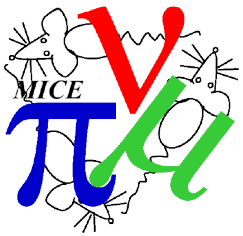
Muon Ionization Cooling Experiment

Pavel Snopok
Illinois Institute of Technology, Chicago, IL
and Fermilab, Batavia, IL

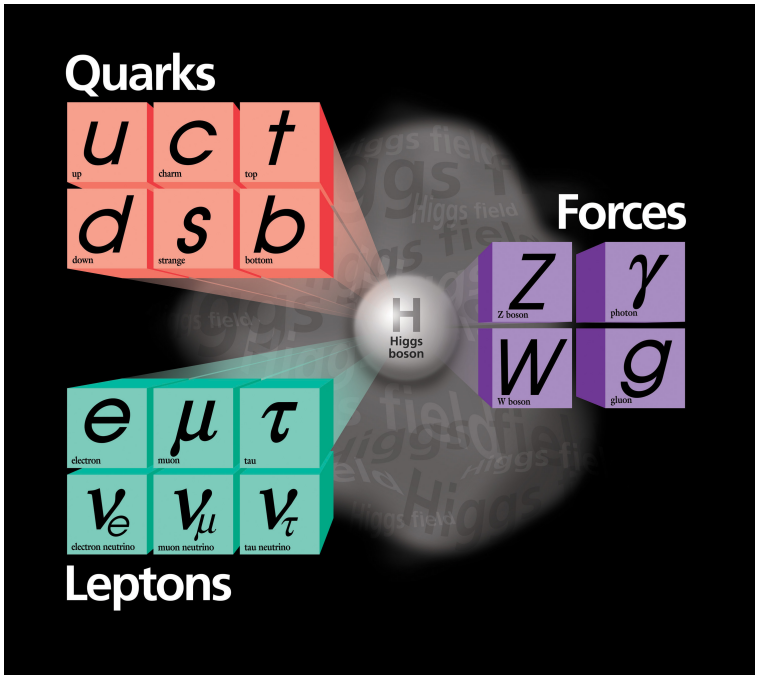
On behalf of MICE
November 11, 2015



ILLINOIS INSTITUTE OF TECHNOLOGY

Fermilab

Why muons?



- Muons are ≈200 times heavier than electrons ⇒ can be accelerated in circular channels:
  - synchrotron radiation is negligible,
  - CoM energy is not limited by radiative effects,
  - compact footprint,
  - Higgs production advantages.
- Muons are elementary particles in the framework of the Standard Model ⇒ clean collisions, particle energy is utilized fully.
- Muons decay ⇒ neutrino beam via $\mu^- \to e^- \nu_\mu \bar{\nu}_e$, $\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$.
- Muons provide a unique tool for addressing fundamental questions in physics, or for exploring the properties of materials.

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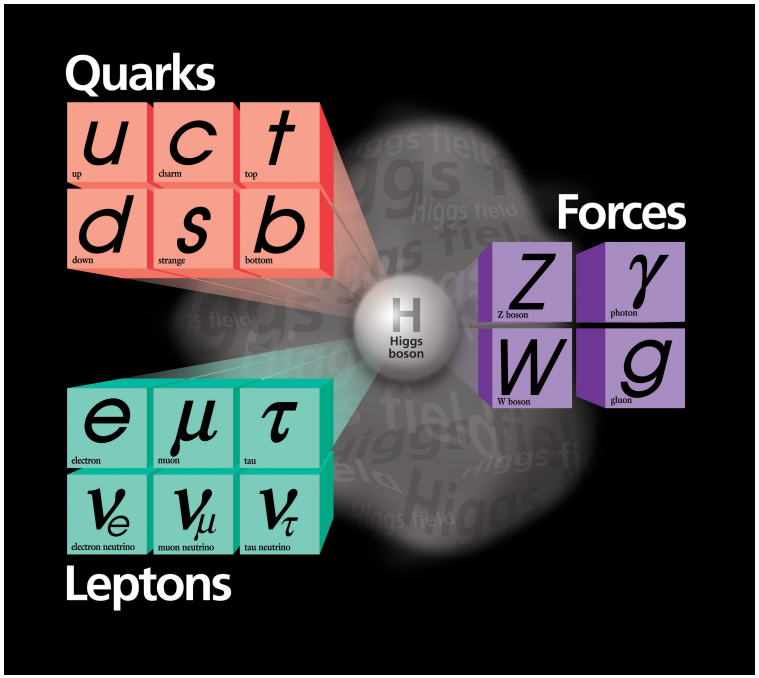

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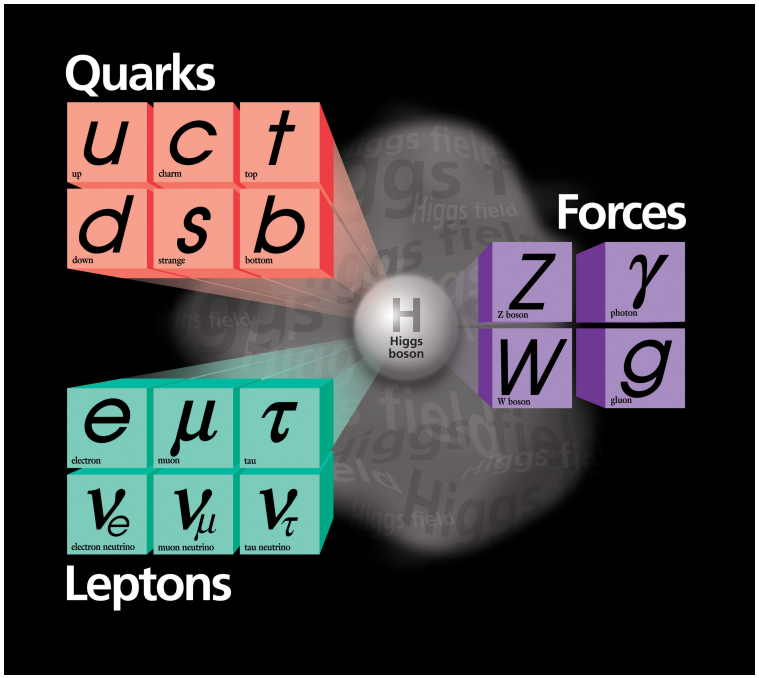

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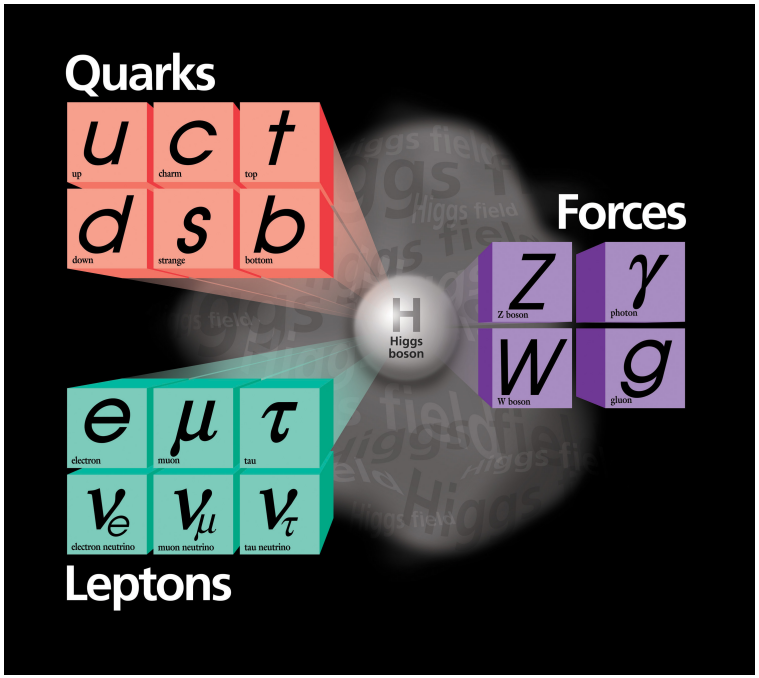

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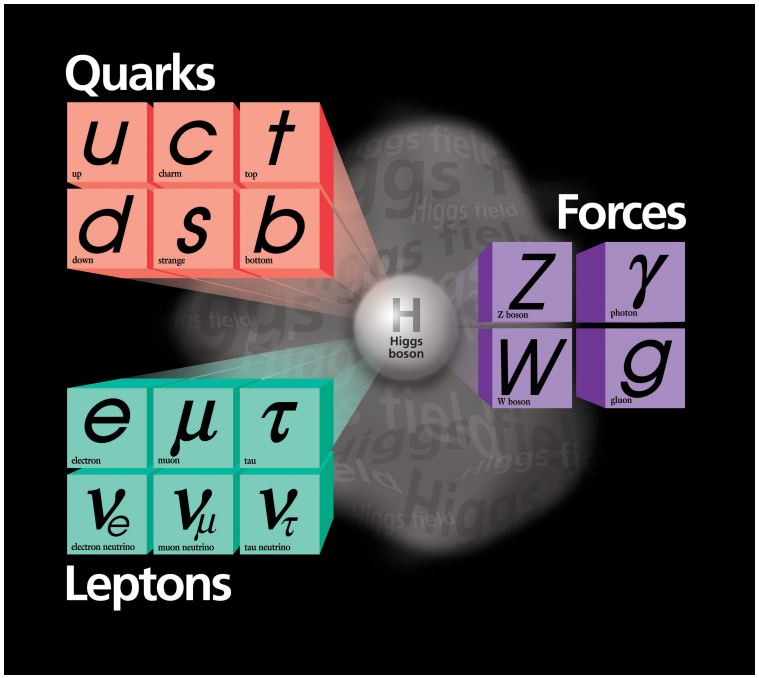

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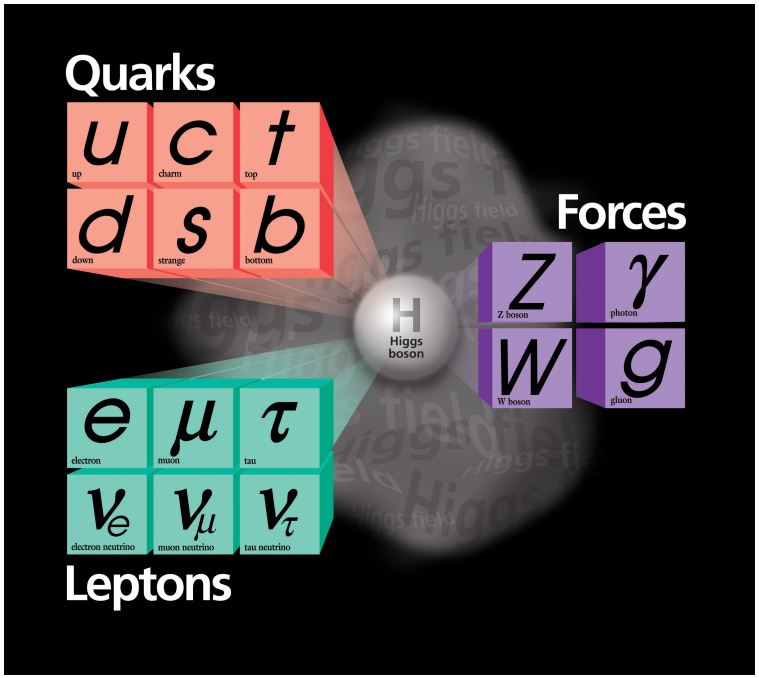

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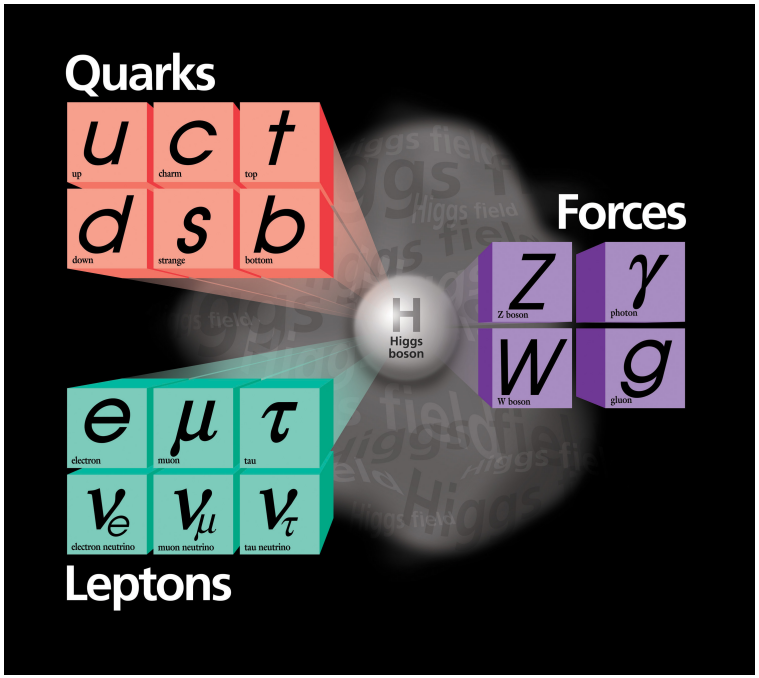

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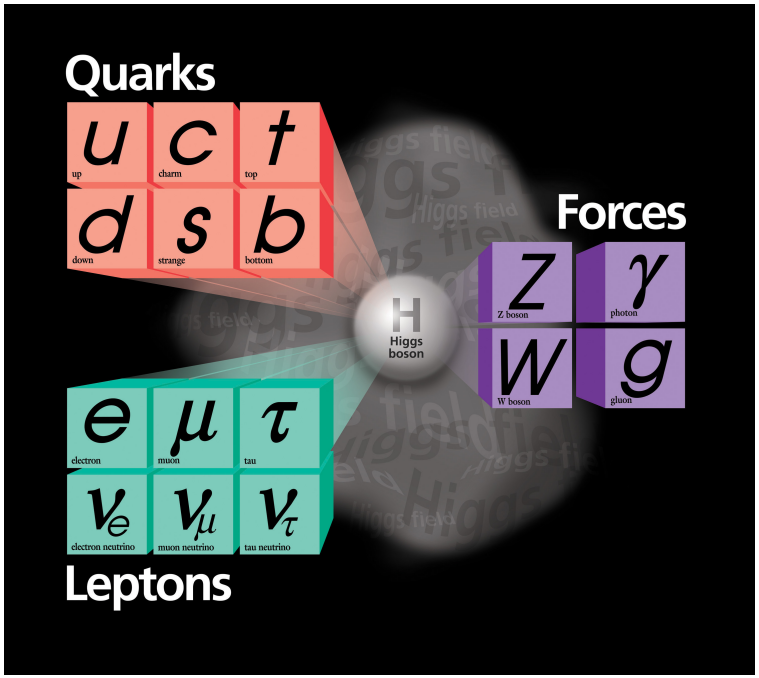

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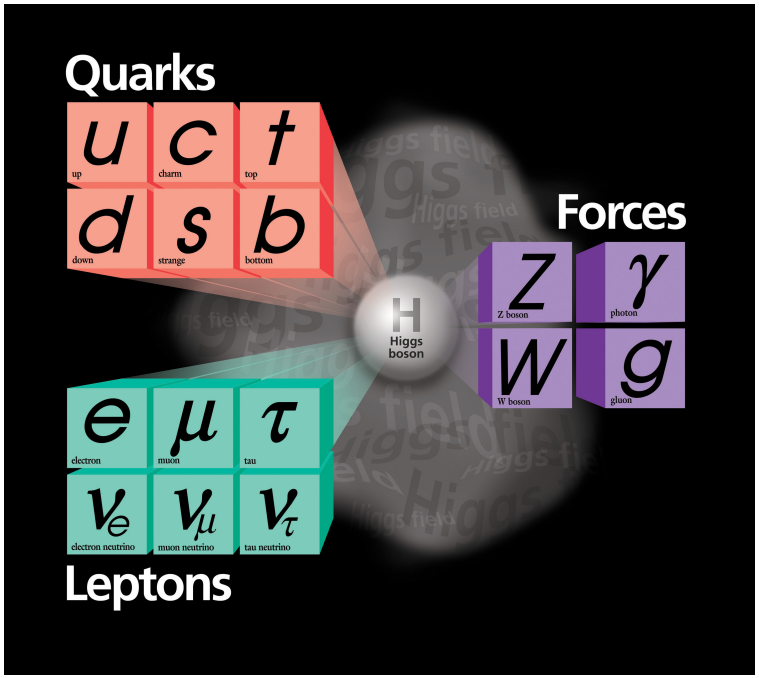

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Challenges

- Muons are unstable, $\tau = 2.2$ μs at rest (relativity helps: at 2 TeV $\tau = 0.044$ s).
  - rule of thumb: 1000 turns in the storage ring.
- Challenge: collect muons, form into a beam, and either accelerate to high energy or stop in a target.
- Challenge: get enough muons to do the job, and concentrate within a small target, or within a very bright beam.
- Challenge: decay products heat magnets and other components, create backgrounds in the detector, radiation damage is an issue.

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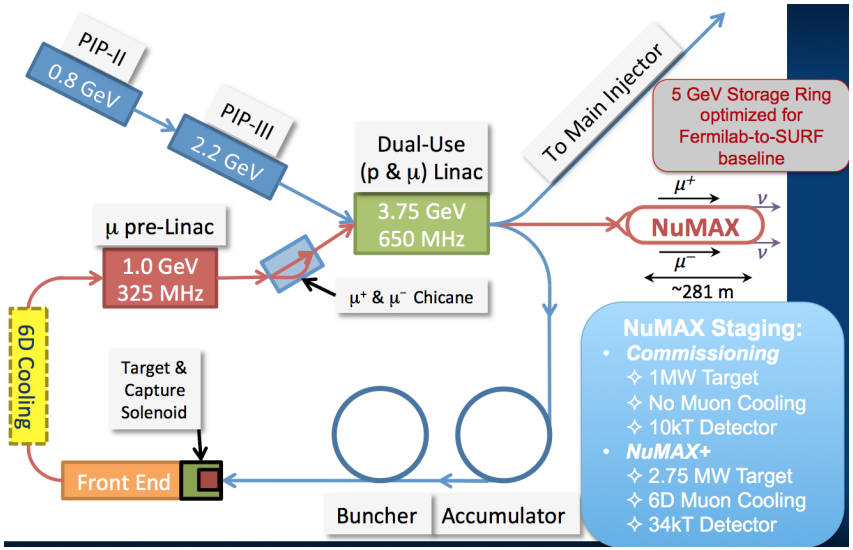
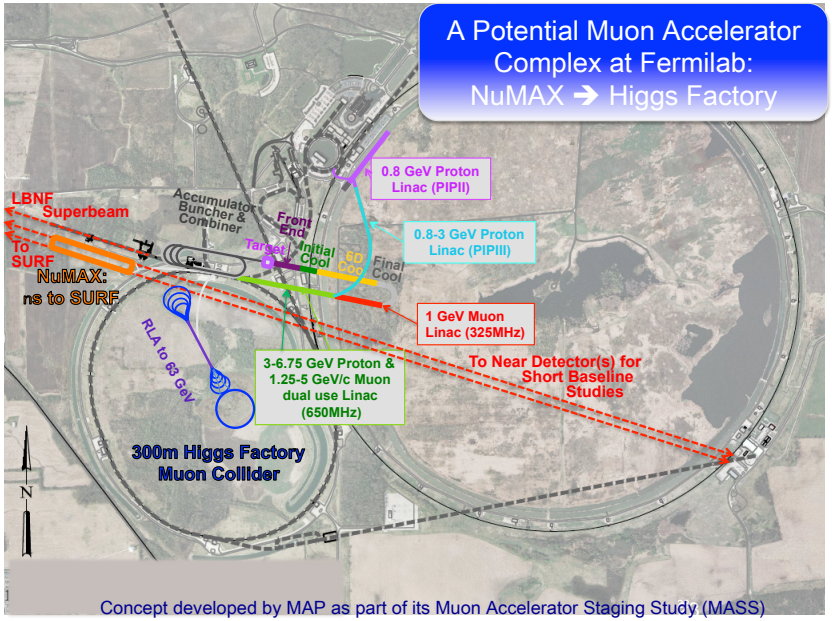
Why do we need muon accelerators?





- Neutrino Factory is a precision microscope that will likely be needed to fully probe the physics of the neutrino sector.
- A multi-TeV muon collider may be the only cost-effective route to lepton collider capabilities at energies > 5 TeV.
- Muon accelerators offer unique potential for the future of high energy physics research.
- Bright muon sources can be used for other applications.

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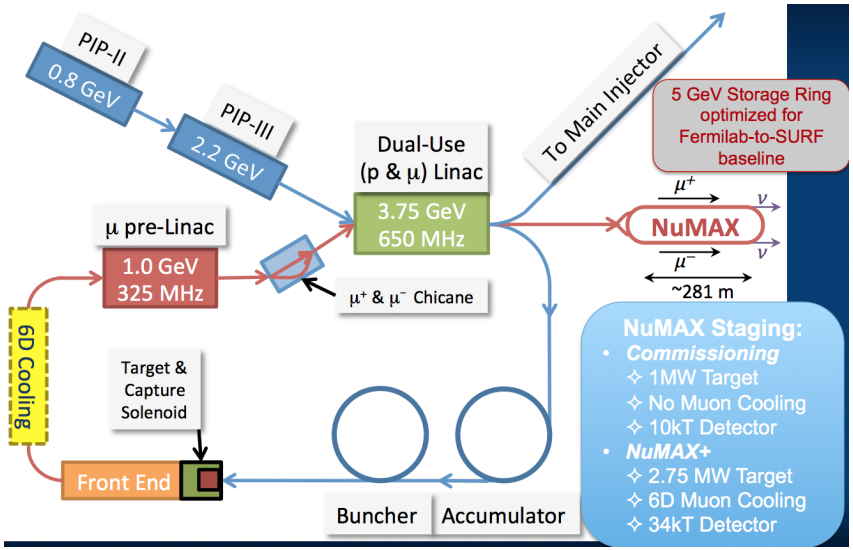

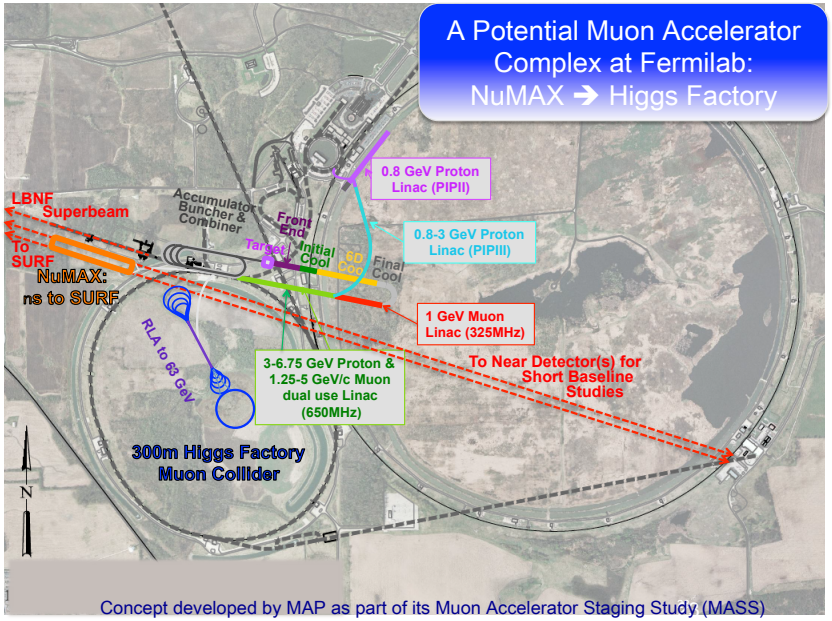

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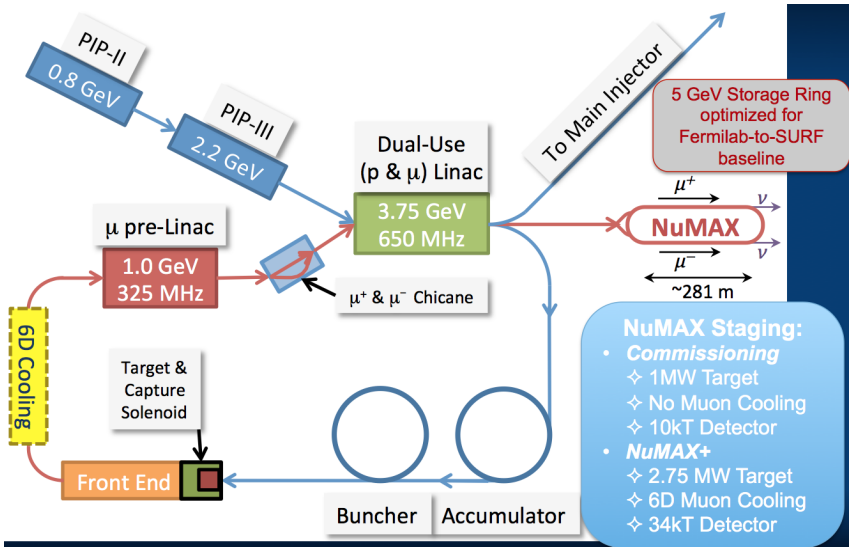

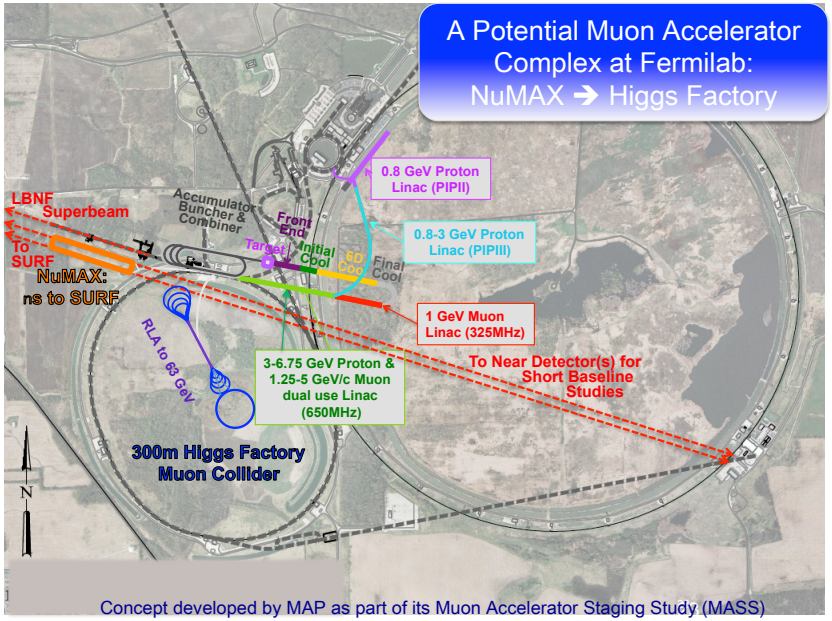

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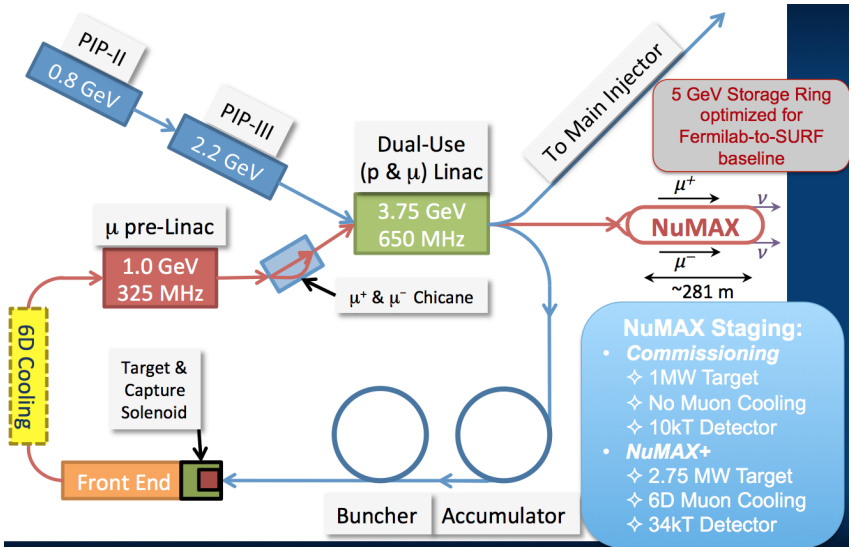

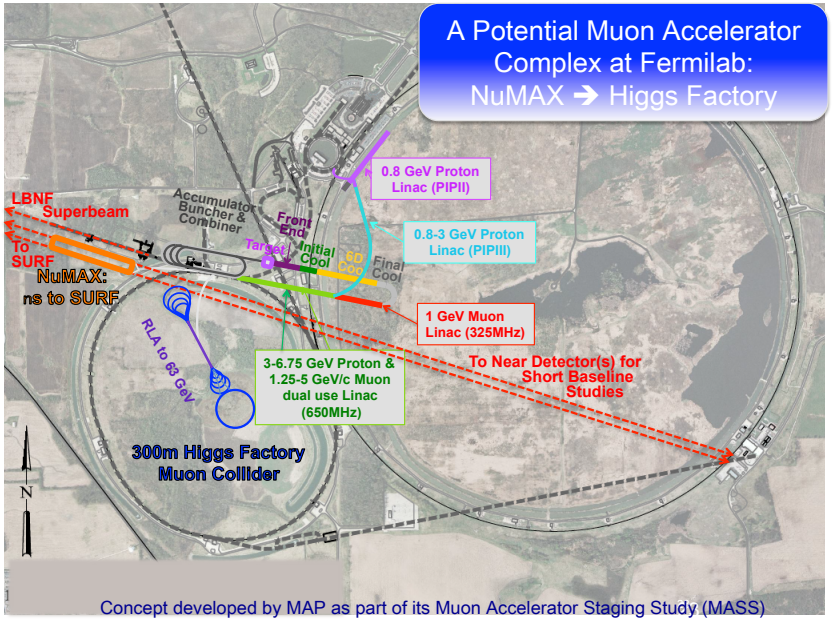

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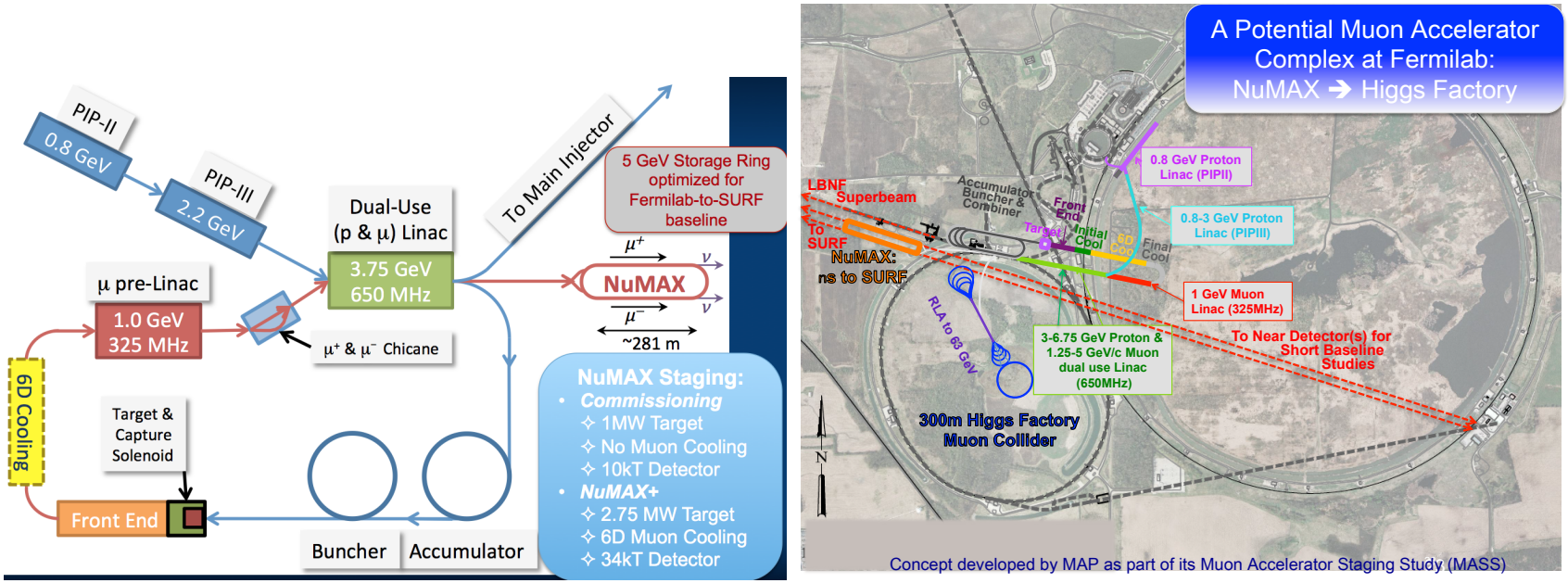

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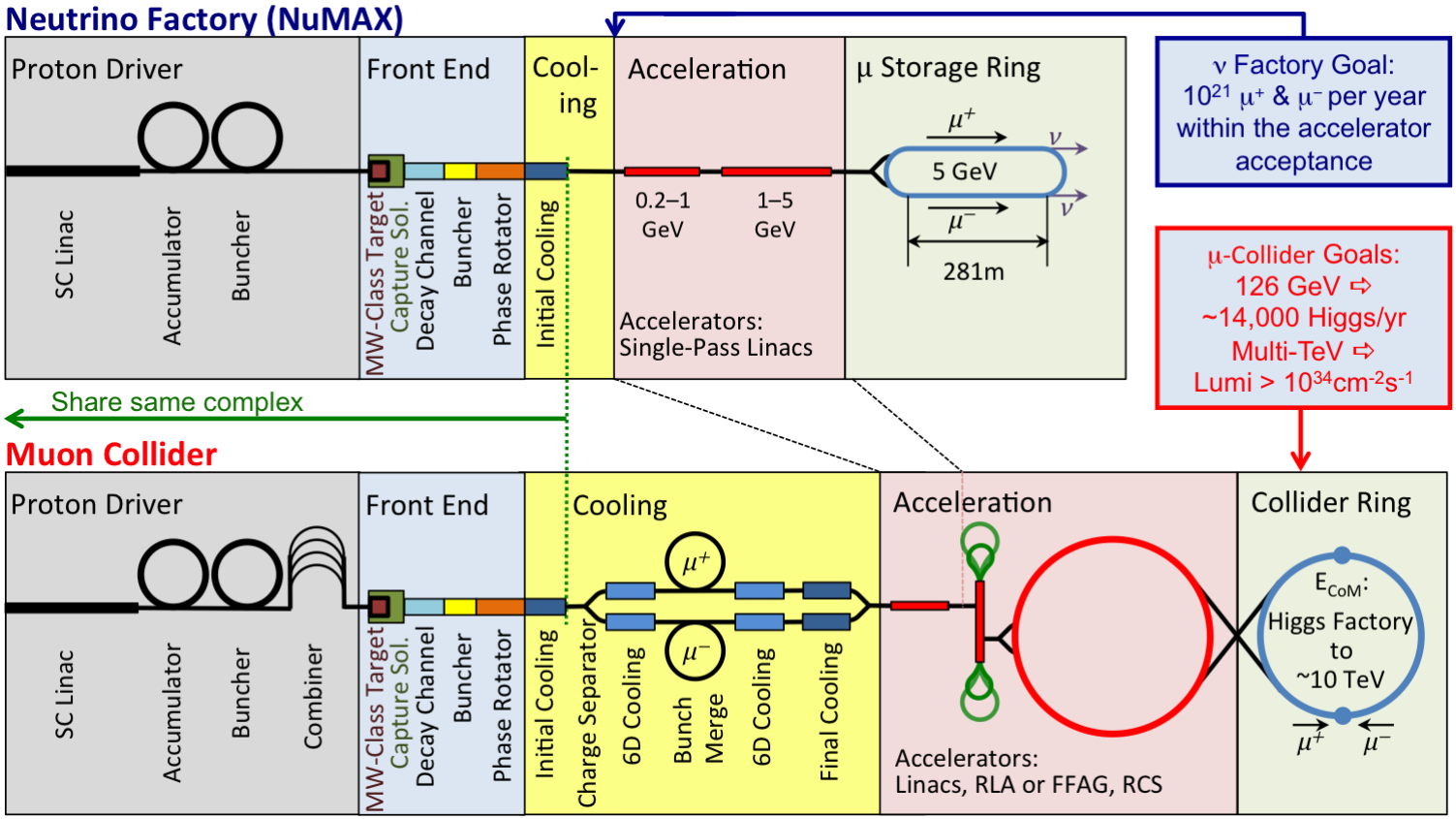
Synergies between NF and MC



- Large part of the front end is common to NF and MC, common technologies down the accelerator chain.
- R&D for both could be staged, and each stage can be used as an R&D platform for the subsequent one.

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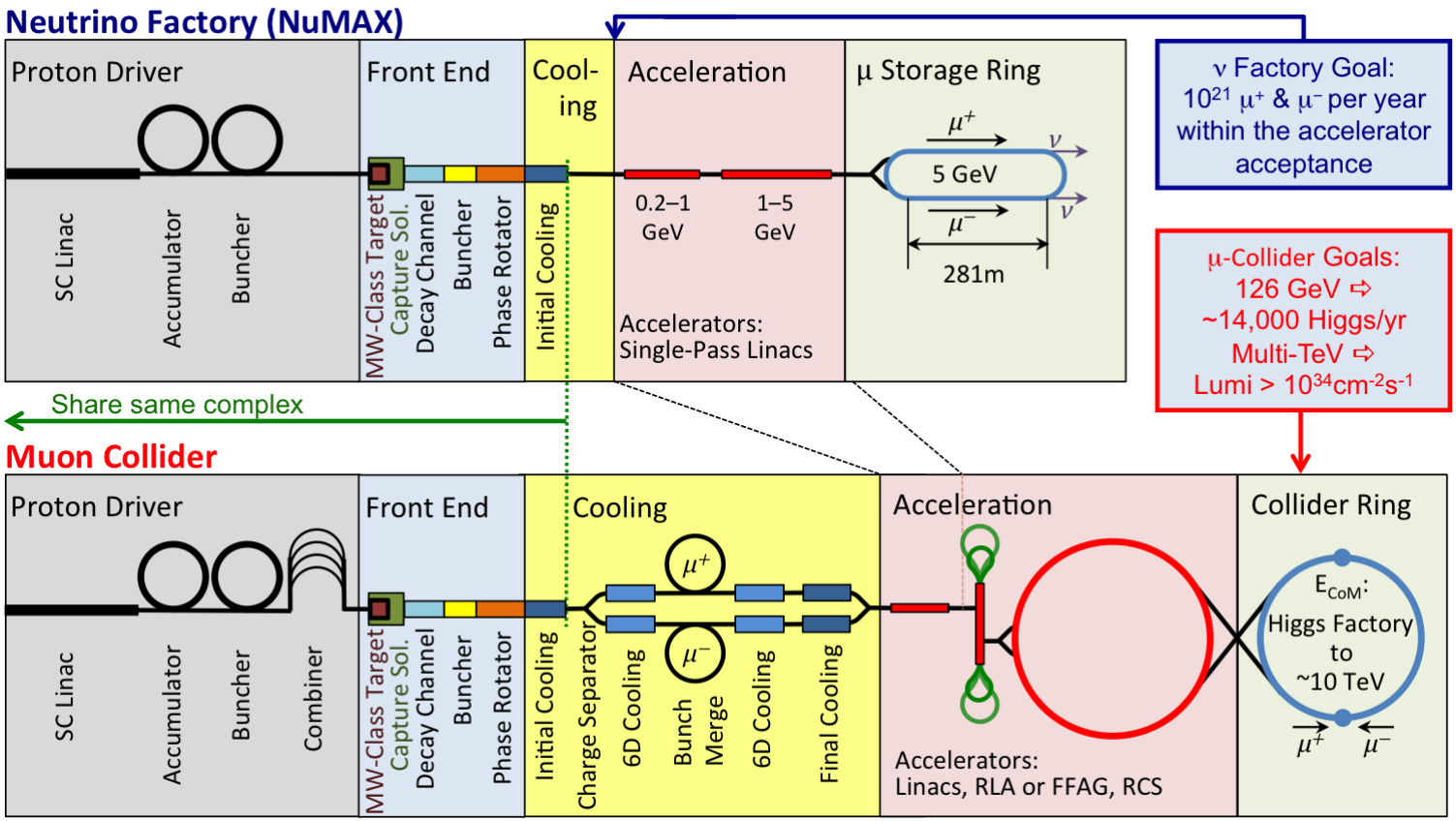

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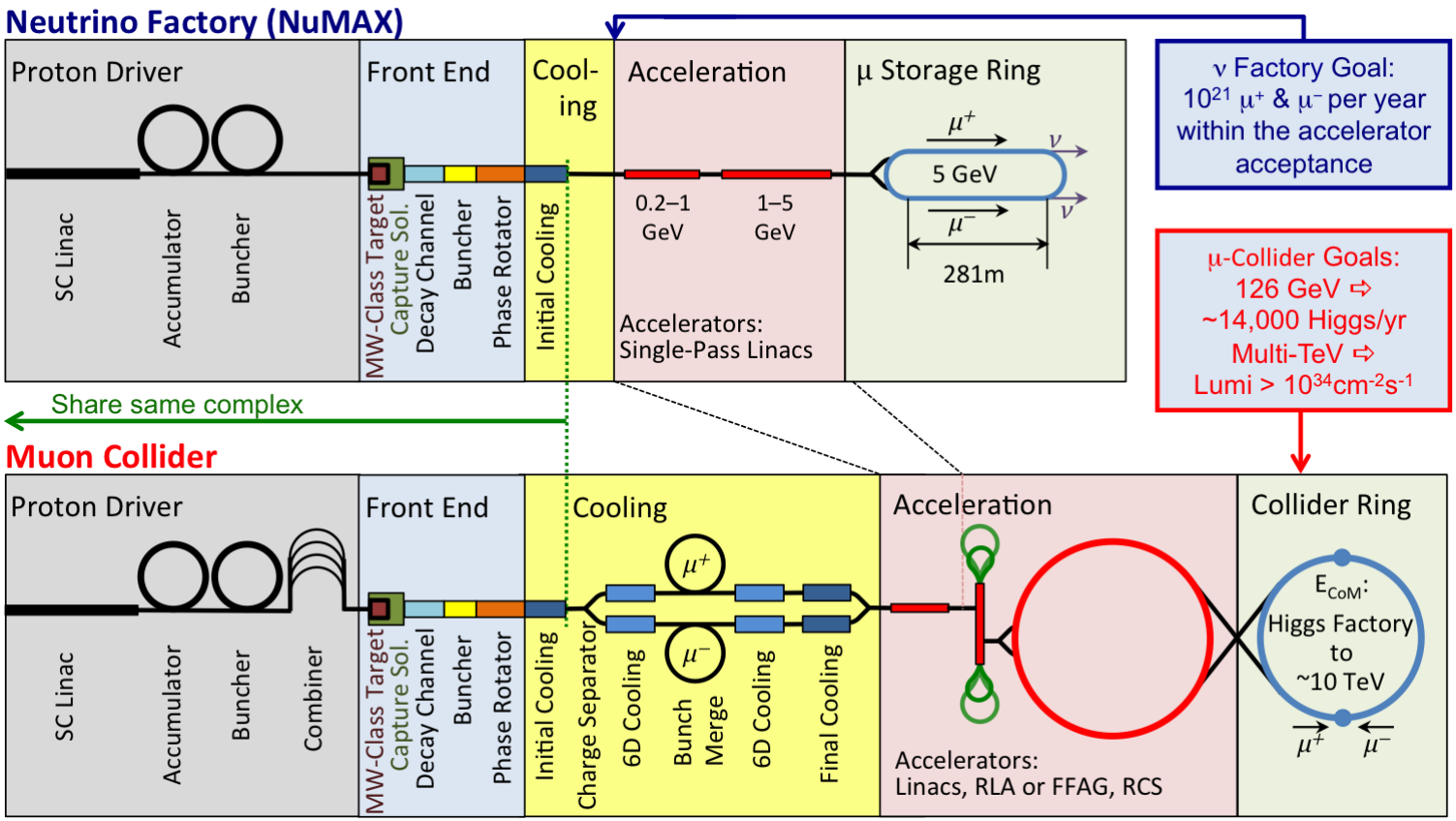

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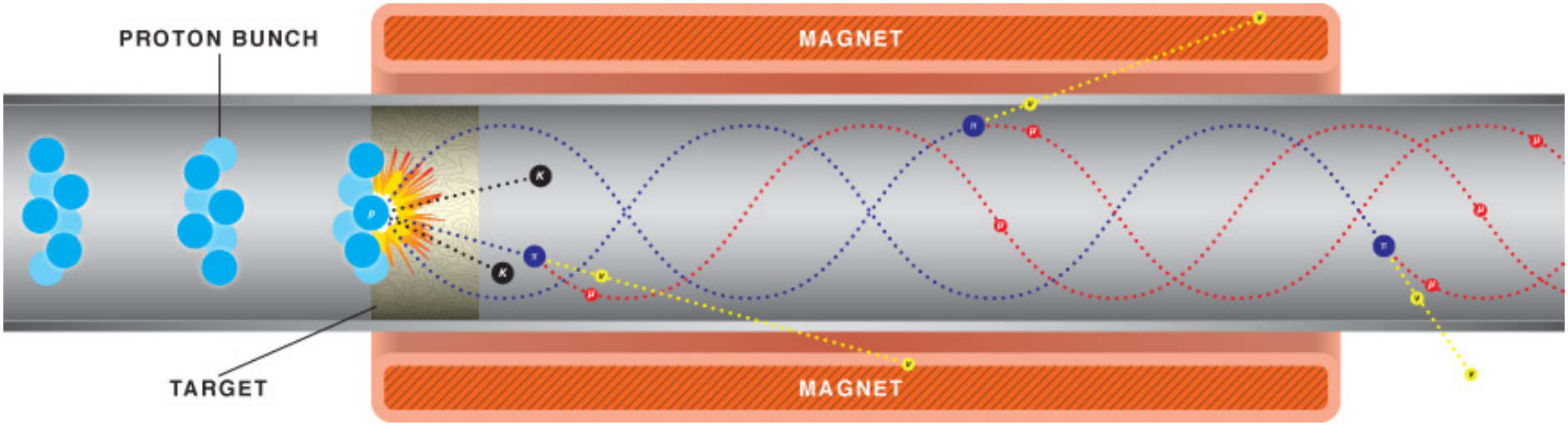
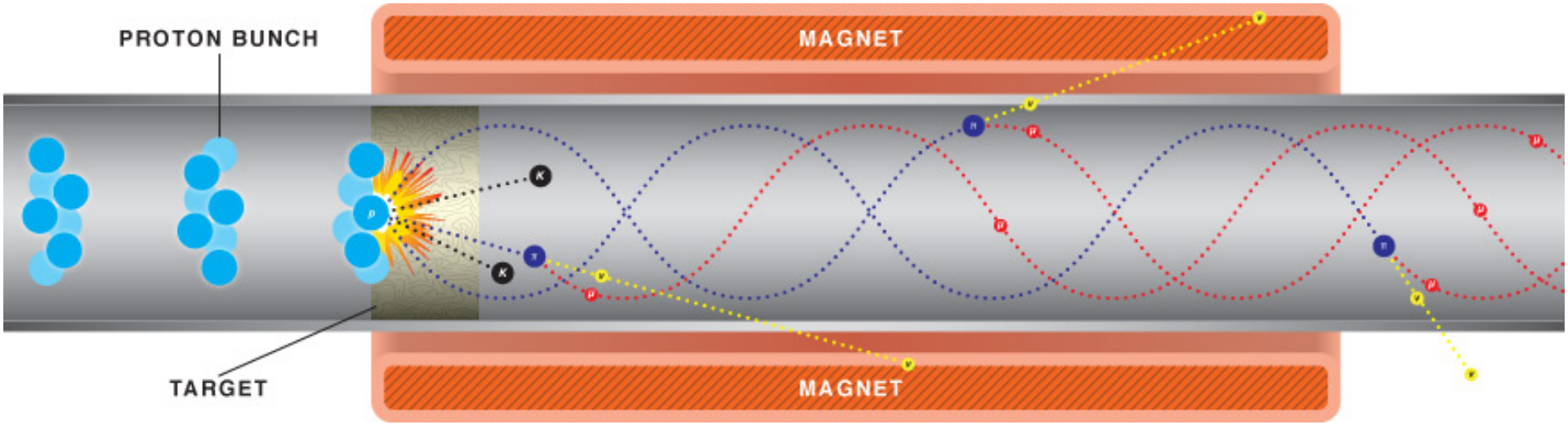
Muon Ionization Cooling: Why Cool?



- Intense muon source: p $\rightarrow \pi \rightarrow \mu$. Very large initial emittance.
- Need to capture as much as possible of the initial large emittance.
- Large aperture acceleration systems are expensive $\Rightarrow$ for cost-efficiency need to reduce emittances prior to accelerating ("cool the beam").
- Cooling requirements range from modest, predominantly transverse, to very ambitious ($O(10^6)$) six-dimensional cooling for the ultimate MC.
- Need to act fast since muons are unstable. The only feasible option is ionization cooling.



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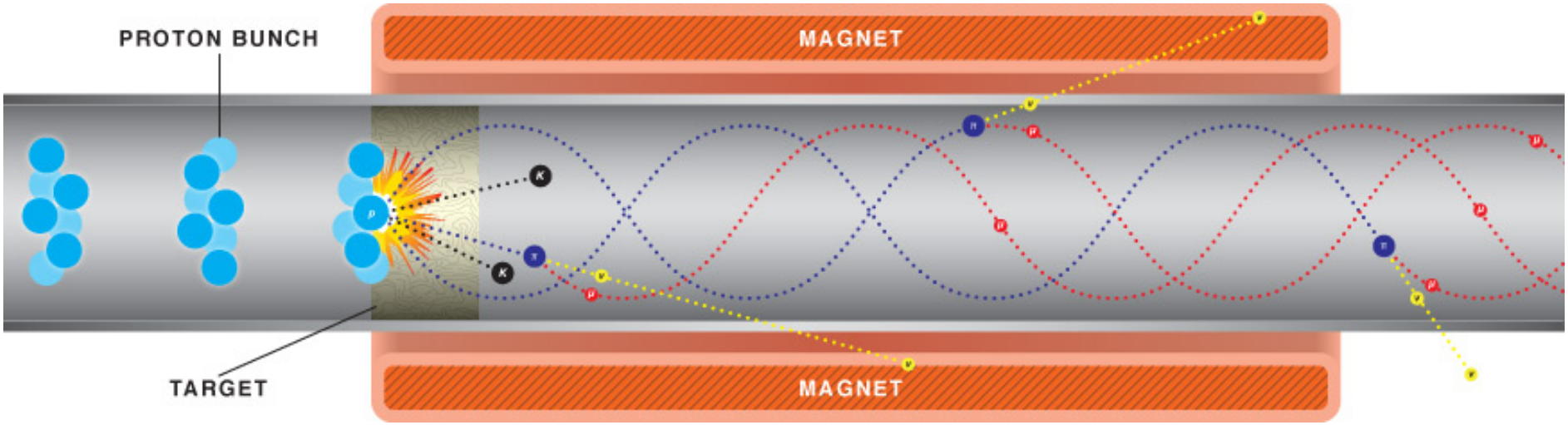

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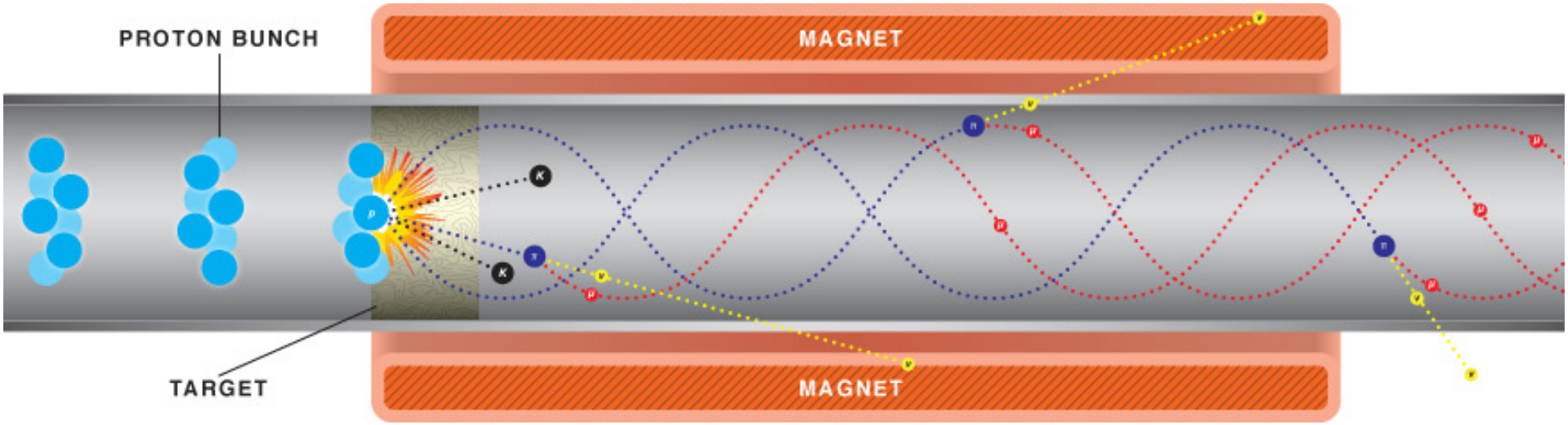

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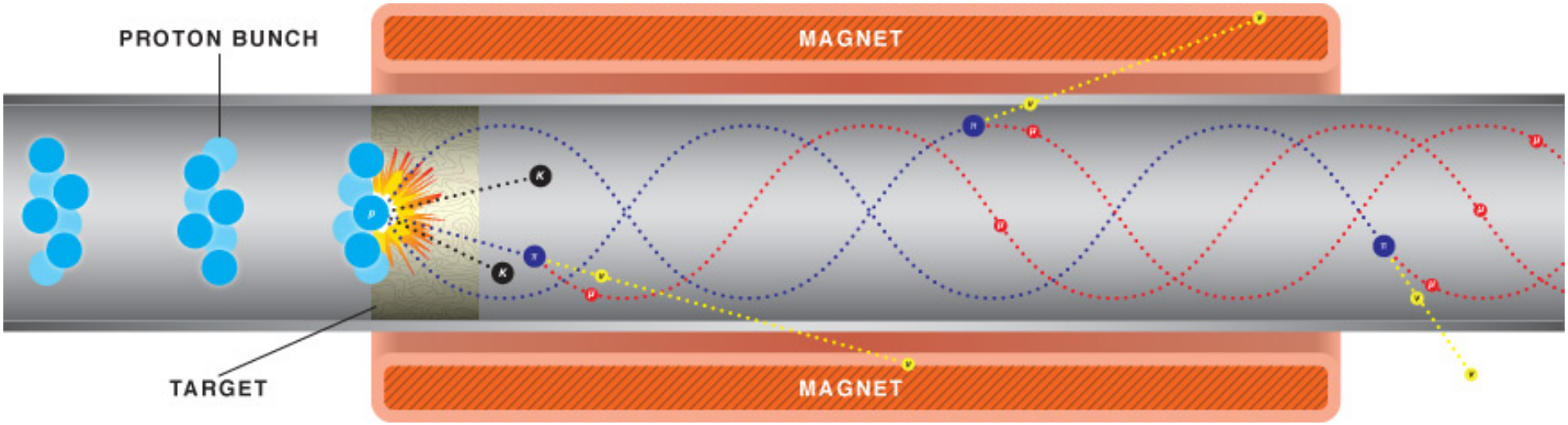

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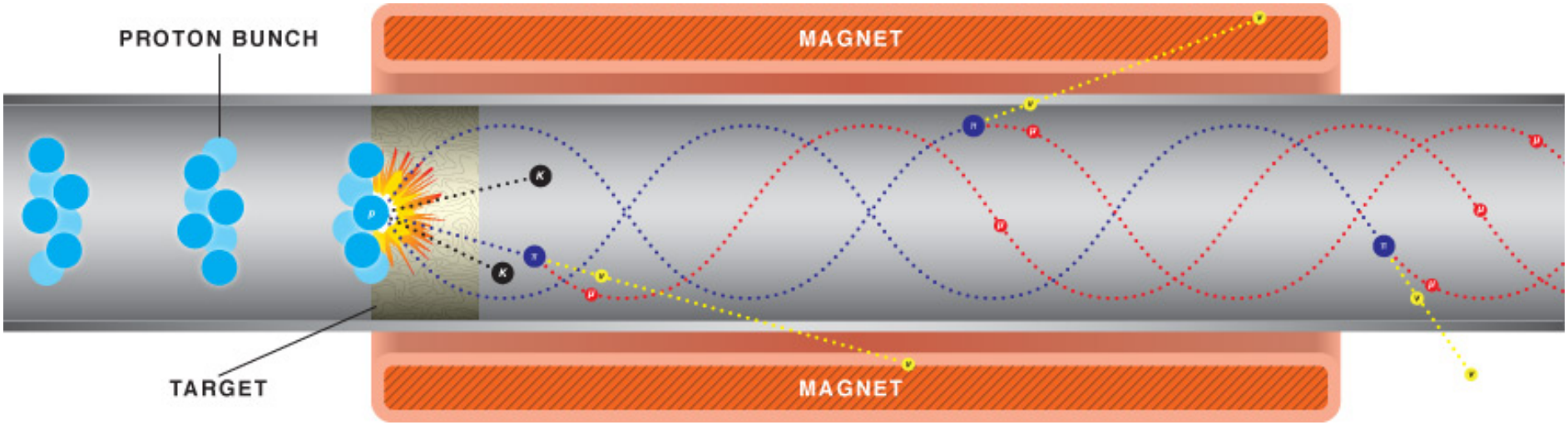

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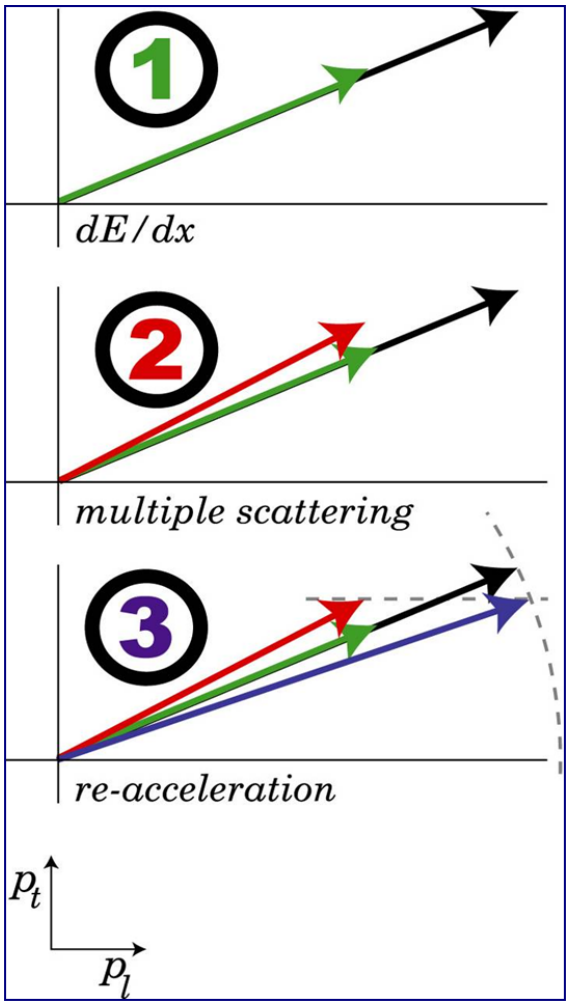
Ionization cooling principle



$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp(13.6\text{ MeV})^2}{2\beta^3 E_\mu m_\mu X_0},$$

where $d\epsilon_N/ds$ is the rate of normalized emittance change within the absorber; βc, E_μ, and m_μ are the muon velocity, energy, and mass; $\beta_\perp$ is the lattice betatron function at the absorber; and X_0 the radiation length of the absorber material. Need low $\beta_\perp$, large X_0.

1. Energy loss in material:
   - all three components of the particle's momentum are affected.
2. Unavoidable multiple scattering:
3. Re-acceleration to restore energy lost in material

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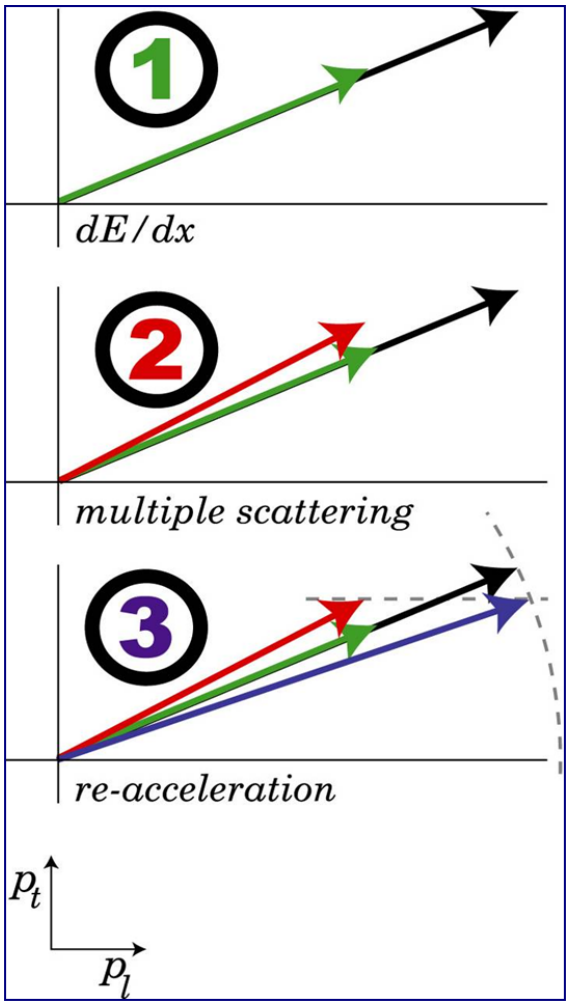

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2. Unavoidable multiple scattering:
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3. Re-acceleration to restore energy lost in material

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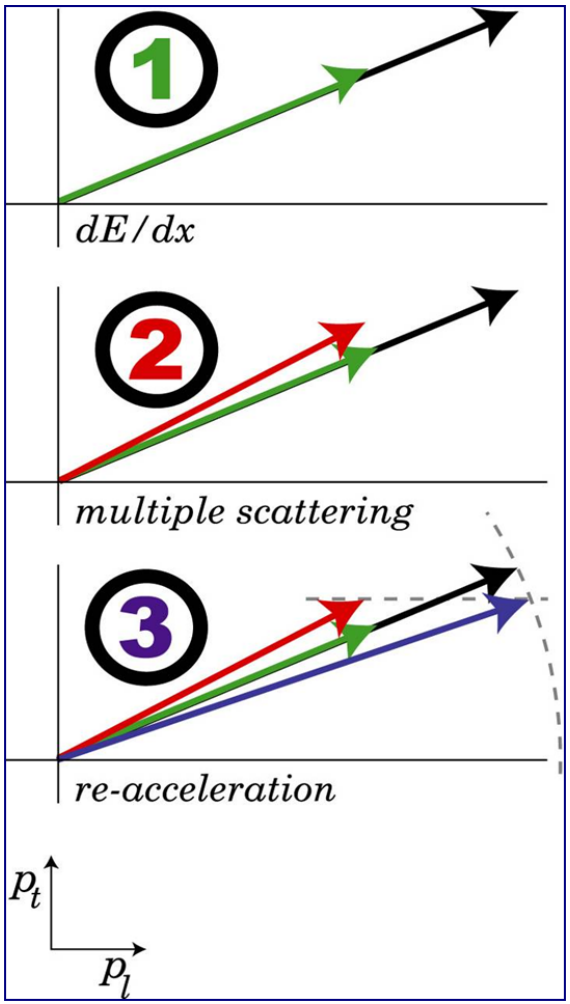

$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp(13.6\text{ MeV})^2}{2\beta^3 E_\mu m_\mu X_0},$$

where $d\epsilon_N/ds$ is the rate of normalized emittance change within the absorber; βc, E_μ, and m_μ are the muon velocity, energy, and mass; $\beta_\perp$ is the lattice betatron function at the absorber; and X_0 the radiation length of the absorber material. Need low $\beta_\perp$, large X_0.

1. Energy loss in material:
   - all three components of the particle's momentum are affected.
2. Unavoidable multiple scattering:
   - can be minimized by choosing the material with large X_0, hence, low Z.
3. Re-acceleration to restore energy lost in material

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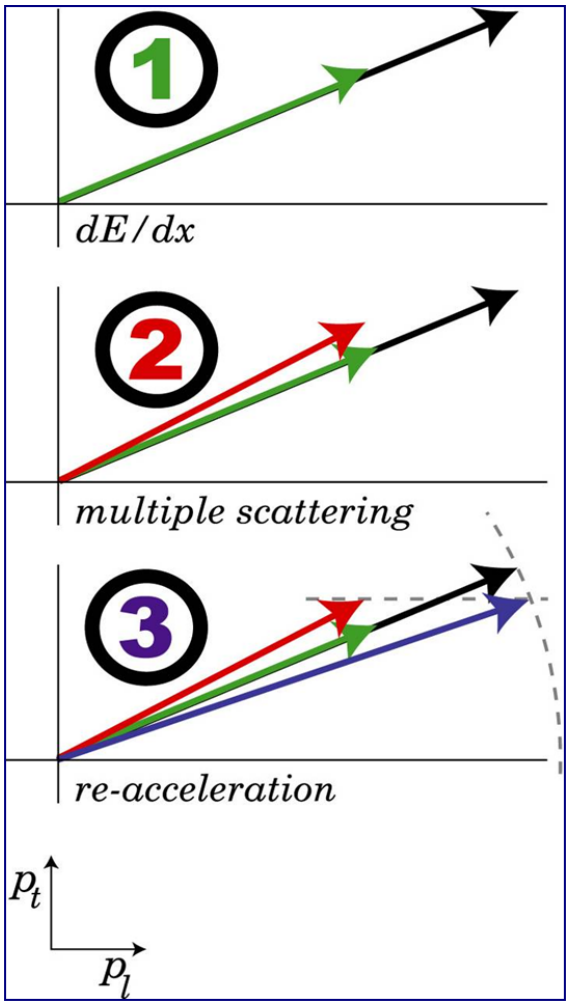

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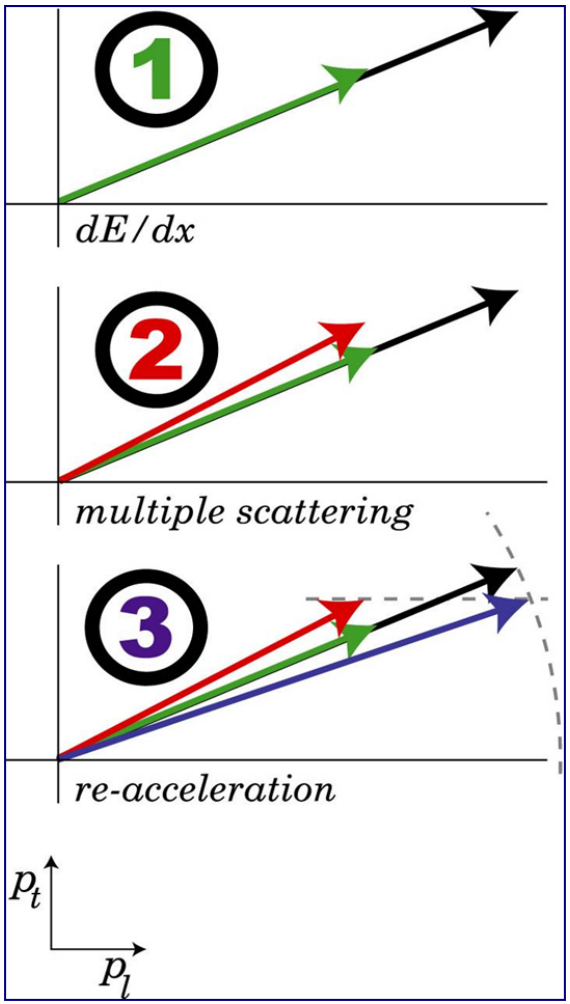

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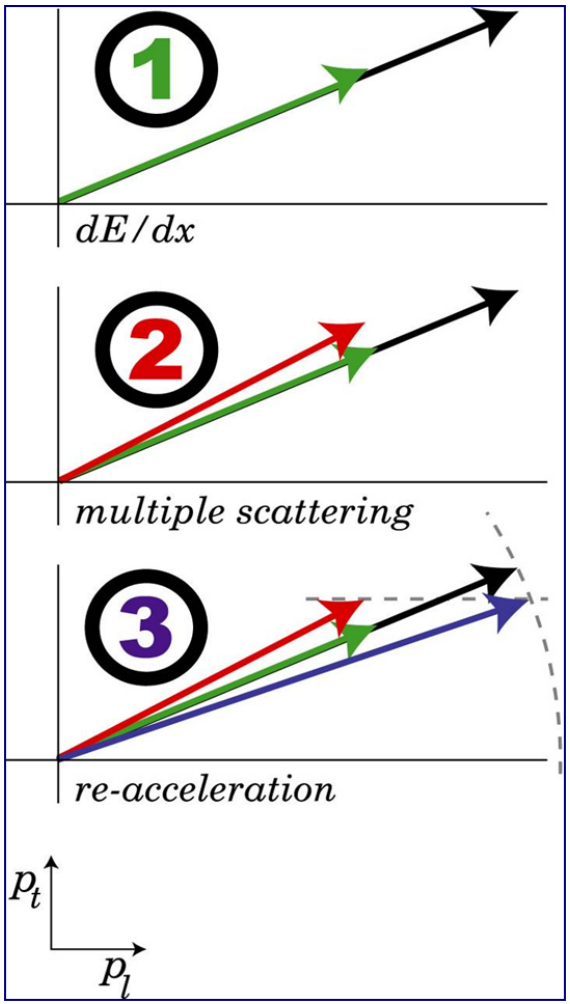

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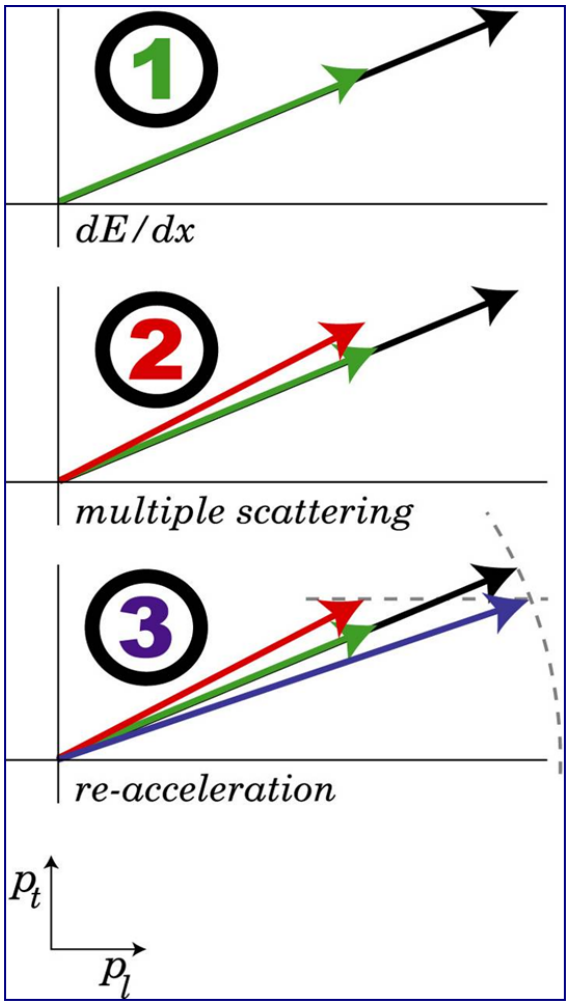

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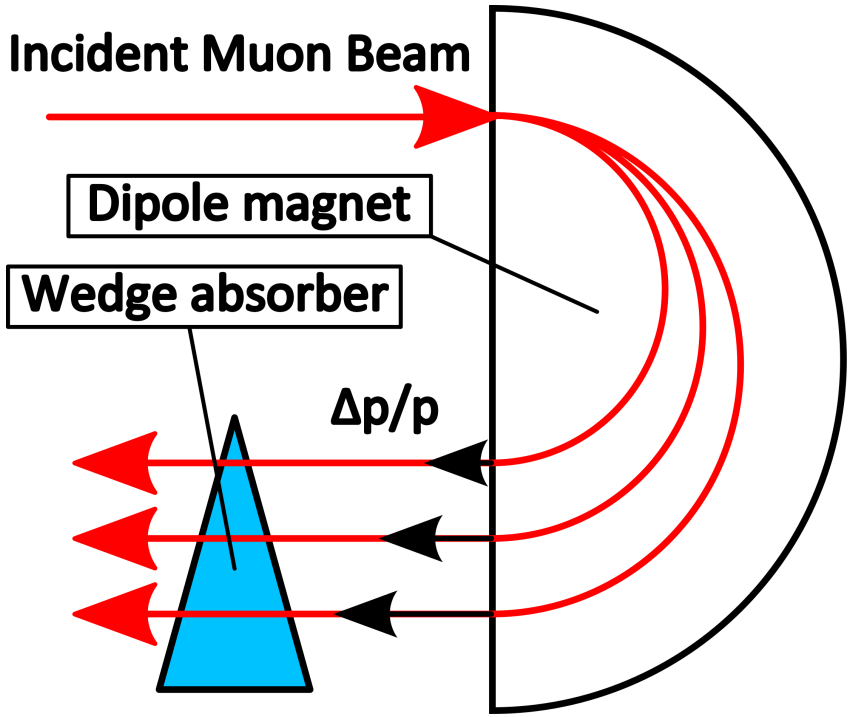
Emittance exchange or “How to cool in 6D”



Emittance exchange principle:

- pass dispersive beam through a wedge-shaped absorber;
- particles with more momentum pass through more material;
- beam energy spread is reduced;
- beam transverse size is increased.

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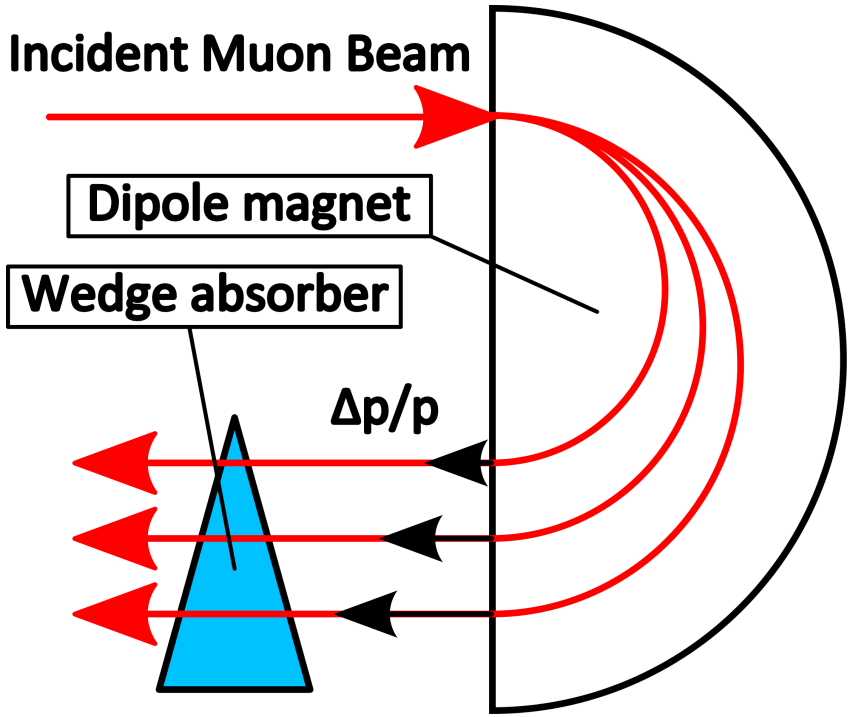

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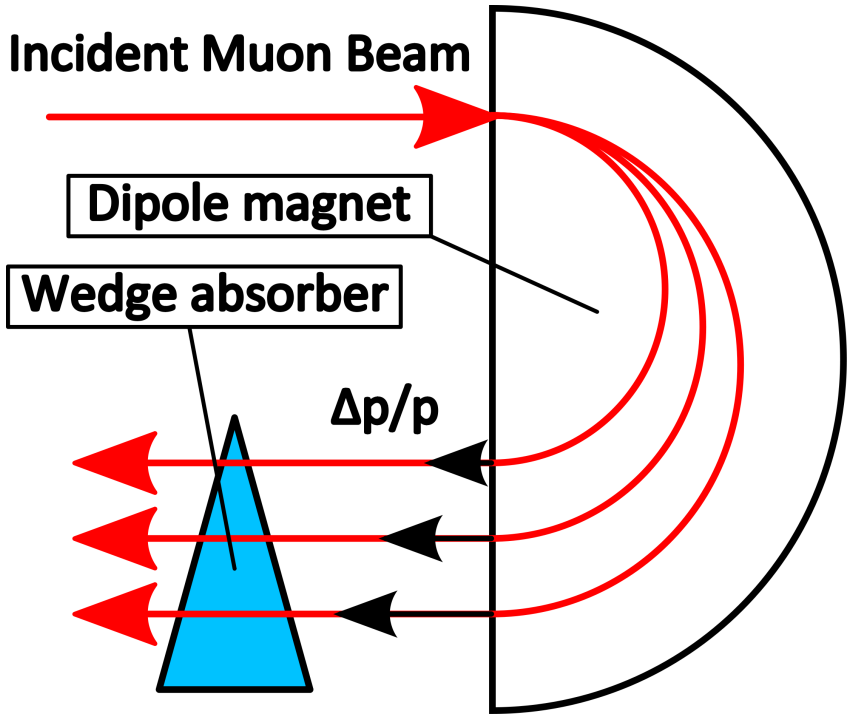

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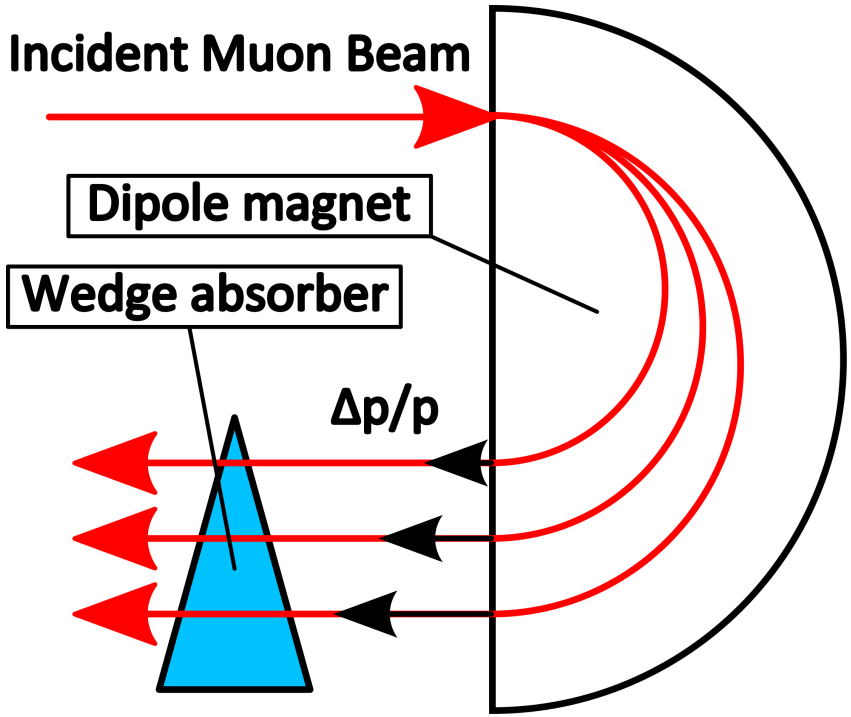

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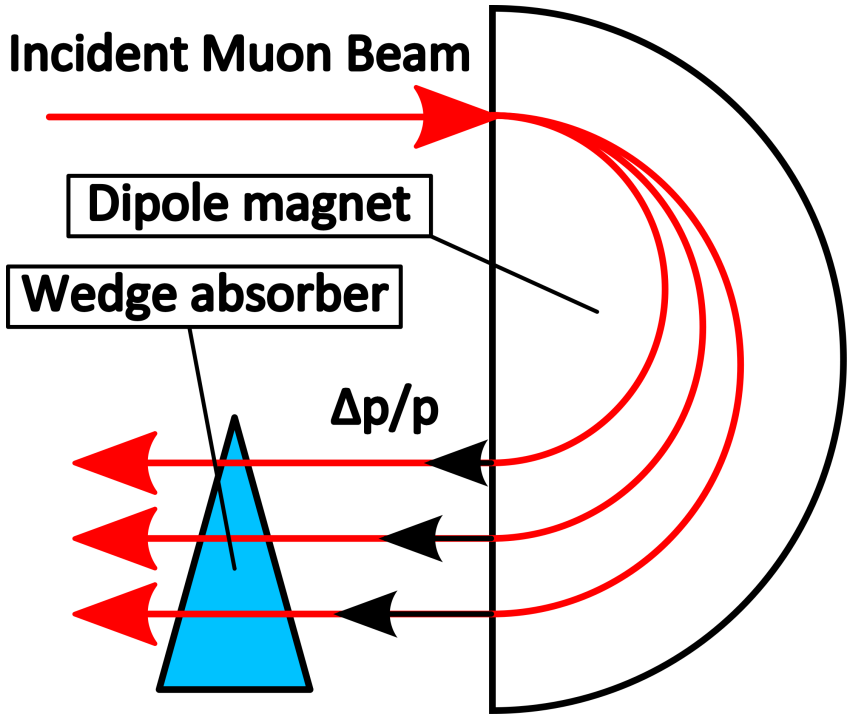

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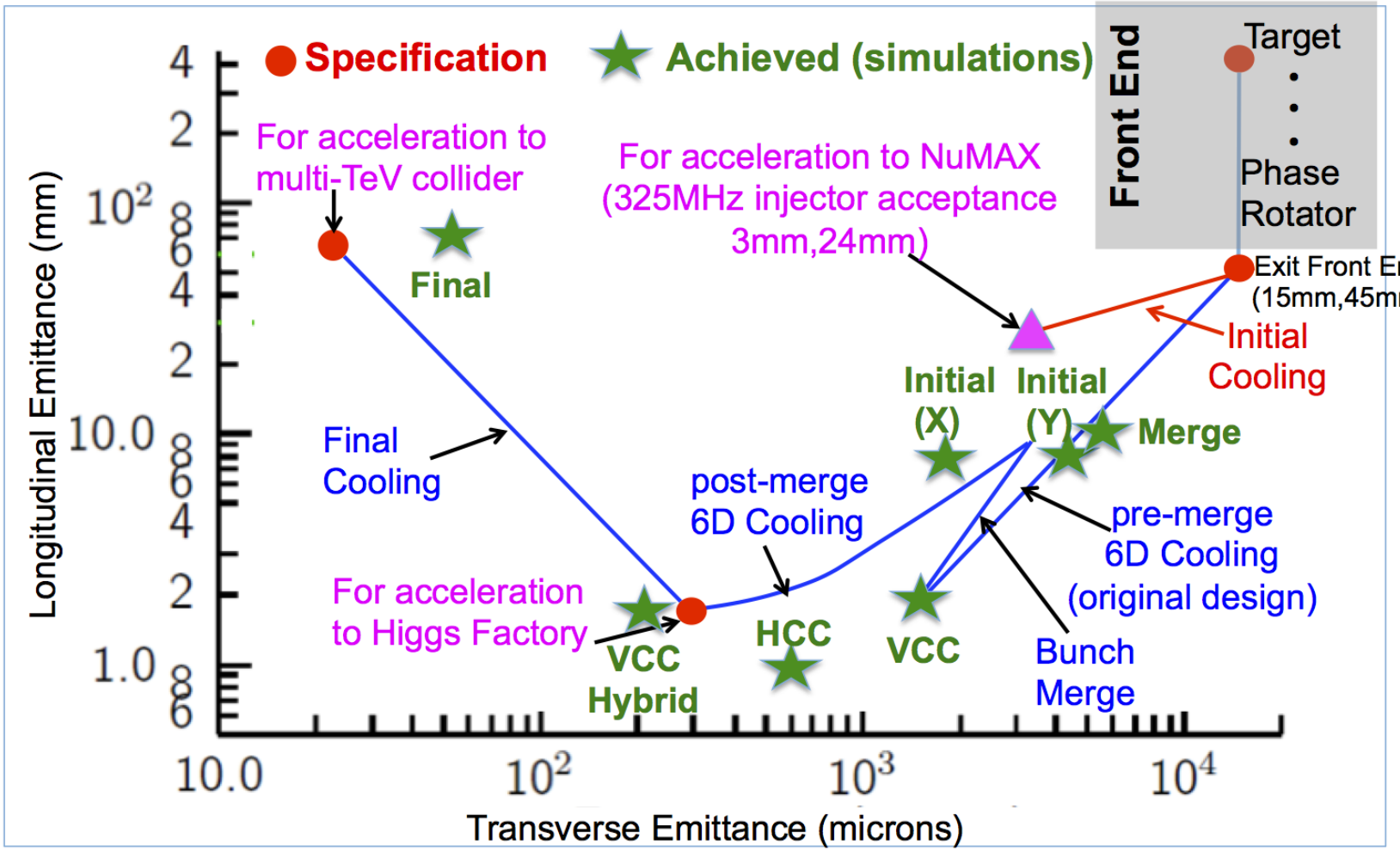
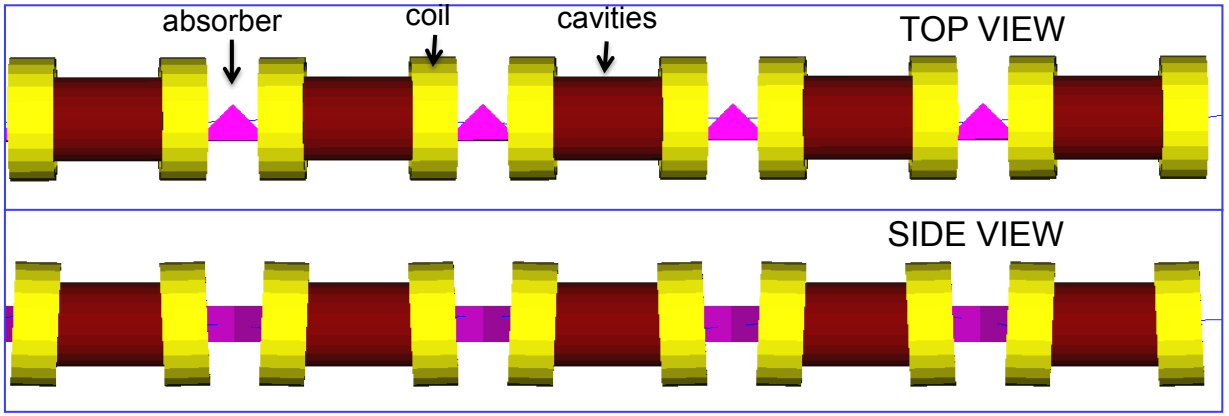
Cooling channels

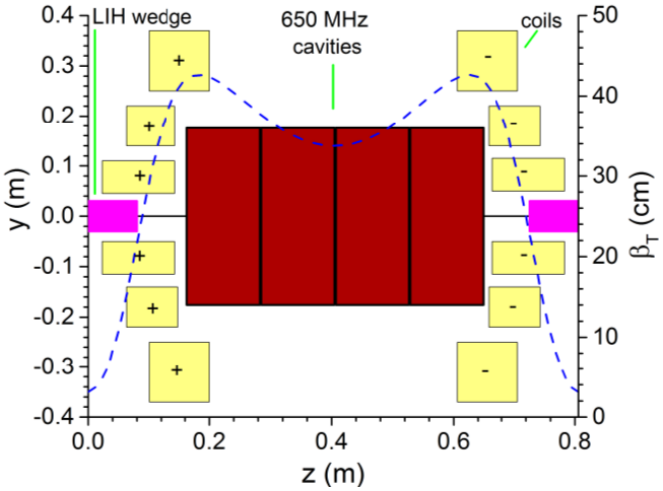
Emittance evolution diagram



Cooling channels for different applications

Vacuum RF cooling channel (VCC)





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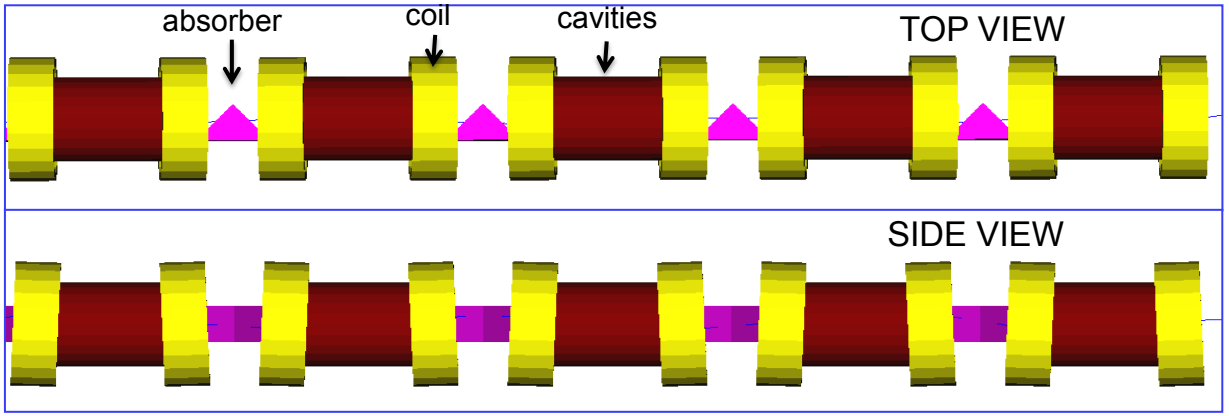

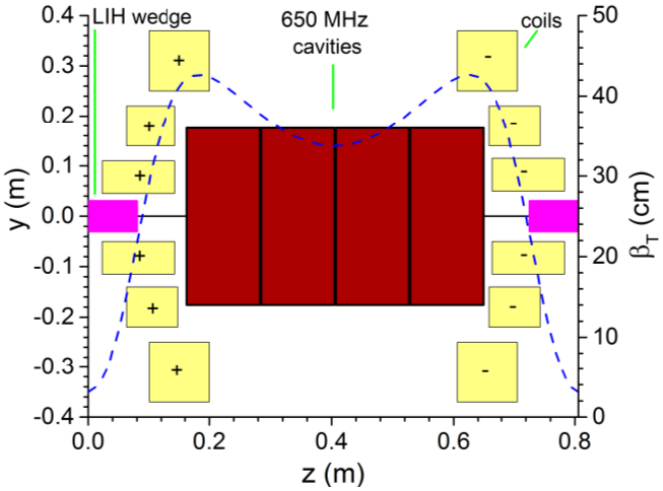

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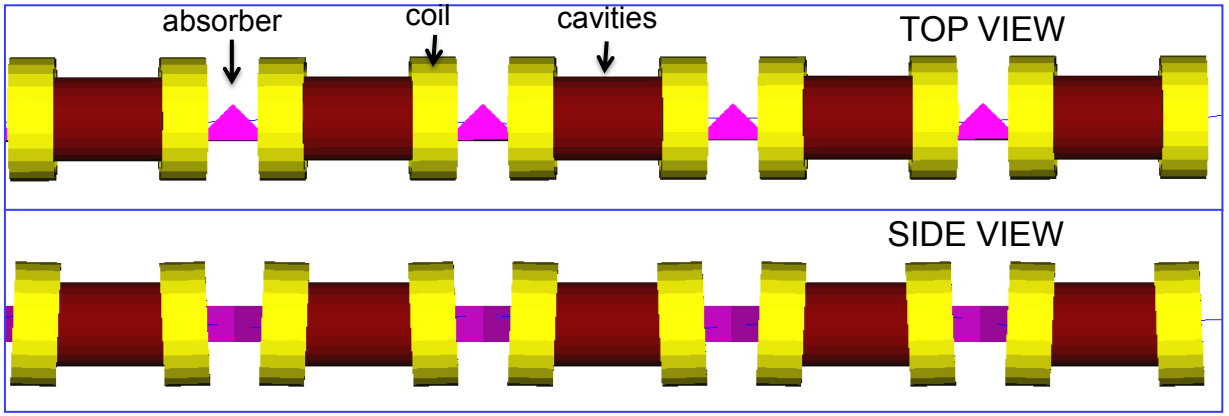

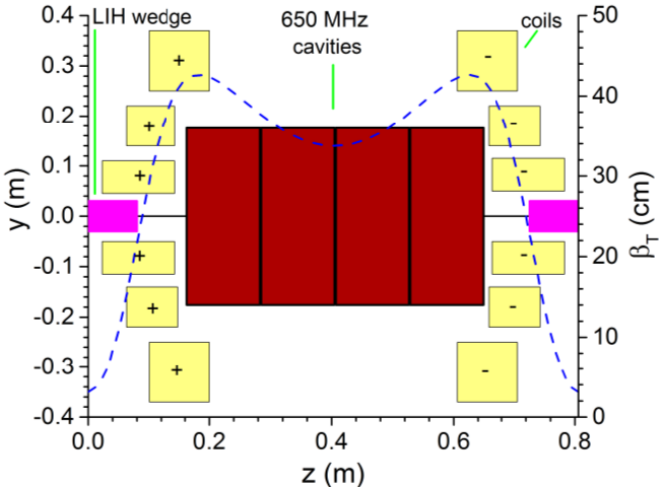

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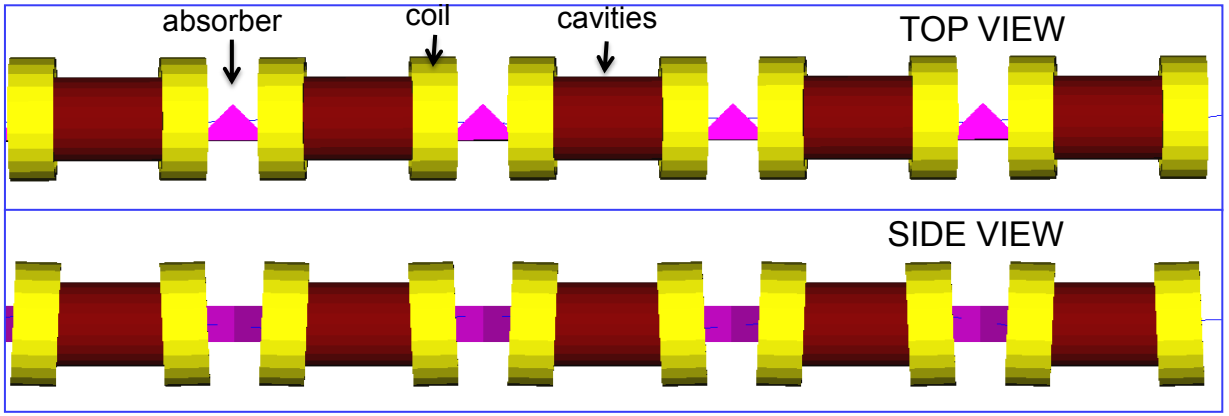

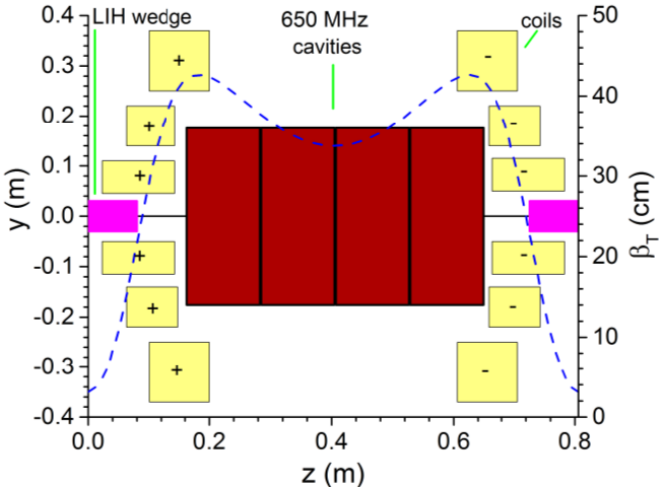

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- Channel is tapered:
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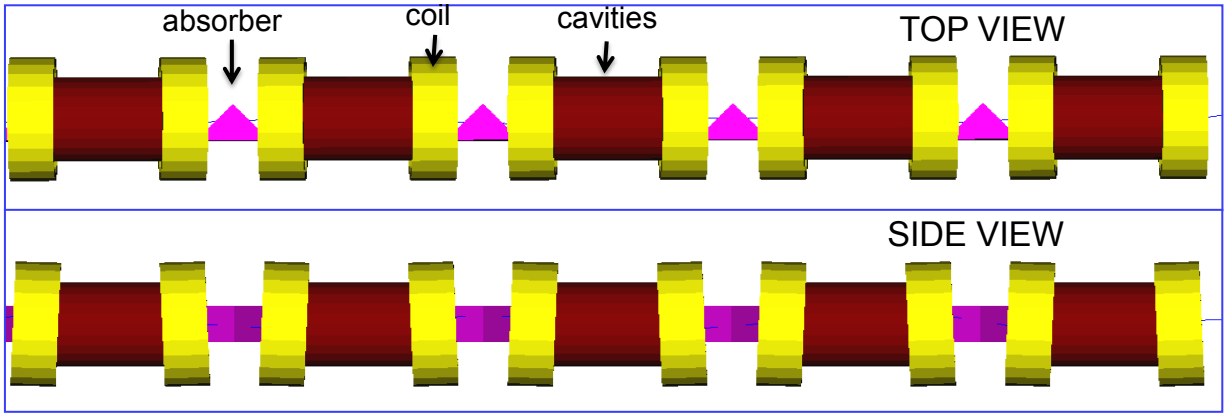
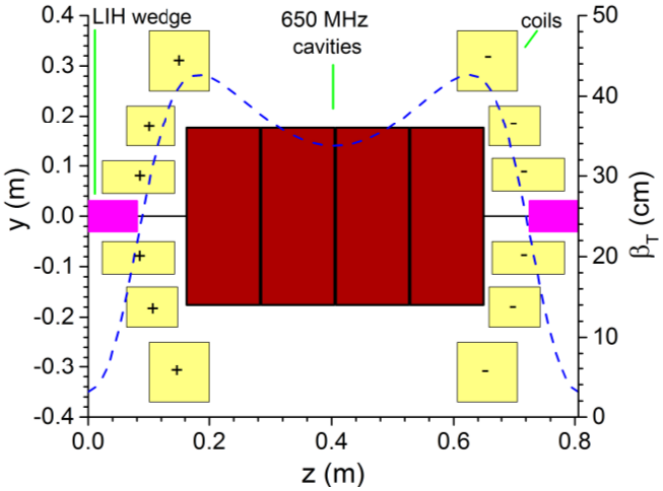
  - later stages: cells 20 cm long, 650 MHz RF, axial B=2.3 T, beta function 25 cm, coils near axis/RF

Vacuum RF cooling channel (VCC)





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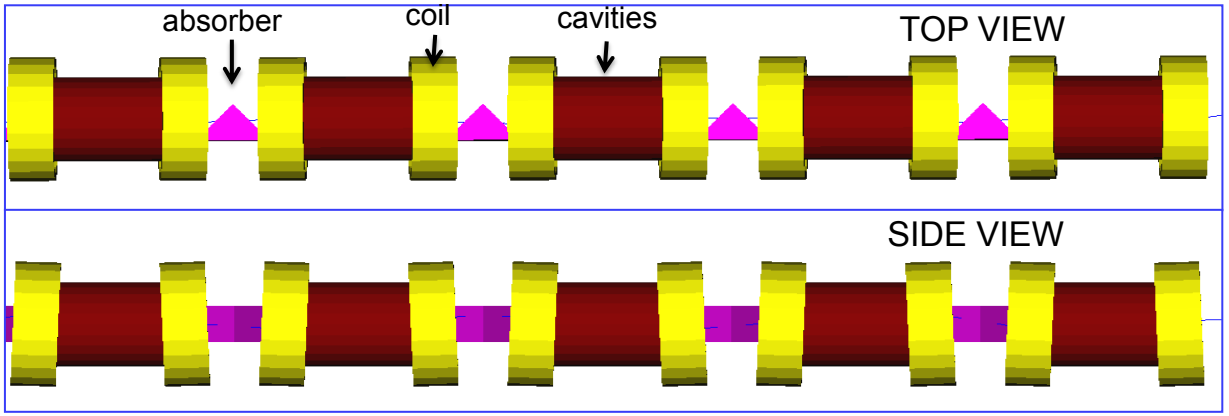

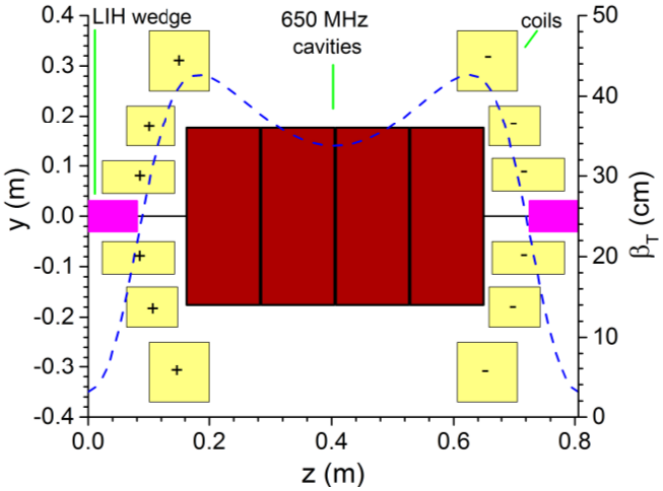

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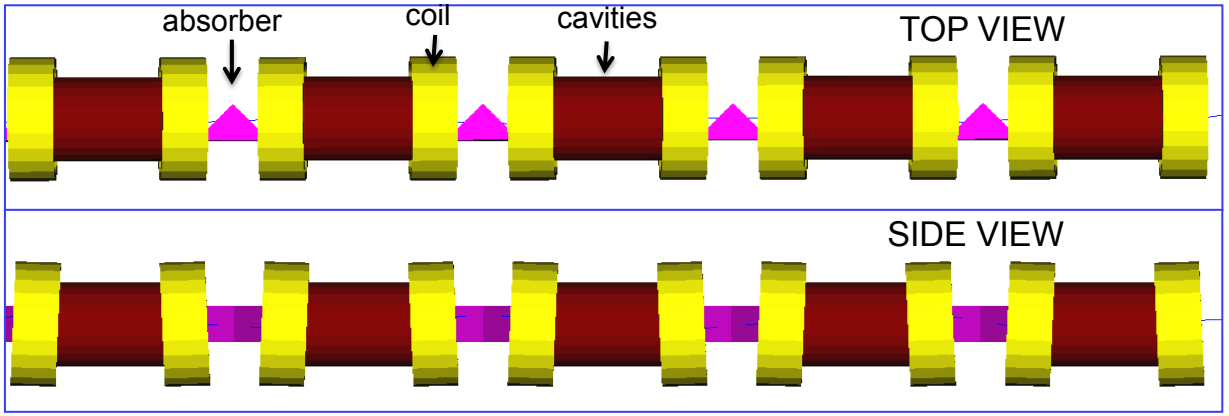

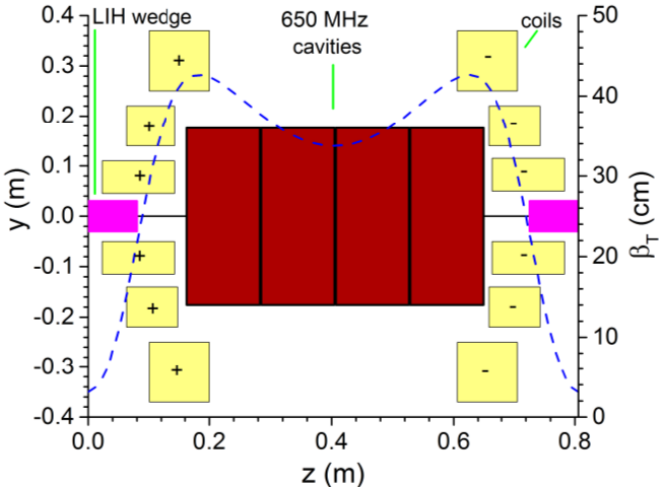

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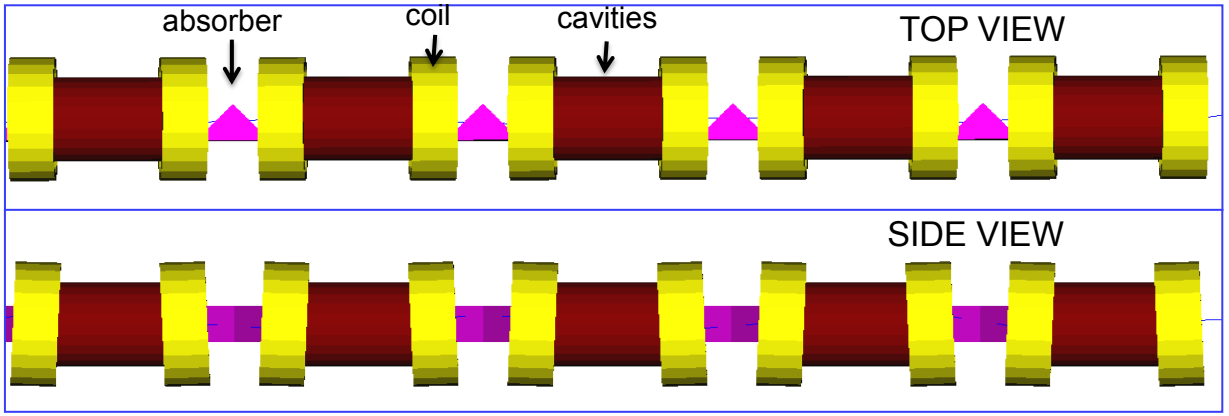

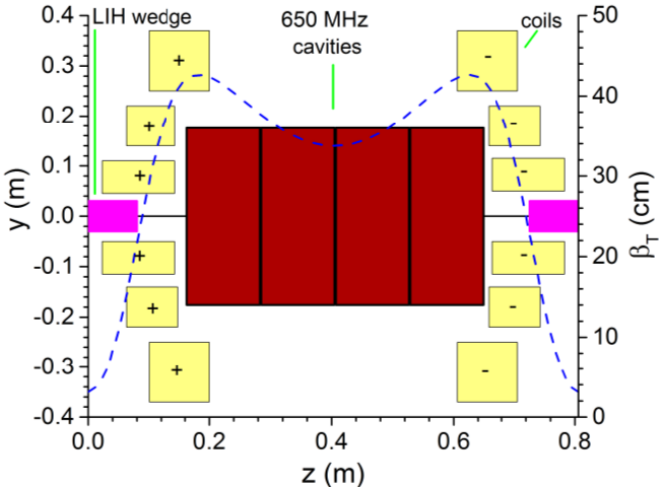

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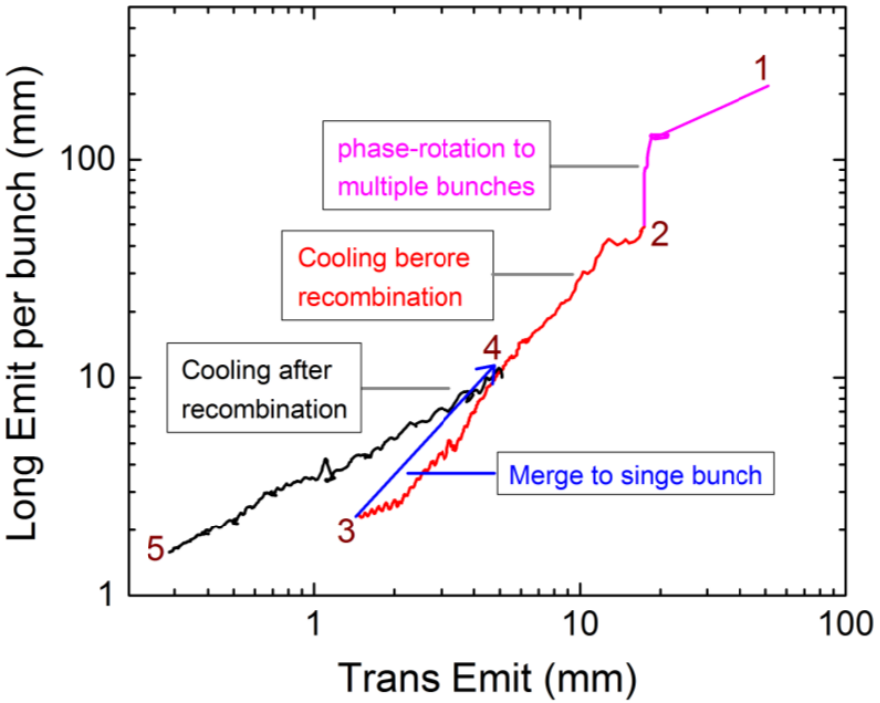
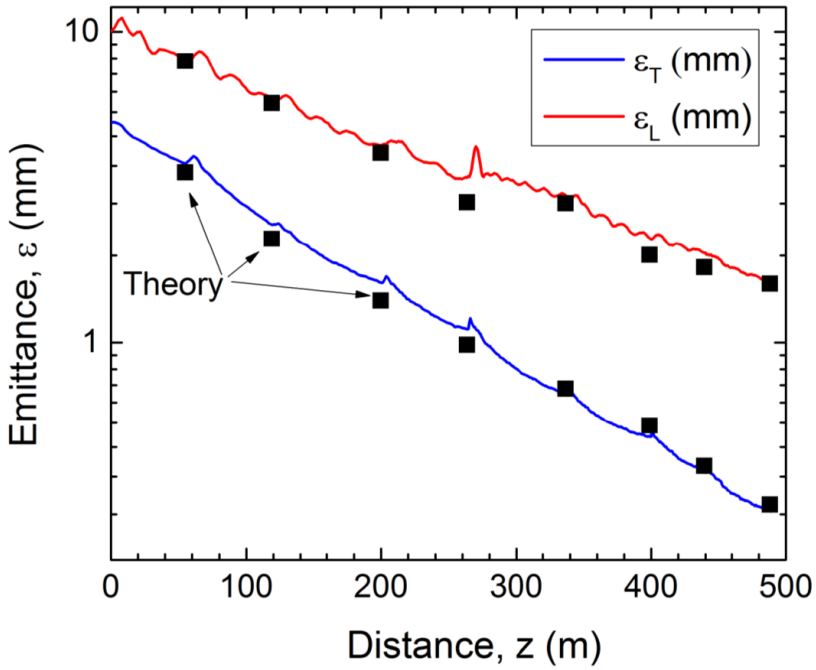
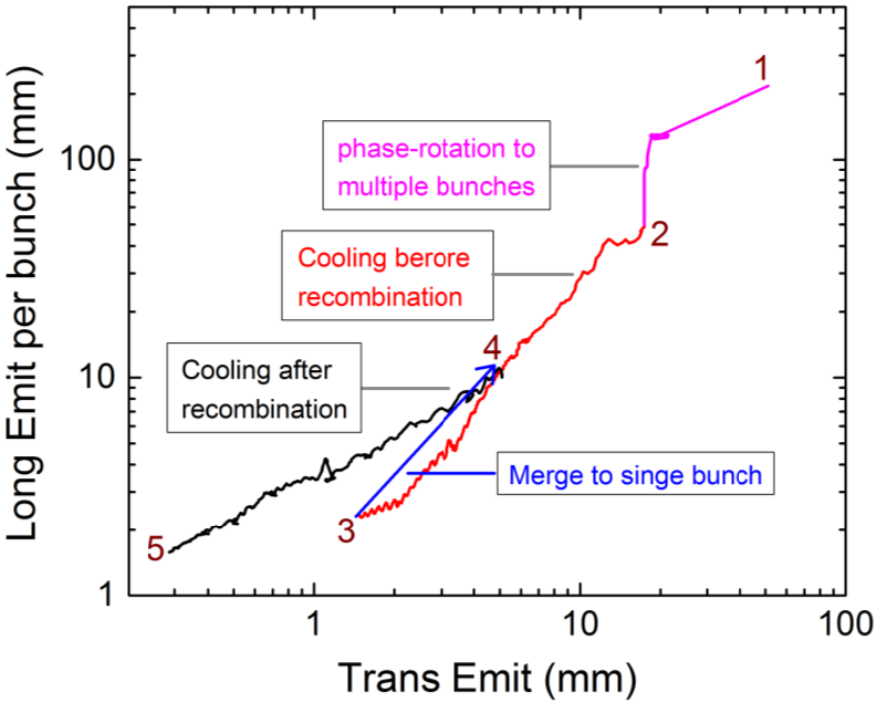
Emittance reduction in VCC

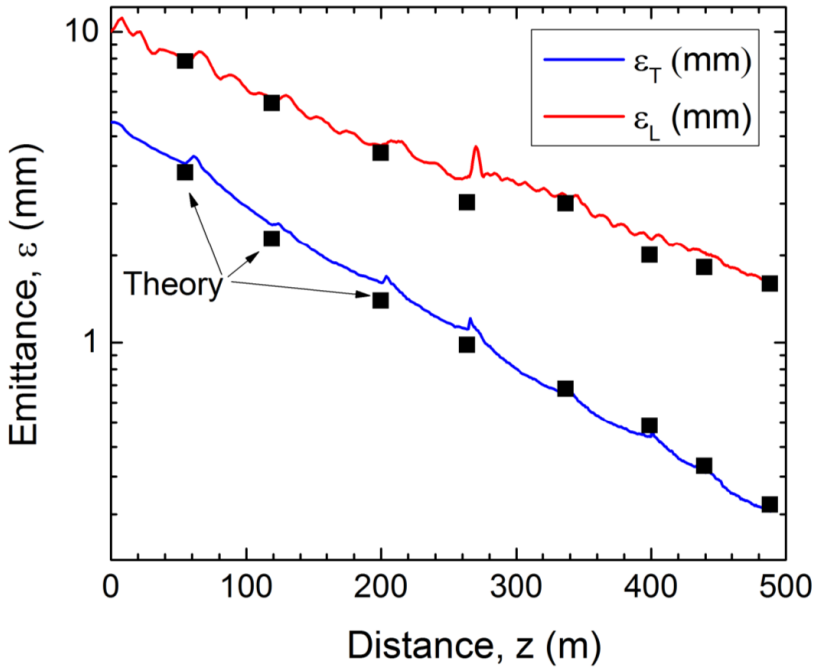




- Emittance evolution plot (left): reaching design goals of 0.3 mm in transverse and 1.5 mm in longitudinal emittance.
- Emittance evolution after bunch merge (right): good agreement with theoretical predictions.
- Detailed end-to-end simulations.
- 6D emittance reduction by a factor of 10^5.

Emittance reduction in VCC





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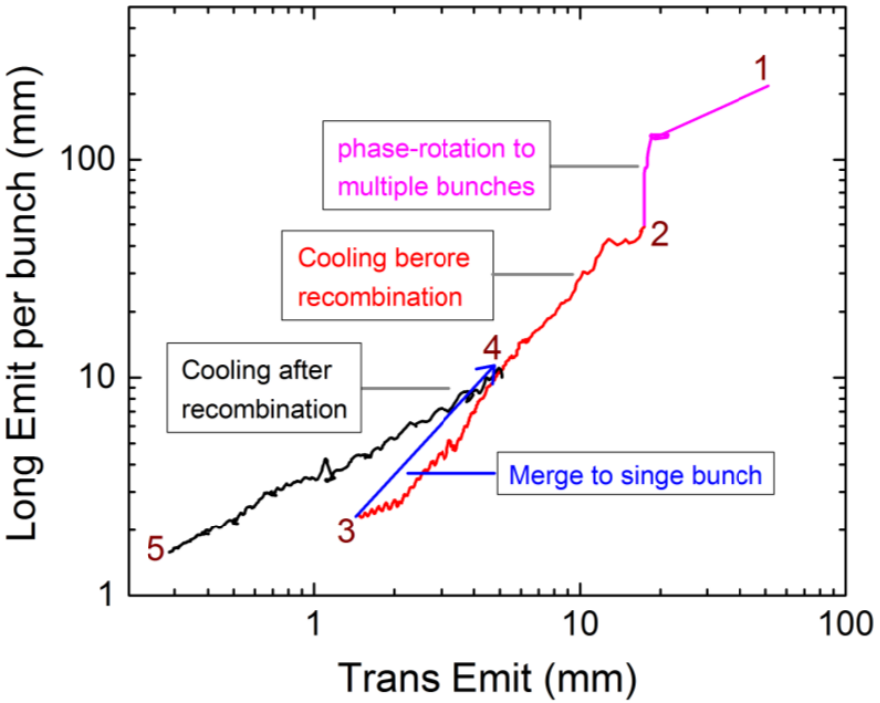

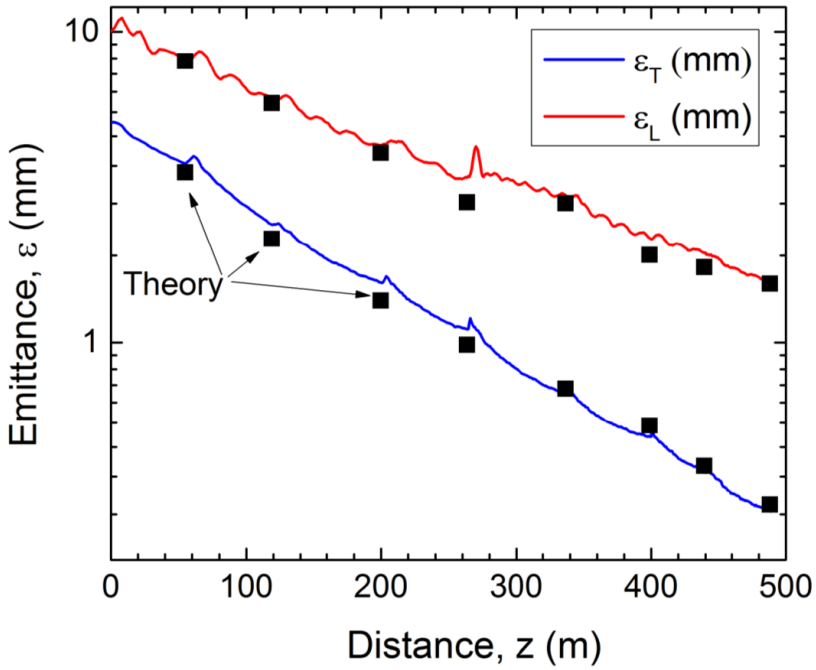

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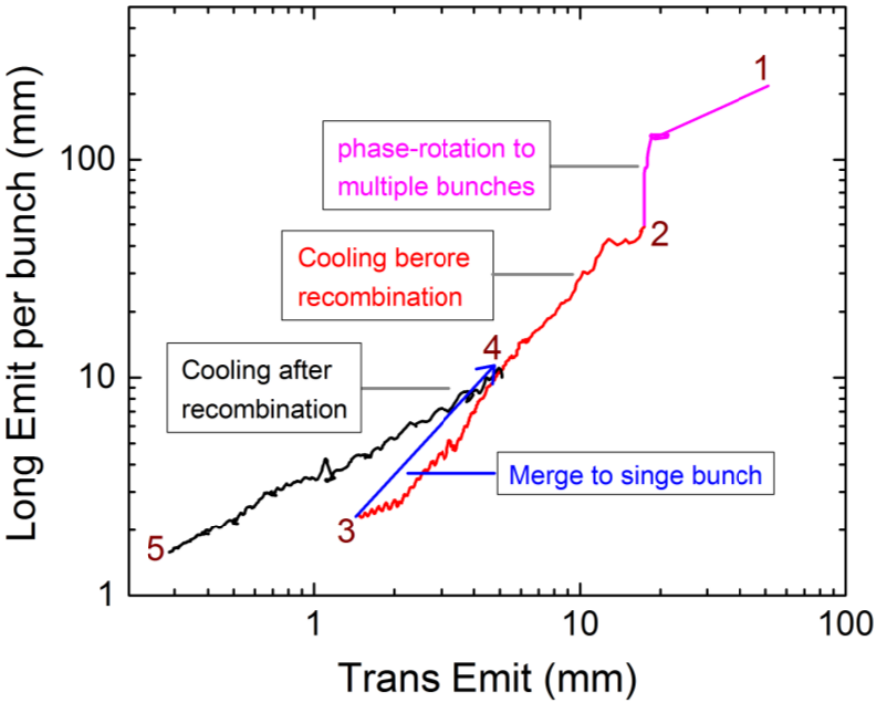

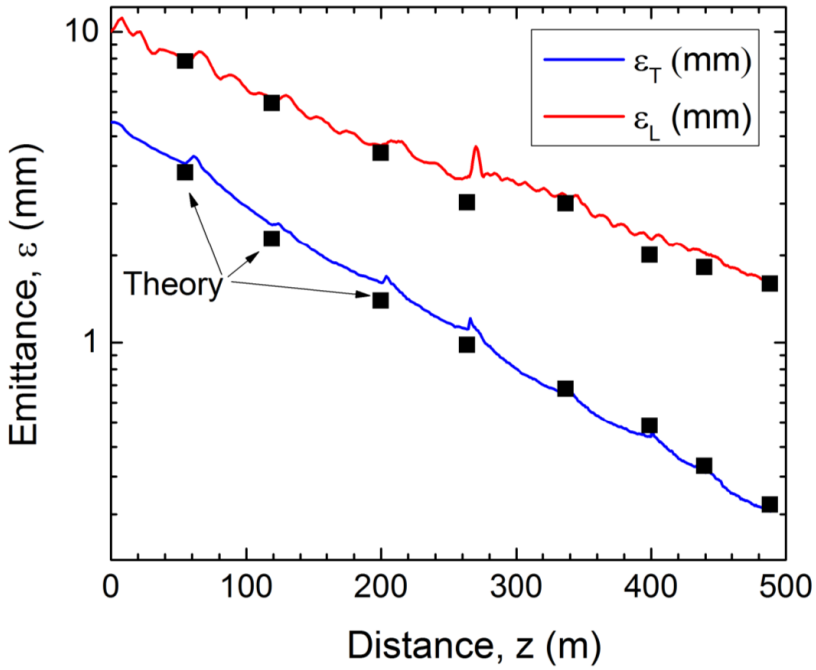

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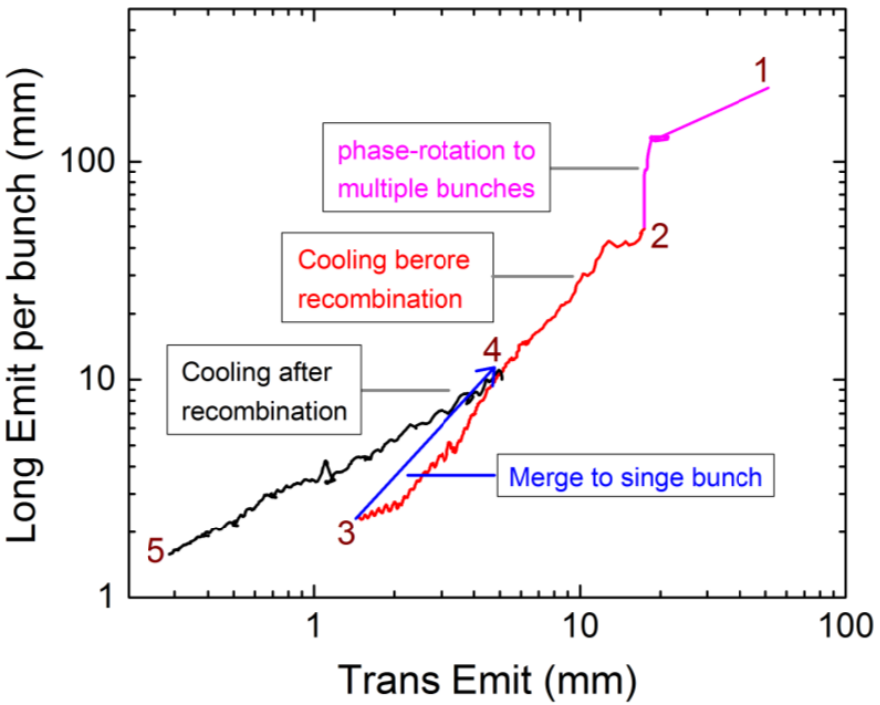

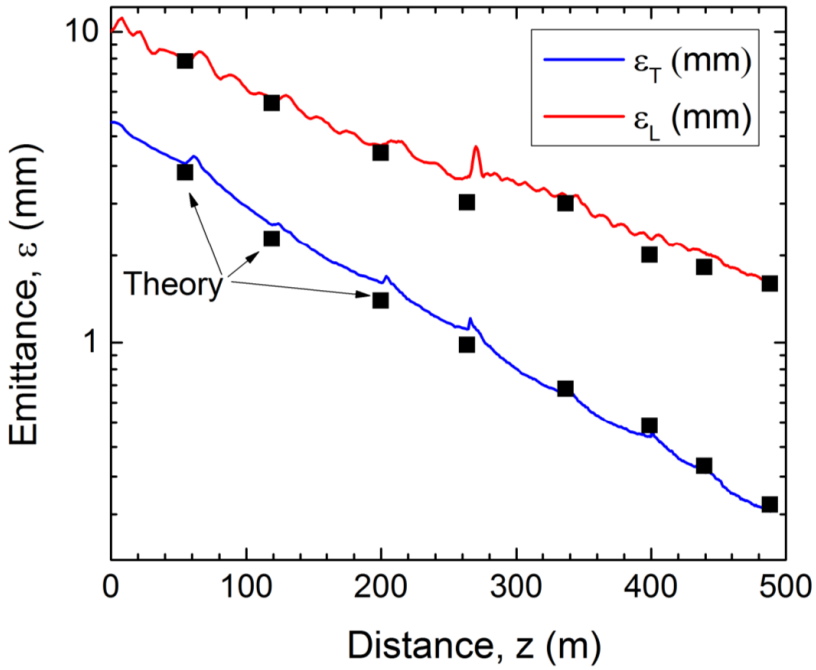

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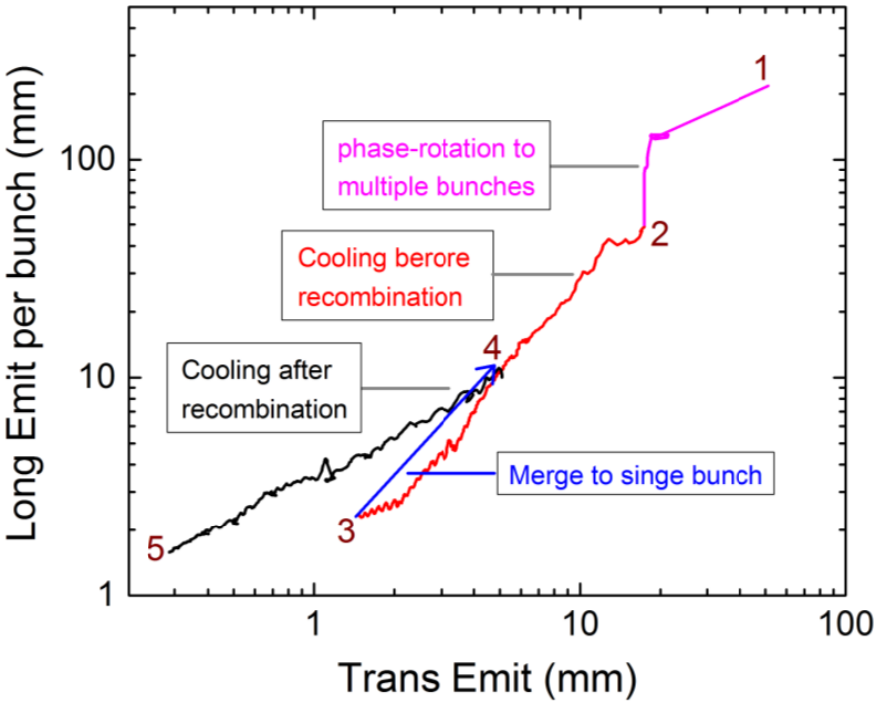
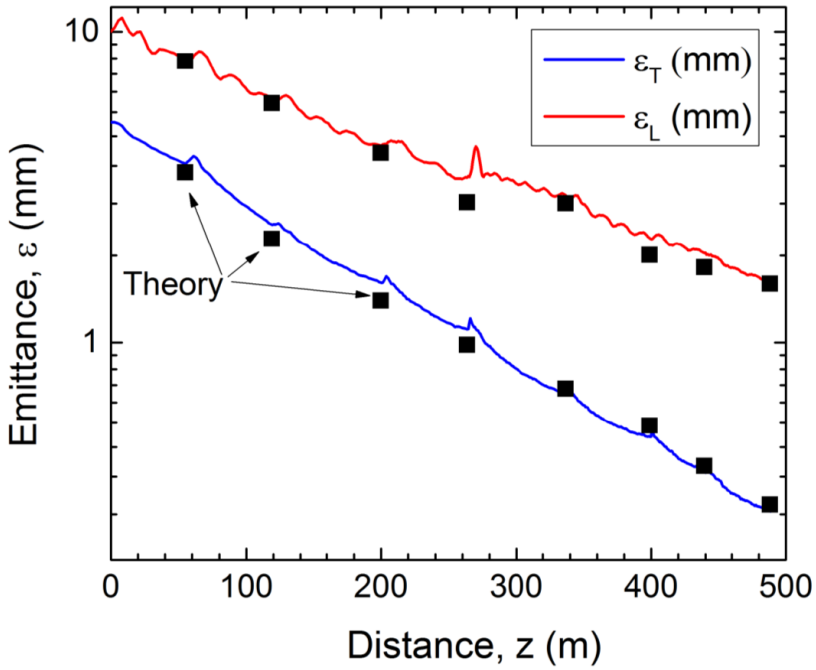
Emittance reduction in VCC

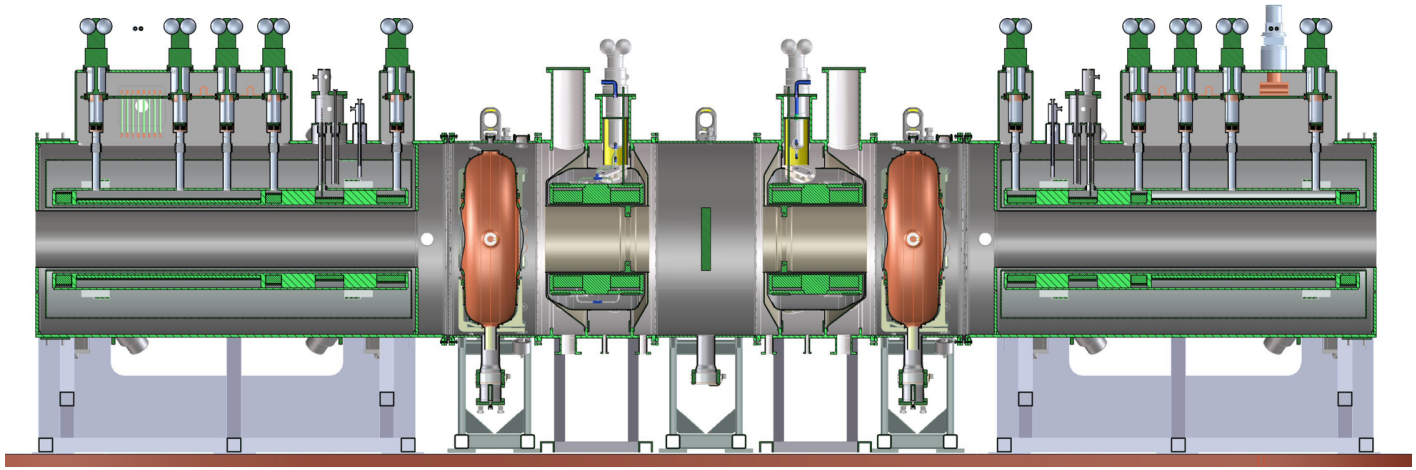




- Emittance evolution plot (left): reaching design goals of 0.3 mm in transverse and 1.5 mm in longitudinal emittance.
- Emittance evolution after bunch merge (right): good agreement with theoretical predictions.
- Detailed end-to-end simulations.
- 6D emittance reduction by a factor of 10^5.
  - Meets Higgs Factory emittance requirements.

MICE: Muon Ionization Cooling Experiment

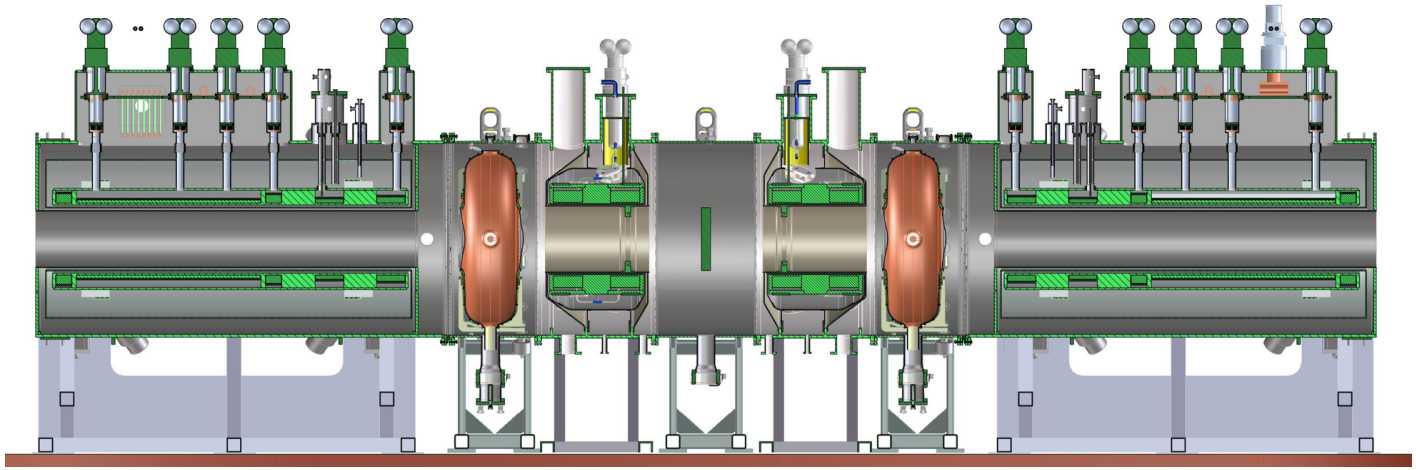
MICE and its objectives



MICE – international experiment at Rutherford Appleton Laboratory in UK

- Design, engineer and fabricate a section of cooling channel.
- Place the cooling apparatus in a muon beam and measure its performance in various modes of operation and beam conditions, thereby investigating the limits and practicality of ionization cooling.
- Measure a reduction in transverse beam size with a precision of 1%.
- Develop and thoroughly test simulation and data analysis software.
- Step IV: demonstrate transverse emittance reduction (2015-2016).
- Cooling demonstration configuration (shown in the figure): demonstrate sustainable transverse cooling with re-acceleration (2017-2018).

MICE and its objectives



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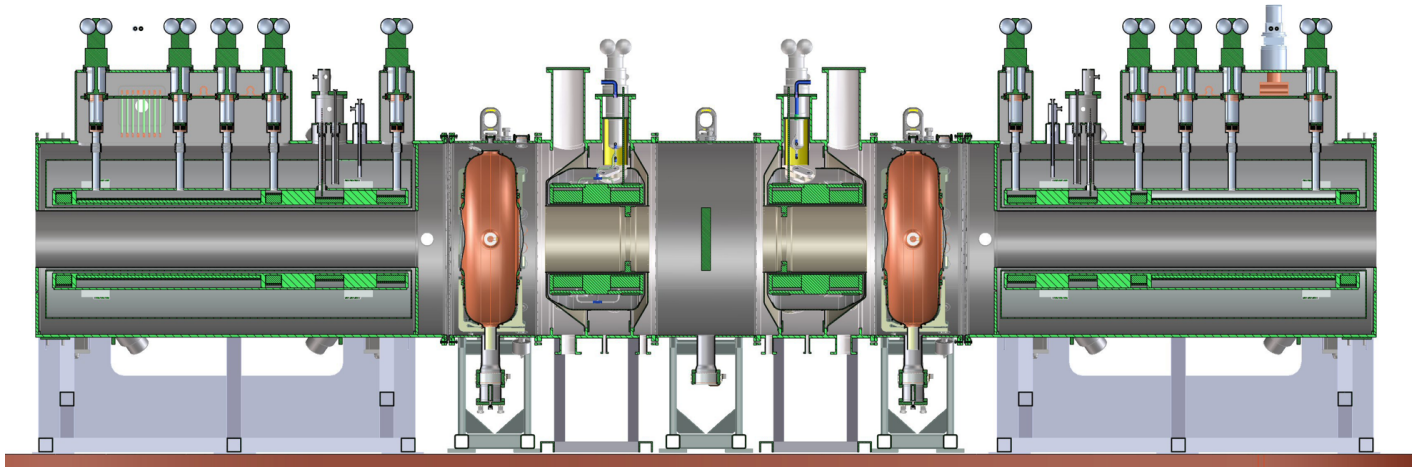

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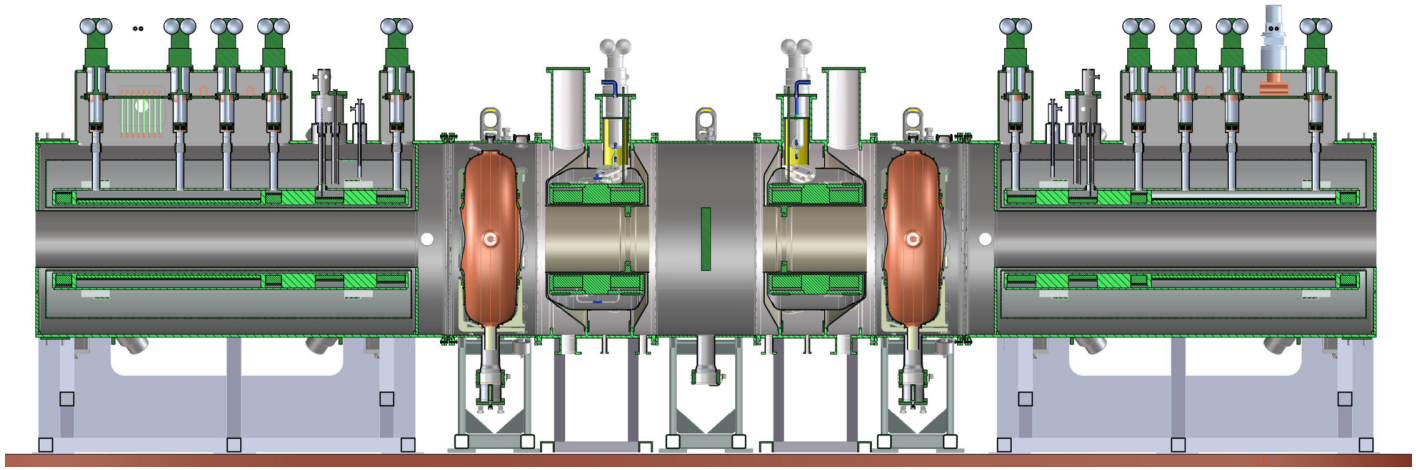

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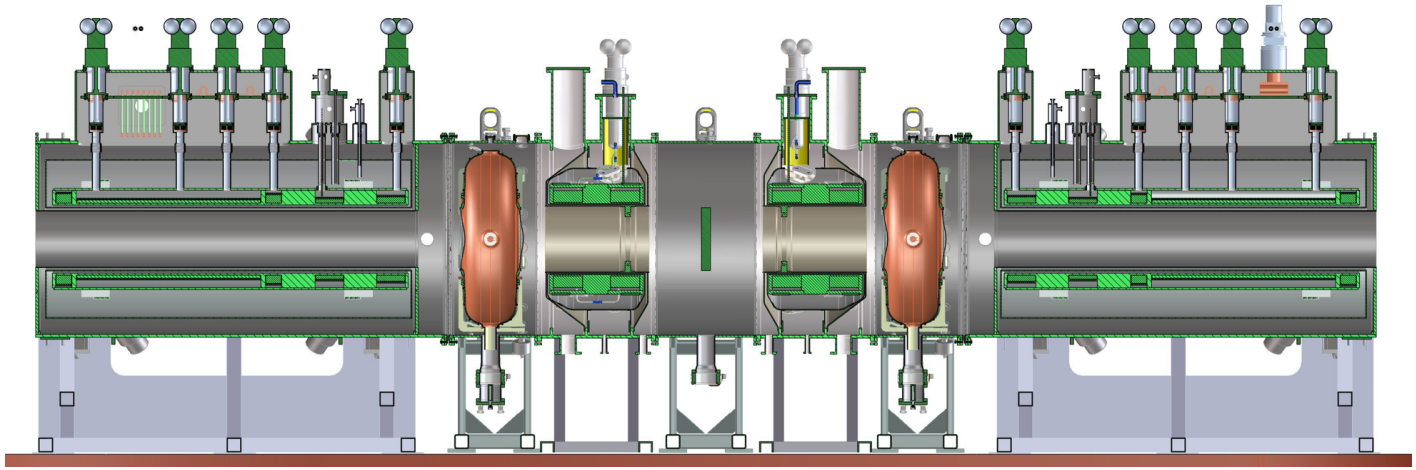

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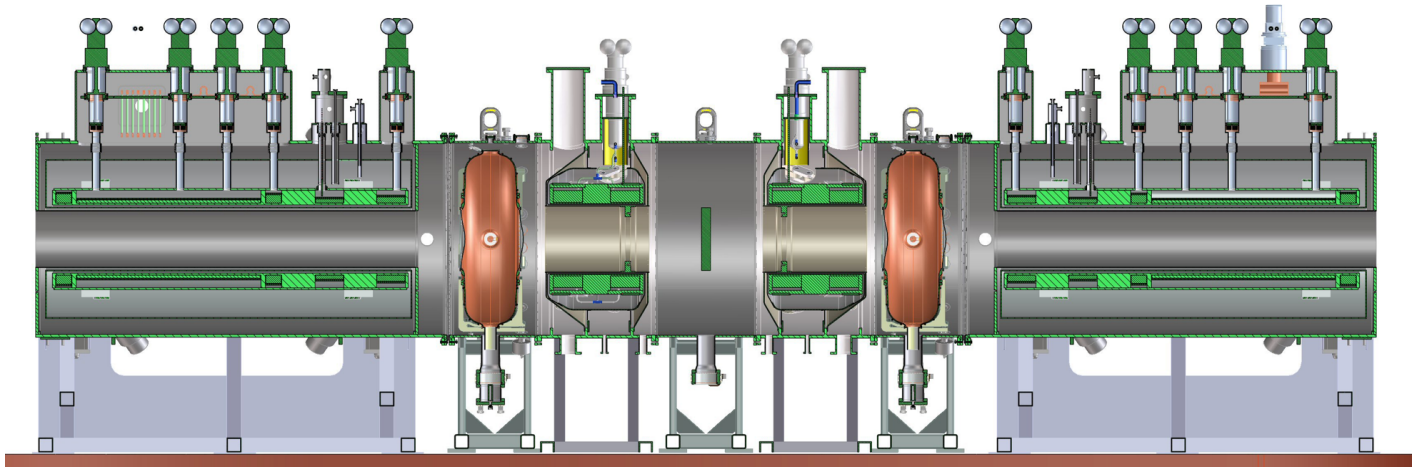

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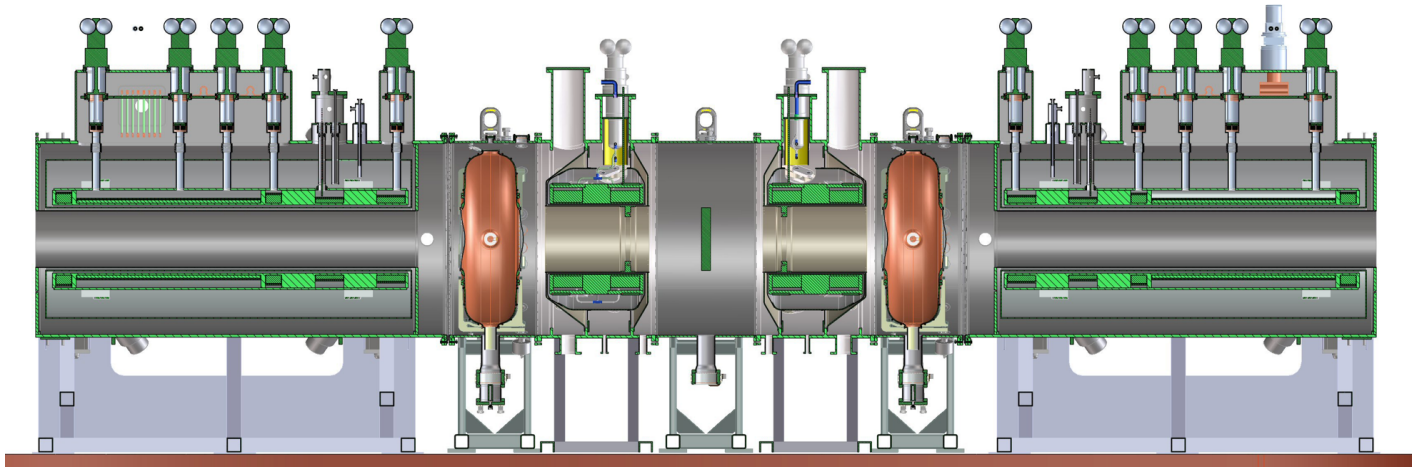

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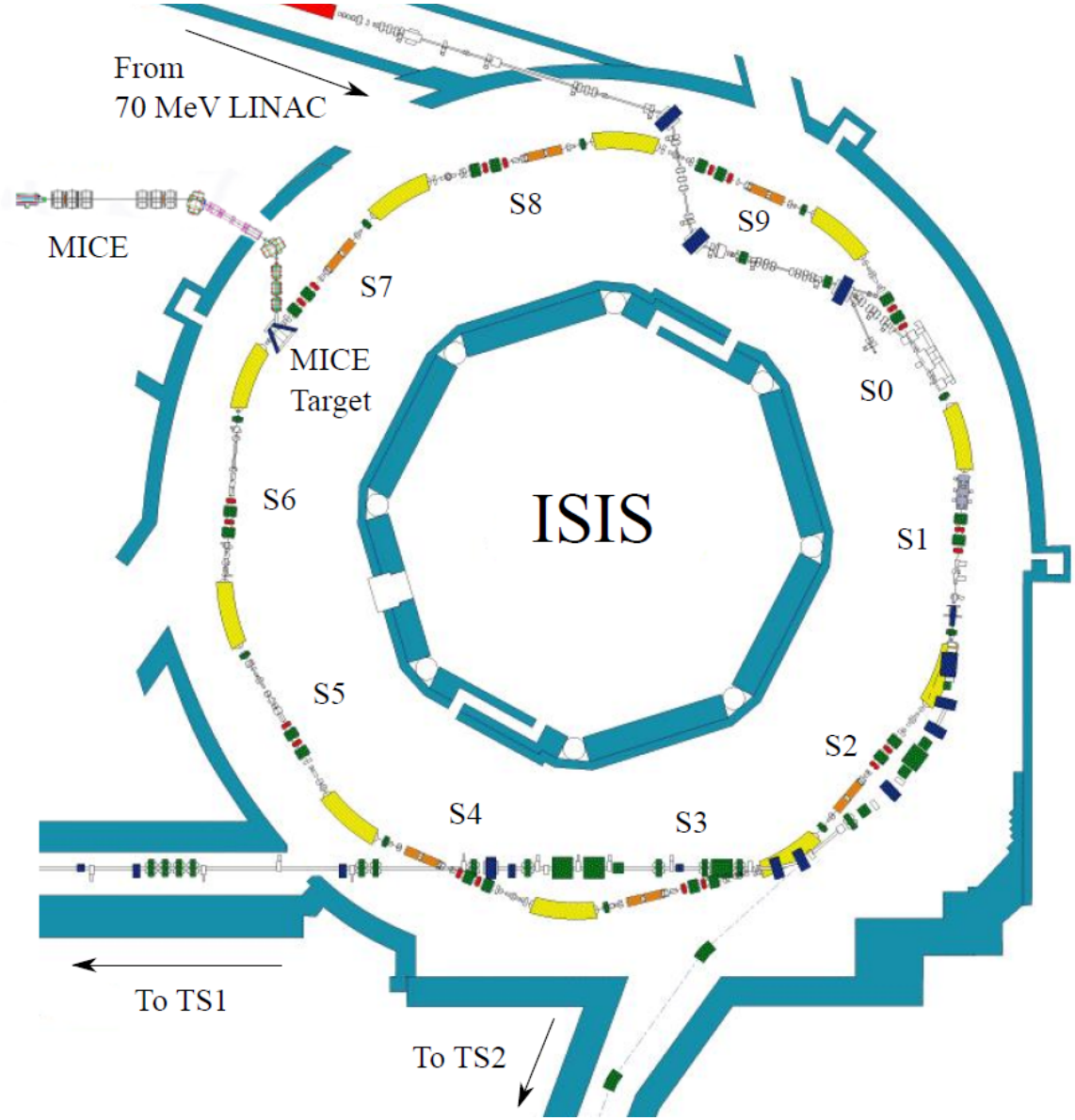
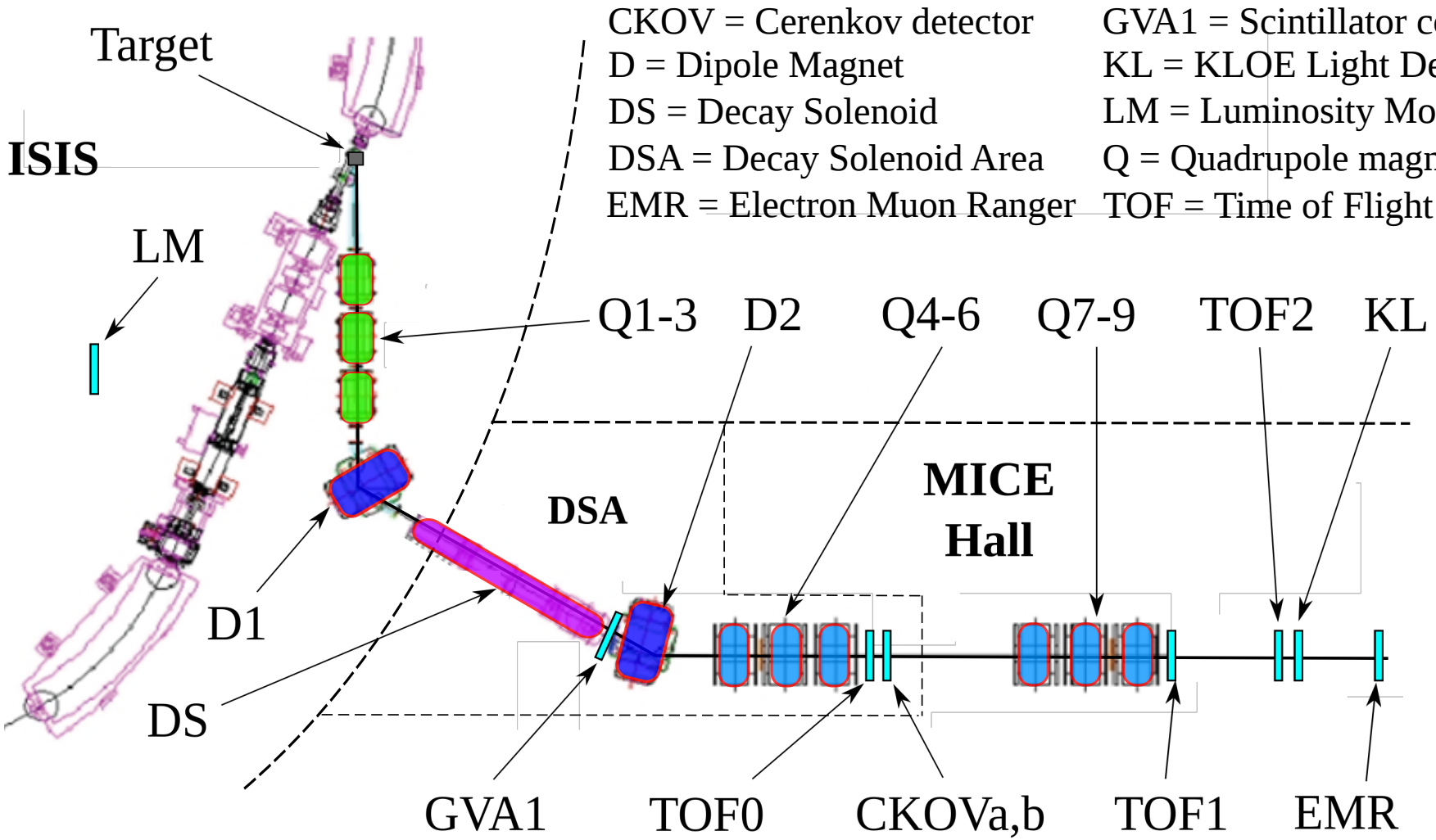
MICE and ISIS



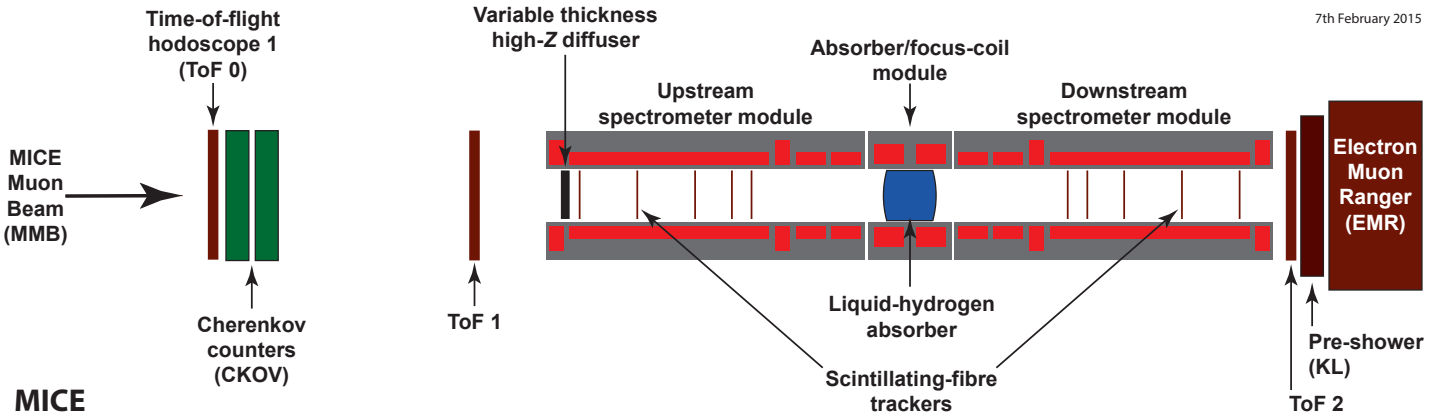
ISIS proton synchrotron and MICE beam line

MICE beam line

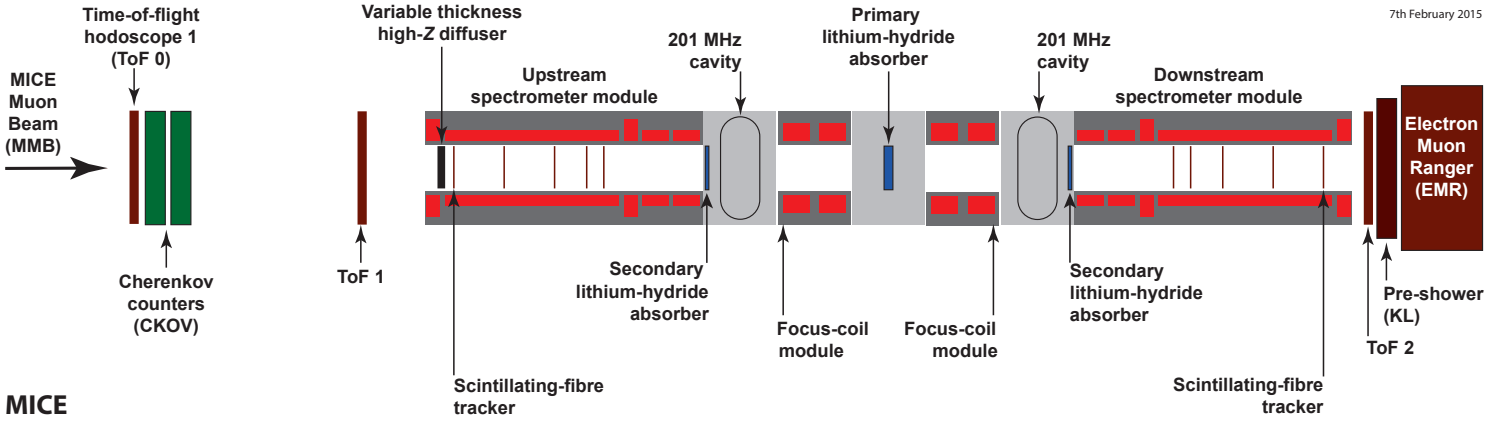


MICE beam line, MICE Step IV is placed between TOF1 and TOF2; EMR, KL, TOF2 are moved in their final positions

MICE configurations

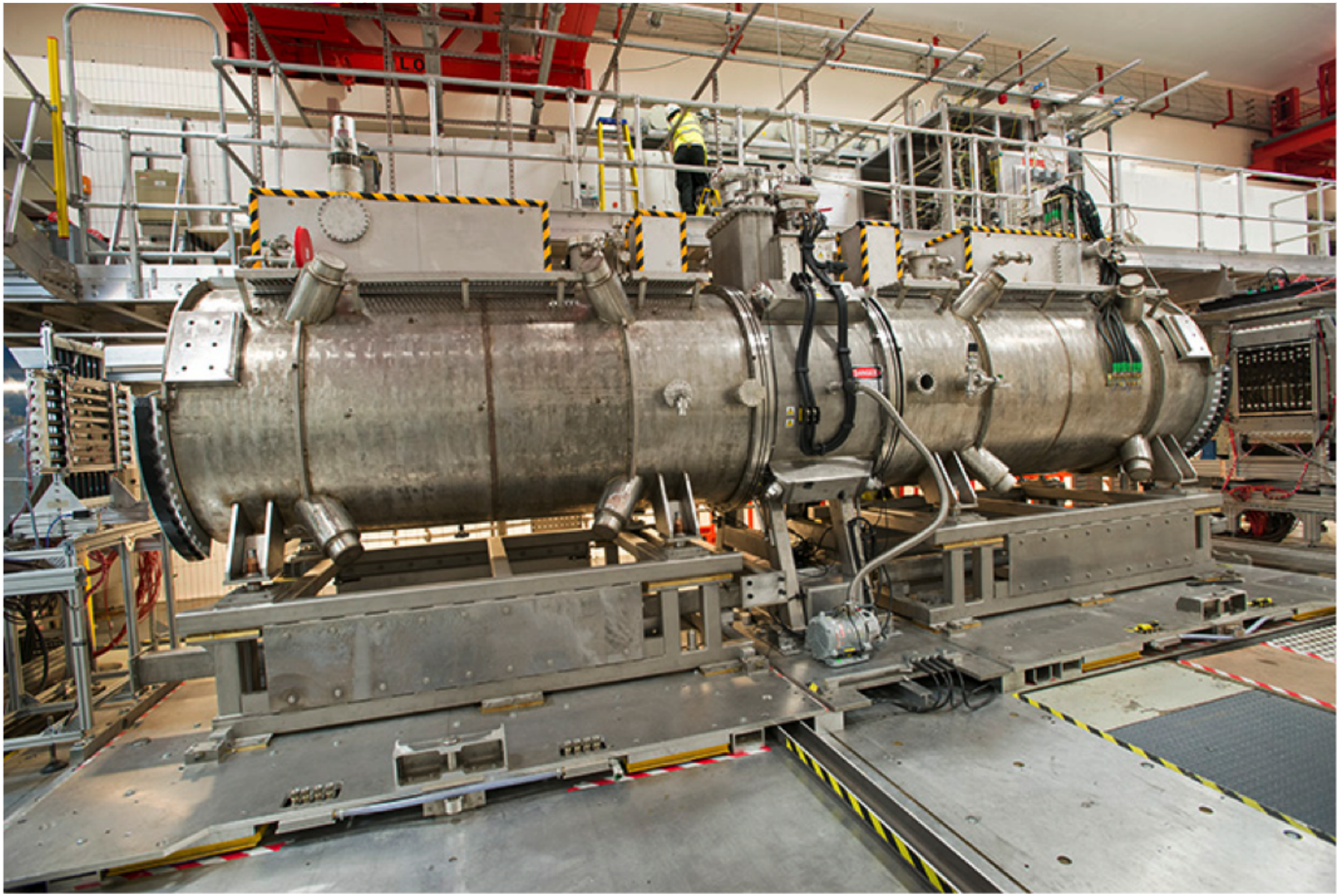


MICE Step IV



MICE Ionization Cooling Demonstration Step

MICE Step IV on the floor



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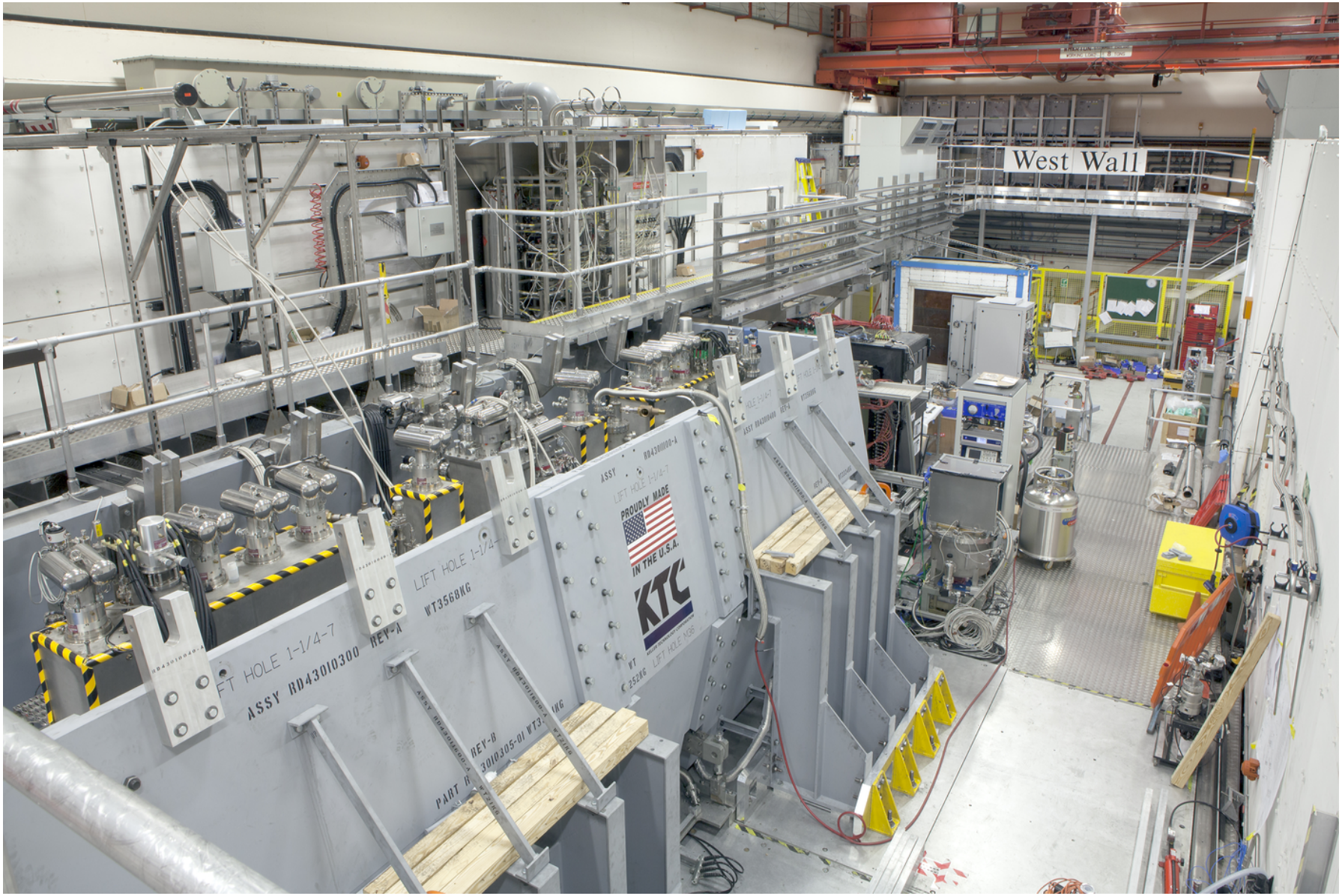
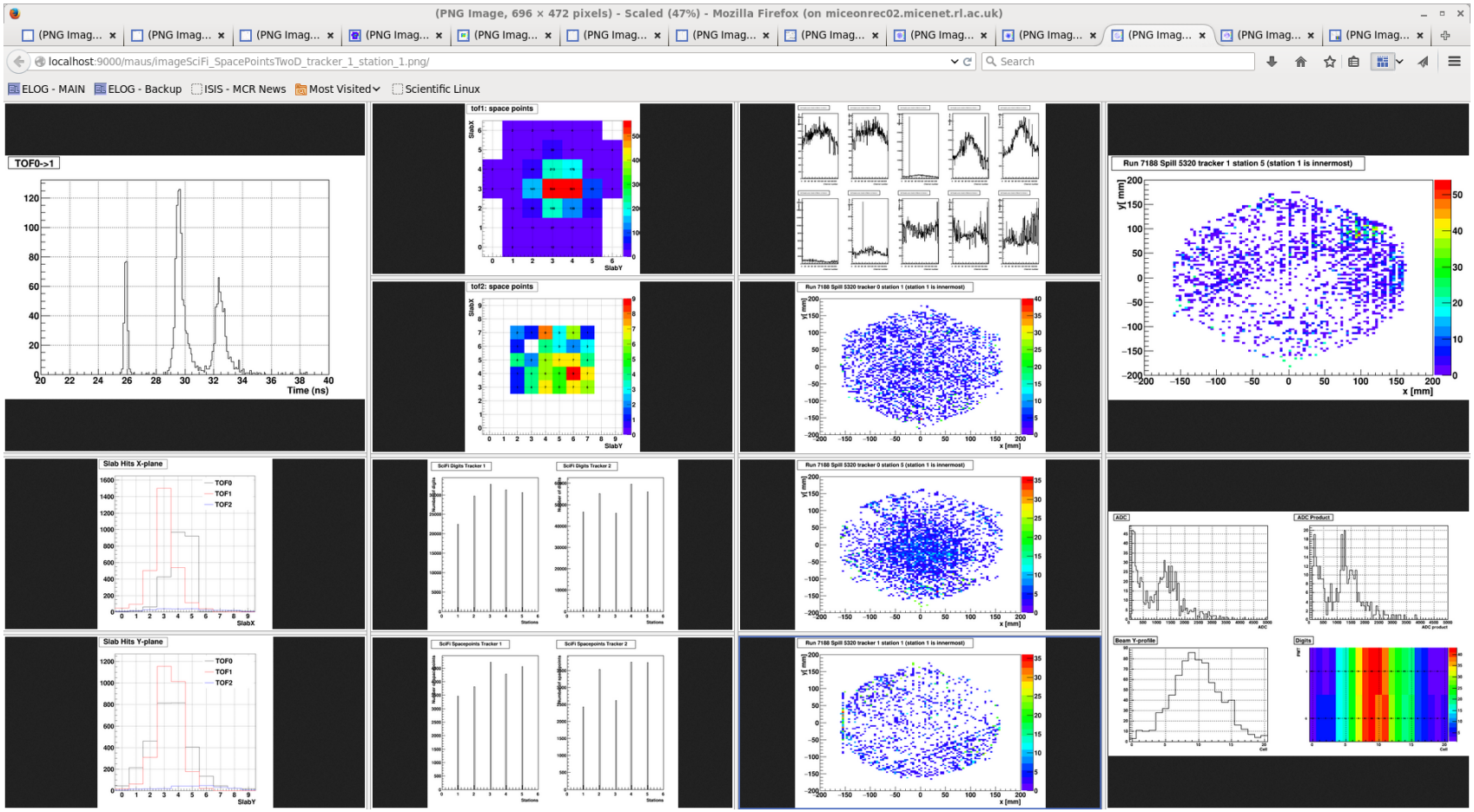


MICE online reconstruction of data



- MICE has multiple detectors for particle localization and identification: Time-of-Flight, Cherenkov, sci-fi trackers, KL calorimeter, Electron Muon Ranger.

MICE highlights and challenges

- High resolution particle-by-particle diagnostics:
  - measure individual particle's position and momentum to get fully correlated beam measurements;
  - reject beam impurities.
- Large aperture superconducting magnets:
- High gradient RF cavities:
- Liquid and solid low-Z absorbers:

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  - Upstream and Downstream Spectrometer Solenoids (CSU and CSD);
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  - magnetically coupled to mutually induced quench.
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  - two 10.5 MV/m, 201.25 MHz RF cavities;
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  - 65 mm thick lithium hydride disks.

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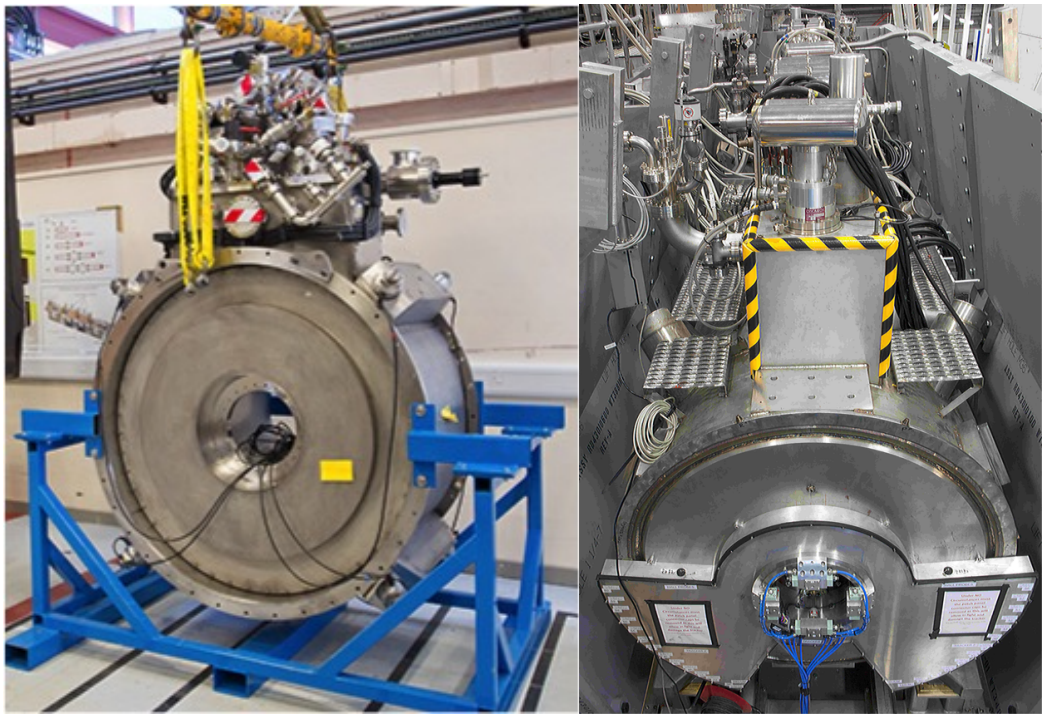
Superconducting magnets



- Focus Coil on the beamline and cooling down.
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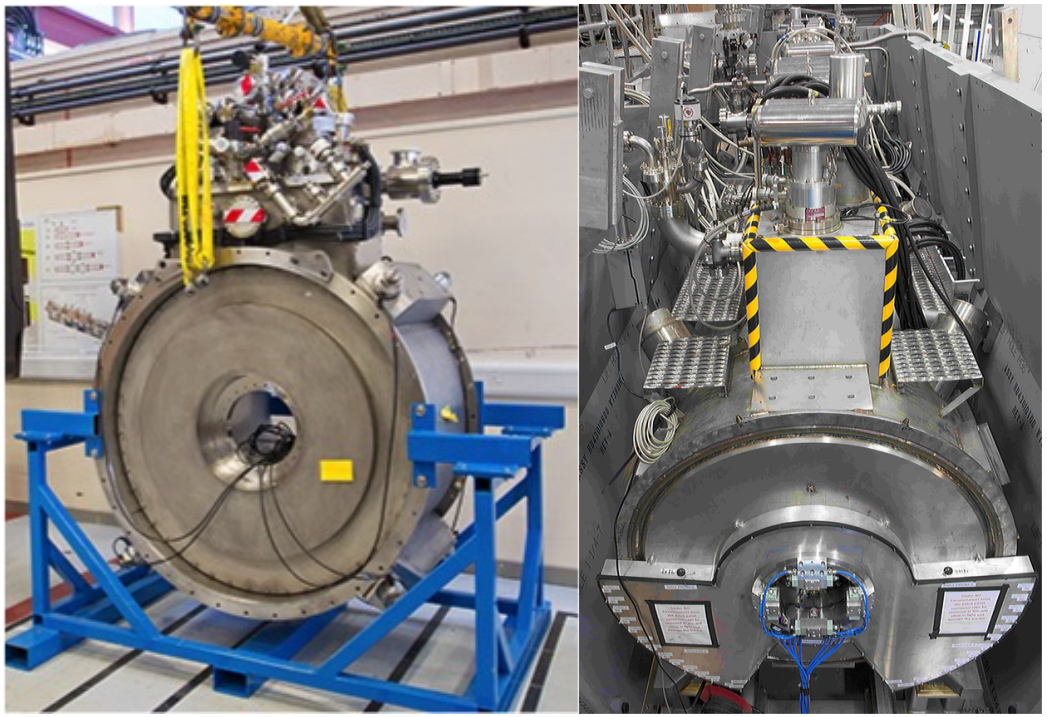
Superconducting magnets



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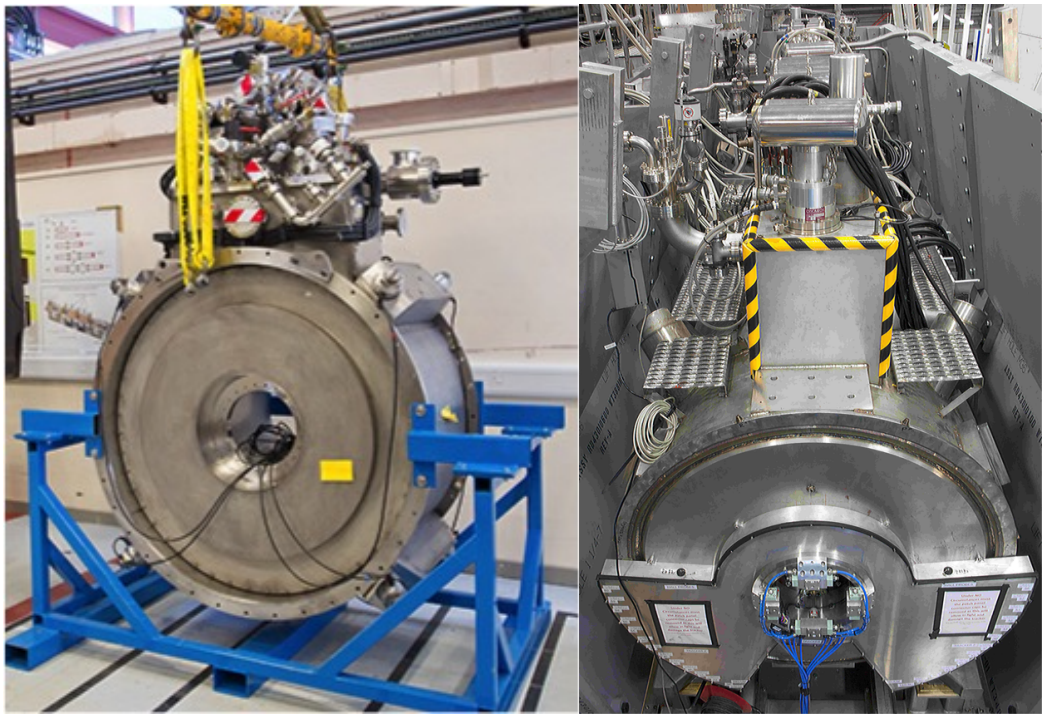

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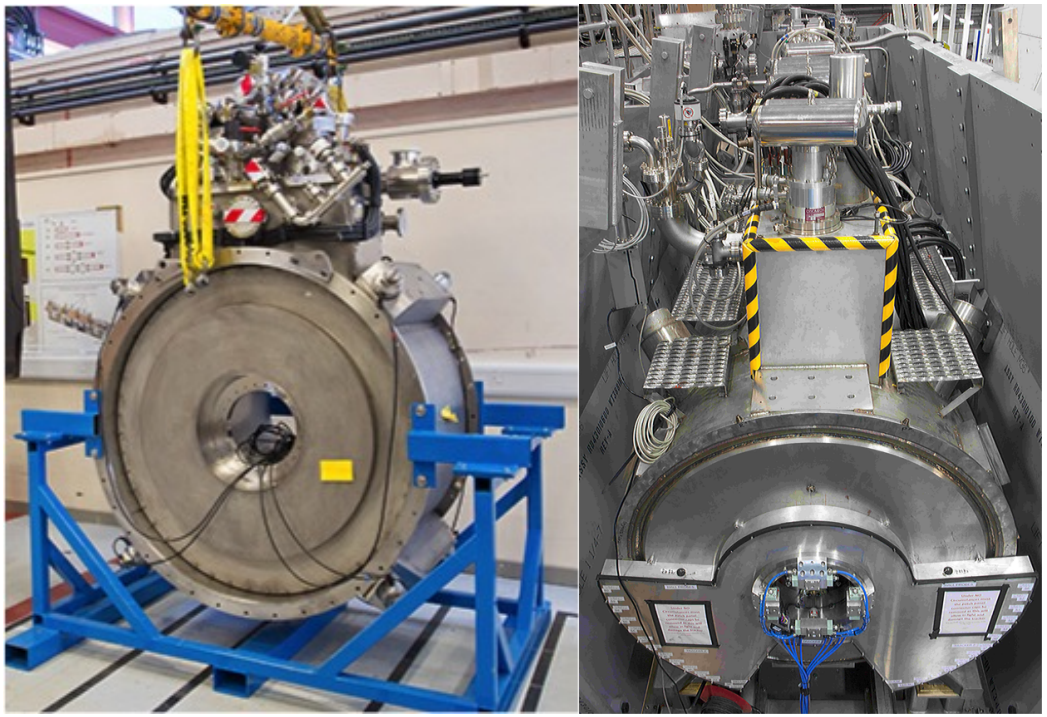

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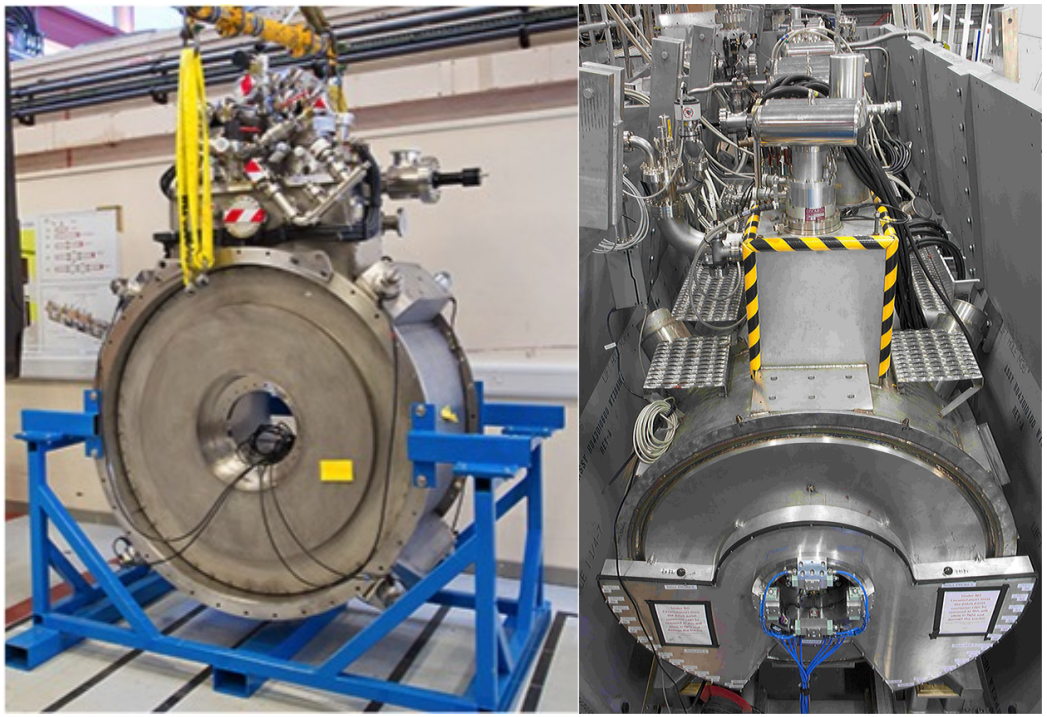

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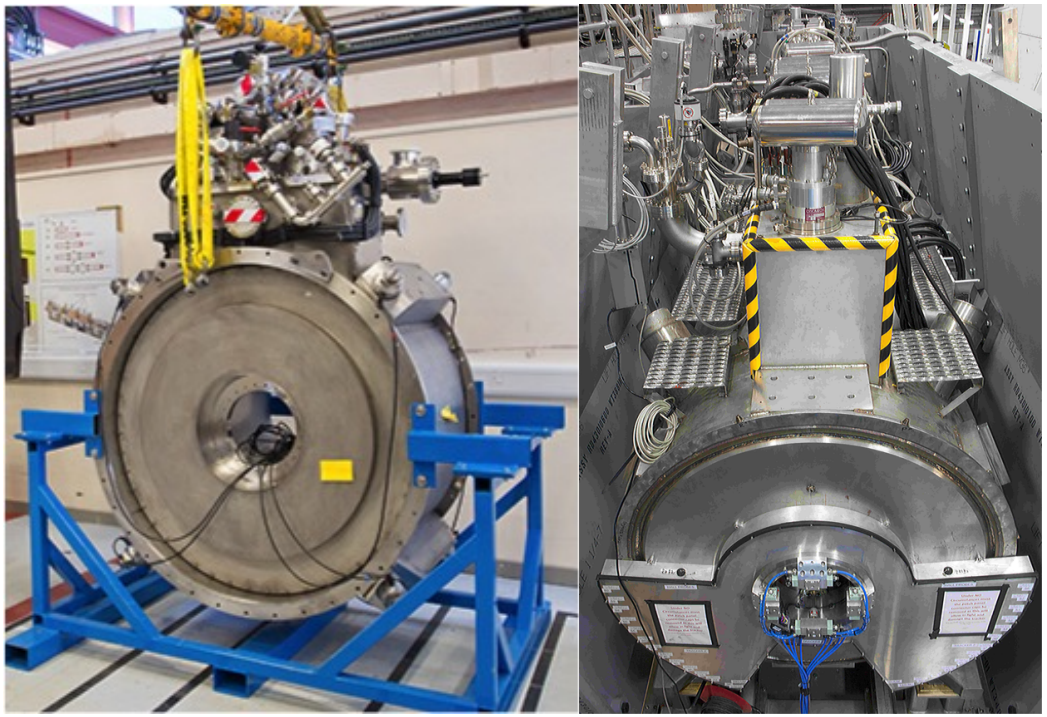

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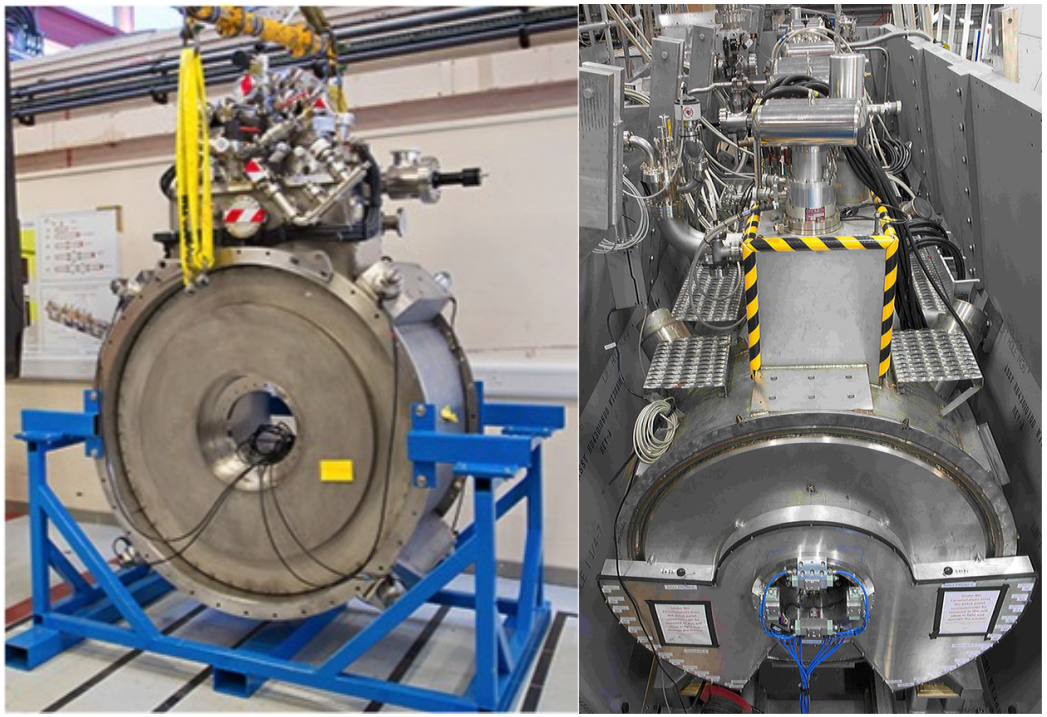

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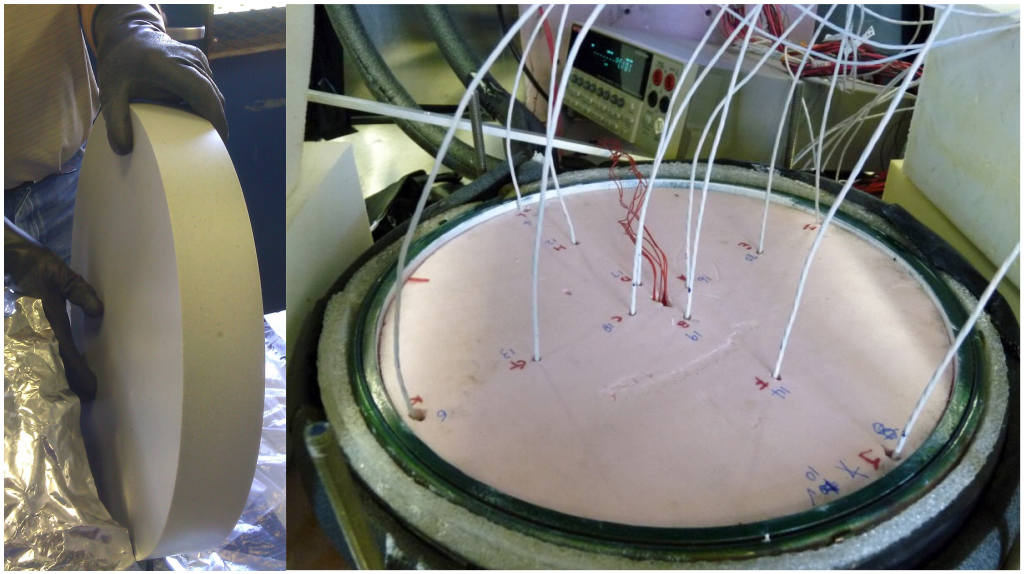
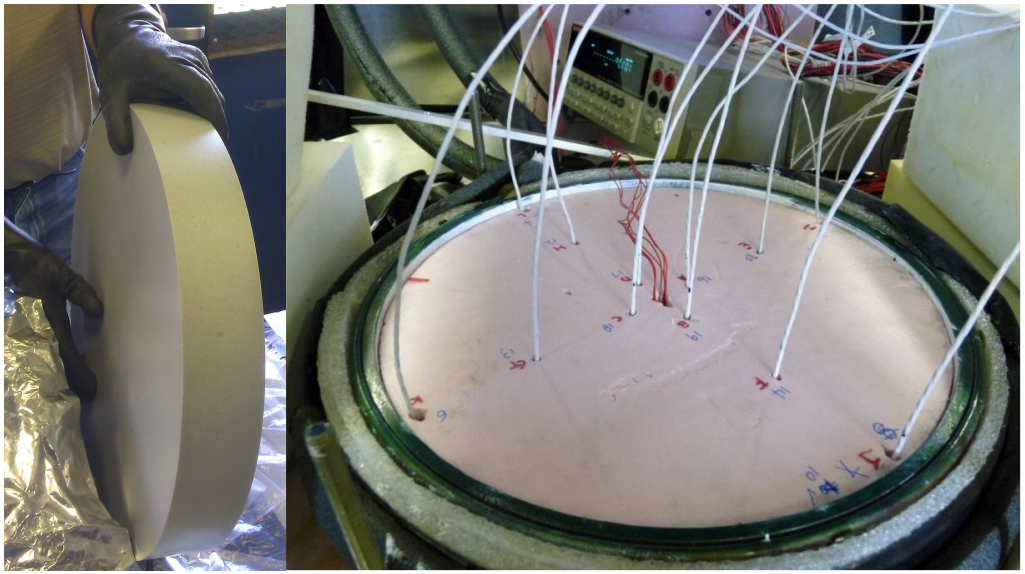


- 350 mm thick liquid hydrogen absorber:
  - 21 liters;
  - enclosed by four 150 micron curved Al windows;
  - installed;
- 65 mm lithium hydride absorber:

Absorbers



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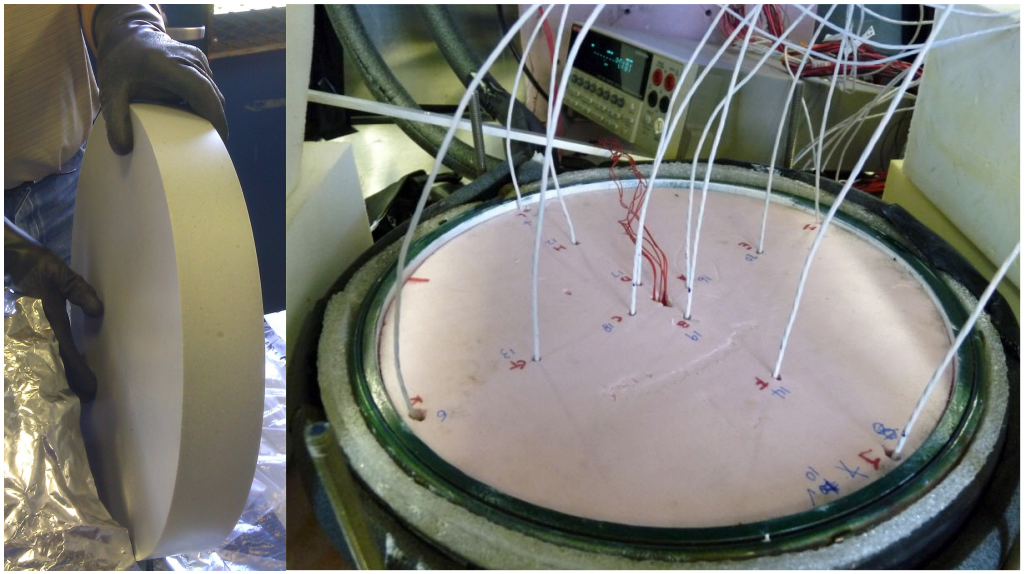

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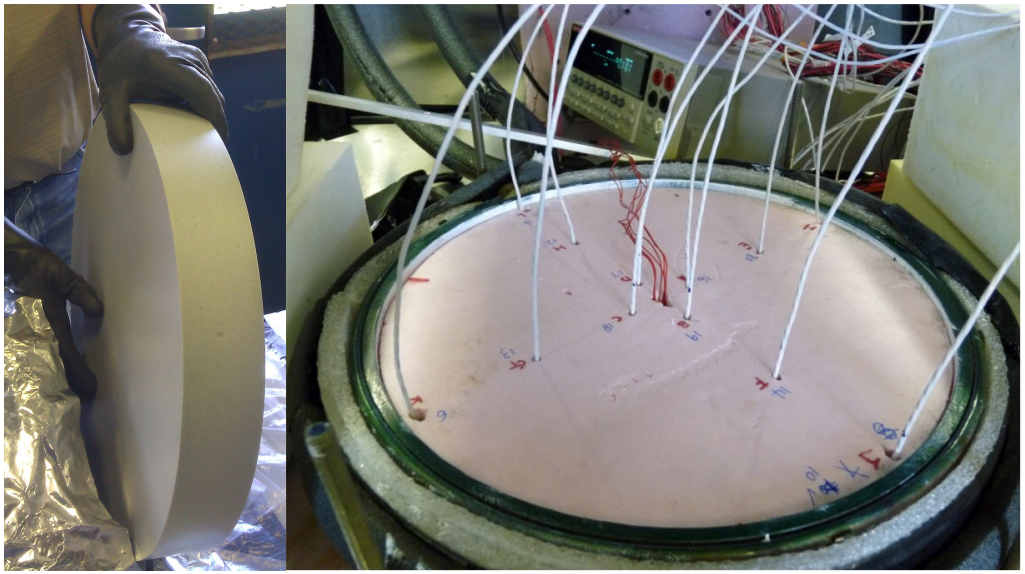

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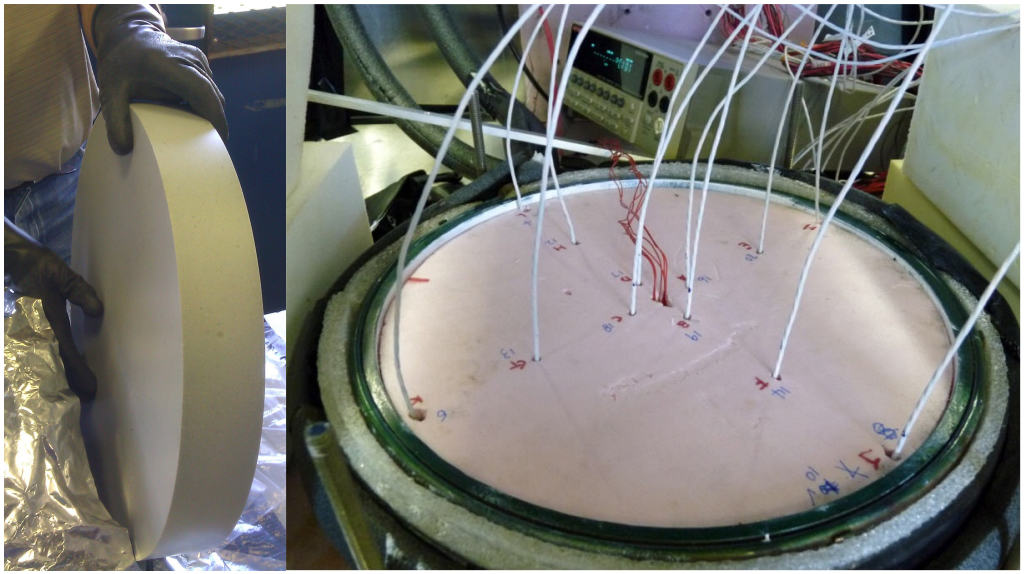

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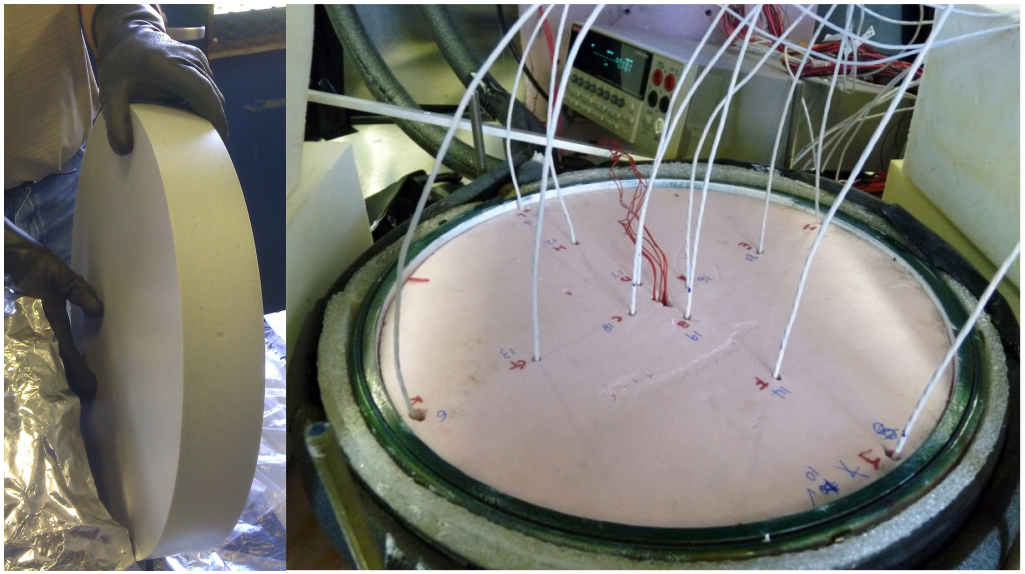

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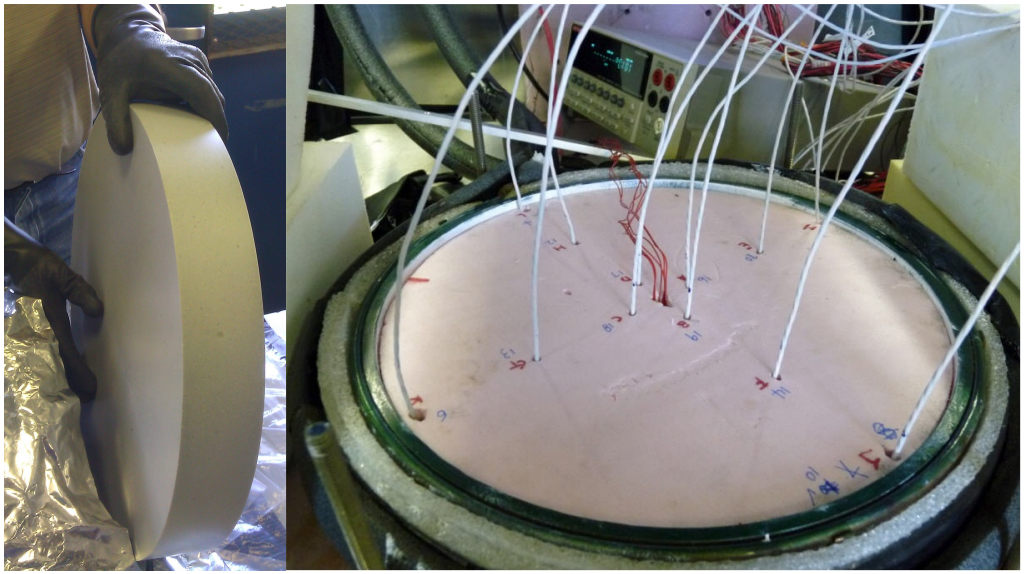
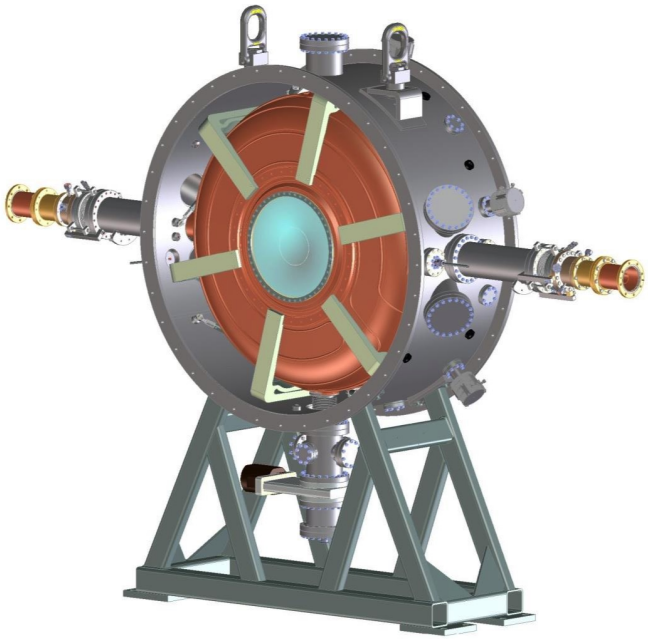
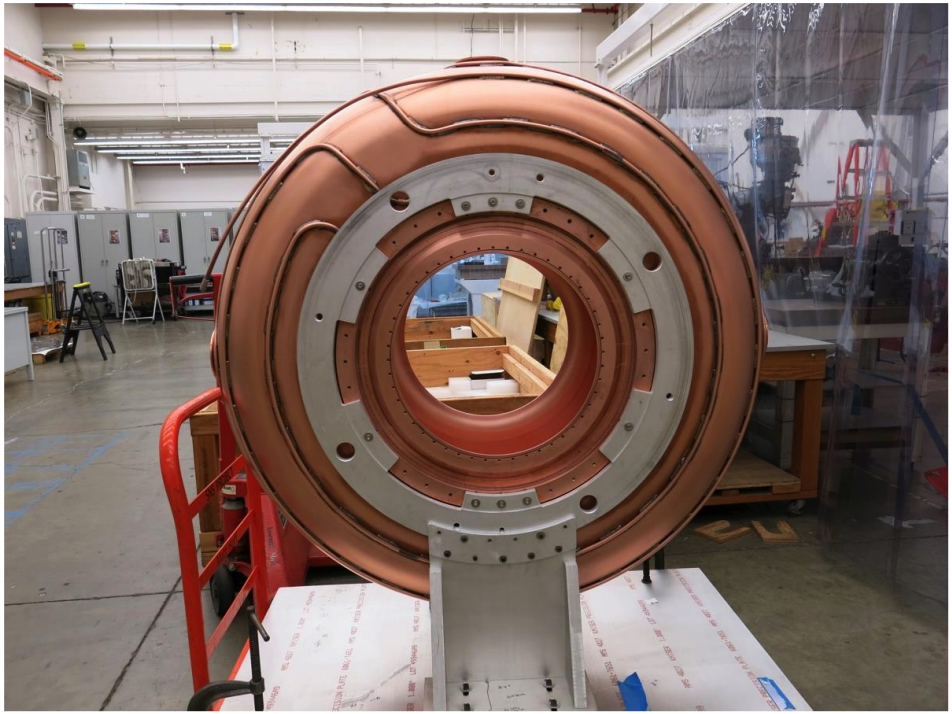


- 350 mm thick liquid hydrogen absorber:
  - 21 liters;
  - enclosed by four 150 micron curved Al windows,
  - installed.
- 65 mm lithium hydride absorber:
  - will be installed, replacing LH2 absorber, early in 2016 for Step IV.

RF cavities





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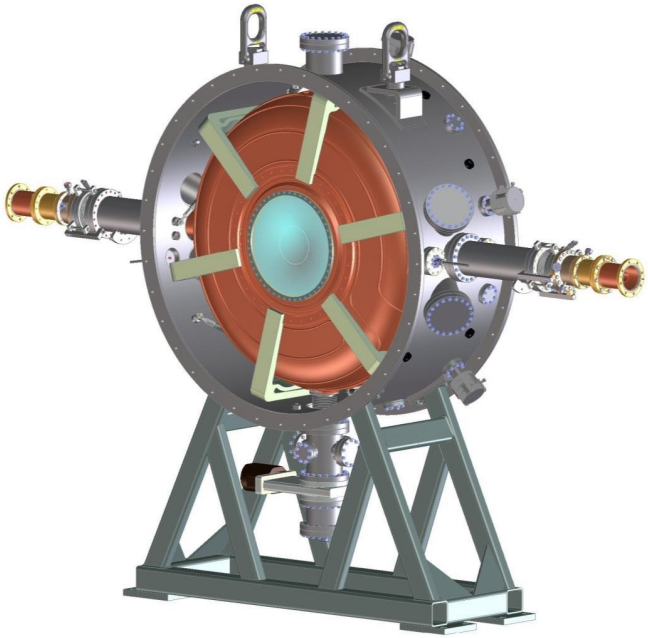

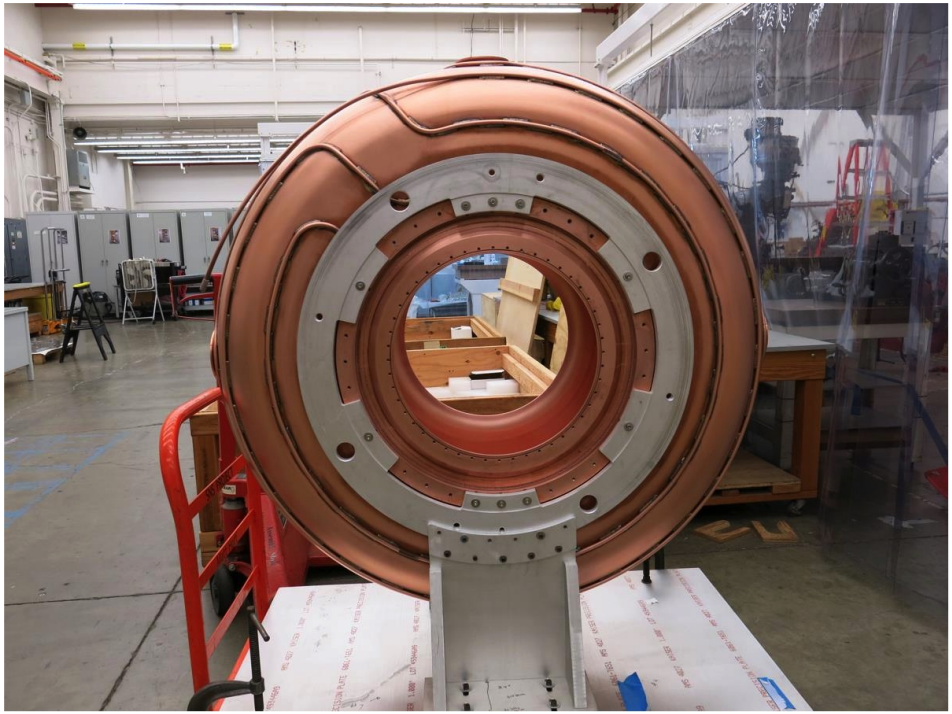

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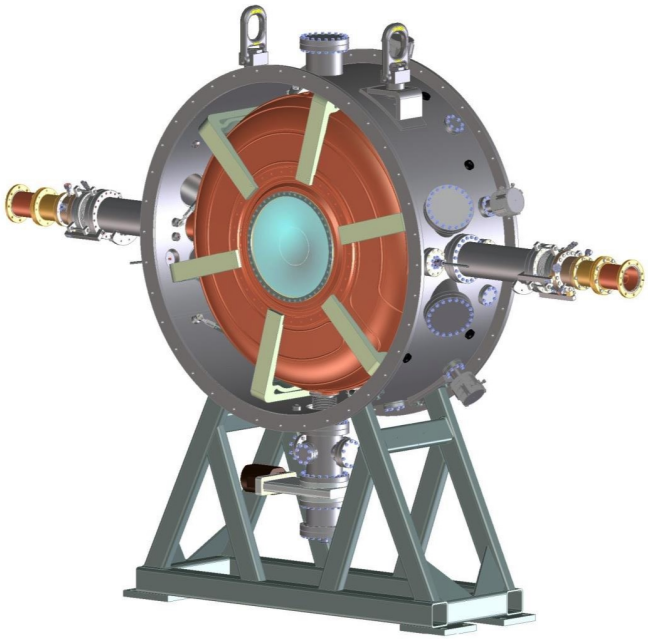

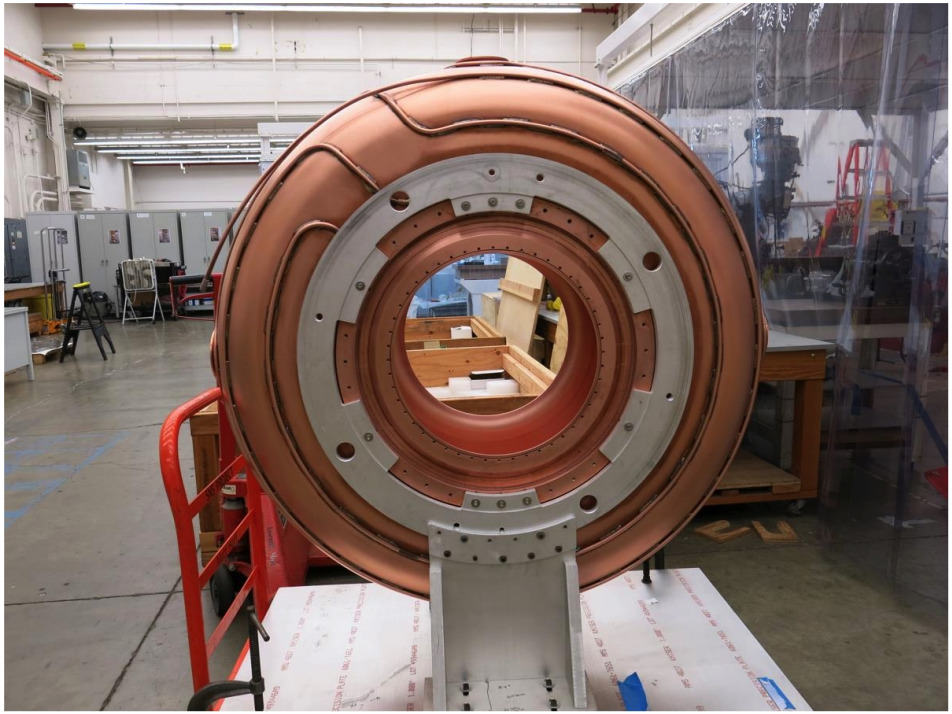

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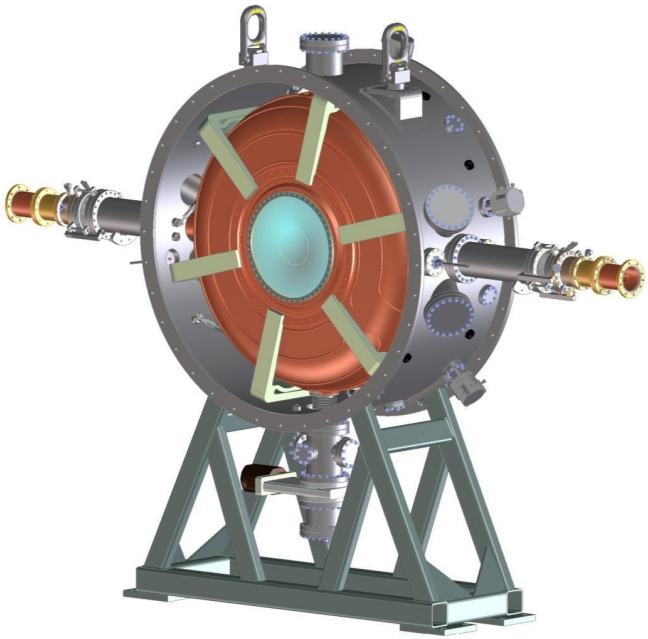

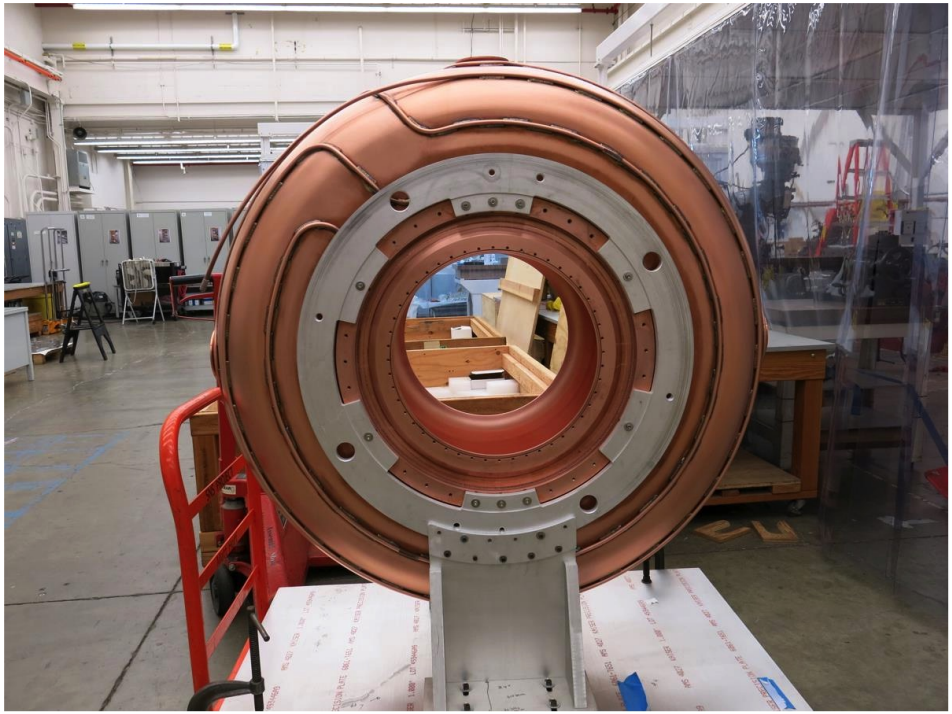

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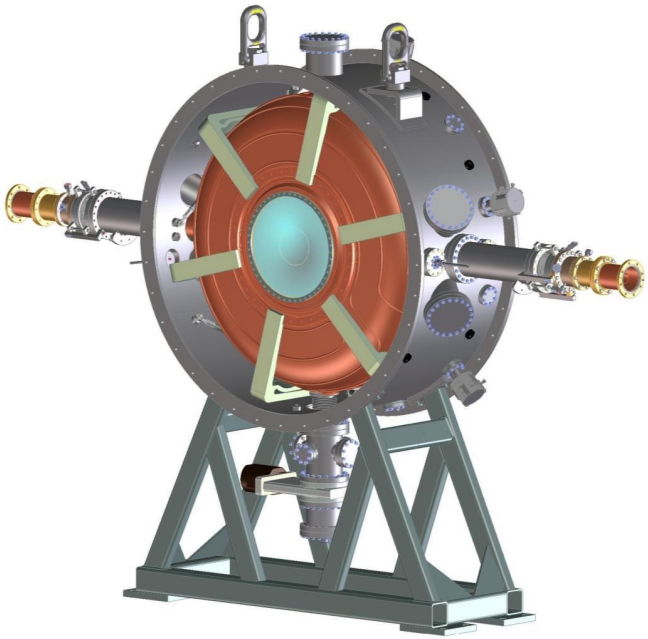

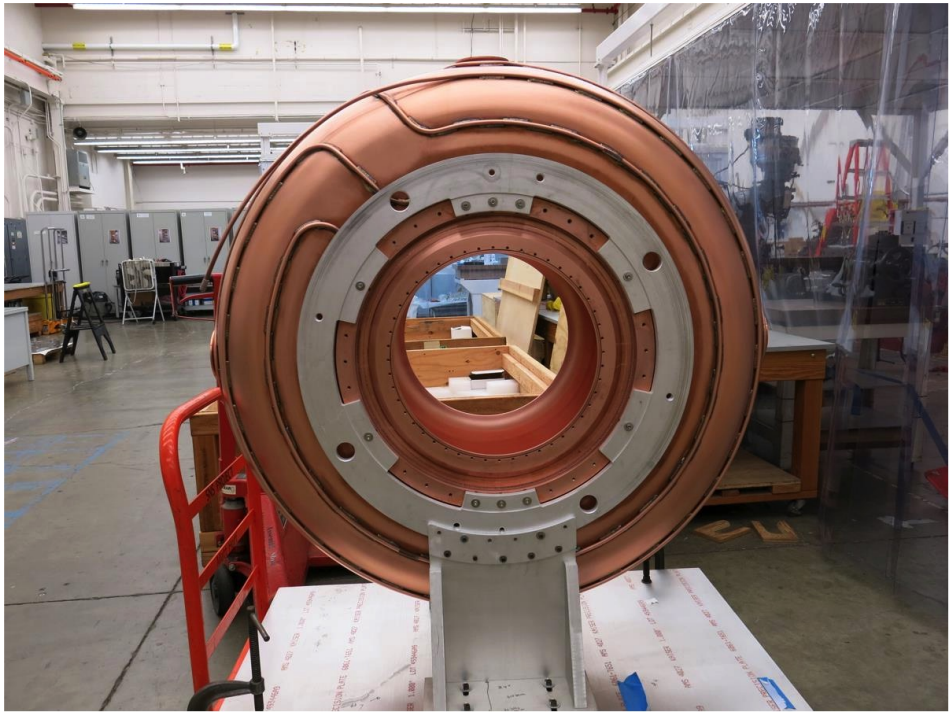

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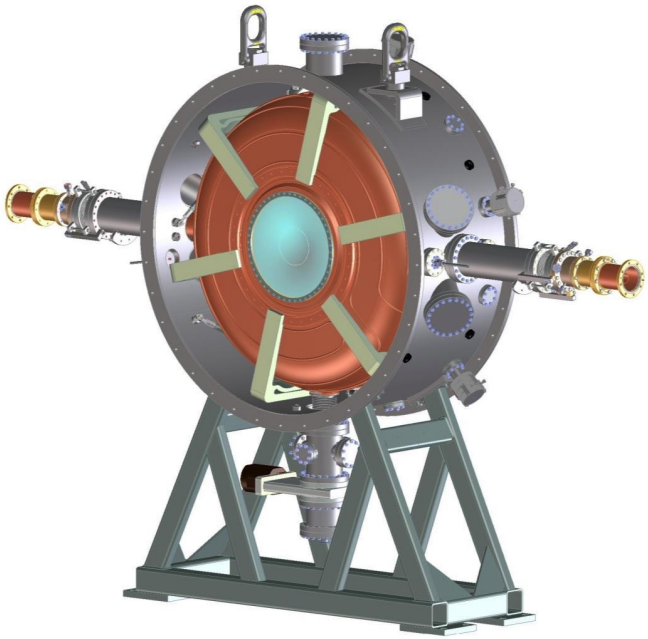

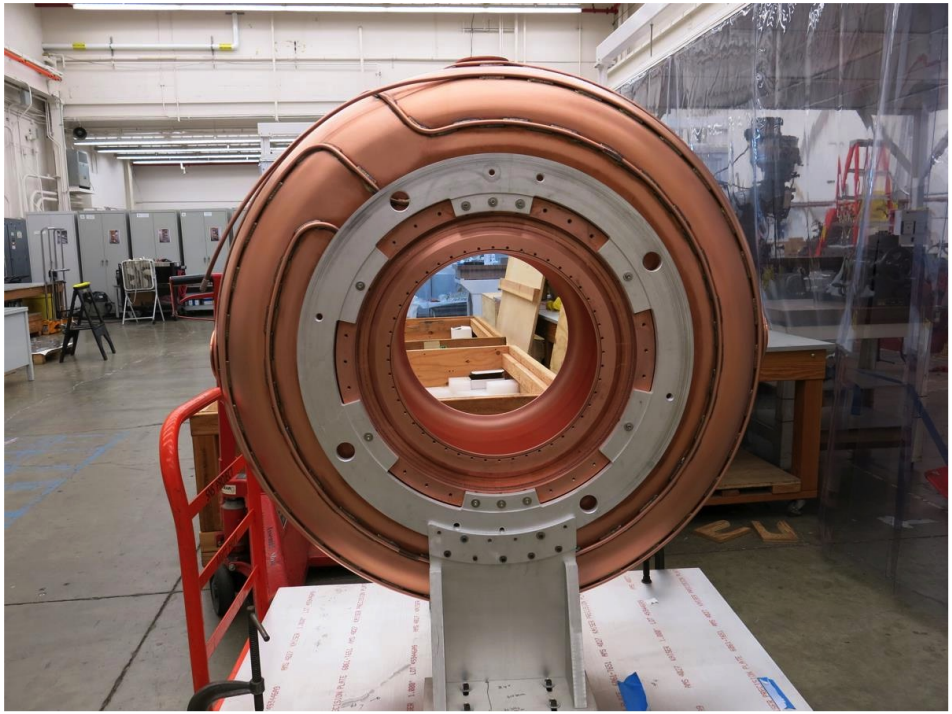

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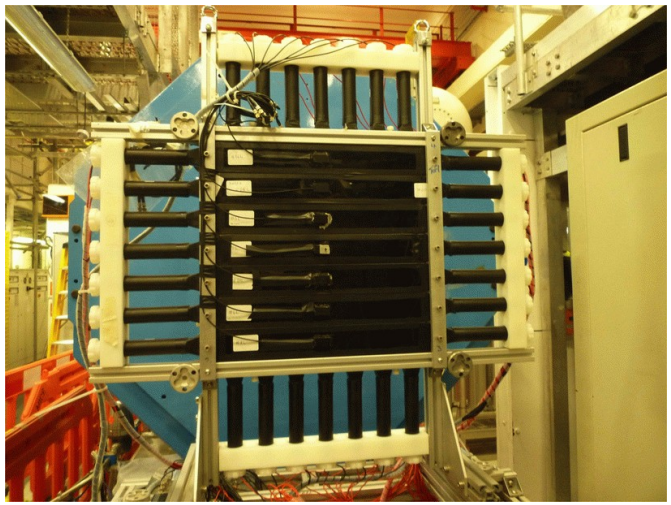

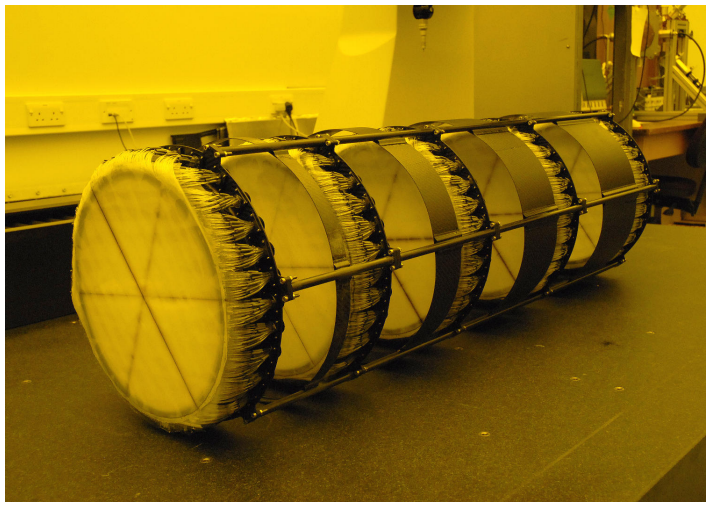

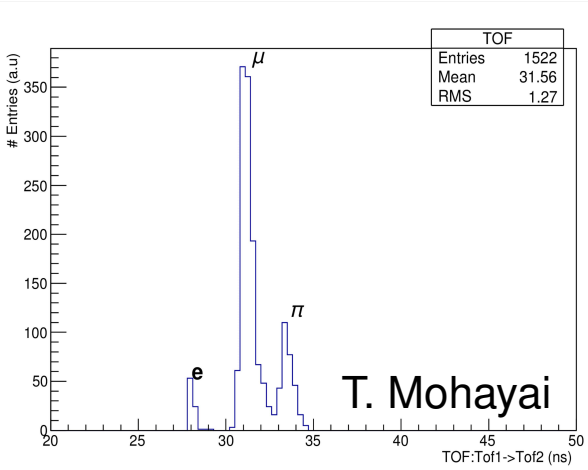

- Three scintillating TOF stations:
  - time resolution $\sim$ 50 ps;
  - commissioned in 2009.
- Two Scintillating Fiber Trackers:
  - position resolution $\sim$ 0.7 mm;
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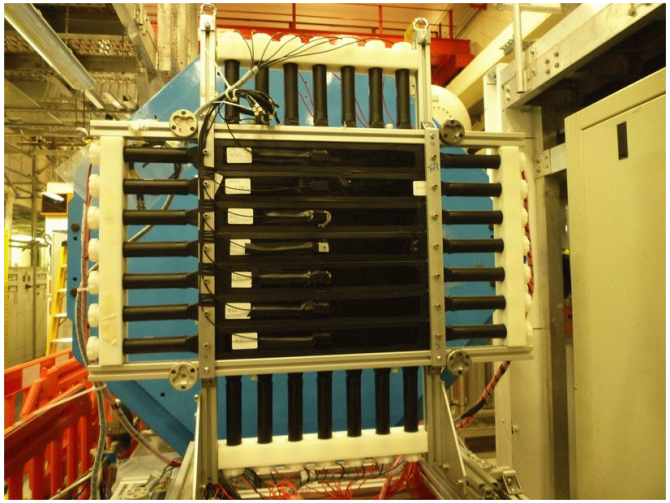
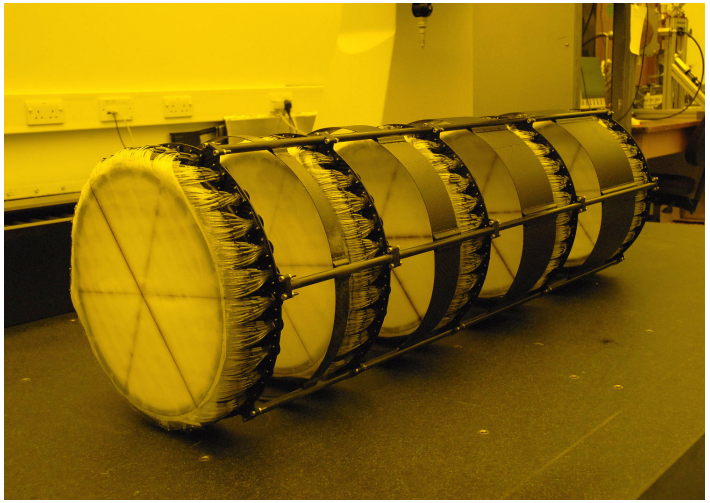
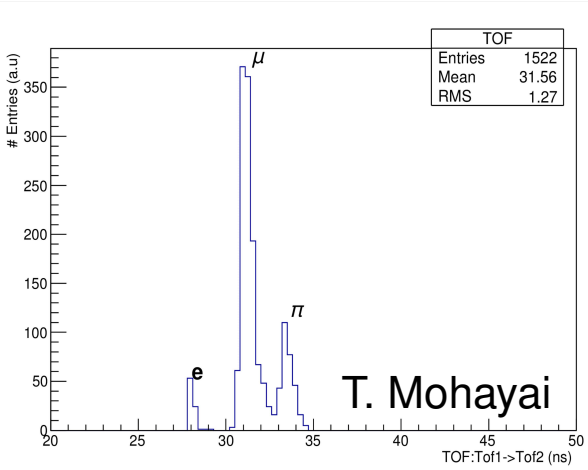
- Threshold Cherenkov counter.
- KL pre-shower detector.
- Electron-muon ranger.

Detectors







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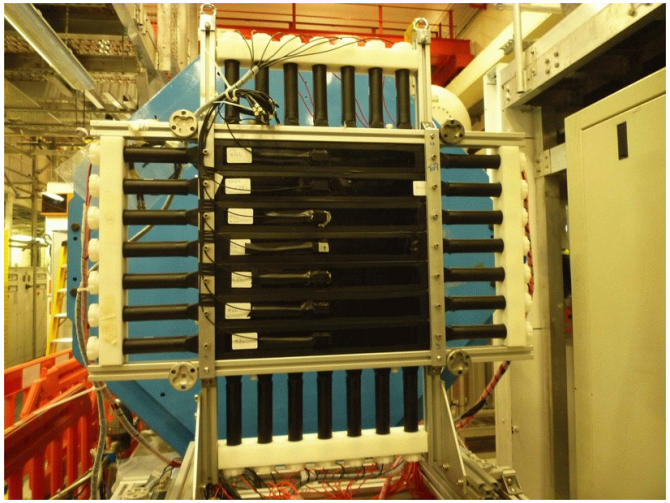

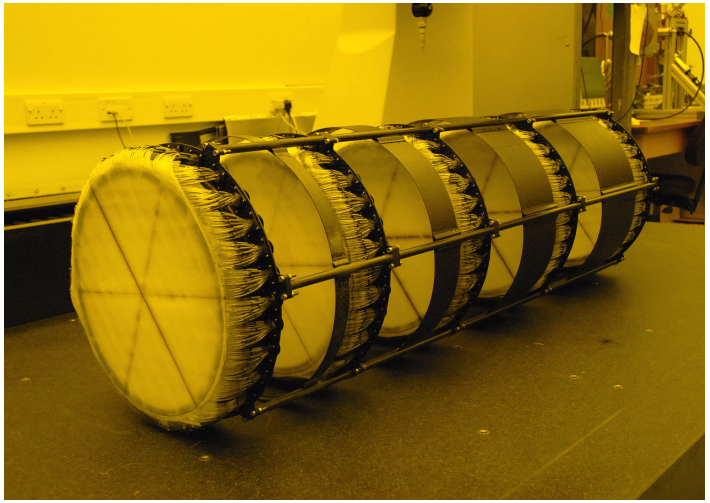

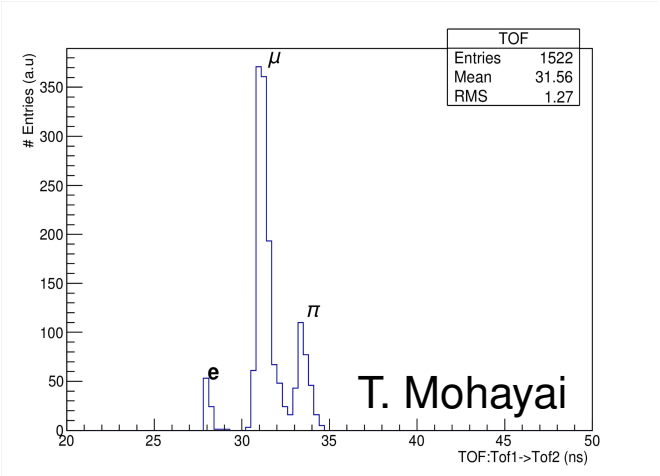

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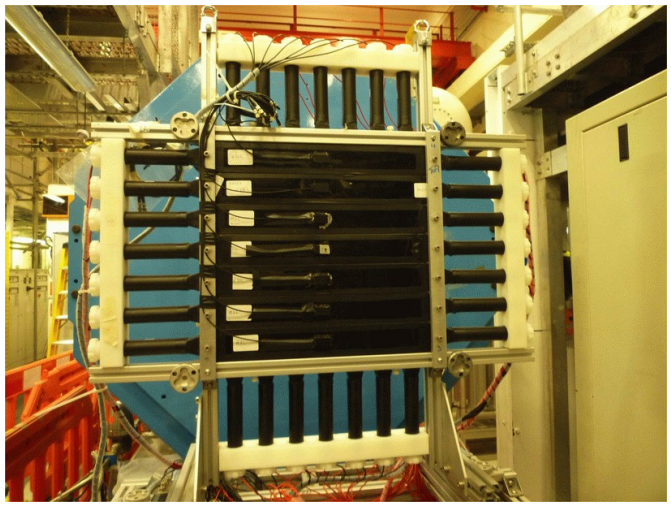

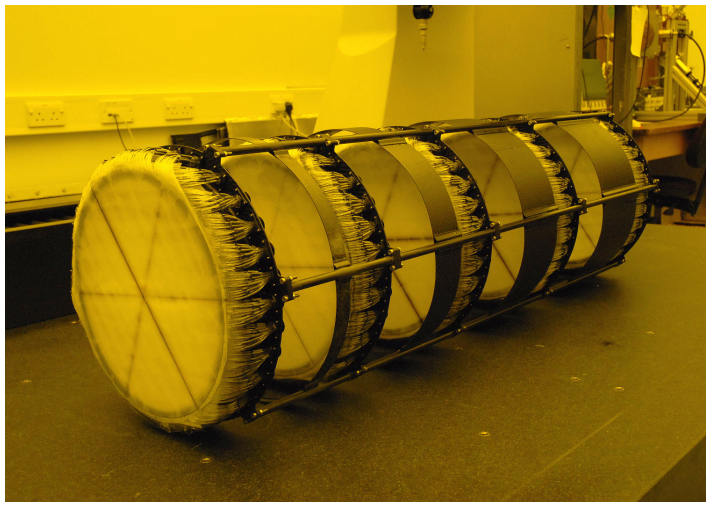

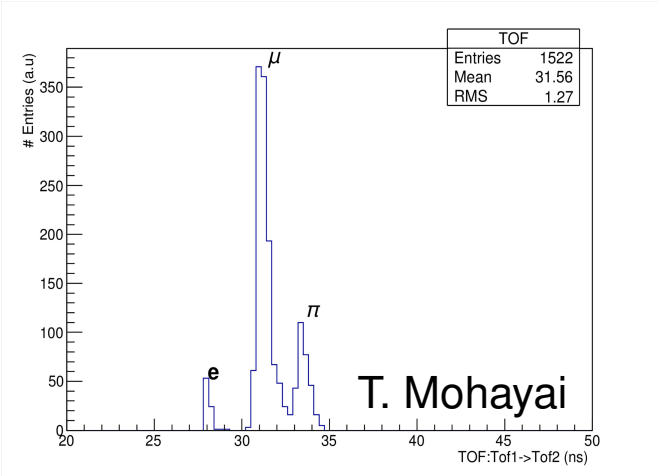

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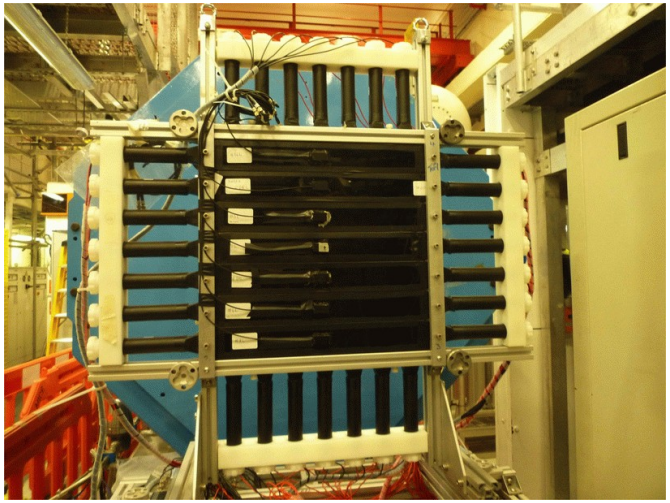

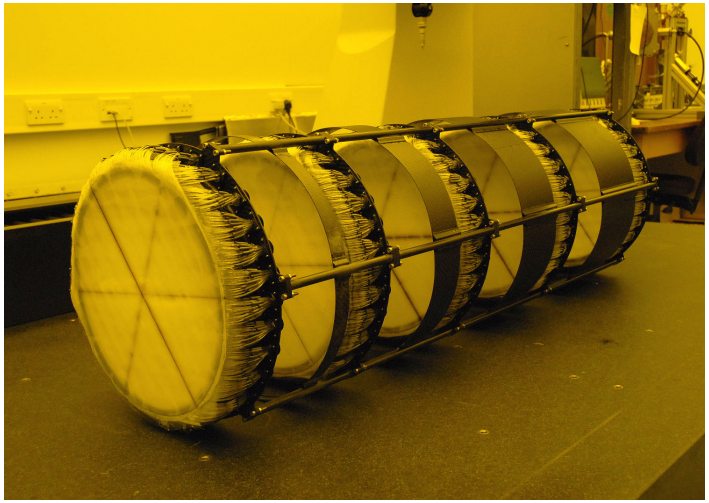

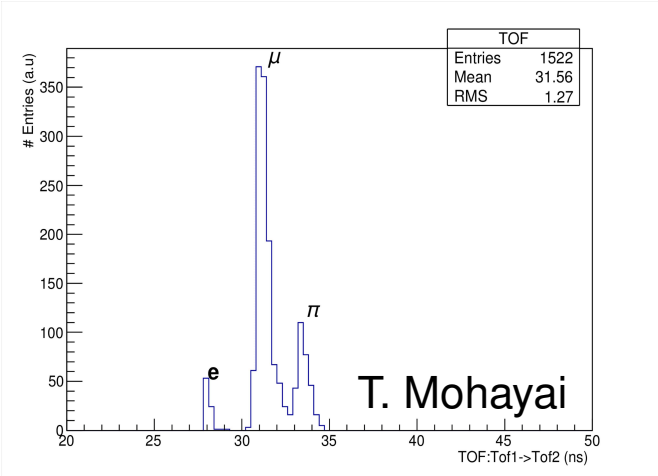

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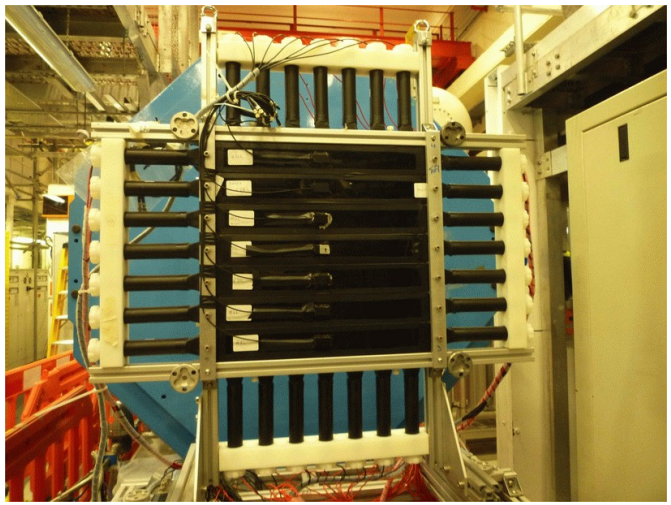

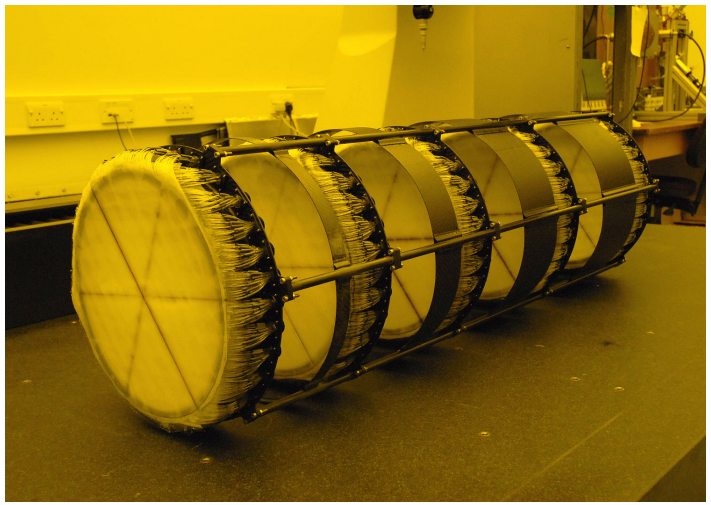

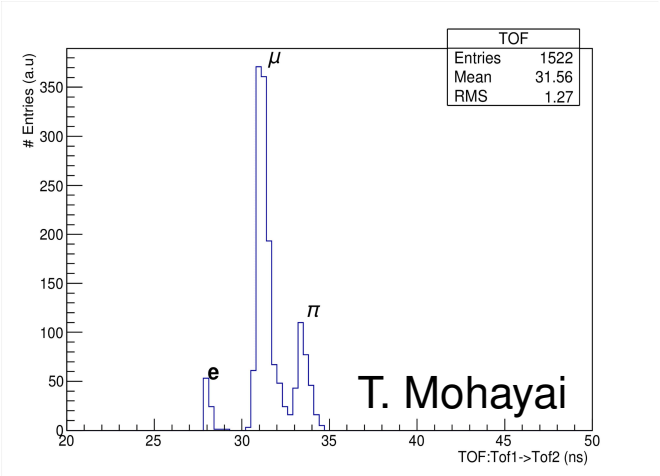

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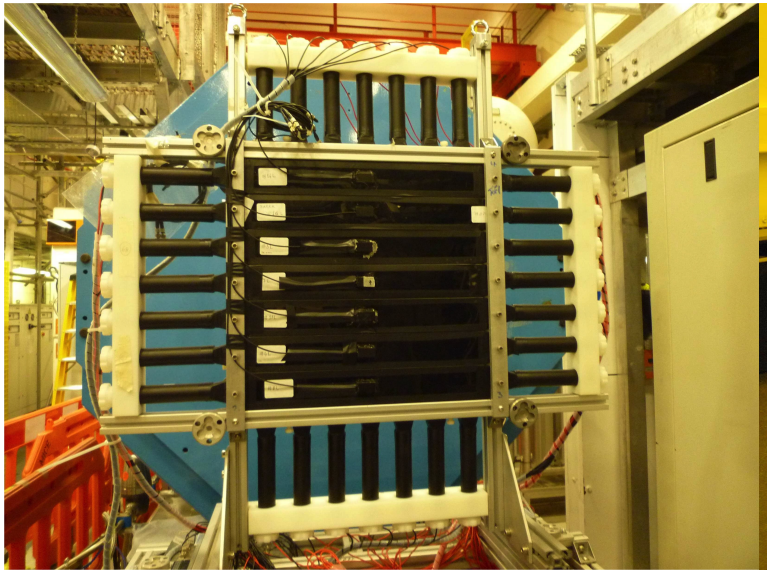

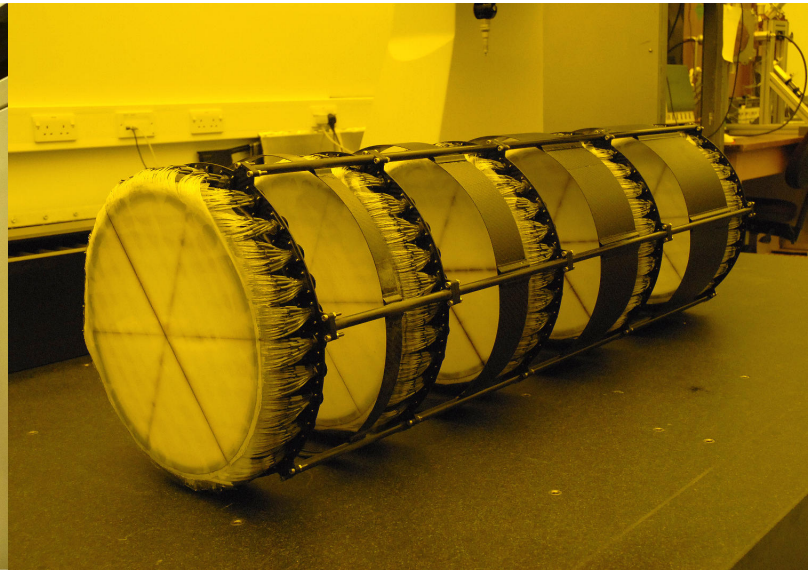

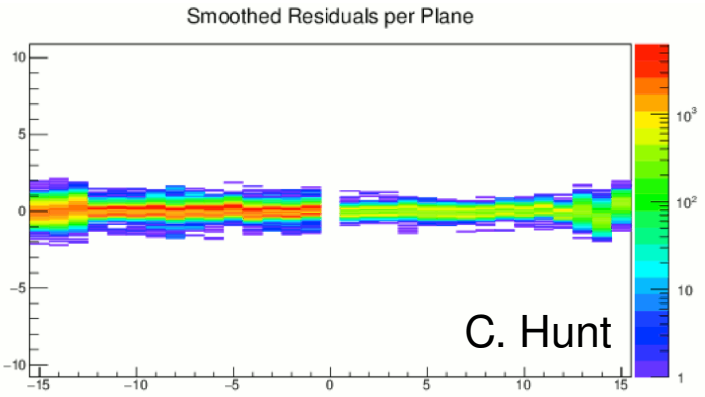

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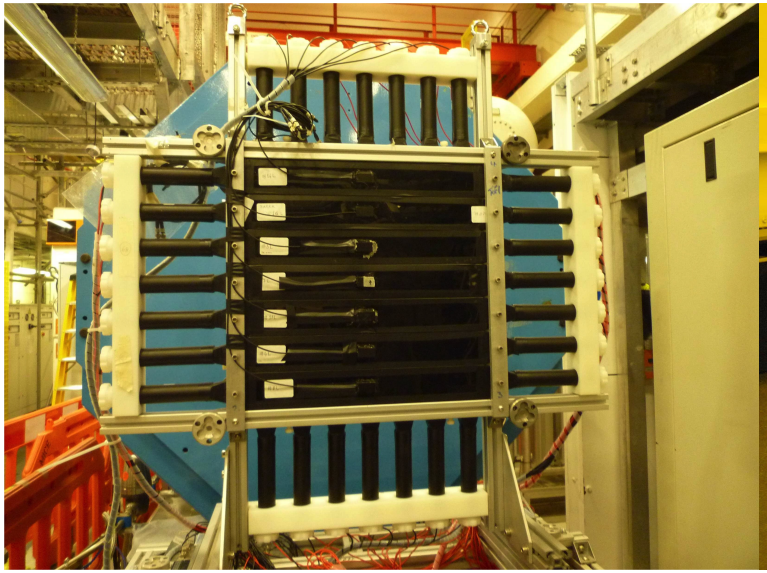

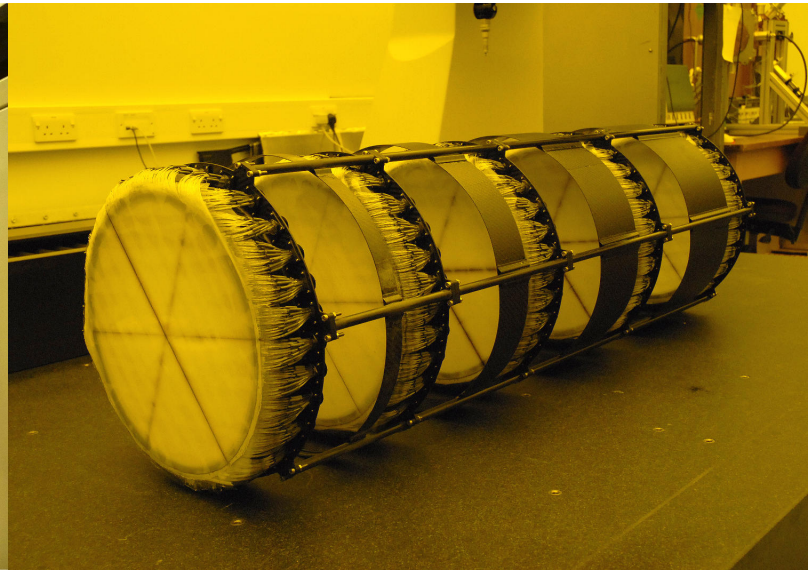

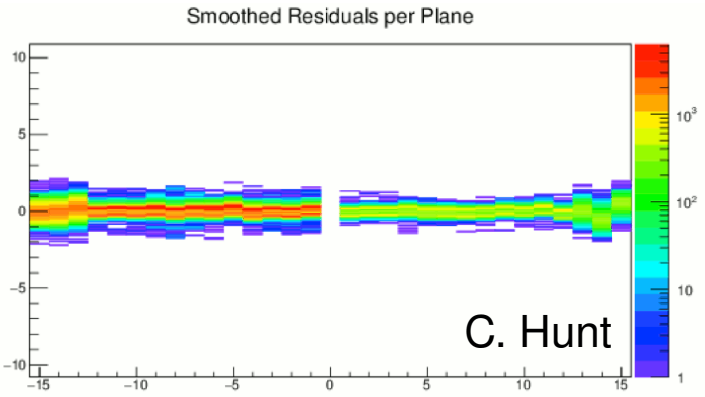

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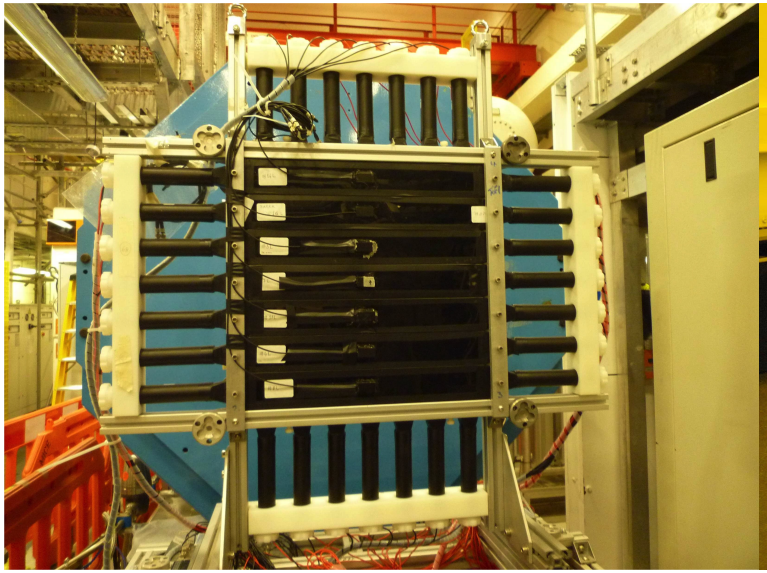

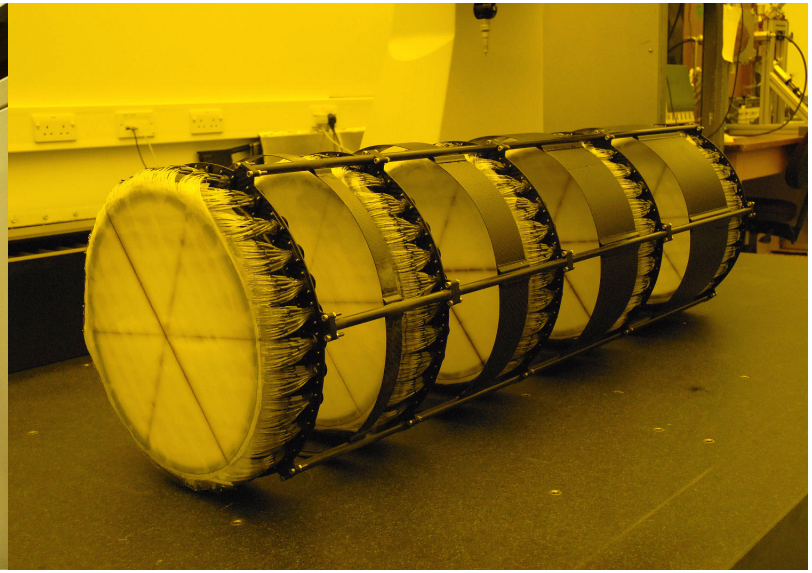

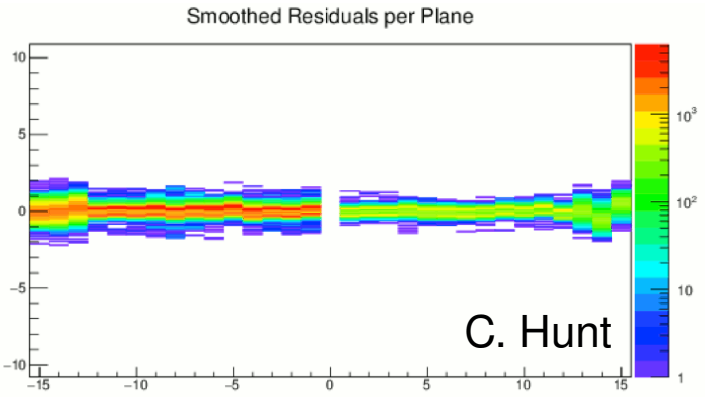

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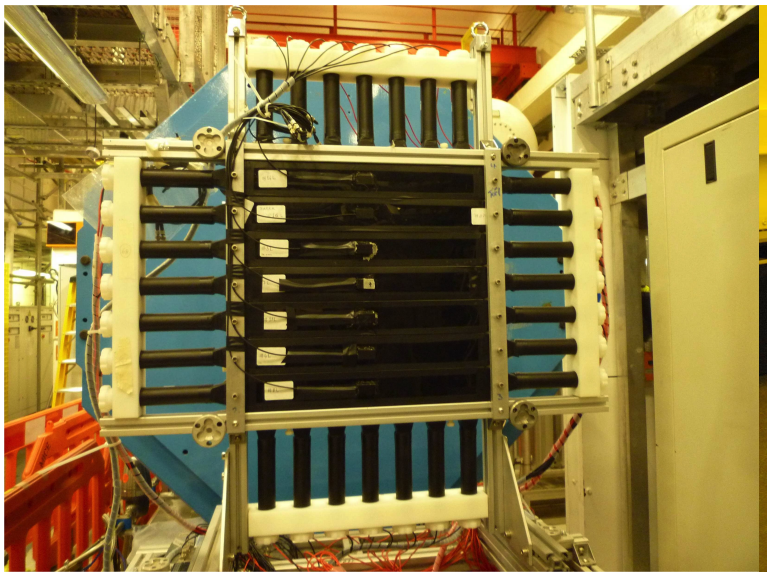

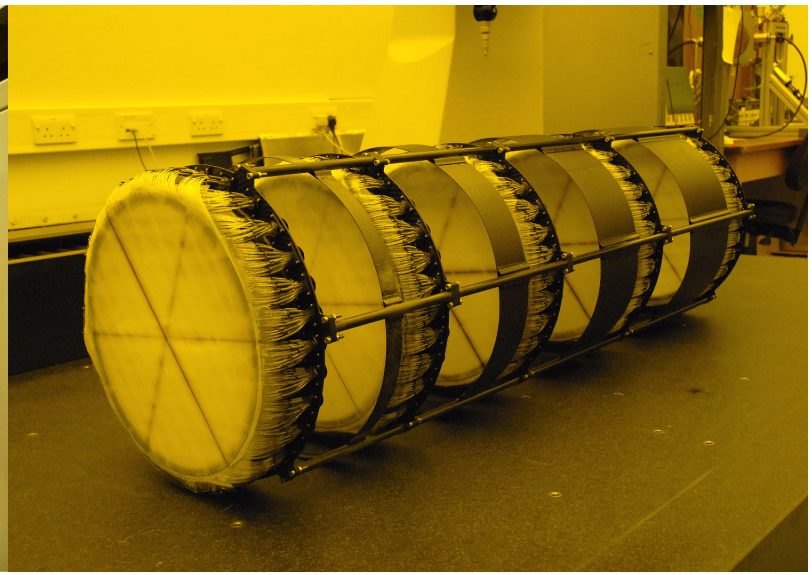

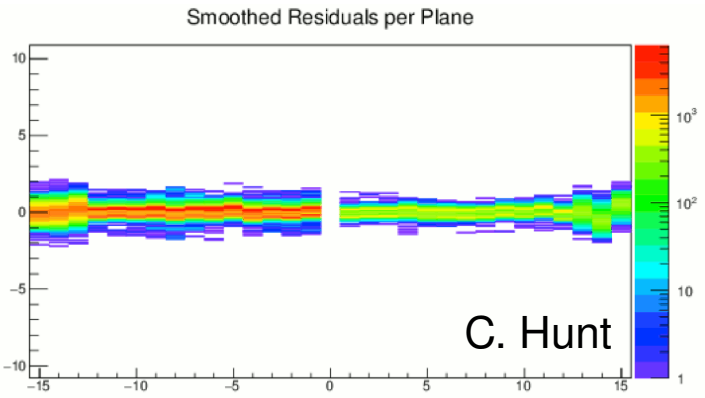

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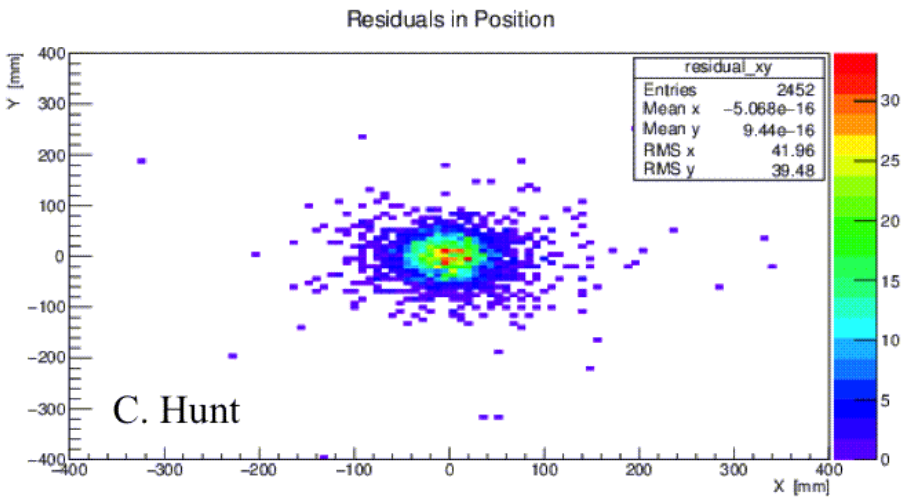
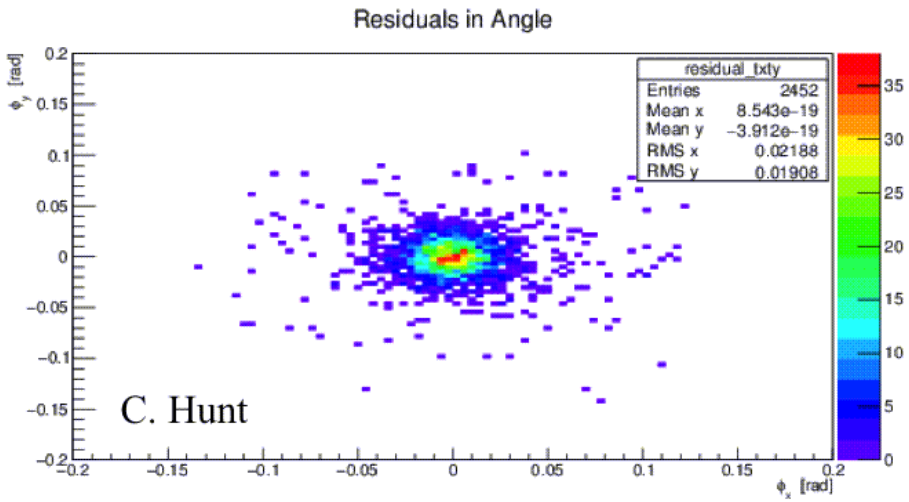
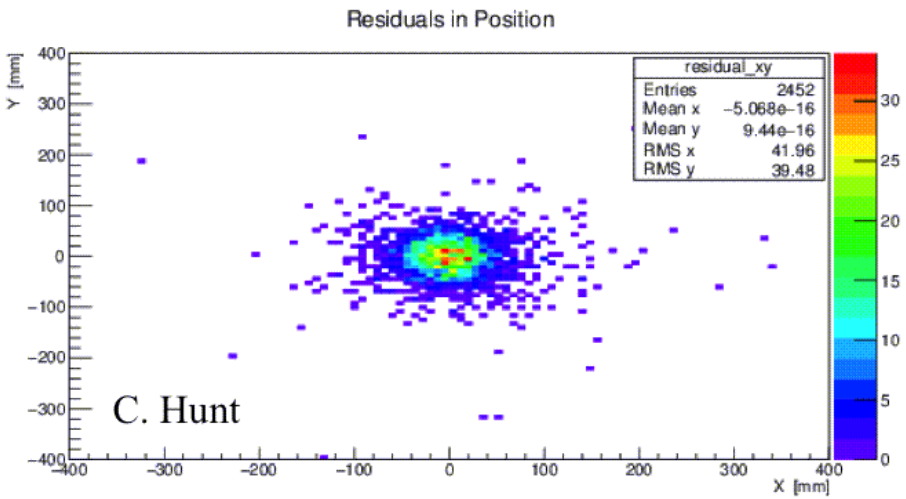
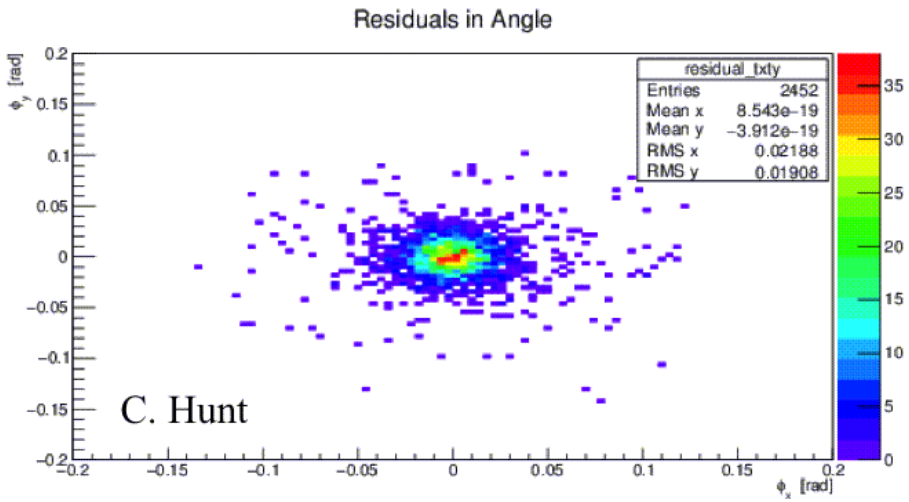




- Beam-based alignment of detectors
  - Project measured tracks between detectors with magnets off.
  - Compare position of tracks with expected position.
- Alignments at (expected) nominal level.
- Final numbers await error analysis.

Beam-based detector alignment





- Beam-based alignment of detectors
  - Project measured tracks between detectors with magnets off.
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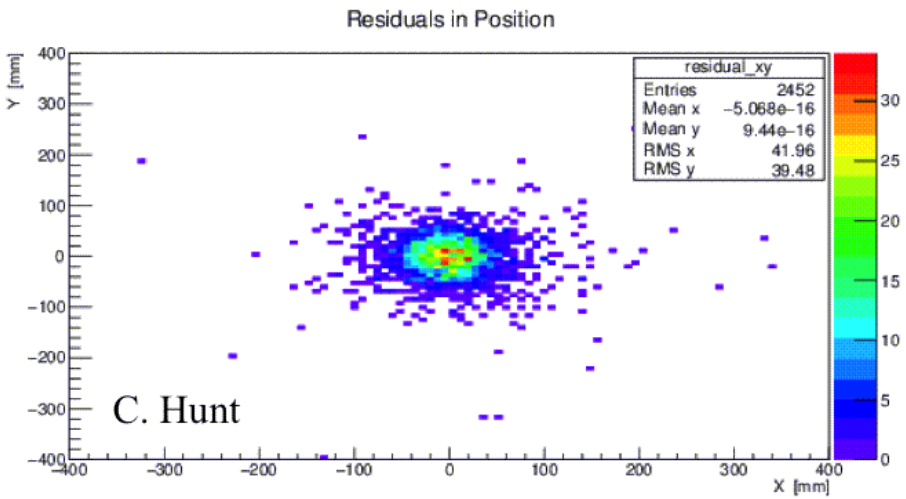
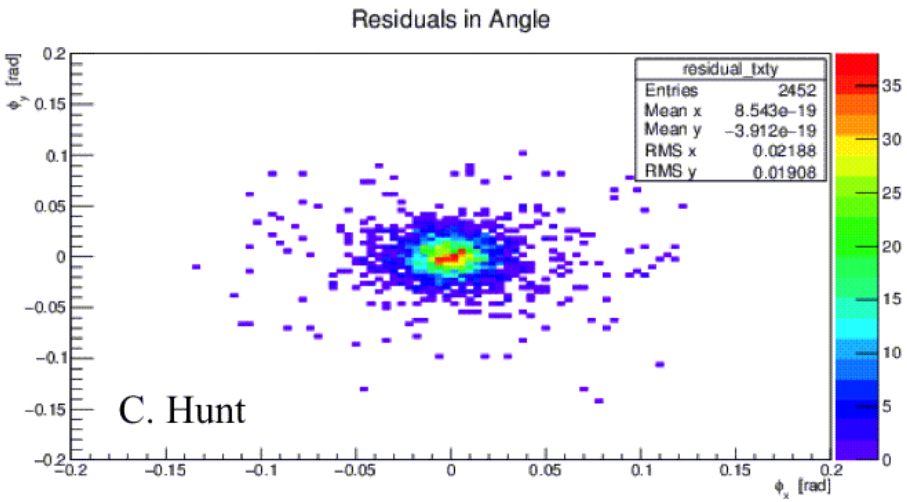
Beam-based detector alignment





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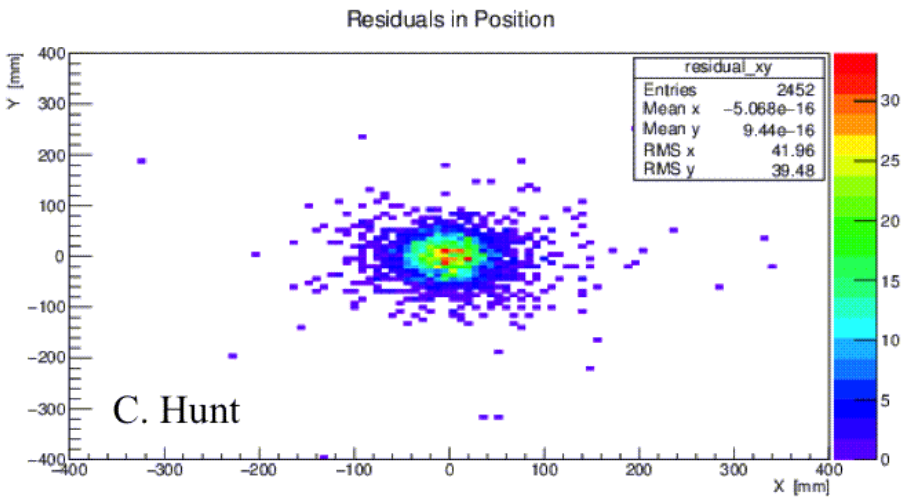

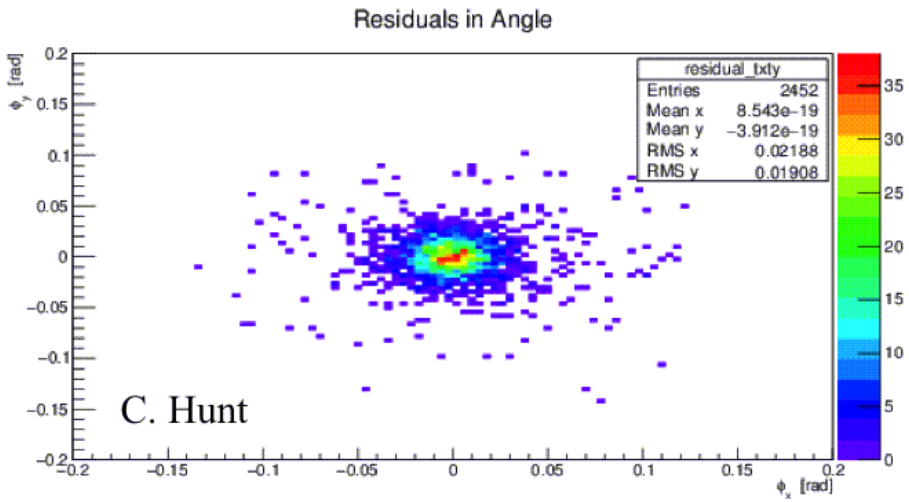

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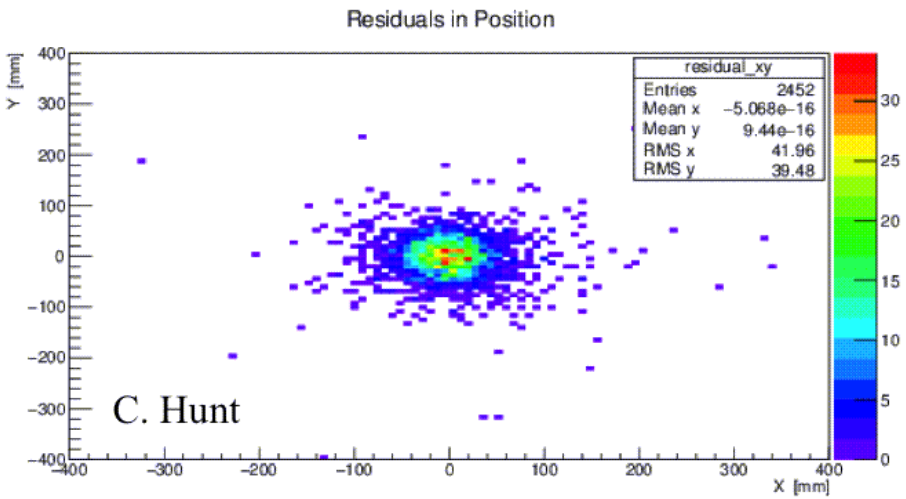
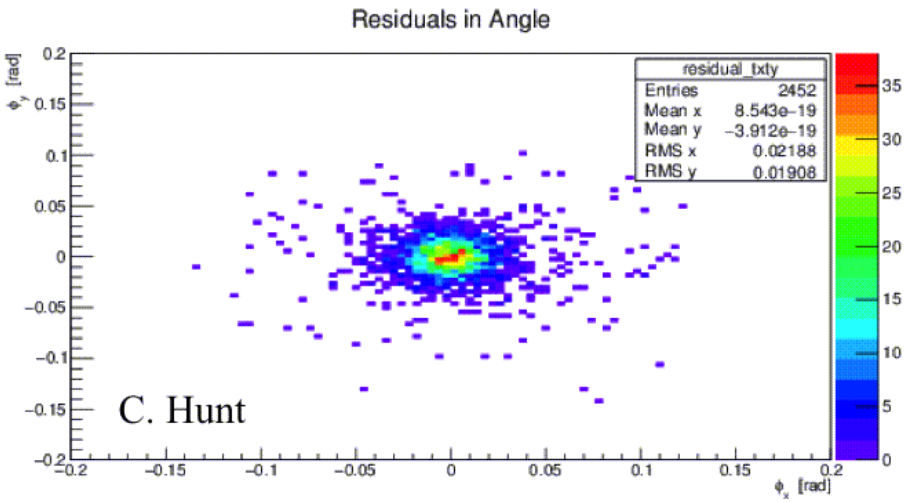
Beam-based detector alignment





- Beam-based alignment of detectors
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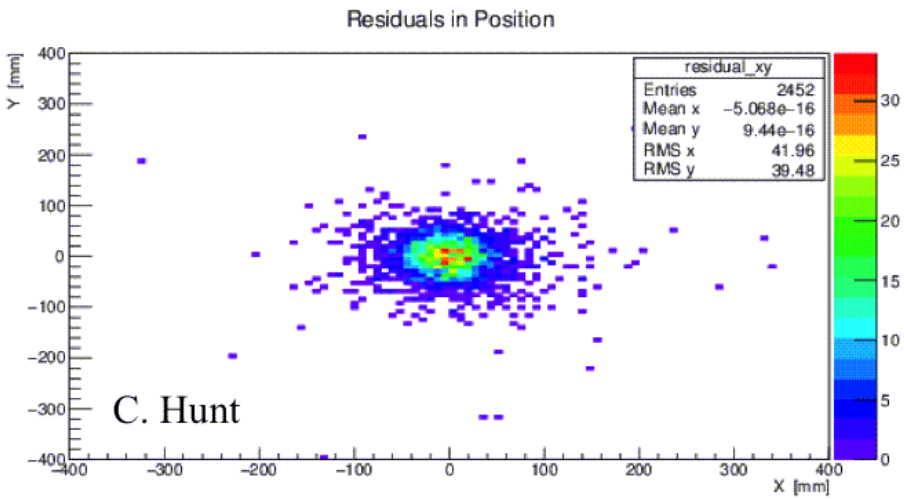

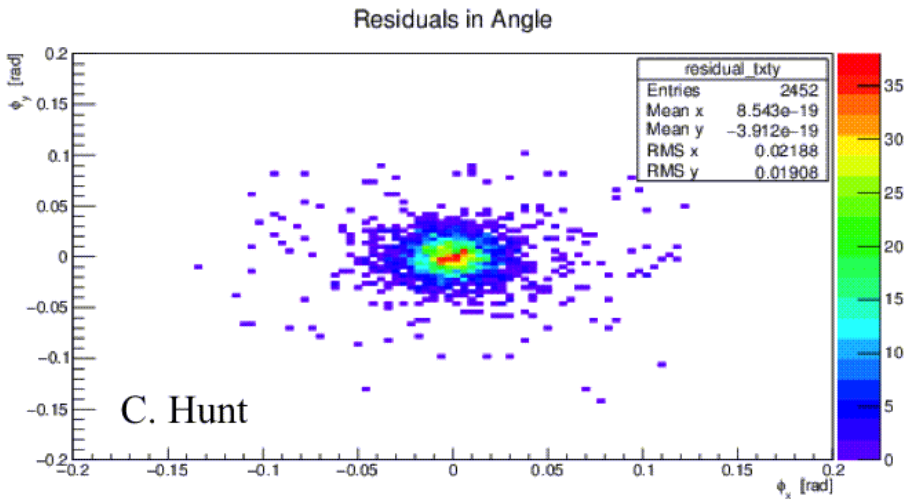

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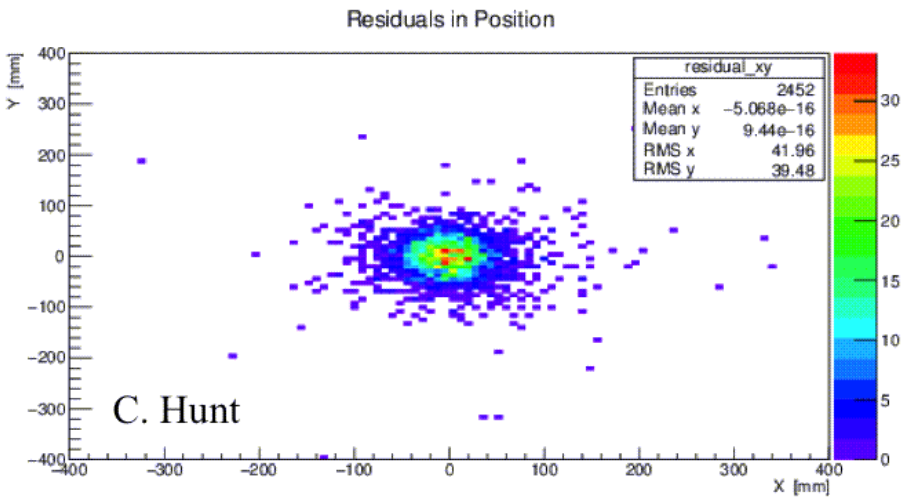

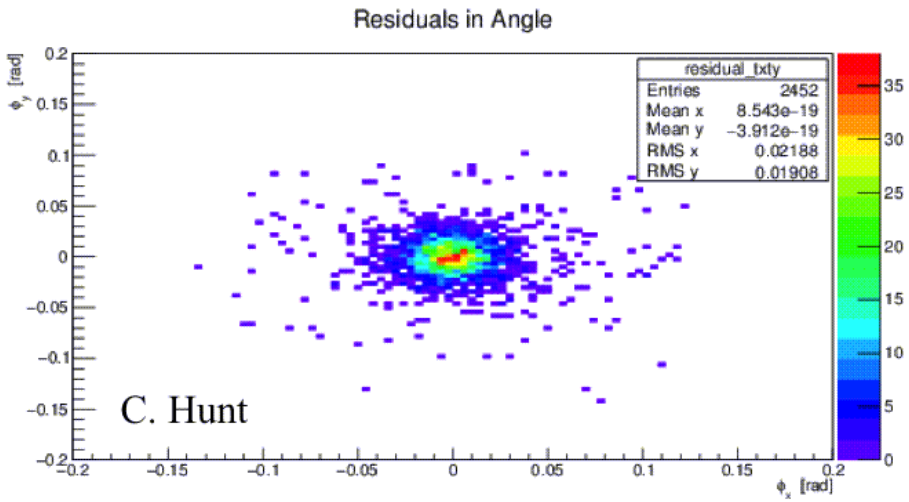

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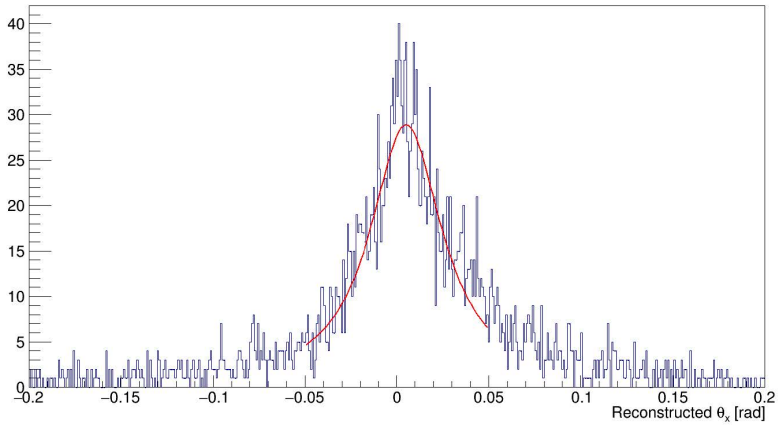

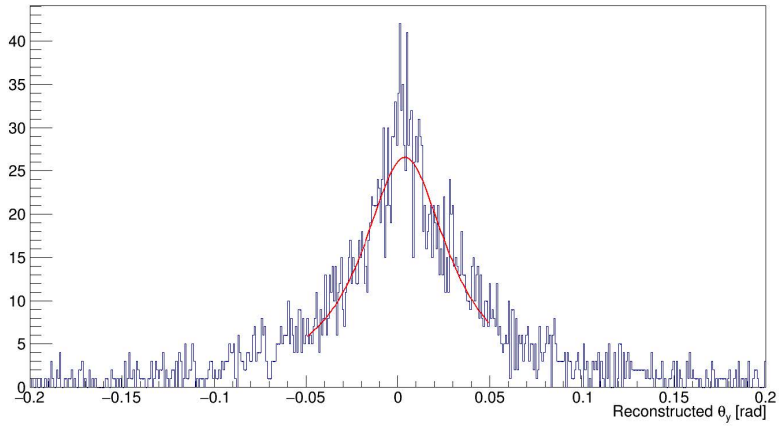

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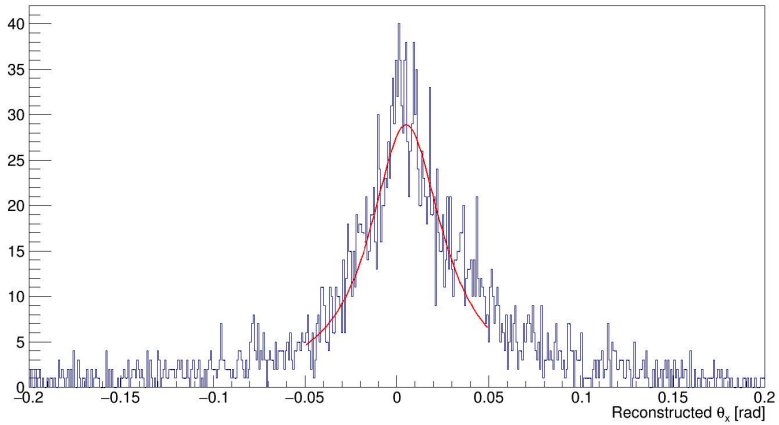

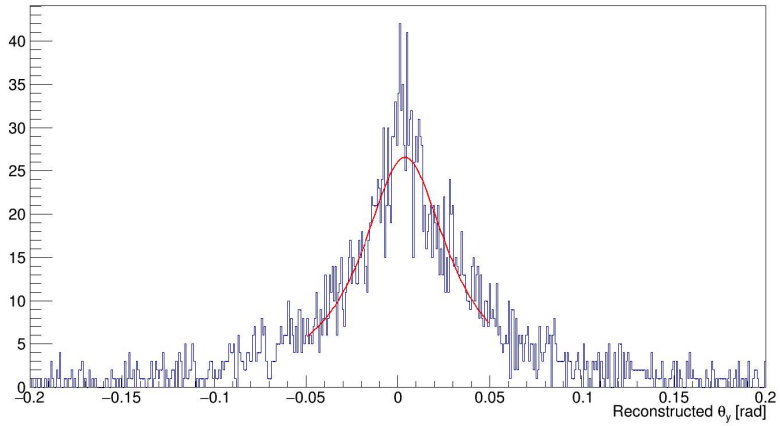

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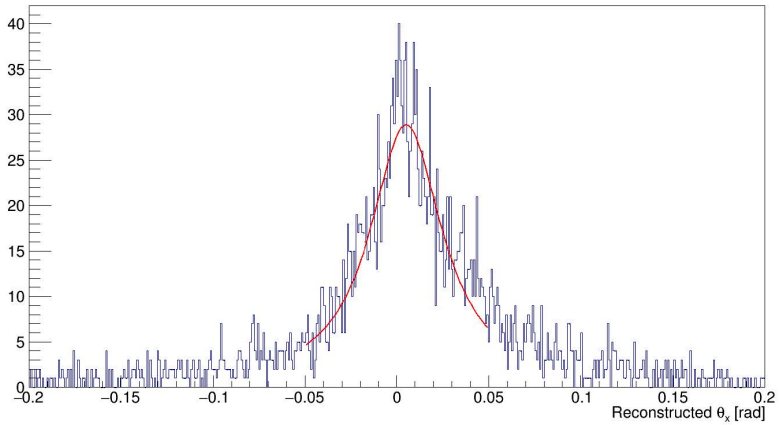

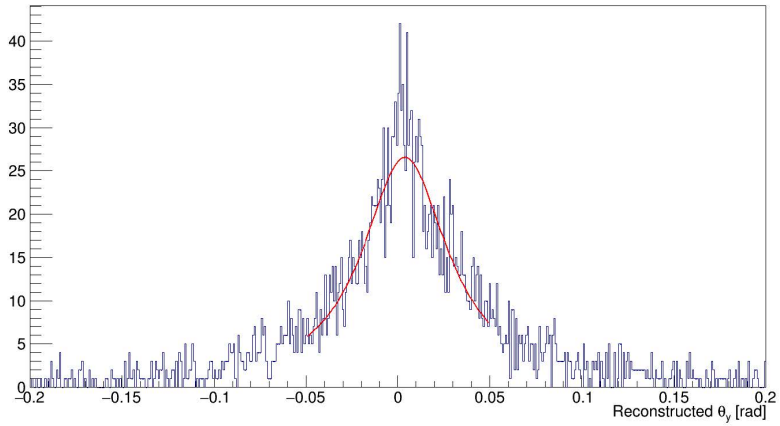

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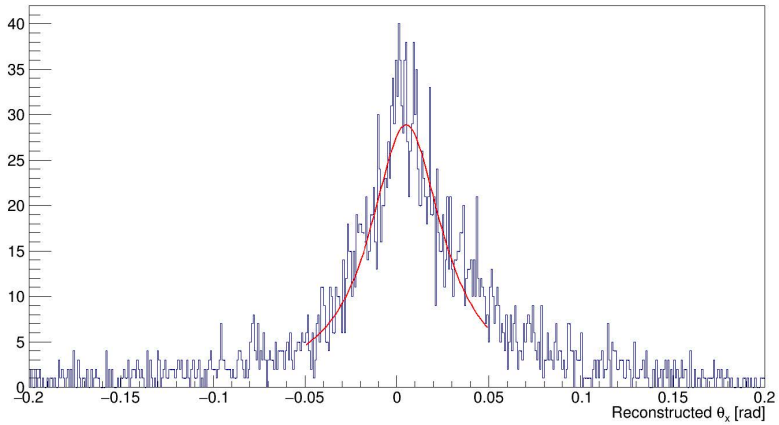

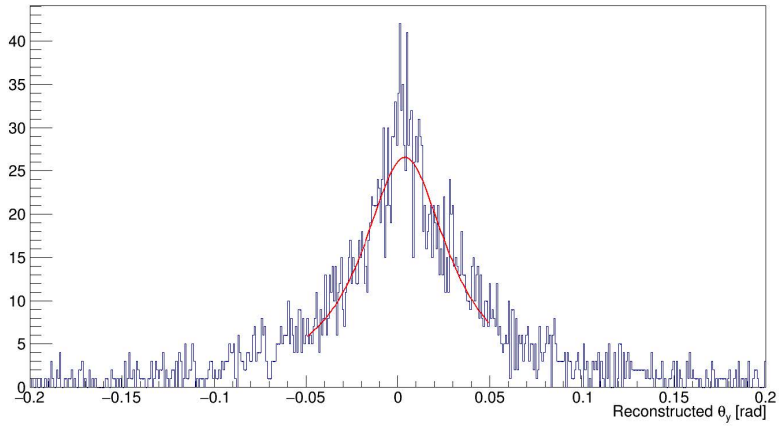

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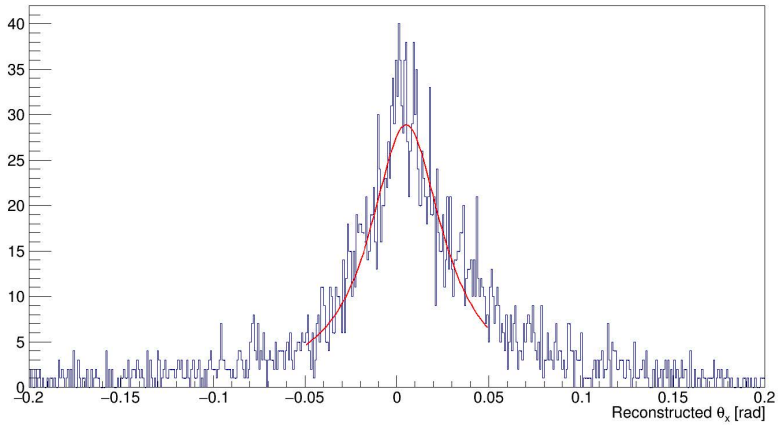

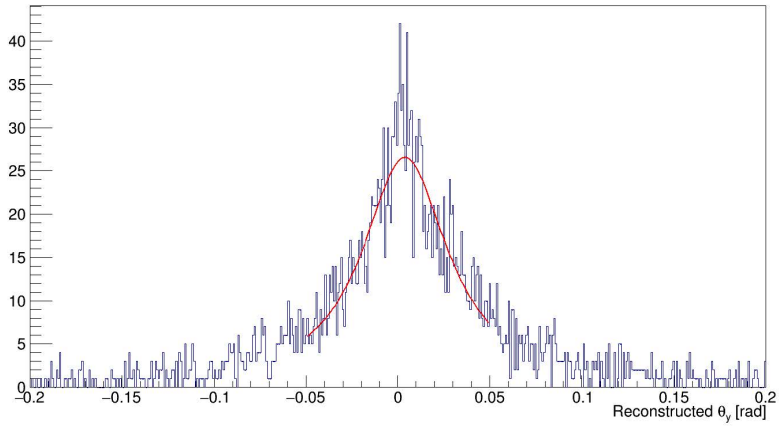

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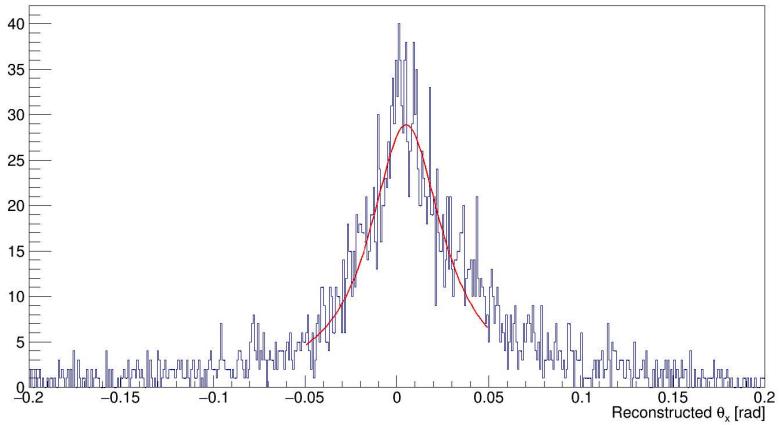

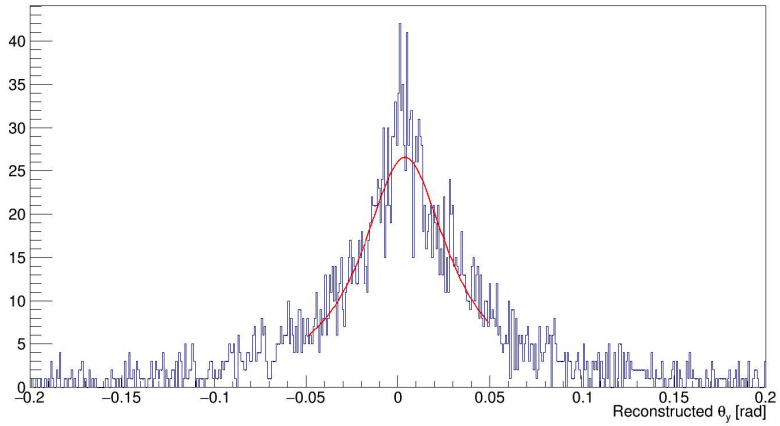

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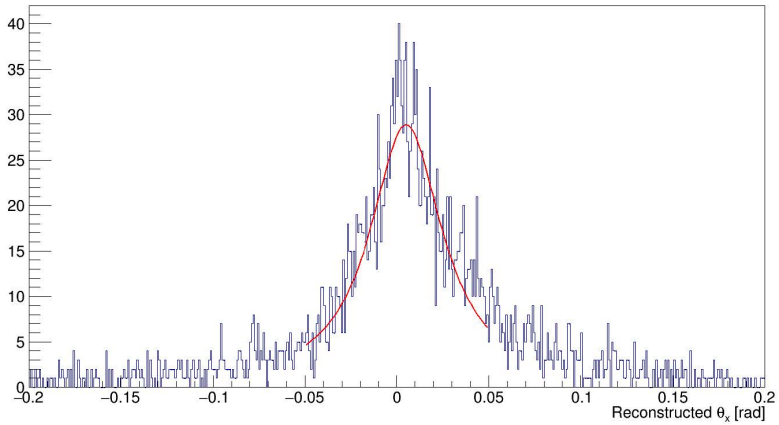

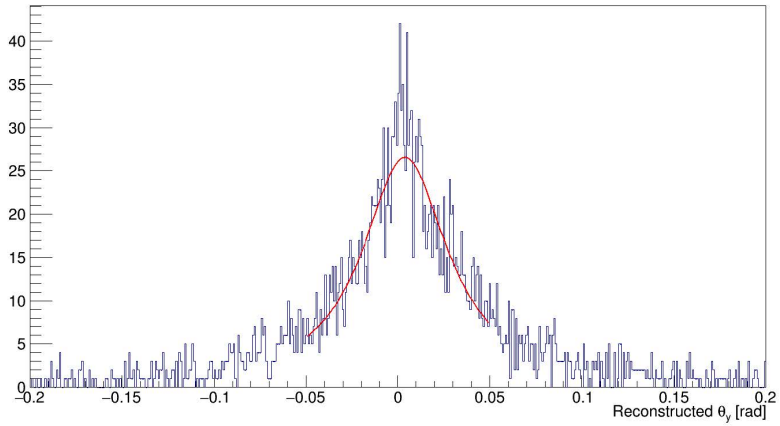

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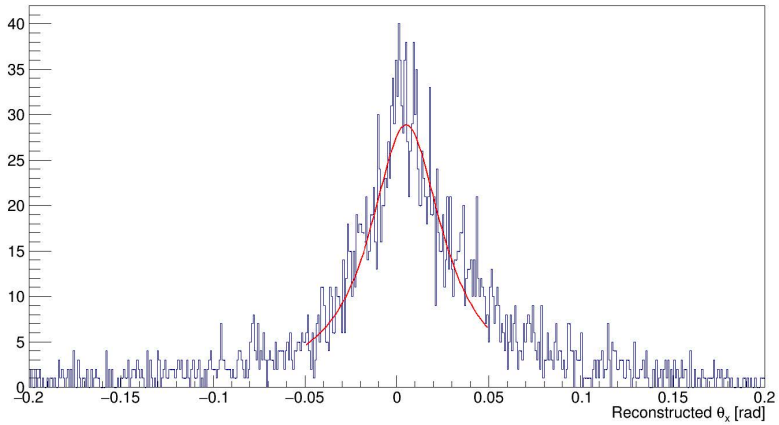

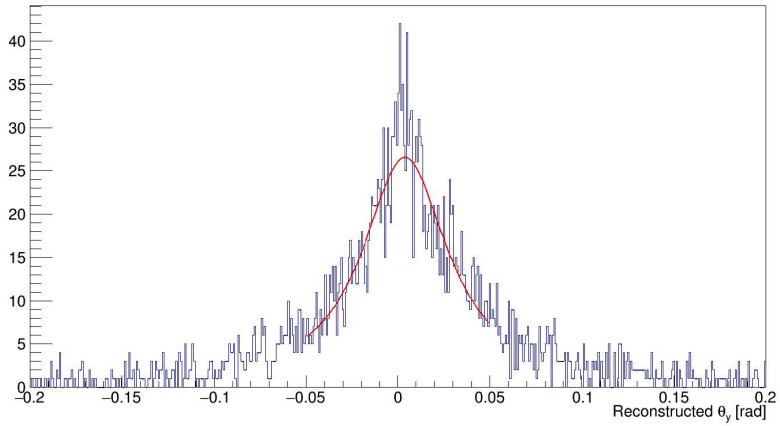

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Step IV plan

- Continue beam based alignment.
  - Alignment with solenoids at full fields (4 T).
- Characterize diagnostics:
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  - resolution of phase space variables.
- Demonstrate beam optics:
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- Study normalized emittance reduction under a variety of beam conditions.
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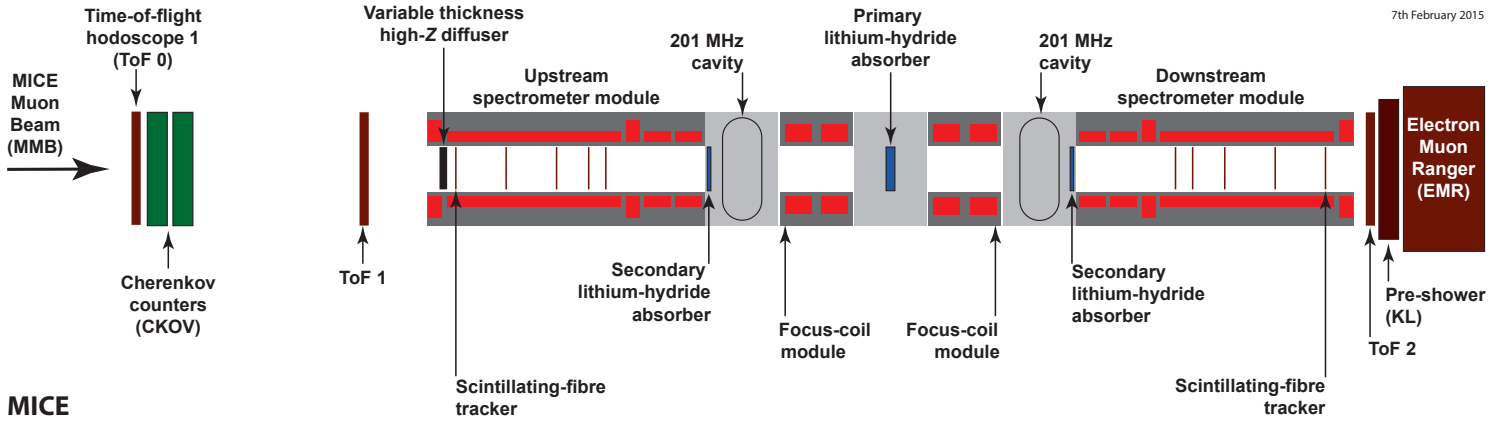
Demonstration of ionization cooling



- Includes a full cooling half-cell.
- Includes RF cavities.
- Shows geometric emittance reduction including re-acceleration (sustainable cooling).

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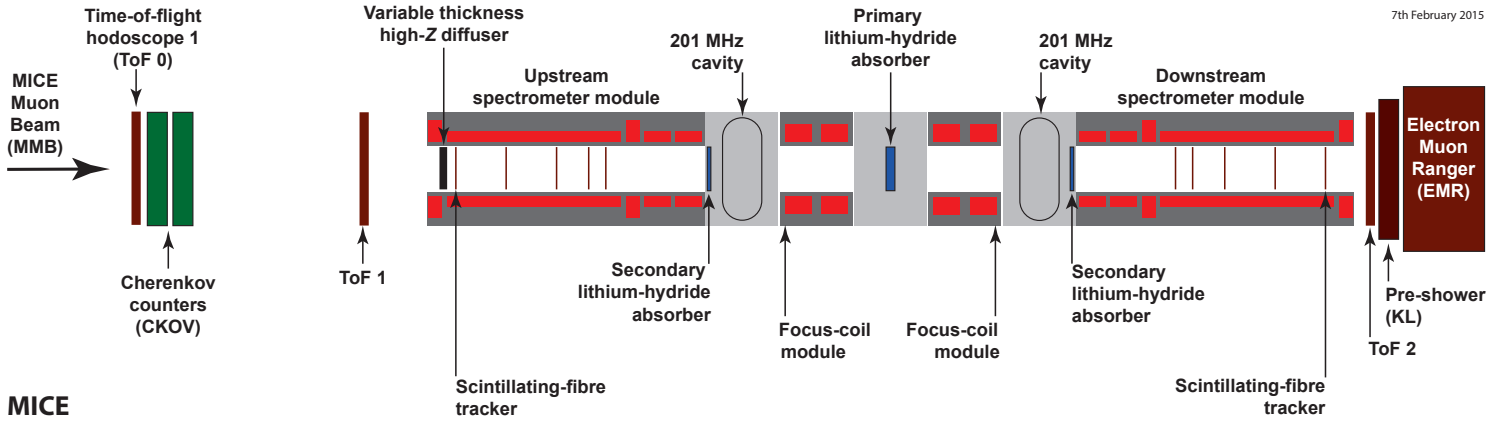

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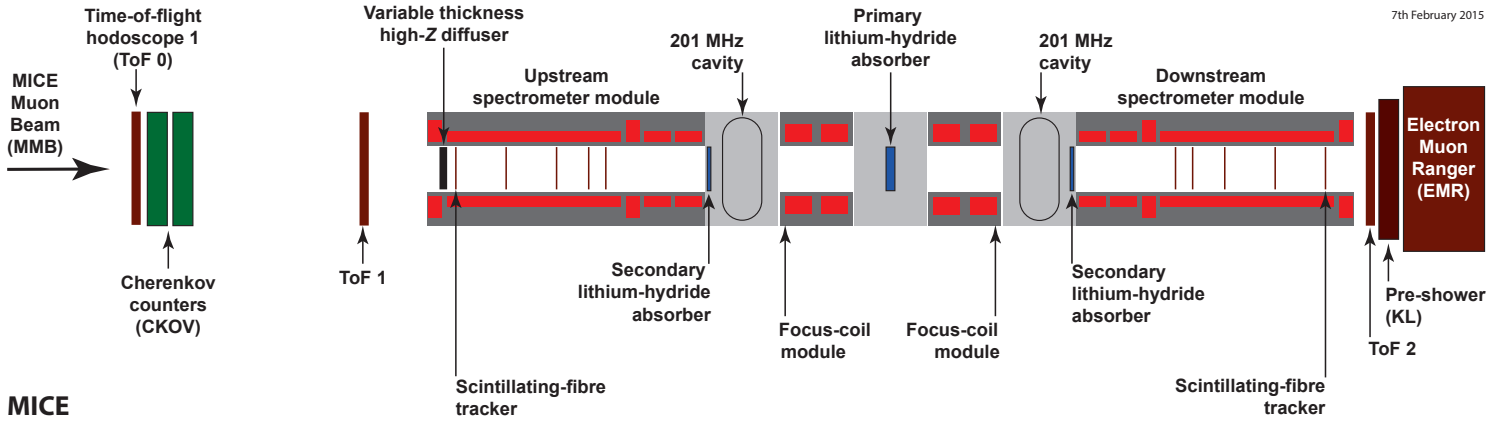

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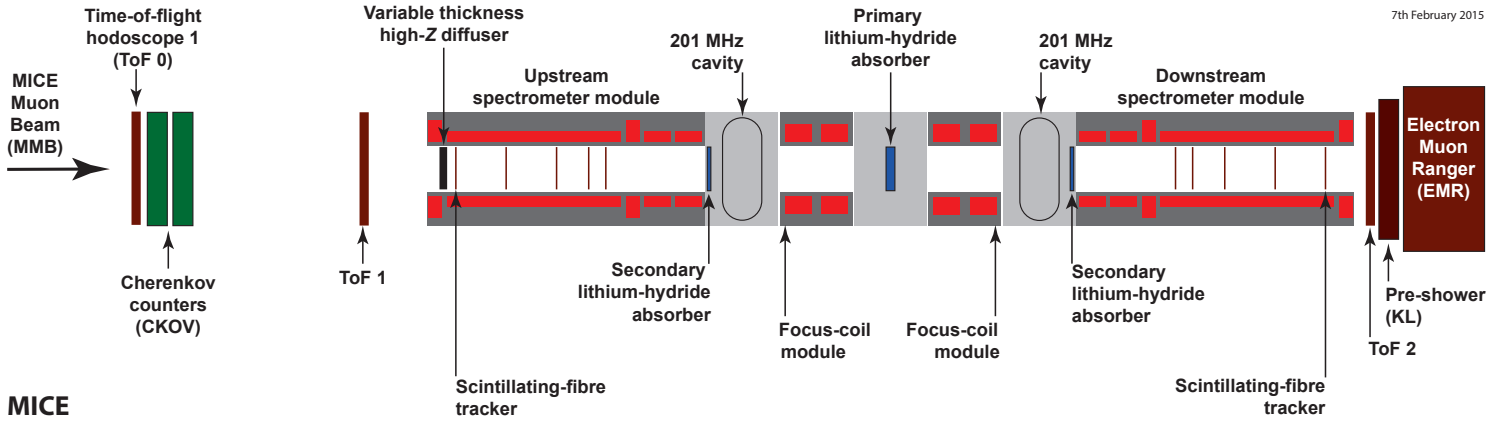

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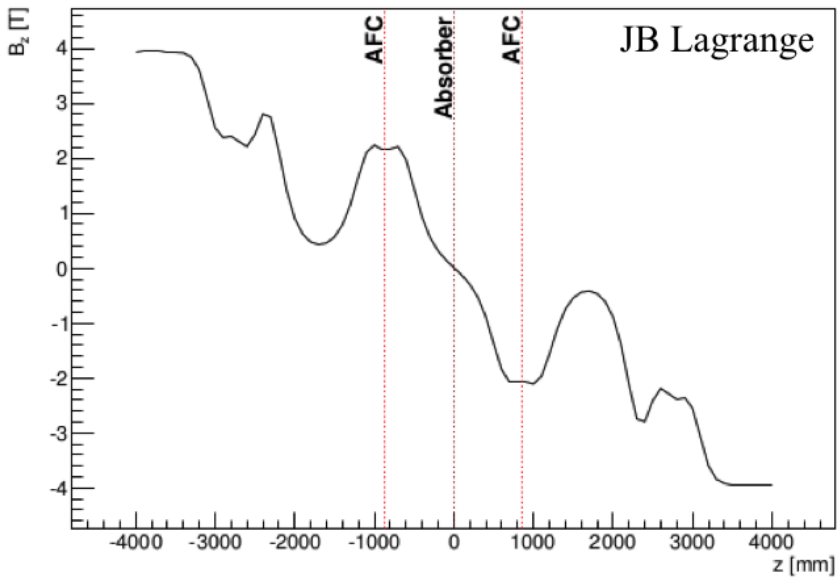

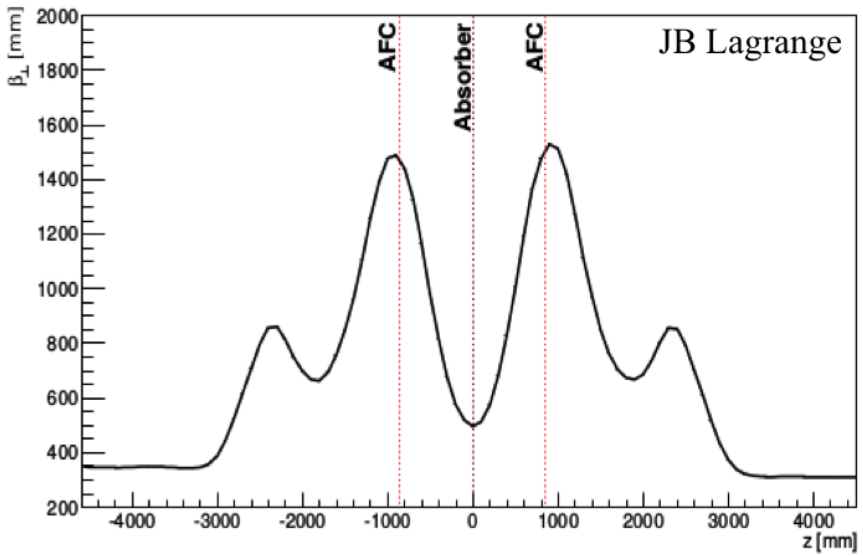

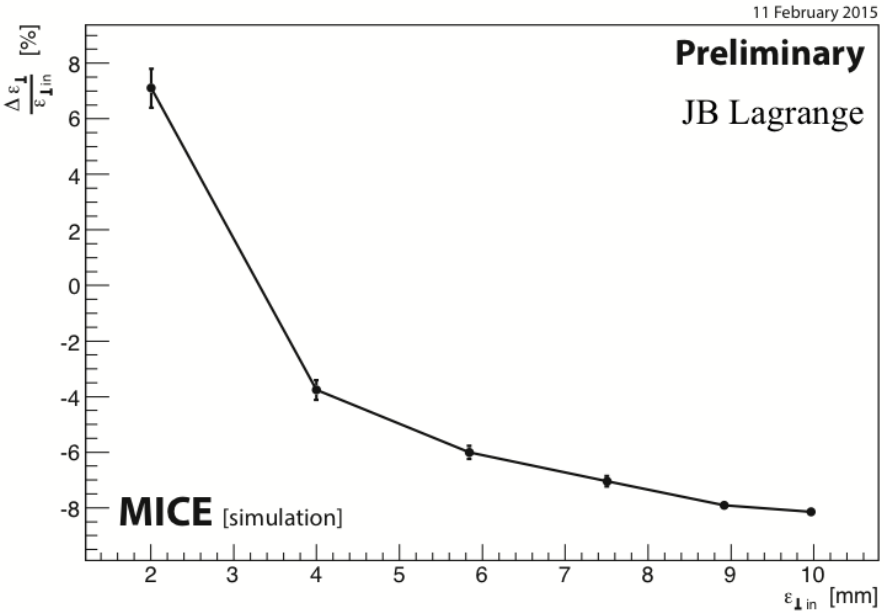

- Two Focus Coil modules.
- Lithium hydride absorber and two secondary absorbers.
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- Equilibrium emittance around 3 mm – to be measured.
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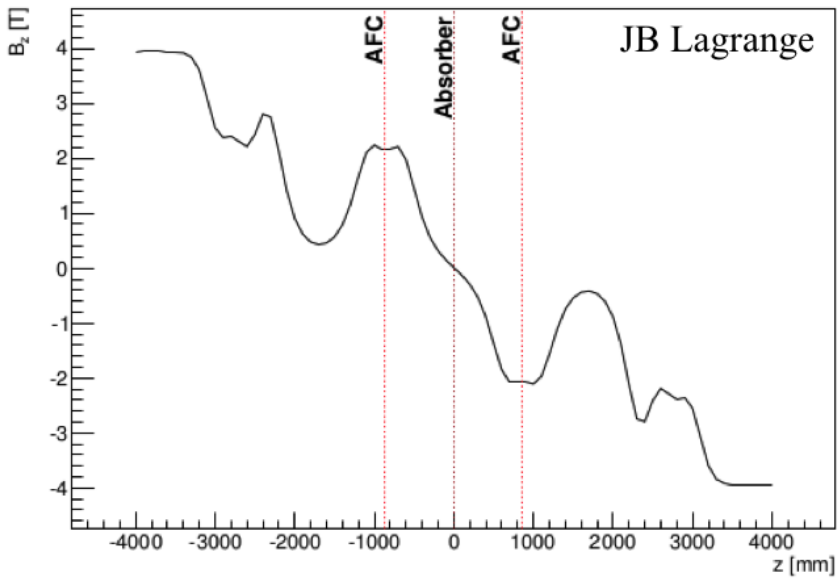

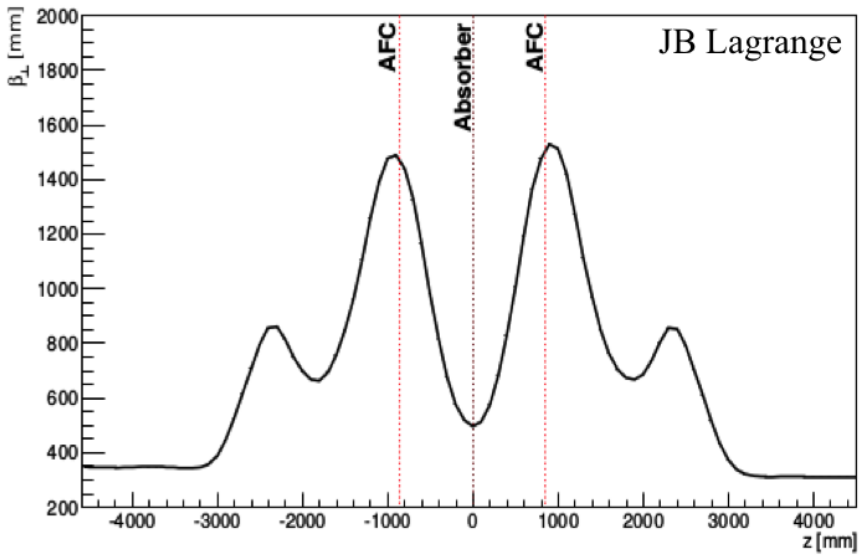

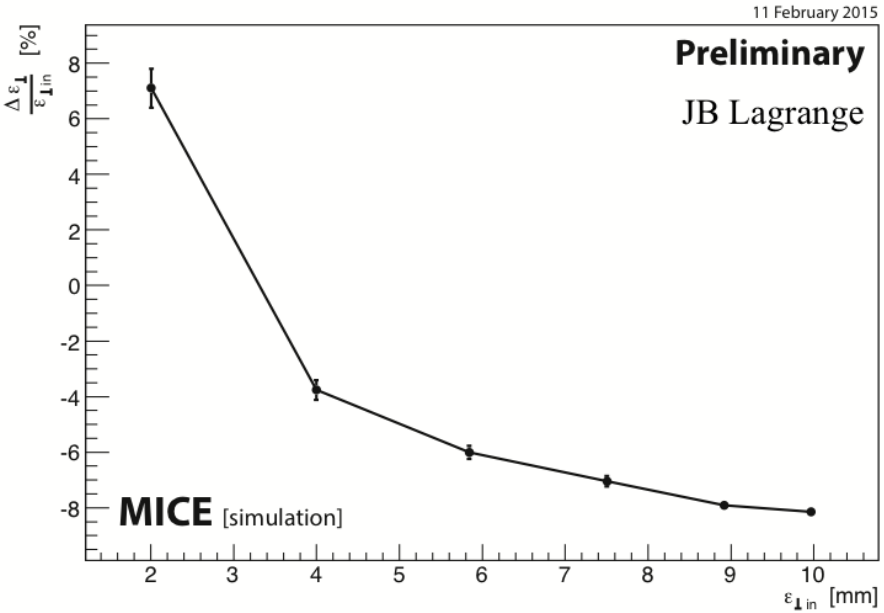

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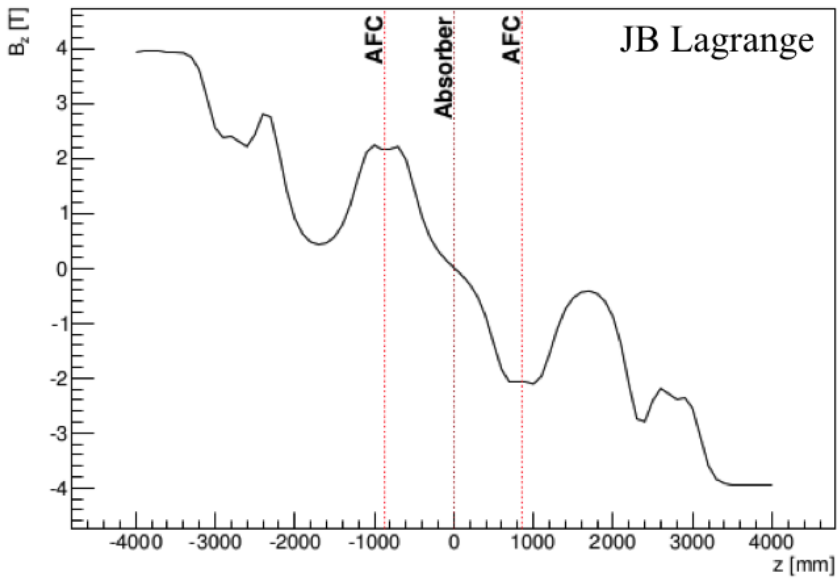

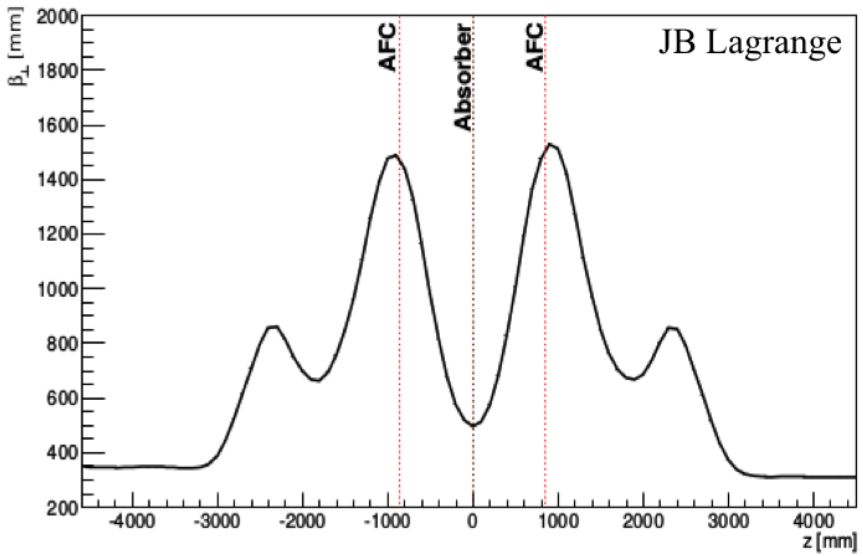

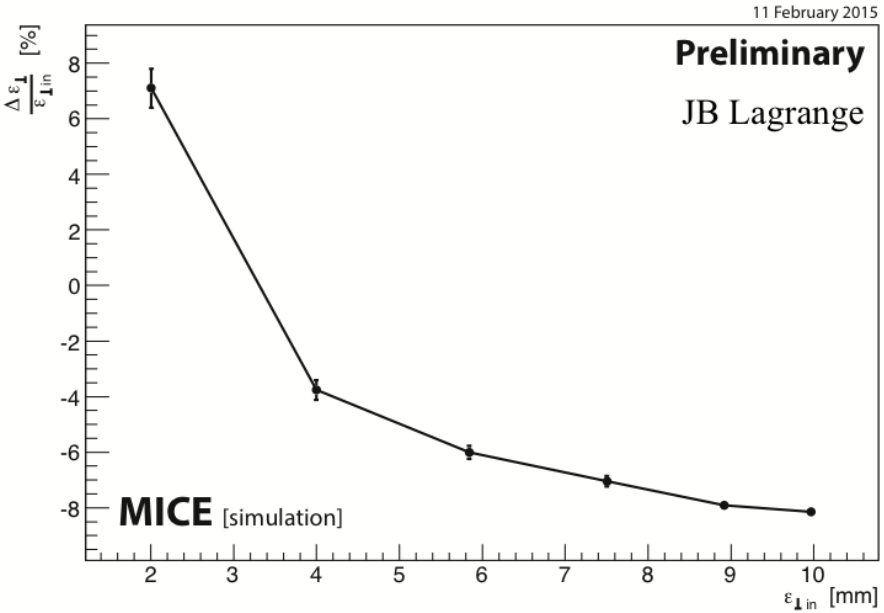

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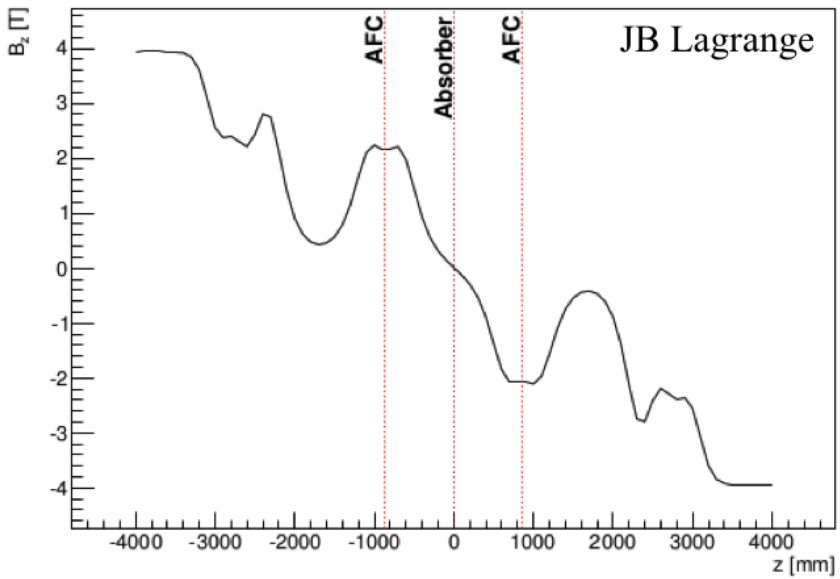

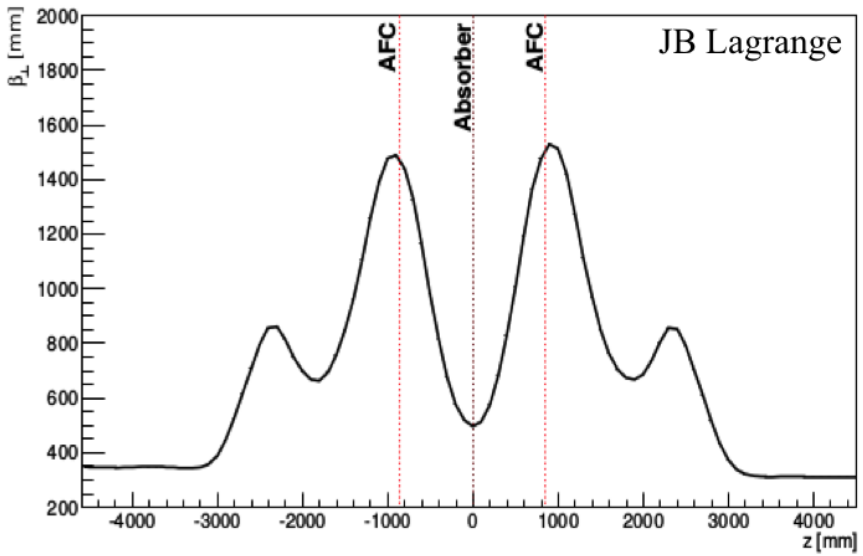

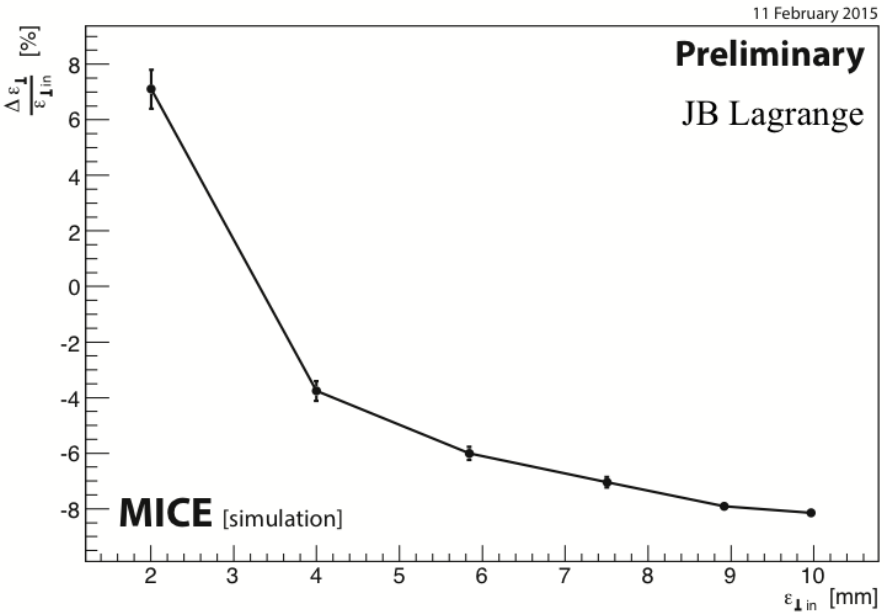

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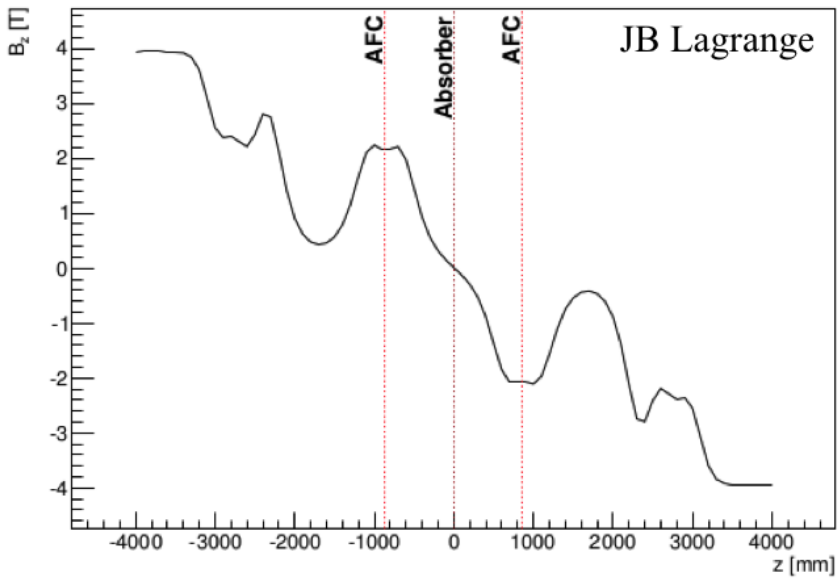

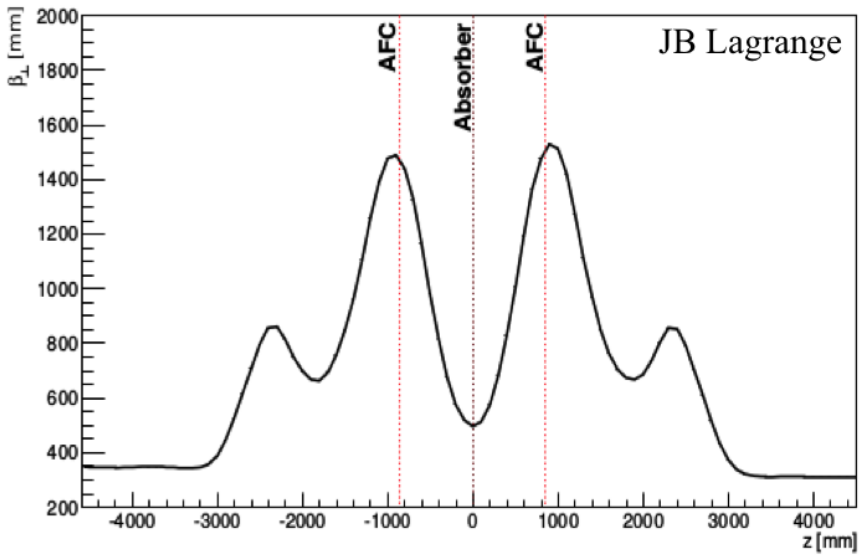

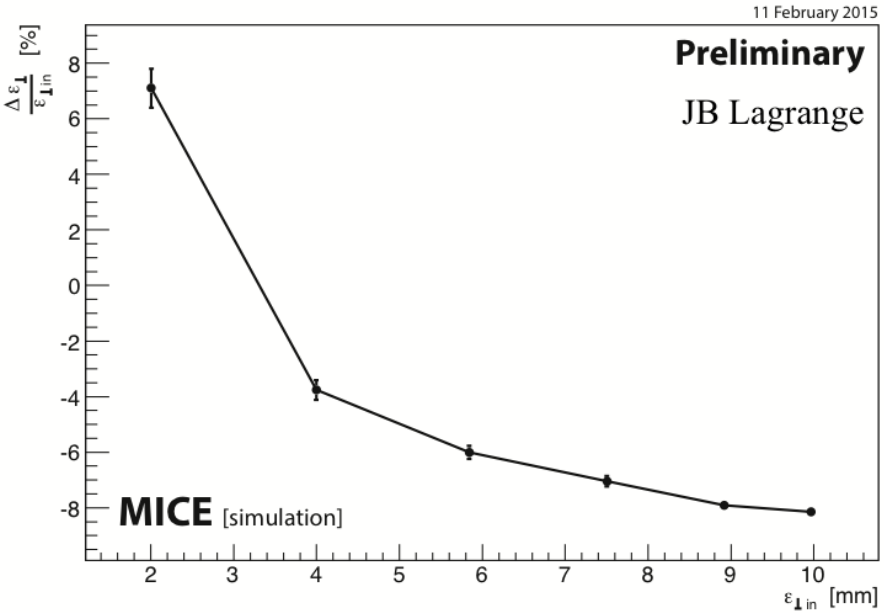

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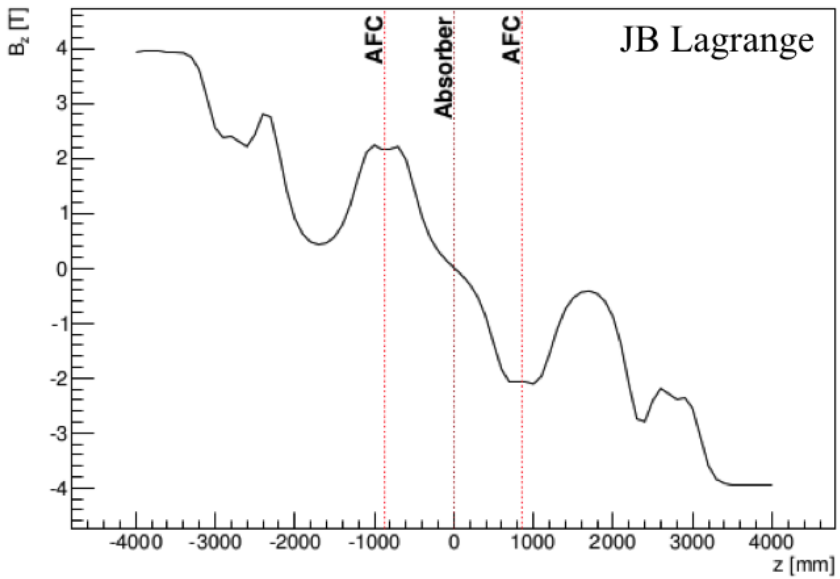

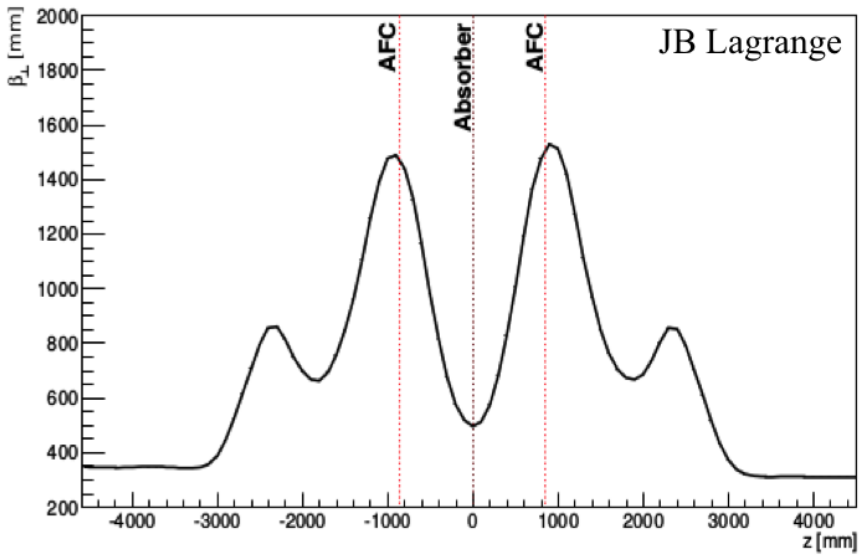

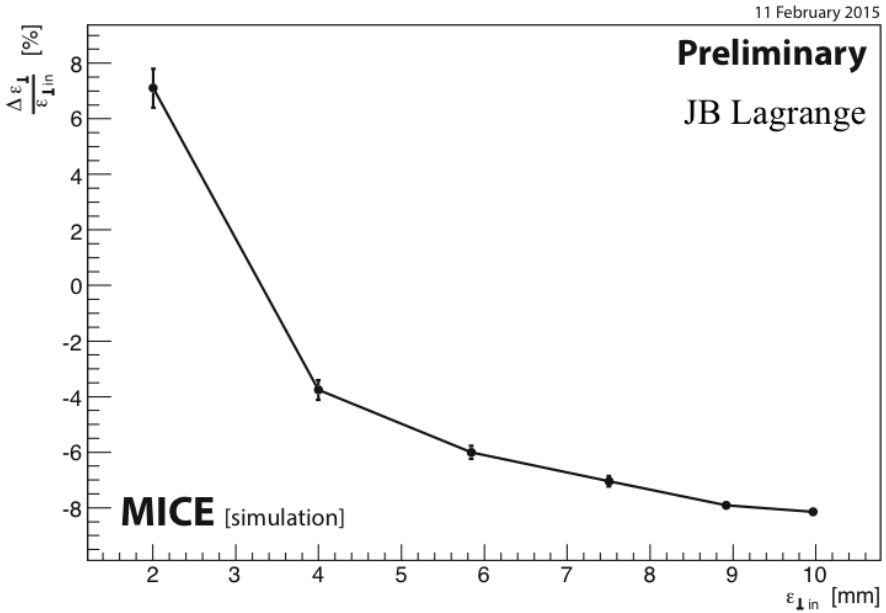

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Thank you!