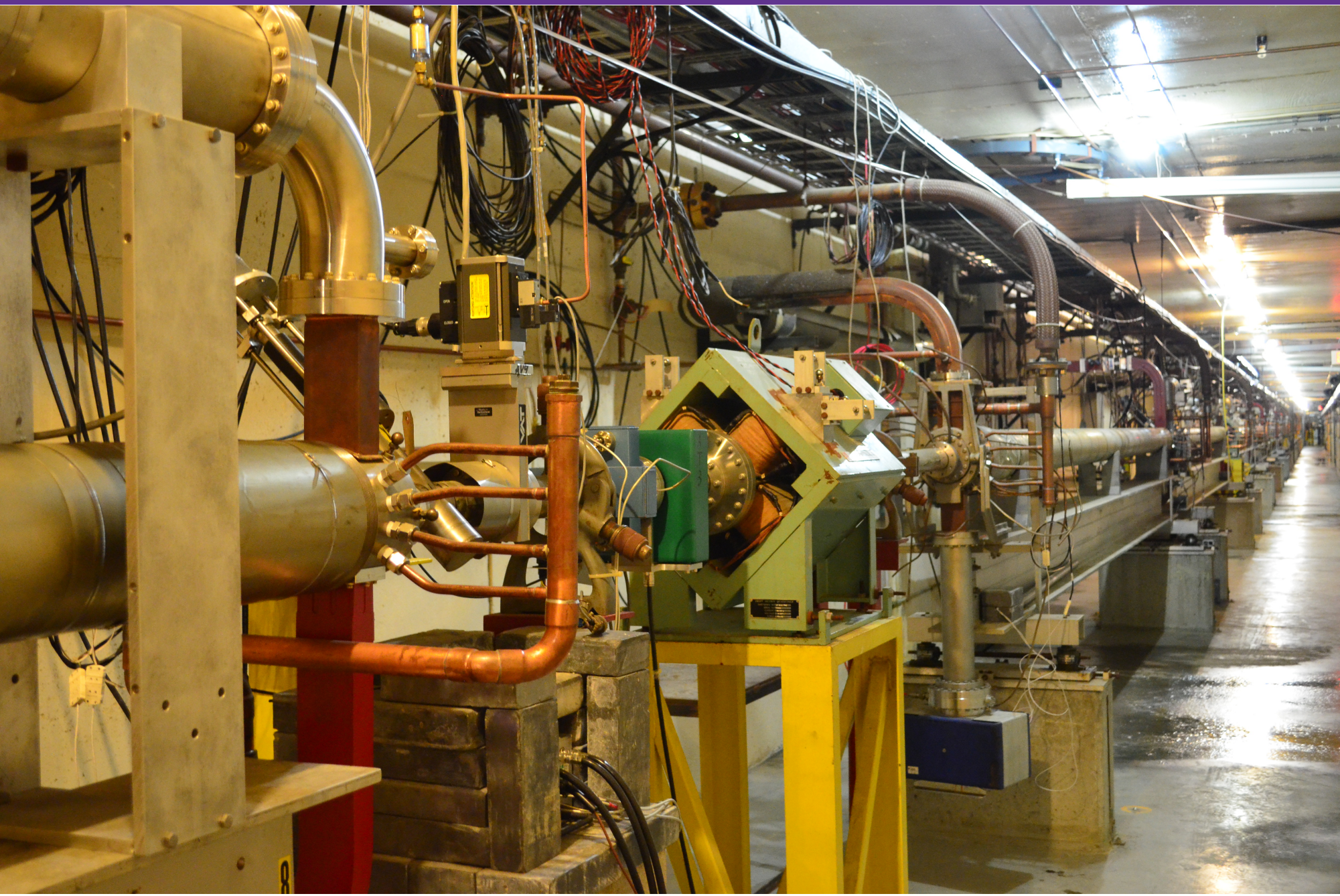

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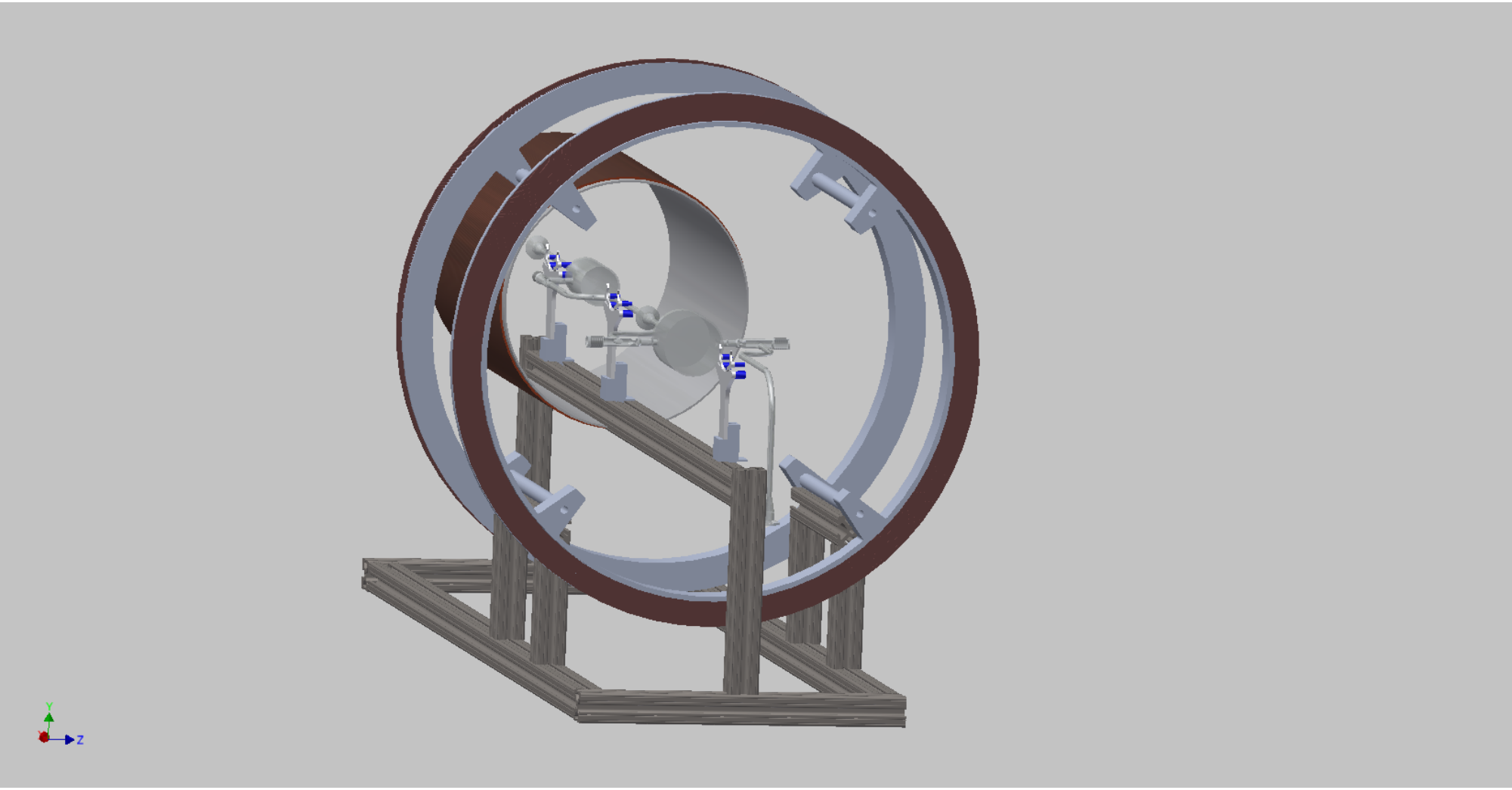

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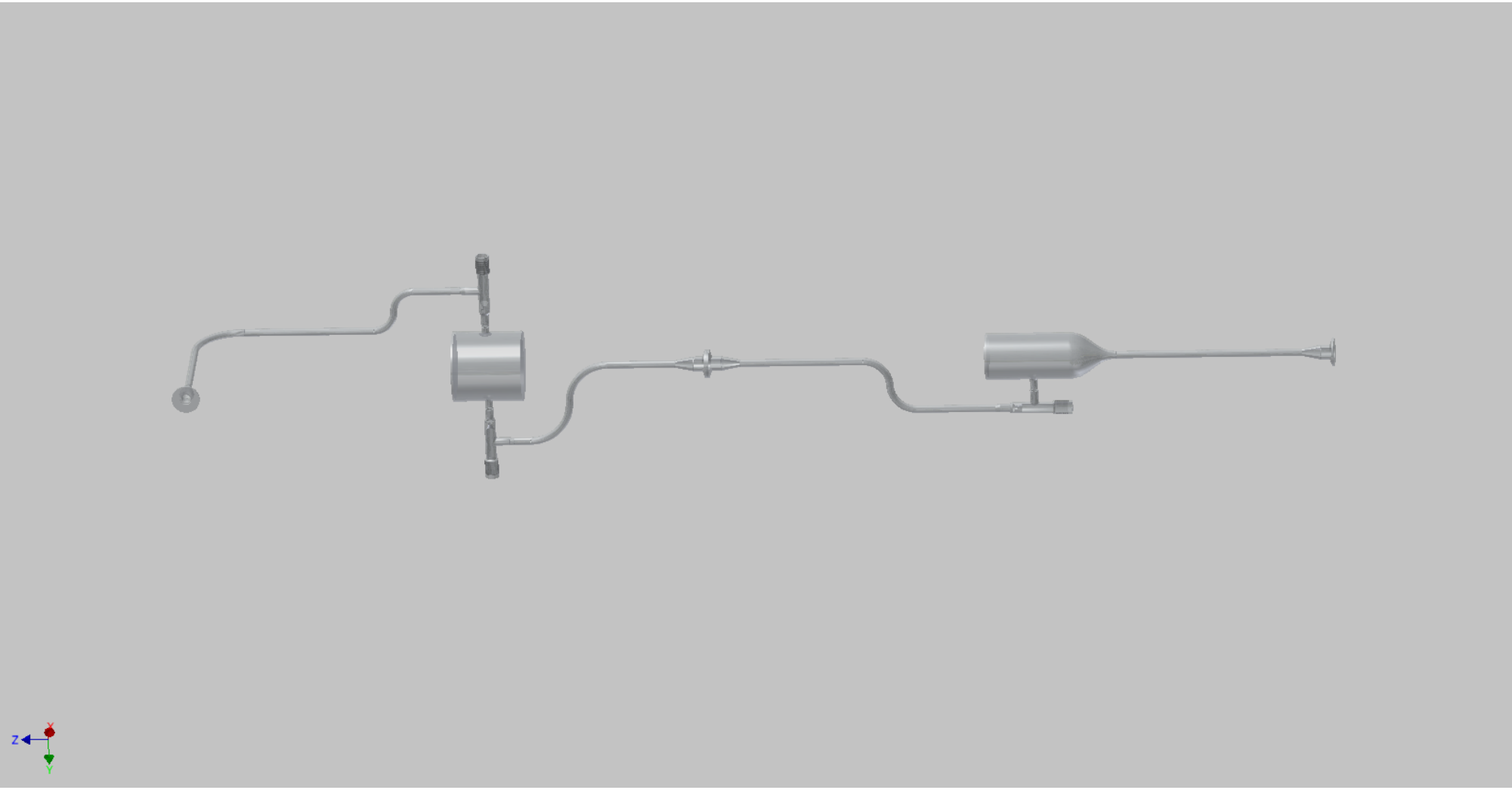

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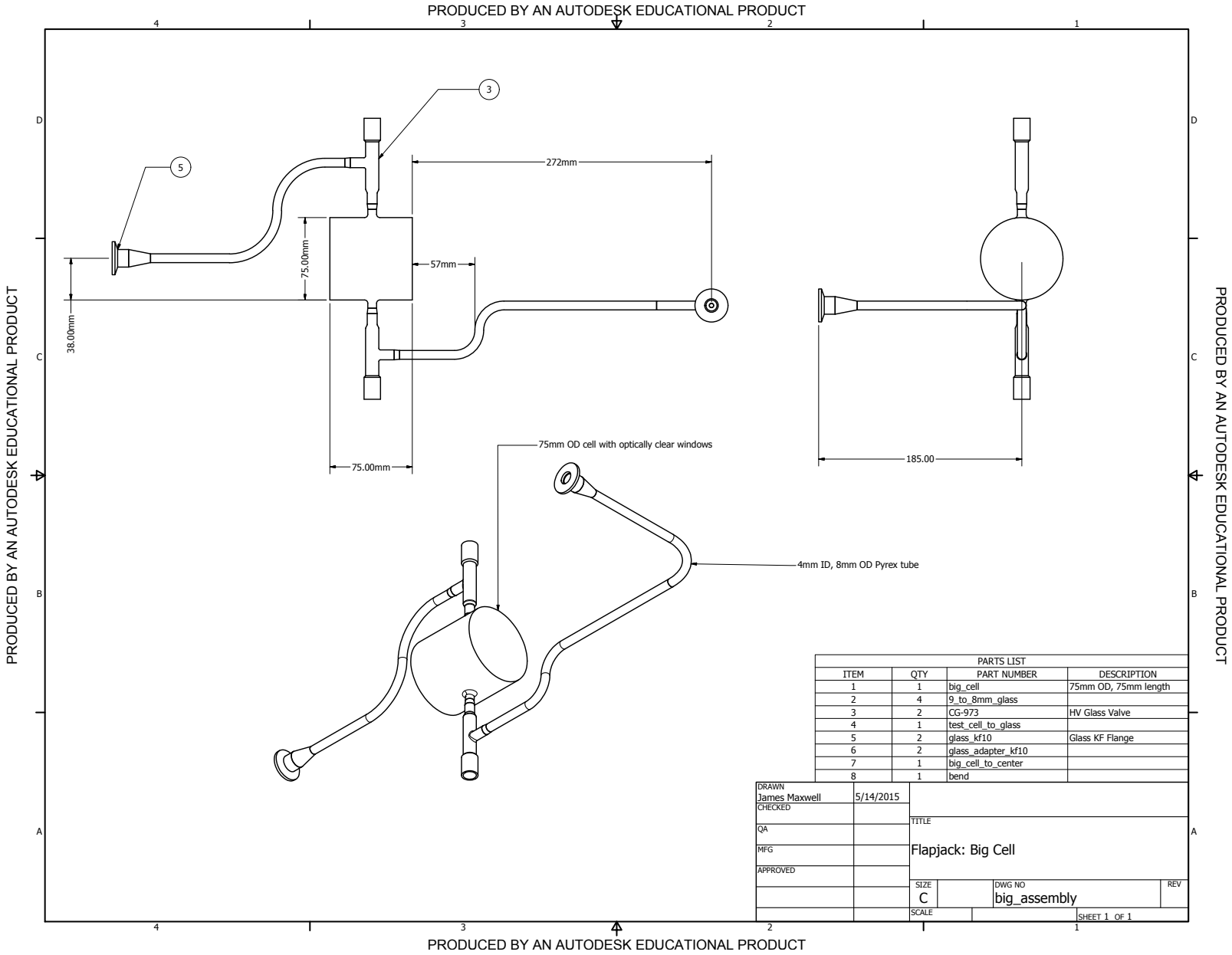

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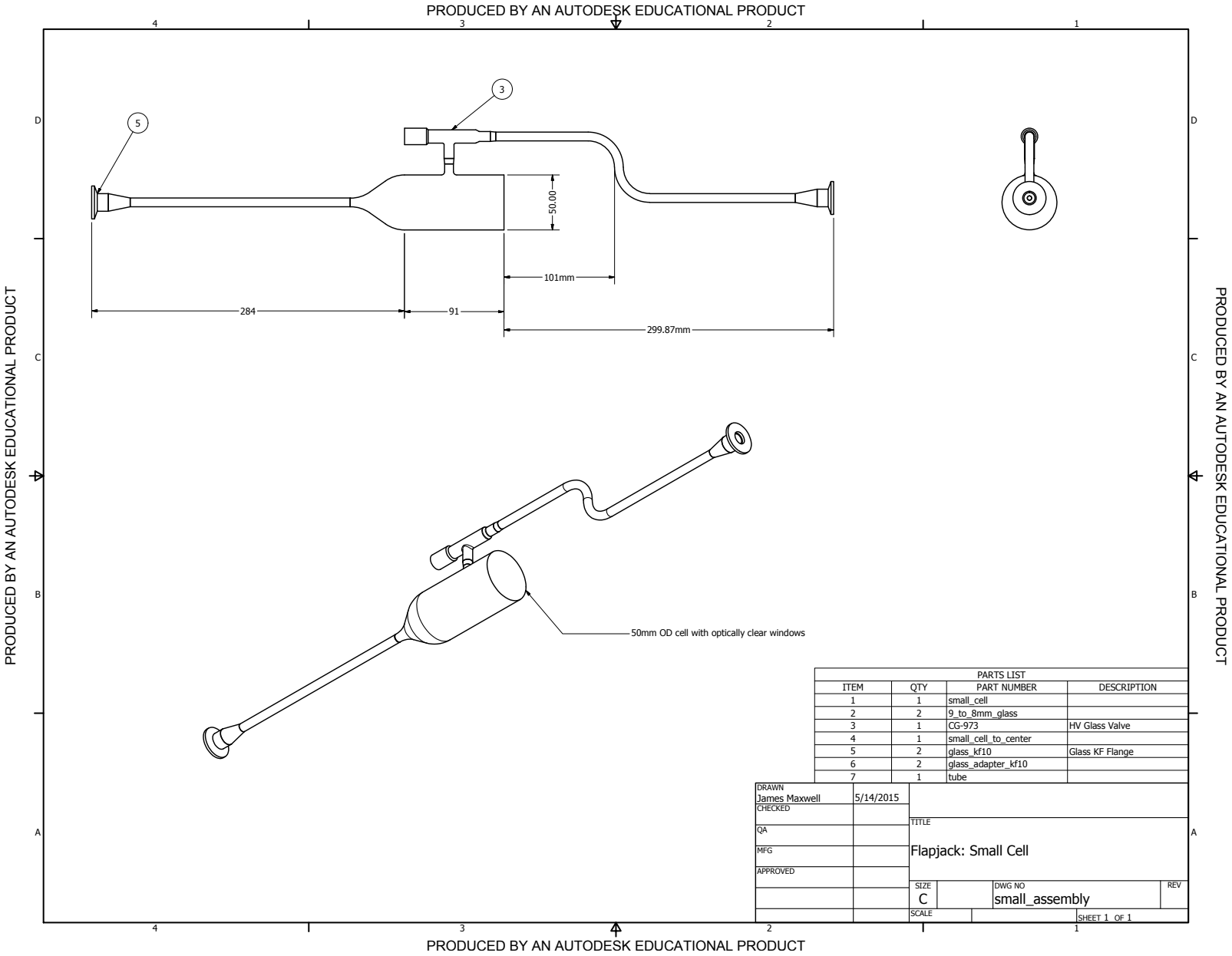

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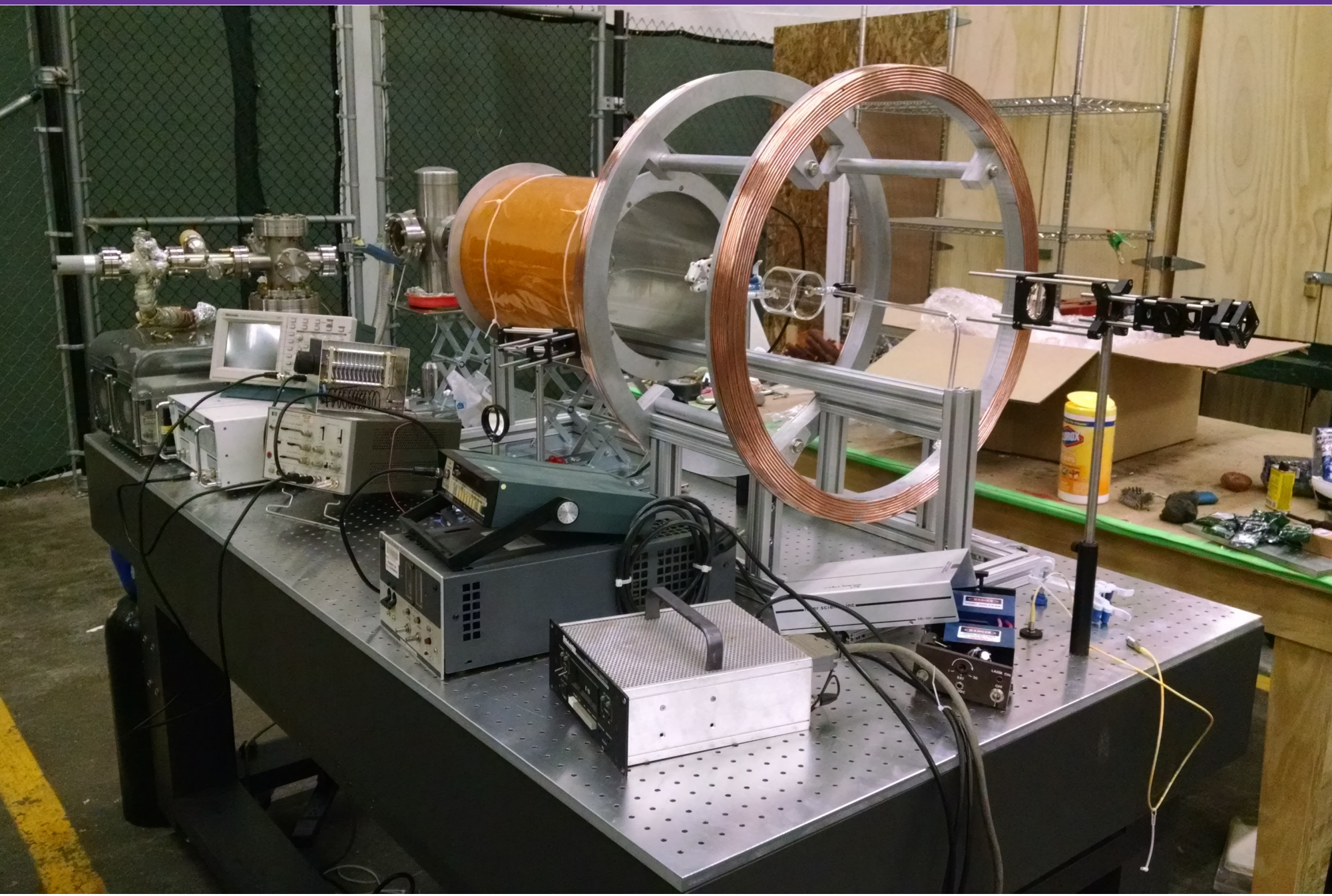

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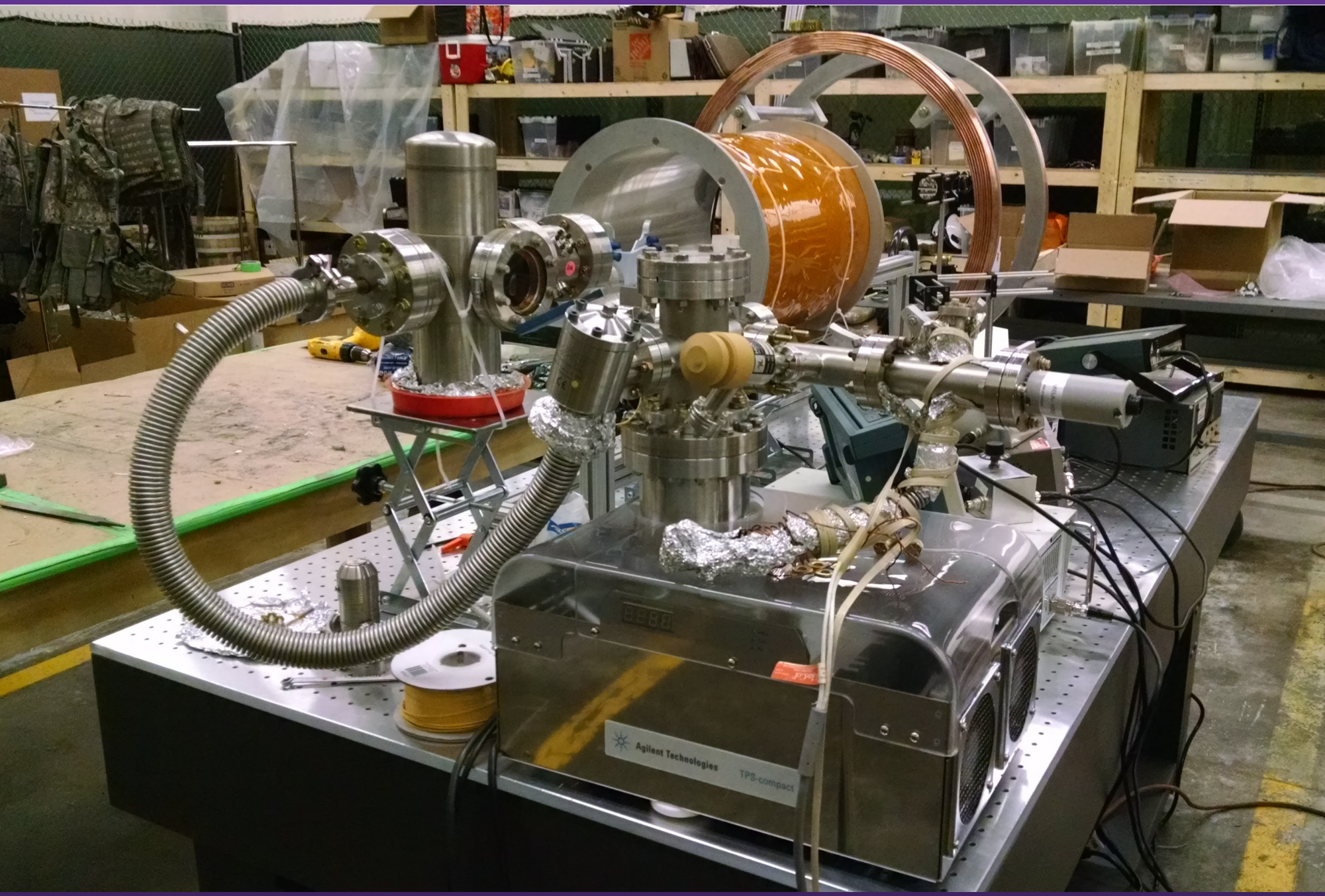

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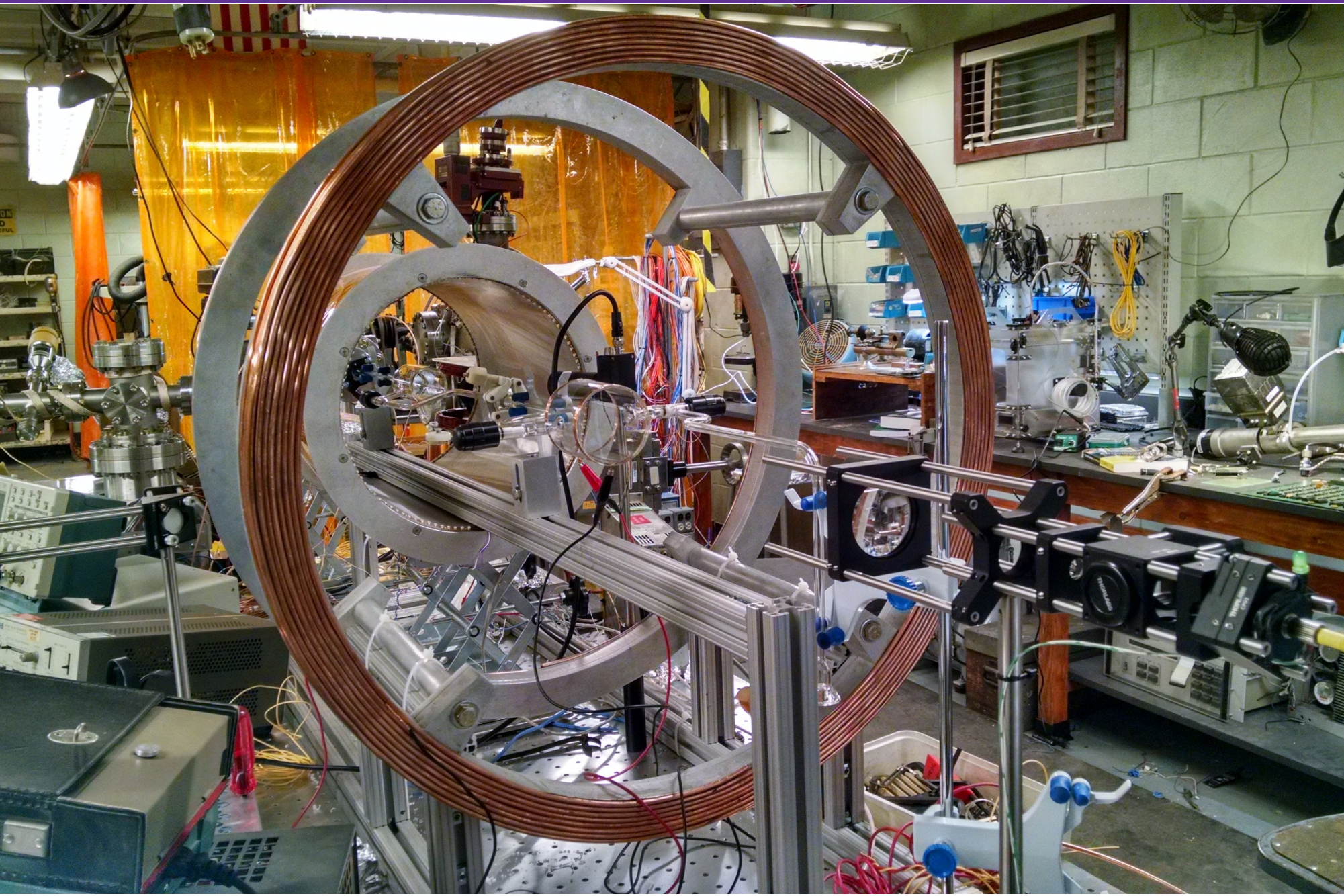

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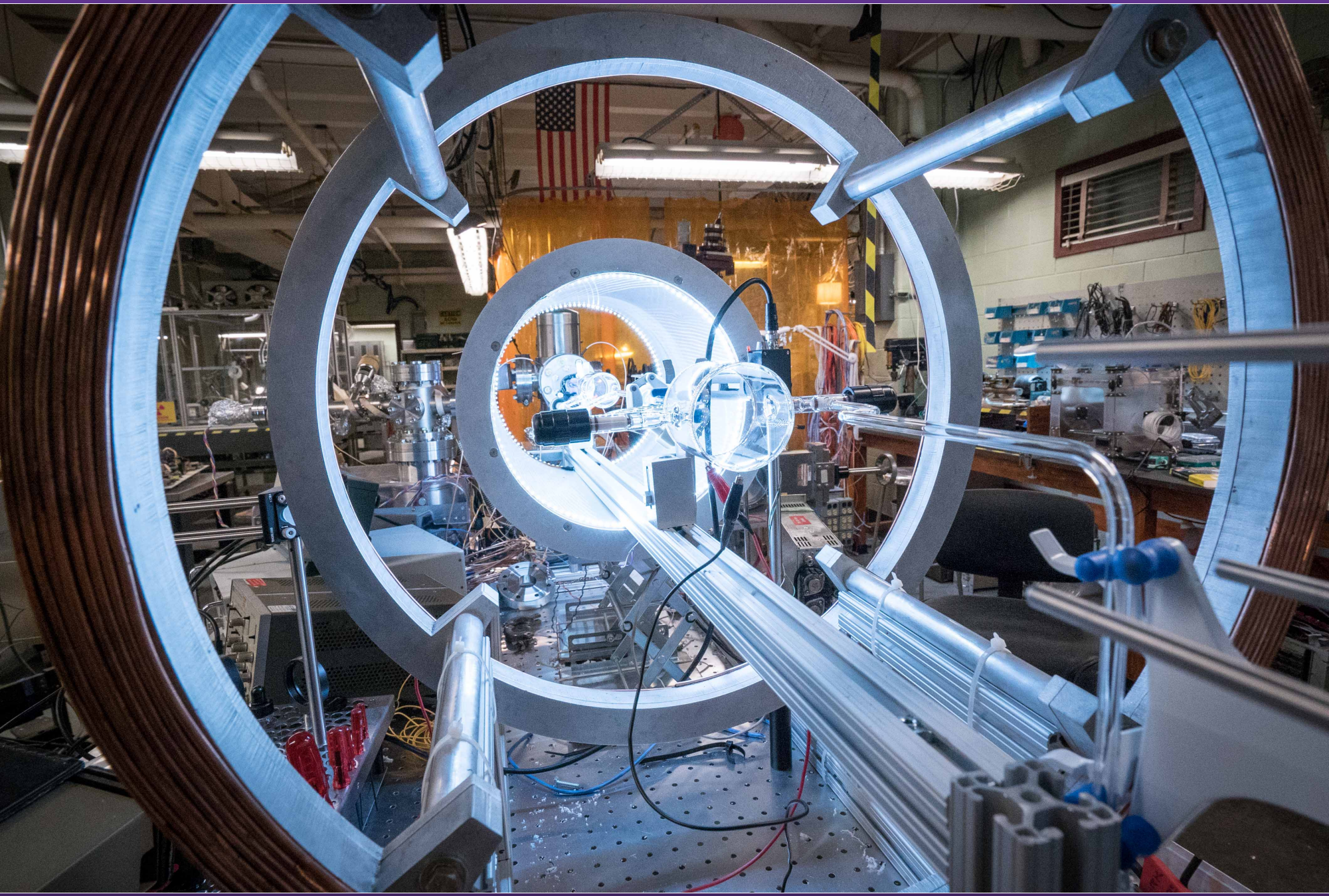

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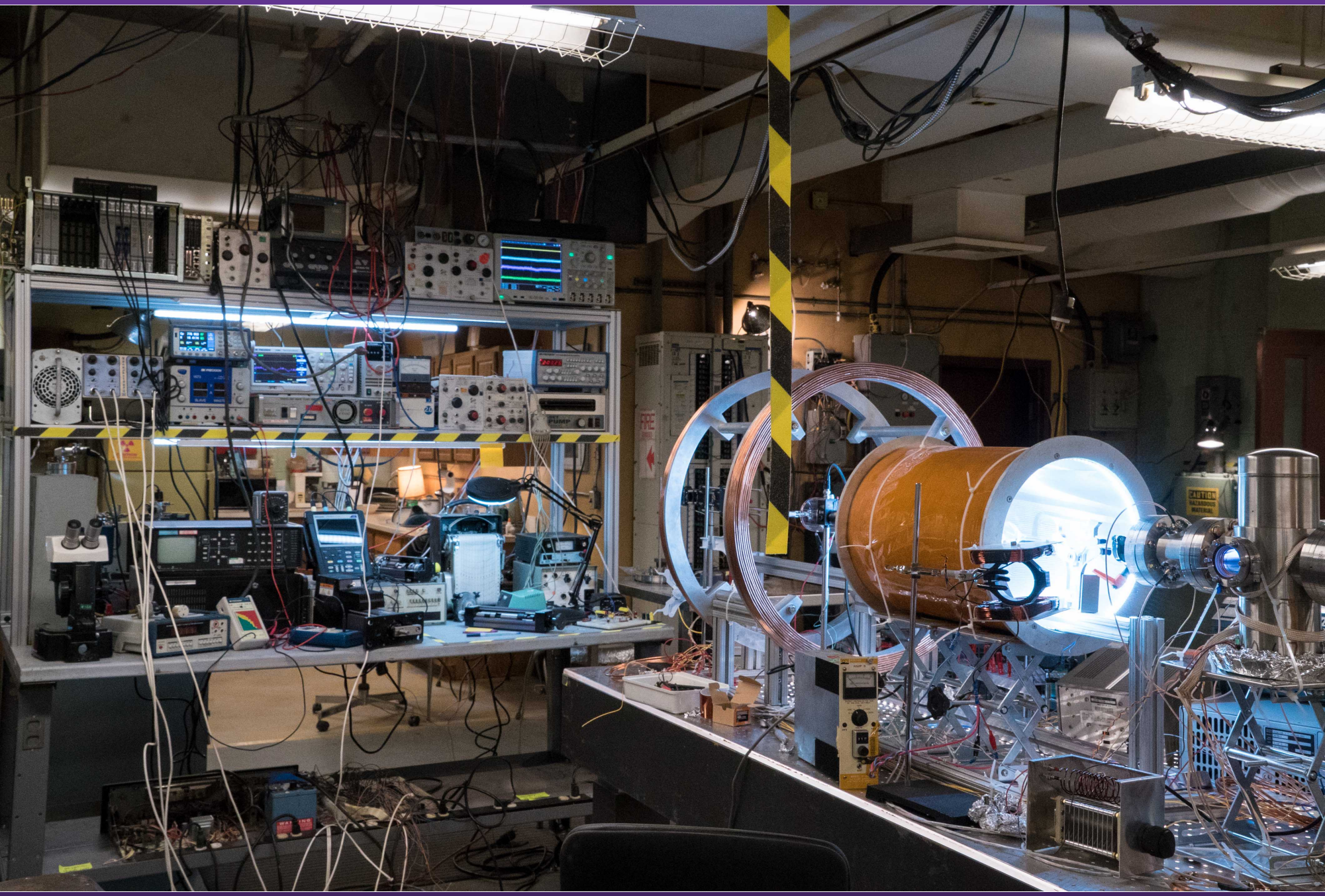

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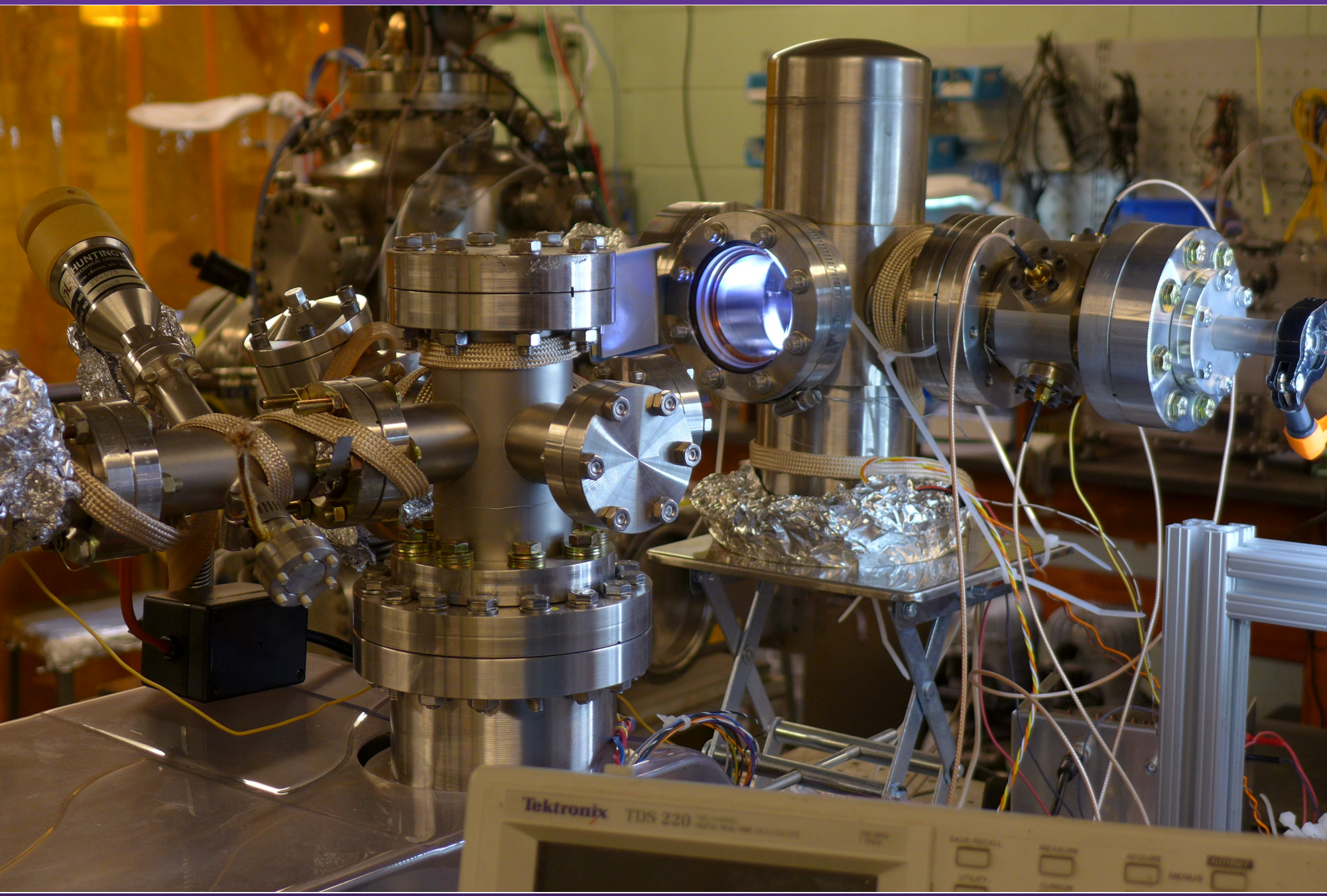

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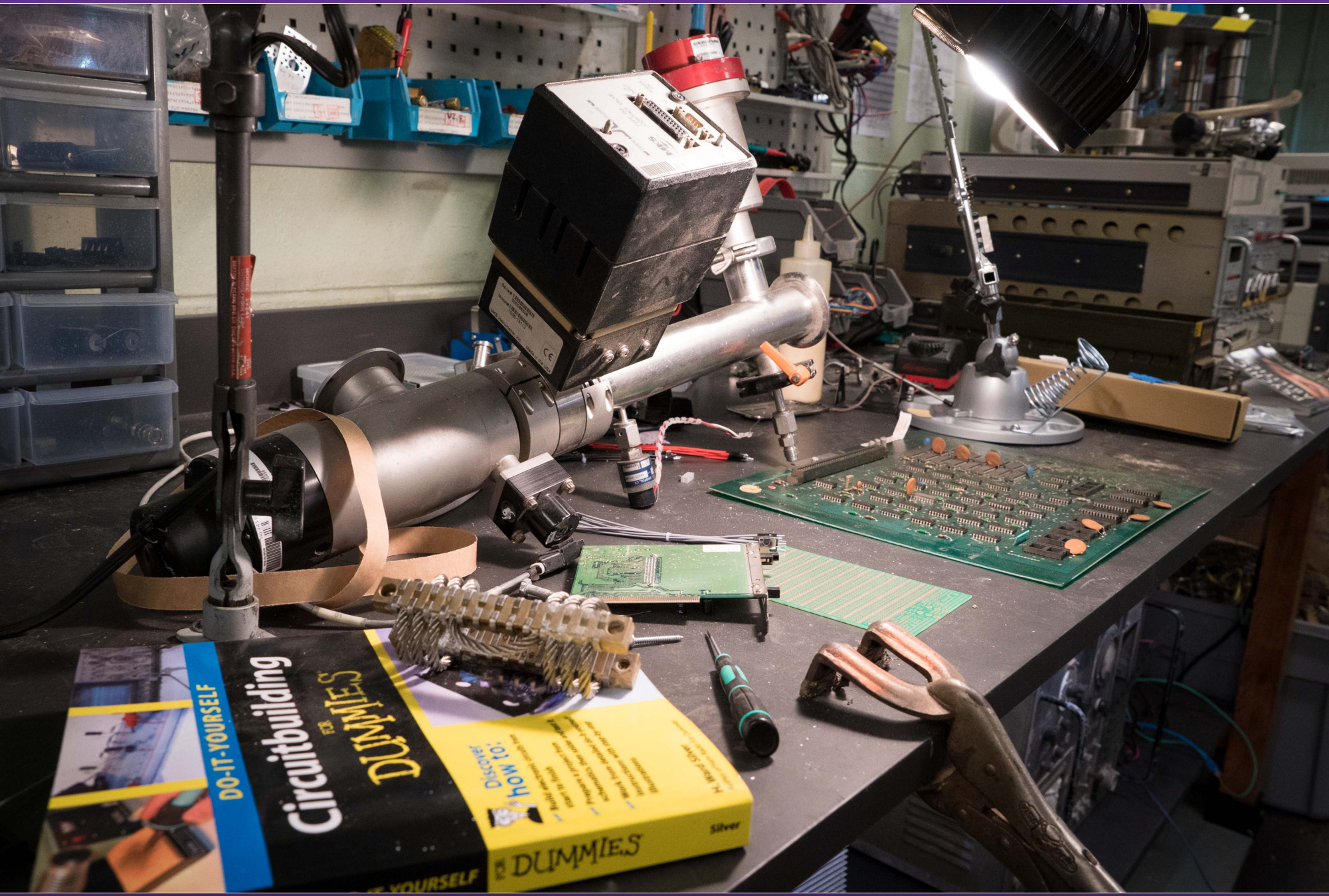

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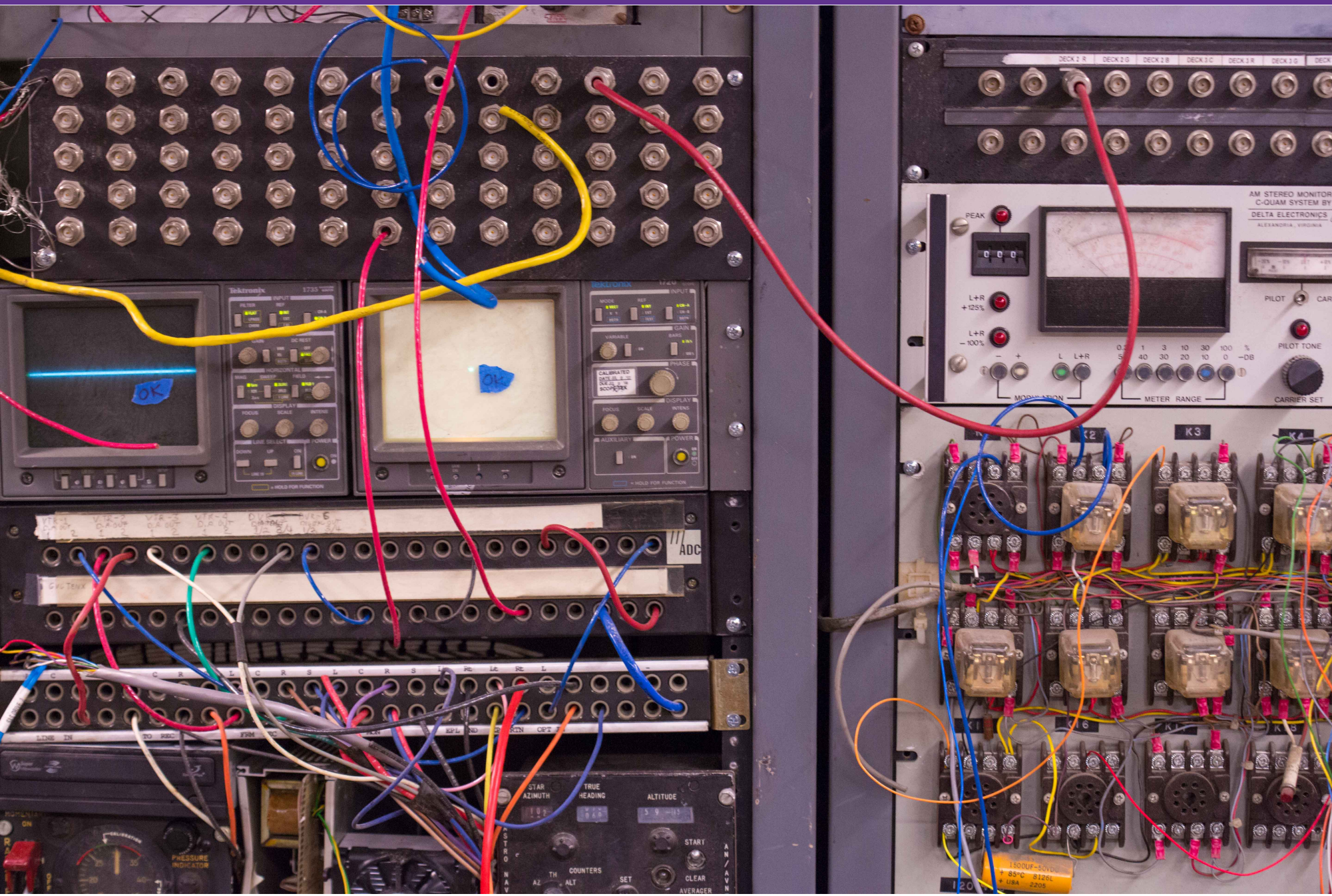

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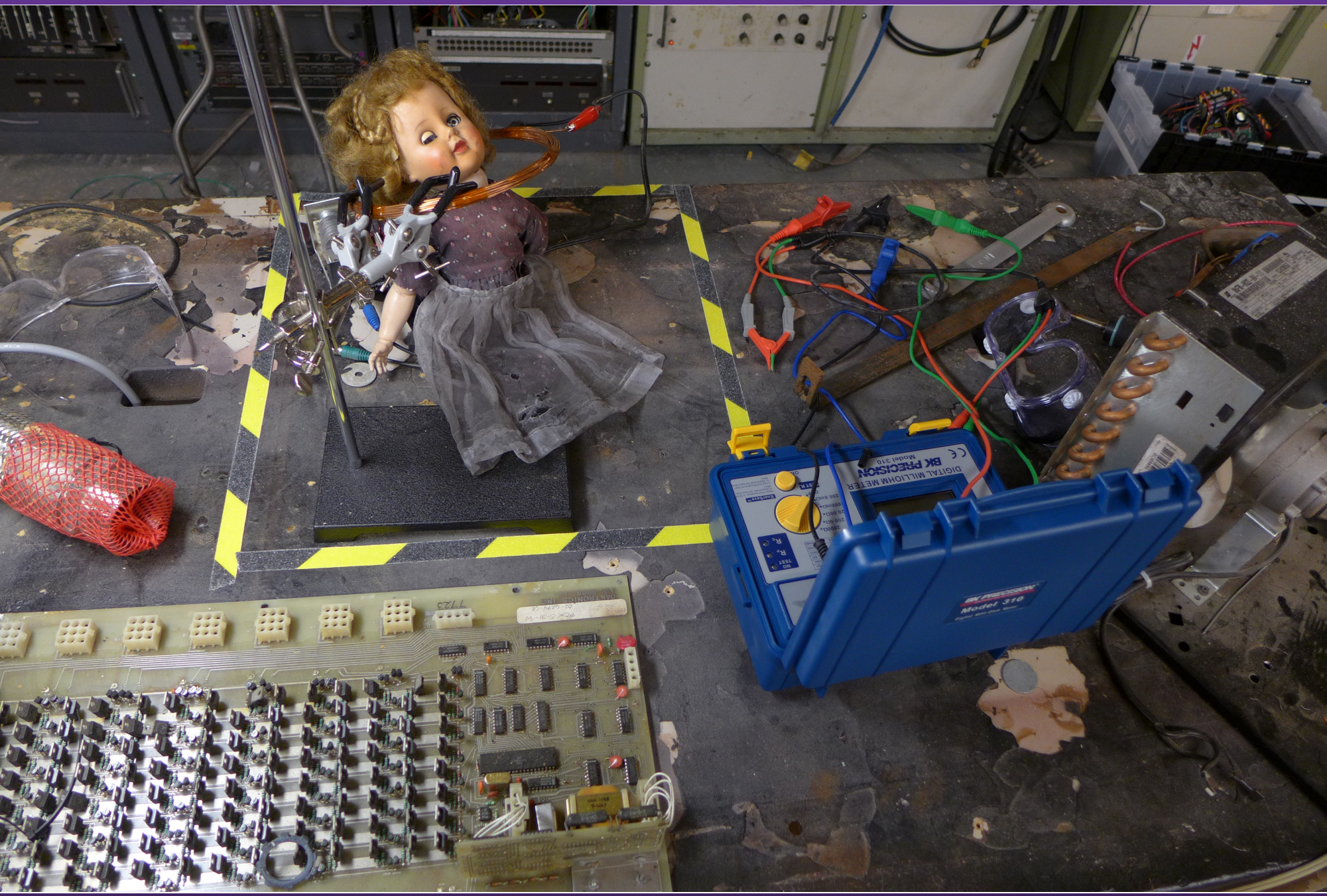

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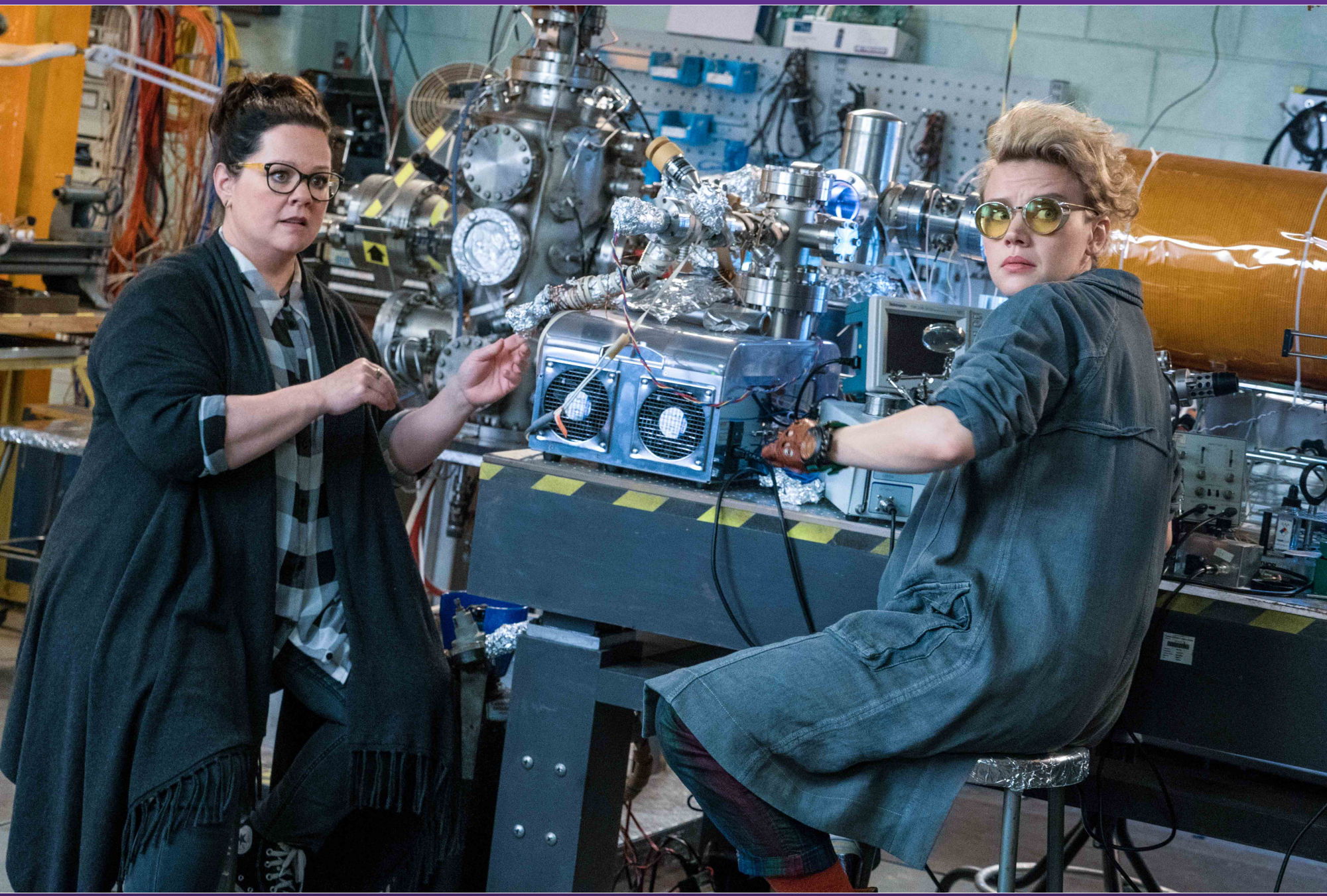

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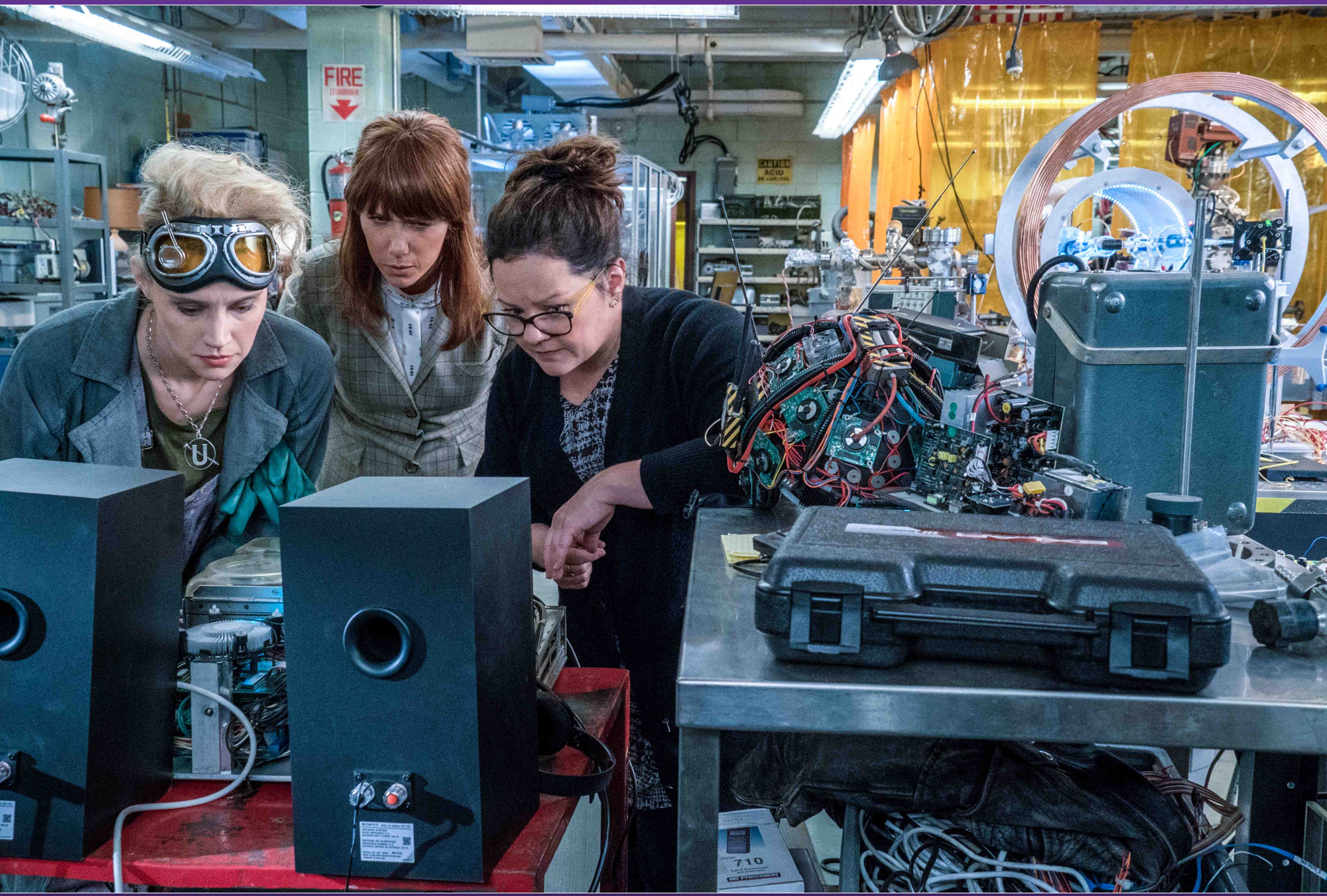

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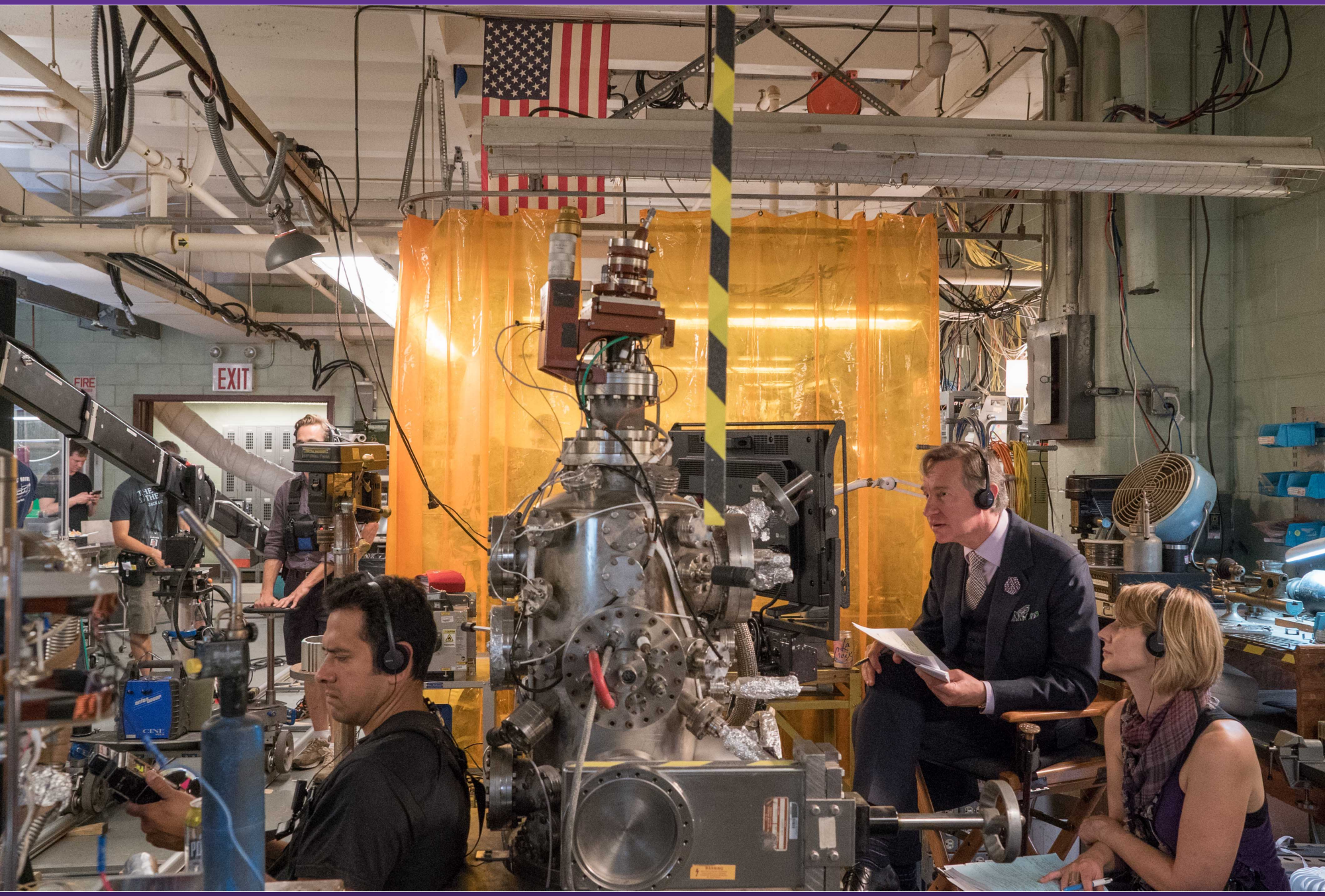

He3 Polarizer on Film

A New Proton Pack

Proton Pack Design

What are Ghosts? How do you catch them?

- "Unphysical" occurrences isolated in time & space
  - Dark matter? Fields, particles outside Standard model?
- Spectral Ether: a new gauge field through which unknown entities can interact with our world
  - Localized excitation of the ether, "spectral foam," results in regions in space and time where significant coupling exists between spectral matter and Standard Model particles
  - "Ethereal polarization," good/bad slimes from GB 2
- Proton Pack?
  - Absorbs spectral energy via unidentified secondaries generated by beam of high energy protons
  - "Unlicensed nuclear accelerator" on your back

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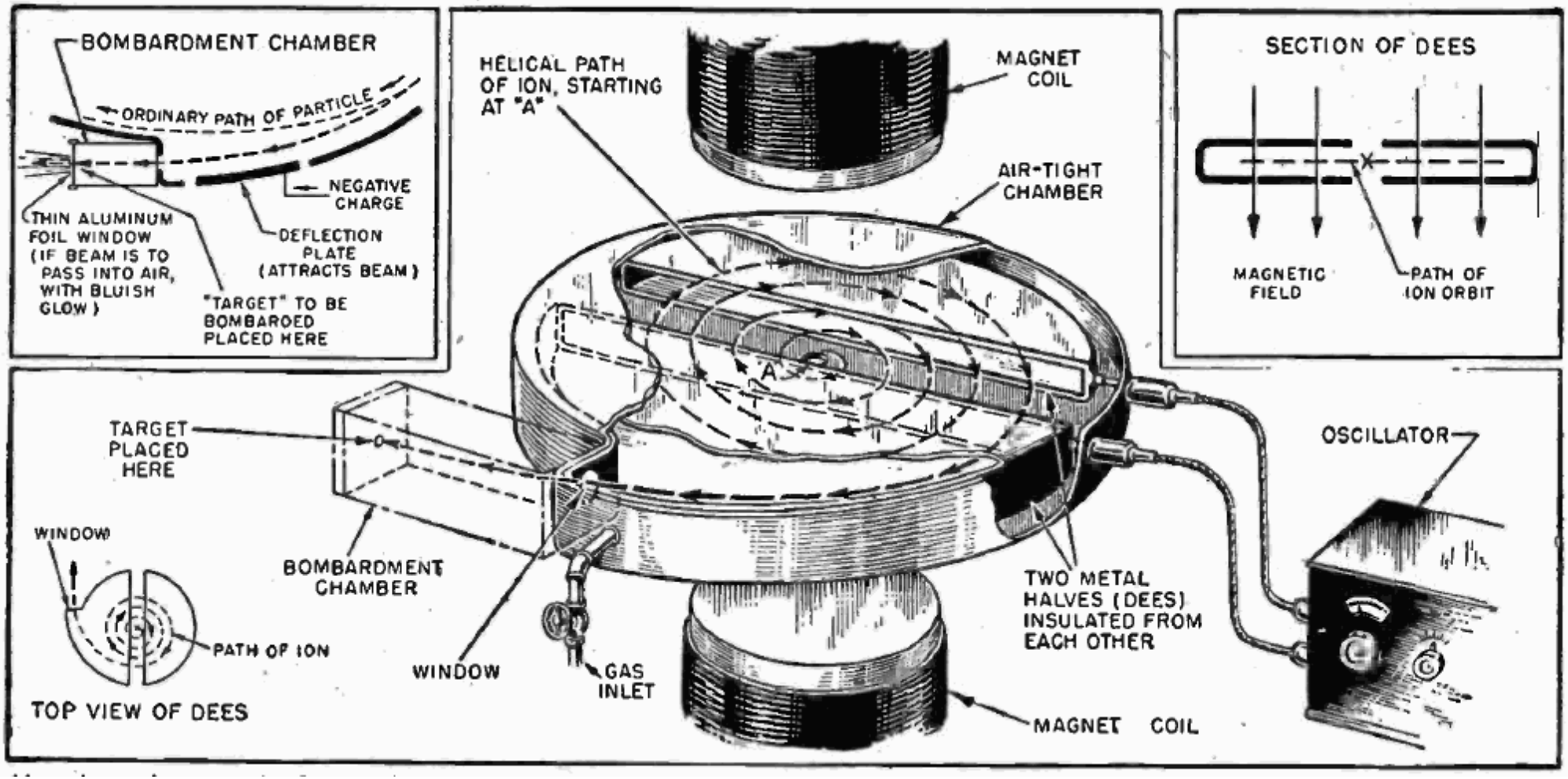
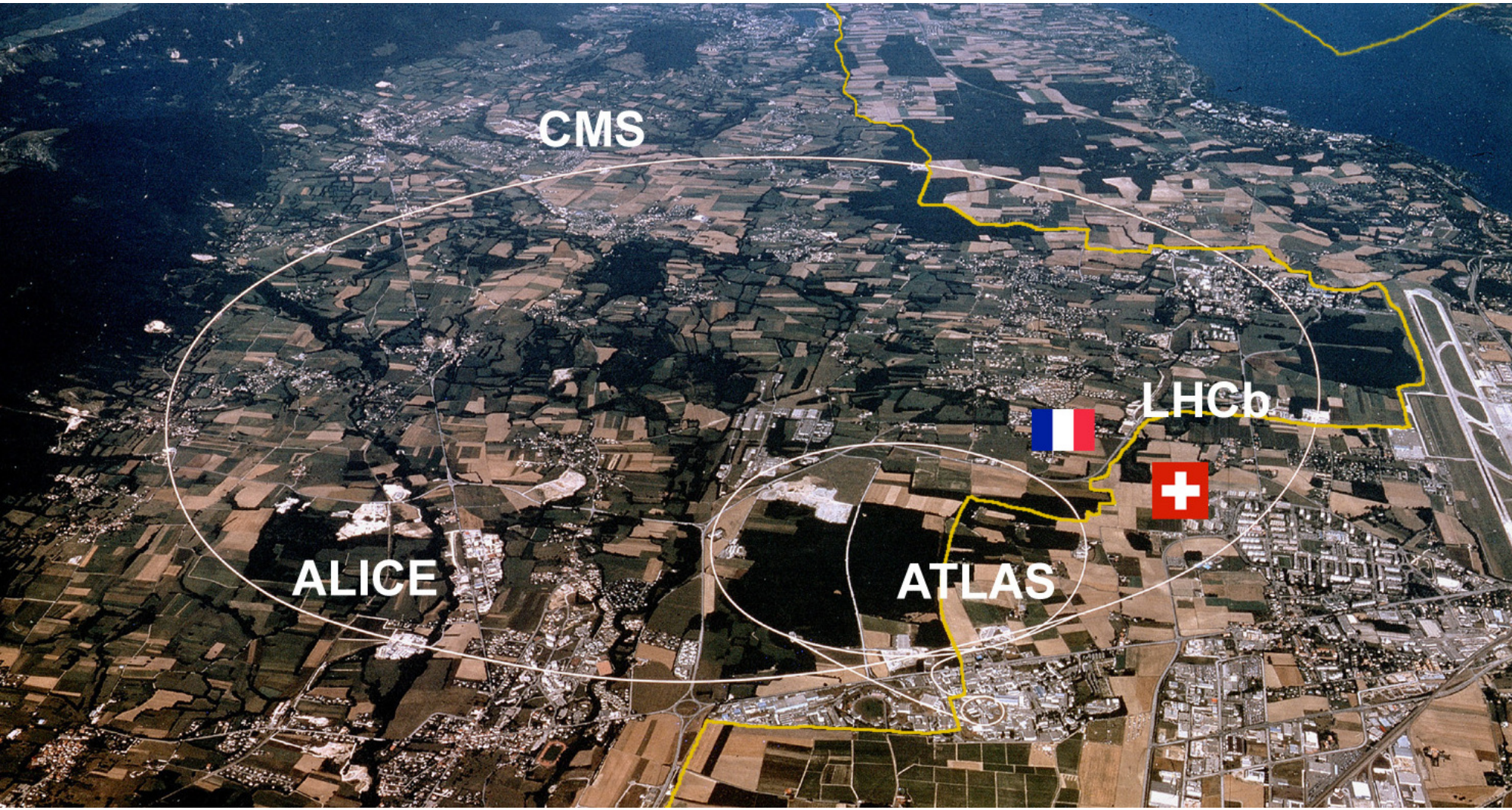
Cyclotron: 1932

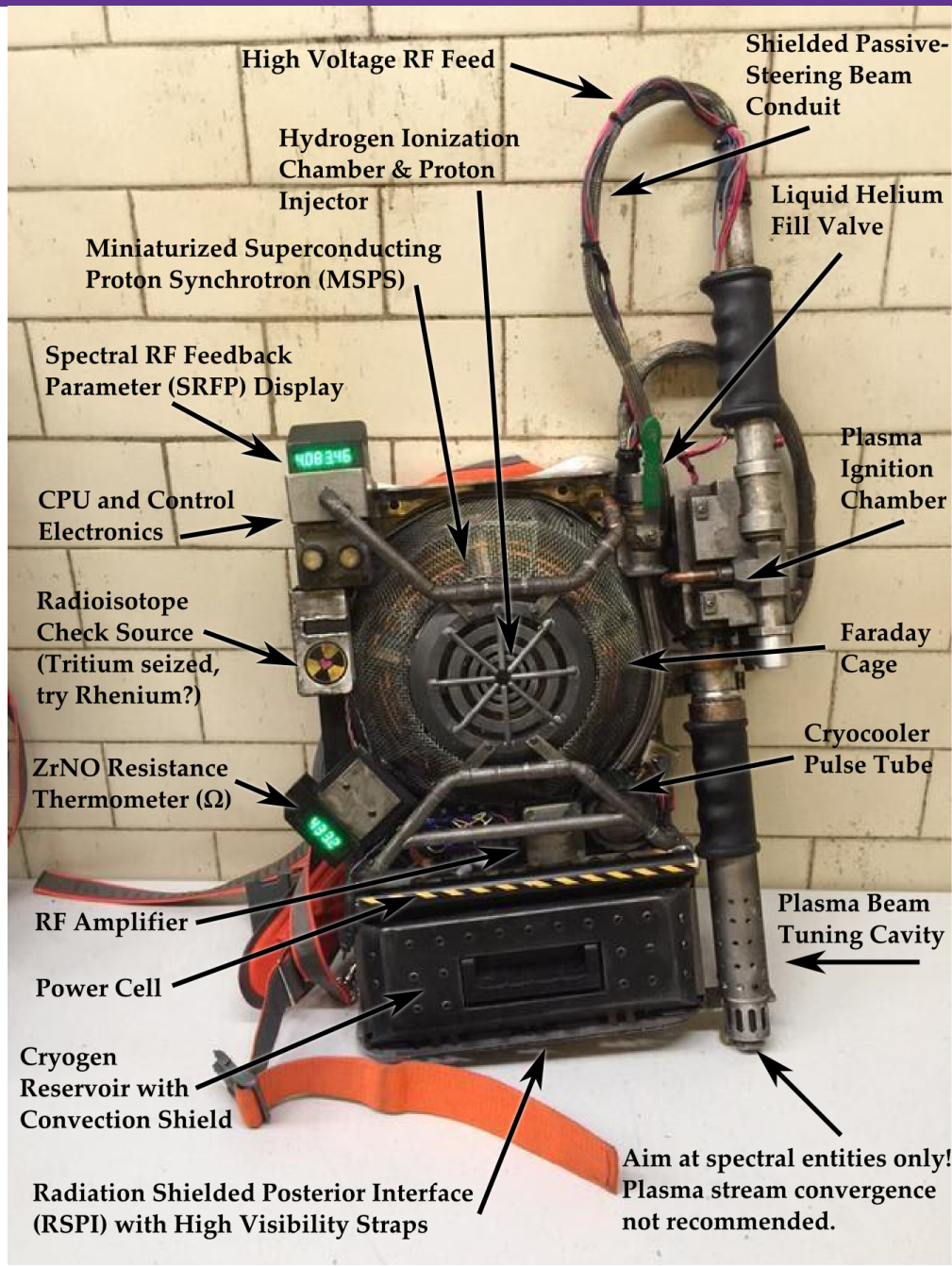


Synchrotron: 1945

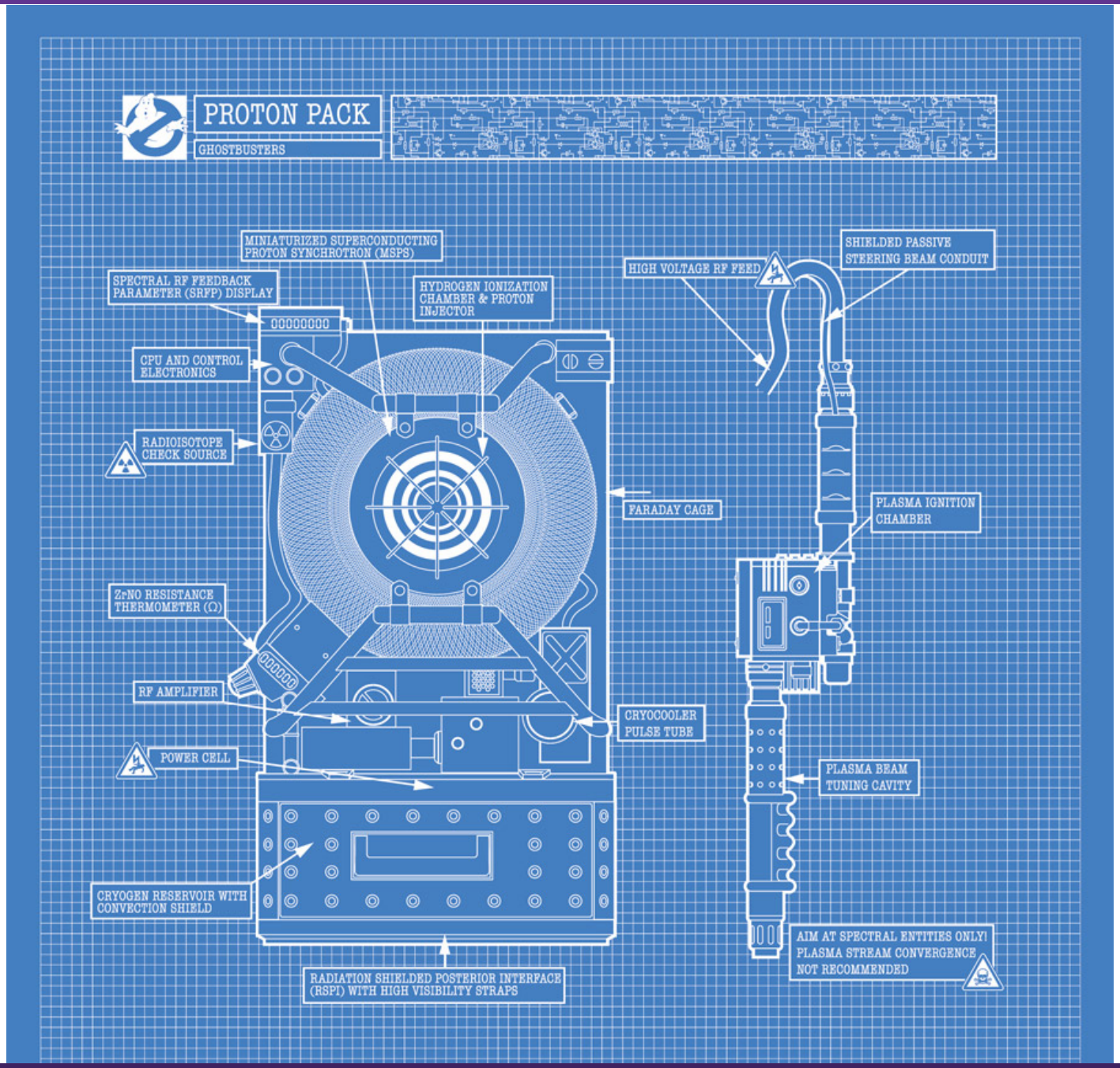


New Proton Pack

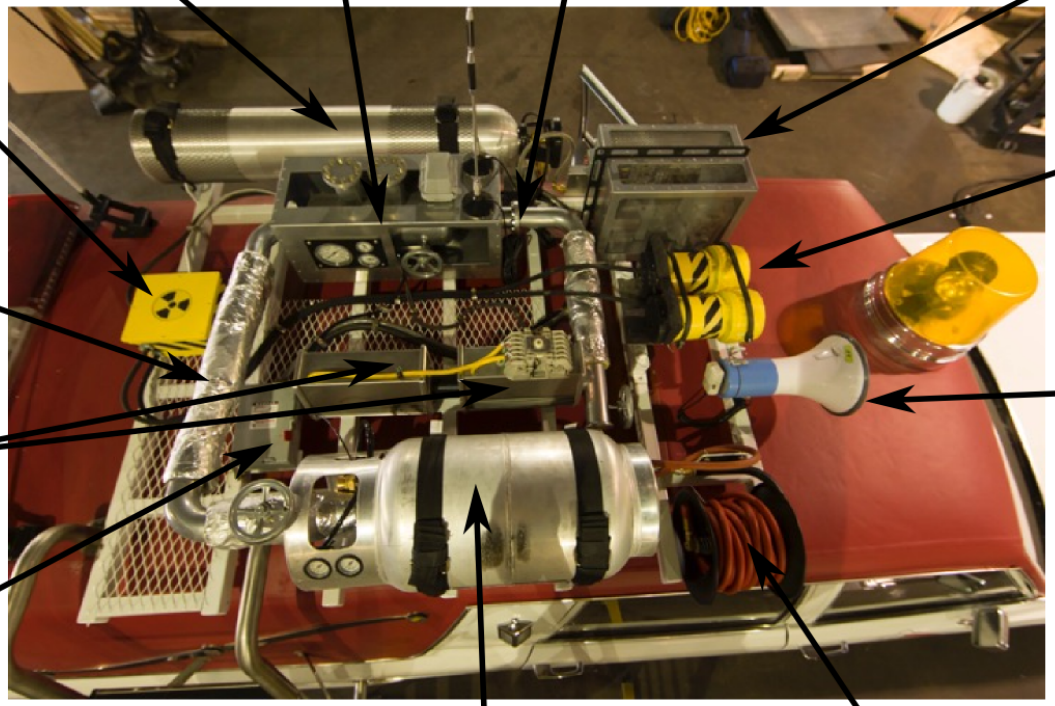
- Miniature Superconducting Proton Synchrotron
  - RF plasma ECR proton source
  - Cryogen reservoir with cryocooler for active cooling
  - "Magic" beam steering
  - Plasma beam halo
- Timeline:
  - Saturday night: "Can you label this?"
  - Sunday: PANIC
  - Sunday night: "How's this?"
  - Monday: Tweet



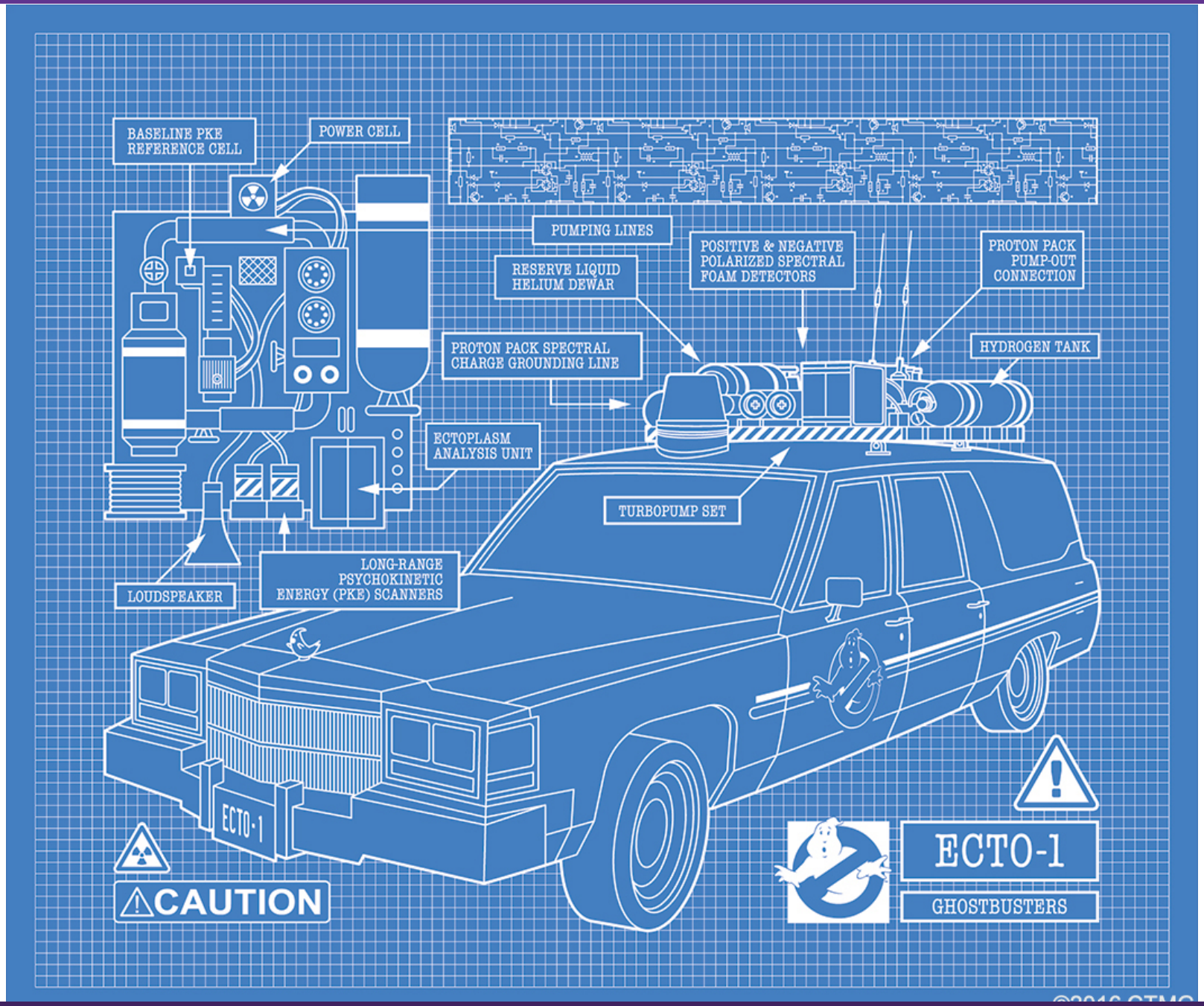
Proton Pack Design



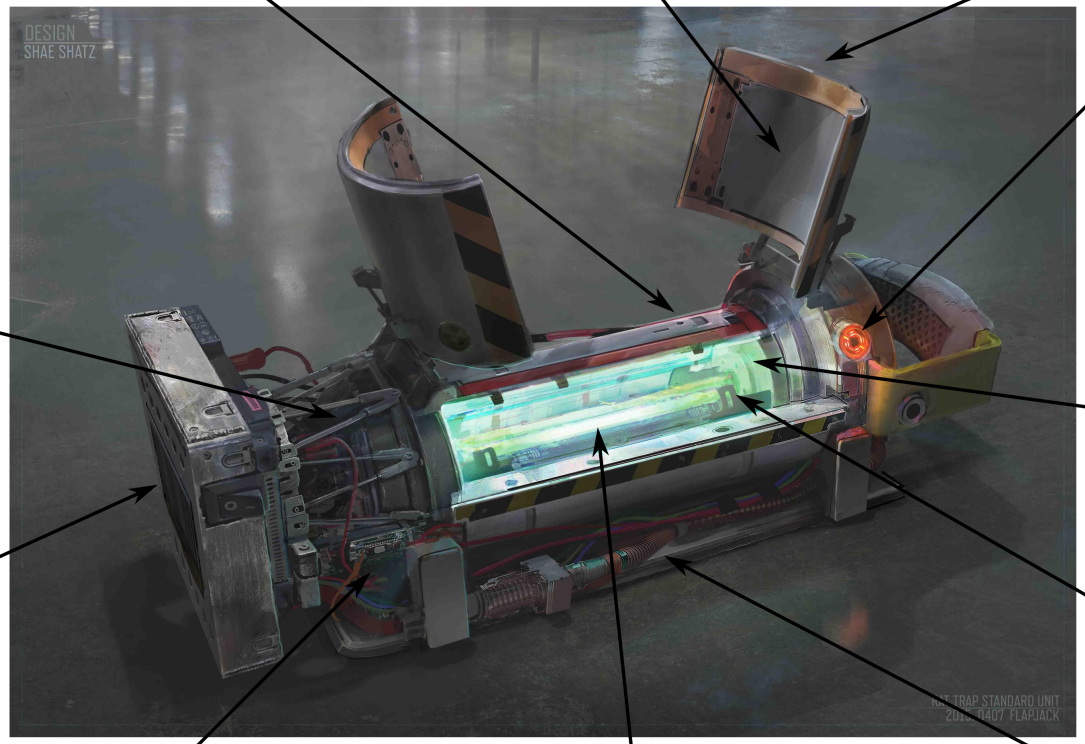
Proton Pack Design


Turbopump Set
Hydrogen Tank
Proton Pack
Pump-out Connection
Ectoplasm Analysis Unit
Power Cell
Long-range
Psychokinetic Energy
(PKE) Scanners
Pumping Lines
Loudspeaker
Positive & Negative
Polarized Spectral
Foam Detectors
Baseline PKE
Reference Cell
Reserve Liquid
Helium Dewar
Proton Pack Spectral
Charge Grounding Line

Proton Pack Design



Proton Pack Design



Spectrally Reflective Plating

Veto Shield

Shielded Containment Doors

Occupancy Indicator

Polarized Spectral Foam Generator

Resonant Holding Cavity

Heat Sink

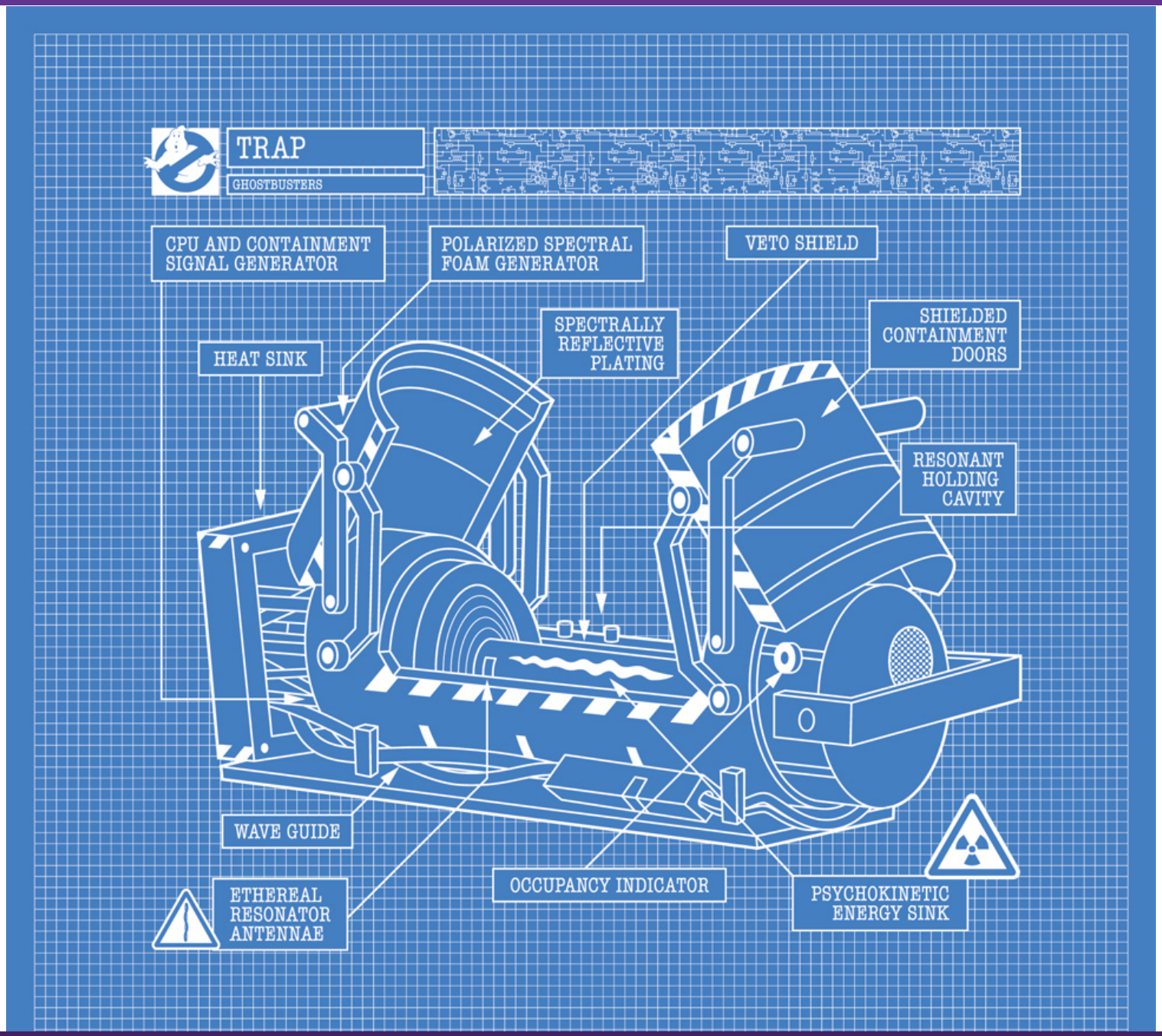
Ethereal Resonator Antennae

CPU and Containment Signal Generator

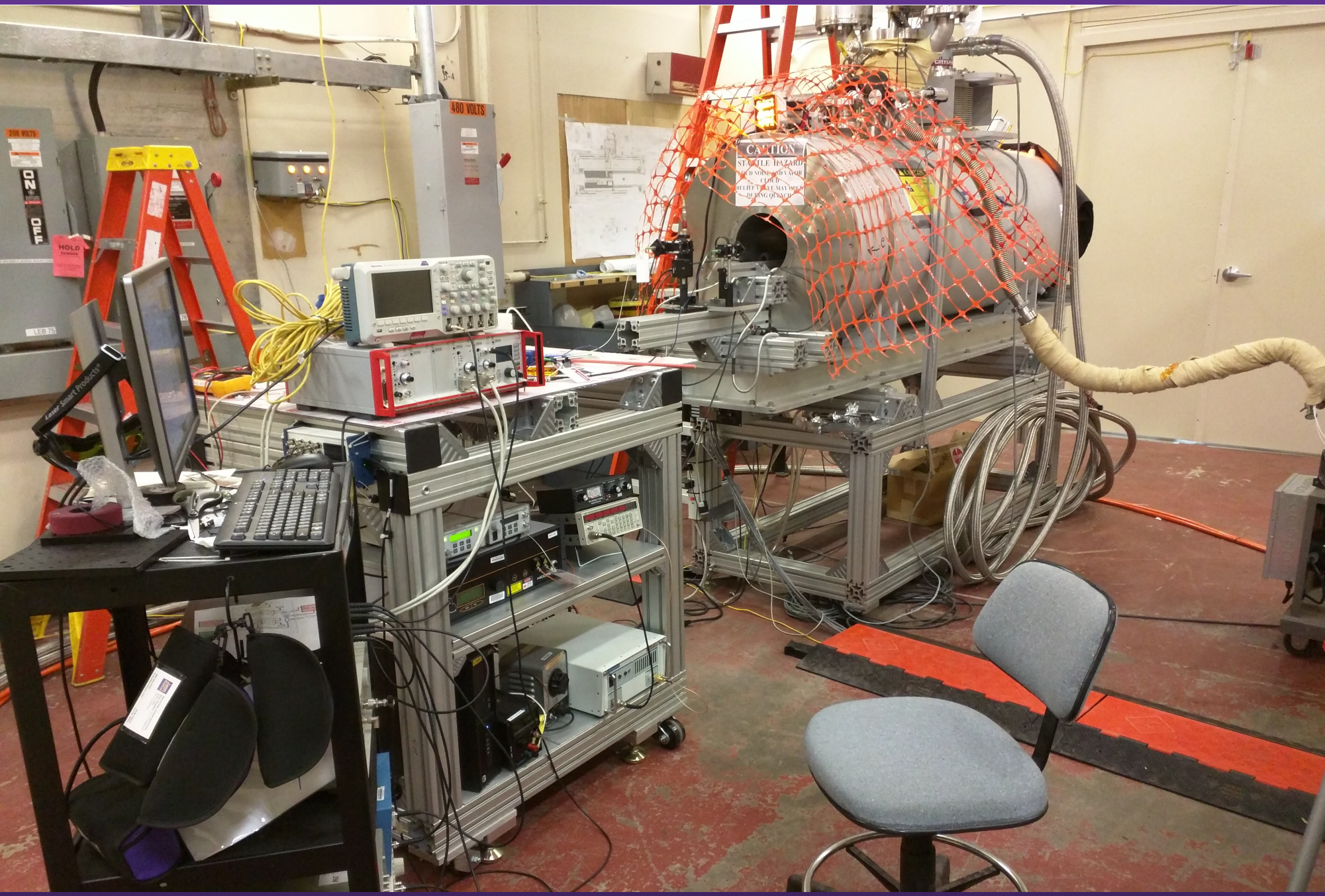
Psychokinetic Energy Sink

Waveguide

Proton Pack Design



Other Fun Stuff



Other Fun Stuff

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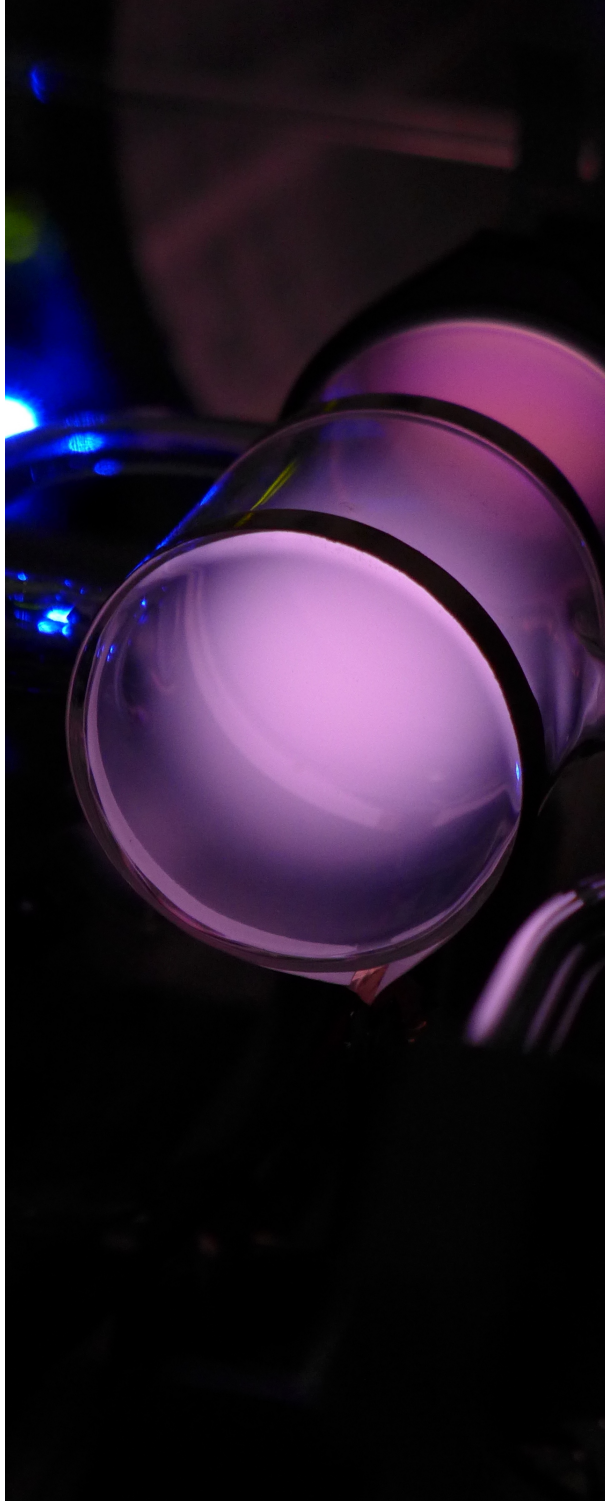
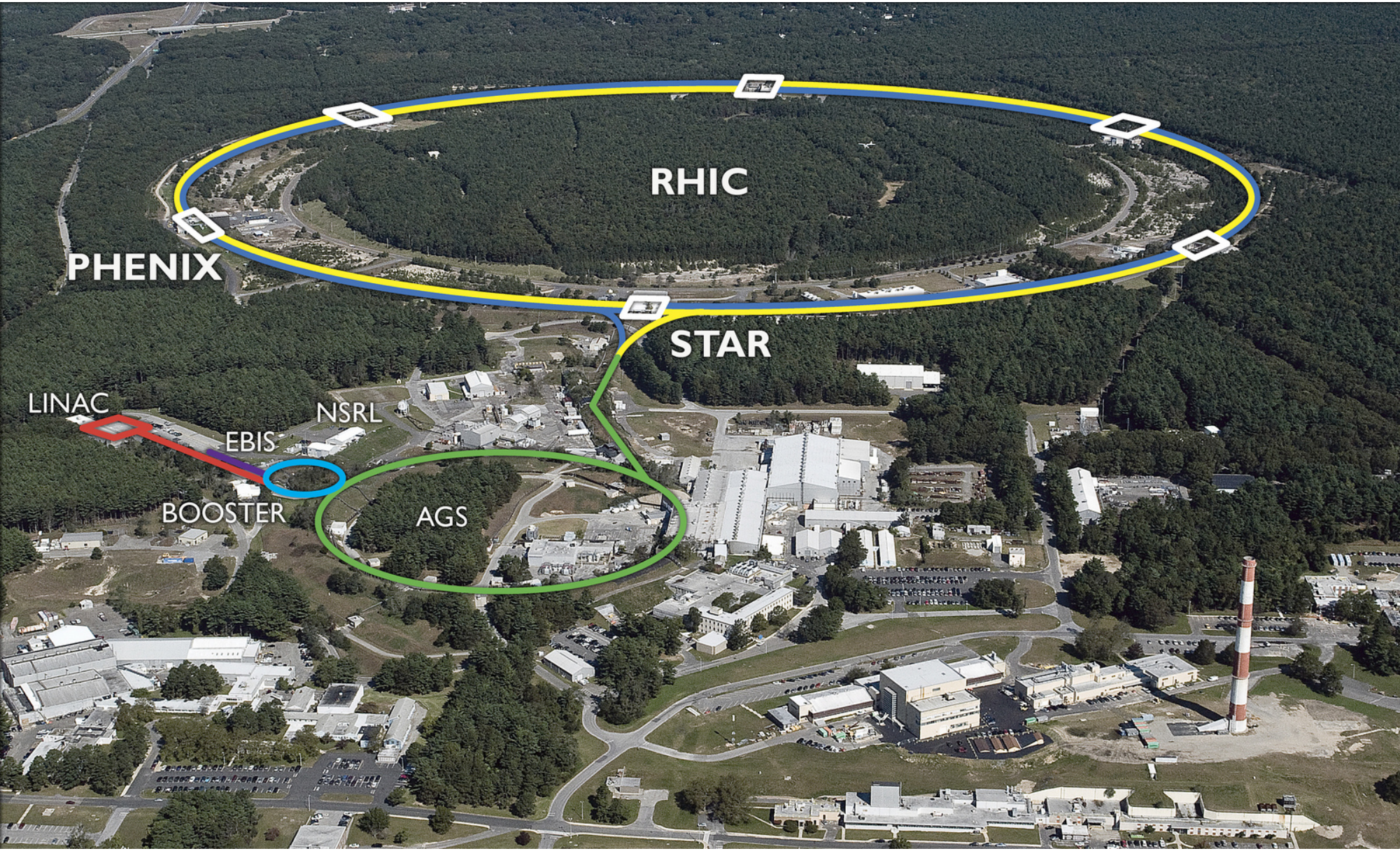
Other Fun Stuff

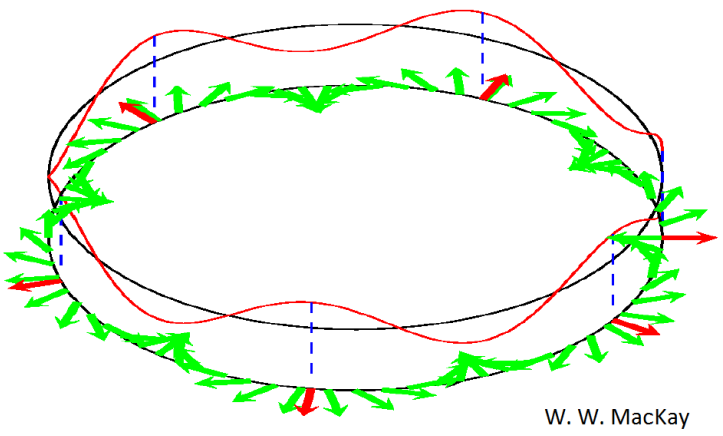
Who you gonna call?!

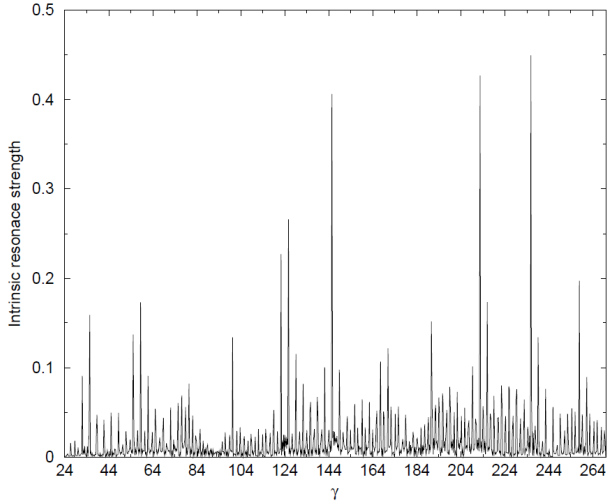



RHIC
PHENIX
STAR
LINAC
NSRL
EBIS
BOOSTER
AGS

Maintaining Polarization in a Circular Collider

- Spinor precesses as bent in B field
- Depolarizing resonances
  - Spin precession frequency = frequency of perturbing B field
  - Imperfection: $\nu_s = G\gamma = n$
  - Intrinsic: $\nu_s = G\gamma = Pn + \nu_y$
  - Anomalous g-factor G
  - Resonances for p in RHIC[9]$\rightarrow$
- Siberian Snakes to the rescue
  - Rotate spin 180°, allow the wobble to unkink itself
  - Partial snakes can be used for some imperfections





[9] Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.

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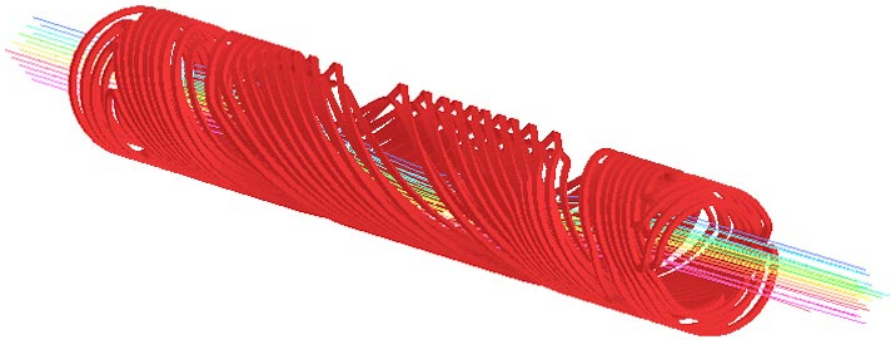

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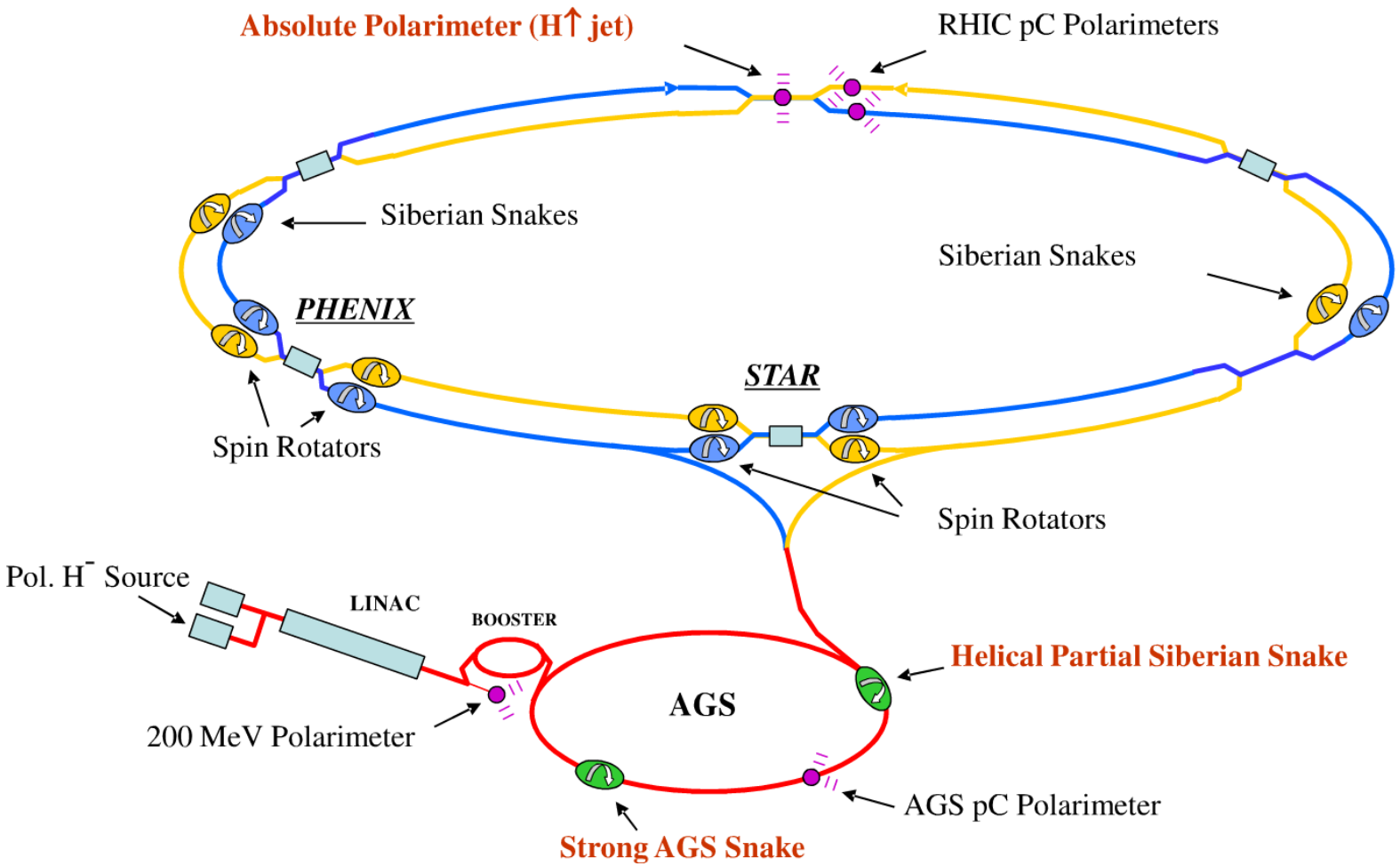
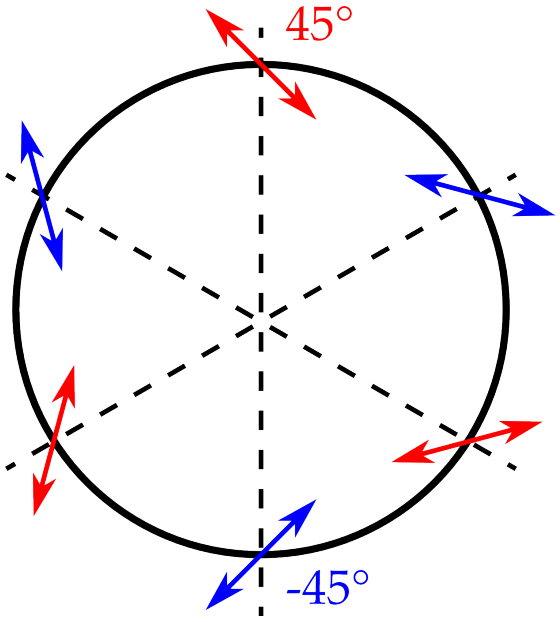
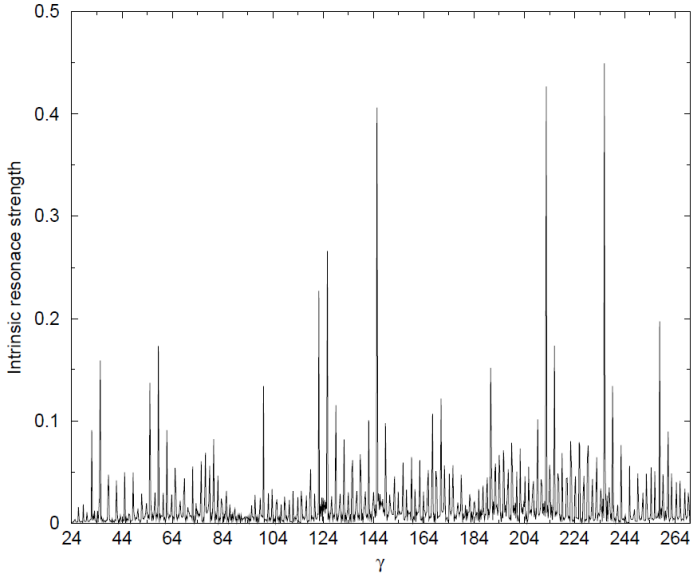
RHIC Spin Manipulation



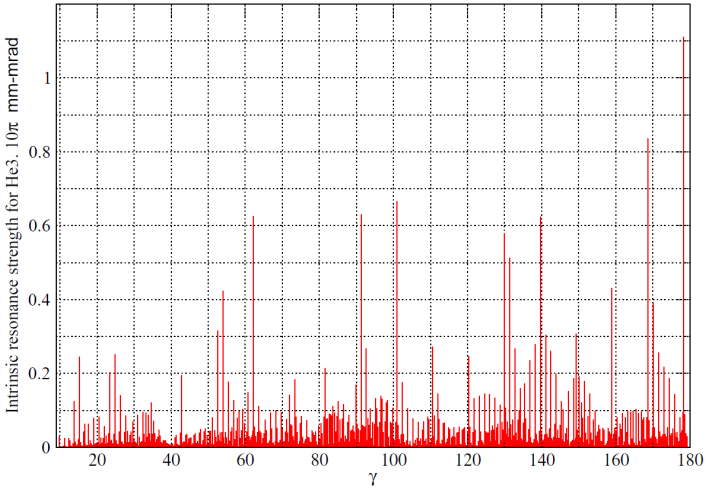
Polarized ^{3}He at RHIC

- ^{3}He's anomalous g-factor is larger than p: more & stronger resonances
- Need 6 siberian snakes per ring[10]





p resonances



^{3}He resonances

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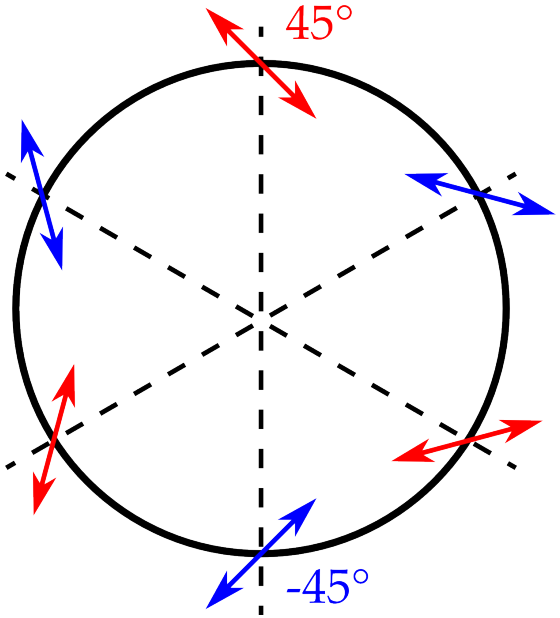
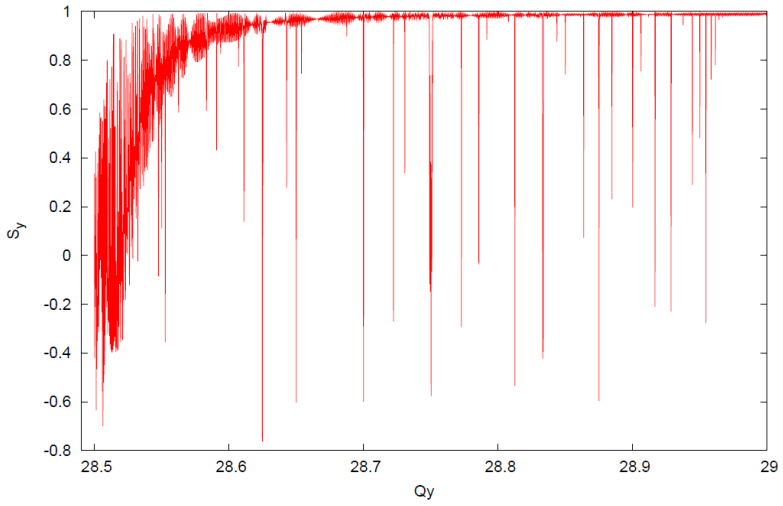
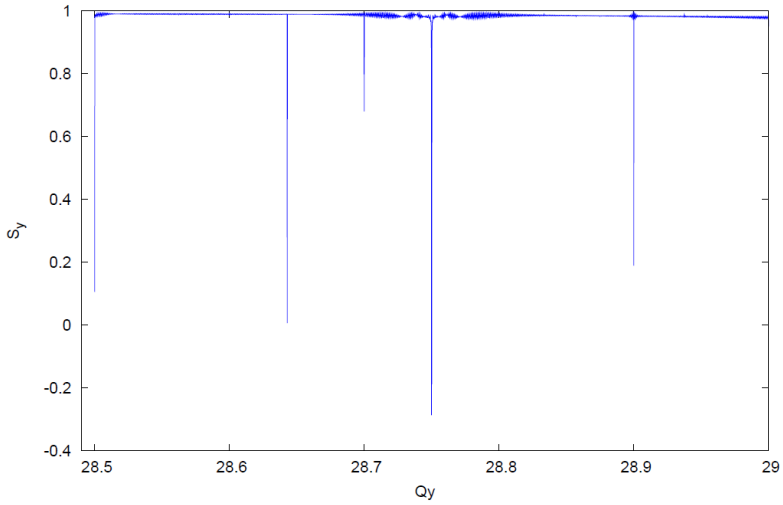




2 snakes



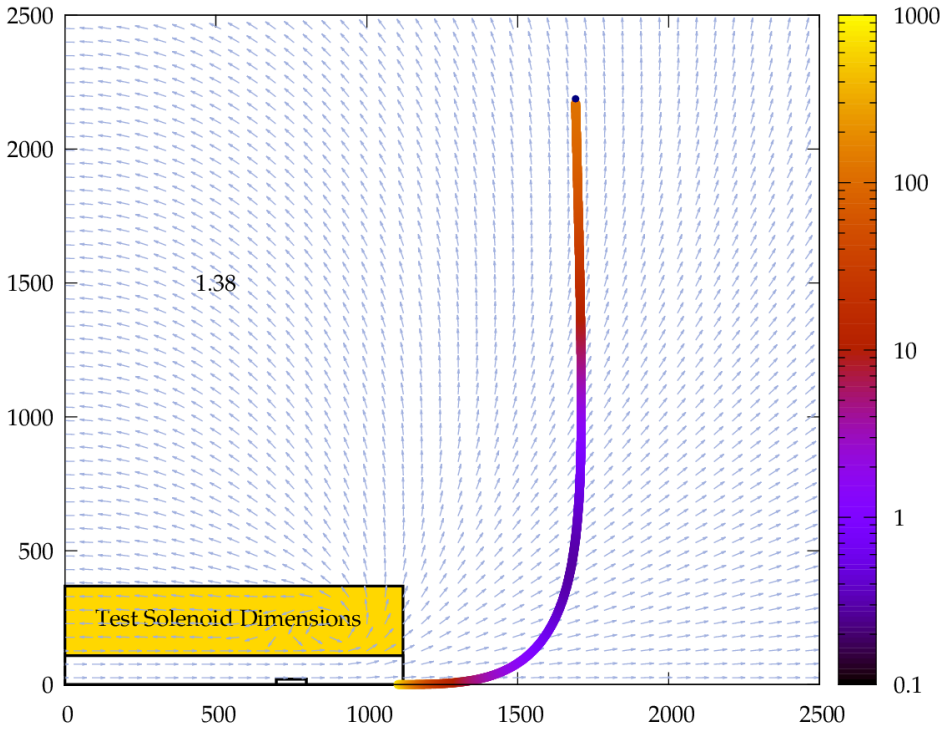
6 snakes

[10] Bai, Courant *et al.*, BNL-96726-2012-CP, 2012.

Transfer Path Relaxation Studies

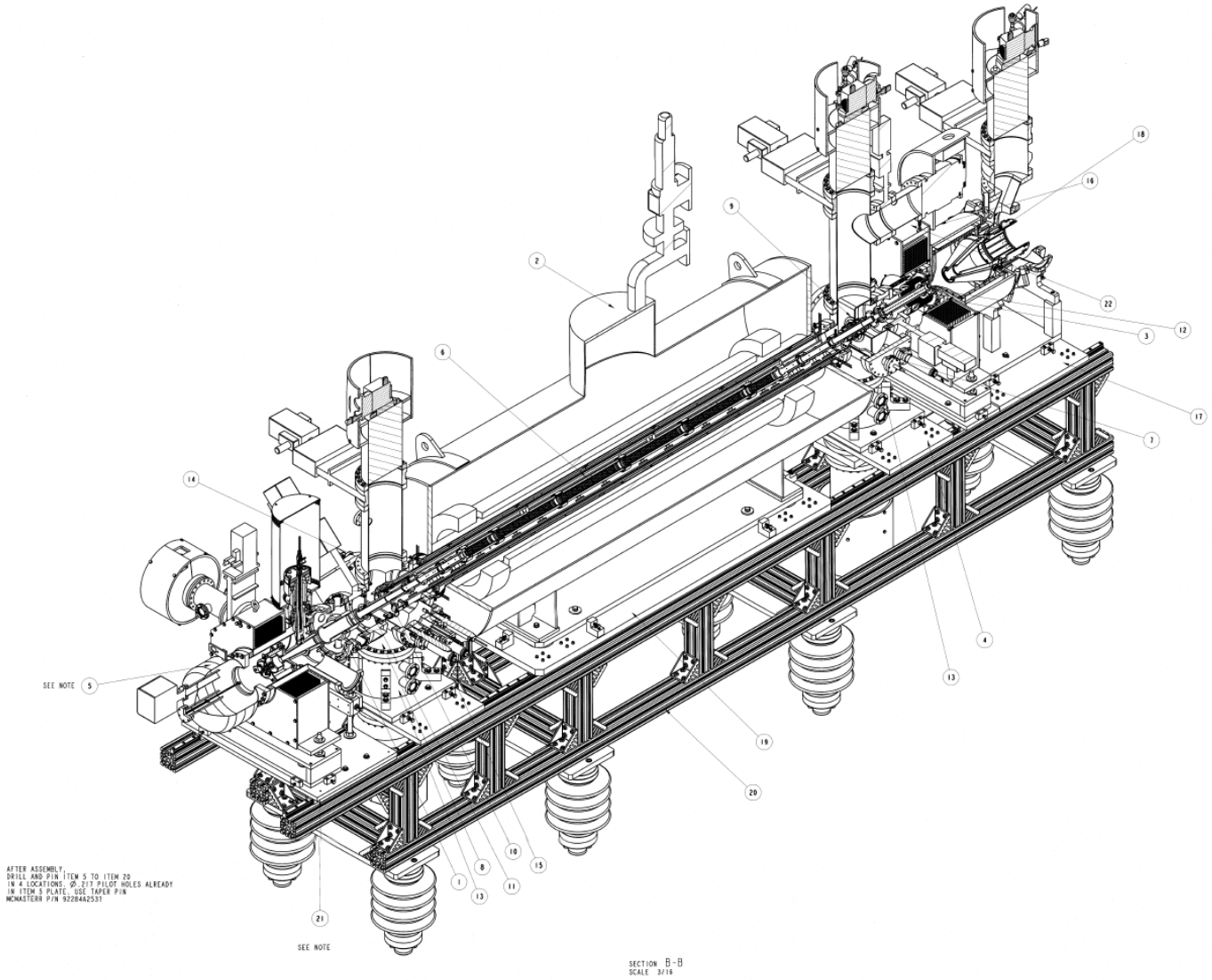
- Investigating possible paths into EBIS with solenoid field map, calculating relaxation time at each point

- Algorithm compromises between relaxation time and transfer length to pick next step in path
- Average inverse relaxation times to qualify path
- Two transfer lines to be made for upcoming test
  - "Best" case, avoiding depolarization
  - Real case, following EBIS feed-throughs



(Color scale in seconds)

Constraints on Path into EBIS



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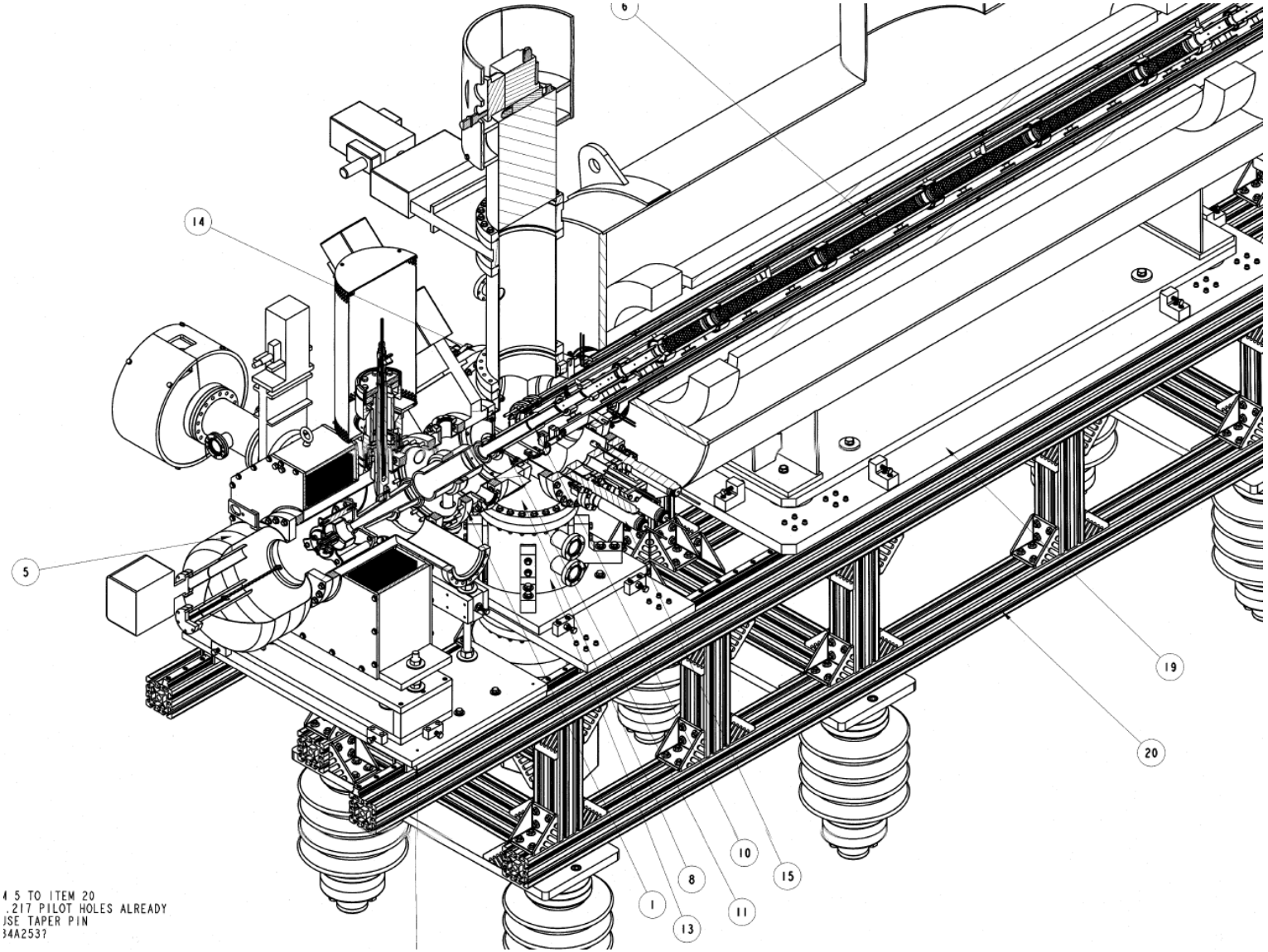

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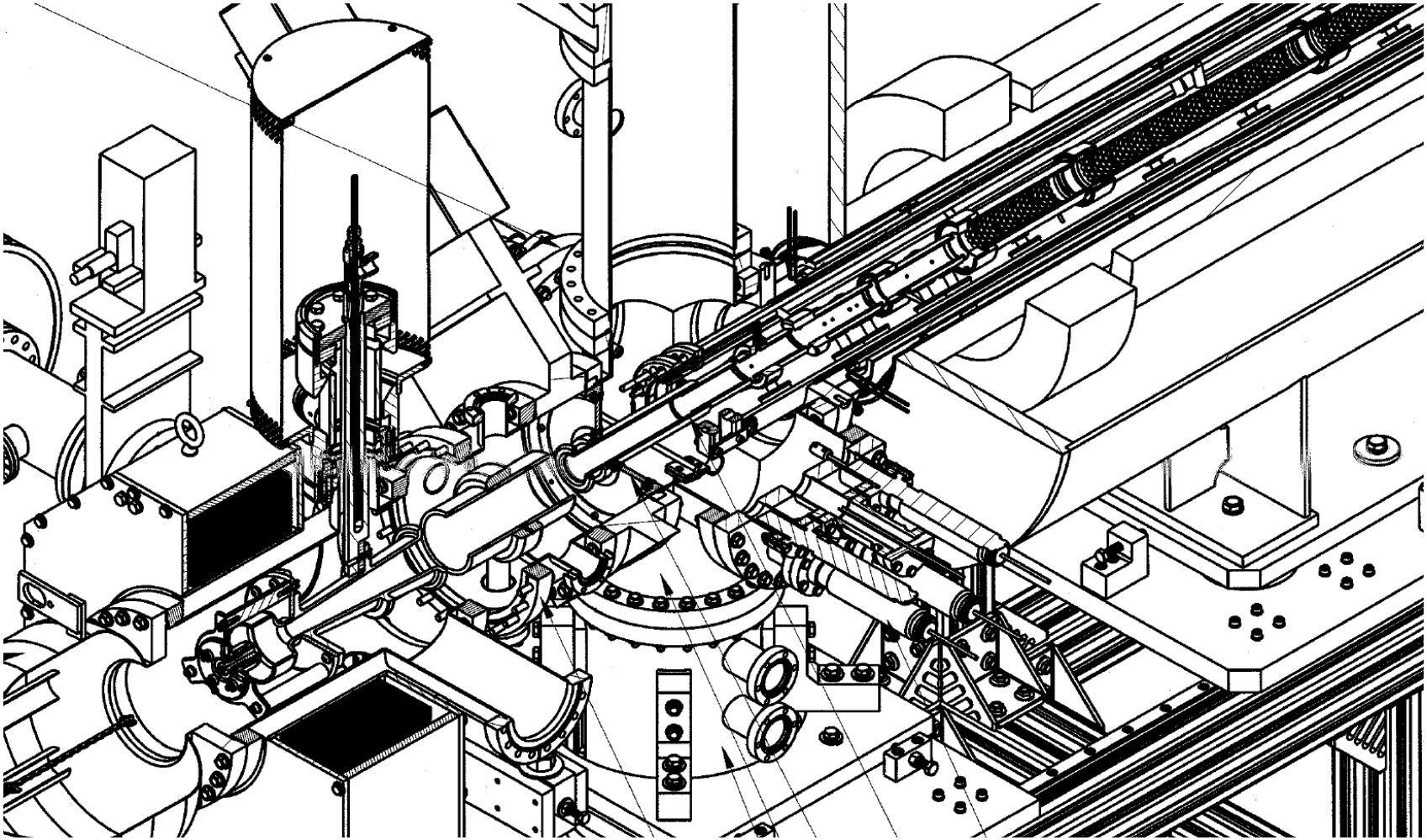
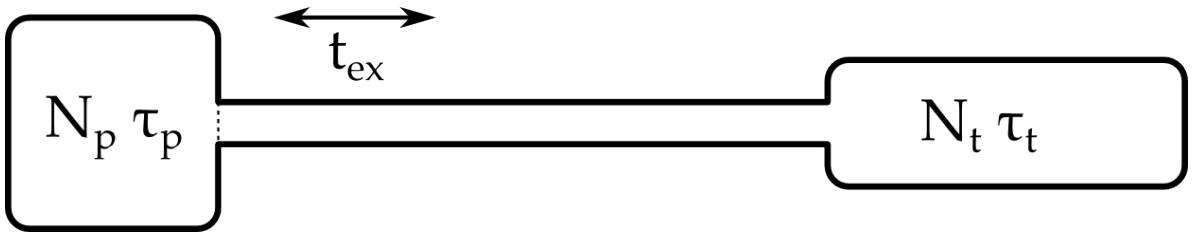


Test of Polarization Diffusion Measurement

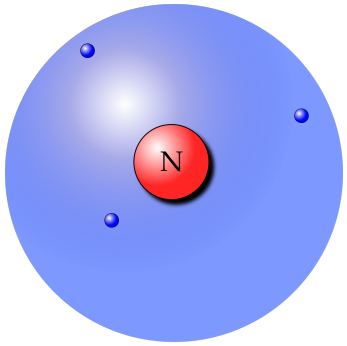


$$\begin{pmatrix} \dot{P}_p(t) \\ \dot{P}_t(t) \end{pmatrix} = \begin{pmatrix} -\left(\frac{1}{\tau_p} + \frac{N_t}{N}\frac{1}{t_{\mathrm{ex}}}\right) & \frac{N_t}{N}\frac{1}{t_{\mathrm{ex}}} \\ \frac{N_p}{N}\frac{1}{t_{\mathrm{ex}}} & -\left(\frac{1}{\tau_t} + \frac{N_p}{N}\frac{1}{t_{\mathrm{ex}}}\right) \end{pmatrix} \begin{pmatrix} P_p(t) \\ P_t(t) \end{pmatrix}$$

- 5 variables describe system (initial pols, decays, transfer)
- Solution is sum of two exponentials
- Relate to 4 fit parameters of measured relaxation curve

$$P_p(t) = a_s e^{-t/\tau_s} + a_l e^{-t/\tau_l}$$

The Makeup of Matter



- Atoms consist of electrons around a nucleus
- Nuclei consist of protons and neutrons
- Nucleons consist of 3 quarks
  - Quarks get their mass from the Higgs Mechanism
  - Mass of u quark $\sim$ 2 MeV, d quark $\sim$ 5 MeV
  - Mass of proton (uud) is 938 MeV. Wait, what?

- In QCD, the nucleon is made of 3 valance quarks, a sea of virtual quark–anti-quark pairs, all bound by gluons
- Nearly all the mass is generated by flurry of activity from quarks and gluons jiggling at near c, and q-$\bar{q}$ pairs springing into and out of existence

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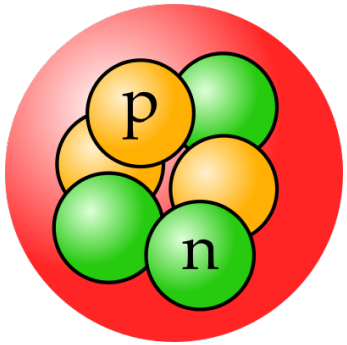

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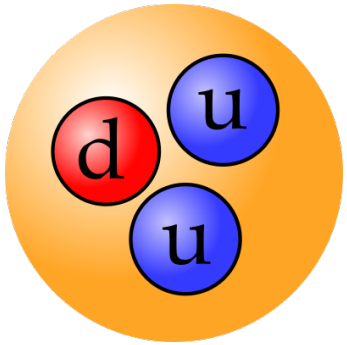

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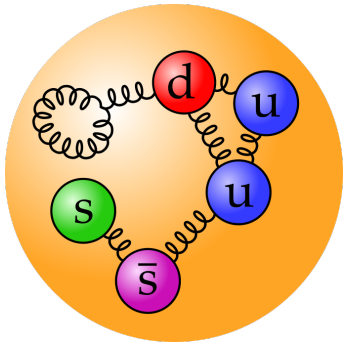

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Understanding the Strong Force

Electromagnetic Force (QED)

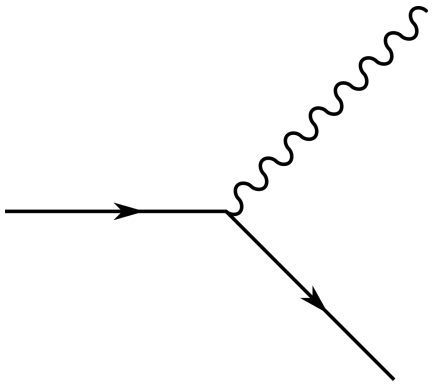
Particles of charge $(+-)$ interact via mediating photons, which are neutral

- 1 vertex for radiation/absorption

Strong Force (QCD)

Particles of color charge (RGB) interact via mediating gluons, which carry color charge

- Vertex for gluon radiation
- 2 vertices for gluon self-coupling



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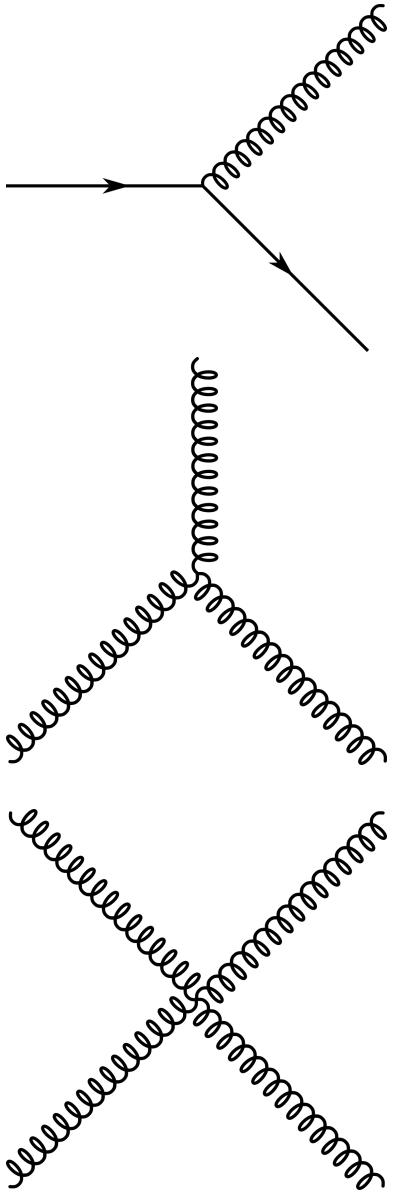

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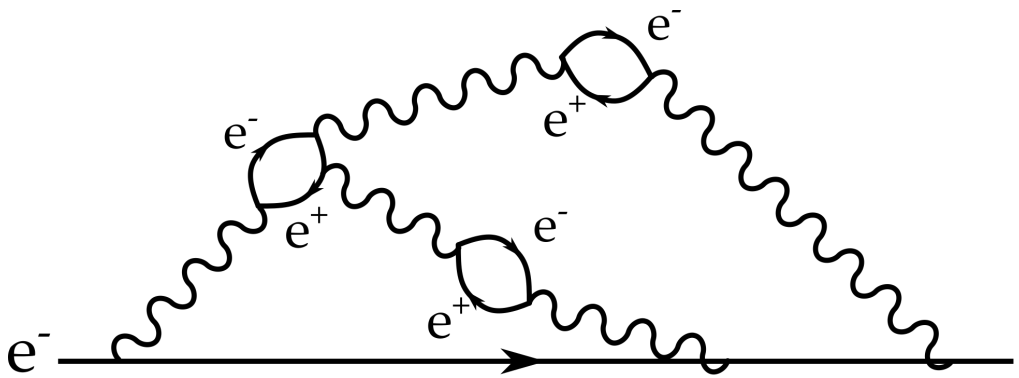

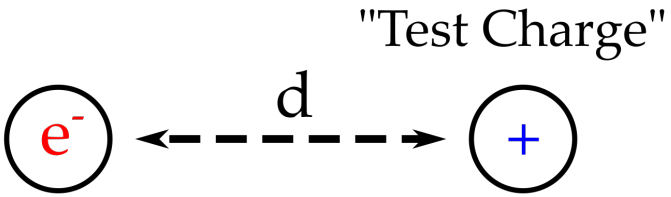

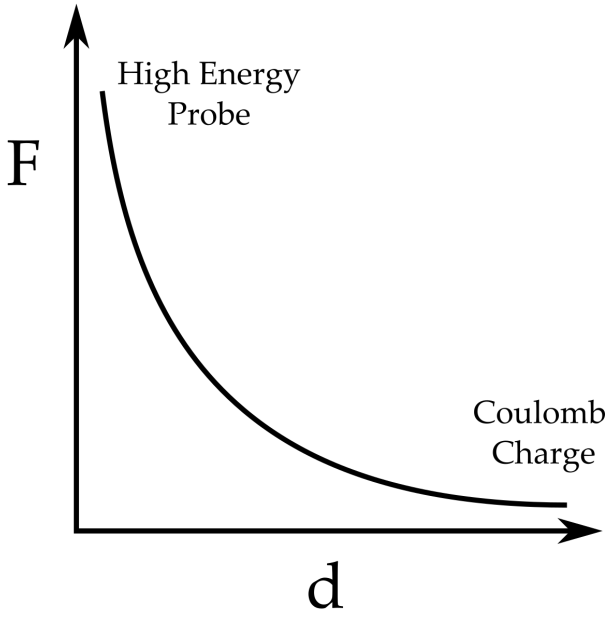

In electrodynamics, a bare negative charge begets particles and anti-particles which serve to "screen" the bare charge at a distance. A high energy probe with a very short distance scale penetrates the cloud, seeing larger electronic charge.

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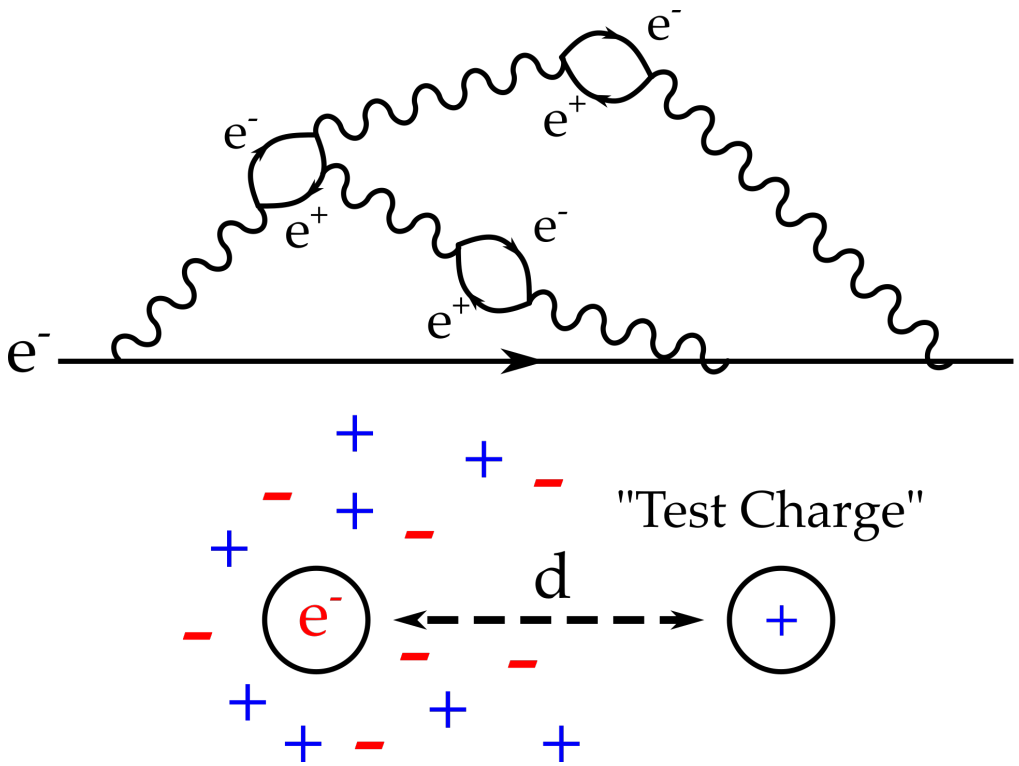

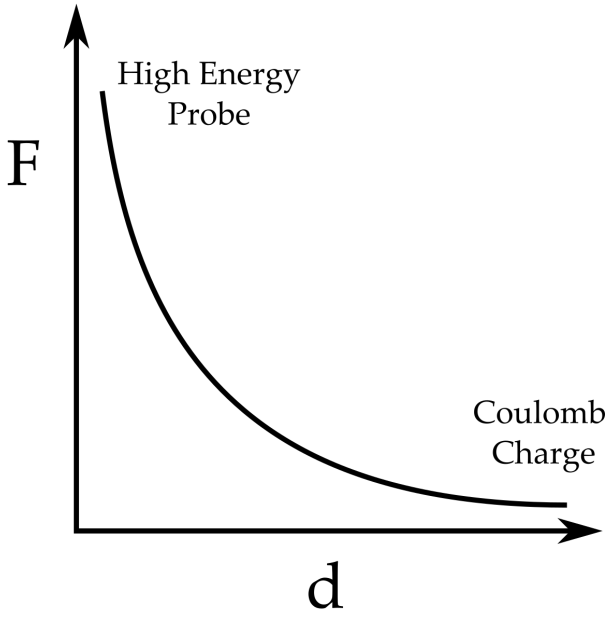

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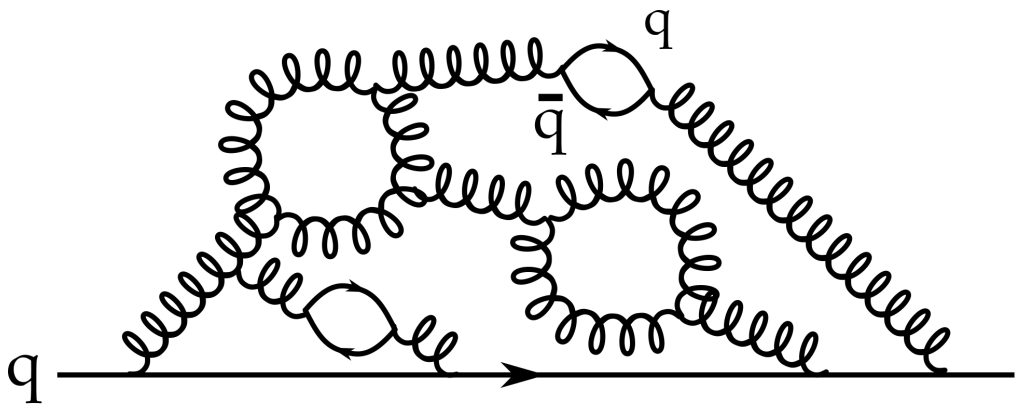
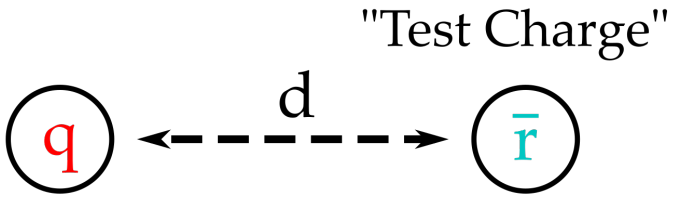
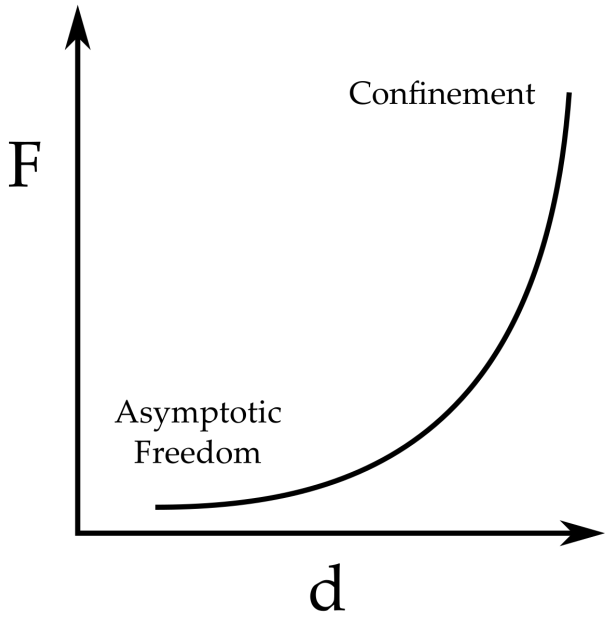
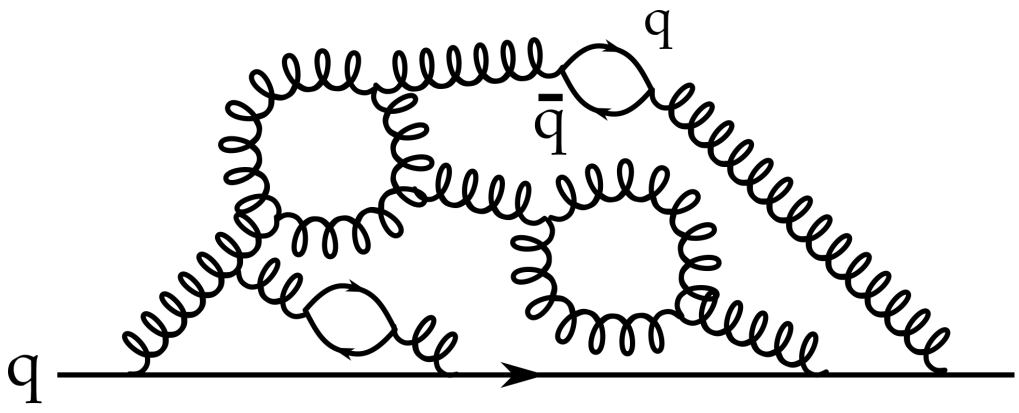


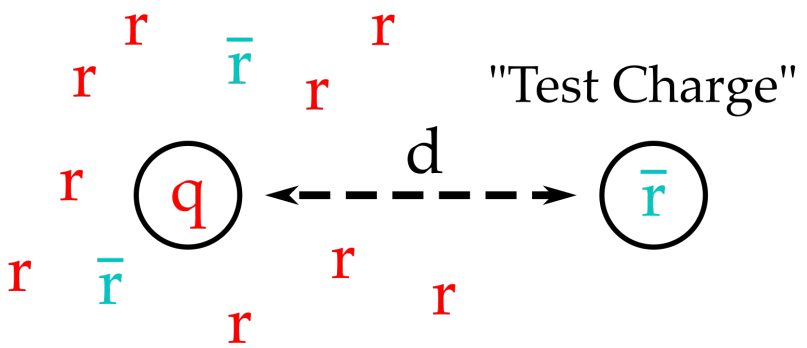


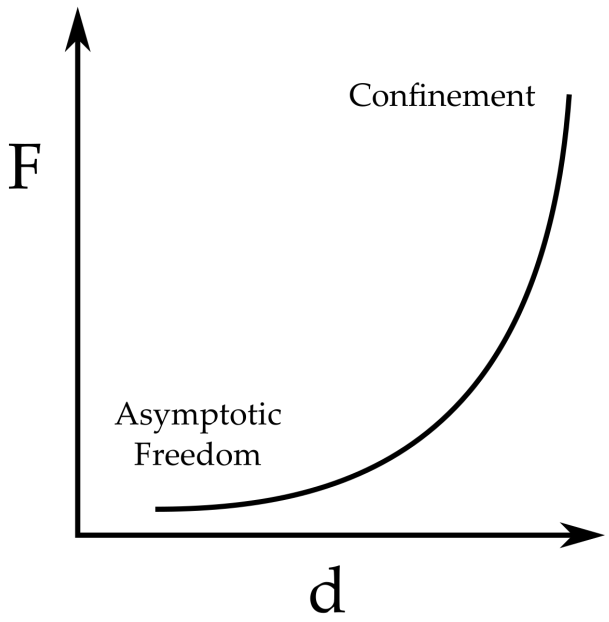


In chromodynamics, a bare red charge begets more red charge, serving to "anti-screen" at a distance, leading to "confinement". A high energy probe with a short distance scale sees smaller charge, "asymptotic freedom."

Understanding the Strong Force







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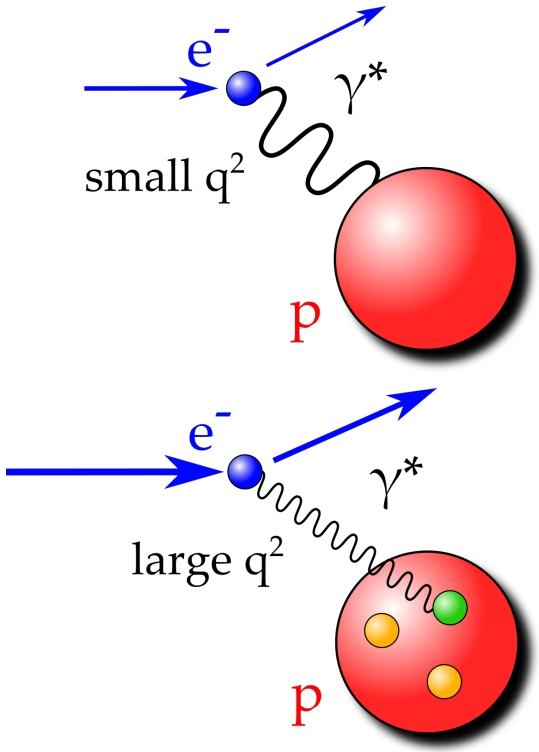
Scattering Probes of Nuclear Structure

- We need a "microscope" to see inside the nucleus
  - But, you can't see something if it's smaller than the wavelength of light you are using
  - Need "light" with very small wavelength

- An electron scatters off a proton via a photon
  - An electron beam can provide a beam of "virtual photons"
  - The more 4-momentum exchanged (Q^2), the smaller the virtual photon, the higher resolution you can achieve



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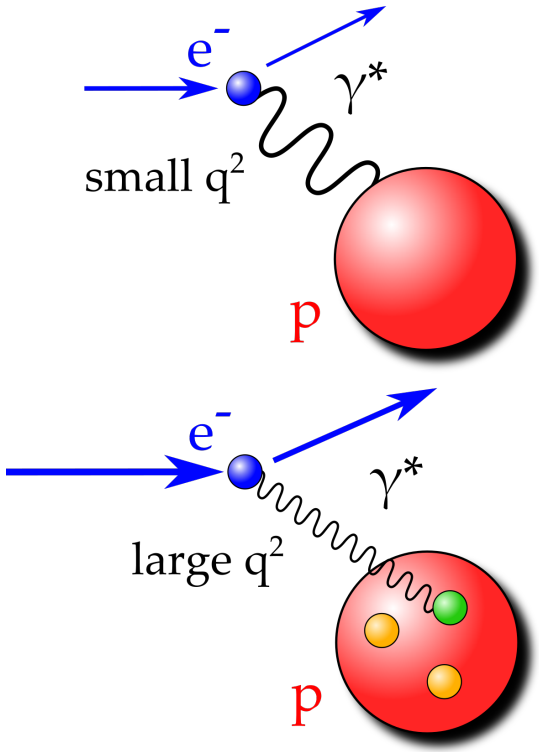

Pushing the Frontier

- Once we have enough momentum transfer to see quarks, what's next?
  - Kinematics determine what we are probing
    $Q^2 = 4EE' \sin^2(\theta/2), \qquad x = Q^2/(2M(E - E'))$
  - Bjorken x is "momentum fraction" of struck quark
- At high x, we see a quark with "asymptotic freedom"
- At low x, we see a quark bound by a mess of gluons
- The next Nuclear Physics machine will reach the extreme low x region
  - Move from a fixed nuclear target and electron probe beam (SLAC, JLab) to a nuclear beam colliding with a electron beam

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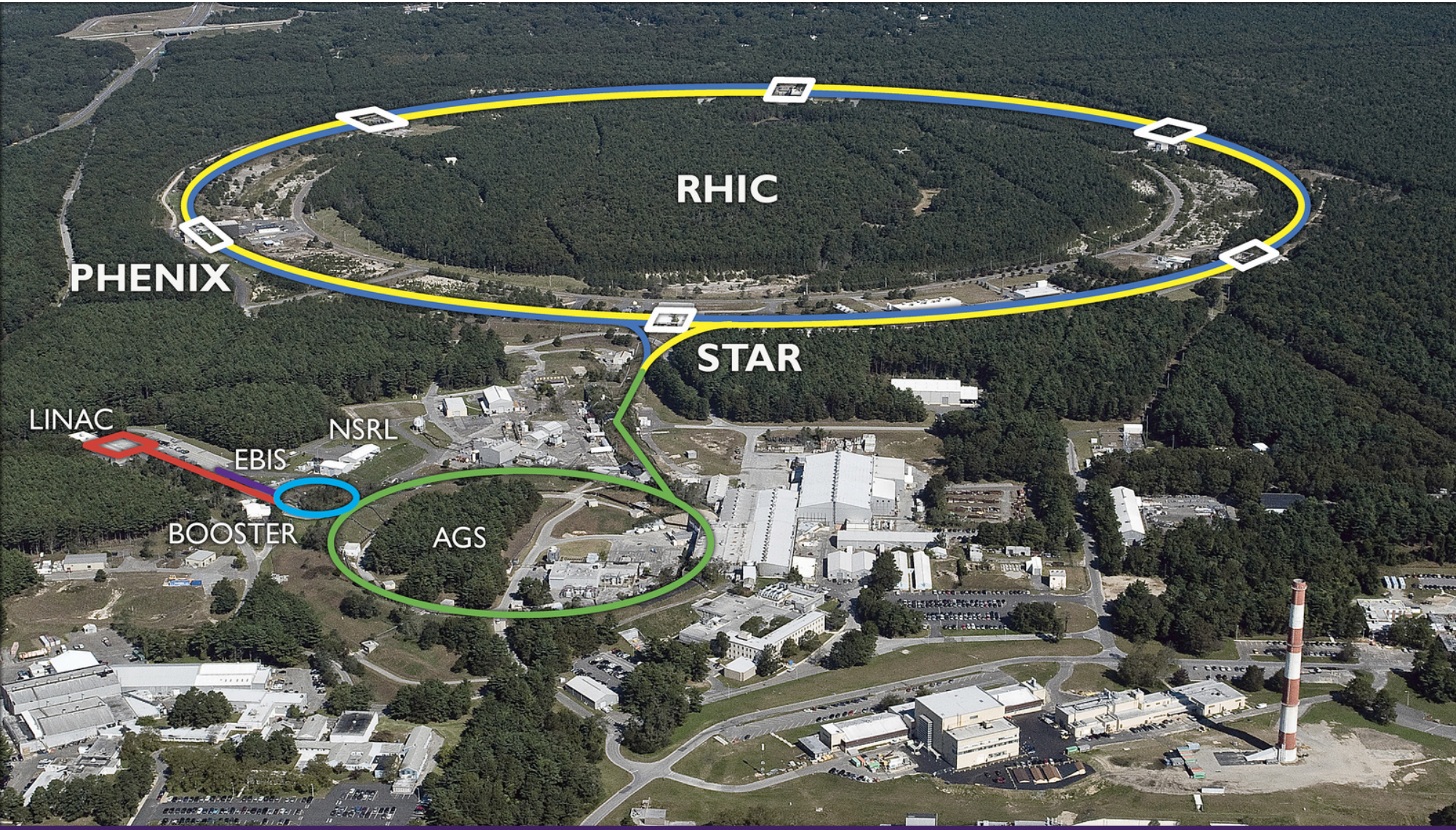

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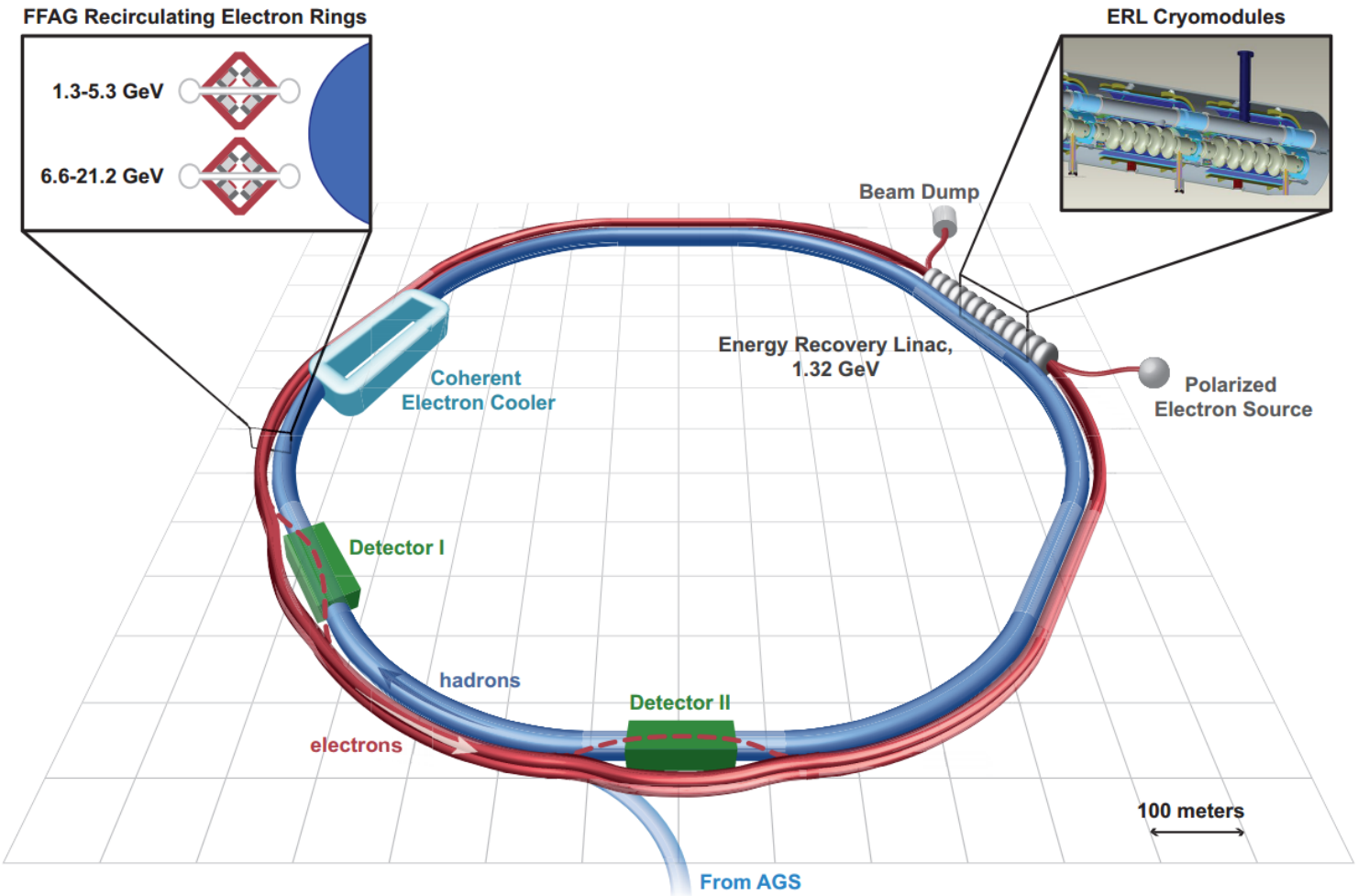
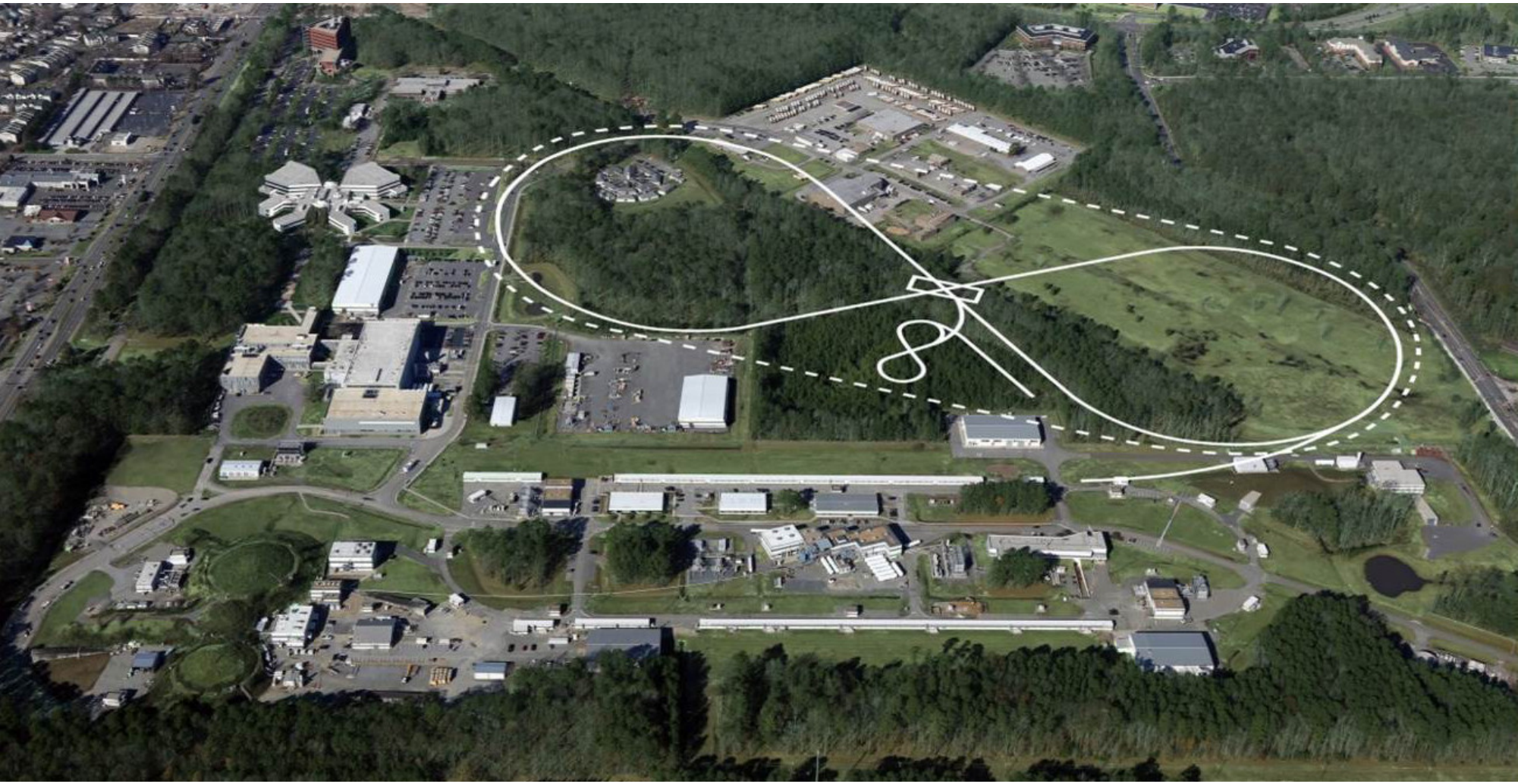


16 GeV polarized electrons and 250 GeV polarized protons

Electron Ion Collider (JLab EIC)



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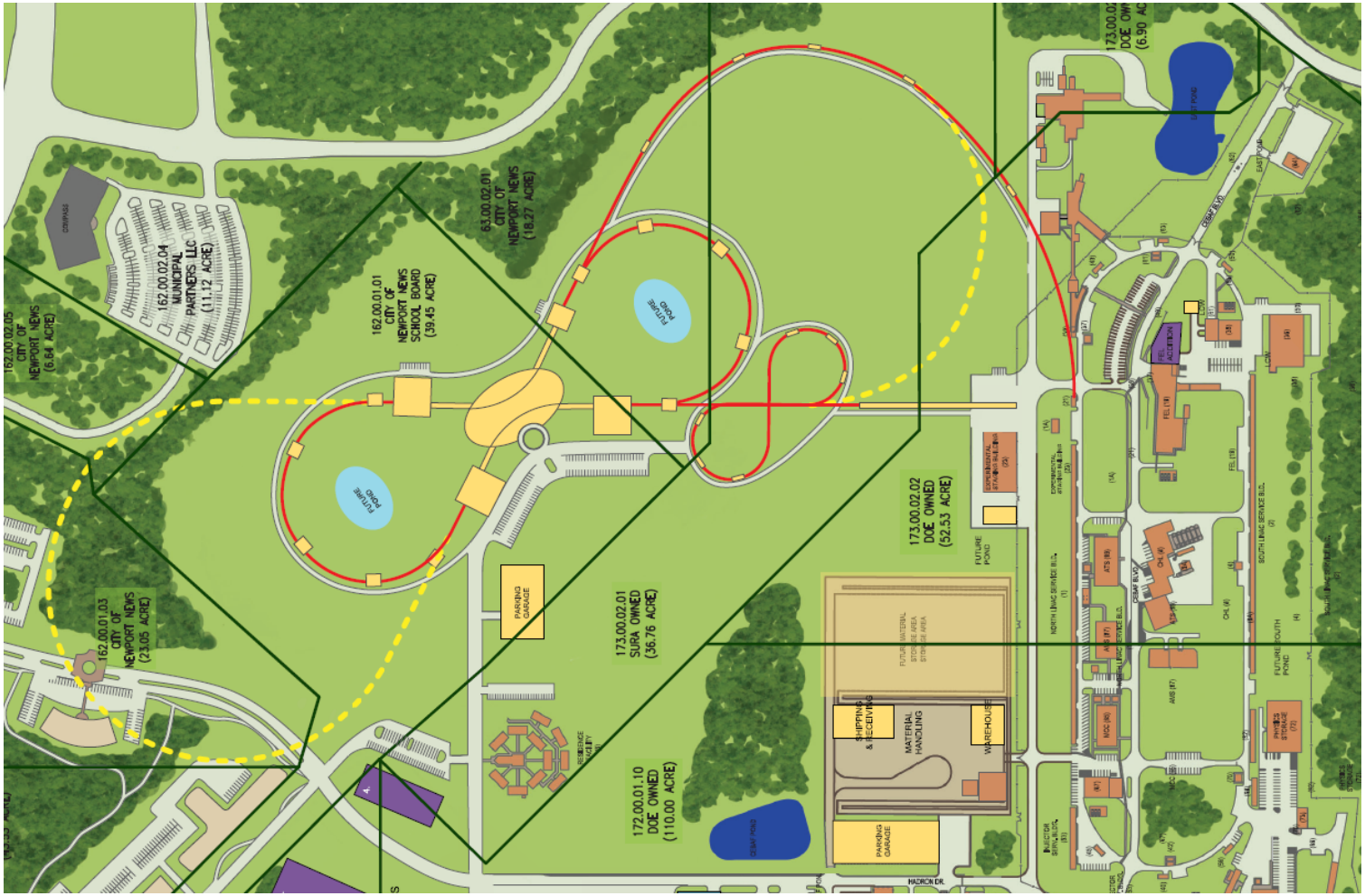

10-20 GeV polarized electrons and 100-250 GeV polarized protons

Thoughts on Probe Measurement Error

- Intense probe can cause over-estimation of polarization
  - Talbot: as much as 5% at M=0% and 1% at M=10%

$$M(r/r_0) = \frac{r/r_0 - 1}{r/r_0 + 1}, \quad \sigma_M(r/r_0) = \frac{2\sigma_{r/r_0}}{1 + (r/r_0)^2}$$