Overview of the nEDM@SNS Project

4th International Workshop on Searches for a Neutron Electric Dipole Moment

Les Houches, Feb 14-19, 2021

Wolfgang Korsch (University of Kentucky)

for the nEDM@SNS Collaboration

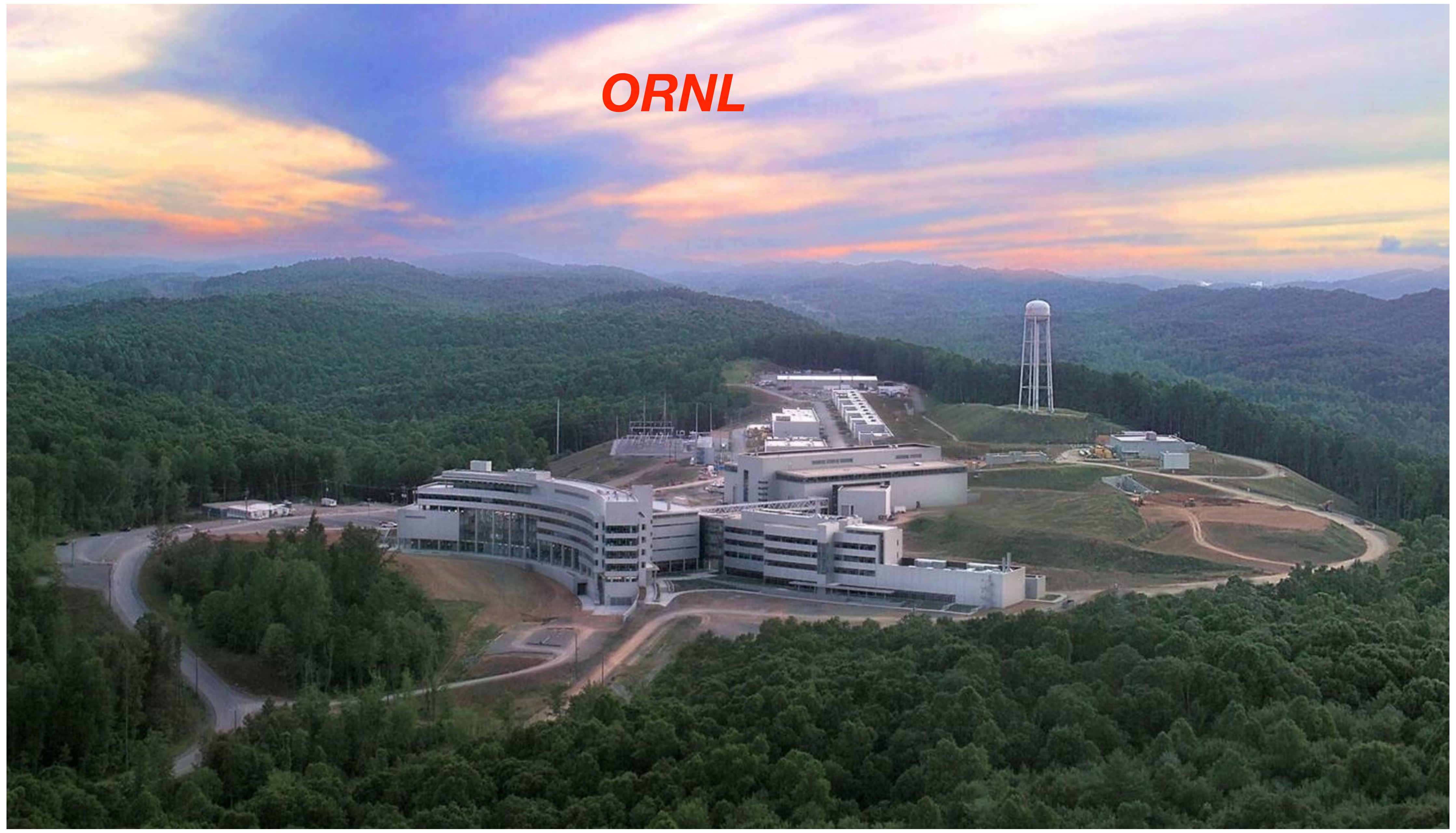
Funding Agencies

nEDM@SNS Collaboration

Co-spokespeople: V. Cianciolo, B. Filippone
Chief Senior Scientist: R. Golub
Chief Engineer: J. Ramsey

Experiment Director: P. Huffman
Experiment Manager: B. Plaster

Collaboration: ~95 members



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Physics concept: R. Golub and S. K. Lamoreaux, Phys. Rep. 237, 1 (1994)

Basic Concept of Experiment

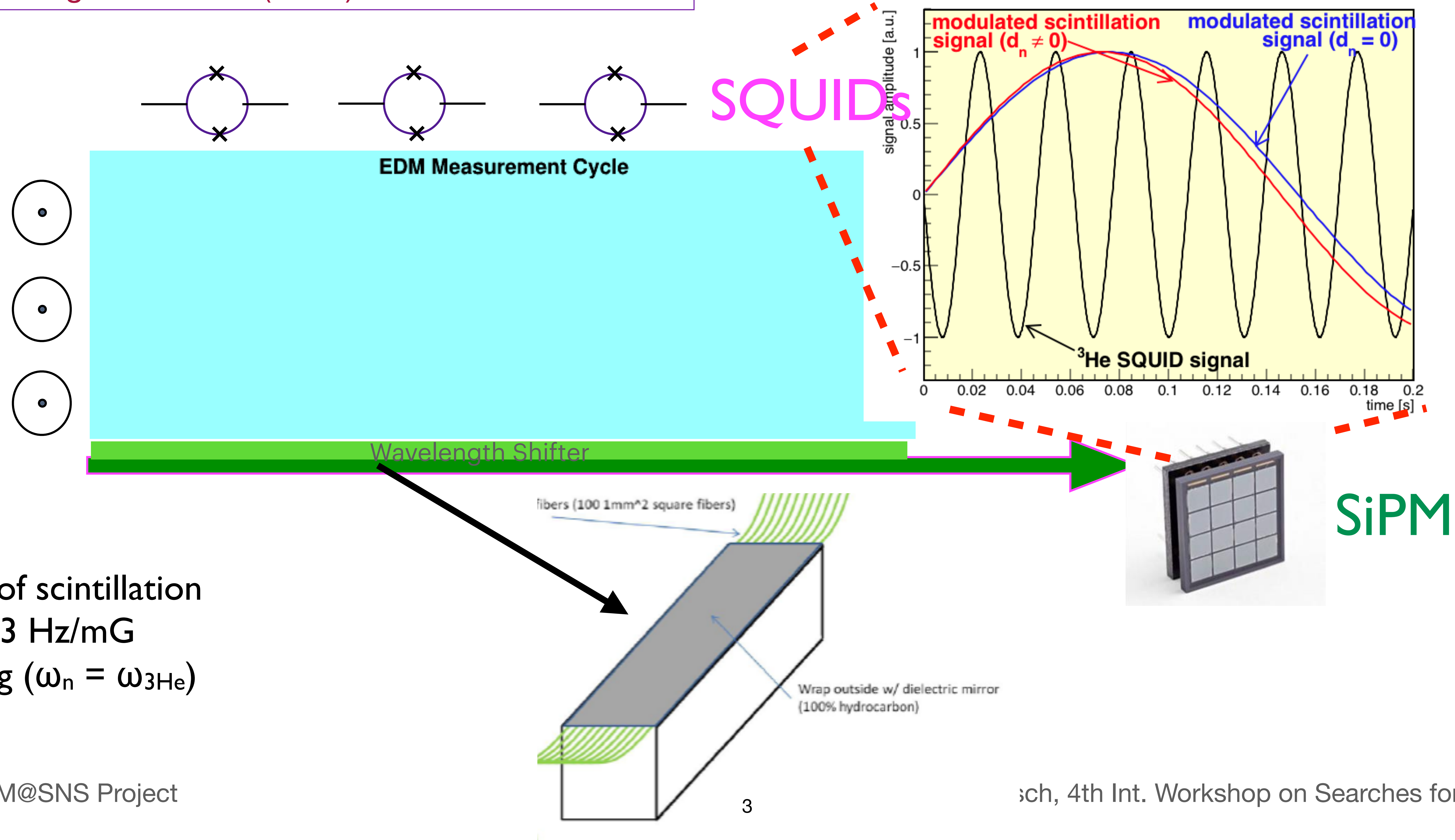
Take advantage of the strong spin-dependent cross section:

- store polarized UCNs in a box and add polarized ^{3}He
- $n + {}^3He^{++} \rightarrow p + t + 764$ keV
- detect scintillation light in SFLHe ($^4He_2^*$)

G. Greene: "The reason for the existence of helium is to measure the neutron EDM"

E-Field

B-Field



Free precession mode

modulation of scintillation light: ~0.3 Hz/mG
spin dressing ($\omega_n = \omega_{3He}$)

Some Features of the nEDM@SNS Experiment

Basic sensitivity equation:

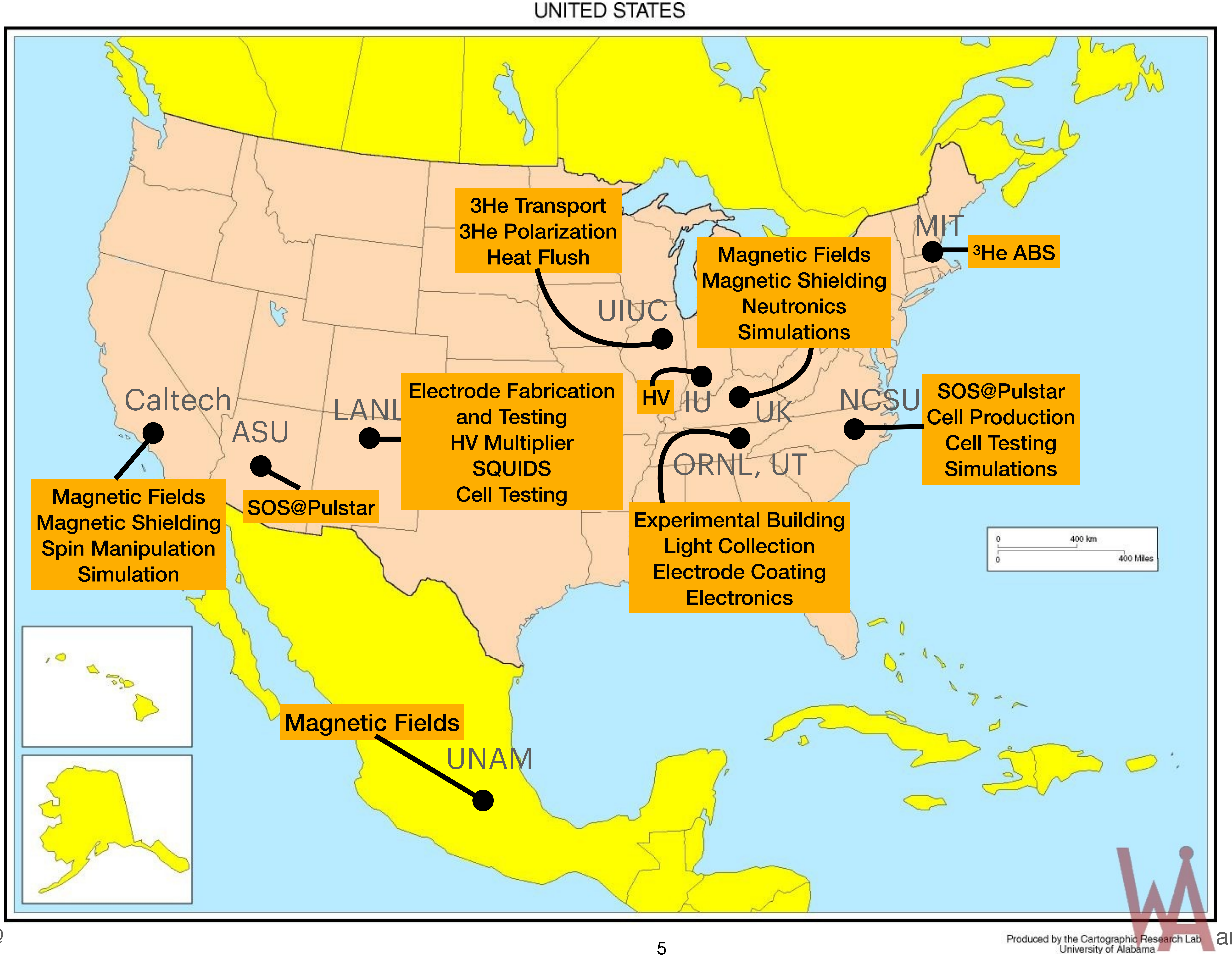
$$\sigma_d = \frac{\hbar}{2\,|\mathbf{E}|\,T_m\sqrt{mN}}$$

- E → electric field
- T_m → time per cycle
- $\sqrt{mN}$ → # of cycles × # of neutrons per cycle
- no background
- stable B- and E-fields

Goal: $|d_n| \lesssim 3 \times 10^{-28}$ e-cm @ 90% C.L.
(in three calendar years)

- ***Large number of trapped UCNs***
  - down-scattering of 0.89 Å neutrons via photons in SF^4He
  - store neutrons in LHe target cells
- ***Use two cells with E-fields in opposing directions***
  - two measurements at the same time → better systematics
- ***LHe as a HV insulator***
  - higher electric fields
- ***mu-metal magnetic shield enclosure + superconducting shield***
  - reduction of magnetic field variation
- ***Stable B_0 field using superconducting magnet***
- ***Use of ^3He co-magnetometer***
  - correct for systematic effects due to changing B-fields
- ***Variation of LHe temperature to study v x E systematics***
  - study and minimize geometric phase
- ***Precession frequency measurements via two techniques***
  - Critical spin dressing
  - free spin precession
  - compare methods → different systematic effects

nEDM@SNS Efforts in the US and Mexico



- Polarized Neutrons
- Polarized Helium-3
- Magnetic Field and Magnetic Shielding
- High Voltage (Electric Field)
- Systematics

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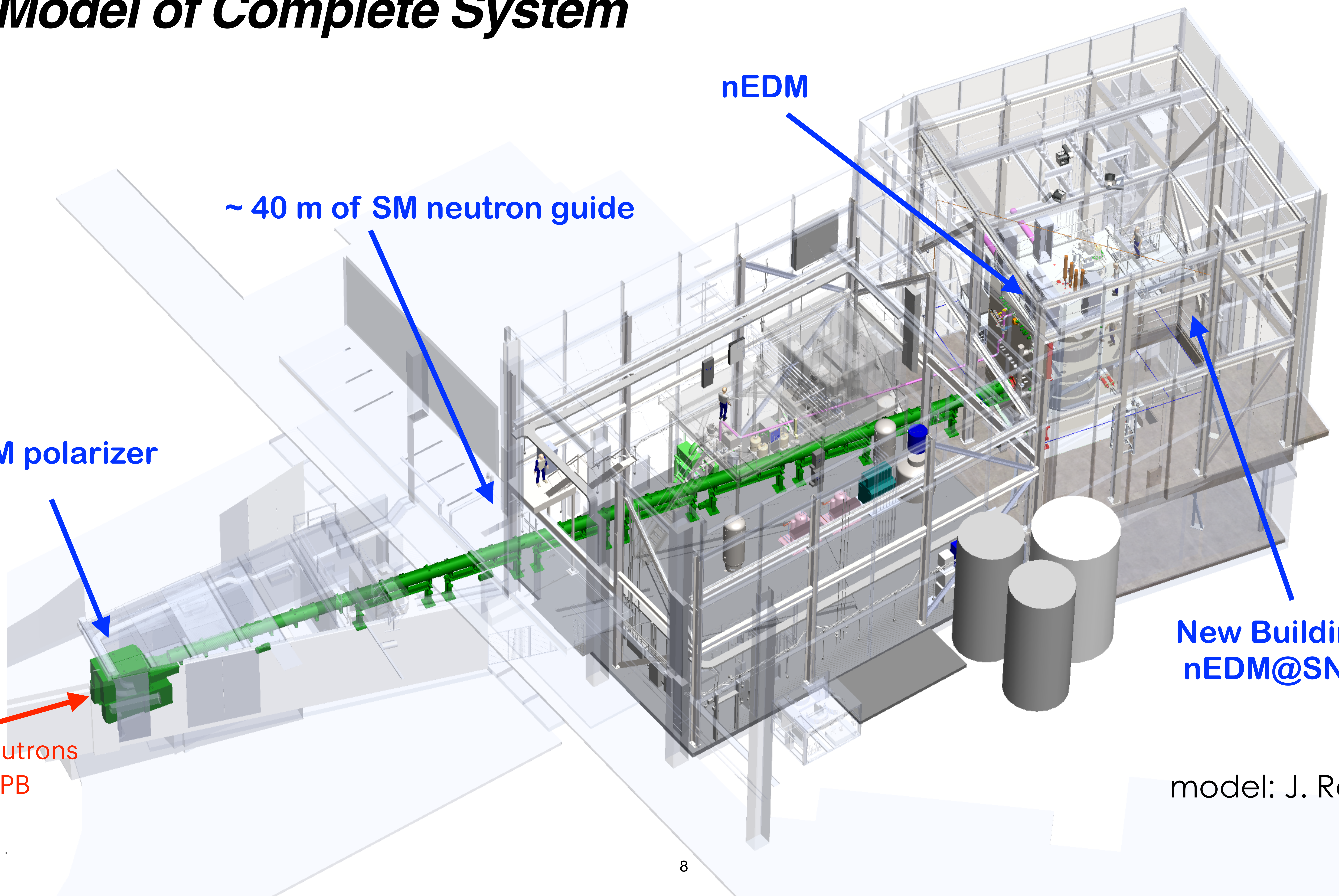
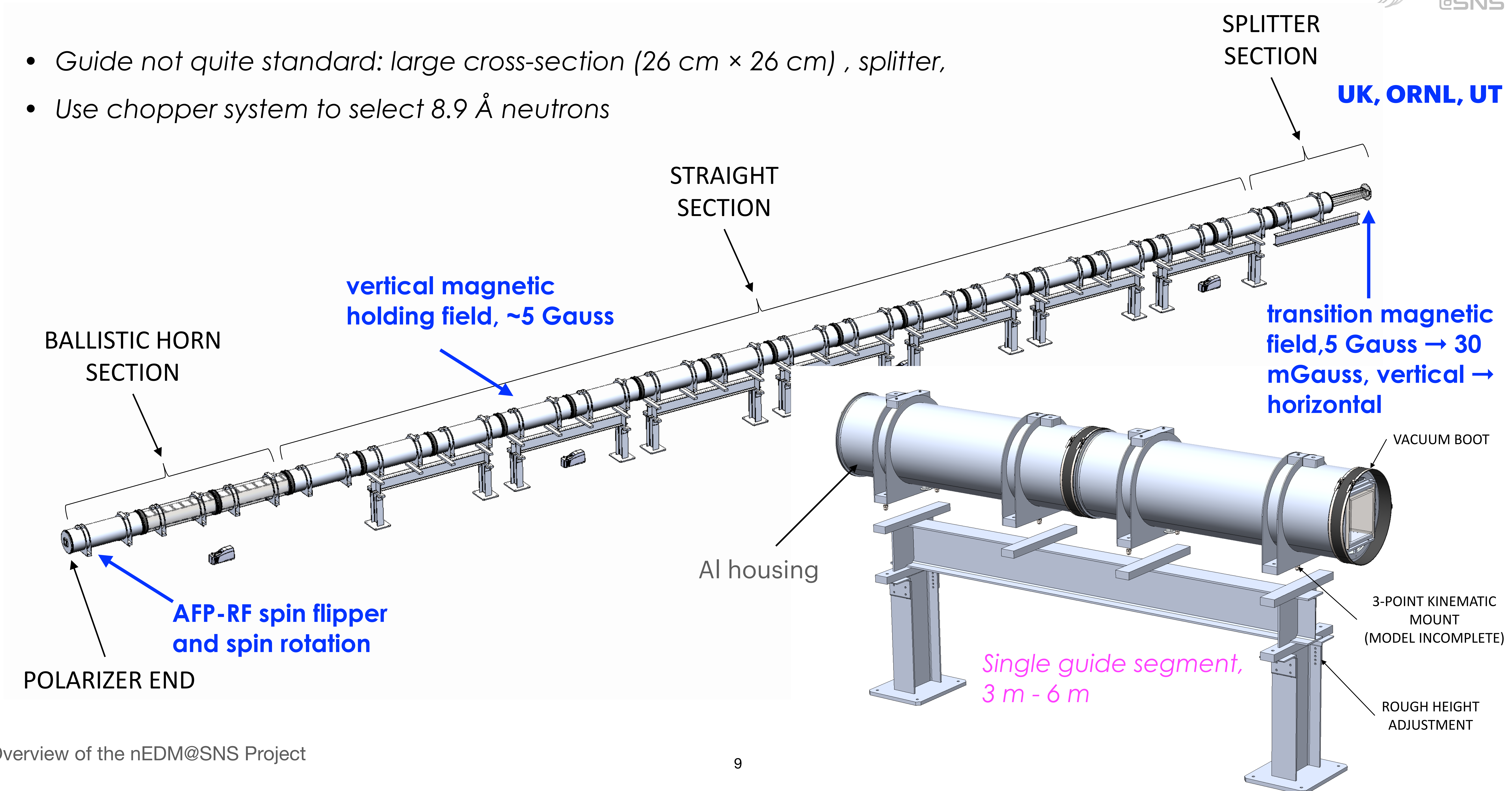
CAD Model of Complete System

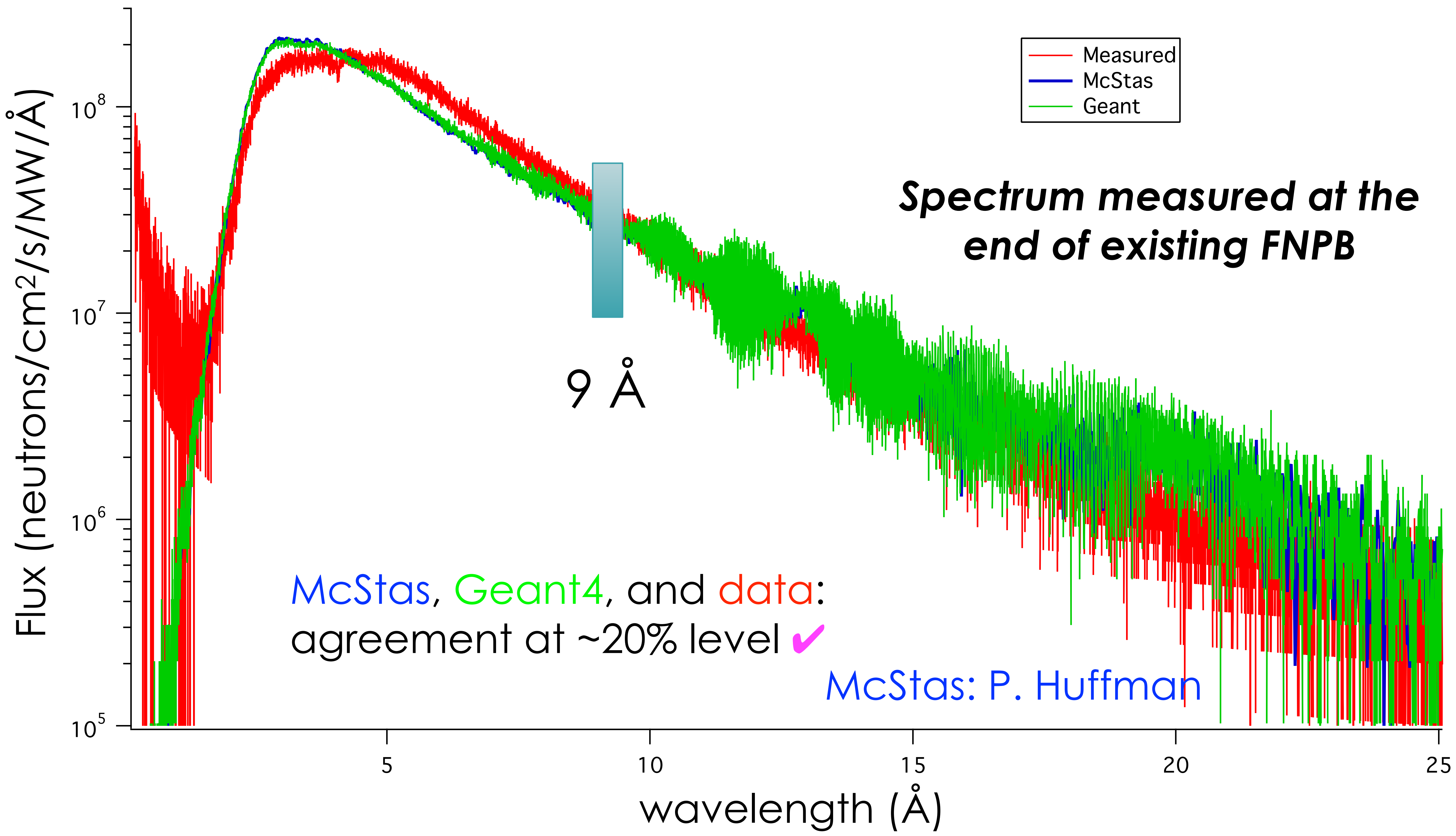


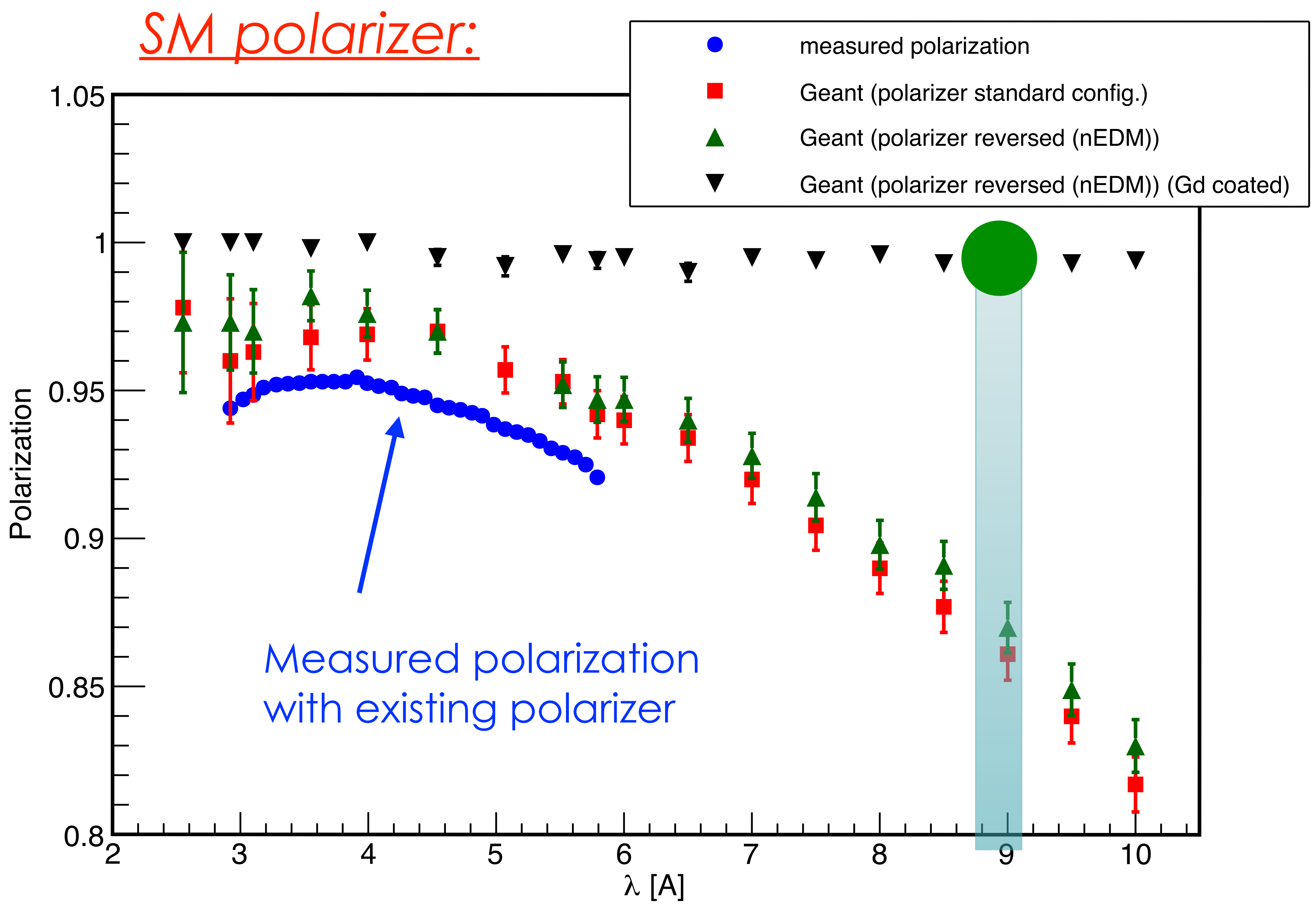
Neutron Guide and Magnets

- *Guide not quite standard: large cross-section (26 cm × 26 cm) , splitter,*
- *Use chopper system to select 8.9 Å neutrons*



Neutron Flux and Polarization



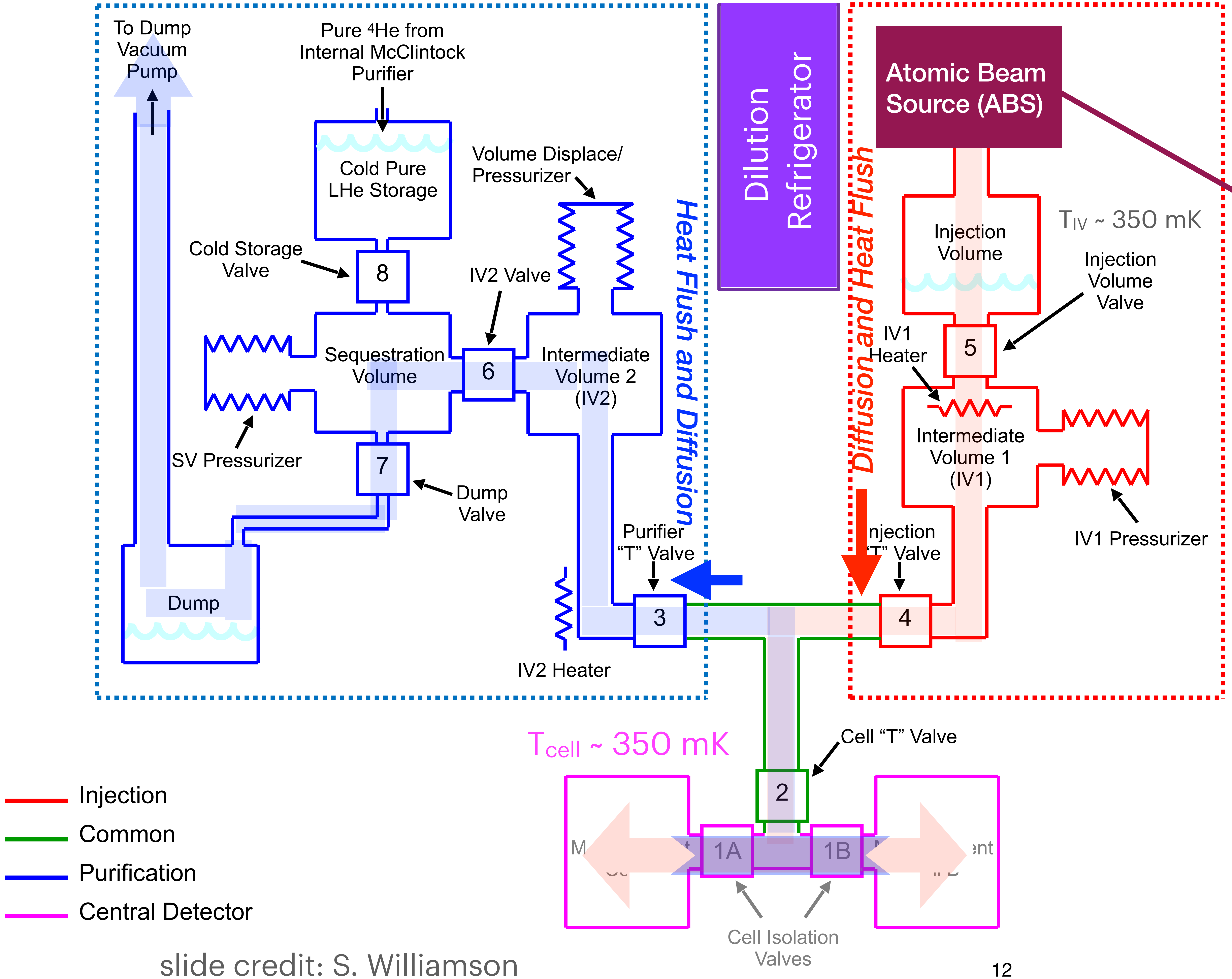


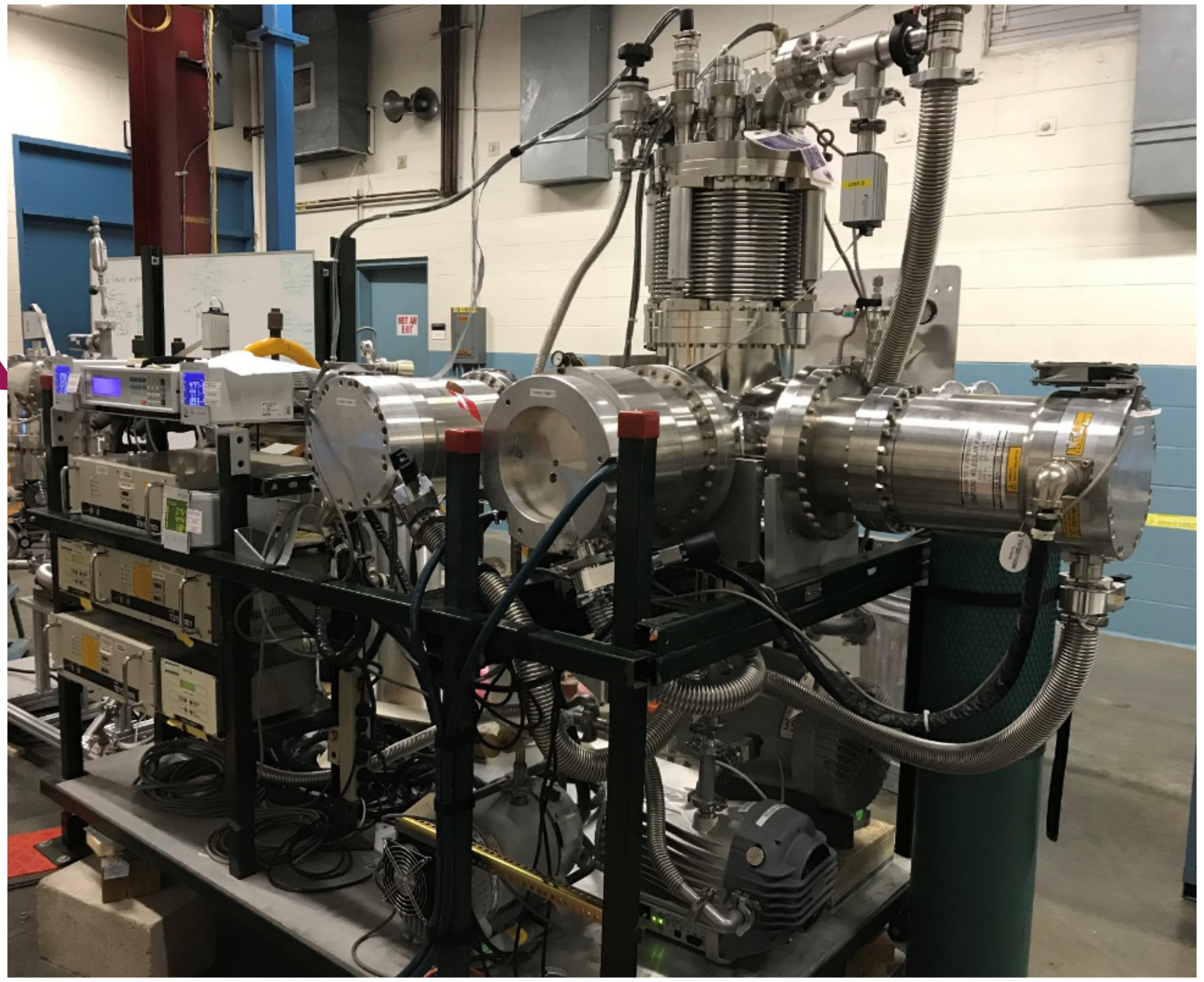
neutron flux into two cells: $\frac{d\phi}{d\lambda} \approx 6 \times 10^6\ n/s/cm^2/MW/\text{Å}$, P > 95% ➔ ~0.26 UCN/s/cm³ at 2 MW

Conceptual guide design finished!!

- Polarized Neutrons
- Polarized Helium-3
- Magnetic Field and Magnetic Shielding
- High Voltage (Electric Field)
- Systematics

Production and Transport of ^{3}He





details: talk by Mark Broering

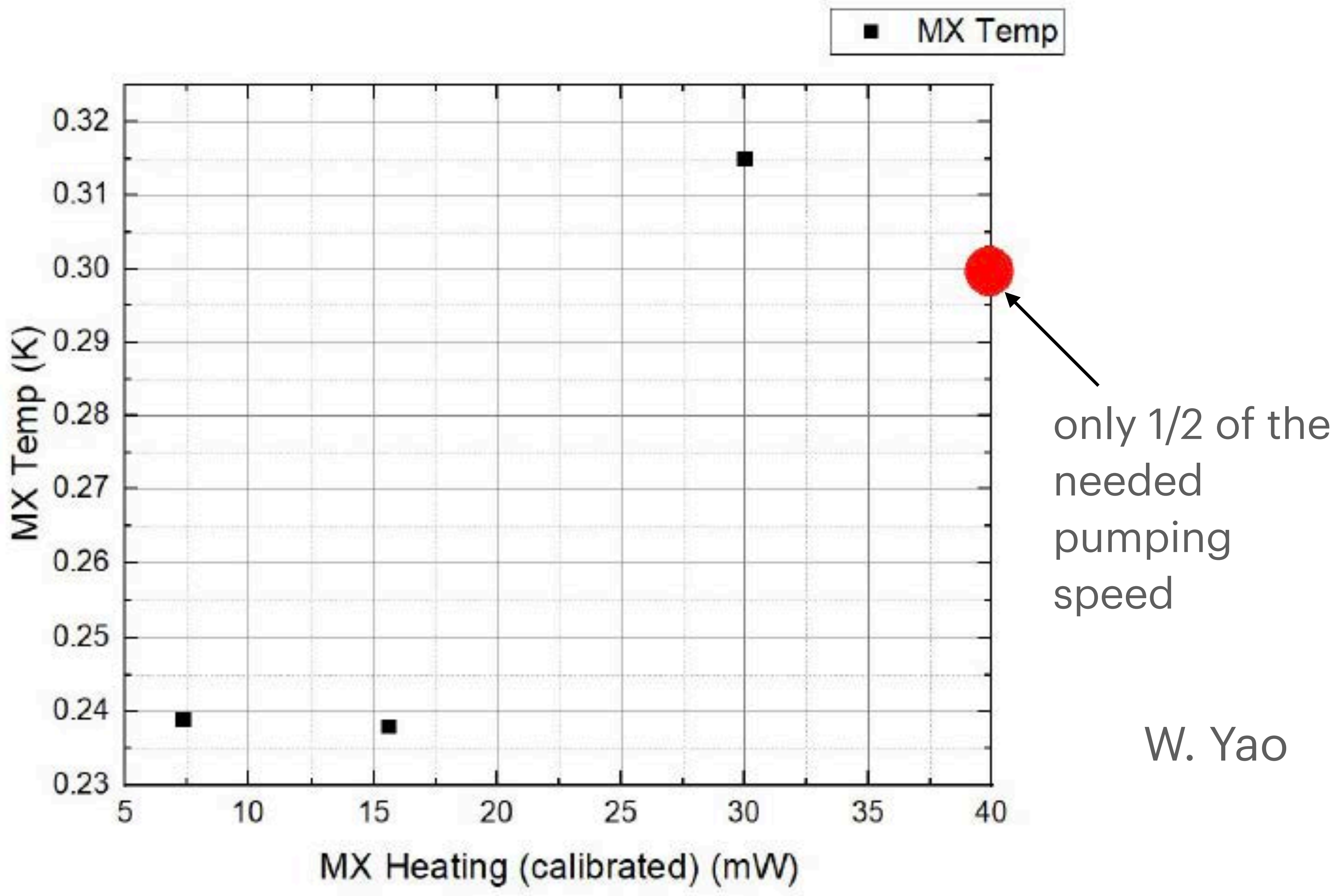
ABS at MIT-Bates

ABS will be mounted vertically

Goal:
injection flux: 10^{14} ^{3}He/s, P ≳ 98%

slide credit: S. Williamson

Non-magnetic Dilution Refrigerator Development



W. Yao

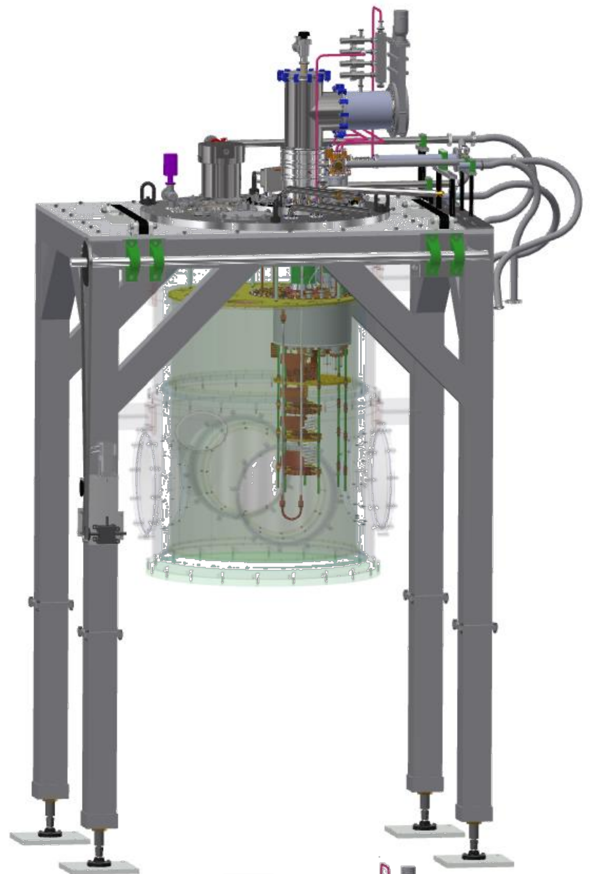
Non-magnetic dilution refrigerator successfully constructed.

Need two non-magnetic high-power dilution refrigerators.

UIUC Lab

Polarized ^{3}He Transport and Purification

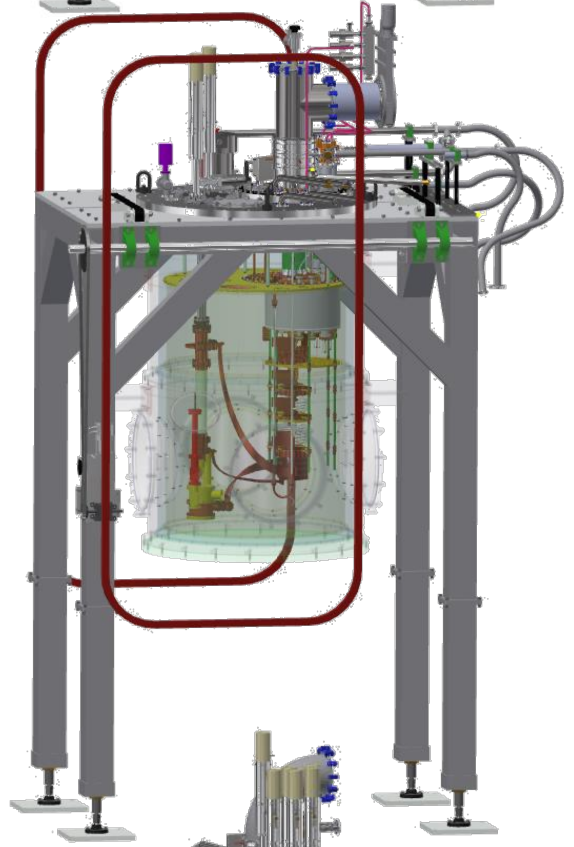
1. Completion and commissioning of the DR – essentially complete



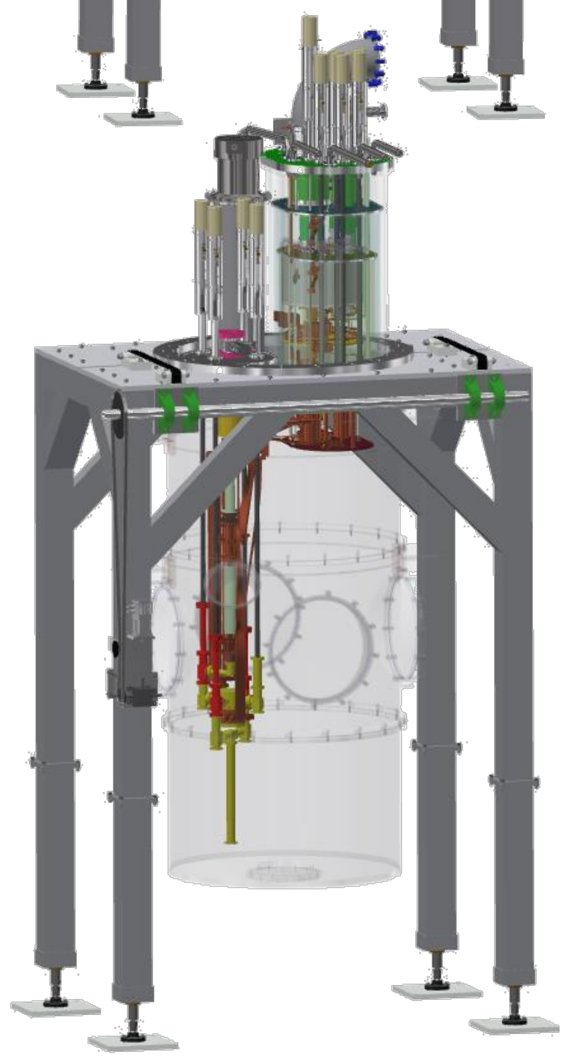
2. Fabricate/assemble/test injection system components – current phase

Use test-stand vacuum system and top flange.

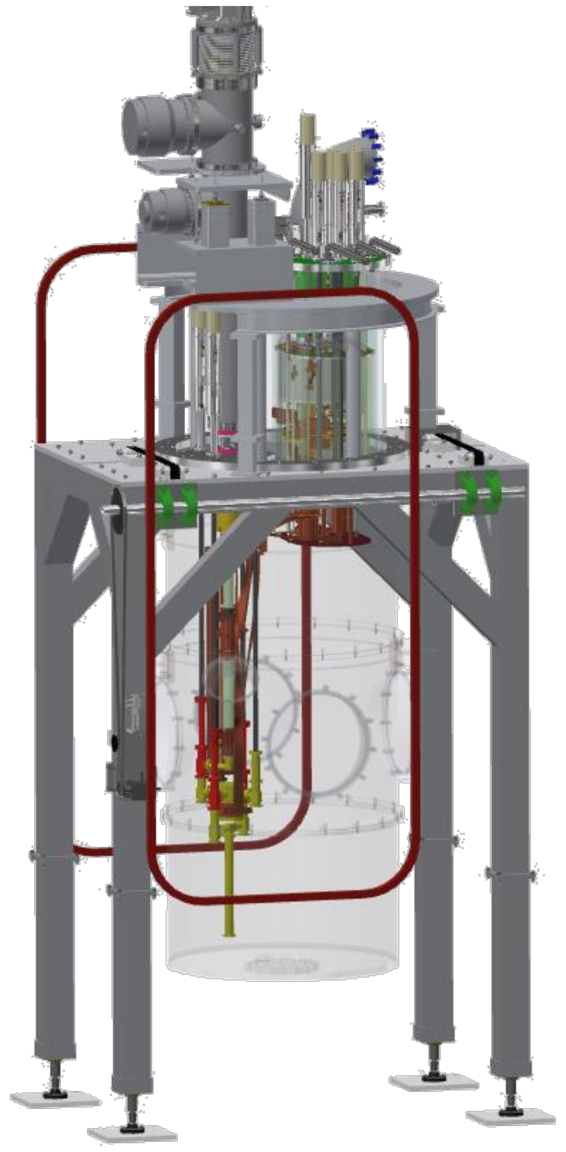
- Includes *in situ* “High field” wall depolarization testing.
- Holding field coils, MEOP ^{3}He polarization.



3. Fabricate/assemble/test purification system components



4. High-field polarization transport
   - ABS and support.
   - Holding field coils,
   - “Real beam line” including ABS interface.
   - Check heat flush transport to test volume.



5. Low-Field Polarization Testing at ORNL
   - Segmented vacuum chamber, SQUID polarization measurement, spin-transport coils

more details: talk by Christian White

slide credit: S. Williamson

- Polarized Neutrons
- Polarized Helium-3
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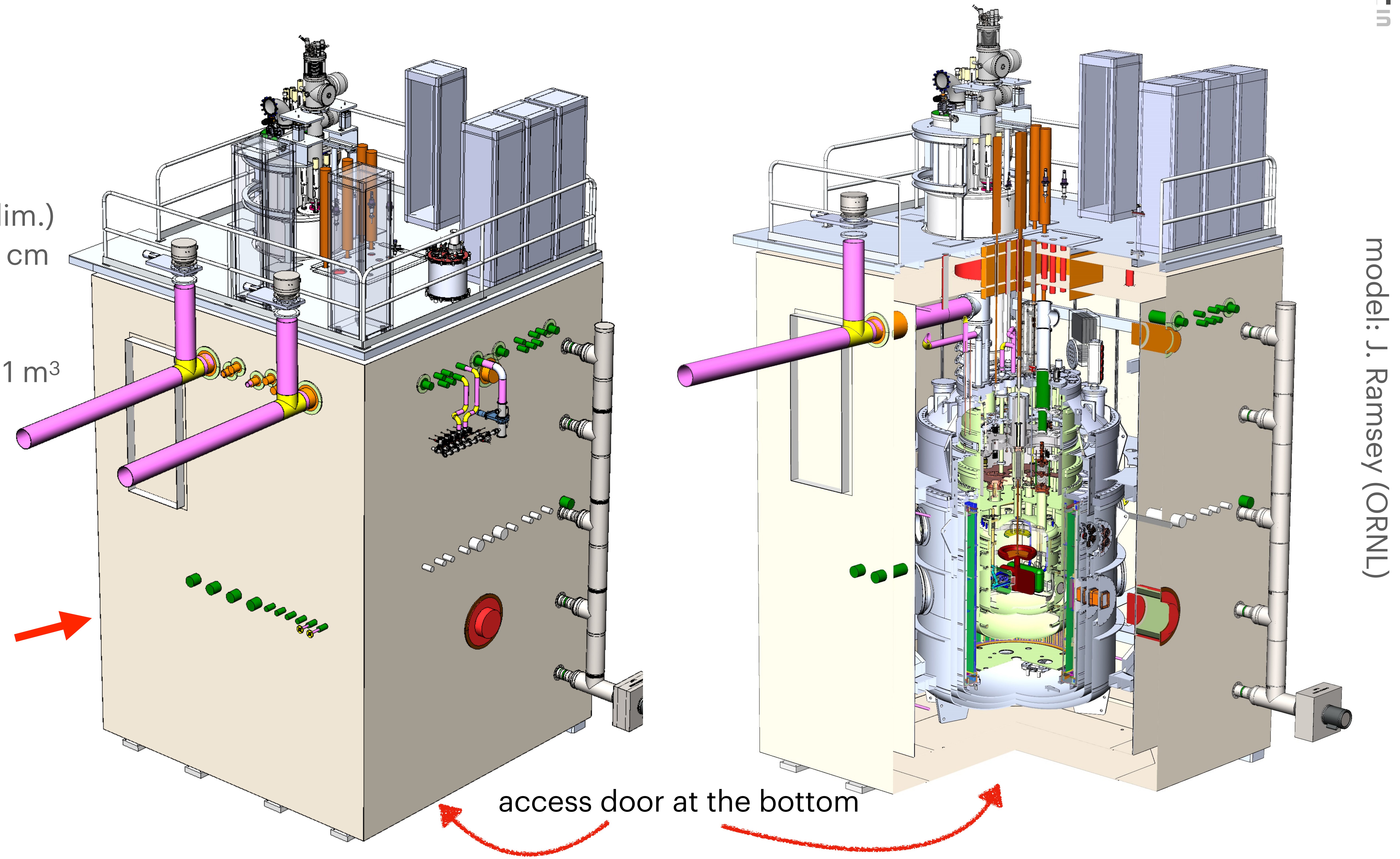
nEDM Magnetic Shielding Requirements

Outer shielding:

- Field compensation coils (not shown)
- Magnetic shielding enclosure
  - 4.1 m × 4.1 m × 6.1 m (inner dim.)
  - 2 × 3 mm μ-metal layers, 40 cm separation
  - residual field < 10 nT
  - gradient < 2 nT/m in central 1 m^3
  - SF 100 @ 0.01 Hz

Inner shielding:

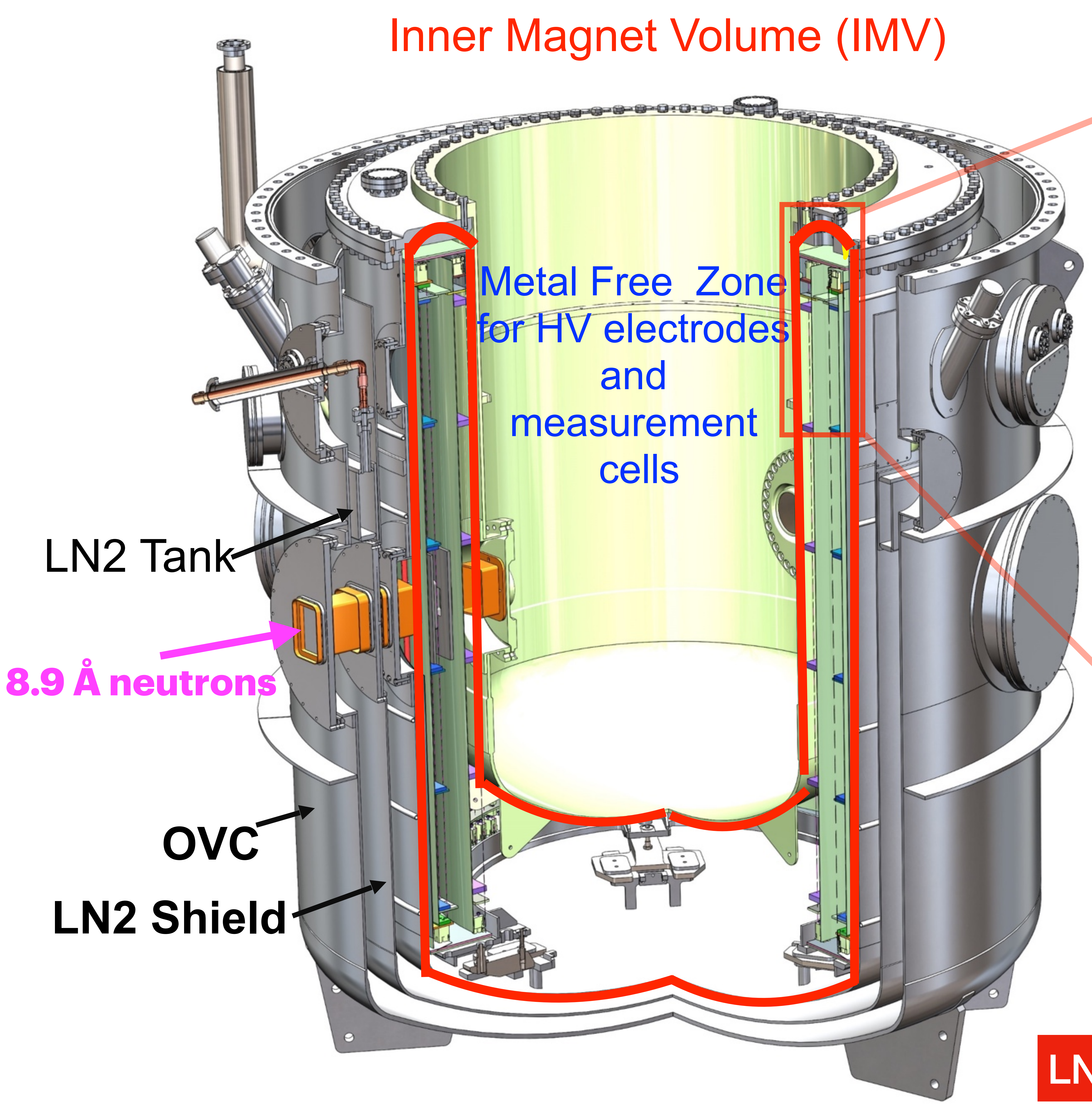
- Superconducting Pb
- SF ~1000

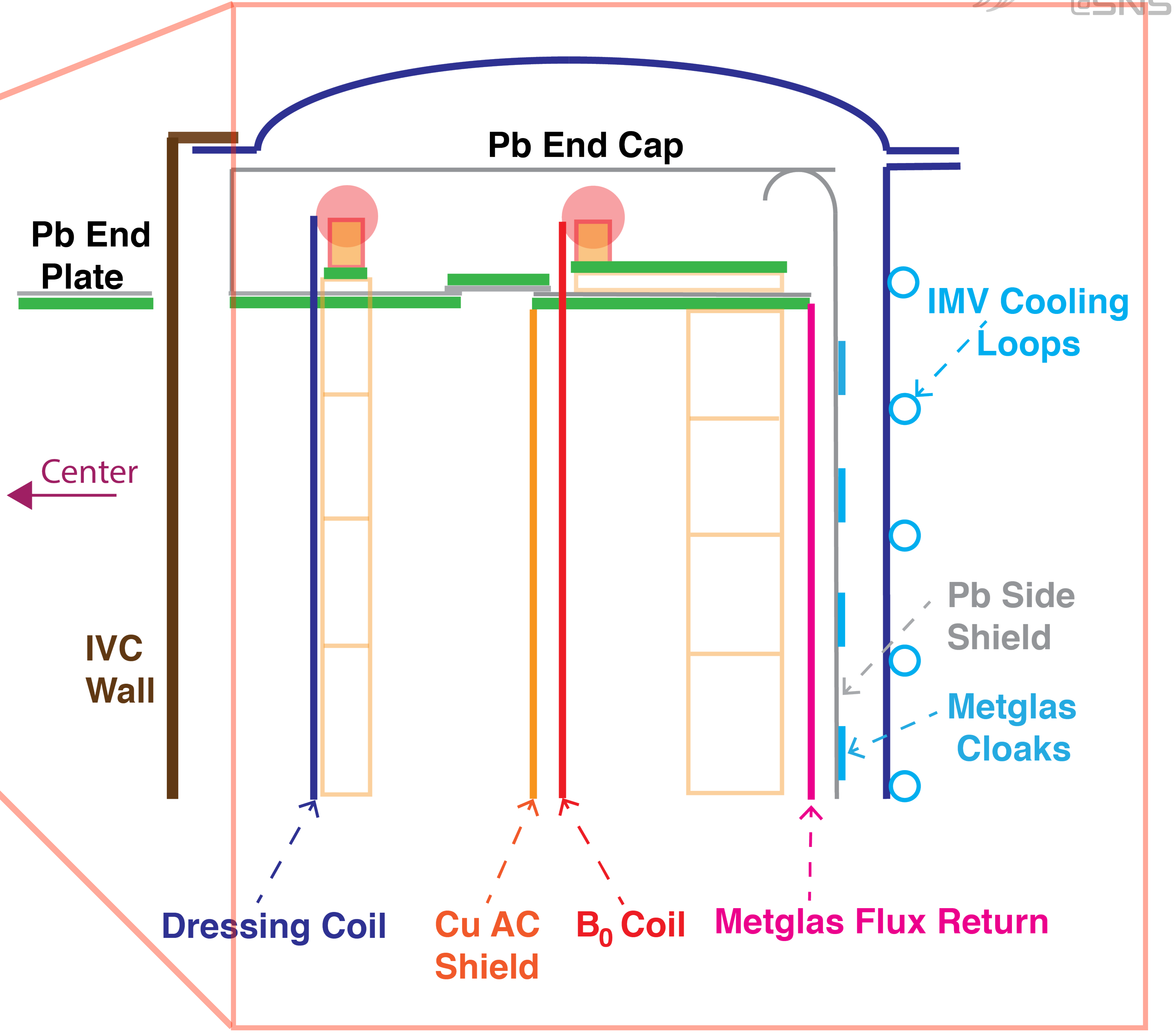


- *2 layer μ-metal magnetic shielding enclosure*
- *presently being designed at IMEDCO*

B. Plaster

Magnet Package



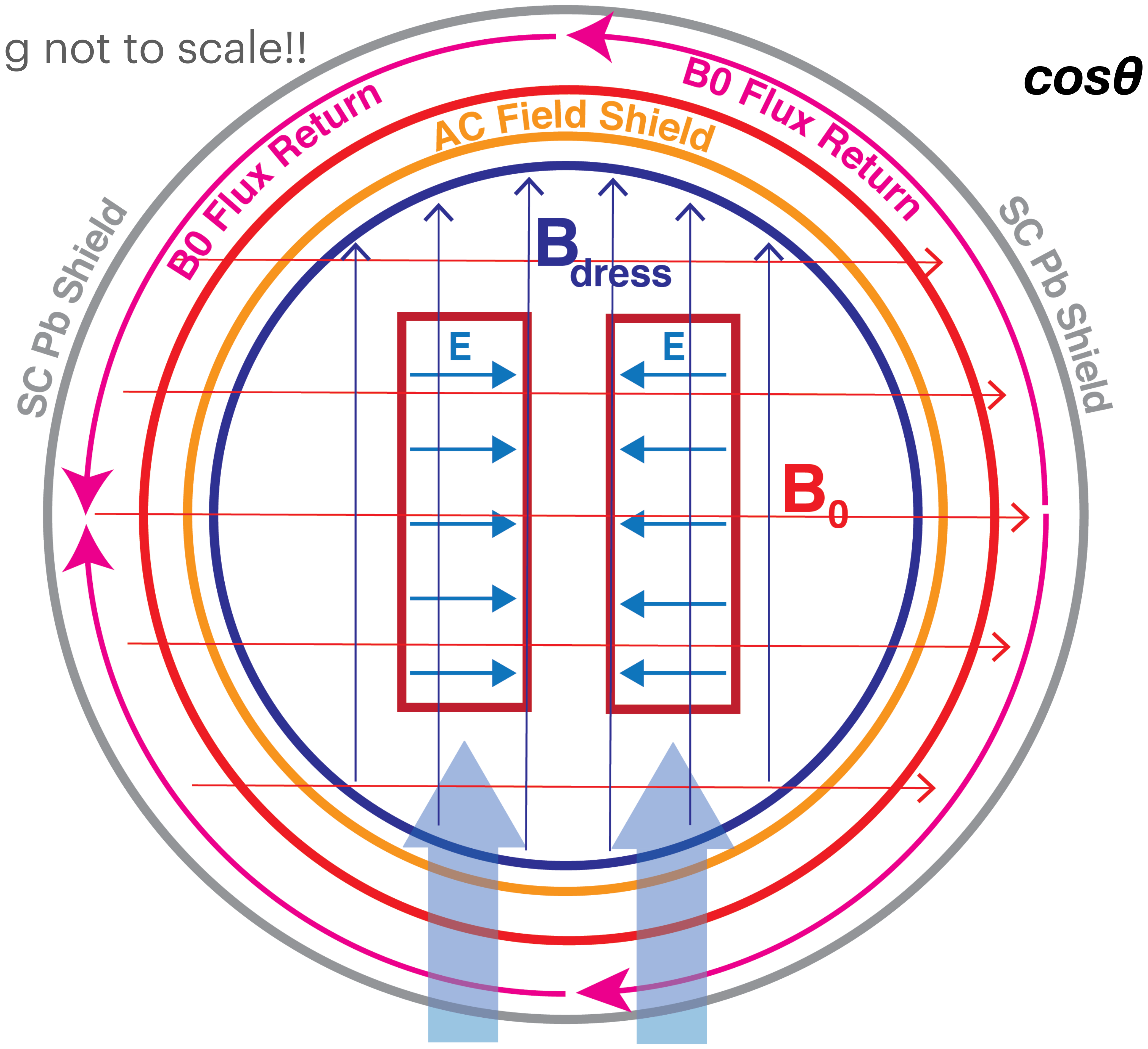


LN2 shield successfully cooled to 88K @ CIT

slide credit: B. Filippone

Magnetic Field System

Drawing not to scale!!



Required specs for B-field uniformity achieved in 1/3-scale prototype.

cosθ Coils

B_0 Coil: (Superconducting Cu-clad NbTi wire)

30 mG and uniformity of 3 ppm/cm

uniformity is crucial for the transverse coherence time T_2 of UCN and ^{3}He

Dressing Coil: (Superconducting Ti/Pb Solder Wire)

AC field < 0.5 G and uniformity of 45 ppm/cm

also used as $\pi/2$ spin flip

Shim & Gradient Coils: (SC NbTi wire)

DC fields: cosθ, Solenoid, Gradients wound on dressing coil

B_0 Flux Return:

Metglas 2826M, location accuracy < 1 mm

improve field uniformity, mitigating the effect of errors in wire placement and reducing field distortions due to the cylindrical superconducting Pb shield

Superconducting Pb Shield:

Further shield the ambient environmental magnetic fields and stabilize magnetic drifts over the measurement time

AC Field Shield:

A copper film shields the Megtlas from eddy-current heating due to dressing field

Final Components

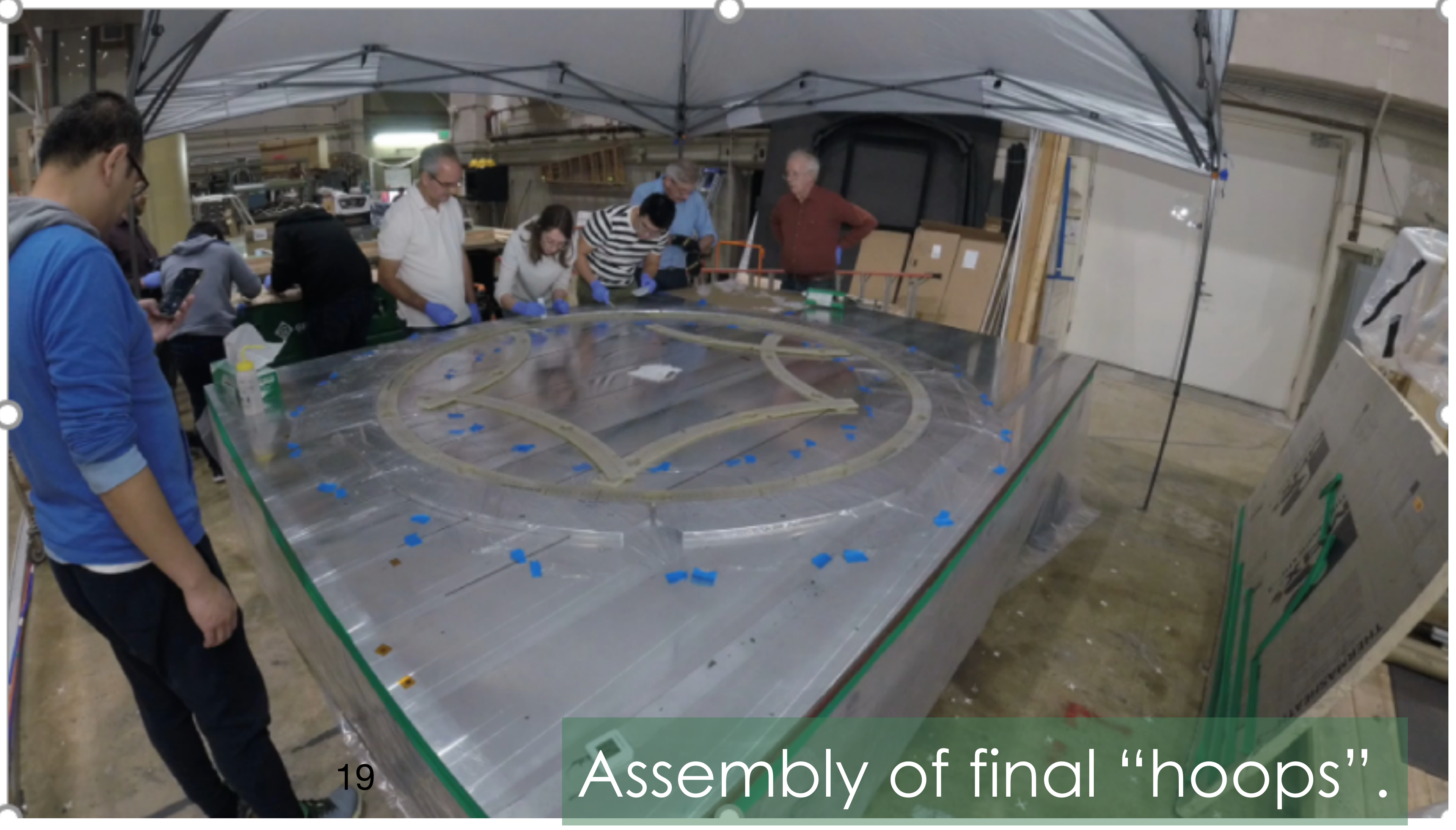

Lower Outer Vacuum Vessel

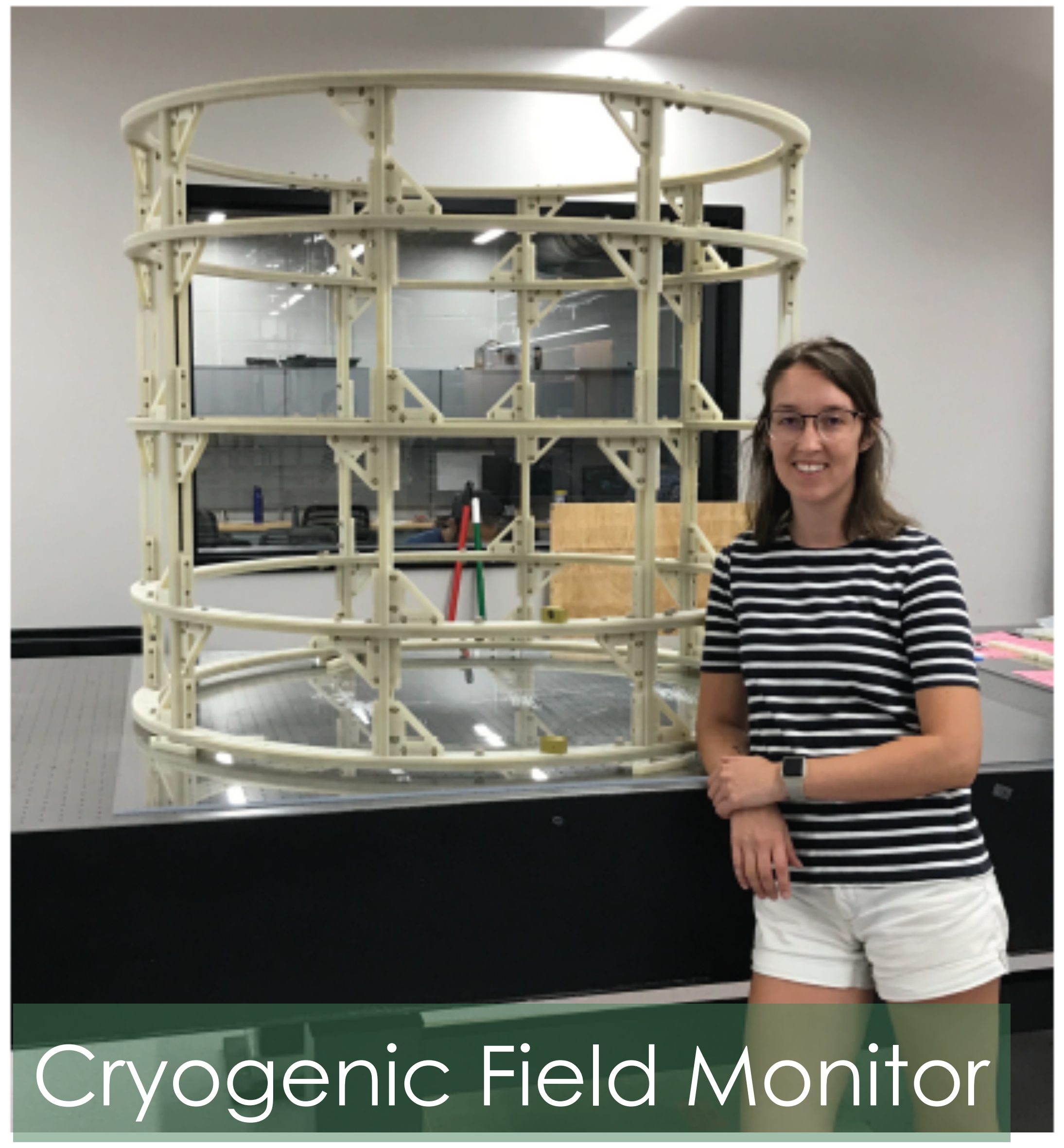
Lower 77K Shield


Inner Magnet Volume (IMV)


Magnet cryocooler

Caltech Lab


Assembly of final "hoops".


Cryogenic Field Monitor

details: talk by Alina Aleksandrova

- Polarized Neutrons
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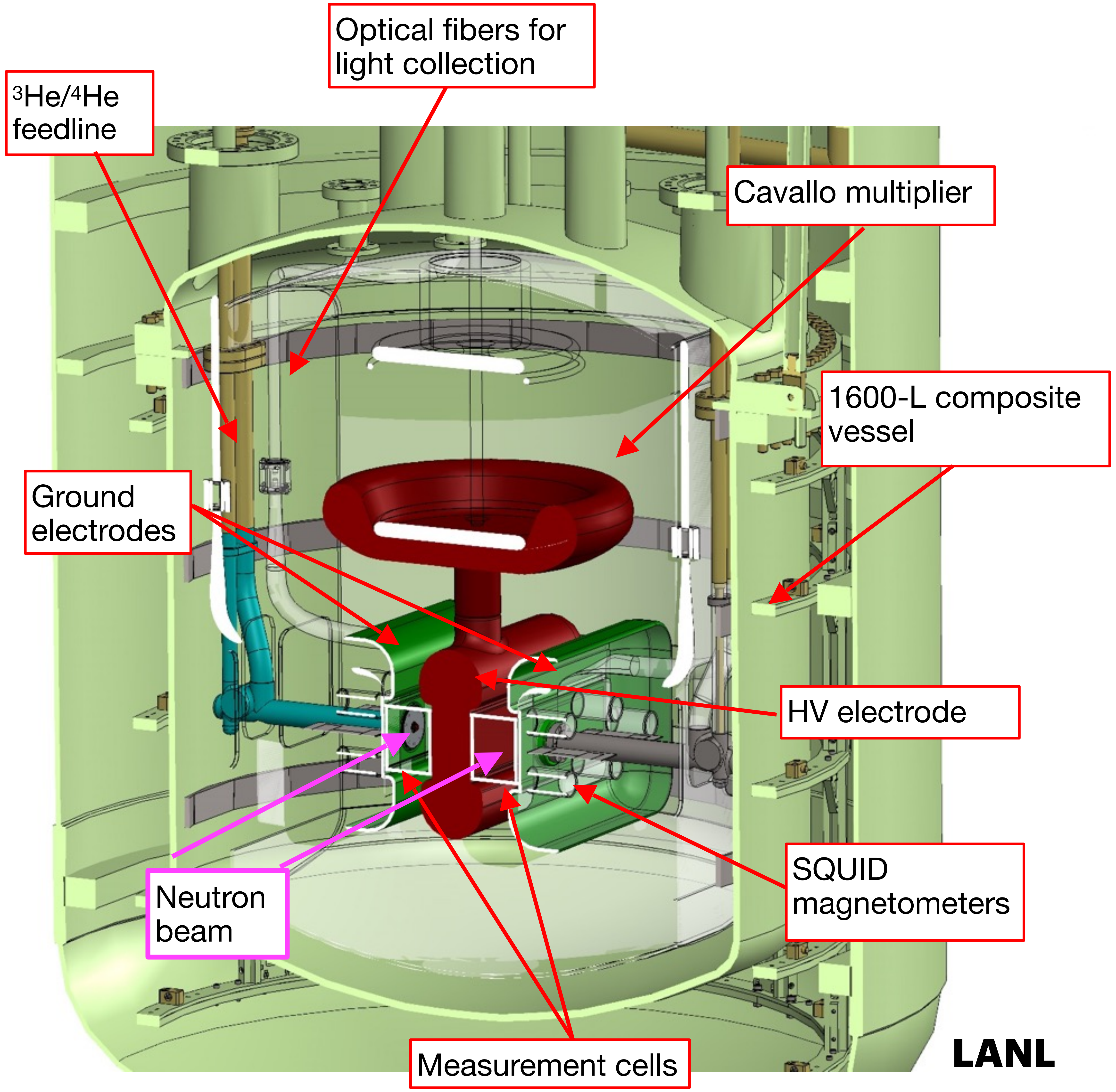
The HV System



Goal: E-field: 75 kV/cm → ~635 kV !!

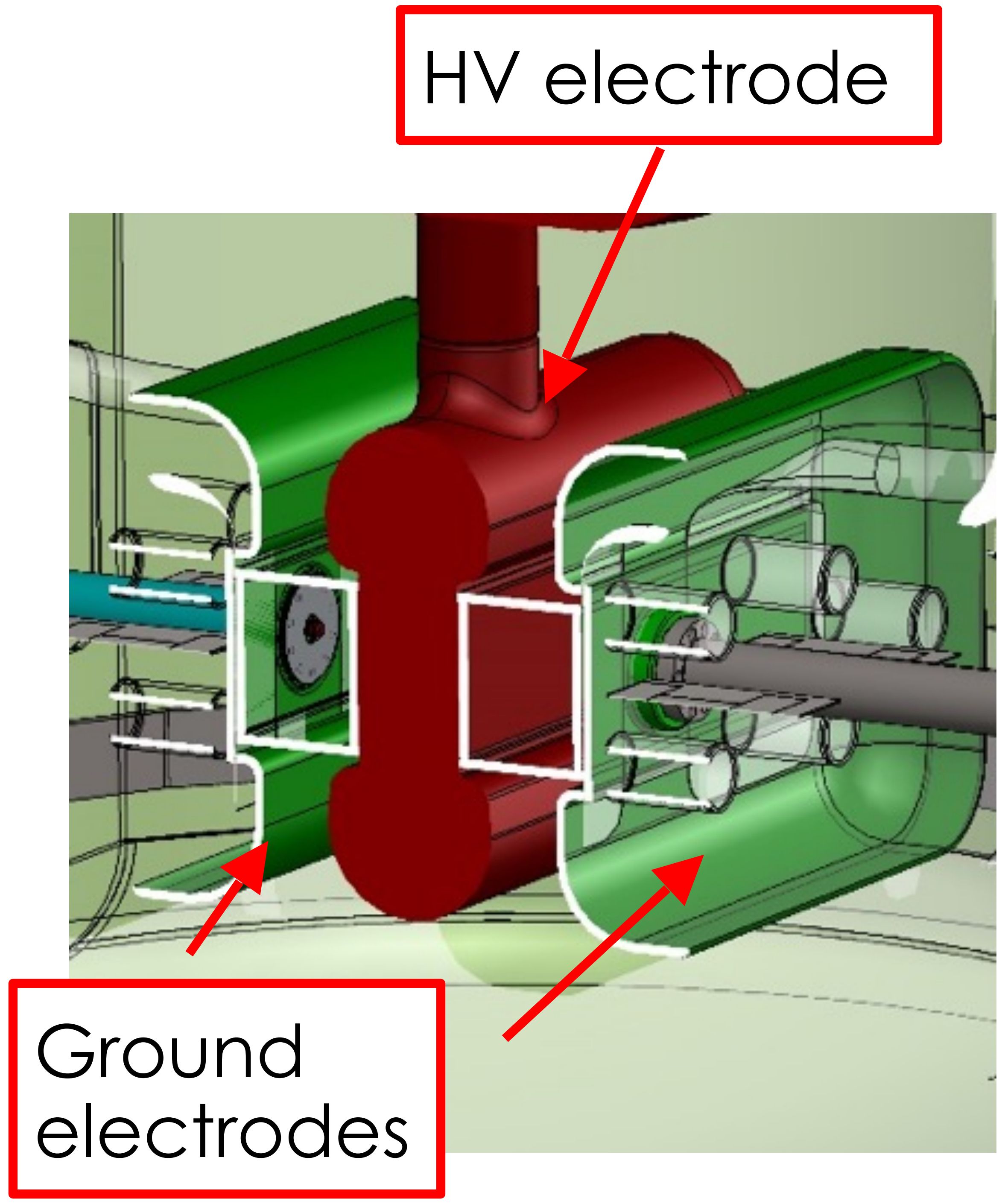
Three development stages:

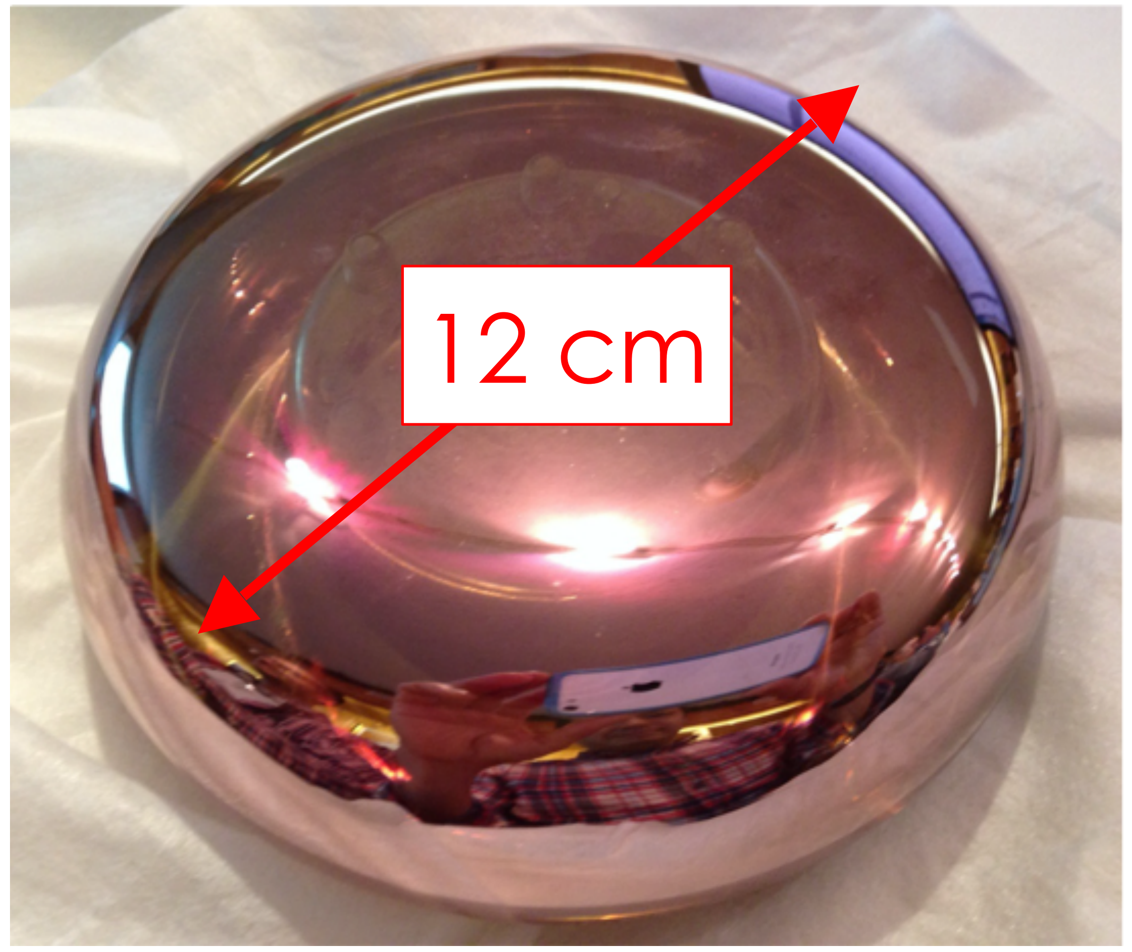
- **Small-Scale HV System (IU, LANL)**: study dielectric strength of SF4He as a function of pressure and temperature (finished)
- **Medium-Scale HV System (LANL)**: electrode tests → shape, surface, material (SS, PMMA), stability (finished)
- **Half-Scale HV System (LANL)**: electrode tests → size (scalability), surface, stability, material (in construction)
- **Full-Scale HV System**

Measurement Cell Electrodes

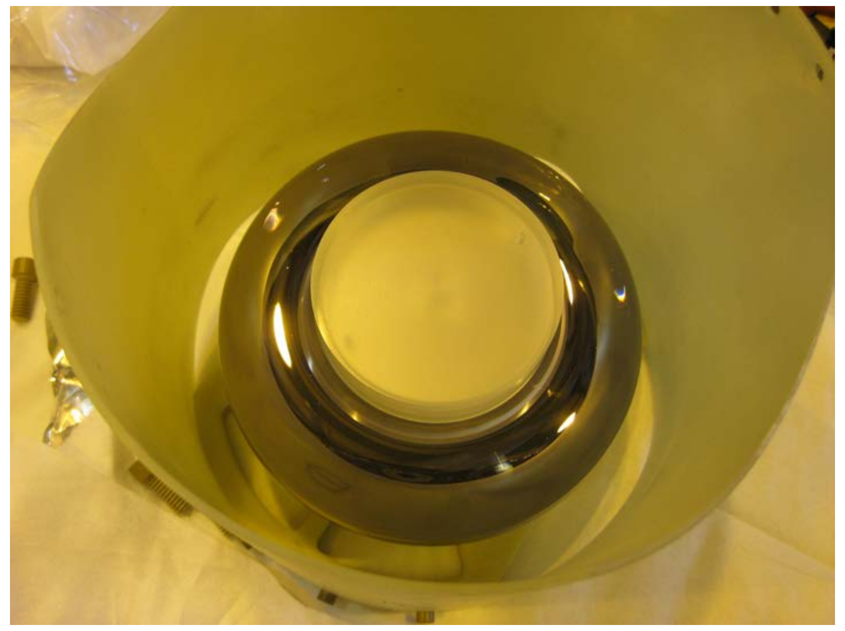
- **Ultimate goal:**
  - $E_{Cell} > 75$ kV/cm
- **Material requirements:**
  - Conductive coating on PMMA to match the CTE to the measurement cells and to keep magnetic Johnson noise and eddy current heating low
  - $100\ \Omega/\square < \sigma < 10^8\ \Omega/\square$
- **Current design:**
  - PMMA with ion implanted Cu or GeCu coating
- **Challenge:**
  - Understanding how breakdown depends on various parameters, including: electrode surface condition, electrode area & gap size, LHe pressure & temperature
  - Finding suitable materials that meet all the requirements
- **Development status:**
  - *Demonstrated stable E>85 kV/cm in the MSHV system with coated PMMA electrodes (~1/5 scale)*
  - Data-based area scaling method developed, allowing us to predict the performance of the full scale system
  - Currently commissioning the HSHV system, to confirm the scaling and test the electrode design and candidate materials with a ½ scale prototype
- **Risks:**
  - Coated PMMA electrode surfaces not performing as well as electropolished SS
  - Coated PMMA electrode surface changing its properties for each thermal cycling

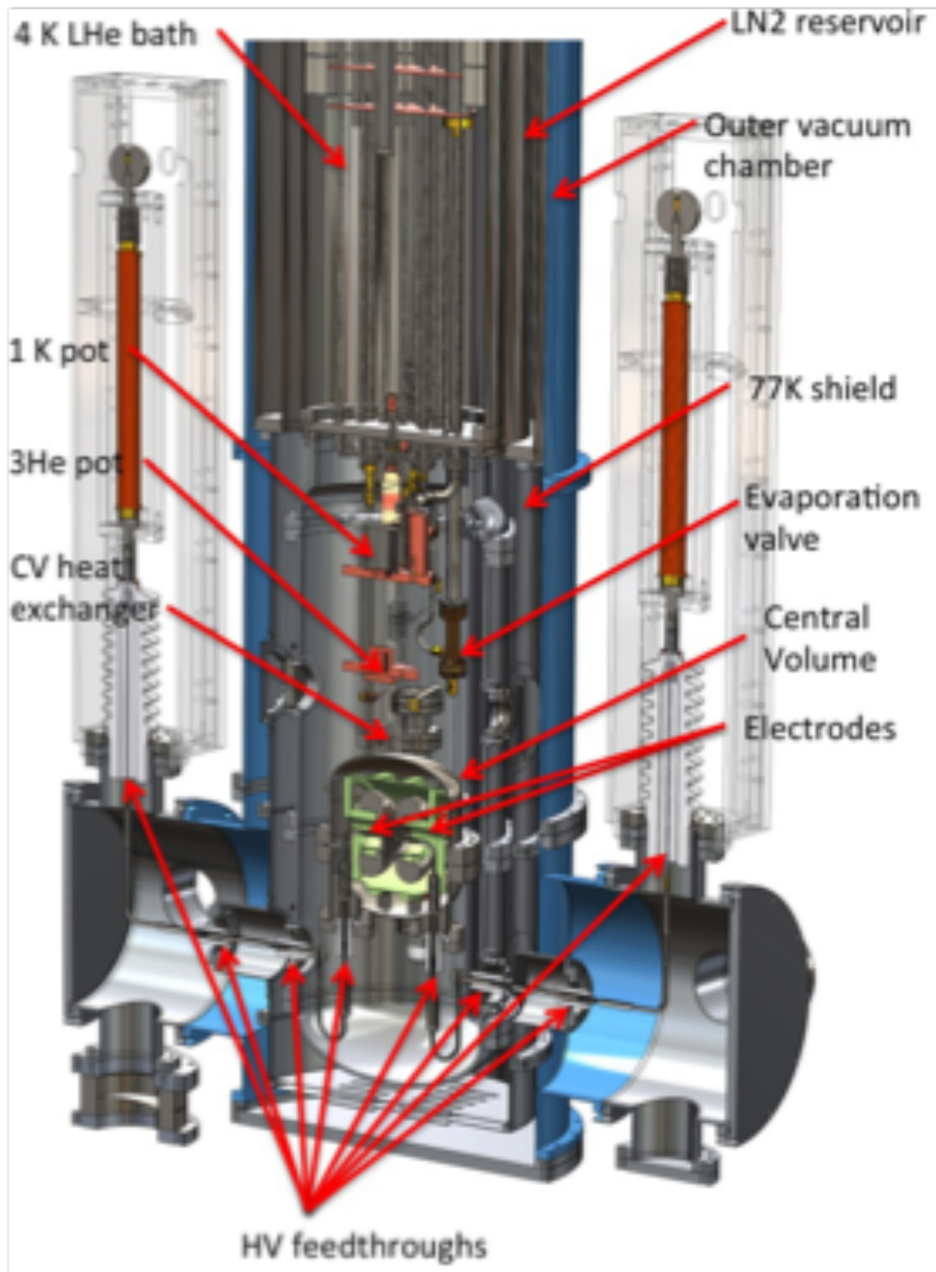
slide credit: T. Ito





PMMA electrode with Cu implantation for MSHV.
E> 85 kV/cm achieved.





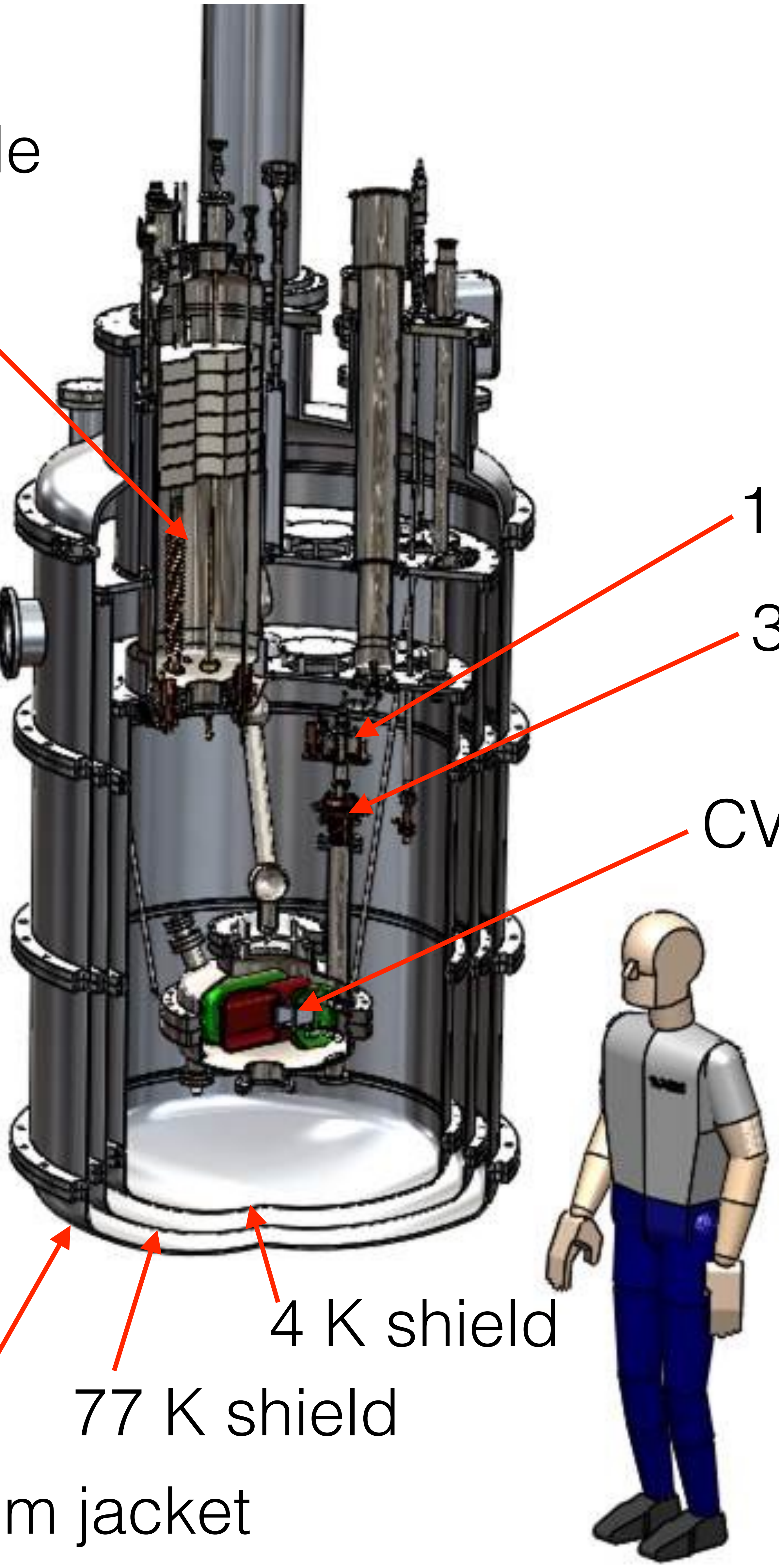
MSHV system

details: talk by Nguyen Phan

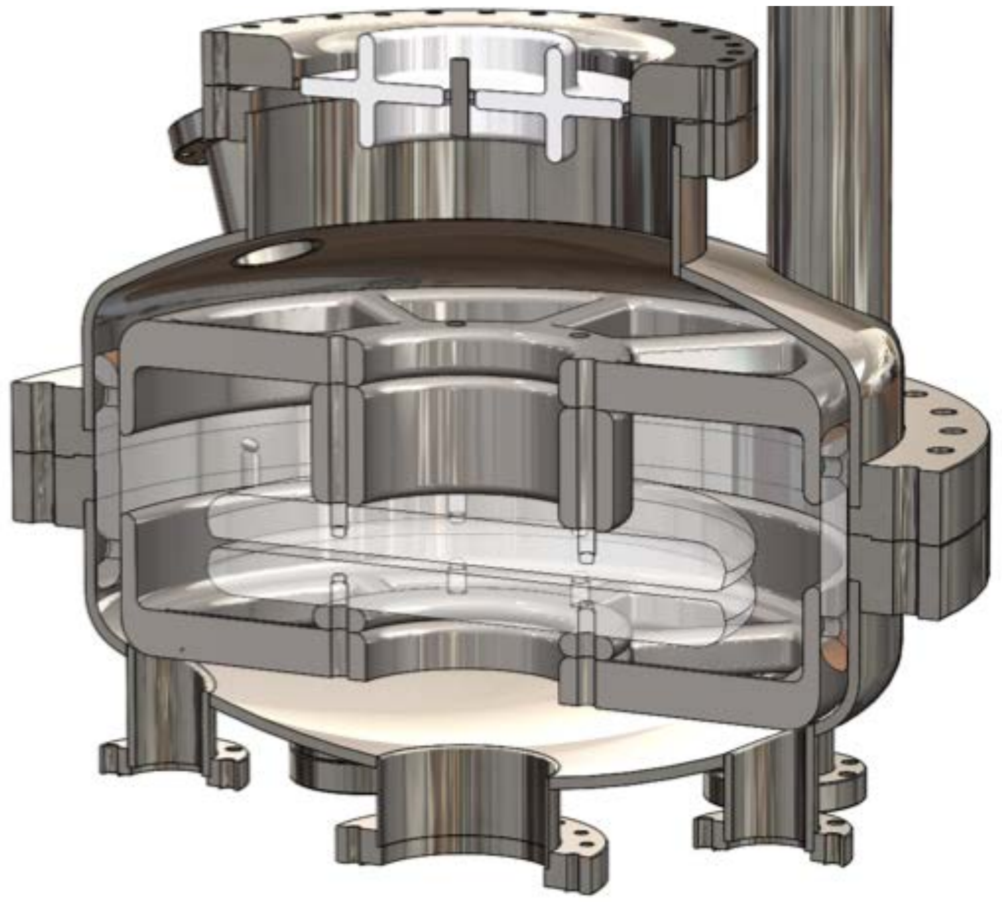
HV Electrode Testing

A half-scale electrode system is immersed in 40 liter LHe volume cooled to 0.4 K. HV performance test will be performed with 200 kV direct HV feed. The cryostat is currently being commissioned.

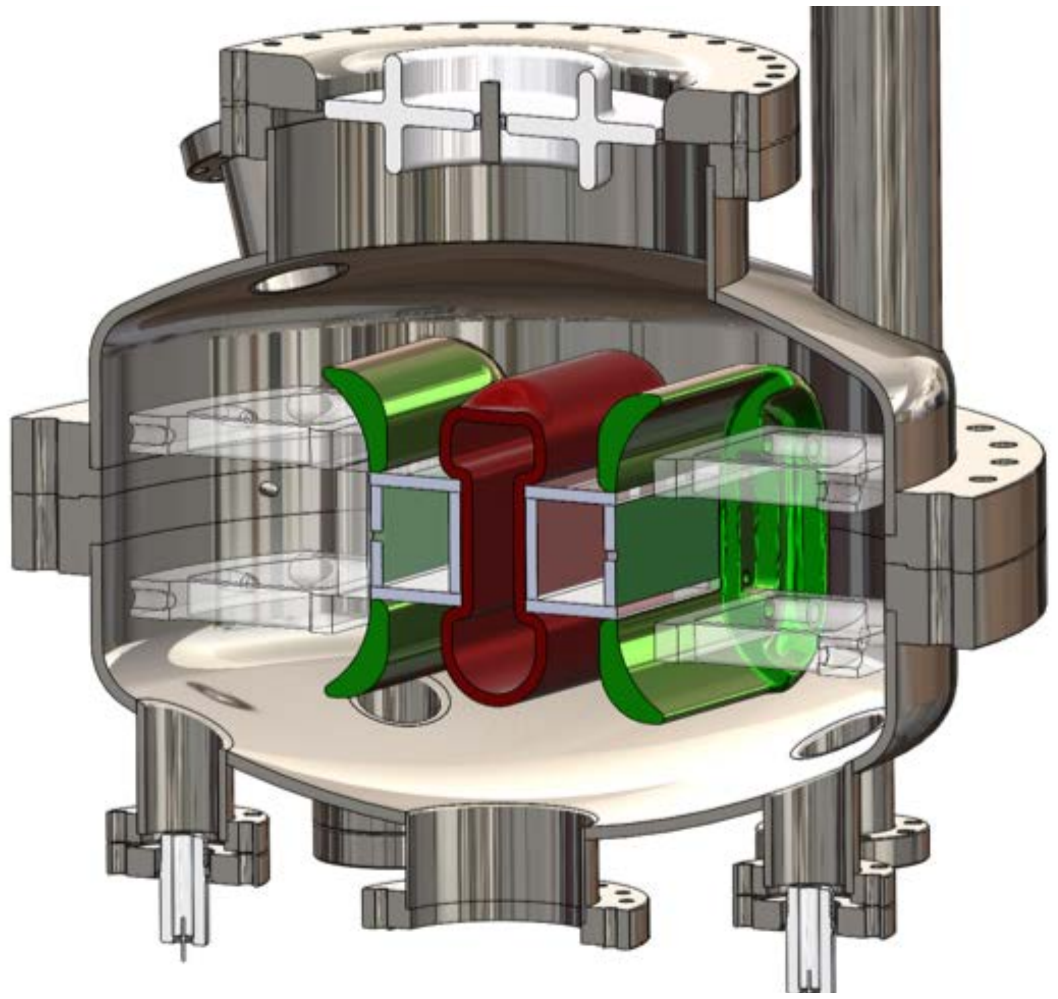
LANL Lab



T. Ito



Uniform field electrodes



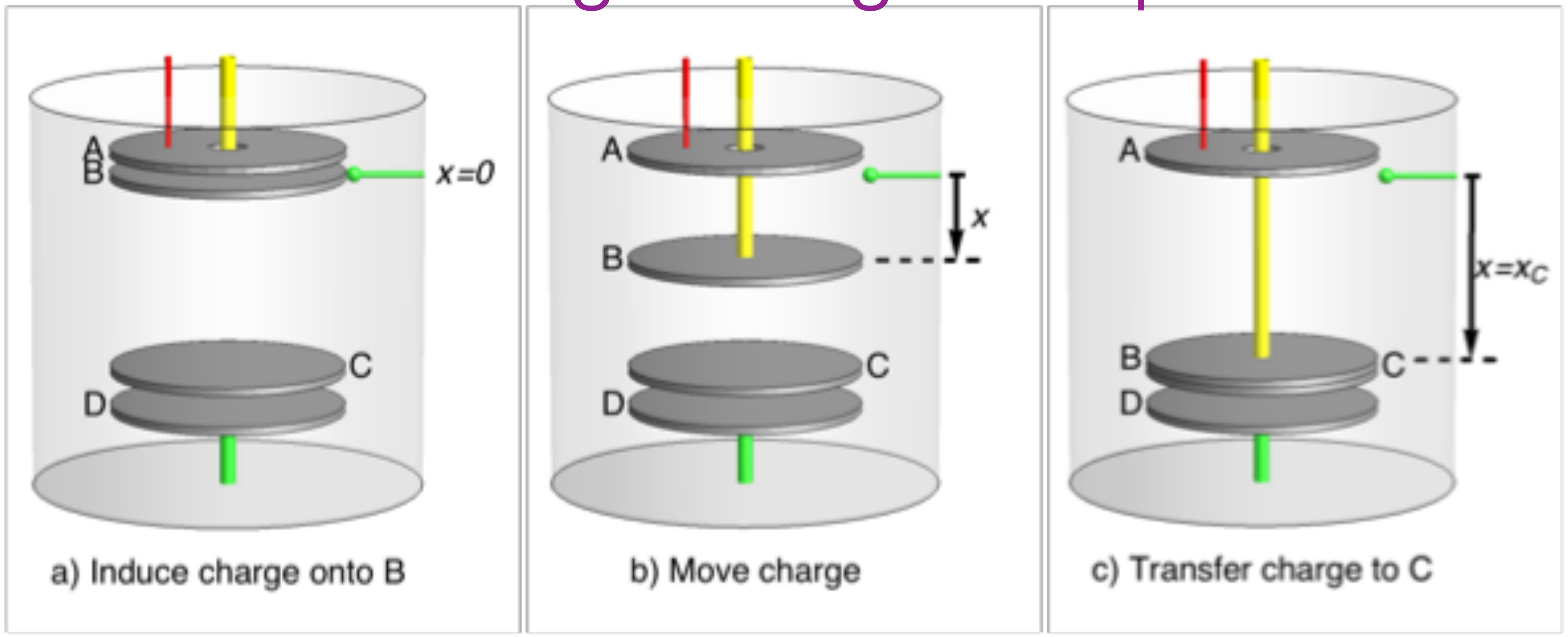
1/2 scale measurement cell electrodes

details: talk by Grant Riley

Cavallo HV Multiplier

Challenge: E > 75 kV/cm for a gap size of ~10 cm → ~635 kV!!

Cavallo high voltage multiplier

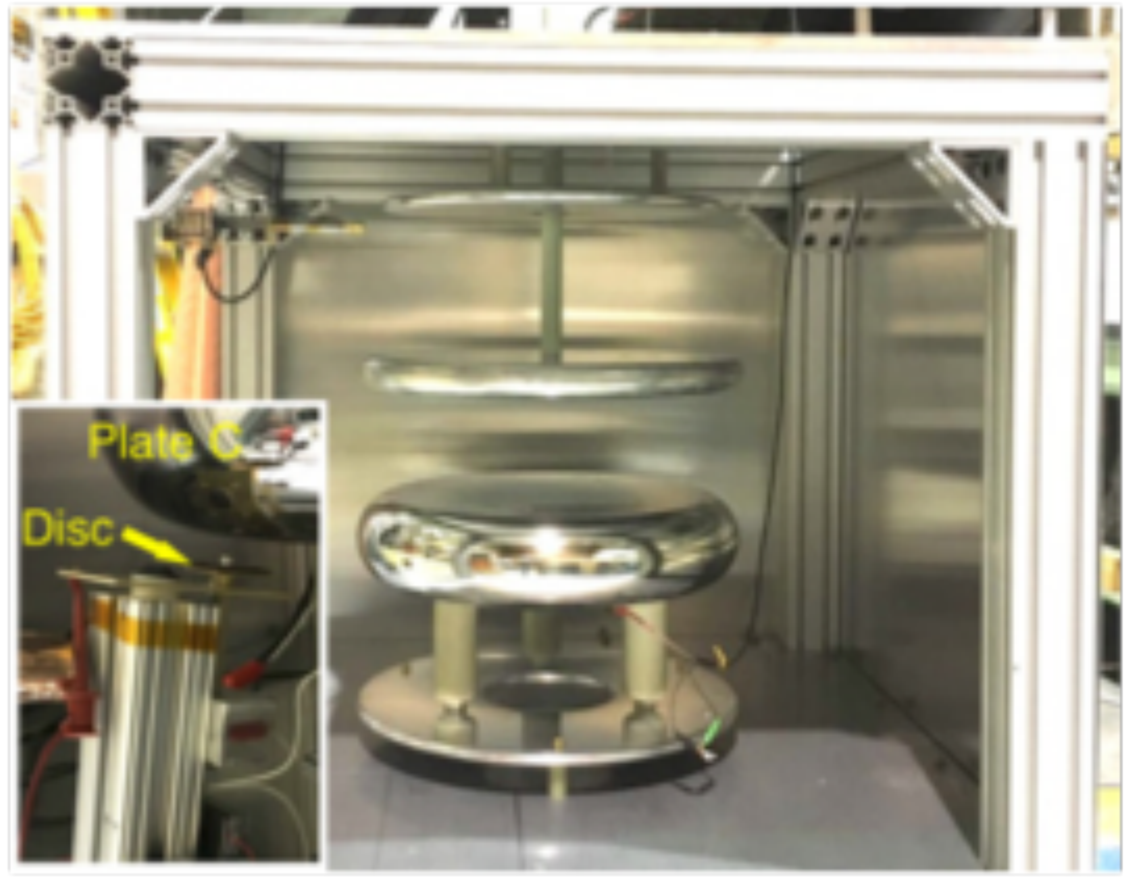


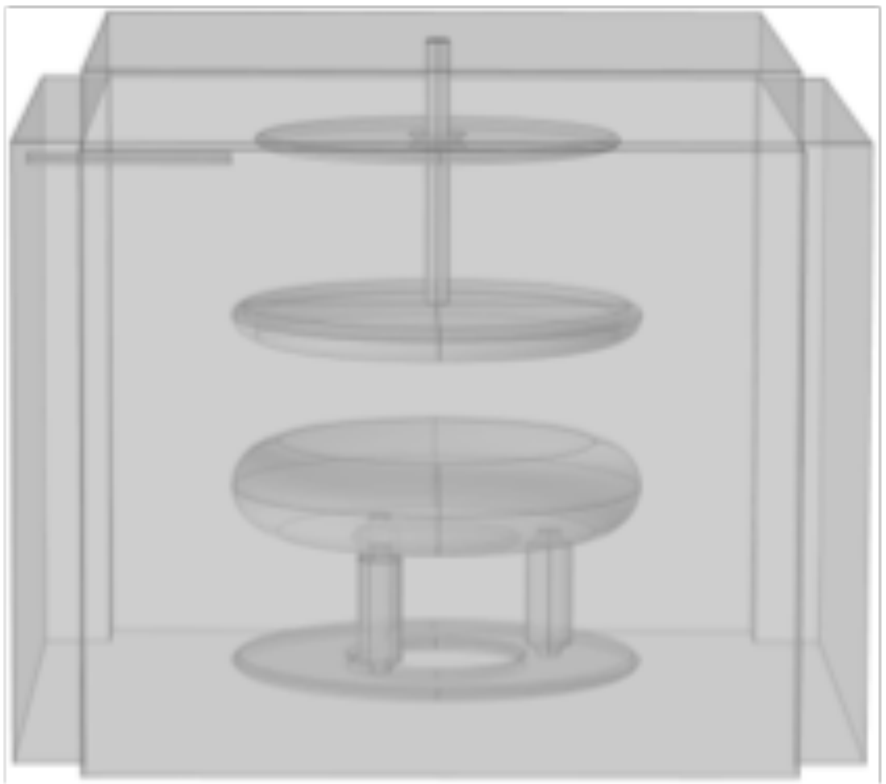
- Achievable potential is limited by
  1. Capacitance between C and B in initial position. Total charge loaded onto B is
     - $Q_B^0 = -C_{AB}^0 V_A - C_{BC}^0 V_C$
  2. Stray capacitance to B when contacting C. Charge remaining on B is
     - $Q_B^1 = C_{AB}^1 (V_C - V_A) + C_{BG}^1 V_C$

  Maximum possible V_C potential is when $Q_B^0 = Q_B^1$

$$V_C^{\max} = \frac{C_{AB}^0 - C_{AB}^1}{C_{BC}^0 + C_{AB}^1 + C_{BG}^1} V_A$$

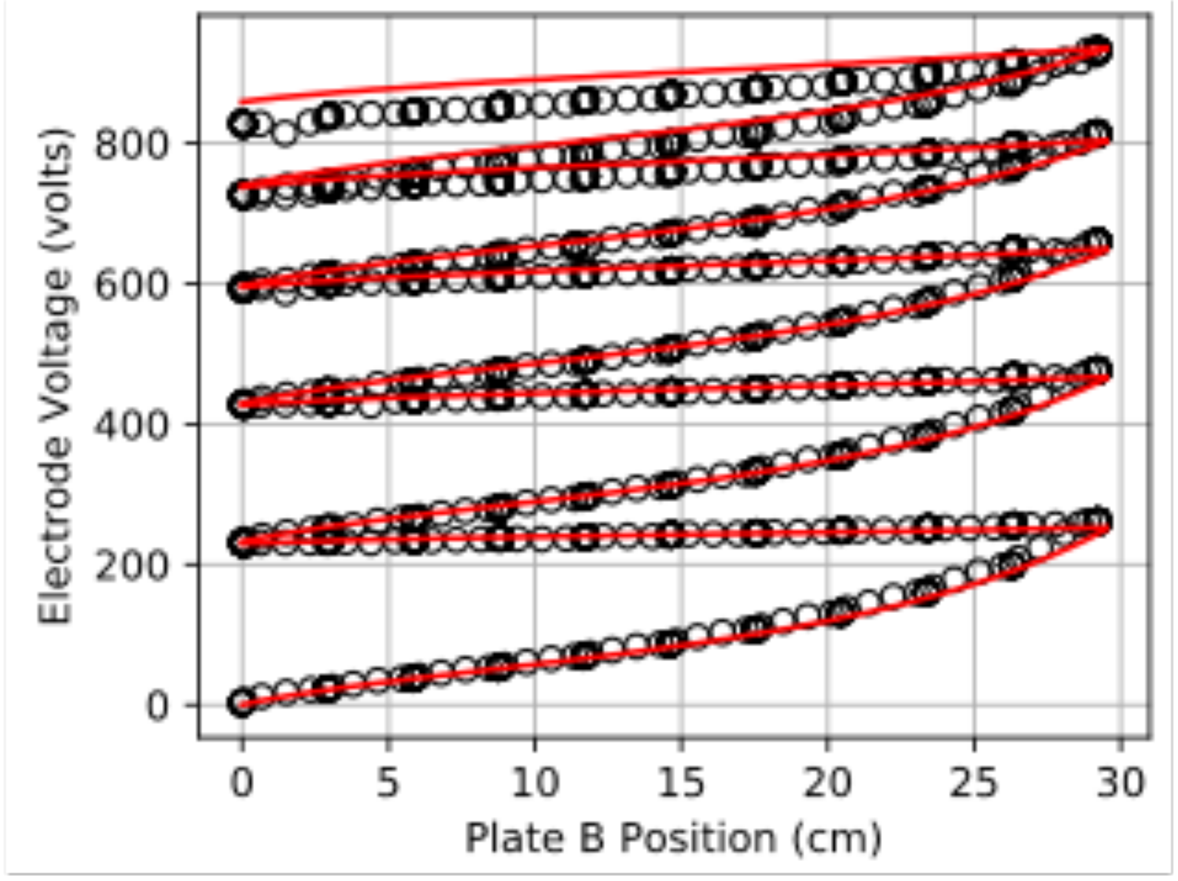
Room temperature demonstrator





COMSOL geometry

LANL



○ Measurement
— Calculation

Cryogenic test in preparation

details: talk by Marie Blatnik

slide credit: T. Ito

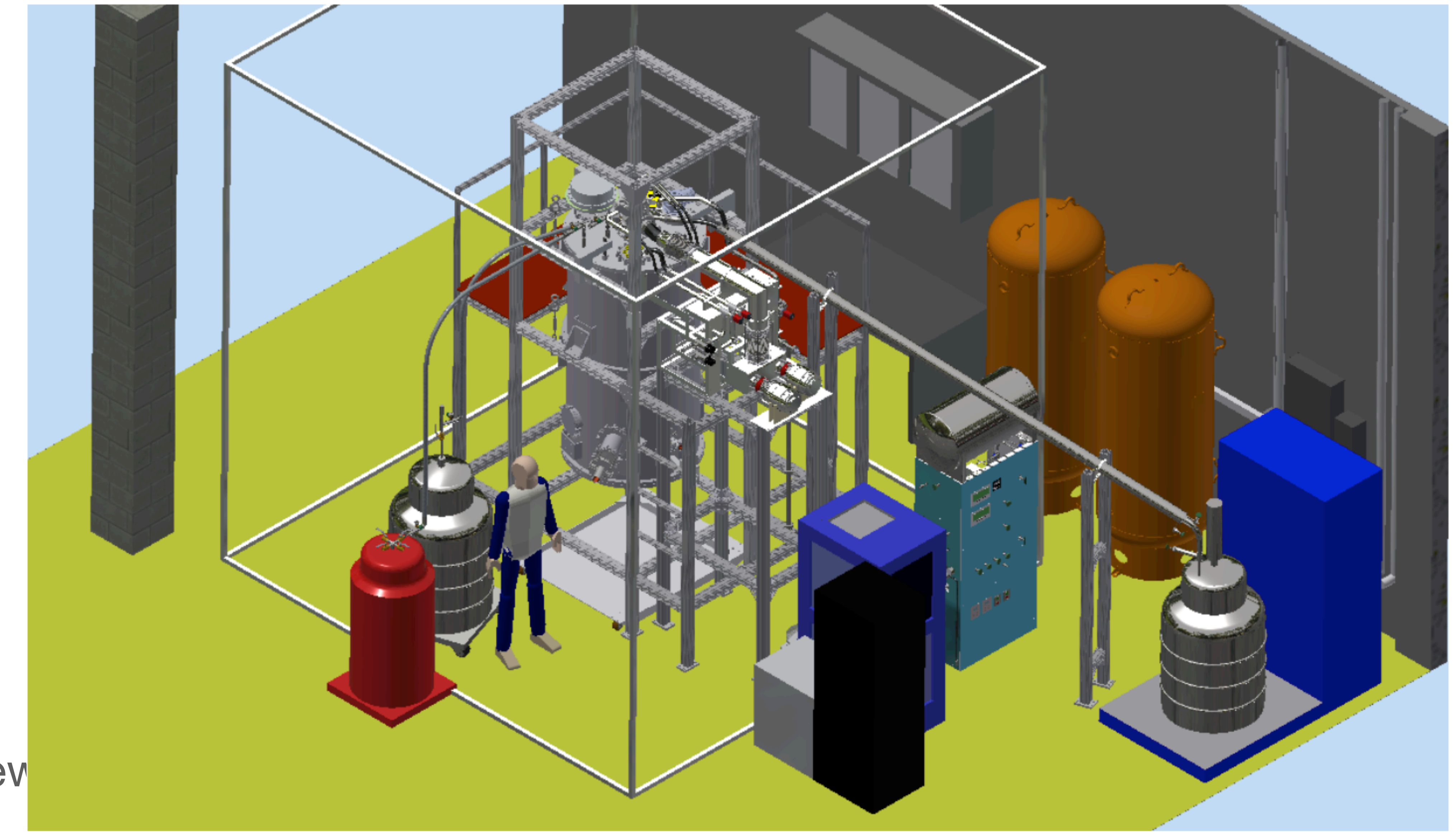
S.M.Clayton et al. JINST **13** P05017 (2018)

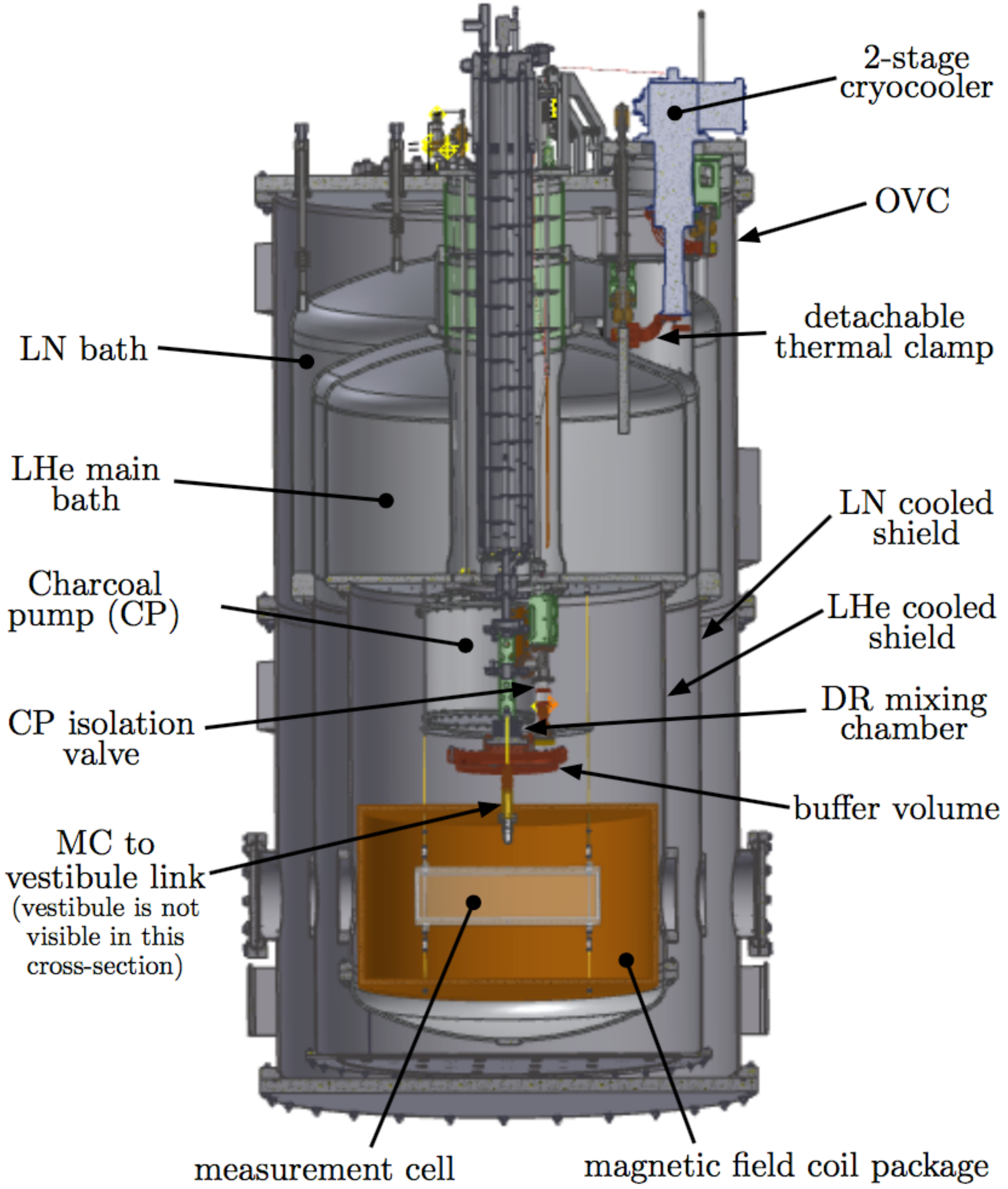
- Polarized Neutrons
- Polarized Helium-3
- Magnetic Field and Magnetic Shielding
- High Voltage (Electric Field)
- Systematics

Systematics and Operational Studies (SOS) @ Pulstar

Perform systematic studies relevant for nEDM@SNS at the NCSU Pulstar reactor

- UCNs from Pulstar
- polarized ^{3}He from MEOP source
- one measurement cell only
- no electric field
- smaller size than nEDM@SNS → faster thermal cycling
- study spin dressing
- study control of initial phase between n-^{3}He spins
- study geometric phase
- characterize production measurement cells
- ....





details: talks by Adam Dipert, Chris Swank

Systematics and Operational Studies (SOS) @ Pulstar

Dewar commissioning with cryocooler and DR finished

NCSU Lab

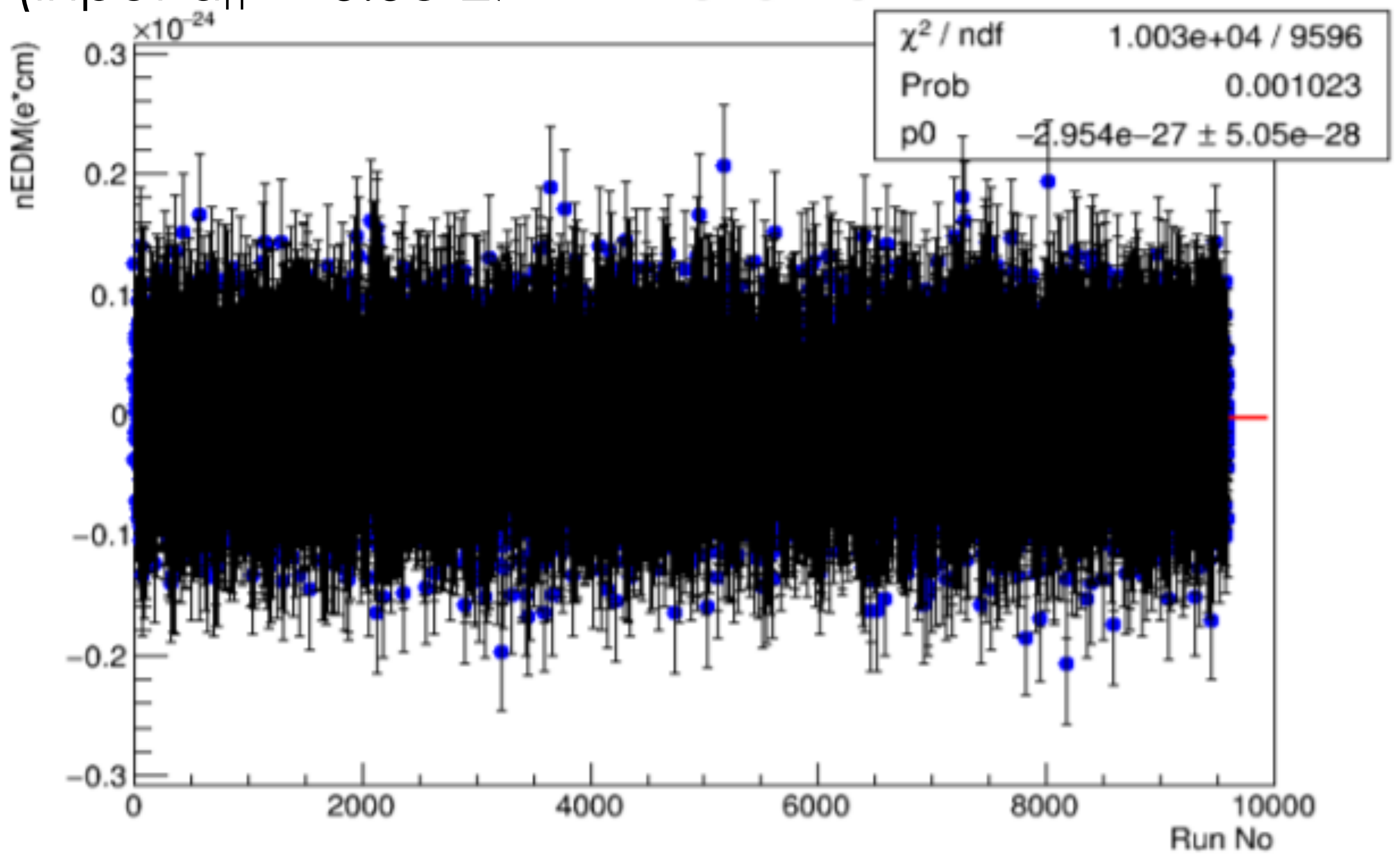
Requirements:

- T_2 at least 700 s
- ^{3}He polarization $\gtrsim$70%
- UCN density 1-10 n/cm^3
- SQUID noise level 0.2-0.25 fT/√Hz (3He concentration x=10^{-10}, SNR=20, 1 run)
- $T_{cell} \gtrsim$ 300 mK (during operation)
- 10 ppm stability and noise on power supply for spin dressing

Data Analysis and Simulations

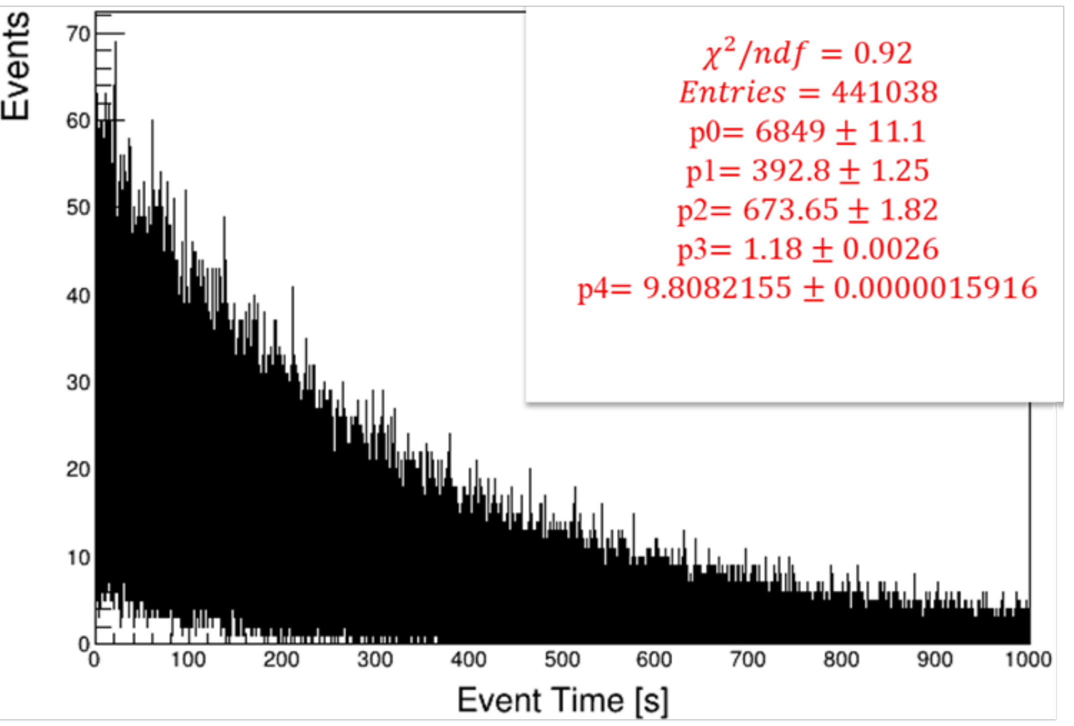
nEDM = =(-2.954±0.505)e-27 e*cm

Mock Data Challenge at full sensitivity
(input d_n = -3.3e-27

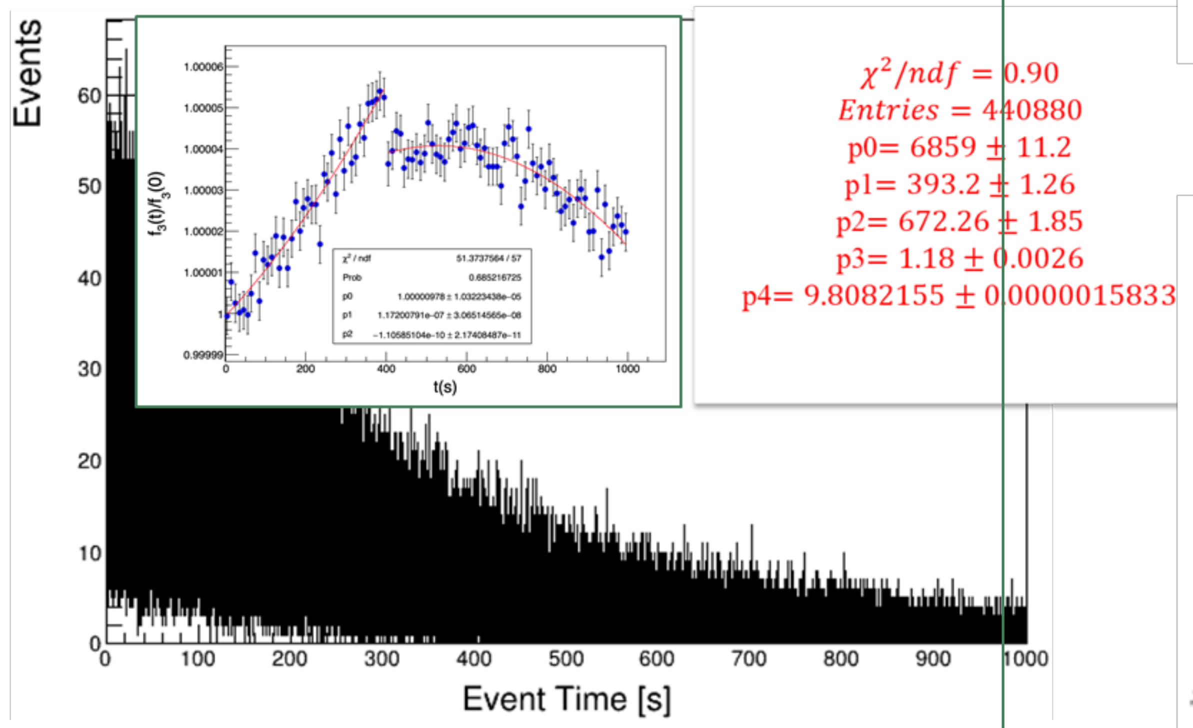


Preparing to handle non-uniform B-fields
M. Behzadipour, B. Plaster

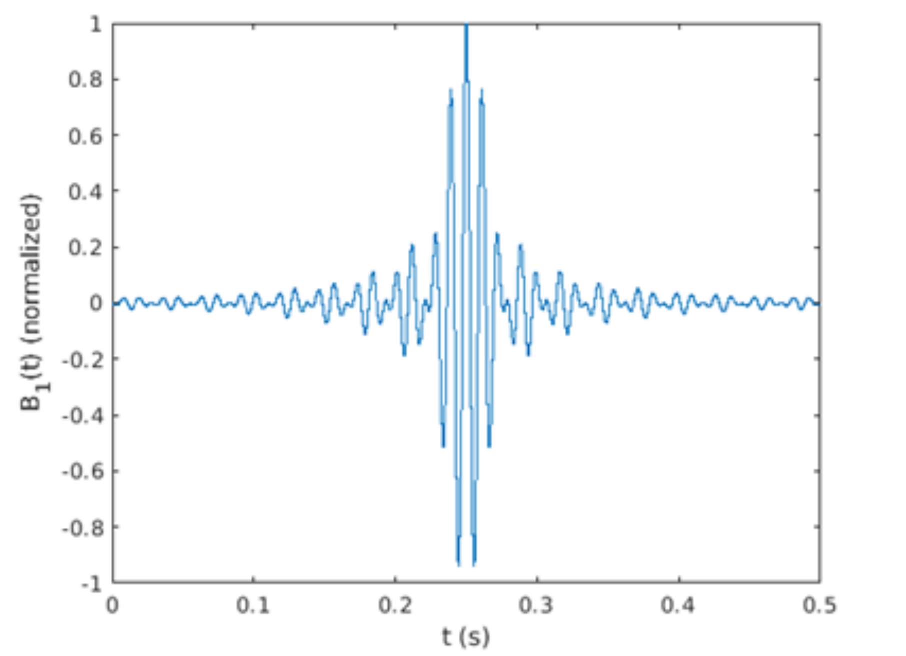
Constant field



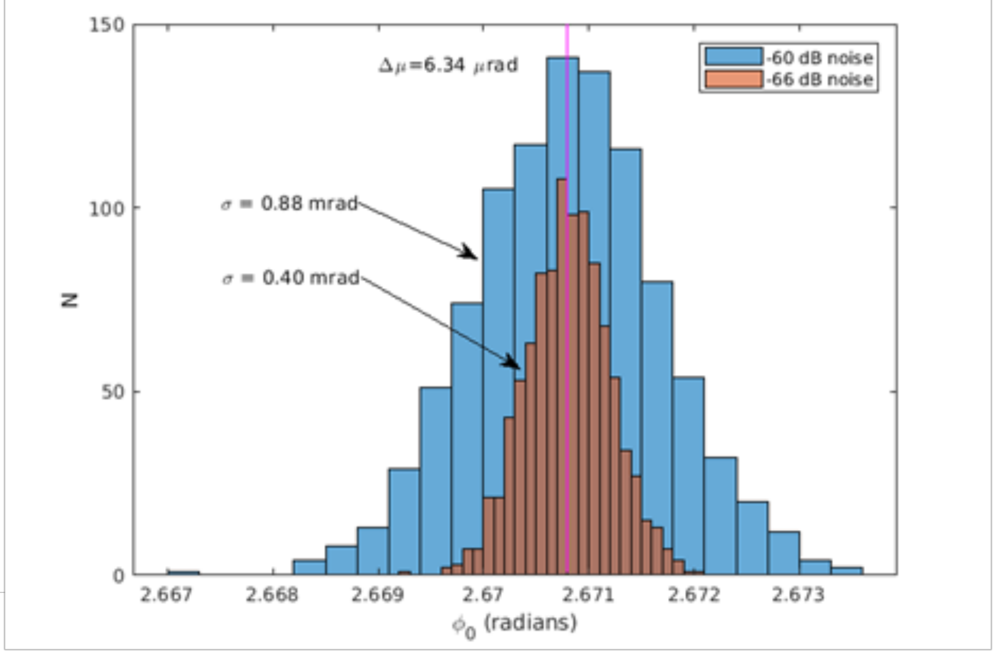
Jumps + drifts → no change in sensitivity



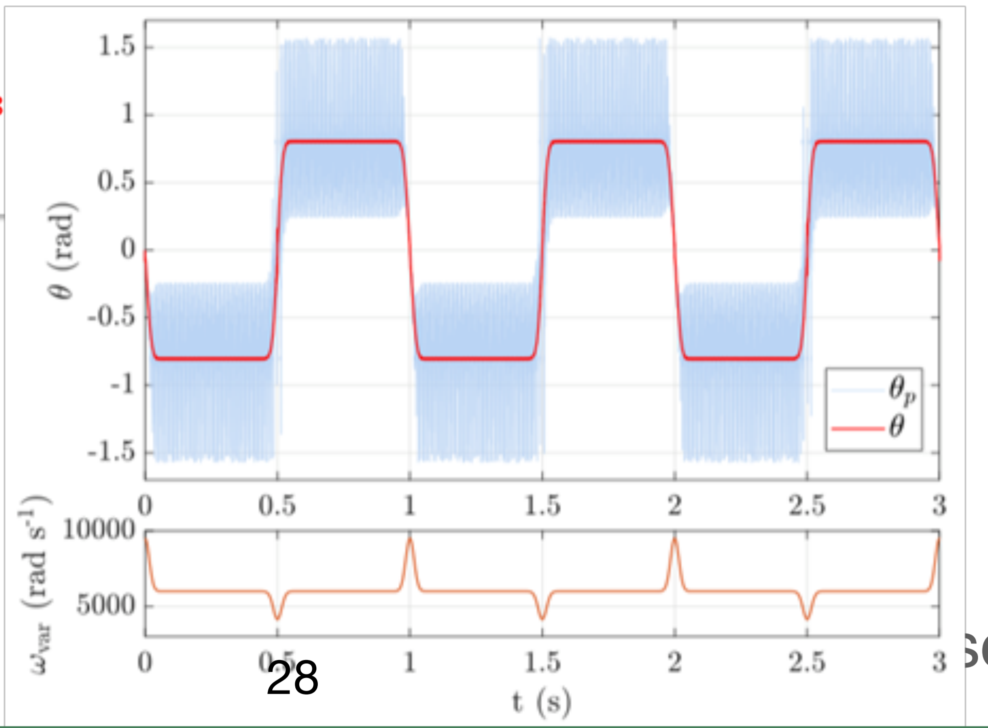
Developing spin-manipulation techniques
(first test at PULSTAR). C. Swank



Stability of ϕ_0 in the presence of AC field noise
(-60 dB needed, realistic amplifier -80 dB measured)

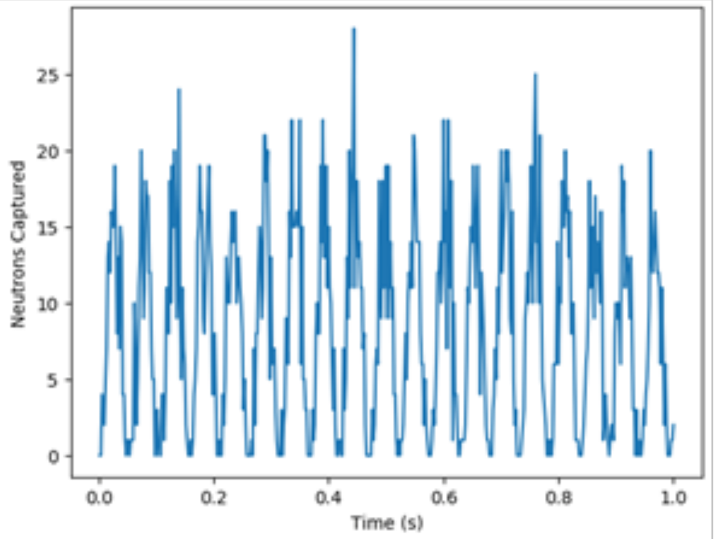


Critical spin-dressing calculation with
pulse modulation. From PRA paper

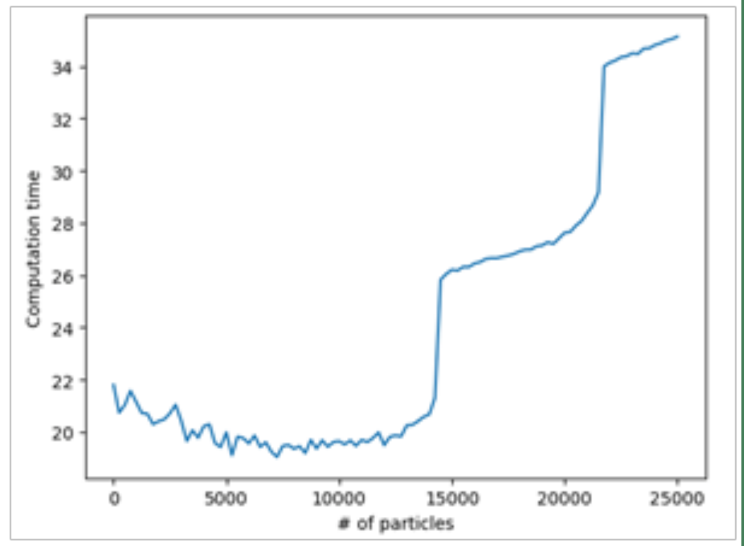


Learning to use GPUs for spin tracking

Simulated UCN
precession on GPU



Processing time per
GPU vs. # particles



M. Kline (SULI), L. Broussard

slide credit: V. Cianciolo

Working Parameters

Quantity	Definition	Value
P_{UCN}	UCN production rate	0.26 UCN/cc/s
N_0	Number of UCNs in each cell at t=0	3.8×10^5
V_{cell}	Measurement cell volume	3000 cc
τ_3	UCN-^{3}He absorption time	500 s
τ_{cell}	UCN-wall absorption time	2000 s
$\|E\|$	Electric field	75 kV/cm
T_M	Measurement time	1000 s
T_f	Cold neutron fill time	1000 s
P_3	^{3}He initial polarization	0.98
P_n	UCN initial polarization	0.98
τ_P	^{3}He & UCN depolarization time	20,000
ε_3	Detection efficiency for UCN-^{3}He capture	0.93
ε_β	Detection efficiency for β-decay	0.5
R_B	Non β-decay background rate	5 Hz

$|d_n| \lesssim 3\times10^{-28}$ e-cm @ 90% C.L. (in three calendar years)

Detailed Talks

- **HV and E-field**
  - Takeyasu Ito, “A study of liquid helium scintillation in the presence of an electric field for the nEDM@SNS experiment”
  - Nguyen Phan, "Understanding electrical breakdown in liquid helium through analysis of the distribution of breakdown fields”
  - Marie Blatnik, ”Electrodes for a Cryogenic Cavallo Apparatus”
  - Grant Riley, “High Electric Field Studies in Liquid Helium for the nEDM@SNS Experiment”
  - W.K., “Impact of Cell Charging on Cryogenic EDM Searches”
- **Helium-3**
  - Mark Broering, “Development of a polarized 3He atomic beam source for the nEDM@SNS experiment”
  - Thomas Rao, ”3He Polarization and Injection System for the nEDM@SNS SOS apparatus”
  - Christian White, ”Design, testing, and characterization of the helium-3 removal system”
- **Magnetic Field and Magnetic Shielding**
  - Alina Aleksandrova, ”Magnetic Field System in the nEDM experiment at the SNS”
  - Chris Crawford, "Time stability of an external holding field inside a superconducting mesh.“
  - Clark Hickman, “Creation of a superconducting switch to close the B0 coil in the nEDM@SNS experiment”
- **SOS@Pulstar**
  - Adam Dipert, “Systematics and Operational Studies for the nEDM@SNS Experiment”
  - Chris Swank, “Systematic effects studies at the Systematic and Operational Studies apparatus (SOS@PULSTAR)”
- **Neutron Transport and Storage**
  - Kavish Imam, “Measurement of Neutron Polarization and Transmission for the nEDM@SNS Experiment”
  - Kent Leung, “Cryogenic UCN storage, super-thermal production, and live spin analysis for measurements of static nEDMs, oscillating EDMs, and the neutron magnetic moment”
- **Light Collection**
  - Vince Cianciolo, “nEDM@SNS Light Collection System”
  - Devon Loomis, “Measurement Cell and Light Collection System Simulations for the nEDM@SNS experiment”

Timeline and Summary

- **Timeline:**
  - Detailed DOE/NSF Review (February 2021) - timeline is budget driven
    - new baseline start-date: 2028
    - possibility of receiving stimulus money? Start-date: 2026

- **Construction of subsystems is well under way**
  - EB2 and neutron guide are "shovel ready" subsystems
  - all other subsystems are well into construction phase

More details: J. Inst. , 14, P11017 (2019), "A new cryogenic apparatus to search for the neutron electric dipole moment"

Exciting times are ahead of us! Thanks.