Neutrino Factory R&D Efforts

Daniel M. Kaplan

Muon Accelerator Program

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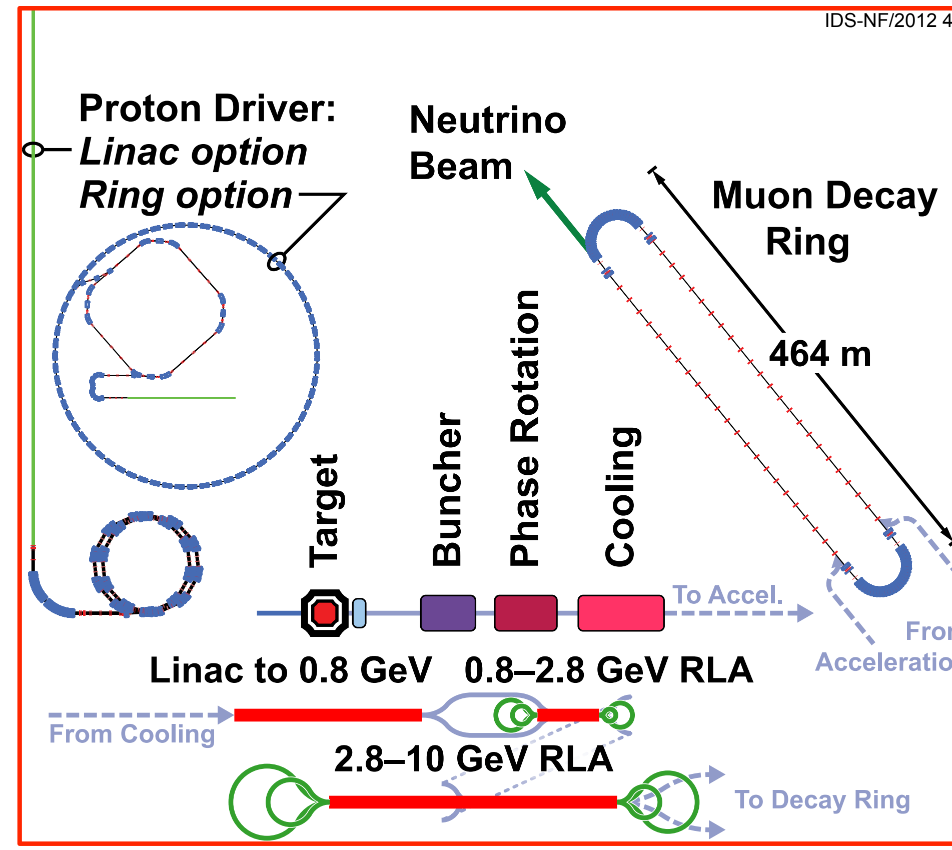
Outline

- Overview
- Required R&D and
- R&D Status
- Conclusion

Neutrino Factory

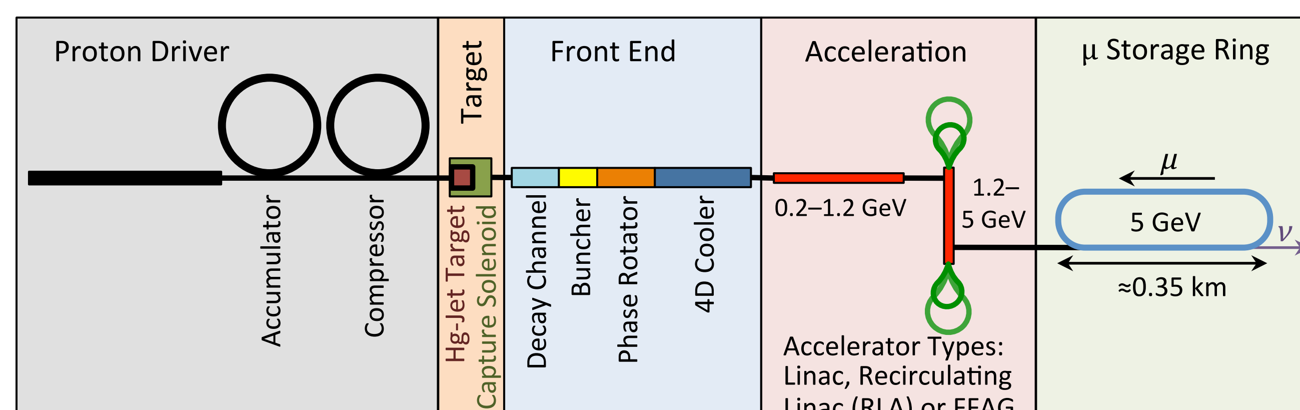
- The most powerful facility proposed for ν osc. & CPV
- Two designs currently under development:
- International Design Study for the Neutrino Factory (IDS-NF)
  - generic
  - E_μ = 10 GeV, L = 2,000 km } chosen as optimal for CPV given $\sin^2 2\theta_{13} \approx 0.1$



- U.S. Muon Accelerator Program (MAP) design
  - specific to FNAL→SURF (Homestake, S. Dakota)

    ⟹ L = 1,300 km

    ⟹ E_μ = 5 GeV is optimal



Neutrino Factory

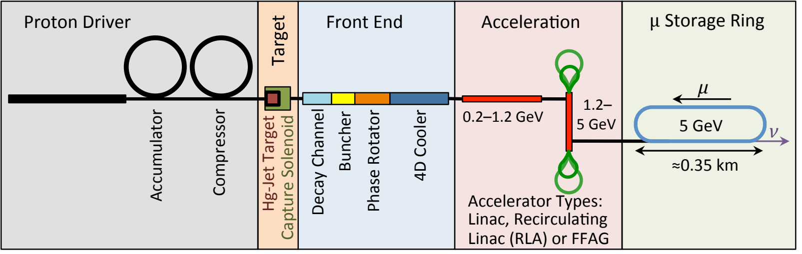
- Note CPV optimum vs. distance is broad

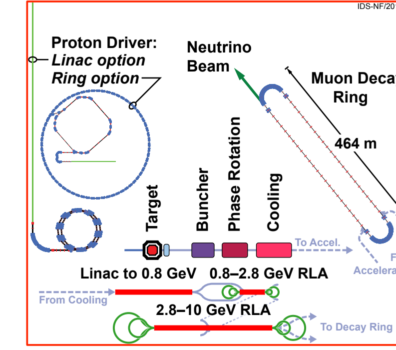
$\Longrightarrow$ for fixed *L*/*E*, no particular advantage to *L* = 2,500 vs 1,300 km,

  - provided detector efficient at the resulting lower neutrino energies
  - which, e.g., (magnetized) LAr or totally active scintillator detector would certainly be
  - and magnetized iron might be good enough

Neutrino Factory R&D Topics

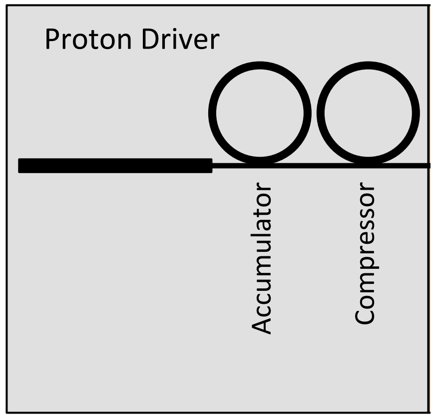
1. Neutrino Factory conceptual design
2. Multi-MW Proton Driver
3. Multi-MW target facility
4. Muon capture, bunching, & cooling
5. Muon acceleration
6. Muon decay ring
7. Detectors





I. Conceptual Design

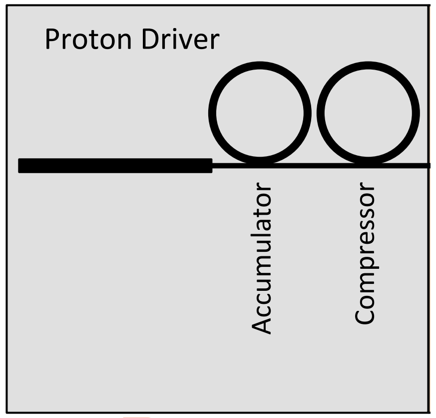
- Developed in series of studies, starting with:
  - Prospective Study of Muon Storage Rings at CERN
    [B. Autin, A. Blondel, and J. Ellis, eds., CERN 99-02, ECFA 99-197 (1999)]
  - (U.S.) Feasibility Study of a Neutrino Source Based on a Muon Storage Ring
    [N. Holtkamp and D. Finley, eds., Fermilab-Pub-00/108-E (2000)]
  - (U.S.) Feasibility Study-II of a Muon-Based Neutrino Source
    [S. Ozaki, R. Palmer, M. Zisman, J. Gallardo, eds., BNL-52623 (2001)]
  - A Feasibility Study of a Neutrino Factory in Japan
    [NufactJ Working Group, Y. Kuno, and Y. Mori, eds., May 24, 2001, KEK Report (2003)]
- Current (nearly complete):
  - International Design Study for the Neutrino Factory (IDS-NF)
    - Reference Design Report in preparation
- Snowmass White Paper: "Enabling Intensity and Energy Frontier Science with a Muon Accelerator Facility in the US" [arXiv1308.0494]



2. Proton Driver

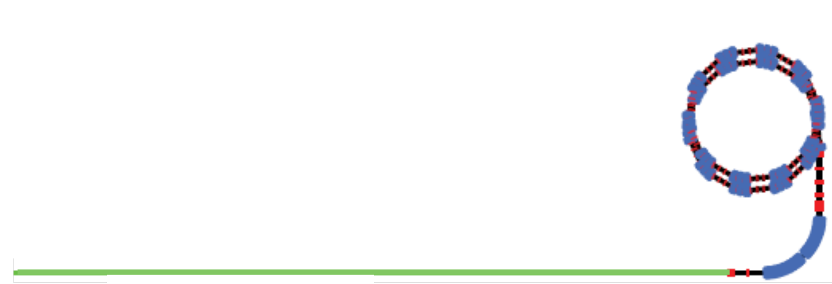
- Goals*: P = 4 MW @ $E \approx$ 3–8 GeV with $\leq$ few-ns bunch width & 50 Hz repetition rate
  - can ease space-charge issues using groups of ≈3 bunches with ≈100 μs spacing [see Target discussion]
- Approaches:
  - linac with accumulator & compressor rings
  - synchrotron
  - FFAG

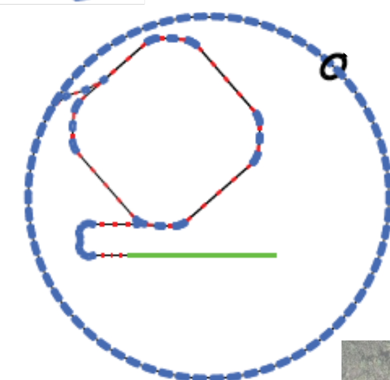
* for ~ 10^{21} ν/year



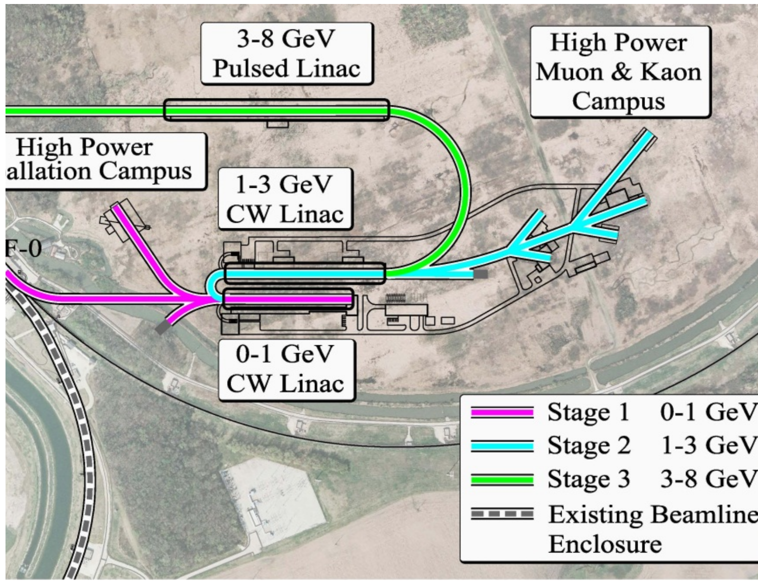
2. Proton Driver

- **Proposals:**
  - HP-SPL at CERN
    - 4 MW 5 GeV superconducting linac





  - ISIS upgrade at RAL
    - 5 MW 3.2 GeV RCS driven by 800 MeV linac
  - Project X at FNAL (only "active" proposal)
    - Stage II: I MW 3 GeV CW linac ➙ "NuMAX"
      - later upgrade to 3 MW ➙ "NuMAX+" (+ cooling)



    - Stage IV: 4 MW 8 GeV pulsed linac ➙ Muon Collider

see M. Palmer, Delahaye plenary talks

sterile ν + cross sections

see nuSTORM WG3 session

    - "Stage 0": nuSTORM ring using existing FNAL complex

3. Target Facility

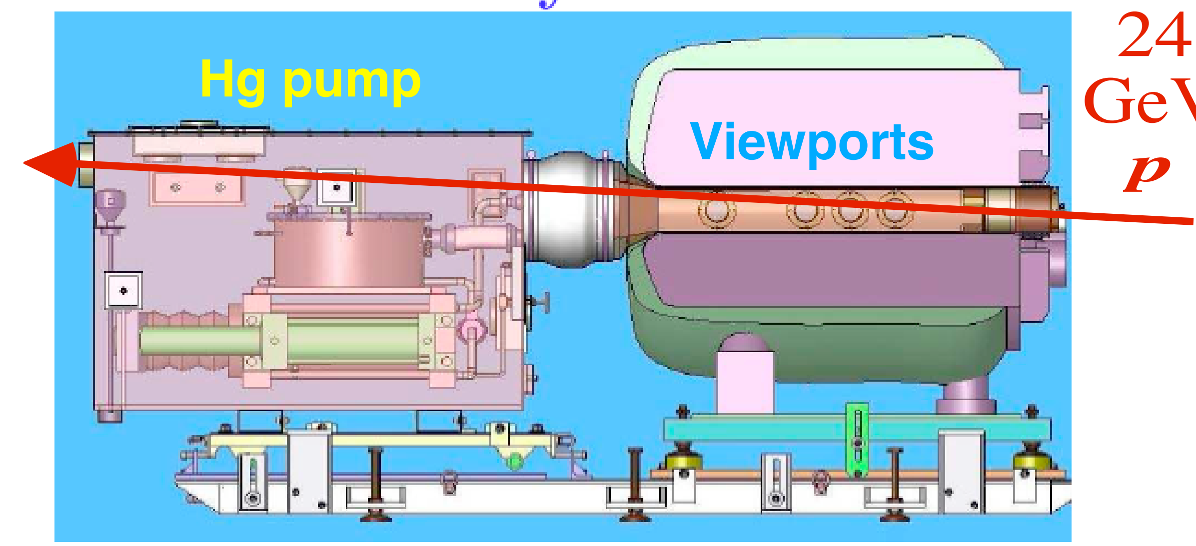
- 1st stage: conventional 1 MW target (e.g., graphite)
- Next stage:
  - multi-MW beam likely to melt almost any solid target!
  - so why not use liquid? e.g. Hg or Pb-Bi eutectic
    - high-*A* ⇒ makes ≈equal #s of μ^+ and μ^-
    - can remove radioactive spallation products by distillation
  - container risky (erosion, shock) ⇒ use free jet
- Proof of principle: MERcury Intense Target (MERIT) Experiment @ CERN

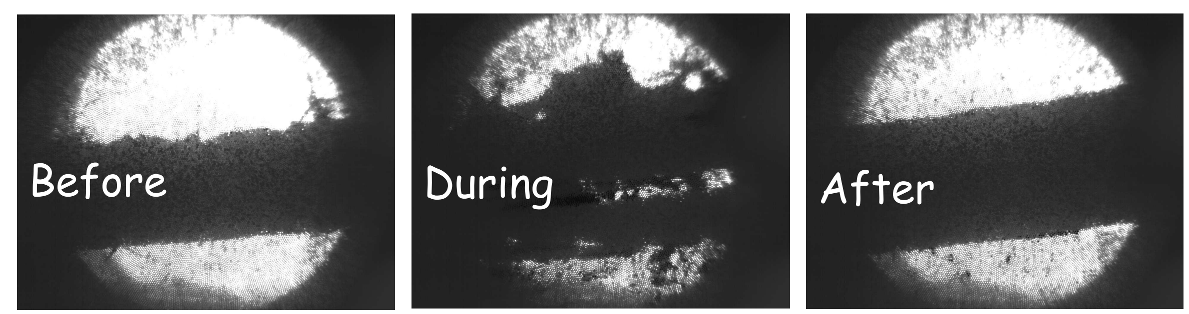
MERIT

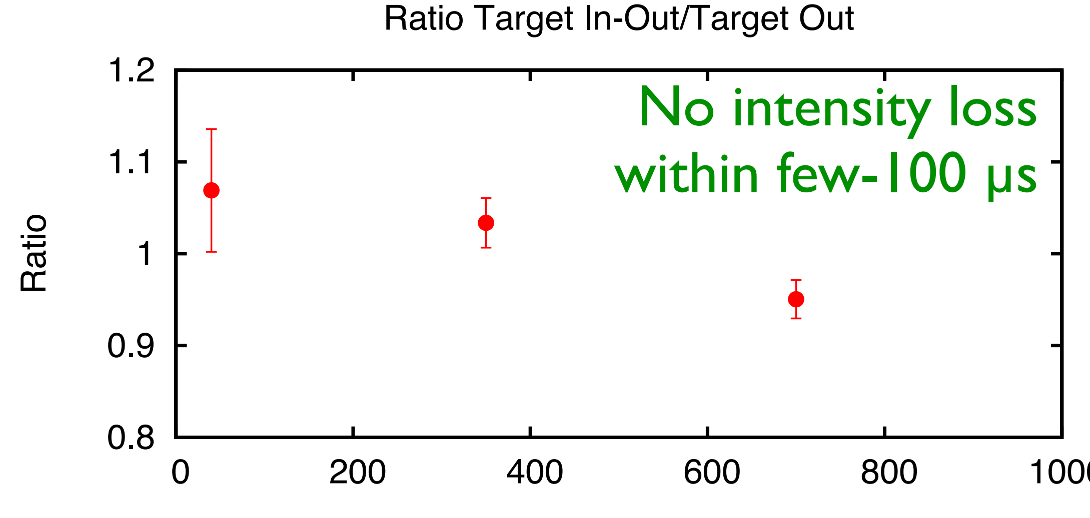
- Experiment carried out @ CERN nTOF facility in 2007
- BNL/CERN/ORNL/ Princeton/RAL/SUNYSB collaboration
  - Hg jet, 1 cm diam, 20 m/s, jet axis at 33 mrad to magnet axis ($B \leq 15$ T)
  - concept demonstrated workable up to ≈8 MW

    [K. McDonald *et al.*, Proc. IPAC'10]

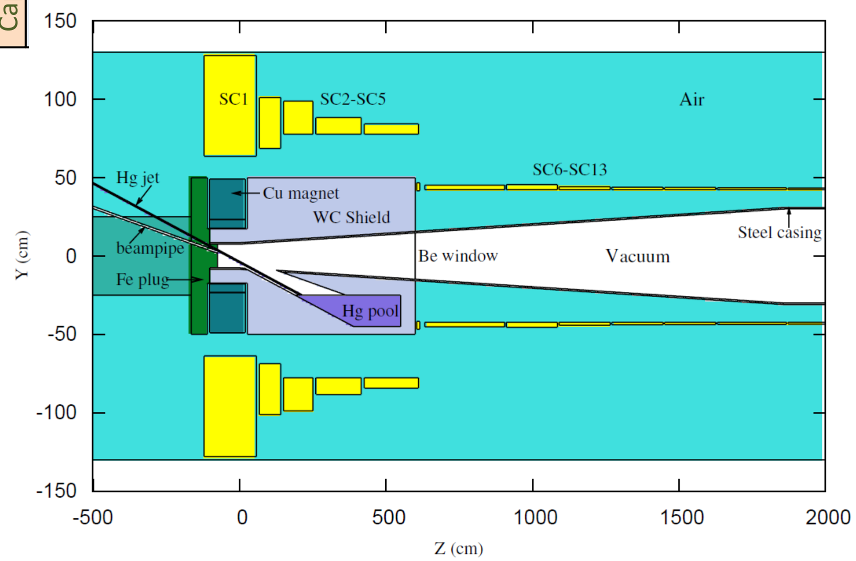
MERIT cutaway view:

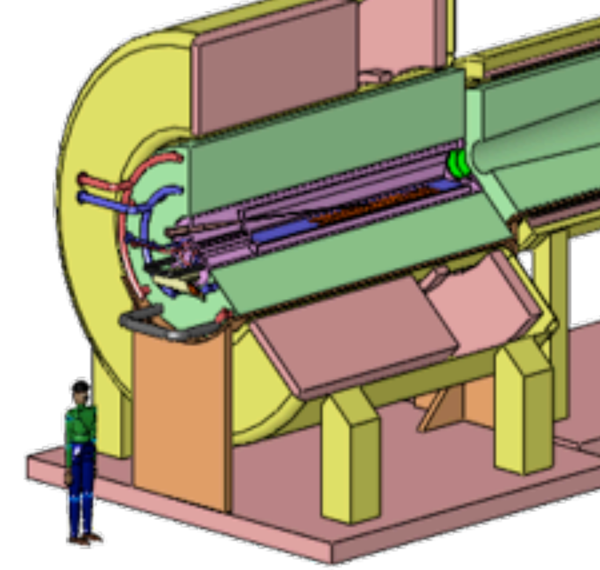


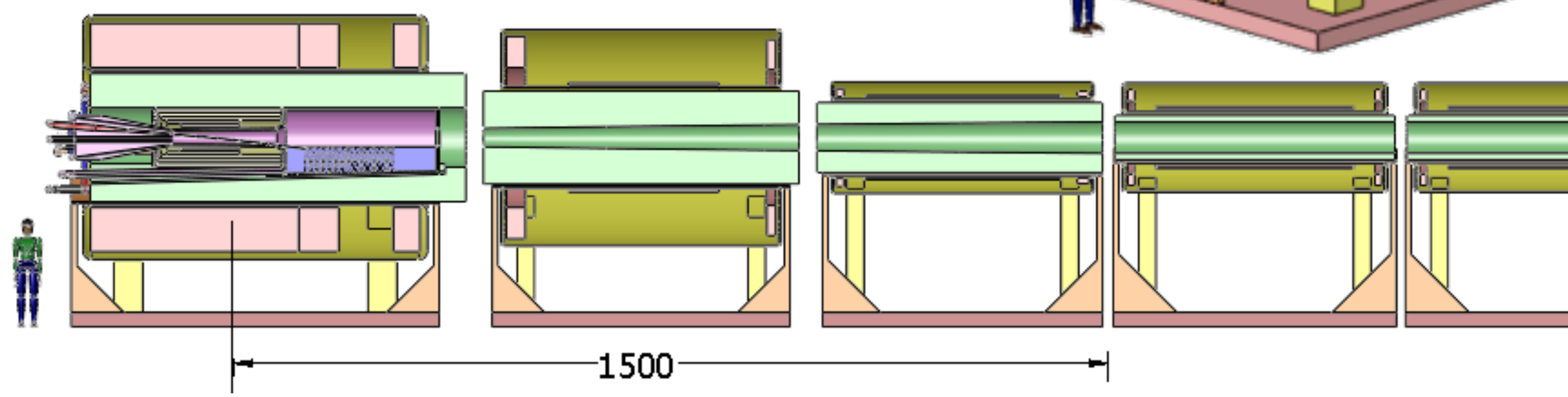




3. Target Facility

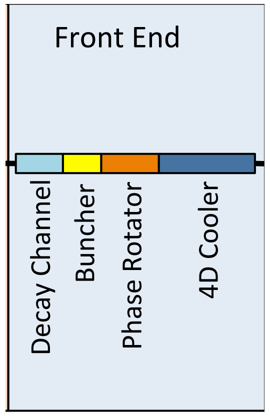




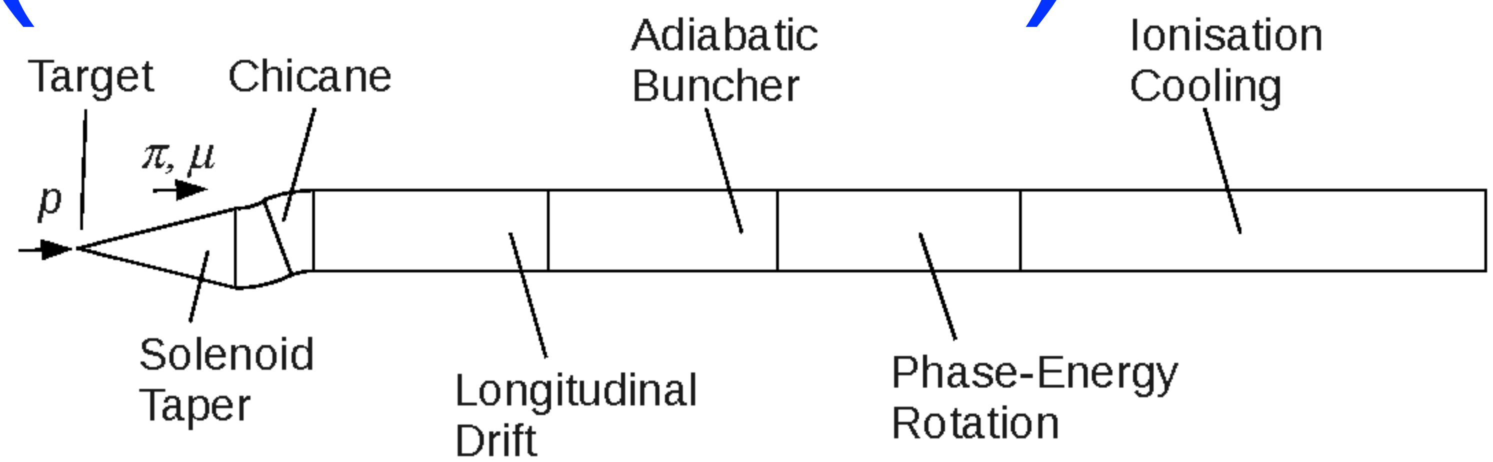


- 20 T hybrid (or HTS?) solenoid at target for efficient pion capture
- Requires massive shielding installation & robotic maintenance & handling capability
- But no obvious showstopper
- Design now being evaluated for 3 GeV p beam

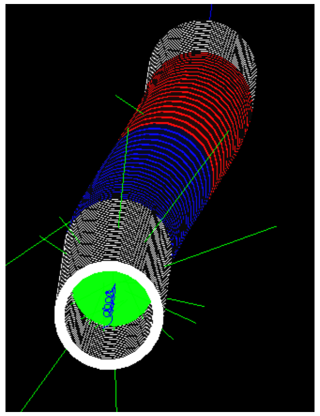
see McDonald, Sayed WG3 talks

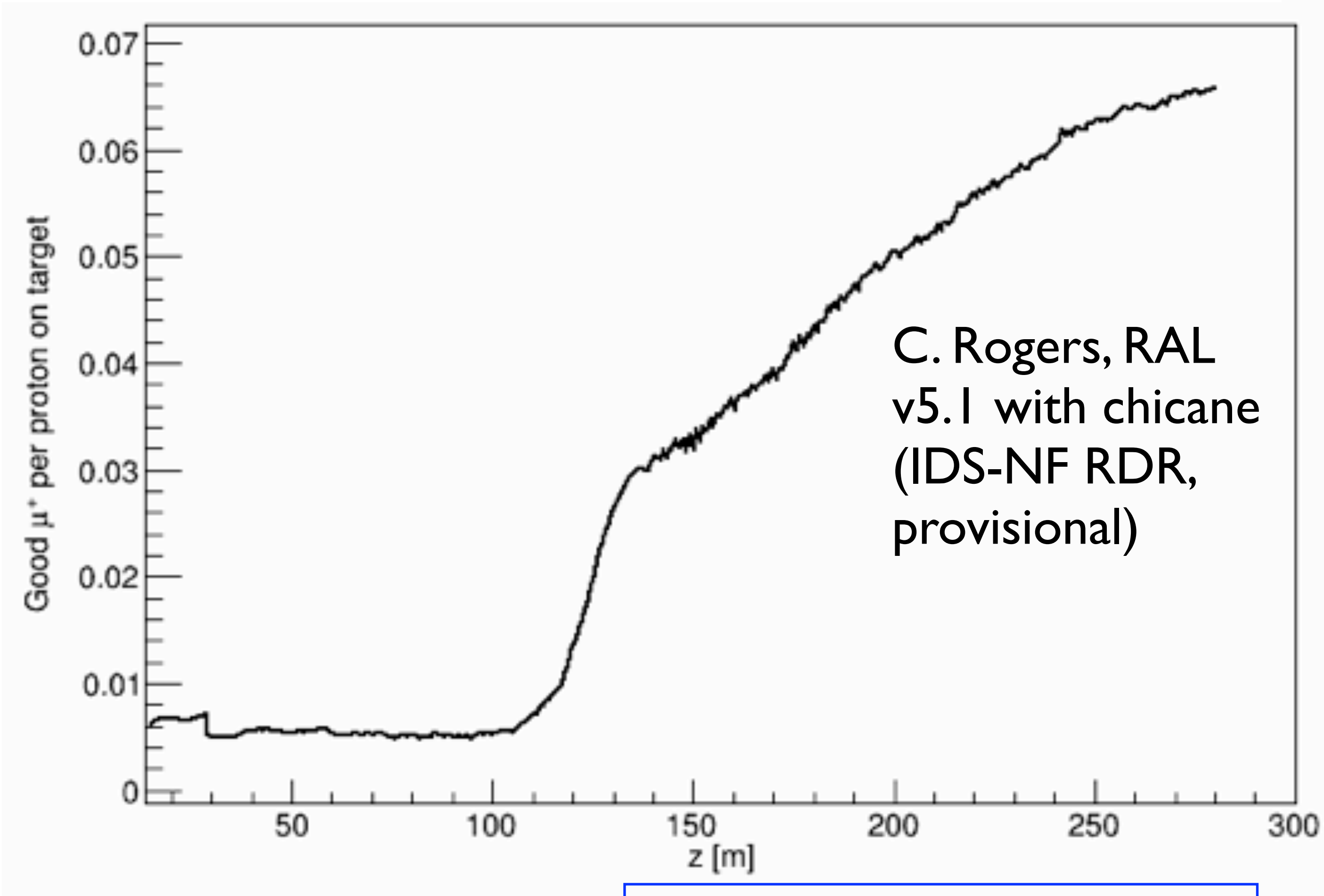


4. Capture, Bunching, & Cooling ("Front End")



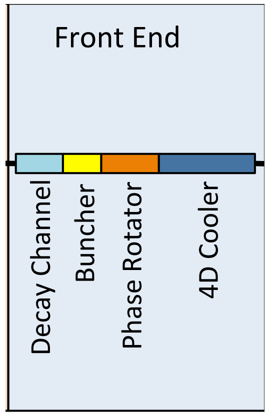
- IDS-NF design evolution
  - add chicane to control losses
  - ionization cooling gains x 2.5 in good muons





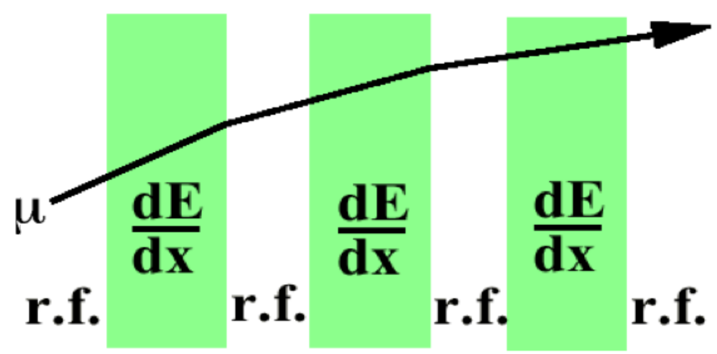
- NF cooling requires (normal-conducting) RF gradient in few-tesla field

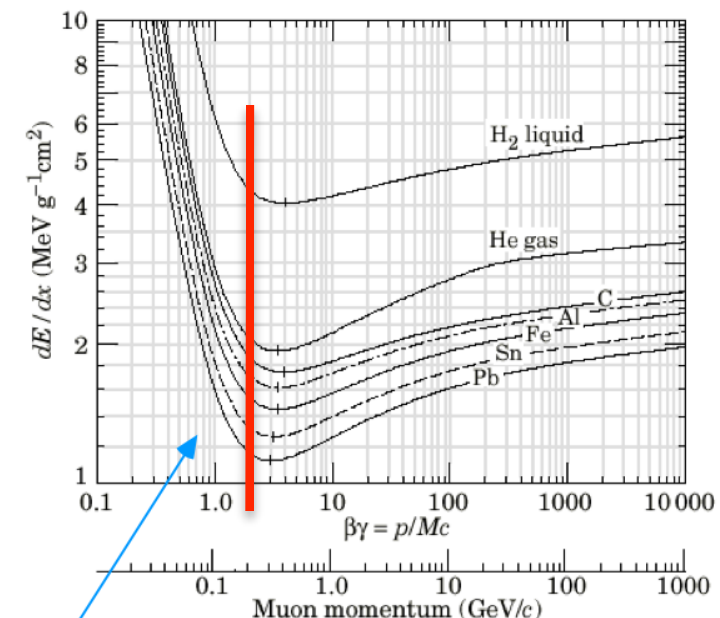
see Neuffer WG3 talk



Muon Cooling R&D

- Muons quickly cool via ionization
- Low-Z absorber material is best
- Want low β to minimize heating via MCS ⇒ RF in magnetic field





– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \dfrac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta^{rms}_{space} \end{cases}$$

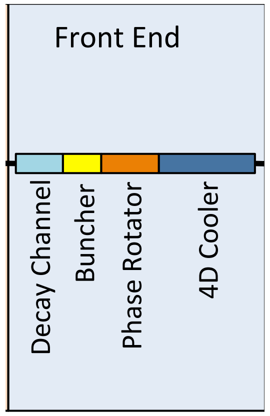
ionization energy loss

multiple Coulomb scattering

– RF cavities between absorbers replace ΔE

– Net effect: reduction in $p_\perp$ at constant $p_{||}$, i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \text{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$ (emittance change per unit length)

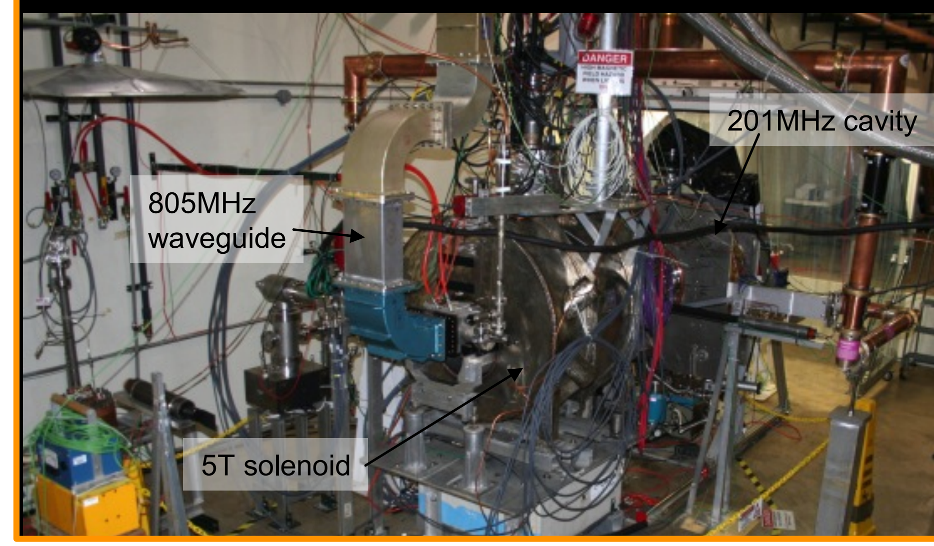


Muon Cooling R&D

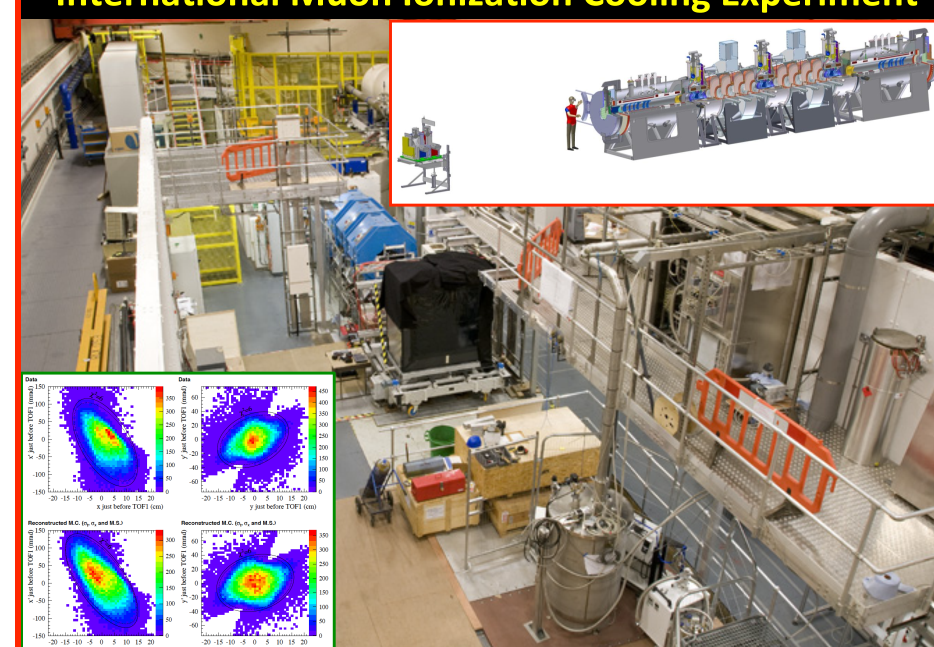
- RF cavity operation in *B* field under investigation in Fermilab MuCool Test Area (MTA)
  - not a go/no-go issue, but one of cost-effectiveness
- Muon Ionization Cooling Experiment (MICE) at RAL will demonstrate & characterize cooling

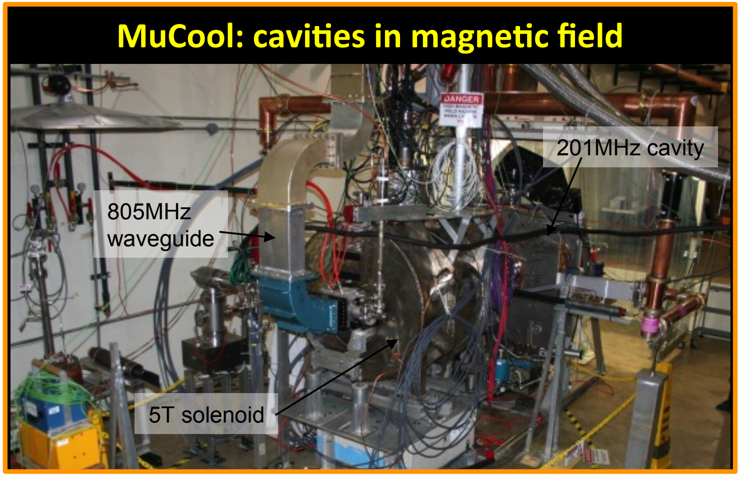
see Adey, Kaplan WG3 talks

MuCool: cavities in magnetic field

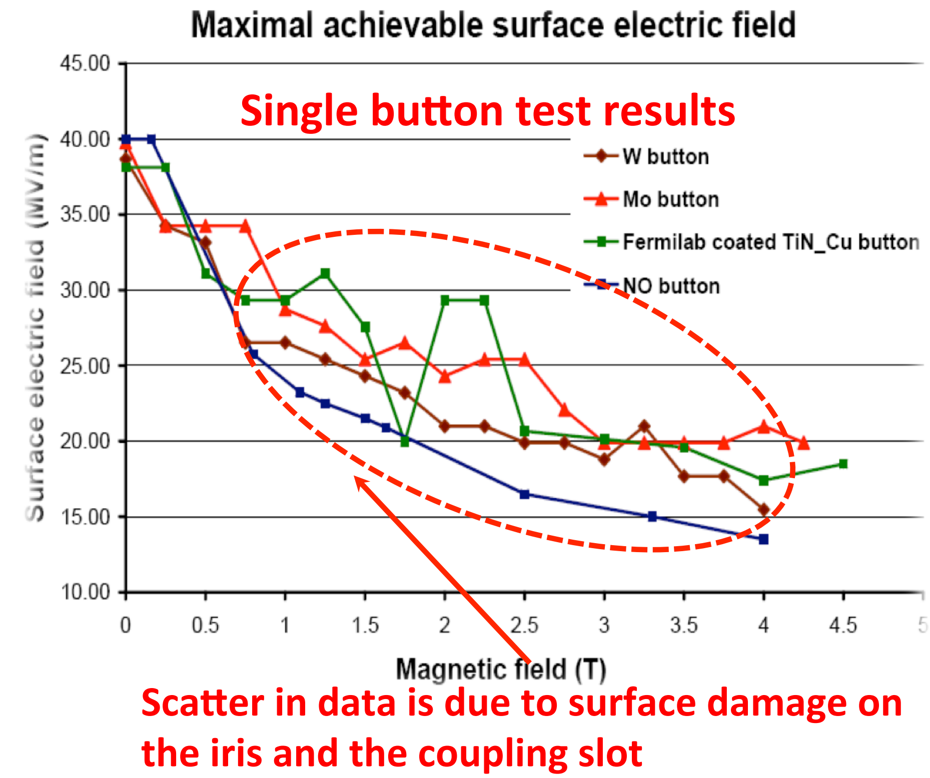


International Muon Ionization Cooling Experiment

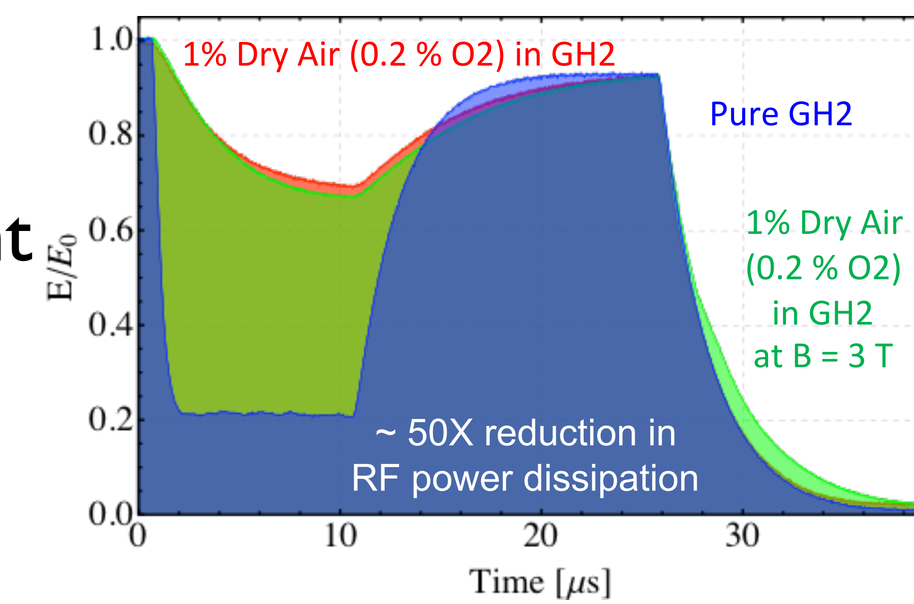


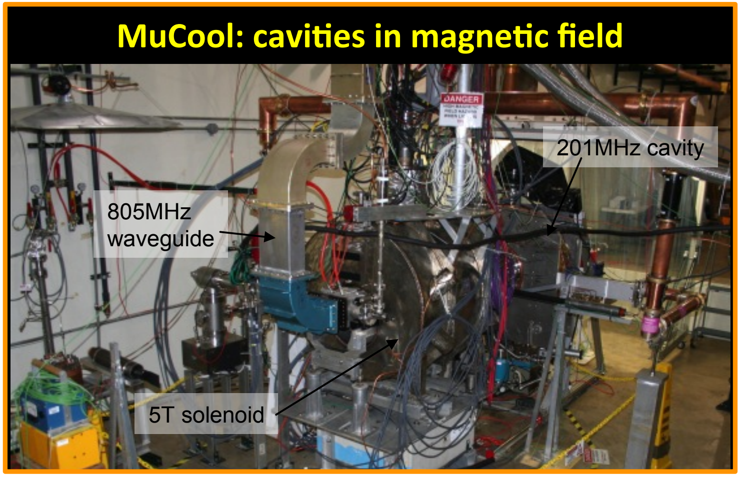


MuCool R&D

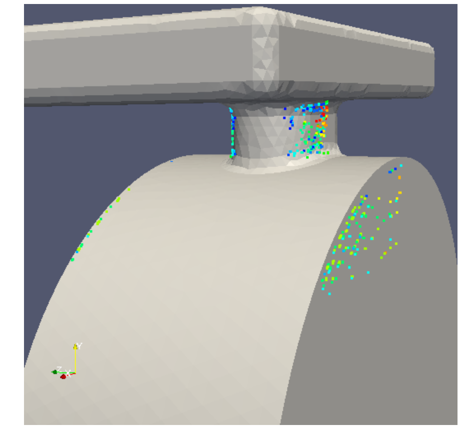


- Efficient ionization cooling requires RF cavity operation in multi-tesla magnetic field
  - technologies under test at MTA:
    - vacuum RF cavities
      - exploring coupler and materials issues
    - high-pressure H_2-filled RF cavities
      - combine functions: breakdown suppressant *and* ionization-cooling energy absorber
  - encouraging recent progress

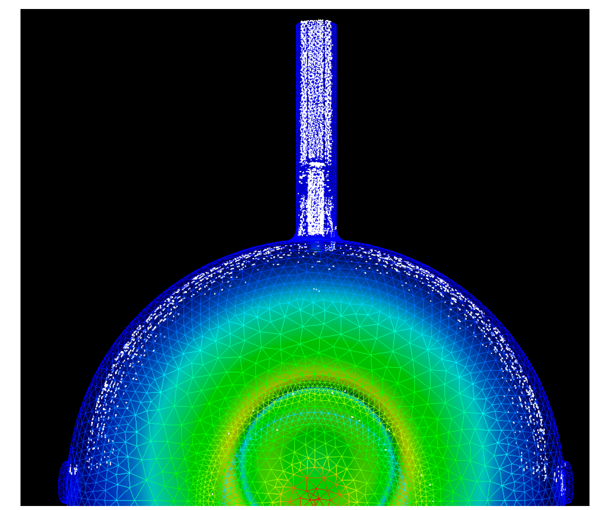


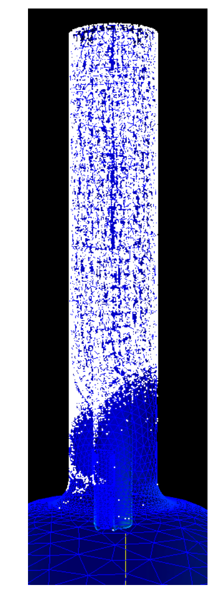


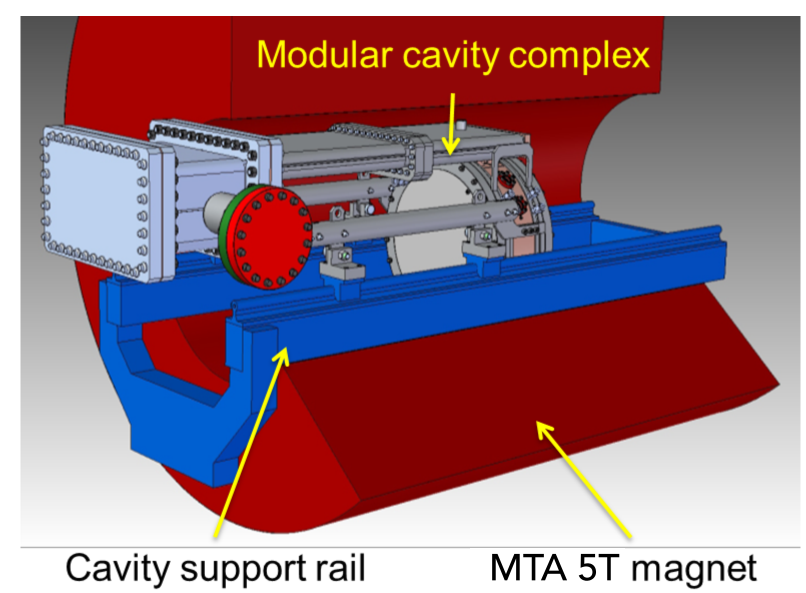
MuCool R&D

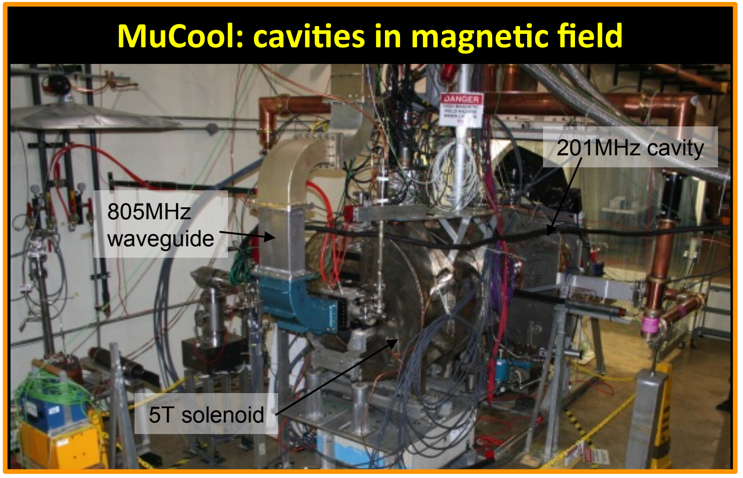


- Many efforts in progress:
  - vacuum RF cavities
    - evidence for coupler breakdown in previous 3 T high-gradient tests
      - SLAC ACE3P multipacting calculations leading to improved coupler designs
    - Be better than Cu at high gradient?
      - LBNL & SLAC collaborating on modular cavity with interchangeable endwalls, featuring improved coupler design
      - fabrication in progress



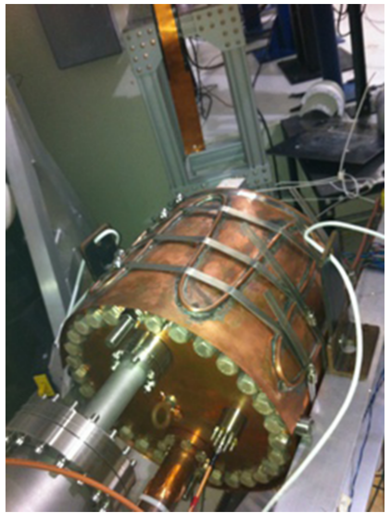


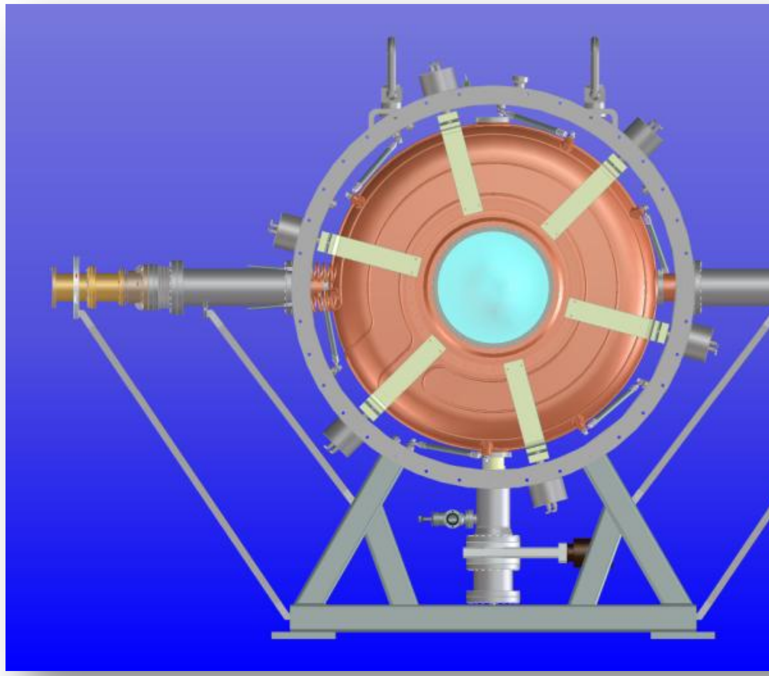




MuCool R&D

- Many efforts in progress:
  - vacuum RF cavities (cont'd)
    - "All Season" cavity
      - further tests planned at 5 T



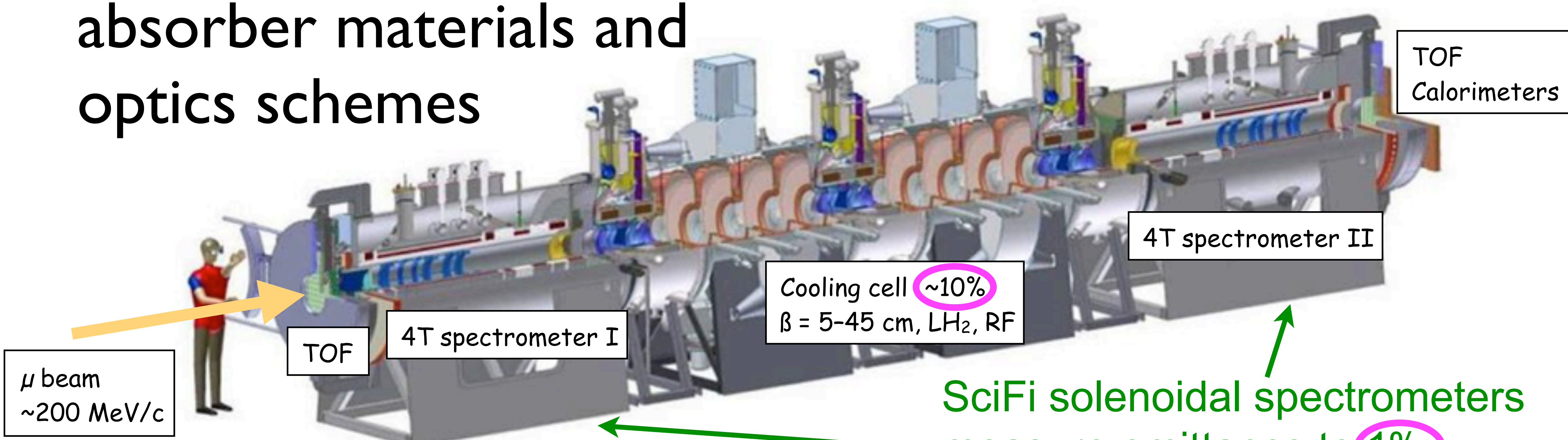


    - gearing up for further 201 MHz cavity tests
      - including improved coupler design
      - and full test of tuning mechanism in "single-cavity" cryostat
      - and large 3 T "Coupling Coil" magnet (under test)

MICE

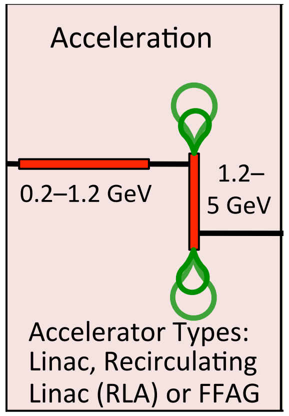
- International Muon Ionization Cooling Experiment at UK's Rutherford Appleton Laboratory (RAL)

- Flexibility to test several ionization-cooling absorber materials and optics schemes



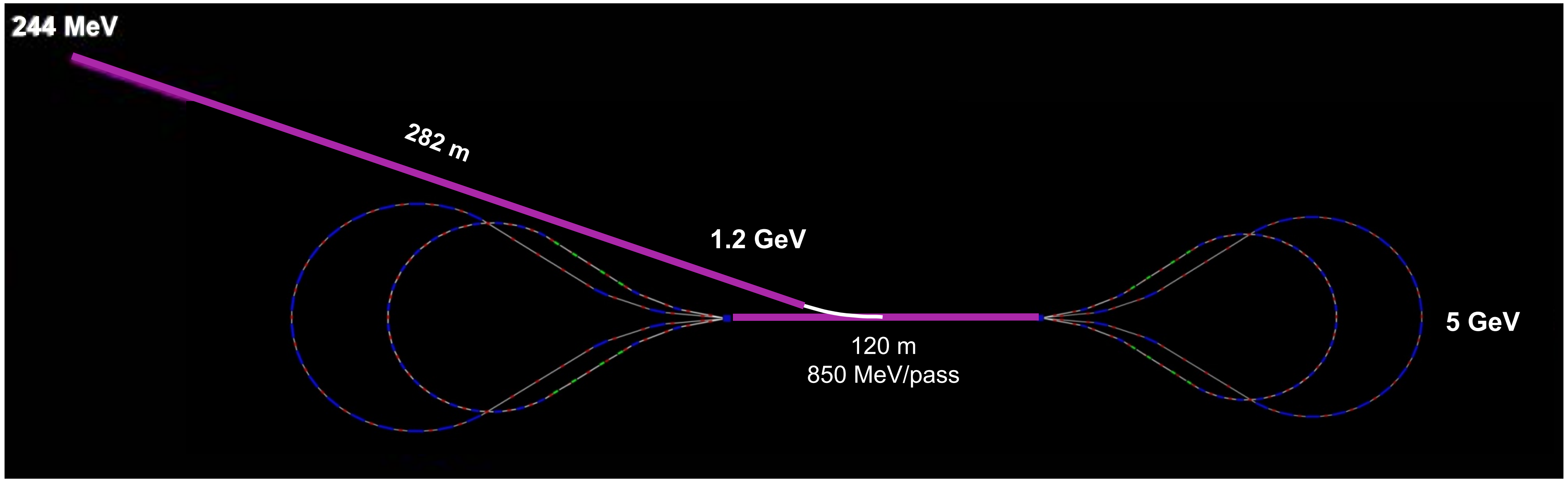
- Status: under construction, program complete by ~2020
  - with first results ~ 2015

see Adey, Kaplan WG3 talks

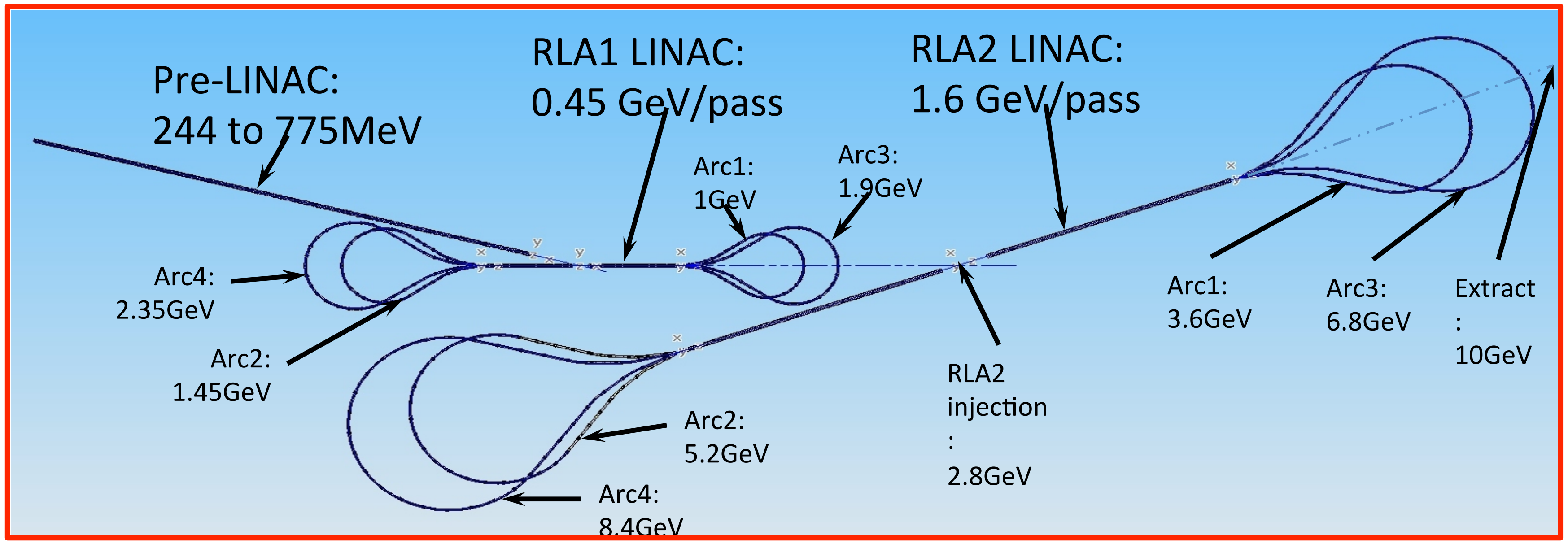


5. μ Acceleration

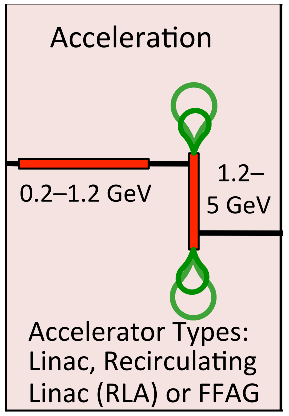
- MAP: linac plus "dogbone" RLA to 5 GeV



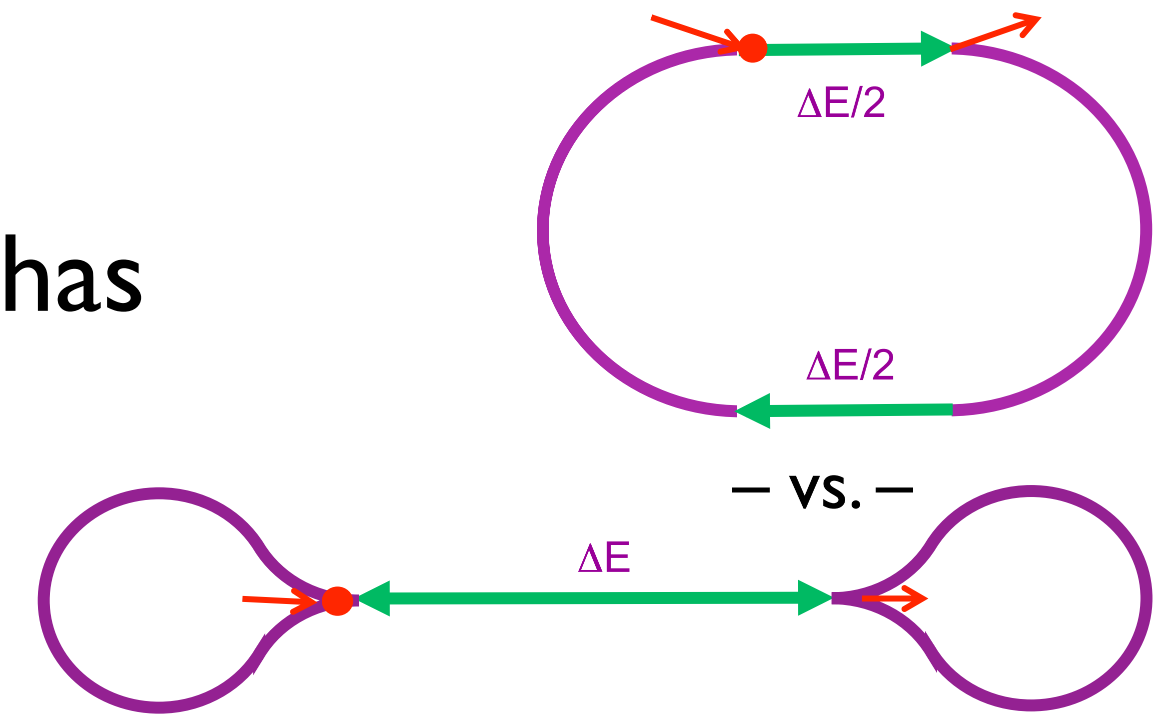
- IDS-NF: 2 RLAs to 10 GeV



see Bogacz WG3 talk

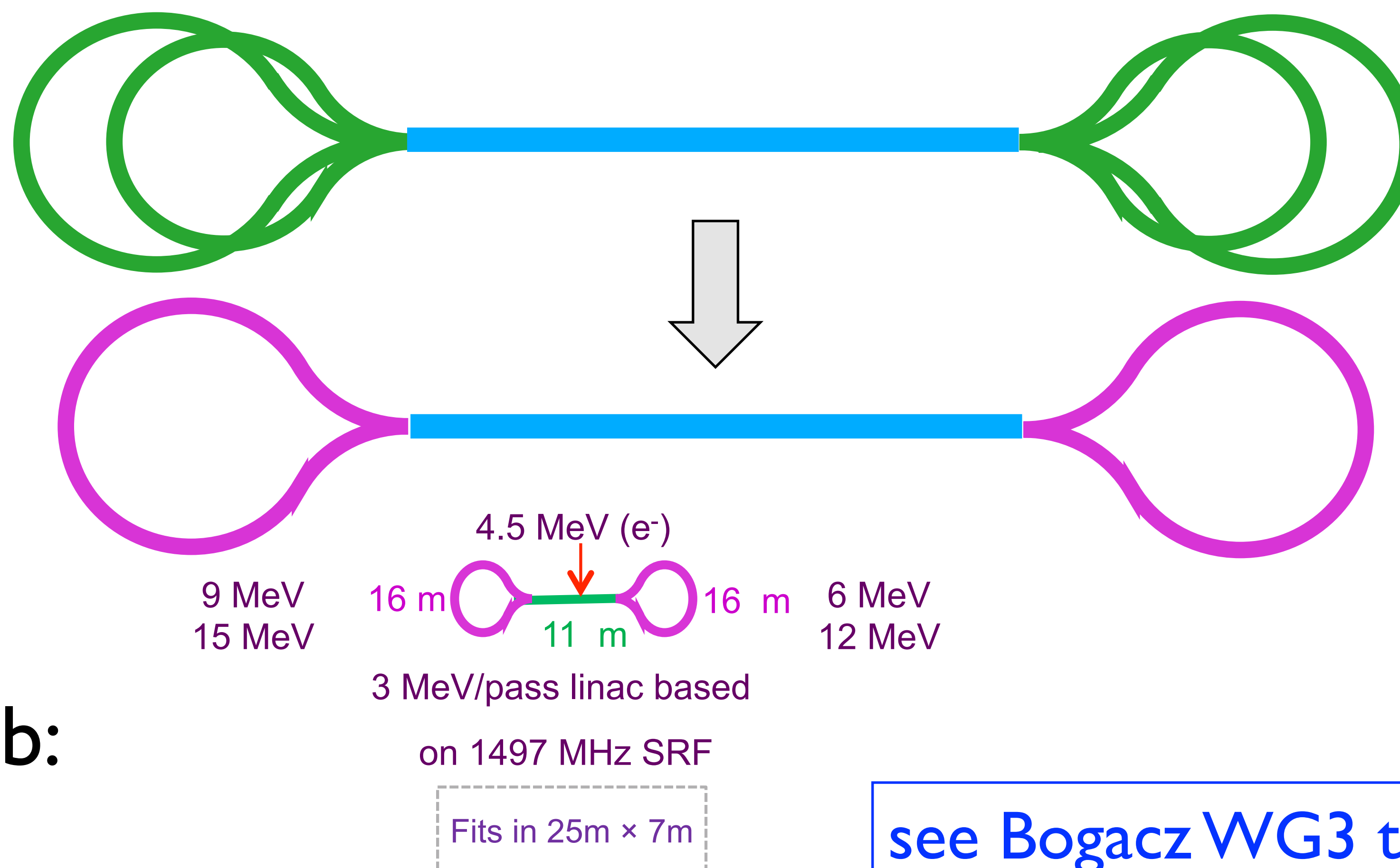


5. μ Acceleration



- Note dogbone RLA geometry has twice the ΔE per pass, easing switchyard design

- Multi-pass arcs under development:
  - using FFAG-like arc optics
    - proposed JEMMRLA electron demo @ JLab:



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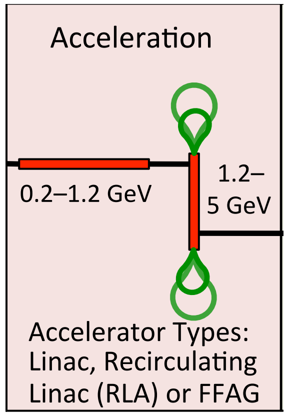
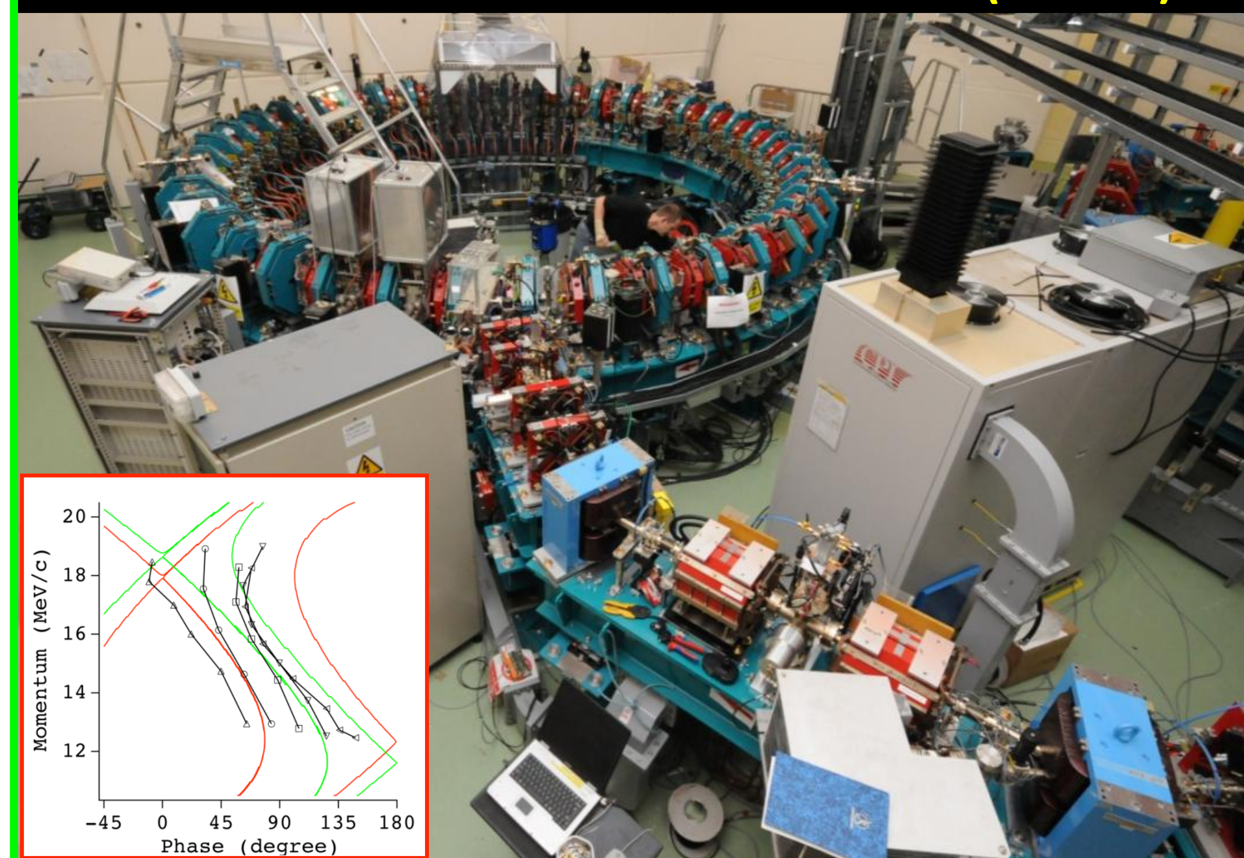
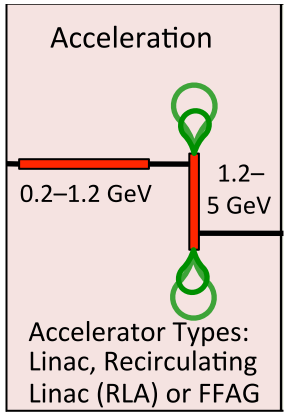


5. μ Acceleration

- Alternate to RLA: FFAG
  - EMMA demo @ Daresbury Lab
- Not the IDS-NF baseline
  - all-RLA design technically simpler
  - but FFAG could be valuable for muon collider

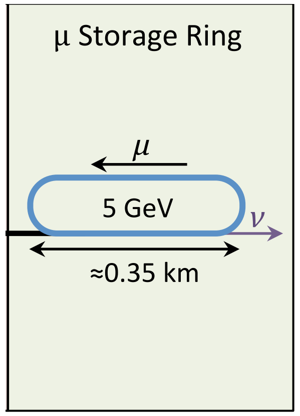
Electron Model of Muon Acceleration (EMMA)





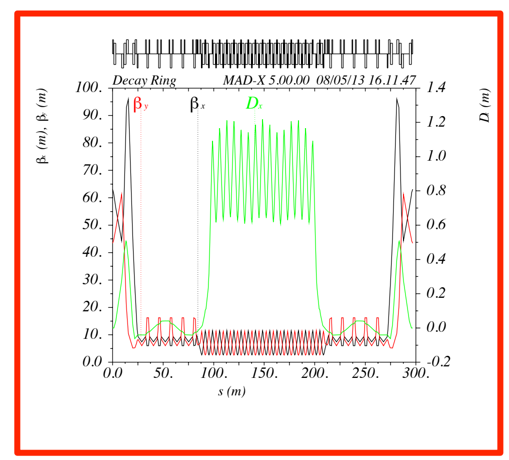
5. μ Acceleration

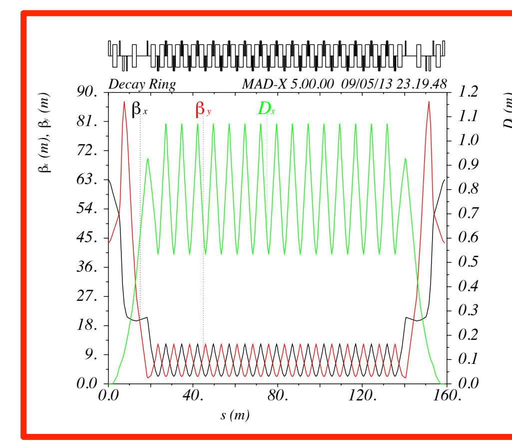
- Designs assume use of low-frequency superconducting RF, due to large beam
  - 201 MHz sputtered-Nb on Cu cavity built and tested at Cornell
  - high-gradient performance marginal
- Now moving to 325 MHz
  - allows use of explosion-bonded Nb on Cu
    - or possibly electroformed Cu on Nb
  - prototype under construction



6. Decay Ring

- 10 GeV lattice designed for IDS-NF
- Can be scaled for E_μ = 5 GeV

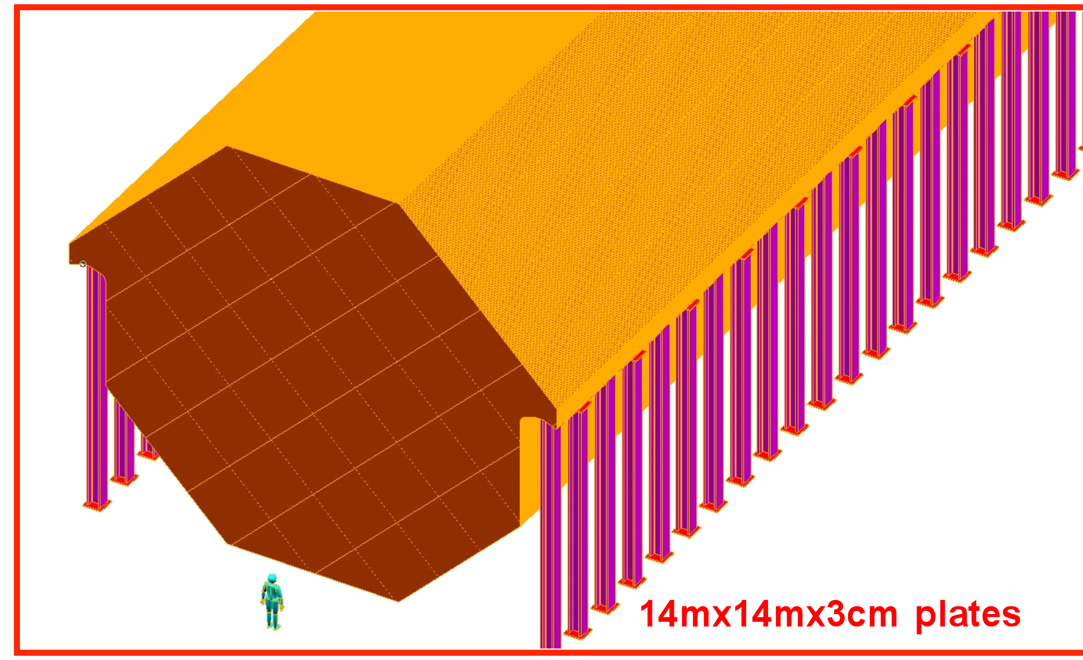




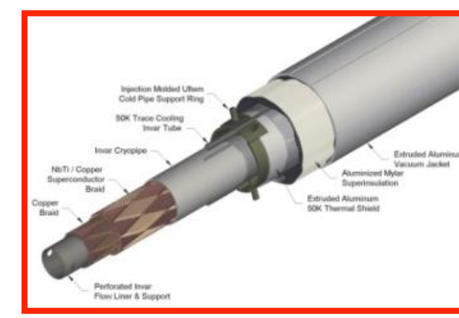
7. Detectors

- Oscillated vs. non-oscillated events differ in lepton sign

  ⟹ detector must be magnetized



- Baseline is Magnetized-Iron Neutrino Detector (MIND) à la MINOS
  - "SuperBIND" proposed for nuSTORM



    - using superconducting transmission line for high I → high B
- Or magnetized LAr (R&D needed)
- Or Totally Active Scintillator Detector (TASD)

Conclusions

- Neutrino Factory design has become a mature field
- MuCool and MICE will reduce risk
- BUT – despite some open technical questions,

➡ one could build a Neutrino Factory *now*

  - with, in a staged scenario, cooling & multi-MW target as future upgrades

- In practice, need to wait for Project X ⇒ 2020s