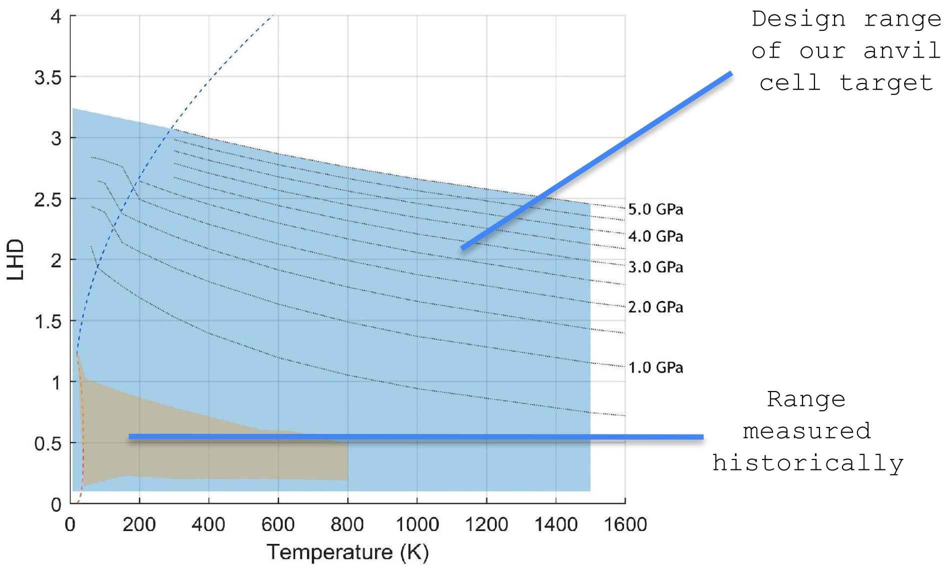
Status of Muon-Catalyzed Fusion Experiments at PSI

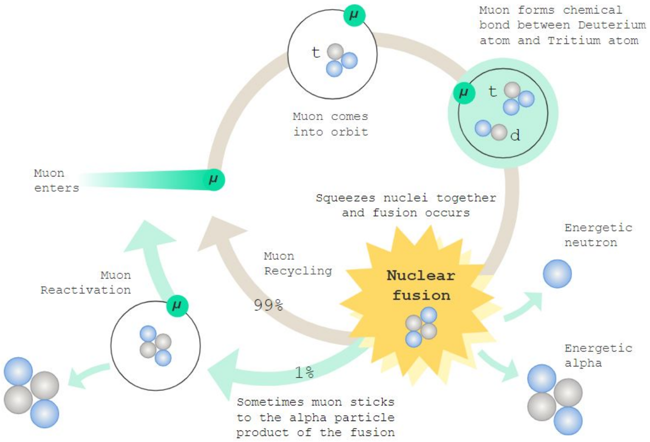
By Ara Knaian for
The MuFusE Collaboration

International Conference on muCF and Future Applications, Liverpool, July 2-3

Goals of our collaboration

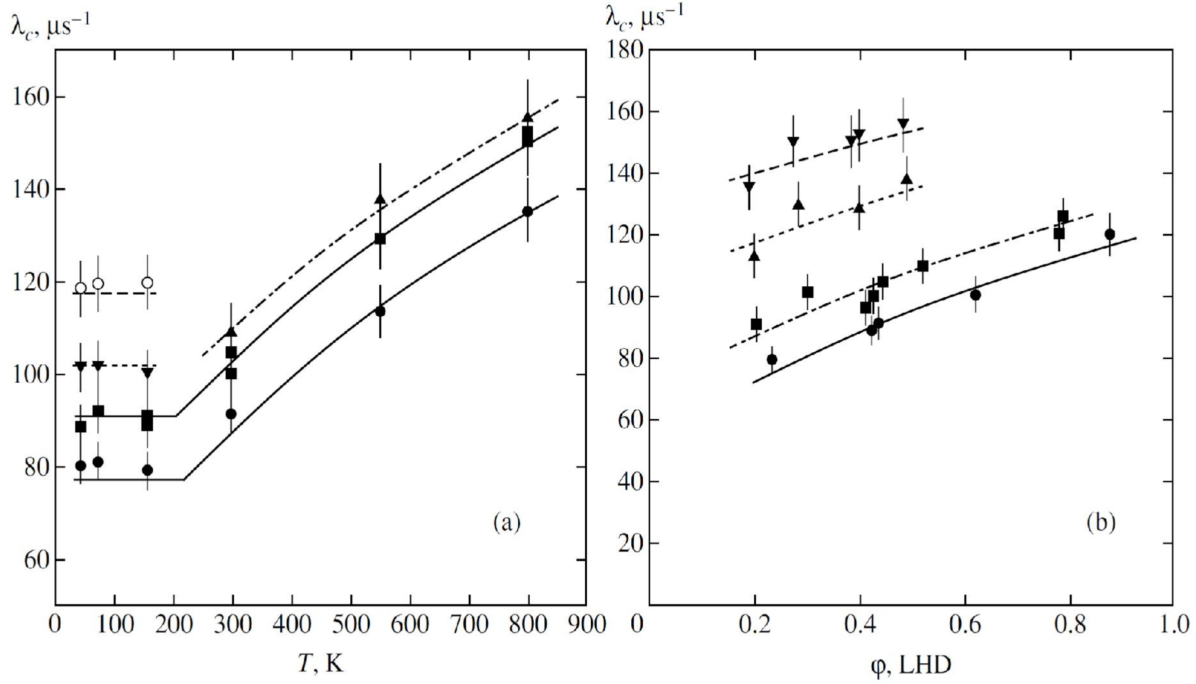
- Measure DT cycling rate and sticking fraction at high density and temperature
- Create open-source physics process models for GEANT4





Background

Fusion rate increases with temperature and density

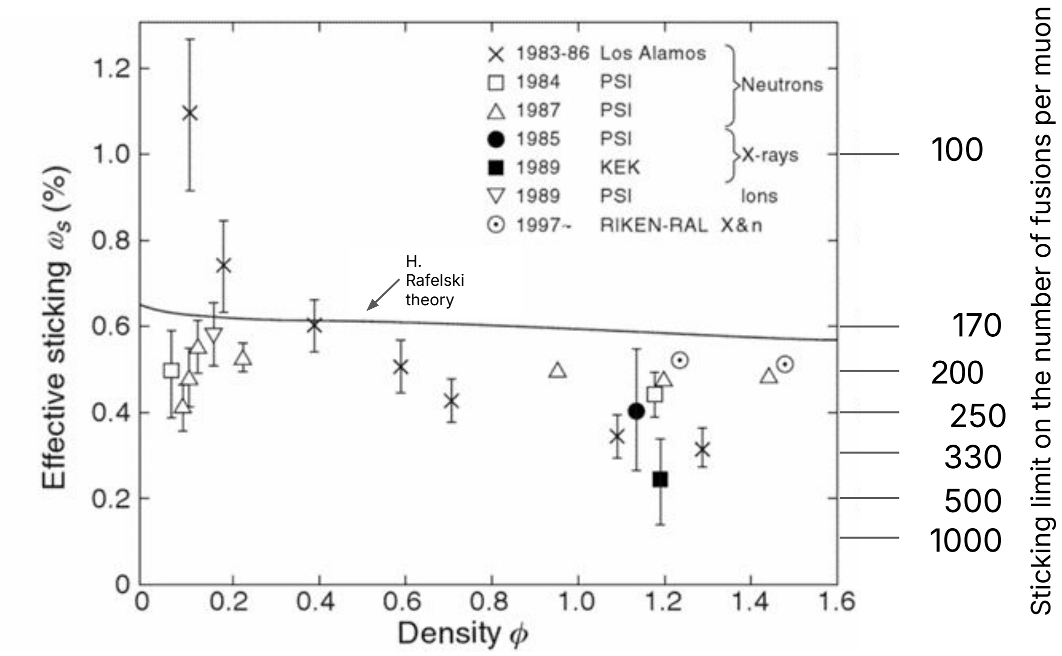


Experimental Data from JINR measurements on DT

Ref: V.R. Bom et. al, JETP, 2005

Background

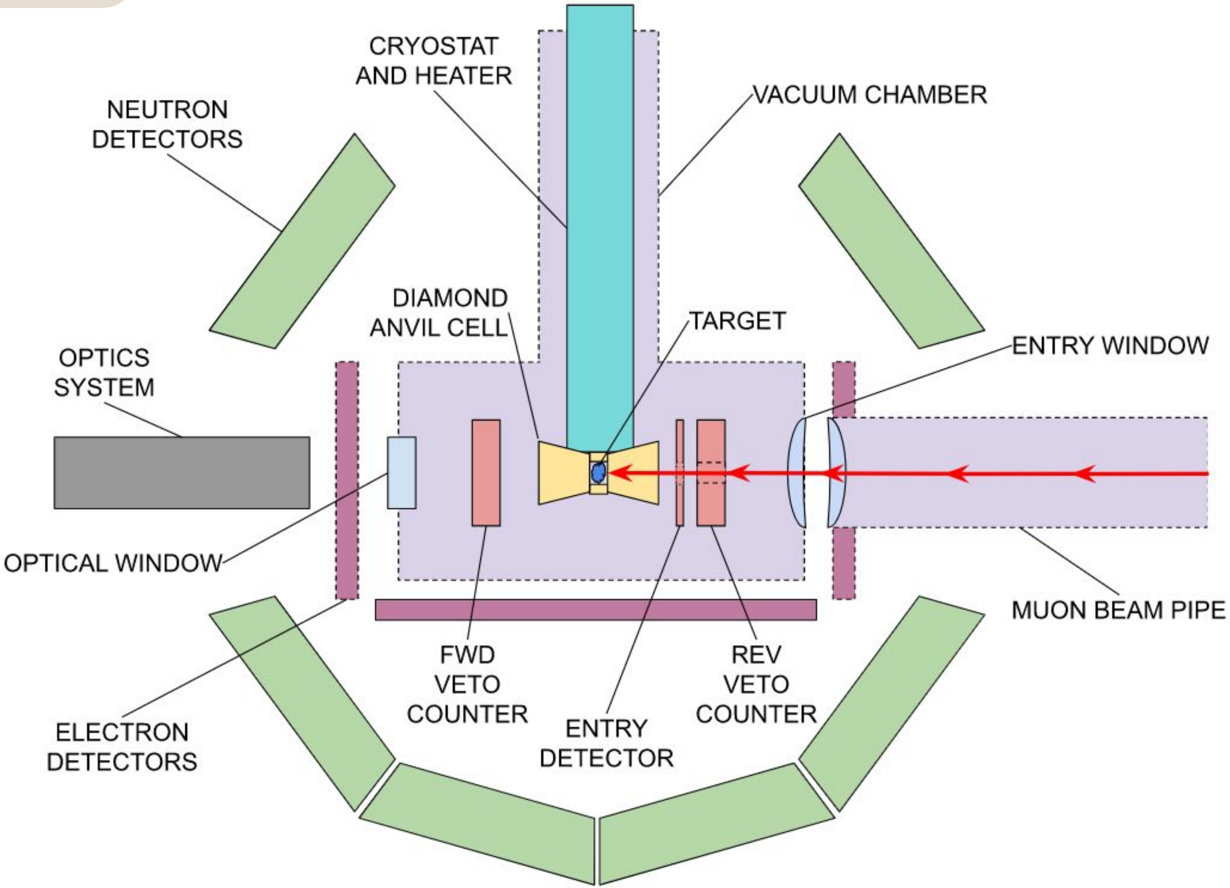
Sticking may decrease with density



Ref: K. Nagamine, 2008

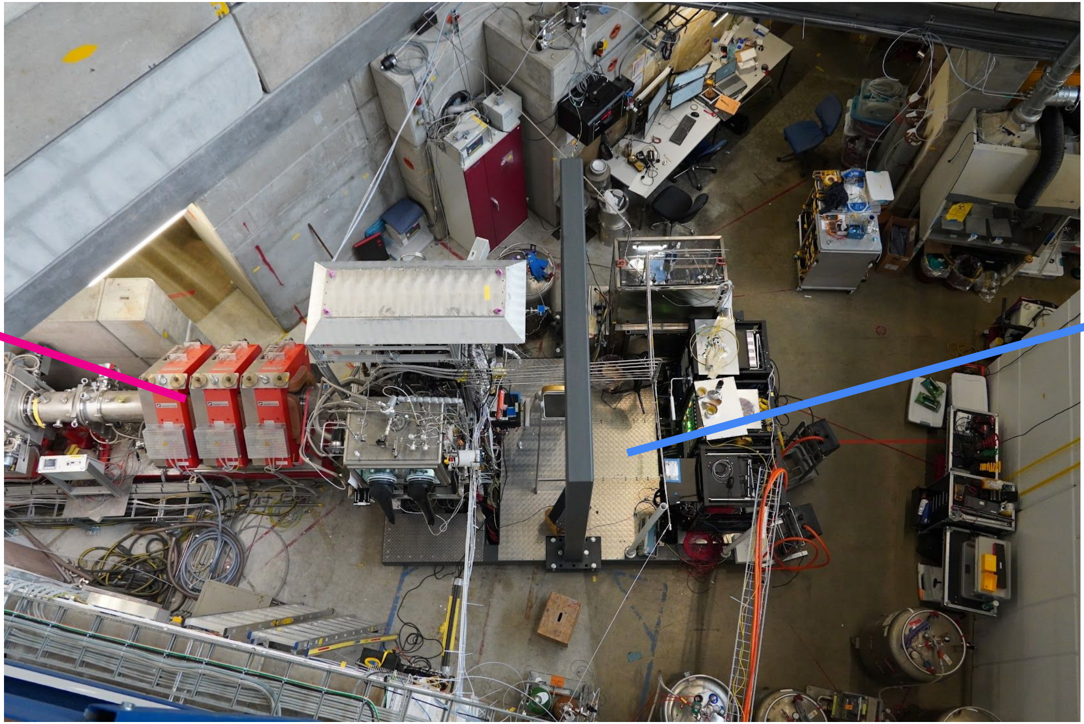
- Both experiment and theory predict that sticking decreases with density.
- Data from four experimental groups is shown.
- At high density, the measured sticking is uniformly lower (better) than predicted by theory
- Density is stated as a fraction of liquid hydrogen atomic number density.

Our Experiment



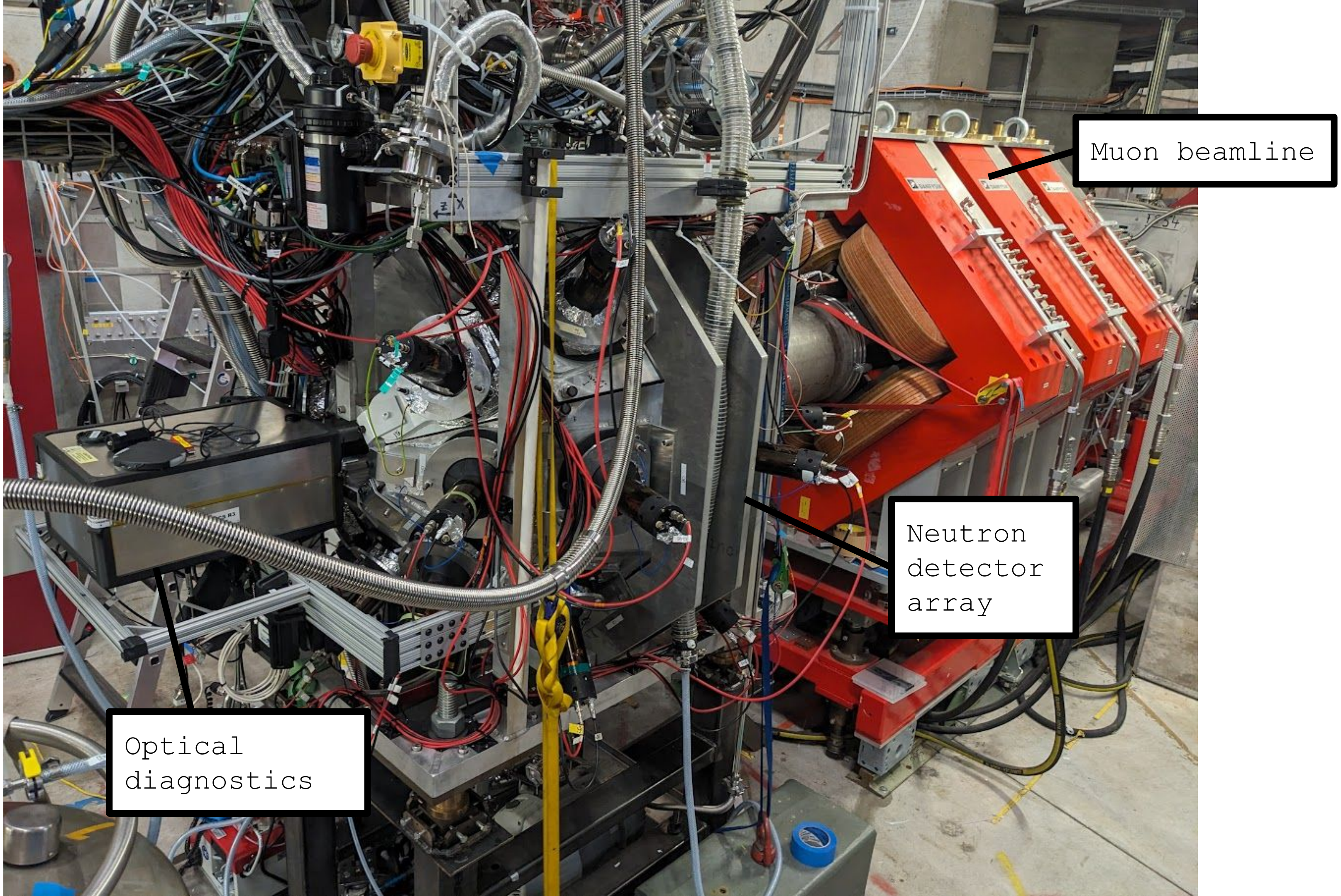
The MuFusE Experiment

πE1 μ Beam



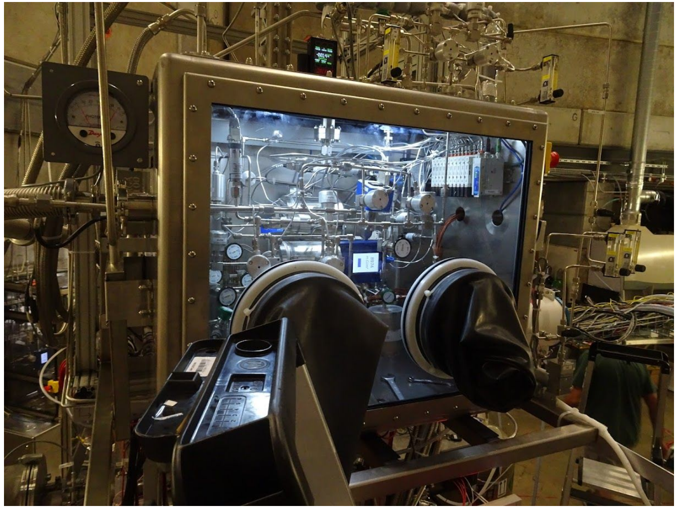
MuFusE Platform

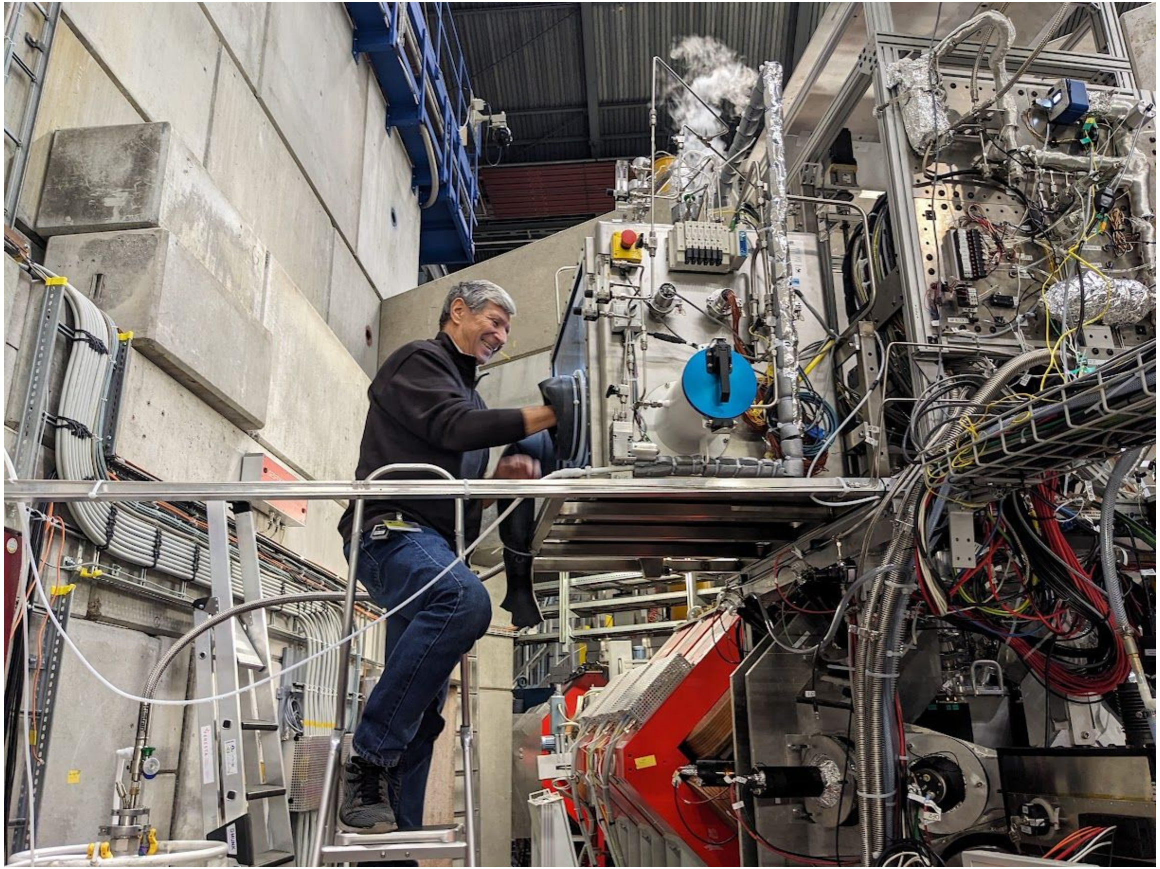
MuFusE operates at the piE1 secondary beamline at the Paul Scherrer Institute's High-Intensity Proton Accelerator. MuFusE integrates deuterium/tritium gas handling, particle detector systems, a compact optics setup for *in situ* cell diagnostics, and 100+ slow-control sensors.


Muon beamline
Neutron detector array
Optical diagnostics

Craning Into piE1...

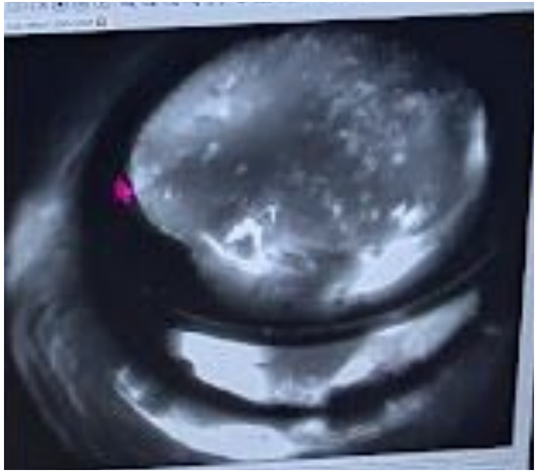
Loading Tritium into the U-beds

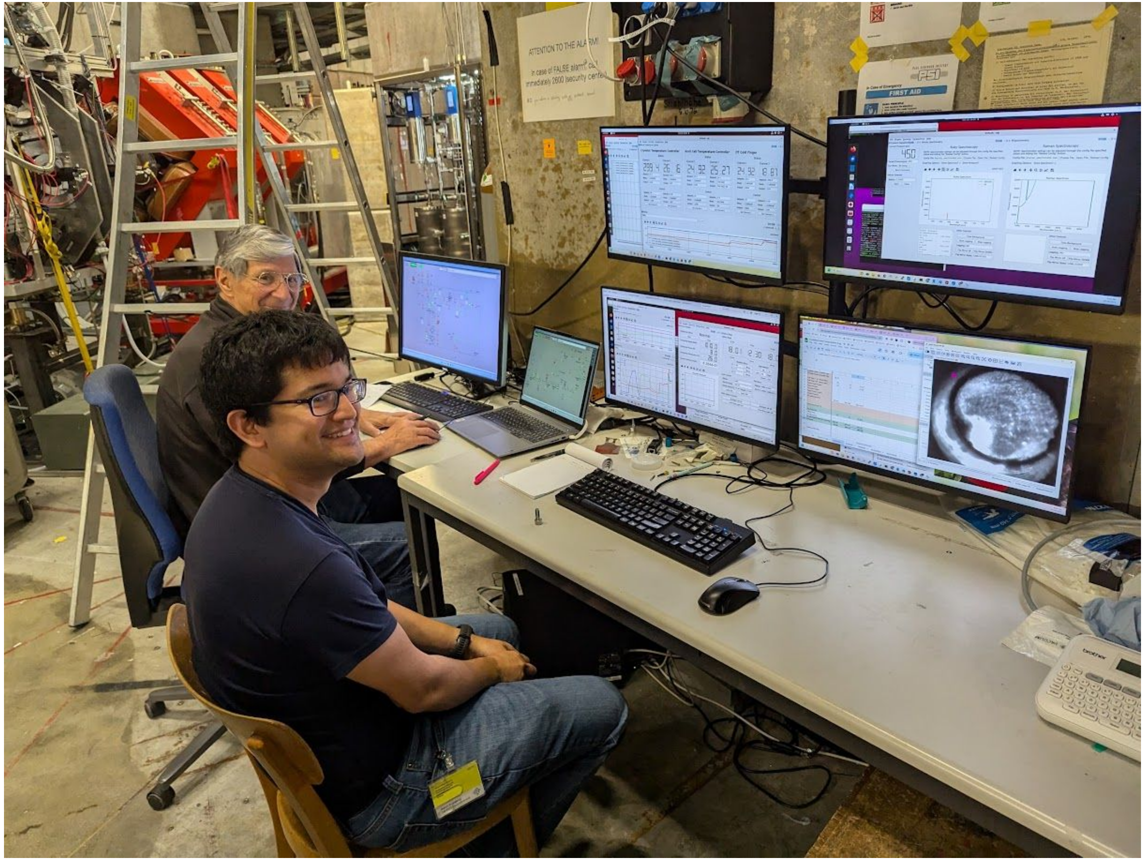




Loading the Cell with Liquid DT

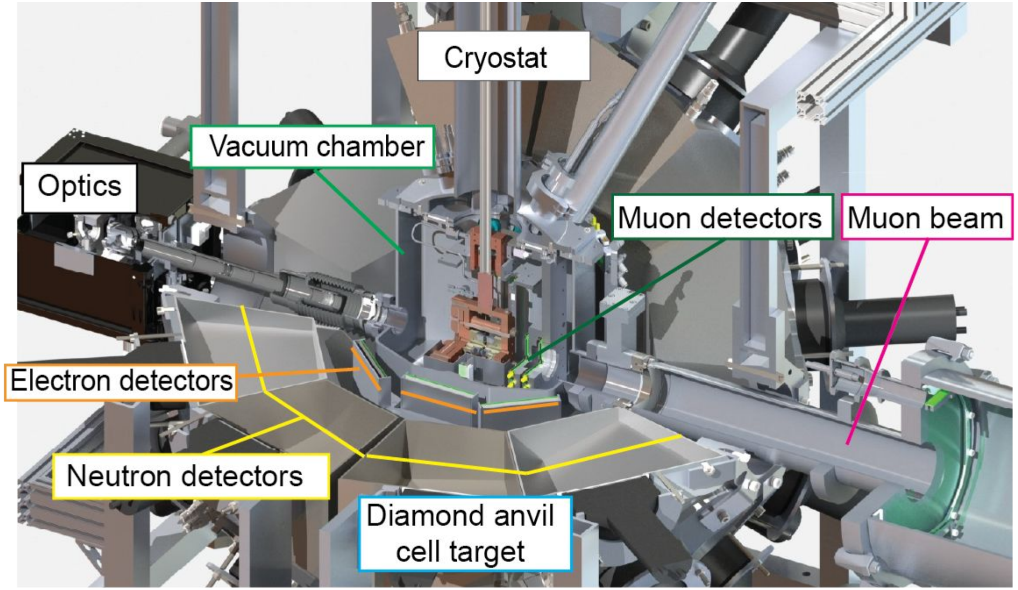
acceleron

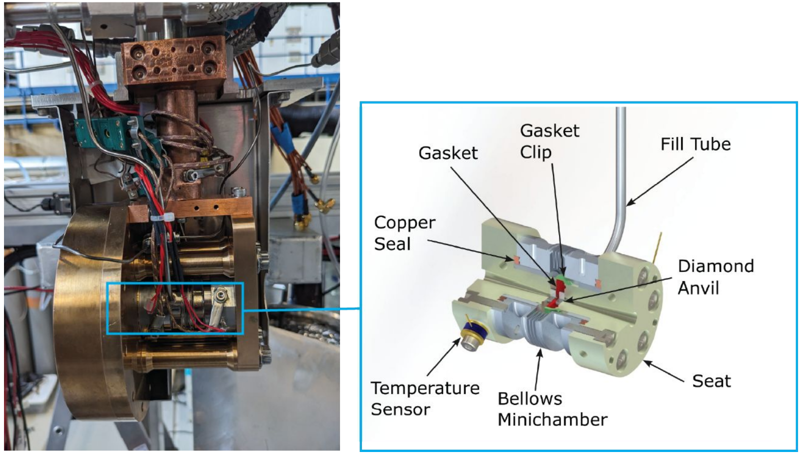




DT gas handling system paper in review and soon to be available on arXiv!

Diamond Anvil Cell

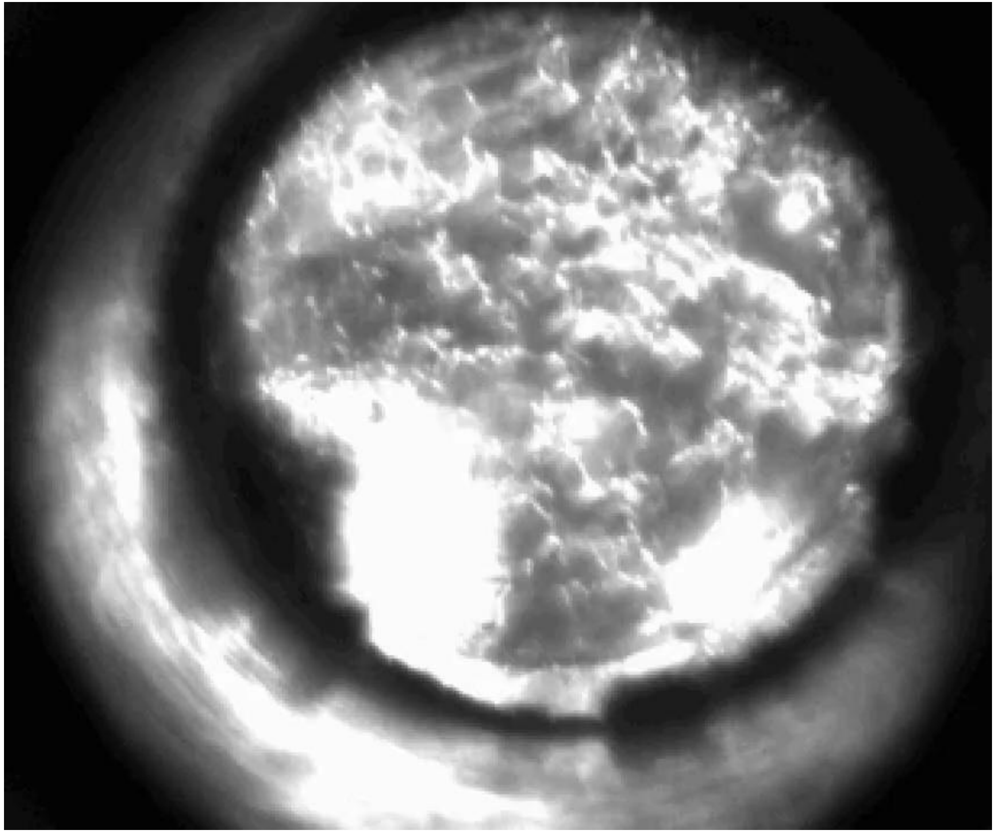




DAC compresses DT mixture to extreme pressures (densities up to 2.2 LHD)

DAC paper submitted for publication and soon to be available on arXiv!

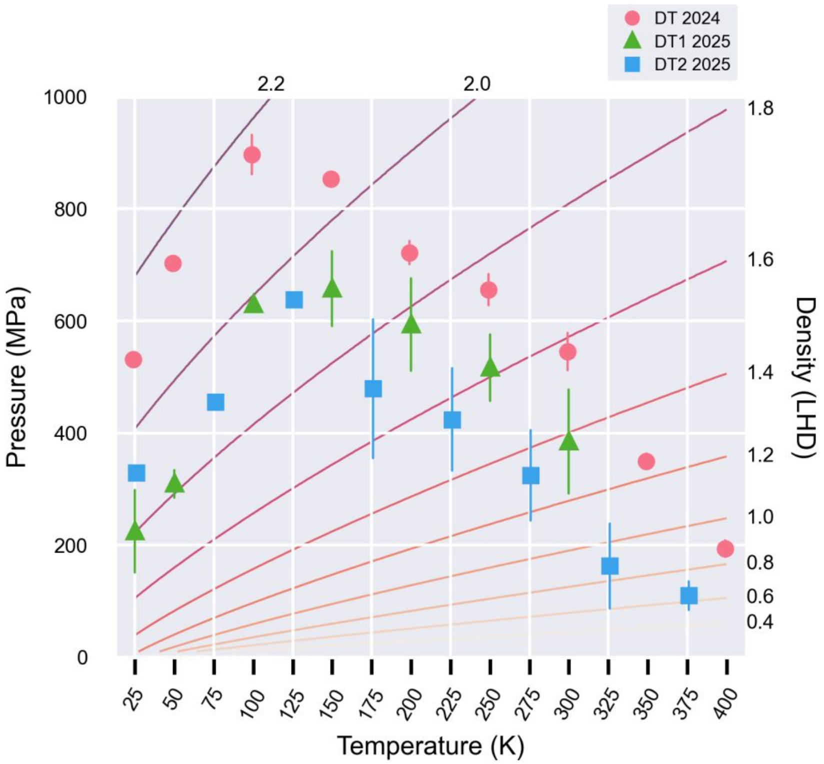
Compression of the Liquid DT to a Solid



2024/2025 Beam Campaigns

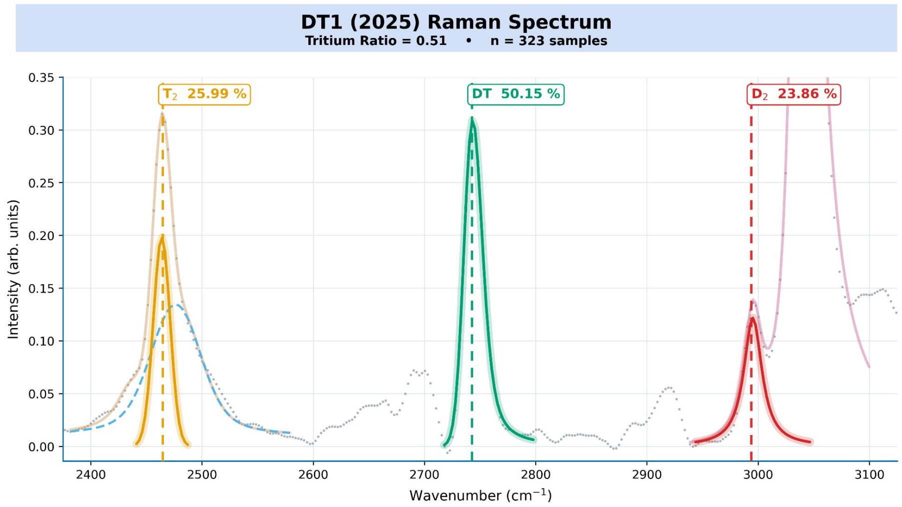
acceleron

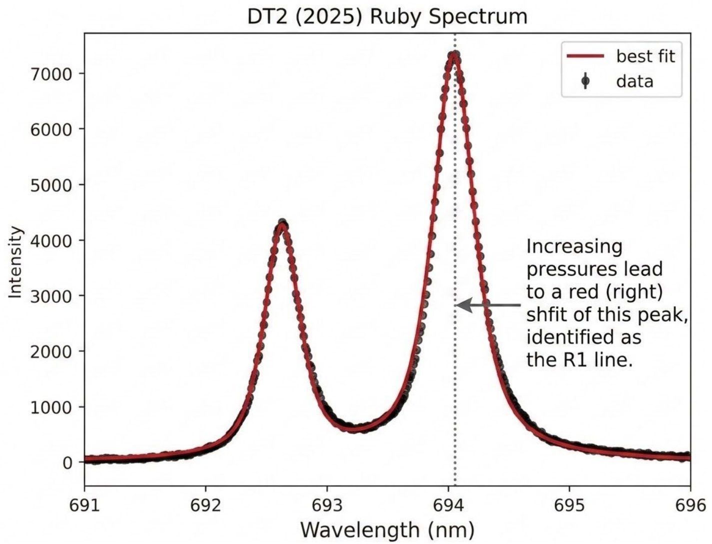
- MuFusE achieved first tritium-operation in our diamond anvil cell in October 2024
  - World-record static DT pressure of 990 MPa: ~3 times higher than previous highest
  - First μCF data collected at densities φ > 1.45 LHD
- For 2025, significant engineering work to increase DAC volume, upgrade detectors and optics, and improve DAQ to handle fusion neutron pileup during DT operations
- Data collected from 5 hydrogen compressions during 2025 beam period:
  - 3 DD + 2 DT cell compressions



Monitoring of Cell Composition and Pressure

acceleron





D_2, DT, T_2 cell contents measured via *Q*-branch Raman Spectroscopy. Relative peak areas are used to determine total Tritium Ratio (T atoms / all H isotope atoms).

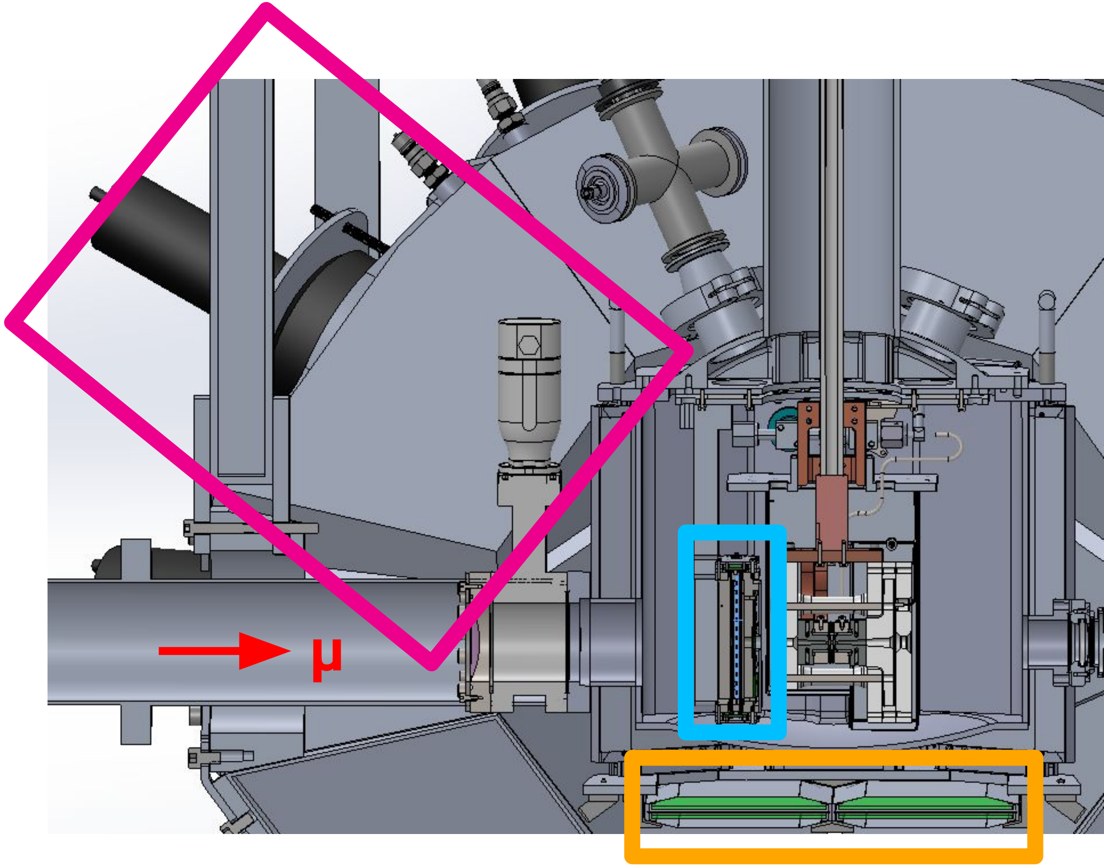
Cell pressures measured with Ruby fluorescence spectroscopy. Temperature-corrected R1 line shift from baseline corresponds to increasing pressures.

MuFusE Detector Systems

acceleron

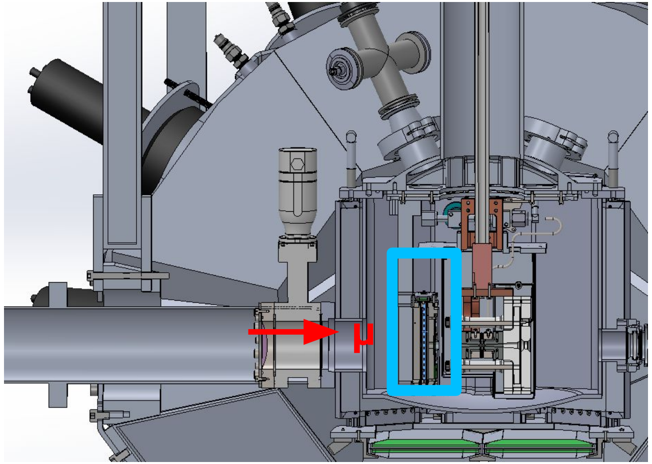
MuFusE uses 3 detector systems to measure μCF reactions:

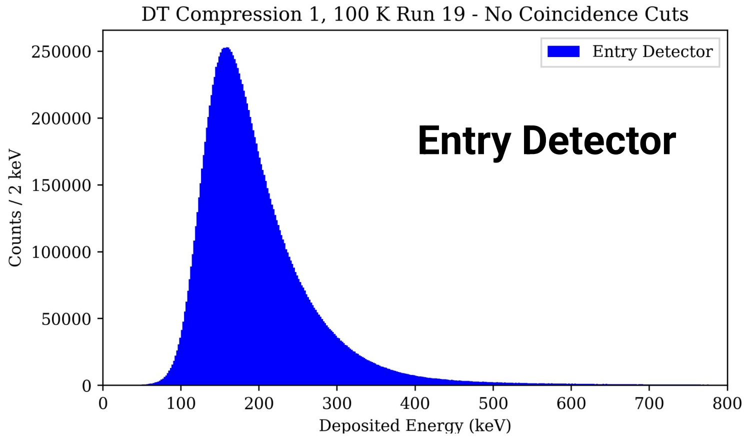
- **Muon entry detector & veto assembly:** measure muons entering the DAQ from piE1 beam
- **Neutron detector ball:** segmented array of liquid scintillator neutron detectors measure fusion activity
- **Electron detector panels** surrounding cryostat resolve muon decay electrons

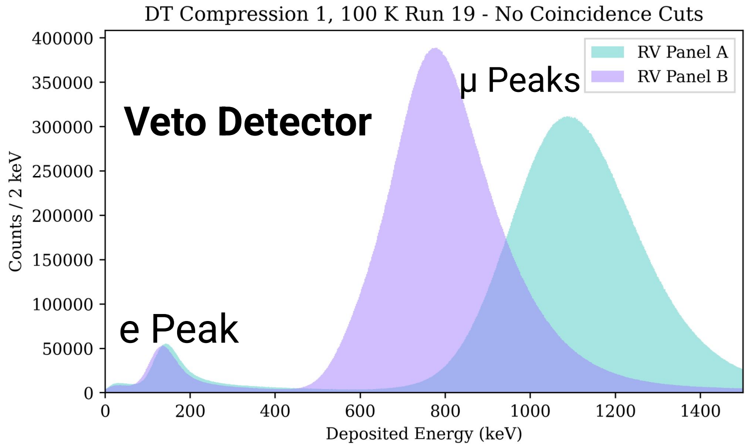


MuFusE Detector Systems

acceleron





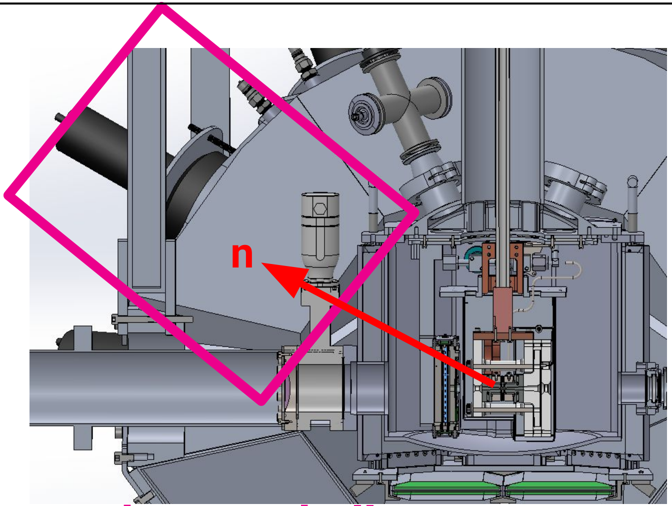


Muon entry detector & veto assembly:

- Muons entering the diamond anvil cell are registered by the muon entry detector, triggering neutron detector waveform acquisition
- Thick veto panels filter off-axis muons and resolve electron contamination within beam

MuFusE Detector Systems

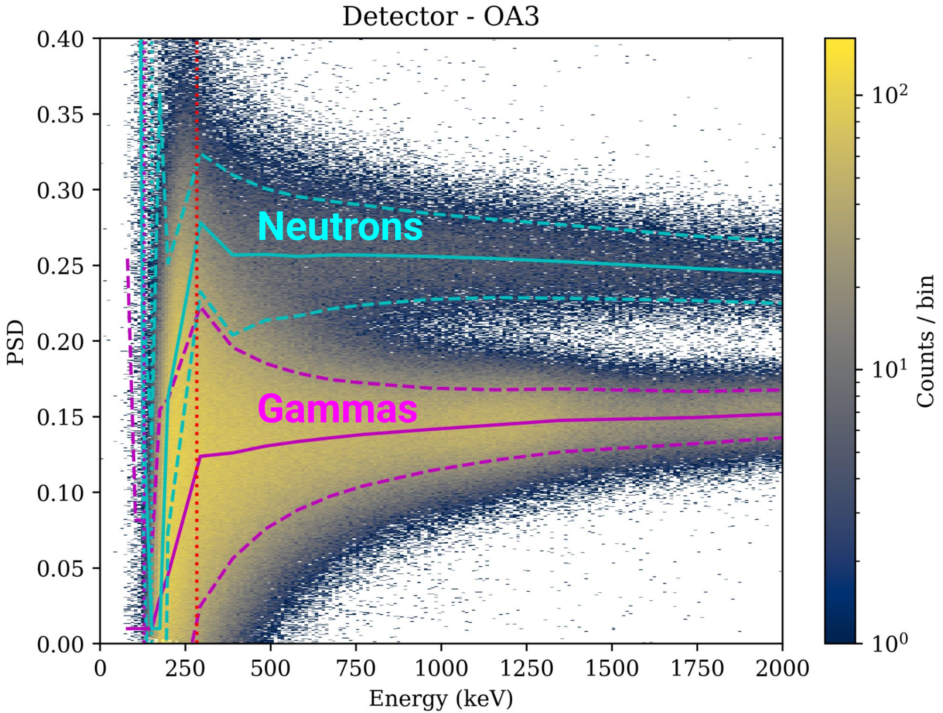
acceleron



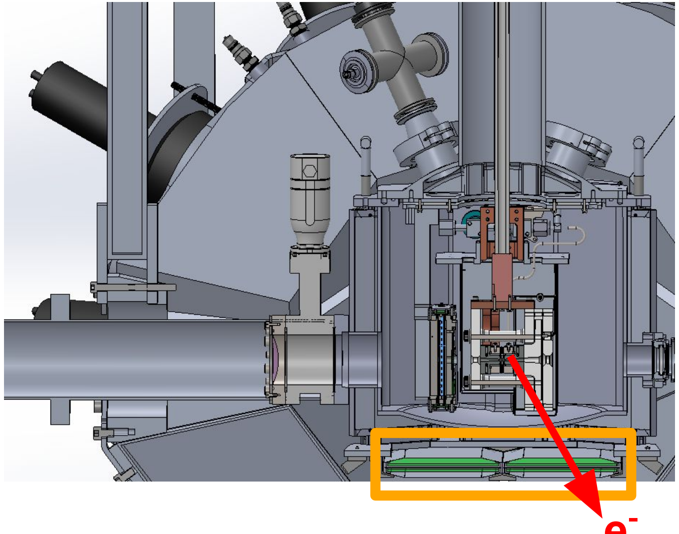
Neutron detector ball:

- Array of up to 28 liquid scintillator neutron detectors with pulse-shape discrimination resolve fusion-neutron-induced activity
- Full waveforms are recorded for fusion events
- ~65% solid-angle coverage around DAC

PSD Performance during AmBe Calibration

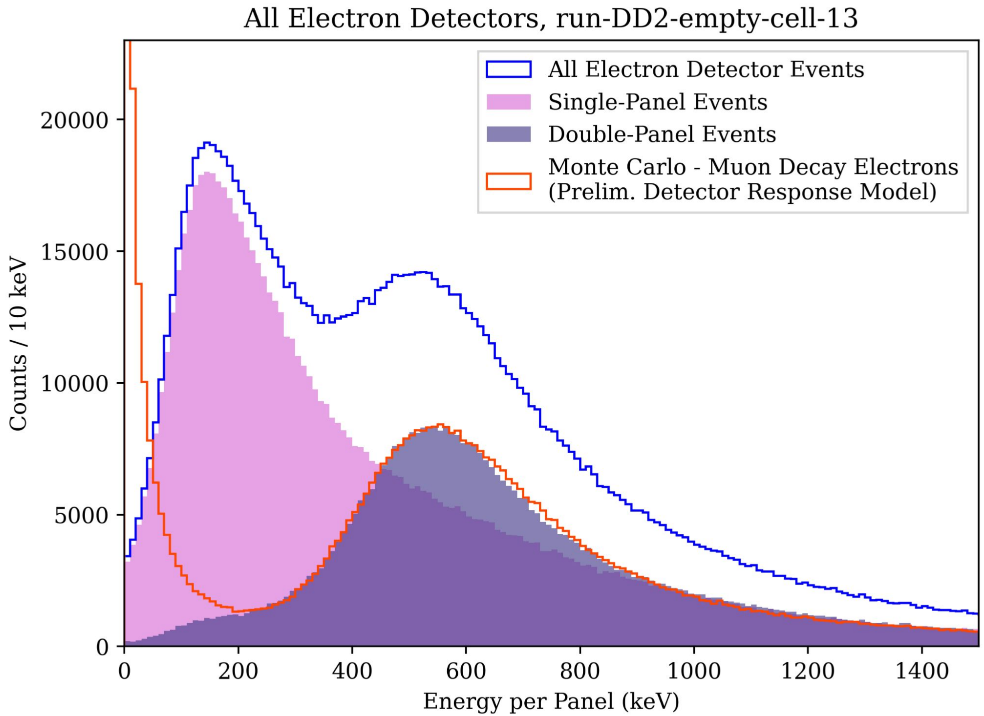


MuFusE Detector Systems



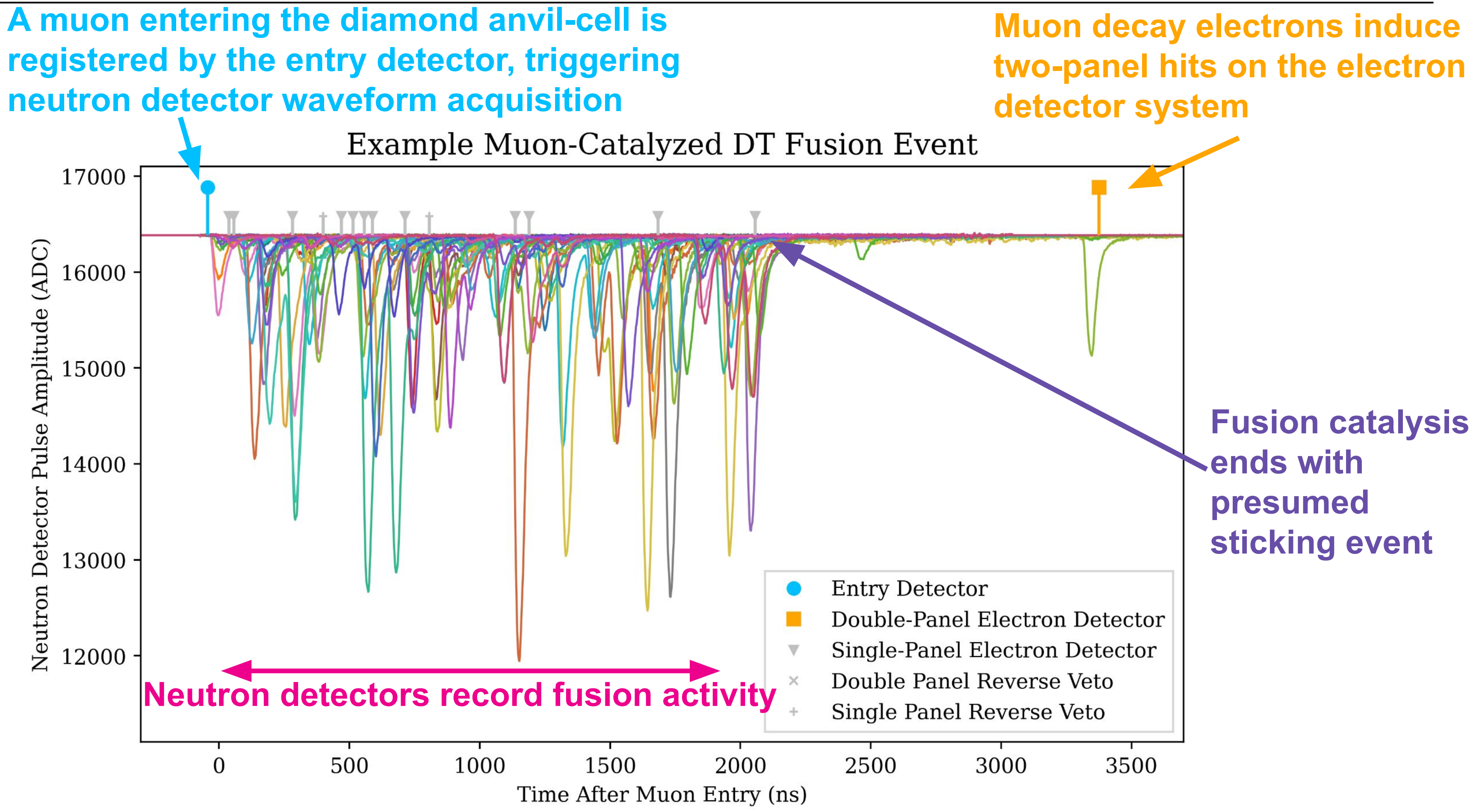
Decay electron detector panels:

- Array of 8 panels surrounding cryostat
- Double-panel design suppresses accidental events from fusion neutrons



MuFusE Detector Systems

acceleron

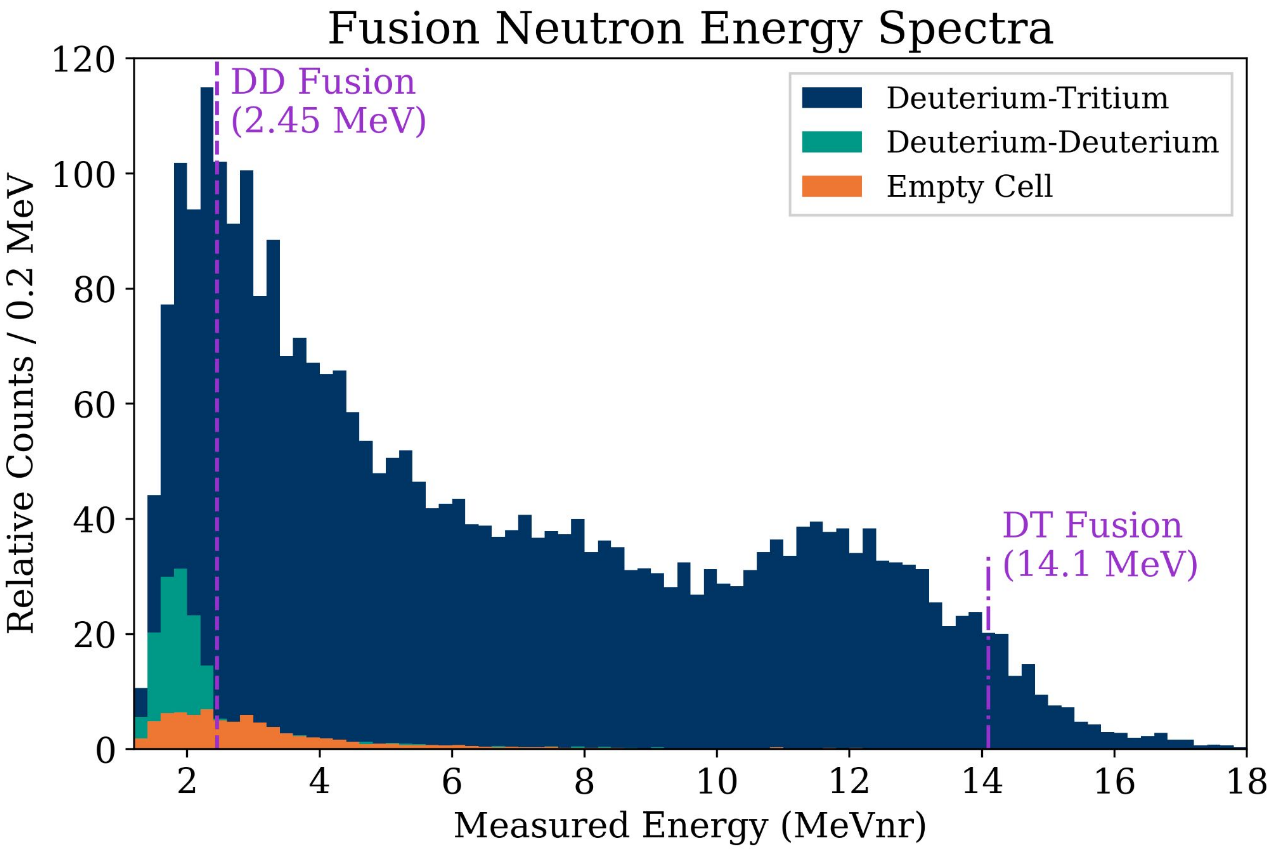


Fusion Observation!

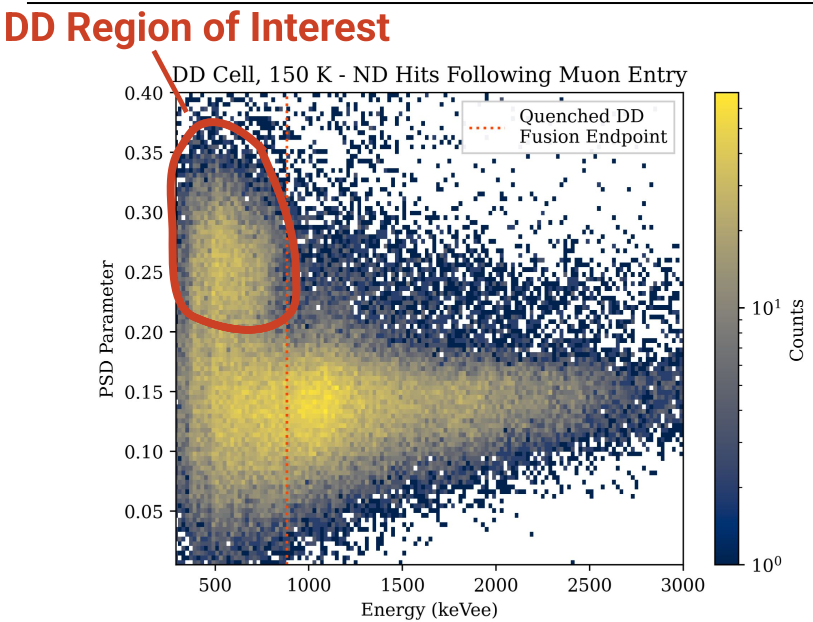
We observe both DD & DT μCF neutrons from our diamond anvil cell!

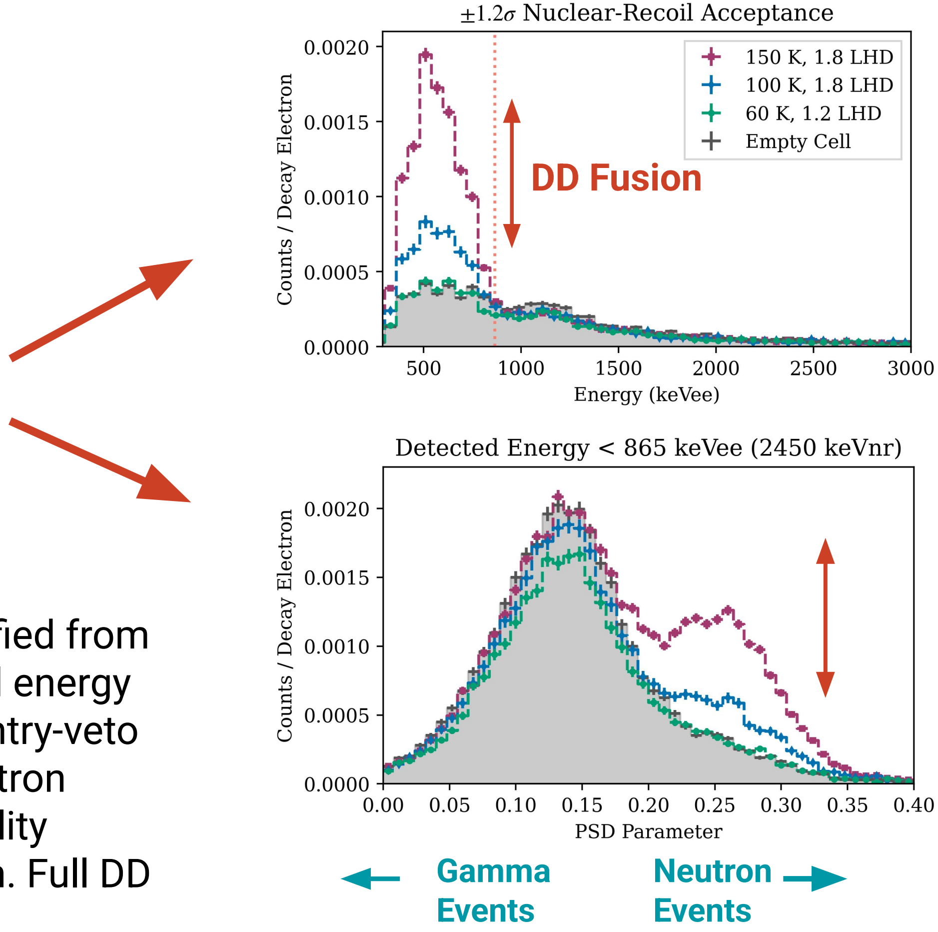
Events selected using pulse-shape discrimination.

DT events *undercounted* here due to pileup - accounted in full kinetics analysis workflow.



MuFusE 2025 - DD Run 2 Results

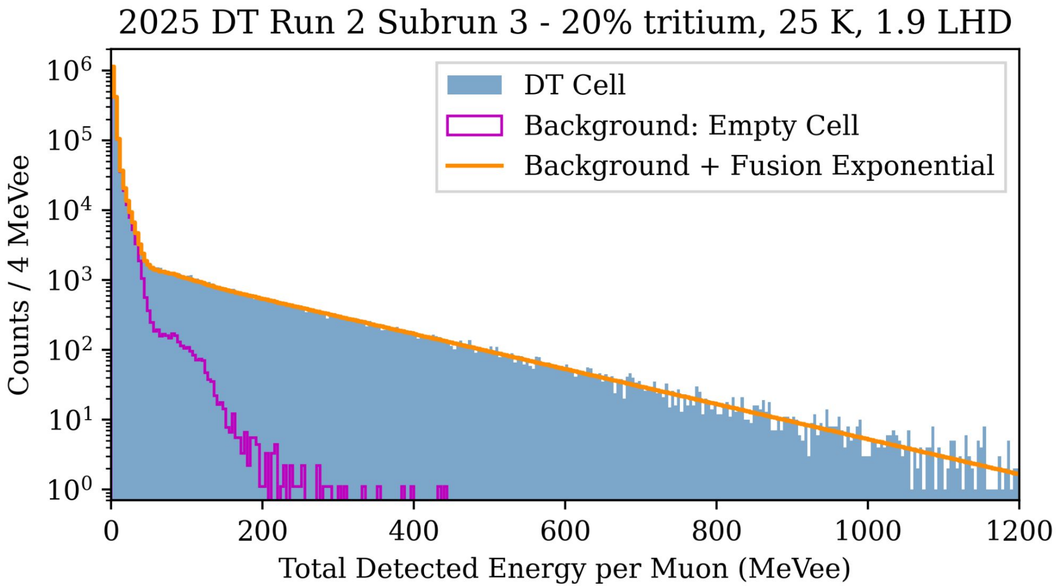


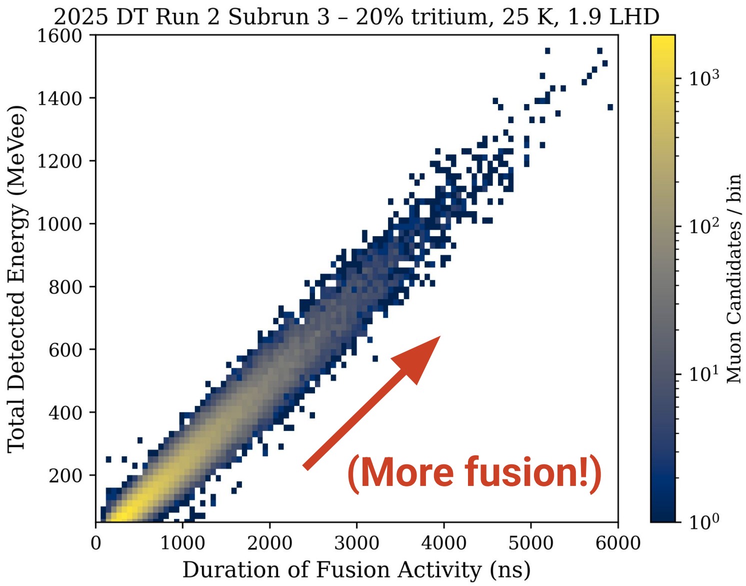


We observe **DD fusion neutrons** at >5σ, as identified from scintillator pulse-shape discrimination (PSD) and energy deposition in neutron detectors, after applying entry-veto and electron-detection selections. Individual neutron detectors are selected above their PSD resolvability threshold to ensure reliable particle-identification. Full DD kinematics still in progress.

MuFusE 2025 - DT Results (T<150K)

acceleron

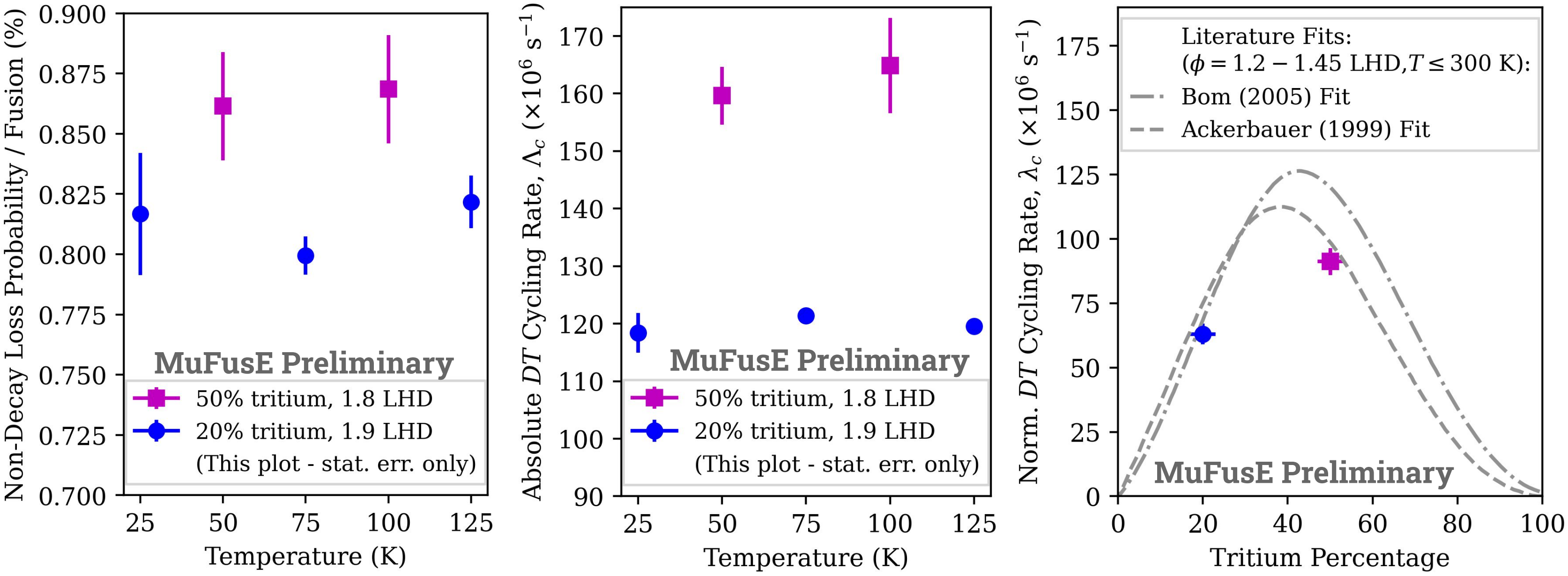




DT analysis techniques use total energy received by neutron detectors to mitigate fusion neutron pileup effects.

Signature of DT fusion cycle is joint exponential distribution of total detected energy & duration of fusion activity per muon: prolific signal unambiguously resolved above background.

MuFusE 2025 - DT Results (T<150K)



Total cycling rates & non-decay loss probabilities determined from loss timescale of fusion events together with total detected energy yields.

50% tritium compression exhibits fastest absolute cycling rate observed in an equilibrated isotopologue mixture. In progress: analysis of sub-process kinetics, higher temperature runs, and loss sources.

Next Steps

- Data analysis for last-neutron-to-electron time spectrum to quantify loss mechanisms including:
  - Wall losses due to muonic alphas
  - Wall losses due to hot muonic atoms
  - Transfer to impurities (He-4, N, O)
  - Transfer to He-3
- Better-quantify impurities using online hydrogen-elimination mass spectrometer
- Runs in larger cells (including cm-scale)
- Runs in smaller cells

Acknowledgements

A. Adamczak[o], J.A. Allen[a], A. Antognini[c,m], E. G. Badaracco[d,i], J. Betances[a,n], N.J. Brennan[a], R. Chaney[a], W. Cutler[f,j], J. Davies[e], C. Forrest[e], A P. Gandhi[d], V. Glebov[e], A. Golossanov[c,f], D.M. Harrington[a], J.T. Hinchen[a], P.A. Holden[a], C. Izzo[d], C. Johnstone[d], J.D. Kalow[a], K. Kem[a], M. Khandaker[a], M. Kiburg[d], I. Kiniti[a,n], A.N. Knaian[a,c,d,f], L.E. Knaian[f], E. Koukina[f], K. Lau[a], J. Larson[k], K.R. Lynch[b,d], N.A. MacFadden[a,g], A. Mazzacane[d], P.A. McDaniel[a] , S.O. Newburg[a,f], E. Niner, K. Payne[a], C.C. Petitjean[c] , R. Ridgeway[d] , A. Sampat[a], W. Shamyda[e,l], W. Stadolnik[a,j], I.D. Spool[a] , S. Tripathy[b,d], D. Zajac[a,j]

acceleron ETH zürich arpa·e CHANGING WHAT'S POSSIBLE Fermilab PAUL SCHERRER INSTITUT PSI

YORK UR LLE Berkeley UNIVERSITY OF CALIFORNIA UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN