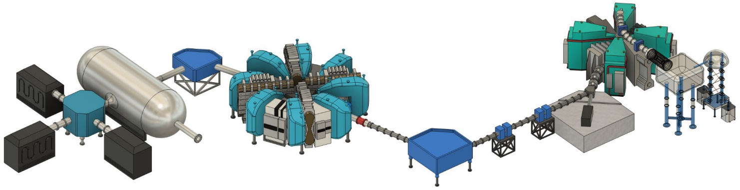
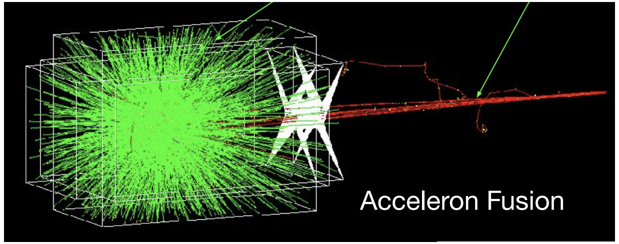


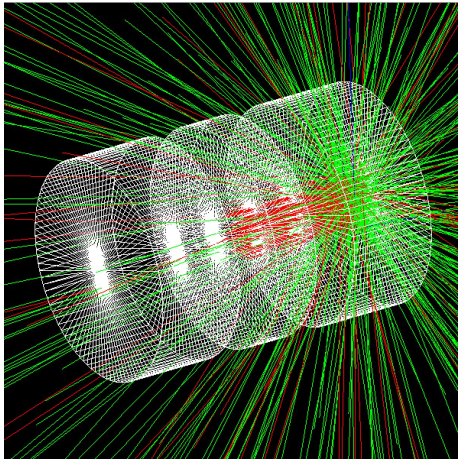


acceleron

Muon Catalyzed Fusion (MCF)

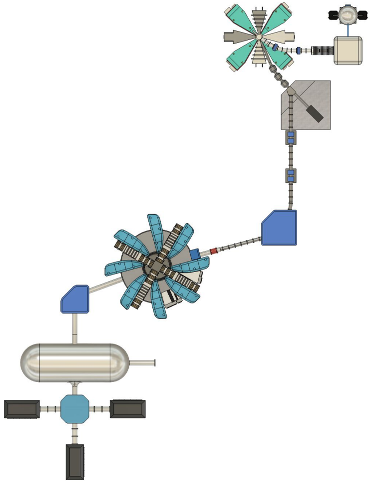
Himani Mishra and Thomas Rimer

04.24.2026



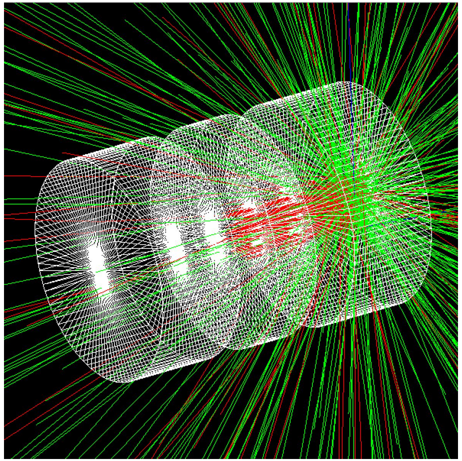
1. MCF Reaction Dynamics and Geant4 Simulation - Himani

2. Designing a Muon Source in CAD - Thomas



1. MCF Reaction Dynamics and Geant4 Simulations - Himani

a. MCF Reaction
b. Geant4
c. Simulation Geometry
d. Reaction Rates & Constants
e. Experiments - Initial Energy, Temperature, Pressure, T:D Ratio
f. Reaction Dynamics Takeaways

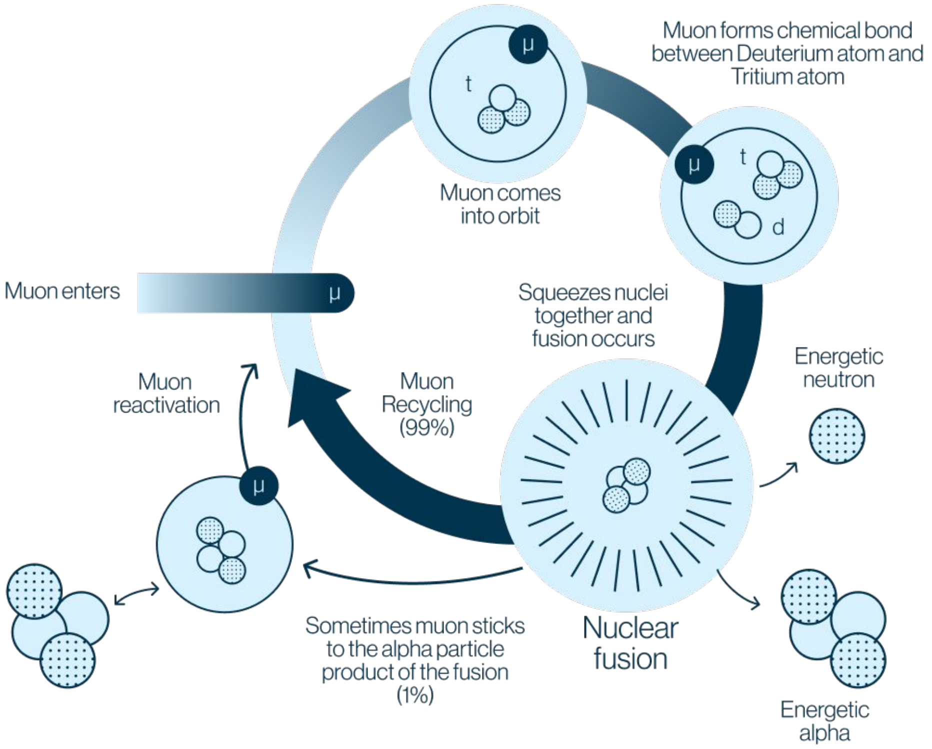


The Reaction

- Muon: a negatively charged particle, ~207 times mass of electron
  → **Catalyzes the reaction!**
- Reaction:
  - Alpha Sticking: dtμ → αμ + n + 14.1 MeV
  - No Alpha Sticking: dtμ → α + μ + n + 14.1 MeV

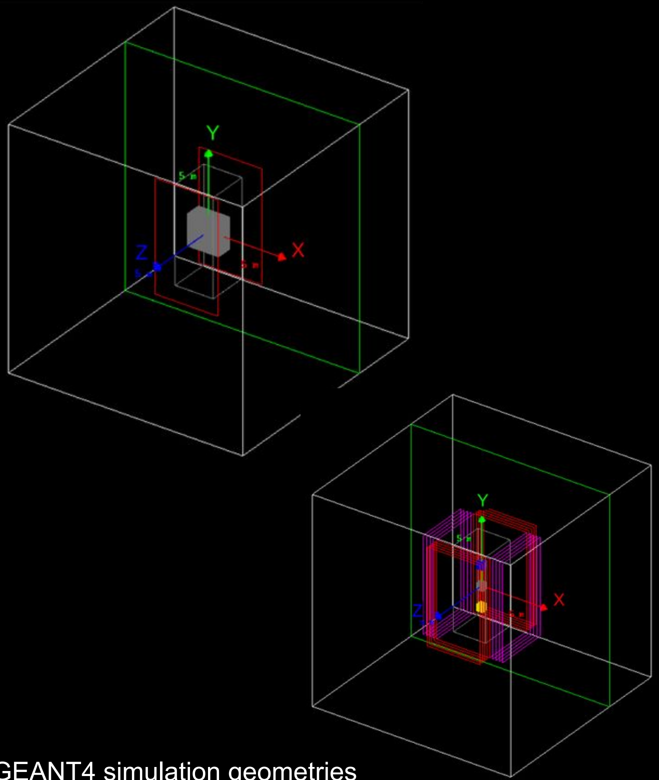
→ Advantage: low temperature 1300 K << 100 million K

→ Challenge: Alpha sticking + Muon generation



https://www.acceleron.energy/

Geant4

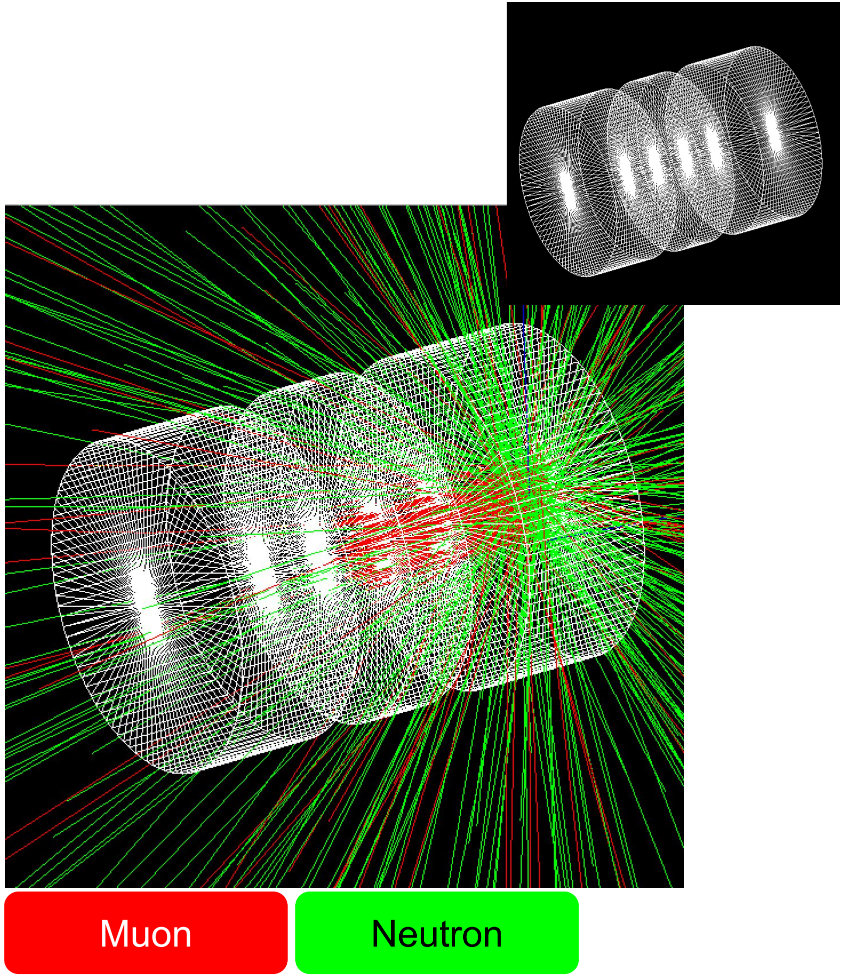


[GEANT4 simulation geometries]

Simulation Geometry

- Simplified geometry
  - 2.5 mm diameter diamond, 0.5 mm thick
  - High pressure DT gas cell target at 3 LHD
- 500 muons - 4.1 MeV which are slowed down to **0.7 MeV** at diamond anvil cell entry

→ Geant4 is not useful for visualization but incredibly useful for dynamics statistics

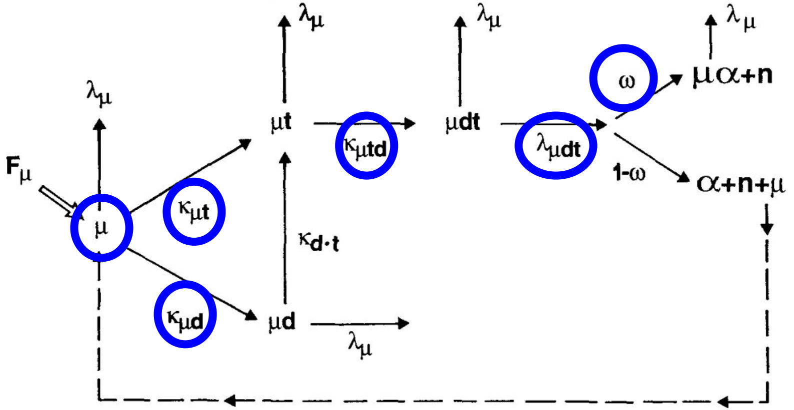


Constant Parameters

Harms, Table 12.1

Process	Parameter	Value
Muon decay	λ_μ	$0.45\times10^{6}\ s^{-1}$
μ-d-t fusion	$\lambda_{\mu dt}$	$1.1\times10^{12}\ s^{-1}$
Muonic atom formation	$\kappa_{\mu d}$	$1.2\times10^{-12}\ cm^{3}\ s^{-1}$
Muonic atom formation	$\kappa_{\mu t}$	$1.2\times10^{-12}\ cm^{3}\ s^{-1}$
Muonic molecule formation	$\kappa_{\mu dt}$	$0.25\times10^{-14}\ cm^{3}\ s^{-1}$
Isotope exchange process	$\kappa_{d\cdot t}$	$0.5\times10^{-14}\ cm^{3}\ s^{-1}$
Muon sticking probability	ω	0.007

Harms, Figure 12.4



Reactivation probability = 0.30

Nuclear capture rate: $3.0 * 10^{-4}$ / ns

Alpha Sticking: dtμ → αμ + n + 14.1 MeV

No Alpha Sticking: dtμ → α + μ + n + 14.1 MeV

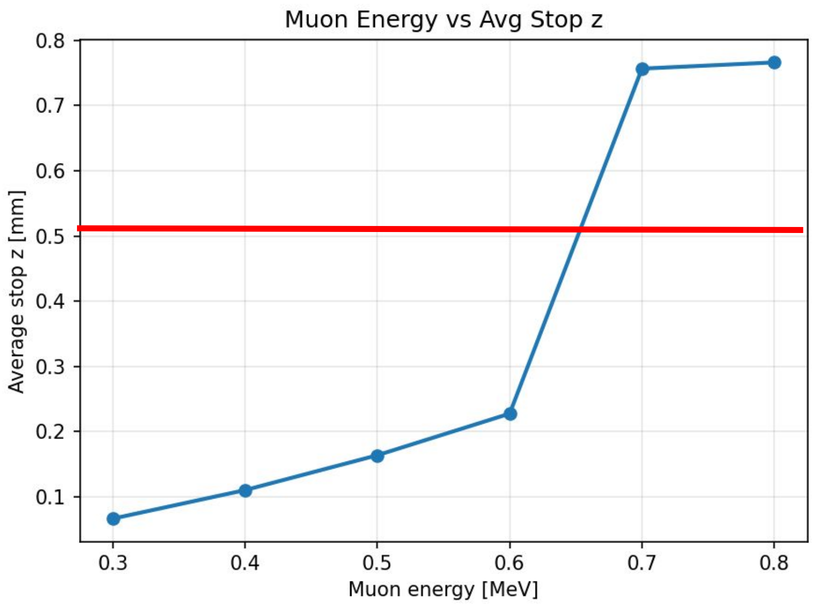
Four Experiments

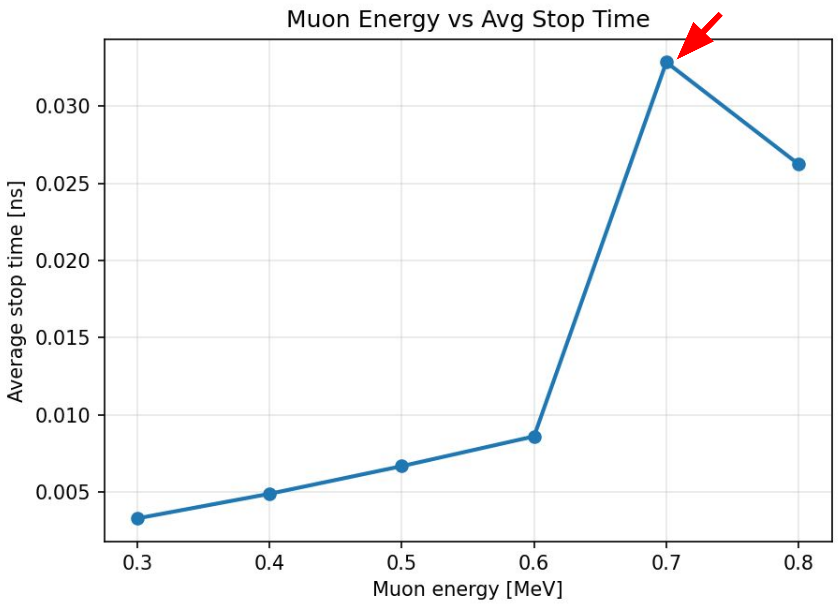
1. **Initial Muon Energy:** 0.3-0.8 MeV
2. **Temperature**: 7, 10, 100-1700 K
3. **Pressure**: 1-10 GPa
4. **T:D ratio**: 0.1-0.9

→ Muon stopping time + location

→ Number of reactions
→ Number of fusion reaction per stopped muon
→ Energy generated
→ Muonic molecule formation rate (rate limiting step)
→ Neutron flux

Initial Muon Energy → Muon Stopping Location + Time

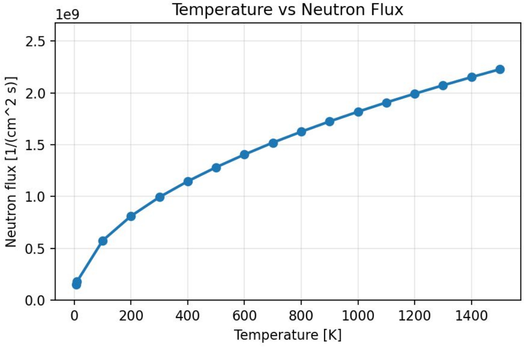


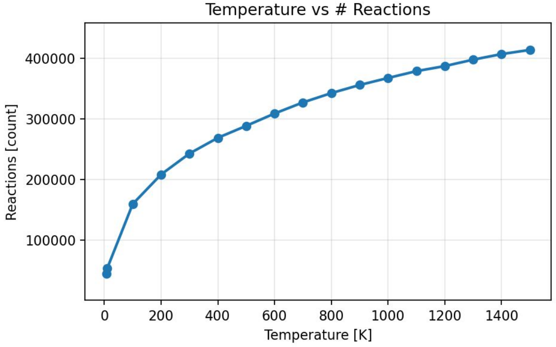


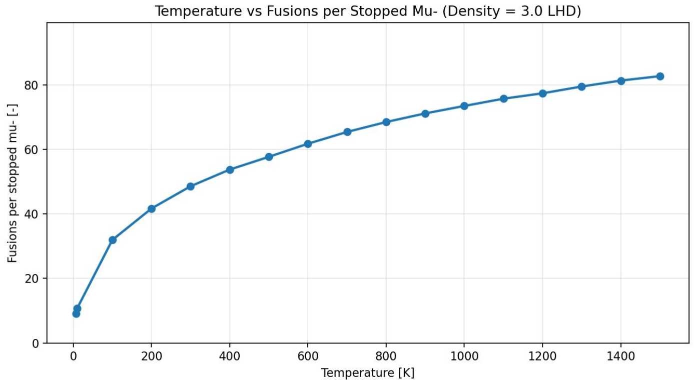
→ need muon to enter diamond at ~0.7 MeV

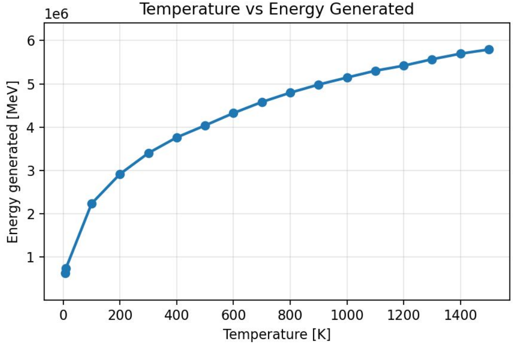
→ takes around 0.03 ns for muon to reach target from diamond anvil cell entry
→ sudden decrease due to muon slamming into back of diamond anvil cell

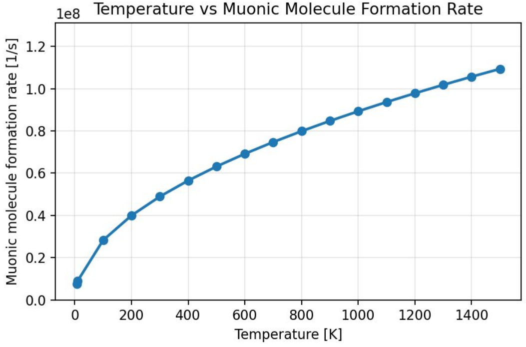
Temperature P = 5 GPa







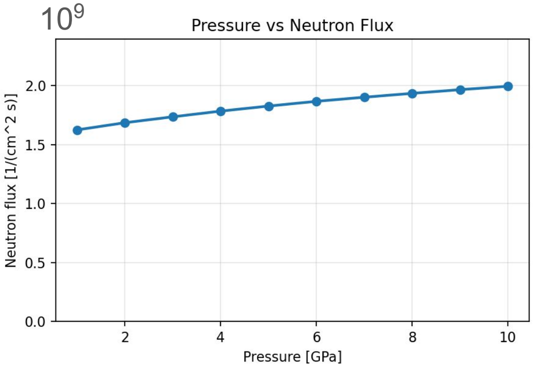


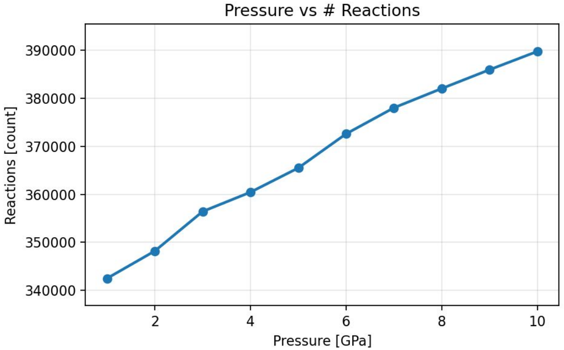


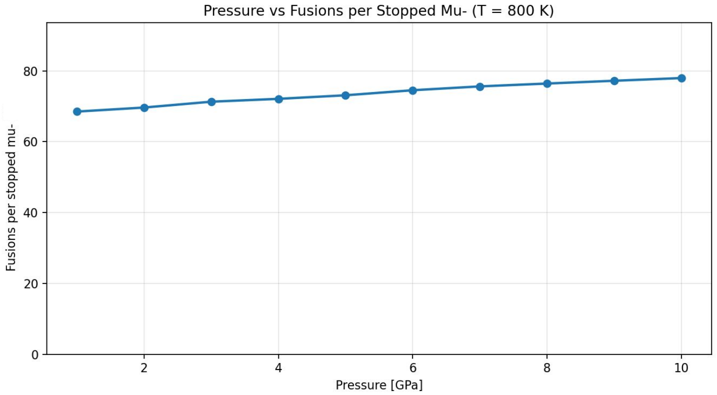
T ↑ →

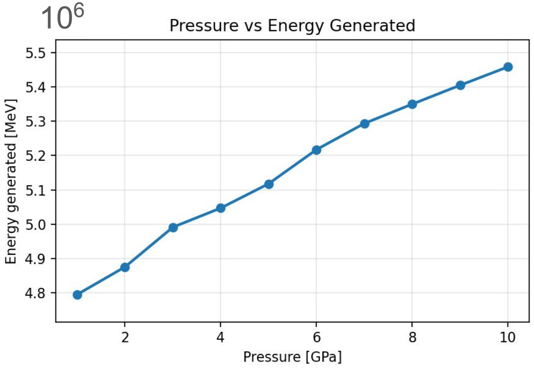
↑ # reactions
↑ energy produced
↑ neutron flux
↑ muonic molecule formation rate

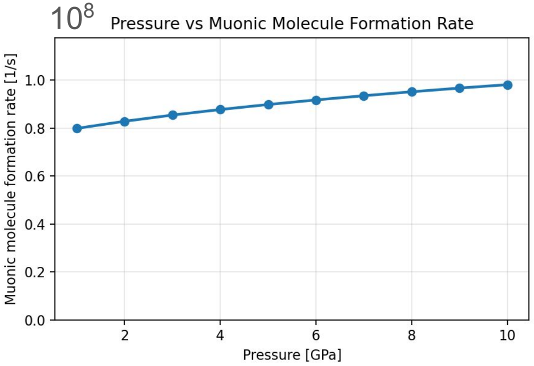
Pressure T = 800 K







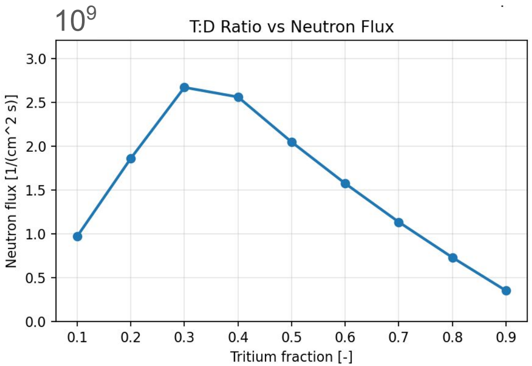


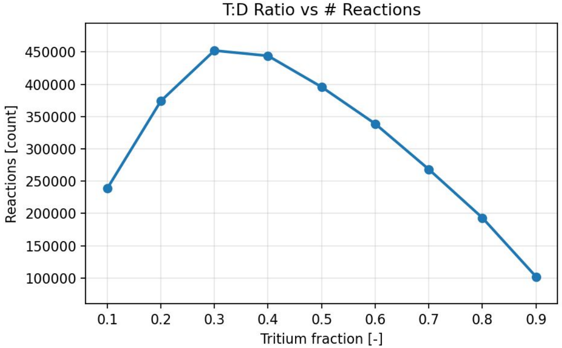


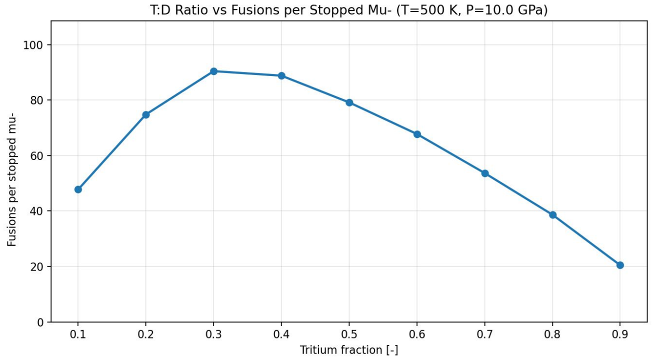
P ↑ ⟶

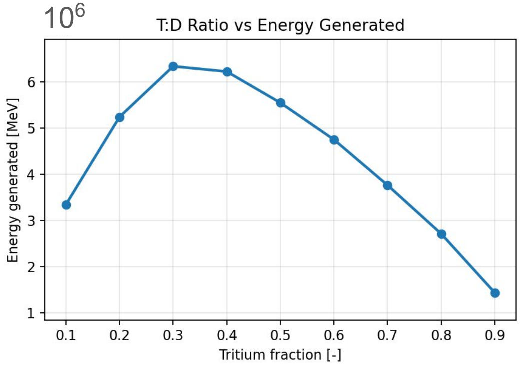
↑ # reactions
↑ energy produced
↑ neutron flux
↑ muonic molecule formation rate

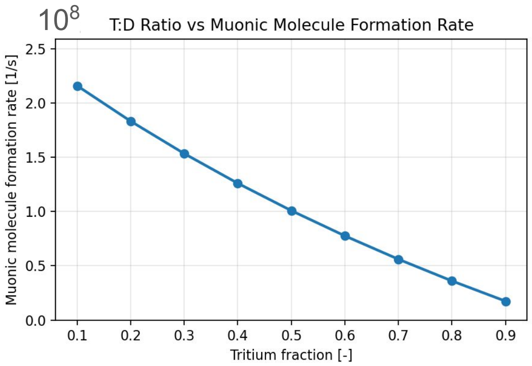
T:D Ratio T = 500 K, P = 10 GPa











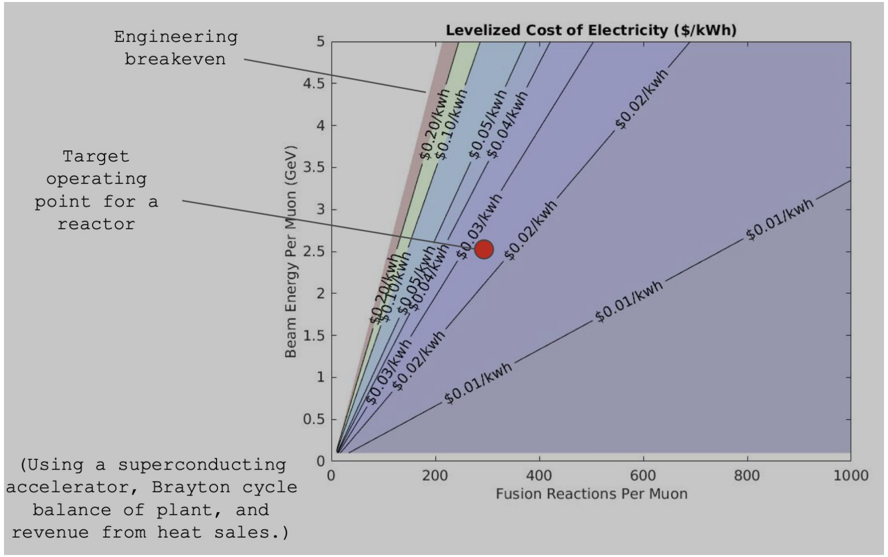
- 30% T:D best for # reactions and energy generated
- Acceleron: 35% Tritium used
- Muonic molecule formation rate compromised slightly and neutron flux high (as has been with greater number of reactions)

Takeaways for MCF Dynamics

→ Ideal temp: 500-800K
→ Ideal pressure: as high as possible, without causing diamond cracking (10 GPa)

- 10 GPa, 800K, 30% T:D ratio

→ Initial muon energy (at least 0.7 MeV)
→ 300 reactions/muon is the goal - must solve alpha sticking and reactivation issue



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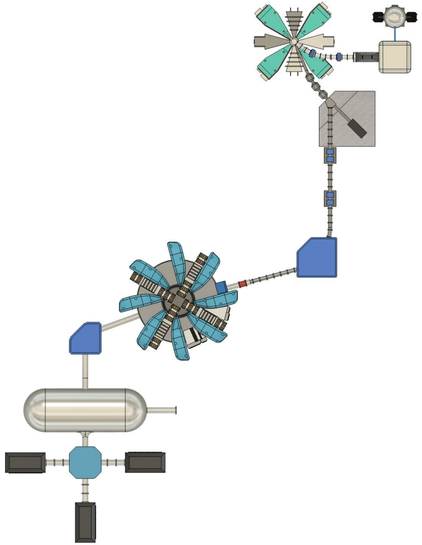
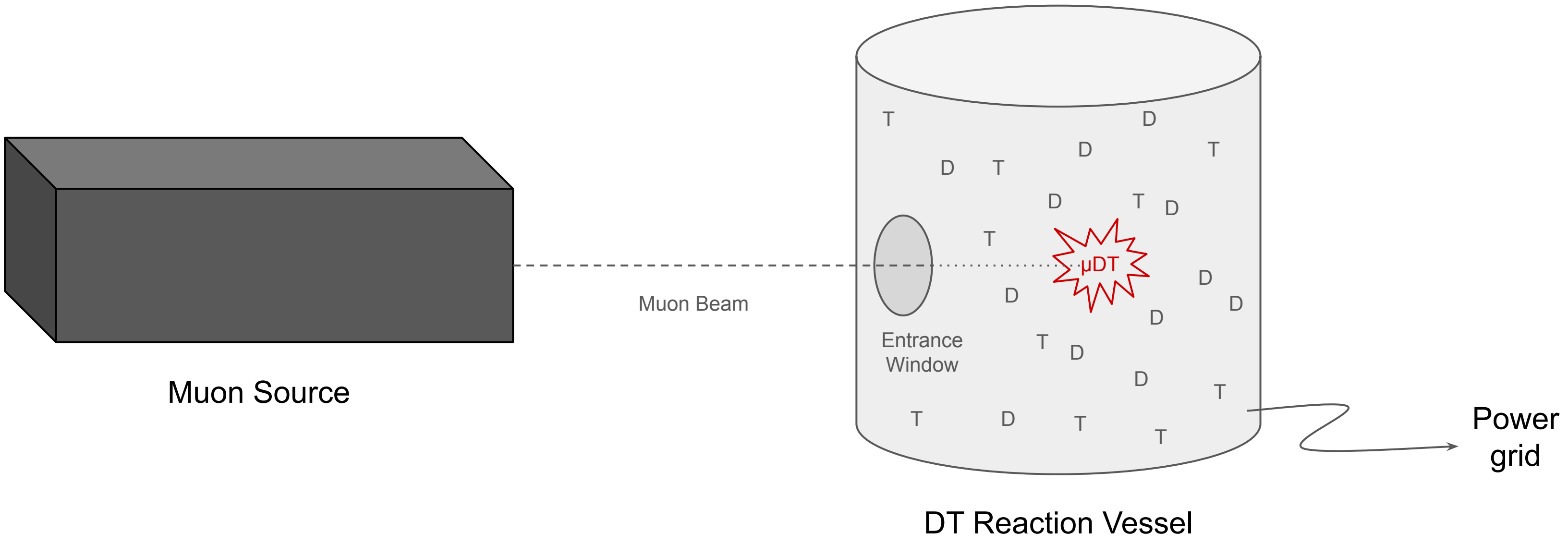
[7] Geant4 Collaboration, "Geant4 Source Code: Hadronic Stopping Processes," GitHub repository (accessed 2026), https://github.com/Geant4/geant4/tree/b4a16de652ec244f7a0ecc0a5cacfee21930bf75/source/processes/hadronic/stopping/include.

2. Designing a Muon Source in CAD - Thomas

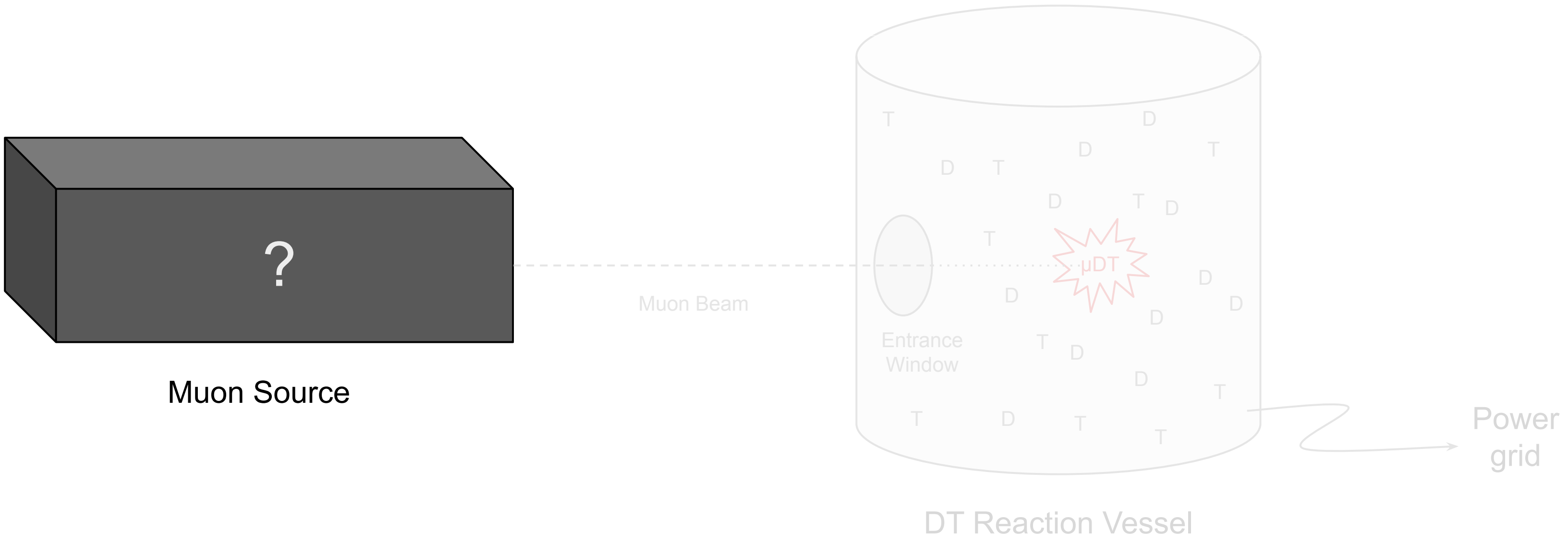
a. Review of muon sources/muon generation
b. Overview of CAD
c. Pre-Accelerator
d. Injector
e. Transfer Optics
f. Primary Accelerator
g. Target



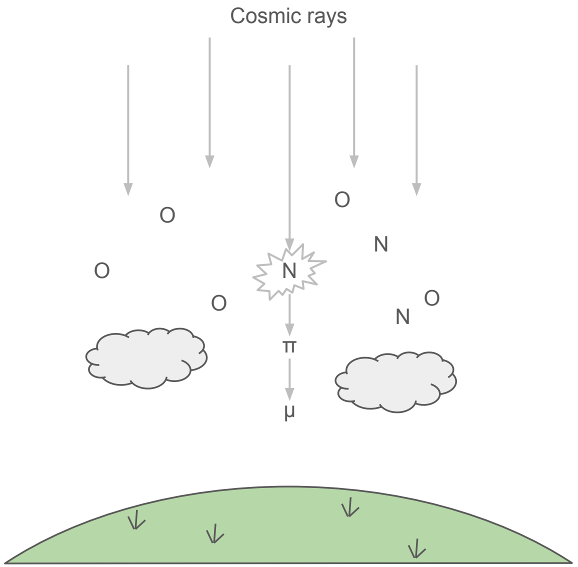
What’s a Muon Source?



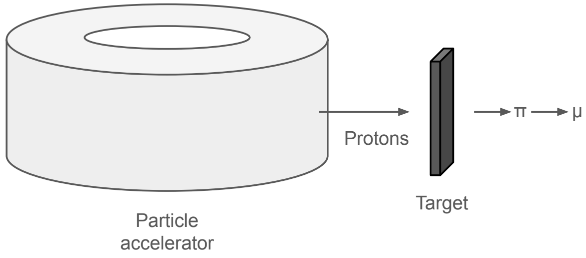
What's a Muon Source?



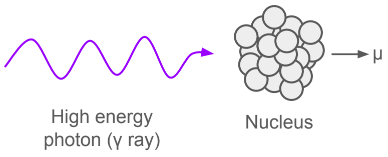
Ways to generate muons



Cosmic Ray Spallation



Particle Accelerators



Photoproduction

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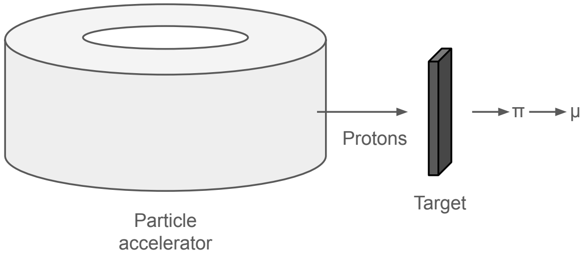


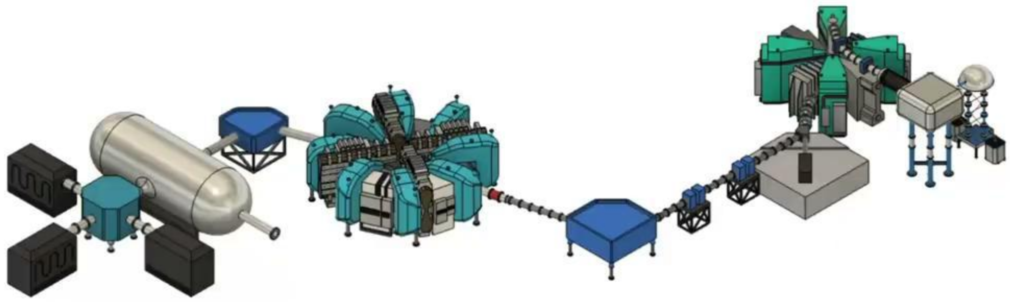
Particle Accelerators

Photoproduction

My Proposed Muon Source

Amalgamation of existing muon facility designs and research papers

- 🇨🇭**PSI (primary)**
- 🇨🇦TRIUMF
- 🇬🇧ISIS



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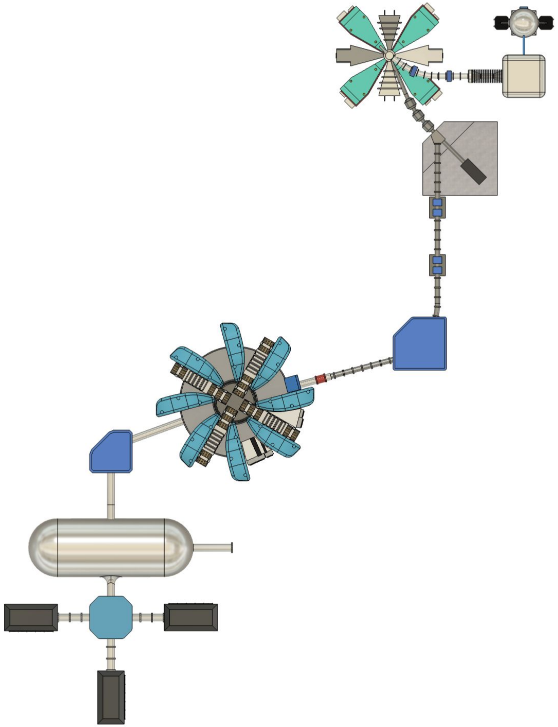
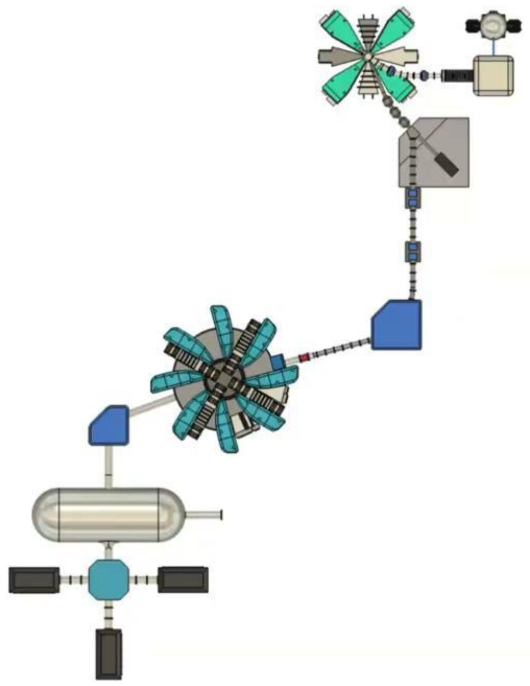


Pre-Accelerator

- Preconditions protons for initial cyclotron (injector)
- Cockcroft-walton (CW) architecture
  - Diode/capacitor tower recitifes low-voltage AC → high-voltage DC
  - 810 kV (4% speed of light)
- Proton source
  - 1100 W, 2.45 GHz microwave H gas cavity
  - 10-12 mA (~10 trillion protons)
- Acceleration
  - 60 keV (source) + 810 keV (acceleration) = 870 keV output



Pre-accelerator > Injector > Transfer optics > Primary Accelerator > Target

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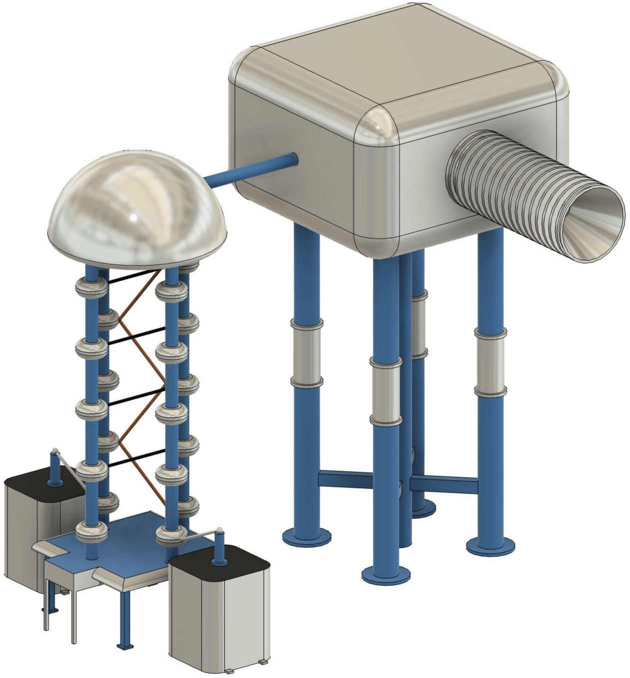
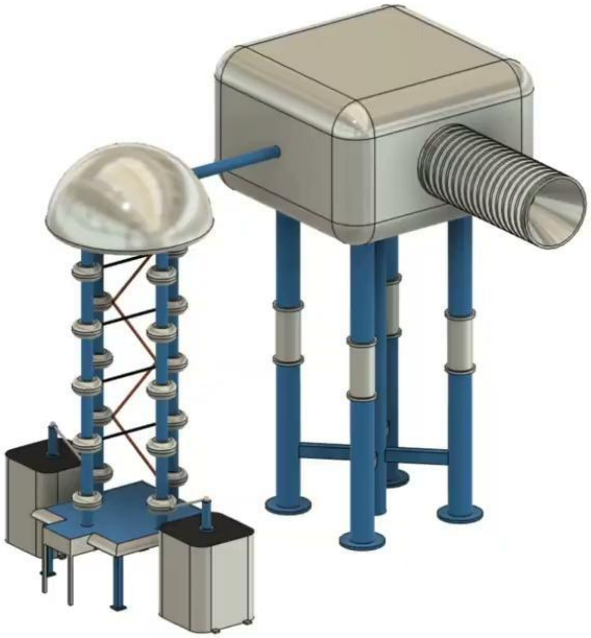


Pre-accelerator > Injector > Transfer optics > Primary Accelerator > Target

Injector

- Preconditions protons for primary cyclotron
- Separated sector cyclotron
  - 4 magnets
  - 2 RF resonators (50 MHz)
  - 2 secondary RF resonators (150 MHz)
- 72 MeV ouput (38% speed of light)
- 2.2 to 2.4 mA output beam current
- Acceleration routine
  - Injected in middle via 2x 90° turns
  - 80 orbits inside
  - Electrostatic extraction



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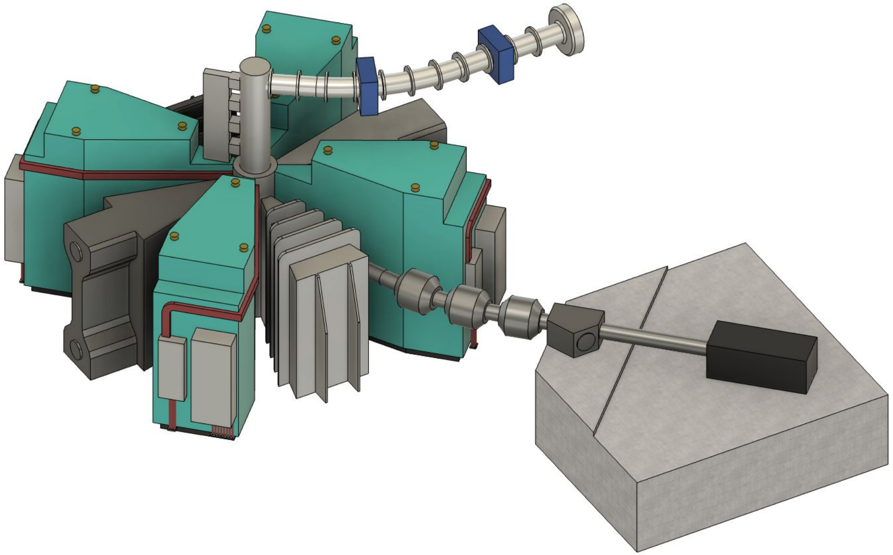
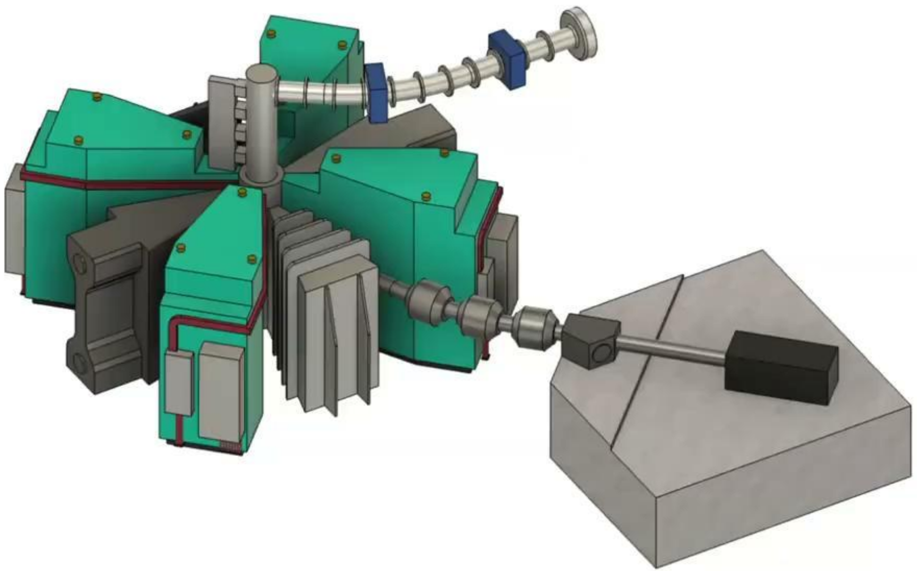


Transfer Optics

- Transports protons from injector to primary accelerator
- Evacuated stainless steel tube
- Dipole magnets used for steering in corners
- Quadrapole magnets squeeze beam
  - Always come in pairs (horizontal & vertical compression)
- Beam dump shielded block of metal
  - Used for startup and emergency stop
  - ~10 ms to 100 ms to melt through stainless steel
  - Emergency system detects fault in 100 μs



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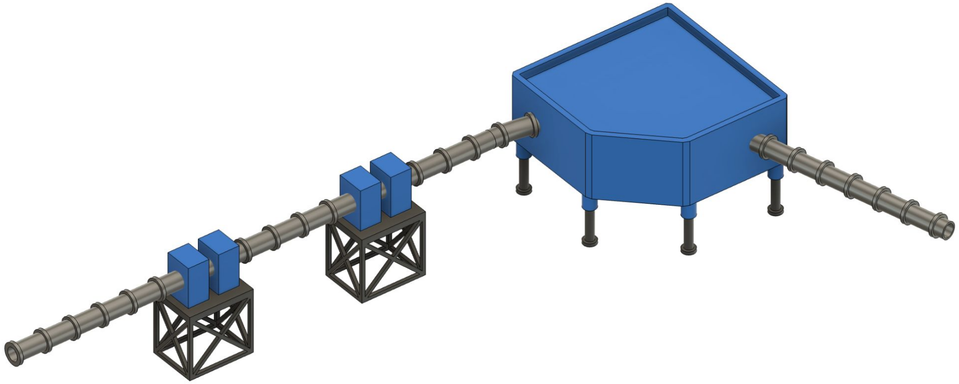
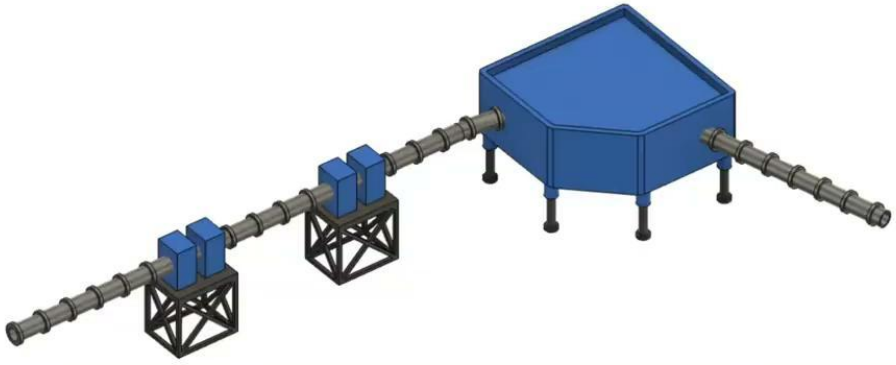


Primary Accelerator

- Accelerators preconditions protons up to final KE
- Ring cyclotron
  - 8 sector magnets
  - 4 RF resonators (50 MHz)
- 15 meter outer diameter
- 186 orbits to reach extraction
- Final beam characteristics
  - 1.4 MW
  - 5 - 7 mm beam diameter
  - 2.2 mA output current
  - 590 MeV output (79% speed of light)



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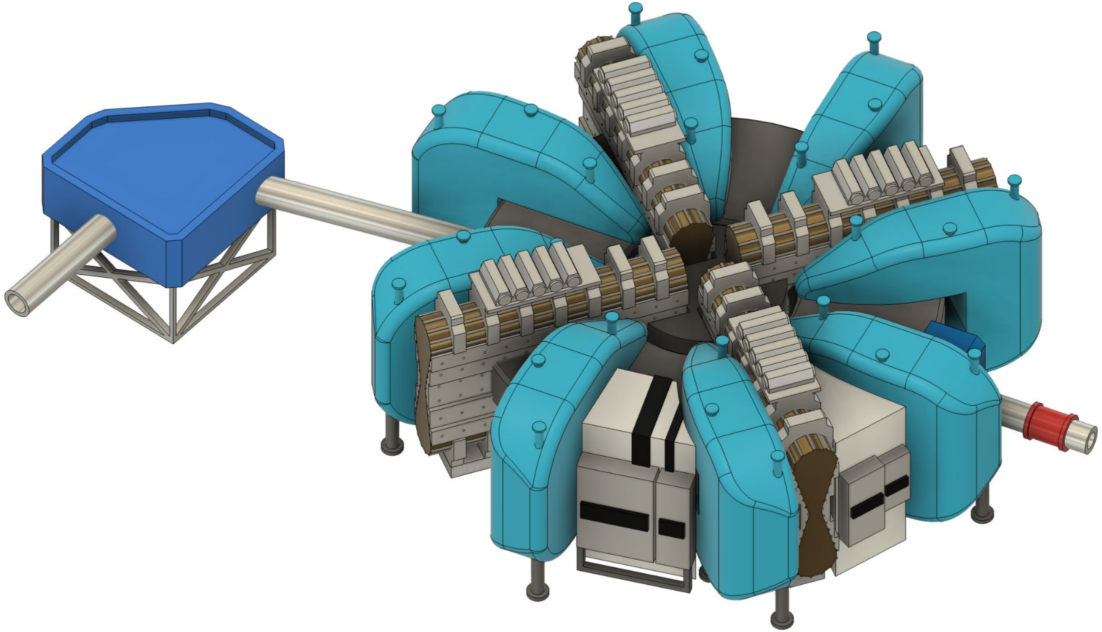
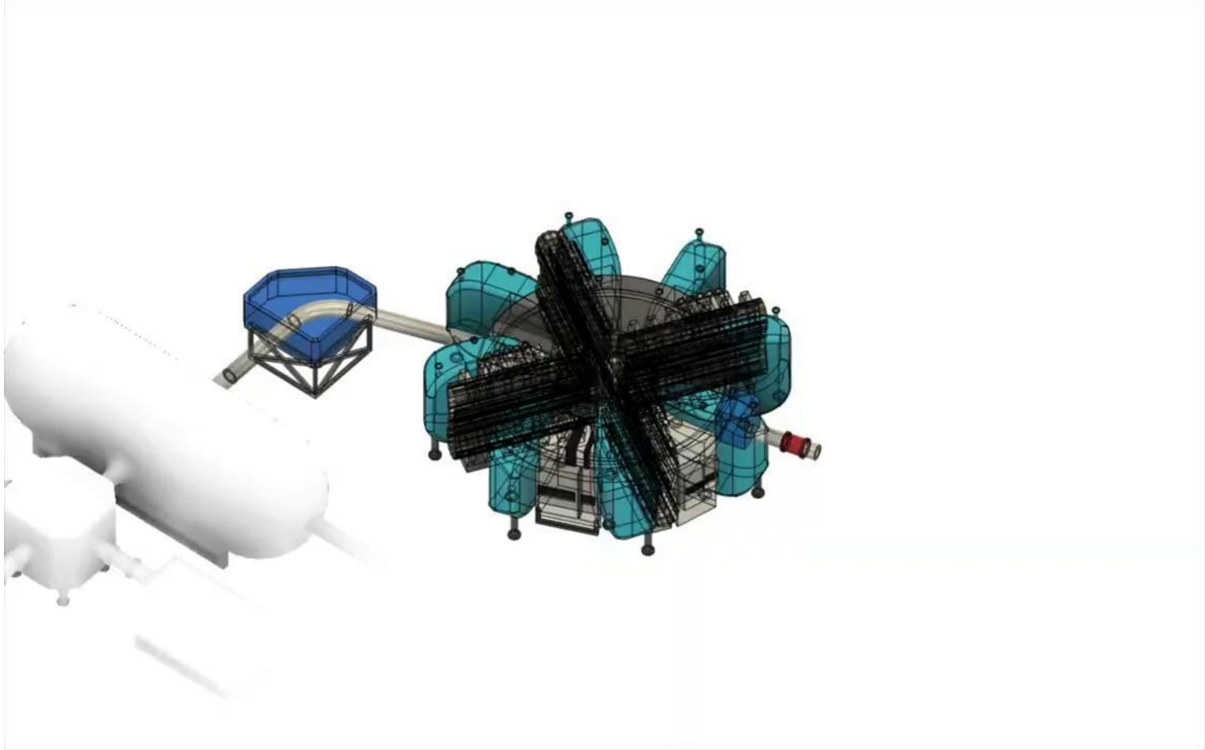


Target

- Produces Muons from impinging protons on nuclei
- Two spinning carbon wheel targets
- Carbon (isotropic graphite)
  - Low Z avoids nuetrons/Bremsstrahlung
  - High thermal conductivity & sublimation temp
- 5 cm thick
  - Minimizes internal pion absorbion
  - Minimizes total heat flux
- Beam dump
  - Proton beam split between 3 metal beam dumps
  - Cooling recovers heat



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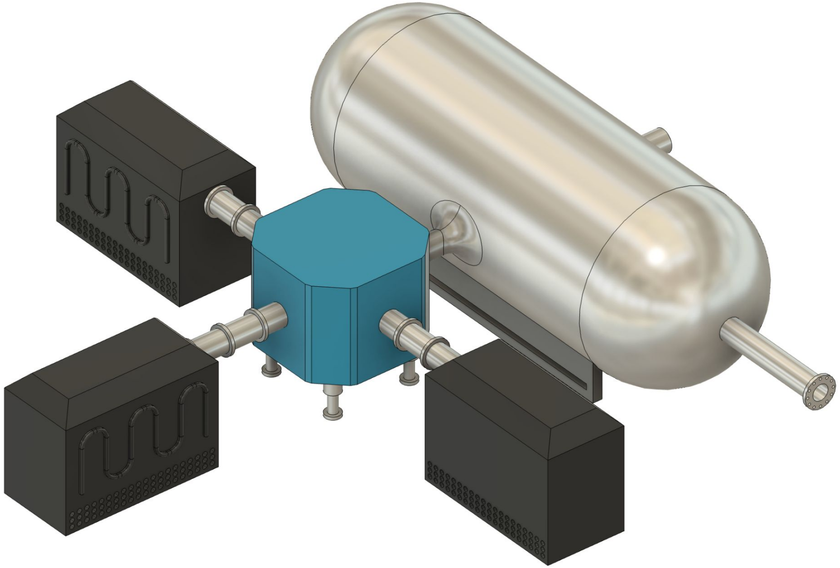
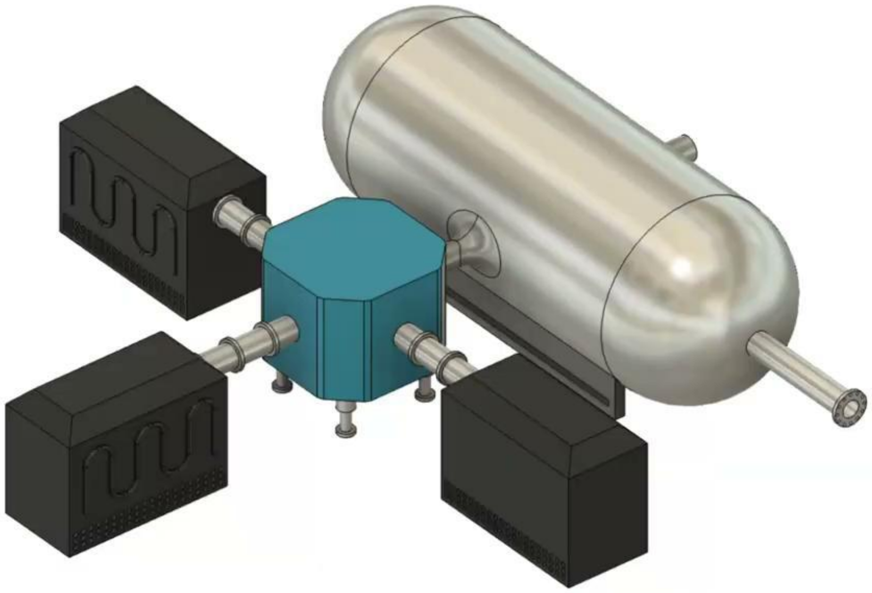


Summary

- Cockcroft-Walton pre-accelerator generates protons, gets them to ~810 keV
- Injector further accelerates protons to 72 MeV, injects into primary accelerator
- Cyclotron accelerats protons to final energy of 590 MeV
- Protons smashed into target producing pions, which decay into muons



Pre-accelerator > Injector > Transfer optics > Primary Accelerator > Target

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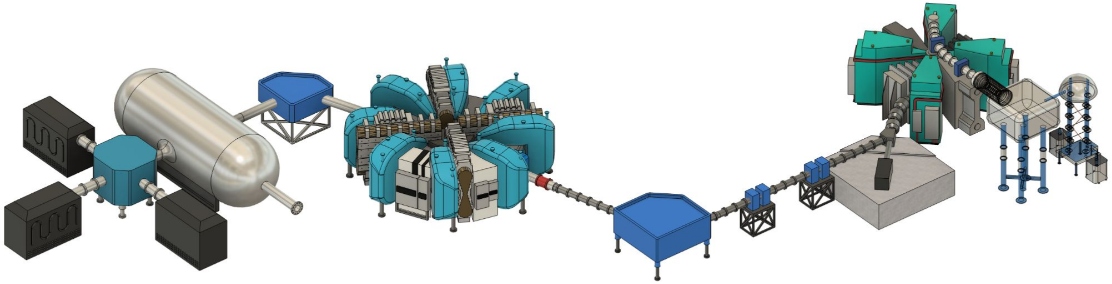
- Injector further accelerates protons to 72 MeV, injects into primary accelerator
- Cyclotron accelerates protons to final energy of 590 MeV
- Protons smashed into target producing pions, which decay into muons



Pre-accelerator > Injector > Transfer optics > Primary Accelerator > Target

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Thank you!

Supporting Slides

Thomas

Layout of PSI

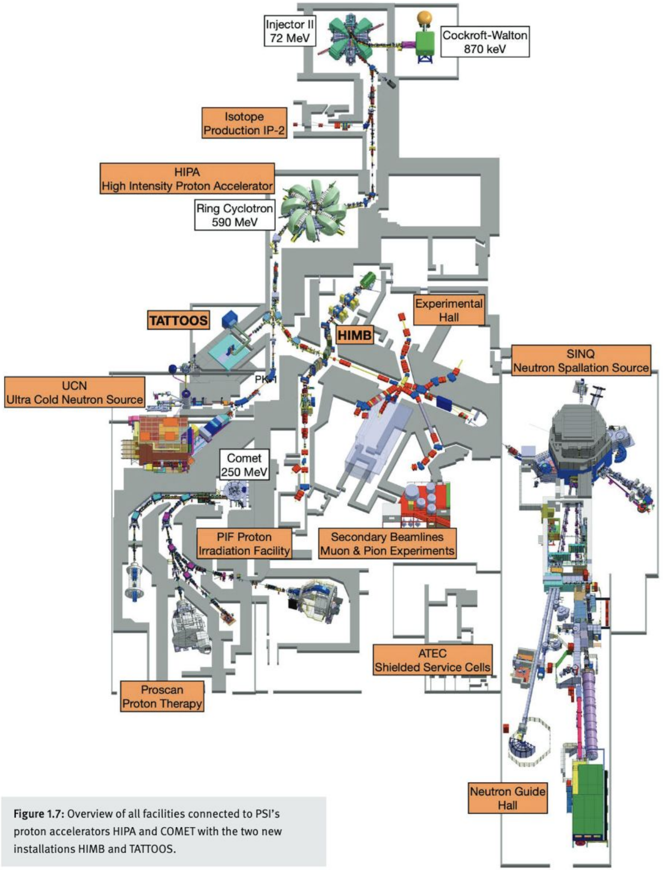
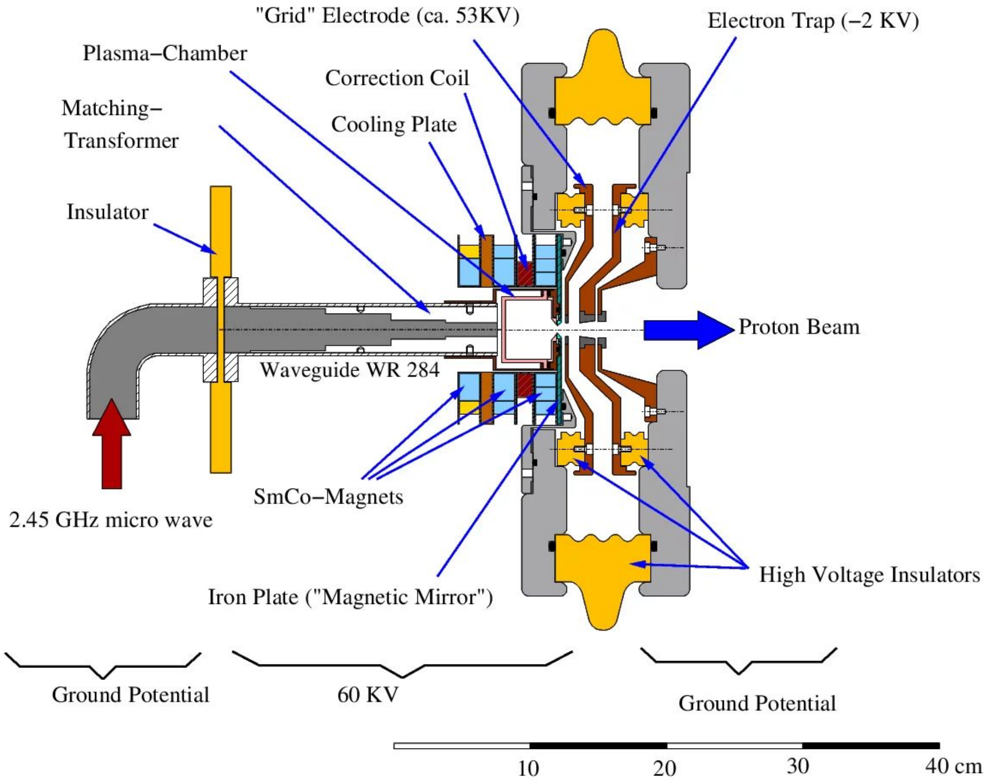
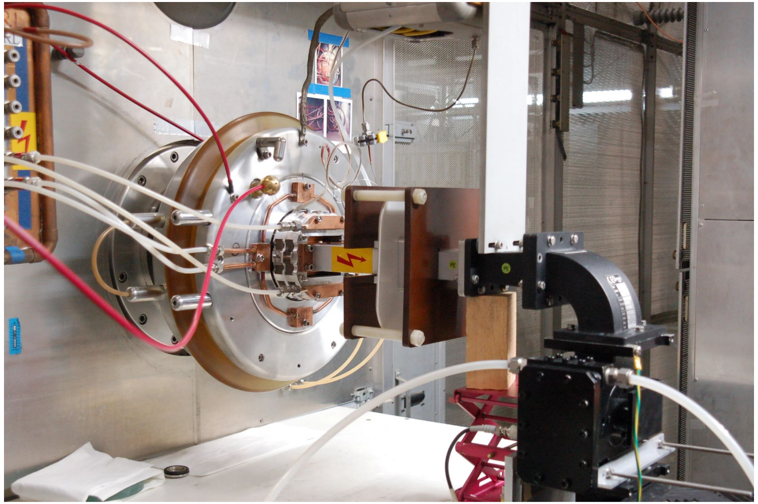


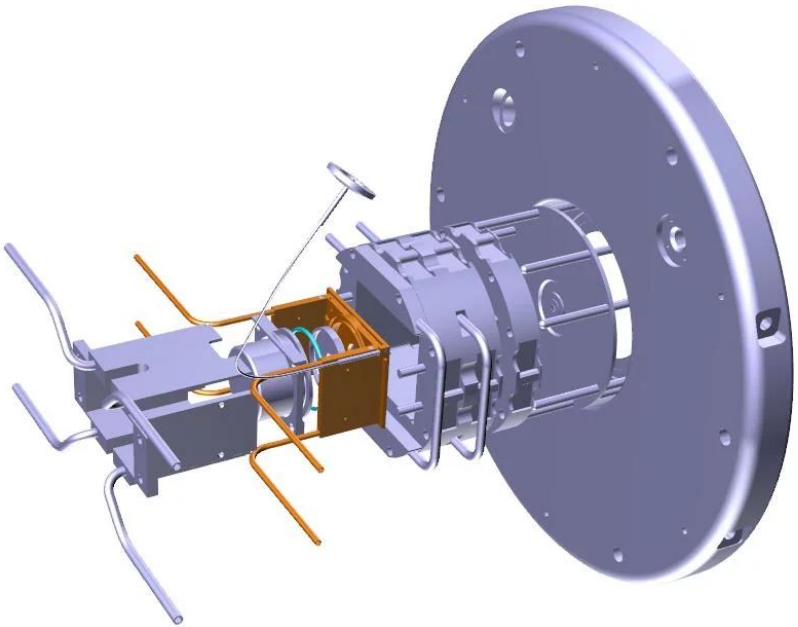
Figure 1.7: Overview of all facilities connected to PSI's proton accelerators HIPA and COMET with the two new installations HIMB and TATTOOS.

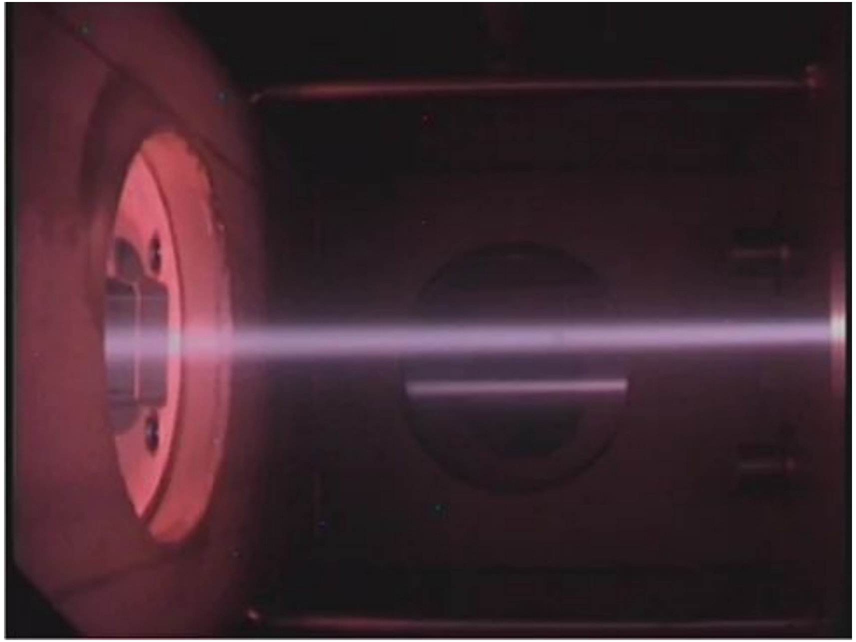
H+ Source (PSI) (Slide 1/2)





H+ Source (PSI) (Slide 2/2)





Proposed High Pressure DT Cells

Figure 6.7: µSR uniaxial pressure cell available currently at PSI. From [Hicks, 2017].

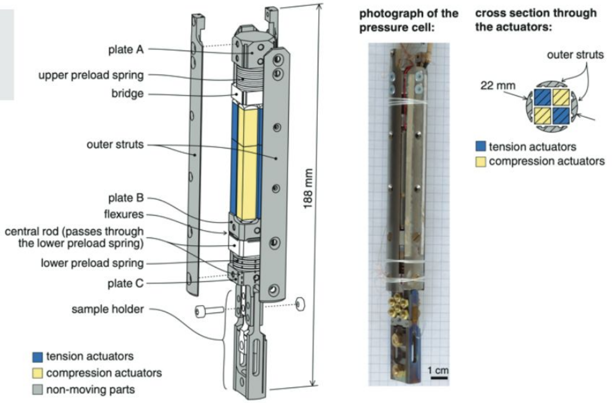
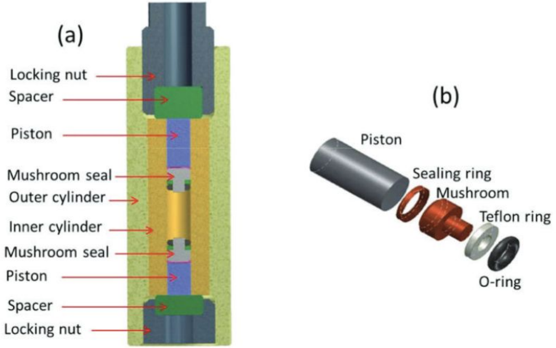


Figure 6.6: (a) Cross-sectional view of the PSI double wall piston-cylinder pressure cell for µSR;
(b) Details of the pressure seal.
From [Khasanov, 2016].



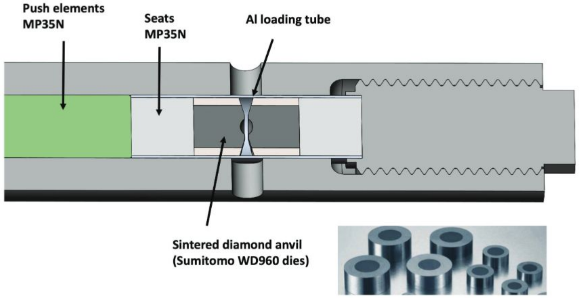


Figure 6.8: Concept of novel µSR high-pressure anvil cell currently under development within the SNF R'Equip project ExtremeP.

Radial Beam Intensity of Primary Accelerator

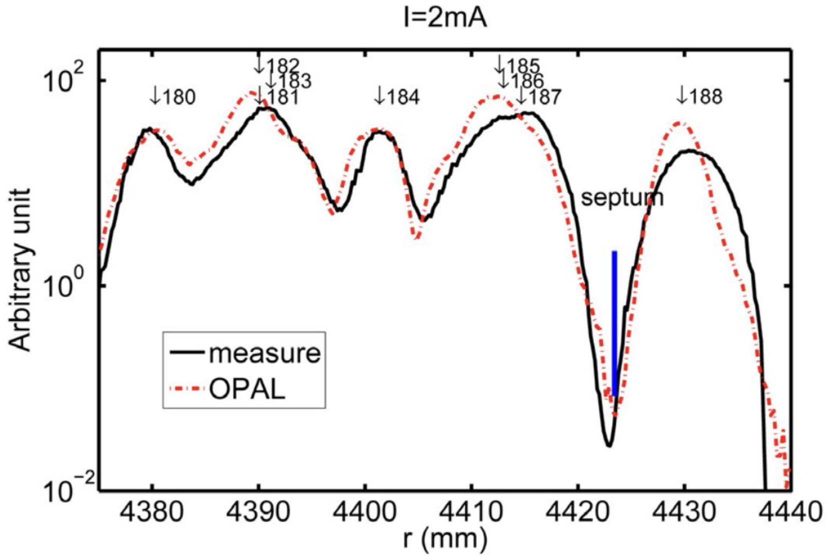
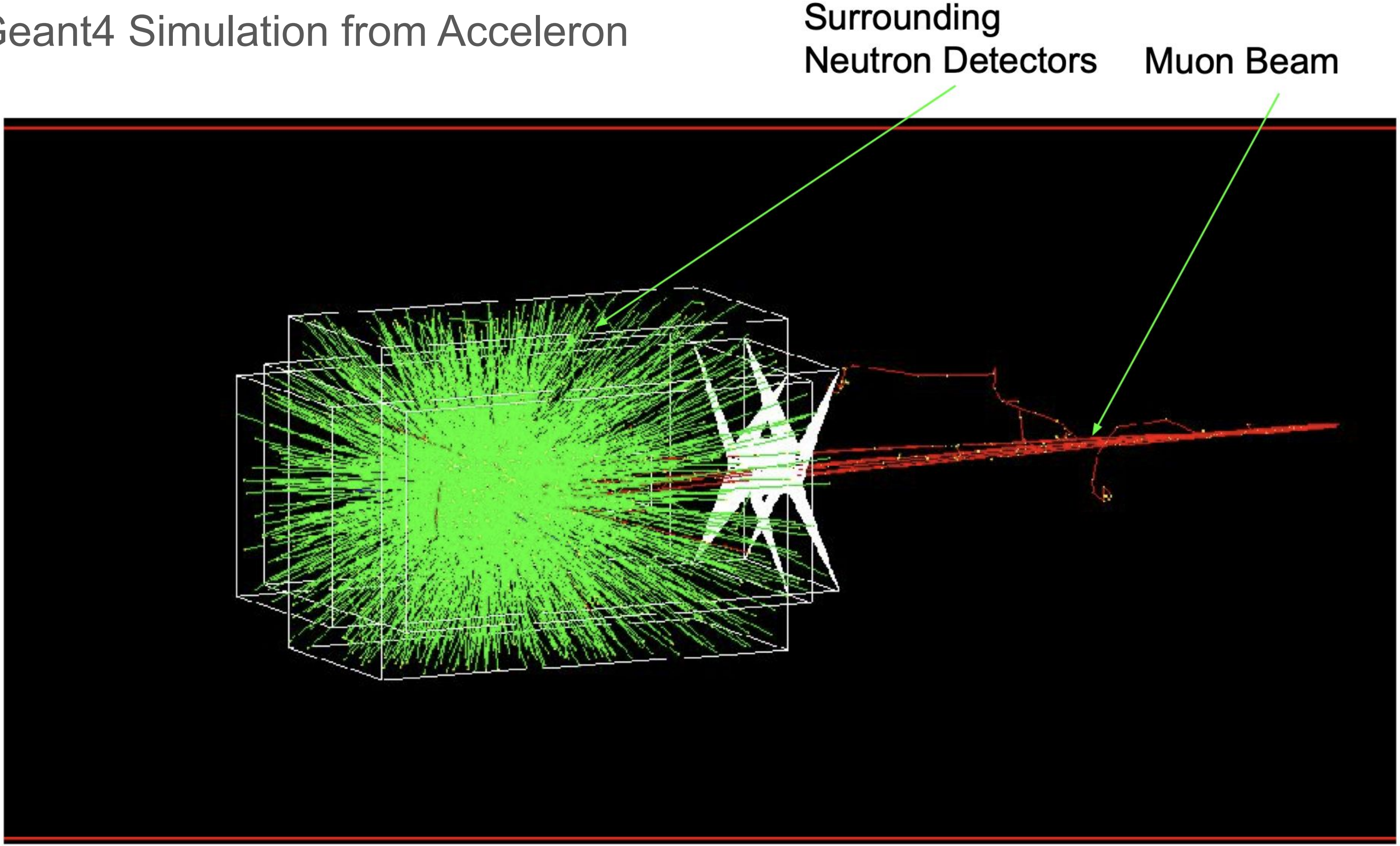
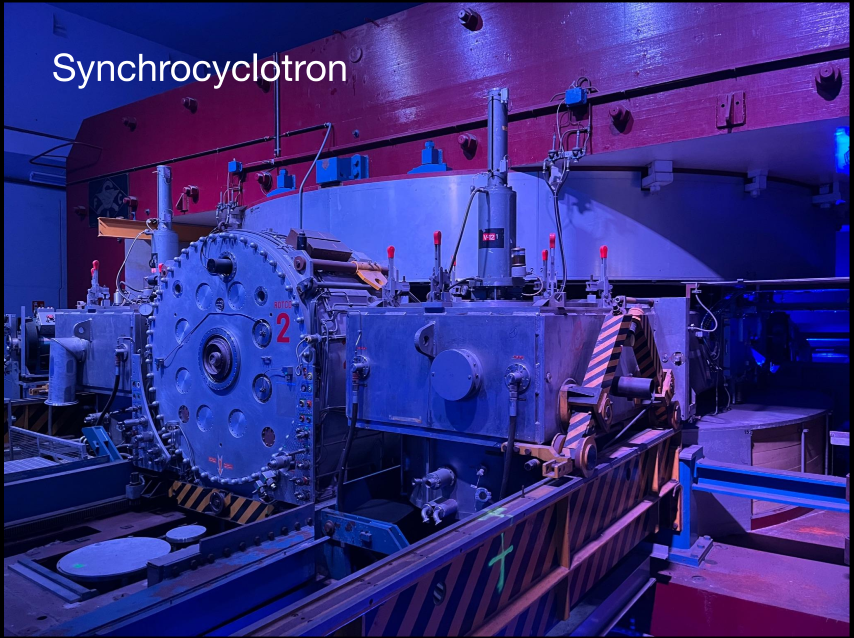


Figure 3: Radial beam profile with indicated turn numbers at extraction. The density is minimized at the location of the extraction electrode.

Himani

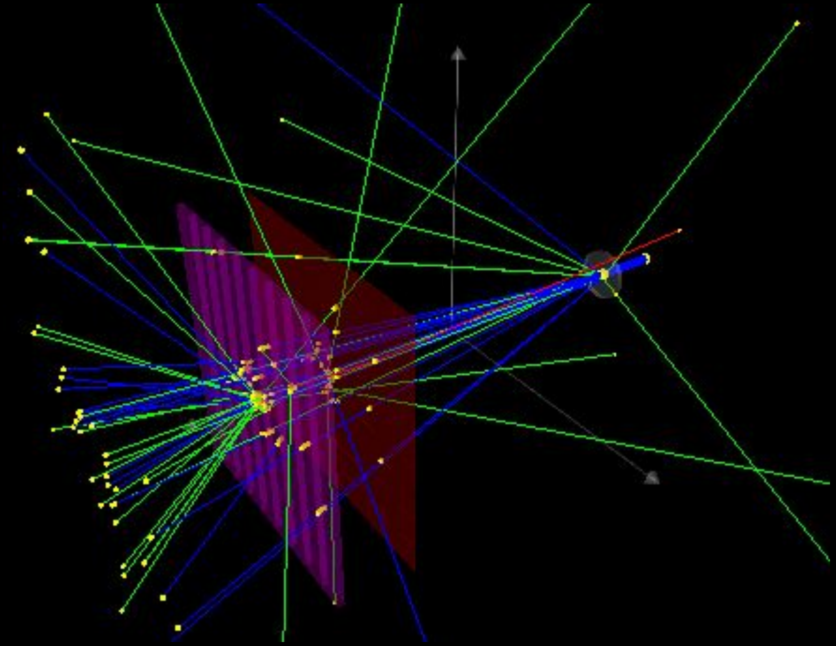
Geant4 Simulation from Acceleron





CERN Experiments Using Geant4

Geant4



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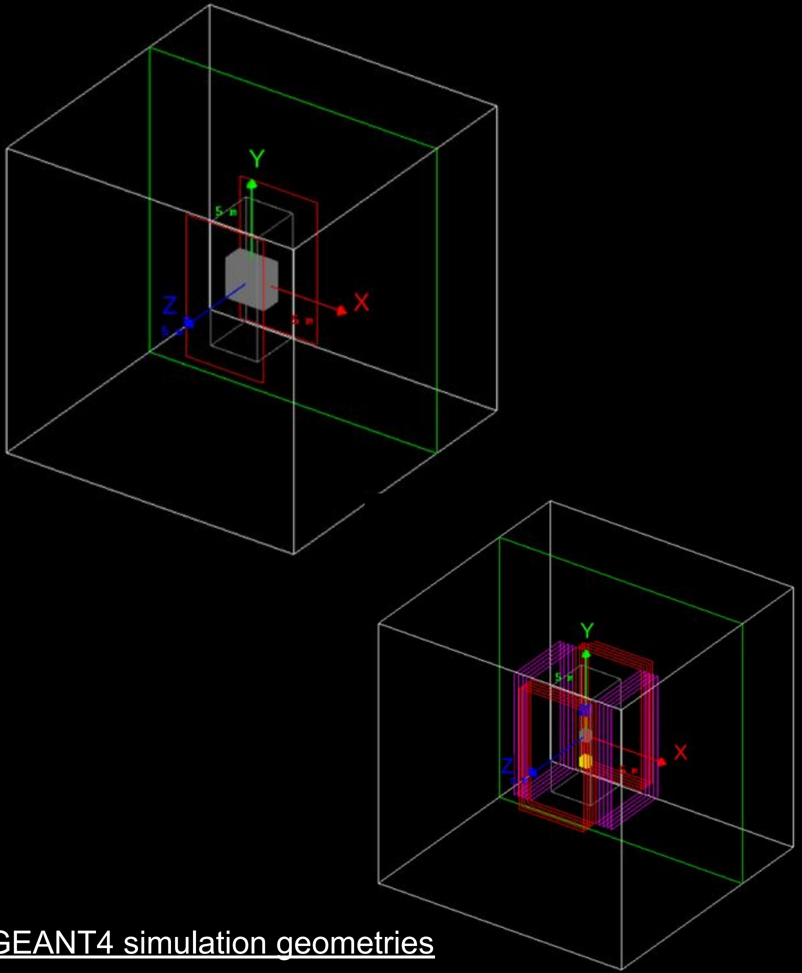

GEANT4 simulation geometries