Neutrino Factory and Muon Collider Collaboration

Overview

MUTAC Review

April 6, 2009

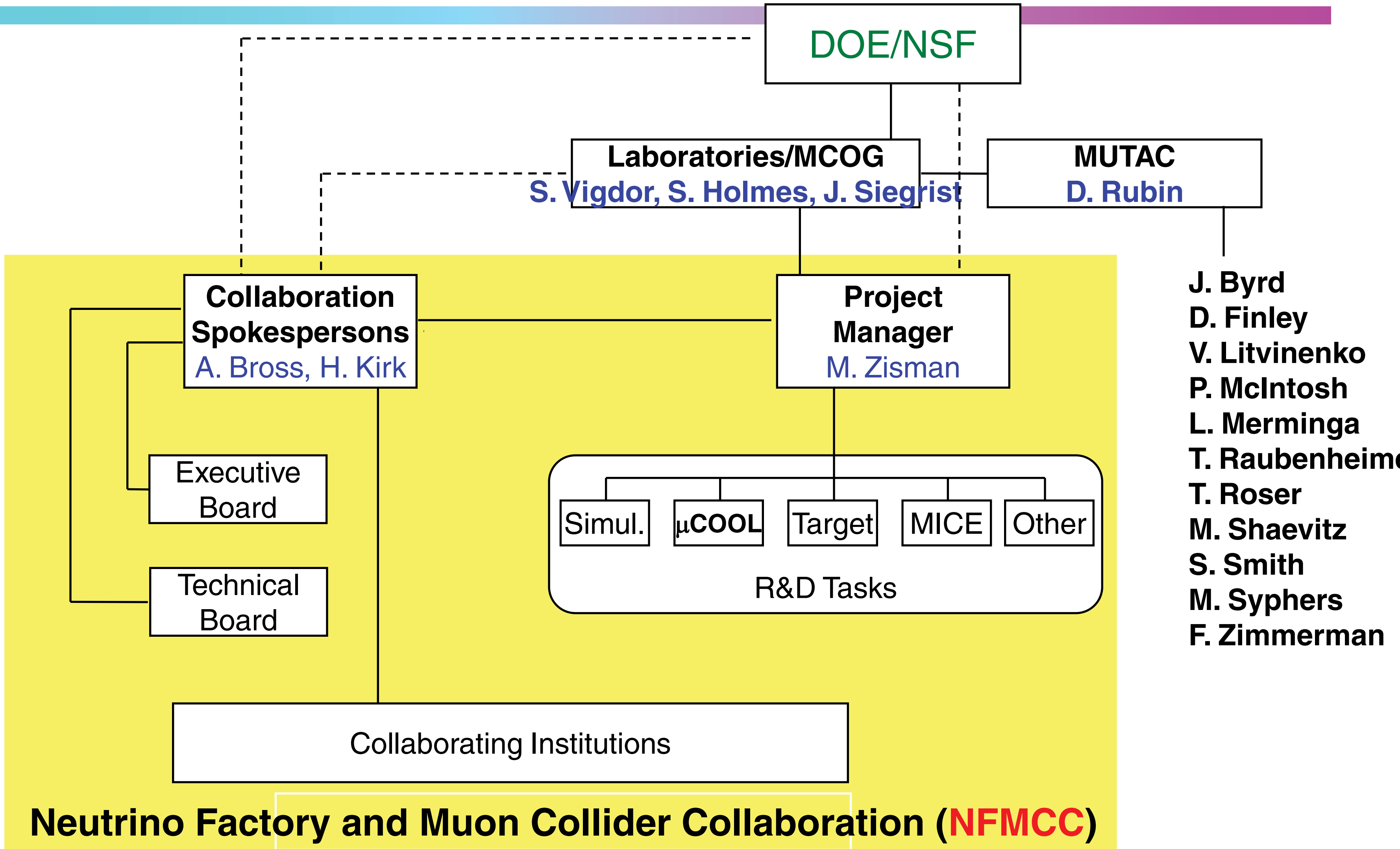
Alan Bross

NFMCC Mission

To study and develop the theoretical tools, the software simulation tools, and to carry out R&D on the hardware that is unique to the design of Neutrino Factories and Muon Colliders

- **Extensive experimental program to verify the theoretical and simulation predictions**

Current Organization



Collaborating Institutions

US

National Labs
ANL*
BNL*
FNAL*
LBNL*
ORNL*
TJNAF*

Universities
Cornell
Illinois
IIT*
Indiana
Iowa
Michigan State
Mississippi*
Northern Illinois
Princeton*
UC-Berkeley*
UC-Davis
UC-Los Angeles*
UC-Riverside*
Wisconsin

International

National Labs
Budker
CERN
DESY
INFN
JINR, Dubna
KEK
RAL
TRIUMF

Universities
Karlsruhe
Imperial College
ICST-Harbin*
Lancaster
Max Planck
Osaka
Oxford
Pohang
Tel Aviv

Corporate Partners
Muons Inc.
Tech-X Corporation

*Currently Funded via the NFMCC

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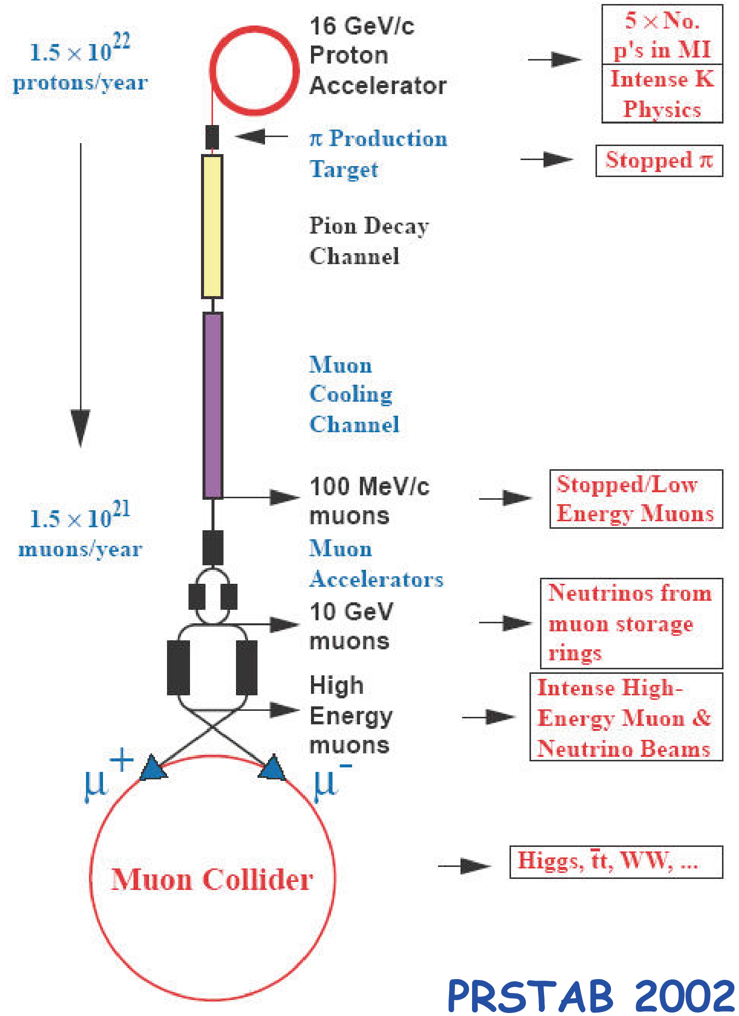
Motivation for Muon Acceleration R&D

Why are we so excited about this work?

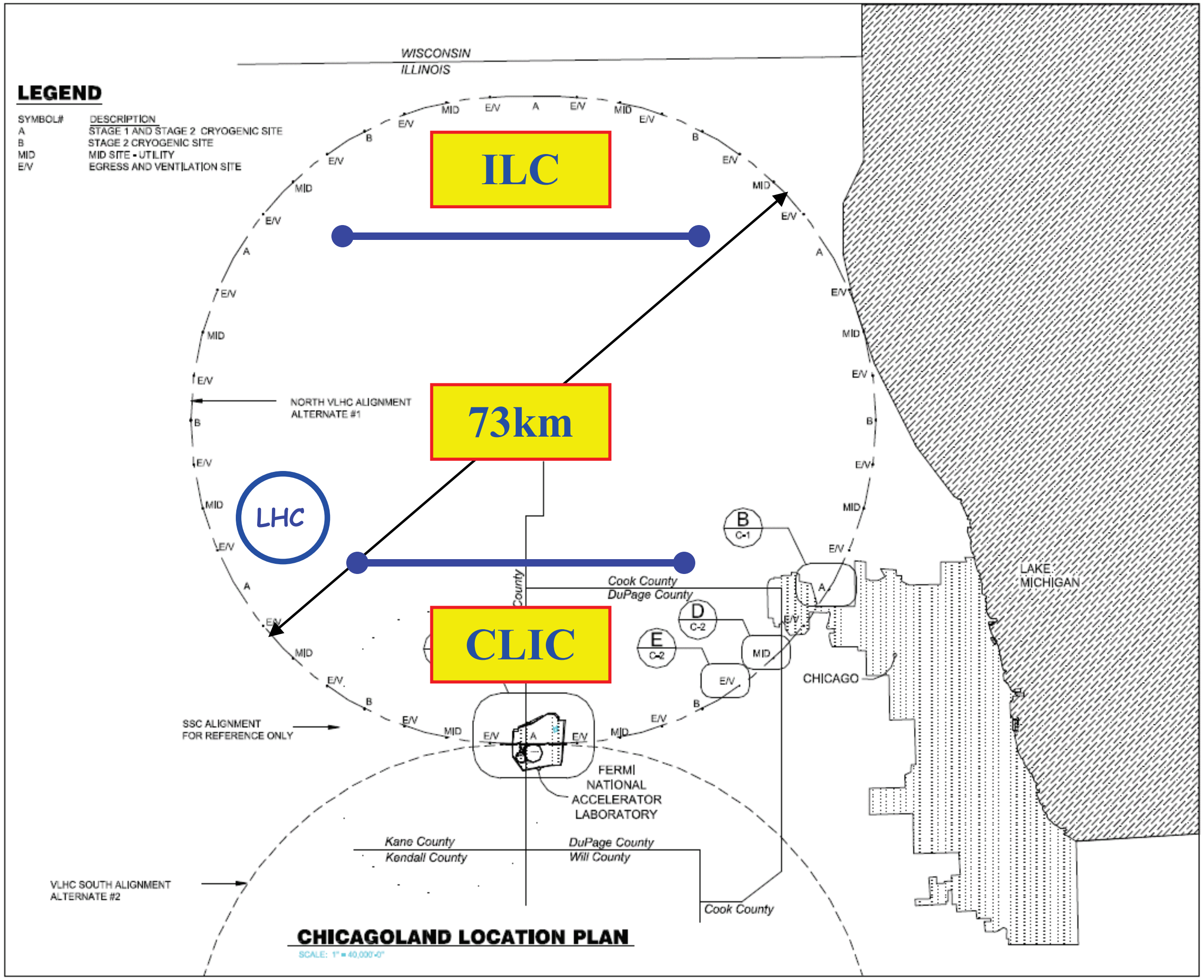
Evolution of a Physics Program



PRSTAB 2002

1. Intense Low-energy muon physics
   - μ e conversion experiment
2. Neutrino Factory
   - Low Energy 4 GeV
   - High Energy 25 GeV
3. Energy Frontier Muon Collider
   - 1.5 - 4 TeV+

Footprint and the Energy Frontier



The VLHC is the largest machine to be seriously considered to date

Stage 1 - 40 TeV

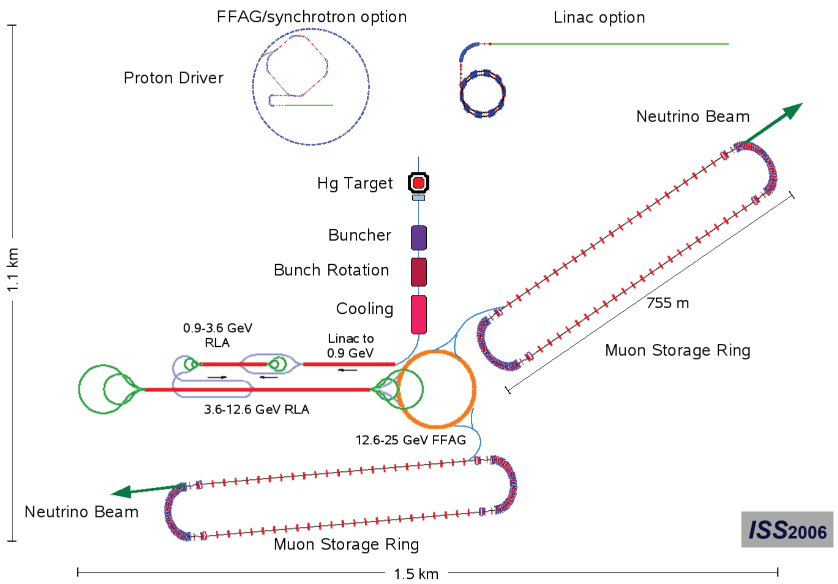
> 2 TeV

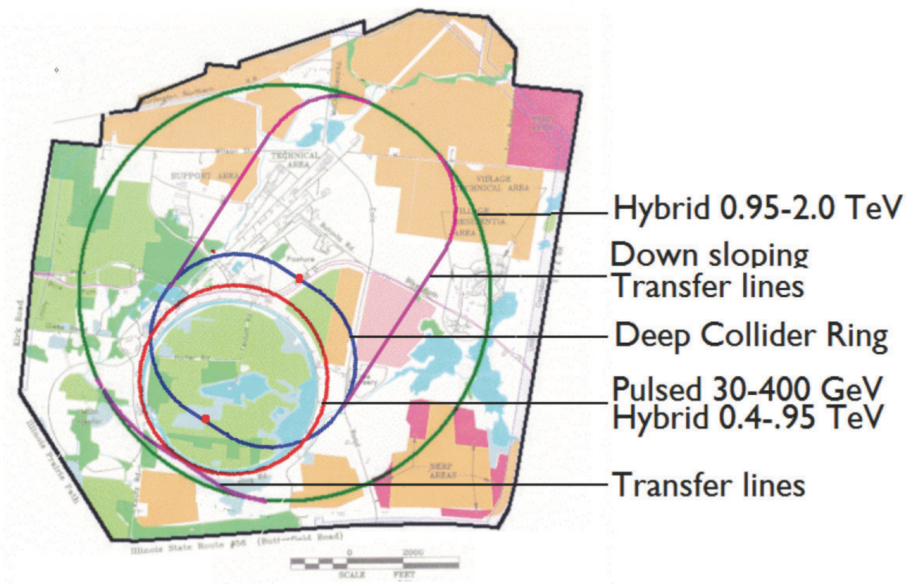
ILC $\Rightarrow$ 0.5 TeV

CLIC $\Rightarrow$ 3 TeV

Muon Facilities are different

Neutrino Factory ⇒ Muon Collider





- **Neutrino Factory**
  - IDS Baseline (FS1, FS2(a) ISS)
    - 25 GeV μ storage ring

- MC: One Concept
  - 4 TeV Center-of-Mass
    - Rapid-Cycling Synchrotron Acceleration

SMALL FOOTPRINT

NF Motivation - Physics Reach (ISS)

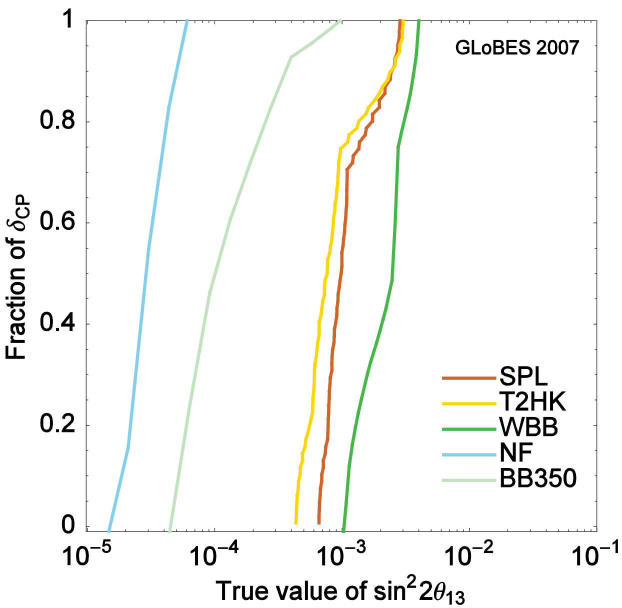
arXiv:0710.4947v2 [hep-ph]

- The NF still gives the best Physics Reach in 3ν mixing model

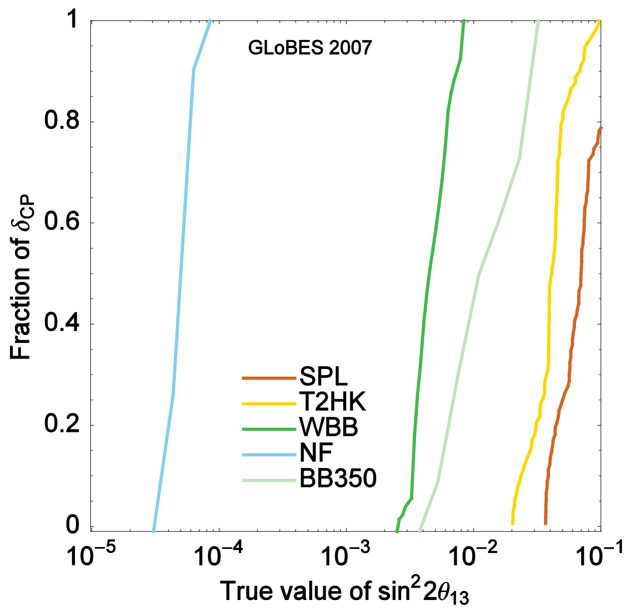
  And NF presents best opportunity to exploit New Physics

3σ contours shown

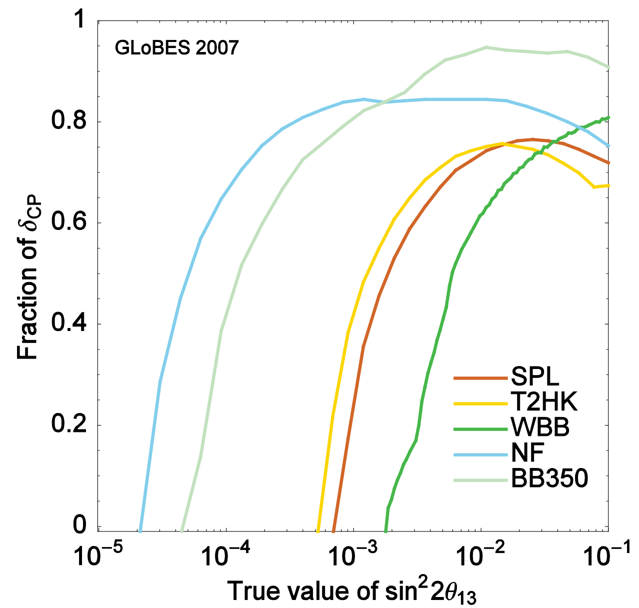
$\sin^2 2\theta_{13}$



Hierarchy



δ *CP*



SPL: 4MW, 1MT H_2OC, 130 km BL
T2HK: 4 MW, 1MT H_2OC, 295 km BL
WBB: 2MW, 1MT H_2OC, 1300 km BL

NF: 4MW, 100KT MIND, 4000 & 7500 BL
BB350: γ=350, 1MT H_2OC, 730 km BL

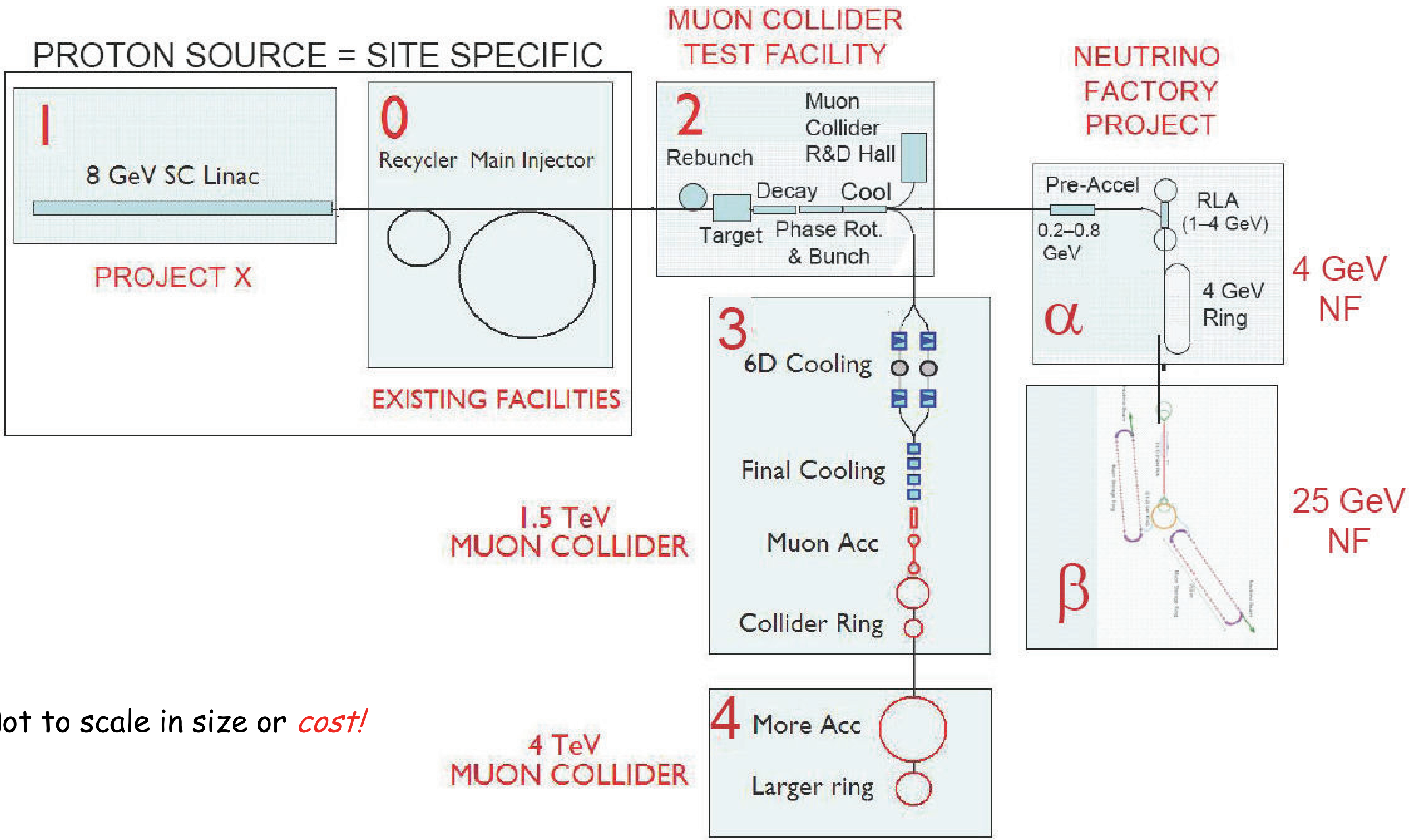
Muon Collider - Motivation

Reach Multi-TeV Lepton-Lepton Collisions at High Luminosity

Muon Colliders may have special role for precision measurements. Small ΔE beam spread - Precise energy scans

Small Footprint - Could Fit on Existing Laboratory Site

Evolution of Muon Facility @ Fermilab



Not to scale in size or *cost!*

Needs Common to NF and MC Facility

- Proton Driver
  - Project X
    - PD for MC likely can work for NF but not necessarily vice versa
- Target, Capture, and Decay
  - create π's; decay into μ's
- Phase Rotation
  - reduce ΔE of bunch
- Cooling
  - reduce emittance of the muons
    - Cost-effective for NF
    - Essential for MC
- Acceleration
  - Accelerate the Muons
- Storage Ring
  - store for ~1000 turns

80% Overlap in initial R&D

But there are Key Differences

Neutrino Factory

- Cooling
  - Reduce transverse emittance
    - $\varepsilon_\perp \sim 7$ mm
- Acceleration
  - Accelerate to 25 GeV
    - May be as low as 5-7 GeV
- Decay Ring
  - No intersecting beams

Muon Collider

- Cooling
  - Reduce 6D emittance
    - $\varepsilon_\perp \sim 3\text{-}25\ \mu$m
    - $\varepsilon_L \sim 70$ mm
- Acceleration
  - Accelerate to 1-2 TeV
- Collider Ring
  - Intersecting beams

Key R&D Issues

- High Power Targetry – NF & MC *(MERIT Experiment)*
- Initial Cooling – NF & MC *(MICE (4D Cooling))*
- RF R&D - NF & MC *(MuCool, MCTF, Muons Inc.)*
  - Investigate operation of vacuum RF cavities in presence of high magnetic fields
  - Investigate Gas-Filled RF cavities
    - Operation in B field and Beam-Induced Effects
  - While obtaining high accelerating gradients (~16MV/m)
- Intense 6D Cooling – MC (MCTF, Muons Inc.)
  - RFOFO "Guggenheim"
  - Helical Channel Cooling (Manx Proposal)
  - Parametric Resonance Ionization Cooling
- High Field Magnets
  - HTS magnet R&D (in collaboration with National HTS Collaboration)
- Bunch Recombination
- Acceleration– A cost driver for both NF & MC, but in very different ways
  - FFAGs *(Electron Model with Many Applications – Applicable for Muon Acceleration)*
  - Multi-turn RLAs
- Storage Ring(s) – NF & MC
- Theoretical Studies NF & MC (Joint NFMCC & MCTF)
  - Analytic Calculations
  - Lattice Designs
  - Numeric Simulations

Note: Almost all R&D Issues for a NF are currently under theoretical and experimental study

Scientific Program

Targetry R&D: Mercury Intense Target Experiment (MERIT)

Co-Spokespersons: Kirk McDonald, Harold Kirk

Ionization Cooling R&D: MuCool and MICE

MuCool Spokesperson: Alan Bross

US MICE Leader: Dan Kaplan

Simulations & Theory

Coordinator: Rick Fernow

Collaborating on EMMA

Collaborating on the International Design Study for a Neutrino Factory (IDS-NF)

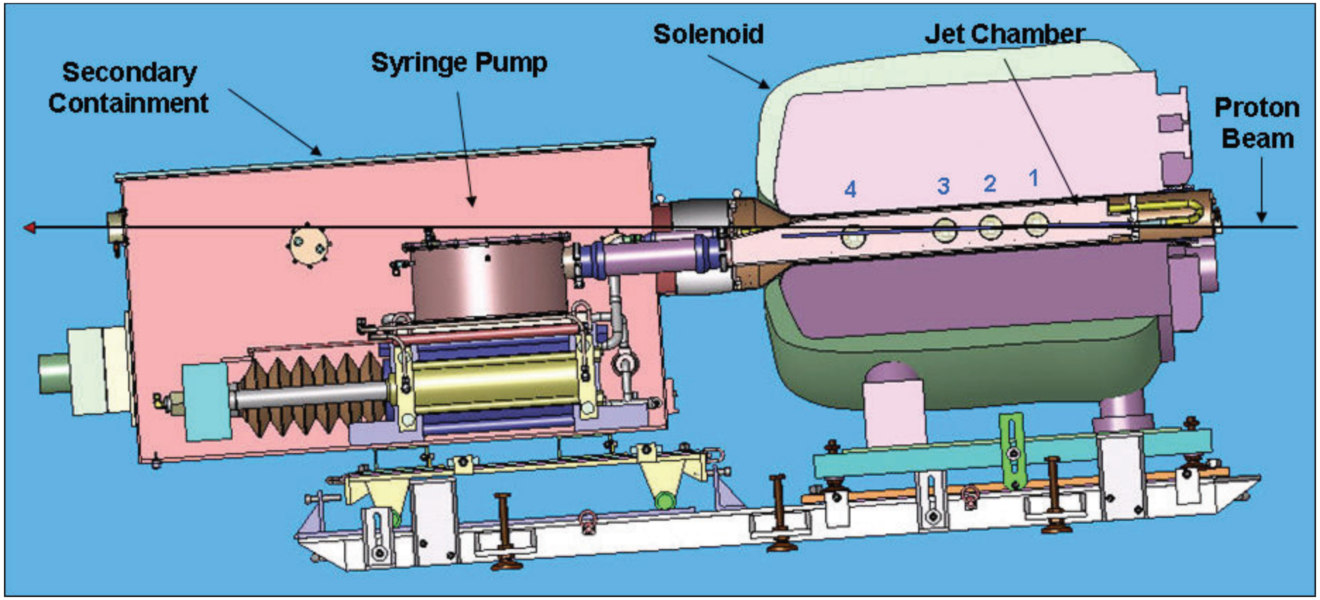
Fermilab Muon Collider Task Force

V. Shiltsev, S. Geer

MERIT

Mercury Intense Target
Liquid-Hg Jet

The Experiment Reached 30TP @ 24 GeV



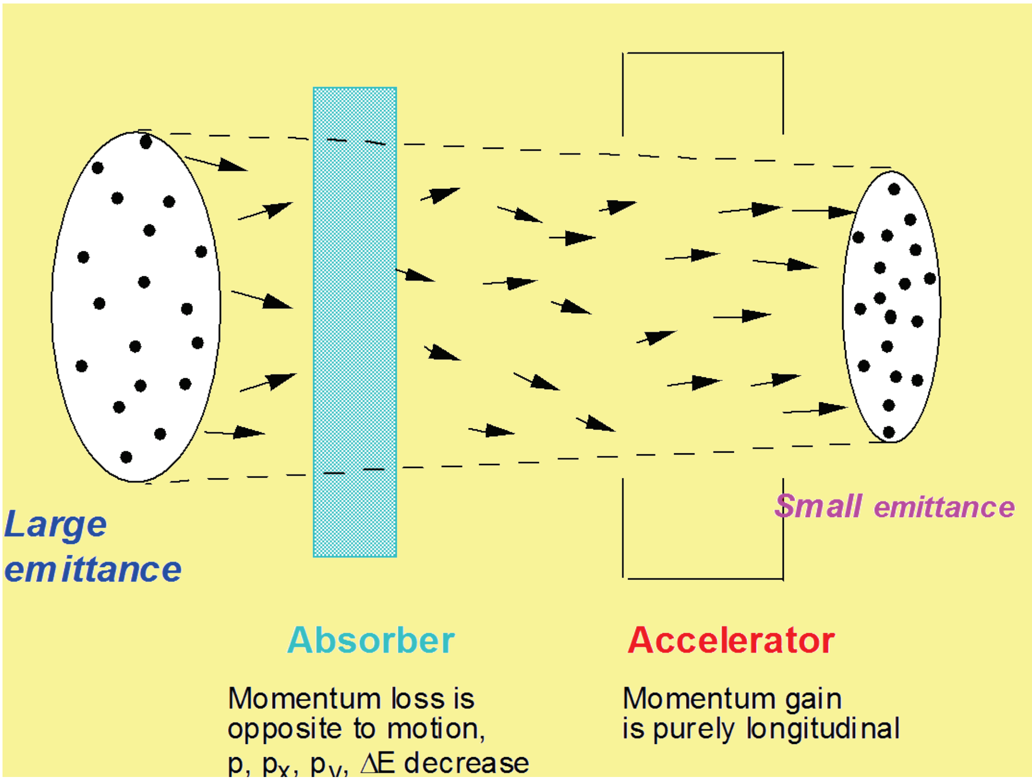
- Beam pulse energy = 115kJ
- B-field = 15T
- Jet Velocity = 20 m/s
- Measured Disruption Length = 28 cm
- Required "Refill" time is then 28cm/20m/s = 14ms
  - → Rep rate of 70Hz

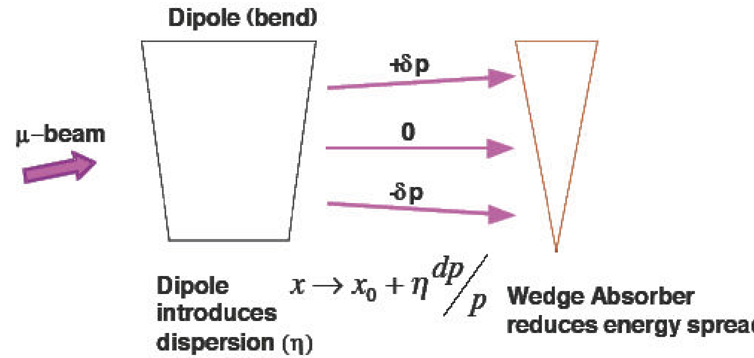
➔ Proton beam power at that rate is 115kJ *70 = 8MW

Muon Ionization Cooling R&D

MuCool and MICE

Muon Ionization Cooling





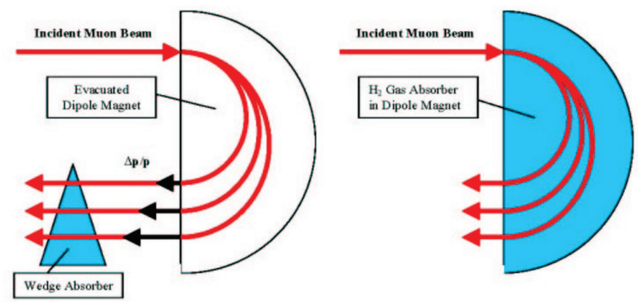


Figure 1. Use of a Wedge Absorber for Emittance Exchange

Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

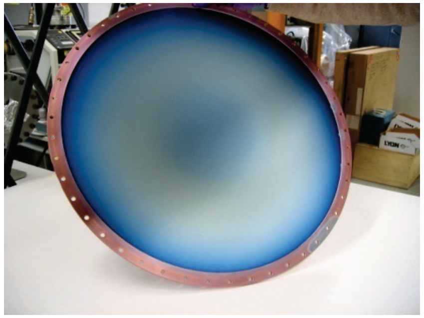
Muons, Inc. Innovation in Research

Transverse

Longitudinal - Emittance Exchange

MuCool
Component R&D

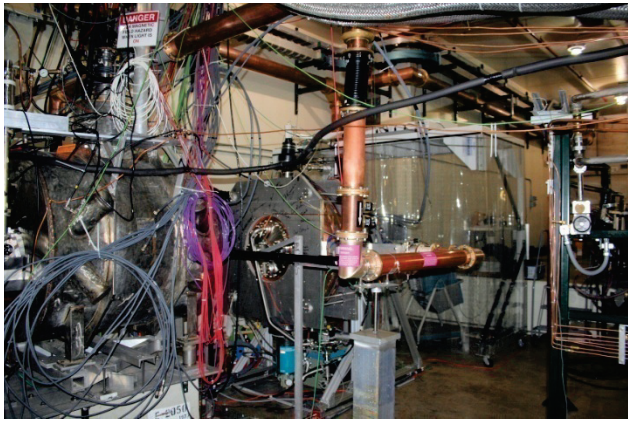
- **MuCool**
  - Component testing: RF, Absorbers, Solenoids
    - With High-Intensity Proton Beam
  - Uses Facility @Fermilab (MuCool Test Area –MTA)
  - Supports Muon Ionization Cooling Experiment (MICE)



42 cm ∅ Be RF window

MuCool Test Area

MuCool
201 MHz RF Testing



MuCool
LH_2 Absorber
Body

RF Test Program

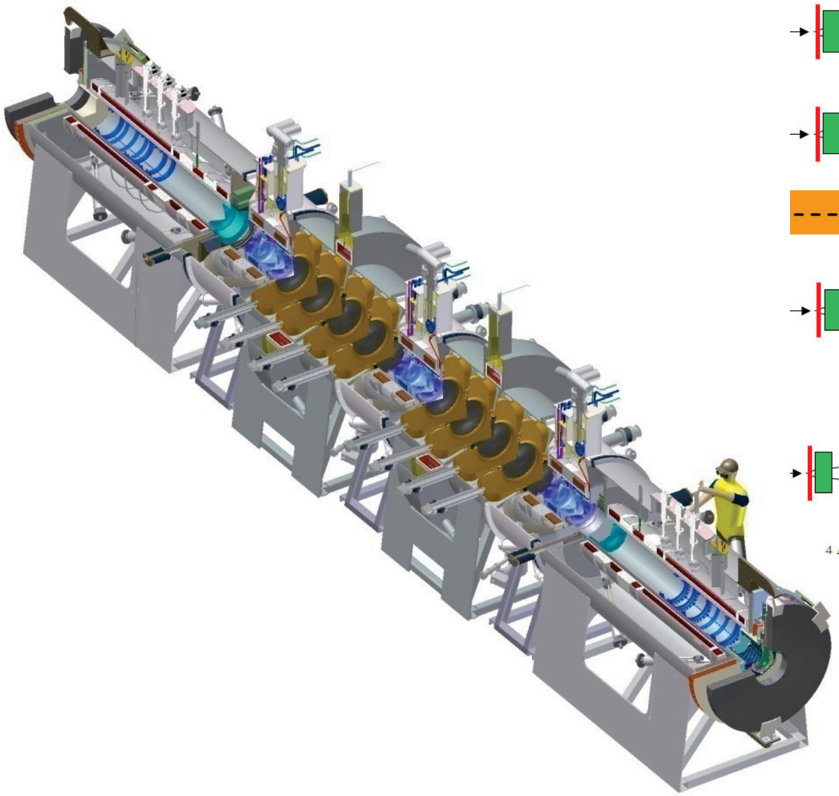
MuCool has the primary responsibility to carry out the RF Test Program

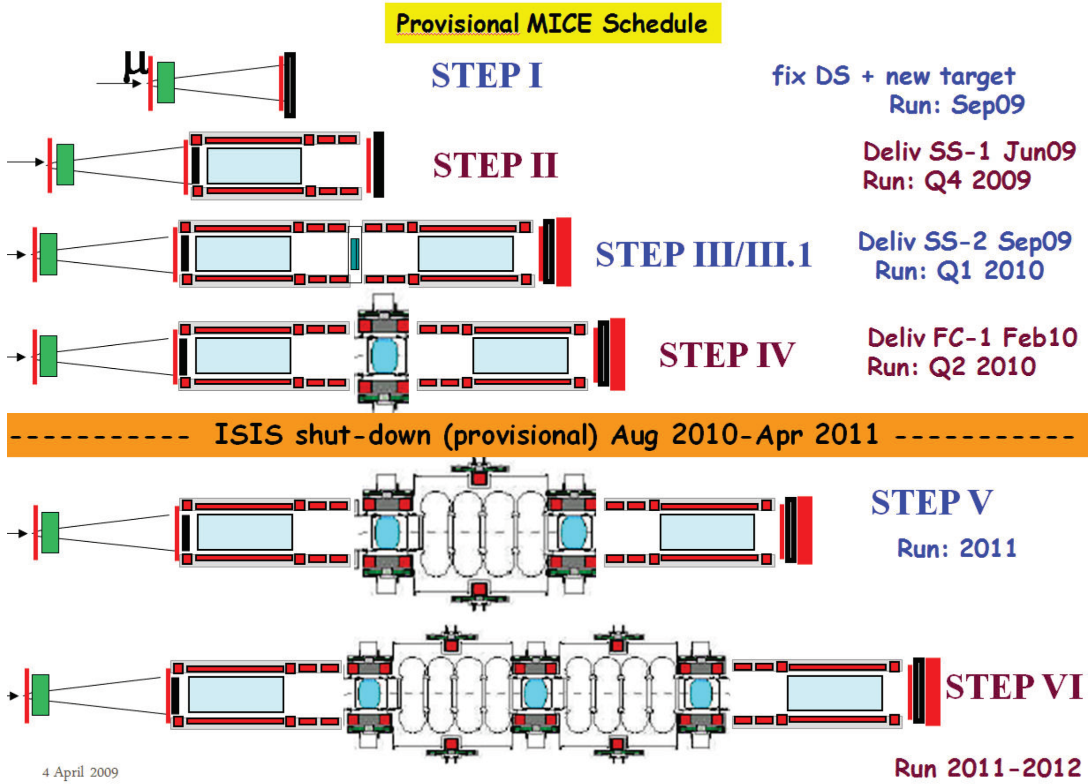
- Study the limits on Accelerating Gradient in NCRF cavities in high magnetic field
- It has been proposed that the behavior of RF systems in general can be described (predicted) by universal curves
  - Tensile Stresses are important in RF Breakdown events
    - Study of RF cavity performance with different materials
      - Coatings, base materials (Cu, Al, Be), Temperature effects
- This applies to all accelerating structures
- Fundamental Importance to both NF and MC – RF needed in
  - Muon capture, bunching, phase rotation
  - Muon Cooling
  - Acceleration

Arguably the single most critical Technical challenge for the NF & MC

Muon Ionization Cooling Experiment (MICE)

MICE
Measurement of Muon Cooling
Emittance Measurement @ 10^{-3}
First Beam February 2008





International Design Study for a Neutrino Factory

The IDS-NF

Fermilab

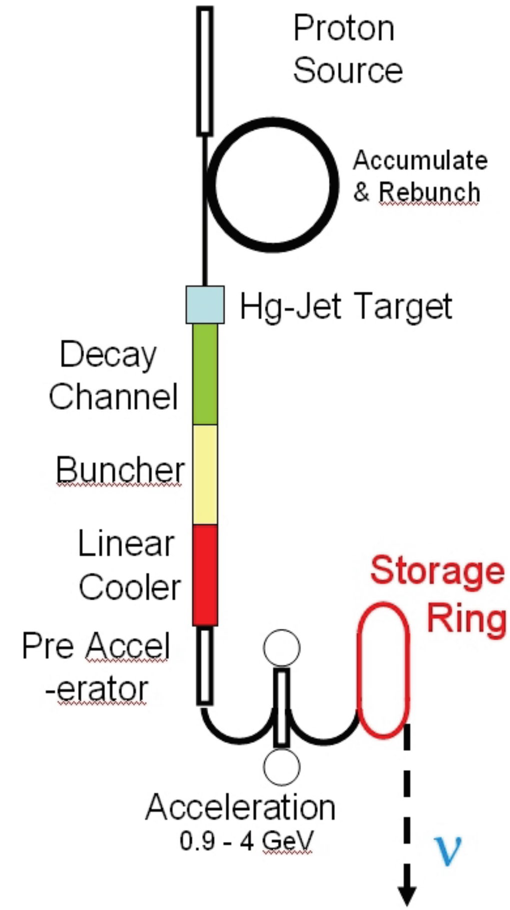
IDS-NF

- Takes as starting point - International Scoping Study ν-Factory parameters
  - ~4MW proton source producing muons, accelerate to 25 GeV, Two baselines: 4000km & 7500km
- IDS Goals
  - Specify/compute physics performance of neutrino factory
  - Define accelerator and detector systems
  - Estimate cost and schedule
  - Identify necessary R&D items
- IDS Deliverables
  - Interim design report (c. 2010)
    - Engineering designs for accelerator and detector systems
    - Cost and schedule estimates
    - Work plan to deliver reference design report
      - Report production itself
      - Outstanding R&D required
  - Reference design report (c. 2012)
    - Basis for asking for the transition into a Project

IDS-NF Option: 4 GeV ν-Factory

- Fermilab to DUSEL (South Dakota) baseline -1290km
- 4 GeV muons yield appropriate L/E_{ν}
- Use a magnetized totally active scintillator detector

Geer, Mena, Pascoli
Phys. ReV D 75, 093001 (2007)
Bross, Ellis, Geer, Mena, Pascoli
Phys. ReV D 77, 093012 (2008)



Ankenbrandt, Bogacz, Bross, Geer, Johnstone, Neuffer, Popovic
Fermilab-Pub-09-001-APC; Submitted to PRSTAB

Design Studies

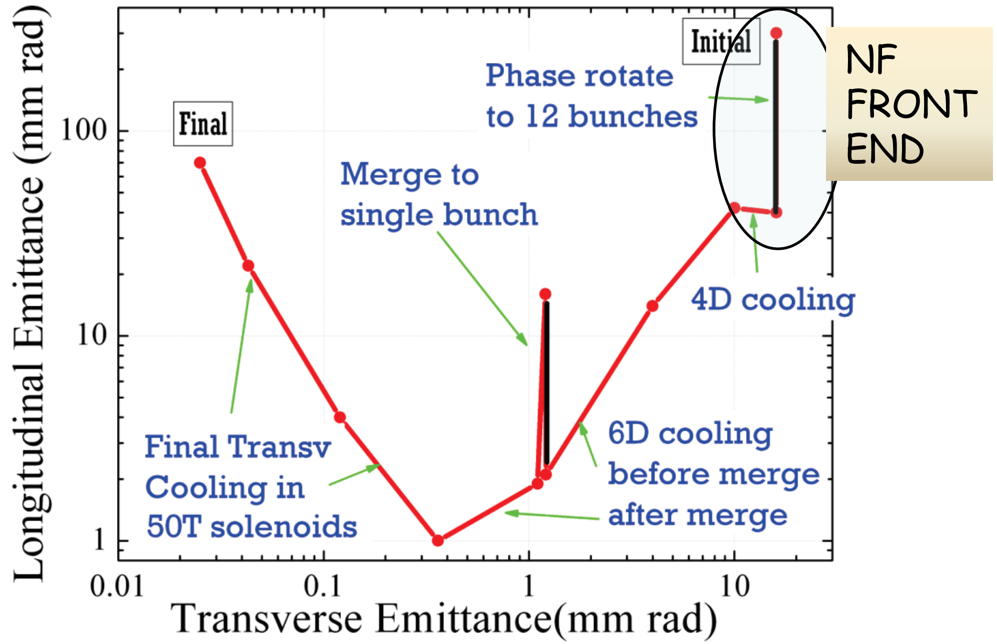
Muon Collider

Design Studies

- Muon Collider Design and Simulation work has reached a new level of intensity
  - Work in all areas
    - Cooling
    - Acceleration
    - Ring and IR
    - Start on Detector design considerations

Muon Collider Design Progress

- Muon Collider designs start with a NF front-end, but require a much more ambitious cooling channel (6D cooling ~ $O(10^6)$ c.f. 4D cooling ~ $O(100)$.
- In the last 5 years concepts for a complete end-to-end self con-sistent cooling scheme have been developed

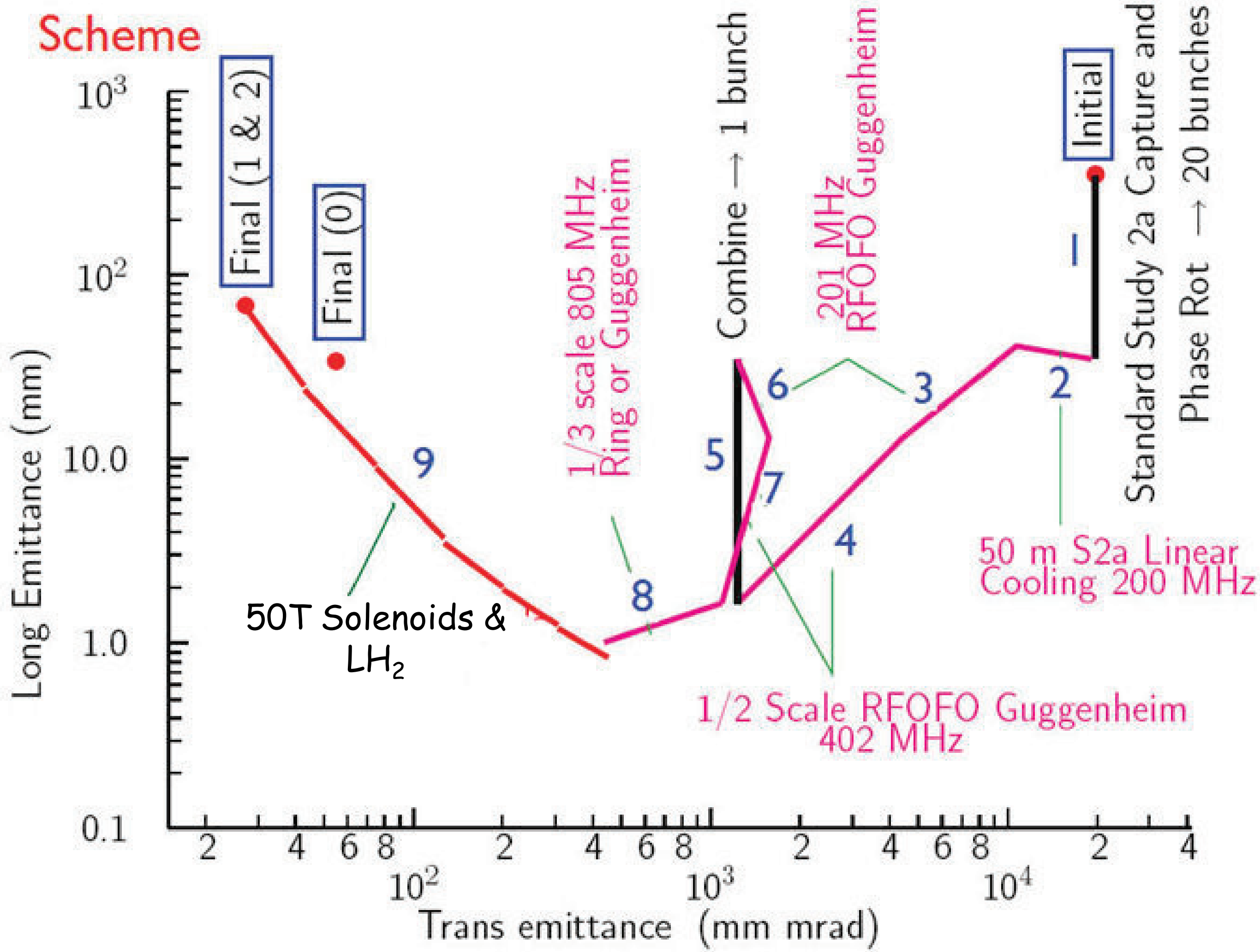


Requires beyond state-of-art components: need to be developed

Hardware development and further simulations need to proceed together to inform choices between alternative technologies

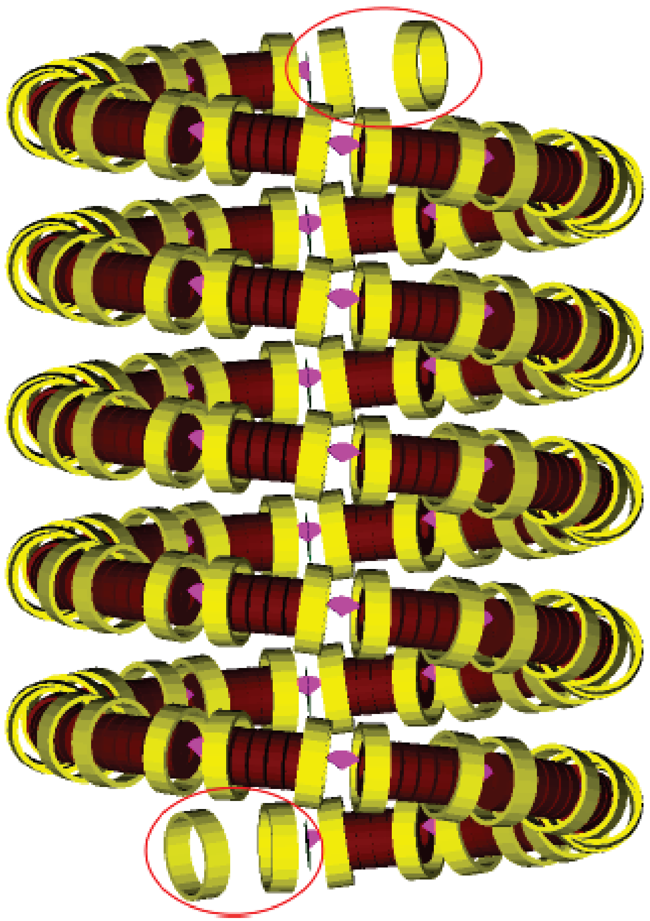
- Also progress on acceleration scheme & Collider ring design, but the cooling channel presently provides the main Muon Collider challenge

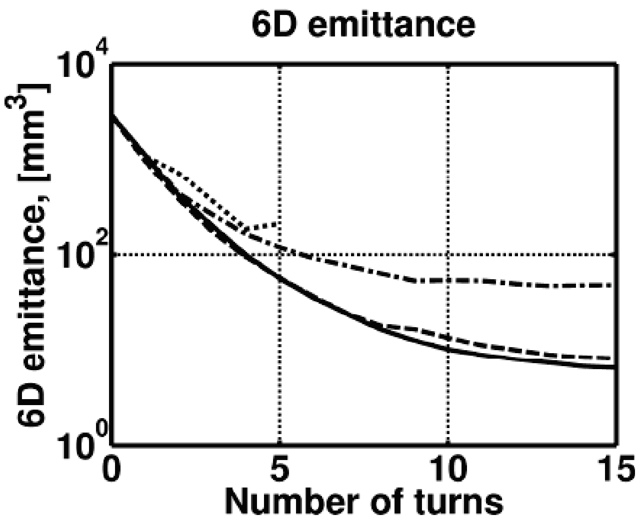
A Muon Collider Cooling Scenario

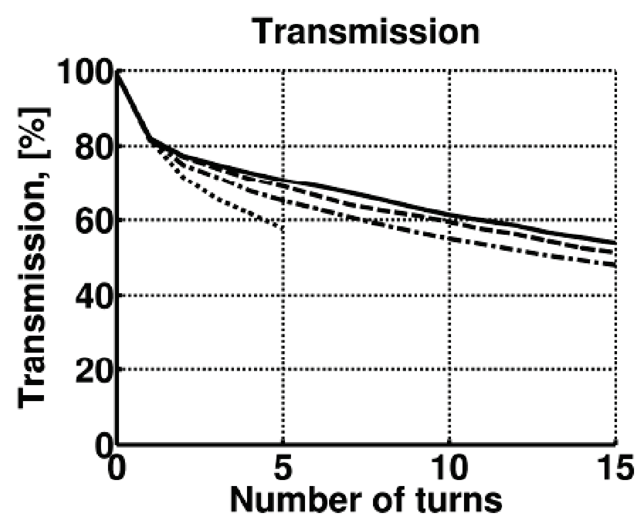


Guggenheim RFOFO - Simulations

Multilayer scheme







Parameters of Different MC options

	Low Emit.*	High Emit.**	MCTF07	MCTF08	
$\sqrt{s}$ (TeV)		1.5			
Av. Luminosity ($10^{34}/cm^2/s$) *	2.7	1	1.33-2		
Av. Bending field (T)	10	6	6		
Mean radius (m)	361.4	500	500 ⇒	495	
No. of IPs	4	2	2		
Proton Driver Rep Rate (Hz)	65	13	40-60		
Beam-beam parameter/IP	0.052	0.087	0.1		
β^* (cm)	0.5	1	1		
Bunch length (cm)	0.5	1	1		
No. bunches / beam	10	1	1		
No. muons/bunch (10^{11})	1	20	11.3		
Norm. Trans. Emit. (μm)	2.1	25	12.3		
Energy spread (%)	1	0.1	0.2		
Norm. long. Emit. (m)	0.35	0.07	0.14		
Total RF voltage (GV) at 800MHz		$407\times10^3\alpha_c$	0.21**	0.84** ⇒	0.3†
Muon survival $N\mu/N\mu0$		0.31	0.07	0.2	?
μ+ in collision / proton		0.047	0.01	0.03	?
8 GeV proton beam power	3.62***	3.2	1.9-2.8	?	

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*Muons Inc.

**Palmer et. al.

Muon Accelerator R&D
Conclusions

- Neutrino Factory
  - Compelling case for a precision neutrino program
    - With present assumptions Neutrino Factory out-performs other options. However, more is needed before concluding this is the right path
      - What the on-going Neutrino Physics program tells us
      - Process must include cost and schedule considerations
        - International Design Study
- Muon Collider
  - New concepts improve the prospects for a multi-TeV Muon Collider
    - Advanced concepts for 6D muon ionization cooling
  - Front-end is the same (similar) as for a Neutrino Factory

The Way Forward

- **Technical Progress**
  - The MERIT experiment has come to a successful completion
    - Analyzing Data
  - MuCool is preparing for an exciting new phase
  - MICE is moving ahead
    - With some bumps along the road
  - We have strong participation in the IDS for a Neutrino Factory
- **Major Progress on the MC**
  - December 2008 Submission of a joint NFMCC – MCTF 5 Year Proposal to DOE
    - Produce Muon Collider Feasibility Design Study
      - First Defendable costing
- **Resource Limitations**
  - The collaboration is still funding limited and progress in a number of areas is considerably slower than is technically possible
    - Our 5 Year Plan Proposal Addresses this

Road Map to the Future

- We believe ~2013 will be a pivotal time in HEP
  - LHC Physics Results
  - Neutrino Data from Reactor and Accelerator Experiments
    - Double Chooz Daya Bay
    - MINOS, T2K ,Nova
  - Major Studies for Frontier Lepton-Colliders Completed
    - ILC EDR
    - CLIC CDR
- There are likely to be many exciting results that will point us in *Some* Direction
  - *We Don't Know Which One Yet - But a robust program in Muon Acceleration R&D will permit the NF and the MC to be a credible part of the discussion*
    - 5 Year Plan Proposal is time critical