Fermilab Underground Facilities

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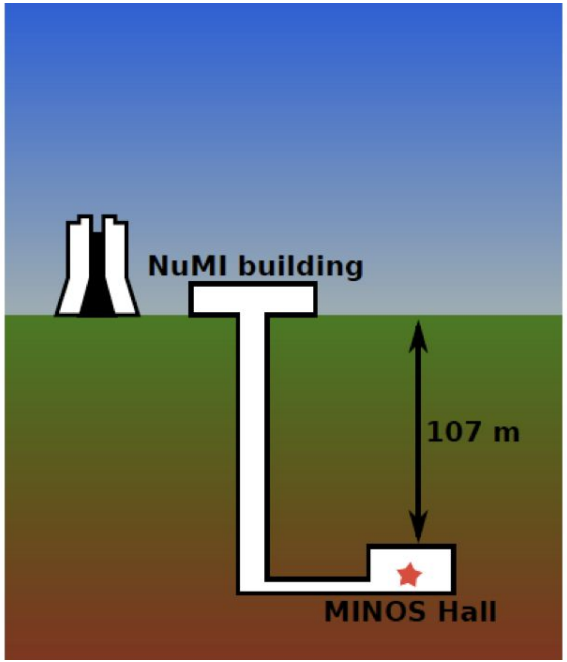
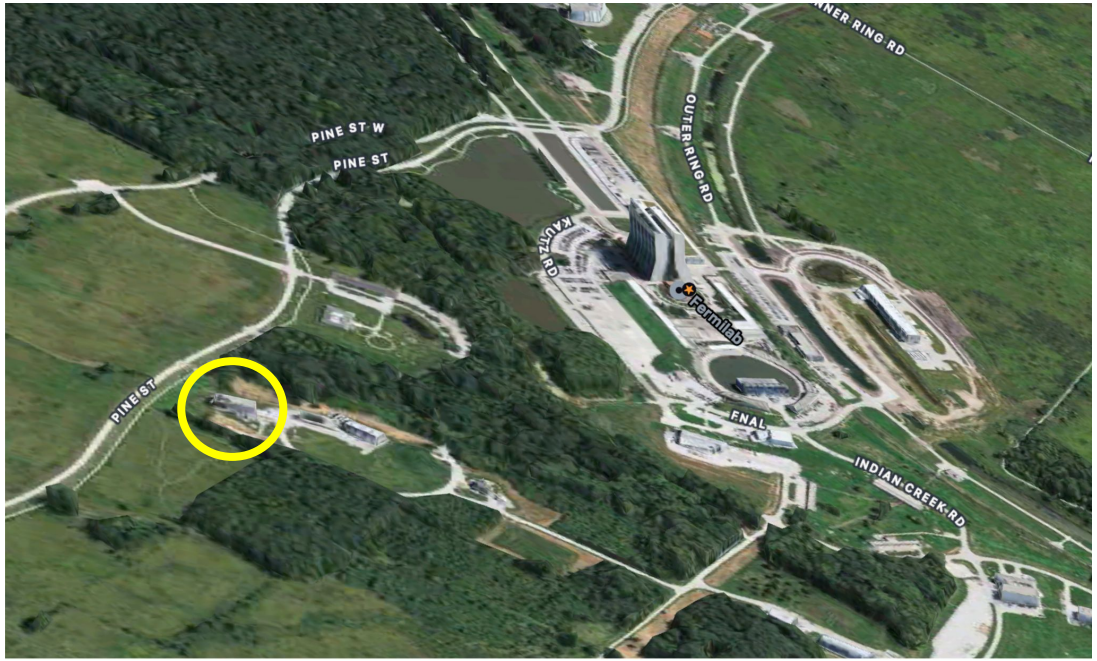
Northwestern Fermilab

QUANTUM SCIENCE CENTER

MINOS Underground Tunnel

- 5 min from Wilson Hall
- 107 m underground

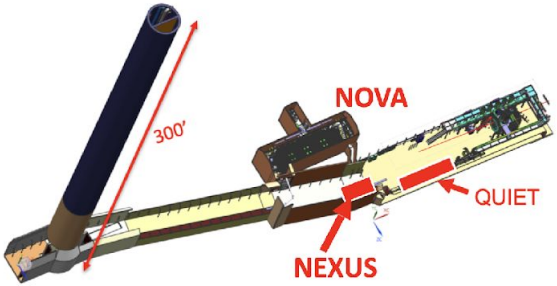




NEXUS and QUIET @ FNAL

Two cryogenic facilities located in the MINOS hall at Fermilab

- 107 m (225 mwe) underground for cosmic radiation shielding
- Reduced muon flux of 7 muons/cm^2/day, more than two orders of magnitude lower than surface muon rate



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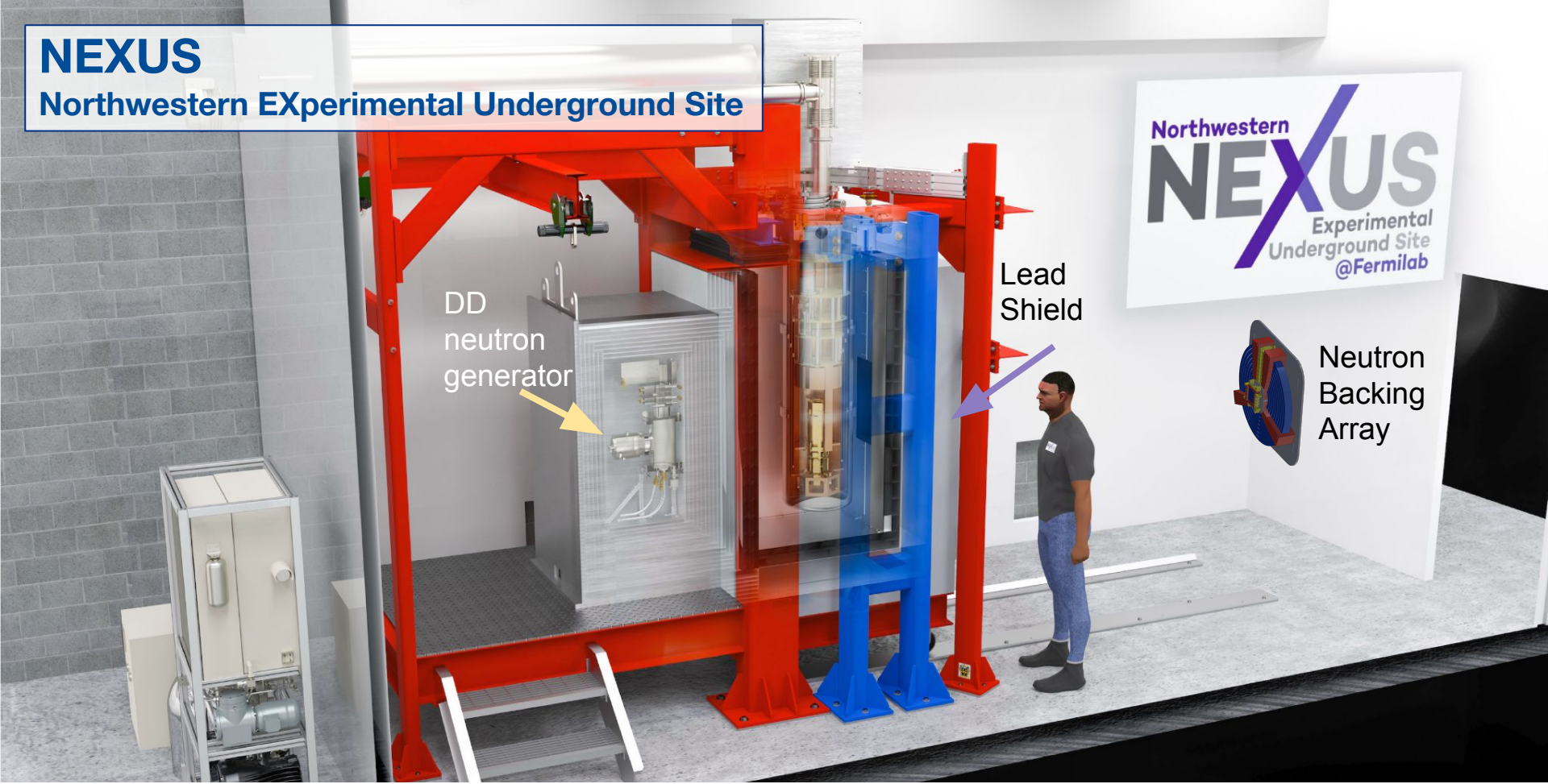
NEXUS
Northwestern EXperimental Underground Site



NEXUS

Northwestern EXperimental Underground Site

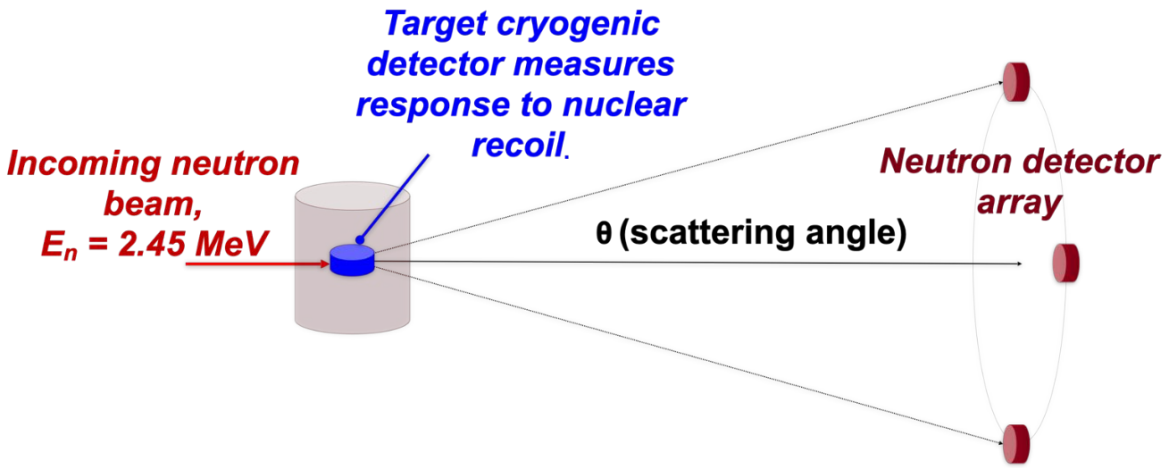
- Dry dilution refrigerator from Cryoconcept with a base temperature 8 mK and cooling power of
- Only underground cryogenic facility fitted with a dedicated neutron calibration system.
- Lead inner and outer shields give a low gamma background environment of 500 evts/kg/day at 100 keV.
- 10 RF lines currently used for qubit and kinetic inductance detector work
- 8 DC SQUID channels used for neutrino and dark matter detector experiments, to be upgrades to 24 channels.

NEXUS

Northwestern EXperimental Underground Site

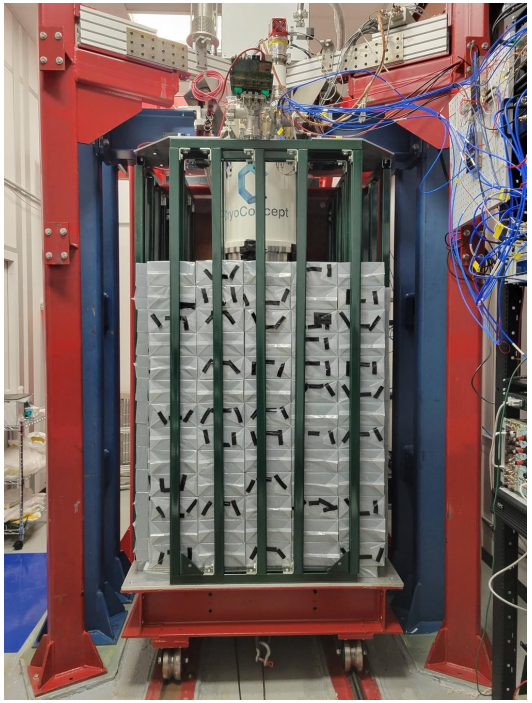
- A standard way characterize detector response to nuclear recoils is with a neutron scattering setup
- Precise knowledge of the scattering angle provides the recoil energy in the detector
- The detector signal can then be calibrated as a function of neutron recoil energy

$$E_{\text{recoil}} = 2E_n \frac{M_n^2}{(M_n + M_T)^2} \left(\frac{M_T}{M_n} + \sin^2\theta - \cos\theta \sqrt{\left(\frac{M_T}{M_n}\right)^2 - \sin^2\theta} \right)$$



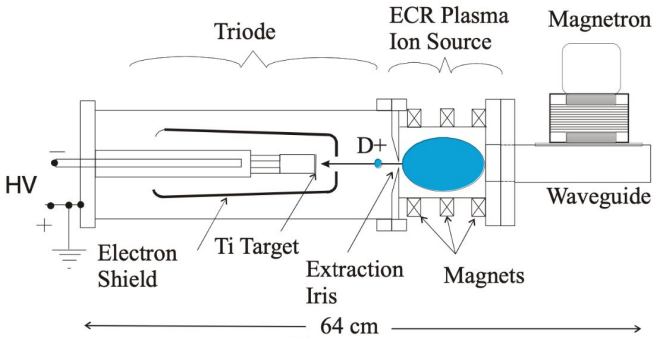
NEXUS

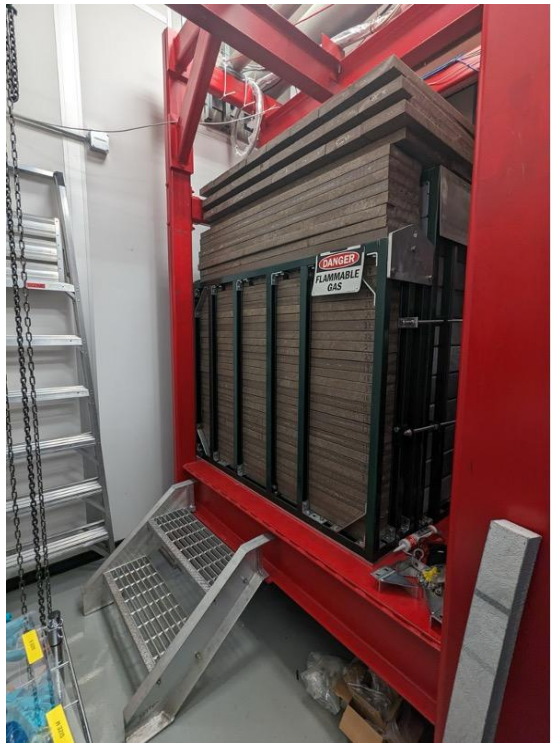
Northwestern EXperimental Underground Site



NEXUS DD Generator

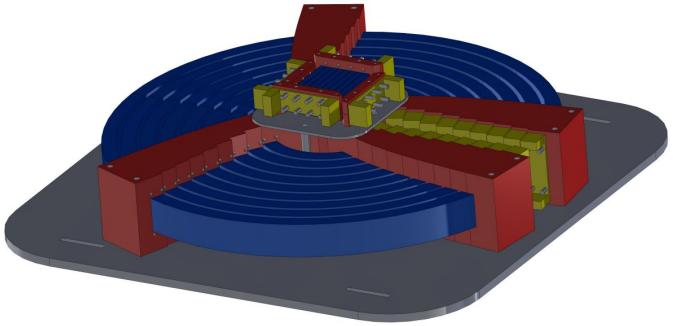
- Adelphi DD-108
- Generates up to 10^8 2.4 MeV neutrons pers second in 4π through D(d,n)He reaction
- Borated and nominal poly shield around DD generator
- Collimated hole to produce beam toward NEXUS detectors



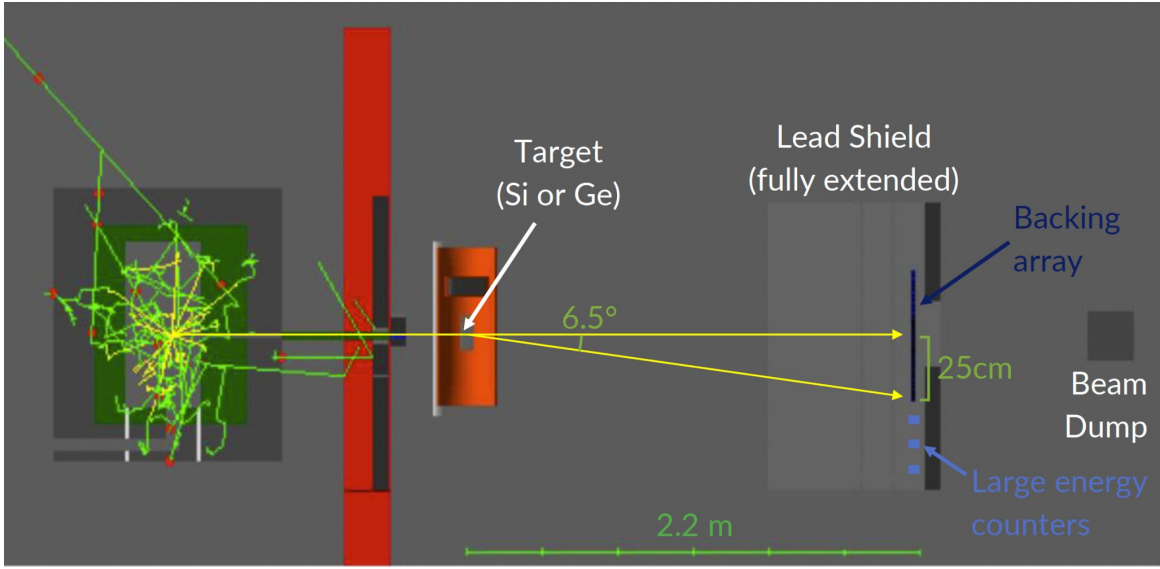


NEXUS Backing Array

- 9 concentric C-shaped bars of EJ200 scintillator with cross-section dimensions of 1.7 x 4 cm
- Each bar is wrapped in reflective material and has 8 SiPMs (Model S13360-6075PE) at each end for co-incidence tagging of events and efficient light collection.
- A central array of 8 horizontal and 8 vertical 0.7 x 0.7 cm bars will be used to center the beam.



Northwestern NEXUS Experimental Underground Site @Fermilab



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NEXUS Backing Array

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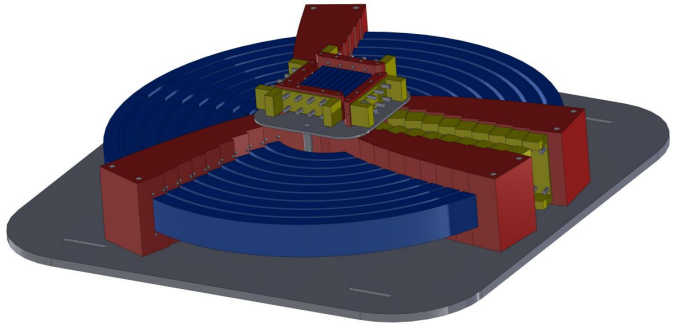

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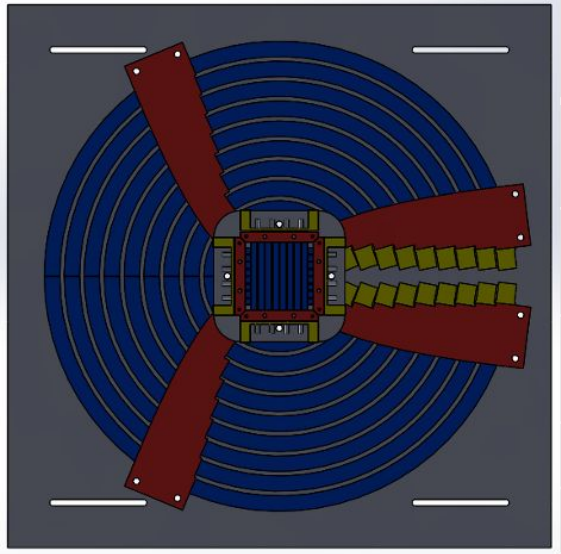
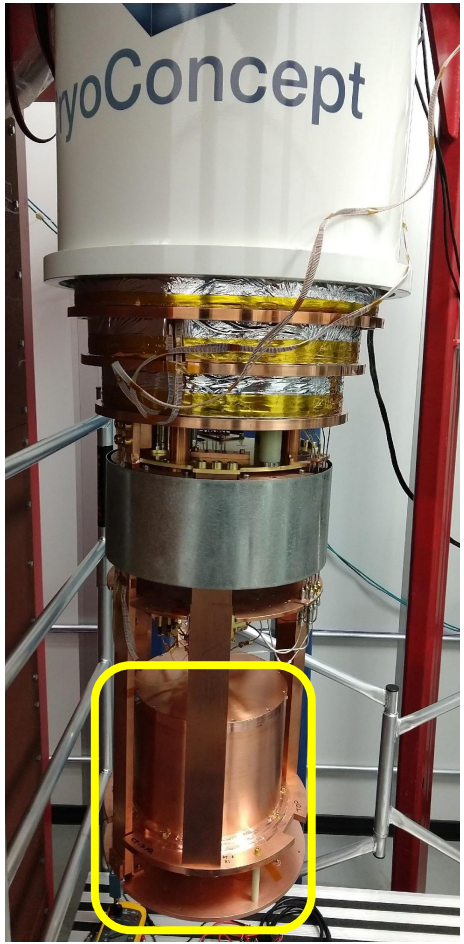
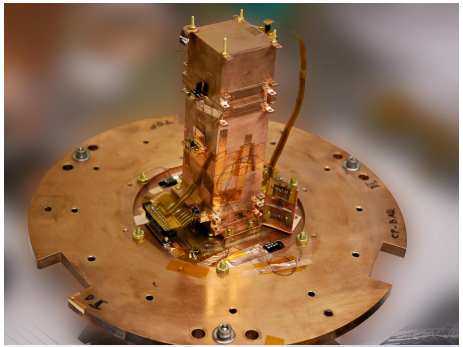


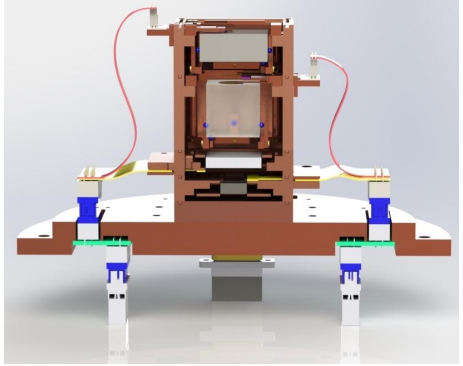
R inner [cm]	6.65	8.85	11.05	13.25	15.45	17.65	19.85	22.05	24.25
R outer [cm]	8.35	10.55	12.75	14.95	17.15	19.35	21.55	23.75	25.95
θ inner [degrees]	1.73	2.30	2.88	3.45	4.02	4.59	5.16	5.72	6.29
θ outer [degrees]	2.17	2.75	3.32	3.89	4.46	5.03	5.59	6.16	6.73
Si [eV]	102	170	255	358	478	615	769	940	1128
Ge [eV]	40	66	99	139	186	239	299	366	439

NEXUS Cryostat

- Cryoconcept Hexadray 200 with Ultraquiet Technology
- Cold volume: 30 cm diameter × 65 cm height
- Cooling power:
  - 200uW @ 100mK
  - 6 uW @ 20 mK
  - Base temp < 10 mK
- Movable 10 cm external lead castle
- Internal Lead Shield:
  - 24 cm diam. x 10 cm
  - Between MC and Payload
- Magnetic shielding: both an external (METGLAS®) and an internal (AMUNEAL A4K) magnetic shield
- 8 DC SQUID channels used for neutrino and dark matter detector experiments, to be upgrades to 24 channels.







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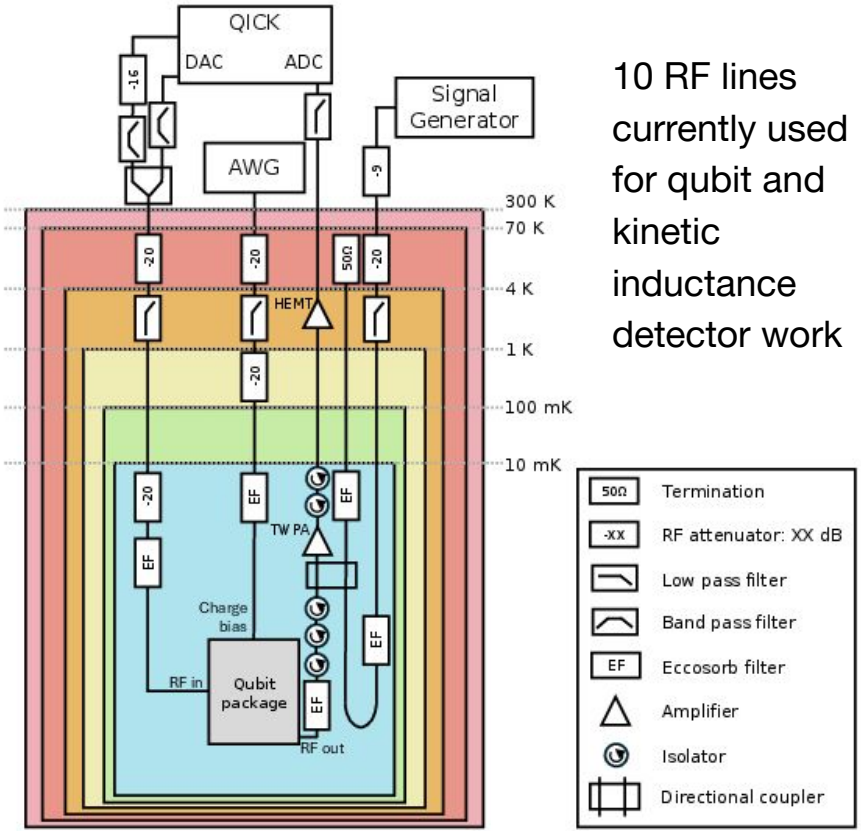
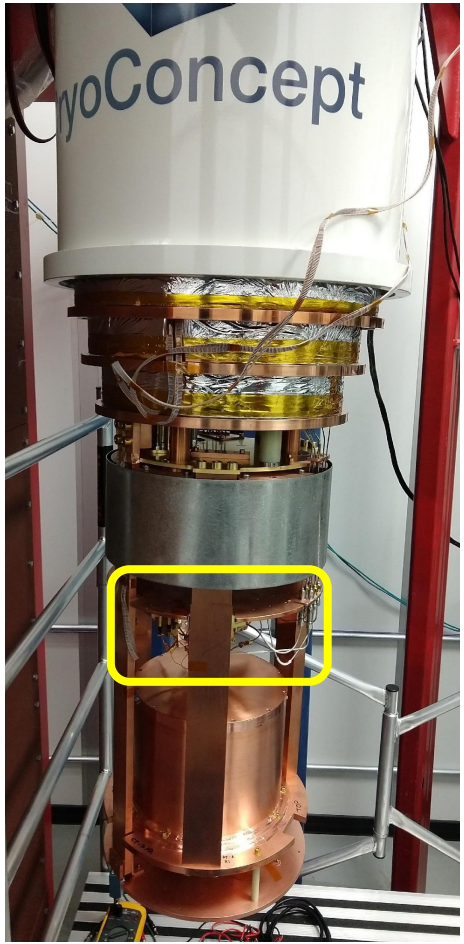
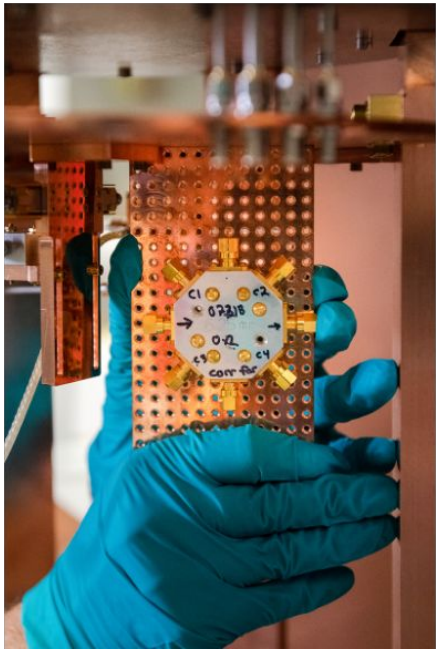
NEXUS Cryostat



10 RF lines currently used for qubit and kinetic inductance detector work





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Dark Matter Searches with SuperCDMS, KIDs, and QSC

- 2 eV energy resolution TES-based 2cm x 2cm x 4mm athermal phonon detectors
- KID LDRD wrapping up now

Neutrino Physics with Ricochet and CUPID

- Developed new modular architecture for neutrino physics detectors
- Deploying at ILL nuclear reactor next year
- R&D for future CUPID upgrades

Low-background Quantum Computing

- Qubit testing underway underground at NEXUS
- Developing R&D program for low-background quantum architectures

SUPER CDMS Cryogenic Dark Matter Search

RICOCHET

CUPID

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QUIET

Quantum Underground Instrumentation Experimental Testbed

QUIET was built to significantly enhance our capabilities in underground quantum work, with the following advantages over NEXUS:

- NEXUS is very high-demand and not dedicated to qubit operations
- Dedicated qubit experimental volume is limited
- Once the DD neutron generator turns on, NEXUS will switch from being a low-background facility to a neutron-calibration (activated) facility

Need a low-background facility dedicated to RF and qubit operations → QUIET

QUIET

Quantum Underground Instrumentation Experimental Testbed

This QSC facility is the first low background underground cryostat dedicated to superconducting qubit operation in the USA

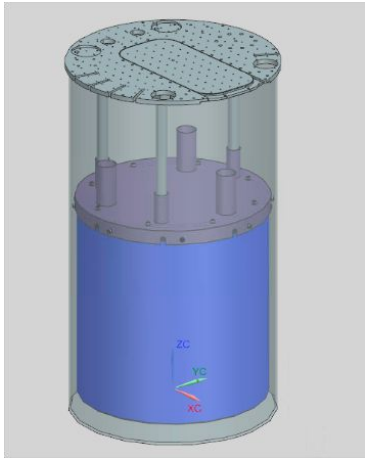
- Oxford Proteox w/ up to 16 NbTi and 48 SS RF lines with removable RF insert.
- 250 ft^2 Class 10,000 clean room
- 50 ft^2 antechamber for gowning and material cleaning
- Design of the QUIET radiation shield and muon veto is underway in parallel
- Initial fridge test reached 8.9mK w/ no issues

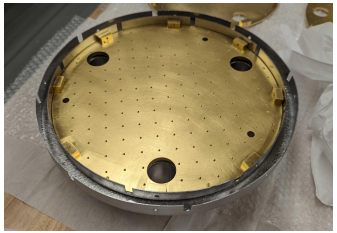
QUIET

Quantum Underground Instrumentation Experimental Testbed

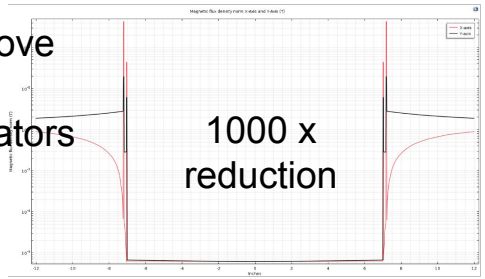
Magnetic Shielding:

Will achieve a large low-magnetic field environment at base temp, allowing ease of mounting several packages without the need for individual magnetic shielding.





Significant volume above shield at base temperature for circulators and other magnetic components.



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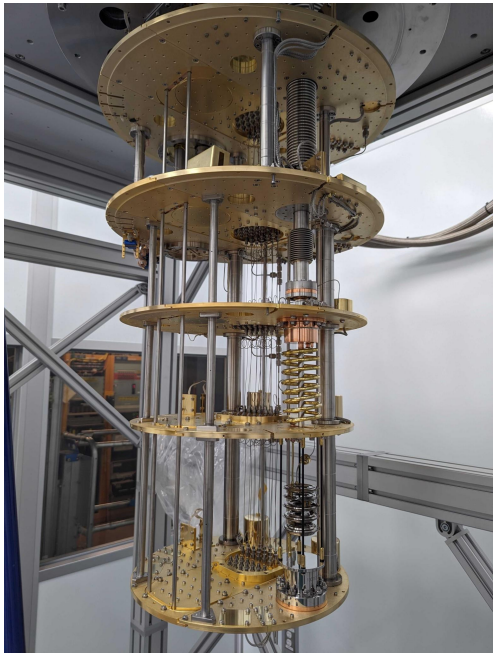
QUIET

Quantum Underground Instrumentation Experimental Testbed

Planned Upgrades:

- Radiation (lead) shield
  - Proteox can hold hundreds of pounds at mixing chamber plate
  - Plan to integrate cold magnetic shielding around cold radiation shield inside of IR-tight qubit package (all inside of 10mK can)
- Muon tagging
  - Muon rate is 7 counts/cm2/day
  - Need to integrate systems to know when NuMI beam is active
- Full QICK Control
  - Three 216 QICK platforms purchased, with room to expand further
  - Includes RF companion board (first tested in NEXUS!) that consolidates all warm-side filtering and mixing
  - Plans to expand to capacity for up to 100 qubits across 10 feed lines



CosmiQ group fridge operations (systems engineering)

Task	Notes	Completion Status	Week of 4/24	Week of 5/1	Week of 5/8	Week of 5/15	Week of 5/22	Week of
Swap out JPA lines	Completed by Kester + Dan	Done						
JPA installation and warm testing	Sealed in can, installed on MCP. Output line: need to install missing NbTi cable. But RF tests down the pump and input lines complete. DC checks down the flux line	Done						
Add in circulator shielding for qubits		Done.						
Amending silicon qubit's location in can (for better shielding): physical hardware modification ("Internal MEMS Setup")	All complete	Done						
MEMS Warm Testing	Kelly+Hannah. Can is off, immediately follow swapping in of new focuser	Done						
Silicon qubit line checkouts	Dan + Kester	Done		x	X	X		
Get better (more permanent) data storage solution	Identified correct hard drives. Dan placed order for drives.	Done		X	X	X		
Perform temperature curve calibration for Lakeshore sensors	Ryan. PT100 needs to be calibrated, and unsure where to get that curve. May need to calibrate using other method							
Reposition lakeshore sensors (MAKE SURE TO PUT TWO IN THE QUBIT CANS AND ONE ON KID) - KID thermometer already in place (see elog)	Leiden: KID, Sapphire can, w/in Qubit can, and then PT100 is in MCP	Done		X	X	X		
MEMS focal length modification: physical hardware modification (HM: honestly probably want to re-peat warm tests post-modification... which involves removing the qubit shielding)	Focuser arrived, plan to install it ahead of Run 2. Plan to do abbreviated version of warm tests	Done		X				
Figure out better alarm/notifications system for fridge	Some combination of Dylan/Ryan/Dan/Tali/Chris. How do we query database for Grafana? Does Grafana allow outgoing alerts/alarms to be forwarded over the WAN/LAN?	Done		X	X	X	X	X
Re-close fridge		Done		X	X	X	X	
Cool-down		Done					X	X
Reset Leiden-thermometer-based alarms	Ryan - to be performed today	Done					X	
Re-assemble warm electronics (qubits)	Tuesday? Perform after safety pause. Kester + Ryan will work on this	Done						X
AIA test: punch out (Si)		Done						X
AIA test: punch out (sapphire)		Not possible						X
AIA test: JPA		In progress						X
AIA test: KID	Test is inconclusive	Done						X
DC current tests for heating (Si qubit)	Likely to be performed and/or monitored remotely	Done						X

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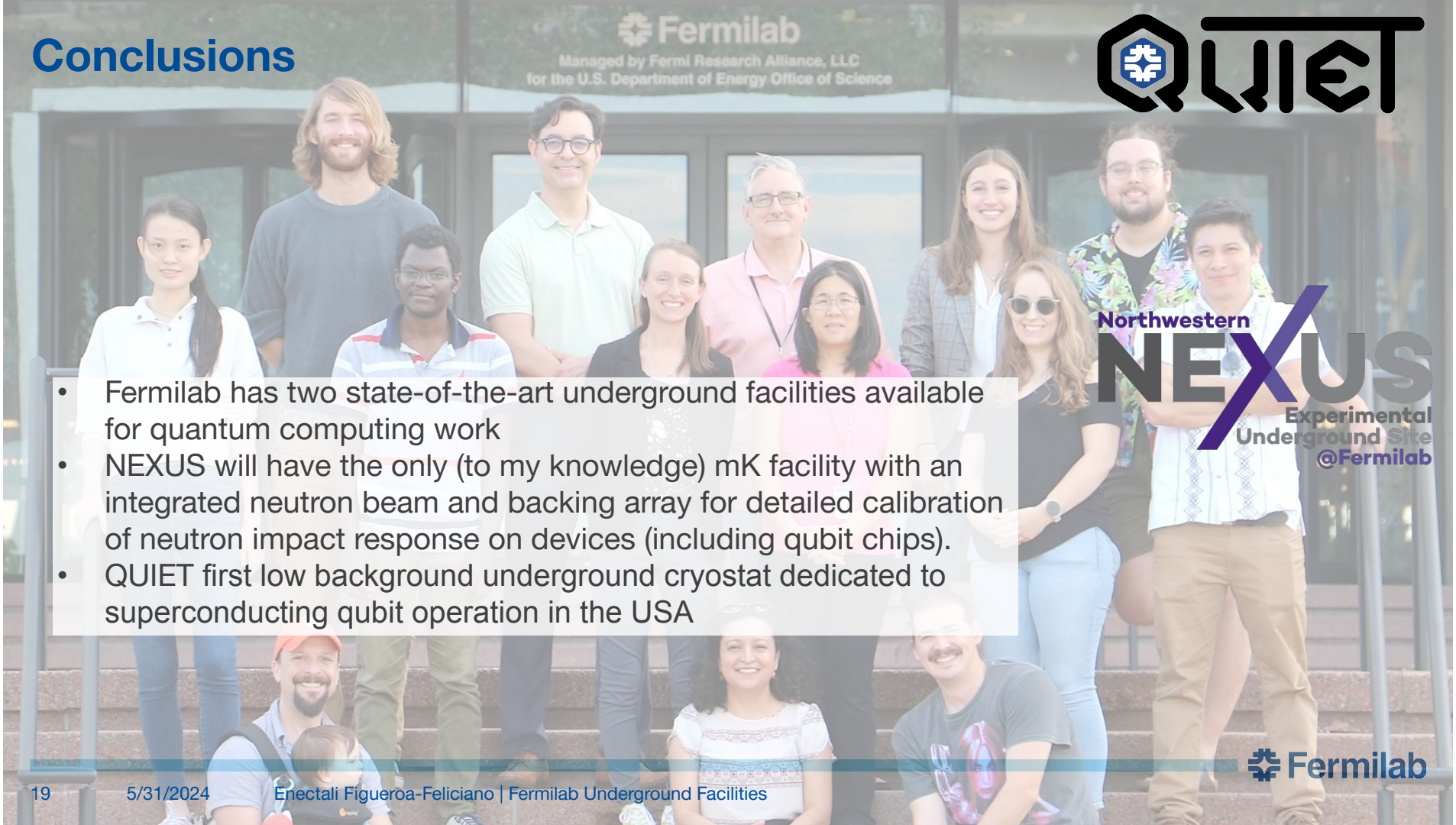
Conclusions



- Fermilab has two state-of-the-art underground facilities available for quantum computing work
- NEXUS will have the only (to my knowledge) mK facility with an integrated neutron beam and backing array for detailed calibration of neutron impact response on devices (including qubit chips).
- QUIET first low background underground cryostat dedicated to superconducting qubit operation in the USA

QUIET

Quantum Underground Instrumentation Experimental Testbed

- Oxford Proteox MX
  - Removable secondary insert containing all RF lines (right)
- Cooling power:
  - Base temp < 10 mK
- Internal Magnetic Shield:
  - Thermally sunk to MCP
- 12(4) input(output) coaxial RF lines installed with room for expansion up to 48(16)