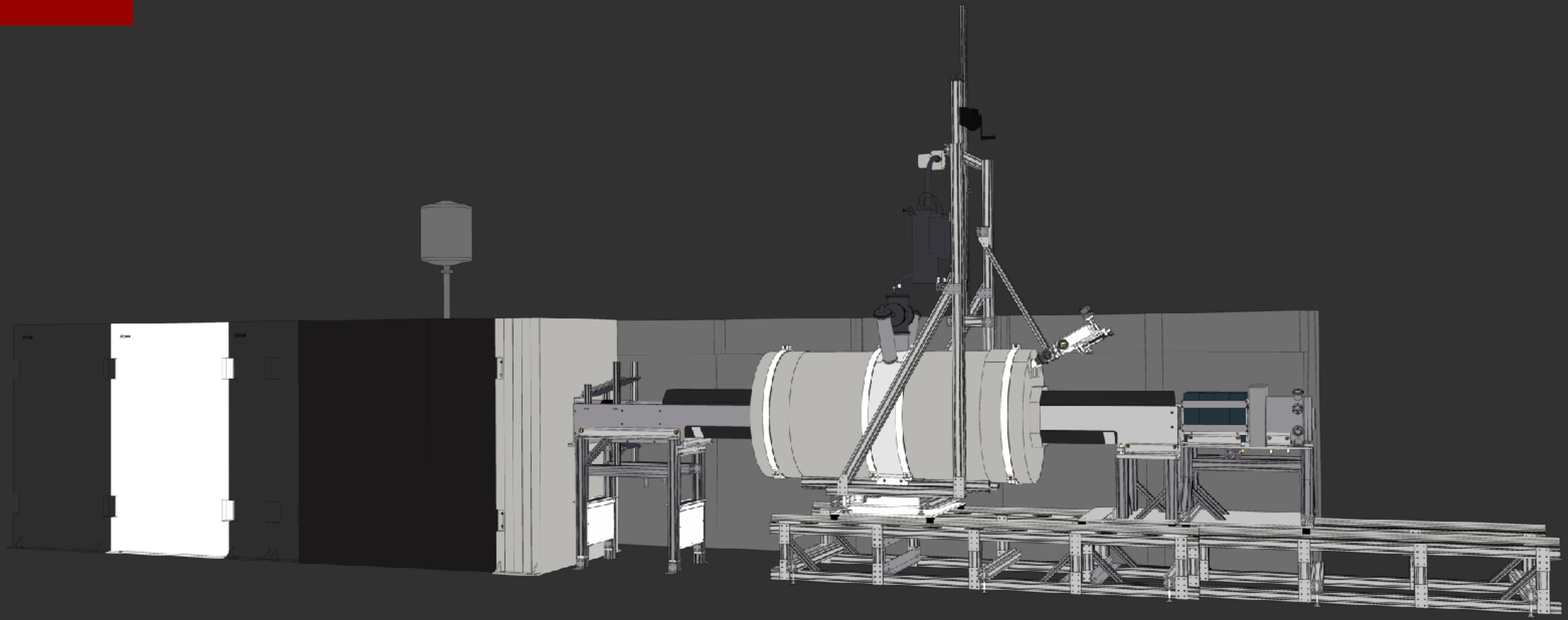
Neutron Optical Polarimetry as a Probe of Fundamental Physics

Kyle Steffen $\in$ {Neutron Spin Rotation Collaboration}



PSTP — September 27, 2019 — Knoxville, TN

Overview

The NSR collaboration operates a “crossed polarizer/analyzer“ neutron polarimeter dedicated to the study of fundamental interactions between polarized neutrons and matter. This apparatus has contributed constraints in various regimes of the SM, GR, and BTSM.

The NSR polarimeter is currently being prepared for installation on the NG-C beam line at the NIST Center for Neutron Research.

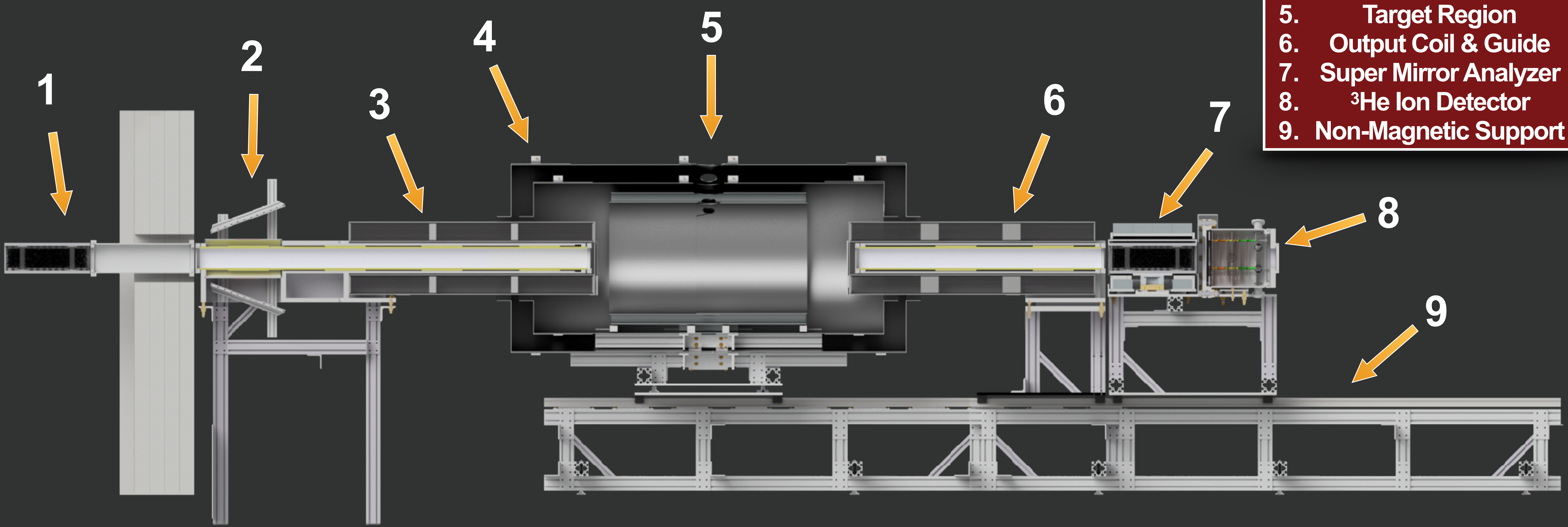
There, it is expected to:

1) reach standard model precision in measuring the NN weak interaction ["n-^{4}He"] and
2) significantly improve constraints on exotic spin-dependent interactions [“F5"]

The NSR Polarimeter

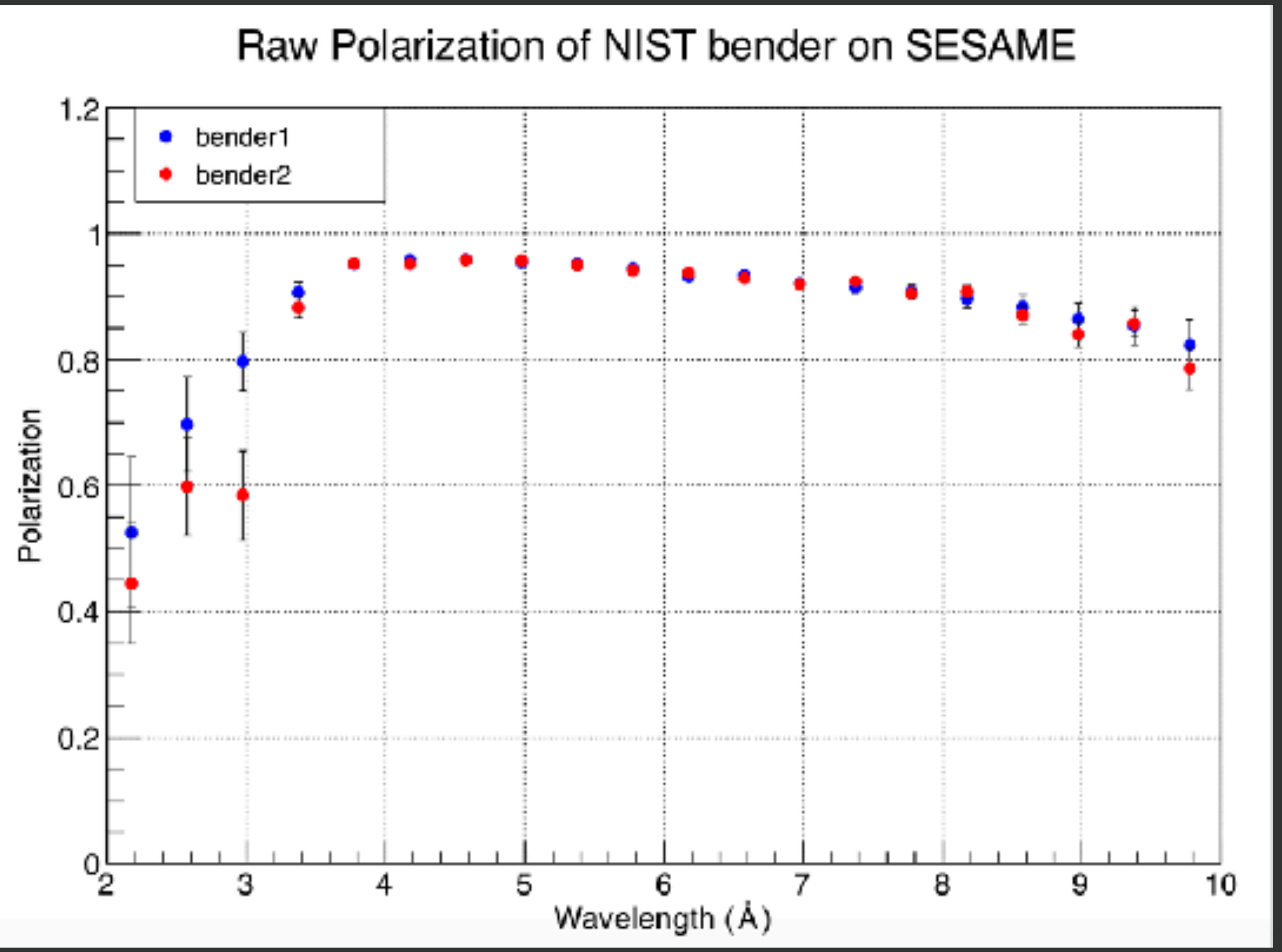
Overall Polarimeter Layout

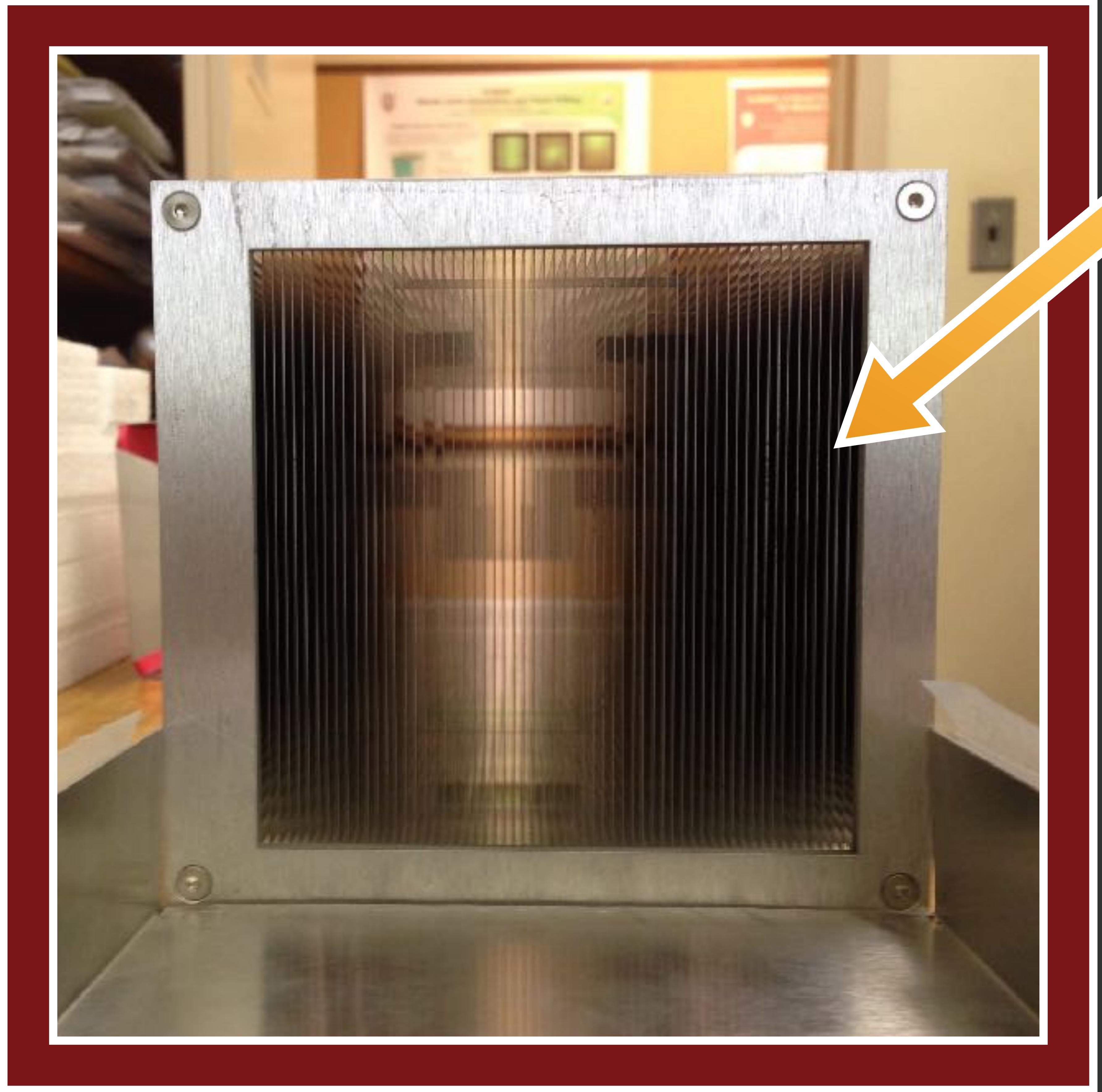
1. Super Mirror Polarizer
2. RF Spin Flipper
3. Input Coil & Guide
4. Mu-metal Shielding
5. Target Region
6. Output Coil & Guide
7. Super Mirror Analyzer
8. ^{3}He Ion Detector
9. Non-Magnetic Support



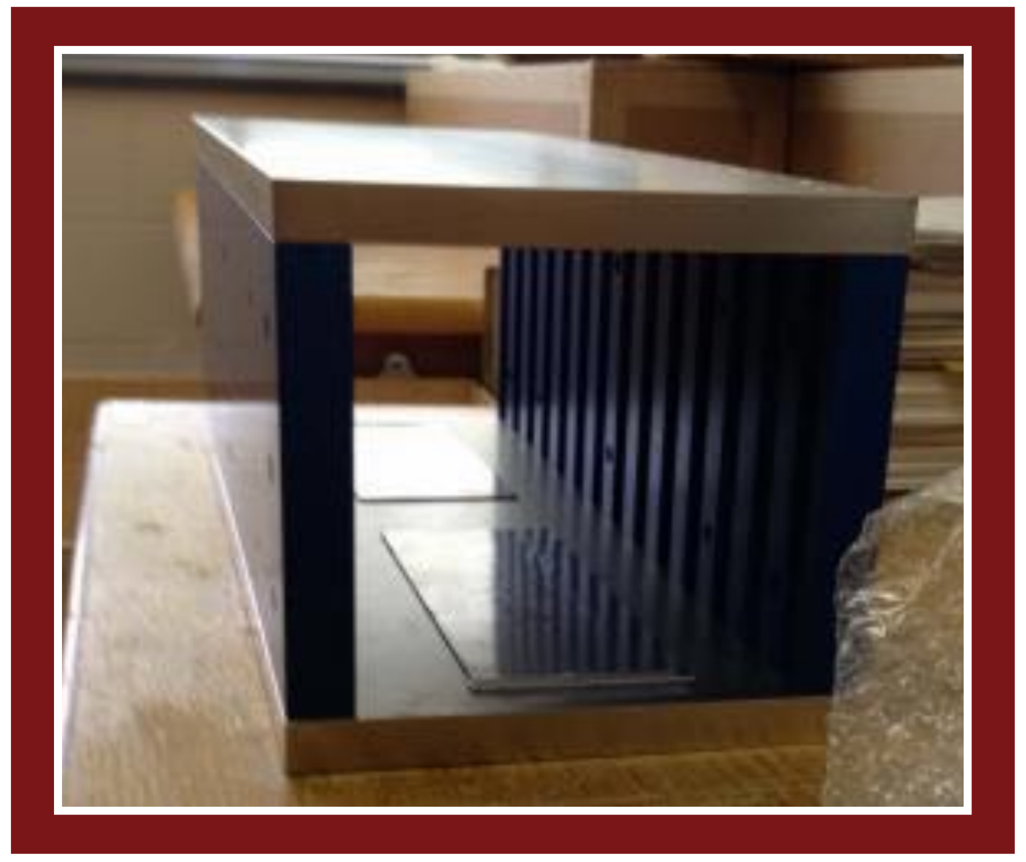
Polarizer and Analyzer

Matched Pair of m=2.5 SwissNeutronics Polarizing Benders Courtesy of NIST





61 Polished Glass Vanes with super mirror Fe/Si coating



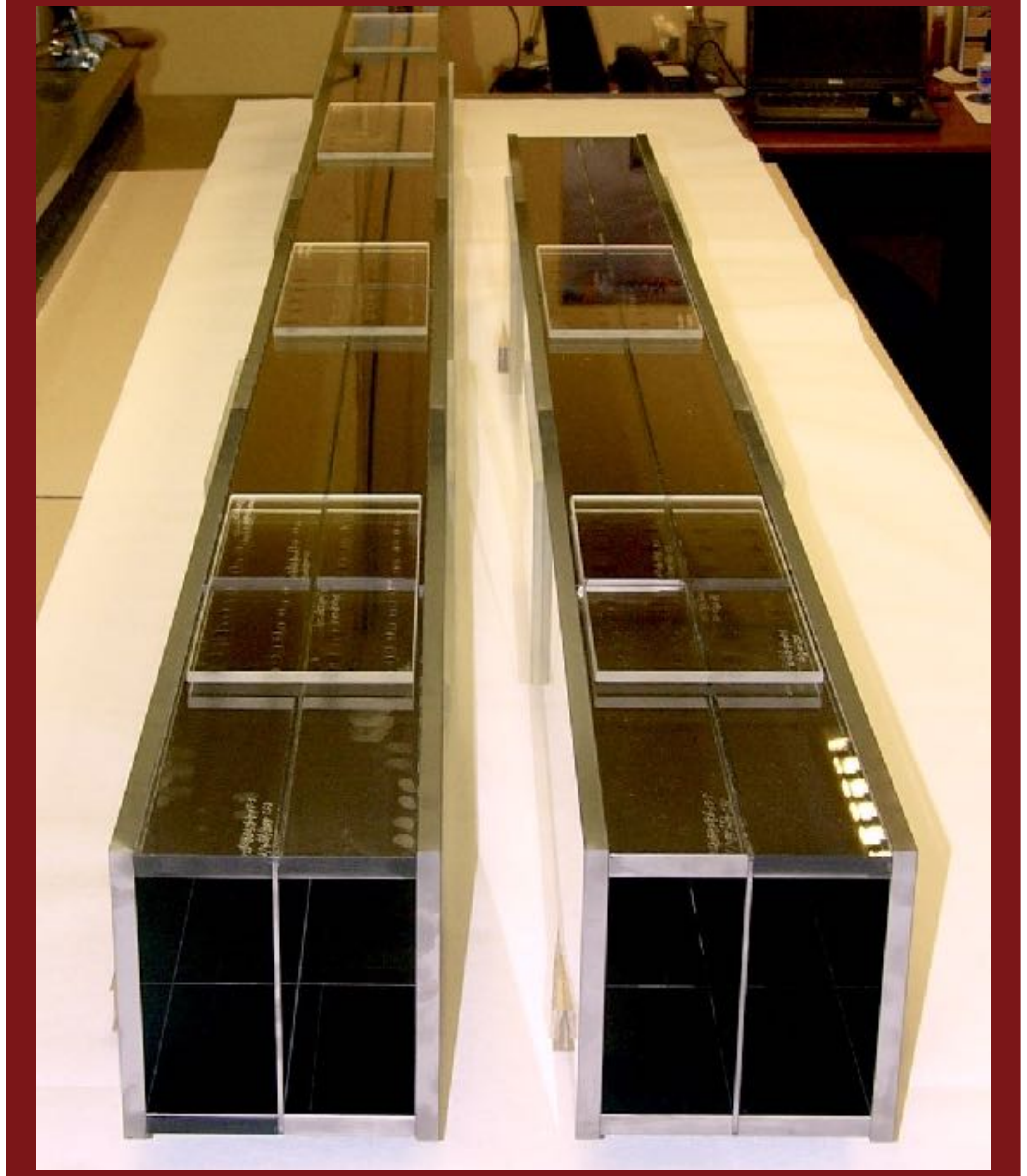
Magnetized housing with 500G internal field

Neutron Guides

m=2 guides Mirrotron super mirror guides courtesy of BARC

Bifurcated for parallel beam geometry — crucial to spin rotation for signal & systematics

Nickel-Molybdenum/Titanium super mirror coating on all interior surfaces

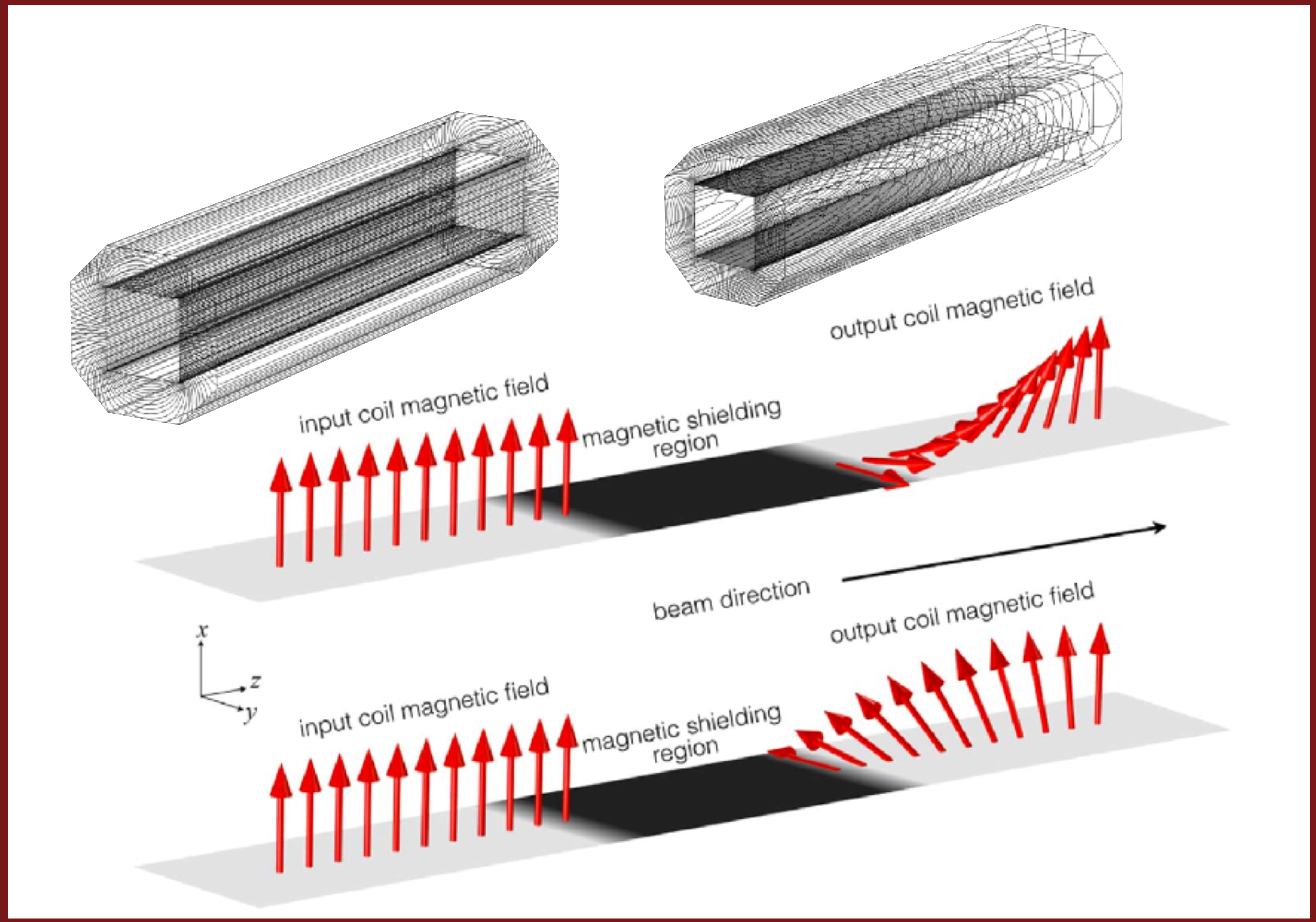


Input and Output Coils

Designed and manufactured by colleagues at UNAM

Adiabatic spin transport of neutrons from polarizer to target — target to analyzer

Endcaps for non-adiabatic transport into and from target region with low leakage fields

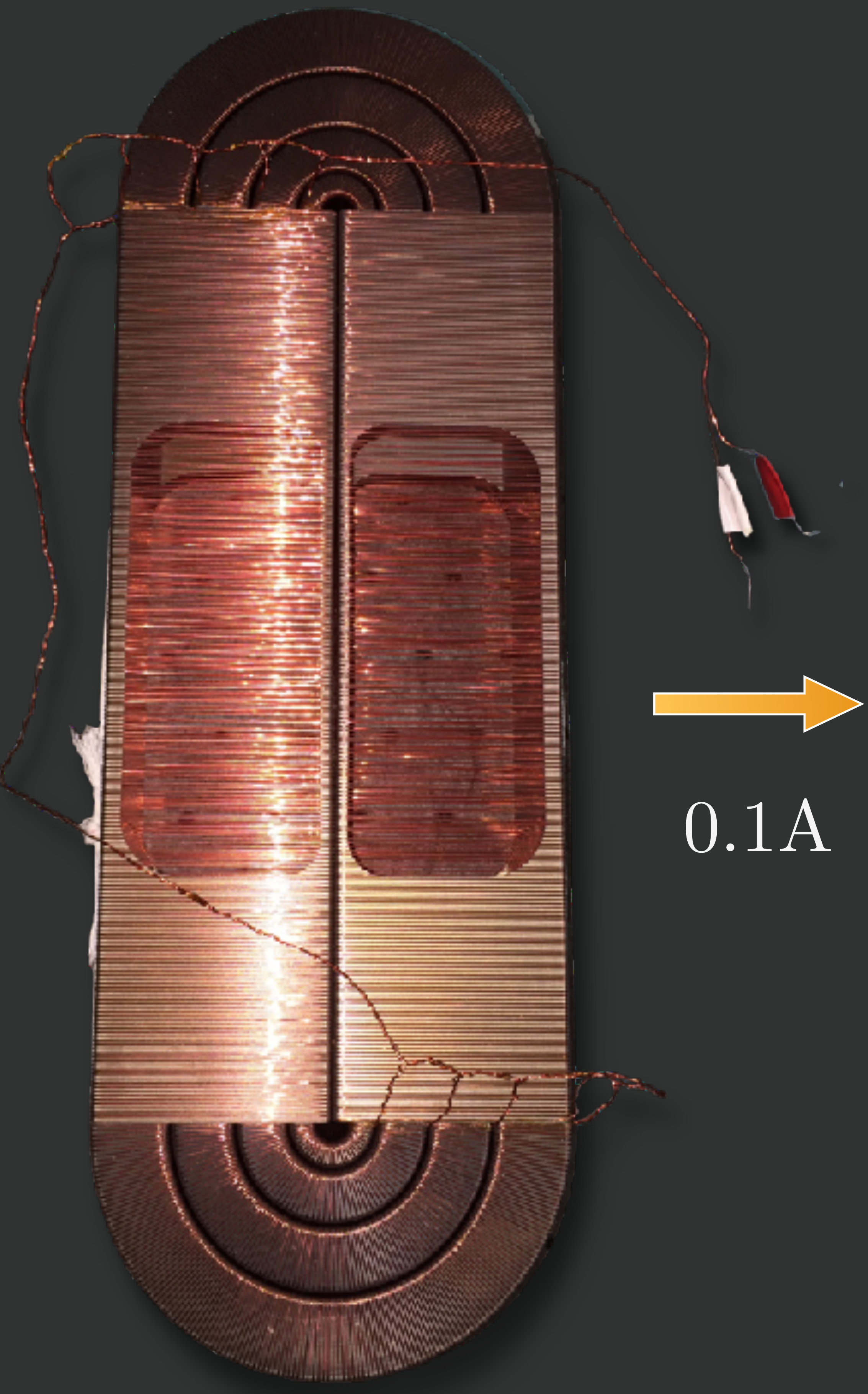


M. Maldonado-Velázquez, et al, Nucl. Inst. Met. Phys. Res., Sect. A 854 (2017) 127–133.

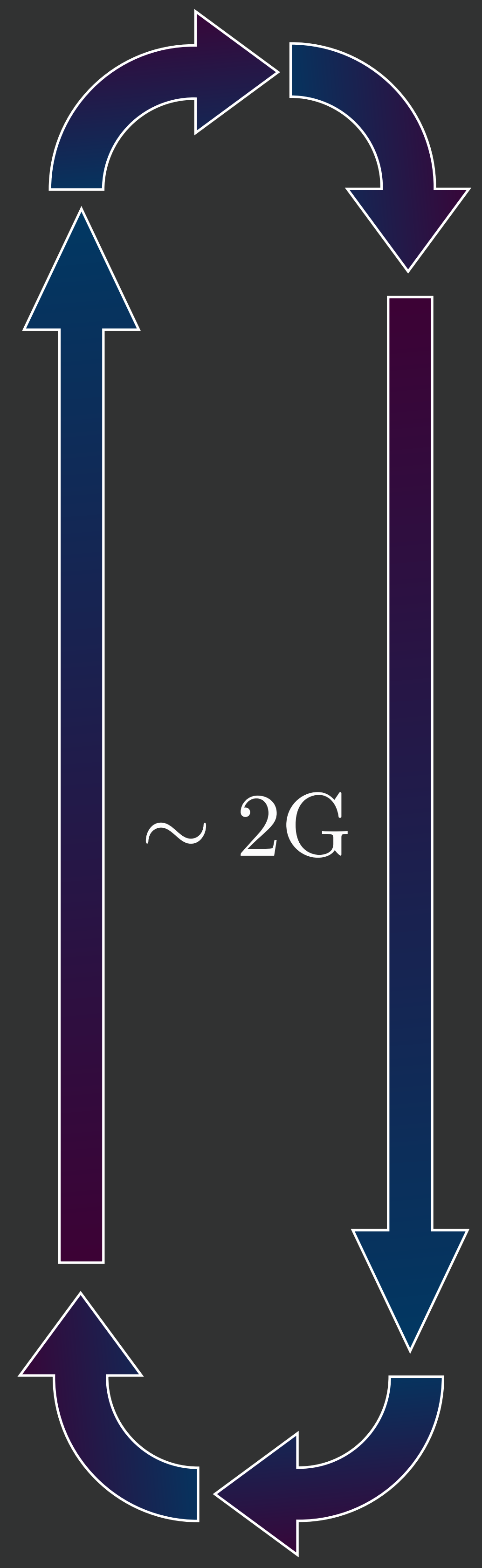
Pi Coil

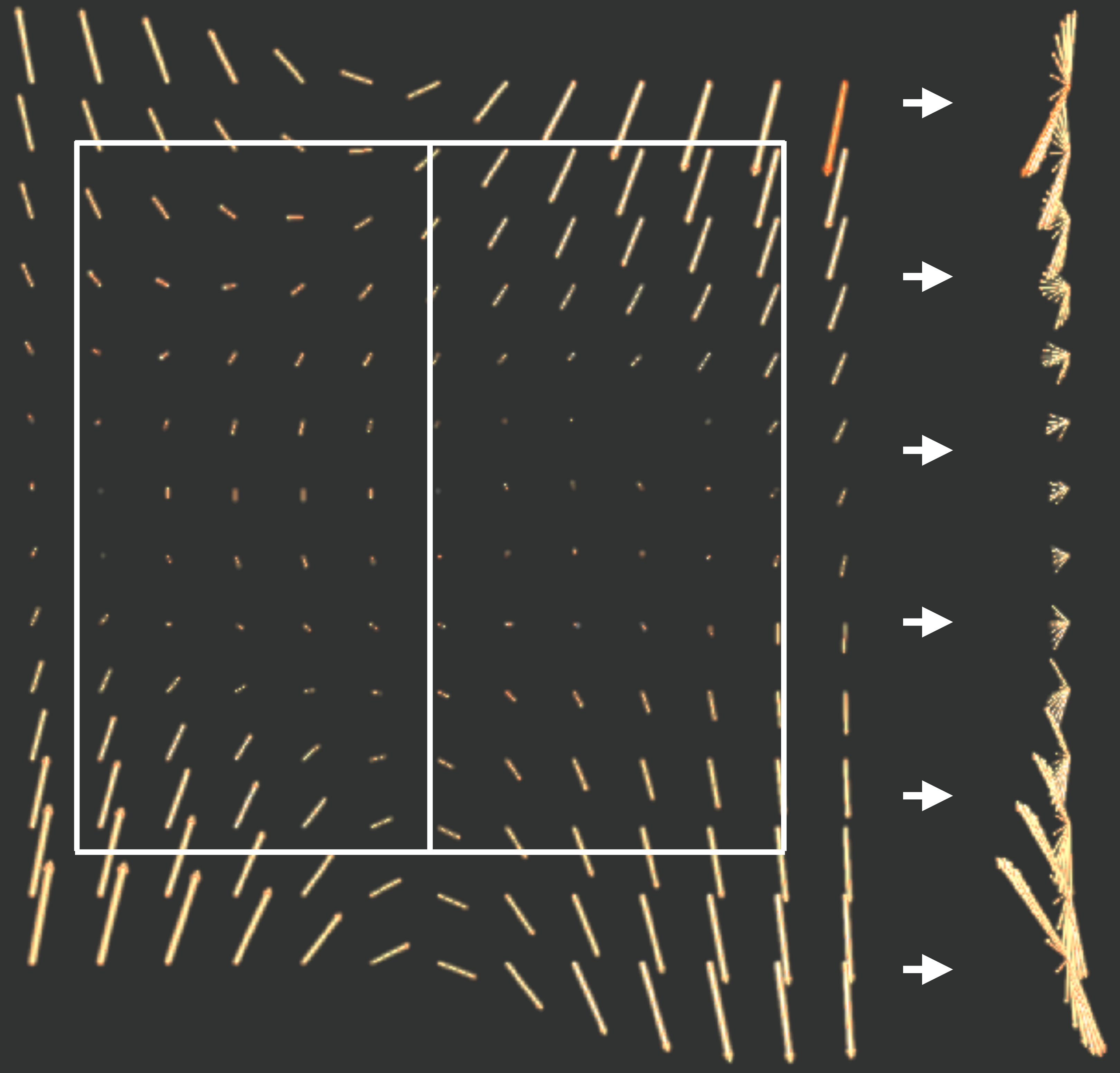
36cm

~ 700ft
~ 215m
of wire



0.1A





Highly contained B-Field with low leakage fields (<mG at 1in)

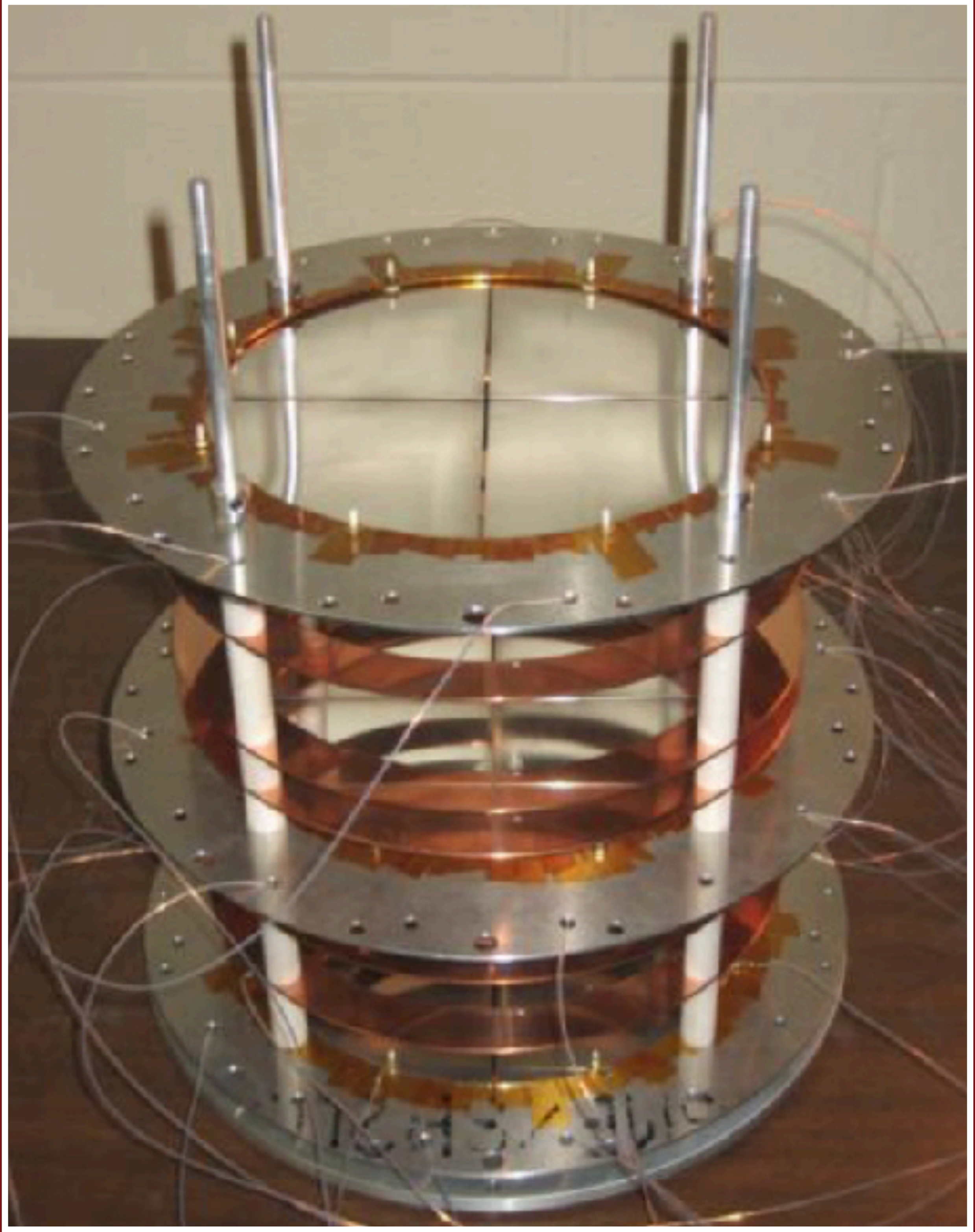
Detection

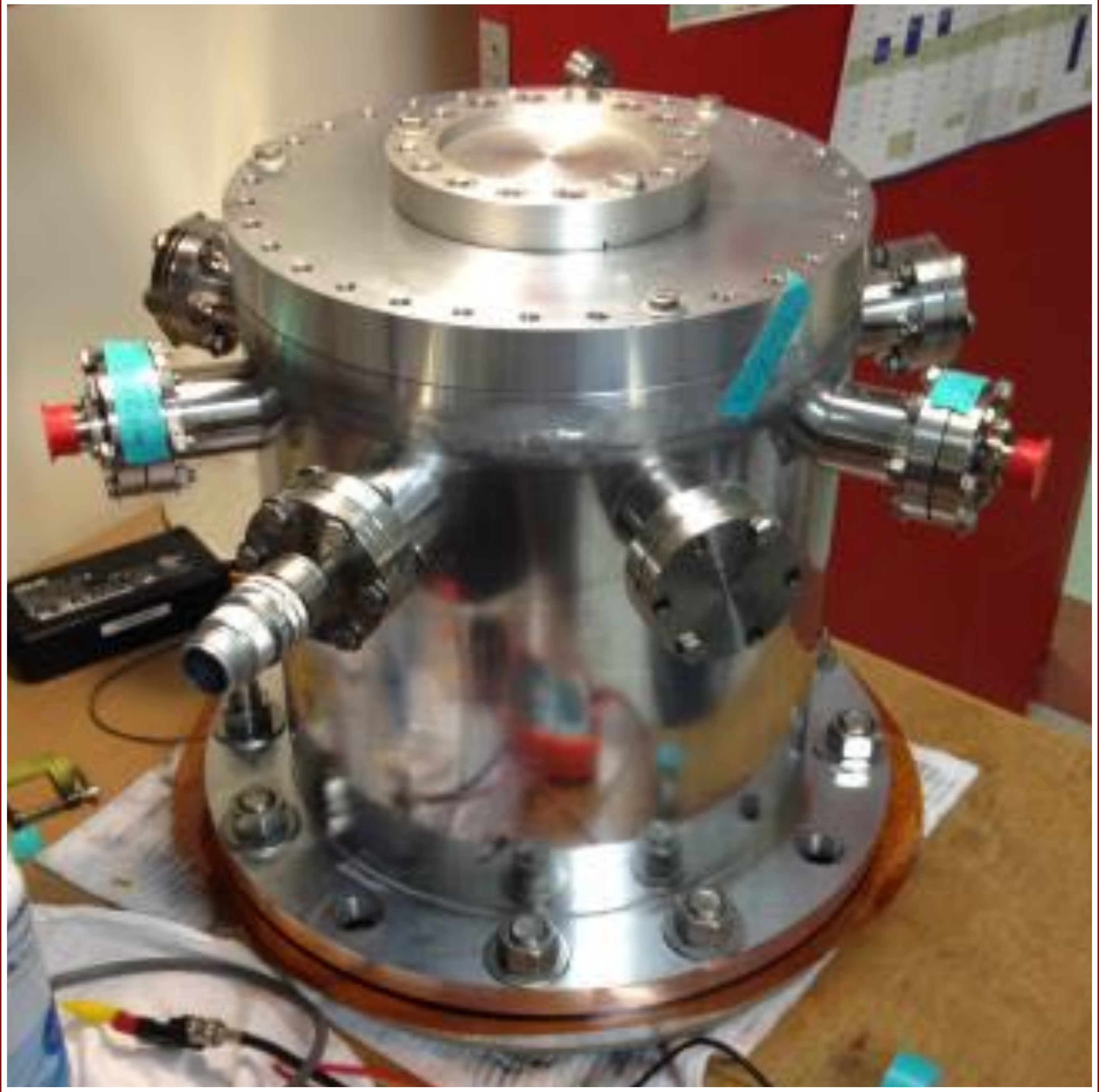
^{3}He gas utilized due to high capture cross section

Longitudinal segments provide energy resolution due to ~1/v velocity dependent cross section

Integrated detector current proportional to neutron flux

Segmented ^{3}He Ionization Chamber

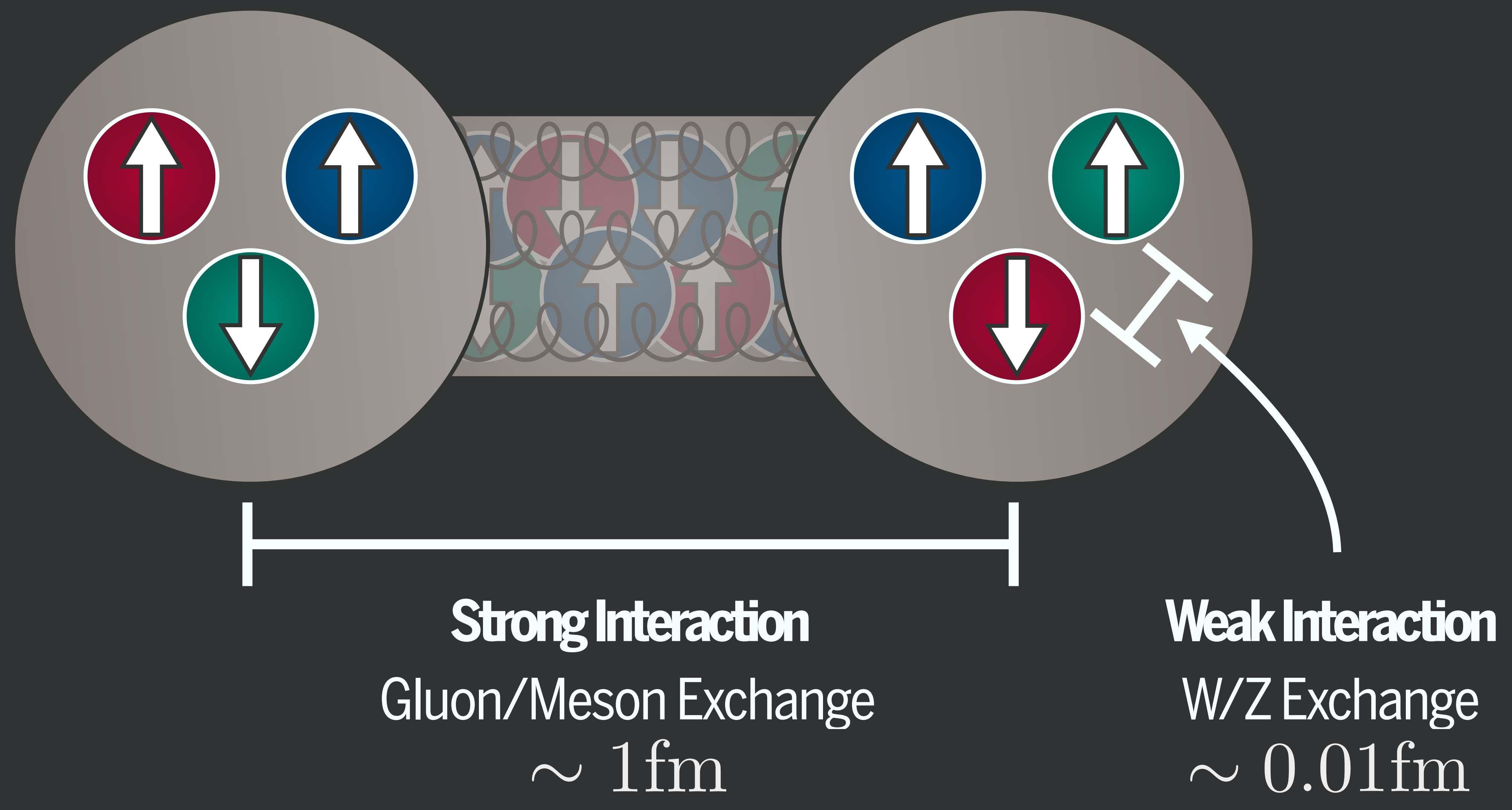




Probing the Weak Interaction in n-^4He

Nucleon-Nucleon Weak Interaction

- W & Z exchange between quarks ~100X smaller range than nucleon size
- Non-perturbative QCD governs hadronic structure and may be better understood by using the weak interaction as a low-energy probe



- Weak/strong interaction amplitudes differ by 7 orders of magnitude — parity violation allows us to filter out the weak interaction from the overwhelming strong interaction background
- Current theoretical work estimates SM observable on the order of: $\left.\frac{d\varphi_{PV}}{dz}\right|_{^4\mathrm{He}} \sim 7 \times 10^{-7}\ \mathrm{rad/m}$

PV Spin Rotation

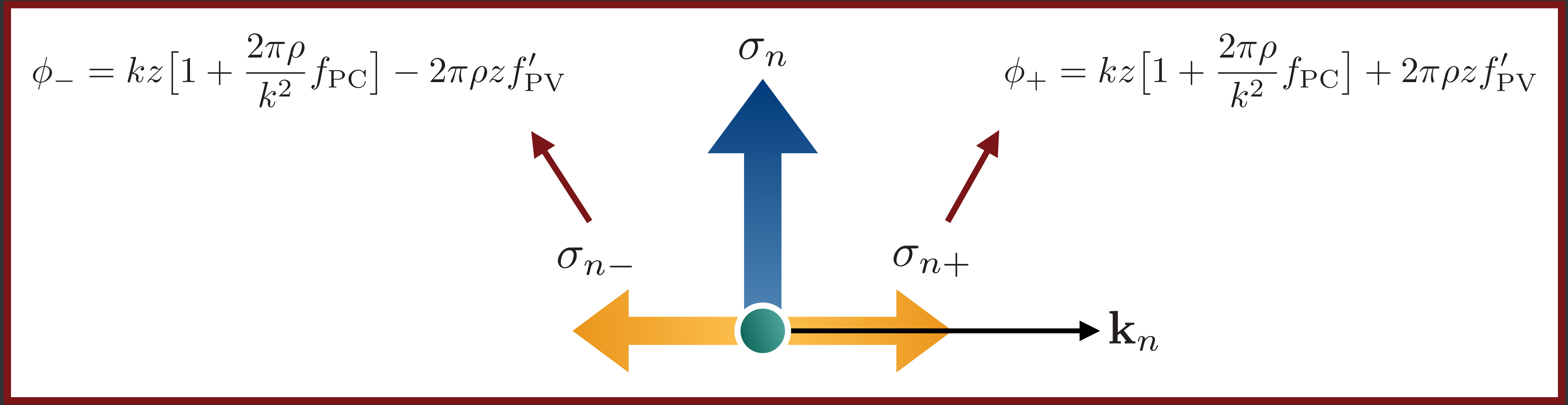
$$n \equiv \frac{k}{k_0} \simeq \sqrt{1 + \frac{4\pi N}{k^2} f(0)}$$

General Forward Scattering Amplitude:

$$f(0) = A + B[\vec{\sigma}_n \cdot \vec{S}_N] + C[\vec{\sigma}_n \cdot \vec{k}_n] + D[\vec{S}_N \cdot \vec{k}_n] + E[\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{S}_N)]$$

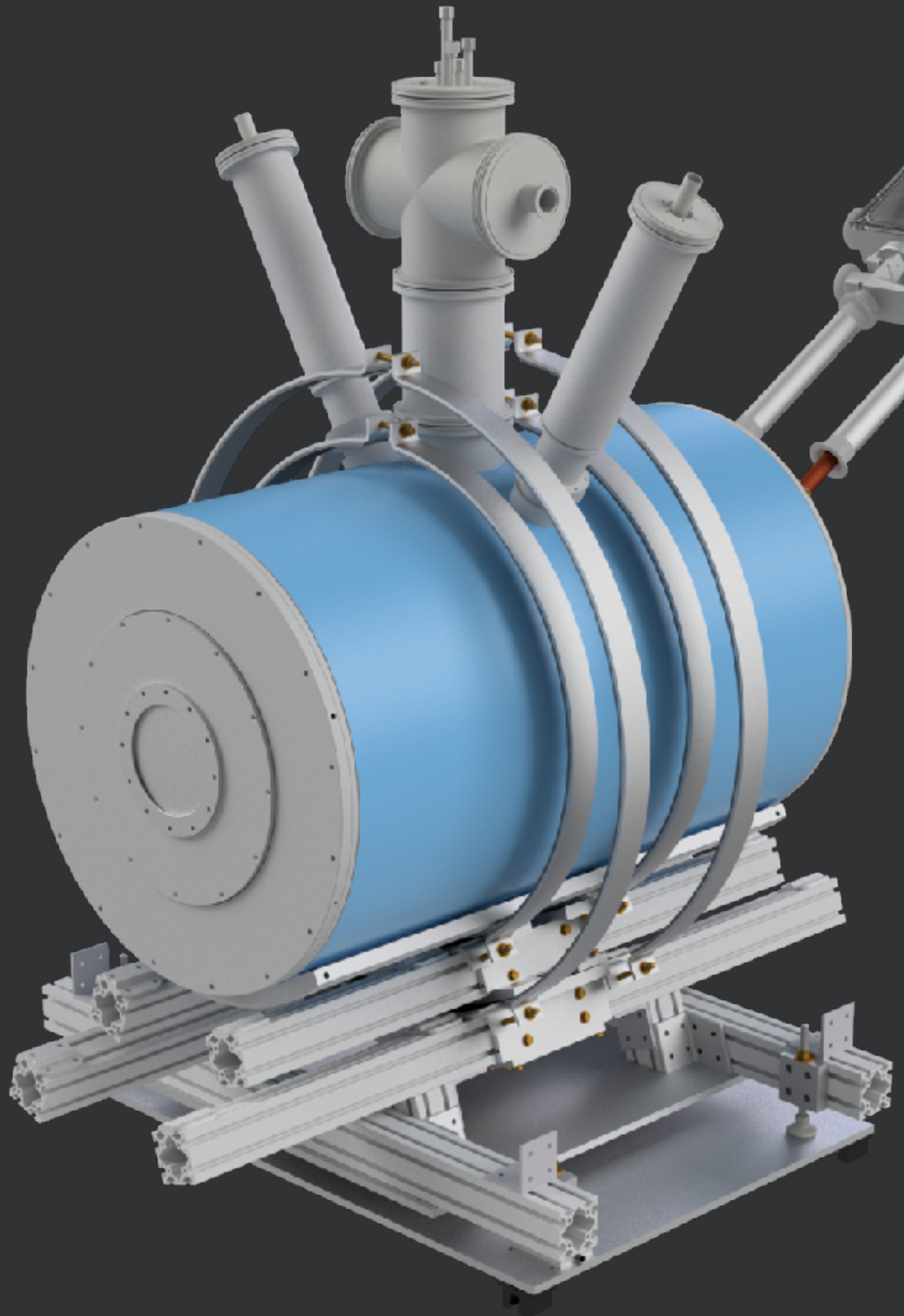
P – odd | P – odd | P,T – odd

Unpolarized Target $\Longrightarrow f(0) = A + C[\vec{\sigma}_n \cdot \vec{k}_n] = f_{\text{PC}} + f_{\text{PV}}(\vec{\sigma}_n \cdot \vec{k}_n)$

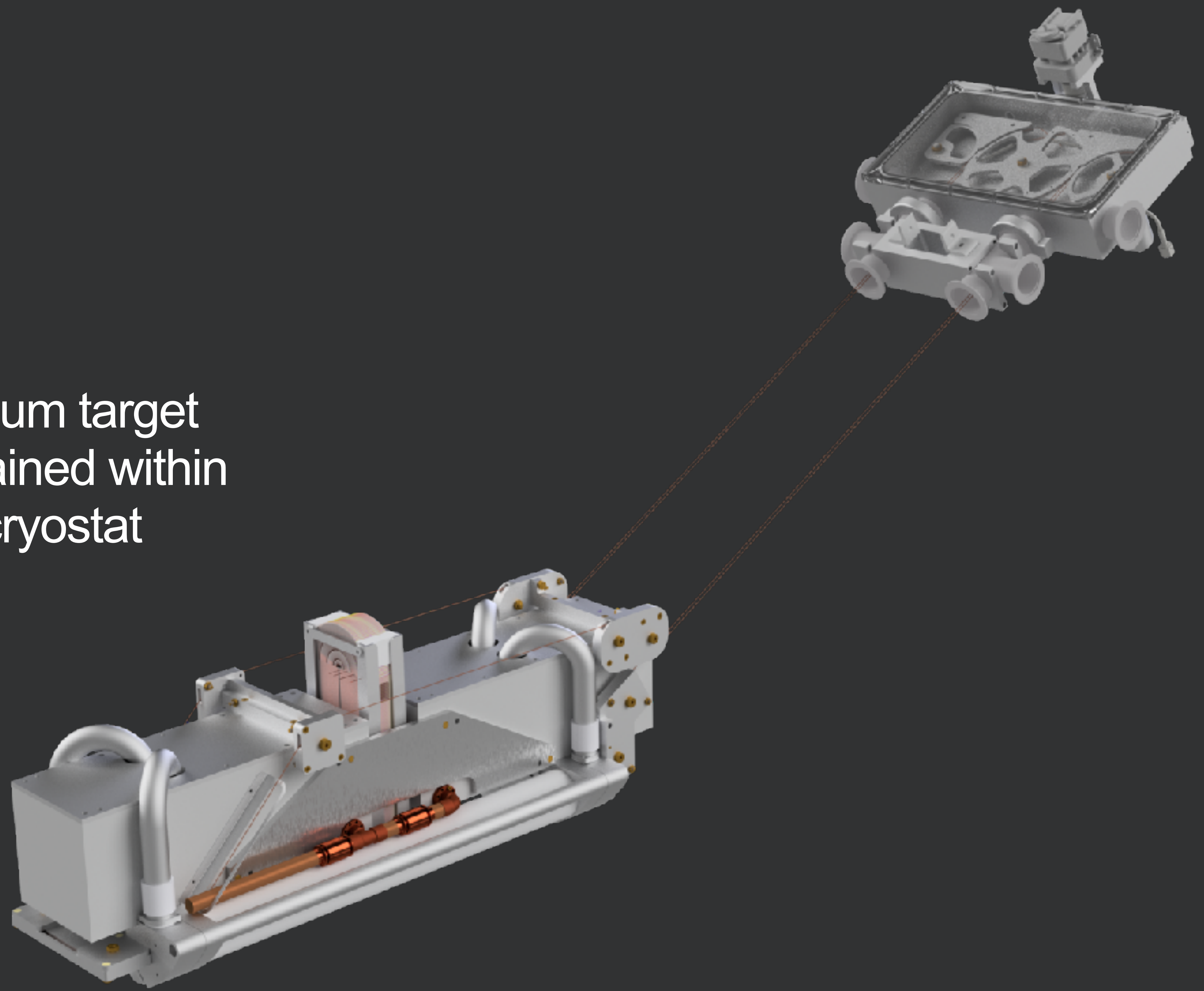


$$\varphi_{\text{PV}} = \phi_+ - \phi_-$$

The n-^{4}He Spin Rotation Target

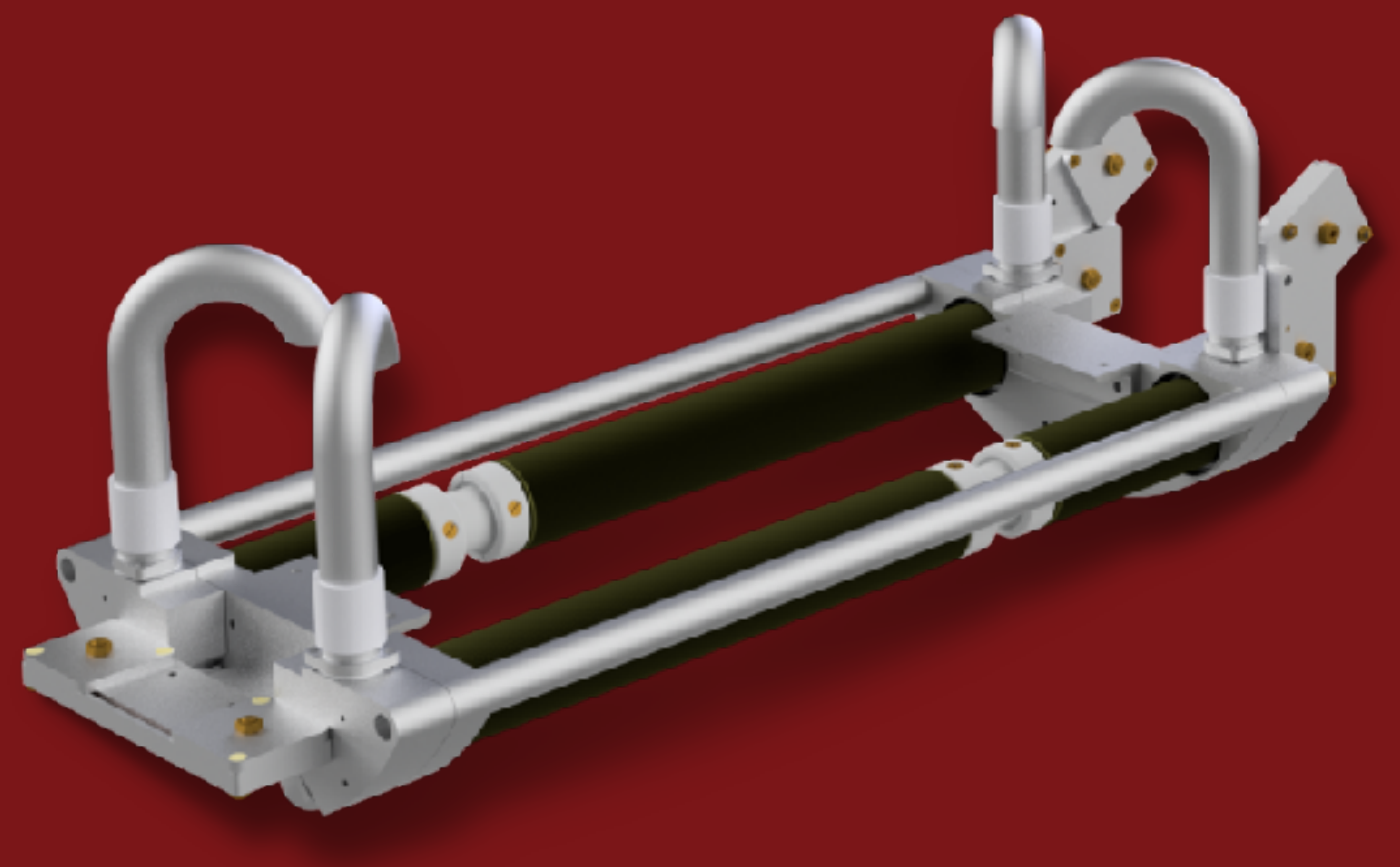


The liquid helium target system is contained within the target cryostat



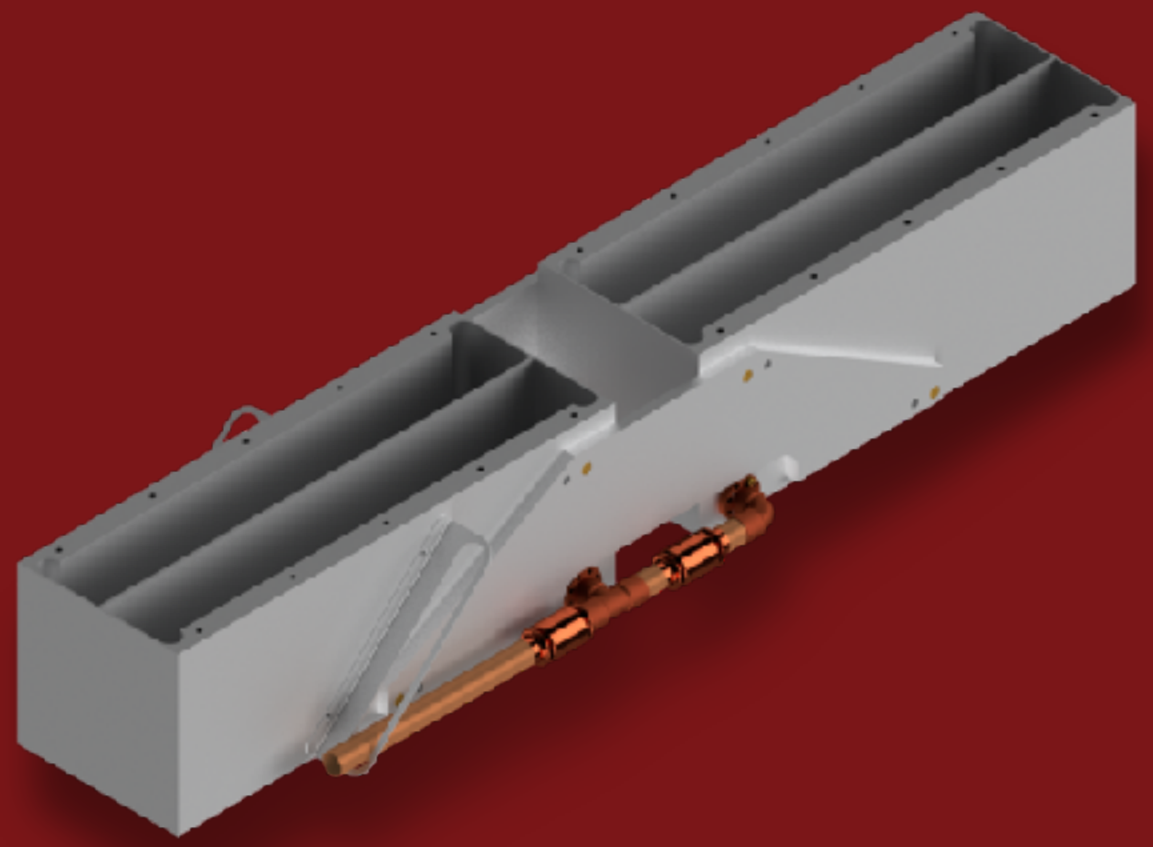
Target Design Overview

Elements of a non-magnetic cryogenic liquid target for measuring parity odd interactions —



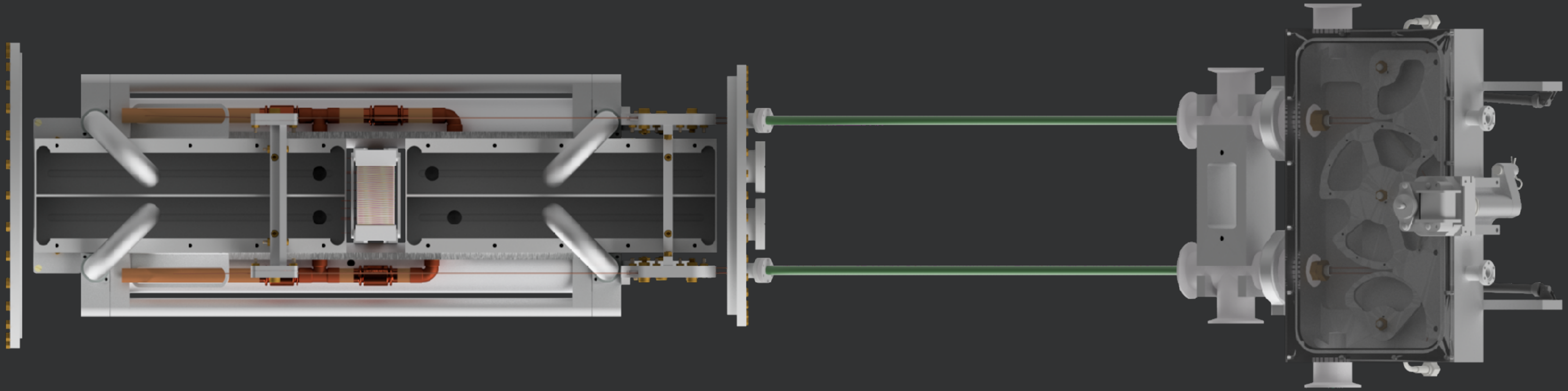
Non-Magnetic LHe Pump +

Room Temperature Drive System +



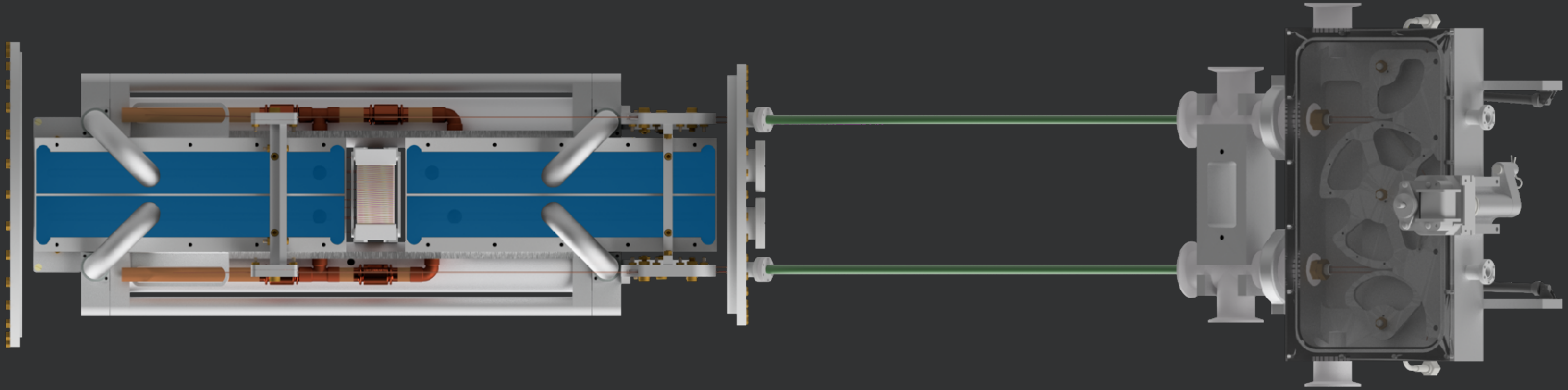
Multi-Chambered Al Target

Target Preparation



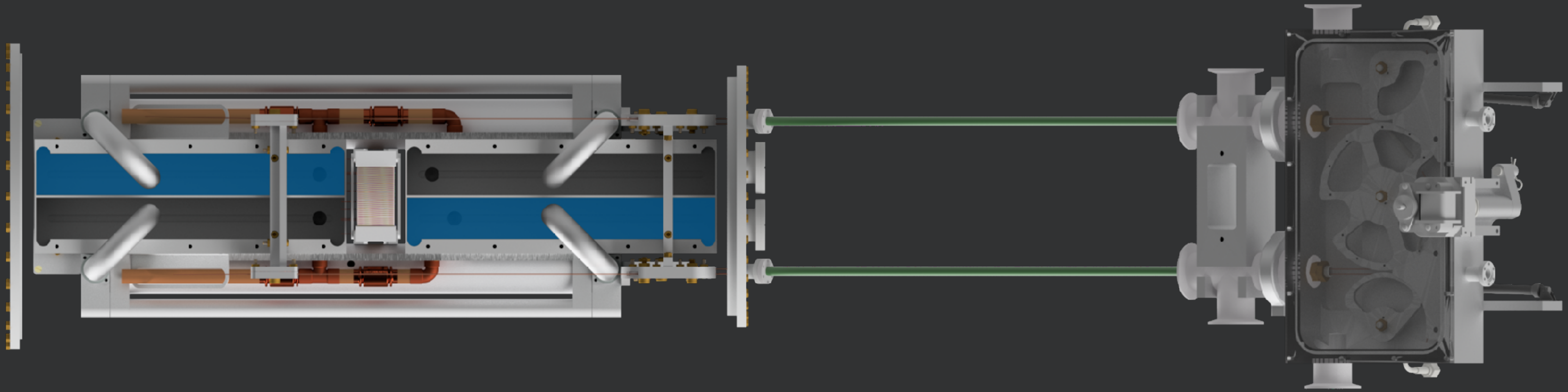
Motor is run to begin target chamber filling process

Target Preparation



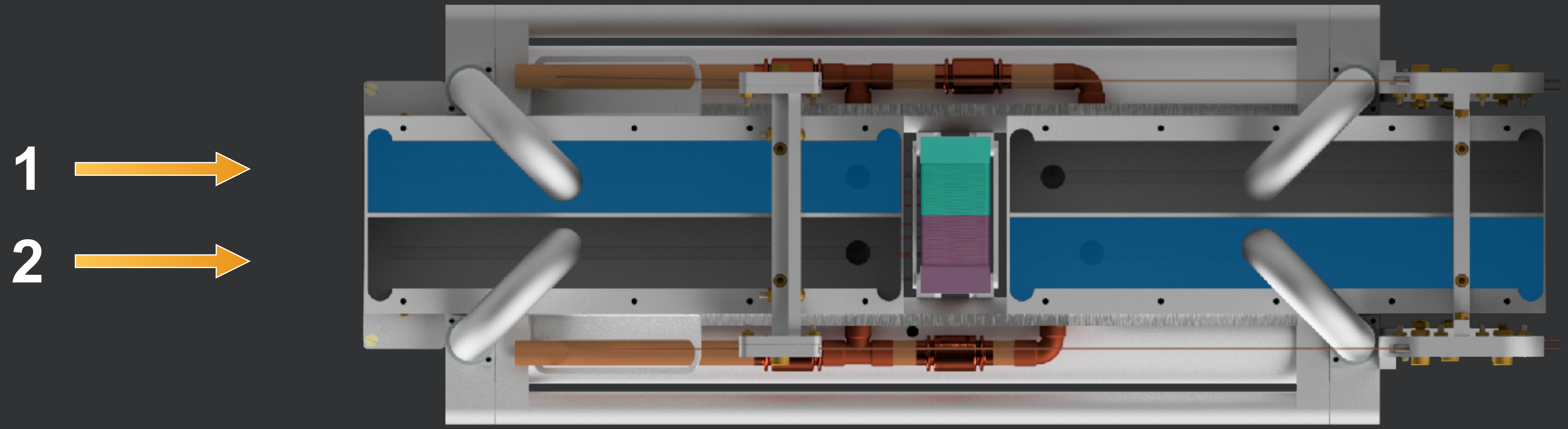
All four target chambers are filled — status is checked by helium level sensors

Target Preparation

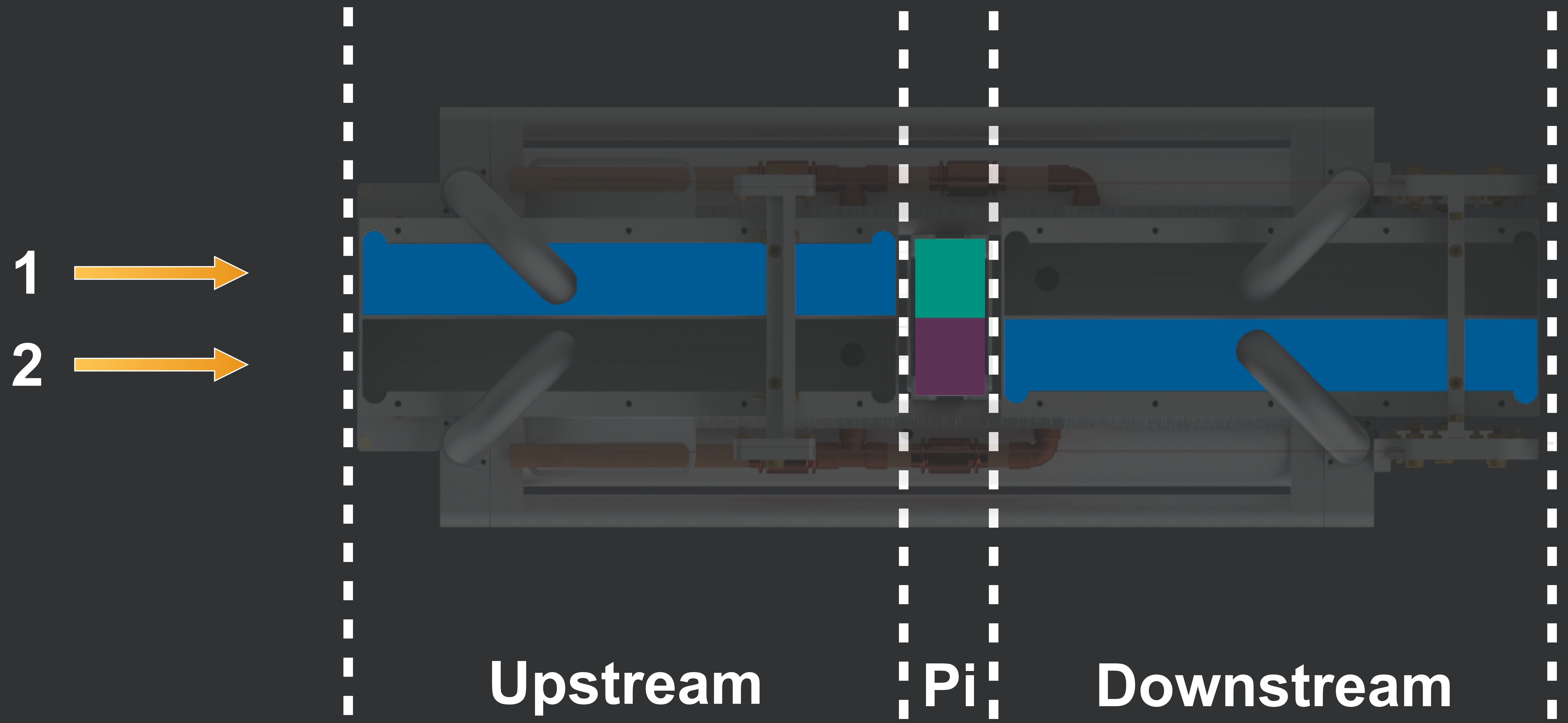


Actuator is triggered to drop one drain pipe — this is now referred to as a target state

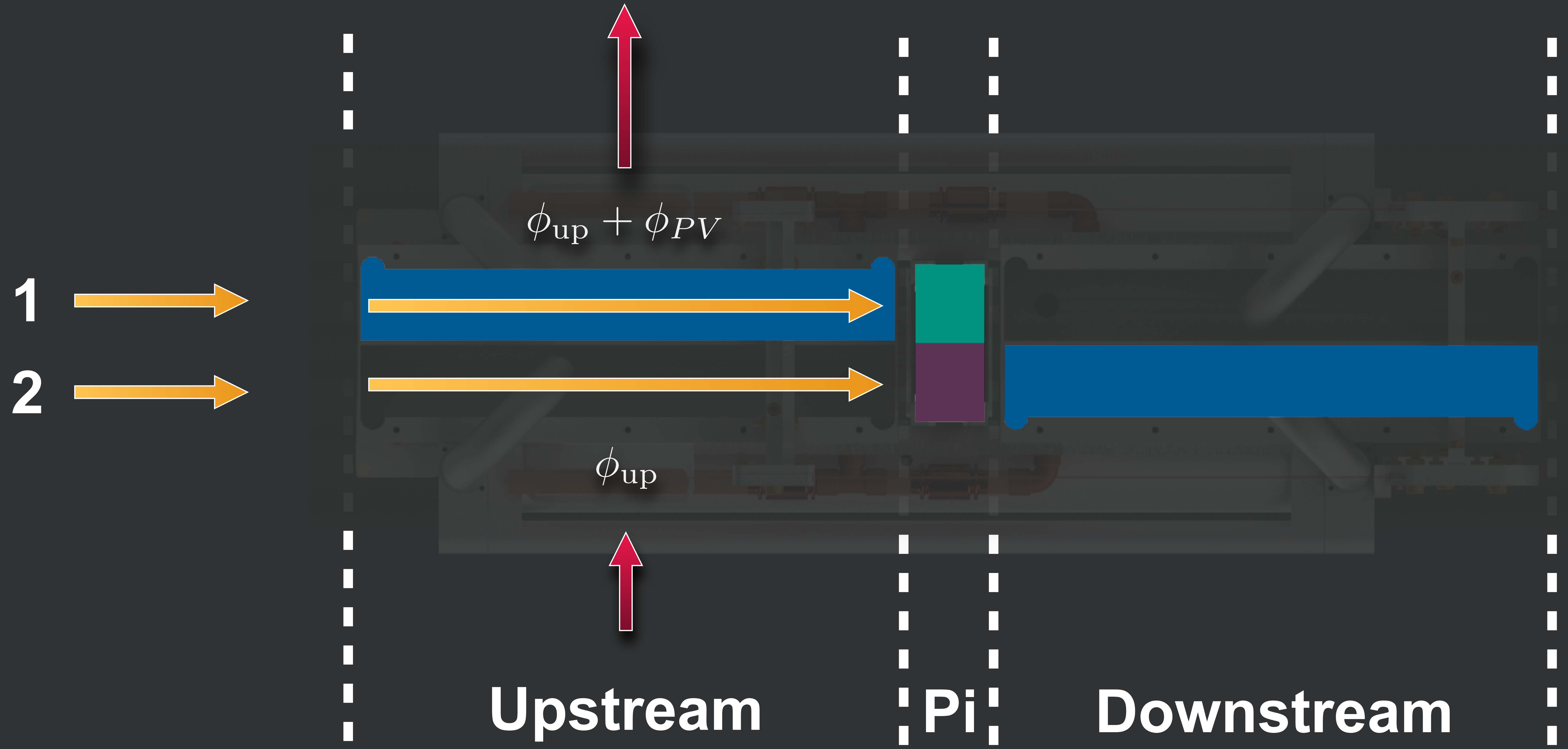
n-4He Observable



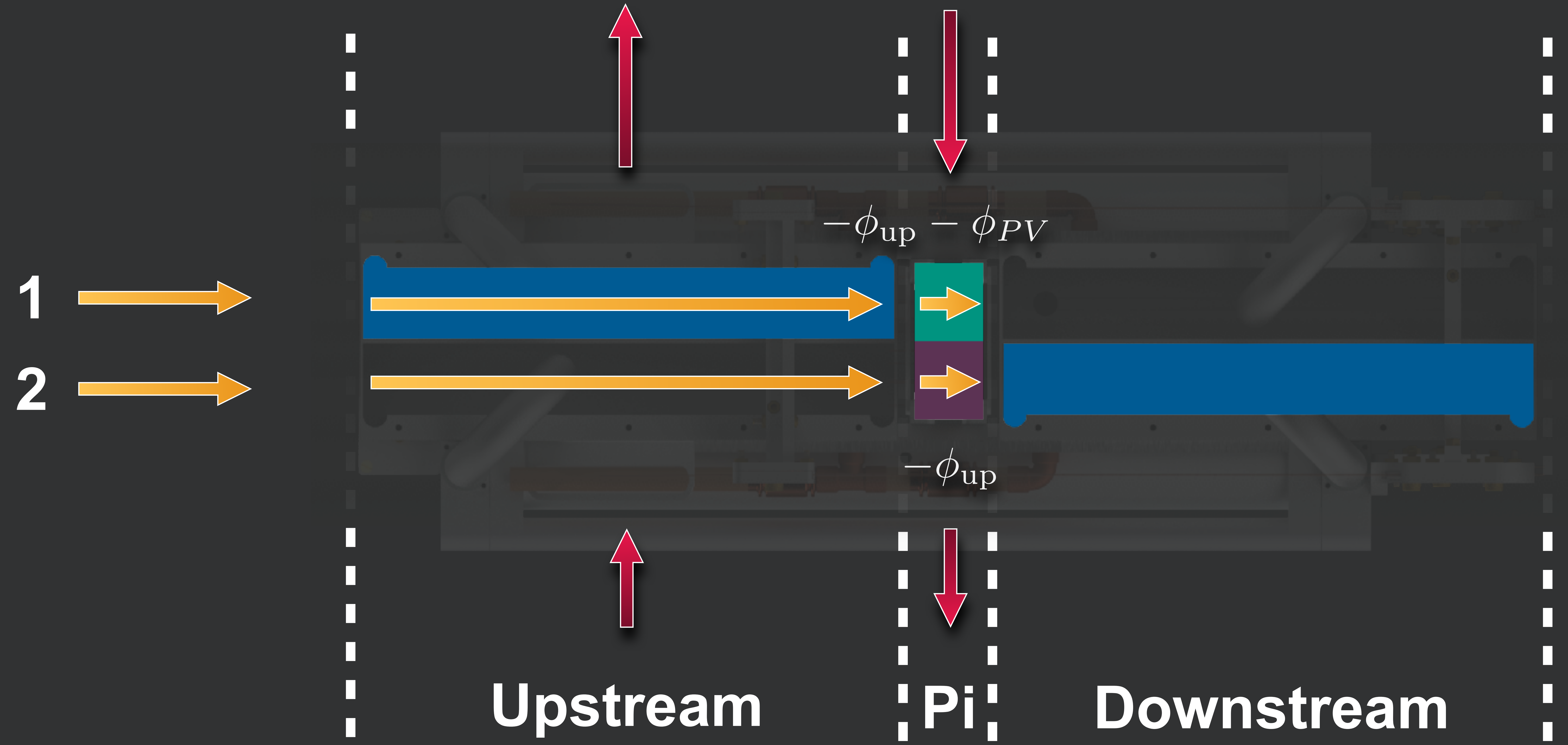
n-4He Observable



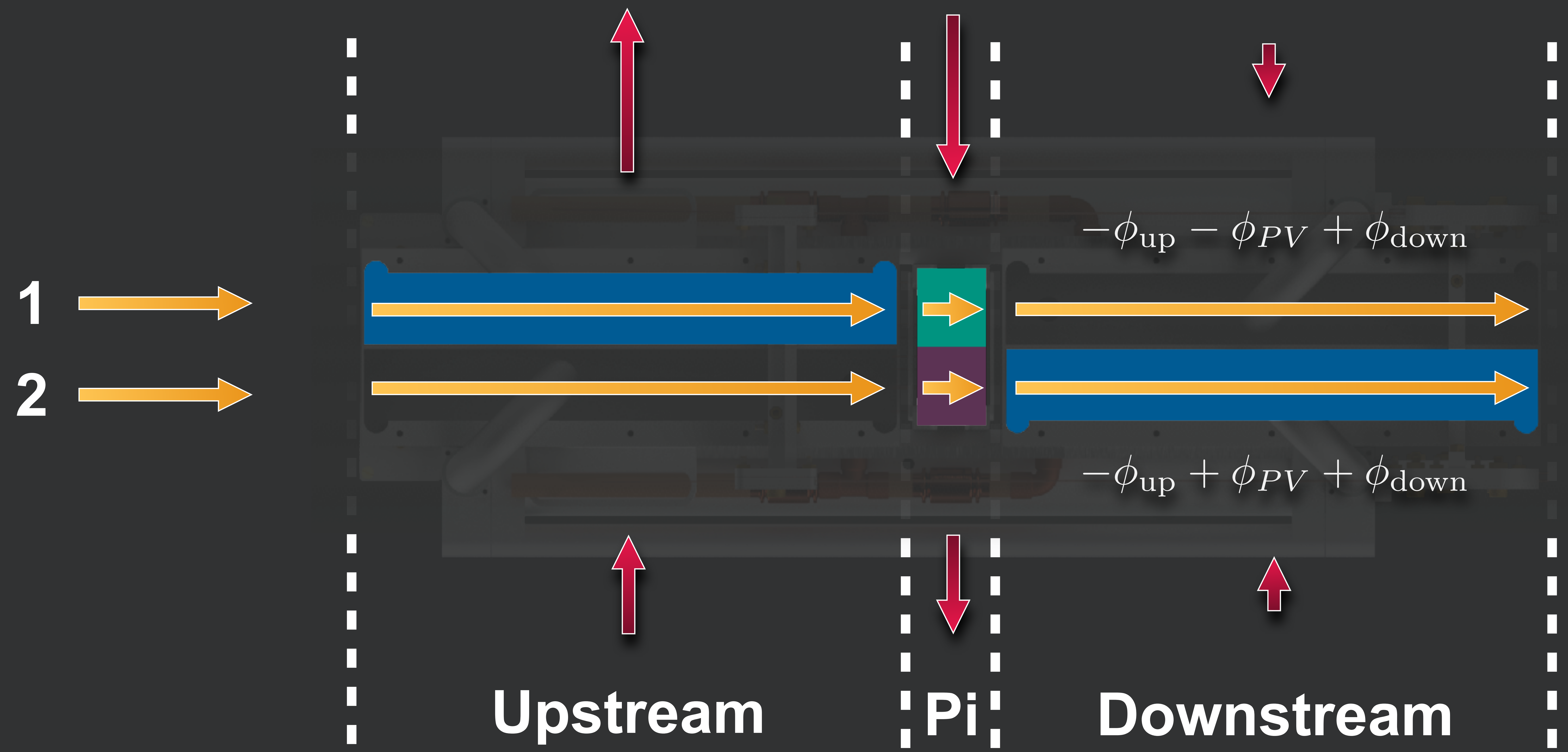
n-4He Observable



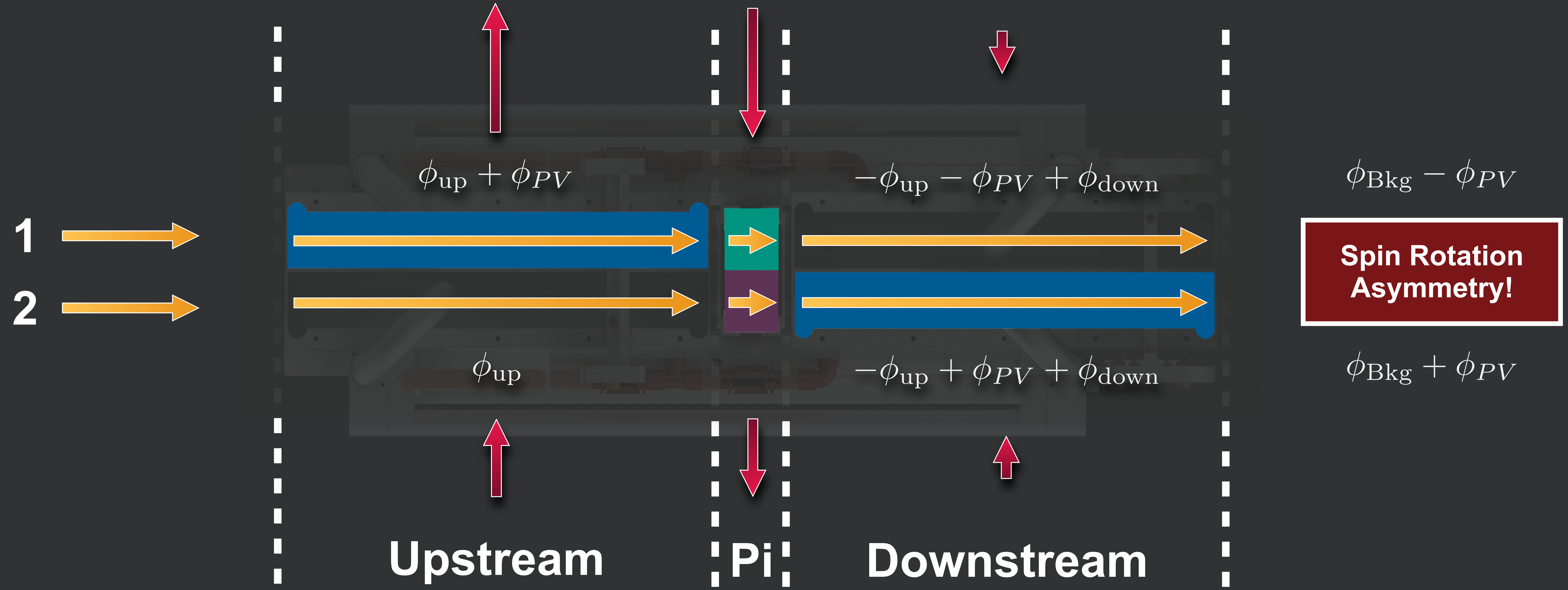
n-4He Observable



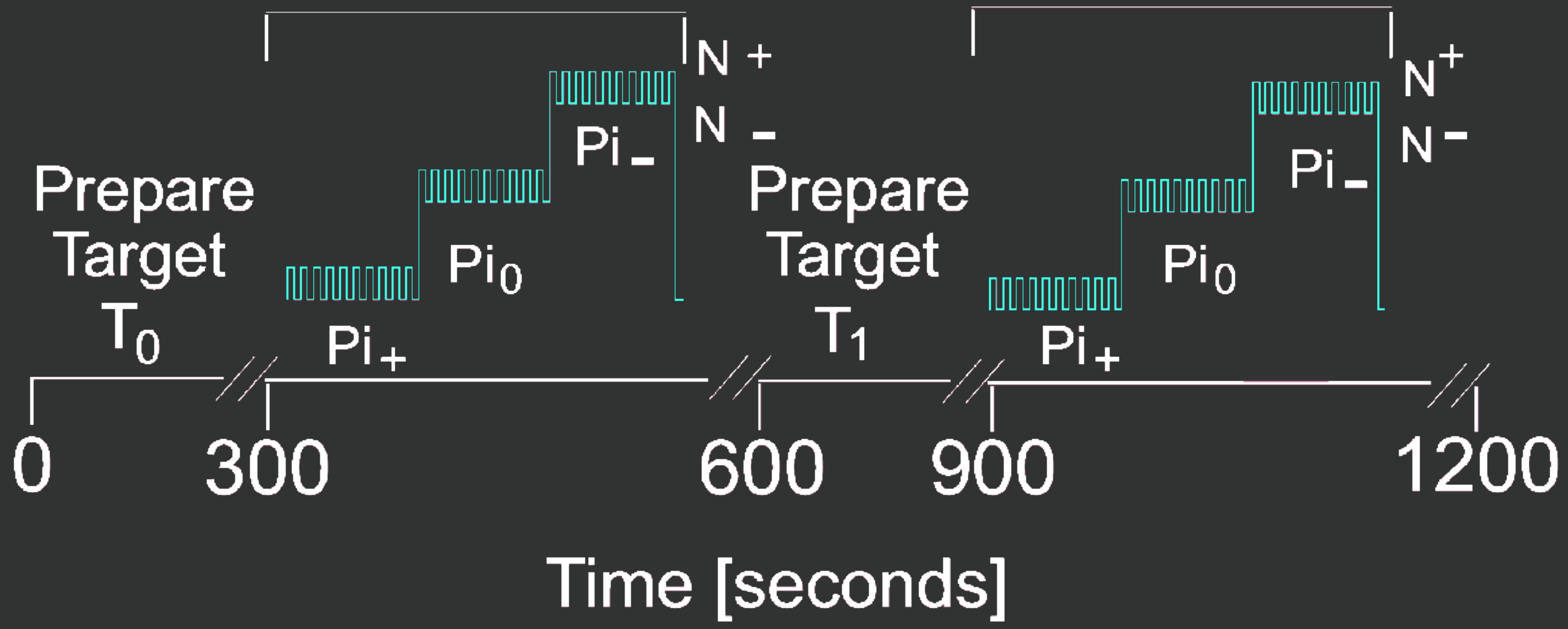
n-4He Observable



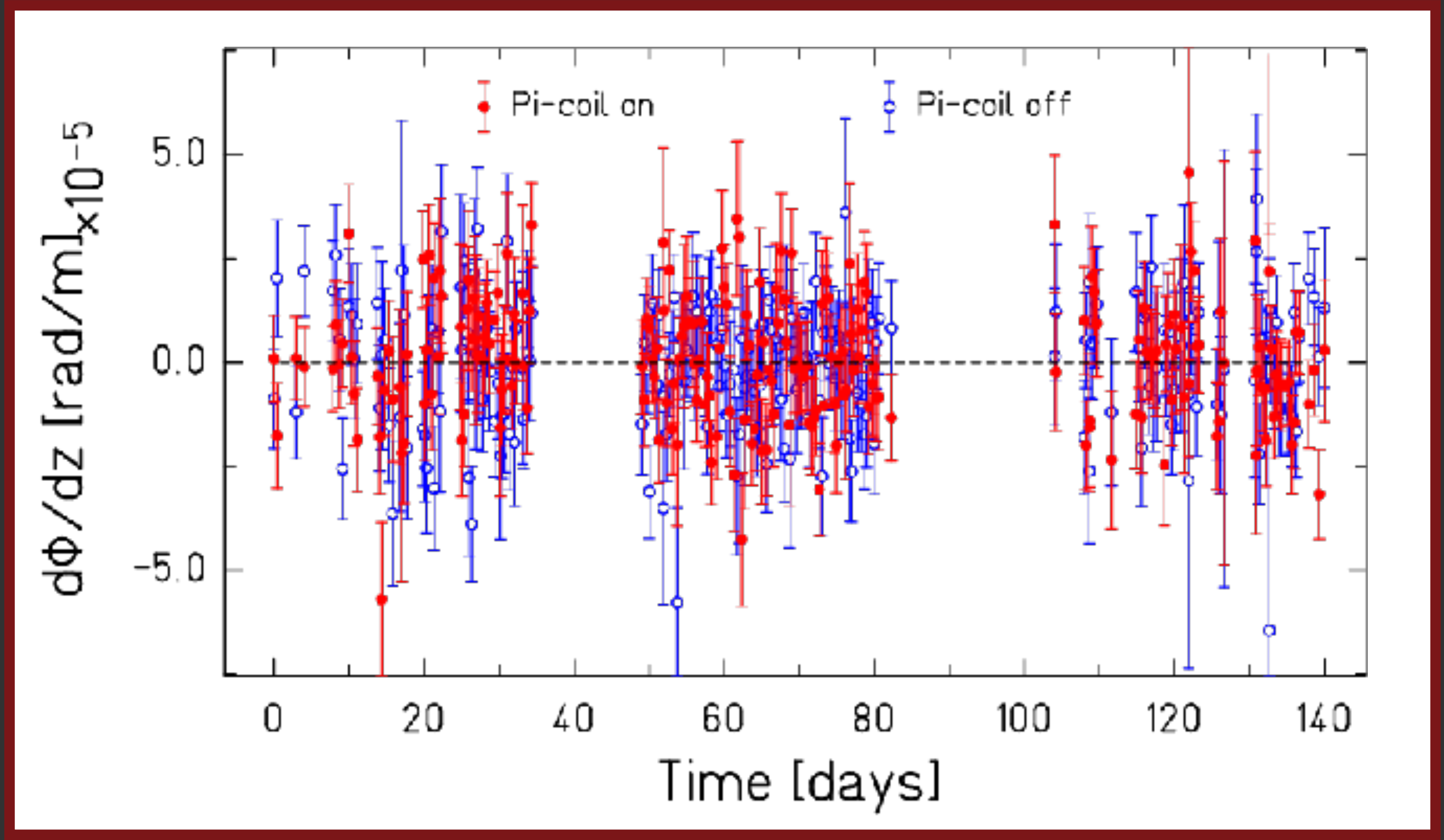
n-4He Observable



Complete Sequence



$$PA\sin\phi = \frac{N_+ - N_-}{N_+ + N_-}$$



W.M. Snow, et al., RSI **86**, 055101 (2015)

Projections

	NSR-II	NSR-III
NG-6 $\longrightarrow$ NC-C Intensity	$4.5 \times 10^8\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$	$8 \times 10^9\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$
NG-6 $\longrightarrow$ NC-C Beam Size	$5\ \mathrm{cm} \times 5\ \mathrm{cm}$	$10\ \mathrm{cm} \times 10\ \mathrm{cm}$
Target Region B-Field Reduction	$100\ \mu\mathrm{G}$	$10\ \mu\mathrm{G}$

Increased data taking live time from new target design and helium reliquification

New Polarizer and Analyzer, Guides, Input & Output Coils, Pi Coil (superconducting?)

NG-C Be Filter cuts $< 4\text{Å}$ preventing pi coil under-rotation

W.M. Snow, et al., PRC **83**, 022501(R) (2011).

W.M. Snow, et al., RSI **86**, 055101 (2015)

H. E. Swanson, et al., PRC **100**, 015204 (2019).

$$\left.\frac{d\varphi_{\mathrm{PV}}}{dz}\right|_{^4\mathrm{He}} = [+2.1 \pm 8.3(stat.)\,^{+2.9}_{-0.2}(sys.)] \times 10^{-7}\ \mathrm{rad/m} \longrightarrow [\pm < 1(stat.) \pm < 1(sys.)] \times 10^{-7}\mathrm{rad/m}$$

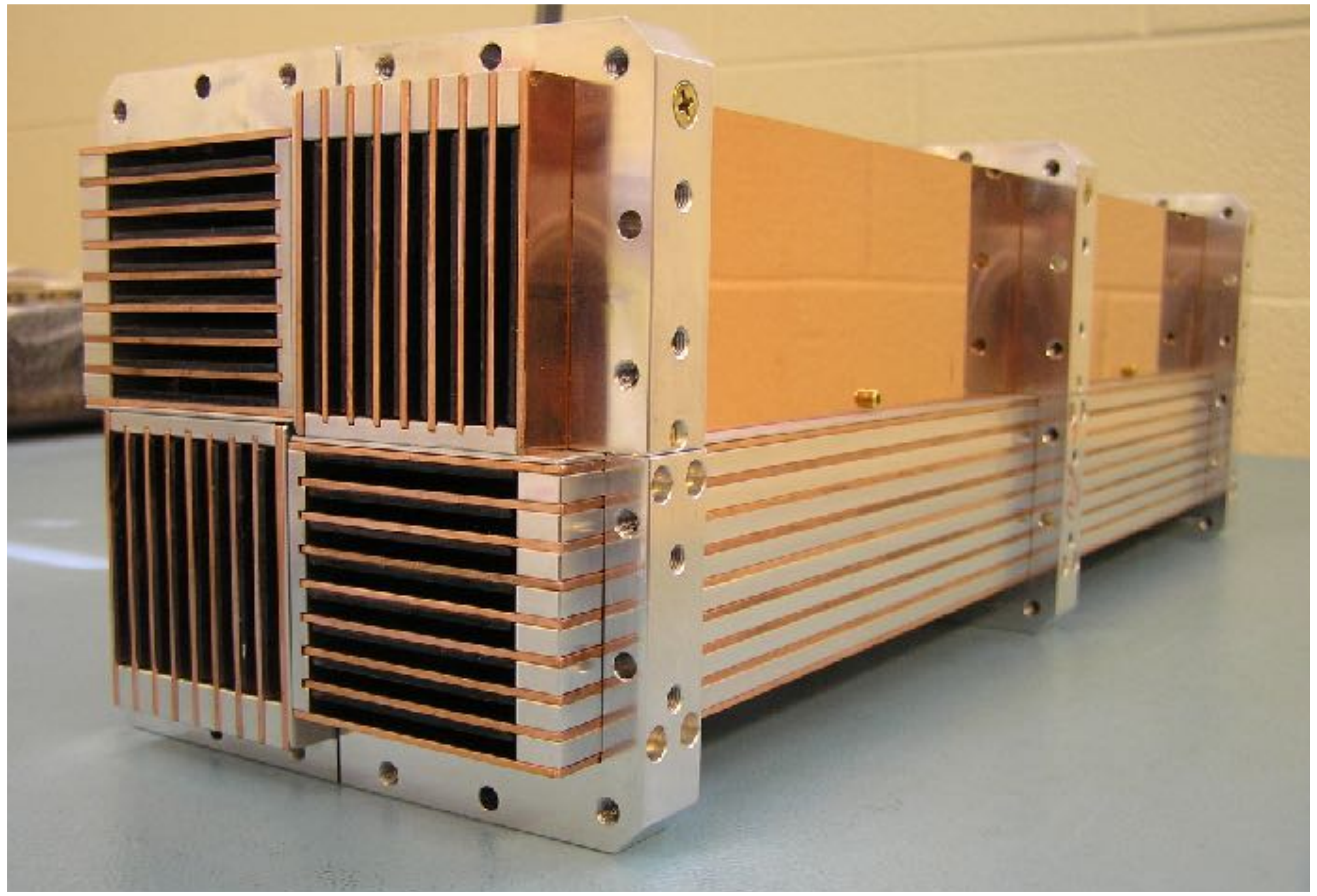
The 2011 null result also constrained:

- Exotic parity violation from meV-mass Z' bosons [***H. Yan, and W. M. Snow,*** *Phys. Rev. Lett. 110, 082003 (2013)*]
- In-matter gravitational torsion [***R. Lehnert et al.,*** *Phys. Lett. B 744, 415 (2015)*]
- In-matter spacetime nonmetricity [***R. Lehnert et al.***, *Phys. Lett. B 772, 865 (2017)*]

J. C. Cook, Rev. Sci. Inst. **80**, 023101 (2009)

Searches for Exotic Spin-Dependent Forces

Target Design

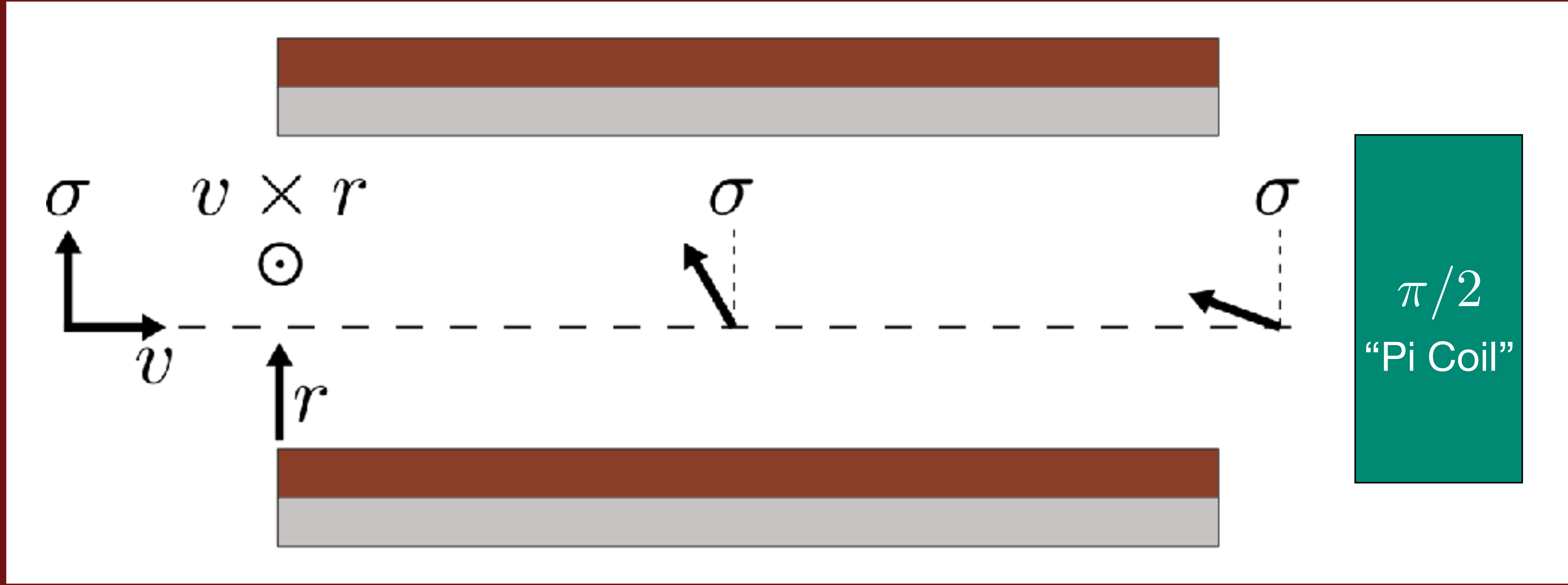


Copper and float glass plates spaced with asymmetric density in each slot

$$\mathcal{L} = \bar{\psi}(g_V\gamma^\mu + g_A\gamma^\mu\gamma_5)\psi X_\mu$$

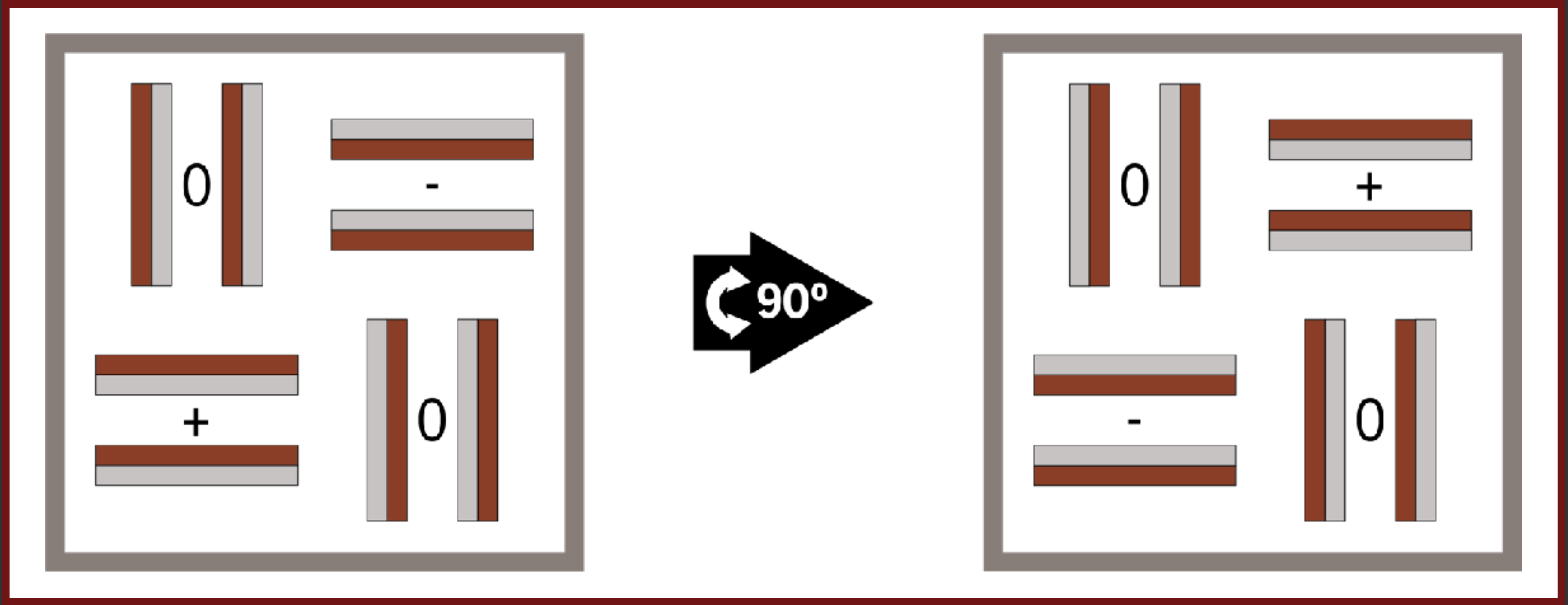
$$\downarrow$$

$$V_5 = \frac{g_A^2}{4\pi m_n}\frac{e^{-m_0 r}}{r}\left(\frac{1}{r}+\frac{1}{\lambda}\right)[\vec{\sigma}\cdot(\vec{v}\times\hat{r})]$$



C. Haddock, et al., Nucl. Inst. Meth., A885, **105** (2018).

Target Rotation Mechanism



Target rotation needed for constraint of systematics — Geneva gear incorporated into vacuum end cap to implement discrete rotations

C. Haddock, et al., Nucl. Inst. Meth., A885, **105** (2018).

Results and Projections

Fall 2016 Run @ LANSCE FP12:

$$\left.\frac{d\varphi}{dz}\right|_{V_5} = [+2.8 \pm 4.6(stat.) \pm 4.0(sys.)] \times 10^{-5}\ \mathrm{rad/m}$$

C. Haddock, et al., Phys. Lett. B **783**, 227 (2018).

2-3 Order of Magnitude Improvement on $\mathrm{mm} - \mu\mathrm{m}$ neutron-matter coupling upper bound

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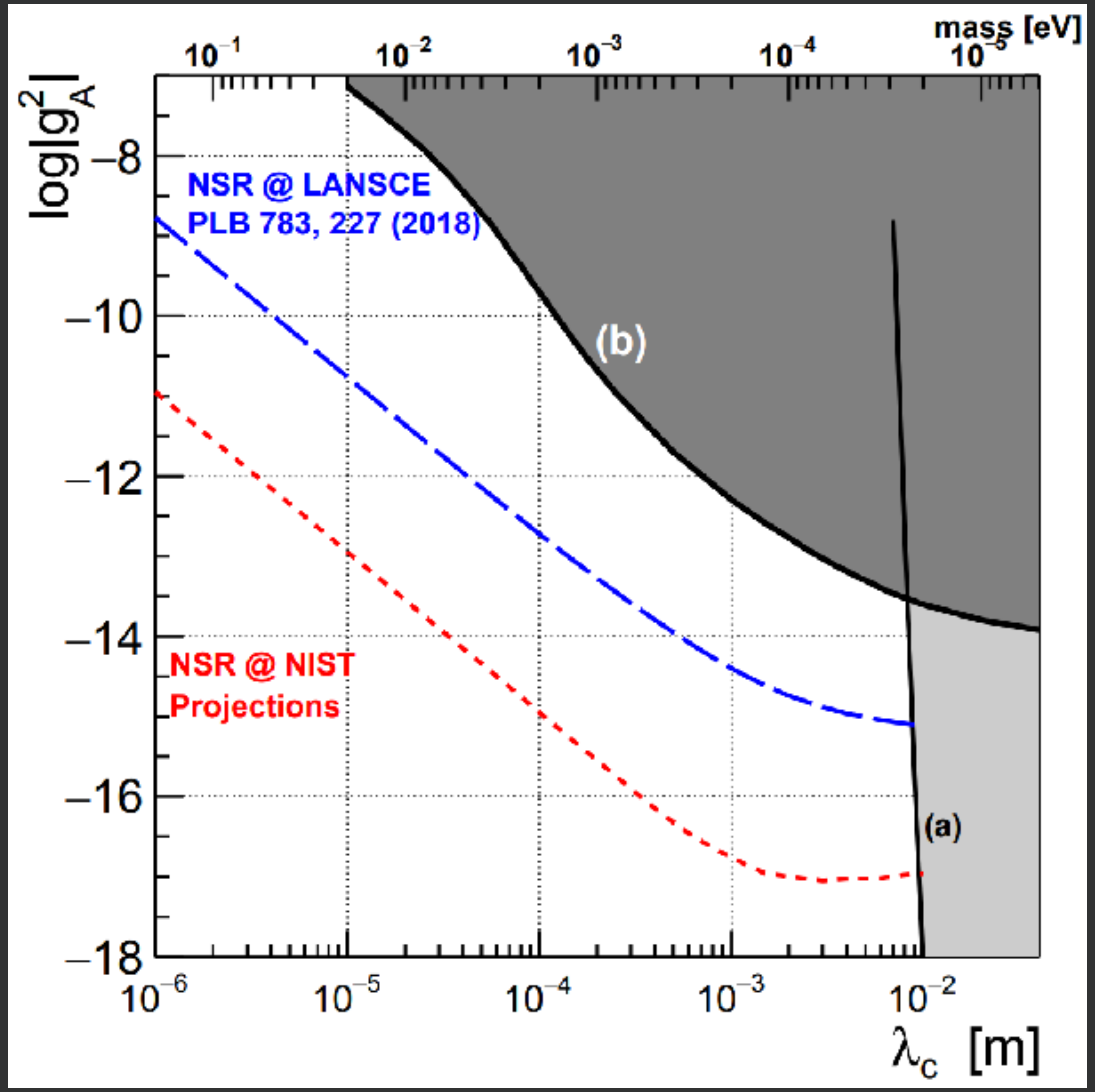
New targets being developed for combined NIST run:

- Tungsten + Float Glass
- Float Glass + Float Glass

Need to further constrain systematics…



(a) $K/^3He$ comagnetometry

G. Vasilakis, et al., Phys. Rev. Lett. **103,** 261801 (2009).

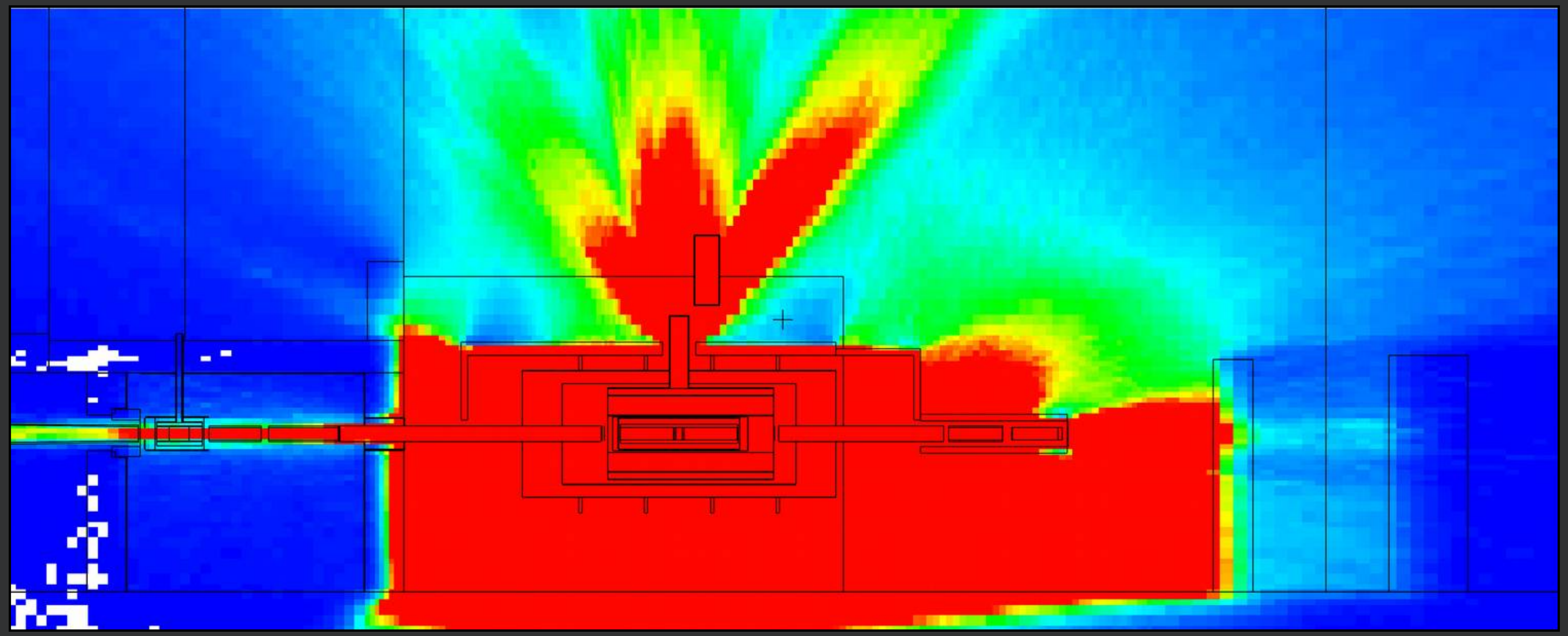
(b) Ramsey spectroscopy

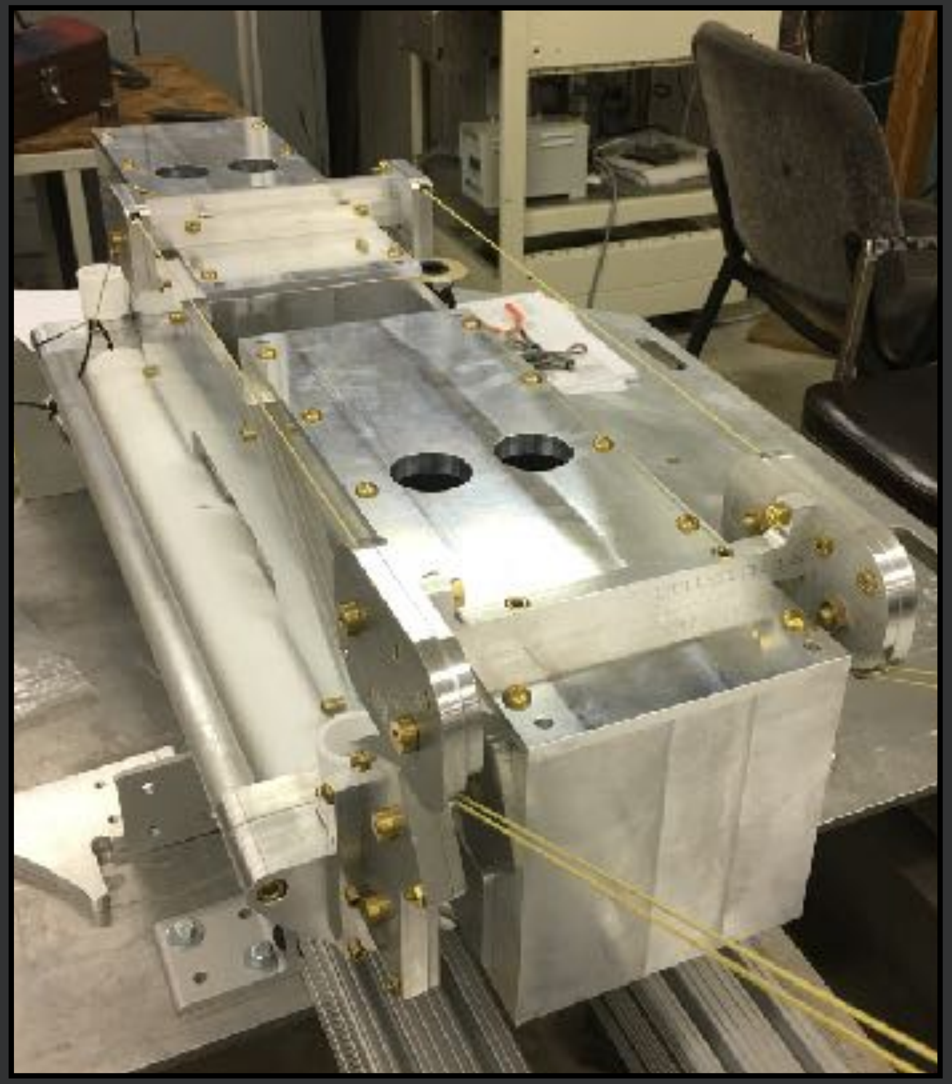
F. M. Piegsa, et al., Phys. Rev. Lett. **108,** 181801 (2012).

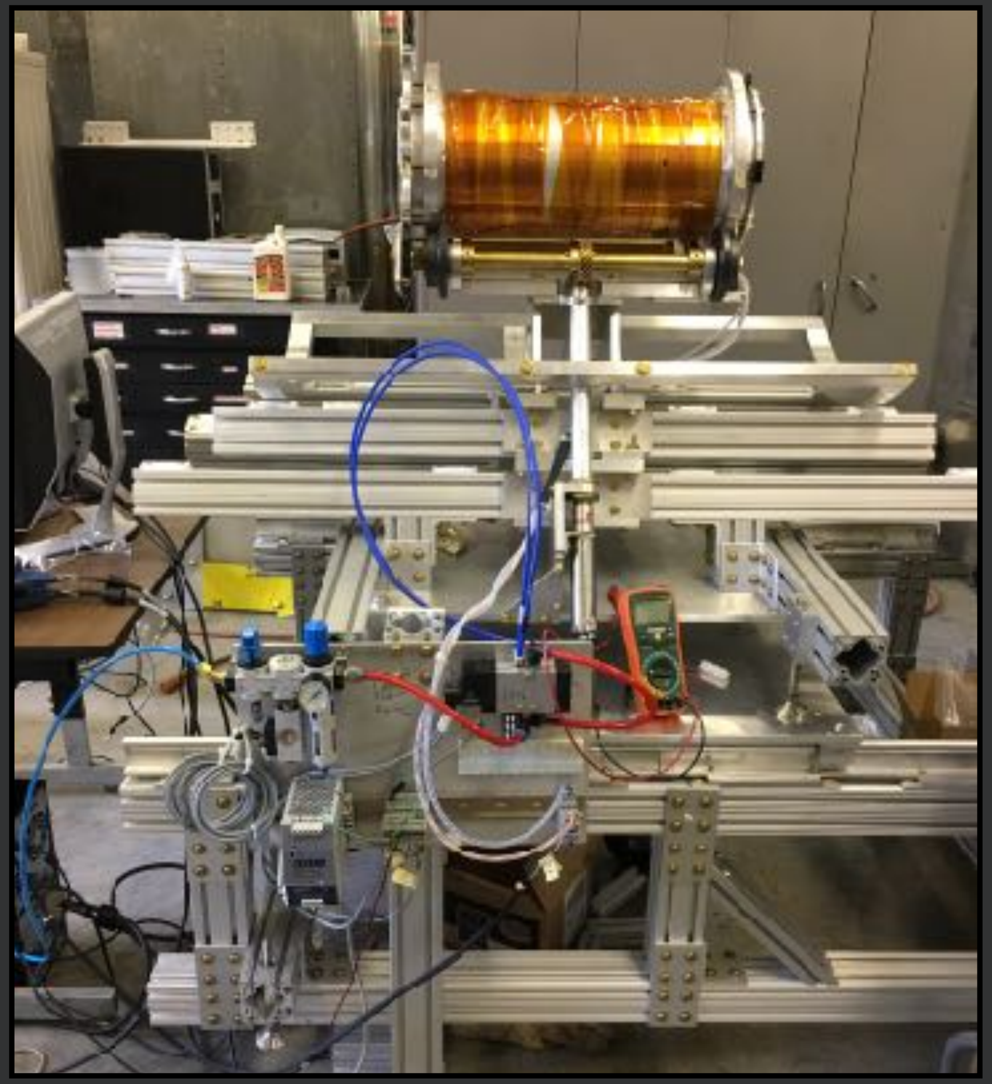
Outlook and Conclusions

NSR Outlook

Initial radiation safety simulations have motivated a flurry of shielding studies — gearing up for massive assembly (8 tons lead + 25 tons concrete)







Both target systems are approaching full assembly — testing through the winter will put us on-track for a beam proposal in 2020

Conclusions

The next generation of n-4He spin rotation will likely reach standard model sensitivity and provide very interesting results for theory and further experiment in the study of the NNWI.

- Significant expansion of our search for exotic spin-dependent interactions will provide an expected 2 orders of magnitude in the further constraint of axial coupling in mesoscopic ranges.

- Neutron Spin Rotation provides an opportunity to utilize polarized neutron optical techniques to probe, at high-precision, a wide variety of physical phenomena.

Neutron Spin Rotation III Collaboration

L. Barron-Palos[2], B.E. Crawford[3], C. Crawford[4], W. Fox[1], J. Fry[1],
C. Haddock[1], B.R. Heckel[5], A.T. Holley[6], S.F. Hoogerheide[7],
M. Maldonado-Velasquez[2], H.P. Mumm[7], J.S. Nico[7], S. Penn[8], S. Santra[9],
M. Sarsour[10], W.M. Snow[1], K. Steffen[1], H.E. Swanson[5], J. Vanderwerp[1]

Indiana University/CEEM [1]
Universidad Nacional Autonoma de Mexico [2]
Gettysburg College [3]
University of Kentucky [4]
University of Washington [5]
Tennessee Technological University [6]
National Institute of Standards and Technology [7]
Hobart and William Smith College [8]
Bhabha Atomic Research Center [9]
Georgia State University [10]

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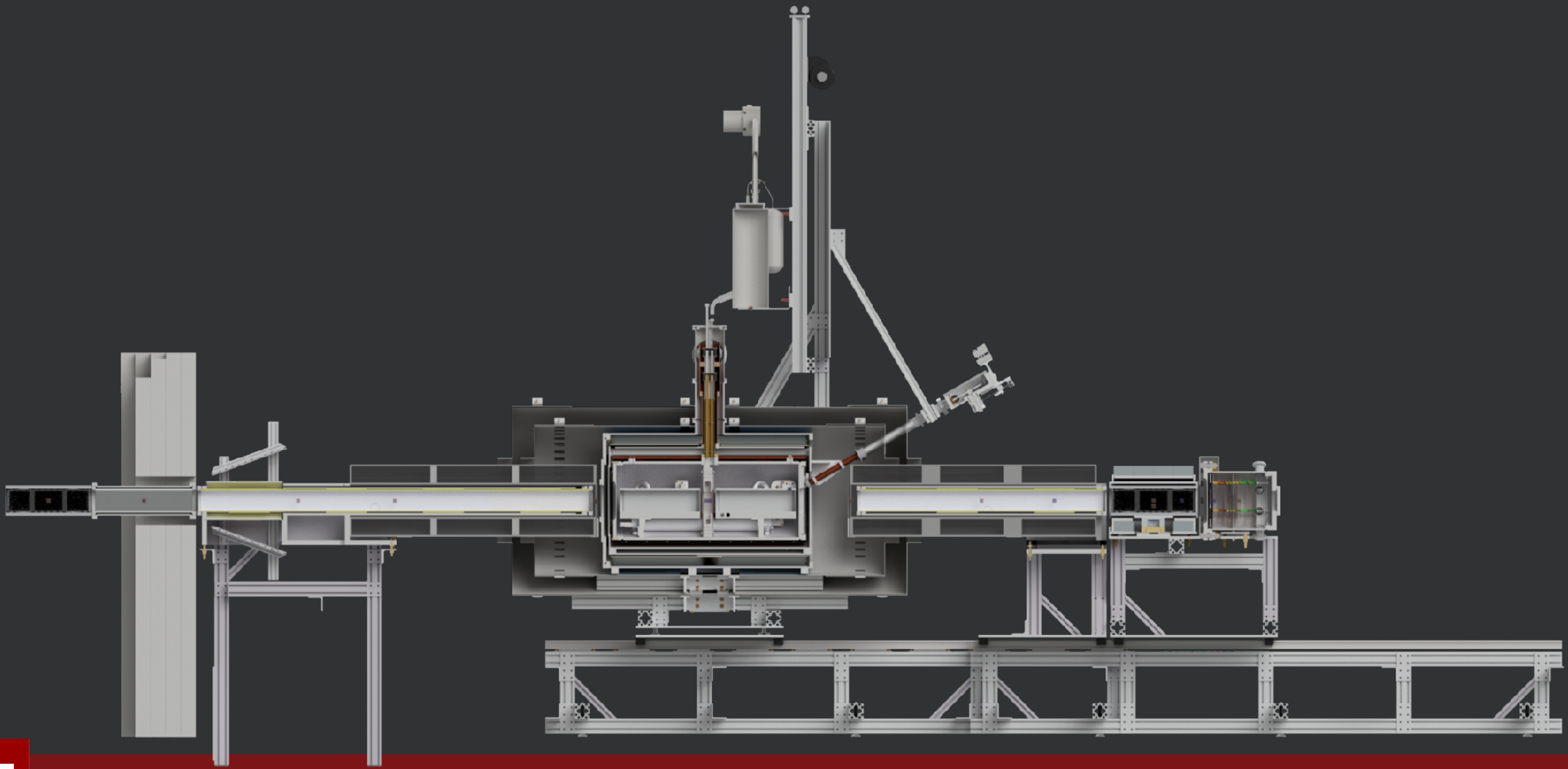
PAPIIT-UNAM: IG101016
BARC

Questions?



Backup Slides

n-4He Systematic Error Estimates

NSR-II → NSR-III

Source	Uncertainty (rad/m)	Method	Uncertainty (rad/m)
L^4He Diamagnetism	$2x10^{-9}$	Calc.	$2x10^{-10}$
L^4He Optical Potential	$3x10^{-9}$	Calc.	$3x10^{-10}$
Neutron E Spectrum Shift	$8x10^{-9}$	Calc.	$8x10^{-10}$
Refraction/Reflection	$3x10^{-10}$	Calc.	$3x10^{-11}$
Non-Forward Scattering	$2x10^{-8}$	Calc.	$2x10^{-9}$
Polarimeter Nonuniformity	$1x10^{-8}$	Meas.	$<1x10^{-8}$
B Amplification	$<4x10^{-8}$	Meas.	$<4x10^{-9}$
B Gradient Amplification	$<3x10^{-8}$	Meas.	$<3x10^{-9}$
PA/target Nonuniformity	$<6x10^{-8}$	Meas.	$<6x10^{-8}$

Total **$1.4x10^{-7}$** → **$<1x10^{-7}$**

W.M. Snow, et al, Rev Sci Instrum. 2015 May;86(5):055101

F5 Systematic Error Estimates

Table 1. A list of systematic effects in our search for the V_5 interaction using a slow neutron polarimeter. These estimates all hold for the internal magnetic fields of 2 mG measured in the apparatus during the experiment using fluxgate magnetometers. We have included all systematic errors associated with analysis after both modes of target cancellation (diagonal averaging followed by 90-degree target rotation). All of the dominant sources of systematic error on this list scale with the size of these residual internal fields.

Source of systematic	Uncertainty (rad)
small angle scattering from ^4He gas	$< 2 \times 10^{-6}$
target mass diamagnetism	2×10^{-7}
neutron-atom spin-orbit scattering	5×10^{-9}
target magnetic impurities	$< 2 \times 10^{-6}$
target misalignment	$< 2 \times 10^{-5}$
electronic crosstalk	$< 1 \times 10^{-8}$
target reflectivity differences	$< 2 \times 10^{-5}$
Total	$< 2.8 \times 10^{-5}$