TUCAN
TRIUMF Ultra Cold
Advanced Neutron source

The precision nEDM measurement with UltraCold Neutrons at TRIUMF

Ryohei Matsumiya (TRIUMF/Canada), on behalf of the TUCAN collaboration,
SPIN2021 Symposium, Matsue, Japan / Online, 2021/10/22

Outline

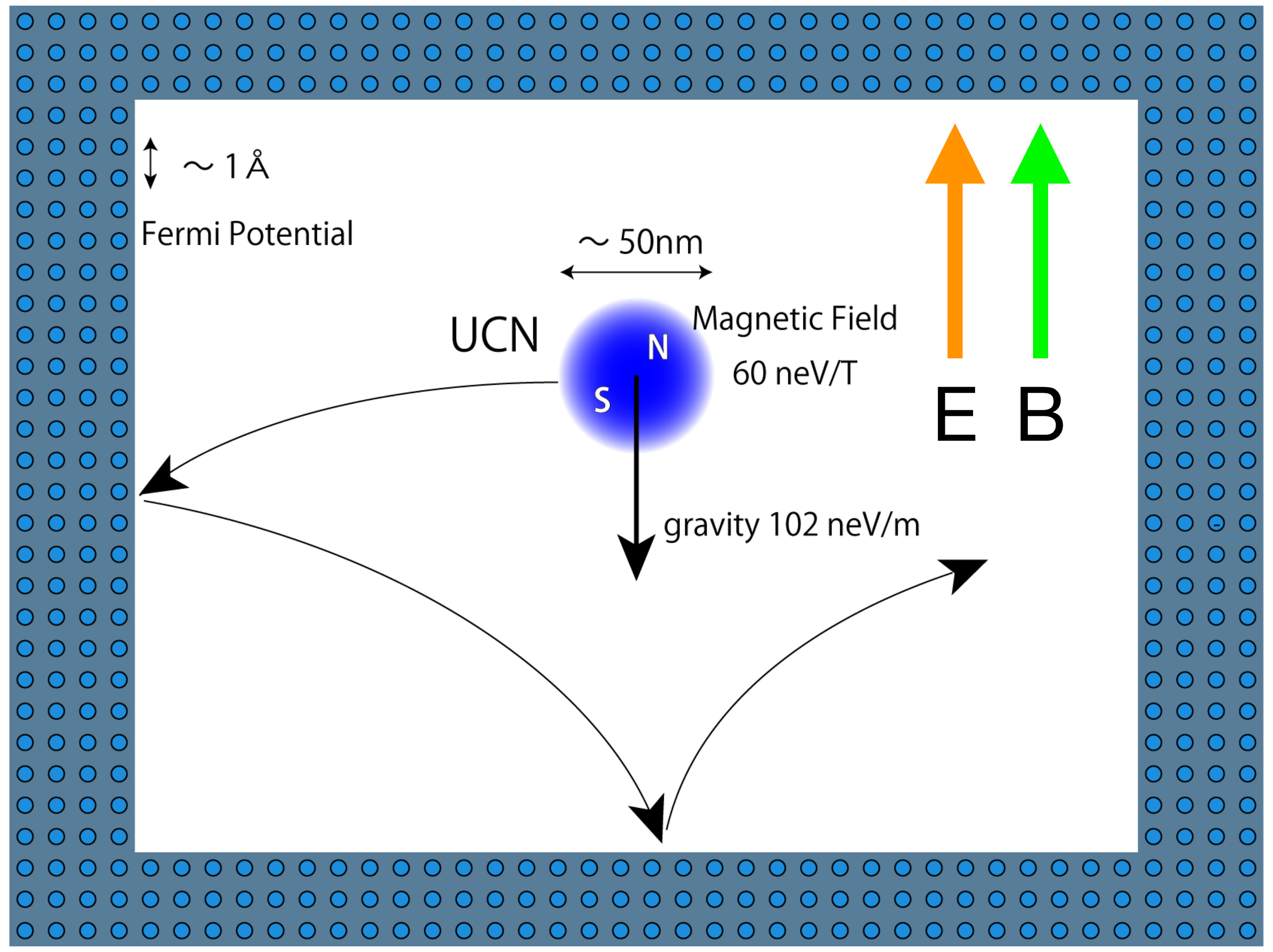
- Introduction
- UCN source (TUCAN source) development
- nEDM Spectrometer
- Summary & Future Plan

Neutron Electric Dipole Moment (nEDM)

- nEDM violates the time-reversal (T) symmetry
- Provides crucial tests of theories beyond the current Standard Model
- nEDM measurements after 1980s use stored ultra-cold neutrons (UCN)
- Current upper limit of nEDM by the PSI-nEDM collaboration

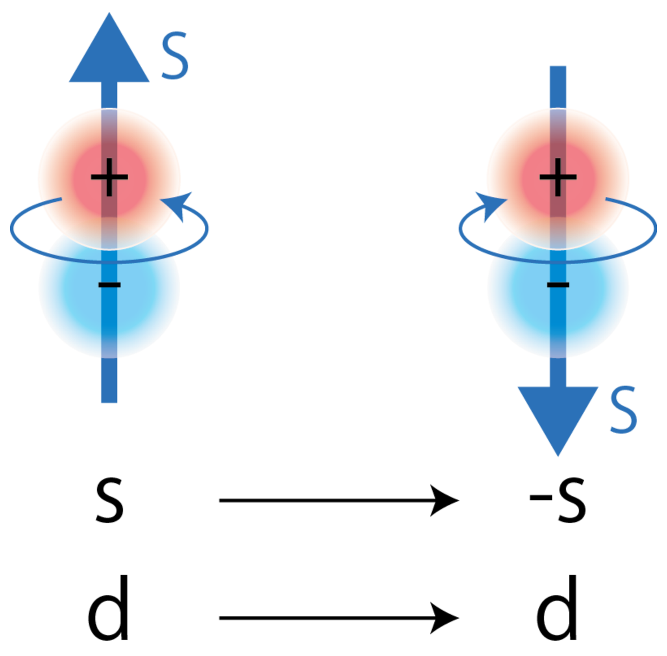
  $|d_n| < 1.8\times10^{-26}$ e·cm (90% C.L), C. Abel et al., PRL 124, 081803 (2020)

- TUCAN's goal: measure the nEDM at 10^{-27} ecm precision with a high-intensity UCN source

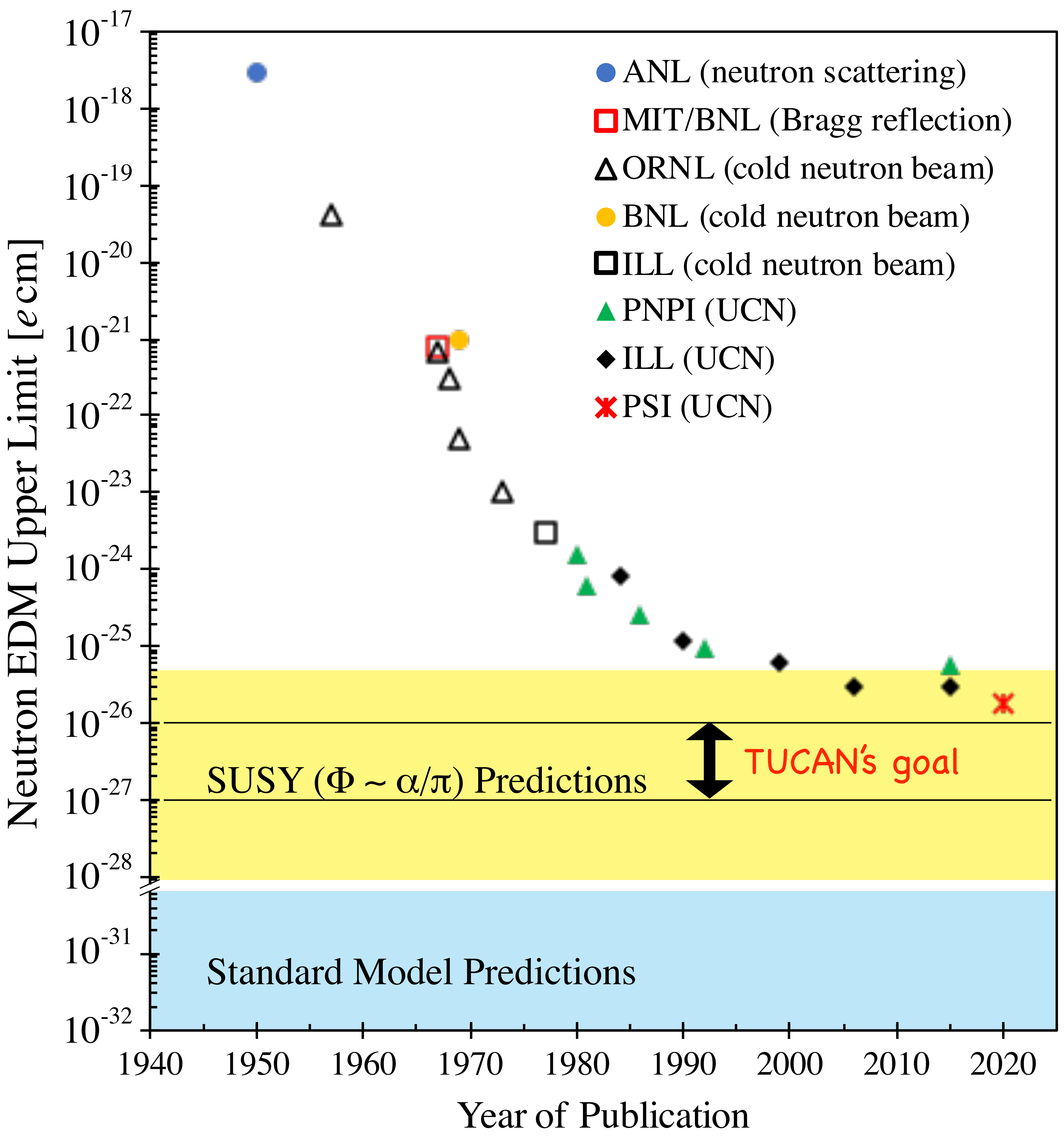


EDM cell

nEDM



T reversal



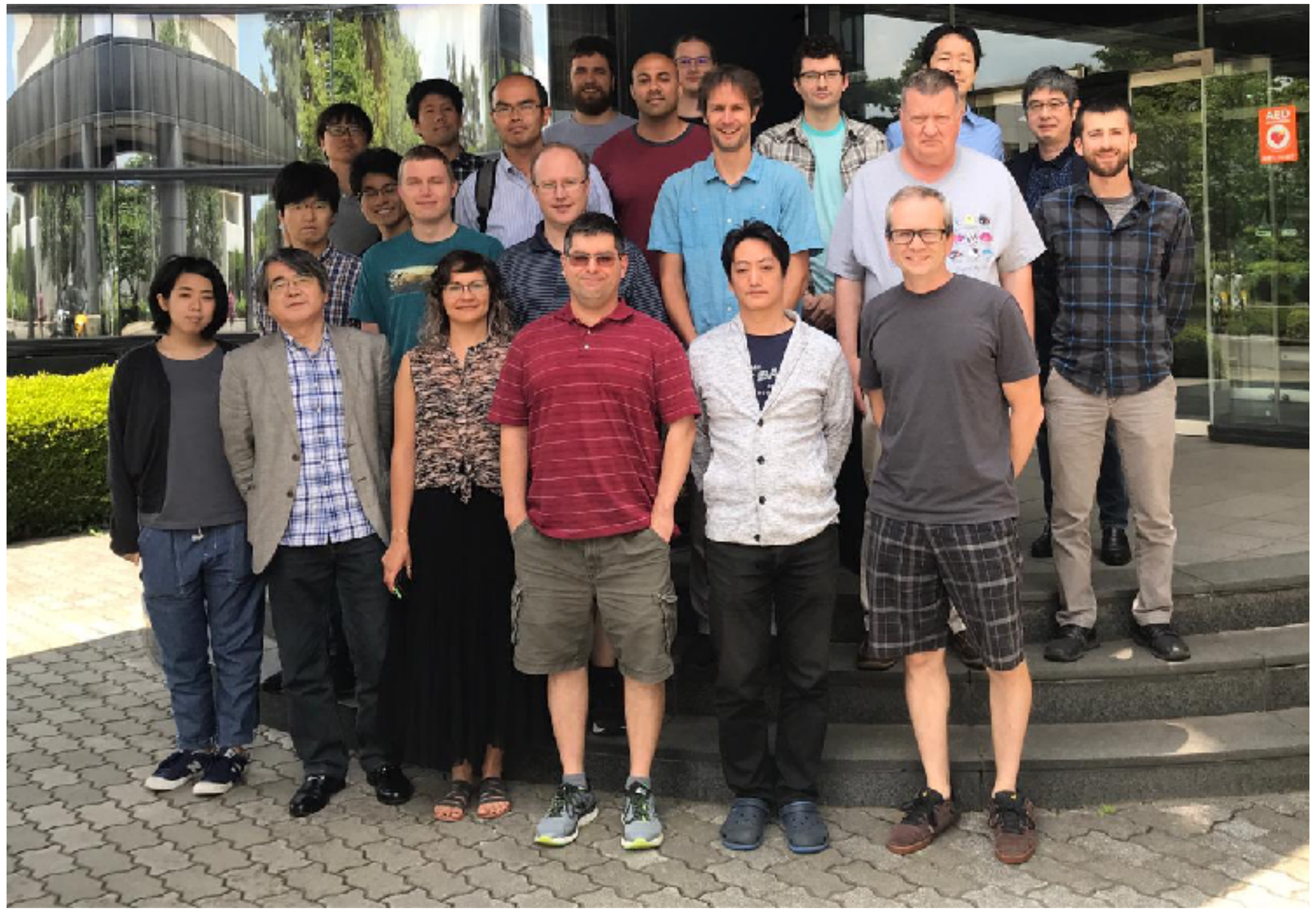
TUCAN collaboration

TRIUMF UltraCold Advanced Neutron

TUCAN

TRIUMF Ultra Cold Advanced Neutron source

- Our goals
    - Build a high-intensity UCN source at TRIUMF
    - Measure the nEDM with 10^{-27} ecm precision
- Expected UCN density
    - 200-400 polarized UCN /cm^3 (filled in the EDM cell)
- The UCN production scheme demonstrated by the prototype UCN source
    - First UCN production at TRIUMF in 2017 (S. Ahmed et al., PRC **99** (2019) 025503)
- Current activities
    - Development of a new upgraded UCN source
    - Development of the new EDM spectrometer



H. Akatsuka, C. Bidinosti, C. Davis, B. Franke, M. Gericke, P. Giampa, S. Hansen-Romu, K. Hatanaka, T. Hayamizu, T. Higuchi, G. Ichikawa, S. Imajo, B. Jamieson, S. Kawasaki, M. Kitaguchi, W. Klassen, A. Konaka, E. Korkmaz, F. Kuchler, M. Lang, M. Lavvaf, L. Lee, T. Lindner, K. Madison, Y. Makida, R. Mammei, J. Mammei, J. W. Martin, R. Matsumiya, M. McCrea, E. Miller, K. Mishima, T. Momose, T. Okamura, O. H. Jin, R. Picker, W. D. Ramsay, W. Schreyer, H. Shimizu, S. Sidhu, I. Tanihata, S. Vanbergen, W. T. H. van Oers, and Y. Watanabe

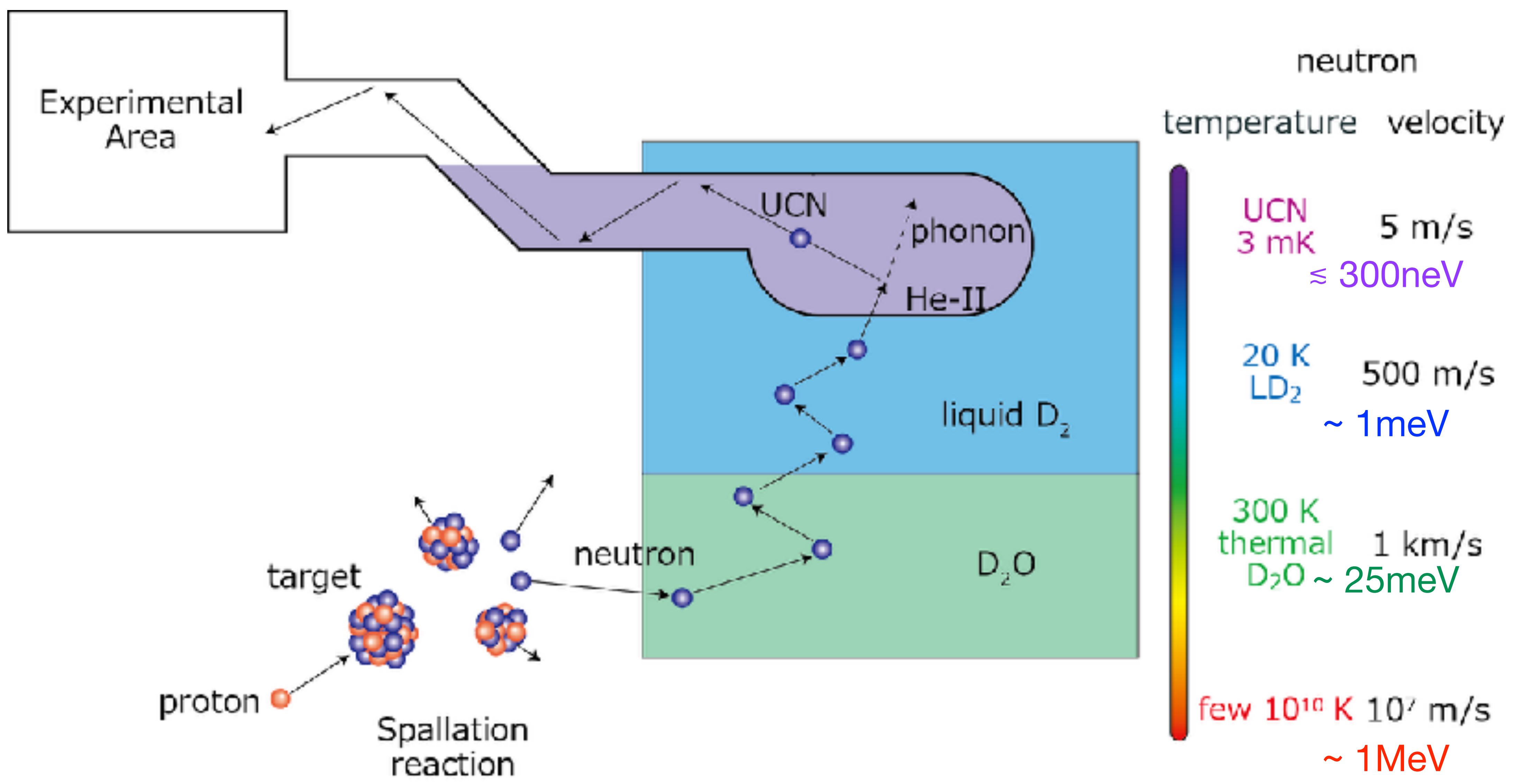
UCN production scheme in TUCAN Source

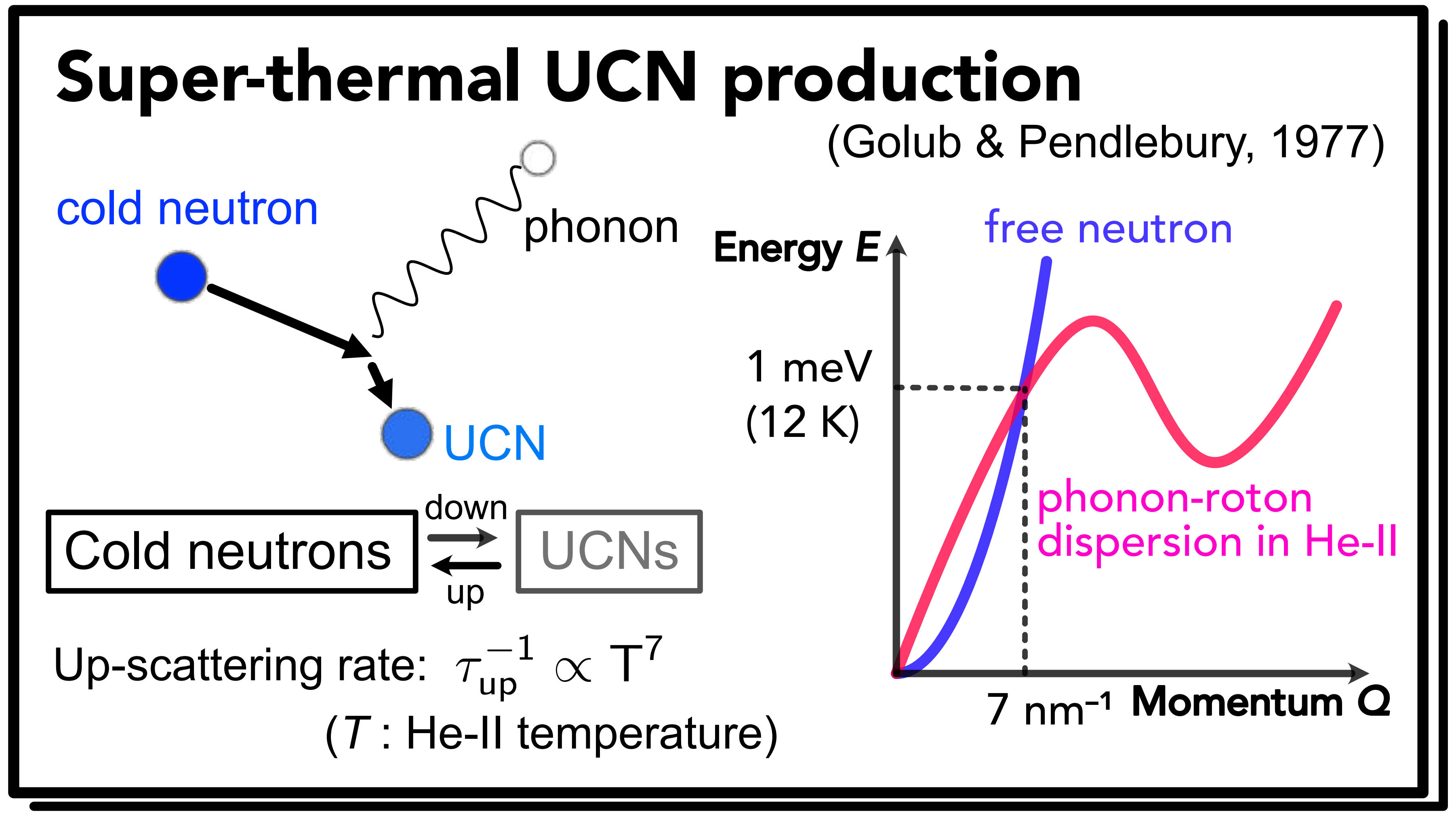
- Combination of
  - Spallation neutron source
  - Neutron moderator
  - Super-thermal UCN production with superfluid He (He-II)

Y. Masuda et al, PRL 108 (2012) 134801

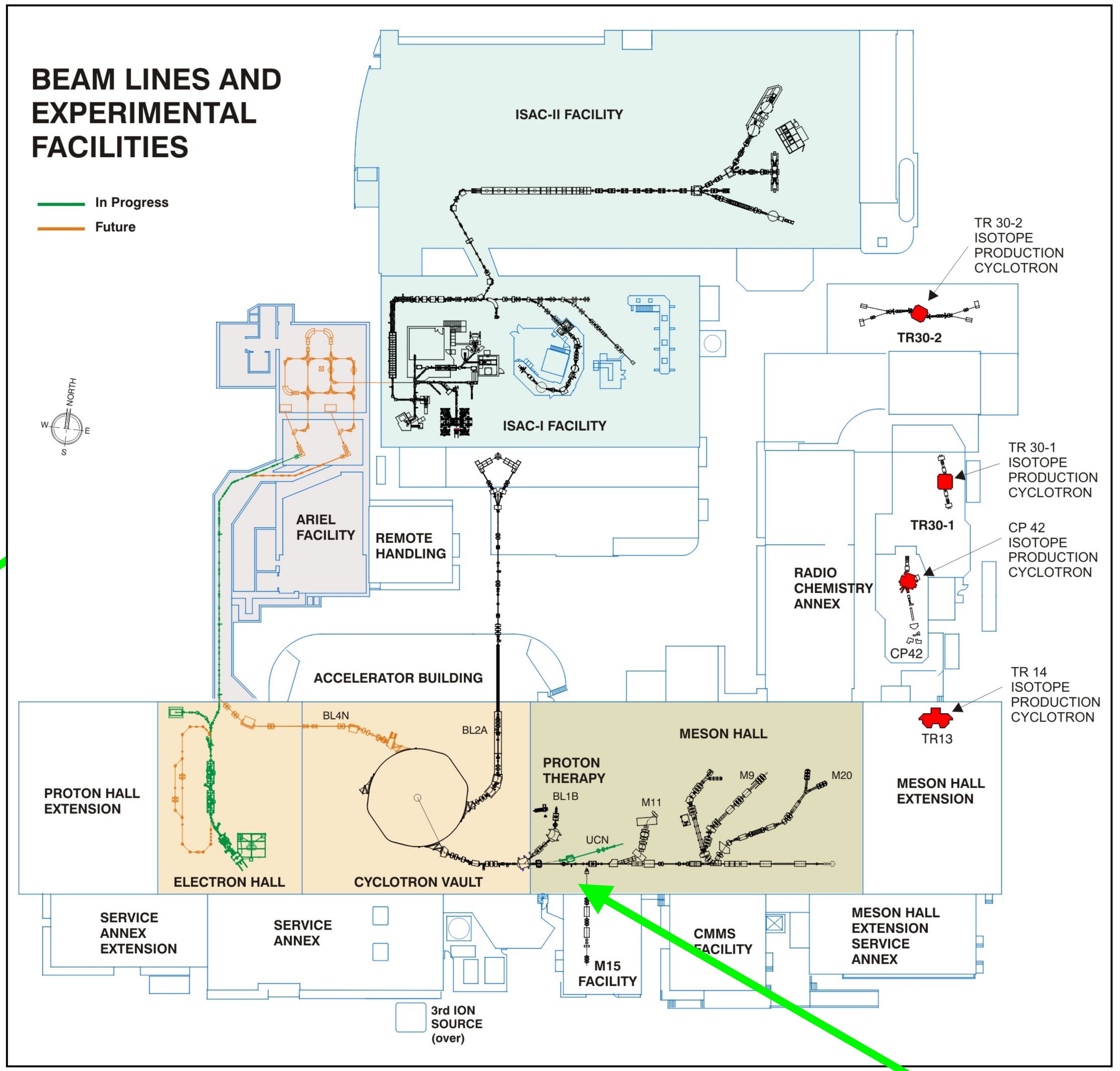
- Spallation Neutron Source
  - Fast neutron produced by accelerator driven proton beam impingement on W target
  - 20kW proton beam line (BL1U at TRIUMF Meson hall)
- RT D_2O and 20K liquid deuterium (LD_2) moderator

- Crucial aspects:
  - Keep the He-II temperature at ~1K to suppress up-scattering by phonons under a heat load of beam irradiation



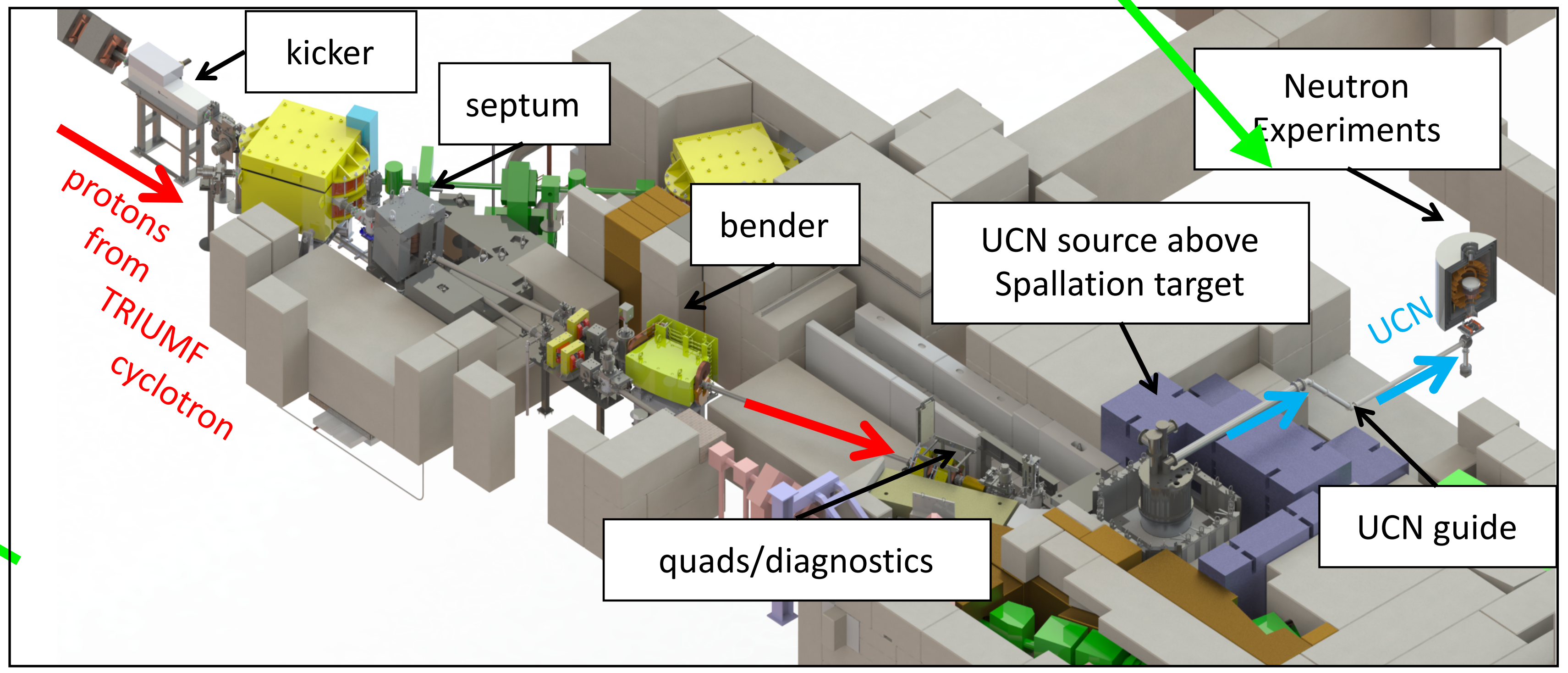


TRIUMF (Vancouver, Canada)



520MeV Cyclotron & beam lines

UCN experimental area



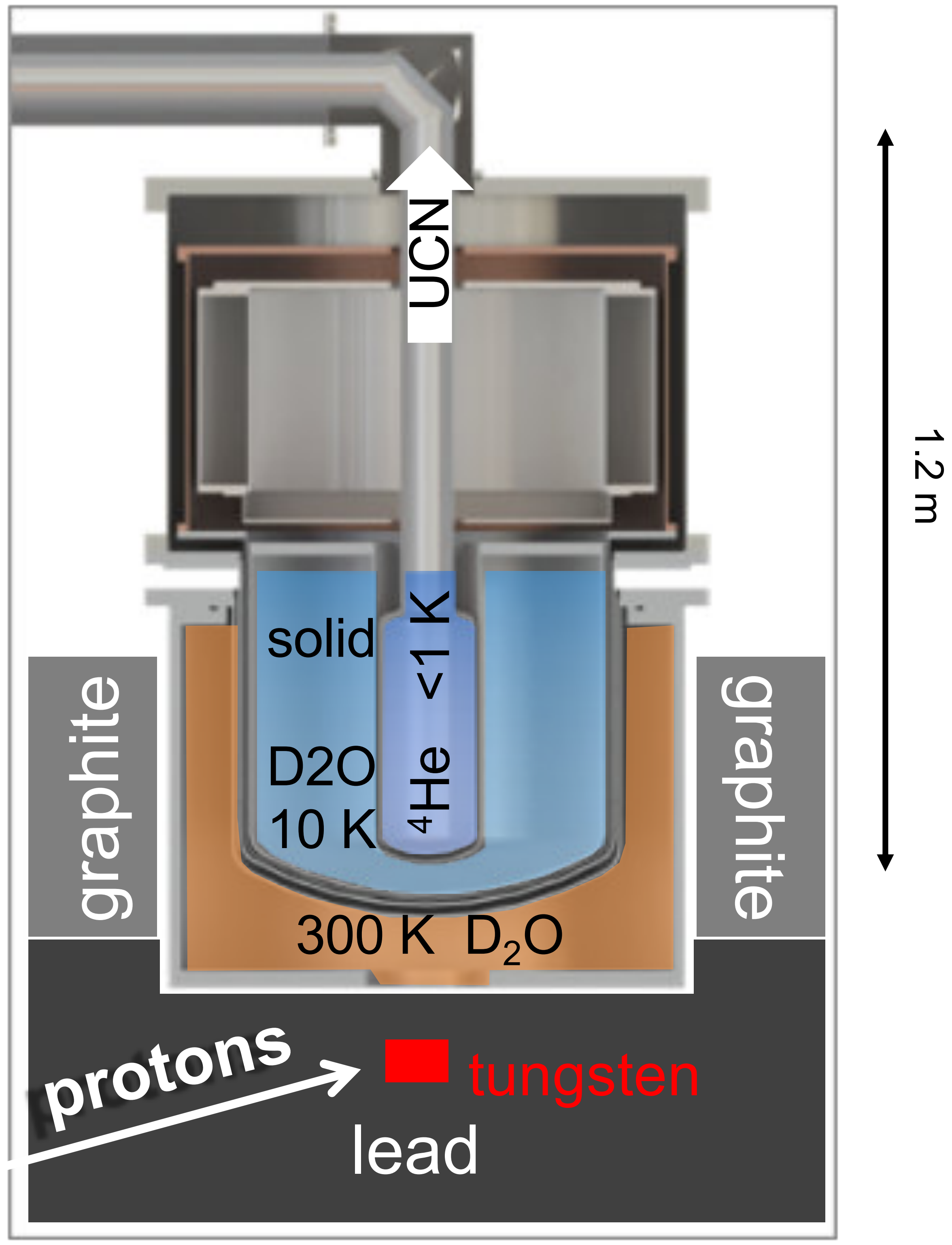
Beam line 1U - 20kW proton beam line

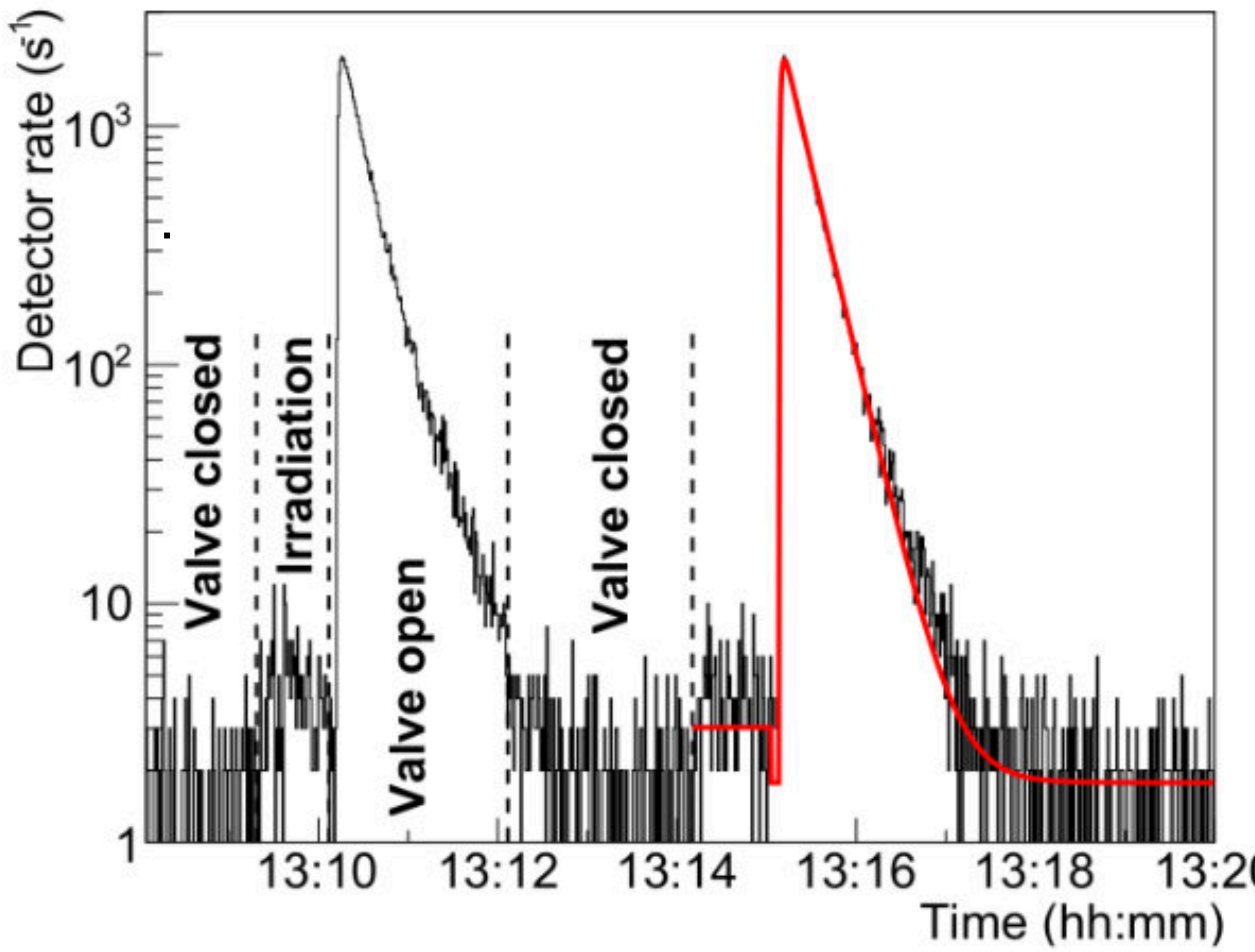
NIM A 927, 101-108 (2019)
Phys. Rev. Accel. Beams 22, 102401 (2019)

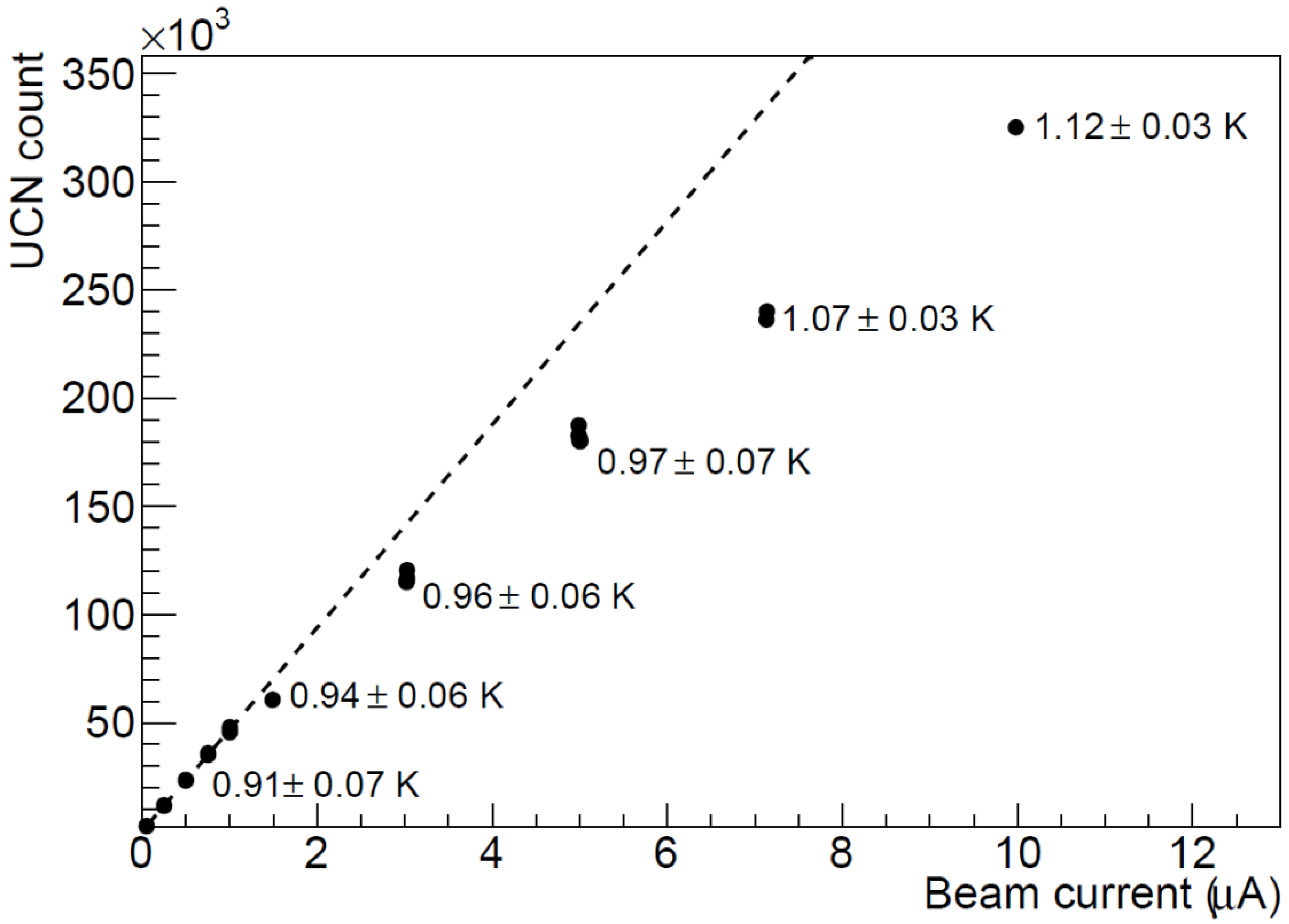
UCN production at TRIUMF in 2017

- ✦ First UCN production at TRIUMF with a prototype UCN source
- ✦ Major results
  - Successful UCN production
  - 3.25×10^5 UCN/cycle @10uA proton beam current
- ✦ Beam power was limited by cooling power of the helium cryostat
- ✦ Higher He-II temperature → larger UCN loss by phonon up scattering in He-II ($\propto T^7$)

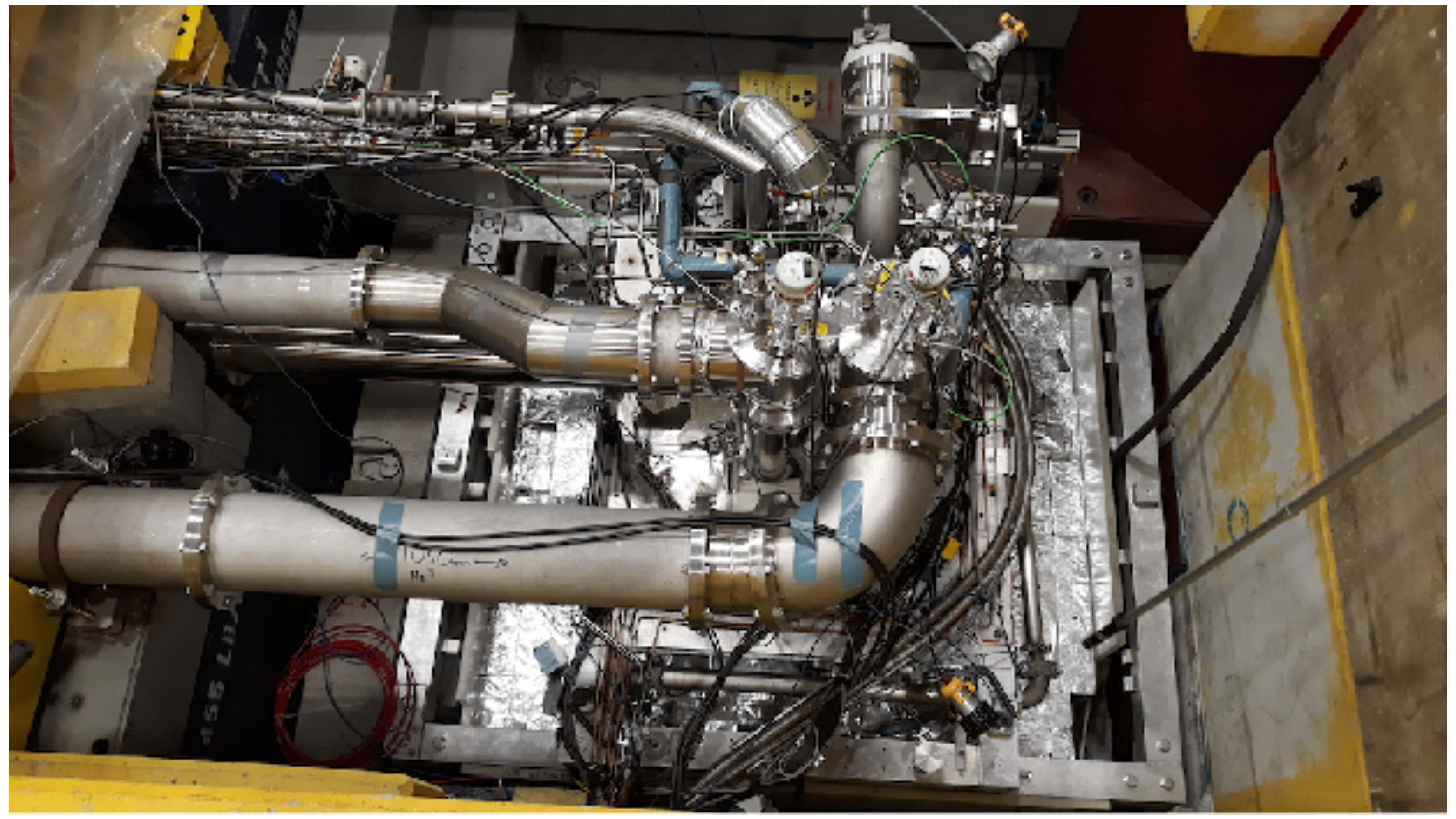
S. Ahmed et al., Phys. Rev. C 99, 025503 (2019)





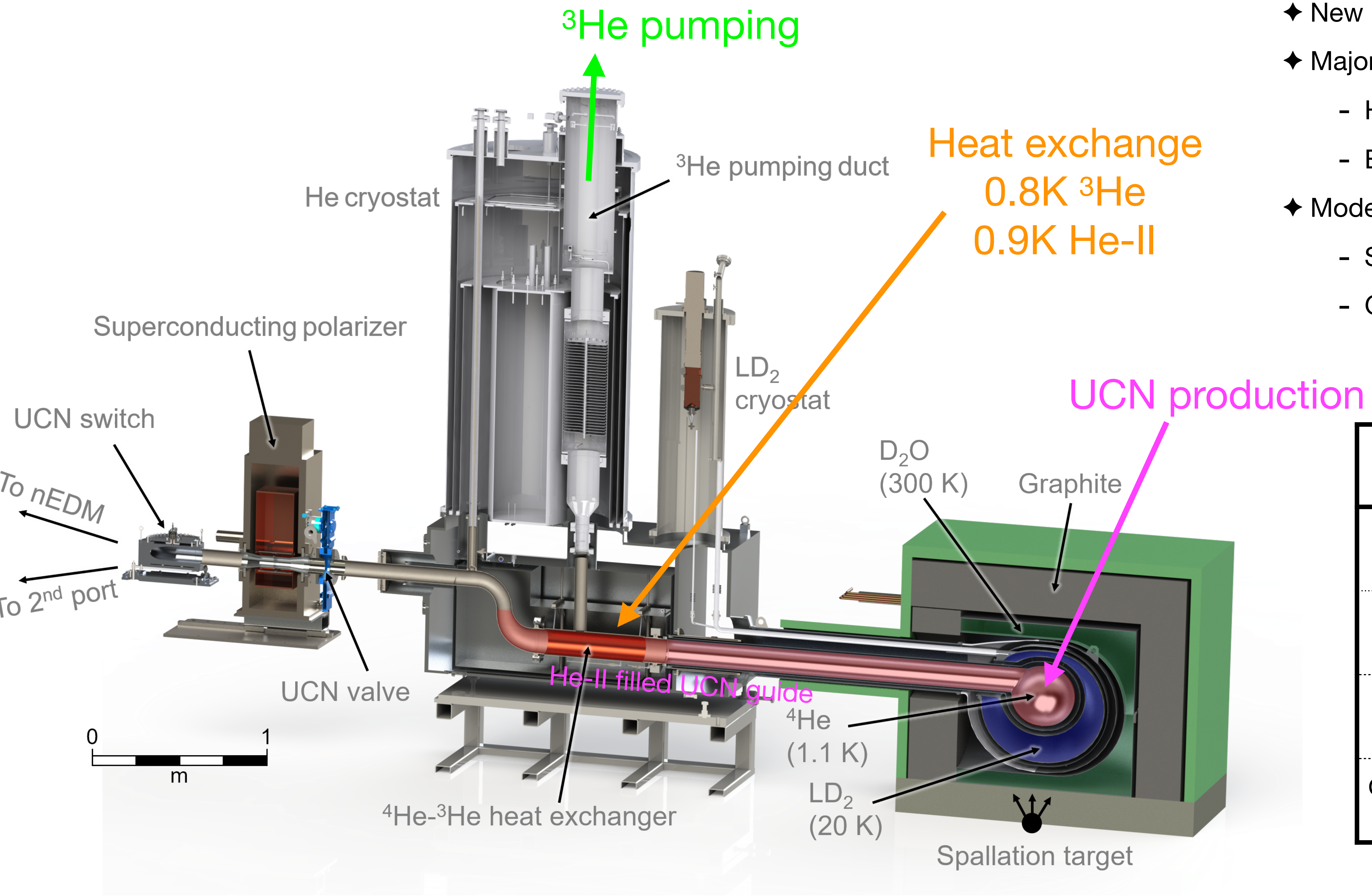


UCN counts v.s. beam current



Top view of the prototype UCN source

Design of the new UCN source - TUCAN Source



- ✦ New UCN source (TUCAN source) under development
- ✦ Major improvements
  - Higher cooling power of the He cryostat (0.4 → 10W)
  - Enables operation of high beam current (1uA → 40uA)
- ✦ Moderator
  - Solid D_2O → Liquid D_2 : increases cold neutron flux around 1meV
  - Geometry optimization by MC simulation

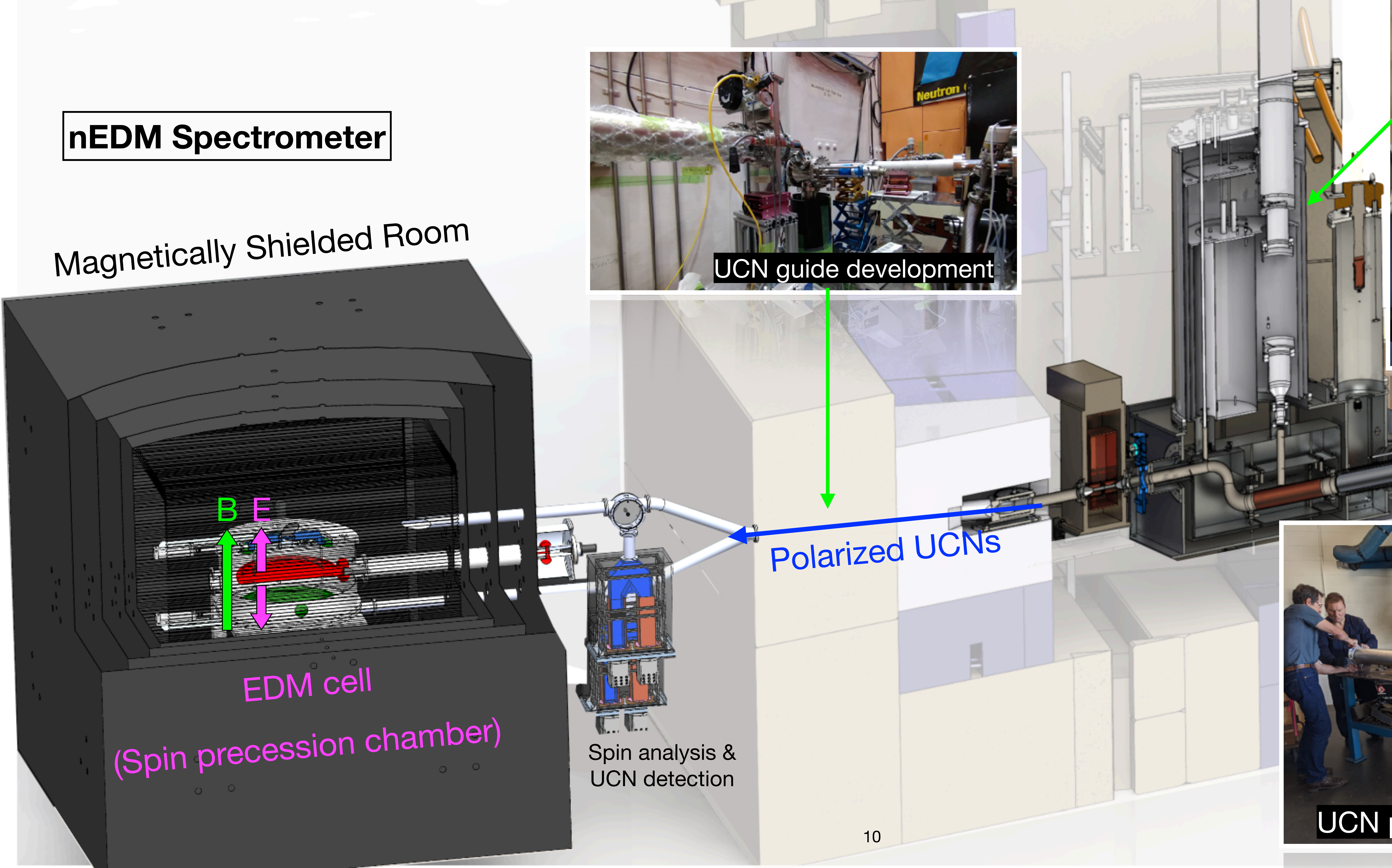
W. Schreyer et al., NIM A 959, 163525 (2020)

	Prototype UCN source	New UCN source	UCN gain factor
Beam current	1uA	40uA	×40
Cold moderator	20K Solid D_2O	20K Liquid D_2	×(2~3)
UCN production volume	8L	27L	×3.4
Cooling power of He cryostat	0.4W	10W	

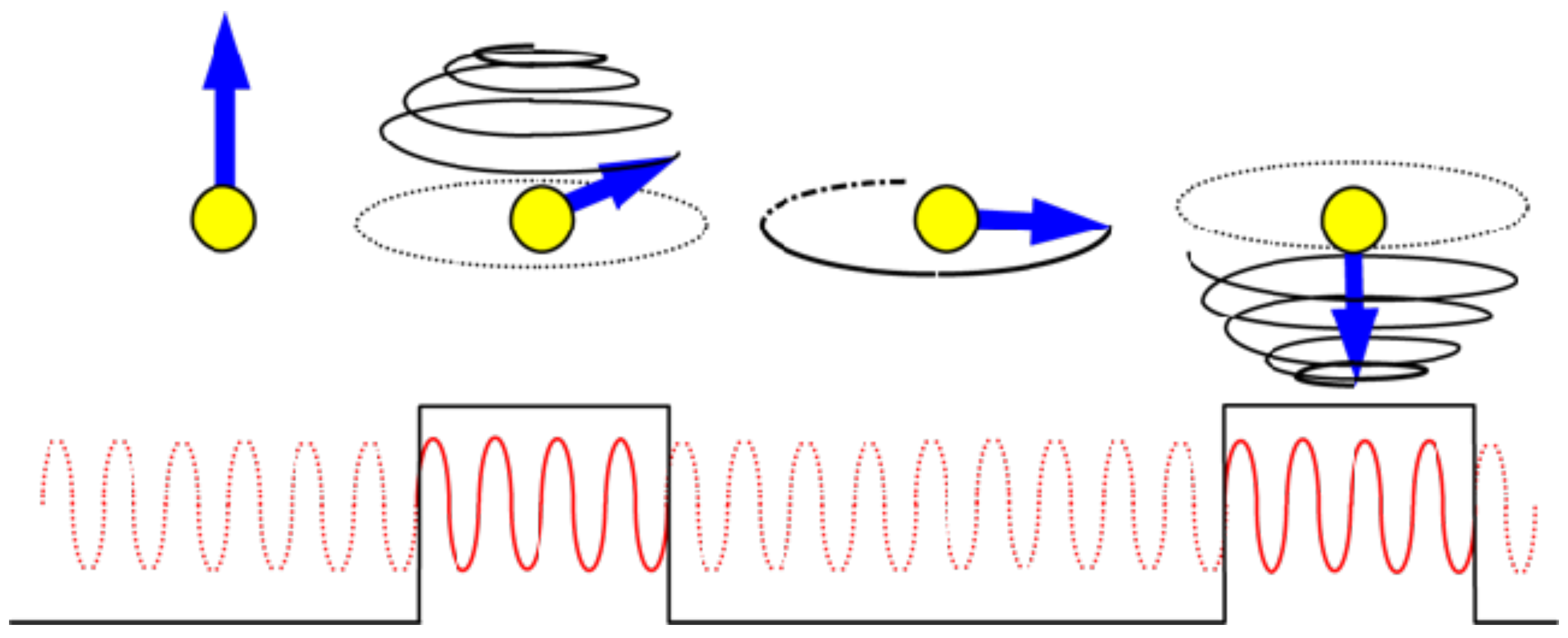
→ Expected UCN yield: (1.4-1.6) × 10^7 UCN/s

Overview of the TUCAN apparatus

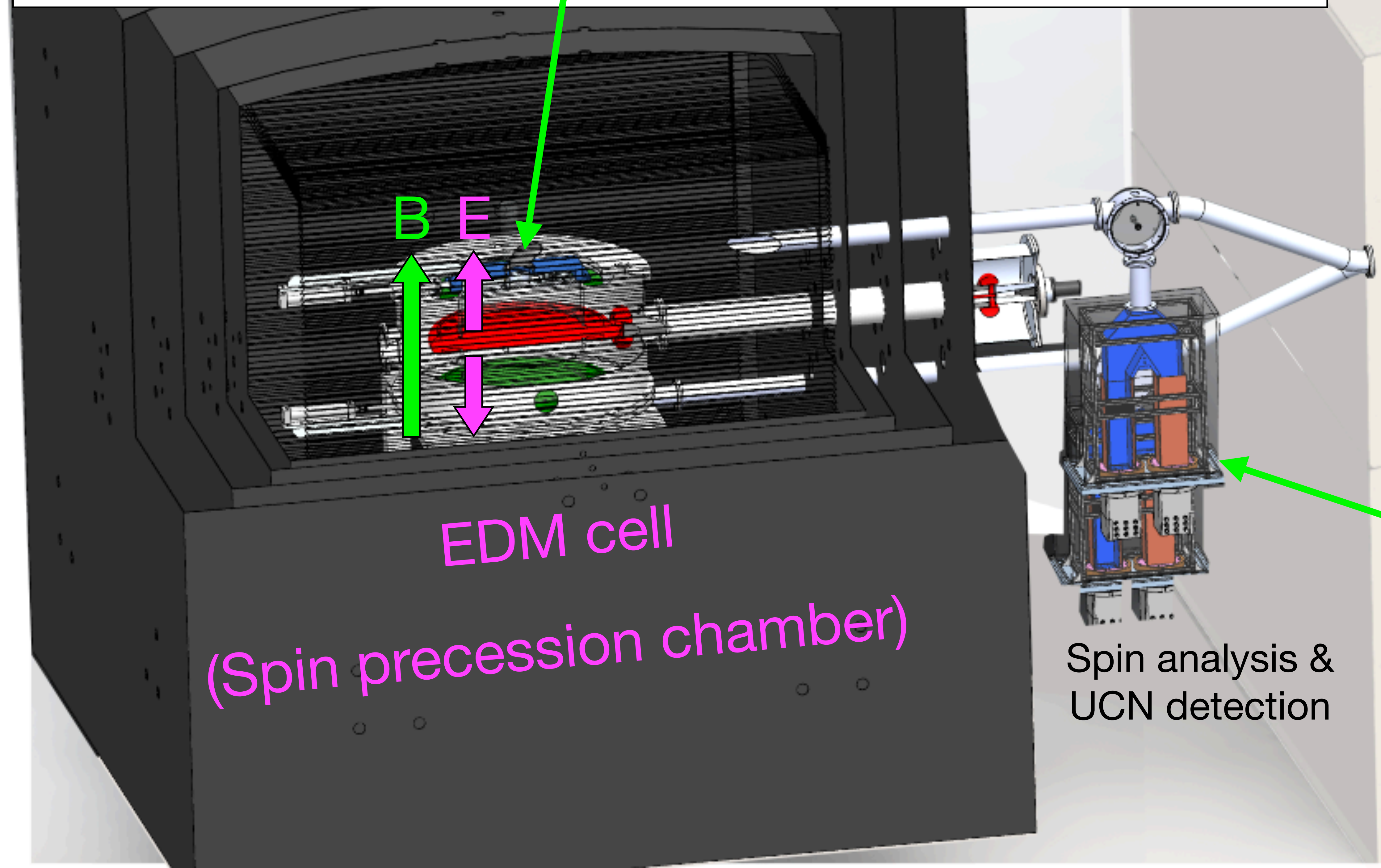
Overview of the TUCAN apparatus

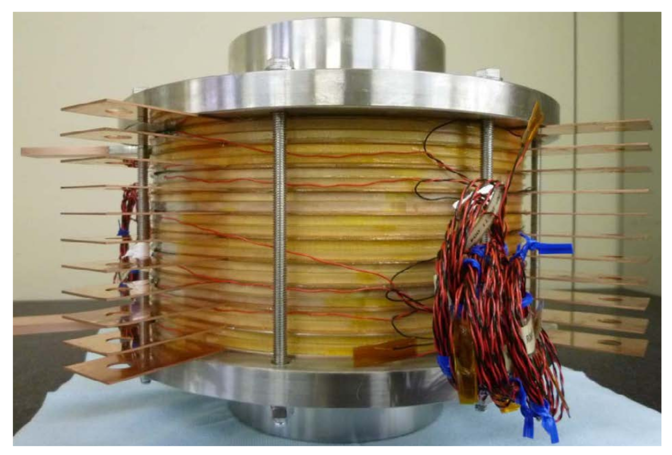


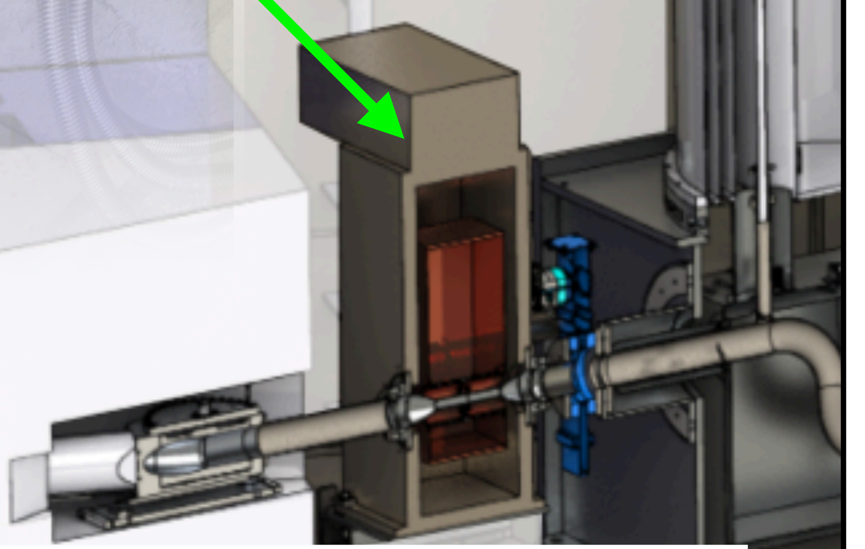
Spin flip by separated oscillating magnetic field (Ramsey resonance)



$$\hbar\omega = \begin{cases} -2\mu_n B_0 - 2d_n E \ (E\uparrow) \\ -2\mu_n B_0 + 2d_n E \ (E\downarrow) \end{cases} \longrightarrow \Delta\omega = -\frac{4d_n E}{\hbar}$$







Magnetic potential

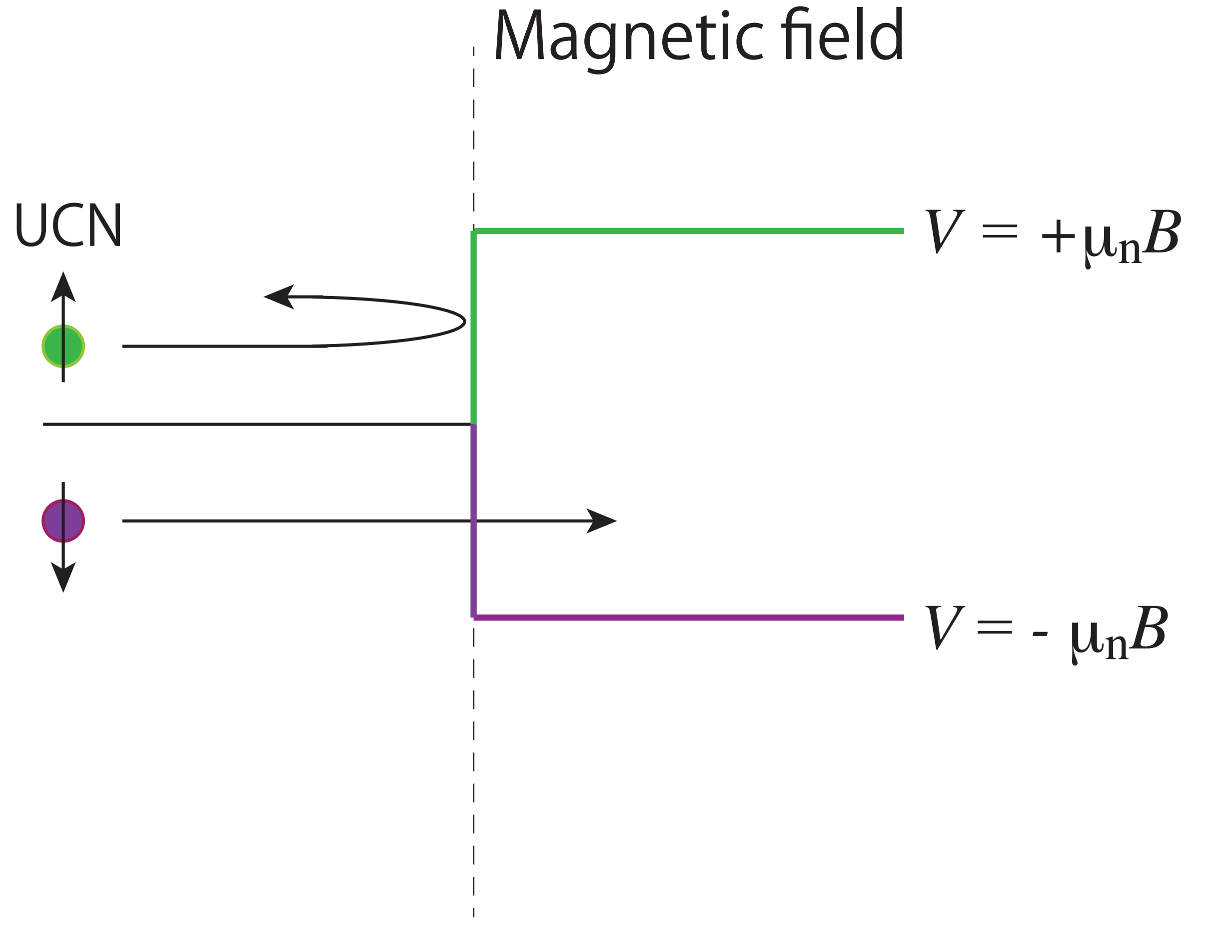
$V = -\boldsymbol{\mu_n} \cdot \boldsymbol{B}$

Potential is spin dependent.

B = 3.5T → $-\boldsymbol{\mu_n} \cdot \boldsymbol{B} = \pm$ 210 neV

E_c ~ 200 neV from our UCN source

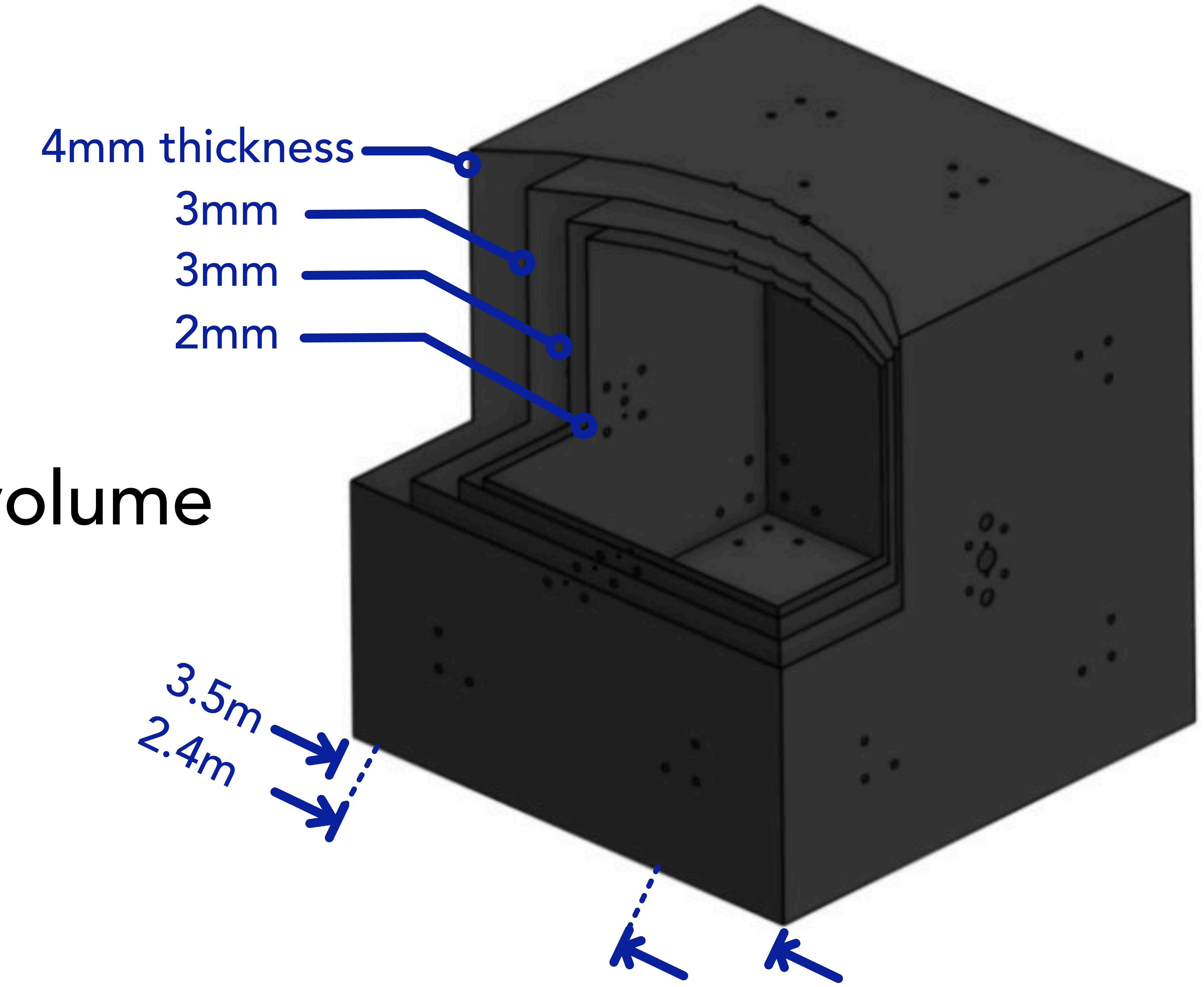
Only one state can pass.



Talk by H. Akatsuka

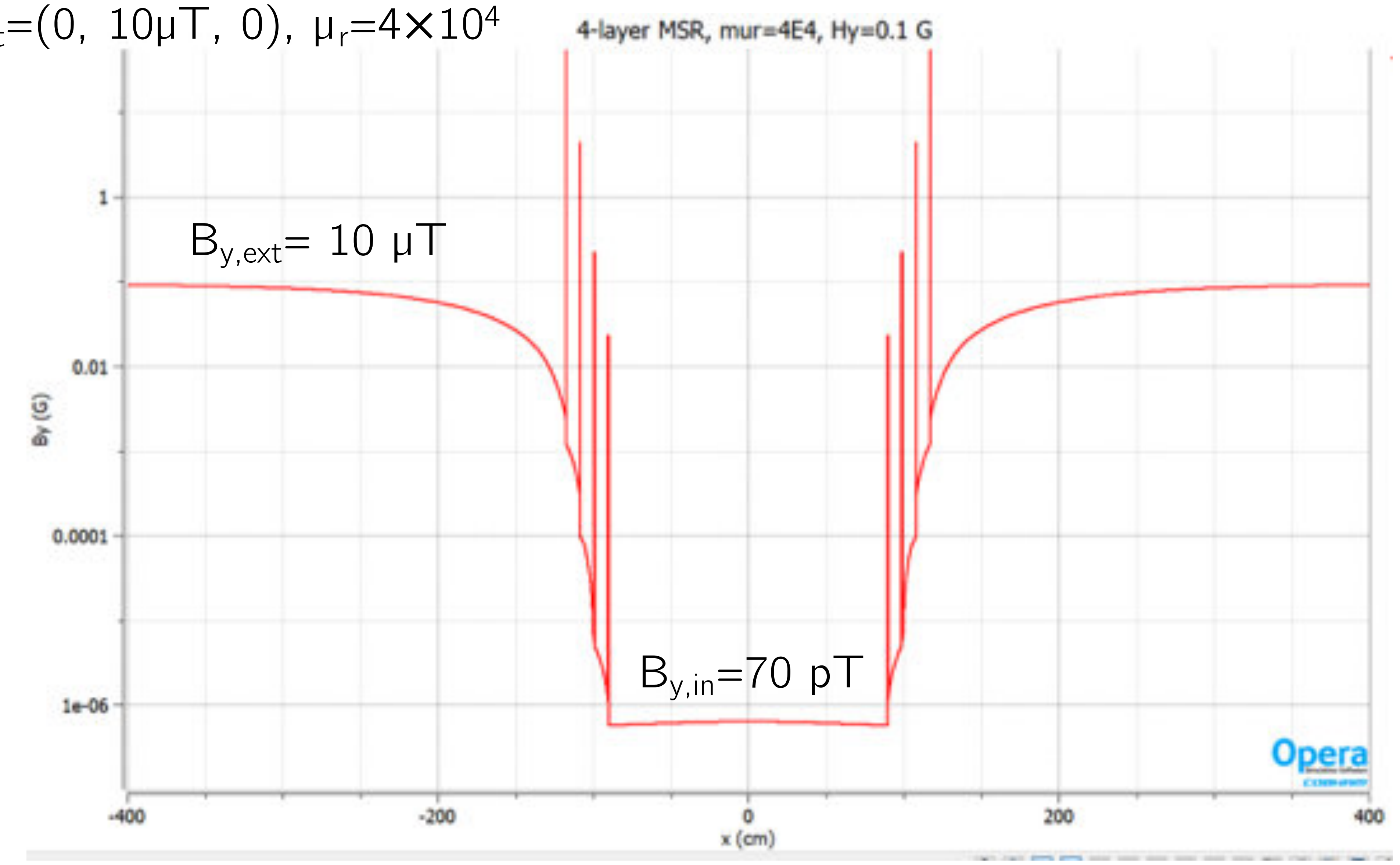

Magnetic field measurement at TRIUMF
MSR
Mapped area
Prototype EDM cell & valve
B
E
EDM cell
(Spin precession chamber)
Hg comagnetometer
(test cell)
External Cs magnetometers
s/n 1

Magnetically Shielded Room (MSR)



- **Requirements for the nEDM measurement:**
  - Shielding factor ~ 10^5 (@10 mHz or higher)
  - Fields < 1nT, gradient < 100 pT/m in the central $(1\ \mathrm{m})^3$ volume
- **TUCAN MSR specifications**
  - 4-layer mumetal shield
  - Size:
    - Outermost layer: $(3.5\ \mathrm{m})^3$
    - Innermost layer : $(2.4\ \mathrm{m})^3$
  - Design shielding factor (@10mHz): ~10^5
    - Confirmed by FEA simulations
  - Currently working on detailed design with the manufacturer (Magnetic Shields Limited)
- **Installation planned in May-Oct 2022**

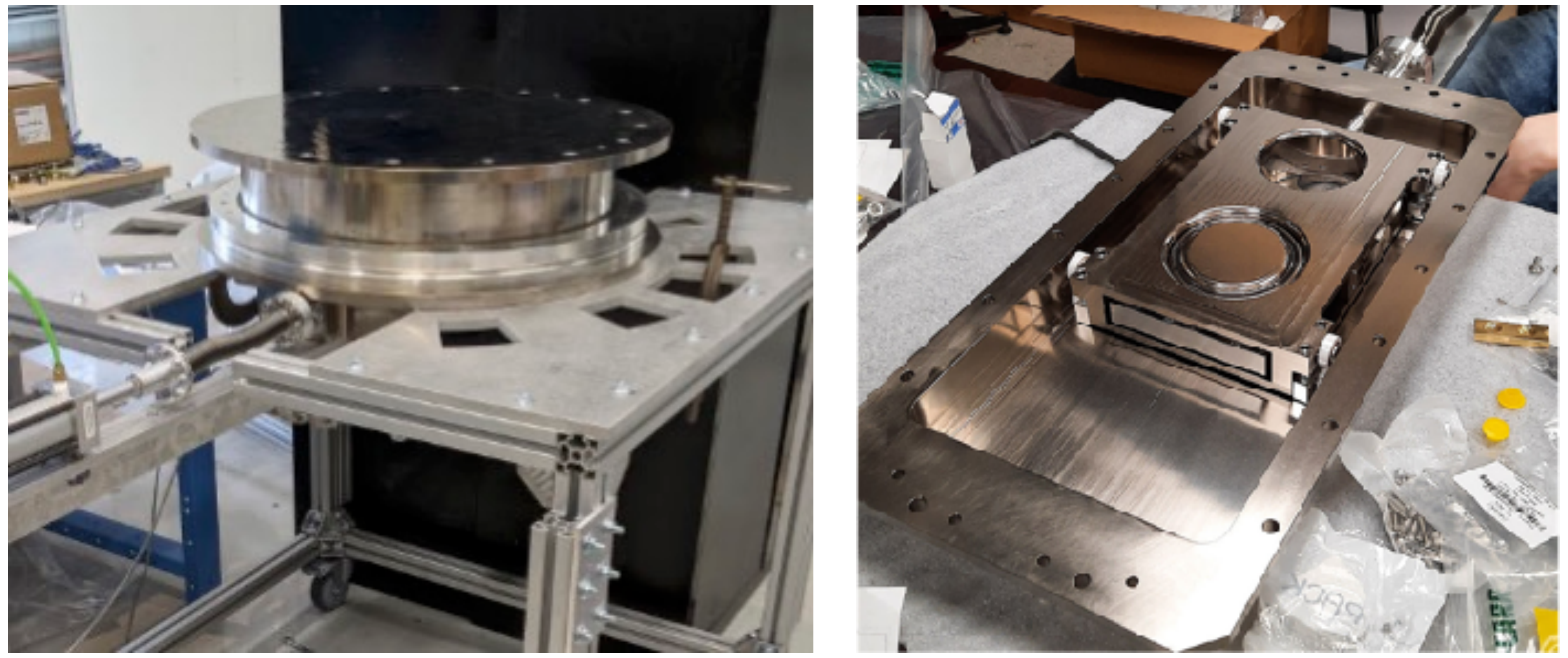
For $\mathbf{B}_{ext}=(0,\ 10\mu T,\ 0)$, $\mu_r=4\times10^4$



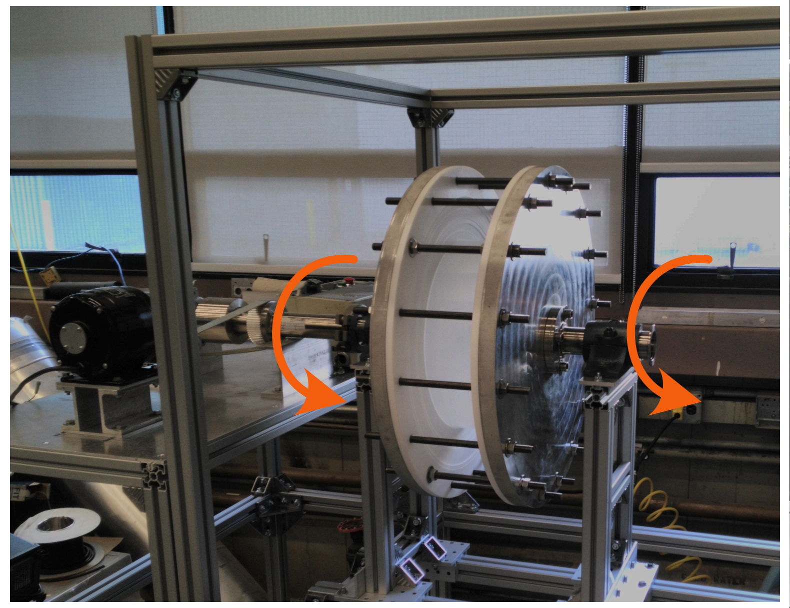
EDM cell, magnetometers

EDM cell

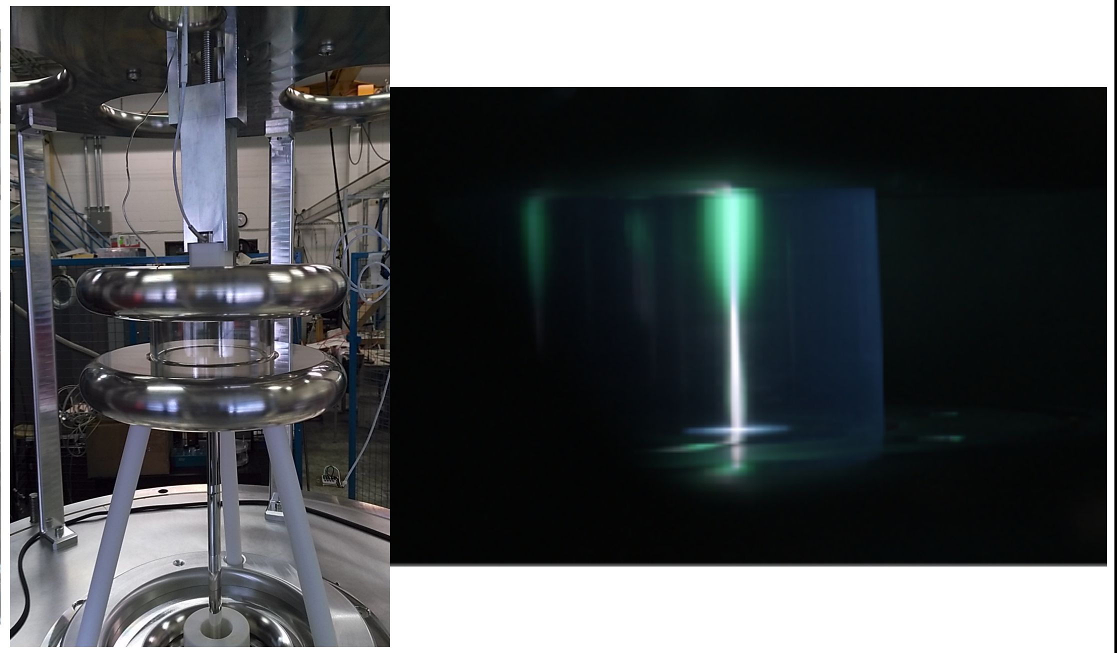
- Electric field simulation
- Prototype EDM cell and valve
    - UCN storage test planned at J-Parc in 2022
- Coating machine for deposition of dPS
- High voltage discharge test - obtained Paschen's curve
- Systematics studies



Prototype EDM cell and valve



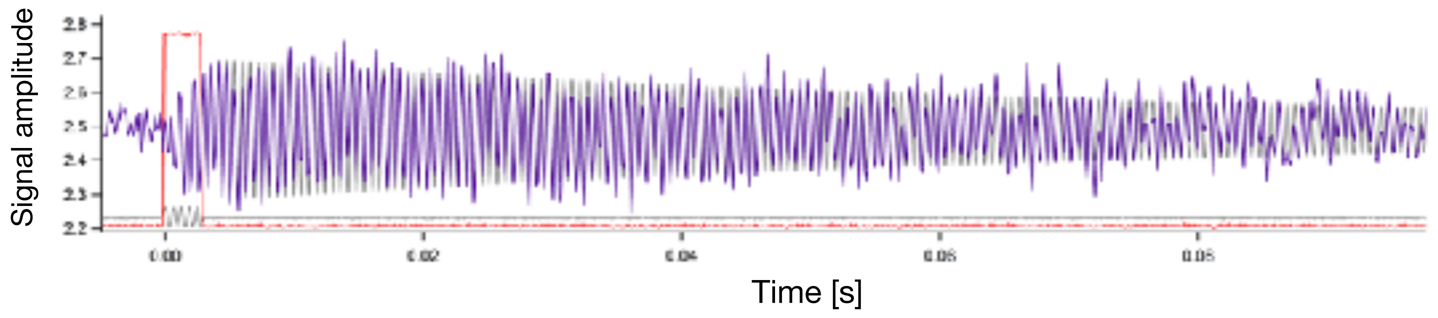
Coating machine



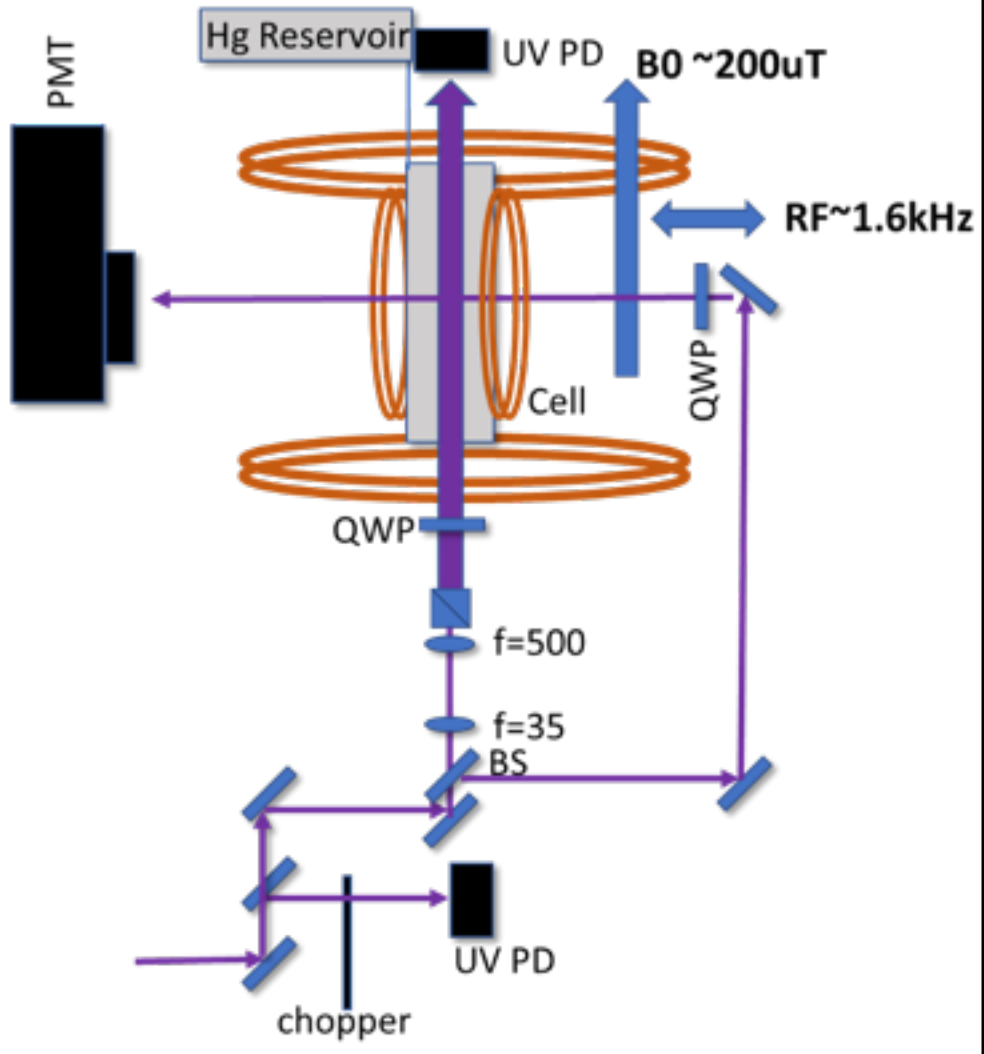
HV discharge test

Magnetometers

- Measure the B_0 fields by observing spin precession of polarized atoms
- ^{199}Hg co-magnetometer
    - Tested at 200uT B_0 field, FID obtained.
    - Planning 1uT tests in magnetic shield

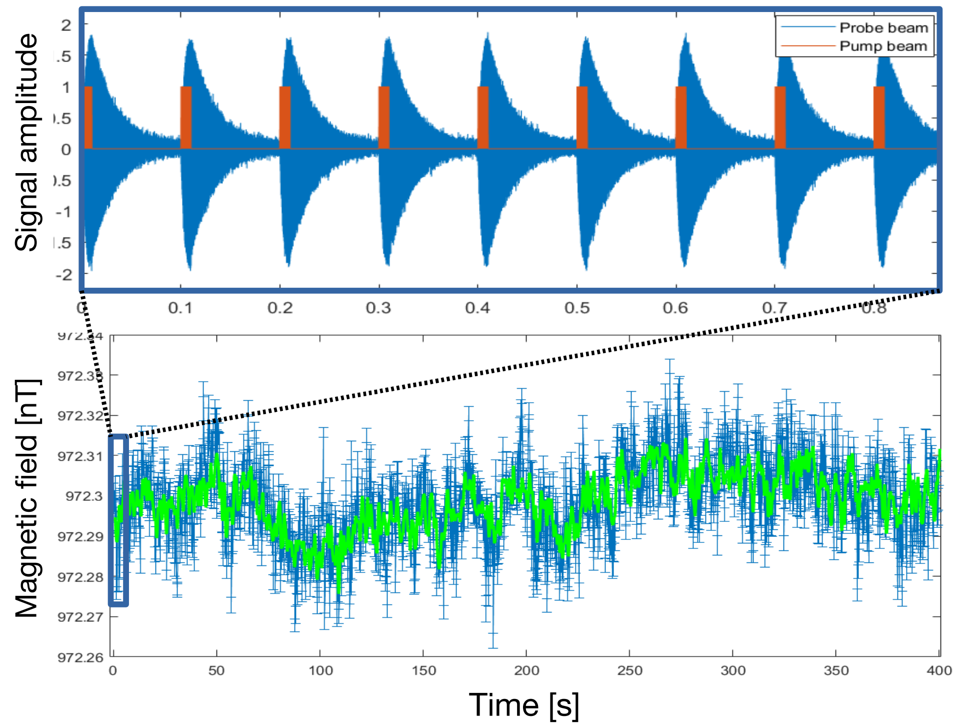


Obtained ^{199}Hg FID signal at 200uT with n=100 averages

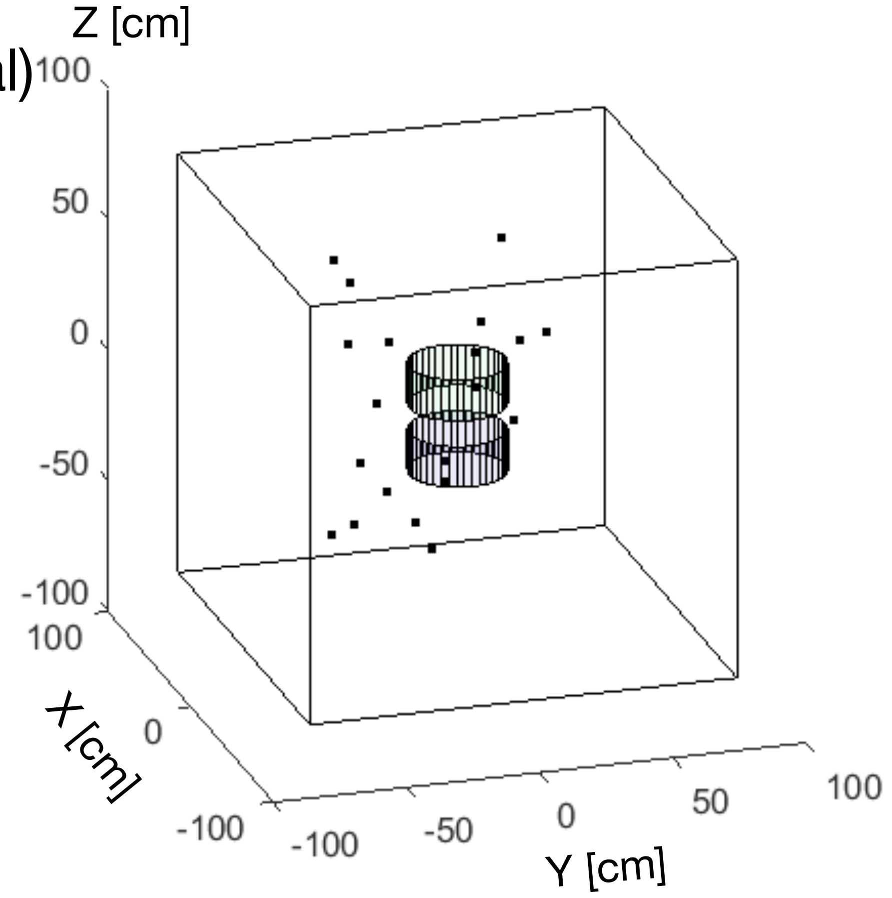


^{199}Hg cell test setup

- External Cs magnetometer array
    - Sub-pT performance after 3-4s integration
    - Completed 5 Cs sensors (24 sensors in total)



Measuring test field with Cs magnetometer



Cs sensor array simulation

EDM sensitivity

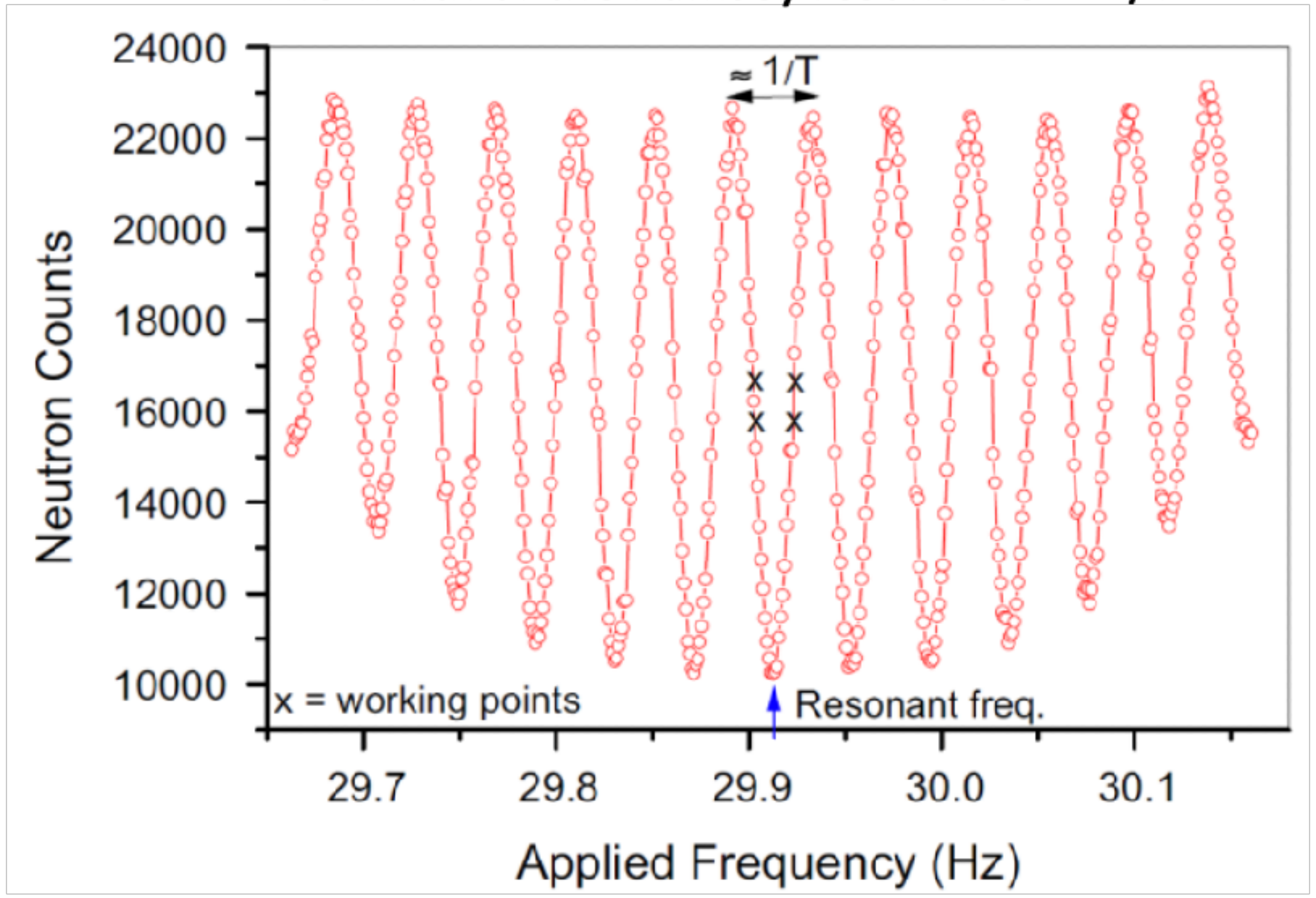
- EDM sensitivity:

$$\sigma(d_n) = \frac{\hbar}{2\alpha ET\sqrt{N_0}}$$

E : Electric field (~10 kV/cm)
T : Free precession time (~100s)
N_0 : number of UCN (**~10^6**)
← the high-intensity UCN source!
α : visibility (polarization, relaxation time) (~1)

➤ For one cycle $\sigma(d_n)$ ~**10^{-25} ecm**
Within 400 days (~10^5 cycles): **10^{-27} ecm (TUCAN goal)**

The width of the Ramsey resonance ∝ 1/T



P.G.Harris et al., NIMA, **440**, 479 (2000)

- 2022 UCN production
- 2023 UCN Source & nEDM spectrometer commissioning
- 2024 nEDM data-taking & Systematic studies begin

Summary & Future Plan

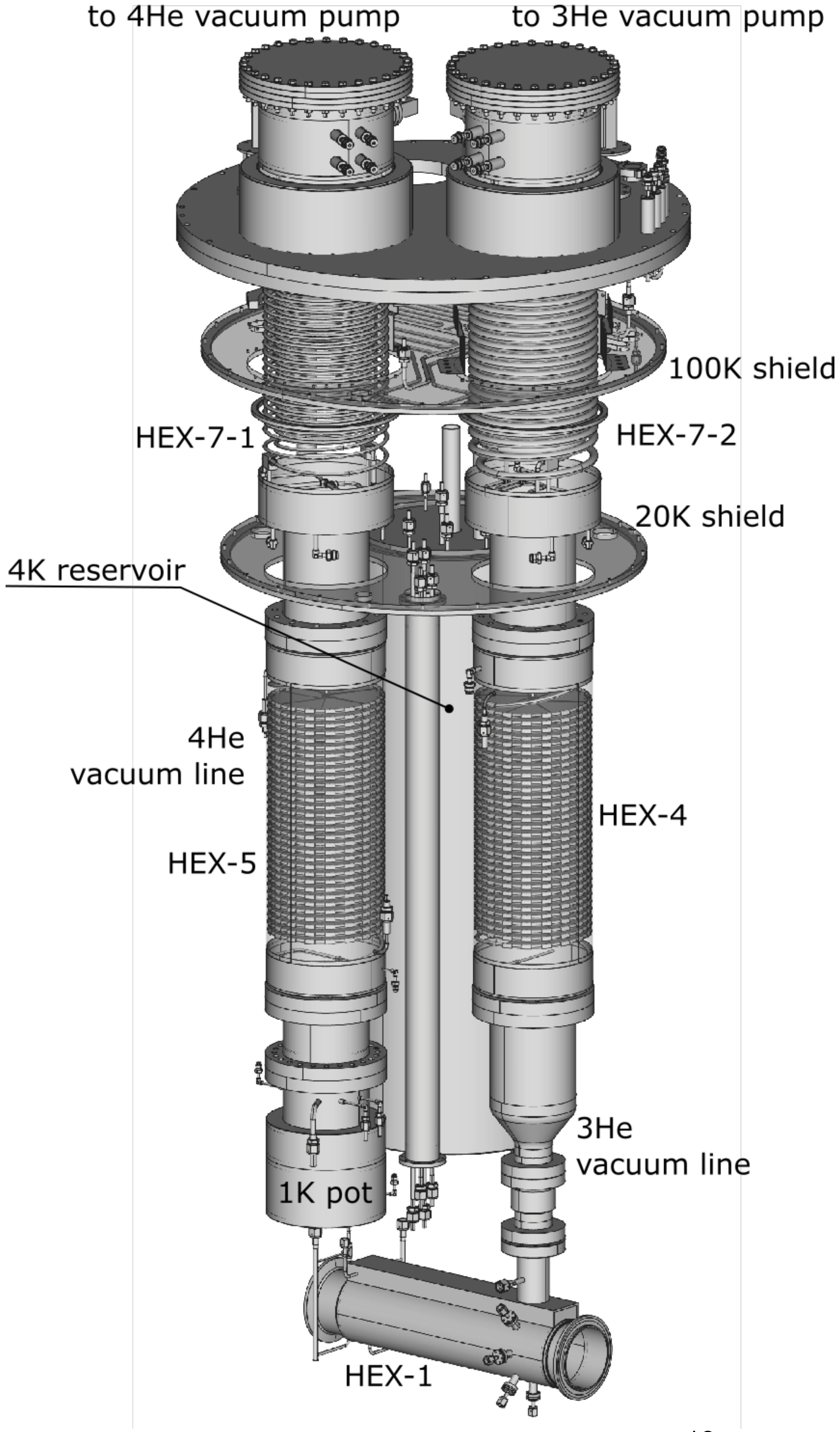
- The new UCN source (TUCAN source) development
  - The proton beam line was constructed and the prototype UCN source was operated at TRIUMF.
  - He cryostat was tested at Japan and shipped to TRIUMF.
  - UCN production volume is in construction. Installation is planned in 2022 cyclotron shutdown.
  - UCN guides were tested at TRIUMF and J-Parc.
- nEDM spectrometer development
  - UCN polarizer/analyzer were developed.
  - Magnetic field mapping at the experimental area was done. MSR will be installed in May-Oct 2022.
  - EDM cell, magnetometers, guiding fields for UCN polarization conservation etc. are under development.
- Schedule
  - UCN production: planned in 2022.
  - Commissioning of the UCN source and the EDM spectrometer: 2023
  - nEDM data-taking: 2024

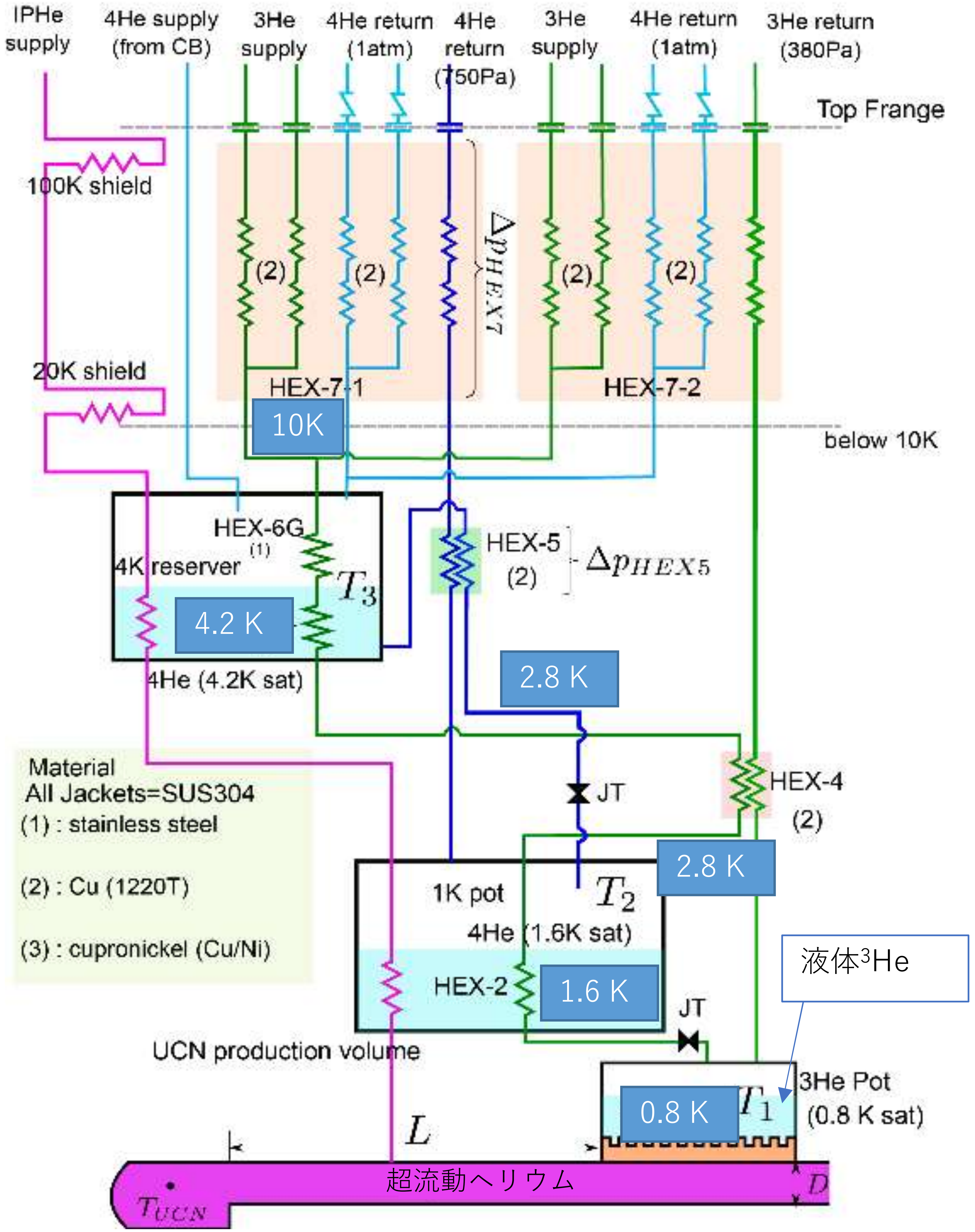
Backup slides

He cryostat flow diagram

HEX7 appearance

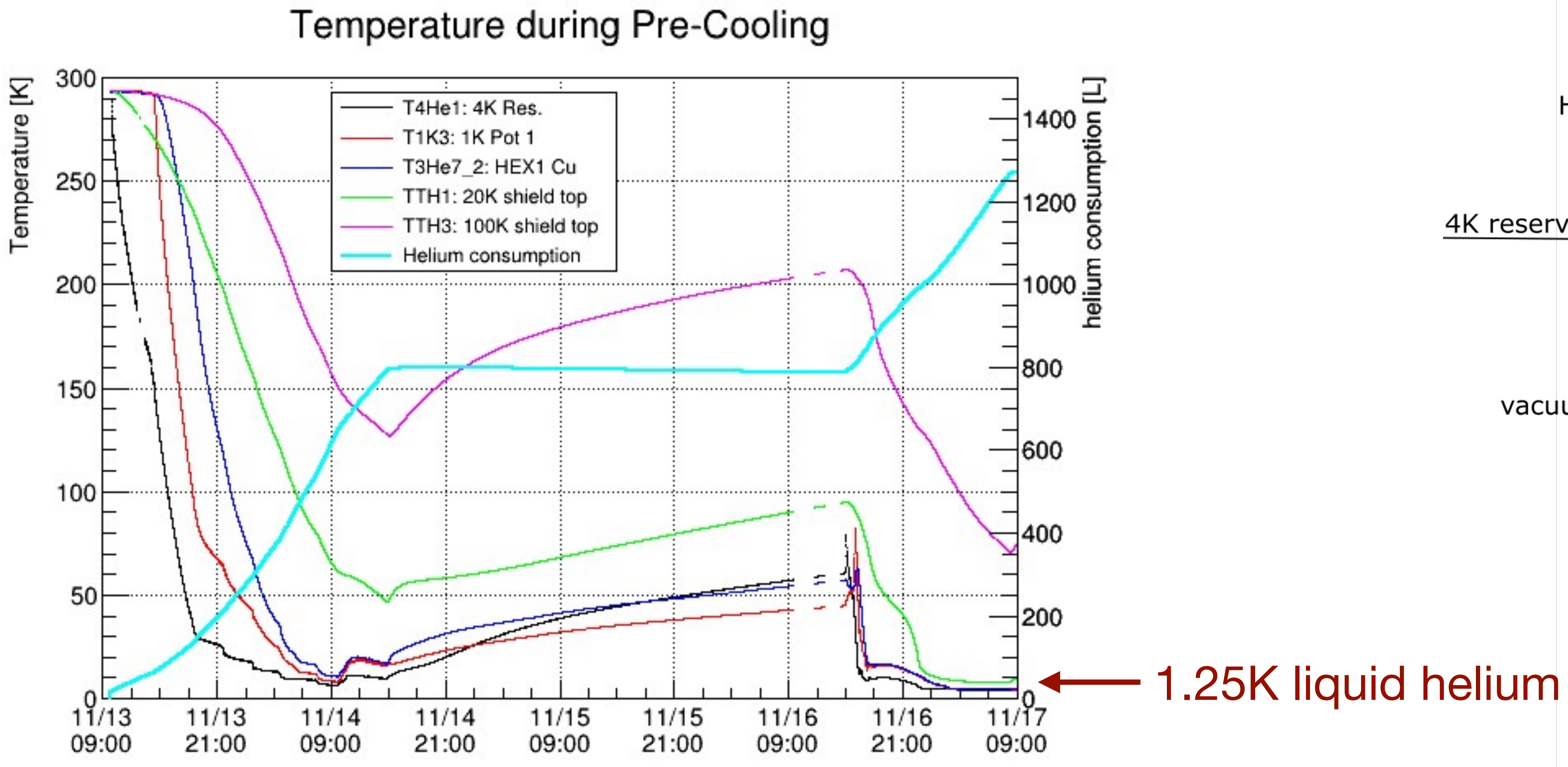
insert of the cryostat

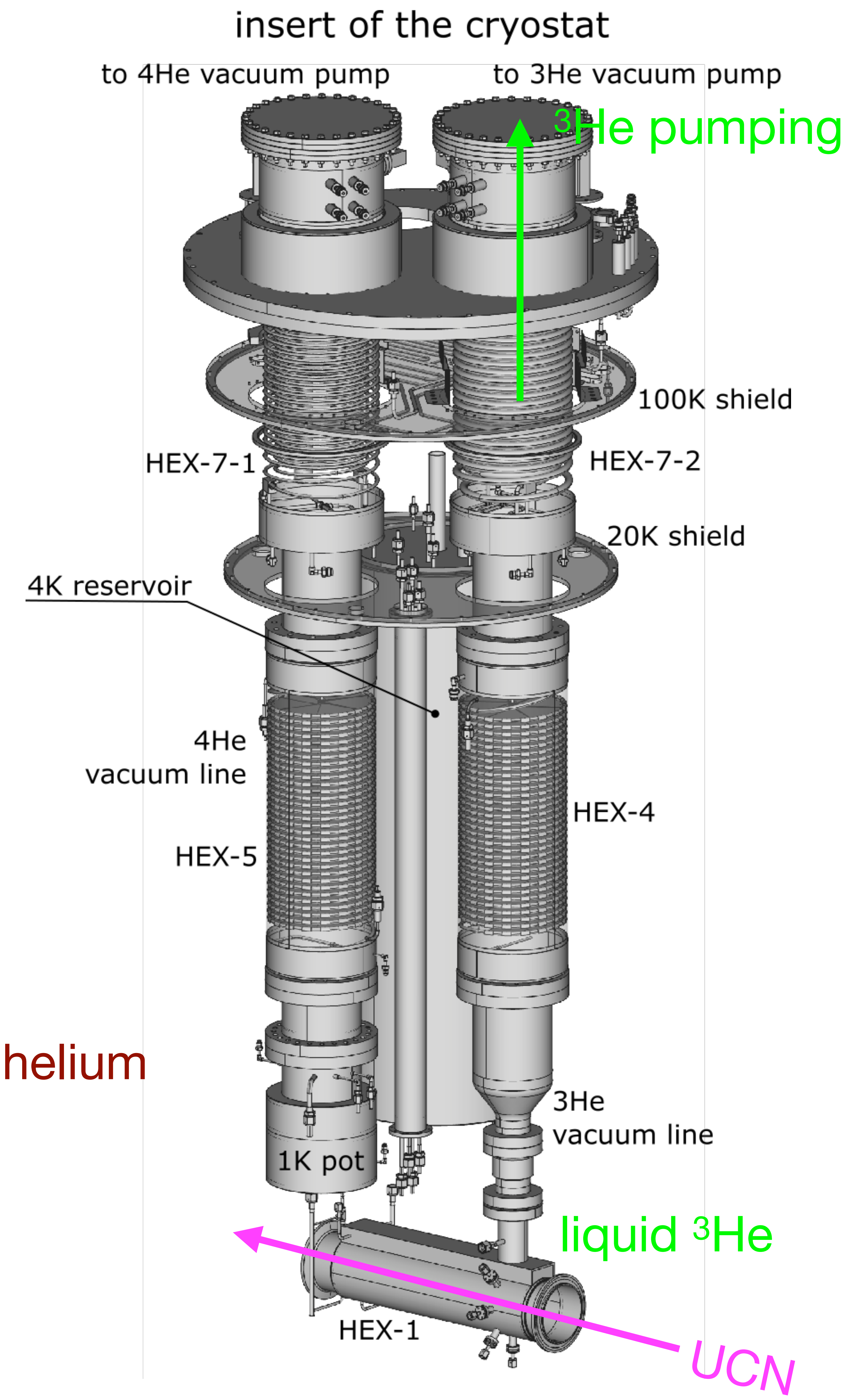




He cryostat cooling test

- He cryostat has been developed in Japan.
- Performed cooling tests of the He cryostat at KEK, Japan in 2020





- He cryostat was shipped to TRIUMF, Canada in 2021 Summer
- Cooling test at TRIUMF is planned in 2021 Winter

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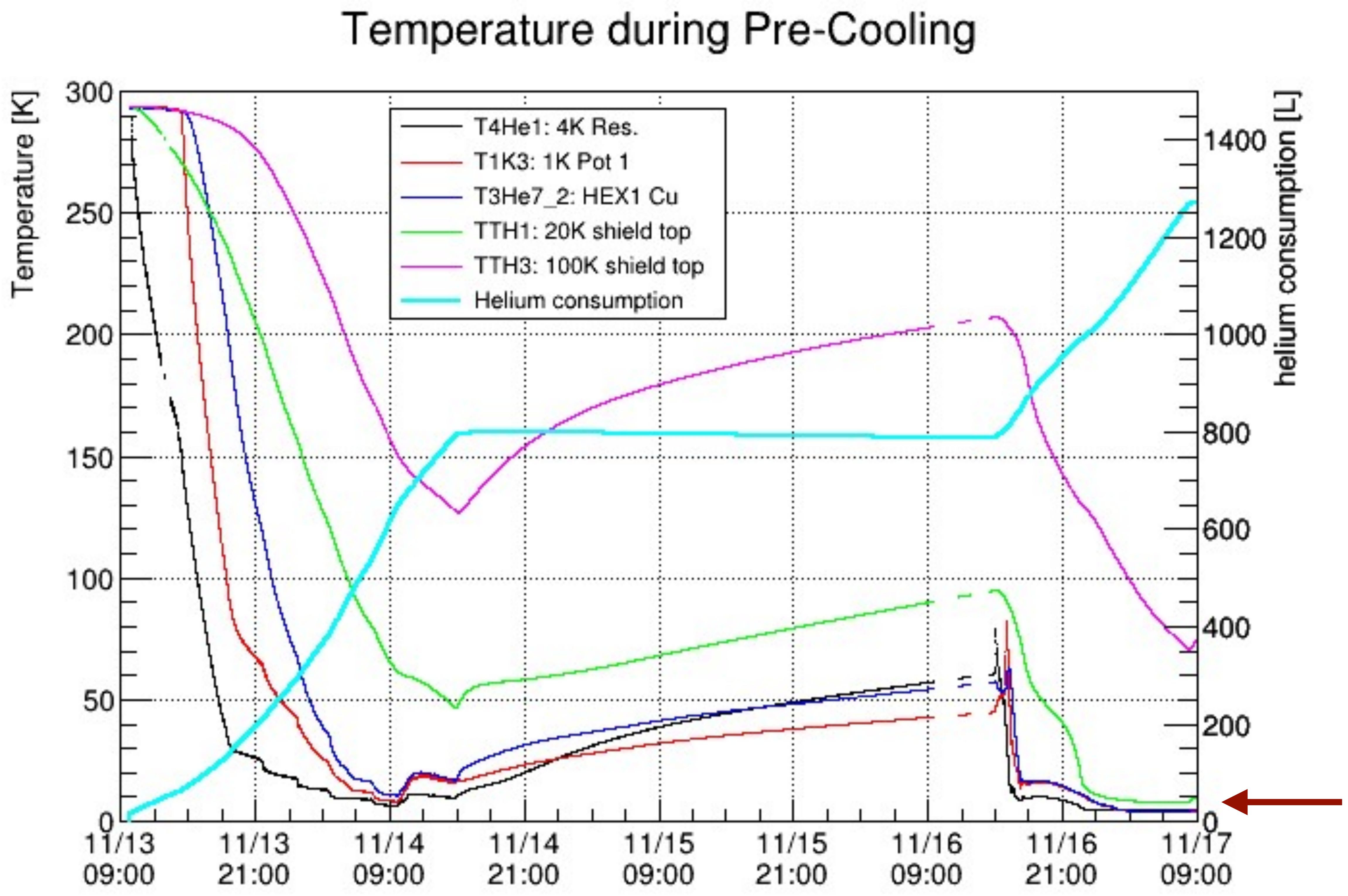
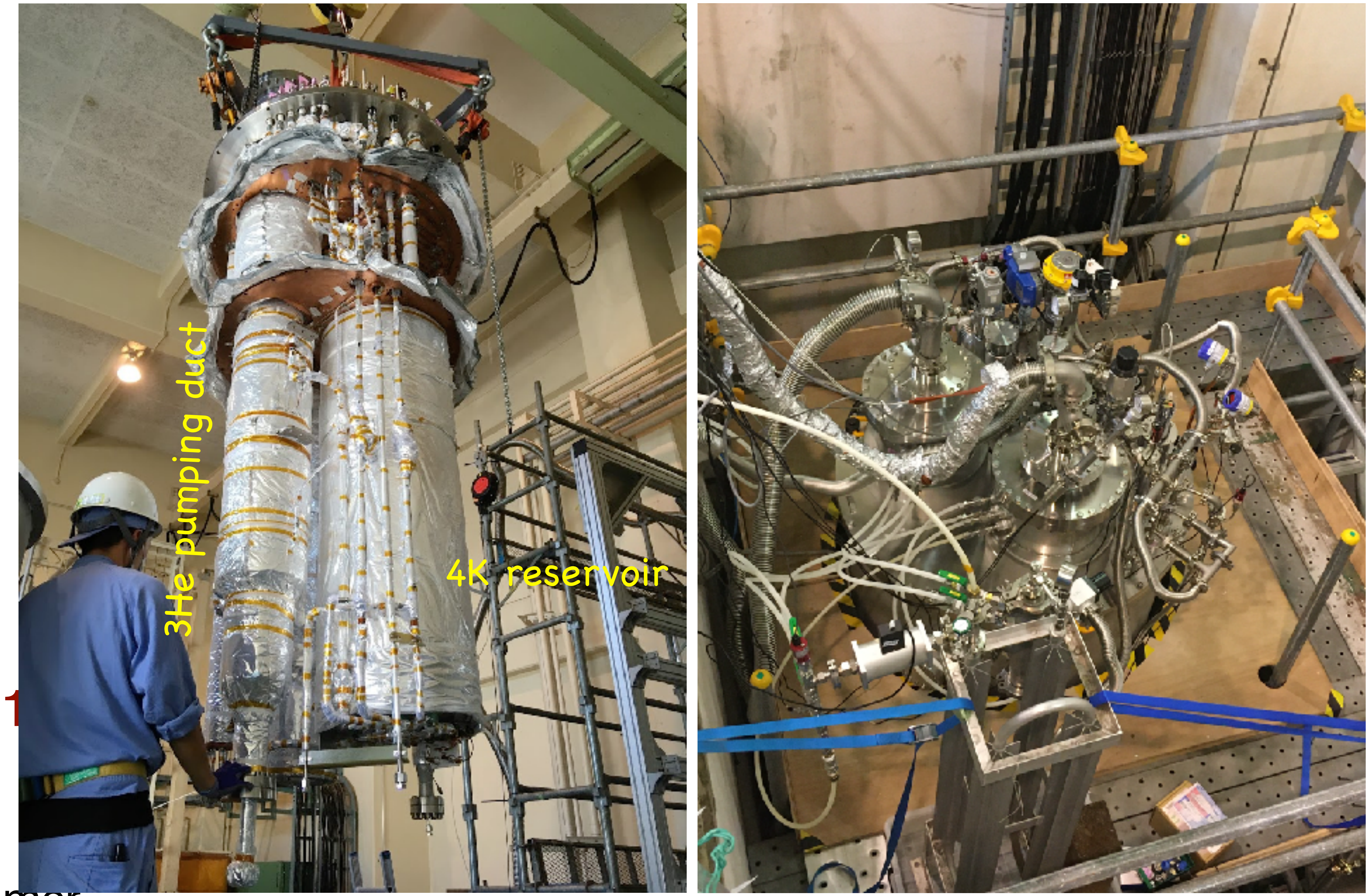




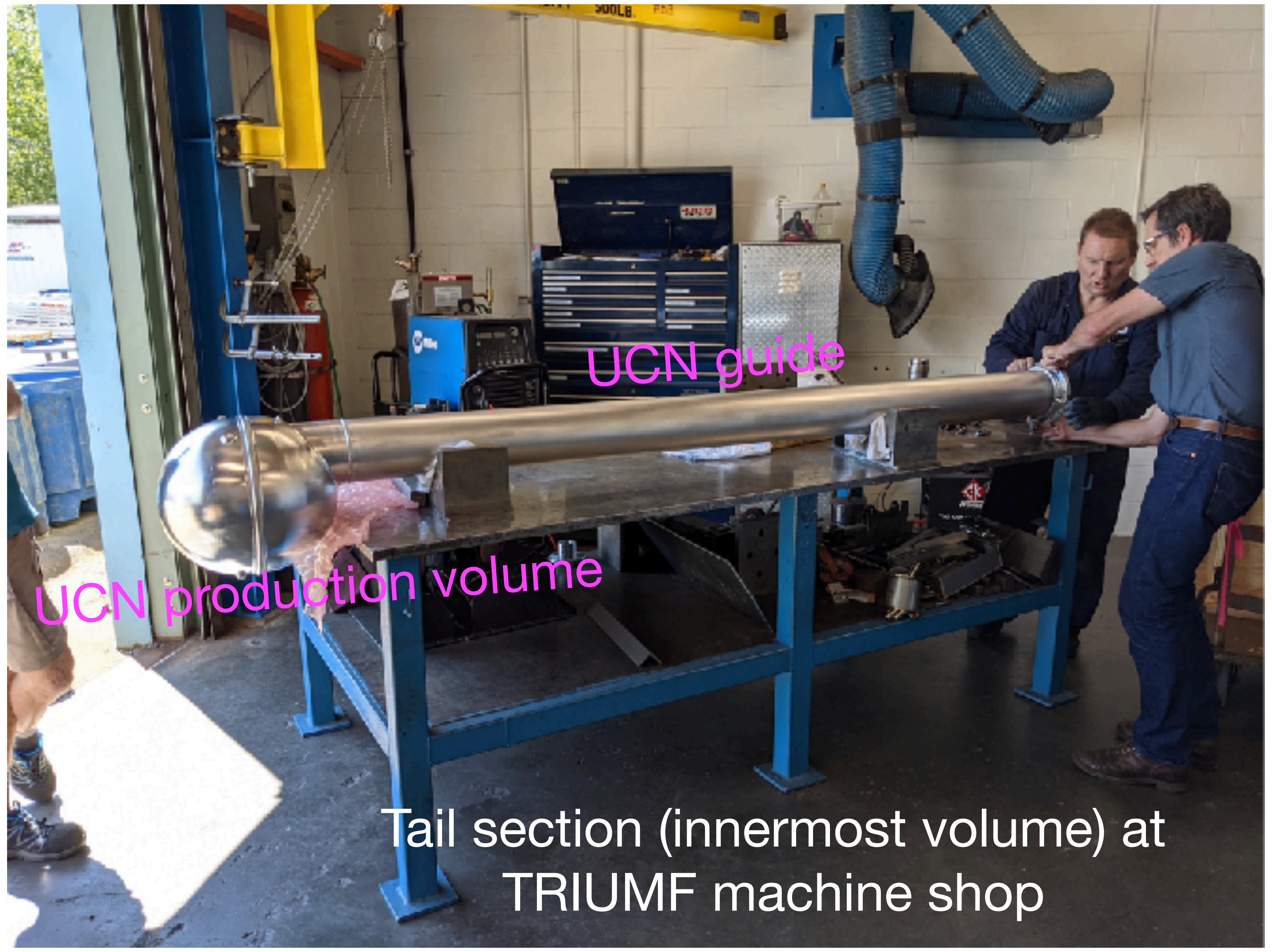
He Cryostat at KEK

- He cryostat was shipped to TRIUMF, Canada in 2021 Summer
- Cooling test at TRIUMF is planned in 2021 Winter

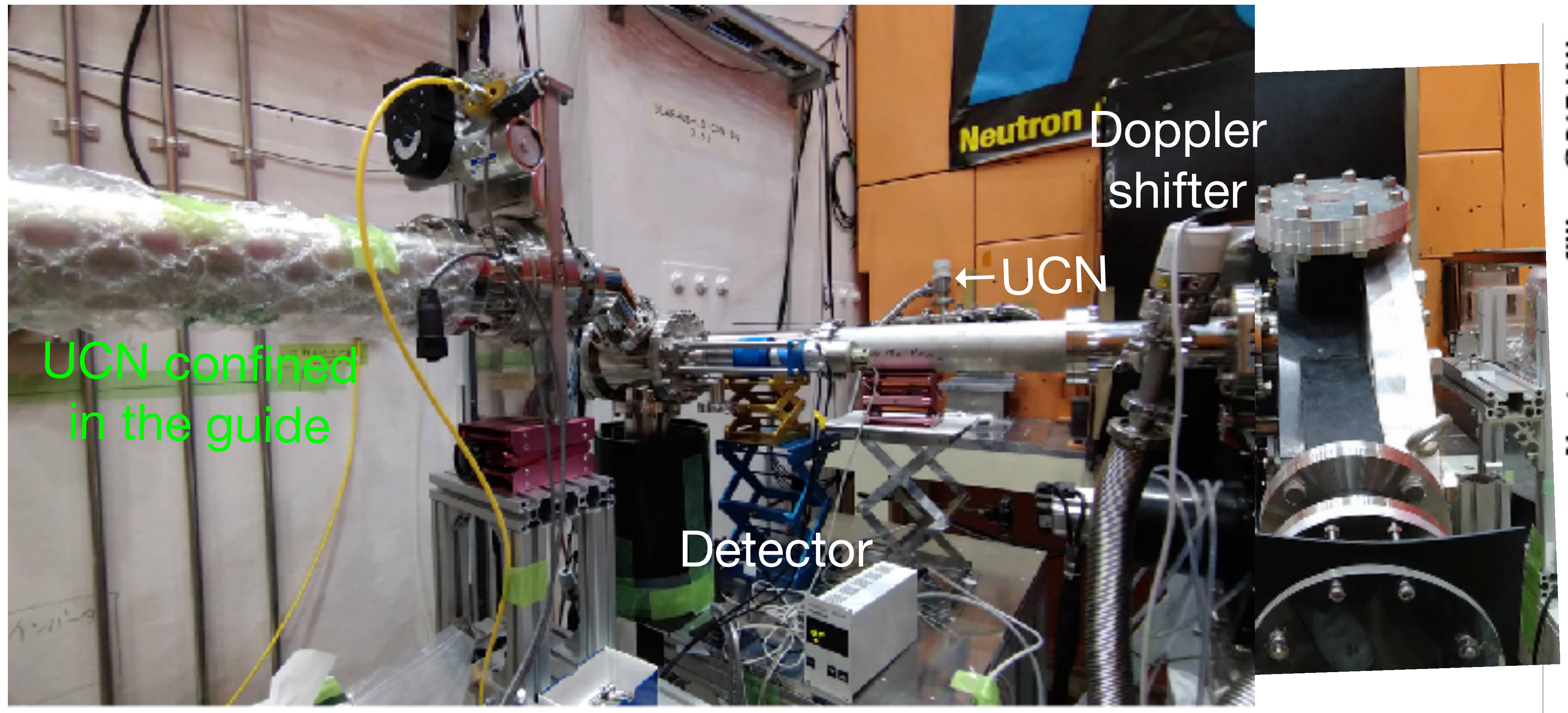
Tail section & UCN guide test

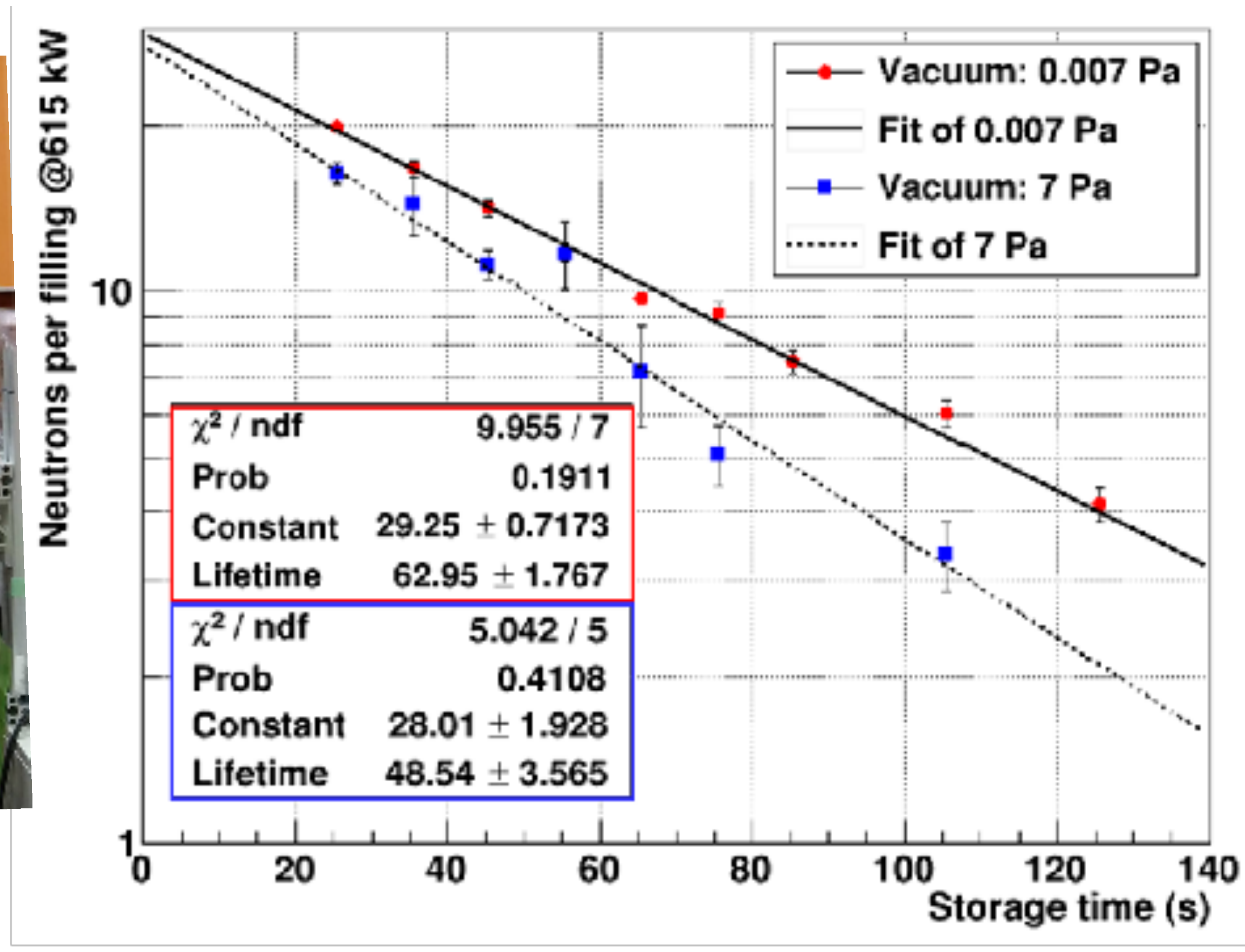
- Tail section (UCN production volume, LD_2 vessel)
  - Designed & Built by TRIUMF
  - UCN production volume + UCN guide has been made
  - Waiting for NiP coating
  - UCN storage test at LANL planned in Sep 2021
- LD_2 vessel
  - Mechanical design finished
  - Pursuing companies for outsourcing
- Tail section installation planned in 2022 shutdown

- UCN storage experiments to test NiP coating were performed at LANL (2020) and J-Parc (2021)
  - Tested NiP coating by some companies.
  - NiP coating by DavTech is the best choice



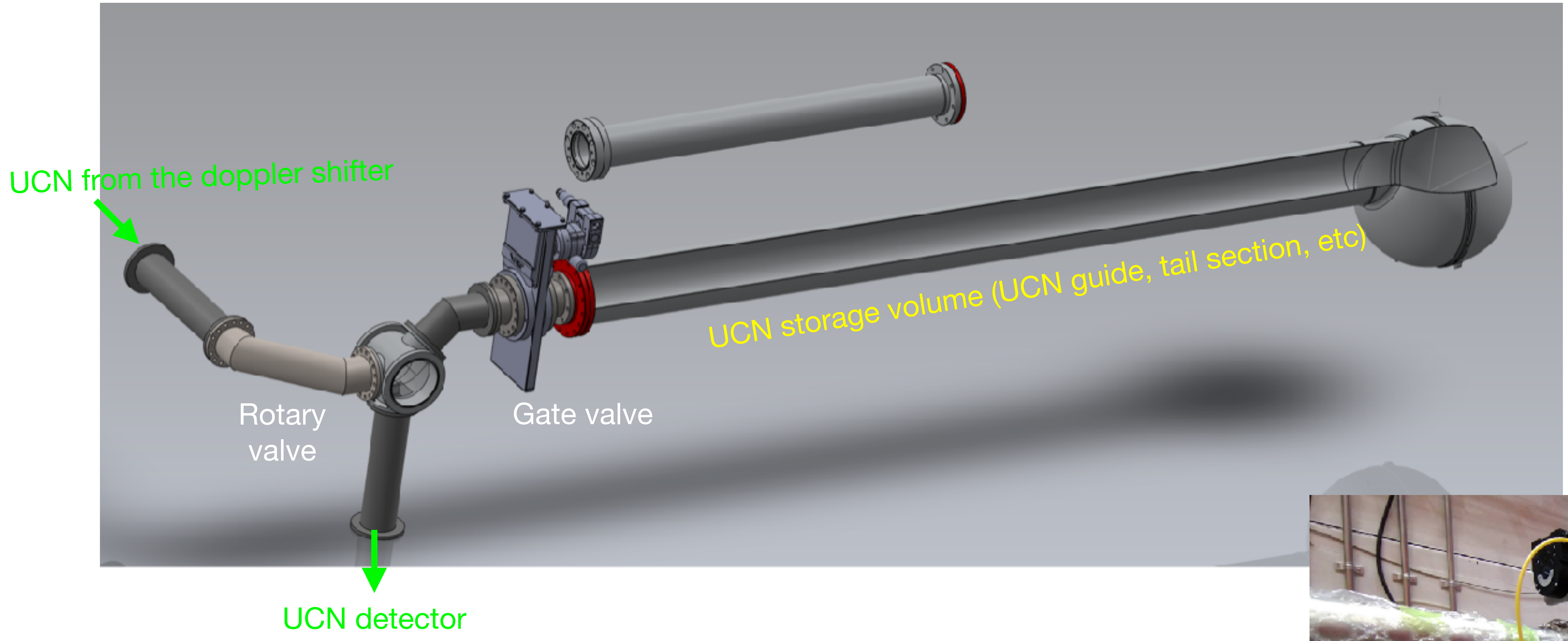
Tail section (innermost volume) at TRIUMF machine shop

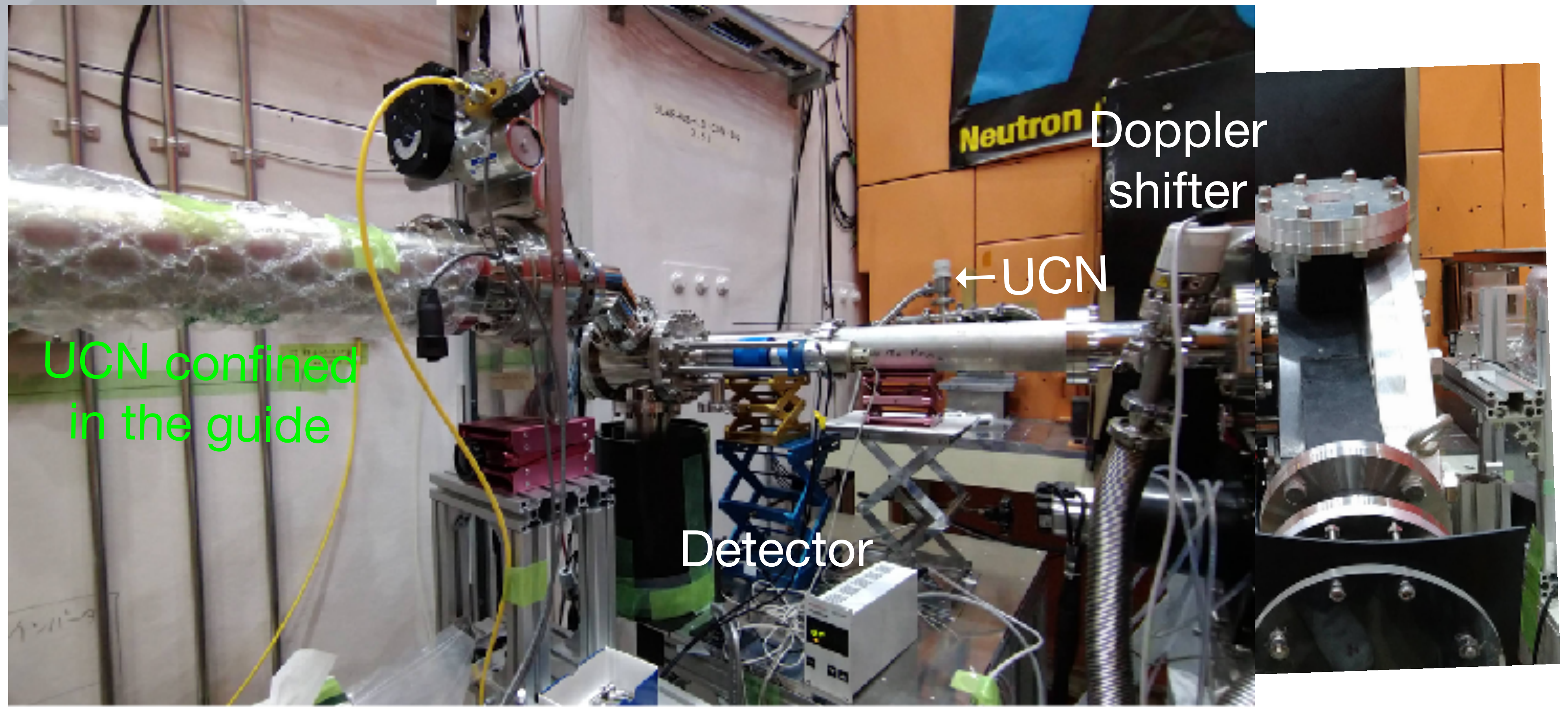




UCN storage lifetime measurement of the NiP coated guide at J-Parc

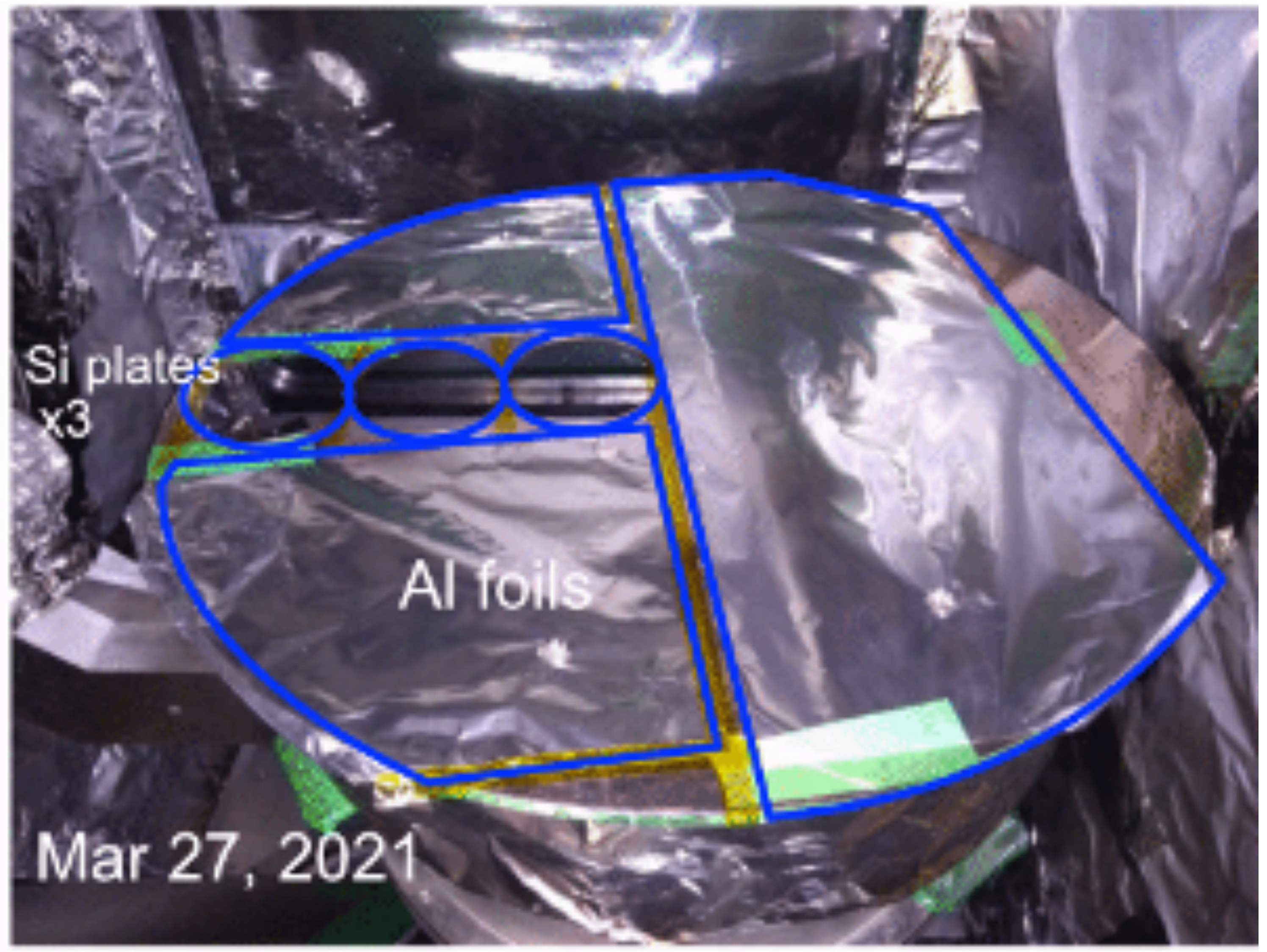
UCN storage measurement with NiP coated UCN guides
Experimental setup at J-Parc



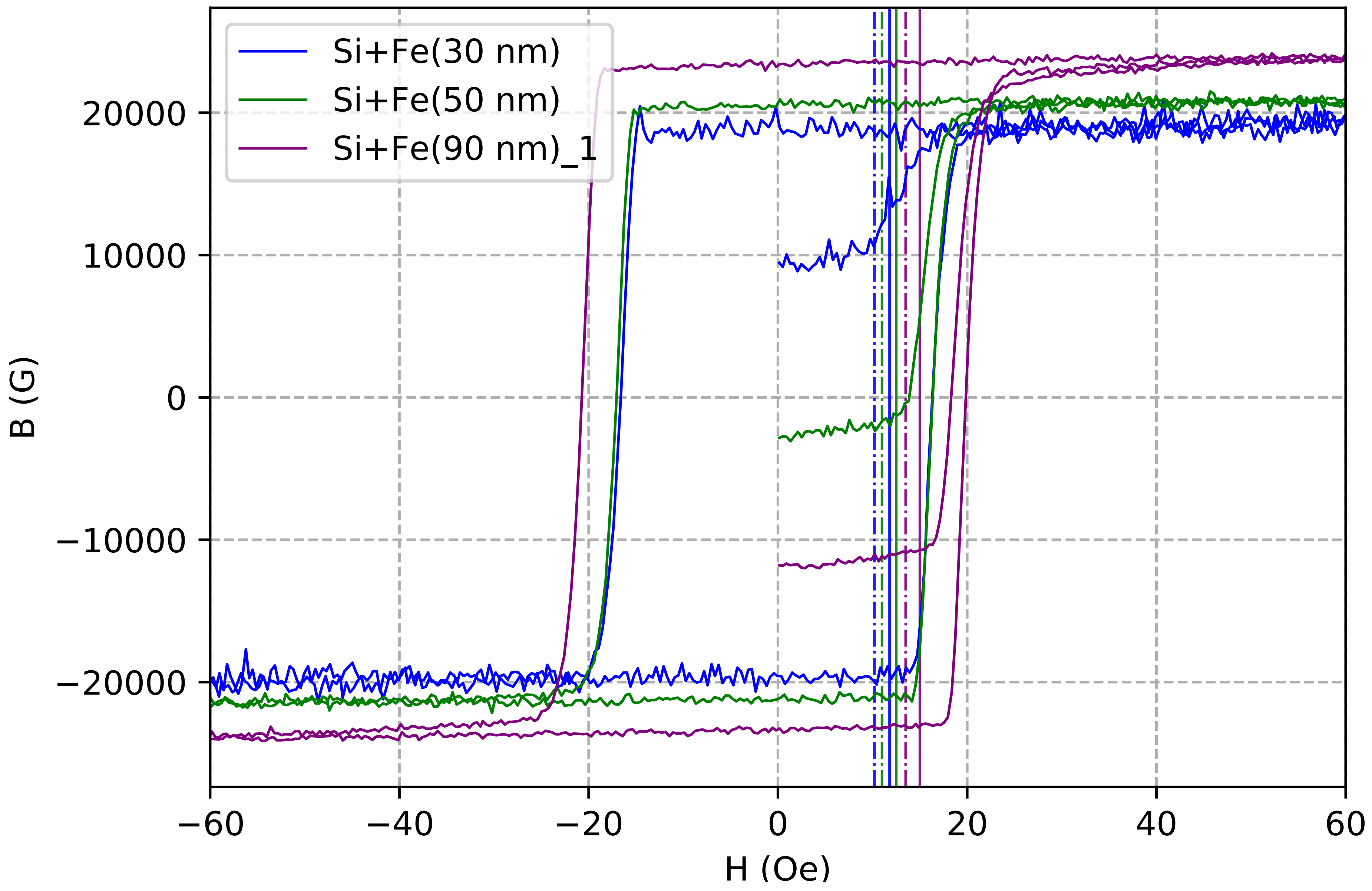


Spin analyzer development

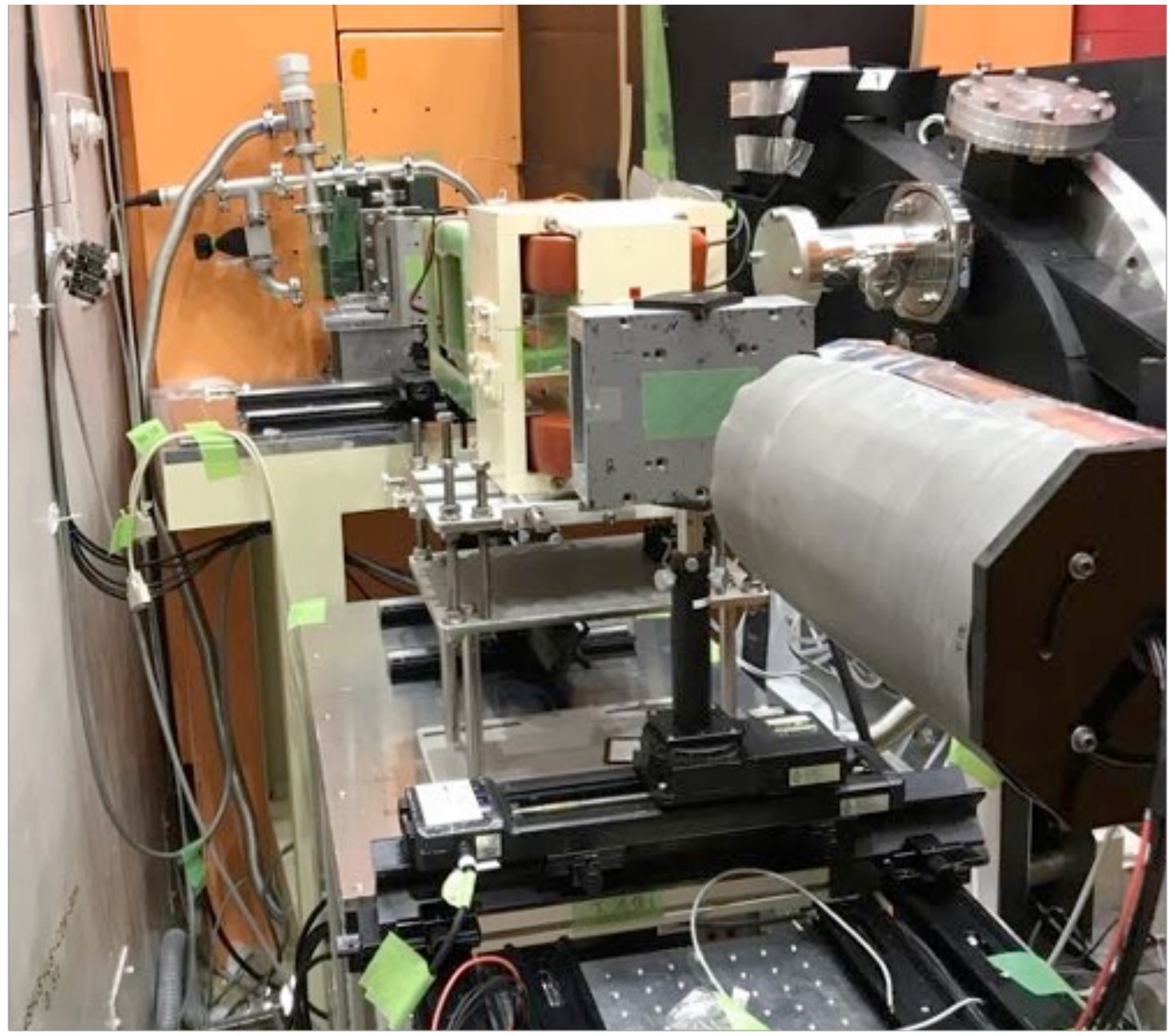
- Iron sputtered silicon/aluminum foil (Fe thickness 30, 50, 90nm) produced with the ion beam sputtering facility at KURNS M. Hino et al, Nucl. Inst. Meth. A, **797**, 265 (2015)
- B-H curve measured with VSM (vibrating sample magnetometer)
- Performance test using cold neutron reflectometry at J-Parc MLF BL05: in analysis
- Performance test with UCN in the future



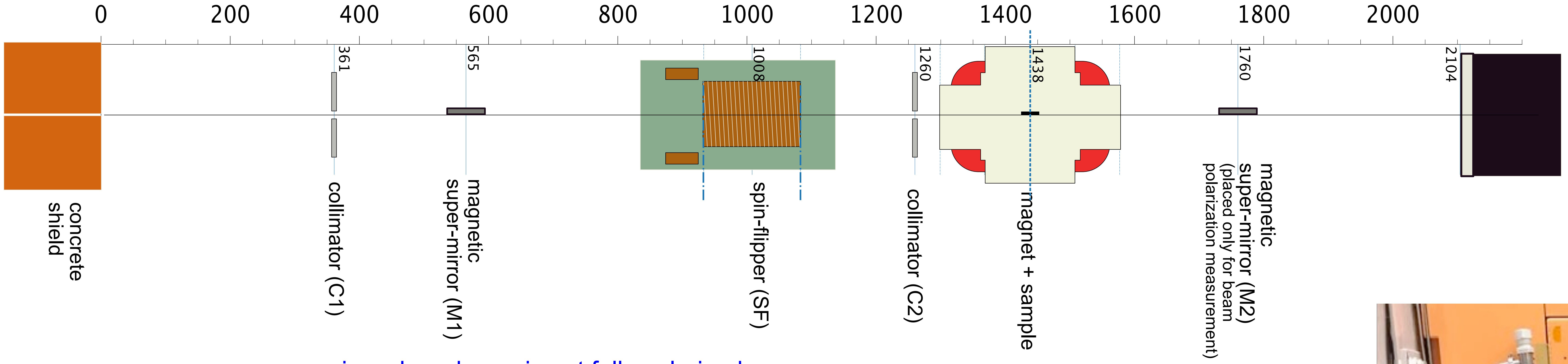
Sputtering facility at KURNS



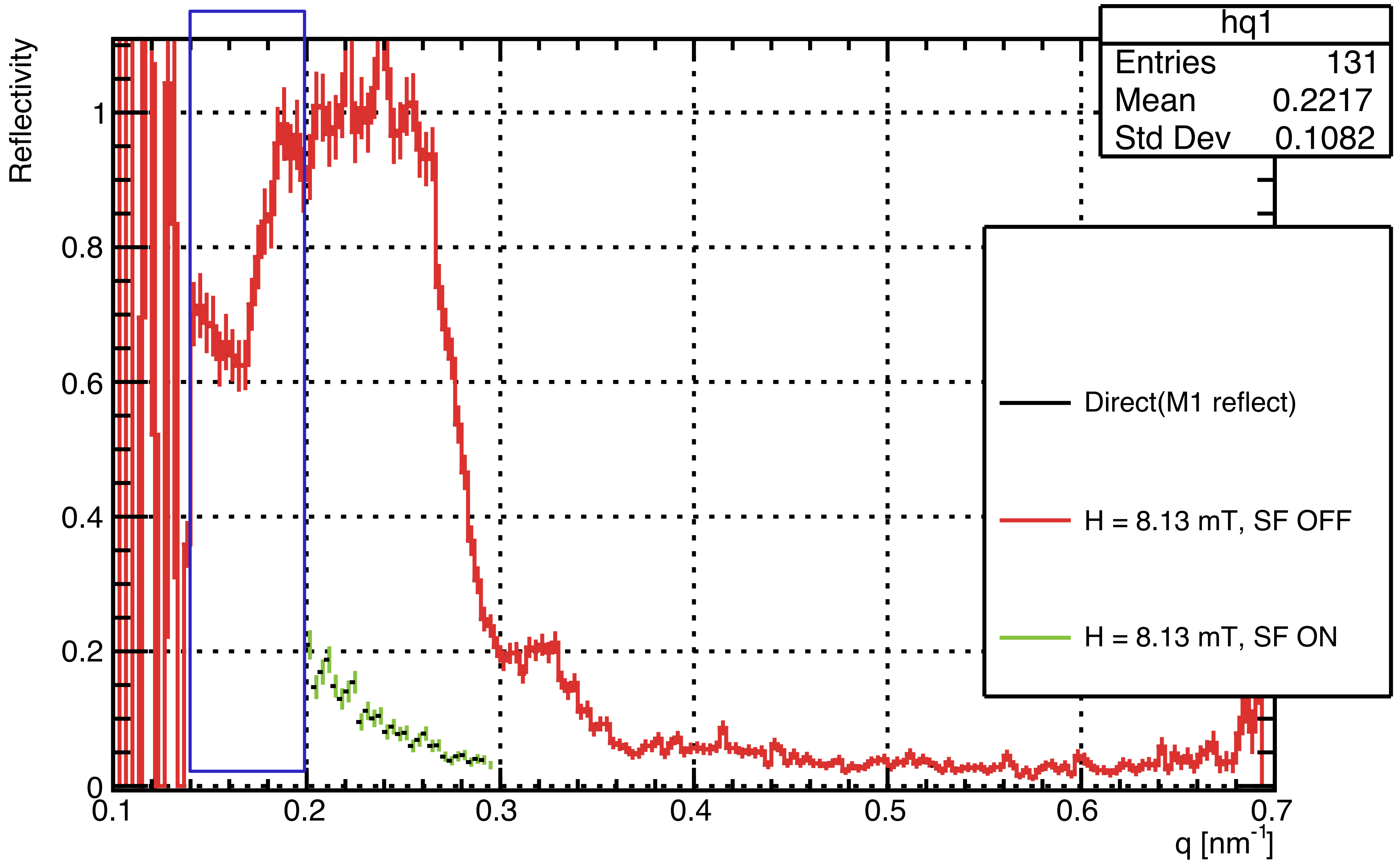
B-H curve of Fe/Si samples

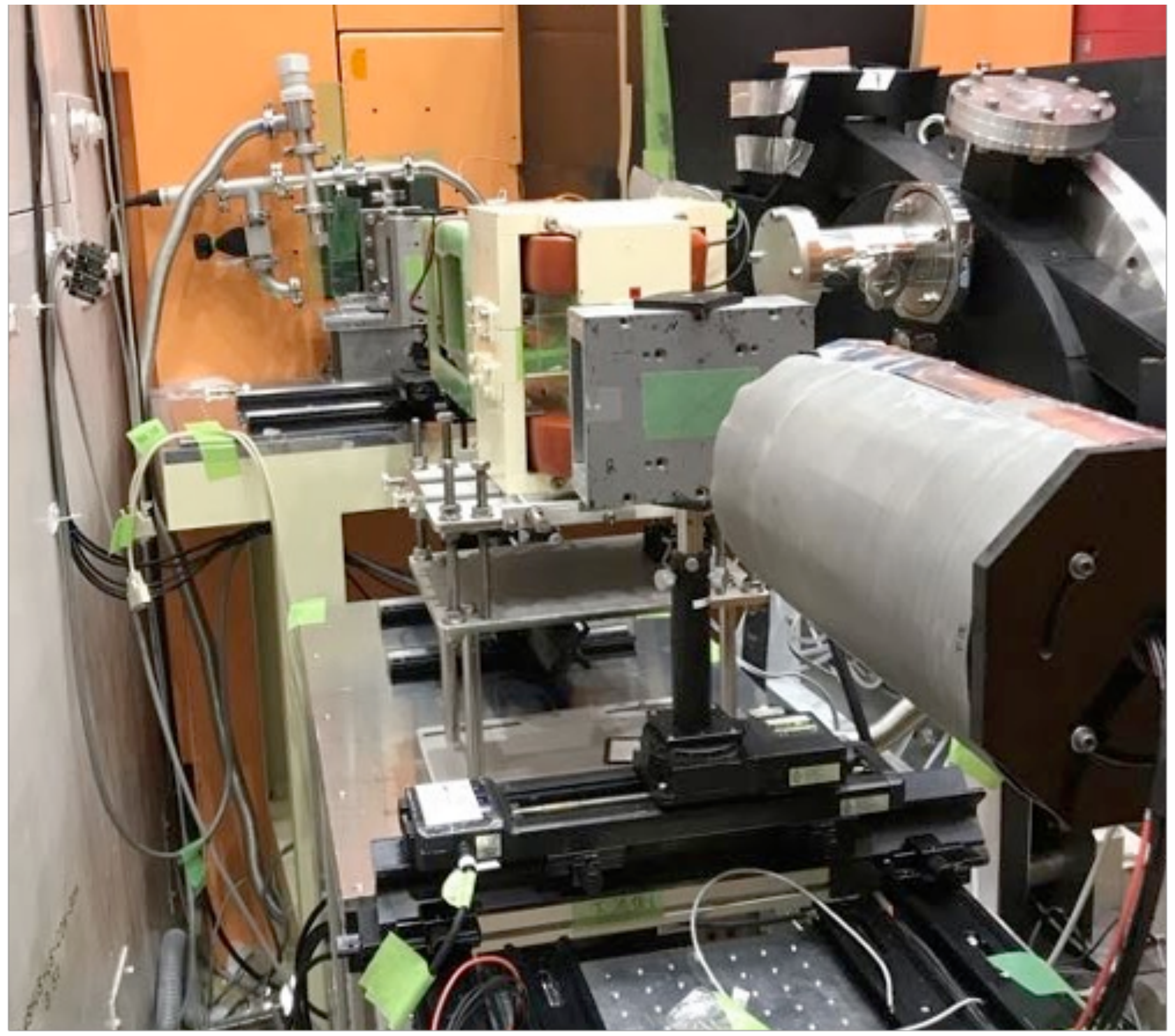

Setup at J-Parc MLF BL05

Spin analyzer development setup at J-Parc



a region where beam is not fully polarized





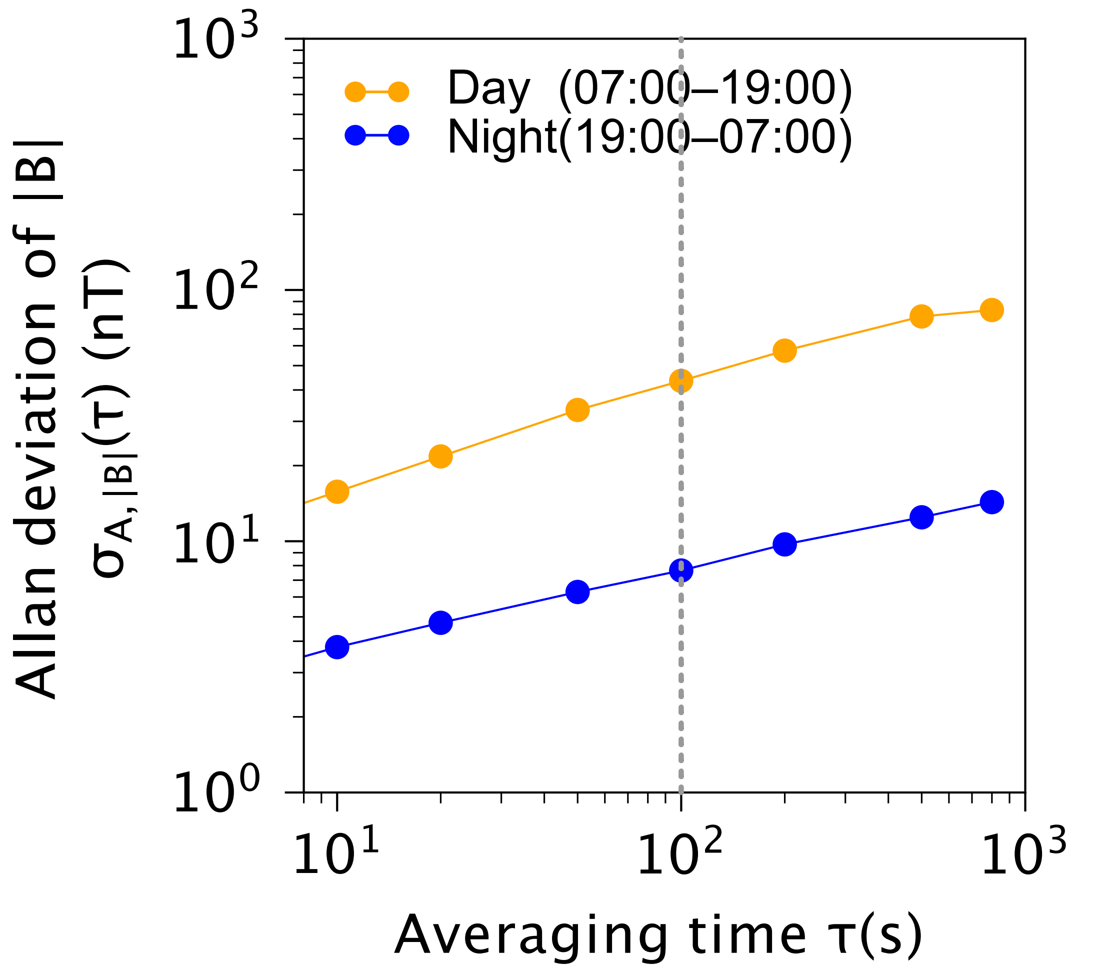
Setup at J-Parc MLF BL05

Magnetic field measurements on-site

- Recent magnetic field measurements on the TUCAN area in TRIUMF Meson Hall
  - Monitoring of ambient magnetic field on the area to estimate typical field fluctuations
  - Three-dimensional mapping of the ambient field on the area

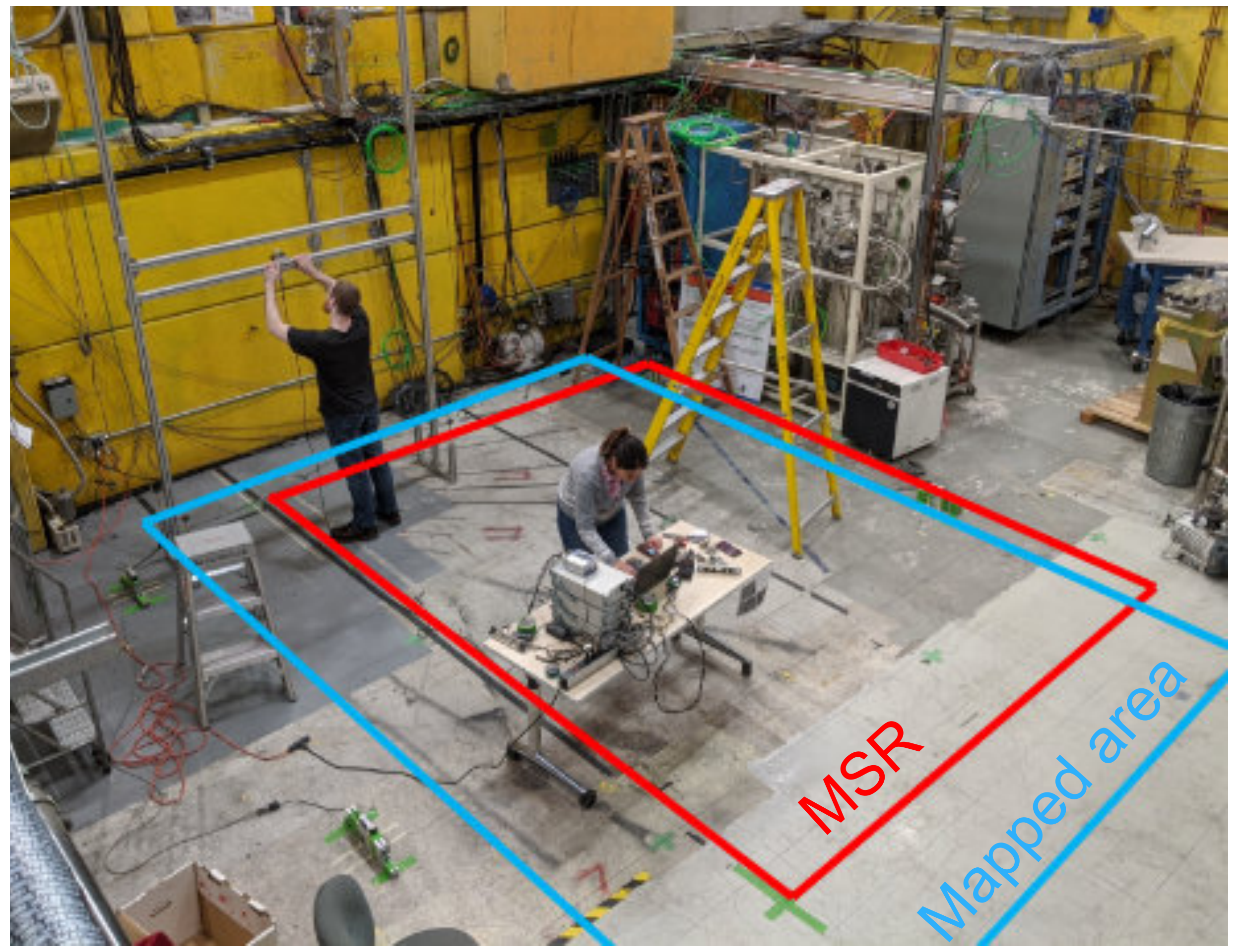
- Results

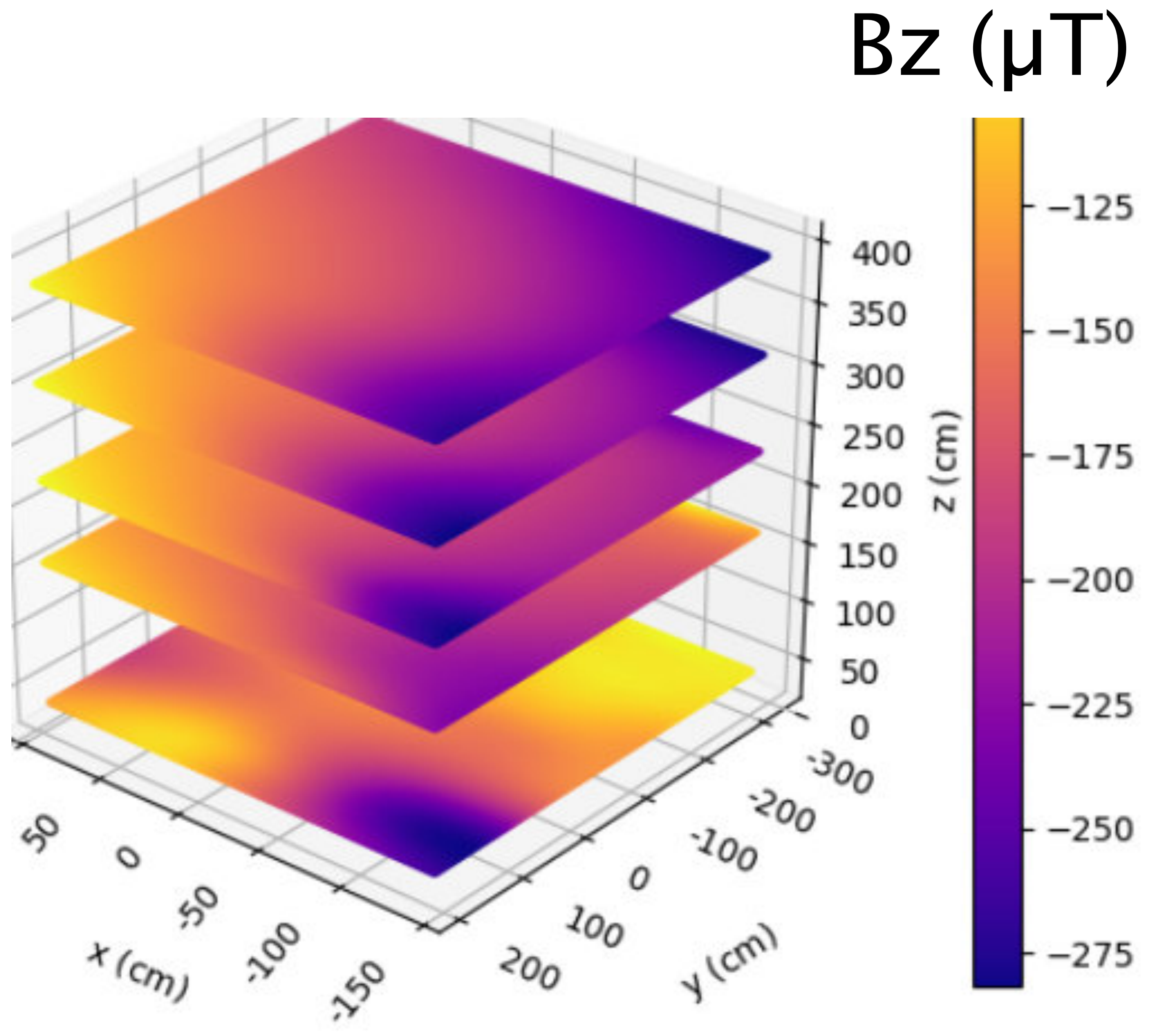
Field fluctuations



Typically **|B| < 150 nT** (@ 100s averaging)
→ **MSR will provide sufficient field stability**

Magnetic field mapping



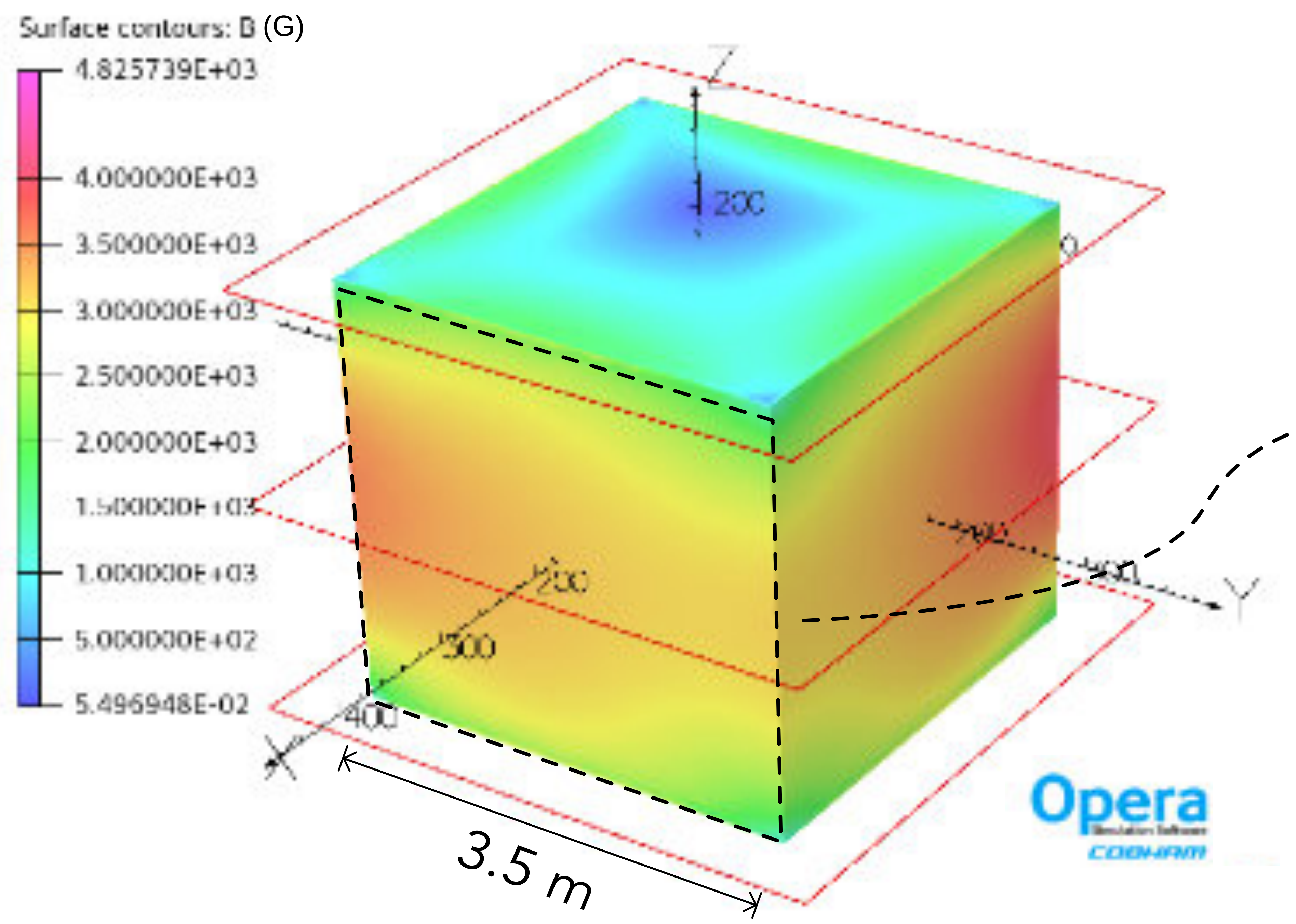


- **|B| ≈ 370 μT** at maximum
- Some hot spots near the floor
- For higher z: dipole-like field from the cyclotron

Saturation risk of the MSR and design of the compensation system

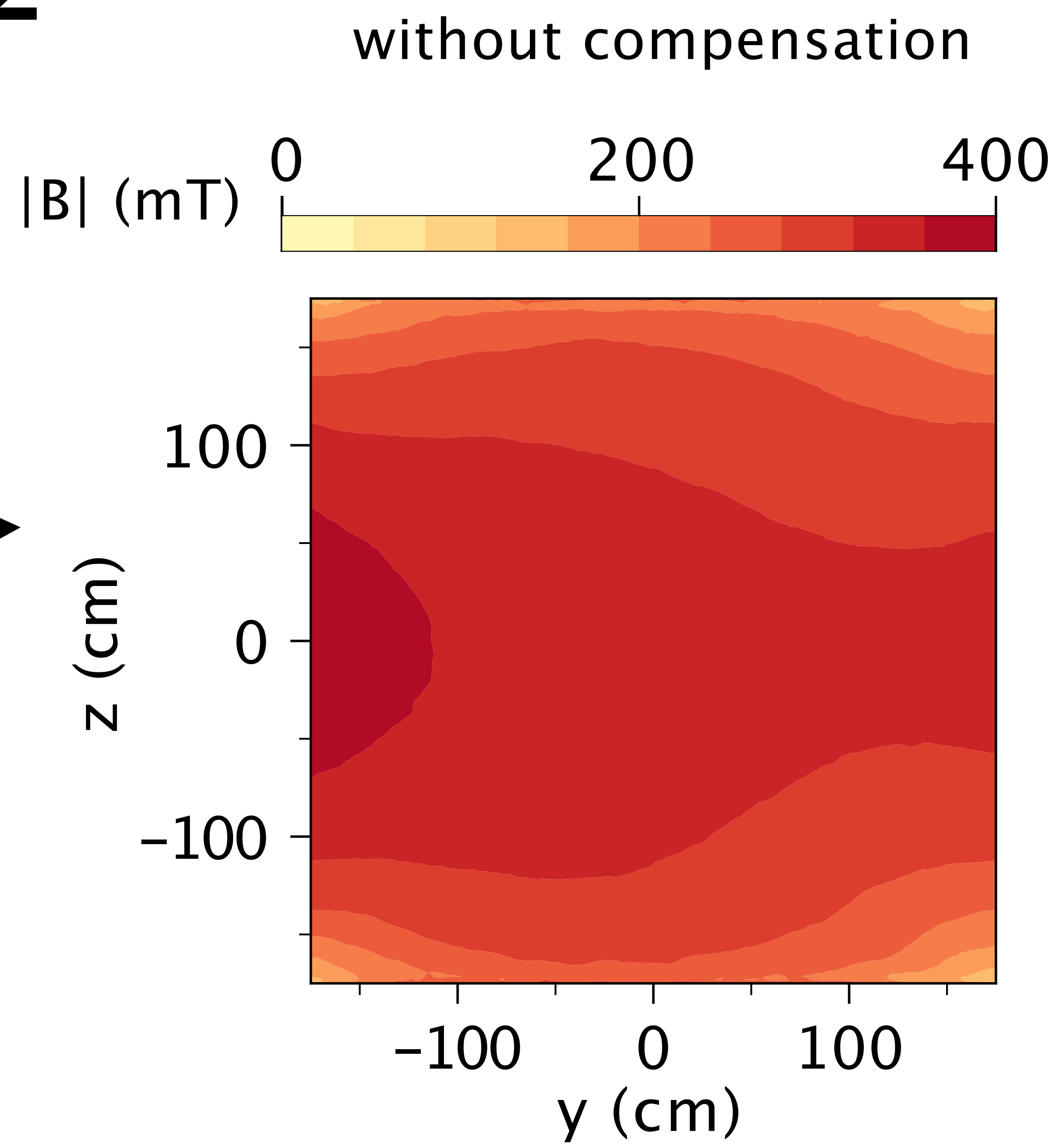
- The background field in the area is up to ≈ 370 μT
  - Produces in-plane B ~ 500 mT in mumetal, x2 around holes
  - Could saturate mumetal near the MSR holes (B_s of mumetal: 700 mT)
- Designing a set of coils which compensate the effects of the background field and guarantee the shielding performance of the MSR

1

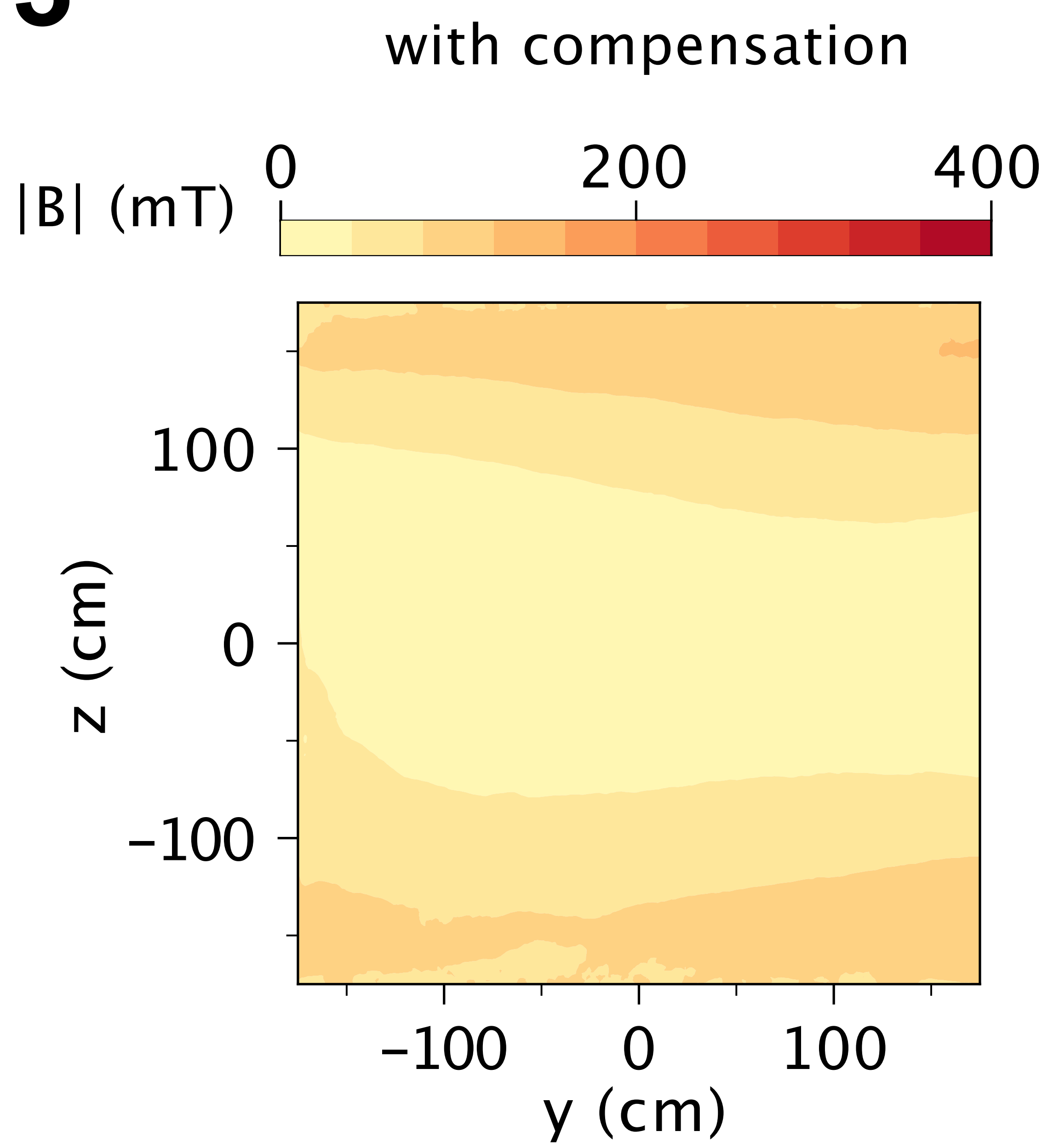


1. MSR placed in a dipole B-field, modeling the cyclotron stray field

2



3



2. In-plane |B| of +x plane: up to 400 mT

3. Coils activated (600, 150, 600 AT): |B| reduced to <150 mT