Establishing Transition-Edge Sensor (TES) Technology for Advanced Nuclear Detection at CNL

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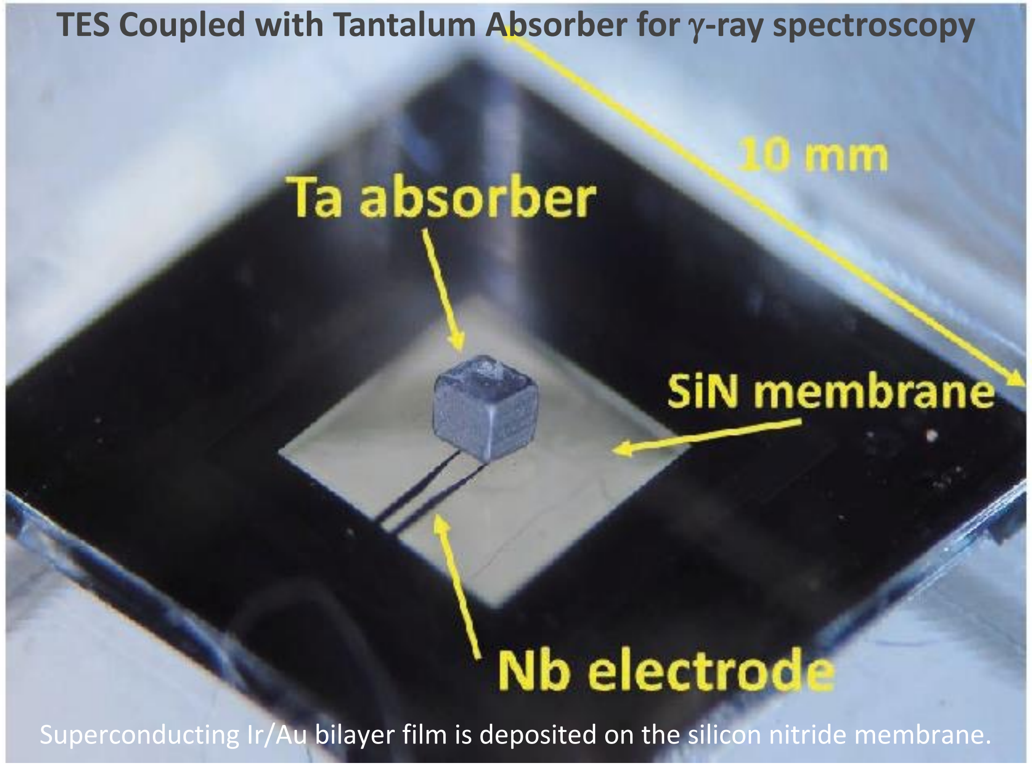
Canadian Nuclear Laboratories

Wednesday, June 26, 2024

SNOLAB User Meeting 2024
June 26-27, 2024



TES Coupled with Tantalum Absorber for γ-ray spectroscopy

Superconducting Ir/Au bilayer film is deposited on the silicon nitride membrane.

https://www.jstage.jst.go.jp/article/transele/E100.C/3/E100.C_283/_article

Presentation outline

- Introduction
    - Canadian Nuclear Laboratories
    - Nuclear detection
    - Current technologies
- TES detectors
    - Nuclear applications of TES detectors (γ-ray, α-particles, neutrons, neutrinos…)
    - Principles and operation (advantages and challenges)
    - Our work so far
- Collaborative opportunities
- Conclusions

Nuclear Detection

CNL Laboratories and Project Sites across Canada

- Chalk River Laboratories, Ontario
- Whiteshell Laboratories, Manitoba
- Historic Waste Program, Port Hope, Ontario
- National Innovation Centre for Cybersecurity, New Brunswick
- Prototype reactors and legacy facilities

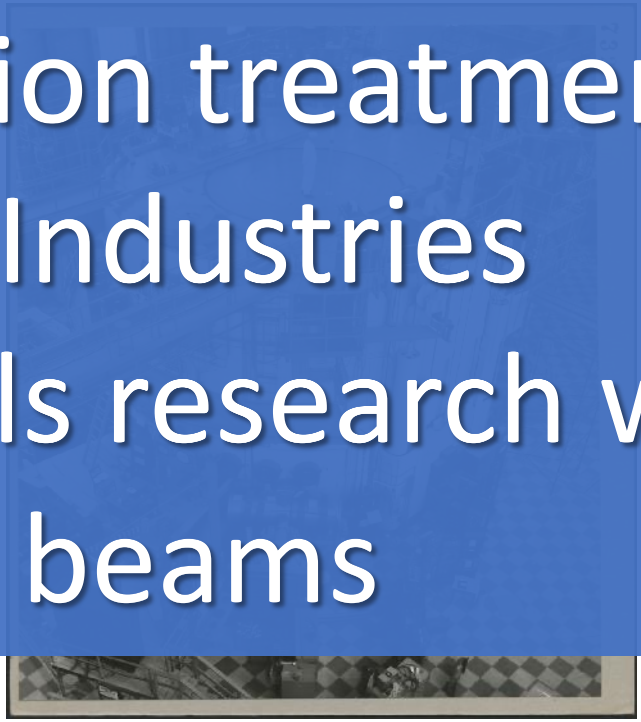
Chalk River Laboratories is the single largest science and technology laboratory in Canada:

  - ~ 9,000 acre site (~200 acre lab complex) with 17 nuclear facilities, 70 major buildings.
  - ~3,100 employees including 1,600 scientific, engineering, and technical staff (expertise in physics, metallurgy, chemistry, biology and engineering, etc.).

https://www.cnl.ca/

CNL origins go back to early 1940s

- ZEEP: 1st reactor outside USA (firs[illegible] with final shutdown in 1970)
- NRX: a research reactor [illegible] and reached 42 MW by 1954 before permanent shutdown in 1993.
- NRU: a major research reactor at 135 MW was first critical in 1957 and permanently shut down in 2018.



Major accomplishments:

- ✓Medical isotopes: more than 500 million treatments
- ✓CANDU Industries
- ✓Materials research with neutron beams

CNL is revitalizing the Chalk River Laboratories campus

The ANMRC will be Canada's largest nuclear research facility. It will hold 23 laboratories, 160 personnel, and essential skills from decommissioning facilities at the site. Construction is expected to finish in April 2028.

https://www.cnl.ca/about-cnl/revitalization-of-the-chalk-river-laboratories/

CNL Strategic Priorities: Vision 2030

Restore and protect Canada's environment

Conducting the largest and most complex environmental remediation in Canada, spanning three provinces

Clean energy for today and tomorrow

Support CANDU and LWR industry; SMR/vSMR demonstration; advanced fuel and materials; and hydrogen sciences

Contributing to the health of Canadians

Ac-225 radioisotope program and radiobiology

V2030

Overview: Science & Technology at CNL

S&T Directorates

- Reactor Fleet Sustainability
- Advanced Reactors
- Hydrogen and Tritium Technologies
- Isotopes, Radiobiology & Environment
- Safety & Security

PROJECT OFFICES

- *Small Modular Reactor Project Office*
- *Isotopes Production Project Office*

CNL’s Safety & Security

Nuclear Detection, Forensics and Response

- Detection and interception of special nuclear materials in transit.
- Advanced CBRNE threat detection techniques.
- Innovation in safeguards and security required for the deployment of advanced reactors.
- Nuclear forensics signatures and analysis methods.
- Methodologies and support for international nuclear treaties.
- Emerging technologies including quantum (e.g., TES detectors).

Cyber Security

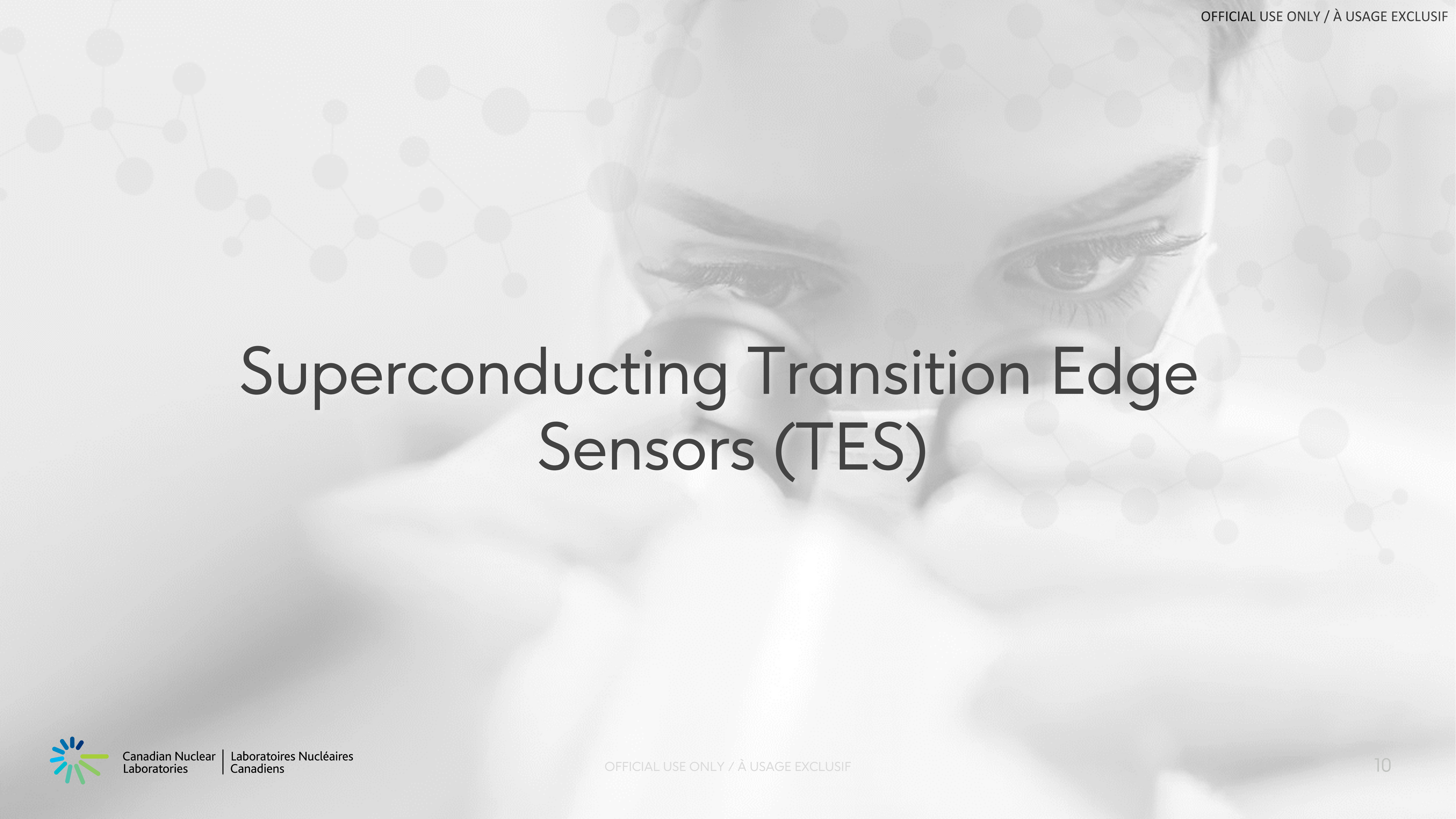
- Cyber security of industrial control systems for nuclear and non-nuclear critical infrastructure.
- A multimillion-dollar cyber security research facility in New Brunswick, including a safe plant display.
- Partnerships with U of New Brunswick, and Canadian Institute for Cybersecurity.
- Created a real-time process control distributed control systems testing platform.
- Used cyber security to examine process environments in real time.

Recent Quantum Technology Developments at CNL

- A cross-directorate effort (S&SD and ARD).
- Team building (and growing).
- Literature review and idea generation.
- Engagements with key stakeholders (e.g., understanding defence's needs and priorities).
- Exploring and establishing collaborations (e.g., CNL-Waterloo Quantum Horizon Workshop Oct 30 – Nov 1, 2023).
- Funding from FNST, CSSP, and CNL's LDST streams.
- Developed a CNL road-map for quantum technology development for defence.
- Expanding to quantum technology development to space sector.

An initiative spanning multiple Directorates!

Created by Zahra Yamani (CNL) using the *Pin Radial with 5 Levels Design* by PRESENTATIONGO (Free PowerPoint Templates and Google Slides Themes).



Superconducting Transition Edge Sensors (TES)

Nuclear detection for safety and security

Areas of importance for nuclear detection:

- ✓ Defence,
- ✓ National security,
- ✓ Nuclear proliferation.

In a variety of settings:

- ➢ Cargo, trucks, cars, boxes, mail/letters, …,
- ➢ Emergencies / incidents and conflict situations (i.e., theatres of war).


Mail


Palletized Cargo


C-Container


Trucks


Field/portable


Luggage


Large boxes


Cars

Nuclear detection: current technologies

Radiation relevant to nuclear safety and security:

- Charged particles: α-, β-particles,
- Photons: γ-rays, X-rays,
- Neutrons: uncharged (not directly ionizing, scattering, nuclear interactions and activation).

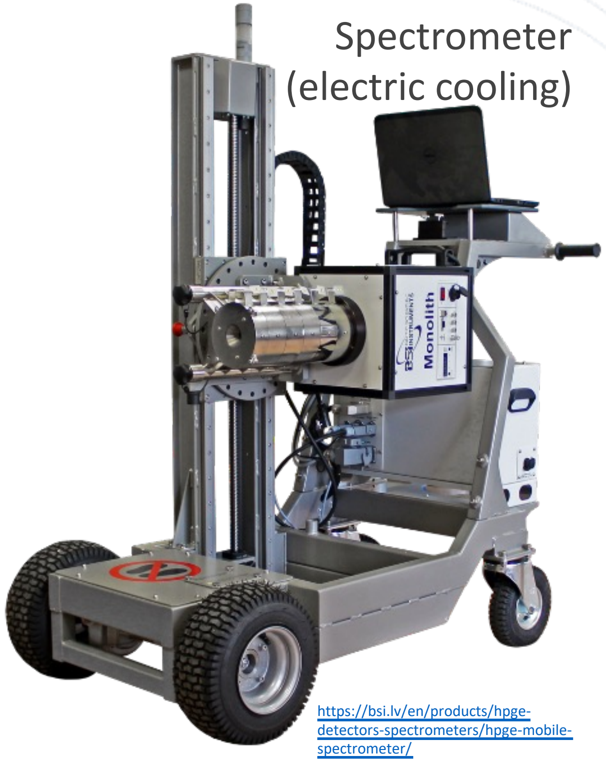
Detection technologies:

- Physical/chemical change in materials: track recording, cloud/bubble chambers, and imaging,
- Charge collection: gas filled detectors, ion chamber, proportional counters, semiconductor solid state, Si-based for charged particles, high purity germanium (HPGe) detectors for photons,
- Collection of scintillation light: inorganic scintillators (NaI(Tl)), organic scintillators (anthracene, C14H10).

LN2-cooled HPGe

http://www.nuclearphysicslab.com/npl/npl-home/spectroscopy/gamma-ray-spectroscopy/gamma-ray-spectroscopy-education/

HPGe Mobile Spectrometer (electric cooling)



https://bsi.lv/en/products/hpge-detectors-spectrometers/hpge-mobile-spectrometer/

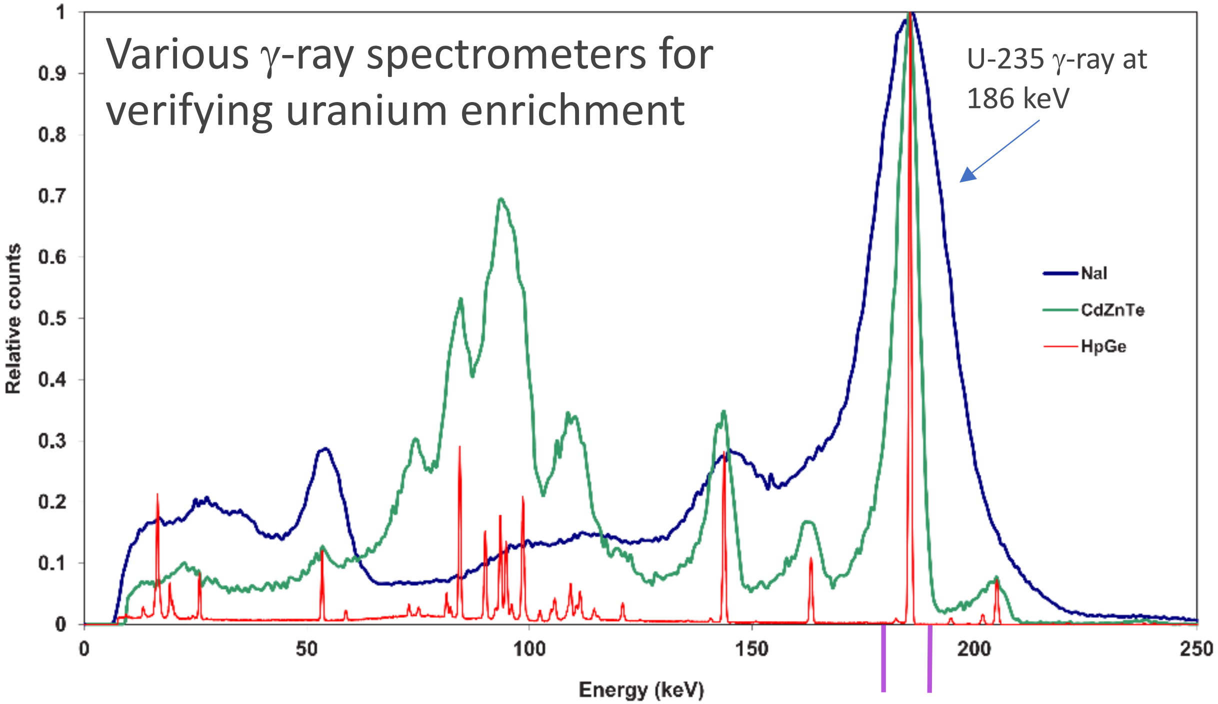
Goals of nuclear detection:

- ✓ Rapid and effective detection,
- ✓ Precise identification, characterization, and imaging of nuclear materials and devices,
- ✓ Detection of distant, shielded, or weak nuclear signatures,
- ✓ In a variety of operational conditions (temperature, ruggedness, power limitation, etc.).

Nuclear isotope detection: γ-spectroscopy

Analysis of nuclear materials:

- Example: Uranium samples generally contain U-238, **U-235**, U-239 (& decay products),
- Current non-destructive techniques to determine isotopic composition:
  - γ-ray spectroscopy,
  - α-particle spectroscopy.



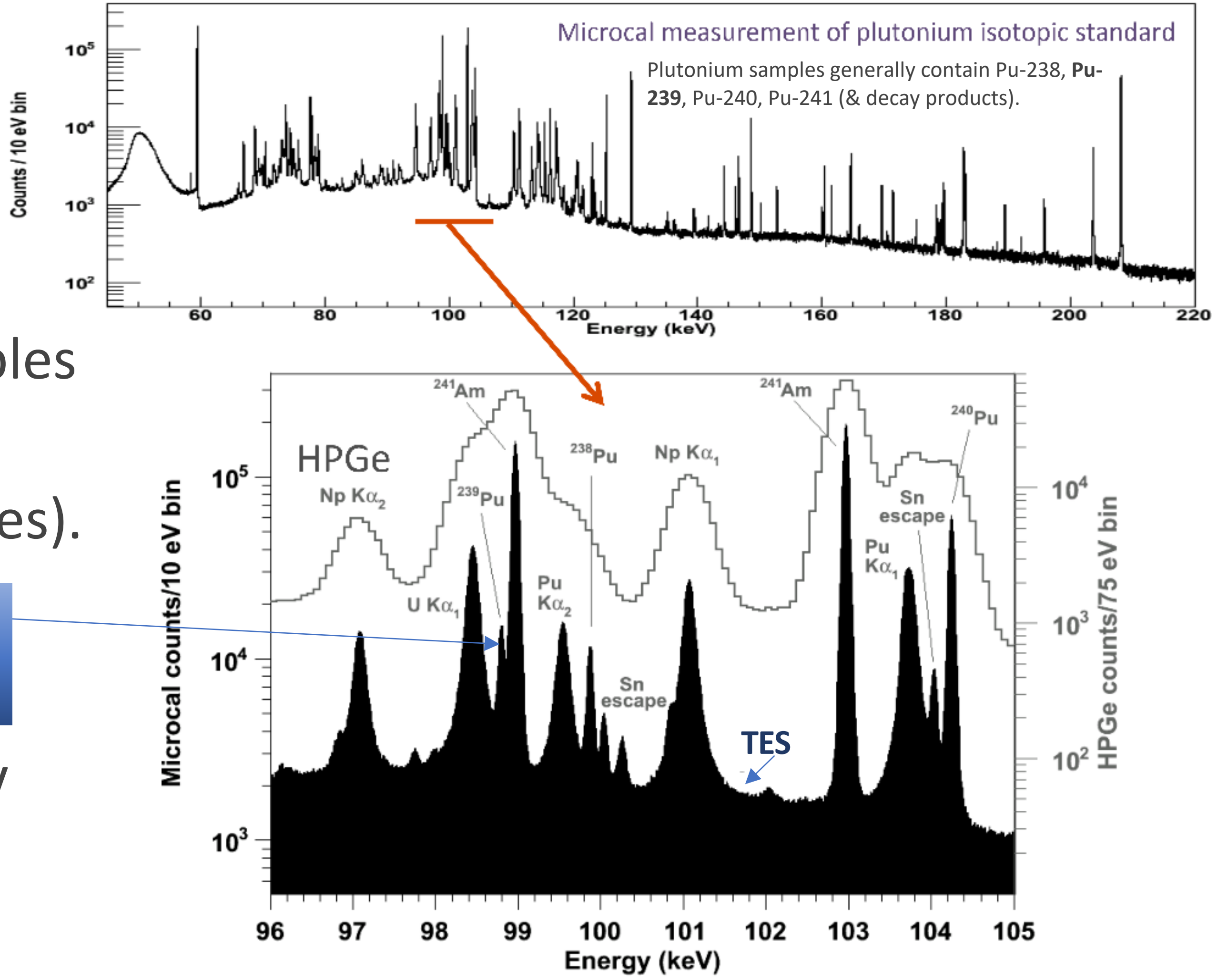
https://www-pub.iaea.org/MTCD/Publications/PDF/nvs1_web.pdf

- Superconducting **transition-edge sensor (TES)** with Superconducting Quantum Interferometer Device (SQUID) readout **outperforms** the best scintillator-based detectors and High Purity Germanium (HPGe) detectors.

Nuclear isotope detection: γ-spectroscopy

Analysis of nuclear materials:

- TES detector offers superior resolution compared to conventional semiconductor technology,
- This is advantageous when assessing samples with a high peak density and overlap.
- Low noise (very low operating temperatures).
- TES-based detectors have 10 times greater energy resolution than HPGe detectors!
- Similarly, Si-based α-detectors with 10 keV resolution cannot resolve 240Pu:239Pu, 238Pu:241Am peaks, also 10 times better resolution for TES-based detectors.



Microcal measurement of plutonium isotopic standard

Plutonium samples generally contain Pu-238, **Pu-239**, Pu-240, Pu-241 (& decay products).

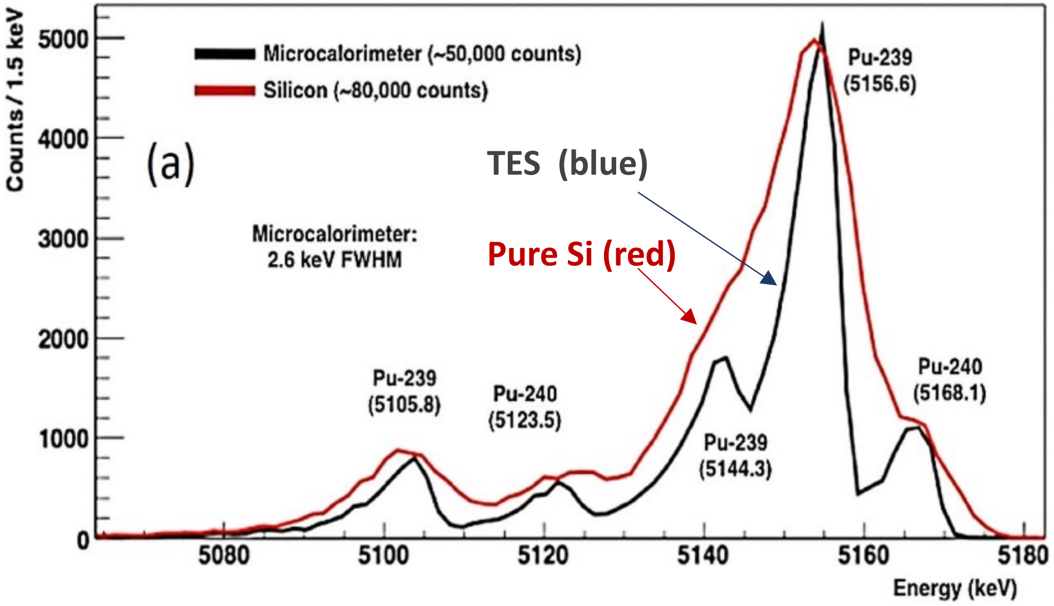
https://www.phenix.bnl.gov/WWW/publish/mxliu/talks/LANL-V/P-25-Hoover.pdf

Nuclear applications of TES detectors

TES-based γ-ray, α-particle spectroscopy, Coherent-Elastic Neutrino-Nucleus Scattering, (& neutron detectors?):

- Isotopic analysis,
- Elemental analysis,
- Characterizing spent nuclear fuel (treaty verification),
- Distinguishing nuclear materials from natural backgrounds (border security),
- Nuclear forensics,
- **Spent fuel and reactor monitoring (antineutrino detection).**

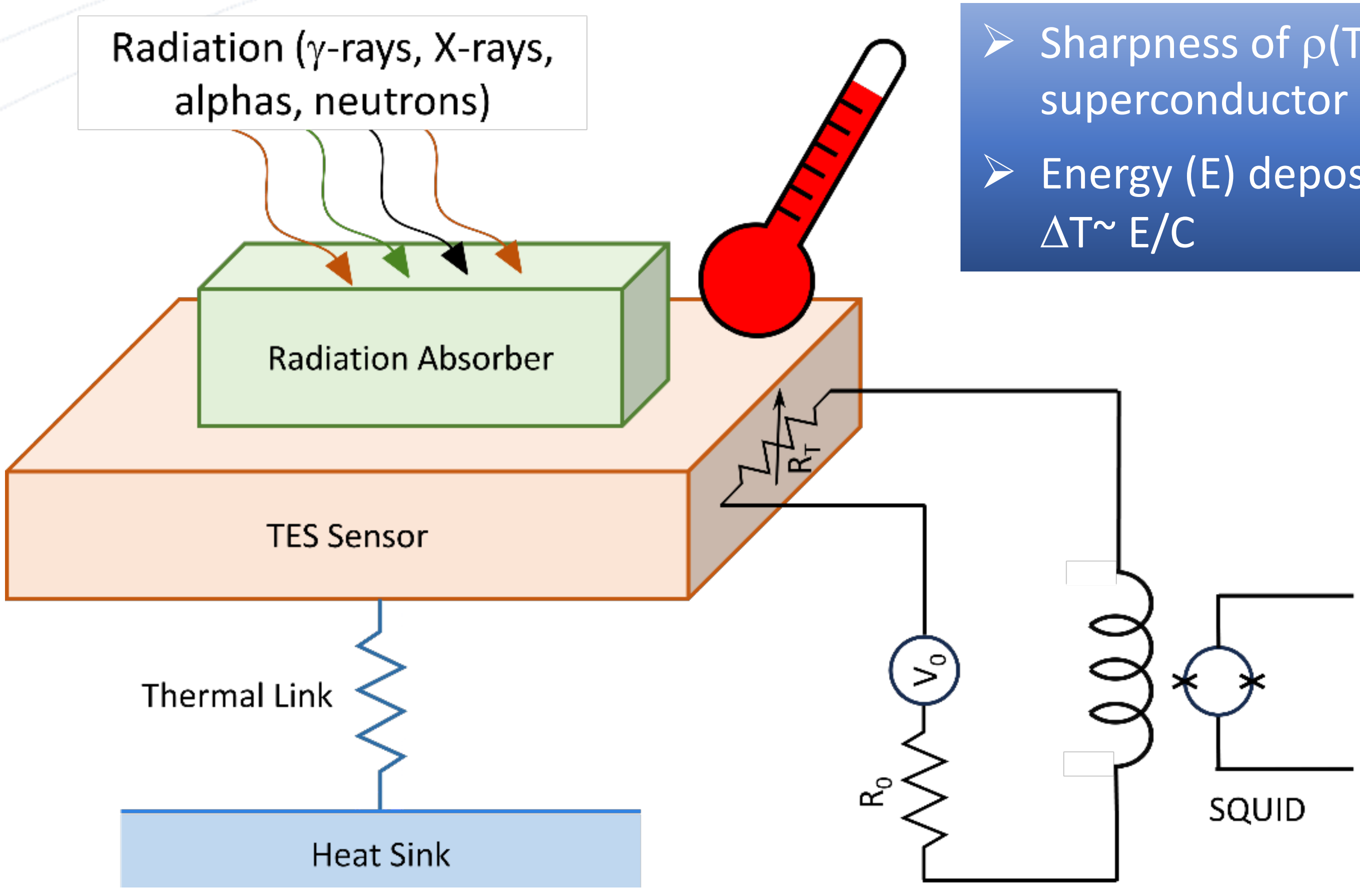
α-spectroscopy



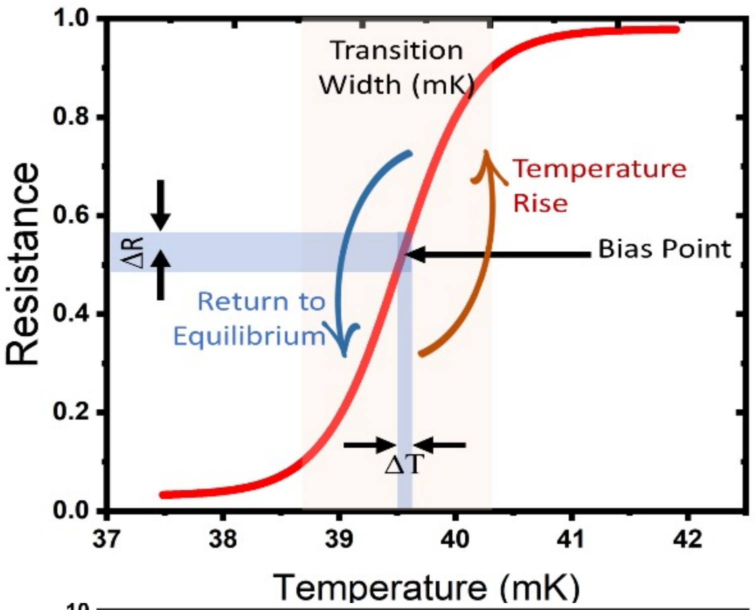
IEEE Trans. on Applied Superconductivity, vol. 21, p. 207, 2011.

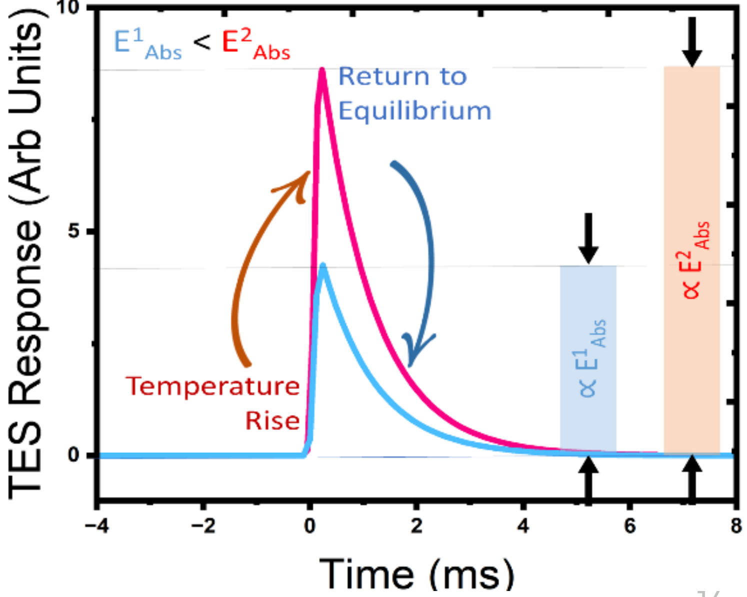
TES detectors: principles and operation

Temperature change determines energy (power) absorption!



- Sharpness of ρ(T) of the superconductor close to Tc
- Energy (E) deposit leads to ΔT~ E/C

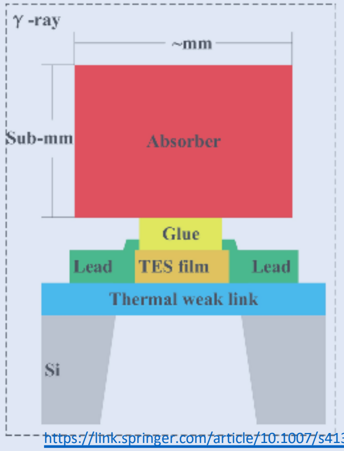




TES applications we are considering

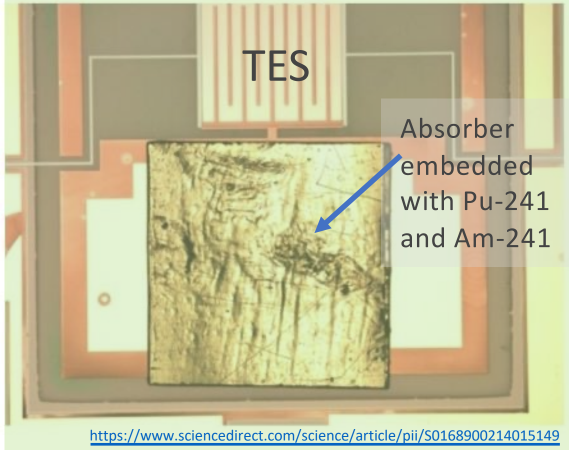
- **γ-ray spectroscopy**: measure several γ–energies for a given isotope (favourable for high peak density and overlap samples),
- **Q-spectroscopy**: embed sample in absorber to measure combined energy of all decay products (α, recoil nucleus, X-rays, γ-rays, e^-) a single energy peak at Q-value (total energy release) for each isotope,
- α-particle spectroscopy: measure several α–energies for a given isotope (sample preparation is a challenge),
- **Neutrons**: neutron detection/spectroscopy?

γ-ray spectroscopy



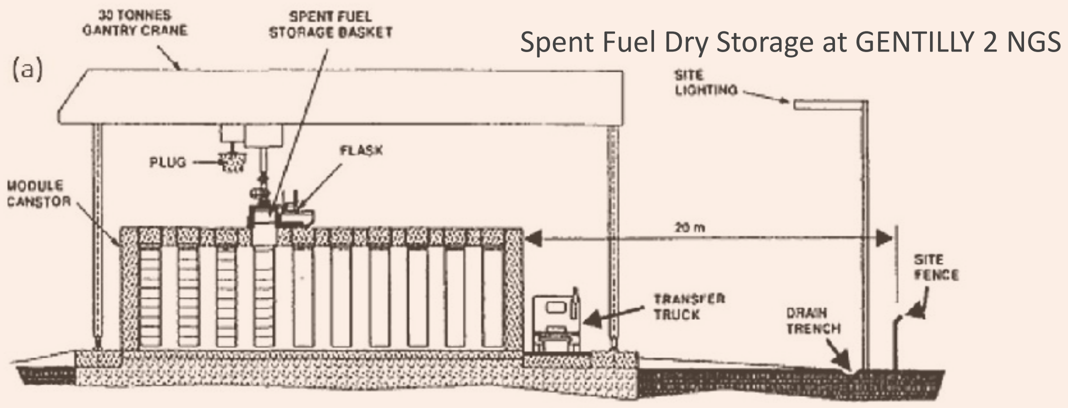
https://link.springer.com/article/10.1007/s41365-022-01071-5

Q-spectroscopy



https://www.sciencedirect.com/science/article/pii/S0168900214015149

Spent Fuel Dry Storage at GENTILLY 2 NGS



https://inis.iaea.org/collection/NCLCollectionStore/_Public/31/006/31006110.pdf

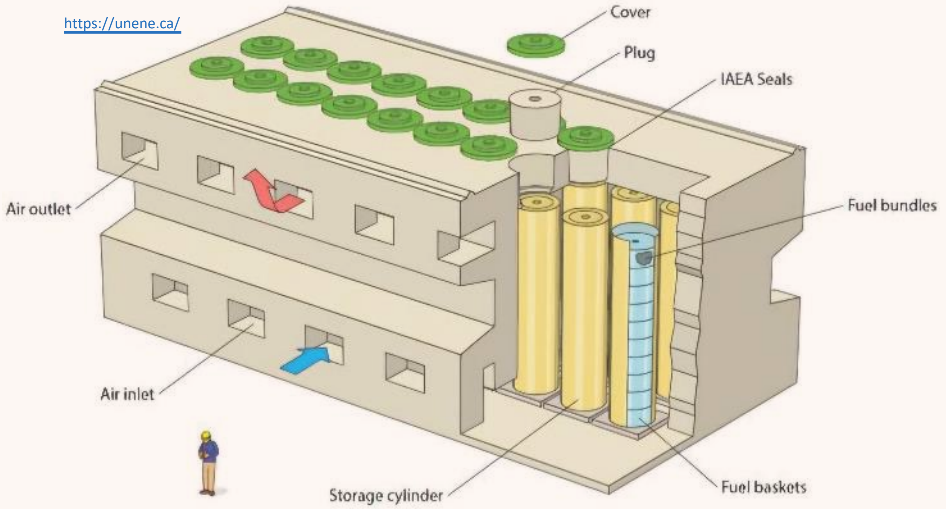
Nuclear spent fuel and reactor monitoring: detect **coherent-elastic neutrino-nucleus scattering (nuclear recoil).**

M. Stringer, A. Erlandson, V. Anghel, and Z. Yamani
Phys. Rev. D 109, 096038 – Published 28 May 2024

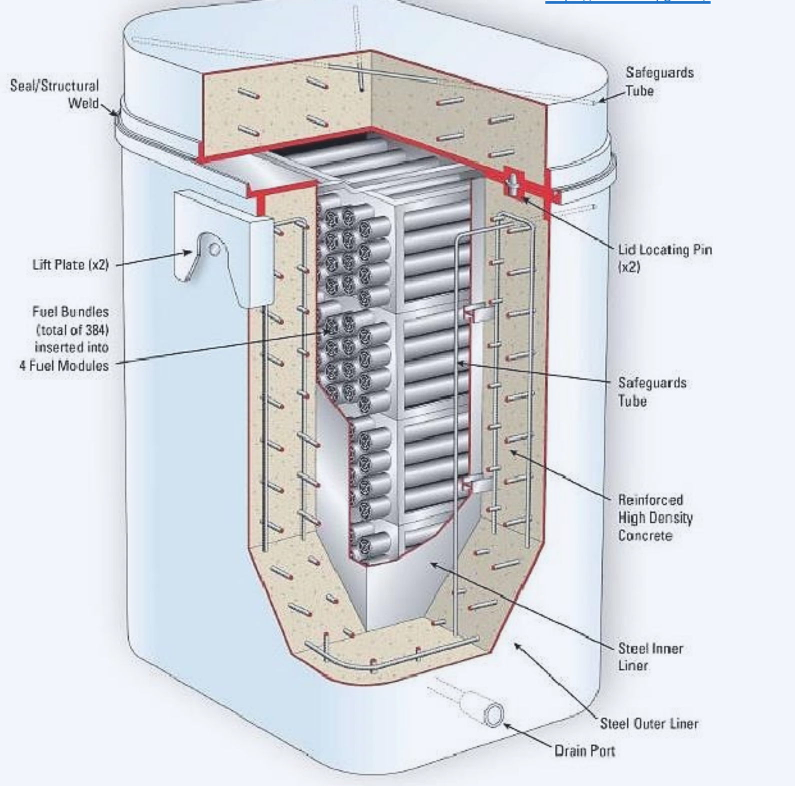
Monitoring CANDU spent fuel using TES: a GEANT4 simulation study

- ➢ Monitoring spent nuclear fuel: crucial to prevent unauthorized spread of nuclear materials.
- ➢ Feasibility of using TES-based detectors for monitoring spent CANDU fuel for two scenarios:

Scenario A: CANSTOR – Fuel Stored in Baskets inside Tubes (Spent Fuel Dry Storage at GENTILLY 2 NGS): One basket holds 1.2 tonnes of spent fuel while one tube 12 tonnes.


https://unene.ca/

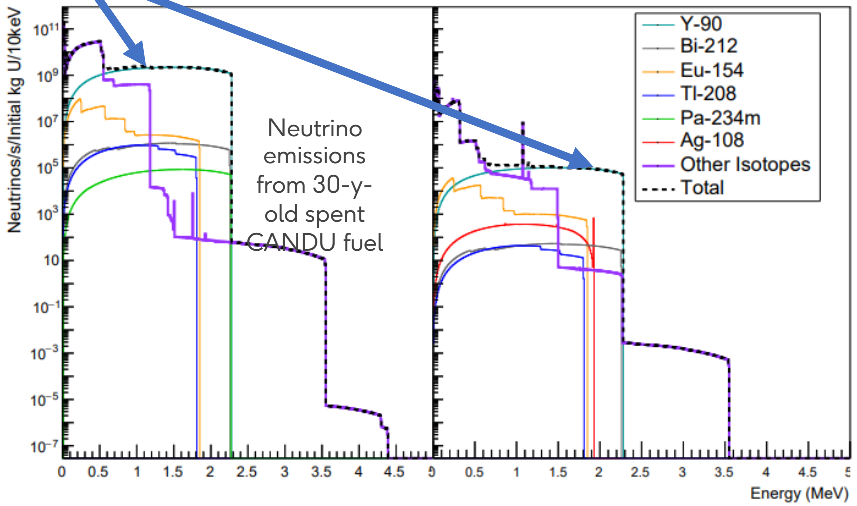
Scenario B: A Dry Storage Container (DSC) contains approximately 7.4 tonnes of spent fuel


https://archive.opg.com/

Neutrino-based safeguards of CANDU spent fuel using superconducting detectors and the CEvNS interaction
M. Stringer, A. Erlandson, V. Anghel , and Z. Yamani, Phys. Rev. D 109, 096038 (2024);
https://journals.aps.org/prd/pdf/10.1103/PhysRevD.109.096038

Monitoring CANDU spent fuel using TES: a GEANT4 simulation study

- ➢ Spent fuel isotopic composition is coupled with isotope neutrino spectra to calculate neutrino emission rates.
- ➢ High activity and energy allow CEvNS signal detection for Y-90 isotope.



Neutrino emissions from 30-y-old spent CANDU fuel

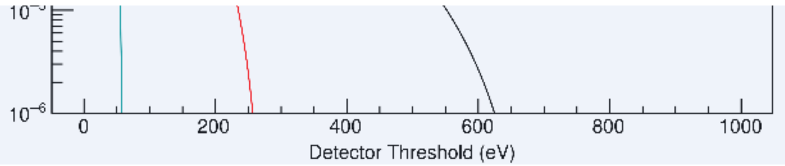
- ➢ TES-based detectors show potential for monitoring spent fuel in large containers (like CANSTOR) but impractical for smaller DSCs due to high background.
- ➢ Multiple or large array detectors to reduce measurement time and improve feasibility.
- ➢ Next: investigate SMR reactor monitoring.

Spent fuel is stored in DSCs near the reactors

nuclearsafety.gc.ca

Additional neutrino background due to the running reactors at the site

background from reactor neutrinos.

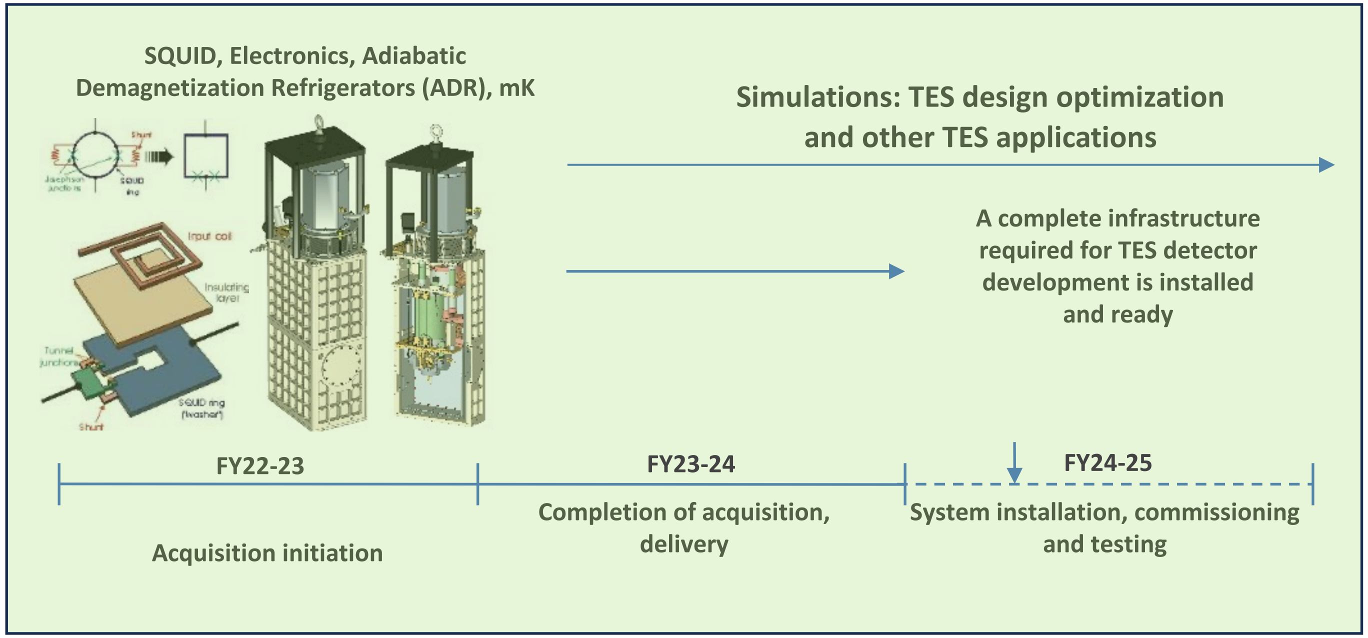


https://journals.aps.org/prd/pdf/10.1103/PhysRevD.109.096038

Establishing TES detector technology at CNL

Activities conducted thus far encompass:

- Setting up low temperature infrastructure and SQUID signal read-out,



SQUID, Electronics, Adiabatic Demagnetization Refrigerators (ADR), mK

Simulations: TES design optimization and other TES applications

A complete infrastructure required for TES detector development is installed and ready

FY22-23

Acquisition initiation

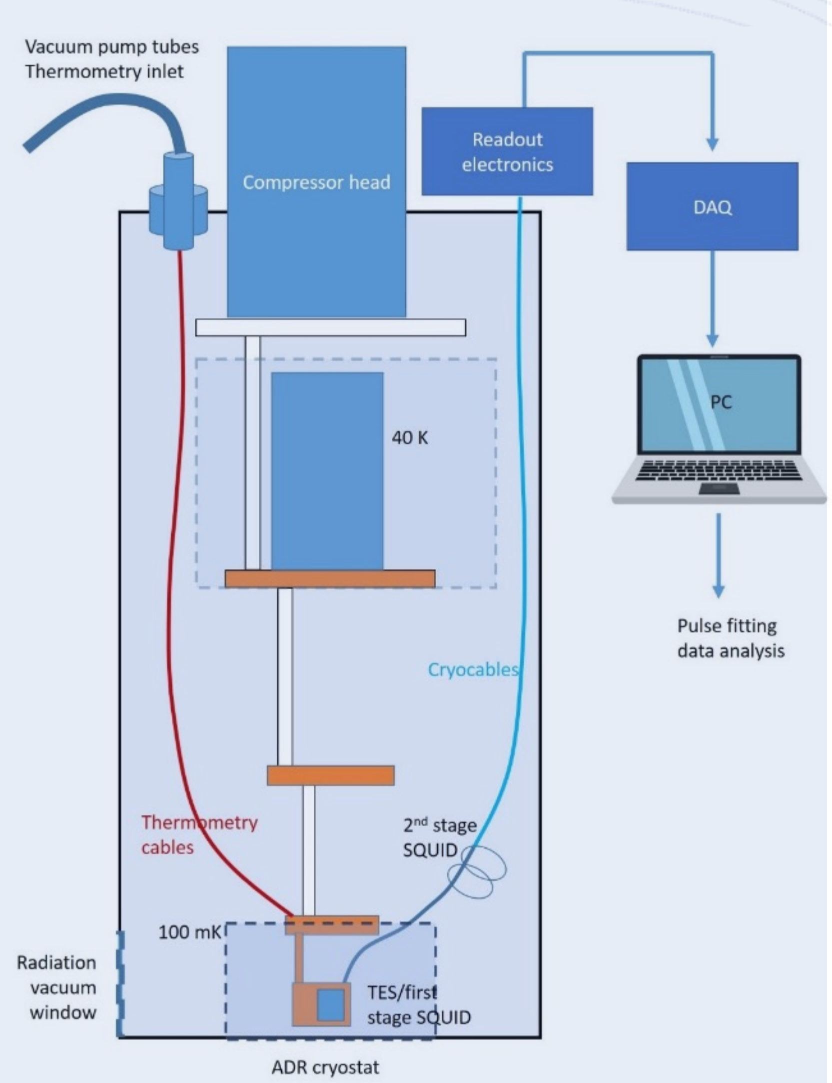
FY23-24

Completion of acquisition, delivery

FY24-25

System installation, commissioning and testing

Funding acknowledgment: CNL, AECL, FNST, DRDC-CSS.



Low temperature infrastructure and SQUID read-out for TES detector.

OFFICIAL USE ONLY / À USAGE EXCLUSIF

Z. Yamani et al., 153-120000-REPT-000016 (CNL).

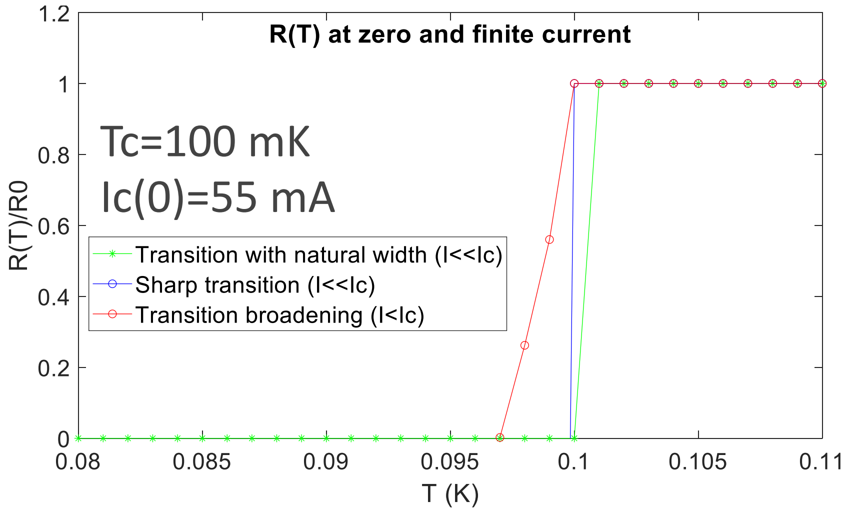
Establishing TES detector technology at CNL

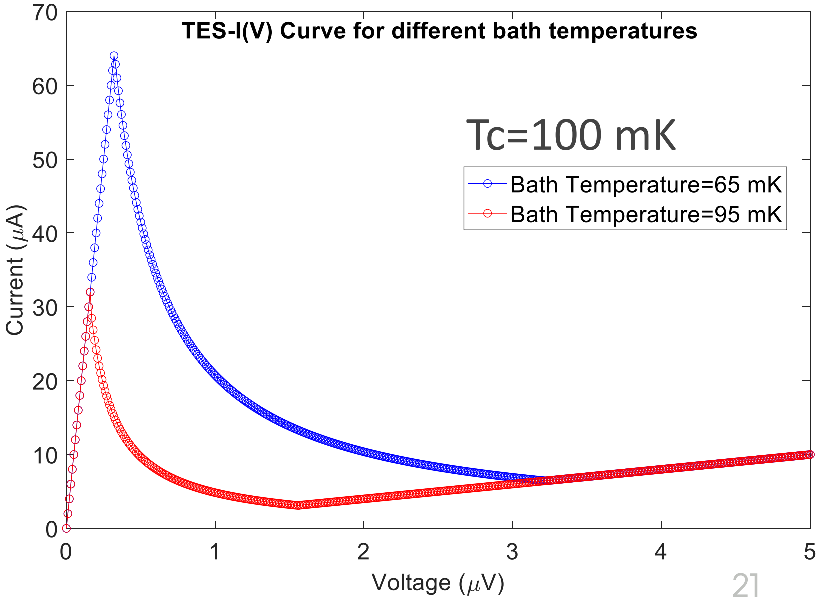
Activities conducted thus far encompass (continued):

- Performing simulations to gain insight and optimize detector parameters (transition temperature, superconductor and absorber materials),
- Performing simulations to explore other types of applications (SMR reactor monitoring).

Opportunities for collaborations:

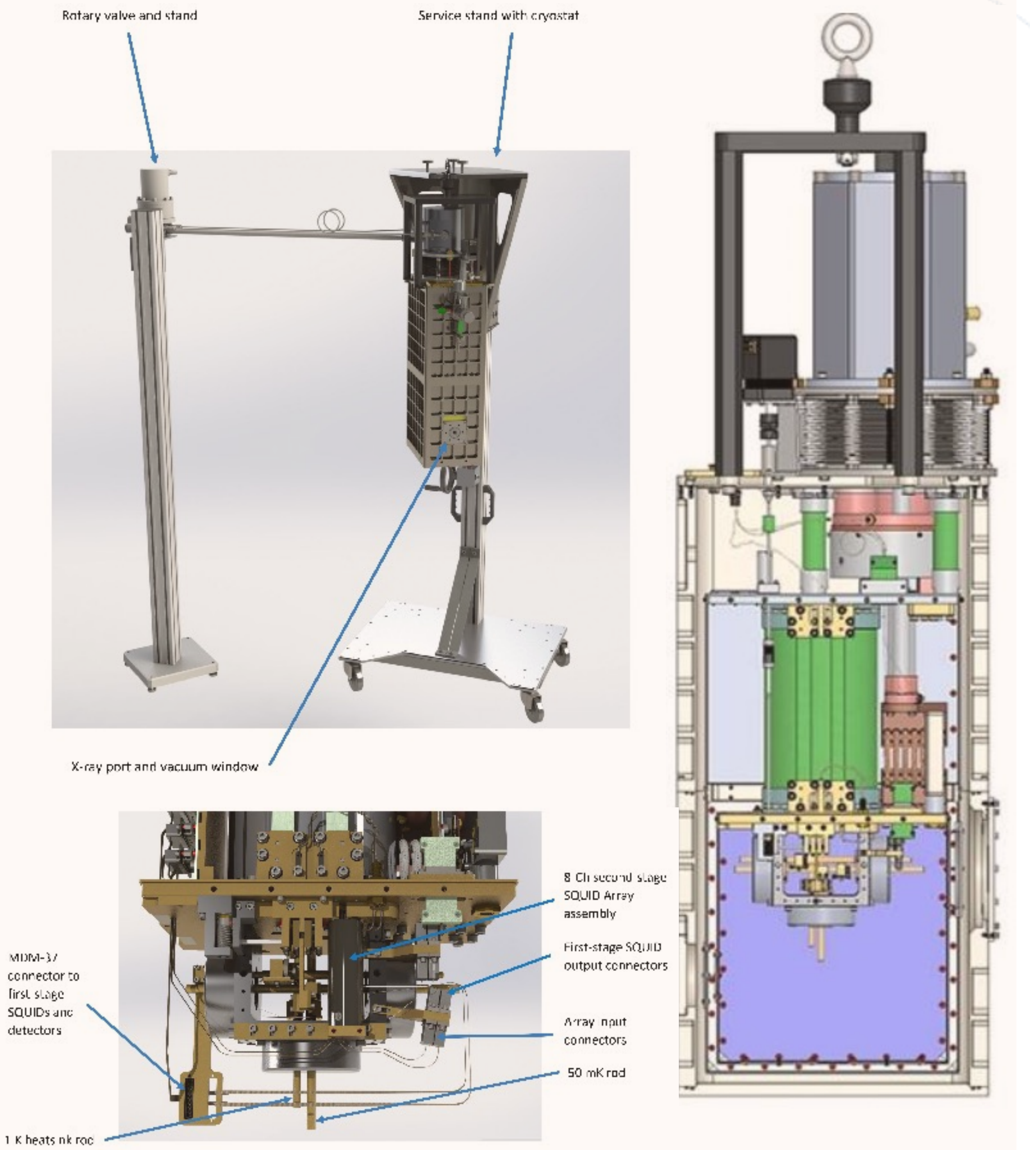
- Microfabrication of TES sensors,
- Simulations, tests, other applications (imaging?),
- Optimization,
- Development of field-able prototype.





Challenges in utilization of TES-based detectors in real-world applications:

- More R&D to make TES-sensors, that
  - ✓ Outperform the existing technologies,
  - ✓ Field-deployable (i.e., border, defence).
- Challenges include
  - ✓ Very low temperatures are required,
  - ✓ Continuous operation must be maintained,
  - ✓ Size, weight, and power,
  - ✓ Fairly complicated setup and operations,
  - ✓ Cost!



TES-based spectrometer

Thank you! ☺ Merci! ☺

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Questions?

Acknowledgements:

M. Stringer, R. Sammon, D. Dean, E. Erlandson, V. Anghel

CNL, AECL, FNST, DRDC-CSS