February 3-4, 2026

VENUS

Imaging Instrument Suite Review from FY23 to FY26

(with excerpts from FY20-22)

Hassina Bilheux, on behalf of the neutron imaging team

Neutron Scattering Division

U.S. DEPARTMENT of ENERGY

ORNL IS MANAGED BY UT-BATTELLE LLC
FOR THE US DEPARTMENT OF ENERGY

The VENUS imaging beamline at the Spallation Neutron Source

- VENUS is a *time-of-flight* imaging beamline capable of separating neutron wavelengths to measure unique sample features/contrast such as:
  - Microstructure, phases, preferred grain orientation, strain with **Bragg edge radiography** of advanced *crystalline* materials (energy, superalloys, etc.)
  - Elemental/isotopic content with **resonance radiography/CT but also temperature gradients**
- VENUS computing infrastructure was designed for the implementation of artificial intelligence tools from data acquisition to data processing/analysis

VENUS Timeline

Prototyping at SNAP (BL3) ~ 10% beam

Last instrument suite review in 2020

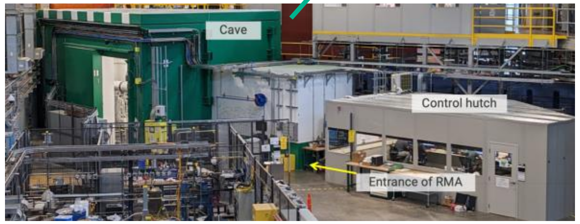
AI projects (2021-2026)

October 2018 → February 2020 → December 2022 → August 2024 → Sept. 2024 - May 2025 → August 2025

Pre-commissioning and commissioning activities

VENUS construction project is funded

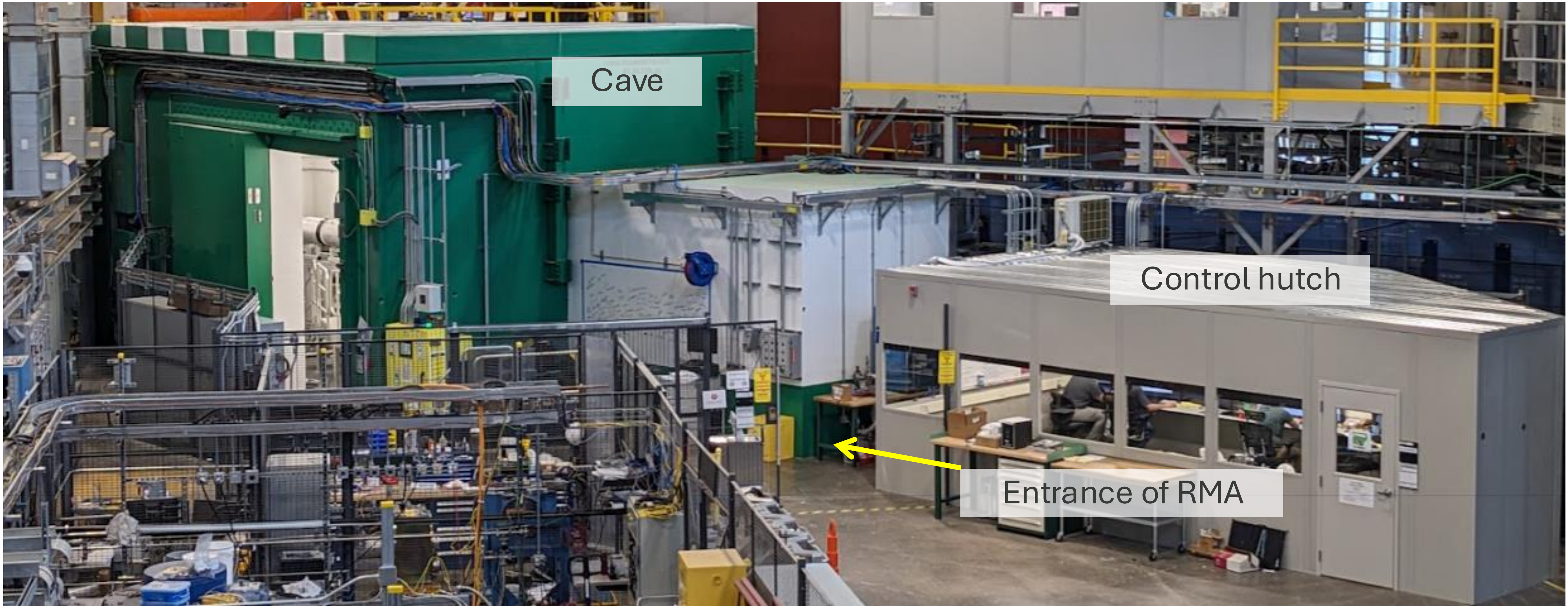
VENUS construction begins.



VENUS construction ends

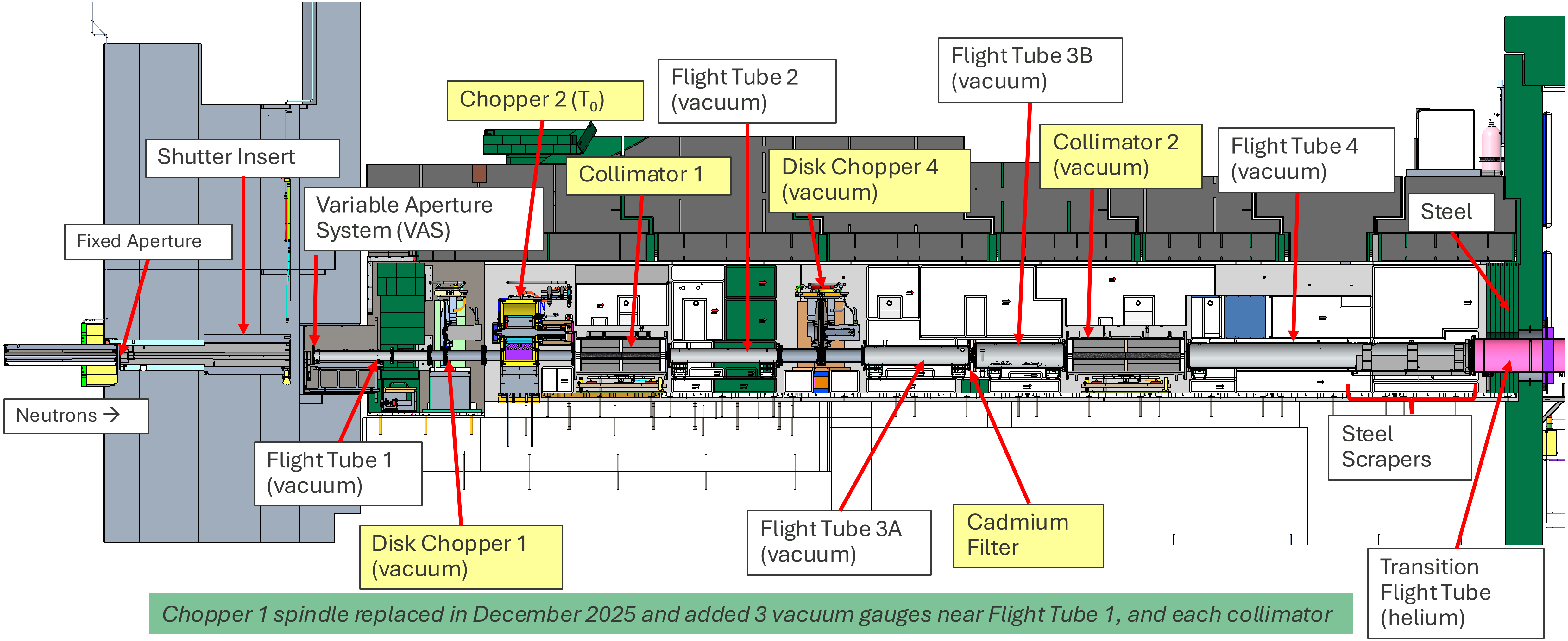
August 2025: The general user program begins!

Photograph of VENUS showing the VENUS cave, control hutch and Radiological Materials Area (RMA)



VENUS front-end components

Shutter hydraulic leak repaired during Summer 2025

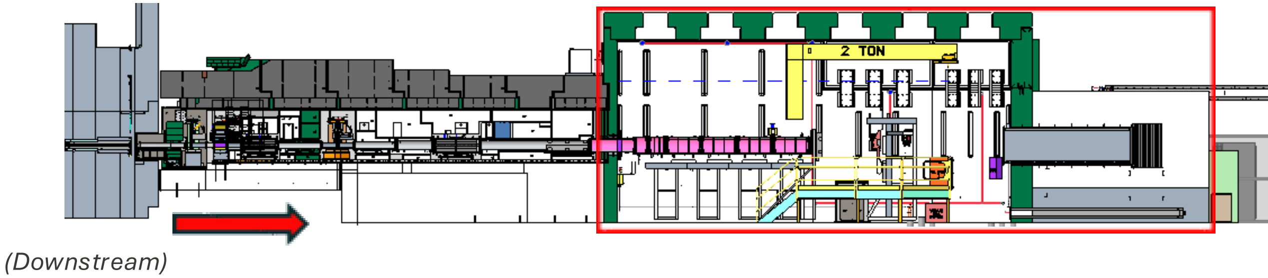


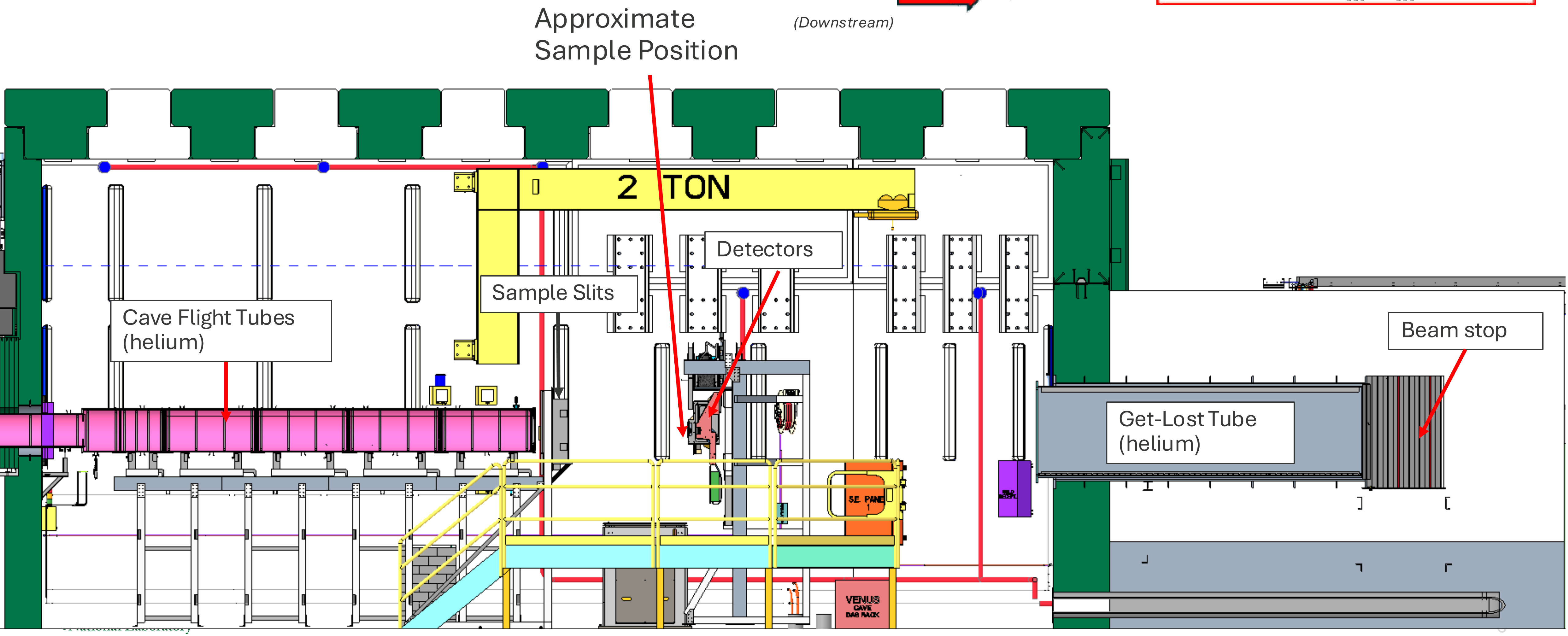
Chopper 1 spindle replaced in December 2025 and added 3 vacuum gauges near Flight Tube 1, and each collimator

Both repairs done efficiently. No impact on commissioning or user program.
Advantageous to be at a mature neutron facility with strong and established expertise.

OAK RIDGE National Laboratory

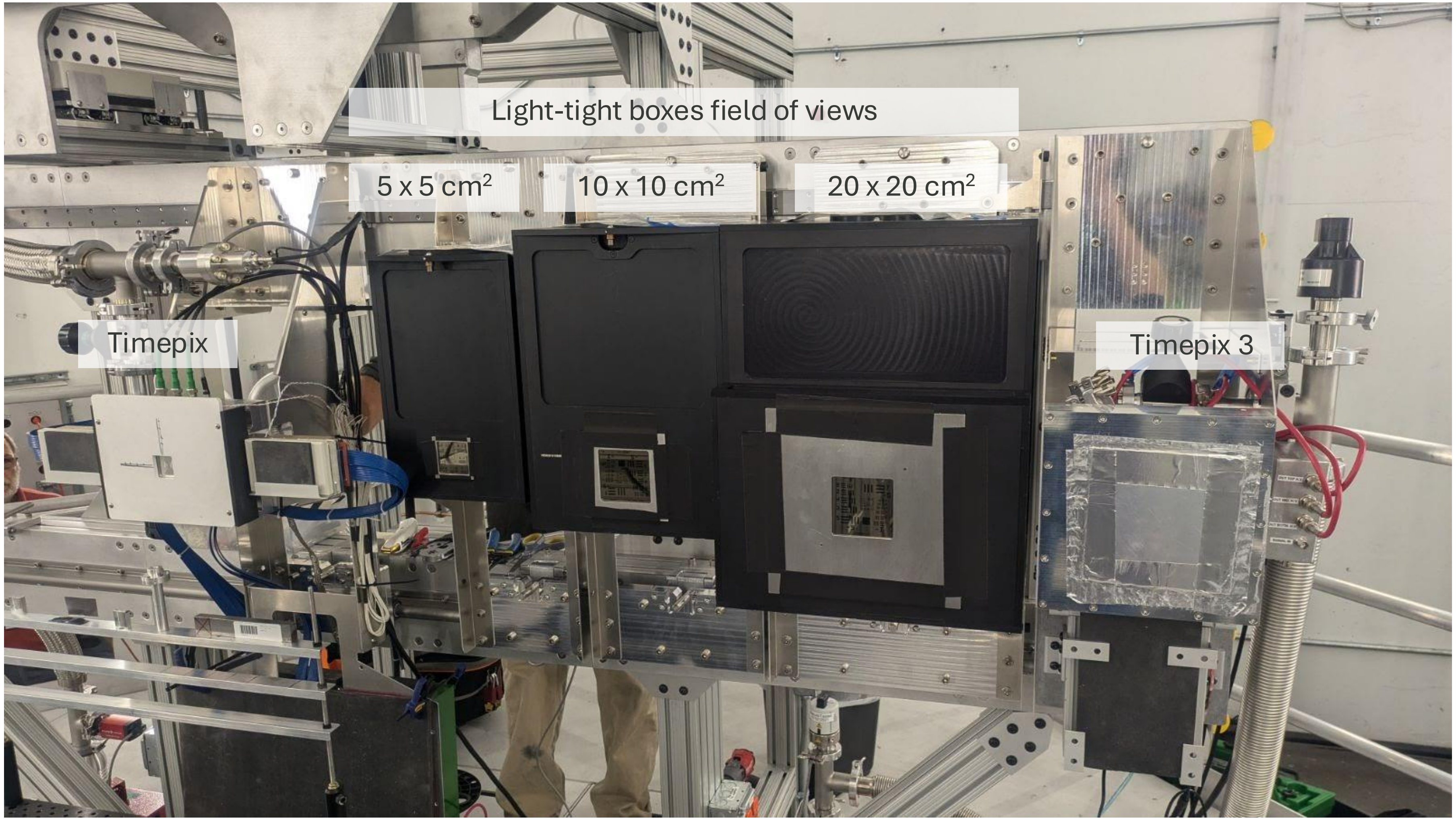
VENUS cave and beam stop





VENUS built for maximum flexibility: large sample and sample environment

All detectors and accessories installed on a rail system for quick change of detectors



From left to right, MCP TPX detector, 5x5cm^2, 10x10 cm^2, 20x20 cm^2 light-tight boxes (without the ANDOR CCD or the QHY sCMOS), and MCP TPX3 detector.

Oak Ridge National Laboratory

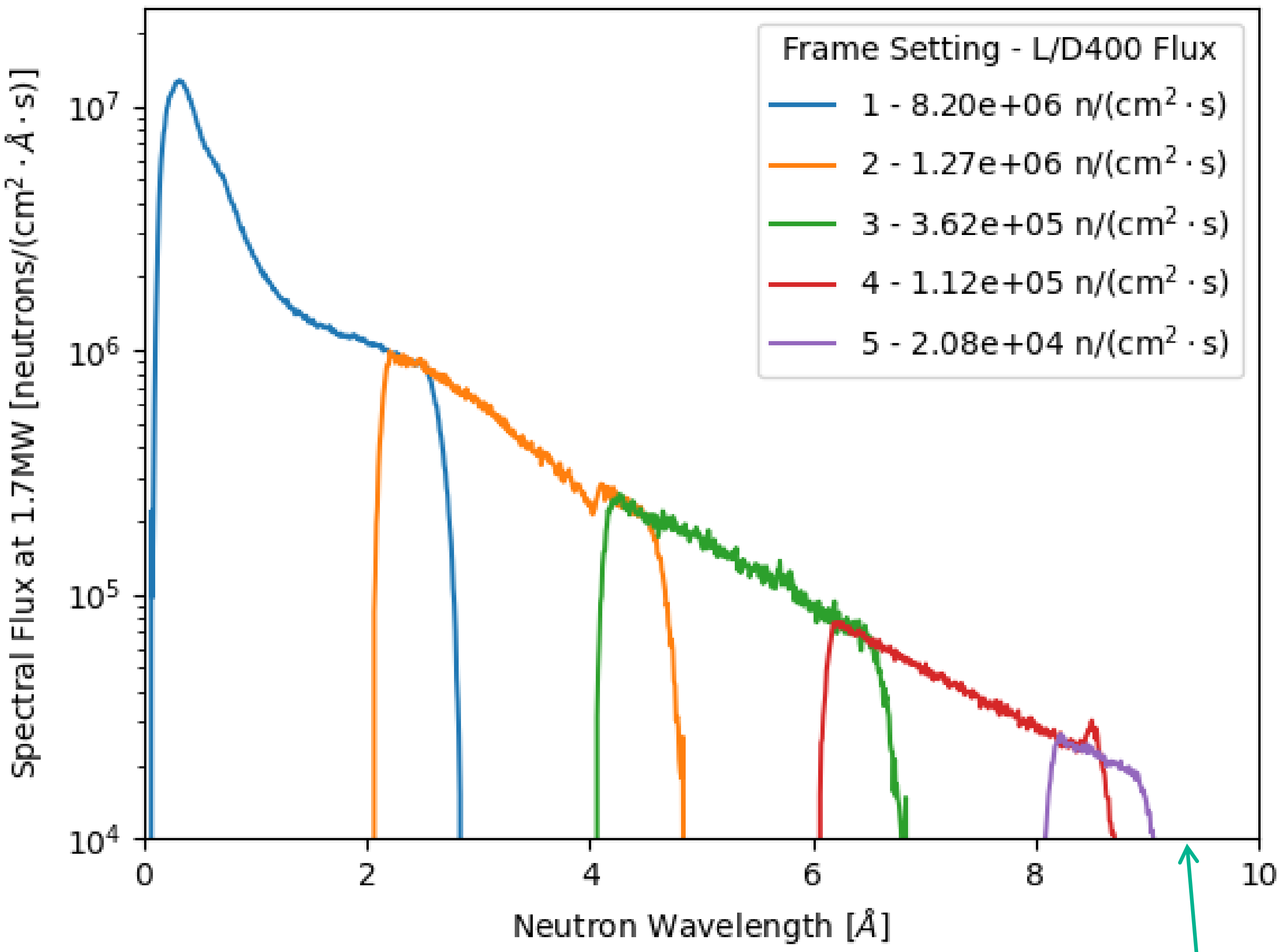
VENUS capabilities have been met

Parameter	Expected Capability	Demonstrated Capability
Source power and repetition rate	2 MW and 60 Hz	1.8 MW as of October 21, 2025, and 60 Hz
Neutron wavelength	**Epithermal, thermal and cold**	✓
Source-to-detector distance	**25 m**	✓
Wavelength band and resolution	2.5 Å @ 60 Hz; ~ 0.15%	✓
Spatial resolution	50-100 μm	✓
Maximum single shot radiograph field-of-view	**20 x 20 cm^2 for thermal and cold neutrons** **4 x 4 cm^2 for epithermal neutrons**	**20 x 20 cm^2 for thermal and cold neutrons** **20 x 20 cm^2 for epithermal neutrons**
Detectors	ANDOR iKon-XL 230, QHY6060, Microchannel plate Timepix1 and Timepix3 detectors	ANDOR iKon-XL 230 CCD**(*)**, QHY**411(**)** sCMOS, Microchannel plate Timepix1 and Timepix3**(***)** detectors
Sample stage	1 m^3 open area, 500 kg maximum weight capacity	✓

(*) received, currently being tested, not implemented in user interface
(**) received, tested and currently being implemented in user interface
(***) received, tested, and currently being implemented in user interface

ANDOR iKon-XL CCD mounted on 20x-20 cm^2 light-tight box

Beam flux as a function of wavelength @ 1.7 MW



T_0 chopper blocks beam again

White beam flux: 9.3×10^6 n/cm^2/s

L/D 400, 4x4 cm^2 beam

Measured with ORDELA beam monitor (10^{-5} efficiency at 1 Å)

Courtesy of Matt Frost, ORNL

VENUS compared to *general user* beamlines RADEN, IMAT and ERNI

TOF Imaging Beamlines	SNS FTS VENUS	J-PARC RADEN	ISIS IMAT	CSNS ERNI
Source power and frequency	2 MW and 60 Hz	1 MW and 30 Hz	40 kW and 10 Hz	1 MW and 25 Hz
Moderator type	Decoupled H	Decoupled H	Coupled H	Coupled H
Available/Usable wavelength/energy range	0.0007 (150 keV) - 9 Å	λ < 8.8 Å	2-6.5 Å	300 MeV (?) – 5 Å
Wavelength resolution	Δλ/λ ~ 0.15 % (λ > 2 Å, at 25 m)	Δλ/λ > 0.2 % (λ > 3 Å, at 23 m)	Δλ/λ < 0.9%	Δλ/λ < 0.5%
Approximate Neutron Beam Flux	~1 x 10^7 n/cm^2/s @ 25 m (L/D 400)	1.7 × 10^7 n/cm^2/s (λ > 0.43 Å, L/D = 180) 1.1 × 10^8 n/cm^2/s (λ < 0.0003 Å, L/D = 180) 3.9 × 10^6 n/cm^2/s (λ = 0.3 Å, L/D = 180)	Max. 3.8 x 10^7 n/cm^2/s (white beam, L/D = 125)	1.0 × 10^7 n/cm^2/s @ 35 m
Source-to-sample distance	25 m	18 or 23 m	56 m	30 and 35 m
Maximum Field-of-View	20 x 20 cm^2	30 x 30 cm^2	20 x 20 cm^2	20 x 20 cm^2
L/D range	400-2000	180-7500	125-2000	62.5-2000
Spatial resolution	~ 25 μm (MCP detector)	> 100 μm (counting detector)	~ 110 μm (MCP detector)	< 50 μm

- VENUS comparable to worldwide sister facilities:
  - Similar flux in thermal/cold neutron range
  - Similar wavelength range as RADEN
  - Wavelength resolution is appropriate for Bragg edge and resonance imaging
  - Comparable field-of-view
  - Similar L/D range
  - Advantage: AI capabilities integrated into VENUS reduces acquisition time for hyperspectral CT by a factor of 5; working on implementing AI-driven segmentation of 3D+ data sets
- *Too soon to compare scientific productivity (next review!)*

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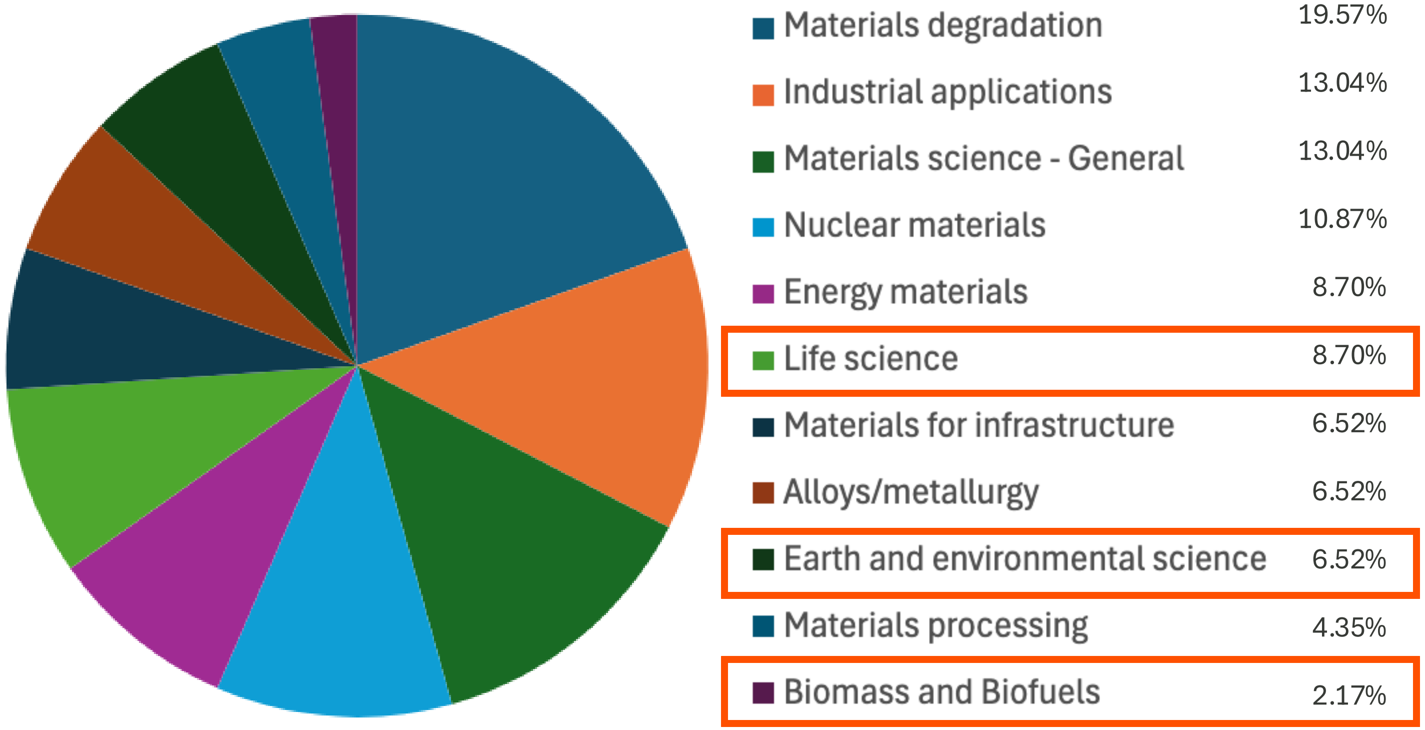
Science at VENUS



14 proposals submitted for 2025B
21 proposals submitted for 2026A, with proposals from experts!

VENUS has been in the general user program for **only 1 cycle (2025B)**:
- 14 proposals submitted for 2025B – 11 allocated beam time + 1 neutron school proposal (5 in FY25 – when this review ends)
- the instrument is still commissioning/integrating major equipment such as TPX3, ANDOR CCD and QHY sCMOS detectors), furnaces, cryostats, etc.

- Diversity in proposals:
  - Strong participations from **materials science and engineering**
  - **Industry** participation based on interaction of beamline scientist at industry meetings
- Beamline scientist activity seeking **life and environmental scientists** to ensure all communities are represented/trained at VENUS from the beginning

Computing infrastructure at VENUS

Log in with your username and password at VENUS and at your home institution

VENUS

- Data Acquisition Controls (DAS-OPI0)
- Remote Data Acquisition Controls (DAS-REMOTE)
- Controls for choppers, VAS, collimators, sample table, sample slits, etc.
- TPX1 on DAQ3 (PC)
- TPX2 on DAQ2 (Linux)
- ANDOR CCD on ??? (Linux)
- QHY411 sCMOS on ??? (Linux)
- Local data storage 320 TB

SNS Server Room

- Data processing server
- Data visualization/analysis server
- Imaging cluster (reconstruction)
- Hype cluster for future strain reconstruction – in collaboration with BNL and Purdue University

HyperCT

Software

- Automated data transfer to SNS servers
- Data correction (TPX1 and TPX3)
- Jupyter Notebooks:
  - Data processing/analysis
- 3 AMIRA licenses for 3D visualization, segmentation and analysis
- iBeatles (Bragg edges)
- PLEAIDES-neutron –in collaboration with LANL
- Collaboration with ESS to define standards – visiting soon

VENUS is challenging our Computer Instrument Scientist

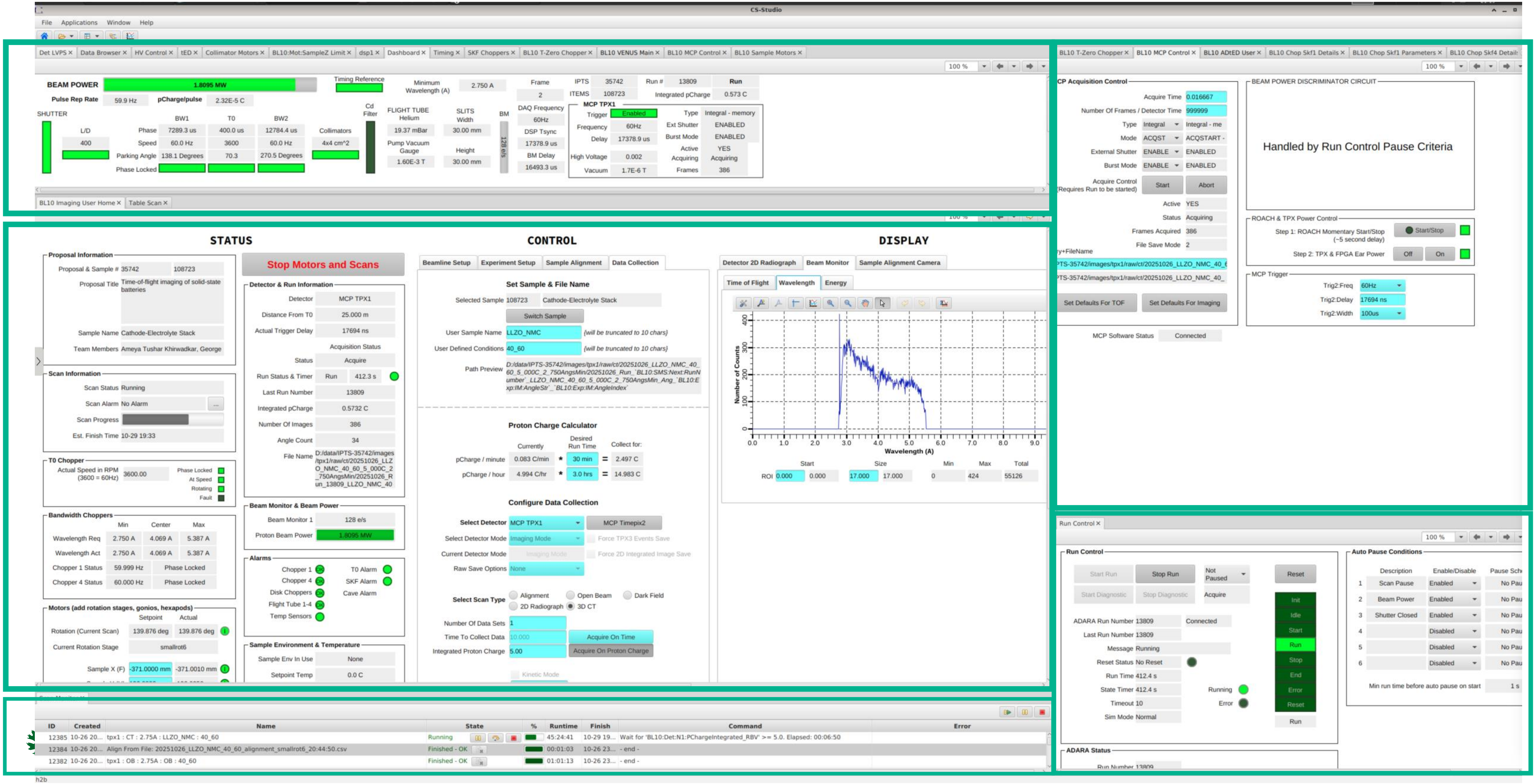
Beamline (Year joined user program)	Current event rate (Million events/s)	Fraction of Computational Instrument Scientist
VULCAN (2009)	0.12	1
SNAP (2009)	0.65	1
NOMAD (2012)	1.78	0.5
VENUS* (2025)	**40**	0.5

(*) with the smallest area detector of 28 x 28 mm^2 of all SNS instruments
The future VENUS field-of-view for time-of-flight imaging will be 200 x 200 mm^2

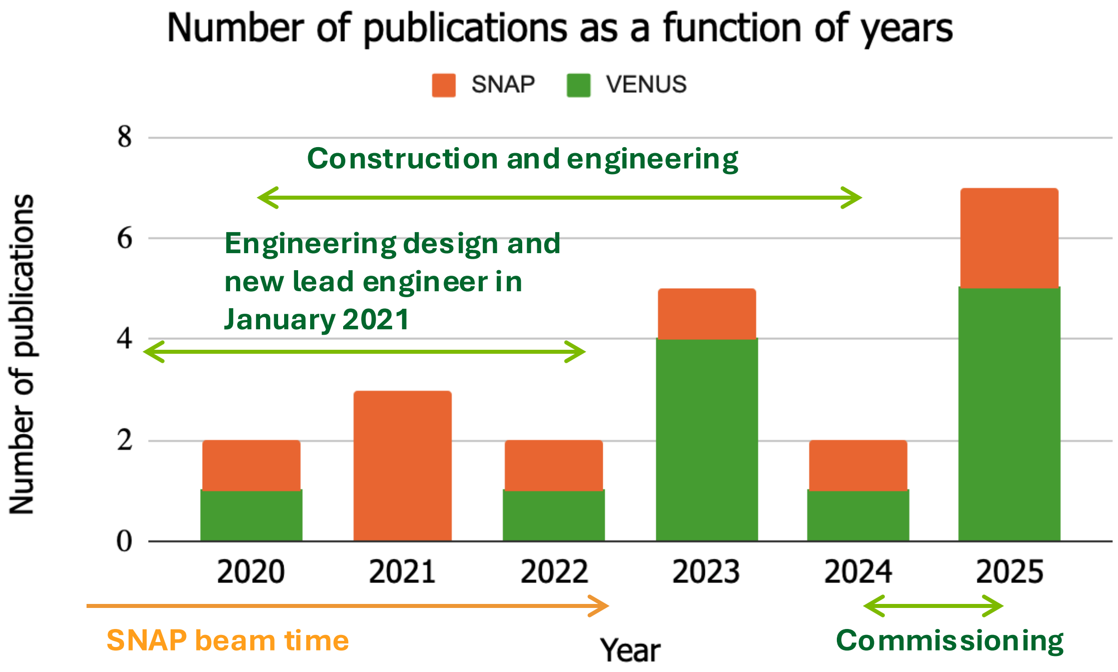
Recent furnace experiment (November 2025):
- 41 Billion events in ~ 2h – software does not exist to handle this yet
- All collected in 1 file was 0.3 T

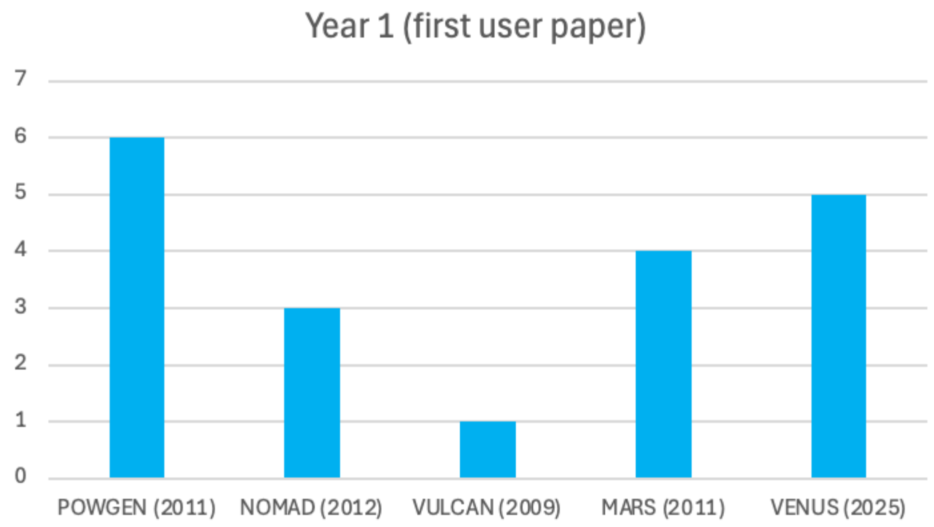
- VENUS has the largest computing infrastructure with several GPU-powered servers, and the Hype Cluster (see next slide)
- Artificial Intelligence tools are imperative at VENUS - but the CIS does not have the time to develop them
- Today's VENUS data rate surpasses the highest rate beamline, NOMAD
- Compared to NOMAD, which an established beamline, VENUS is new and in high demand of software development for the user community:
    - Bragg edge and resonance imaging are relatively novel techniques as compared to diffraction (NOMAD, SNAP, VULCAN)
    - There is no established software tools for TOF imaging data
    - **VENUS will grow in data rate as the TPX4 technology (already at SNS) is deployed across the full 200 x 200 mm^2 field-of-view**

The VENUS EPICS user interface -> save your favorite displays!

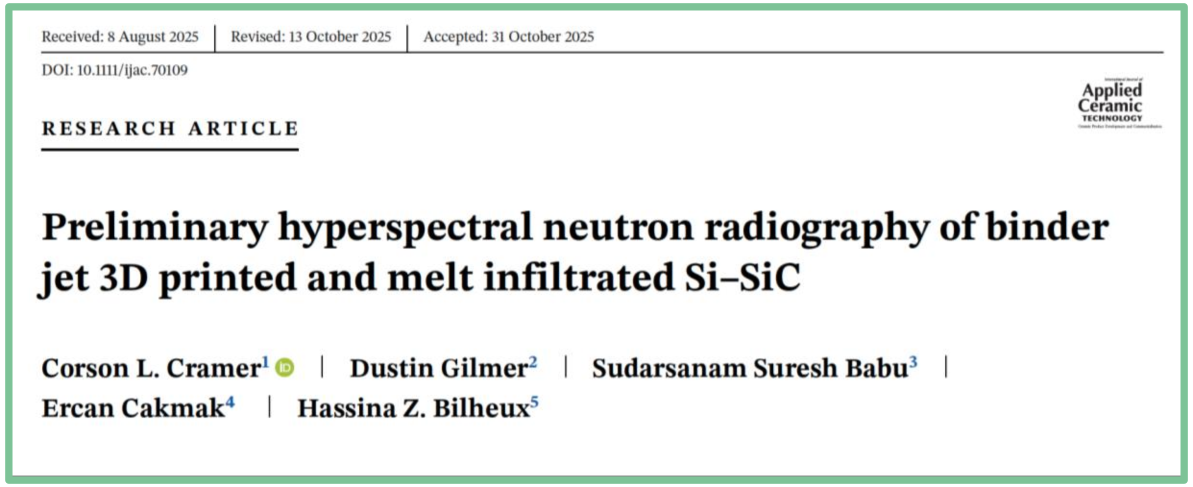


VENUS publications





- Mostly technique papers
- **Our first scientific paper published in October 2025** with data collected with ORNL Manufacturing Demonstration Facility PI during VENUS commissioning (Fall 2024) – data also include SNAP proof-of-principle imaging data of same samples (next slide)



Received: 8 August 2025 | Revised: 13 October 2025 | Accepted: 31 October 2025

DOI: 10.1111/ijac.70109

Applied Ceramic Technology

RESEARCH ARTICLE

Preliminary hyperspectral neutron radiography of binder jet 3D printed and melt infiltrated Si–SiC

Corson L. Cramer[1] | Dustin Gilmer[2] | Sudarsanam Suresh Babu[3] | Ercan Cakmak[4] | Hassina Z. Bilheux[5]

OAK RIDGE National Laboratory

Neutron Bragg Edge Radiography of Pre- and Post- Si infiltrated Si-SiC Monolithic Ceramic made by Binder Jet Additive Manufacturing

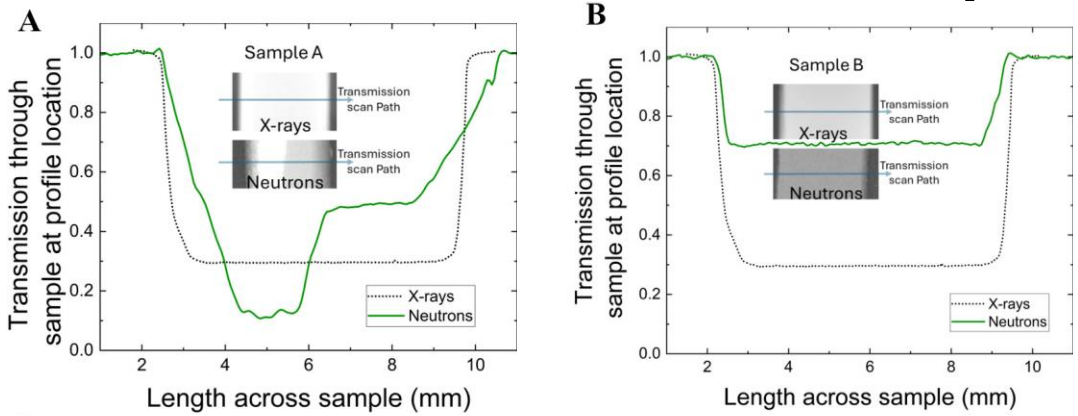
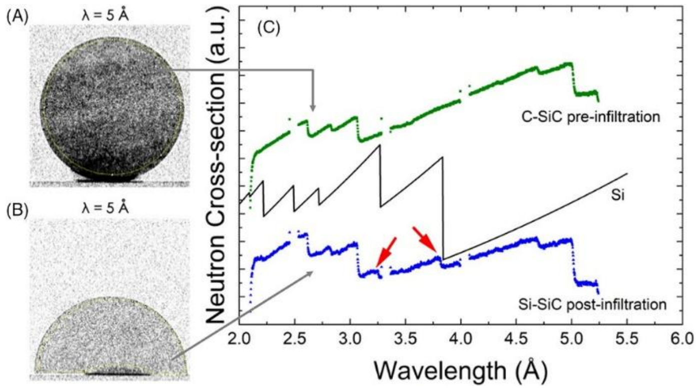


Figure caption (top): Line profiles through sample thickness extracted from X-ray and neutron transmission data across the sample diameters for the pre-(Sample A) and post-(Sample B) infiltrated samples.
(bottom): Neutron radiographs taken at a neutron wavelength of 5 Å and corresponding Bragg edges showing the development of new Bragg edges corresponding to the presence of the Si phase.



C. L. Cramer, D. Gilmer, S. S. Babu, E. Cakmak, and H. Z. Bilheux. "Preliminary hyperspectral neutron radiography of binder jet 3D printed and melt infiltrated Si–SiC." International Journal of Applied Ceramic Technology (2025): e70109. *https://doi.org/10.1111/ijac.70109*

Work was performed on SNS BL-3 SNAP and BL-10 VENUS. The research was also done under the DOE’s Advanced Materials & Manufacturing Technologies Office under the award number DE-EE0009117 titled “Binder Jet Additive Manufacturing of Novel Design, High Temperature, Ceramic Heat Exchangers.”

Scientific Achievement

Pre- and post- silicon infiltrated Si-SiC monolithic ceramics were imaged with neutron radiography.

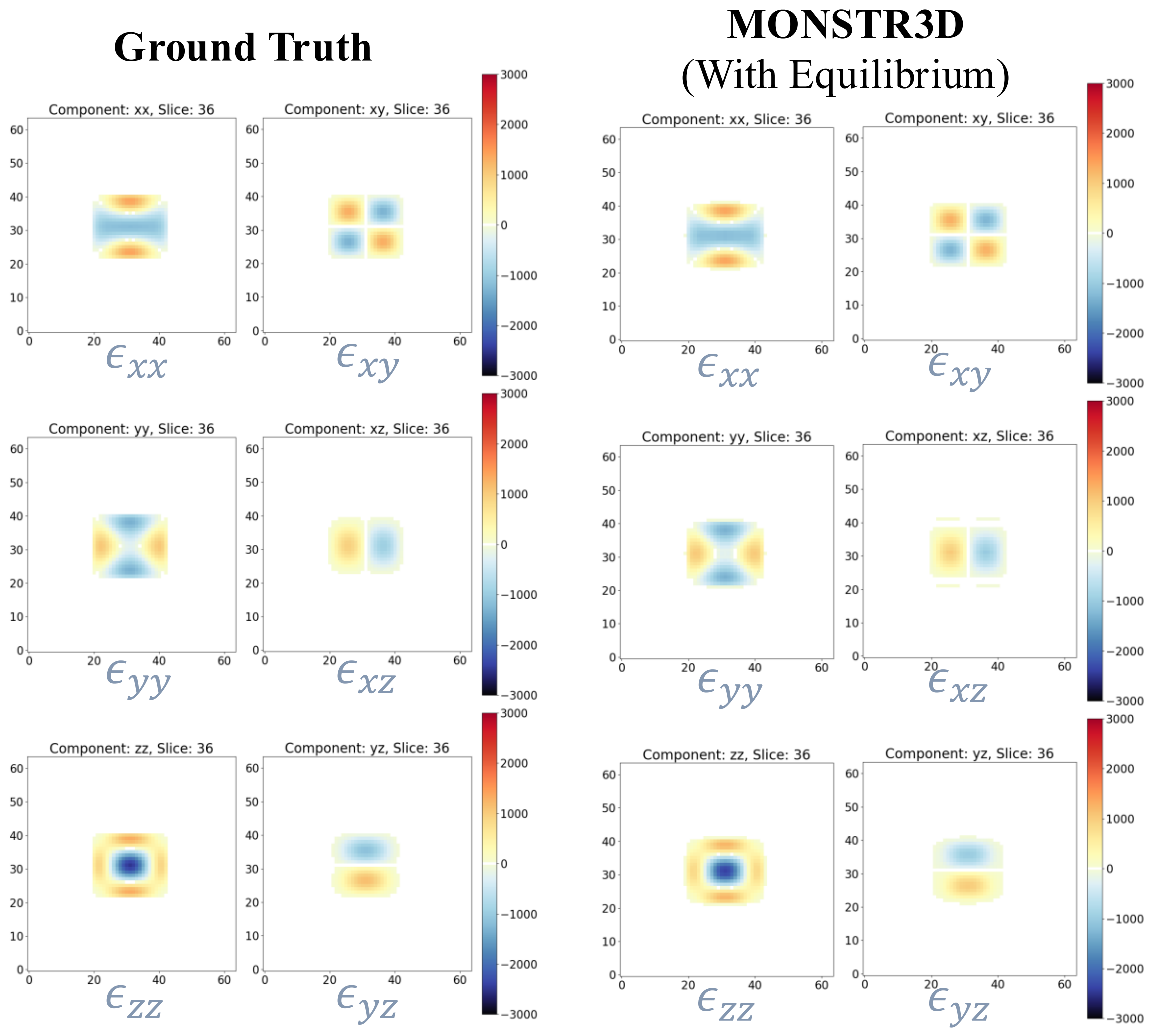
Significance and Impact

This allows for measurement of phases in samples that have uniform contrast with X-rays. This will lead to more informative data in3D printed ceramics

Research Details

- Bragg edges were identified for the materials Transmission was analyzed and compared to X-ray data
- Identification of contrast due to phases was achieved with neutrons

3D strain mapping using simulated data: preparing for Bragg edge strain tomography



Ground truth (left) and reconstructed strain tensor components using MONSTR3D (Model Oriented Neutron Strain Tomographic Reconstruction 3D).

Scientific Achievement

Accurate 3D strain tensor values were reconstructed from simulated data.

Significance and Impact

Novel mathematics were developed by Purdue University to solve the ill-posed problem of strain tomography with Bragg edge data. The algorithm **requires only 3 CT simulated scans**, rather than currently adopted 6 CT scans, thus reducing the experimental time in half.

Research Details

- Modeled data created based on Maxwell potential
- Equilibrium and boundary traction constraints applied to data set
- Normalized root mean square error as compared to the ground truth is 5.27%

HyperCT

PURDUE UNIVERSITY

Some of Artificial Intelligence (AI) activities at VENUS

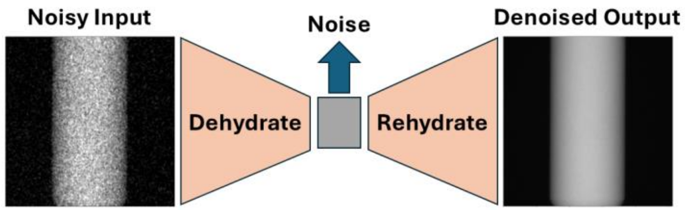
HyperCT

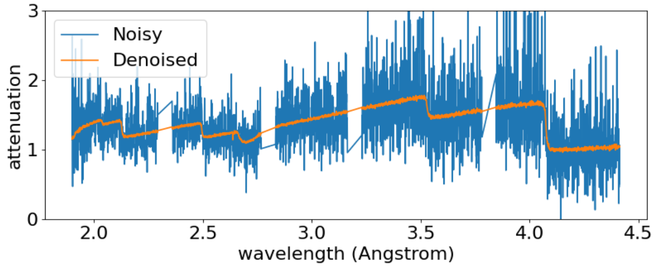
- **DOE Basic Energy Sciences funded project with Purdue University and Brookhaven National Laboratory:**
  - HyperCT AI project (PI: Hassina Bilheux) – FY21-23
  - HyperCT strain AI project (PI: Hassina Bilheux) – FY 24-26

  } 12+ manuscripts

    - Example: Dehydrate/hydrate algorithm demonstrated during NEUWAVE-13, Knoxville, TN, October 27-30, 2025
    - Recently demonstrated 3D strain mapping using Prof. Wensrich's data (University of Newcastle, Australia)

Purdue U. developed a novel unsupervised machine learning algorithm to recover Bragg edges on each pixel! (20 min at 1.8 MW)

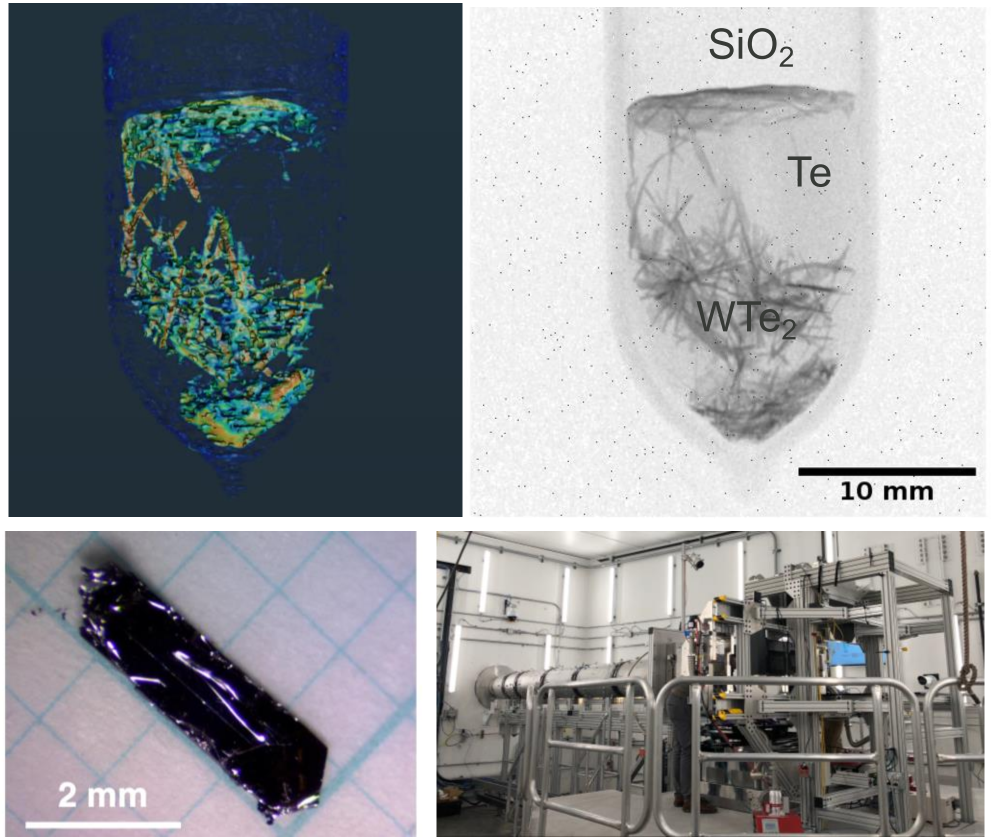




- **Developing super-resolution AI algorithms to recover some of spatial resolution – driven by Chen**
- **VENUS is part of the GENESIS MISSION seed projects: SYNAPS-I** (PI: Alex Hexemer, Lawrence Berkeley National Laboratory)
  - SYNAPS-I (**SY**nergetic **N**eutron **A**nd **P**hoton autonomous **S**cience – **I**maging): Real-time AI processing and interpretation of neutron and X-ray imaging data acquired at DOE's worldclass facilities (5 X-ray facilities and SNS)
    - **ORNL Proposed method to segmentation* challenges: development of foundational models to allow AI-driven segmentation techniques using already acquired hyperspectral neutron computed tomography data acquired at the SNS VENUS beamline.** Research is done in partnership with the University of Illinois-Urbana-Champaign who provided the neutron data

(*) the ability to partition data into meaningful regions before proceeding with data analysis

First VENUS neutron resonance tomography reveals hidden details of crystal growth



Top: Neutron tomography reveals a 3D reconstruction of WTe_2 crystals in solidified Te, while the resonance radiograph (right) provides finer detail. The large crystals (bottom) are used from monolayer devices. The VENUS beamline is shown bottom right.

Crystal growth at Illinois was supported by the Synthesis and Processing Science) Program, and imaging at the Oak Ridge Spallation Neutron Source was supported by the Neutron and X-ray Scattering Program.

2026A: In-situ furnace experiment to observe crystal growth!!!! (never observed before)

Scientific Achievement

A neutron's eye view of the atomically-layered compound WTe_2 reveals crystal arrangement inside the growth medium, which is opaque to visible light and X-rays.

Significance and Impact

Growth of large, high-quality WTe_2 is essential for **nanoscale electronic devices and quantum materials**, and only neutrons can peer into elemental tellurium with wide field of view.

Research Details

- First resonance computed tomography experiment on VENUS using otherwise undistinguishable WTe_2 crystals in solidified Te matrix.
- Resonance dips can differentiate crystals from the matrix.
- Crystal growth is revealed at the Te meniscus, which may be key to crystal size and quality.

ILLINOIS

Future plans

- **EXCITING TIMES FOR VENUS and the scientific community!!!!**
- **Our top request: add another Computer Instrument Scientist with AI expertise to the Imaging Program (both VENUS and MARS)**
- Update VENUS website showing early results and submit VENUS capabilities/commissioning manuscript
- **Must integrate (into EPICS) CCD and TPX3 detectors in time for 2026A - carry-over proposals need them**
- Steadily increase publications at VENUS by develop software tools for the user community
- **Include VENUS in mail-in program** – gives an opportunity for non-expert users to acquire some data and understand what VENUS can do for their research
- Develop VENUS TOF neutron grating interferometry (nGI) using a symmetric grating system and demonstrate **CUPI^{2}D** capabilities (Bragg edge and nGI at a slower pace) at VENUS
- Support Yuxuan Zhang's early career project (neutron dark field tomography)
- **User outreach**:
    - Increase industry participation (aerospace and nuclear companies in 2026A)
        - We plan to participate to conferences where industry is present: ASNT RS, MRS, TMS, etc.
    - Bring new communities to VENUS: food science, polymer science, archeology/paleontology (assuming samples can be released as non-radioactive)
        - Organize mini-workshops/training sessions that are science-area specific at conferences these communities attend – Gordon Research Conferences? Neutrons and Food 2026?

Acknowledgments

- **Thank you for your time in reviewing our imaging program!!!!**
- This research used resources at the Spallation Neutron Source, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory.
- Contributions from VENUS commissioning team: Kevin Yahne, Shimin Tang, Jean Bilheux, Harley Skorpenske, Greg Guyotte, Matt Frost, Chen Zhang, Matthew Balafas, Fumiaki Funama, Brad Bochenek, Bogdan Vacaliuc, Zach Thurman, Kaz Gofron, Alex Sobhani, Jim Kohl
- Operations support teams
- The **VENUS Advisory Committee**
- The VENUS project team
- **VENUS exists thanks to the support of our imaging community** and several previous and current SNS managers

Backup slides

ORNL Neutron Imaging Team <u>as of September 30, 2025</u>

Yuxuan Zhang,
HFIR MARS Scientist

James Torres,
HFIR MARS Scientist

Jean Bilheux,
Imaging Computational
Instrument Scientist

Shimin Tang,
SNS VENUS Scientist, since
November 2024

Chen Zhang
Computational Scientist on
Imaging, since June 2021

Roger Hobbs,
Imaging Scientific
Associate (SA), **since
February 2024**

Kevin Yahne,
Imaging SA, **since June 2024**

Harley Skorpenske,
SNS Group Leader

Sam McKay,
Post-doc, MARS neutron
grating interferometry,
since August 2025

Hassina Bilheux,
SNS VENUS Scientist

ORNL Neutron Imaging Team today

Yuxuan Zhang,
HFIR MARS Scientist
(1/2 time)

James Torres,
HFIR MARS Scientist,
since July 2023

Jean Bilheux,
Imaging Computational
Instrument Scientist

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Harley Skorpenske,
SNS Group Leader

Sam McKay,
Post-doc, TOF neutron
grating interferometry,
since January 2026

VENUS Graduate Student
(6 months, ½ time), **since**
December 2025

Hassina Bilheux,
SNS VENUS Scientist

OAK RIDGE
National Laboratory

ORNL Neutron Imaging Team <u>in the coming weeks</u>

Yuxuan Zhang,
HFIR MARS Scientist
(1/2 time)

James Torres,
HFIR MARS Scientist,
since July 2023

Saurabh Kabra
HFIR MARS Scientist
(1/2 time), starting February 2026

Shimin Tang,
SNS VENUS Scientist, since
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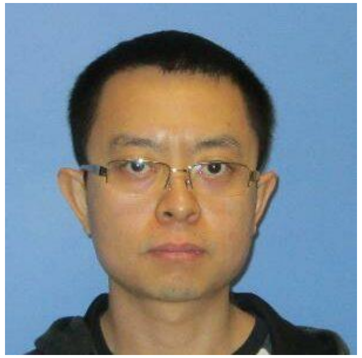
Jean Bilheux,
Imaging Computational
Instrument Scientist



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Sam McKay,
Post-doc, TOF neutron
grating interferometry,
since August 2025

VENUS Graduate Student
(6 months, ½ time), **since December 2025**

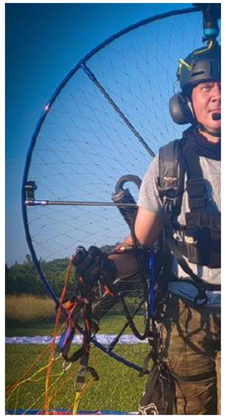
Post-doc, AI

Hassina Bilheux,
SNS VENUS Scientist

Oak Ridge National Laboratory

VENUS User Support ***Core(*)*** Team ~ 4.1 FTE

(*) Directly interacts with user community



Jean Bilheux,
Imaging Computational
Instrument Scientist

Shimin Tang,
SNS VENUS Scientist

Chen Zhang
Computational Scientist
on Imaging

Roger Hobbs,
Imaging Scientific
Associate (SA)

Kevin Yahne,
Imaging SA

Harley Skorpenske,
SNS Group Leader

Hassina Bilheux,
SNS VENUS Scientist

SWOT Analysis – VENUS (see also Gap Analysis Word Doc.!)

Strengths

- Truly unique capabilities in the American continent
- Broad scientific impact across most scientific fields such as materials science, nuclear, aerospace, biomedical, etc.
- Capabilities attractive to industry
- Integration of AI tools from beginning of VENUS
- **AI leadership in collaboration with Purdue U. and BNL**
- Strong synergies within the imaging team and ORNL researchers

Weaknesses

- Several activities not done during the construction project have a high cost (>$50k)
- Hardware (motors, SE, etc.) and data acquisition implementations are behind
- 60% of team at junior level
- **CIS spread too thin across the 2 most data intensive beamlines**
- No energy optimization of detectors (efficiency for epis is mediocre)

Opportunities

- Synergy between VENUS nGI and early career project
- Mail-in program (RT CT scans) may increase VENUS productivity
- Lead worldwide community in state-of-the-art software tools for hyperspectral data
- Lead AI for neutron imaging (with Purdue U.)
- Organize training workshops to educate future users
- Partnerships with industry
- Prompt-gamma spectroscopy imaging

Threats

- **Inappropriate CIS staffing as compared to data throughput of hyperspectral data -> directly impacts publication productivity of instrument**
- Lack of appropriate time-of-flight and white beam detectors for the 20x20cm^2 field-of-view -> delaying/rejecting highly SRC-ranked proposals
- Lack of data storage capacity for event data collection
- Inappropriate network infrastructure for imaging data rate at VENUS -> direct threat to AI tools

VENUS is challenging our Computer Instrument Scientist

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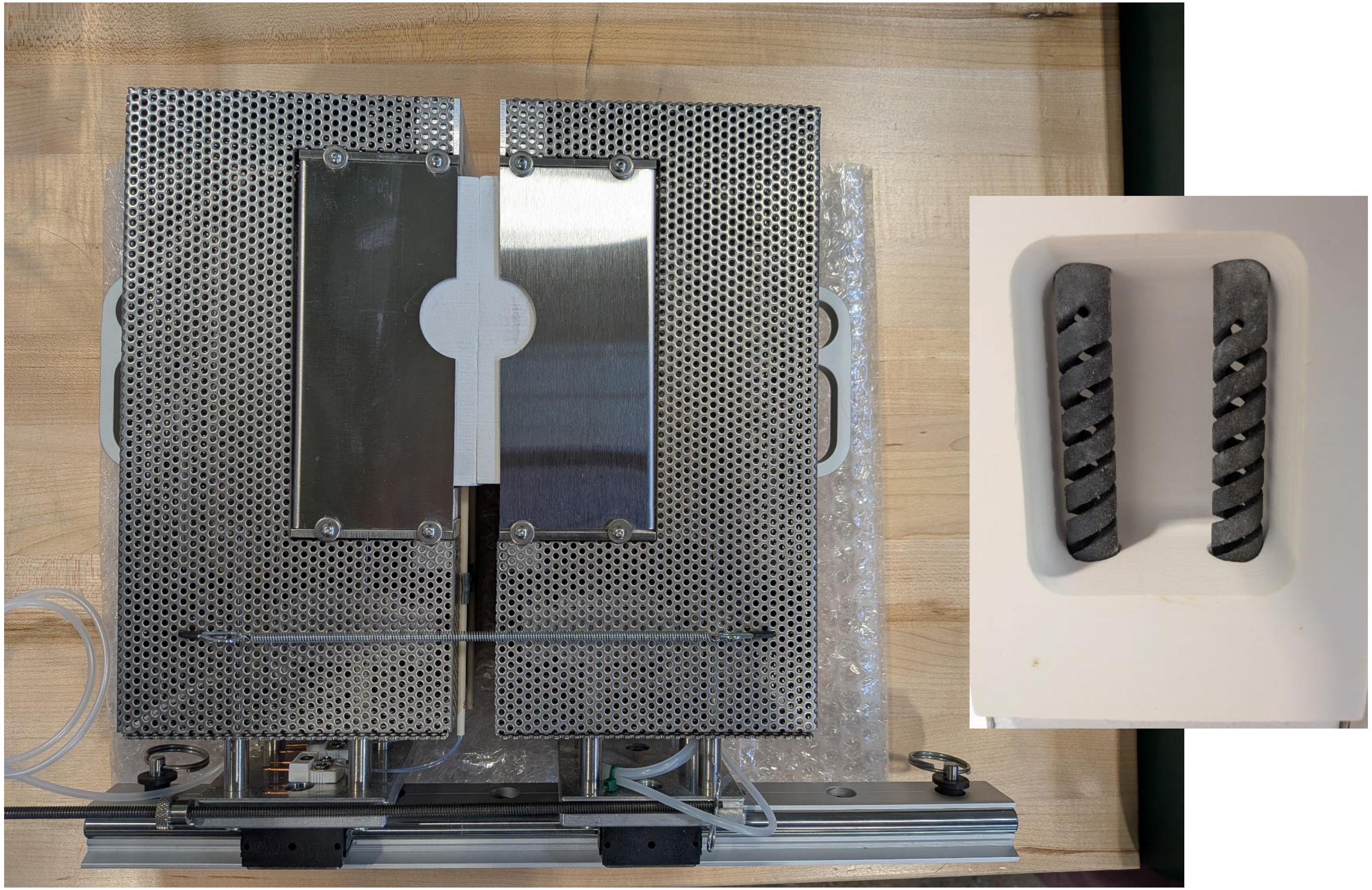
- 41 Billion events in ~ 2h – software does not exist to handle this yet
- All collected in 1 file was 0.3 T

- VENUS has the largest computing infrastructure with several GPU-powered servers, and the Hype Cluster (see next slide)
- Artificial Intelligence tools are imperative at VENUS - but the CIS does not have the time to develop them
- Today's VENUS data rate surpasses the highest rate beamline, NOMAD
- Compared to NOMAD, which an established beamline, VENUS is new and in high demand of software development for the user community:
    - Bragg edge and resonance imaging are relatively novel techniques as compared to diffraction (NOMAD, SNAP, VULCAN)
    - There is no established software tools for TOF imaging data
    - **VENUS will grow in data rate as the TPX4 technology (already at SNS) is deployed across the full 200 x 200 mm^2 field-of-view**

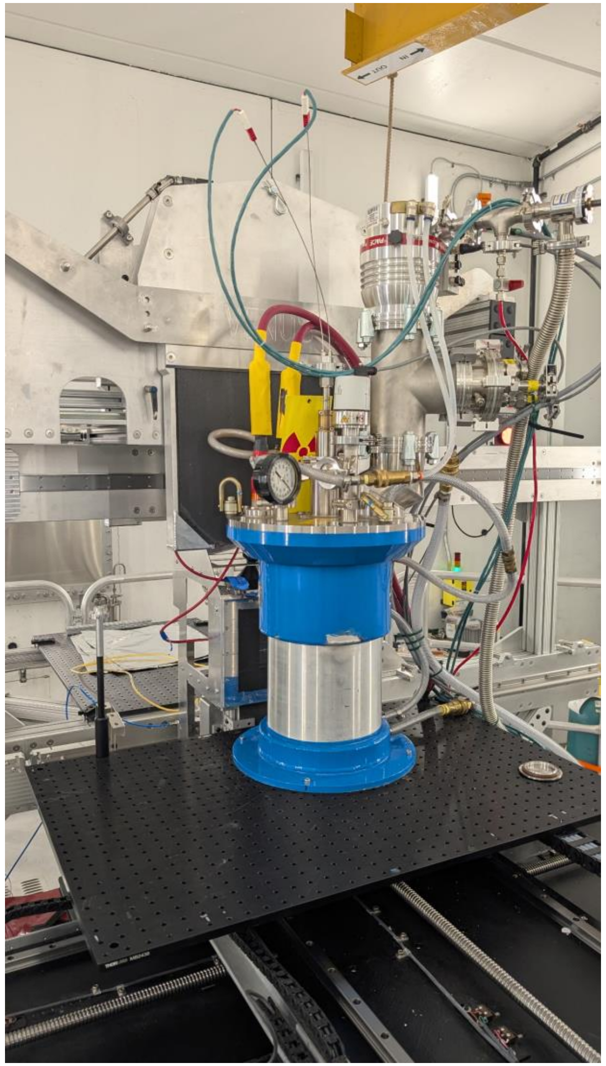
Air furnace available at VENUS



https://www.amtecoincorporated.com/hot-rail-1500-c-furnace-350

SNS Sample Environment (SE) can be implement at VENUS

- Furnace experiment in November 2025 using one of the SNS furnace (see photo) and event data were collected using the MCP TPX3 detector:
    - 41 Billion events in ~ 2h – software does not exist to handle this yet
    - All collected in 1 file was 0.3 T
- 2026A approved user experiments requiring AMTECO furnace, the SNS vacuum furnace and the closed cycle refrigerator (CCR).
    - This means measuring background generated by the SE equipment at different temperatures before users do their measurements
    - Essential to keep calibration/commissioning days at VENUS for these activities – working with SE team to understand these pieces of equipment
- Growth chamber to keep plants alive for a large duration of time (weeks/months)
- Refrigerator and freezer for biomedical and forensic research



HOT-006 vacuum furnace installed at VENUS.