A neutron source to unlock quantum materials for the post silicon era

1. Beyond Moore's law: Quantum materials
2. Quantum materials for energy and information
3. Quantum coherence and entanglement
4. Intertwined electronic orders
5. Driven quantum materials and devices
6. Your feedback!

Community feedback on the STS Grand Challenges November 26, 2024

QM Participants in STS workshop August 2-4, 2024

Collin	Broholm	JHU
Xiaojian	Bai	LSU
Pengcheng	Dai	Rice
Eduardo	Fradkin	UIUC
Laura	Greene	Maglab
Alex	Hoffmann	UIUC
Valeria	Lauter	SNS
Mingda	Li	MIT
Yaohua	Liu	SNS
Mark	Lumsden	SNS
David	Mandrus	UTK
Rob	McQueeny	Ames
Joel	Moore	UC Berkeley
Satoru	Nakatsuji	UTokyo & JHU
Henrik	Rønnow	EPFL
Deepak	Singh	Missouri
Keith	Taddei	ANL
Alan	Tennant	UTK
John	Tranquada	BNL
Yishi	Wang	UTK
Stephen	Wilson	UCSB

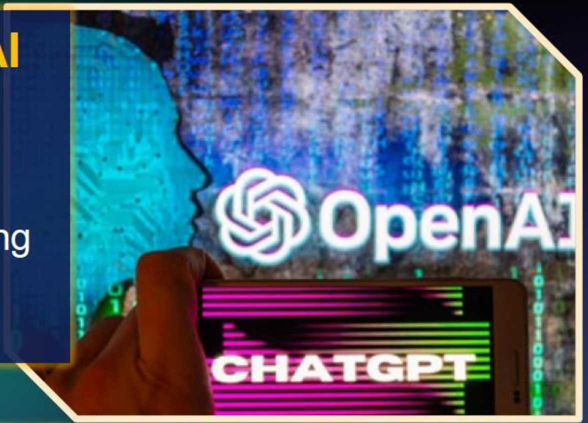
The speedy evolution of AI & ML

In healthcare:
- Medical image analysis
- Predictive analytics
- Robot-assisted surgery
- Clinical decision support
- Remote monitoring

etc.

Natural language AI
- Language translation
- Virtual assistants
- Chatbots
- Social media monitoring
- Document analysis

etc.



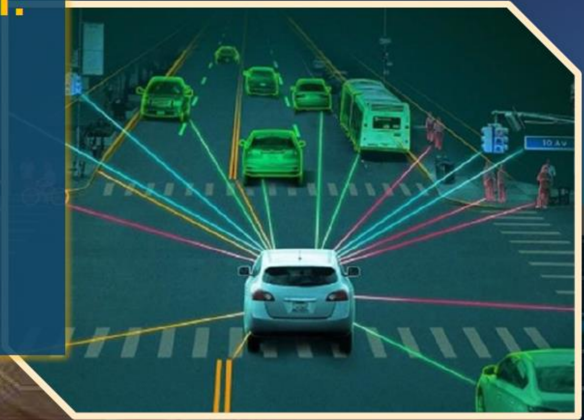
Increased Automation

Improved Personalization

in finance:
- Risk assessment
- Fraud detection
- Algorithmic trading
- Personalized financial advice

etc.

AI in transportation:
- Self-driving vehicles
- Pedestrian detection
- Traffic optimization
- Road condition monitoring
- Parking management
- etc.



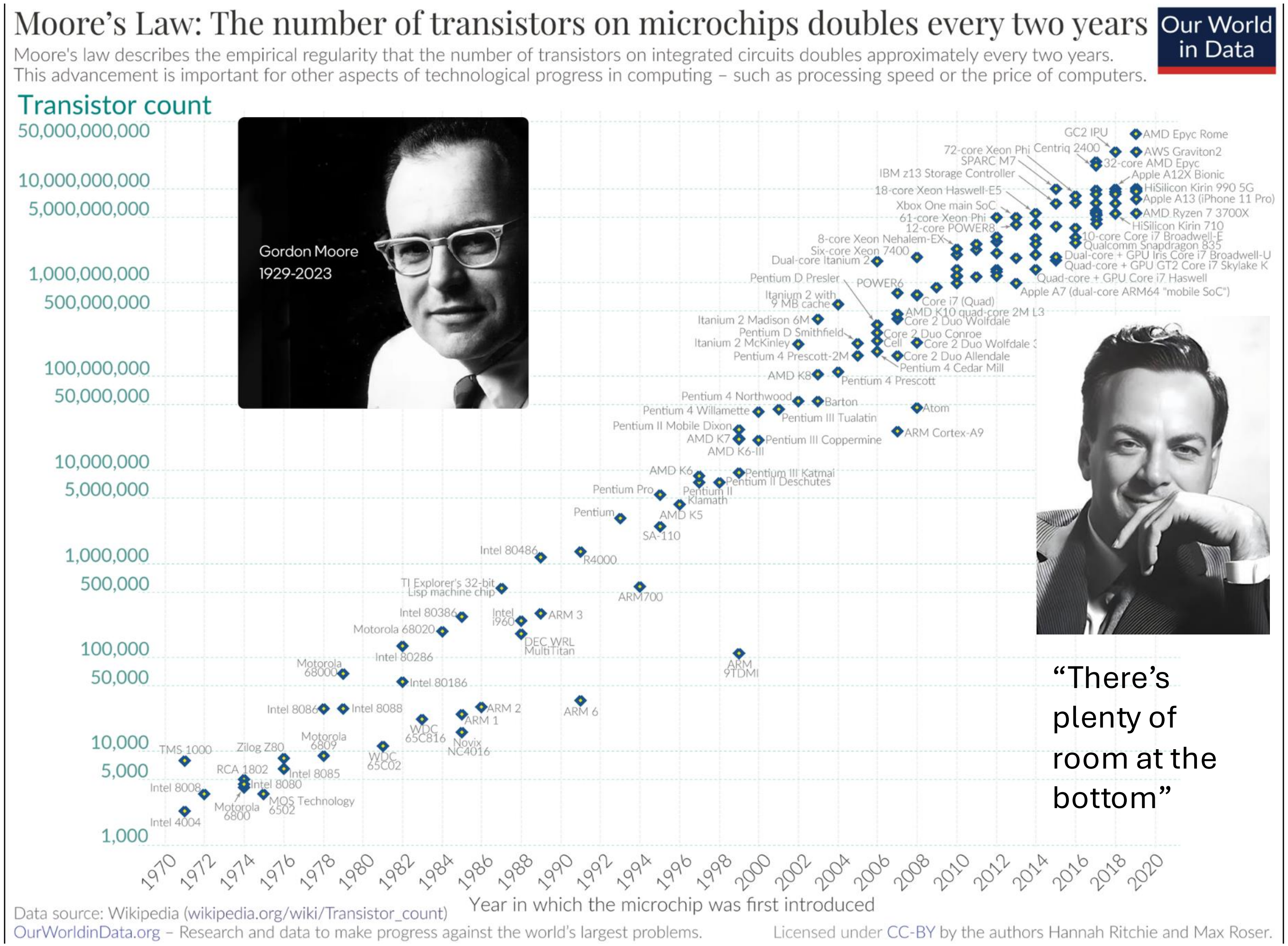
AI

0101 0101 0101 0101

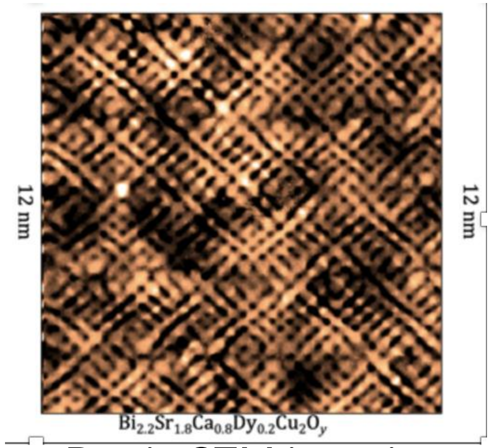
AI has numerous applications in various industries. As AI continues to advance, it has the potential to revolutionize many aspects of society and our daily lives.

Slide from Satoru Nakatsuji, U.Tokyo Trans Scale Quantum Institute

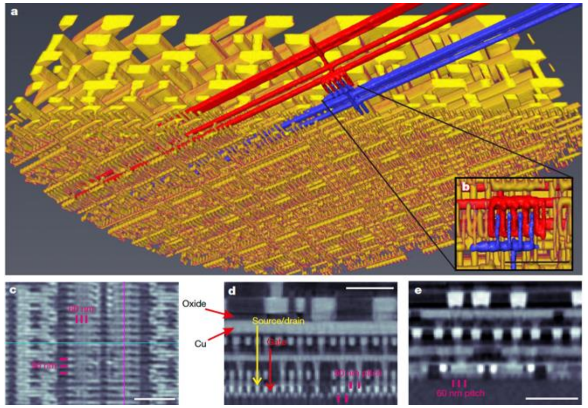
Beyond Moore come quantum materials!



“There’s plenty of room at the bottom”



Davis STM imaging



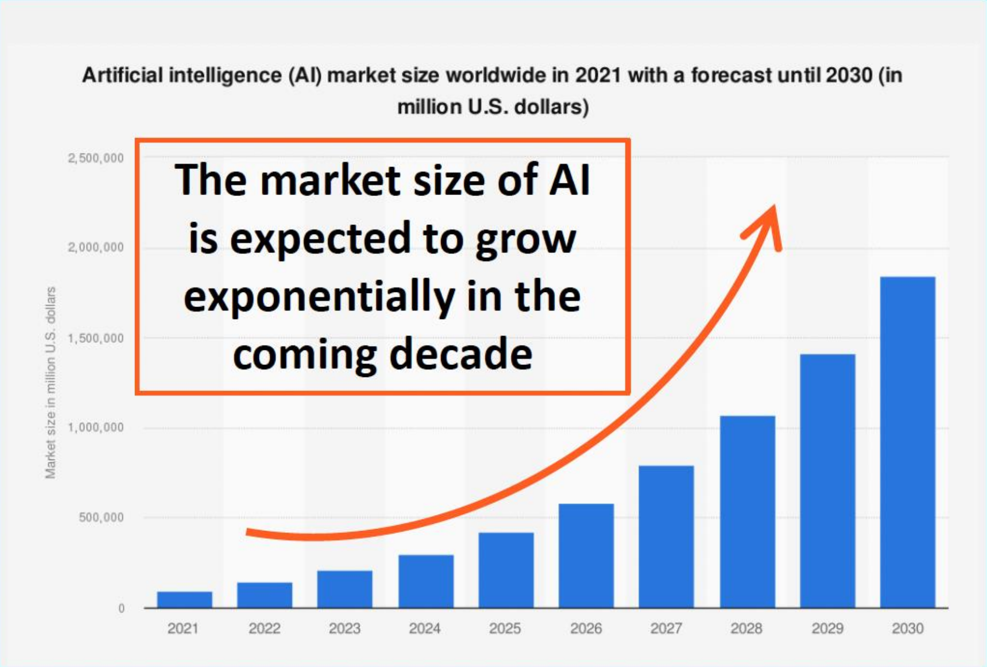
Holler et al. 2017

Bell Laboratories 1947

Challenges in developing AI & ML

Slide from Satoru Nakatsuji, U.Tokyo Trans Scale Quantum Institute

Opportunities | **Future ?** | **Bottlenecks**



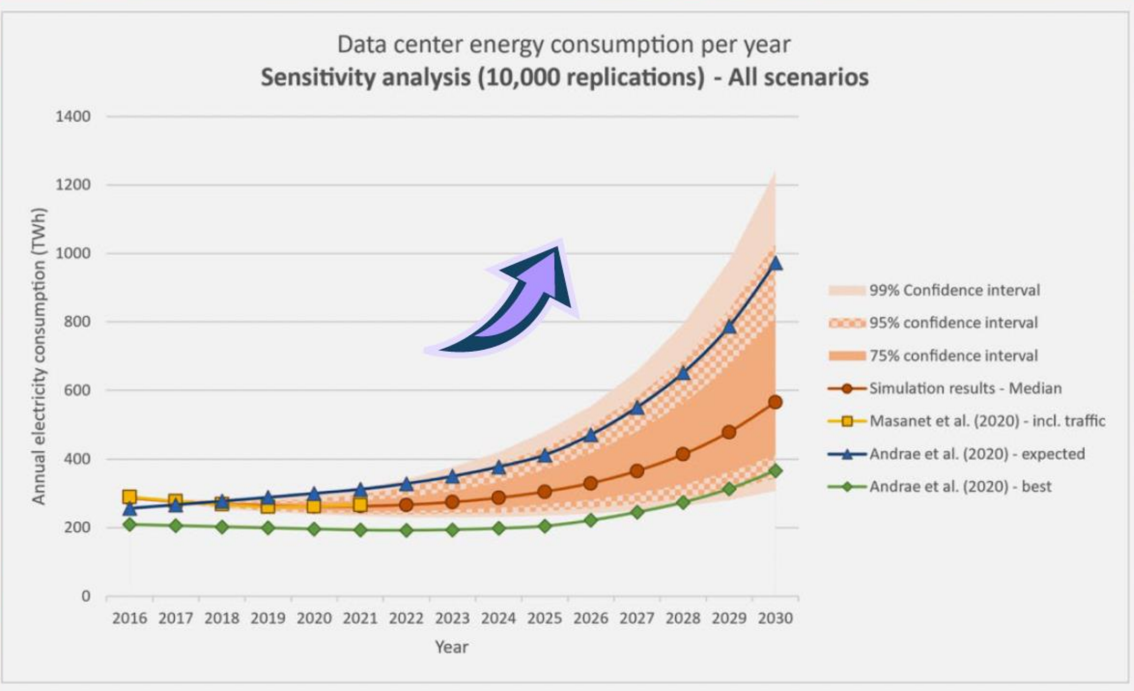


Fig. 7. Effect of both Industrial IoT and Moore's law on data center electricity consumption.

AI and ML put significantly increasing demands on computing resources, leading to the exponential growth in the data center energy consumption.

Source: J. Sevilla et al., "Compute Trends Across Three Eras of Machine Learning," 2022 International Joint Conference on Neural Networks (IJCNN)
M. Koot and F. Wijnhoven, "Usage impact on data center electricity needs: A system dynamic forecasting model ," Applied Energy (2021)

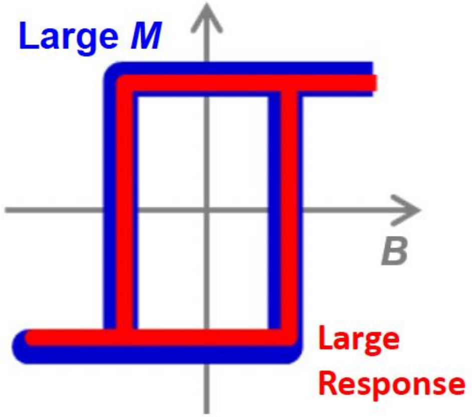
Achieving ultrafast magnetic memory with topological antiferromagnets

Slide from Satoru Nakatsuji, U.Tokyo Trans Scale Quantum Institute

	Ferromagnet	Synthetic Antiferromagnet	Ferrimagnet	Antiferromagnet	Topological Antiferromagnet
Switching speed	~ 10 ns	~ 1 ns	~ 10 ps	~ 1 ps	~ 1 ps
Data processing speed	~ 100 m/s (1 GHz)	~ 1 km/s (10 GHz)	~ 5 km/s (50 GHz)	> 10 km/S (>100 GHz)	> 10 km/s (>100 GHz)
	Large *M* (1-10 T) large response	Small *M* Small response	Moderate *M* Moderate response	Zero *M* (10^{-4}-10^{-3} T) Zero response	Small *M* (10^{-4}-10^{-3} T) Large response

The traditional focus of nonvolatile magnetic memory

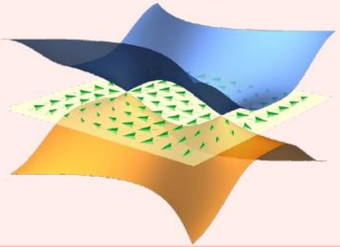
Major bottlenecks:
- Stray field
- Slow processing speed

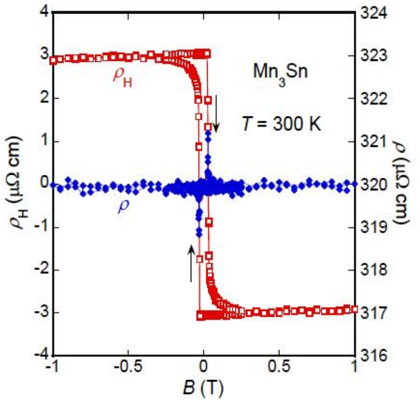


VS.

Topological Weyl antiferromagnet Mn_3Sn

Weyl nodes give a giant fictitious magnetic field of ~ 100 T





Vanishing M but large response as in ferromagnets!

S. Nakatsuji *et al.*, Nature 527,212 (2015)

The STS will be key to sustainable information technologies and to ensuring US scientific and technological competitiveness in the post Moore era

Accelerated discovery of new quantum materials functionality

- **Motivation**
  - CMP and technology is built on exploration of materials space
  - Must optimize quantum collective properties that can defy modelling
- **Unique role of STS**
  - Collective dynamics and magnetic structure for powder, crystal, films
  - Enable science at new extremes of external fields and pressure
  - Data quality and volume to benchmark dynamic modelling and train AI
- **Transformative Science**
  - Discover solid state spin liquids supporting coherent quasi-particles
  - Realize interface functionality
  - Discover non-linear responses for neuromorphic AI

Imaging entanglement and coherence in solids

- **Motivation**
  - Device realizable solid state quantum sensing
  - Topologically protected quantum computing
- **Unique role of STS**
  - High fidelity Q-resolved spectral analysis
  - Unprecedented coherence, resolution, and polarization
- **Transformative Science**
  - Accessing the quantum classical cross over in spin liquid compounds
  - Model-independent solid state entanglement witnesses
  - Noise spectroscopy with coherent neutrons to probe higher order correlations

Harnessing intertwined states of matter

- **Motivation**
  - Intertwined orders are pervasive in quantum materials
  - Key to developing novel electronic functionalities
- **Unique role of STS**
  - Access to low energy excitations associated with intertwined orders
  - Structural probes of magnetism in thin film forms
  - Map phase space versus extreme conditions of field and pressure
- **Transformative Science**
  - Magnetic order in nickelates that can only be synthesizes in thin films
  - Expose Intertwined order at high pressure or high fields

Driven quantum materials

- **Motivation**
  - Time periodic driven systems can realize new functionality
  - Interface materials where functionality is driven by hetero-structuring
- **Unique role of STS**
  - Momentum resolved dynamics over 9 orders of magnitude of energy
  - Structure and dynamics at buried interfaces in engineered structures
- **Transformative Science**
  - Probing the THz dynamics of switching AFM domains
  - Probing idealized spin liquid induced by time periodic drive

Priority Research Directions in Quantum Materials at the Second Target Station

1. Discover quantum materials that approach fundamental limits for information and energy technologies
2. Advance fundamental understanding of quantum coherent and incoherent dynamics in materials platforms
3. Unveil intertwined electronic orders in quantum materials
4. Harness coupling between transport and mesoscopic structures and dynamics in driven quantum materials and devices

The STS will be key to sustainable information technologies and to ensuring US scientific and technological competitiveness in the post Moore era

Seeking your feedback:

- What science was missed
- Questions to clarify proposed science
- Questions to clarify proposed experiments
- What areas are unrealistic or not compelling
- What technical development work is needed

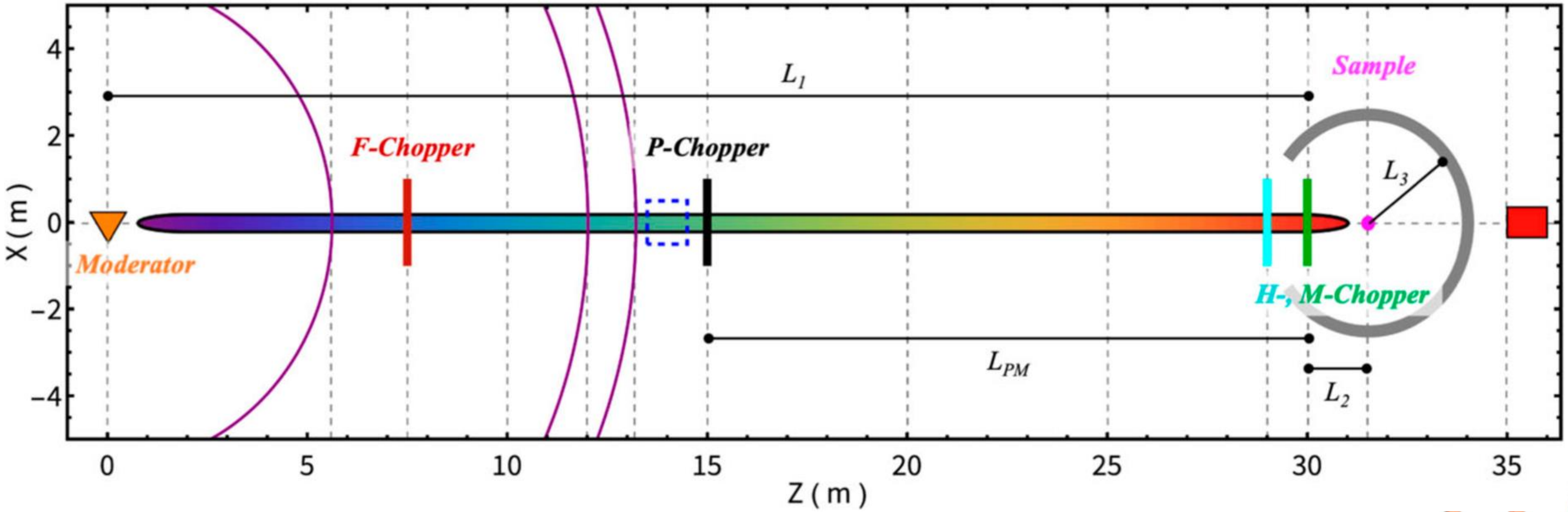
New Science Opportunities at the SNS STS

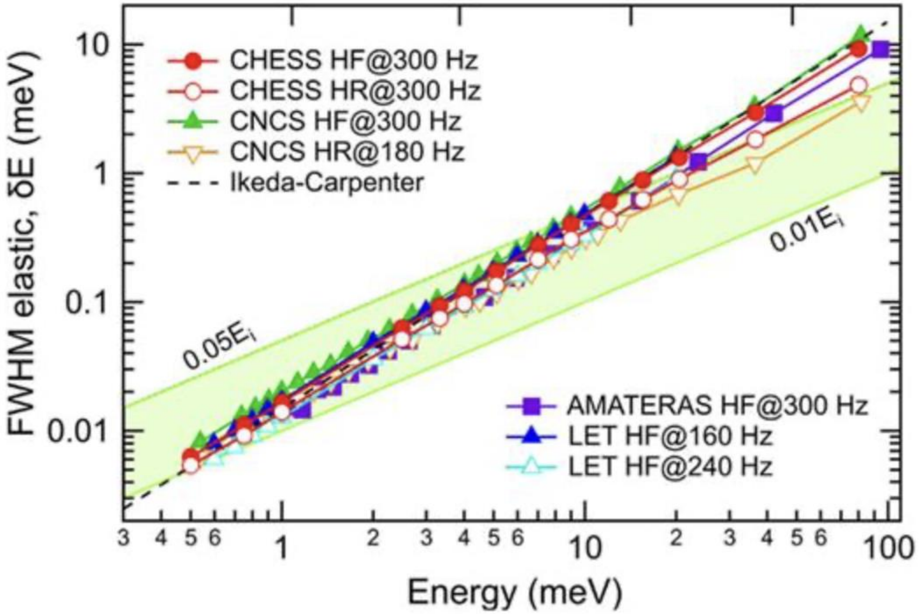
AIP Review of Scientific Instruments

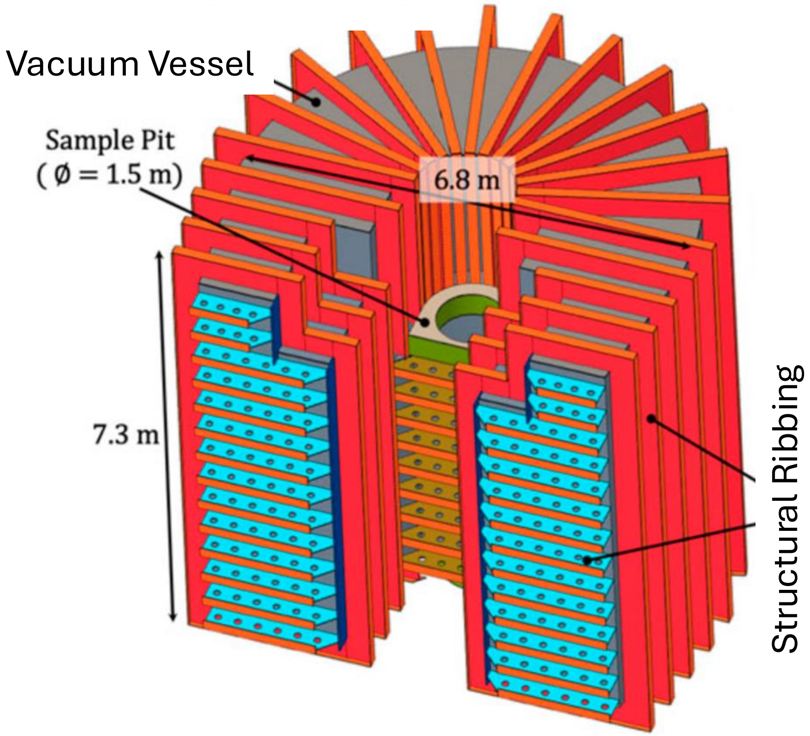
- BWAVES – broadband spectrometer
- CENTAUR – SANS/WANS
- CHESS – cold neutron spectrometer
- CUPI^{2}D – neutron imaging
- EXPANSE – wide-angle neutron spin echo
- EWALD – macromolecular single-crystal Diffractometer
- MENUS – Multi-modal engineering materials beamline for complex materials
- M-STAR – Polarized reflectometer optimized for magnetism
- PIONEER –single-crystal diffractometer
- TITAN – Extreme environments multi-modal instrument
- QIKR – kinetics reflectometer
- VERDI – polarized diffractometer

https://pubs.aip.org/rsi/collection/1617/New-Science-Opportunities-at-the-Spallation

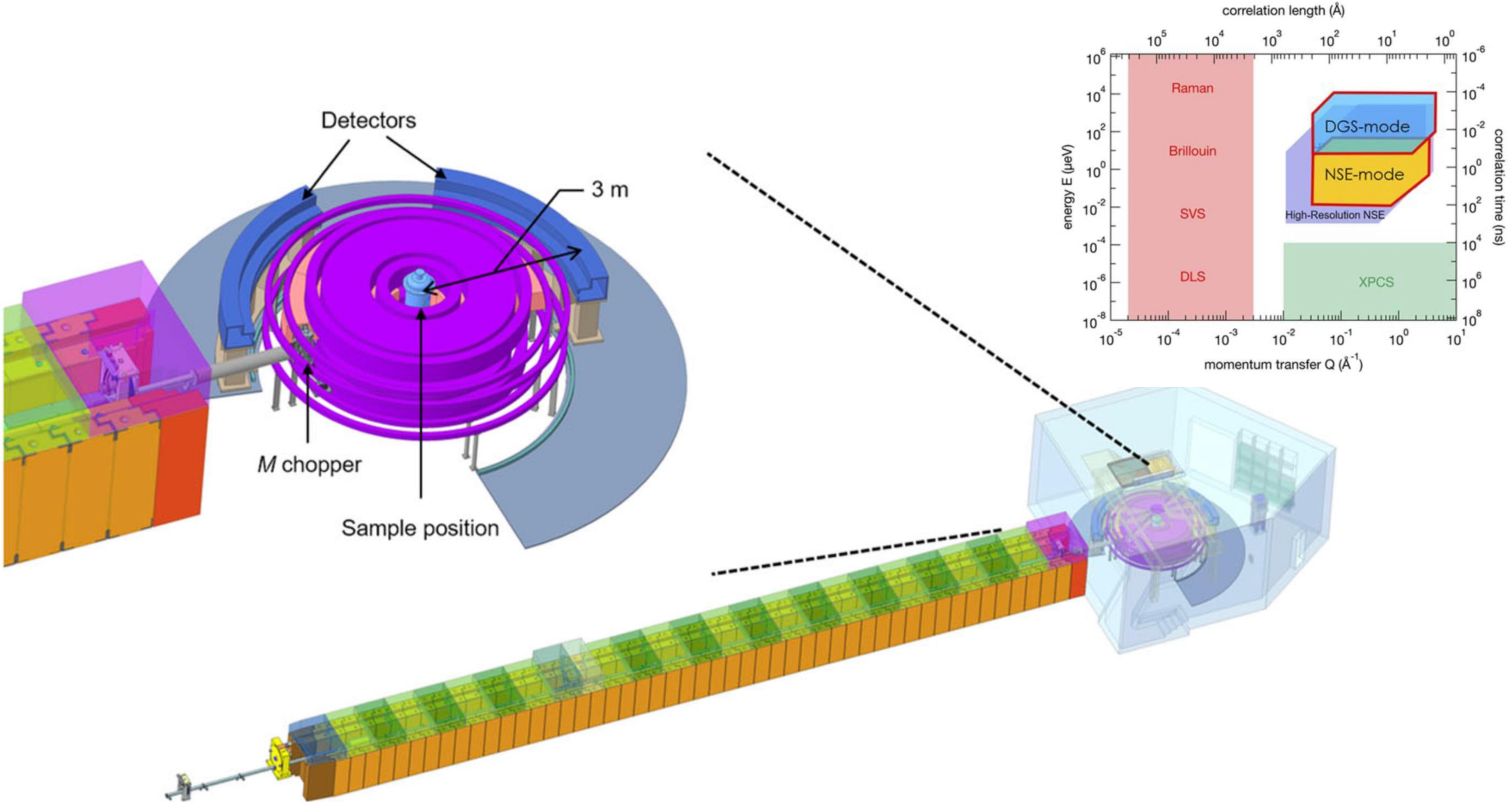
CHESS: New era of quantum materials spectroscopy



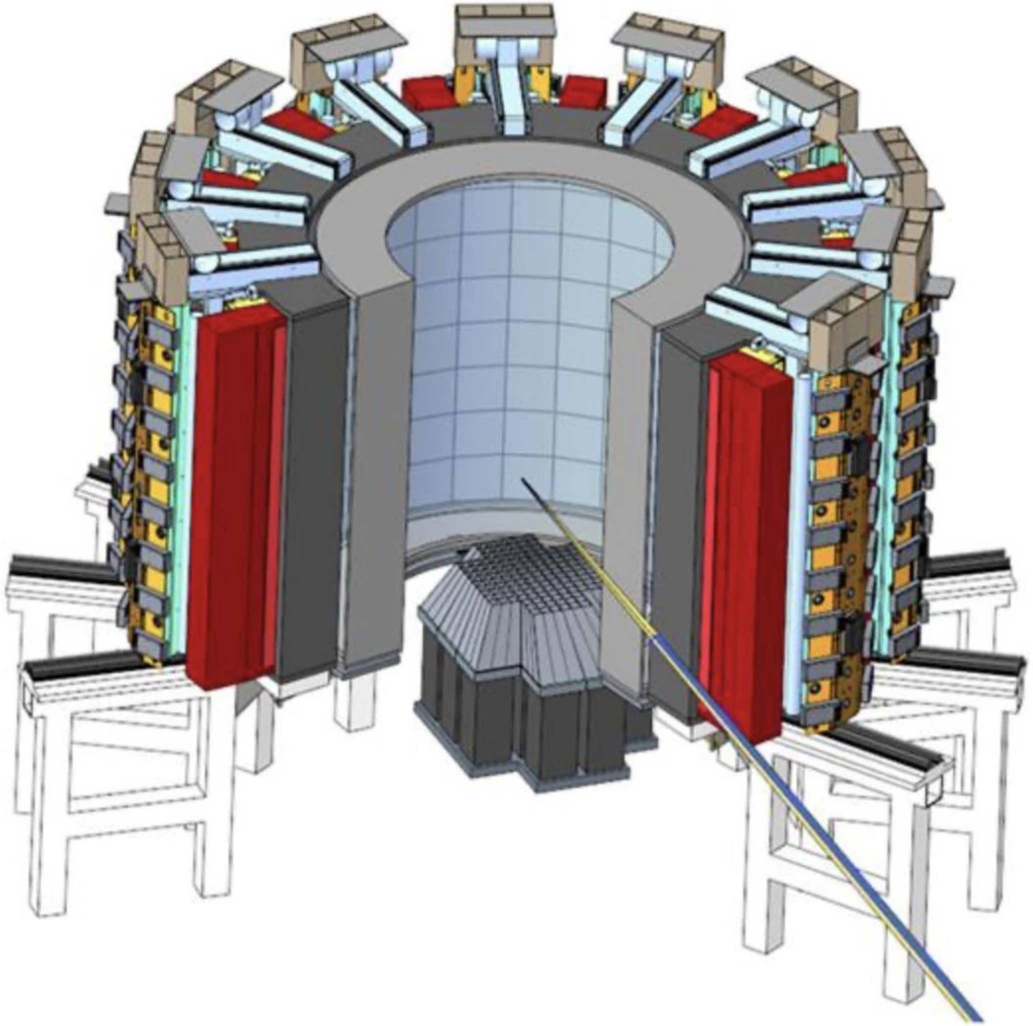


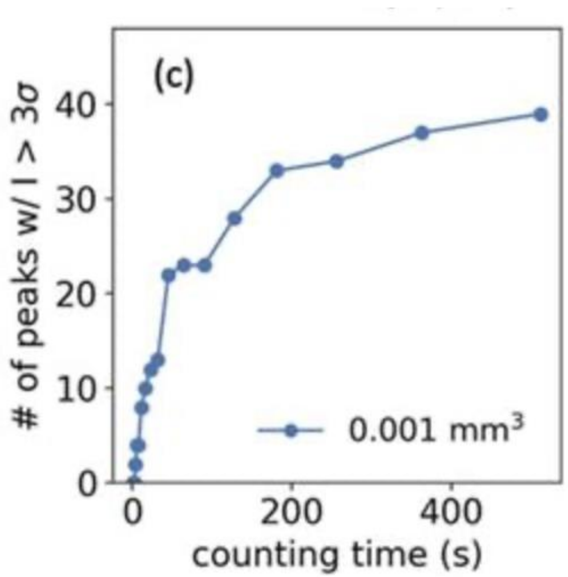


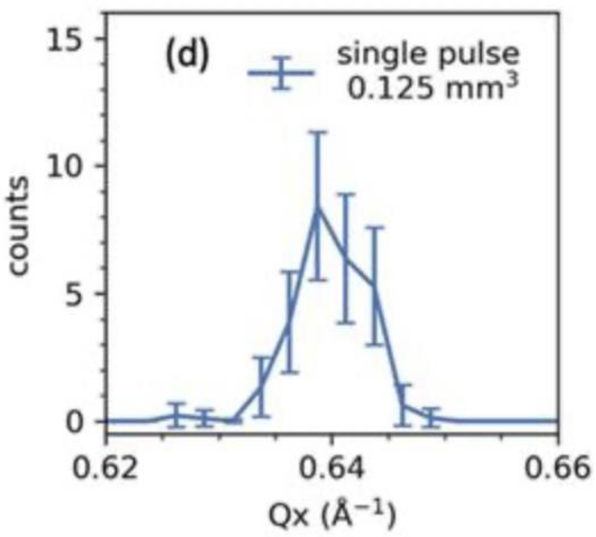
EXPANSE: The extreme quantum regime

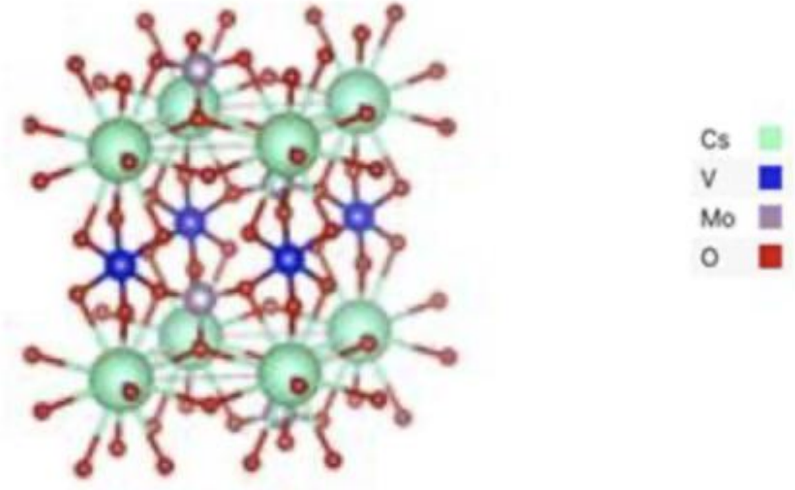


Pioneer: Magnetic structures in crystals and thin films

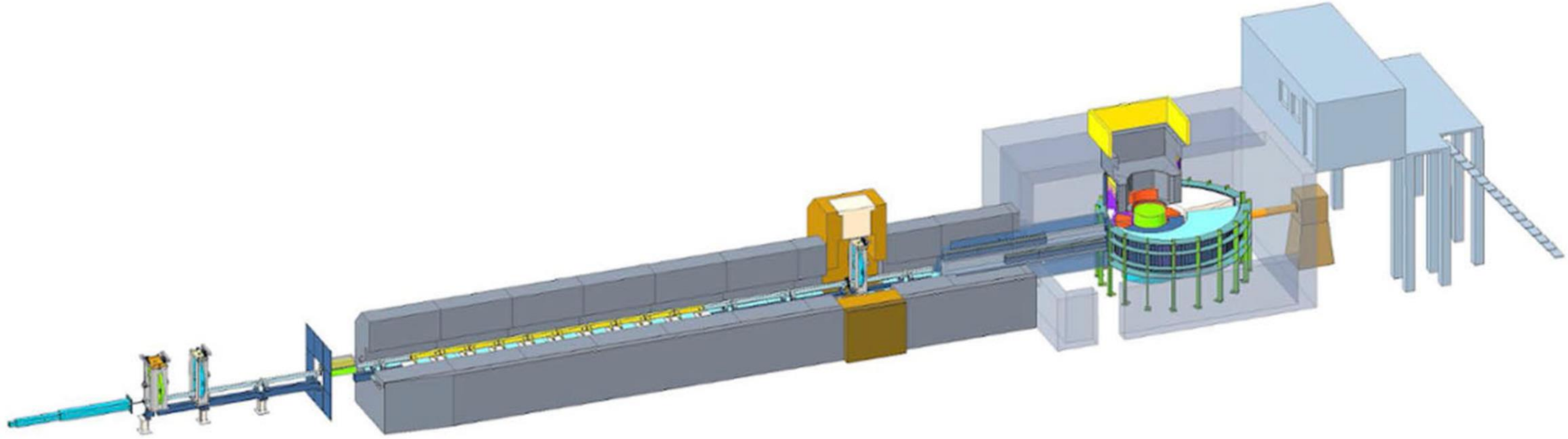


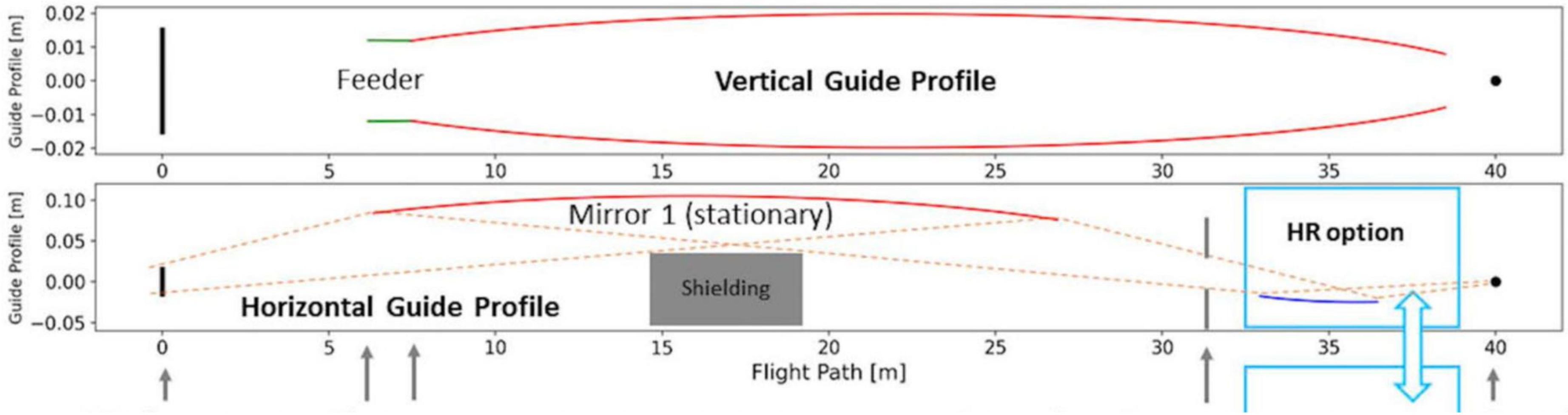




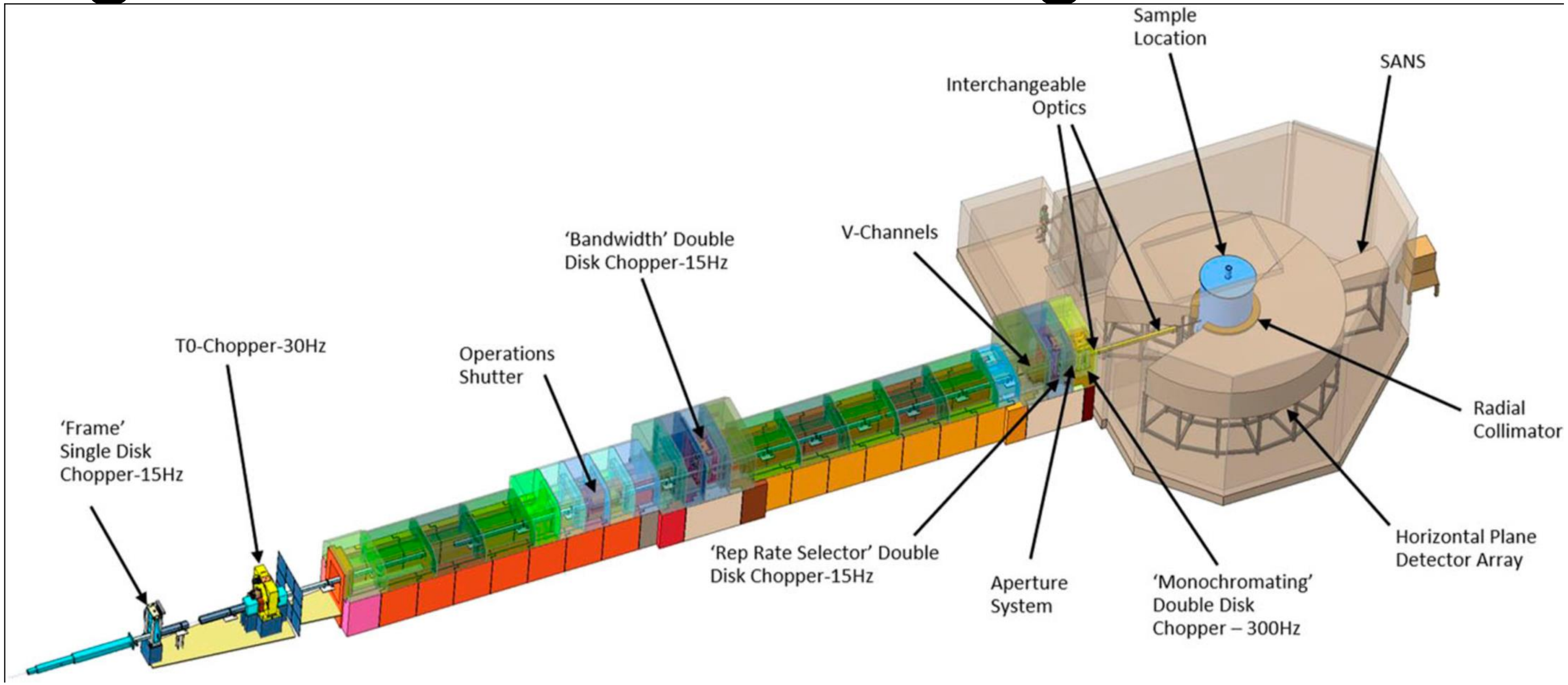


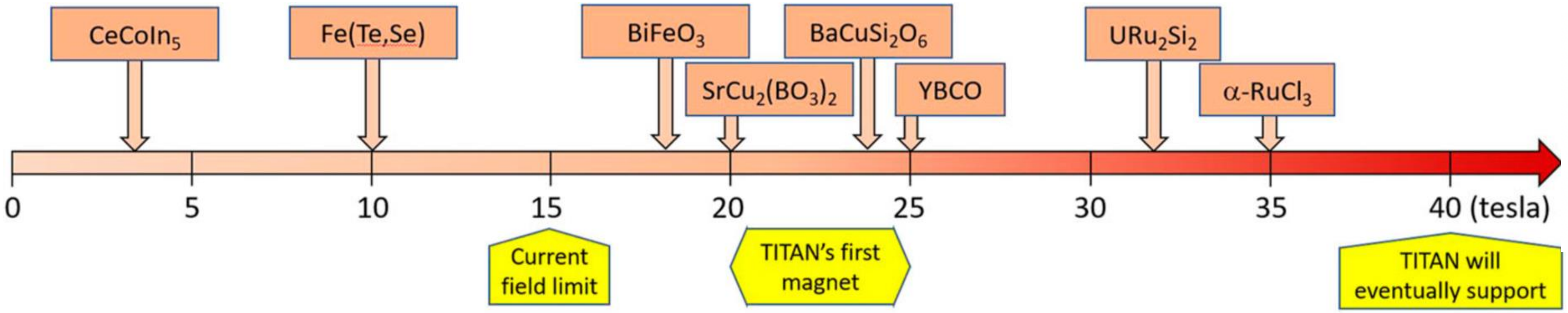
VERDI: Magnetic structures in powders





Transforming quantum materials science through high field neutron scattering





Key Recommendation 6: The United States must establish its leading role in the combination of high-magnetic-field studies with X-ray free lasers (XFELs), synchrotrons, and neutron sources. This could best be accomplished by a National Science Foundation–supported science and technology center focused on the development of novel technology and cutting-edge science applications for quantum and atomic, molecular, and optical high-magnetic-field studies at XFELs, synchrotrons, and neutron sources.

MSTAR: Probing driven quantum materials