Prospects towards a neutron EDM measurement with an advanced ultracold neutron source at TRIUMF

Takashi Higuchi (RCNP, Osaka Univ.)
on behalf of
the TUCAN collaboration

International Workshop on Searches for a Neutron Electric Dipole Moment (nEDM2021)
15.02.2021

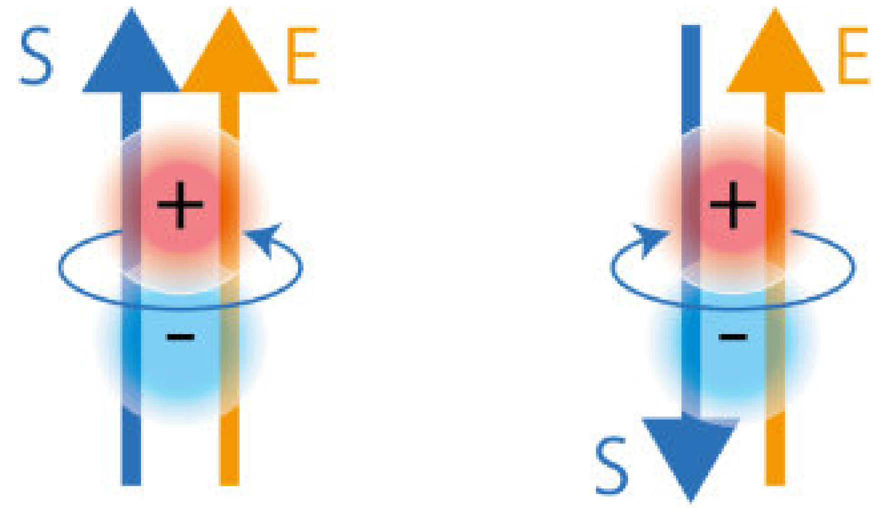
Outline

- **Introduction**
  - The neutron EDM
  - The TUCAN collaboration
    - Goals
    - TUCAN UCN production scheme
- **Overview of the current status**
  - Development of the new UCN source
  - Developments for the nEDM spectrometer
- **Latest developmental works on-site**

Other TUCAN talks on nEDM2021:

- **Feb 16 (Tue) [E-field & precession chamber]**
  - *Rüdiger Picker*
- **Feb 17 (Wed) [UCN production & transport]**
  - *Florian Kuchler*
  - *Jeffery Martin*
  - *Wolfgang Schreyer*
  - *Russell Mammei*
  - *Shinsuke Kawasaki*
  - *Sohei Imajo*
- **Feb 18 (Thu) [Magnetometry]**
  - *Eric Miller*
  - *Wolfgang Klassen*
- **Feb 19 (Fri) [Systematics & sensitivity studies]**
  - *Sean Vanbergen*
  - *Steve Sidhu*
- **Feb 19 (Fri) [B-field production]**
  - *Mark McCrea*

The neutron electric dipole moment (nEDM)



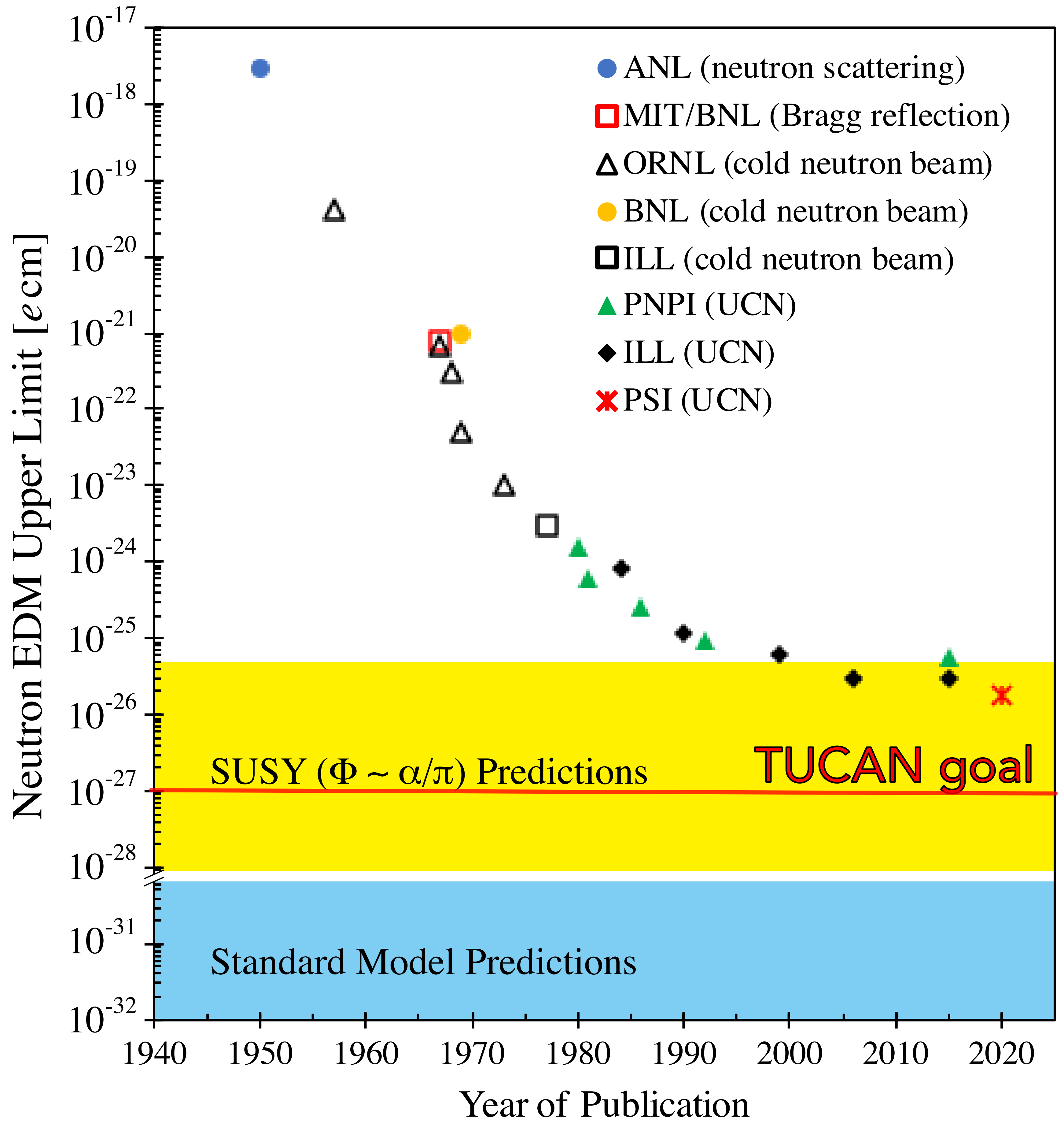
- Violates the time-reversal (T) symmetry
  - Equivalent to CP violation assuming CPT symmetry
- Provides crucial tests of theories beyond the SM
  - SM: ~10^{-32}ecm, SUSYs: 10^{-28}–10^{-26}ecm
- Searched since 1950s, the state-of-the art method employs stored ultracold neutrons (UCNs)
- The latest best limit by the PSI-nEDM collaboration:

$$d_n = (0.0 \pm 1.1_{\mathrm{stat.}} \pm 0.2_{\mathrm{sys.}}) \times 10^{-26} e \cdot \mathrm{cm}$$

$$\Rightarrow |d_n| < 1.8 \times 10^{-26} e \cdot \mathrm{cm}\,(90\%\,\mathrm{C.L.})$$

*C. Abel et al., PRL **124** (2020), 081803*

- TUCAN: aiming a measurement at 10^{-27}ecm precision with a high-intensity UCN source



TRIUMF Ultra-Cold Advanced Neutron (TUCAN) collaboration

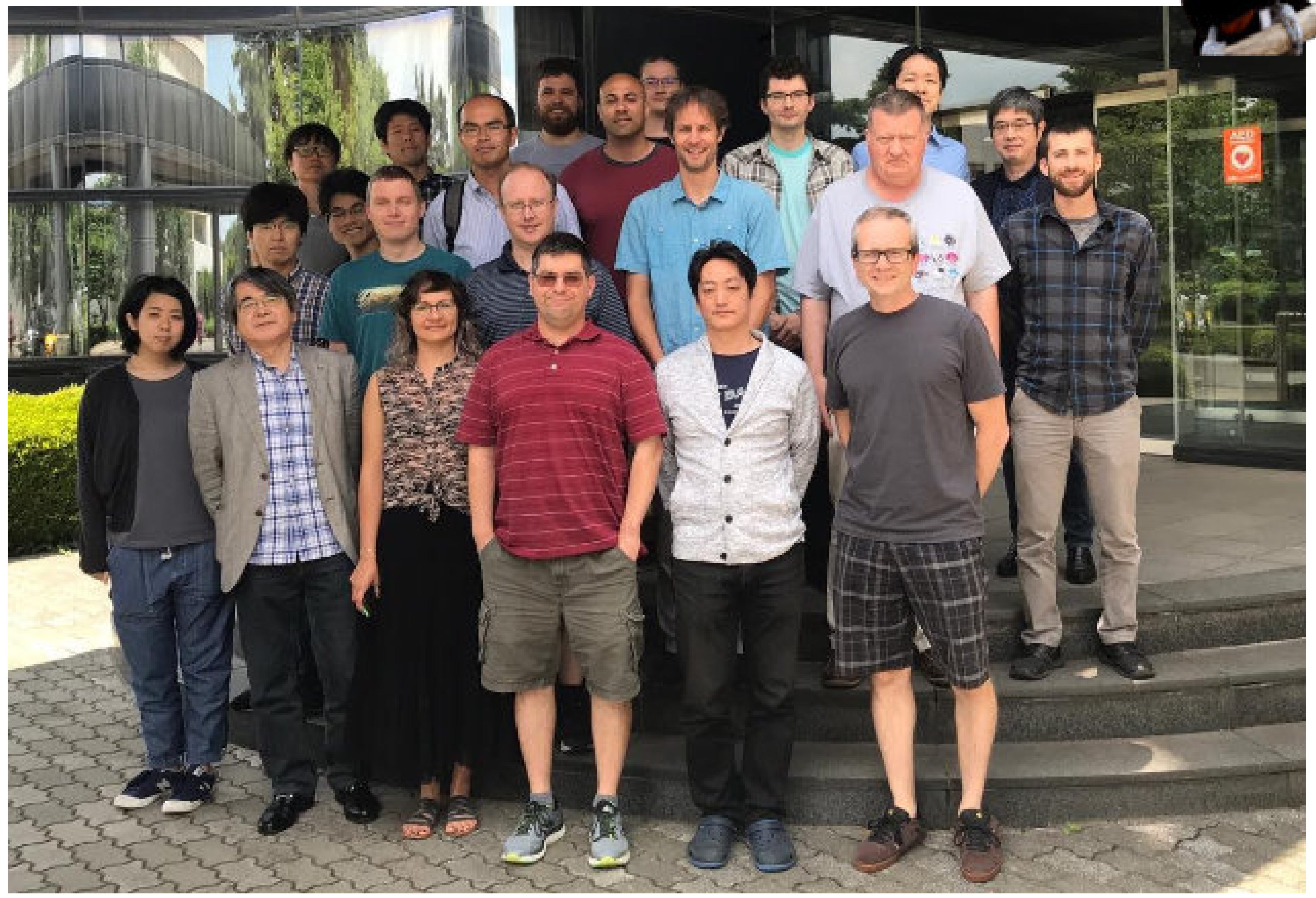
- **Our goals:**
  1. Build a high-intensity UCN source at TRIUMF
  2. Measure the nEDM with 10^{-27}ecm precision

- **Expected UCN density:**
  - **200–400** polarized UCN/cm^3 (filled in the EDM cell)

- **The UCN production scheme demonstrated by a prototype UCN source**
  - First UCN production at TRIUMF in 2017

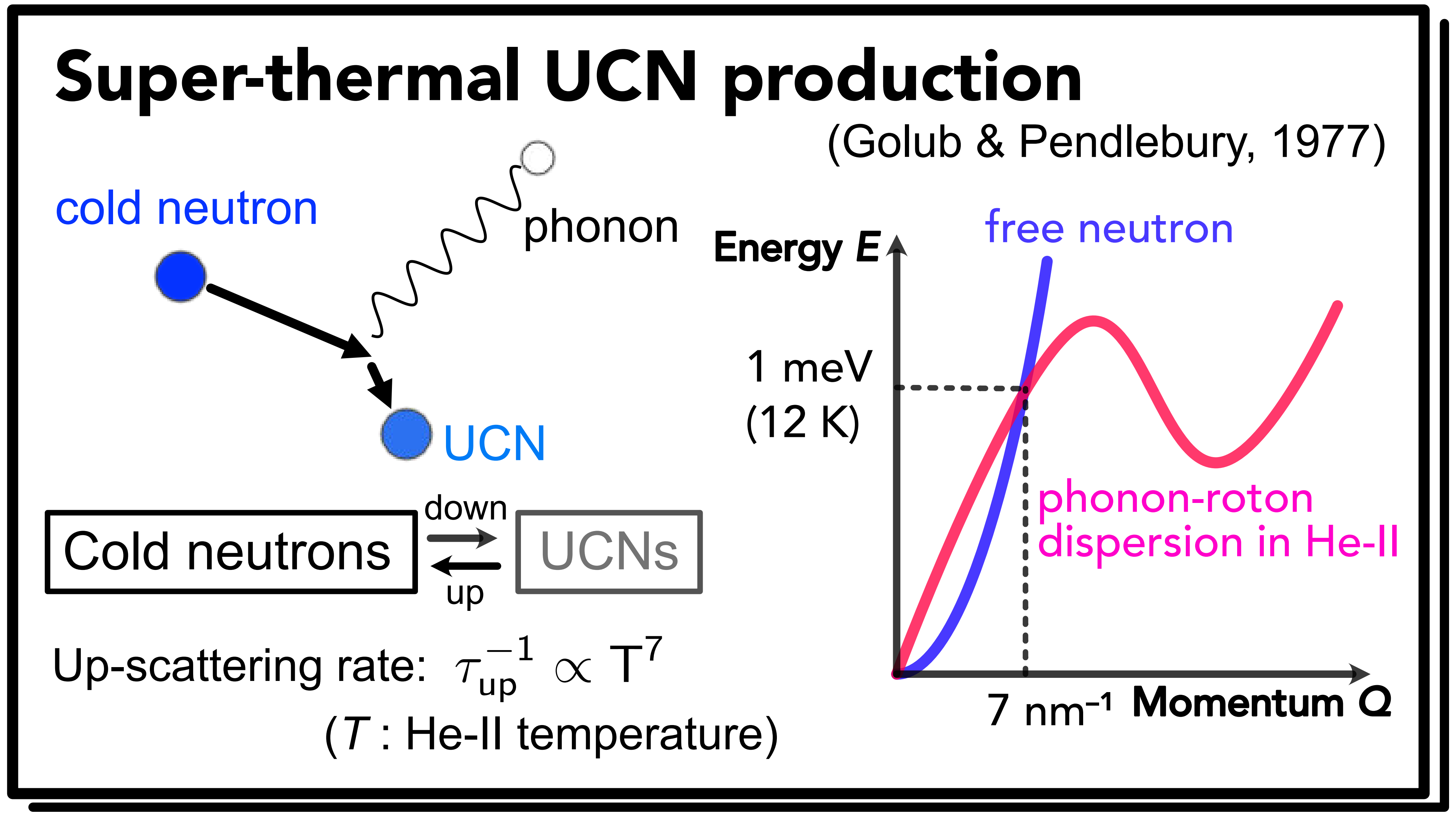
S. Ahmed et al., PRC ***99*** *(2019) 025503*

- **Currently activities**
  - Development of a new upgraded UCN source
  - Development of subsystems of the nEDM spectrometer



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, T.Kikawa, M.Kitaguchi, W.Klassen, A.Konaka, E.Korkmaz, F.Kuchler, M.Lavvaf, L.Lee, T.Lindner, K.Madison, Y.Makida, R.Mammei, J.Mammei, J.M artin*, R.Matsumiya, E.Miller, K.Mishima, T.Momose, T.Okamura, H.Ong, R.Picker, D.Ramsay, W.Schreyer, A.Sher, H.Shimizu, S.Sidhu, S.Stargaerdter, I.Tanihata, S.Vanbergen, W.van Oers, Y.Watanabe*
(: spokespersons)*

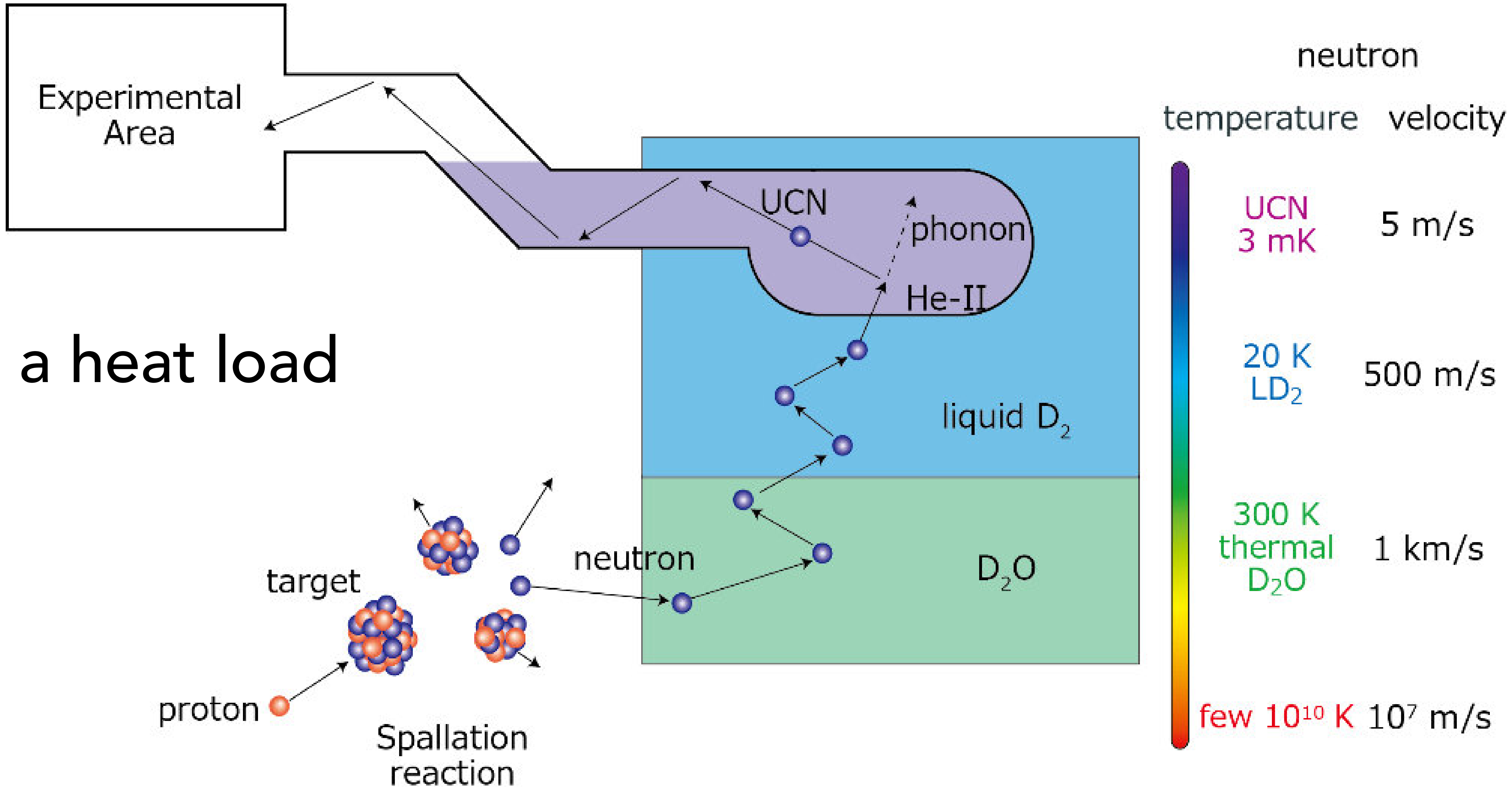
TUCAN UCN production scheme



- **Combination of**
  - Spallation neutron production
  - Super-thermal UCN production with He-II

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

- **Spallation neutrons (~MeV) produced by an accelerator beam are cooled in steps and eventually be converted to UCNs**



- **Crucial aspects:**
  - Keep the He-II temperature at ~1K under a heat load of beam irradiation
  - High cold neutron flux at ~1meV

TUCAN UCN production scheme

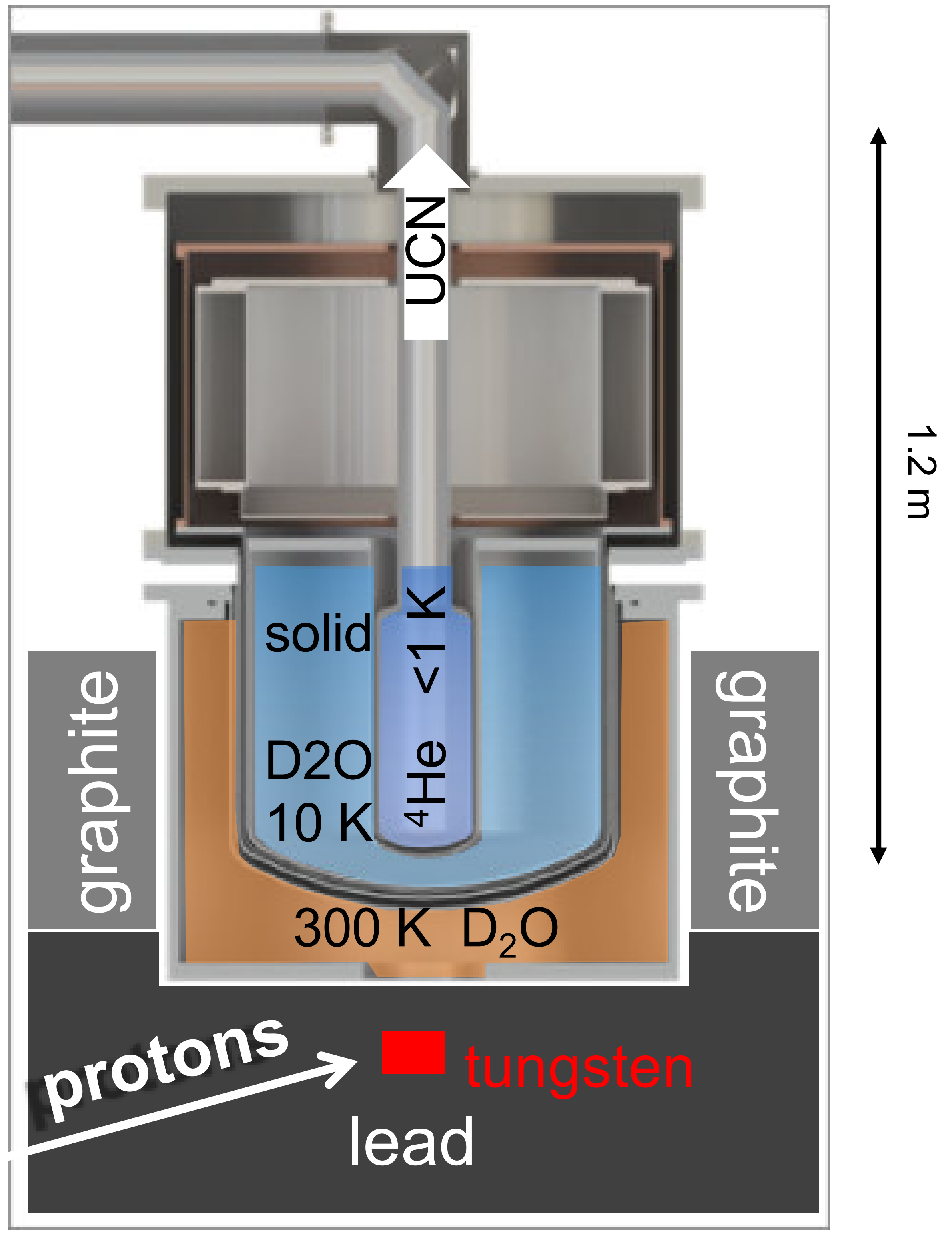
- Demonstrated by the prototype UCN source:
  - Successful UCN production:
    - 2×10^4 UCN/s (3.25×10^5 UCN/cycle) @ 1 μA proton beam current
  - Limited by cooling power of the helium cryostat

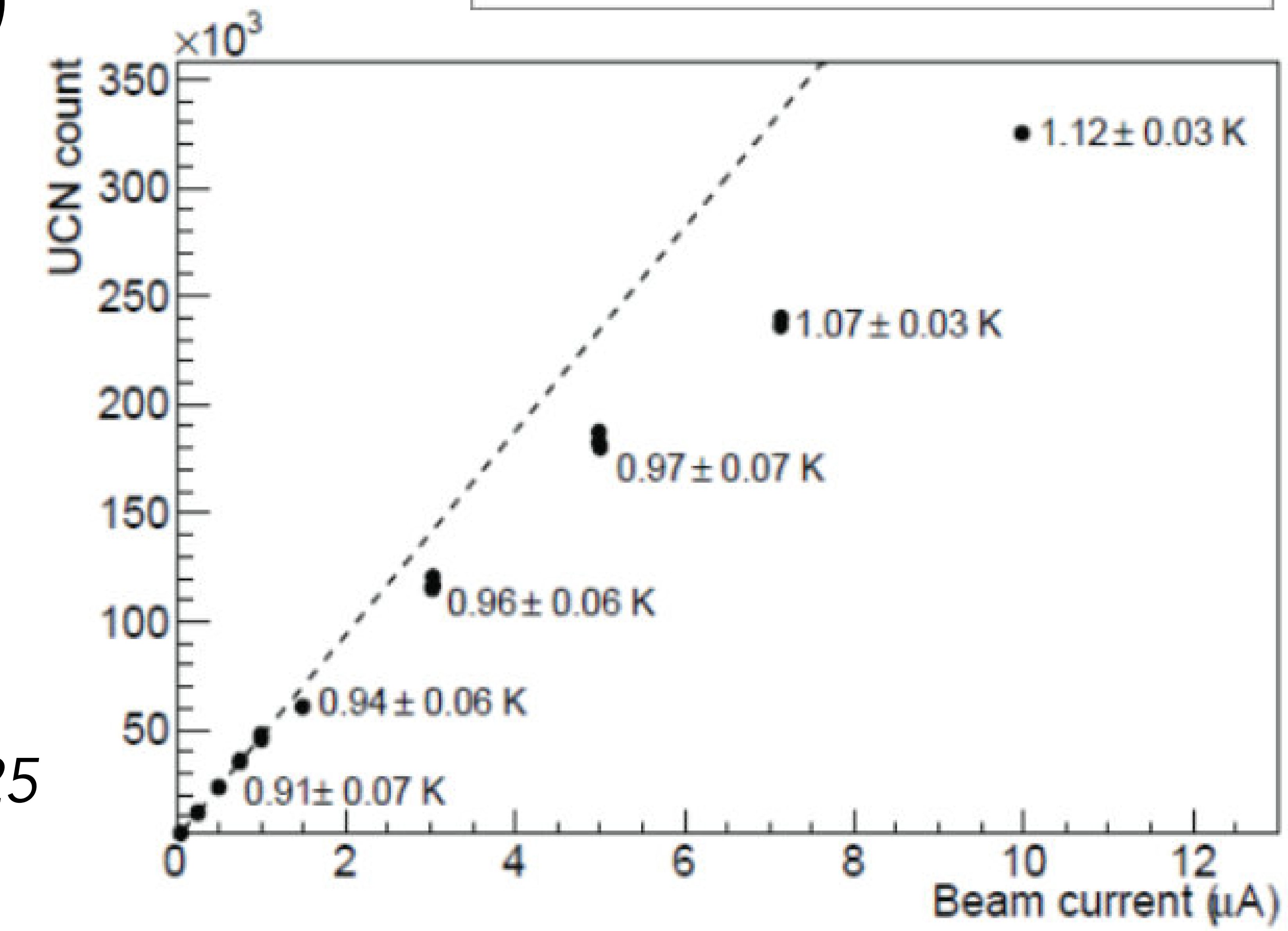
*S. Ahmed et al., PRC **99** (2019) 025503*

- New upgraded UCN source under development:
  - **Helium cryostat cooling power:** 0.4 W → 10 W
    Enables operation at 40 μA beam current (**x40** UCN yield)
  - **Cold-neutron moderator :** sD_2O → LD_2 (x3)
  - **Larger production volume:** 8 L → 27 L (x3)
  - …

➡ Expected UCN yield: **$1.4–1.6\times10^7$ UCN/s**

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





Overview of the new TUCAN source

Florian Kuchler

- UCN production volume, moderator & shielding

Wolfgang Schreyer

- Helium/LD_2 cryostats

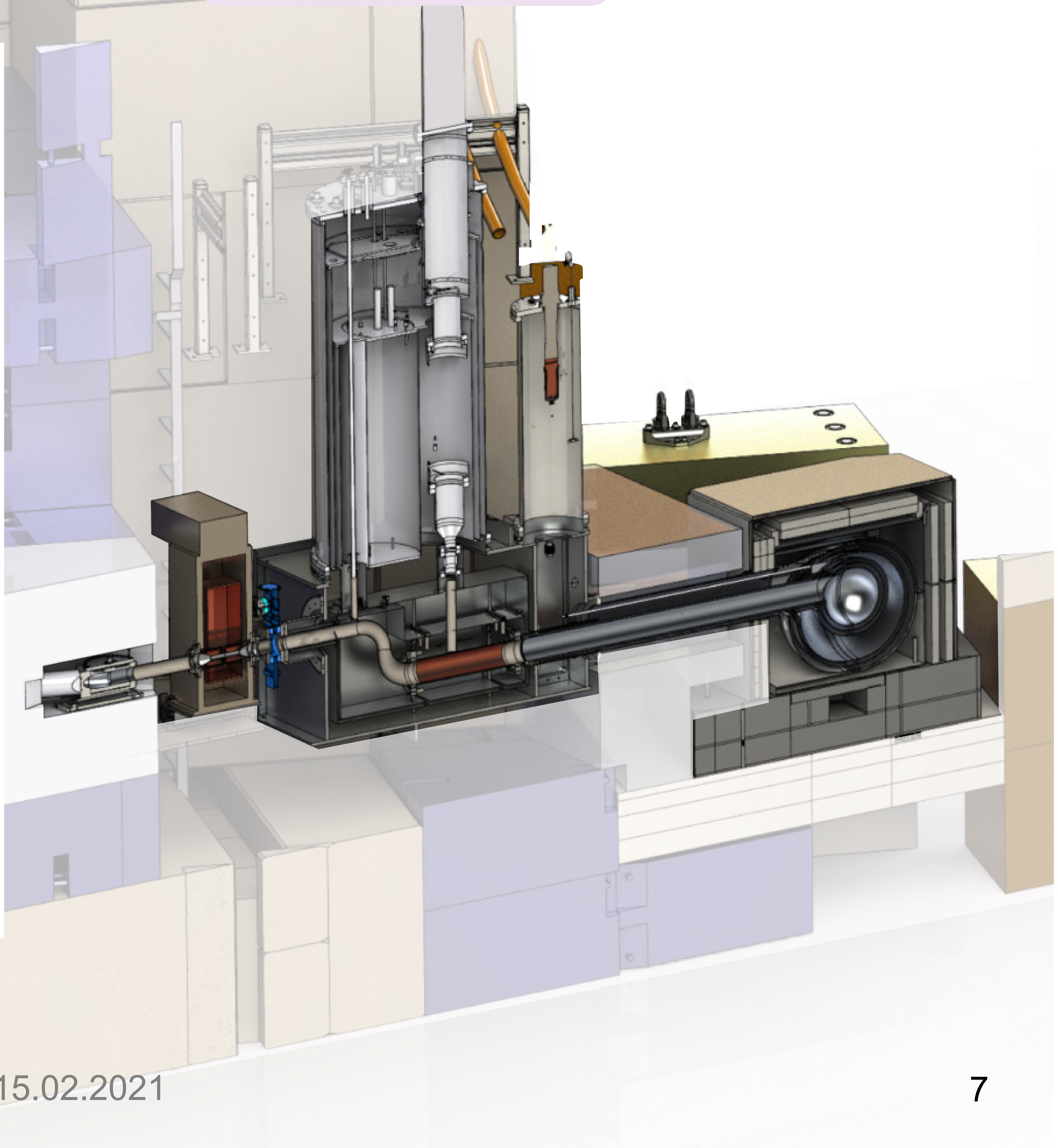
Shinsuke Kawasaki

Jeffery Martin

- High-quality surfaces/coating

Russell Mammei

Sohei Imajo



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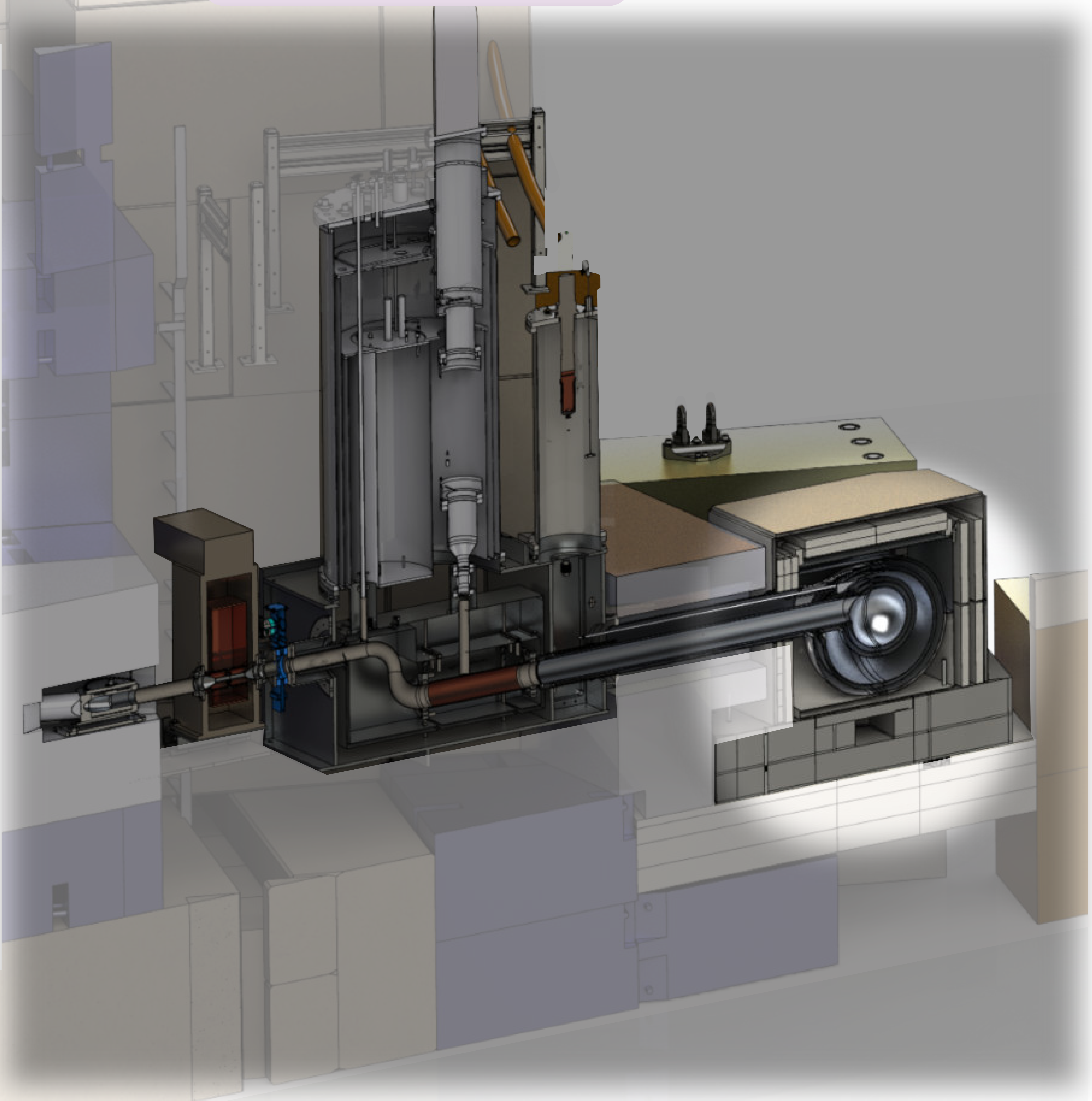

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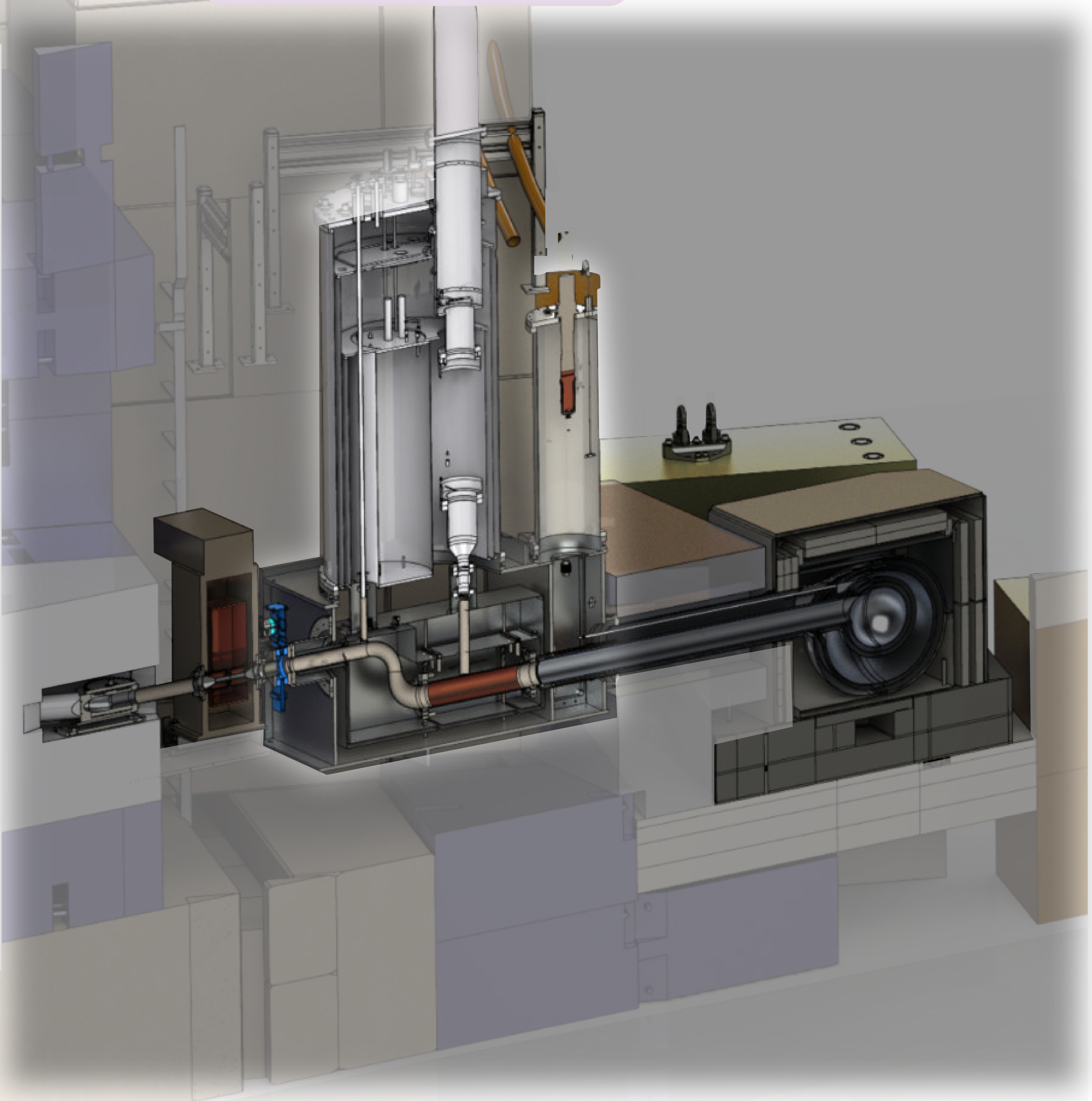

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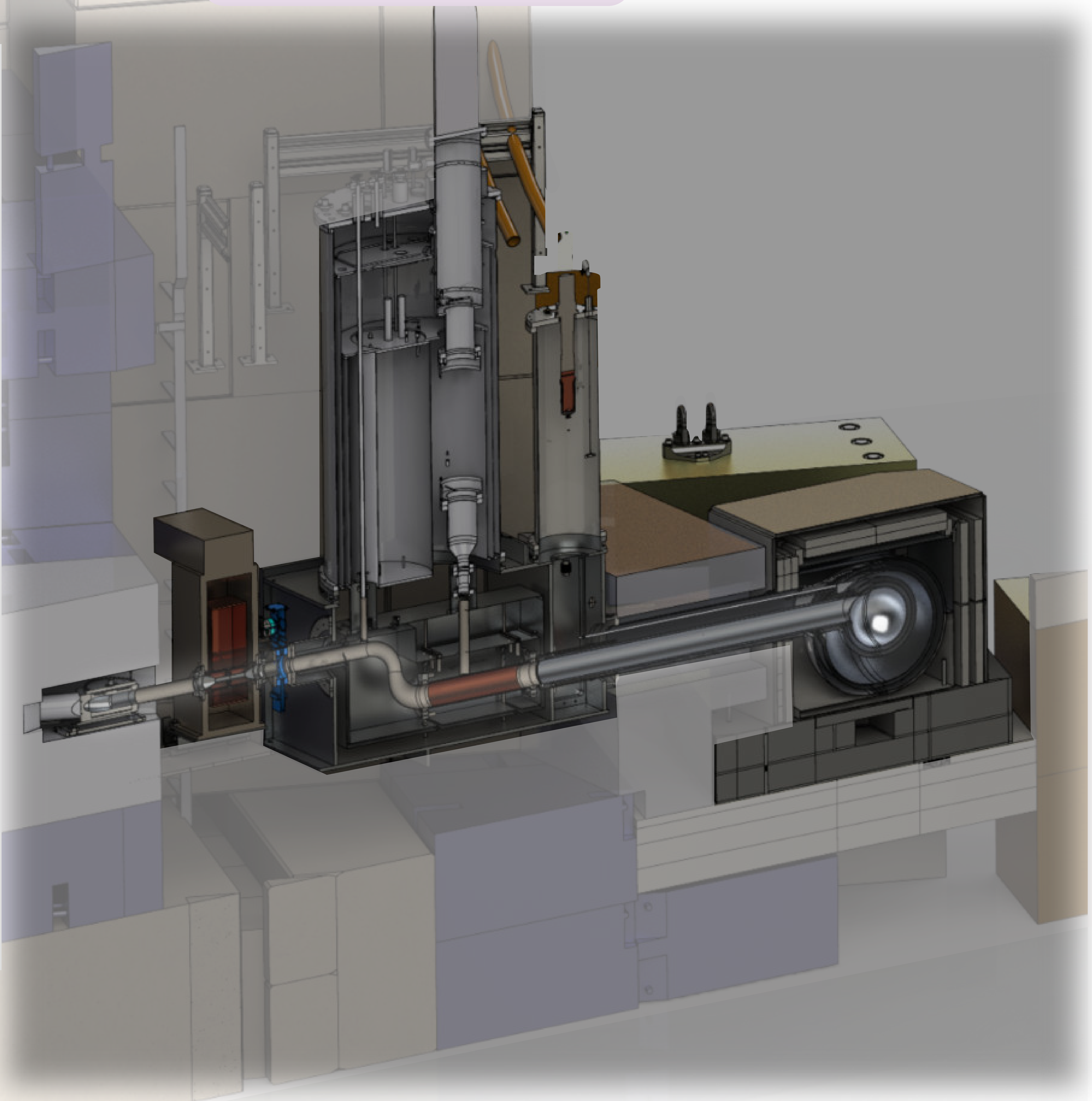

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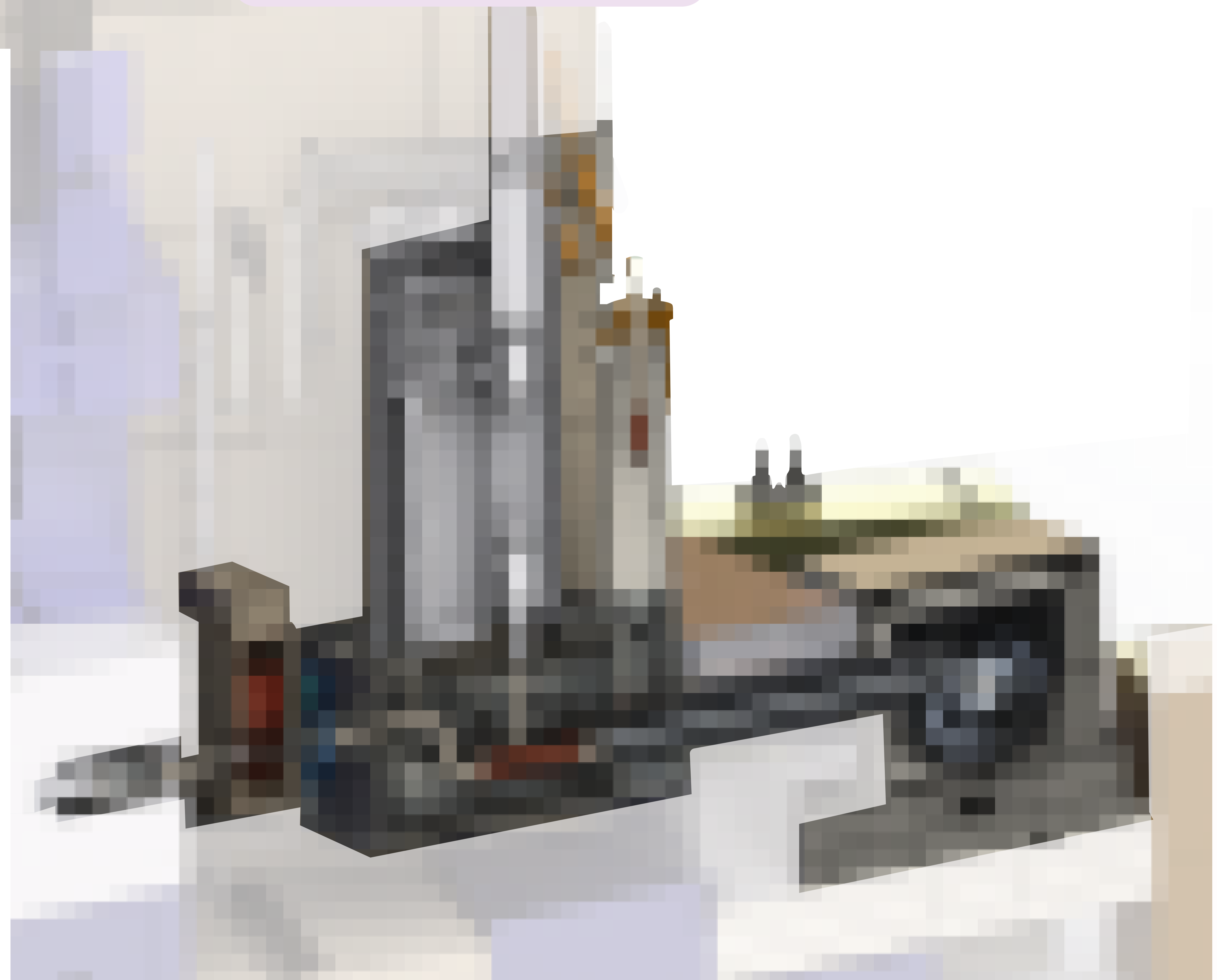

Installation/commissioning of the major components starting in 2021
The first UCN production aimed in summer 2022

Overview of the nEDM spectrometer

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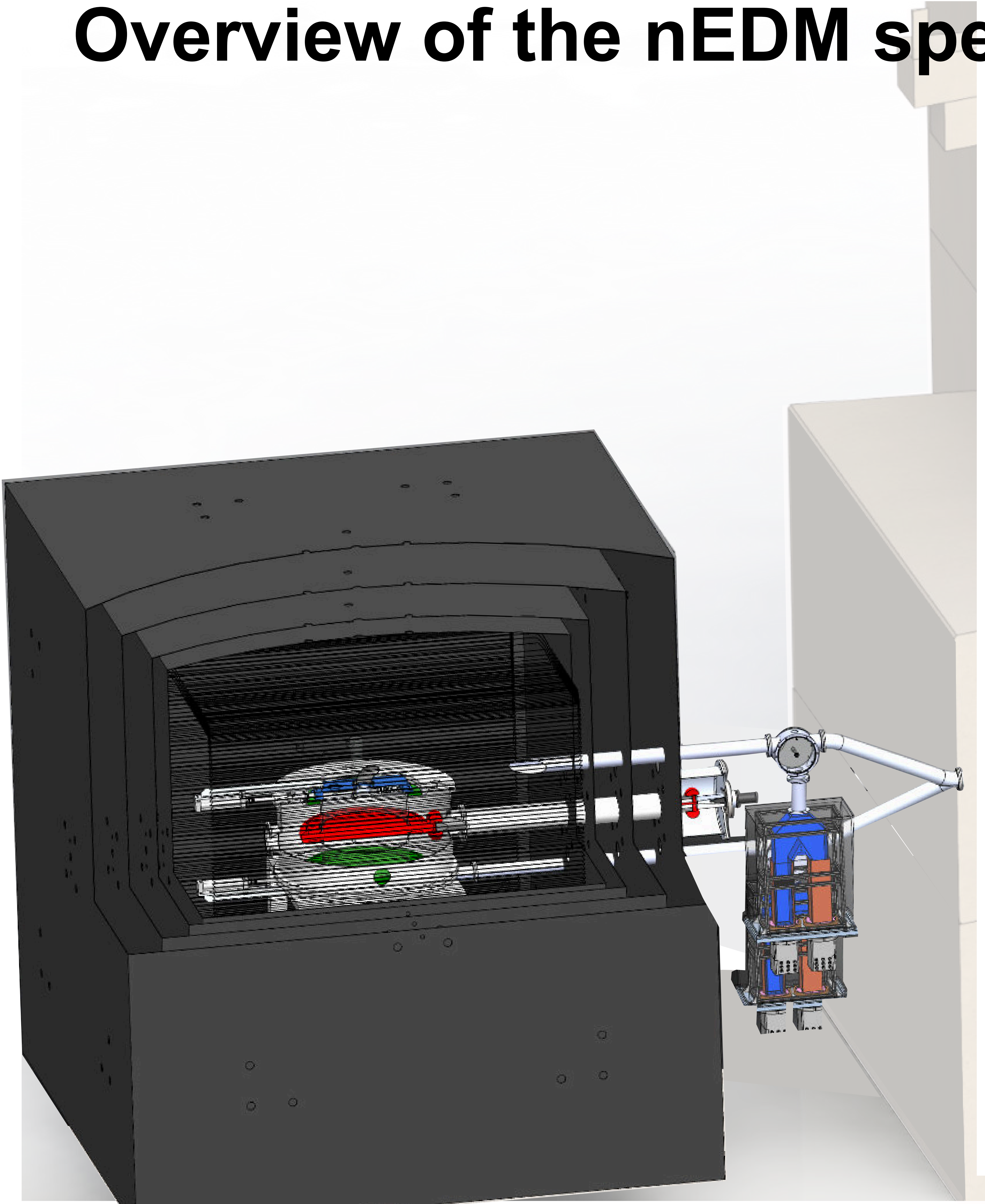

Major subsystems of the nEDM spectrometer

- Precession chamber + high E-field

Rüdiger Picker

- Coil systems (main B_0 coil, shim coils)

Mark McCrea

- Hg co-magnetometer

Eric Miller

- Cs magnetometers

Wolfgang Klassen

- Magnetically Shielded Room

Design optimization and systematic studies

- Source/spectrometer parameters optimized to maximize the statistical sensitivity

Steve Sidhu

- Studies of systematic effects caused by rotational motions of UCNs

Sean Vanbergen

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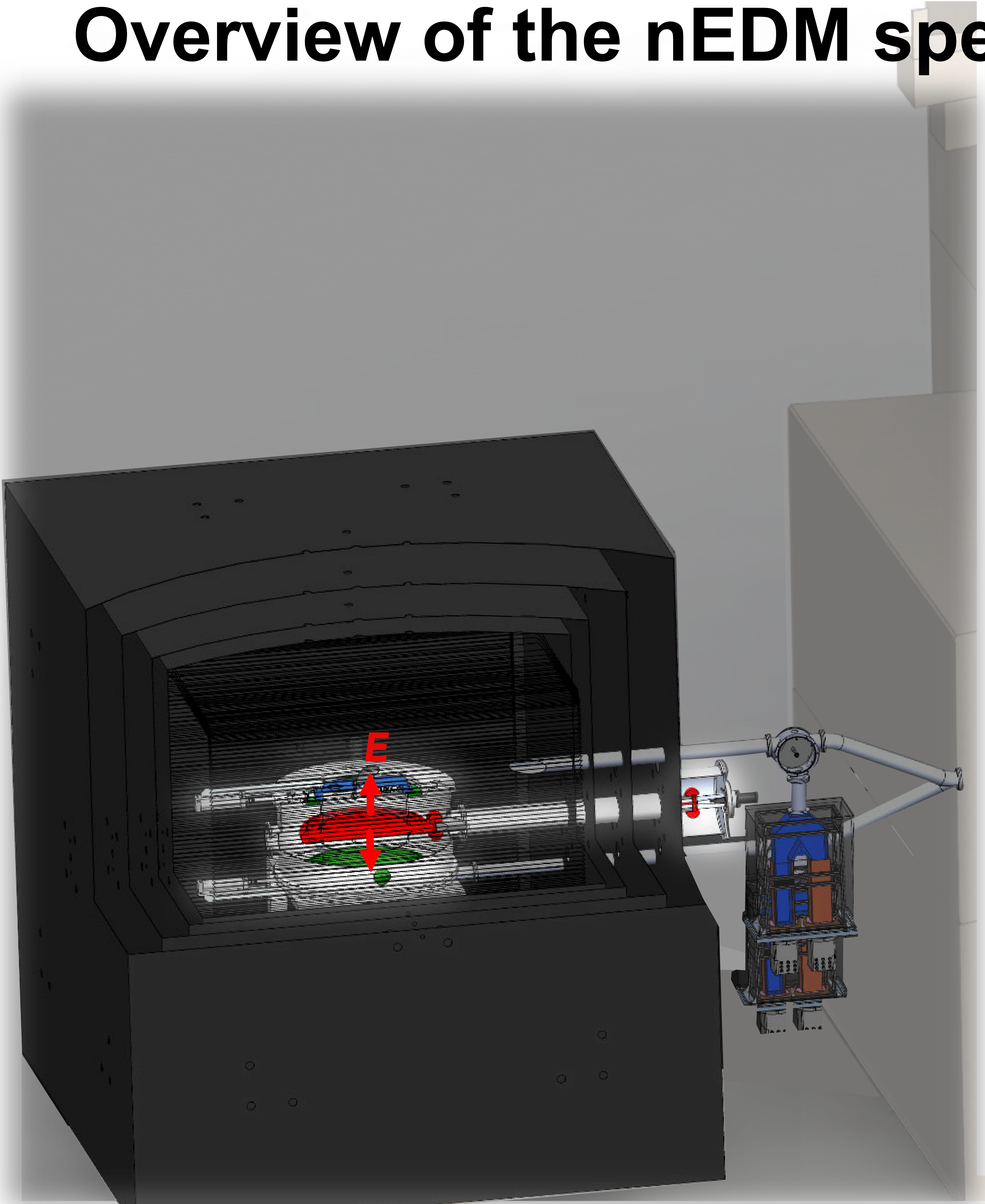

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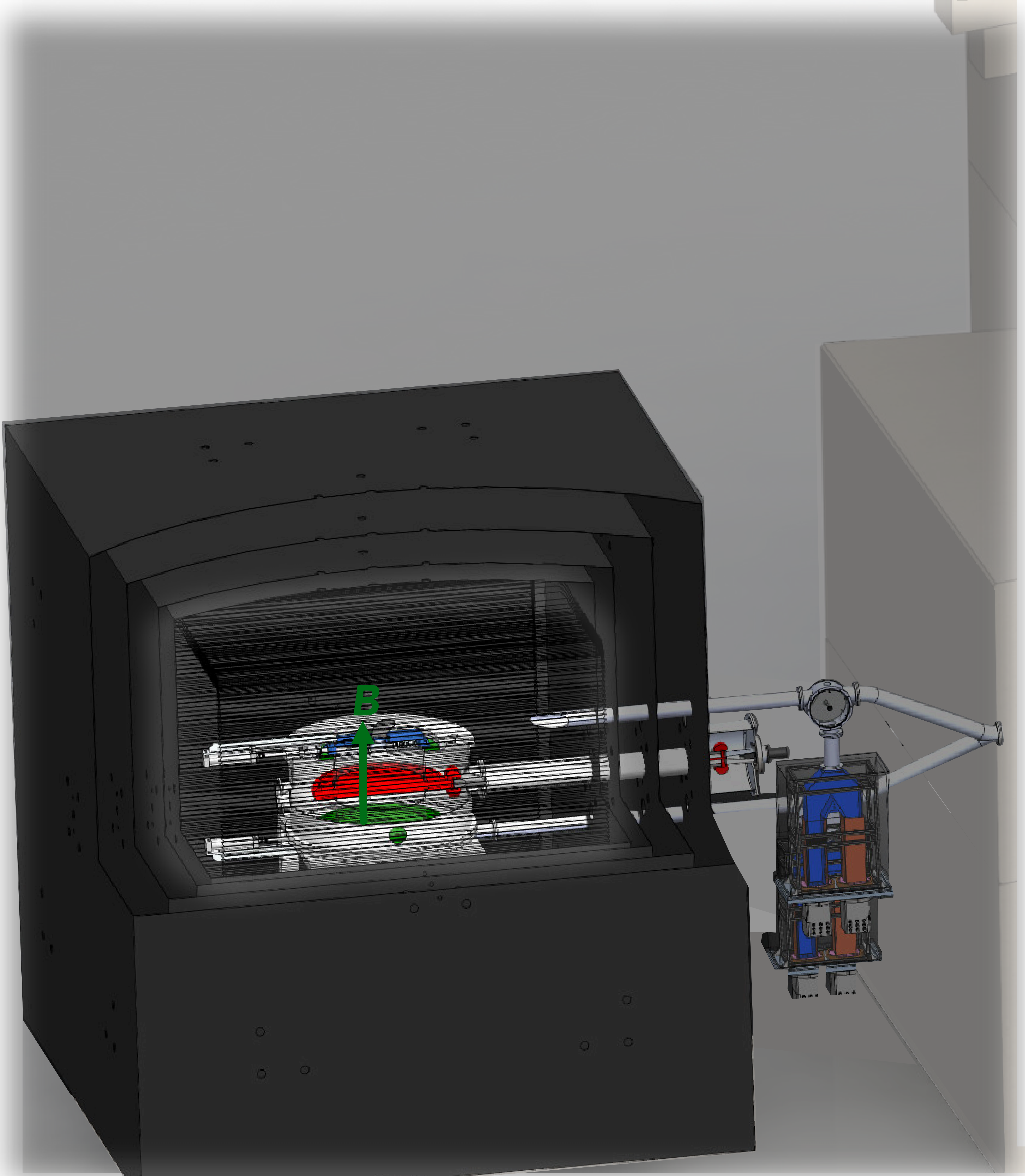

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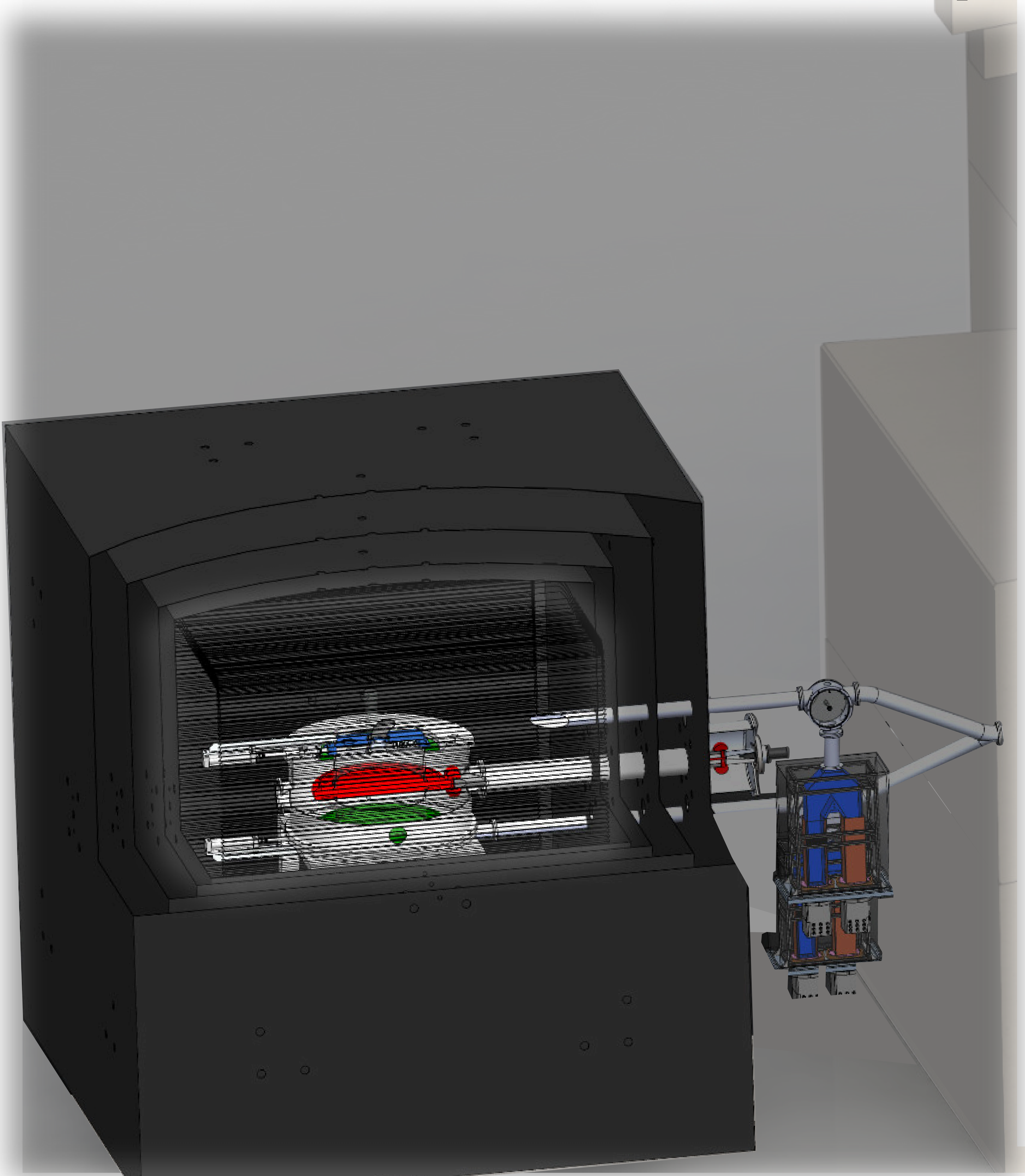

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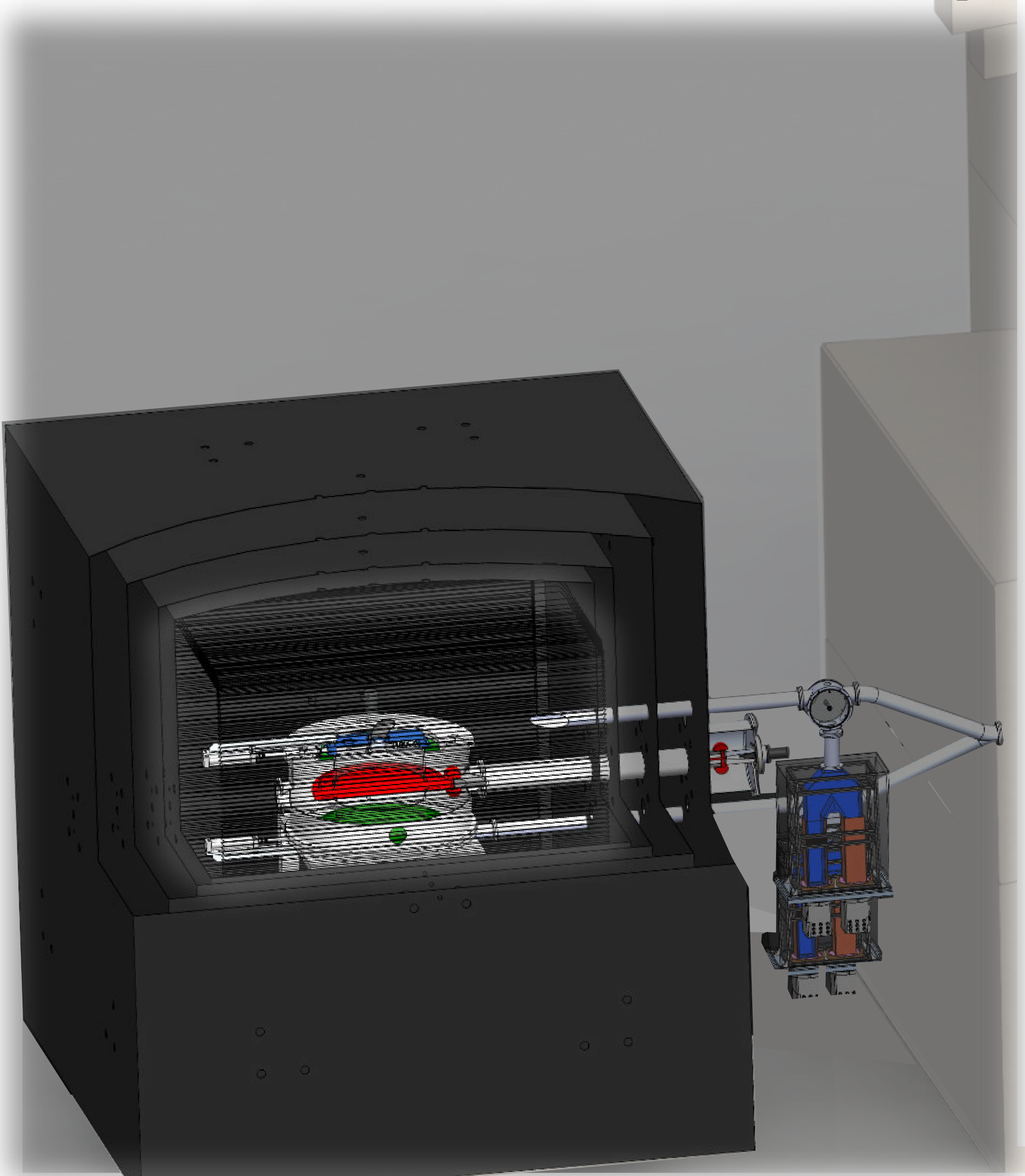

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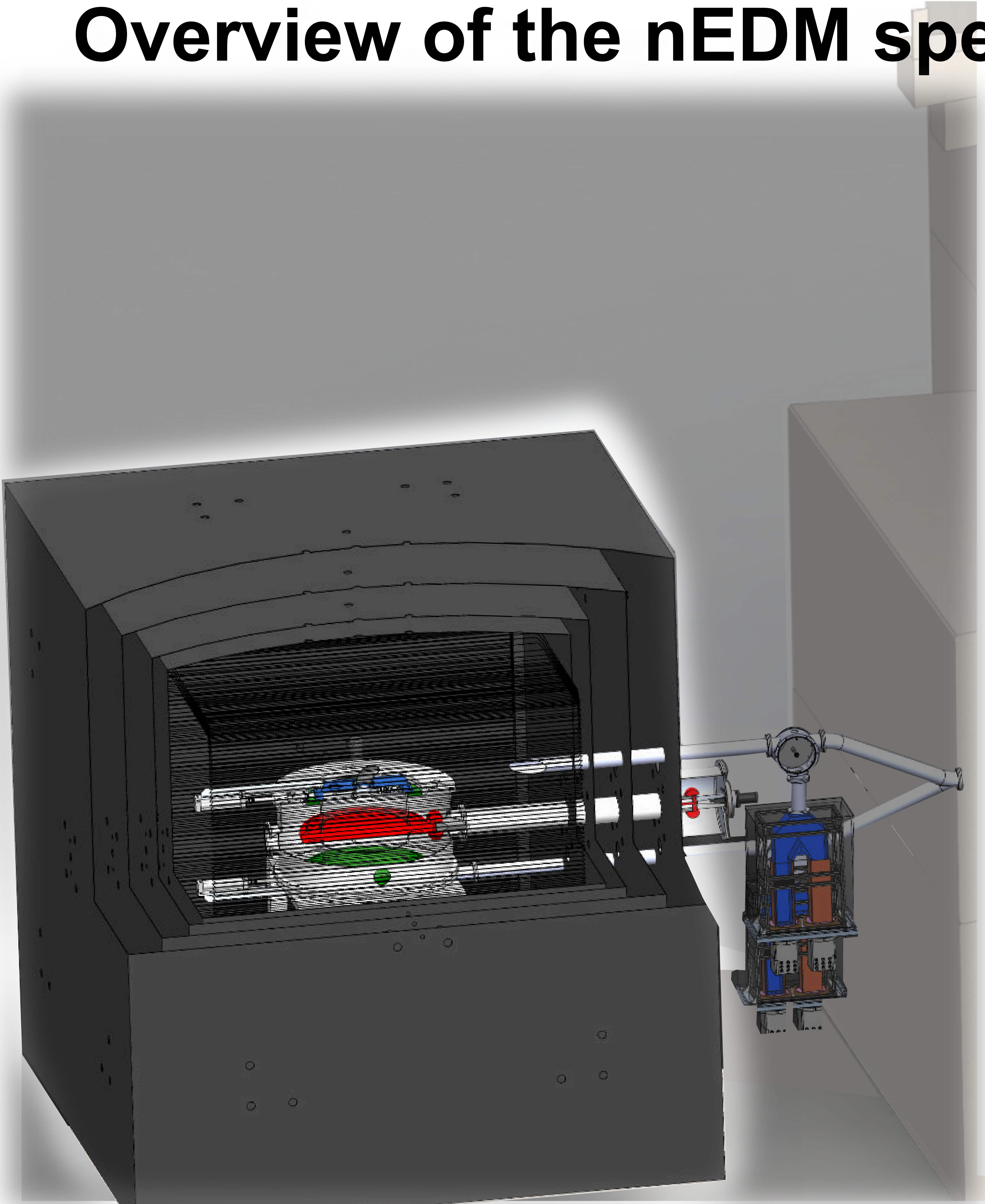

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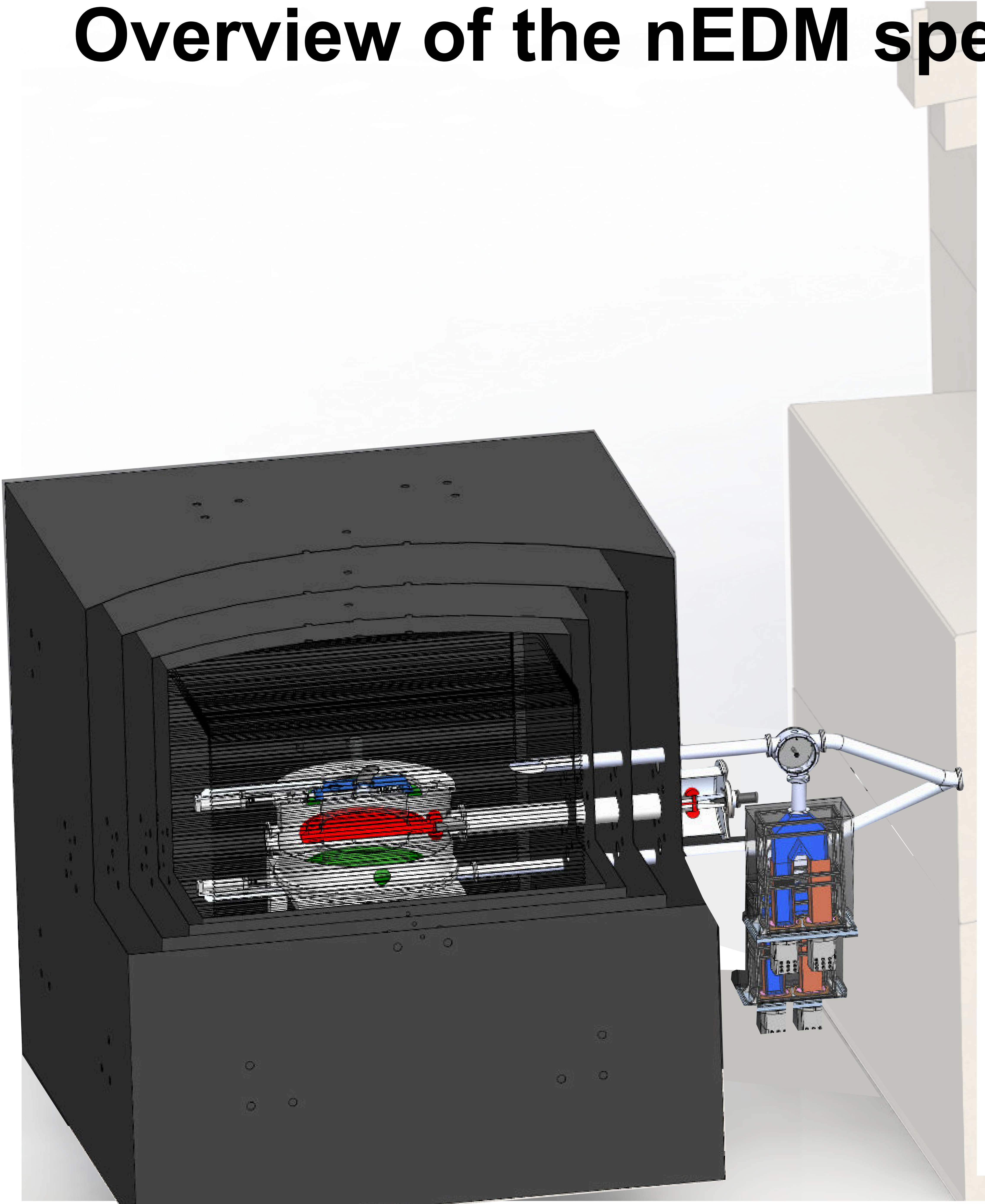

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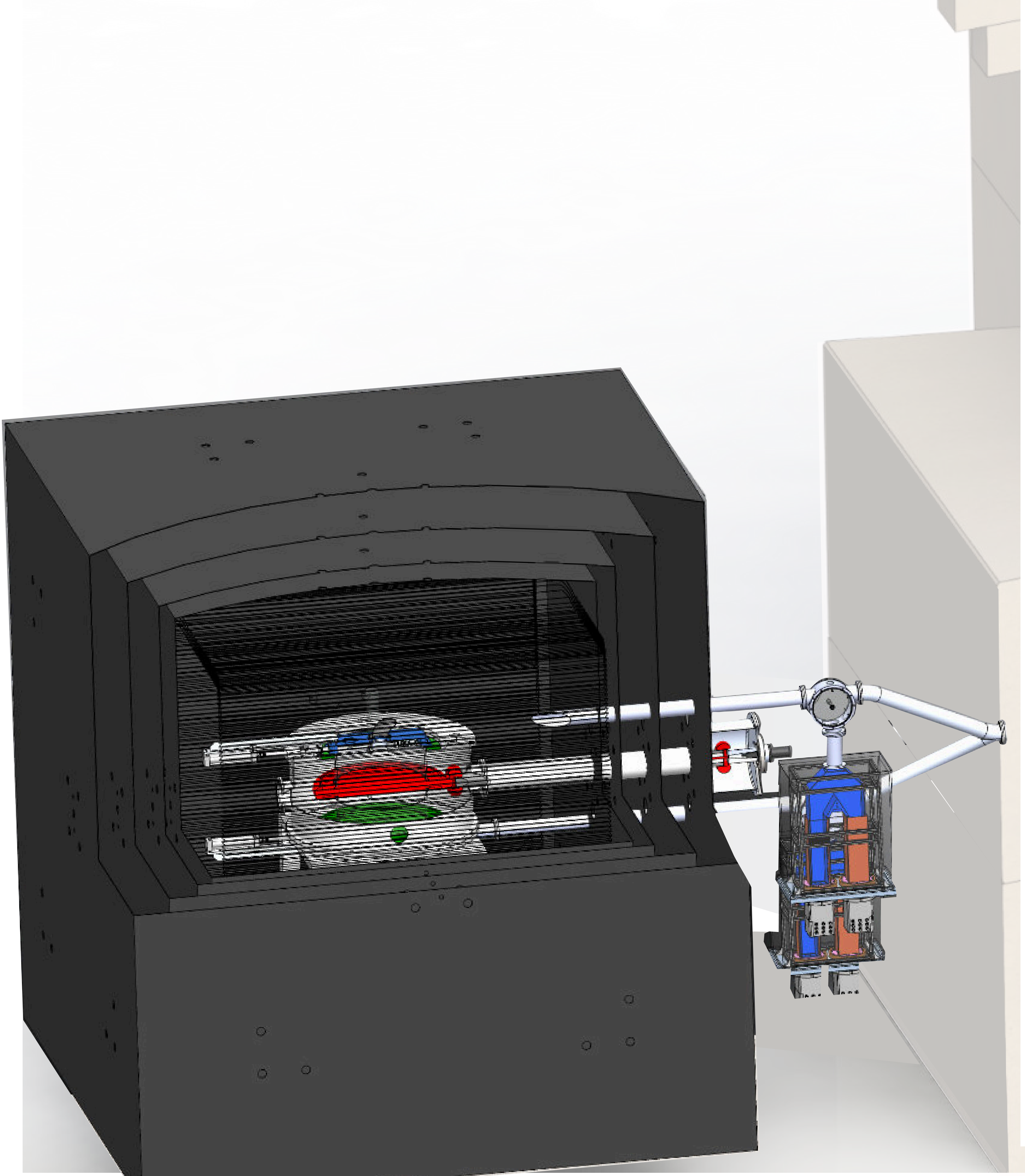

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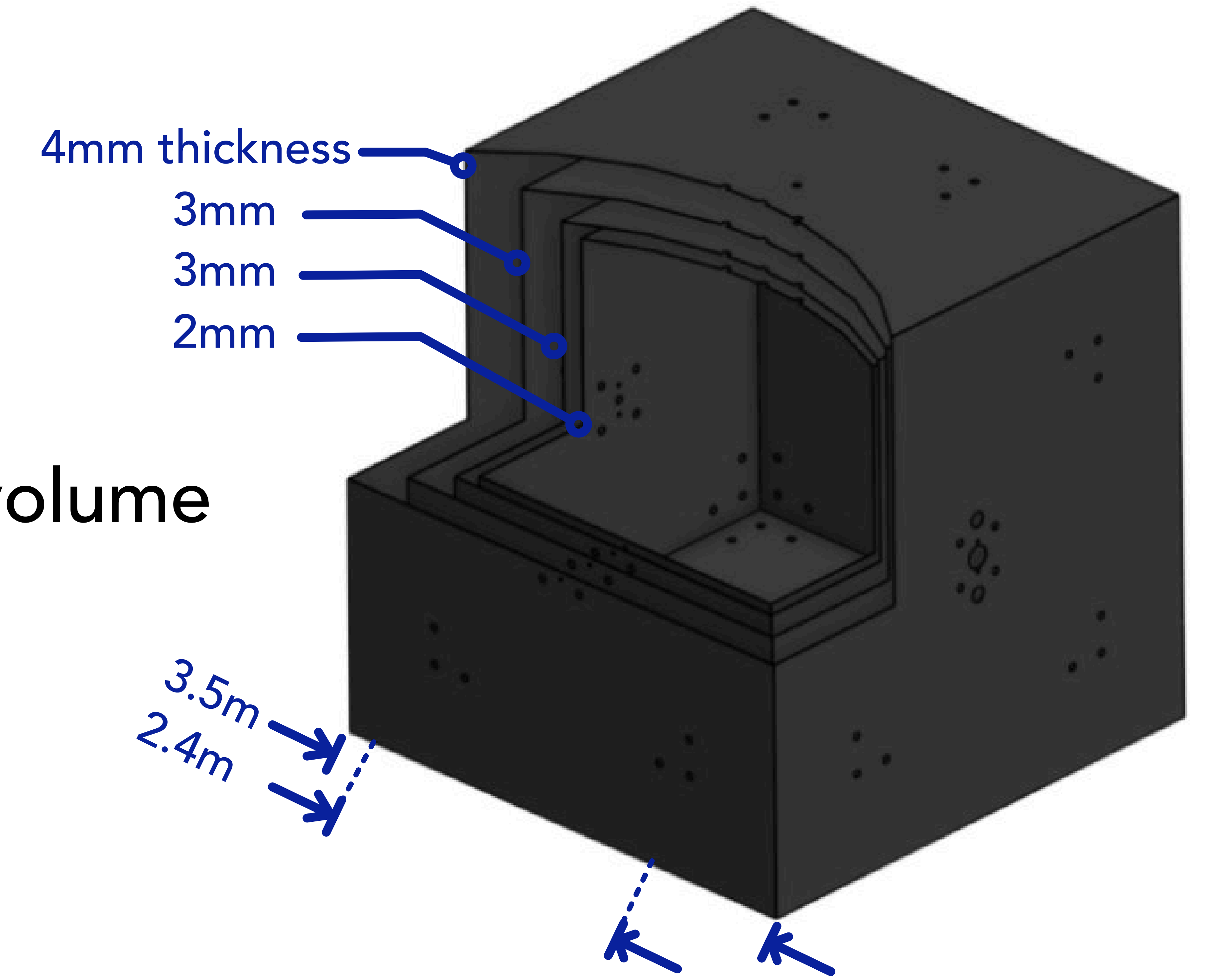
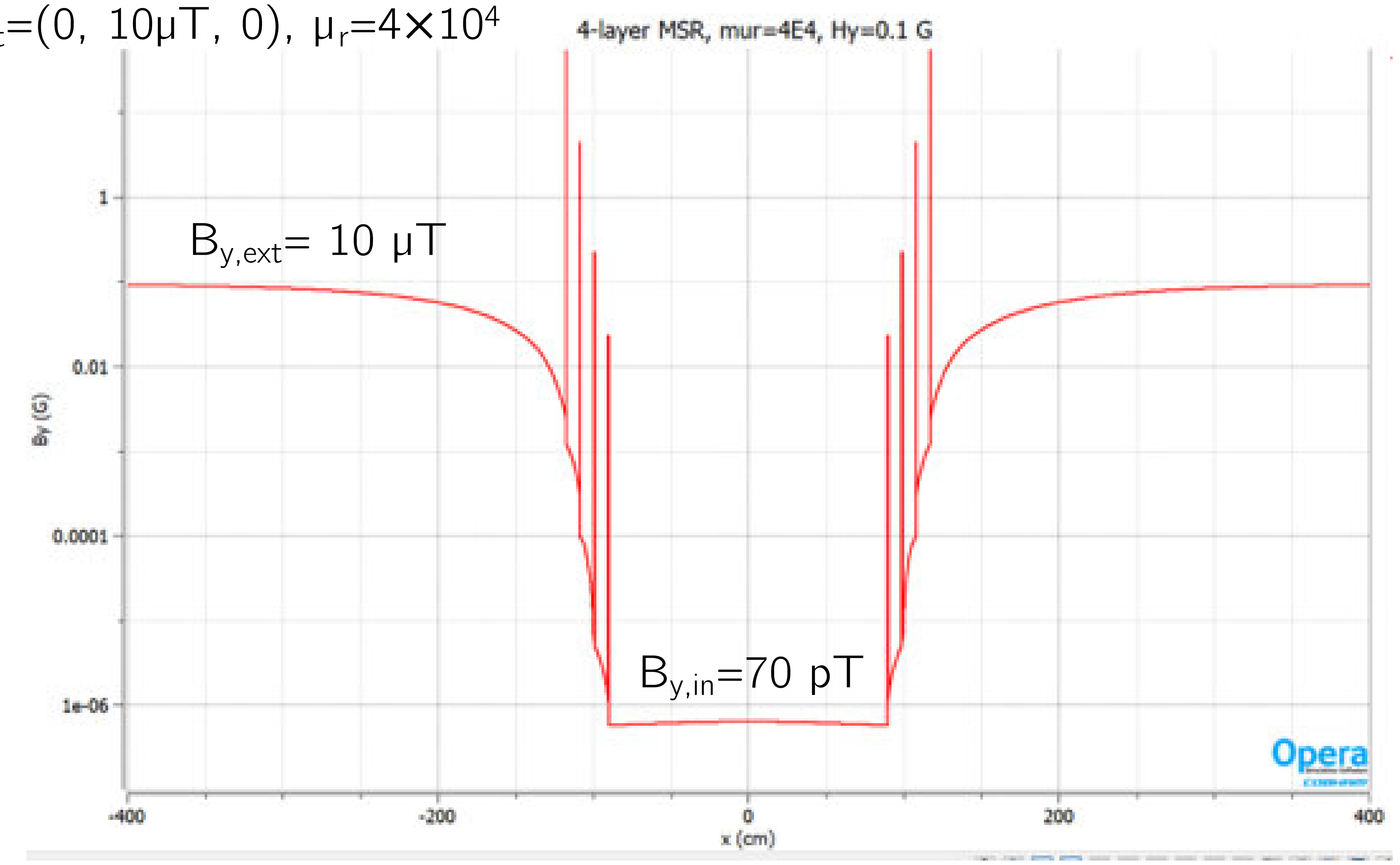
Magnetically Shielded Room (MSR)

- 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 April 2022



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

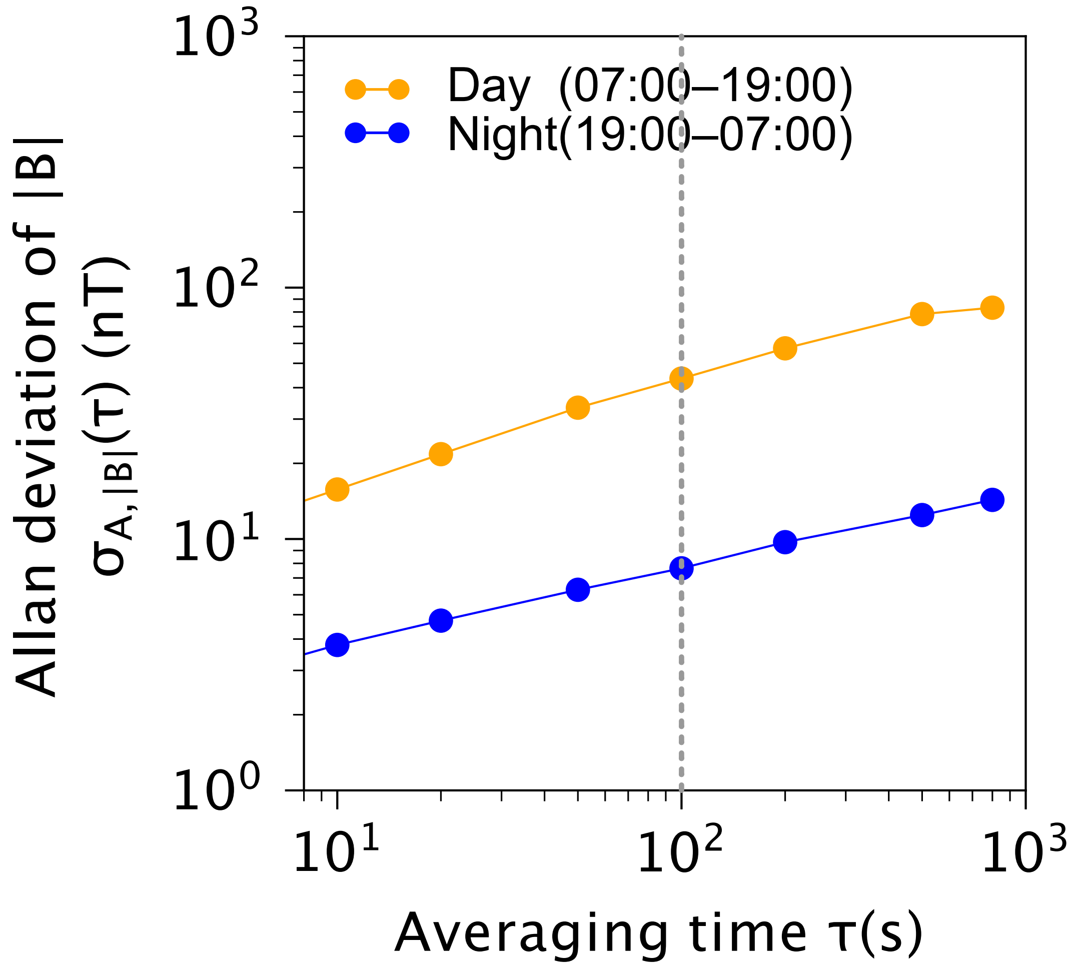


Magnetic field measurements on-site

- 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

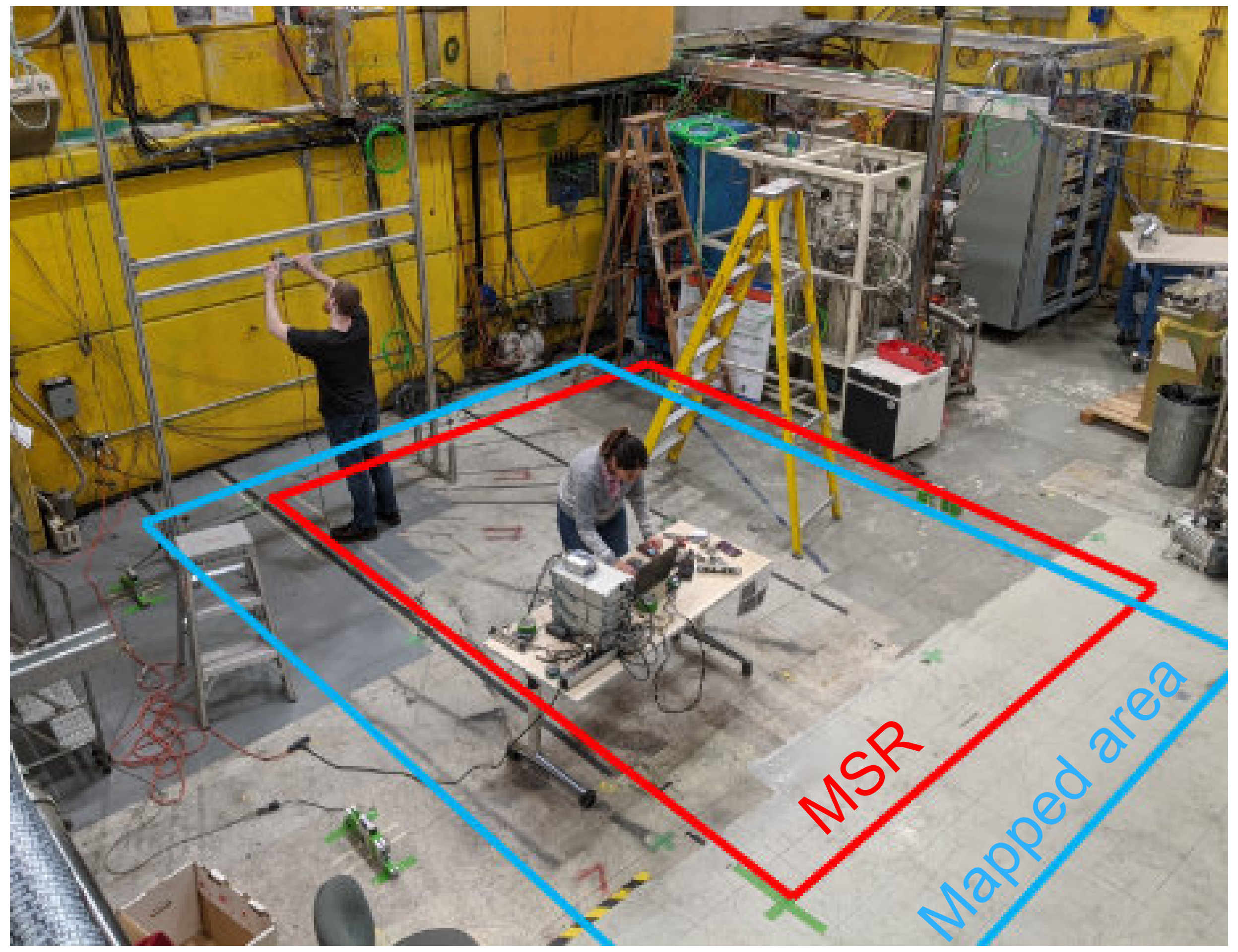
Field fluctuations

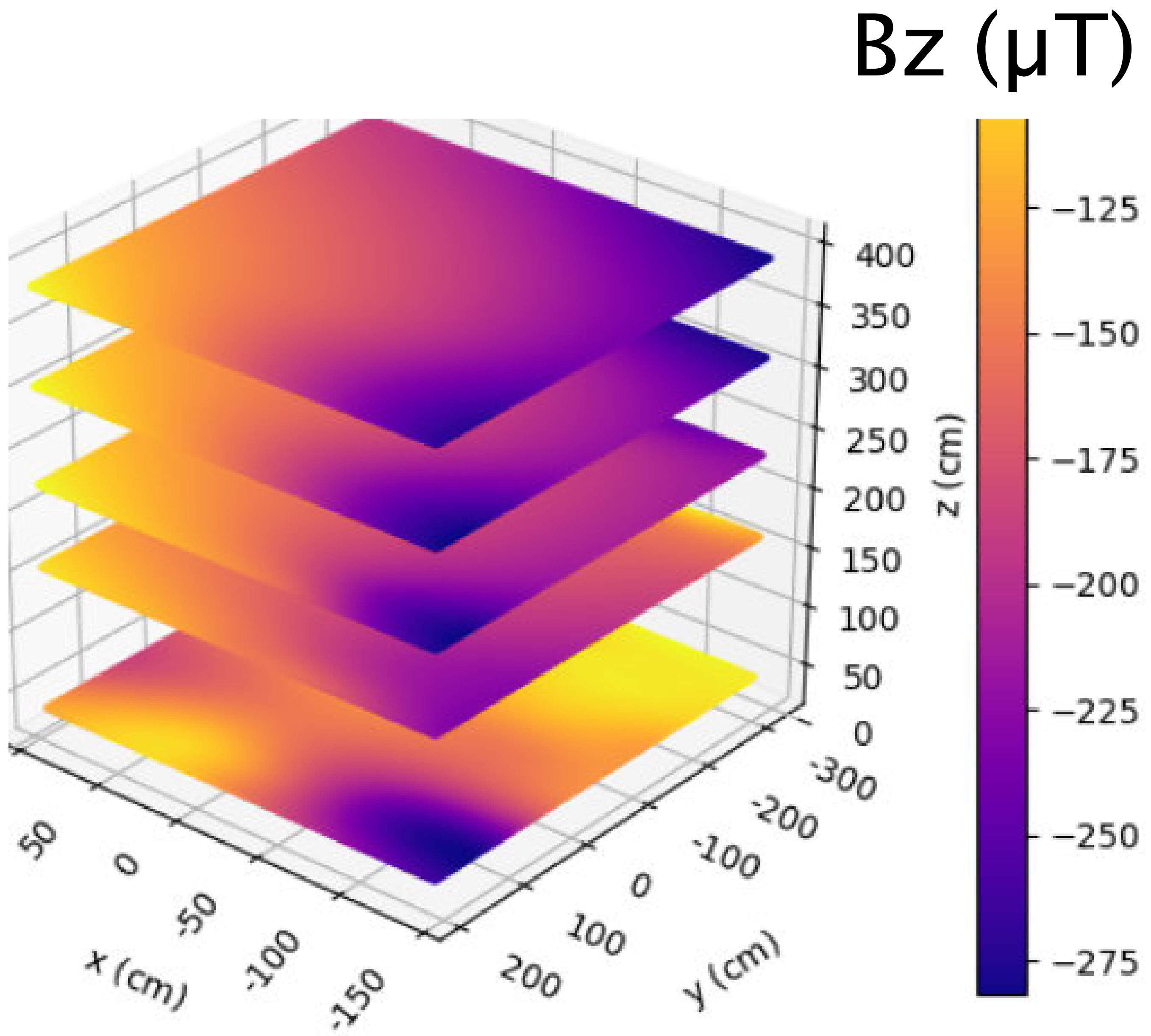


Typically **|B| < 150 nT** (@ 100s averaging)

→ **MSR will provide sufficient field stability**

Magnetic field mapping



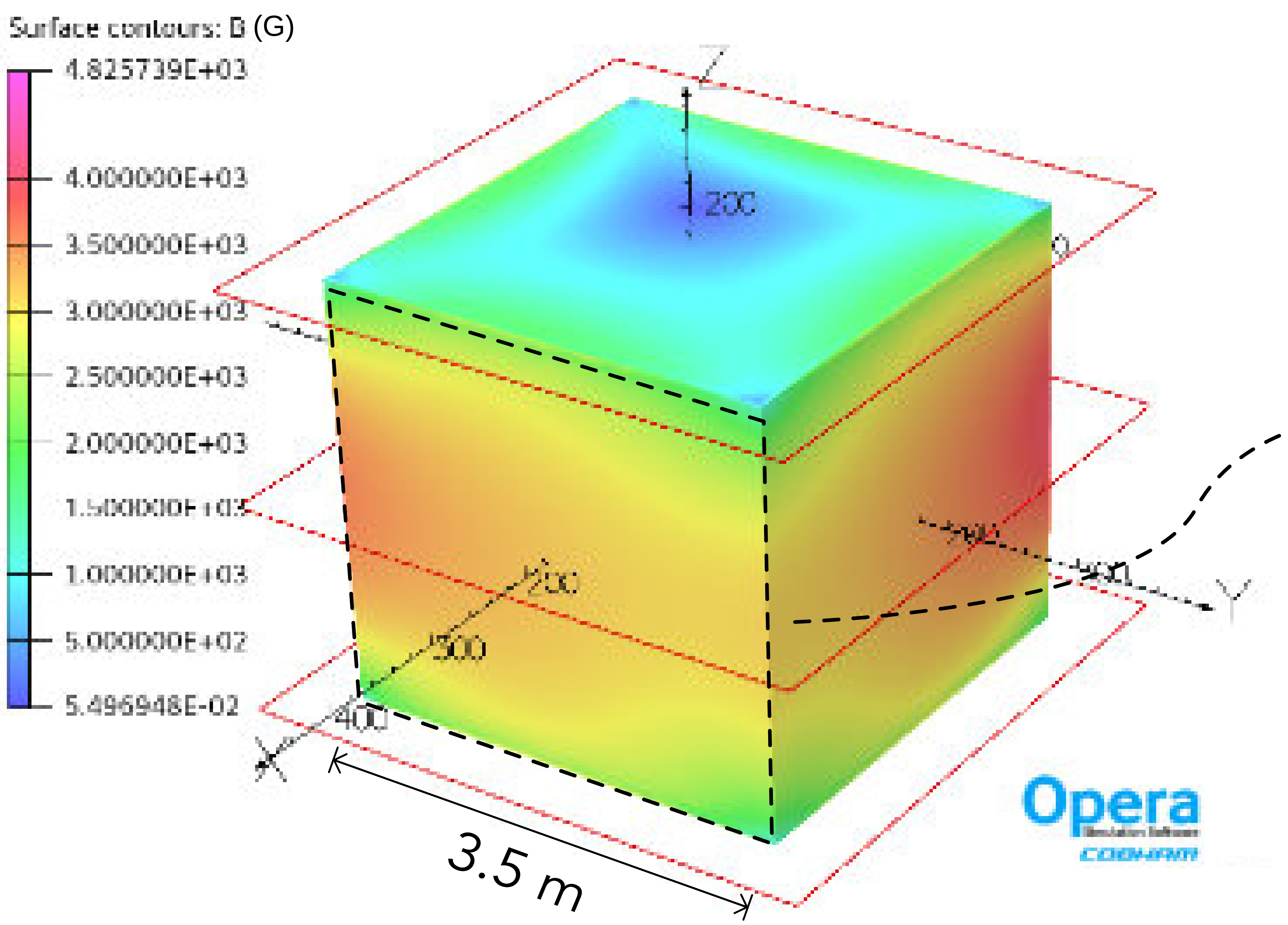


- **|B| ≈ 370 μT** at maximum
- Some hot spots near the floor
- For higher z: dipole-like field from the cyclotron

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



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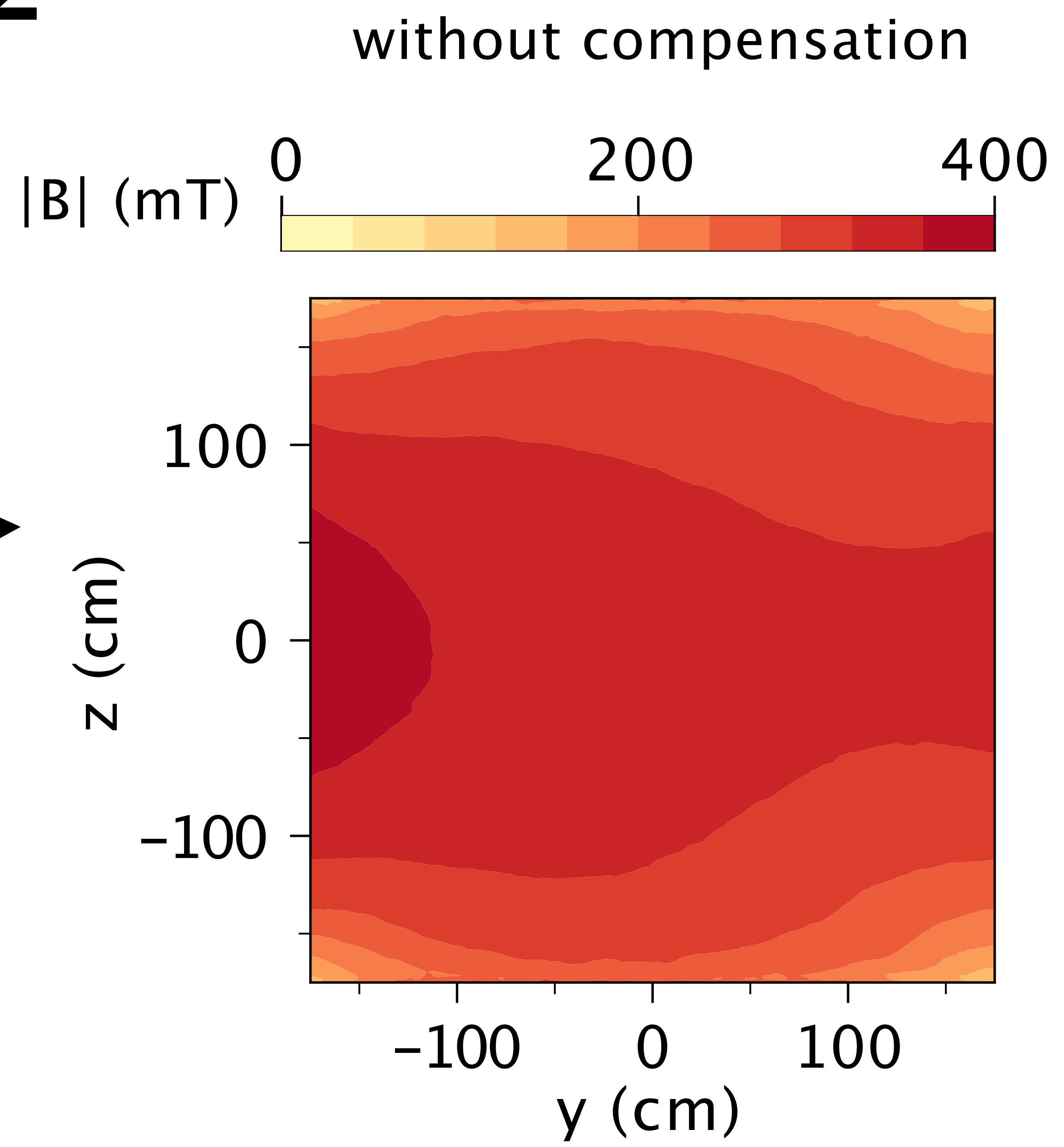

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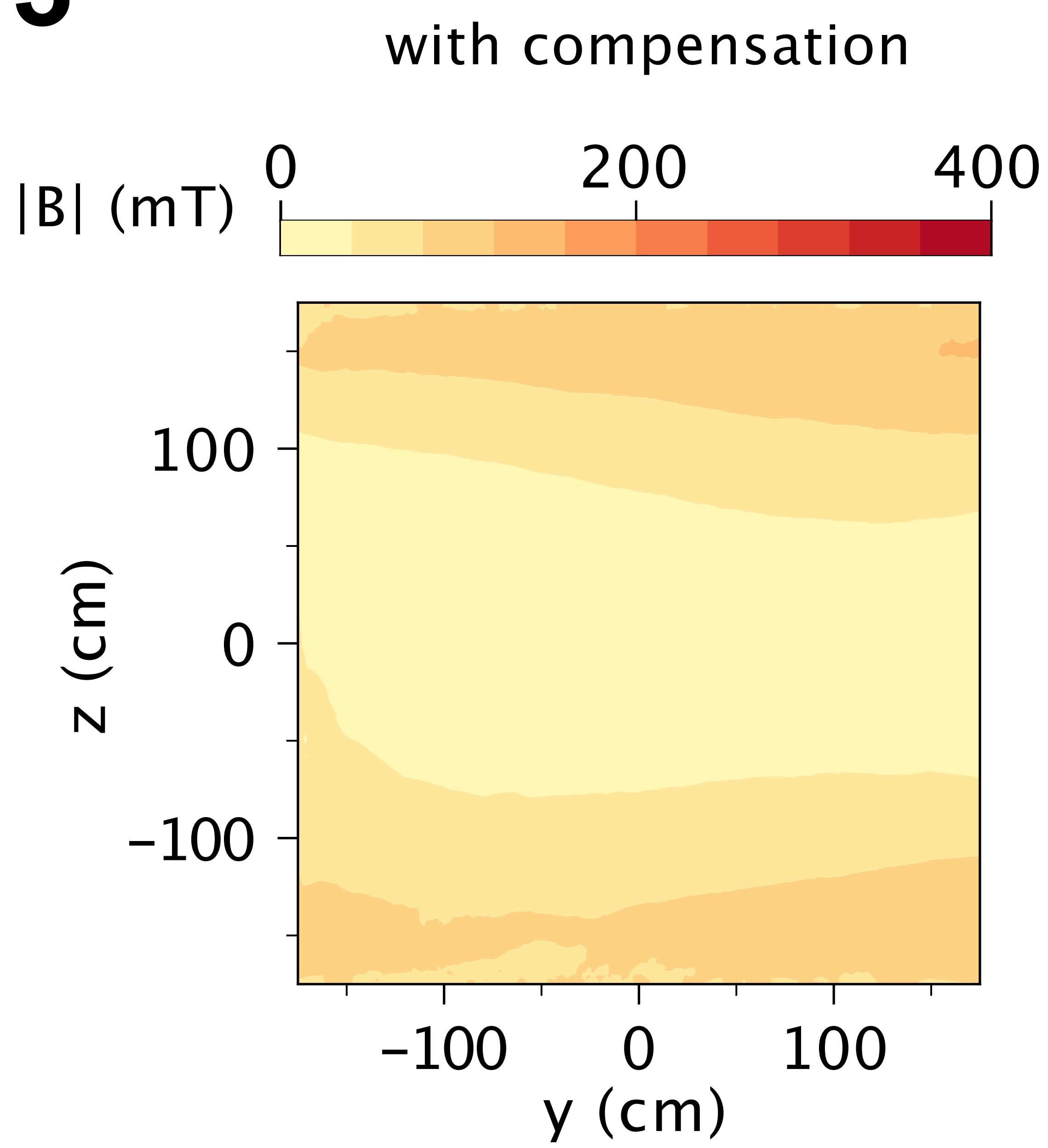


1. MSR placed in a dipole B-field, modeling the cyclotron stray field

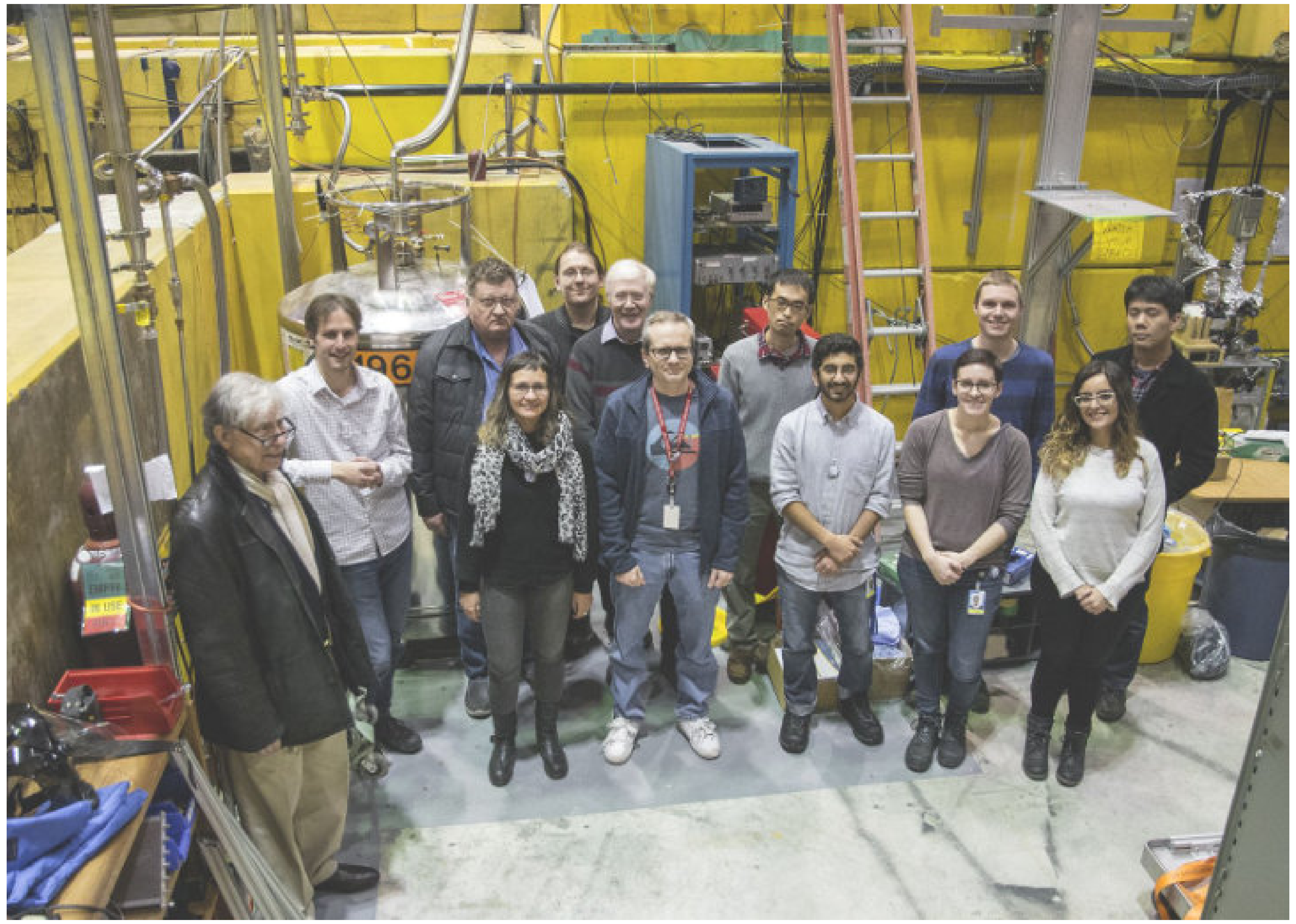
2. In-plane |B| of +x plane: up to 400 mT

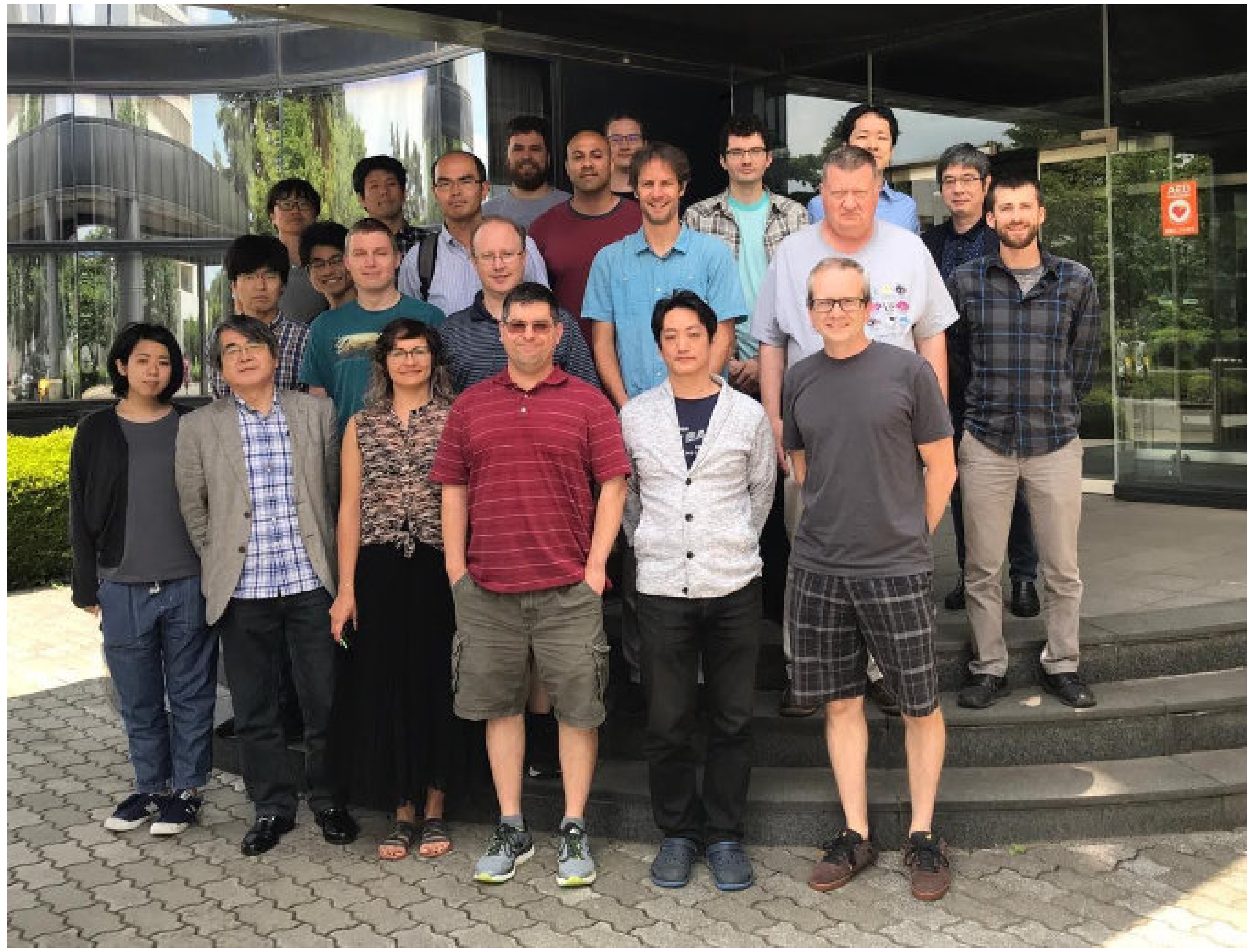
3. Coils activated (600, 150, 600 AT): |B| reduced to <150 mT

Summary

- The TUCAN collaboration:
  - Aiming at a nEDM measurement with 10^{-27}ecm precision by its high intensity UCN source
- The new UCN source under construction:
  - Commissioning of the major components in 2021
  - UCN production from 2022
- The nEDM spectrometer subsystems are under development:
  - Magnetically Shielded Room (MSR) will be installed in 2022, followed by other subsystems

Acknowledgements





Merci !

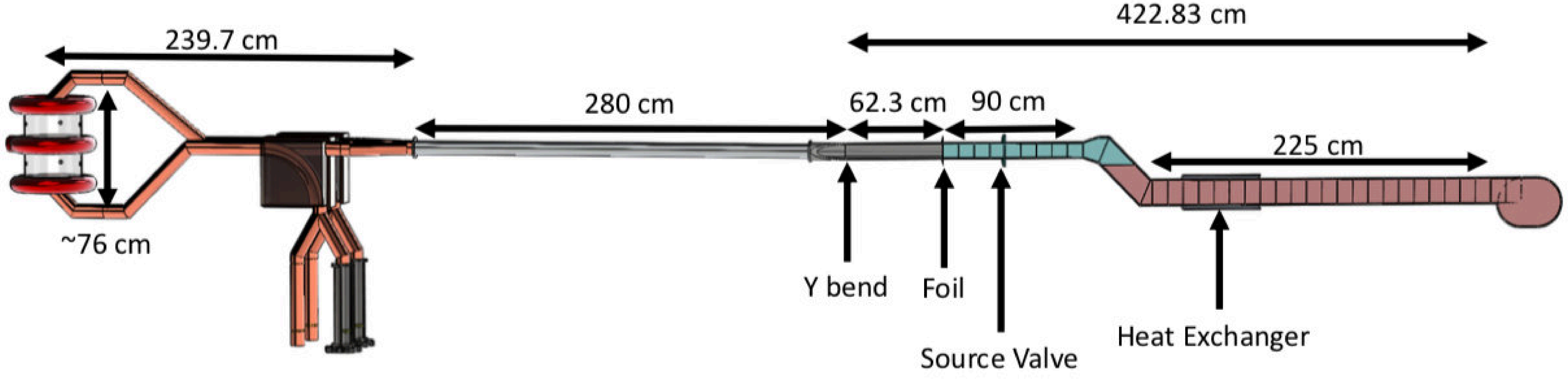
TRIUMF UBC UNBC SFU UNIVERSITY OF MANITOBA THE UNIVERSITY OF WINNIPEG

KEK RCNP NAGOYA UNIVERSITY JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE FOUNDED 1932 NSERC CRSNG INNOVATION.CA CANADA FOUNDATION FOR INNOVATION FONDATION CANADIENNE POUR L'INNOVATION

Appendix

UCN density expectation

- TUCAN EDM cell baseline
  - diameter: 50 cm, height: 16 cm (x2 double-cell) (3×10^4 cm^3)
- Simulation results
  - Filling: $6\text{-}12\times10^6$ UCN/cell (200–400 UCN/cm^3)
  - Counting: $6\text{–}20\times10^5$ UCN/cell (20–60 UCN/cm^3)
  - Time paremeters optimized to maximize the measurement sensitivity

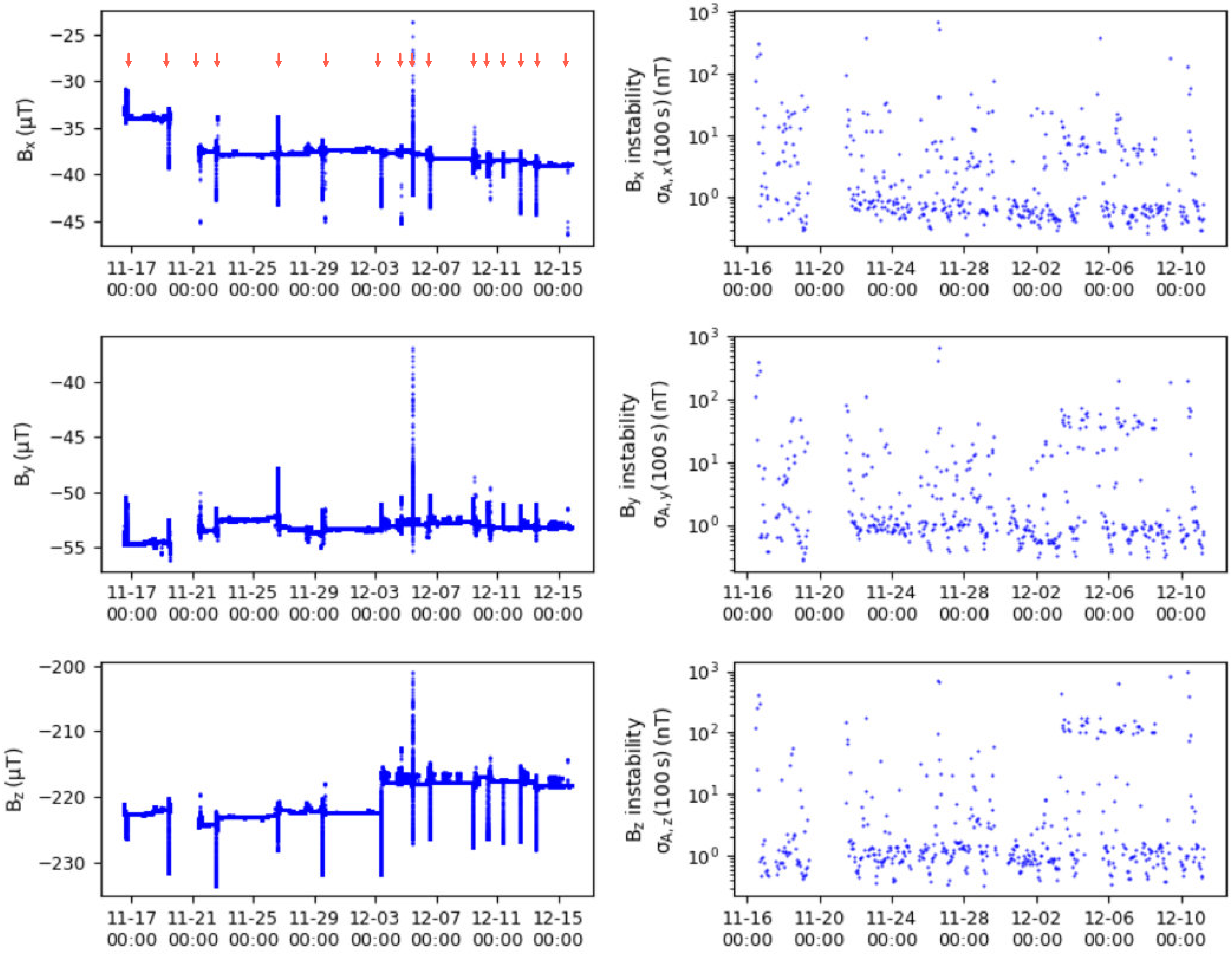


See Steve Sidhu's talk for the details

Magnetic field stability

$\sigma_{A,\,Bi}(100\text{ s})$

- **Magnetic field monitoring**
  - Data analyzed: Oct-Dec 2019
  - Cut each data to 1-hour time window, evaluated the Allan deviation
  - Windows containing crane operations excluded



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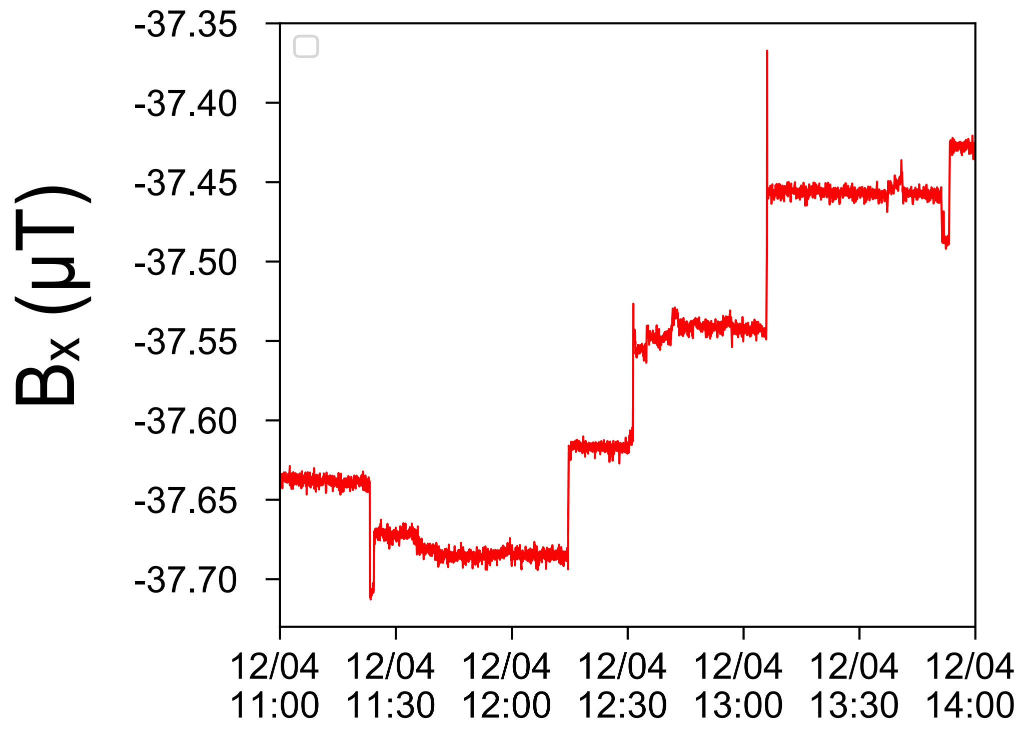
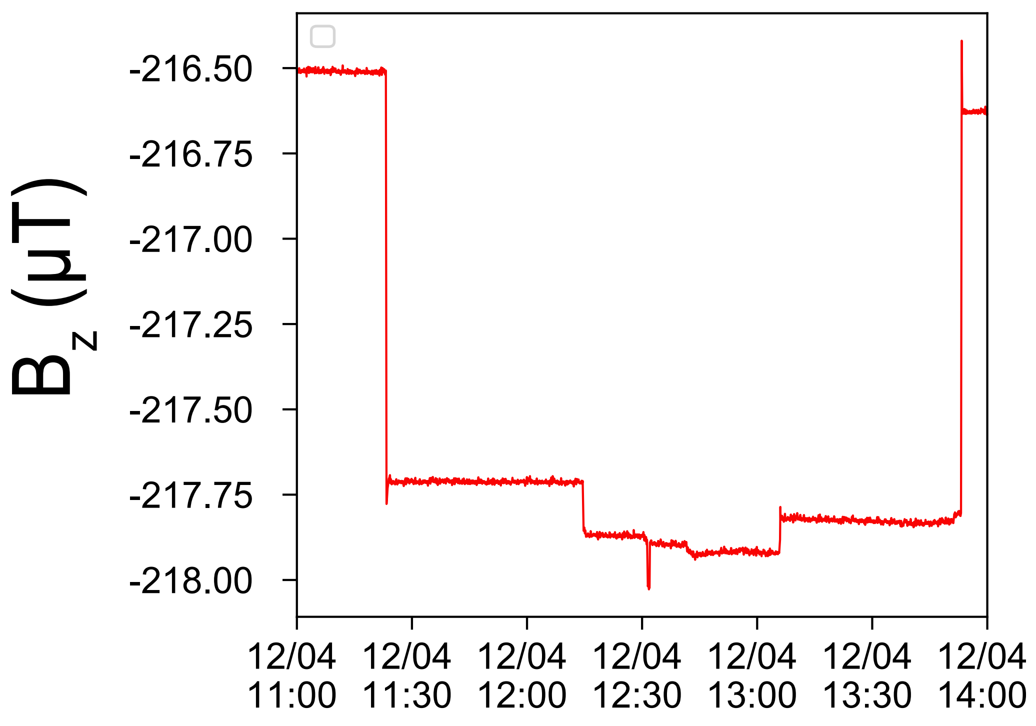
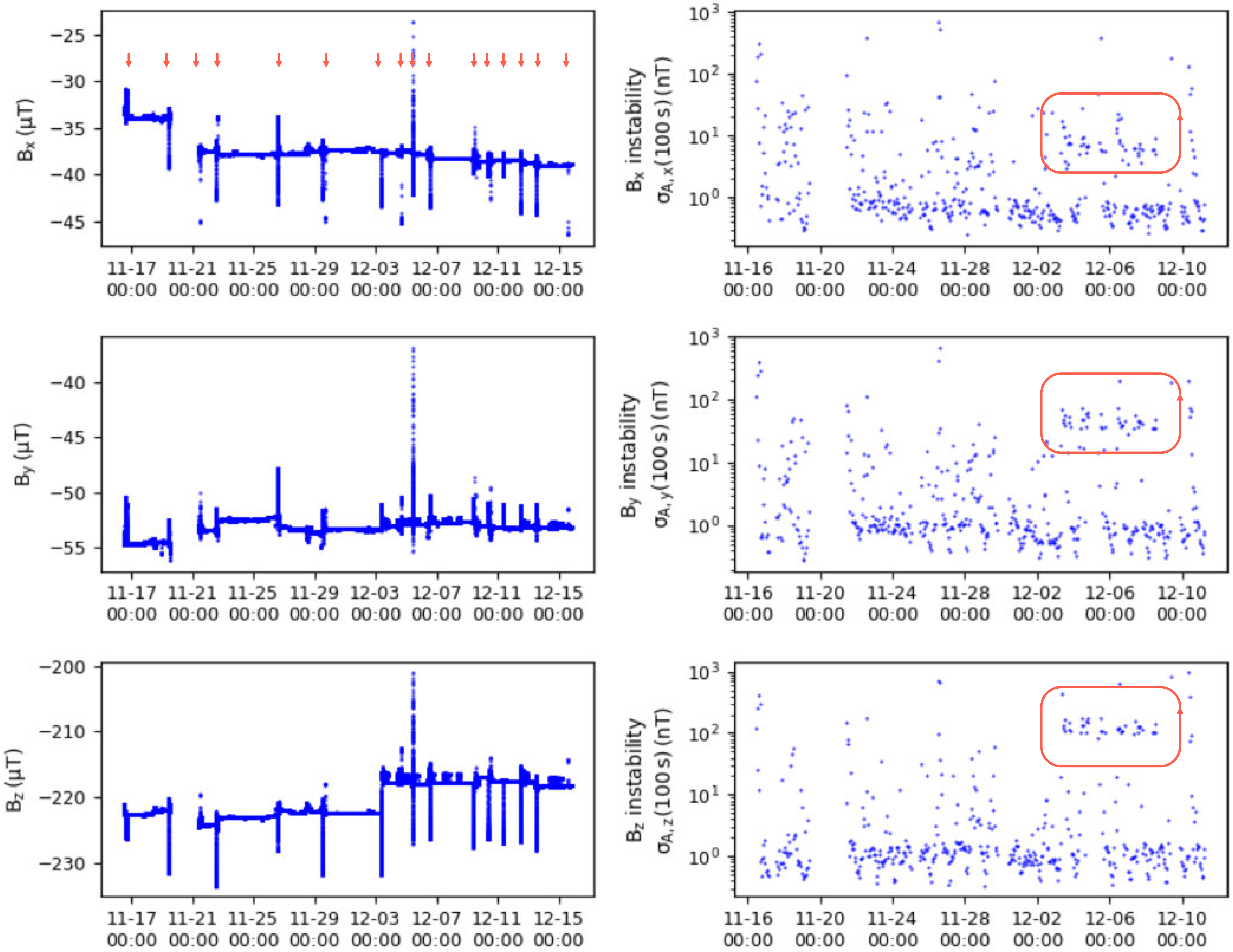


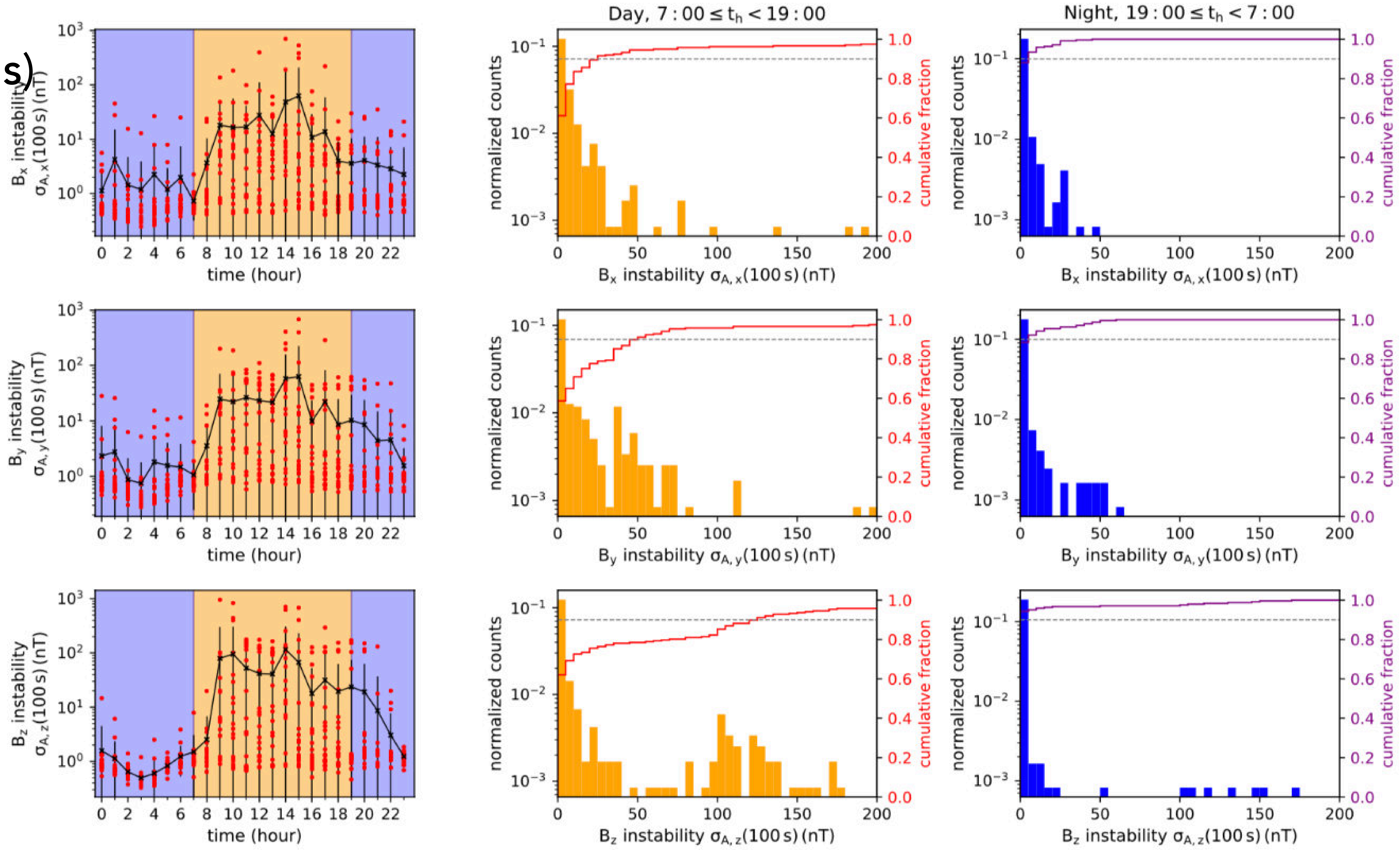


$\sigma_{A,\,Bi}(100\ s)$



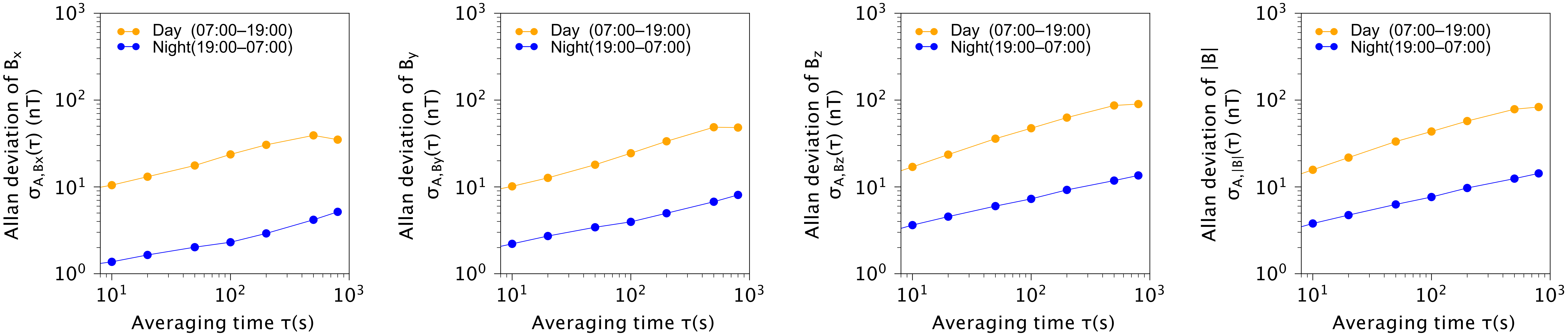
Magnetic field stability

- Distribution of $\sigma_{A,\,Bi}(100\text{ s})$
- $\sigma_{A,\,|B|}(100\text{ s}) < 150$ nT
  For 90% of data bins



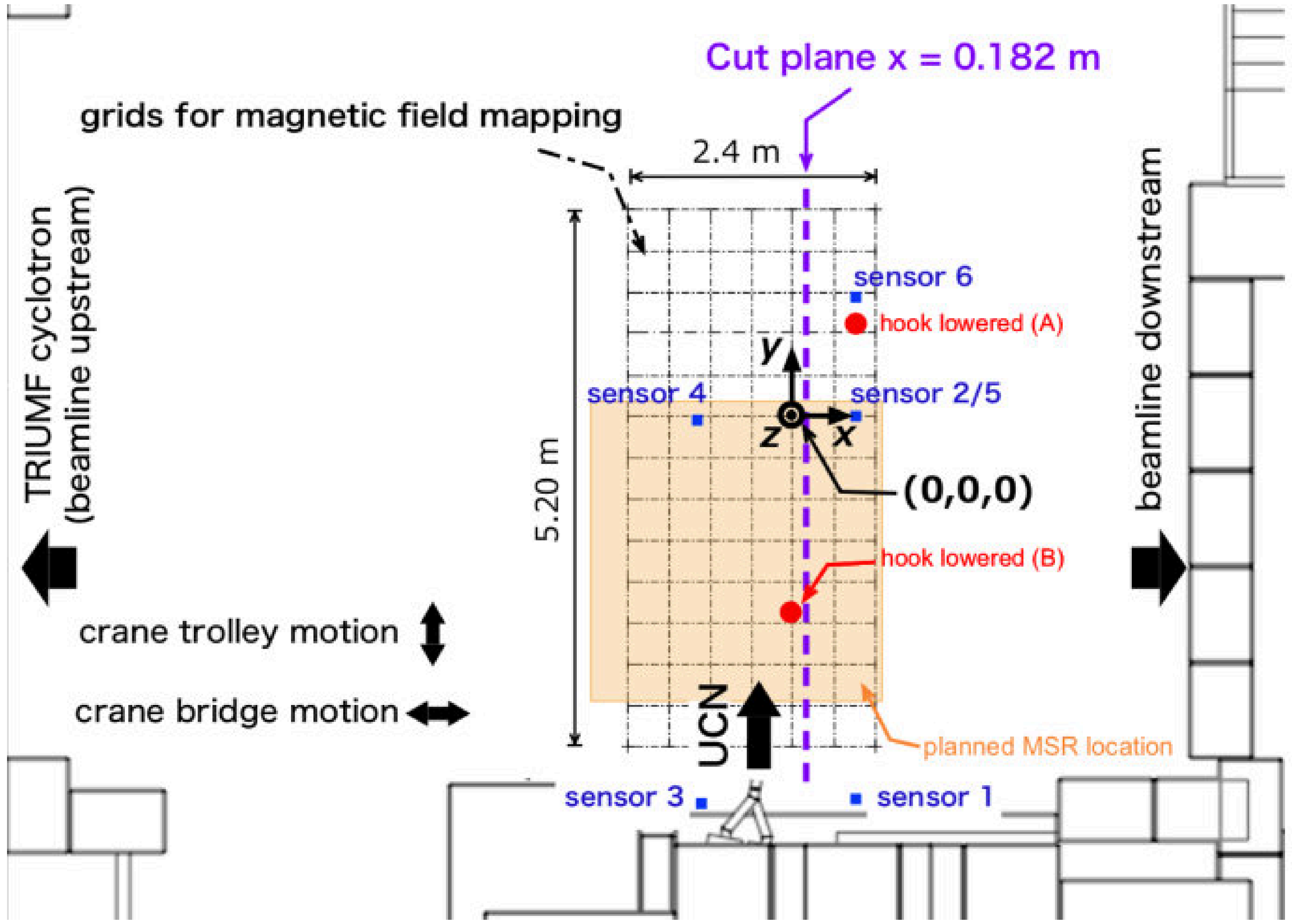
Magnetic field stability

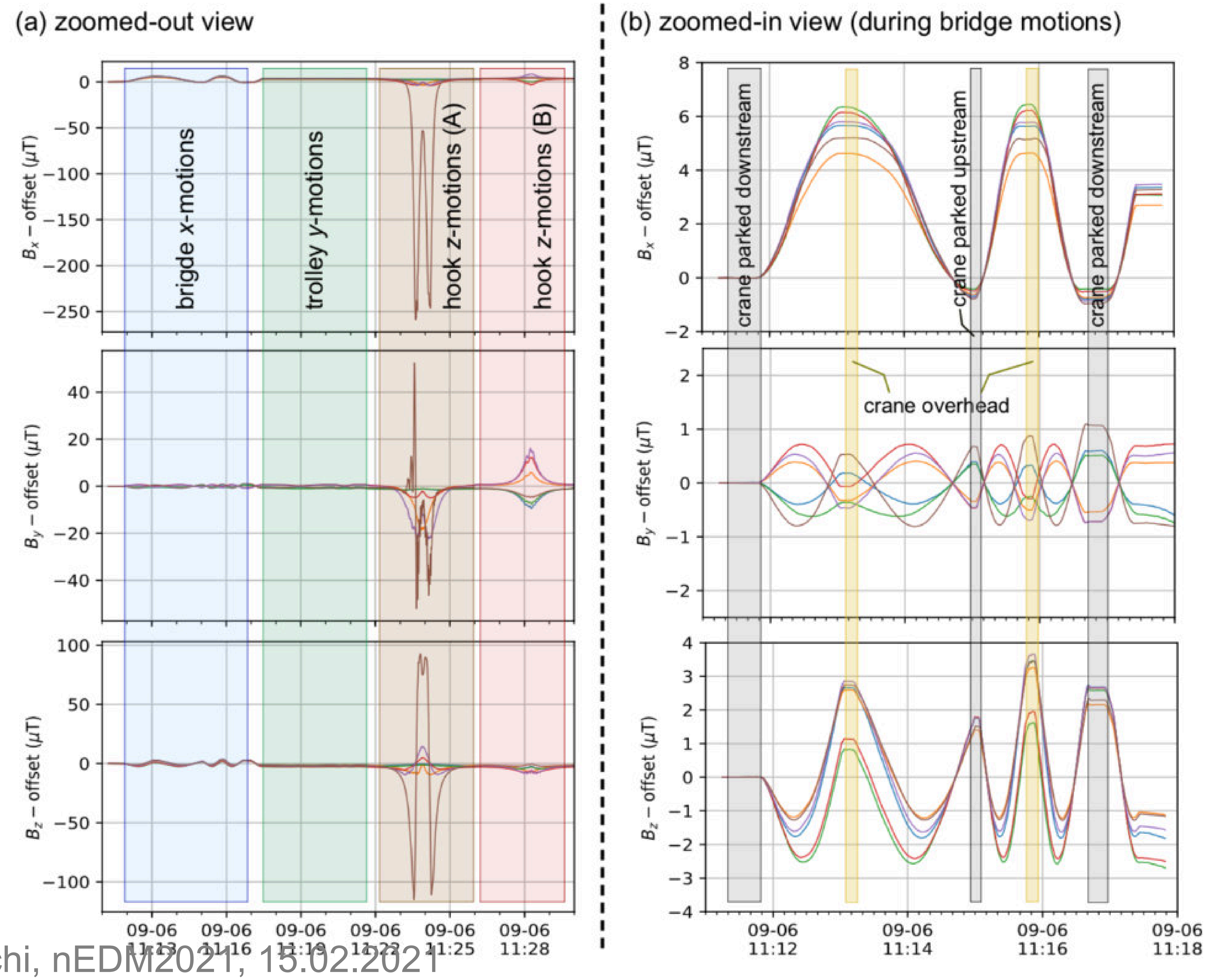
- Allan deviation of in day (07:00–19:00) and night (19:00–07:00) separately averaged
- 1-σ band shown



Magnetic fied perturbations by crane operations

- Magnetic field induced by crane operations characterized by sensors fixded on 6 positions





- For the bridge motions
  - Up to ΔB~10 μT
  - Rather homogeneous changes