Exploring Physics Beyond the Standard Model with a Muon Accelerator Facility

Don Hartill

representing the U. S. Muon Accelerator Program

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http://map.fnal.gov





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Outline

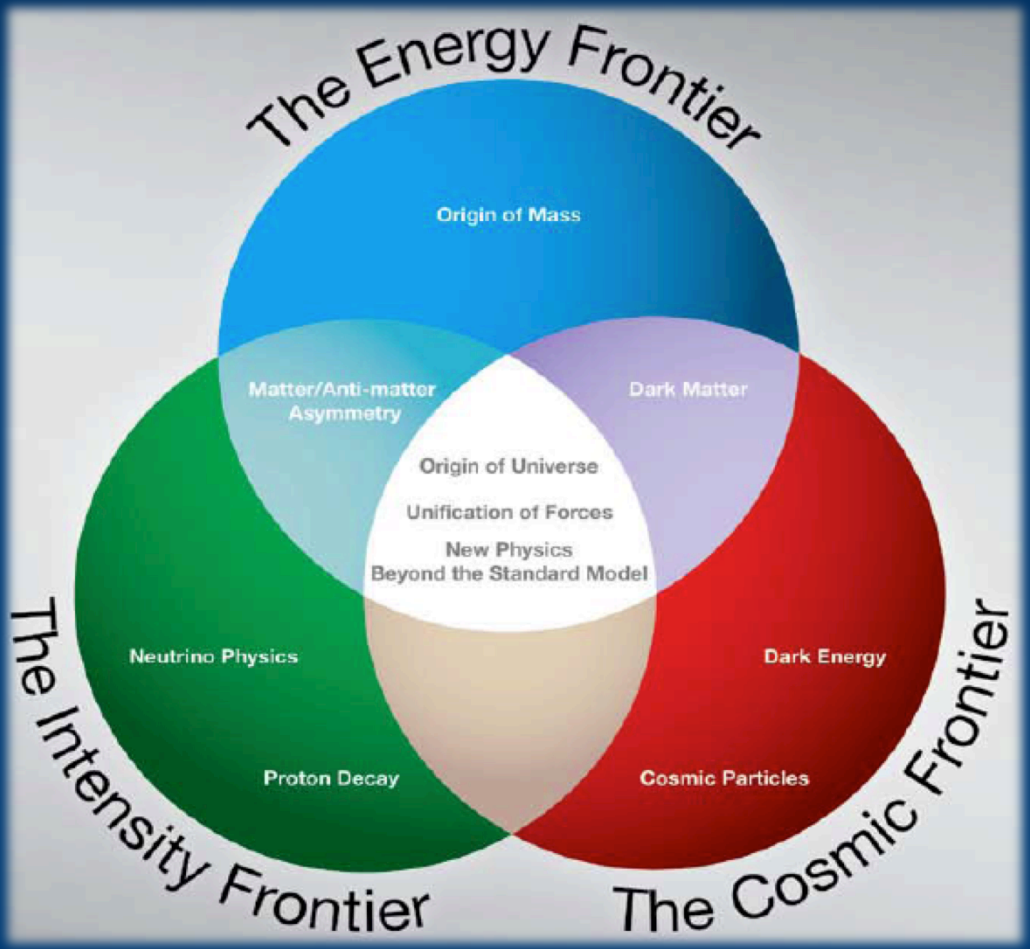
- Motivation
- Introduction to the Muon Accelerator Program (MAP)
- The R&D Challenges
- Recent R&D Progress
- Plans & Conclusion

Why a Muon Accelerator Program?

Muon accelerator R&D is focused on developing facilities for two frontiers:

The Intensity Frontier:
with a neutrino factory producing well-characterized ν beams for precise, high sensitivity studies

The Energy Frontier:
with a muon collider capable of reaching the multi-TeV center-of-mass energies



The U.S. Muon Accelerator Program

- MAP
  - Interim MAP formed October 2009, MAP proposal March 2010.
  - A merger of the efforts of 2 groups: the *NFMCC* and *MCTF*
  - MAP formally approved in March 2011 with the mission:

…to develop and demonstrate the concepts and critical technologies required to produce, capture, condition, accelerate, and store intense beams of muons for Muon Colliders and Neutrino Factories.

The goal of MAP is to deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility.

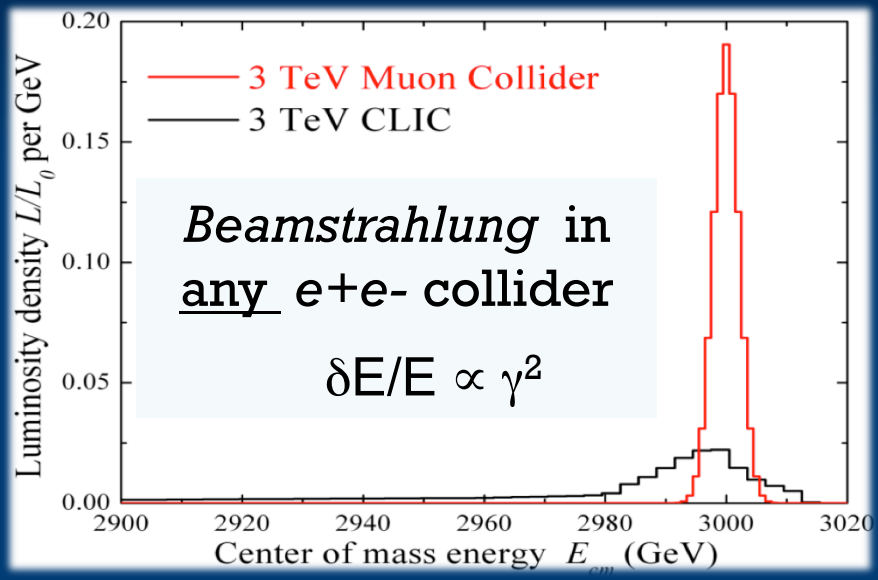
Coordination with the parallel Muon Collider Physics and Detector Study and with the International Design Study of a Neutrino Factory will ensure MAP responsiveness to physics requirements.

U.S. Muon Accelerator Program Effort

- Labs: ANL, BNL, FNAL, JLAB, LBNL, ORNL, SLAC
- Universities: Chicago, Cornell, IIT, Princeton, UC-Berkeley, UCLA, UC-Riverside, UMiss
- Companies: Muons, Inc; Particle Beam Lasers

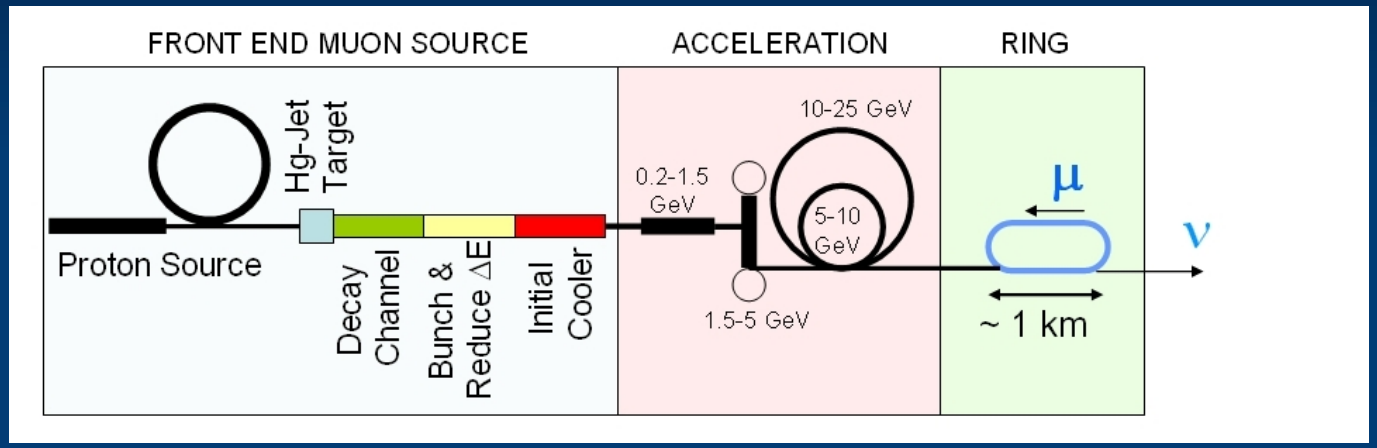
Muon Accelerator Physics

- Large muon mass strongly suppresses synchrotron radiation & beamstrahlung
  - ⇨ Muons can be accelerated and stored using rings at much higher energy than electrons
  - ⇨ Colliding beams can be of higher quality with reduced beamstrahlung

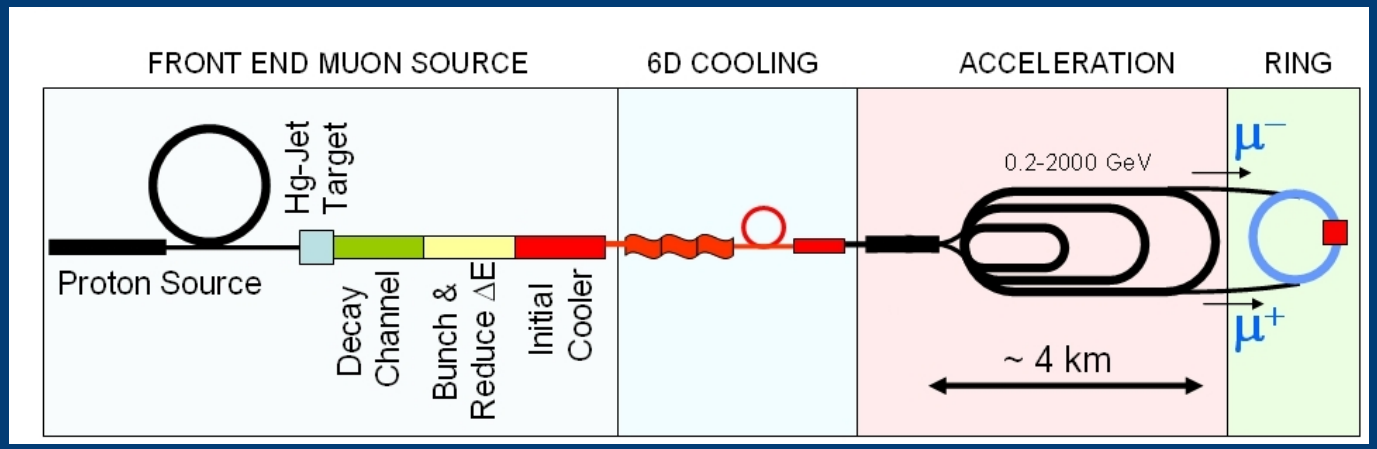


- … but muon lifetime is short:
  - Acceleration and storage time of a muon beam is limited
  - Collider – a new class of decay backgrounds must be dealt with
- … and muons produced in tertiary beams: $p \rightarrow \pi \rightarrow \mu$
  - Offers key accelerator challenges…

Muon Collider - Neutrino Factory Comparison



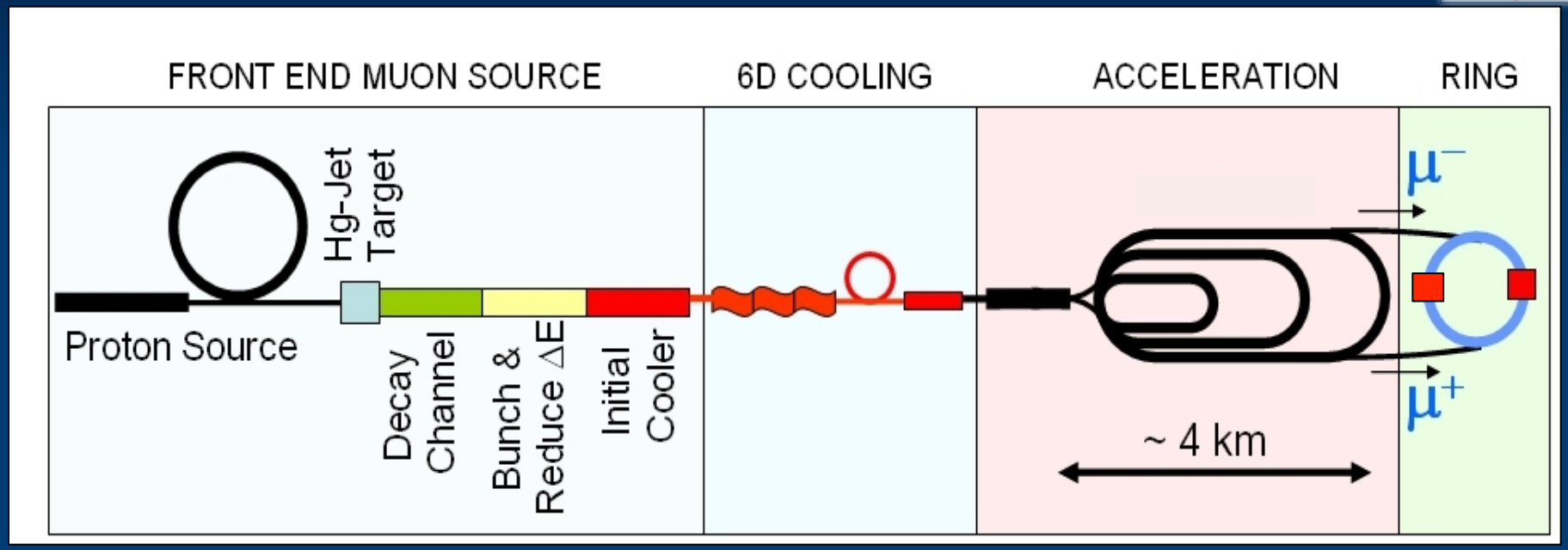
NEUTRINO FACTORY



MUON COLLIDER

In present MC baseline design, Front End is same as for NF

Muon Collider Concept



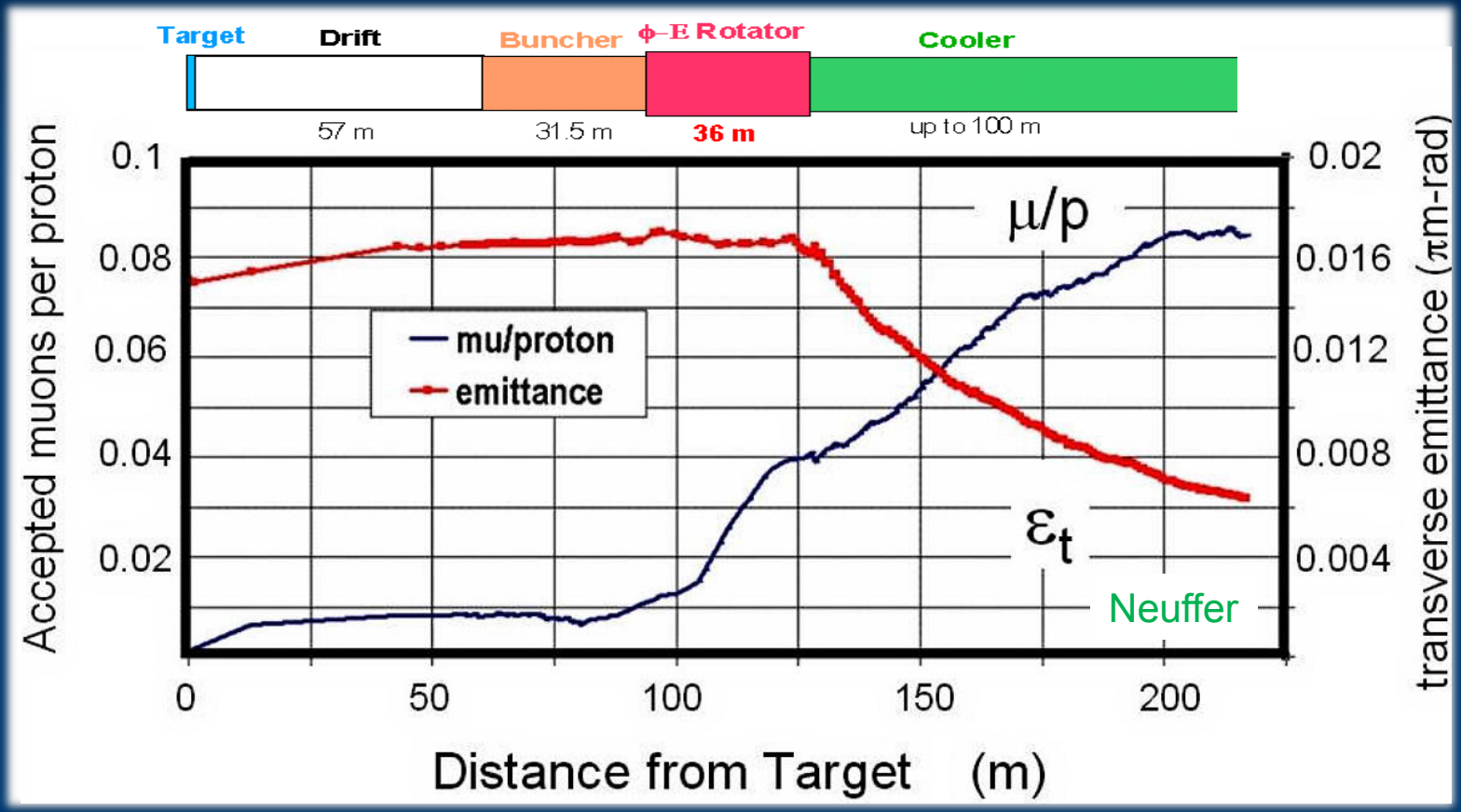
Proton source:
For example
PROJECT X at
4 MW, with 2±1 ns
long bunches

10^{21} muons per year within the acceptance of an accelerator:

$\varepsilon_{\perp N}$=6000 μm
$\varepsilon_{//N}$=25 mm

Collider: $\sqrt{s}$ = 3 TeV
Circumference = 4.5km
$L = 3\times10^{34}$ cm^{-2}s^{-1}
μ/bunch = 2×10^{12}
σ(p)/p = 0.1%
$\varepsilon_{\perp N}$ = 25 μm, $\varepsilon_{//N}$=70 mm
β* = 5mm
Rep Rate = 12Hz

Technical Challenges – Tertiary Production

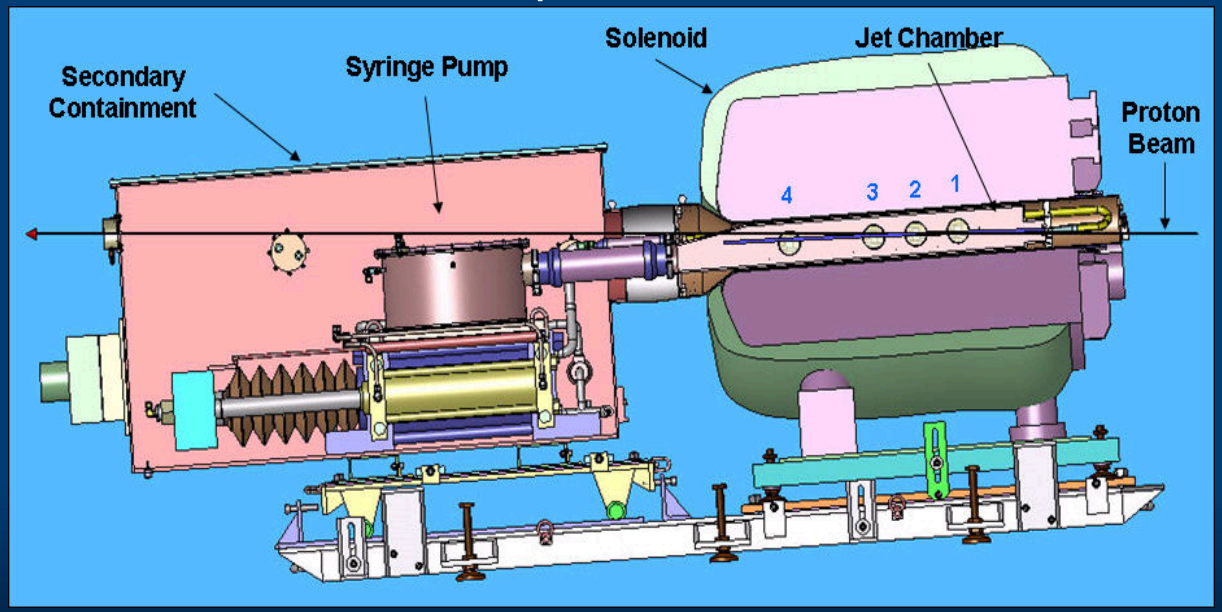


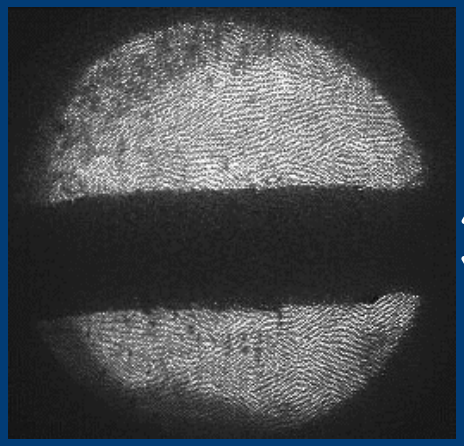
- A multi-MW proton source, *e.g.*, Project X, will enable O(10^{21}) muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

Technical Challenges - Target

- The MERIT Experiment at the CERN PS
  - Proof-of-principle demonstration of a liquid Hg jet target in high-field solenoid in Fall `07
  - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/ pulse beam!

  ⇨ Technology OK for beam powers up to 8 MW with a repetition rate of 70 Hz!



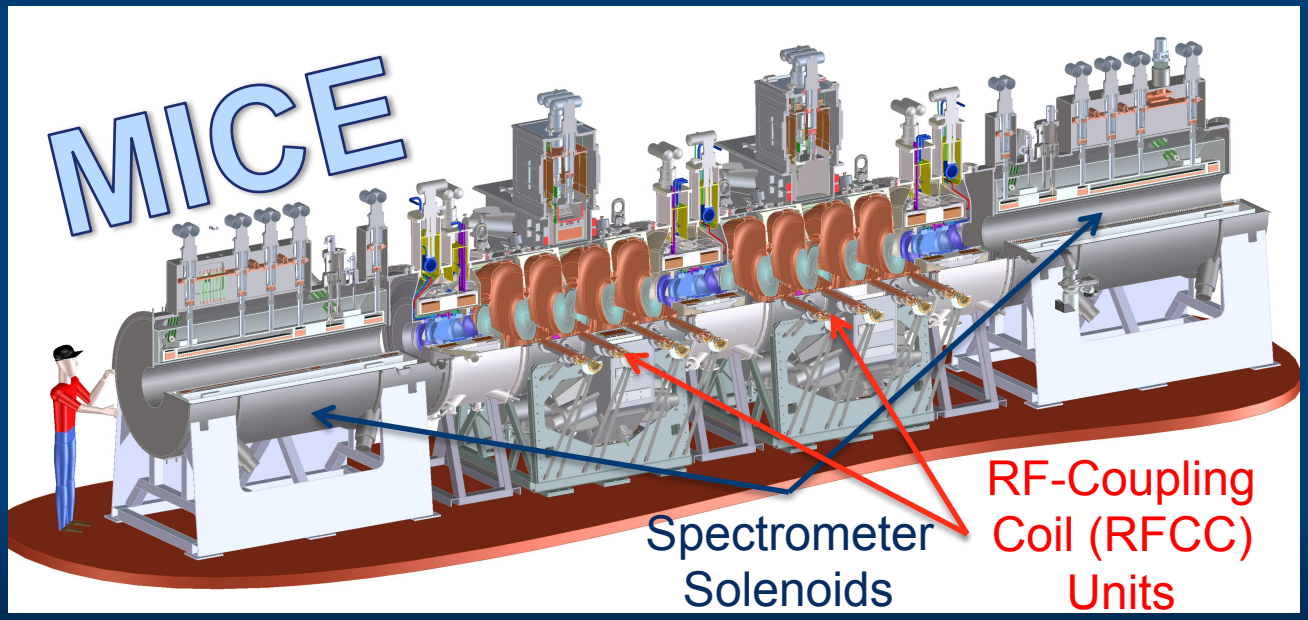


Hg jet in a 15 T solenoid with measured disruption length ~ 28 cm

Technical Challenges - Cooling

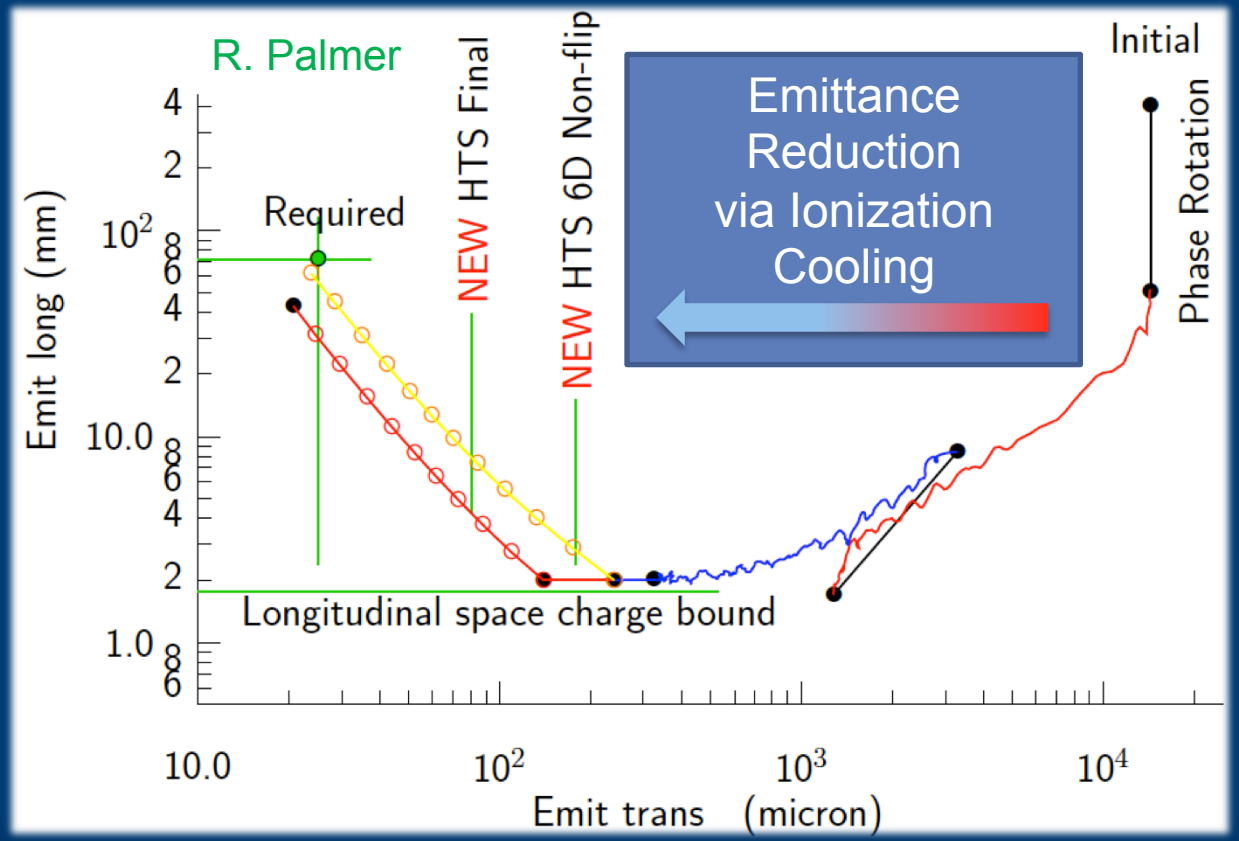
- Tertiary production of muon beams ⇨
  - Initial beam emittance intrinsically large
  - Cooling mechanism required, but no radiation damping
- Muon Cooling ⇨ Ionization Cooling
  - dE/dx energy loss in materials
  - RF to replace p_{long}

The Muon Ionization Cooling Experiment: Demonstrate the method and validate our simulations



Technical Challenges - Cooling

- Development of a cooling channel design to reduce the 6D phase space by a factor of $O(10^6)$ $\rightarrow$ MC luminosity of $O(10^{34})$ cm^{-2} s^{-1}



- Some components beyond state-of-art:
  - Very high field HTS solenoids (30-40 T)
  - High gradient RF cavities operating in multi-Tesla fields

The program targets critical magnet and cooling cell technical demonstrations within its feasibility phase.

Technical Challenges – RF

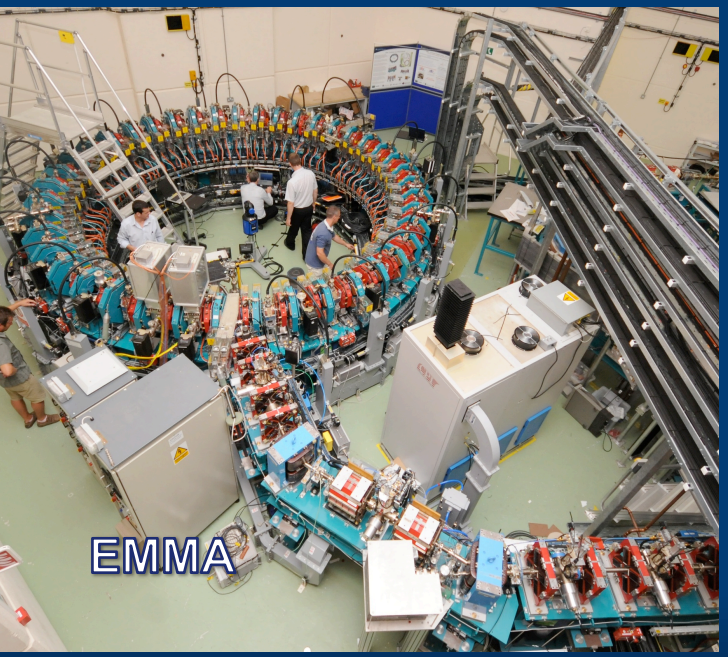
- A Viable Cooling Channel requires
  - Strong focusing and a large accelerating gradient to compensate for the energy loss in absorbers
  - ⇨ Large B- and E-fields superimposed
- Operation of RF cavities in high magnetic fields is a necessary element for muon cooling

  - Control RF breakdown in the presence of high magnetic fields
  - The MuCool Test Area (MTA) at Fermilab is actively investigating operation of RF cavities in the relevant regimes
  - Development of concepts to mitigate the challenges are being actively pursued

Technical Challenges - Acceleration

- Muons require an ultrafast accelerator chain
  ⇨ *Beyond the capability of most machines*

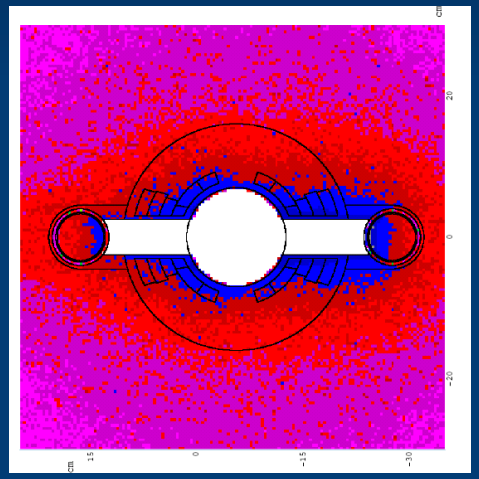
- Several solutions for a muon acceleration scheme have been proposed:



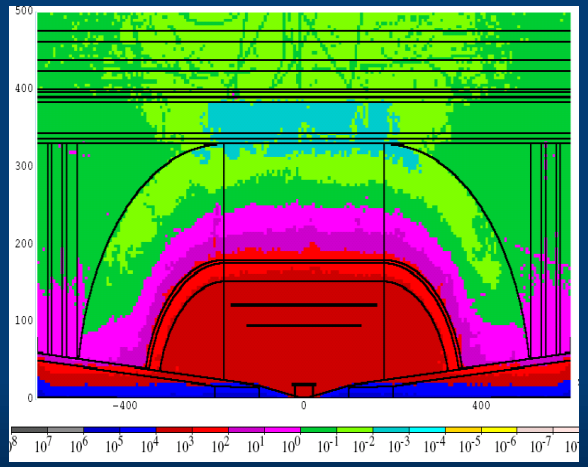
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient (FFAG) Machines
    - EMMA at Daresbury Lab is a test of the promising non-scaling type
  - Rapid Cycling Synchrotrons (RCS/VRCS)
  - Hybrid Machines

Technical Challenges – Ring, Magnets, Detector

- Emittances are relatively large, but muons circulate for ~1000 turns before decaying
  - Lattice studies for 1.5 TeV and 3 TeV CoM
- High field dipoles and quadrupoles must operate in high-rate muon decay backgrounds
  - Magnet designs under study
- Detector shielding & performance
  - Initial studies for 1.5 TeV, then 3 TeV
  - Shielding configuration
  - MARS background simulations



MARS energy deposition map for 1.5 TeV collider dipole



Recent Progress: MICE Magnets

Spectrometer Solenoids

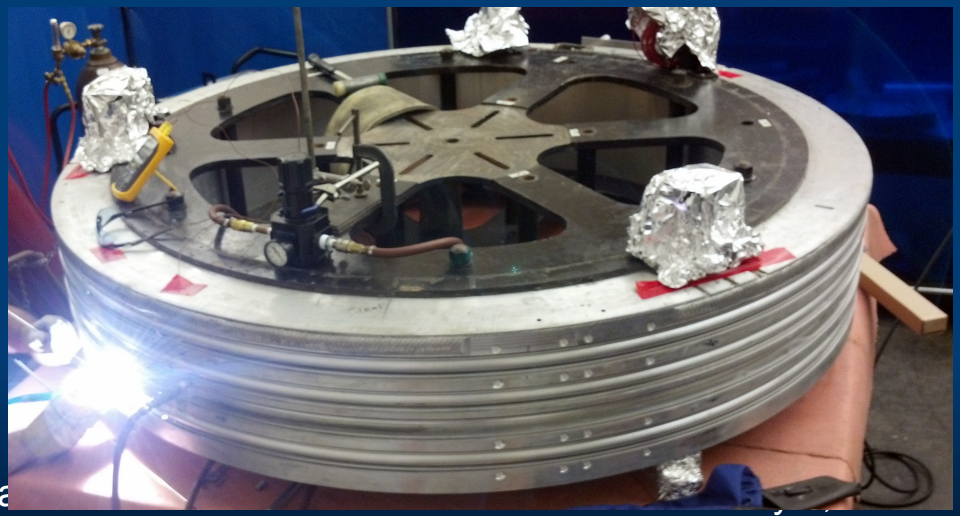
- 1st SS
  - Magnet training in progress
- 2nd SS
  - Cold mass and shield being assembled into vacuum vessel

⇨ Support MICE Step IV (2013-)

Coupling Coils

- First Coupling Coil cold mass being prepared (at LBNL) for training in new Solenoid Test Facility (at FNAL)

⇨ Support MICE Step V/VI (2016-)

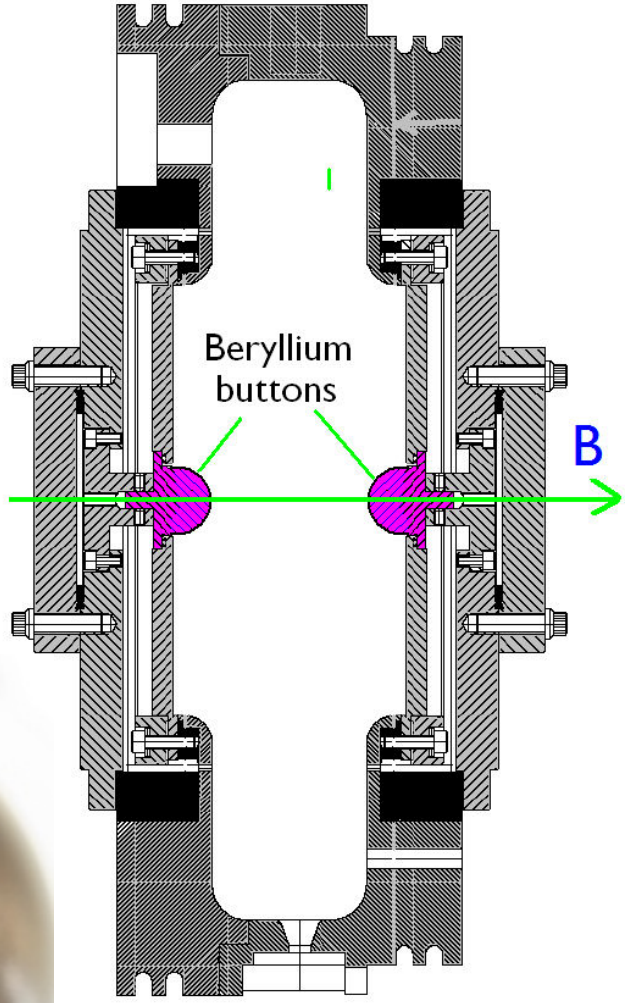


Recent Progress: Cavity Materials

Breakdown tests with Be and Cu Buttons

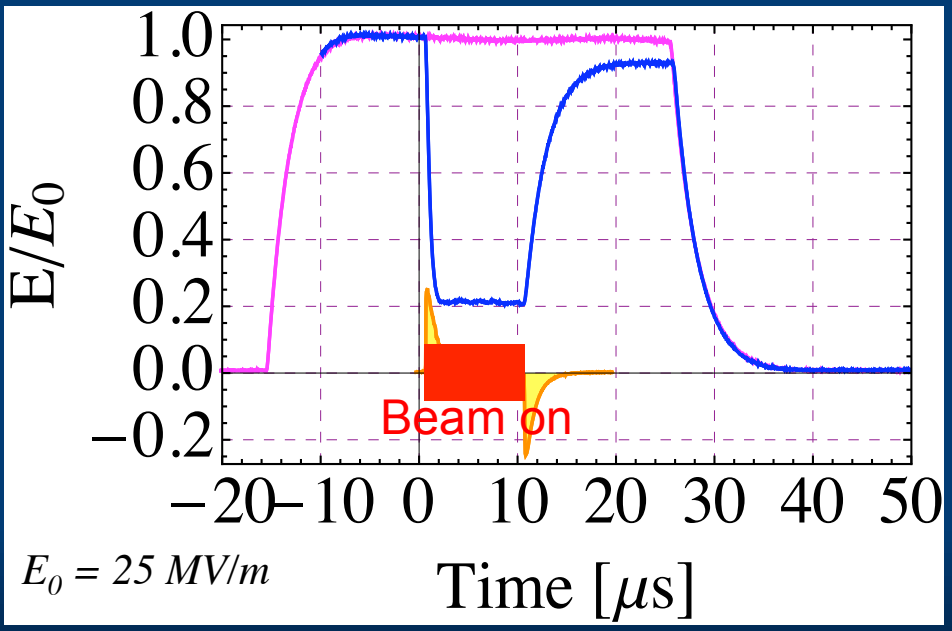
- Both reached ~31 MV/m at 3T
- Cu button shows significant pitting
- Be button shows minimal damage

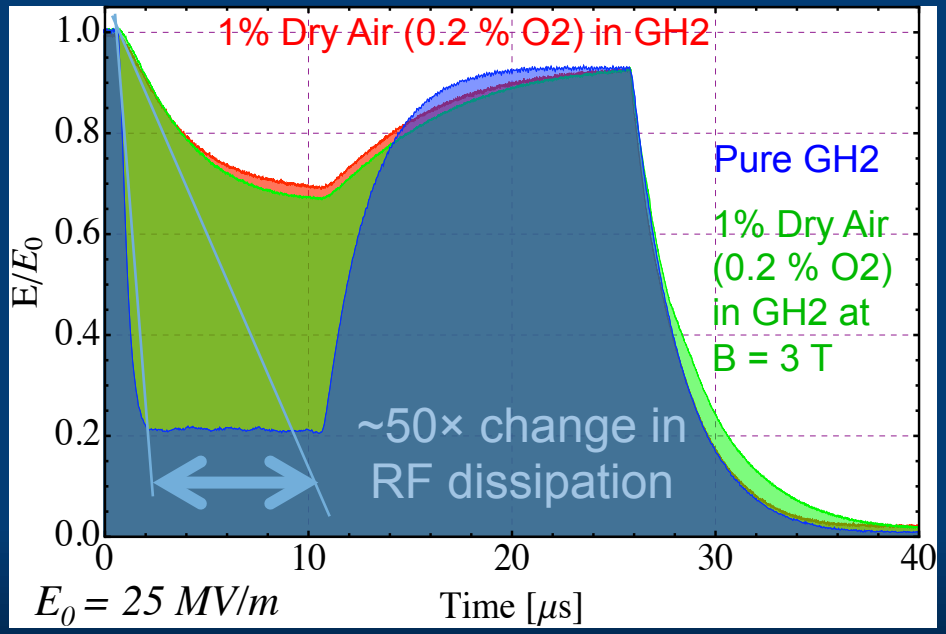
⇨ Materials choices offer the possibility of more robust operation in magnetic fields



Recent Progress: High Pressure RF

- Gas-filled cavity
  - Can moderate dark current and breakdown currents in magnetic fields
  - Can contribute to cooling
  - Is loaded, however, by beam-induced plasma
- Electronegative Species
  - Dope primary gas
  - Can moderate the loading effects of beam-induced plasma by scavenging the relatively mobile electrons





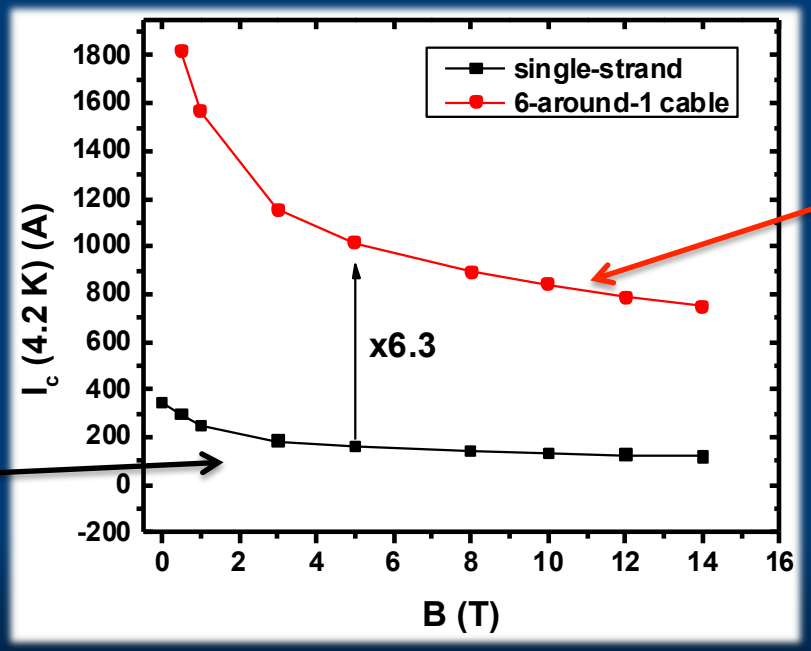
Recent Progress: High Field Magnets

BSCCO-2212 Cable -

Transport measurements show that FNAL cable attains 105% J_c of that of the single-strand

Progress towards a demonstration of a final stage cooling solenoid:

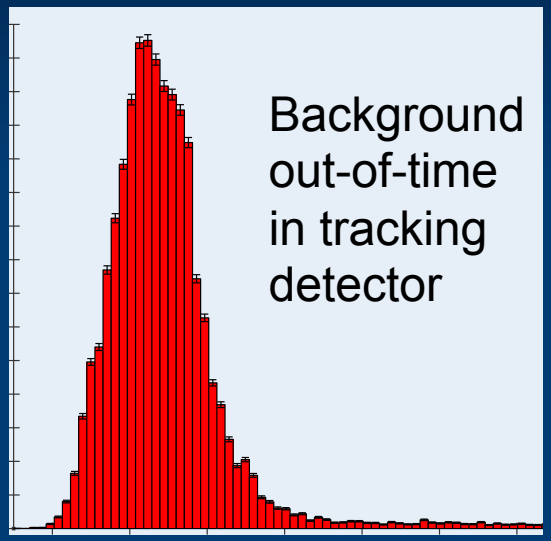
- Demonstrated highest field achieved in a solely High Temperature Superconducting Coil: 15+ T (with 16+ T on coil) – BNL/PBL effort
- Will soon begin preparations for a test with HTS insert + mid-sert in NC solenoid at NHFML ⇨ >30 T



Multi-strand cable utilizing chemically compatible alloy and oxide layer to minimize cracks

Recent Progress: Detector Studies

- Tracking
  - Background & signal have different time & energy characteristics
- Calorimetry
  - Two promising approaches:
    - Dual readout calorimeter with fast timing
    - Pixelated calorimeter with "travelling trigger" (R. Raja) :

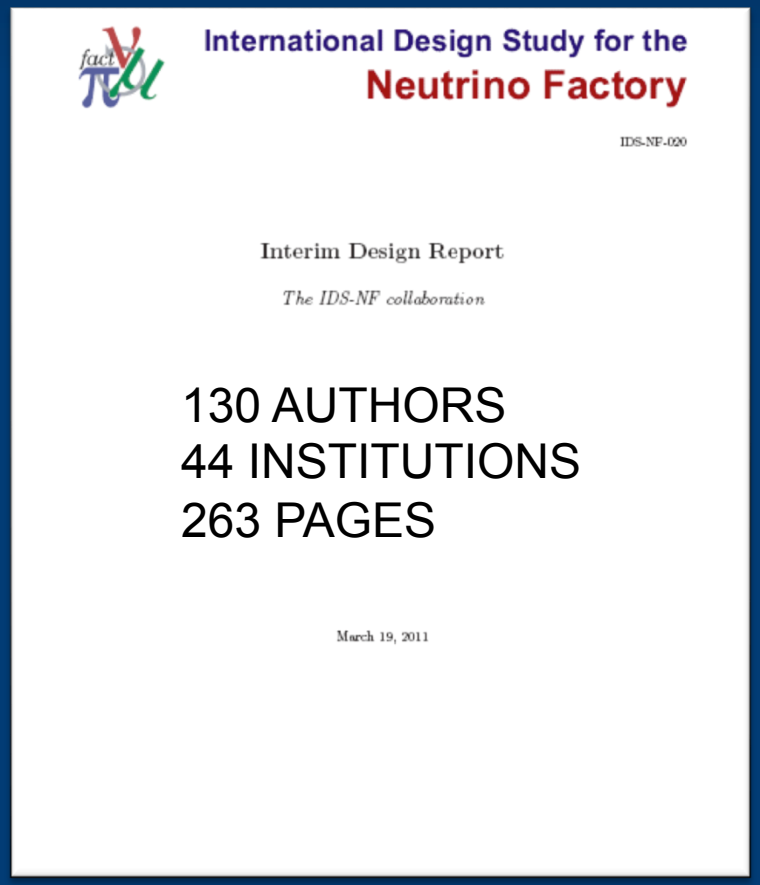


Time of energy deposit with respect to TOF from IP

Table 4. Backgrounds as a function of time cuts and the reduction factors associated with each cut.

Backgrounds before and after time cuts						
Particle Type	Total before cuts	δ t < 2 ns	fraction	Energy after δ t cut GeV	Energy In time GeV	Overall Reduction fraction
EM	1.79E+08	2.17E+06	1.21E-02	962	404.7	2.38E-03
MUONS	8.02E+03	1.83E+03	2.28E-01	1680.9	47.1	2.55E-04
MESONS	1.76E+04	2.66E+03	1.51E-01	270.1	50.7	7.49E-03
BARYONS	4.09E+07	3.93E+05	9.62E-03	8416.8	385.6	2.17E-03

Recent Progress: International Design Study for a Neutrino Factory


International Design Study for the
Neutrino Factory

IDS-NF-020

Interim Design Report

The IDS-NF collaboration

130 AUTHORS
44 INSTITUTIONS
263 PAGES

March 19, 2011

- Interim Design Report completed March 19, 2011. Reviewed by ECFA sub-panel May 5-6, 2011
- Working towards a updated document for “Snowmass 2013”

MAP Feasibility Assessment Phases

Feasibility Assessment: Phase I

FY13 – FY15:

- Identify ***baseline*** design concepts
- Identify high leverage ***alternative*** concepts
- Identify key engineering paths to pursue:
  - RF
  - High Field Magnets
- Develop critical engineering concepts (eg, 6D Cooling Cell)
- Support major systems tests
  - MICE Step IV
  - MICE RFCC construction & testing

Feasibility Assessment: Phase II

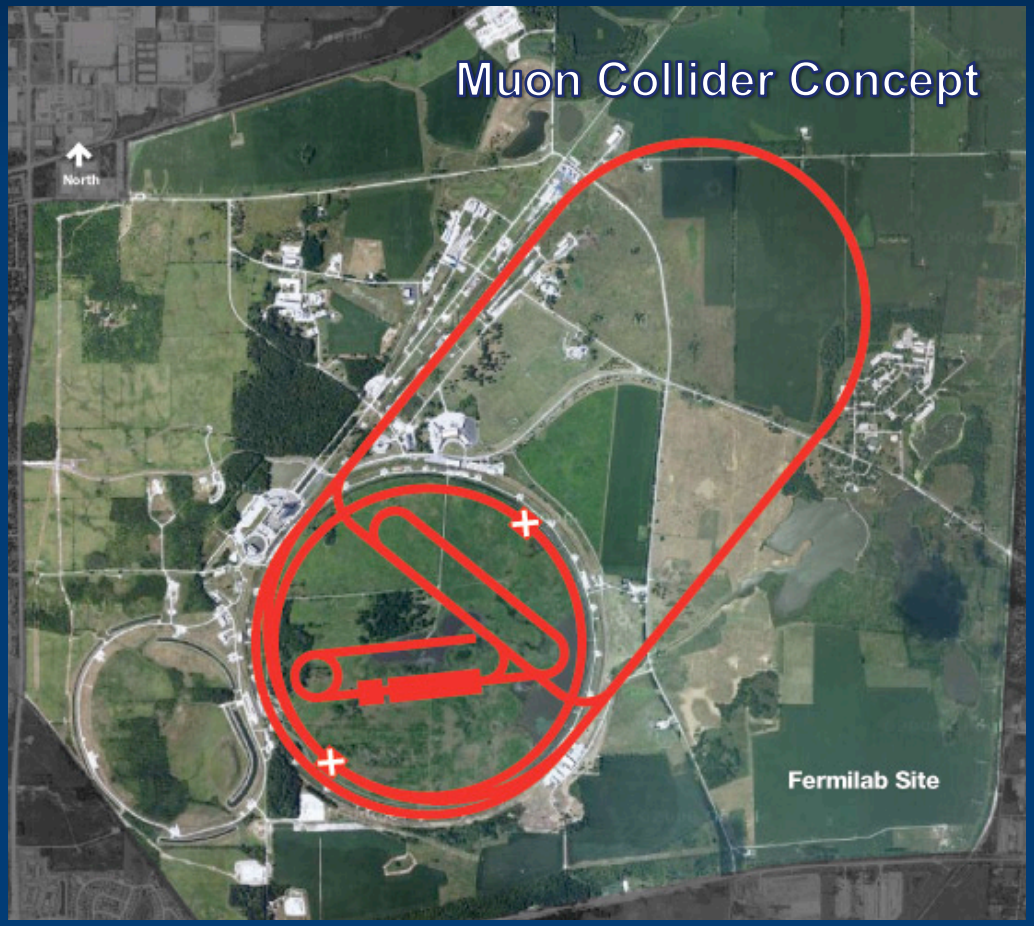
FY16 – FY18:

- Technical demonstration of critical ***baseline*** concepts
  - eg, 6D Cooling cell
- Pursue high leverage ***alternative*** concepts
- Assess technical and cost feasibility of ***baseline*** concepts
- Support major systems tests
  - MICE Step V/VI
  - 6DICE planning

Conclusion

- Over the next 6 years the primary goal of MAP is demonstrating the feasibility of key concepts needed for a muon collider & deliver U.S. contributions to the International Design Study for a Neutrino Factory

⇨ Thus enabling an informed decision on the path forward for the HEP community



A challenging, but promising, R&D program lies ahead!