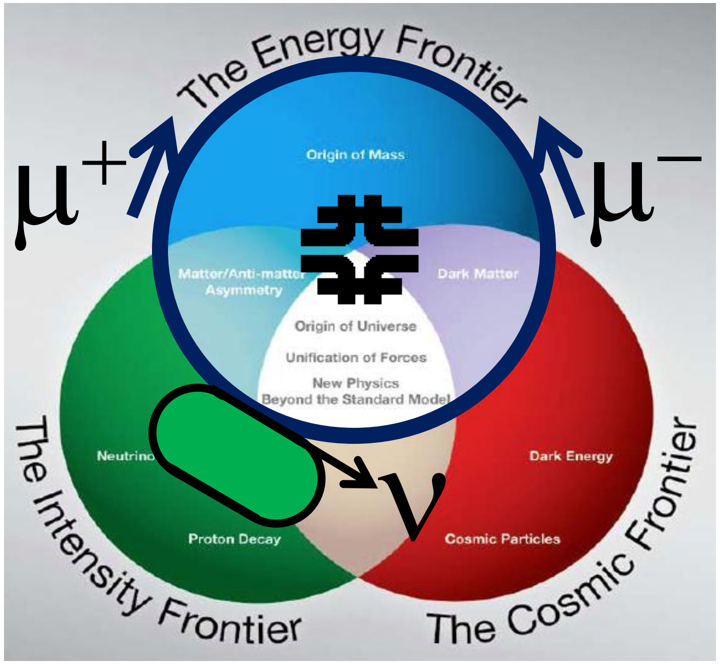


Muon Accelerator Program - MAP

MUON COLLIDER R&D

Steve Geer

Accelerator Physics Center

Fermi National Accelerator Laboratory

(presented by Stuart Henderson)

ICFA Seminar on

Future Perspectives in High Energy Physics

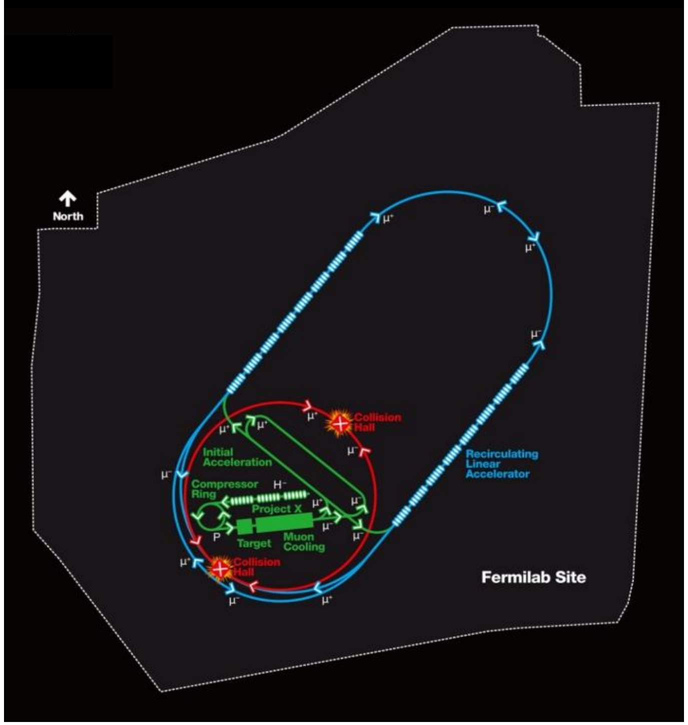
CERN, 3-6 October, 2011

Muon Collider Motivation

If we can master the required technology a Muon Collider provides a very attractive route to reaching multi-TeV energies because muons radiate far less than electrons

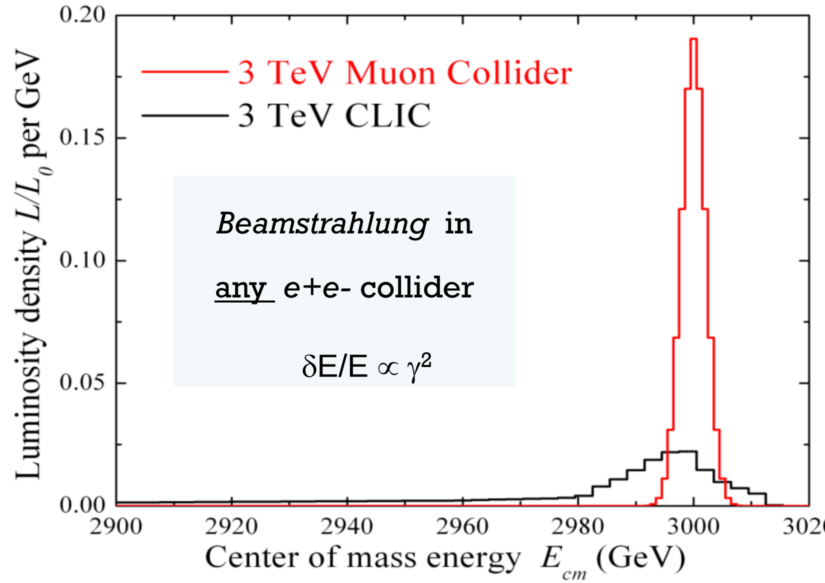
- **Energy reach**: In principle, reach extends well into multi-TeV regime
- **Compact:** Fits on laboratory site
- **Cost effective:** circular/recirculating accelerators; manageable wallplug pwr
- Lends itself very well to **a staged approach**
  - ➢ High power proton source (Project X)
  - ➢ Neutrino Factory
  - ➢ Low-energy Muon Collider (Higgs Factory)
  - ➢ High-Energy Muon Collider

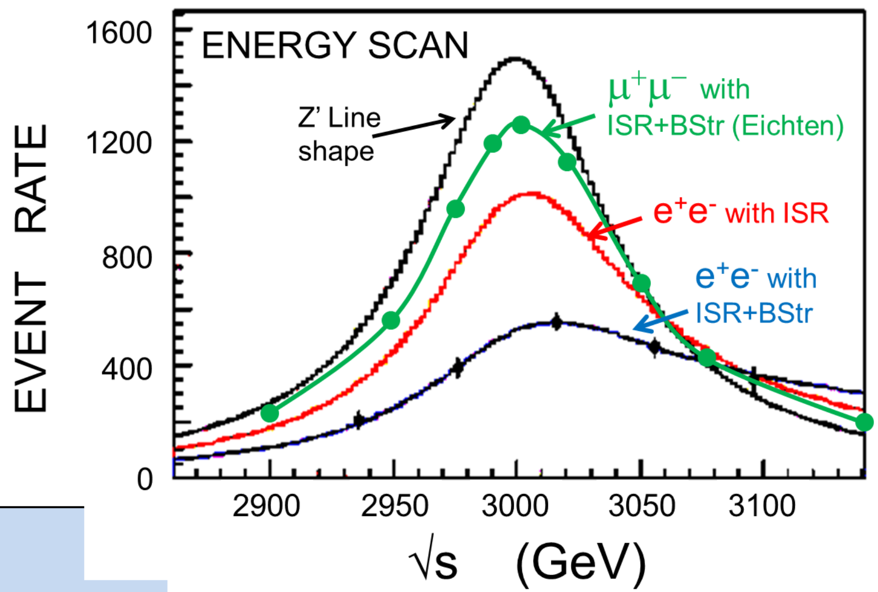
A 4 TeV Muon Collider would fit on the Fermilab Site



Muon Collider Motivation

- Physics potential of multi-TeV colliders has been described
- Narrow energy spread
  - Precision scans; kinematic constraints
- Enhanced s-channel rates for Higgs-like particles
- Multi-pass collisions in ring
  - Relative to LCs, relaxed emittance requirements and IP tolerances
- Readily accommodates two detectors at two IPs
- Manageable bunch spacing (~10 μs)

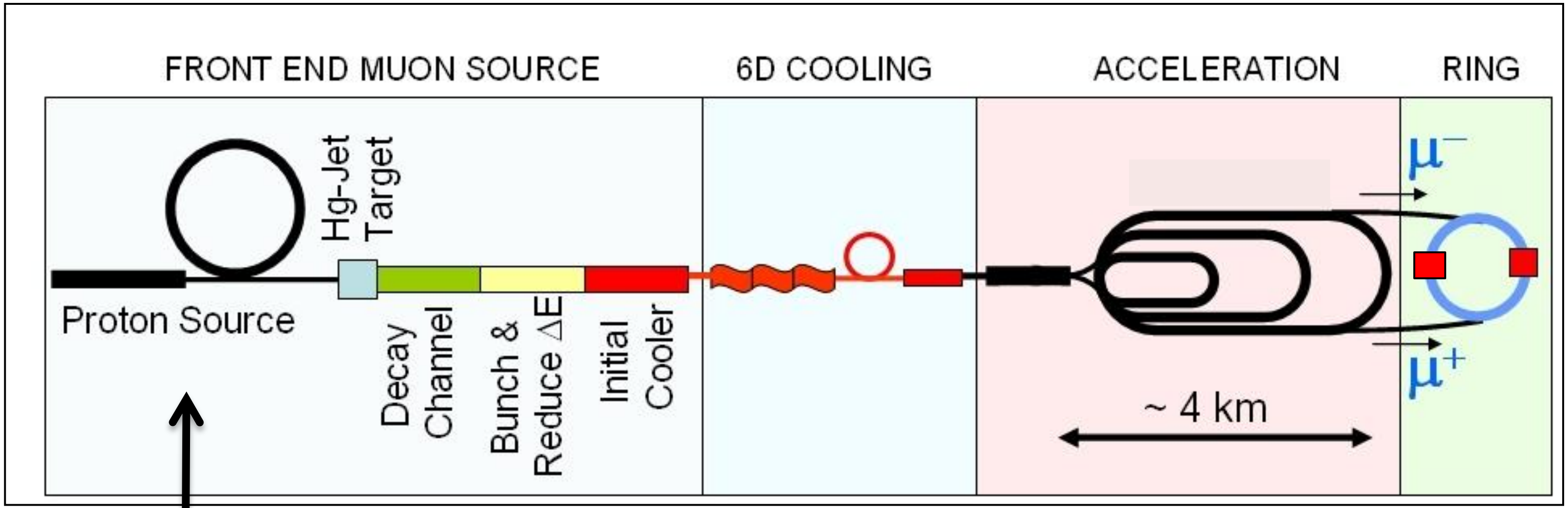




Challenges

- Muons are produced as tertiary particles. To make enough of them we must start with a MW scale proton source & target facility.
- Muons decay ⇒ everything must be done fast and we must deal with the decay electrons (& neutrinos for high energies).
- Muons are born within a large 6D phase-space. For a MC we must cool them by O(10^6) before they decay ⇒ New cooling technique (ionization cooling) must be demonstrated, using components with demanding performance requirements (NCRF in magnetic channel, high field solenoids.)
- After cooling, beams still have relatively large emittance.

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:

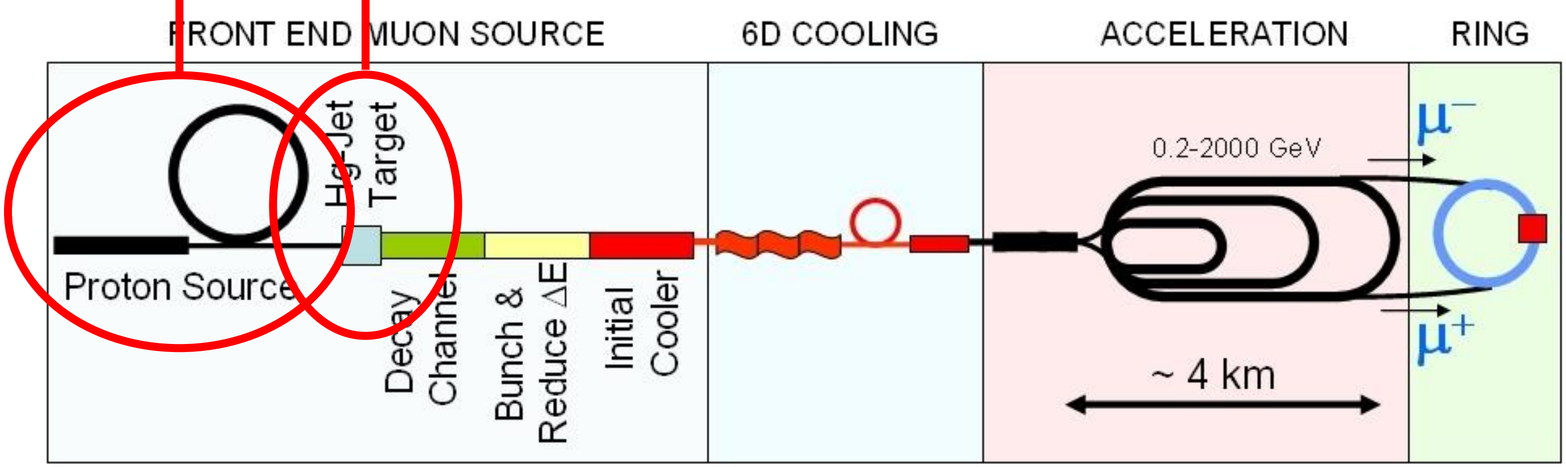
$e_{\perp N}$=6000 μm
$e_{//N}$=25 mm

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

A Muon Collider Has Many Challenging Ingredients

Proton
- Multi-
- Accu in acc comp
- nsec

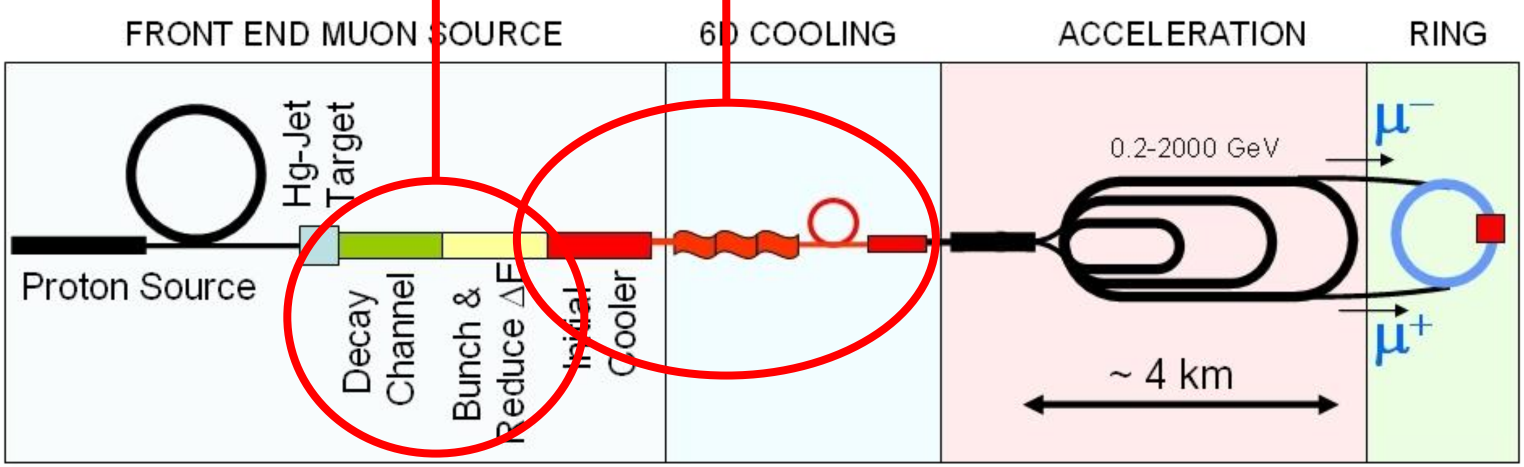
Target System
- Multi-MW with very high peak power deposition
- ~250kJ per beam pulse
- Liquid metal system
- Integrated within strong solenoidal (20T) fields



A Muon Collider Has Many Challenging Ingredients

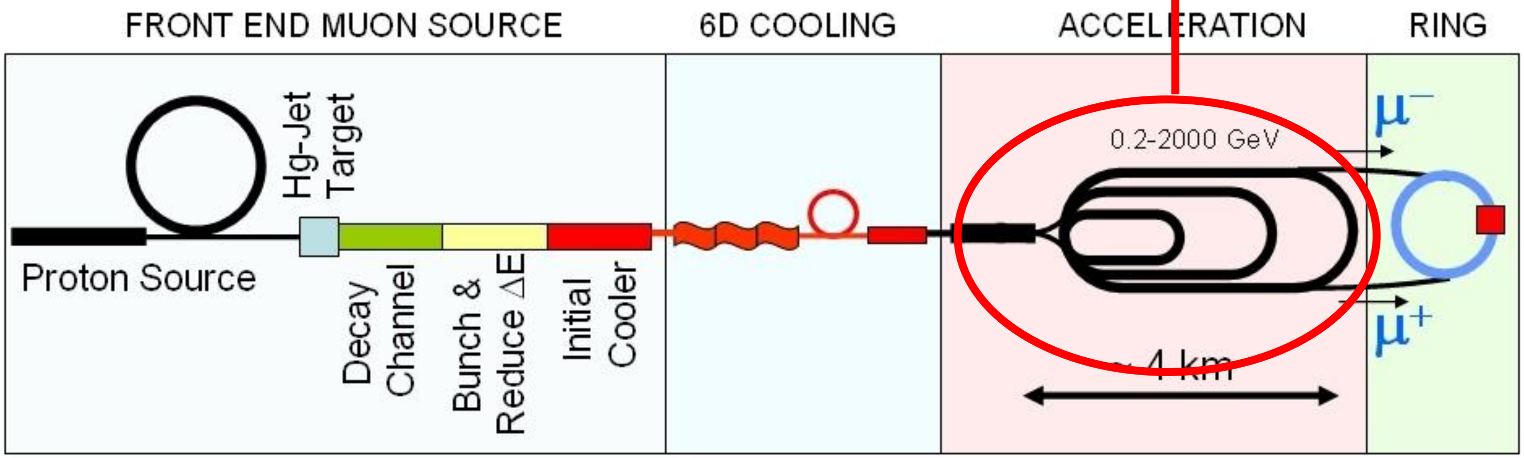
Bunchi
- Bunc
- Phas sma
- Requ oper char

Cooling channel(s)
- Must reduce 6D phase space by a factor of O(10^6)
- Requires superimposed RF and magnetic fields
- 6-d cooling channels require novel configurations
- Final cooling requires very high solenoidal fields beyond present state-of-the-art
- Space-charge effects are important



A Muon Collider Has Many Challenging Ingredients

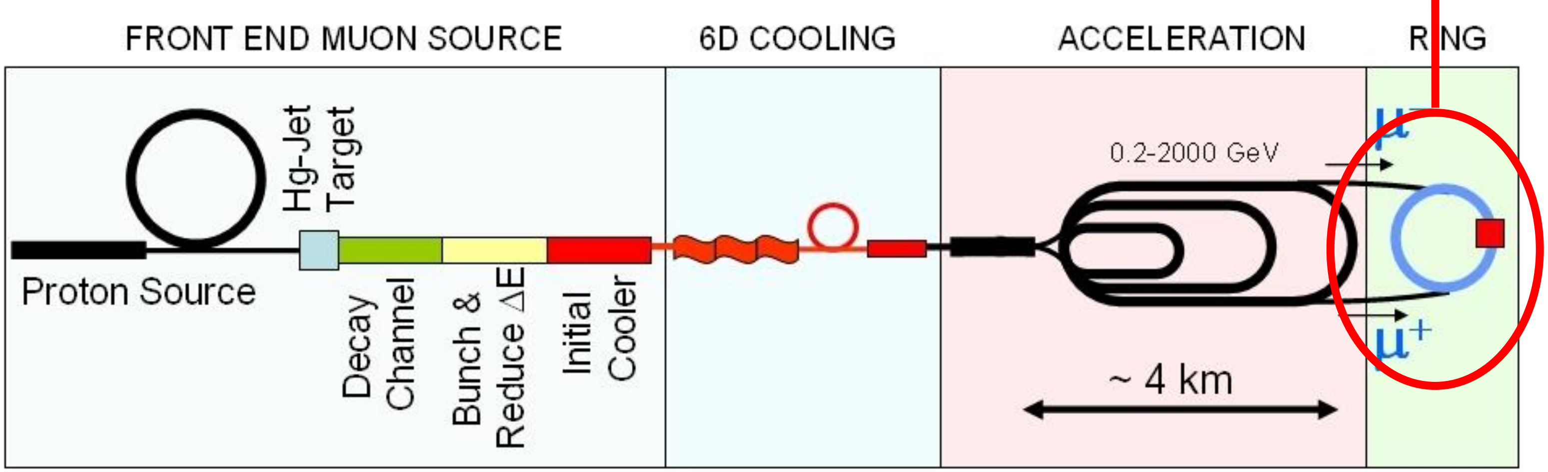
Acceleration
- Multiple acceleration stages required (using recirculating linacs, rapid cycling synchrotrons)
- Design is challenged by large longitudinal emittance, co-acceleration of μ+, μ-, need for good transmission



A Muon Collider Has Many Challenging Ingredients

Muon Collider Ring

- Must bring ~10MW muon power into collision
- Designed to operate at beam-beam limit
- Challenging lattice
  - Large momentum acceptance
  - Small β^* and σ_l
  - Low α_c and large chromatic effects
- Substantial decay electron flux
  - Detector backgrounds and Machine-Detector Interface
  - Decay heat-load (~2MW electron load)
- Neutrino radiation may limit highest energies

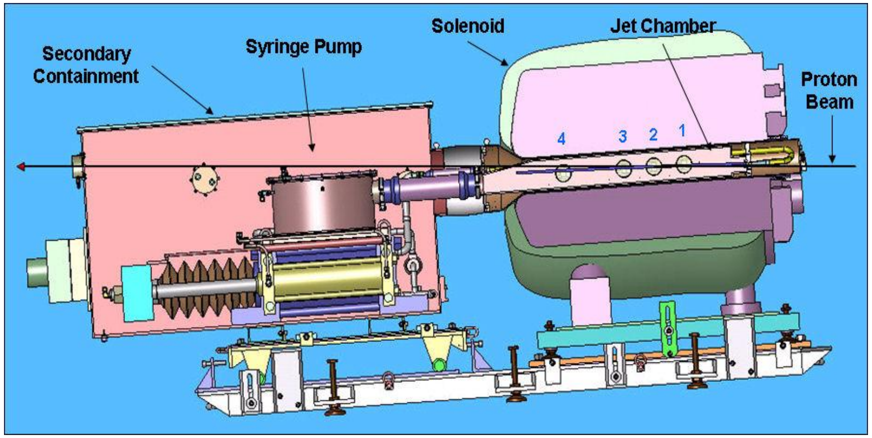


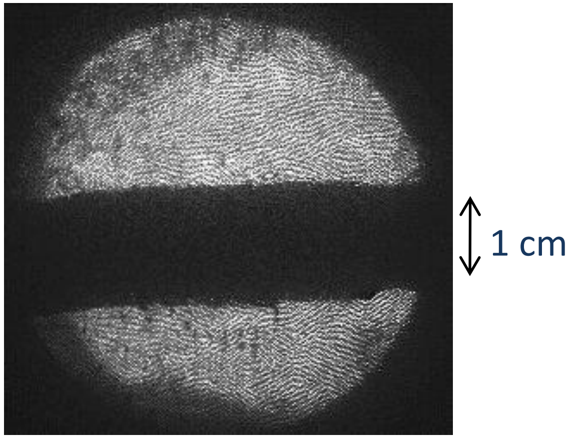
The Muon Accelerator Program (MAP)

- Answering the question of Muon Collider feasibility requires a dedicated, focused R&D effort
- DOE Office of HEP requested (in 2009) a new organization for a national Muon Collider & Neutrino Factory R&D program, hosted at FNAL. This request recognized that progress will only be made by mounting
  - *"…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…"*
- **M**uon **A**ccelerator **P**rogram organization is now in place & functioning: >200 participants from 15 institutions:
  - http://map.fnal.gov/
- Mission: "…to develop and demonstrate the concepts and critical technologies .. for Muon Colliders and Neutrino Factories."
- Goal: "… 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…"

A Decade of Progress: Successful completion of MERIT

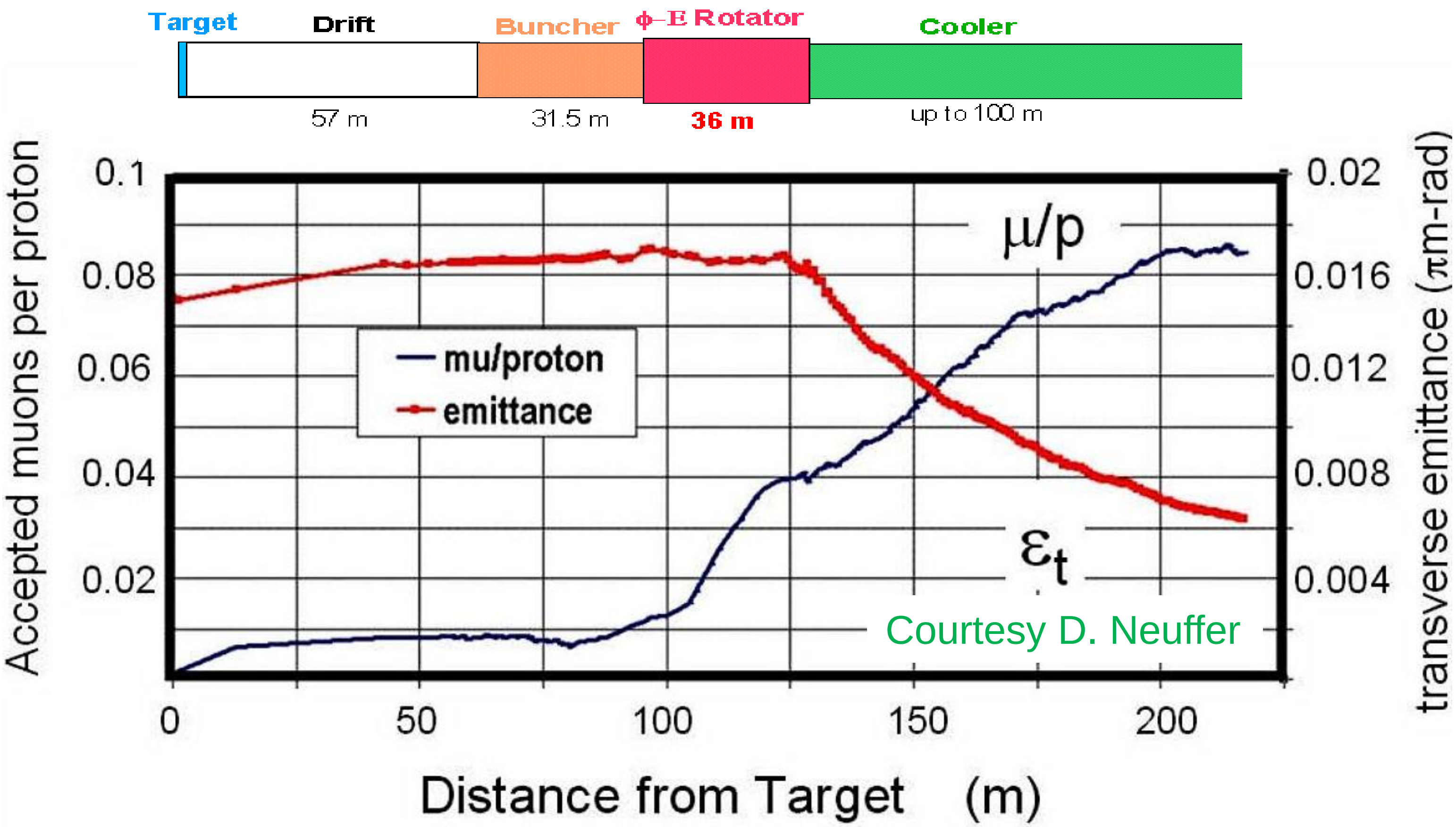
- Proof-of-principle demonstration of a liquid Hg jet target in high-field solenoid ran at CERN PS in Fall 2007.
- Successfully demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid, & hit with a suitably intense beam (115 KJ / pulse !).
- Results suggest this technology OK for beam powers up to 8 MW with rep. rate of 70Hz !





Hg jet in a 15 T solenoid
Measured disruption length = 28 cm

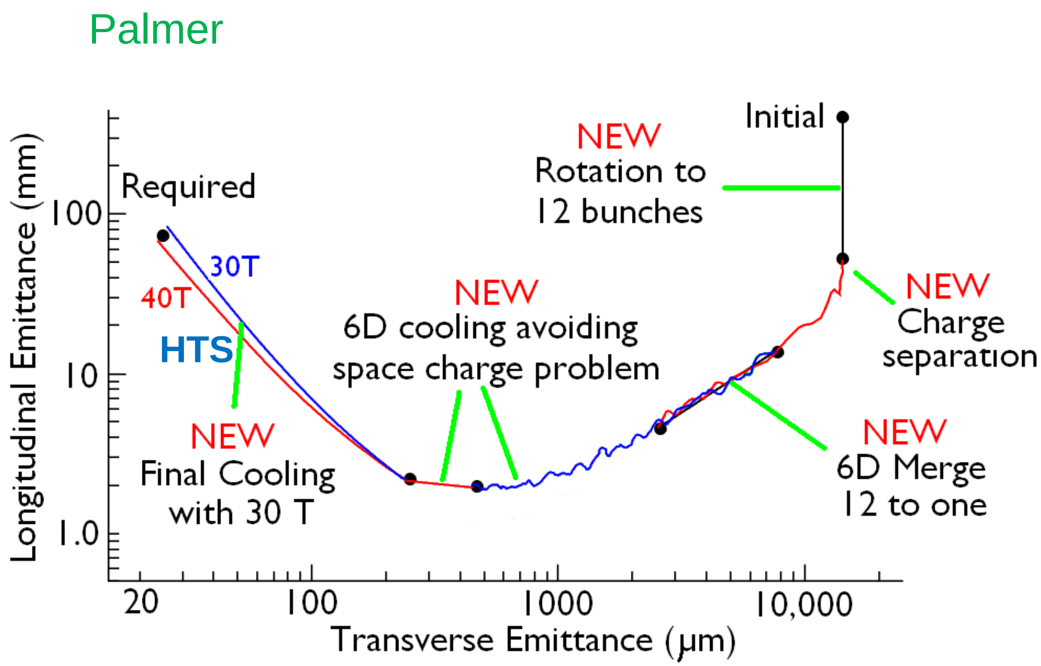
A Decade of Progress: Front-End Design & Simulations



With a 4MW proton source, this will enable O(10^{21}) muons/year to be produced, bunched, cooled & fit within the acceptance of an accelerator.

A Decade of Progress: Ionization Cooling Concepts

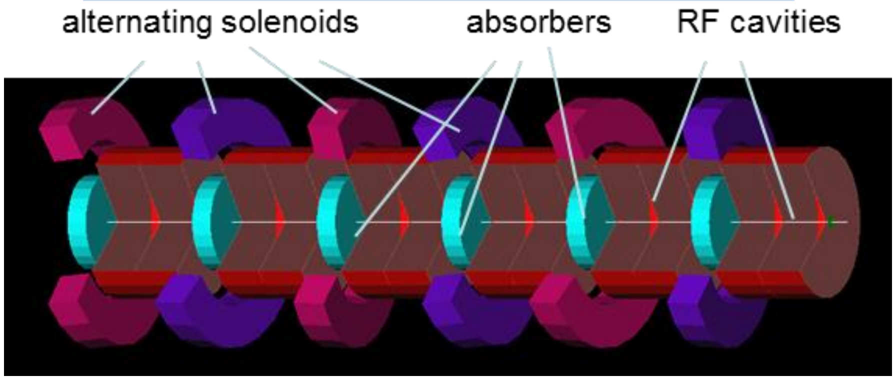
- Development of a cooling channel design to reduce the 6D phase space by a factor of $O(10^6)$ $\rightarrow$ luminosity $O(10^{34})$ cm^{-2} s^{-1}



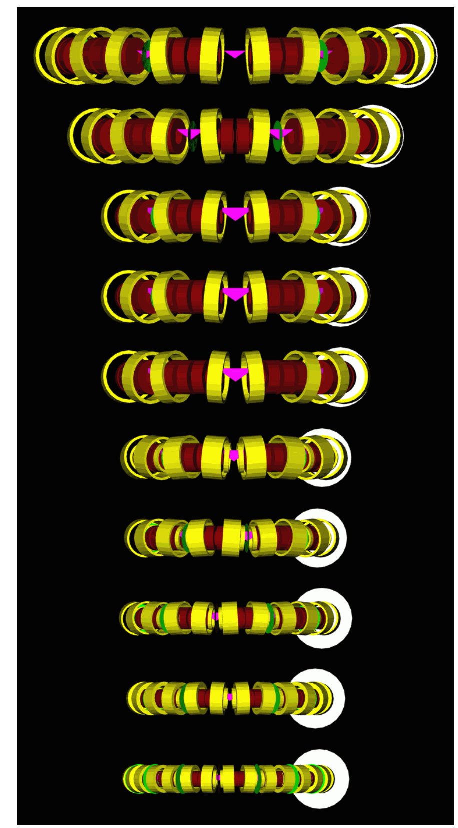
- Some components beyond state-of-art:
  - High gradient RF cavities operating in few Tesla fields & Very high field HTS solenoids
- Challenging are the solenoids in the last stages of cooling:
  - Original design needed 50 T solenoids. Recent improvements suggest 30 T sufficient.

A Decade of Progress: Cooling Concepts

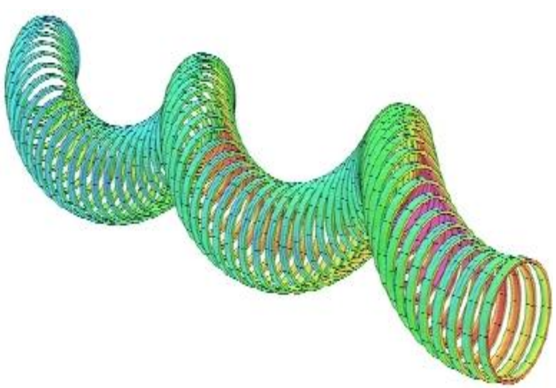
Helical FOFO Snake: Tilted solenoids, RF, LH_2 absorbers

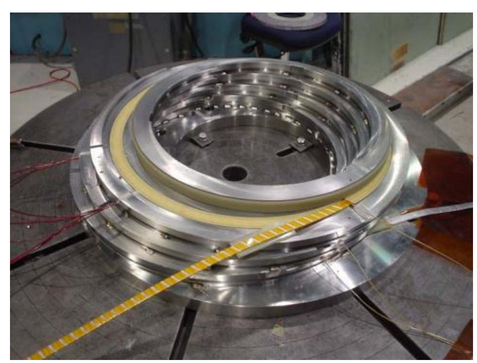


Tapered Guggenheim: Tilted, displaced solenoids, RF, LH_2 absorbers



Helical cooling channel: coils arranged around helical trajectory, RF, H_2 gas filled





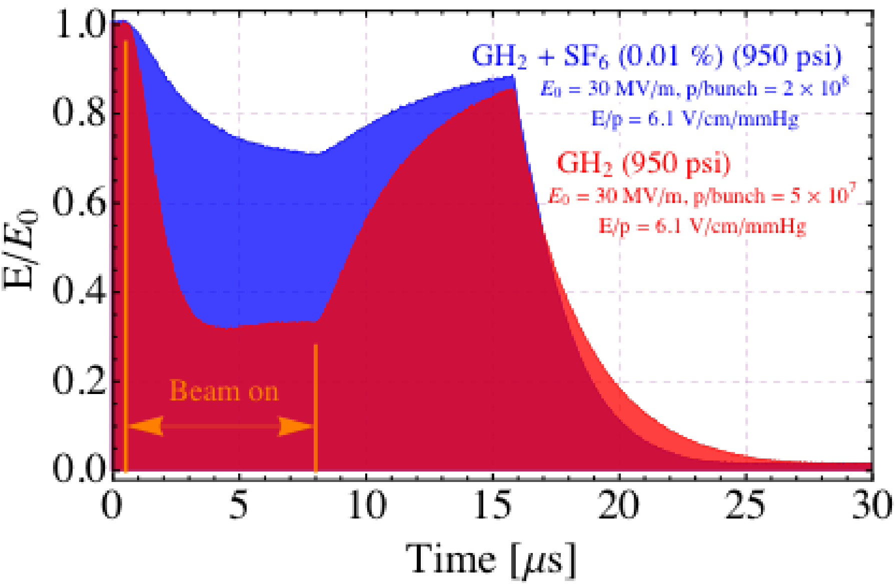
A Decade of Progress
MuCool Test Area (MTA)

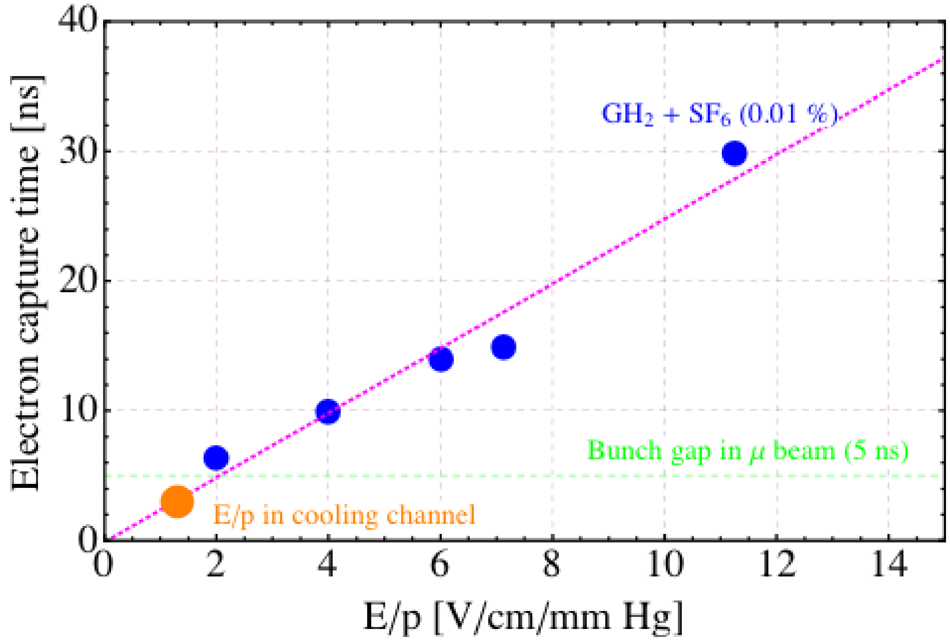
- Arguably, the most important challenge is demonstrating feasibility of high-gradient RF cavity operation in the presence of strong magnetic fields
- The MTA was built at the end of FNAL Linac to provide a platform for ionization cooling component testing ***with a particle beam***
- Brings together high power RF systems, cavities, 5T solenoid, LH_2 handling and 400 MeV proton beam from linac (recently commissioned)

Liq. H_2 absorber (KEK)

High Pressure RF Cavity (FNAL & Muons Inc.)

High-Pressure Gas-Filled RF Cavity Response to Beam





- One ionization cooling approach uses high-pressure gas in RF cavities to both serve as the absorber and to reduce dark current and mitigate breakdown. A key question is what happens with ionizing beam?

- Electron capture time seems to be short enough to recover RF before arrival of next beam bunch, with use of very small amount of dopant gas

Courtesy K. Yonehara, FNAL

A Decade of Progress:

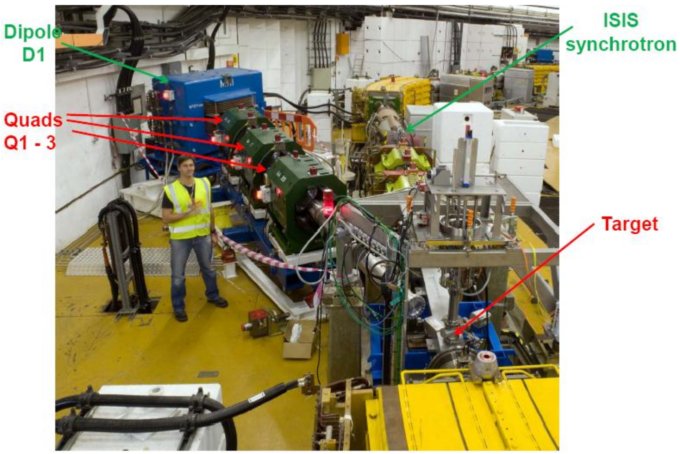
Muon Ionization Cooling Experiment (MICE)

- Multi-stage experiment at RAL

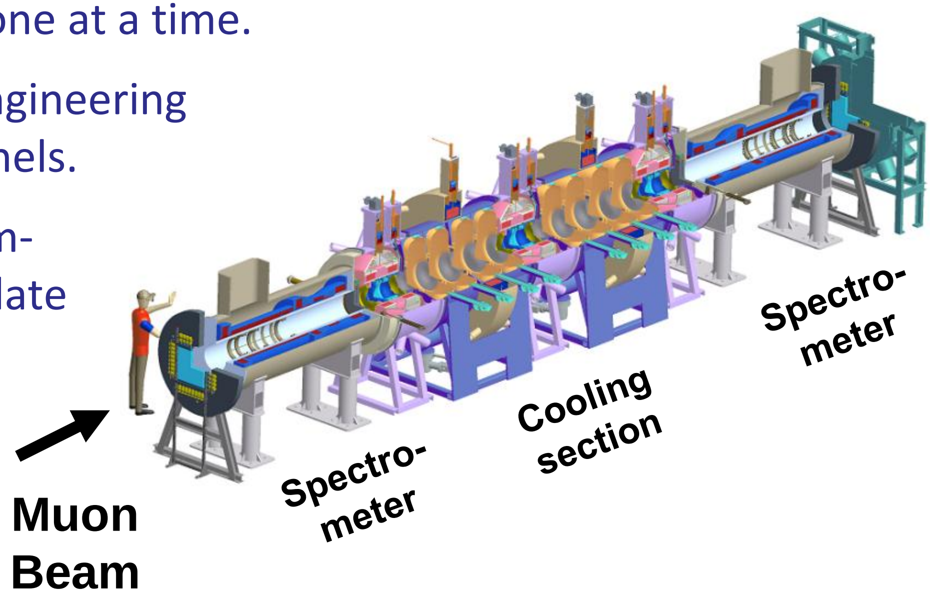
- Tests short cooling section, in muon beam, measuring the muons before & after the cooling section. one at a time.

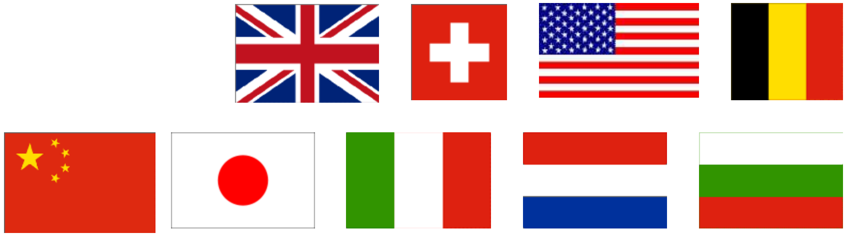
- Learn about cost, complexity, & engineering issues associated with cooling channels.

-Vary RF, solenoid & absorber param-eters & demonstrate ability to simulate response of muons



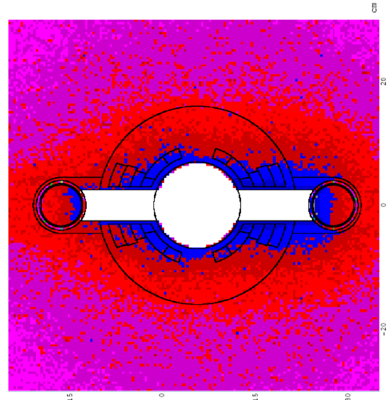
MICE – upstream beamline





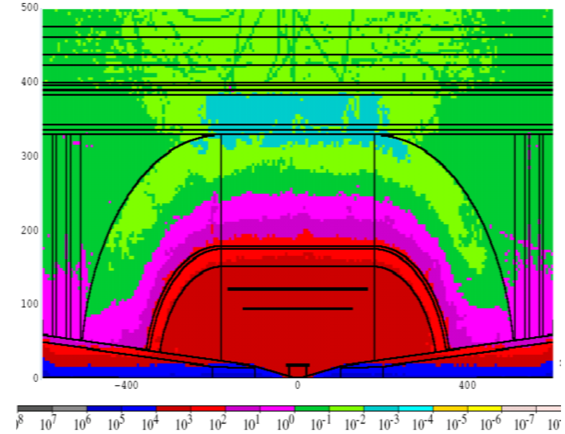
A Decade of Progress: Ring, Magnet & Detector Studies

- Emittances are large, but the muons circulate for only ~1000 turns before they decay.
- Acceptable Ring Lattices exist
- Need high field dipoles & quadrupoles that operate in large muon decay backgrounds



MARS energy deposition map for 1.5 TeV collider dipole

- Have studied open mid-plane magnet design (radiation & heat loads, field non-uniformity & affect on lattice performance) → looks OK. More engineering studies needed.
- Detector shielding & performance studies under way – initially for $\sqrt{s}$=1.5 TeV.
  - Initial shielding configuration exists
  - Initial detector studies beginning
  - Much needs to be understood & optimized



- Recent detector studies on relative timing of prompt physics hits and late background hits suggests that fast timing gates may be very effective at suppressing backgrounds

Muon Collider R&D Plan and Deliverables

- Deliver on commitments to making MICE and the IDS-NF studies a success.
- Focus on key technology development and testing
  - RF cavities in magnetic fields
  - High-field solenoids for final cooling
  - Collider ring magnets configurations that can handle heat-loads
- Deliver a Design Feasibility Study to enable the community to judge the feasibility of a multi-TeV Muon Collider (~FY16):
  - Hardware R&D and experimental tests to guide & validate the design work.
  - an end-to-end simulation of a MC complex based on technologies in-hand or that can be developed with a specified R&D program.
  - Rough cost range.
  - R&D plan for longer term activities (e.g. 6D cooling expt)
- Coordinate with the physics community on physics capabilities, detector and MDI

Summary

A Muon Collider has several very attractive features

- **High energy reach**: well into the multi-TeV regime
- **Compact:** Fits on a site
- **Cost-effective** in construction and operation
  - Manageable wall-plug power: 150-200 MW for 3 TeV machine
- A Muon Collider **lends itself to a staged approach:**
  - Proton driver → Neutrino Factory → (Low-energy MC) → Multi-TeV MC

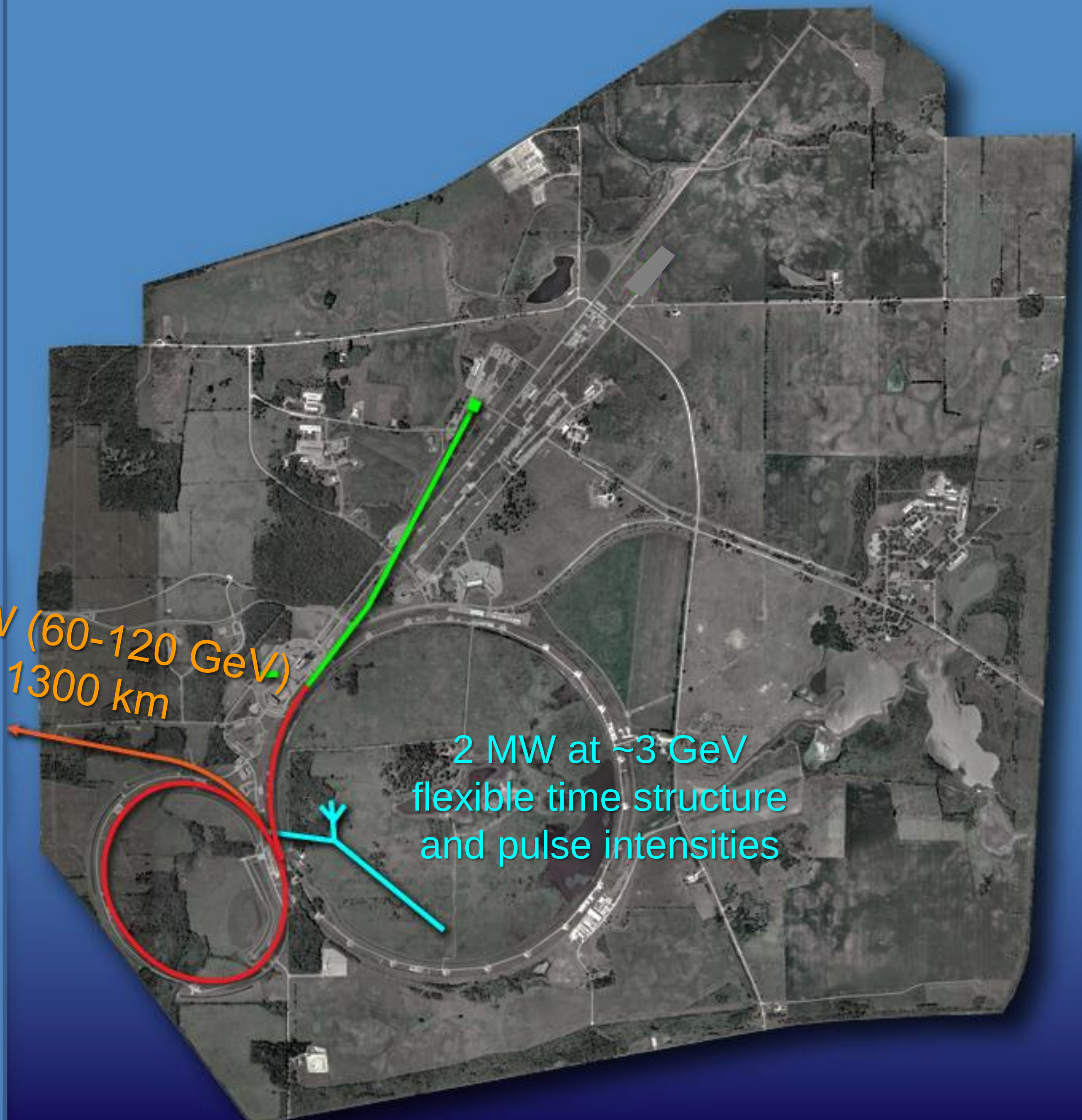
Mastering the technology of a Muon Collider requires overcoming substantial challenges, requiring R&D aimed at extending the state of the art

- MAP is working to show, within ~5 years, that a multi-TeV Muon Collider is feasible with an estimated cost range, and to specify the remaining R&D needed.
- There are many opportunities to contribute: Muon Accelerator R&D has great opportunities for national and international collaboration

START WITH PROJECT X

Neutrinos
Muons
Kaons
Nuclei

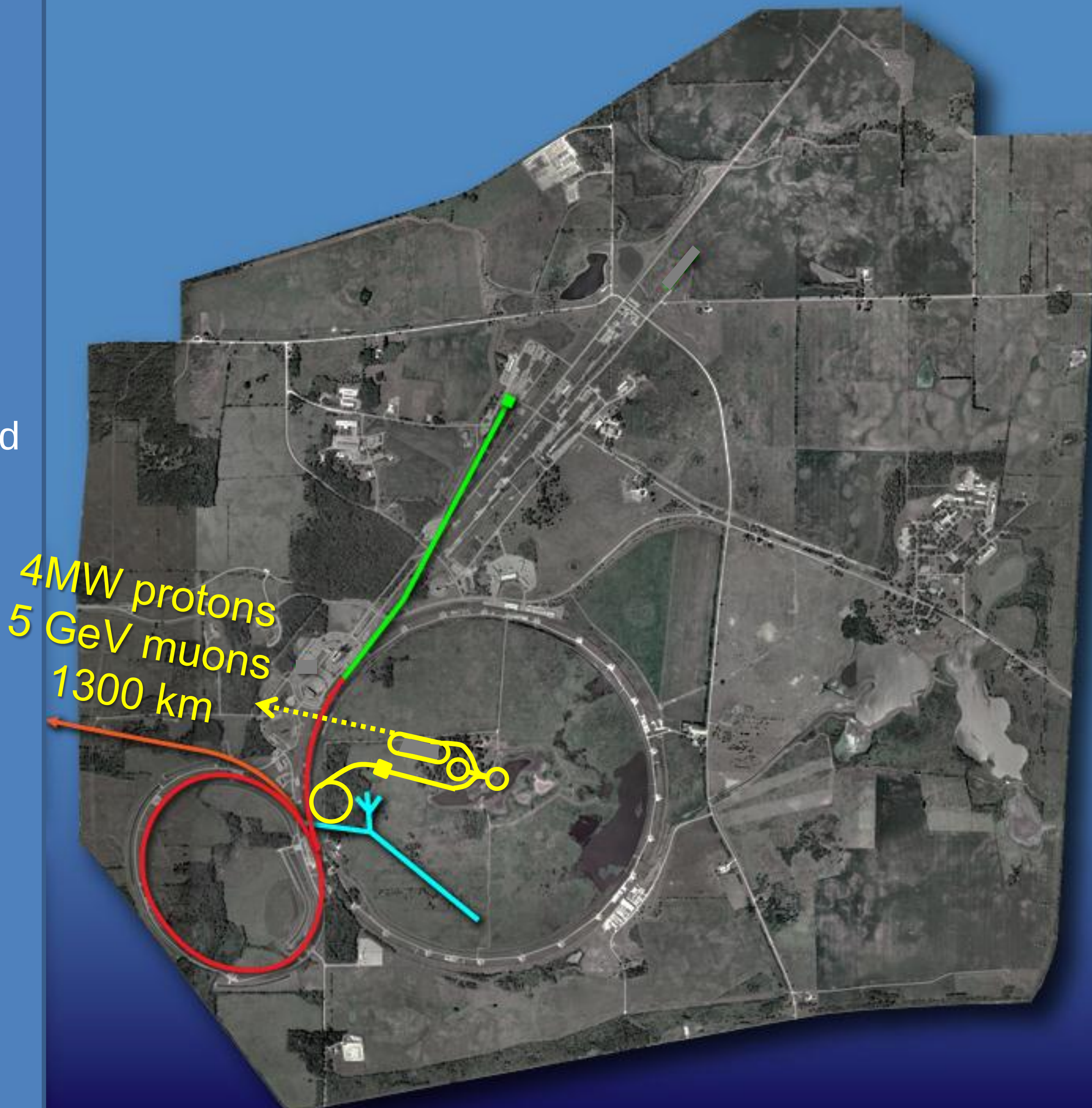
"simultaneously"



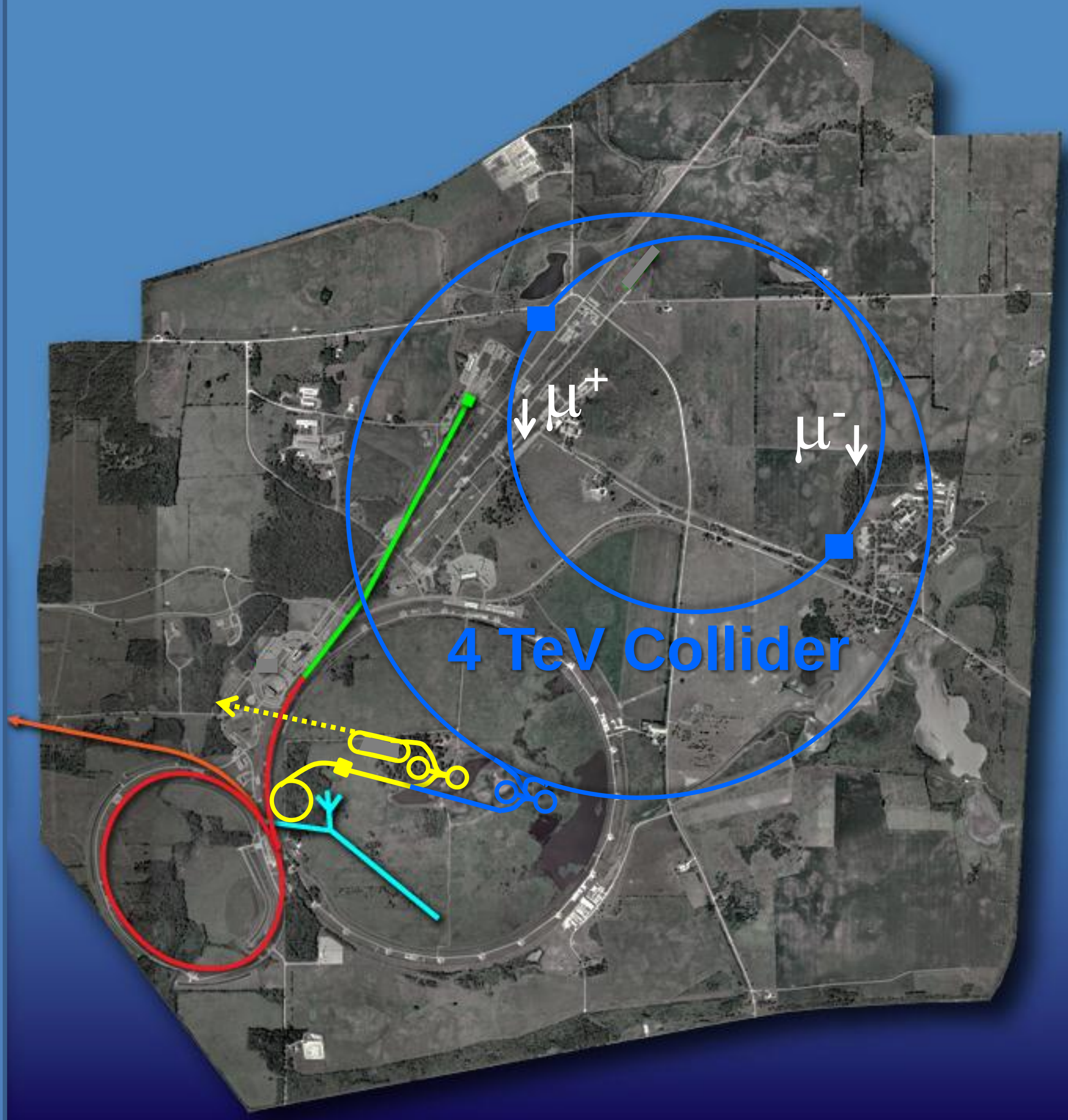
ADD NEUTRINO FACTORY

Enhanced Neutrinos
Enhanced Muons
Muon Collider test bed
Kaons
Nuclei

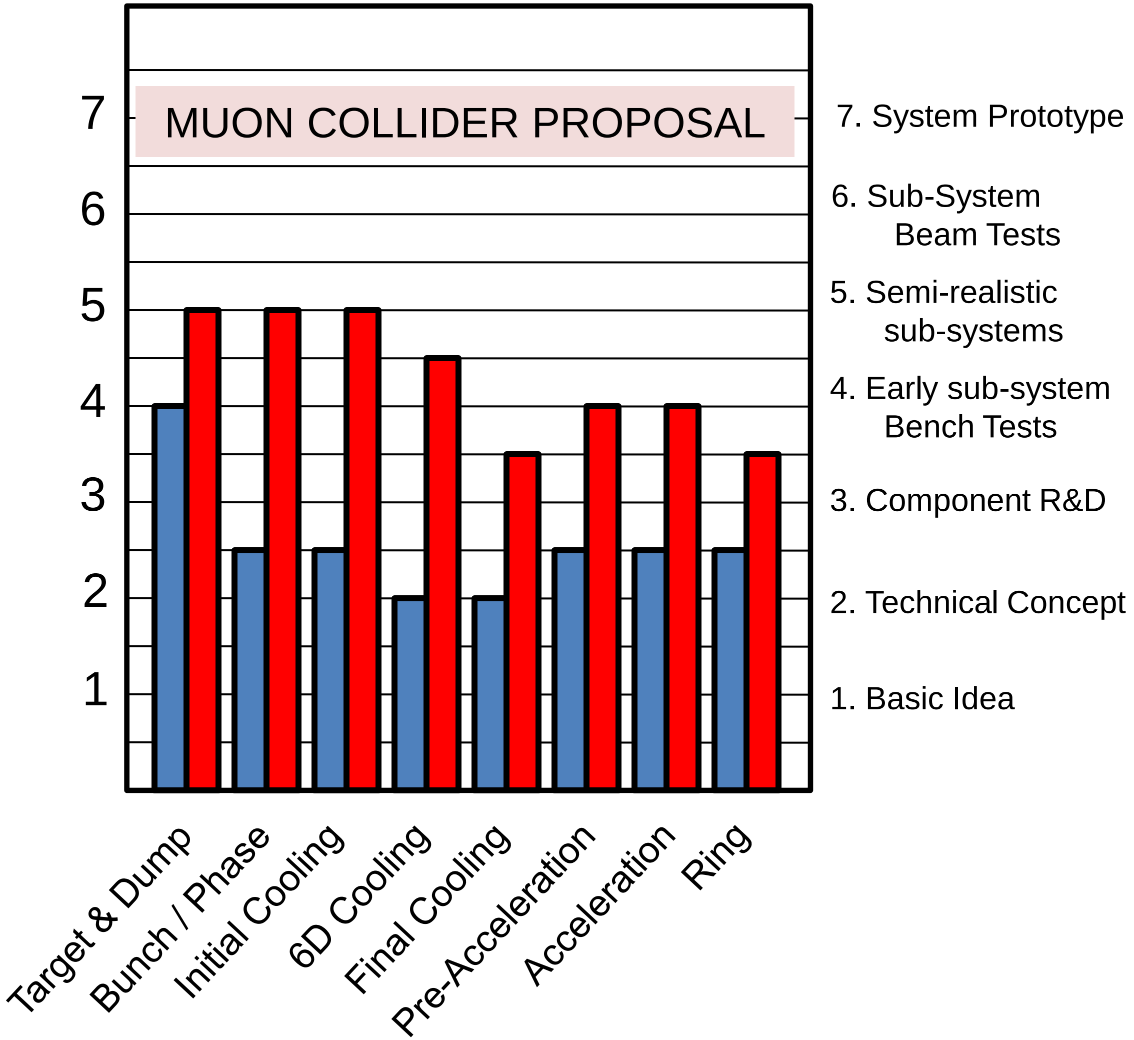
"simultaneously"

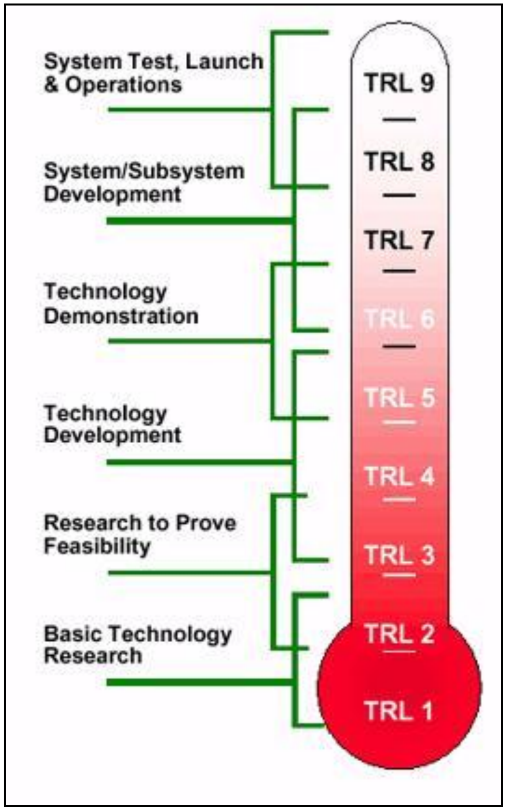


ADD MUON COLLIDER



IMPACT OF MUON COLLIDER DESIGN FEASIBILITY STUDY



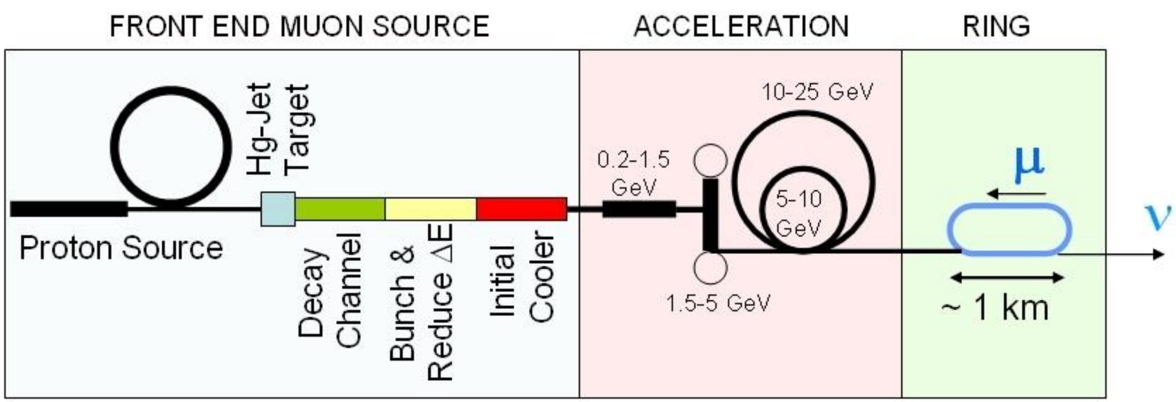


Based on NASA Technology Readiness Levels

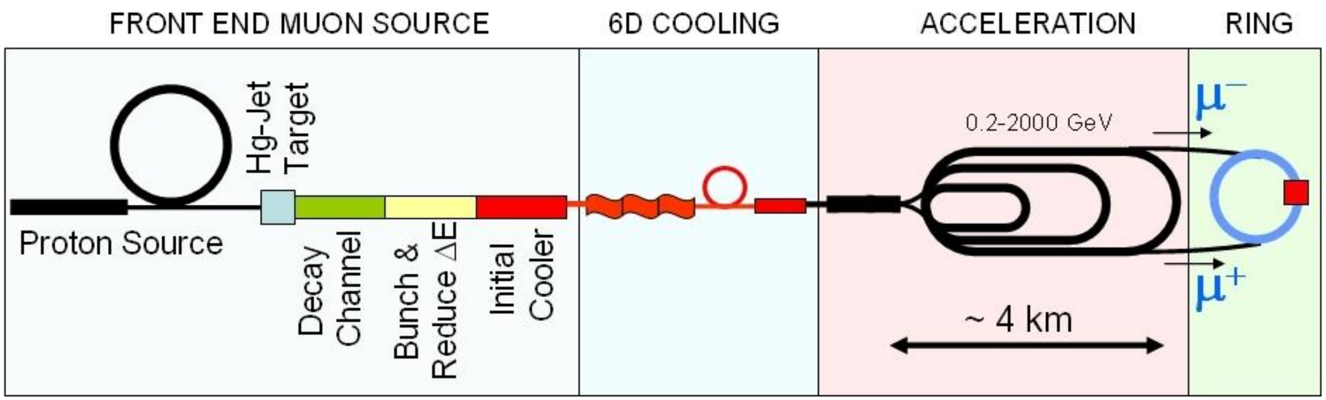
MAP MISSION STATEMENT

The mission of the Muon Accelerator Program (MAP) is 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.

Muon Collider cf. Neutrino Factory



NEUTRINO FACTORY



MUON COLLIDER

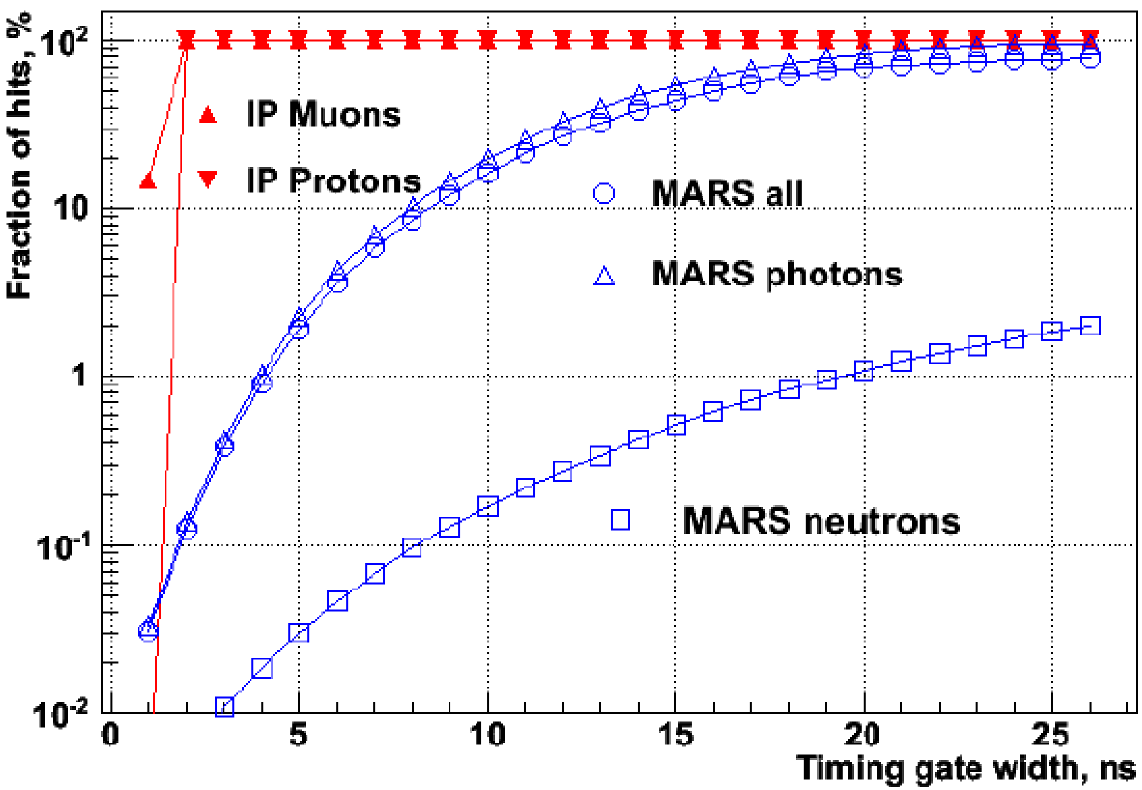
In present MC baseline design, Front End is same as for NF

A Decade of Progress: NF Feasibility Studies

- Successful completion of NF feasibility studies 1, 2, 2a, & International Scoping Study; launching of the ongoing International Design Study for a NF (IDS-NF)
  - Solid basis for planning the MC Design Feasibility Study (DFS)
  - Real progress on understanding how to make enough muons, capture them into bunches, reduce their energy spread, and begin to reduce their transverse phase space (ionization cooling).
- IDS-NF community plans to produce a Reference Design Report (RDR) in ~ 2 years.
  - Interim Design Report (IDR) being finalized now

Background Reduction

- **Choose TOF – T0 time gate width**
  - To detect hits from IP particles with ~100% efficiency (use muons as the fastest, protons as the slowest particles)
  - Then it will define the rejection of the hits from muon collider background particles
  - For now ignore the Si front-end resolution time
  - The gate starts at TOF-T0 = -1ns
- **2-3 ns time gate width ?**



From N.Terentiev (CMU), N.Mokhov (FNAL) , Telluride-2011