Muon Colliders & Neutrino Factories

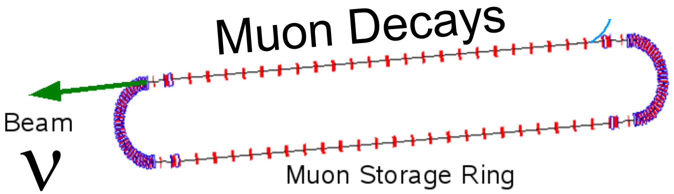
- Why Neutrino Factory & Muon Collider R&D ?
- What are the challenges?
- Design and R&D (emphasis on pieces using linac technology)
- Recent Developments & Future Plans

Introduction

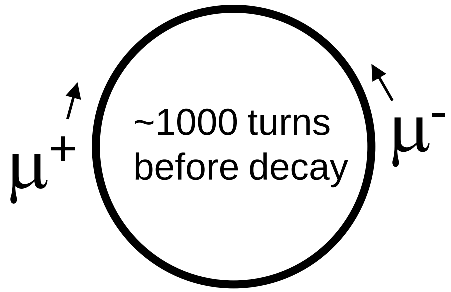
- Over the last decade there has been significant progress in developing the concepts & technologies required to create a muon source that would create $O(10^{21})$ muons per year and fit them within the acceptance of an accelerator.

- This enabling R&D opens the way for:

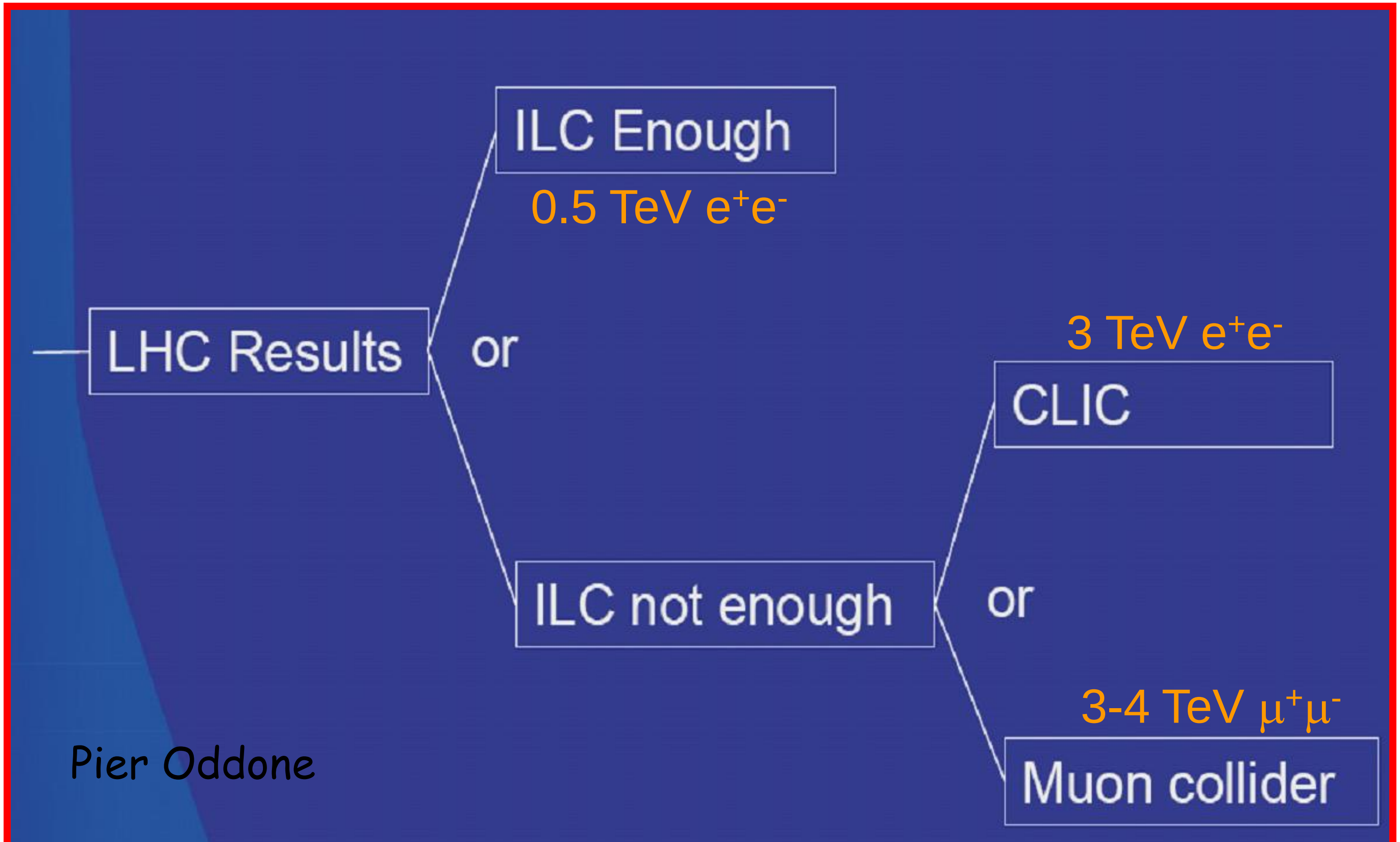
NEUTRINO FACTORIES in which muons decaying in the straight section of a storage ring create a neutrino beam with unique properties for precision neutrino oscillation measurements.



MUON COLLIDERS in which positive & negative muons collide in a storage ring to produce lepton-antilepton collisions up to multi-TeV energies.



Muon Collider Decision Tree



Muon Collider Motivation

- If we can build a muon collider, it is an attractive multi-TeV lepton collider option because muons don't radiate as readily as electrons (m_μ / m_e ~ 207):

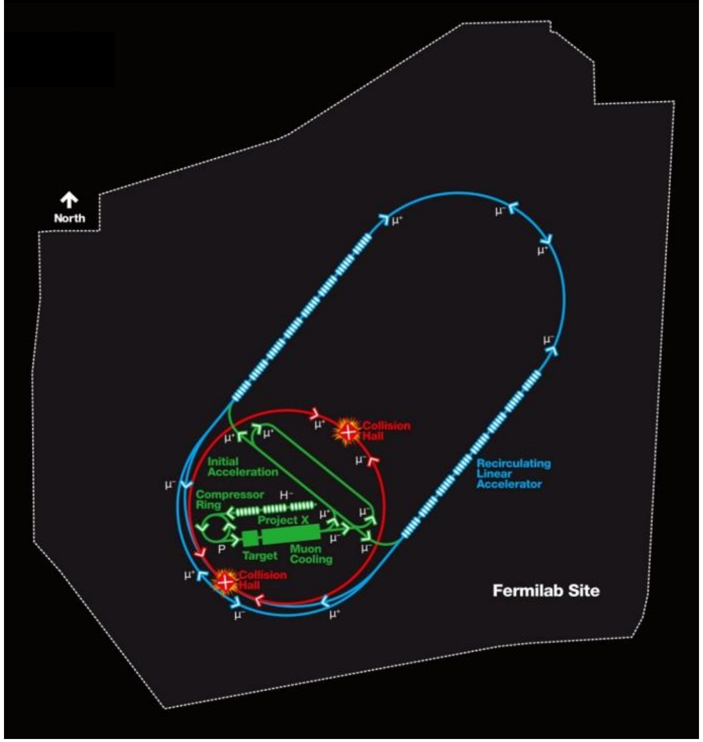
COST

- COMPACT
  Fits on laboratory site
- MULTI-PASS ACCELERATION
  Cost Effective operation & construction
- MULTIPASS COLLISIONS IN A RING (~1000 turns)
  Relaxed emittance requirements & hence relaxed tolerances

PHYSICS

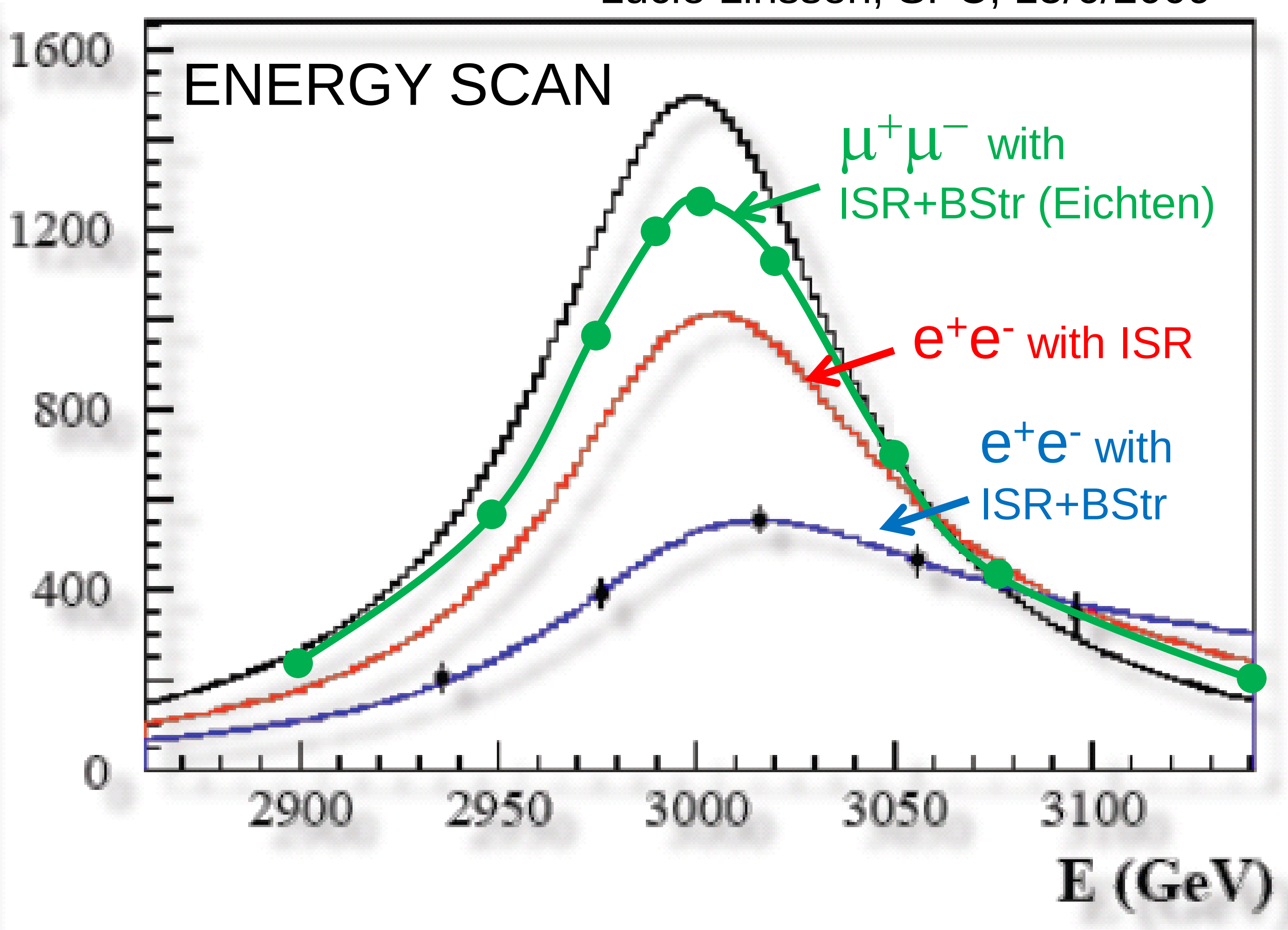
- NARROW ENERGY SPREAD
  Precision scans, kinematic constraints
- TWO DETECTORS (2 IPs)
- ΔT_{bunch} ~ 10 μs … (e.g. 4 TeV collider)
  Lots of time for readout
  Backgrounds don't pile up
- $(m_\mu/m_e)^2$ = ~40000
  Enhanced s-channel rates for Higgs-like particles

A 4 TeV Muon Collider would fit on the Fermilab Site



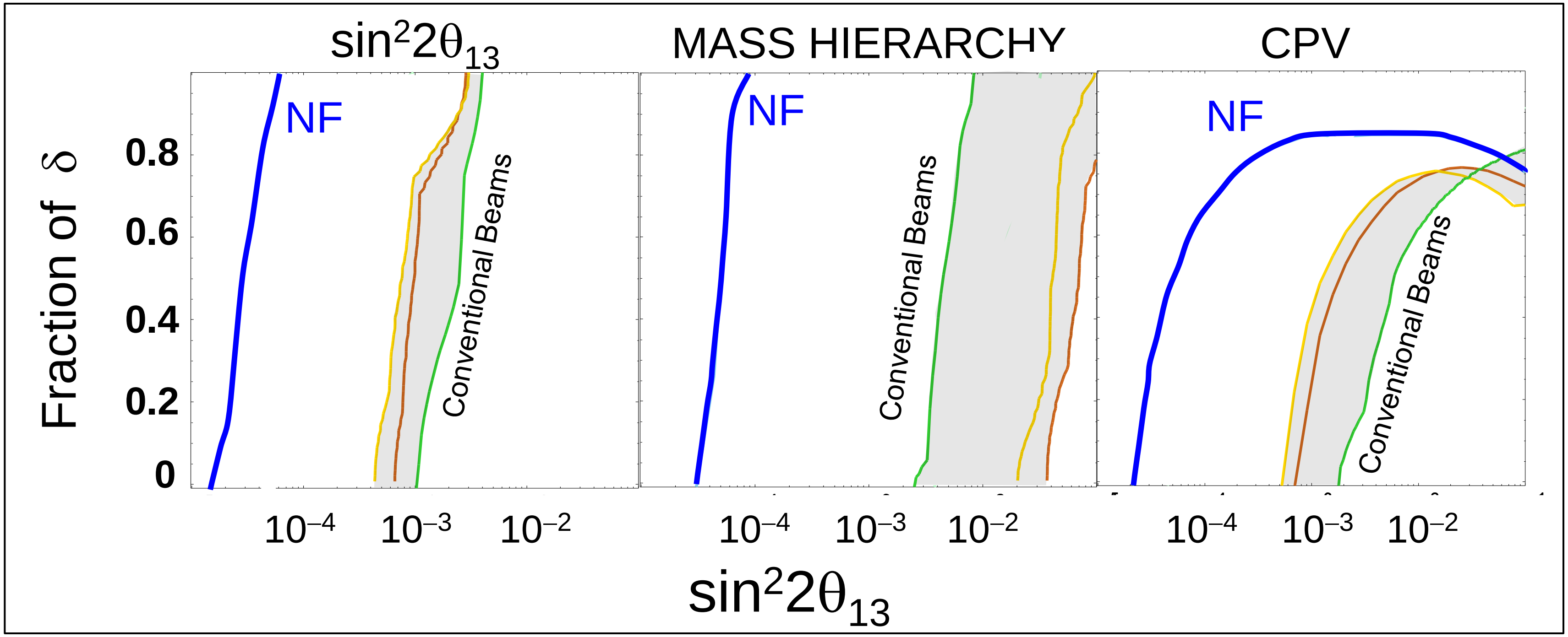
$l^+l^- \rightarrow Z' \rightarrow \mu^+\mu^-$

Lucie Linssen, SPC, 15/6/2009



Neutrino Factory Motivation

- Mono-energetic muon decays would produce a unique neutrino beam consisting of 50% $\nu_e(\bar{\nu}_e)$ & 50% $\bar{\nu}_\mu(\nu_\mu)$ … very well known fluxes & spectrum – hence low systematic uncertainties



- If θ_{13} small, E~25 GeV Neutrino Factory has exquisite sensitivity.
- If θ_{13} "large", E~5 GeV Neutrino Factory has exquisite precision.

Challenges

- Muons are born ($\pi \rightarrow \mu\nu$) within a large phase space

  - To obtain Muon Collider luminosities O(10^{34}) $cm^{-2}s^{-1}$, need to reduce initial phase space by O(10^6)

- Muons Decay (τ_0 = 2μs)

  - Everything must be done fast

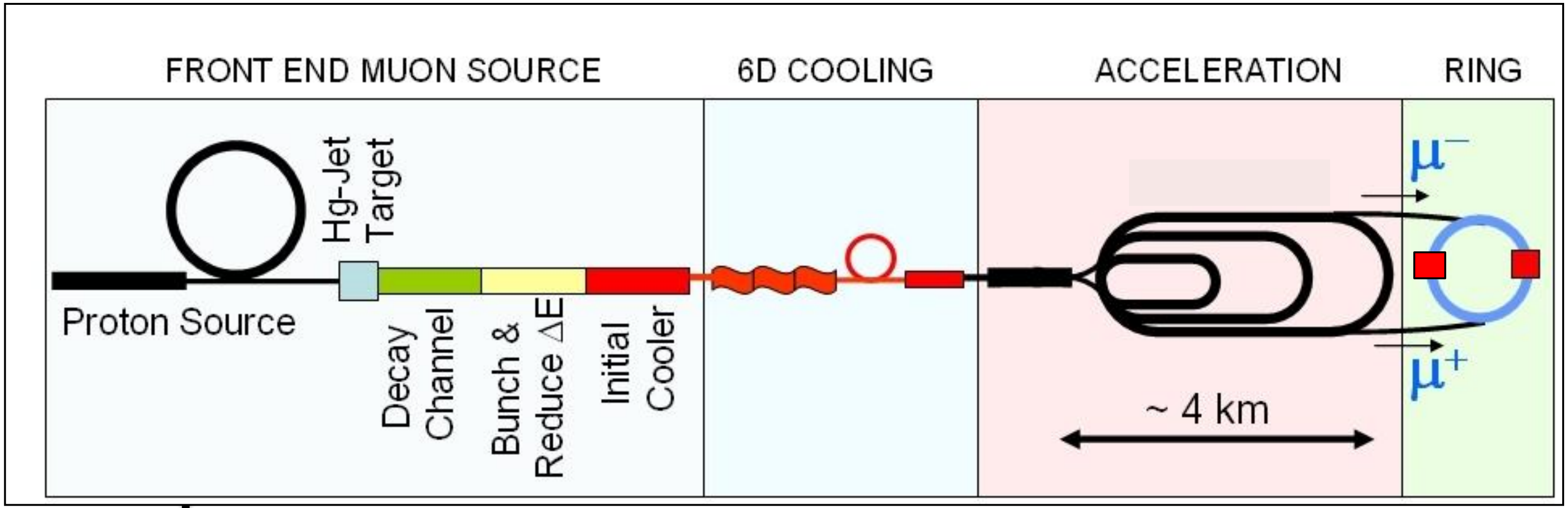
    $\rightarrow$ need ionization cooling

  - Must deal with decay products [electrons and (above ~3 TeV) even neutrinos]

- To get enough muons, must start with a multi-MW proton accelerator

  - e.g. 4MW at 8 GeV

Muon Collider Schematic



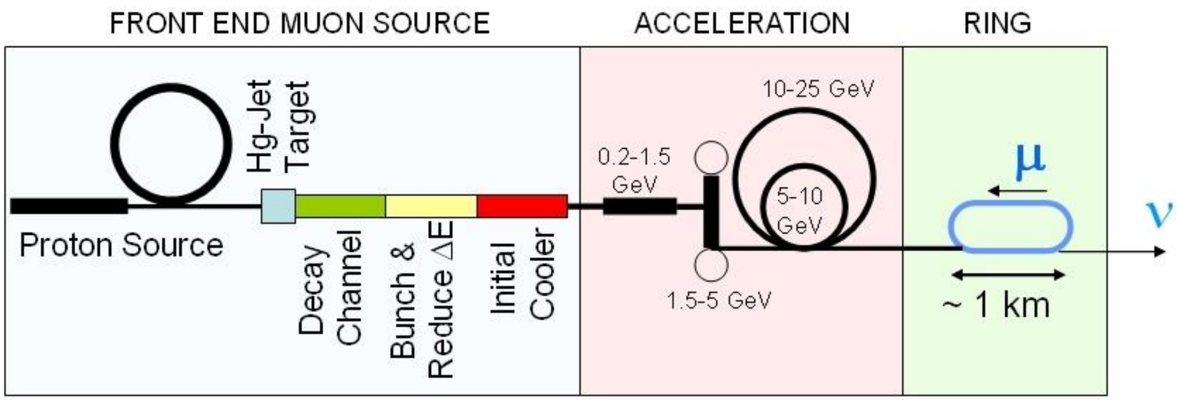
Proton source: Example: upgraded PROJECT X (4 MW, 2±1 ns long bunches)

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

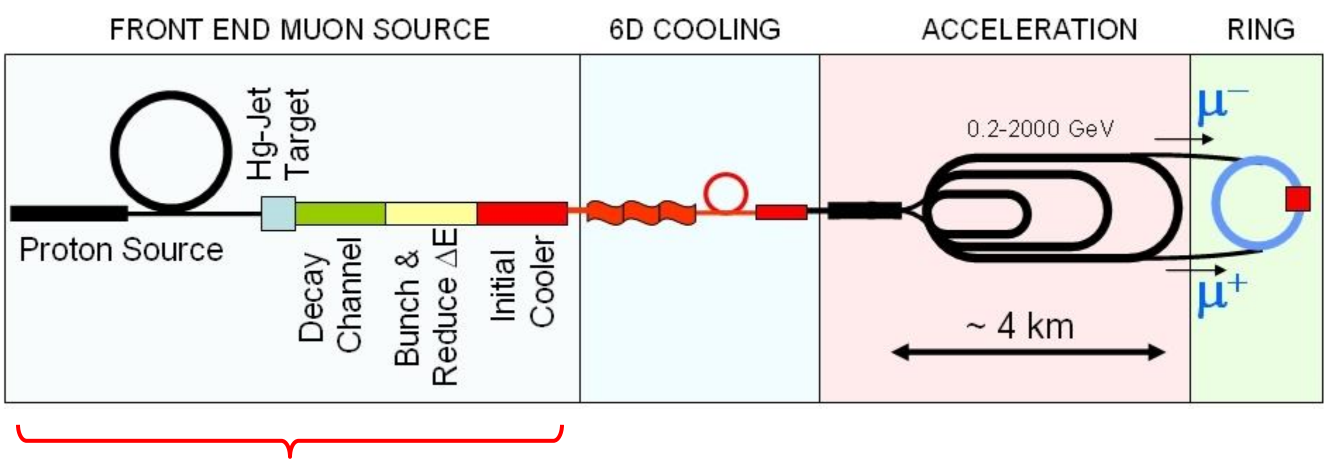
$\varepsilon_{\perp N}$=6000 μm
$\varepsilon_{//N}$=25 mm

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

Neutrino Factory cf Muon Collider



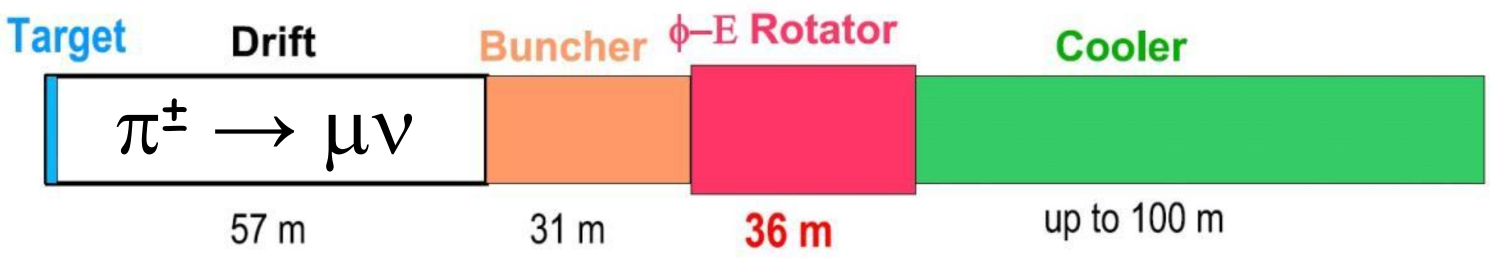
NEUTRINO FACTORY



MUON COLLIDER

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

Front-End



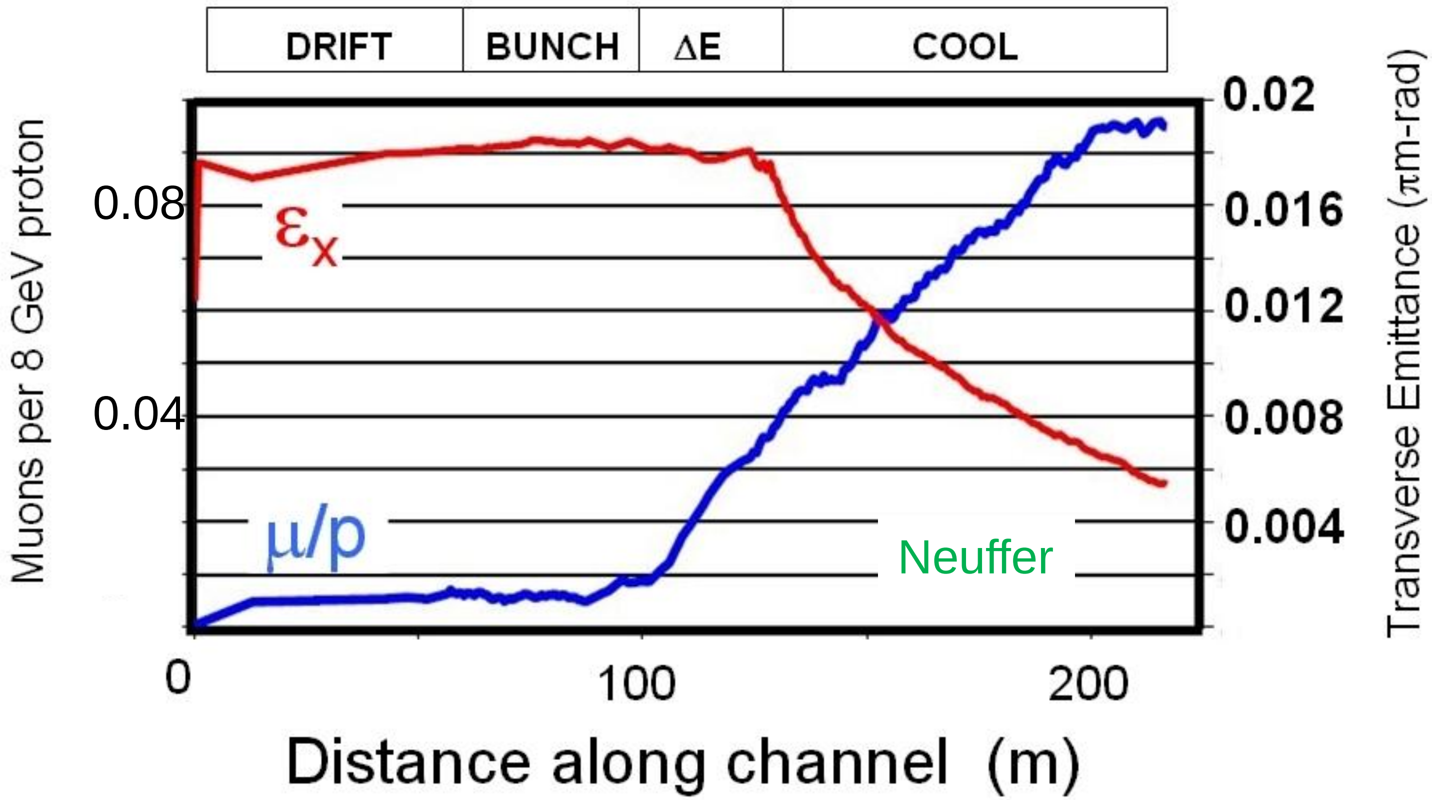
Front-end uses NCRF in a lattice of solenoids

Parameter	Drift	Buncher	Rotator	Cooler
Length (m)	56.4	31.5	36	75
Focusing (T)	2	2	2	2.5 (ASOL)
RF f (MHz)		360 $\rightarrow$ 240	240 $\rightarrow$ 202	201.25
RF G (MV/m)		0 $\rightarrow$ 15	15	16
Total RF (V)		126	360	800

Design Status: Front-End

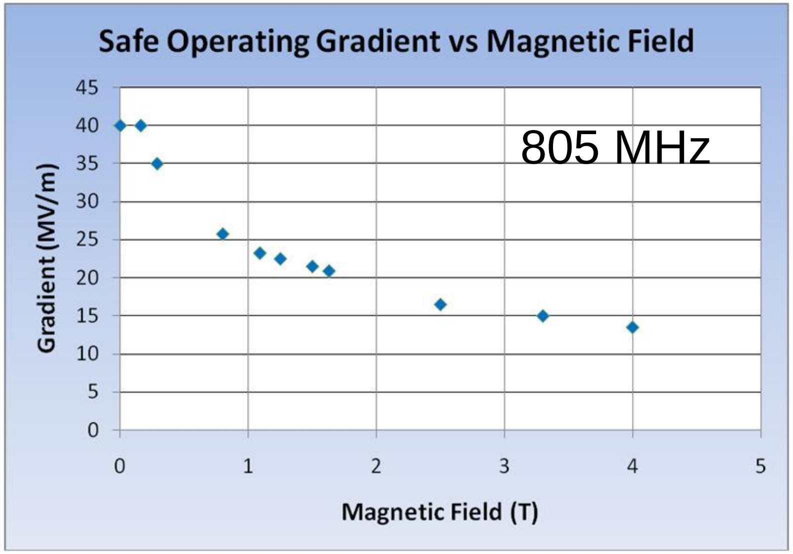
- Front-End concept (up to initial cooling) developed & simulated:

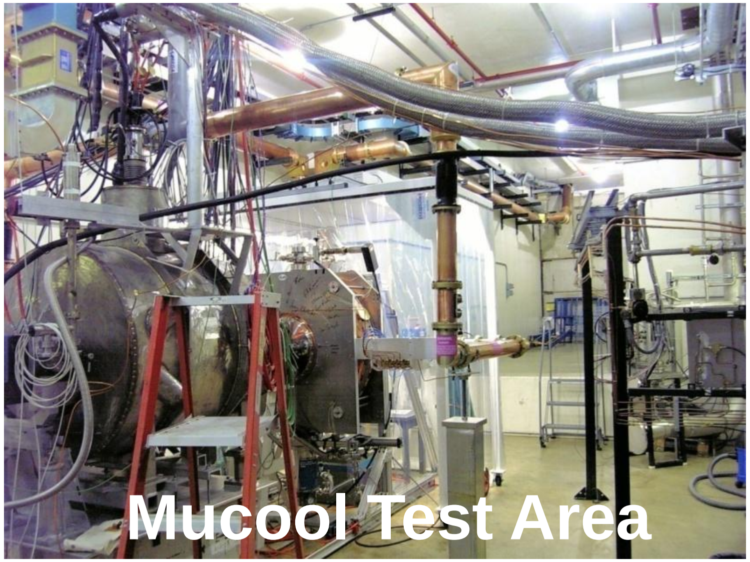
- Concept based on existing technologies, except it requires development of RF cavities within few Tesla fields.



RF in Magnetic Field

- Significant degradation in maximum stable operating gradient for NCRF copper cavities in few Tesla coaxial field



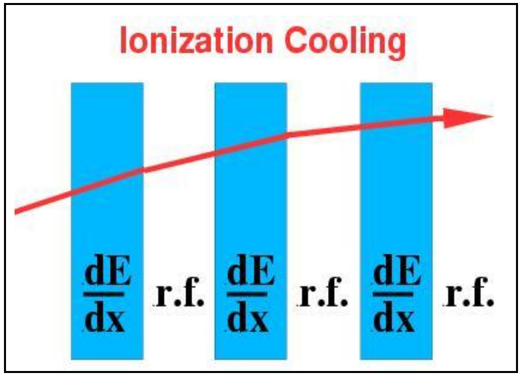


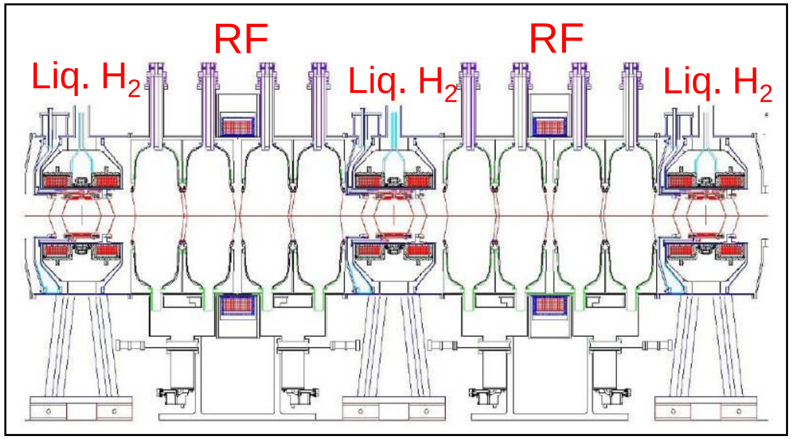
- Ongoing R&D program to maximize gradient in B field: (i) high press-ure gas filled cavities, (ii) Be cavities, (iii) magnetic insulation, (iv) ALD

- Purpose built Mucool Test Area at end of FNAL Linac with 5T magnet, RF power (805 & 201MHz), clean room, H_2 handling, 400MeV beam.

Ionization Cooling Channel

- Must cool fast (before muons decay)
- Muons lose energy by in material (*dE/dx*). Re-accelerate in longitudinal direction → reduce transverse emittance. Coulomb scattering heats beam → low *Z* absorber. Hydrogen is best, but LiH also OK for the early part of the cooling channel.



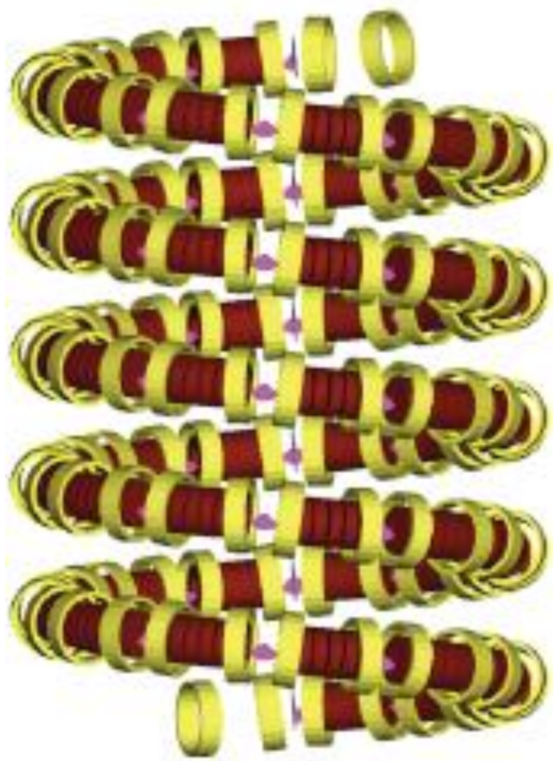


$$\frac{d\varepsilon_N}{ds} = -\frac{1}{\beta^2}\left|\frac{dE_\mu}{ds}\right|\frac{\varepsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\,\mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$

Cooling Heating

- An ionization cooling channel can be thought of as a linac filled with (ionized) material.

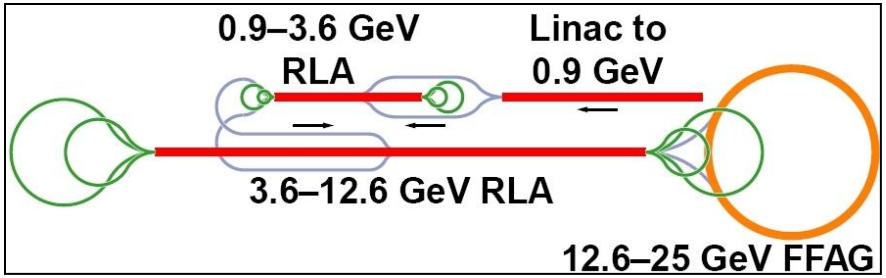
6D Cooling Channel



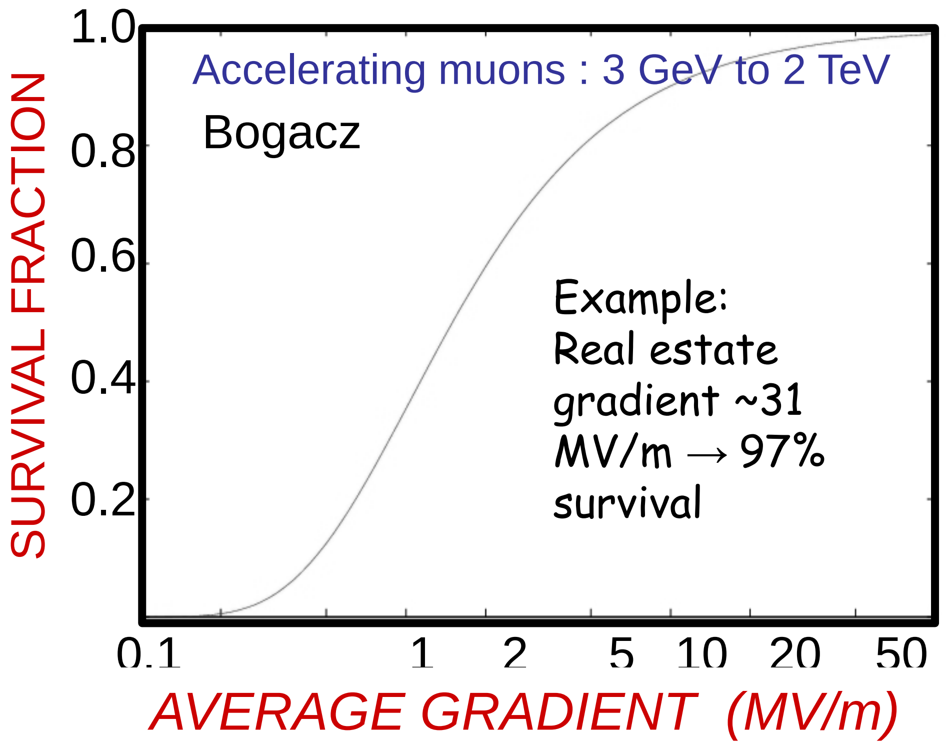
- Ionization cooling works in the transverse directions (4D cooling). OK for a NF, but Muon Collider needs 6D cooling.
- In a 6D cooling channel, need to mix transverse & longitudinal degrees of freedom while cooling. Several different lattices have been developed to do this. Can use solenoids configured in a helix with carefully chosen parameters.
- Simulations show this works well, provided RF operation in magnetic field challenge can be met.
- At end of channel, go back to straight solenoid channel and use highest field solenoids we can get to obtain smallest emittances → HTS solenoid R&D

Acceleration

- Low energy acceleration
  - Developed for IDS-NF
  - Linac followed by 2 dog-bone RLAs & FFAG.



- High energy acceleration
  - Could continue to use RLAs, but believe rapid cycling synchrotrons likely to be more cost effective, e. g. 25-400 GeV, 400 – 750 GeV.
  - R&D on rapid cycling magnets (grain oriented Si Steel) ongoing



A Decade of Progress

- Successful completion of NF feasibility studies 1, 2, 2a, & International Scoping Study; launching of the ongoing International Design Study for a NF (IDS-NF)
  - End-to-end design for a NF (and therefore also MC front-end)
  - IDS-NF aims to deliver a Reference Design Report by ~2013
- Development of a 6D cooling channel concept (consid-ered the most callenging part of a Muon Collider).
- Establishment of an ongoing technology development program (RF studies, magnet studies, …)
- Successful completion of MEcuRy Intense Target (MERIT) expt at CERN, establishment of the MuCool Test Area (MTA) facility at FNAL, & launch of MICE at RAL.

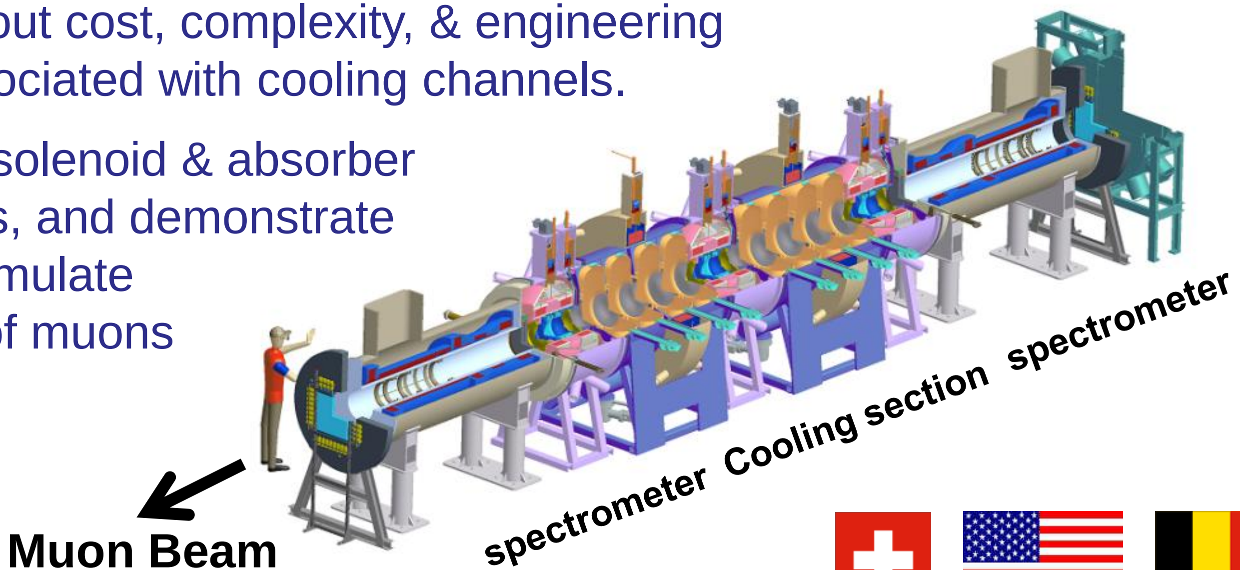
Muon Ionization Cooling Experiment (MICE) at RAL

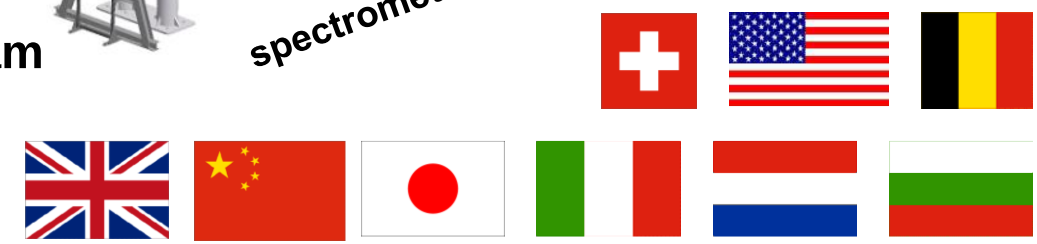
- **Multi-stage experiment to be completed ~2013**

  - Tests short cooling section, in muon beam, measuring the muons before & after the cooling section. one at a time.

  - Learn about cost, complexity, & engineering issues associated with cooling channels.

  - Vary RF, solenoid & absorber parameters, and demonstrate ability to simulate response of muons to channel.





The MAP Initiative in the U.S.

- Oct 1, 2009 letter from DOE Assoc. Director of Science for HEP to FNAL Director:

  "Our office believes that it is timely to mount a concerted national R&D program that addresses the technical challenges and feasibility issues relevant to the capabilities needed for future Neutrino Factory and multi-TeV Muon Collider facilities. ..."

- Letter requested that FNAL Director put in place a new organization for a national Muon Collider & Neutrino Factory R&D program $\Rightarrow$ MAP.
- Initial MAP participants from 14 institutions:
  - ANL, BNL, FNAL, Jlab, LBNL, ORNL, SLAC, Cornell, IIT, Princeton, UCB, UCLA, UCR, U-Miss
- MAP R&D proposal submitted by FNAL Director in March, reviewed in August.

MAP R&D Plan

MAP Website: http://map.fnal.gov

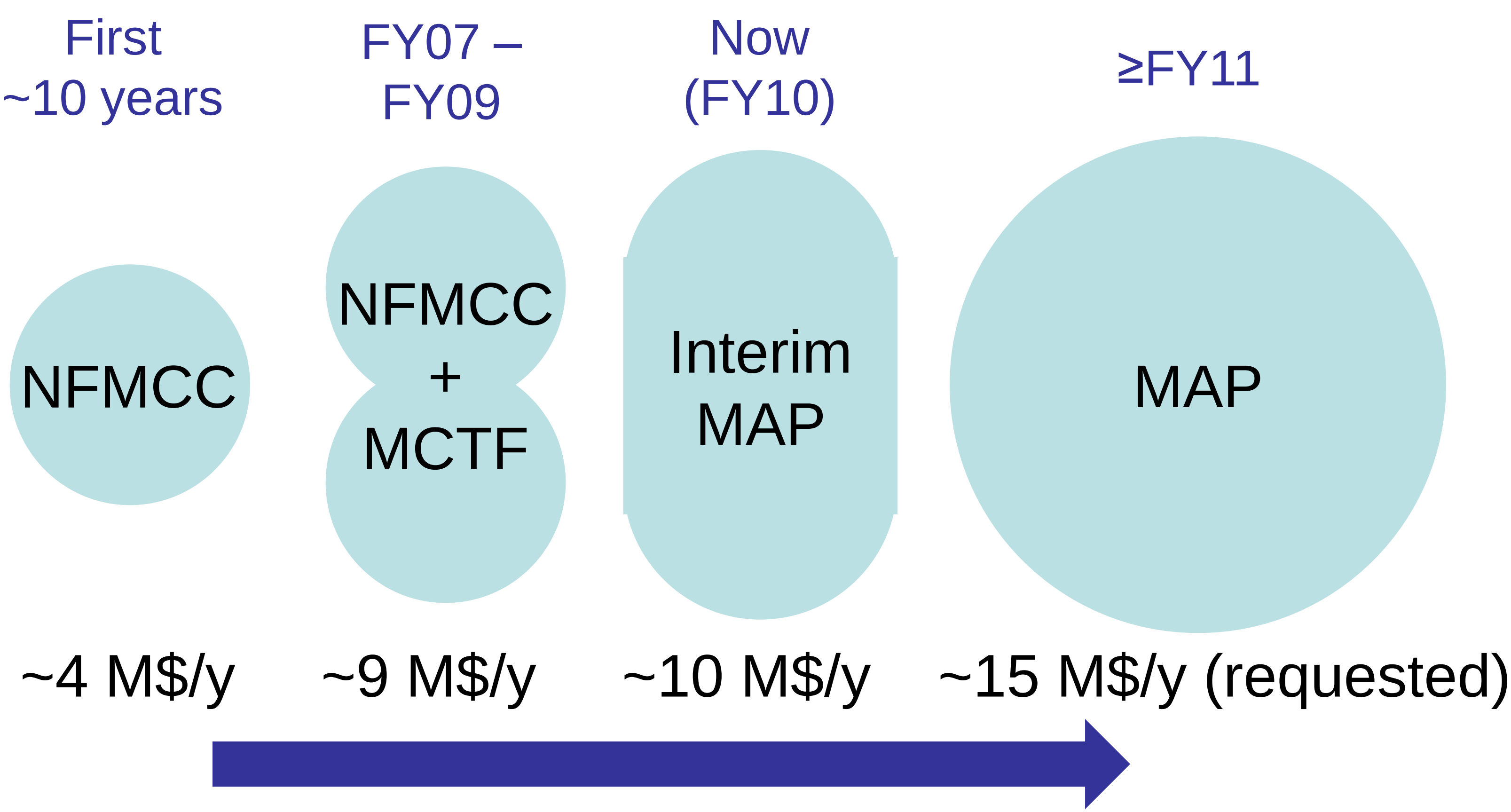
- **Deliverables in 6-7 years:**

  - Muon Collider Design Feasibility Report
  - Hardware R&D results → technology choice
  - MC Cost range
  - Also contributions to the IDS-NF RDR

- **Will address key R&D issues, including**

  - Maximum RF gradients in magnetic field
  - Magnet designs for cooling, acceltn, collider
  - 6D cooling section prototype & bench test
  - Full start-to-end simulations based on technologies in hand, or achievable with a specified R&D program

Growing Support



NFMCC = Neutrino Factory & Muon Collider Collaboration
MCTF = (Fermilab) Muon Collider Task Force

Summary

● Strong physics motivation for Muon Collider & Neutrino Factory R&D and, for Muon Colliders, the hope of making a more cost effective multi-TeV lepton collider.

● After a decade of R&D there has been steady progress towards meeting the challenges (successful NF design/feasibilty studies, conceptual design of 6D cooling channel, MERIT expt …)

● The role of Linac technologies includes the early acceleration stages, and some less conventional challenges (cooling channels with RF in magnetic fields, solenoid lattices including material, …)

● The IDS-NF community aspires to deliver a Neutrino Factory RDR by ~2013

● A new initiative (MAP) has been created in the U.S., which aims to establish, within a few years, the feasibility, of a multi-TeV Muon Collider and its cost range.