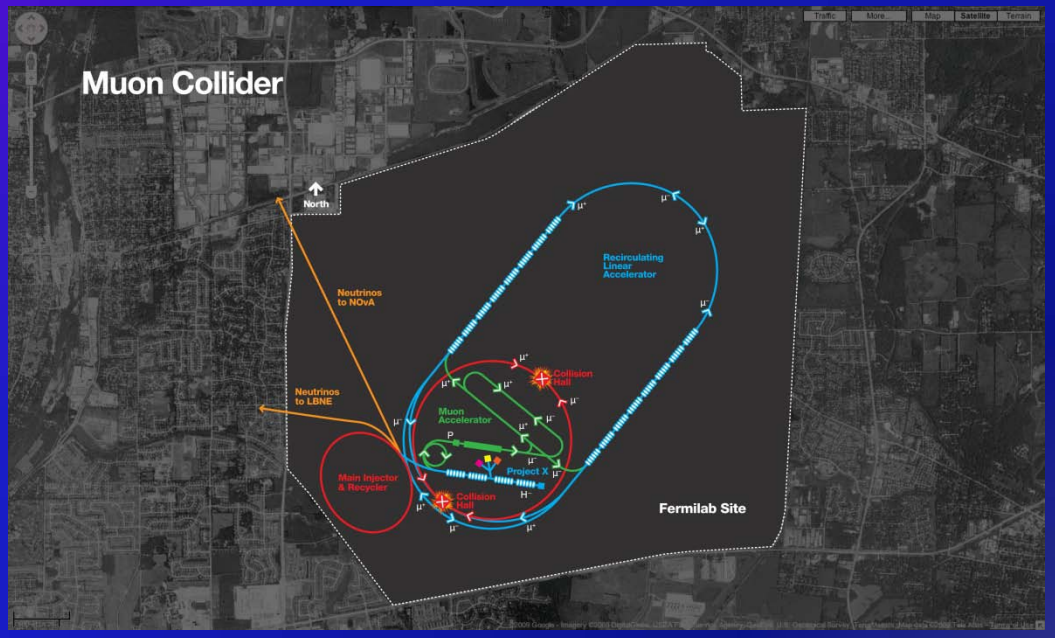


The US Muon Collider R&D Program

"Who Ordered That?"

Exploring the Energy Frontier without ever Going Off Site

Alan Bross
Fermilab

Neutrino Factory and Muon Collider R&D in the US

"Two Mints in One?

Preamble

When he first heard of the discovery of the muon in 1936, Isidor Rabi asked, *"Who ordered that?"* At the time, the muon didn't fit into the understanding of the subatomic world.

- We now know better

- When some physicists argue that Muon Accelerator Facilities should (must) play an expanded role in future High Energy Physics Facilities: Neutrino Factory, Muon Collider
  - Others question – "Who ordered *THAT?*"
    - Some of us think we know better

A Bit of History

Since the late 1990s, the Neutrino Factory and Muon Collider Collaboration (a.k.a. Muon Collaboration) has pursued an active R&D program that has focused on muon production, capture and acceleration. (Out-growth of Snowmass 96 work on 4TeV $\mu^+\mu^-$ Collider.) Initially the physics emphasis was on muon colliders (both a Higgs Factory and an energy frontier machine). By 2000 the focus of the collaboration had shifted to studying the feasibility of a Neutrino Factory. Recently new ideas in muon ionization cooling have reinvigorated the collaboration's efforts on the investigation of energy frontier muon colliders. In 2006 the Muon Collider Task Force was formed at Fermilab R&D program aimed at the technologies required to support the long term prospects of a Muon Collider"

We now have it all rolled into the Muon Accelerator Program MAP

Outline

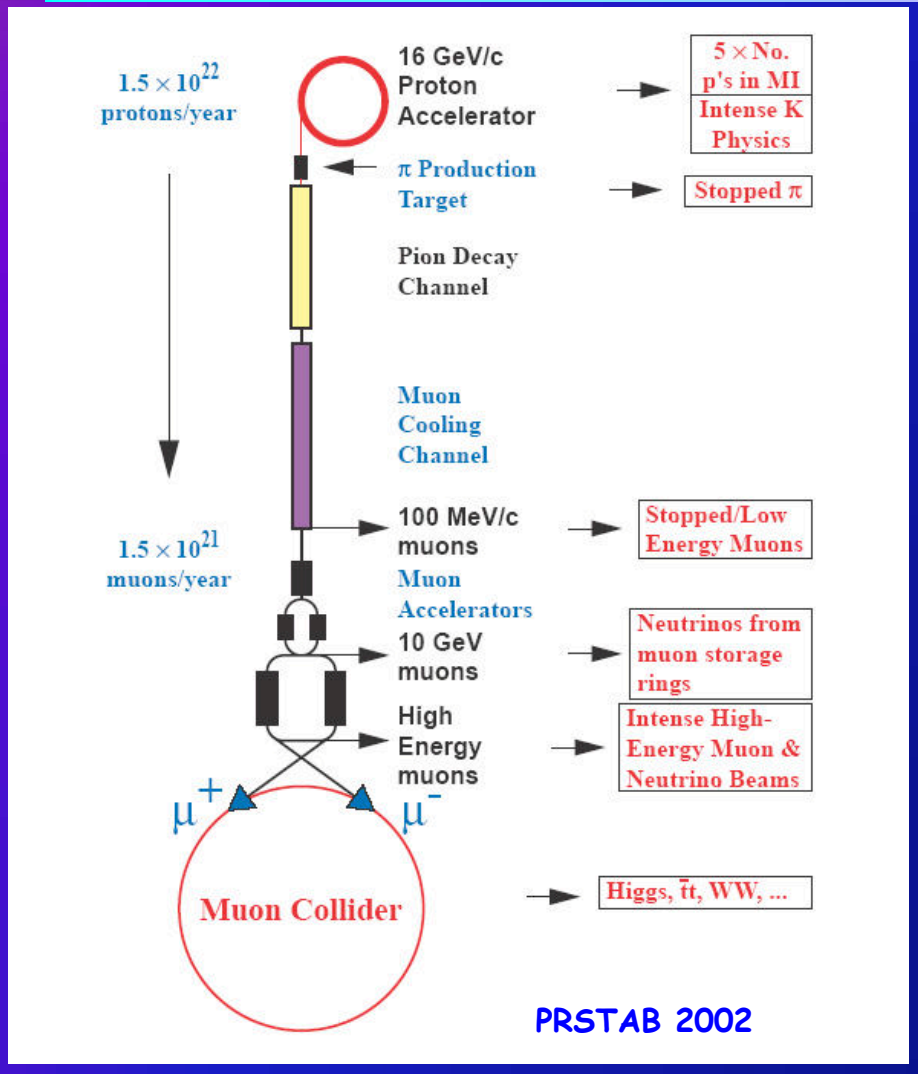
My Talk

- Why Muon Accelerator Facilities? *Inspirational*
  - Physics motivation for and nature of possible future facilities based on ultra-high intensity muon beams
  - Explore the synergy between Neutrino Factory and Muon Collider facilities both from the point of view of the physics program and the accelerator complex
- Muon Collider Fundamentals
- What technologies are crucially central to making the above a reality. *Technical R&D Overview*
- Getting Involved
- I hope to give you Overview of our activities but will have to leave out many technical details
  - http://www.fnal.gov/pub/muon_collider/

Physics in Evolution

What we might do at a Muon Accelerator Facility

Evolution of a Physics Program

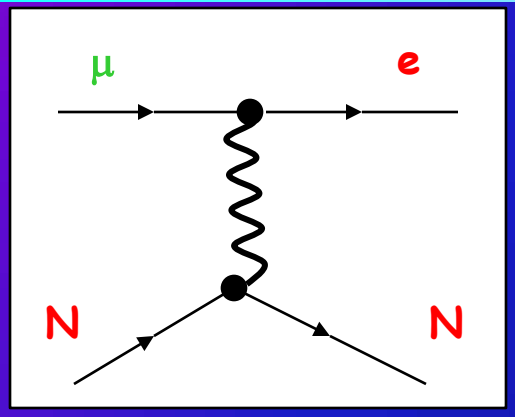


From Snowmass 96

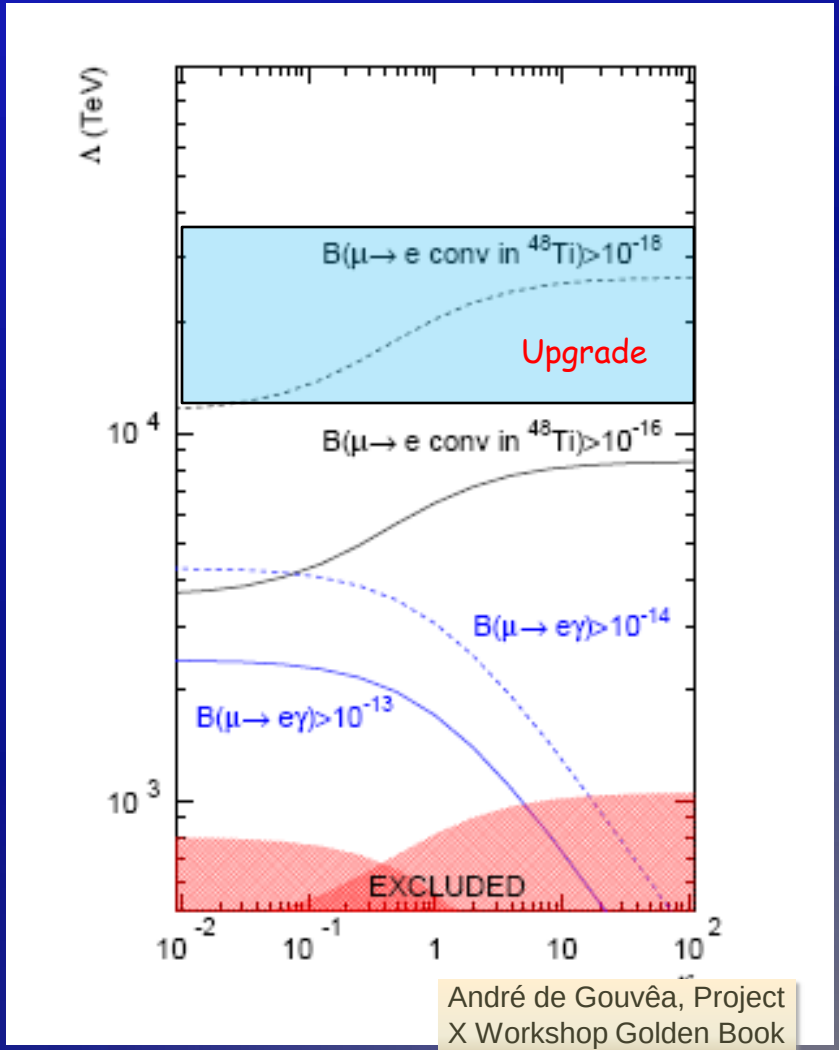
A μ source providing 1-2 X 10^{21} μ/yr supports a rich physics program:

1. Intense Low-energy muon physics (LFV)
   - $\mu \rightarrow e$ conversion experiment
2. Neutrino Factory
   - Low Energy 4 GeV
   - High Energy 25 GeV
3. Energy Frontier Muon Collider
   - 1.5 - 4 TeV+
     - With maybe a lower Ecom machine (Higgs, Z') first.

Low-Energy Muon Physics: $\mu \rightarrow e$ conversion

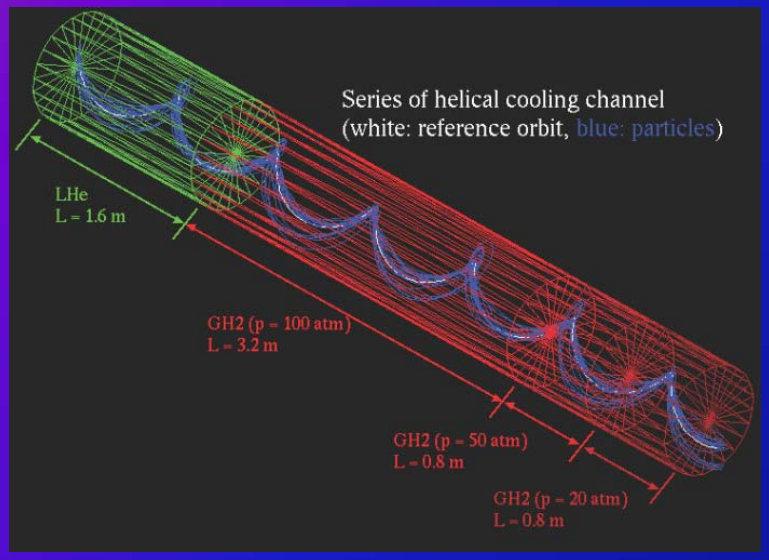


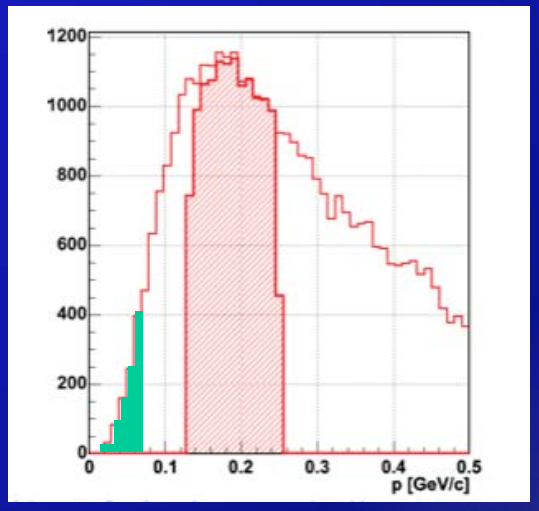
- **Sensitive tests of Lepton Flavor Violation (LFV)**
  - In SM occurs via ν mixing
    - Rate well below what is experimentally accessible
  - Places stringent constraints on physics beyond SM
    - Supersymmetry
      - Predictions at 10^{-15}
- **Mass Reach to $\approx 4 \times 10^4$ TeV**

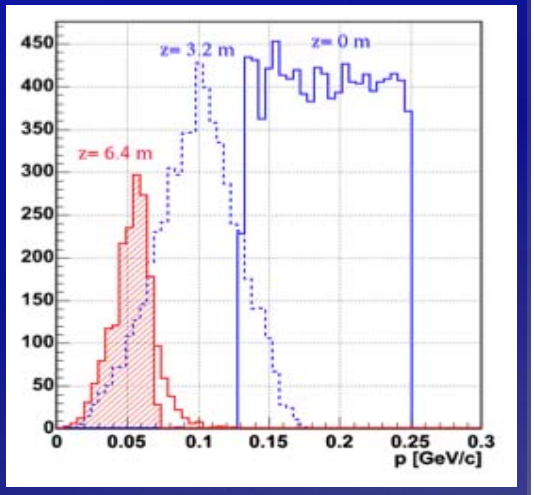


André de Gouvêa, Project X Workshop Golden Book

Muon Ionization Cooling





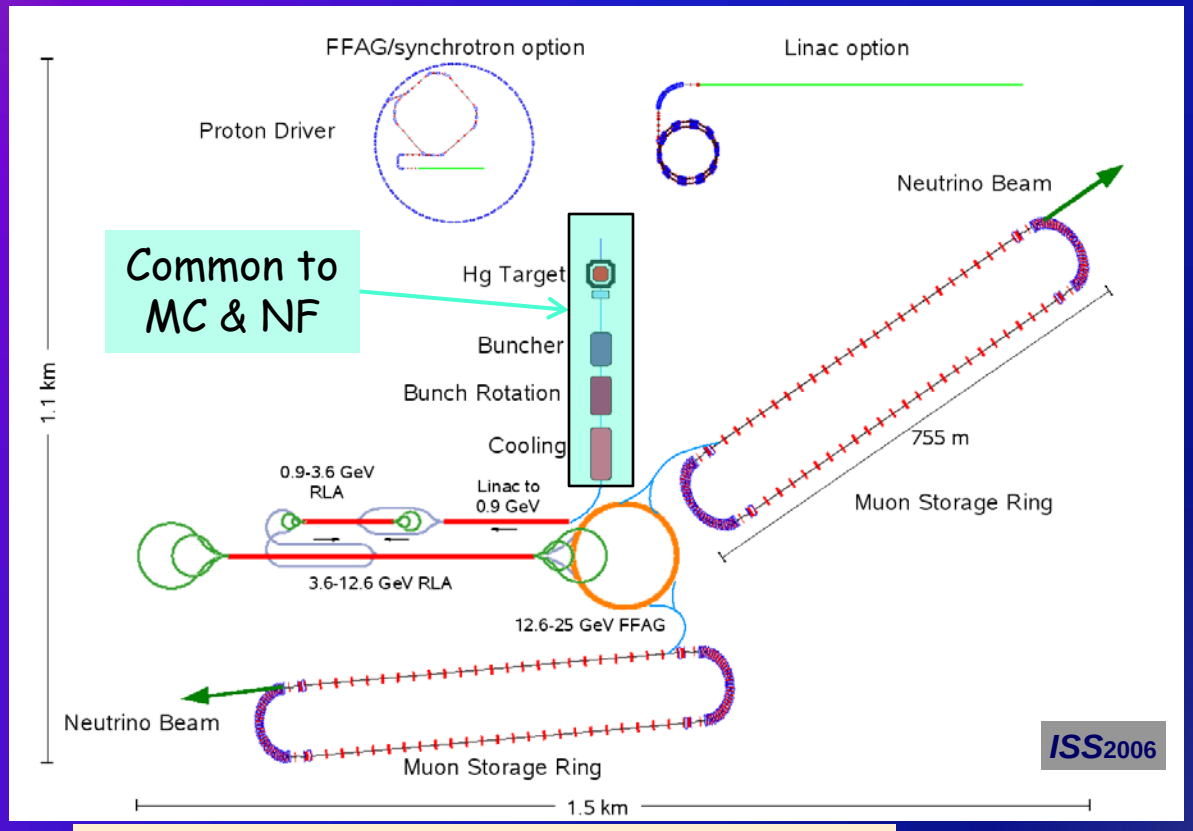


6D Muon Ionization Cooling

- Increase the Intensity of low energy μ beam & improve target stopping power
  - Cooling increases 6D particle density
  - Test bed for Muon Ionization Cooling for NF and MC with intense μ beam

Neutrino Factory Accelerator Facility

Baseline out of International Scoping Study



ISS Accelerator WG report: RAL-2007-023
IDS-NF Interim Design Report – imminent

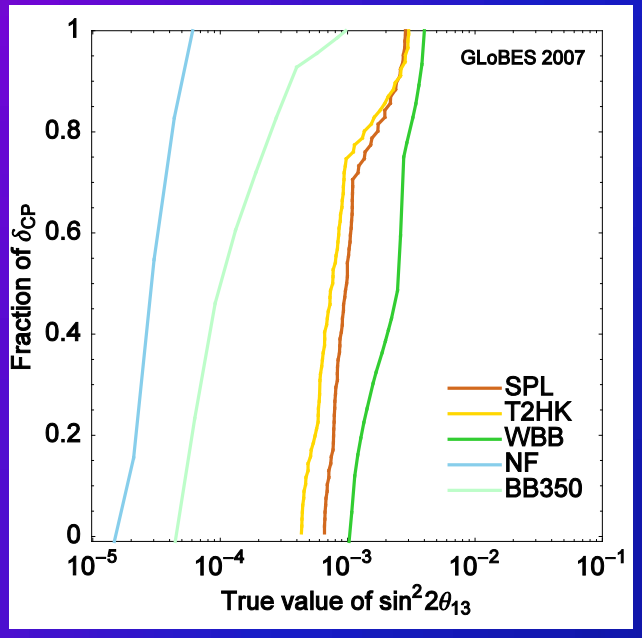
- **Proton Driver**
  - 4 MW, 2 ns bunch
- **Target, Capture, Drift ($\pi \rightarrow \mu$) & Phase Rotation**
  - Hg Jet
  - 200 MHz train
- **Cooling**
  - 30 πmm ($\perp$)
  - 150 πmm (L)
- **Acceleration**
  - 103 MeV $\rightarrow$ 25 GeV
- **Decay rings**
  - 7500 km L
  - 4000 km L
    - Baseline is race-track design
    - Triangle interesting possibility (C. Prior)

International Scoping Study
Physics Reach

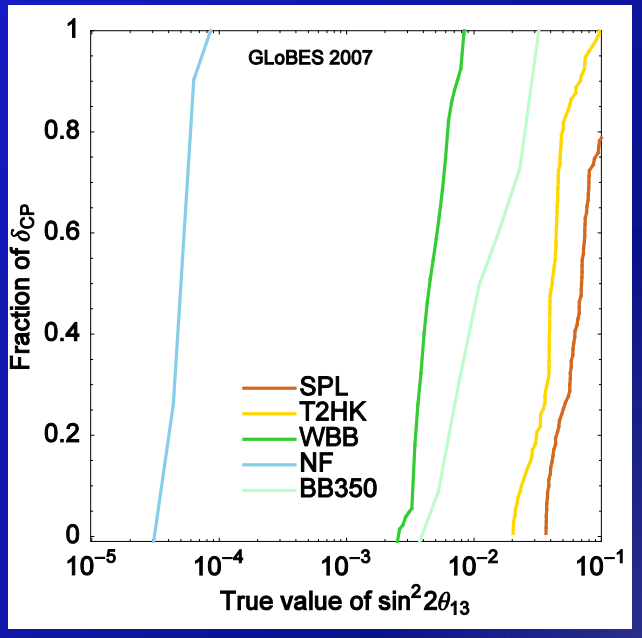
3σ contours shown

ISS Physics Group Report: arXiv:0710.4947v2

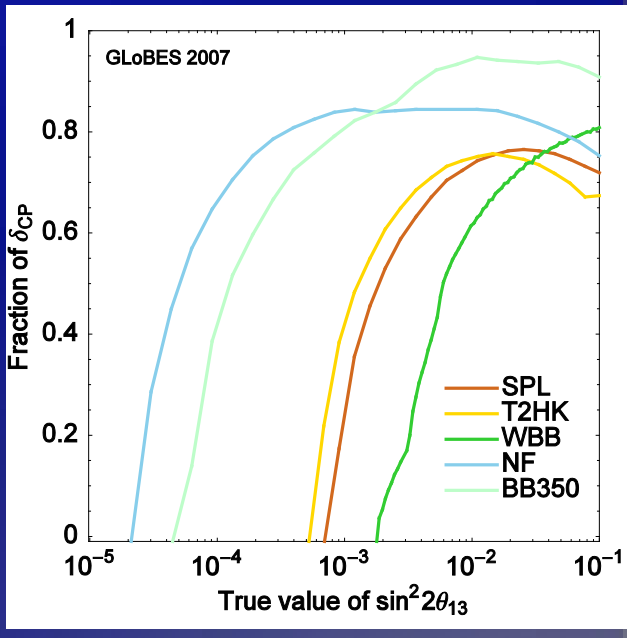
$\sin^2 2\theta_{13}$



Hierarchy



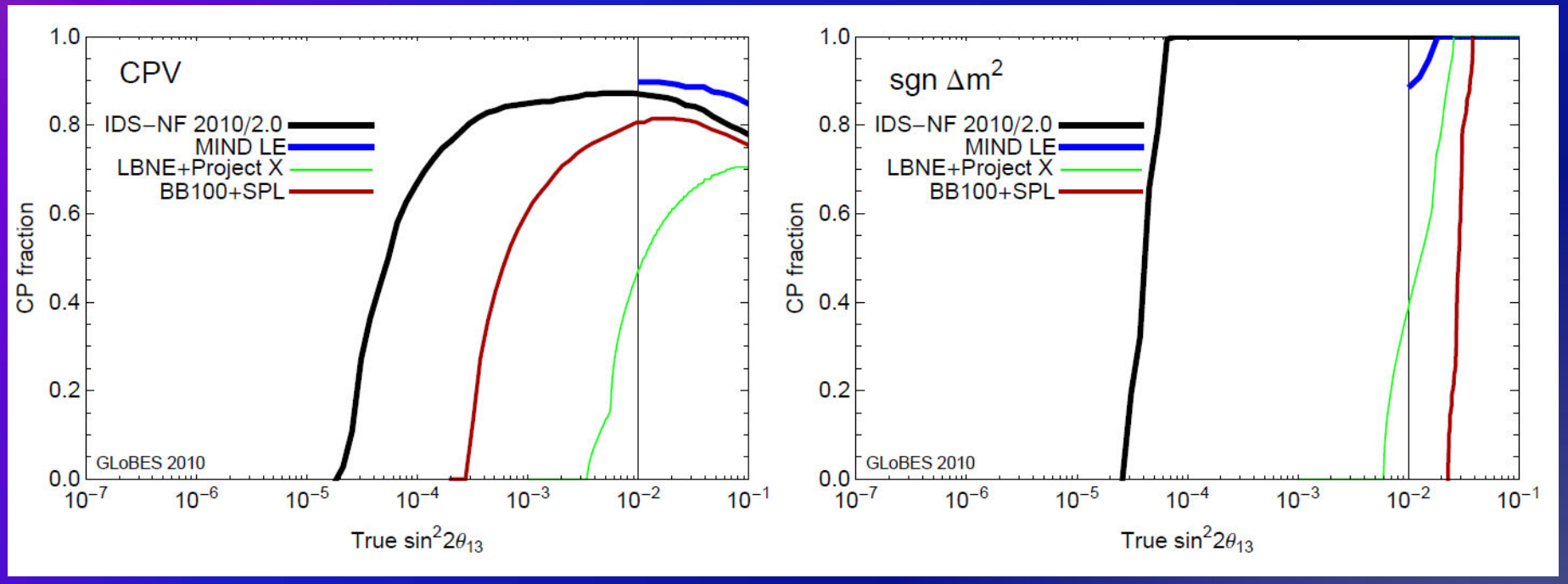
δ *CP*



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

IDS-NF

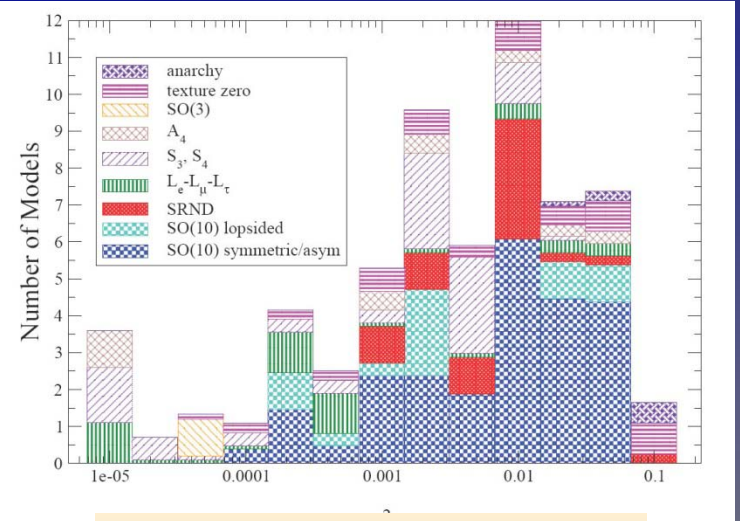


The Neutrino Factory is the facility of choice for the study of neutrino oscillations: it has the best discovery reach; offers the best precision; and, by varying the stored-muon energy, source-detector distance, and perhaps detector technology, it has the flexibility to respond to changes in our understanding of neutrino oscillations and the discovery of new phenomena

Beyond Filling in the Blanks

- Determine parameters with precision sufficient to determine the structure of the underlying theory
  - Explore very large mass scale
- Beyond the SνM
  - NSI
  - Sterile ν
  - Mass Varying ν (MVN)

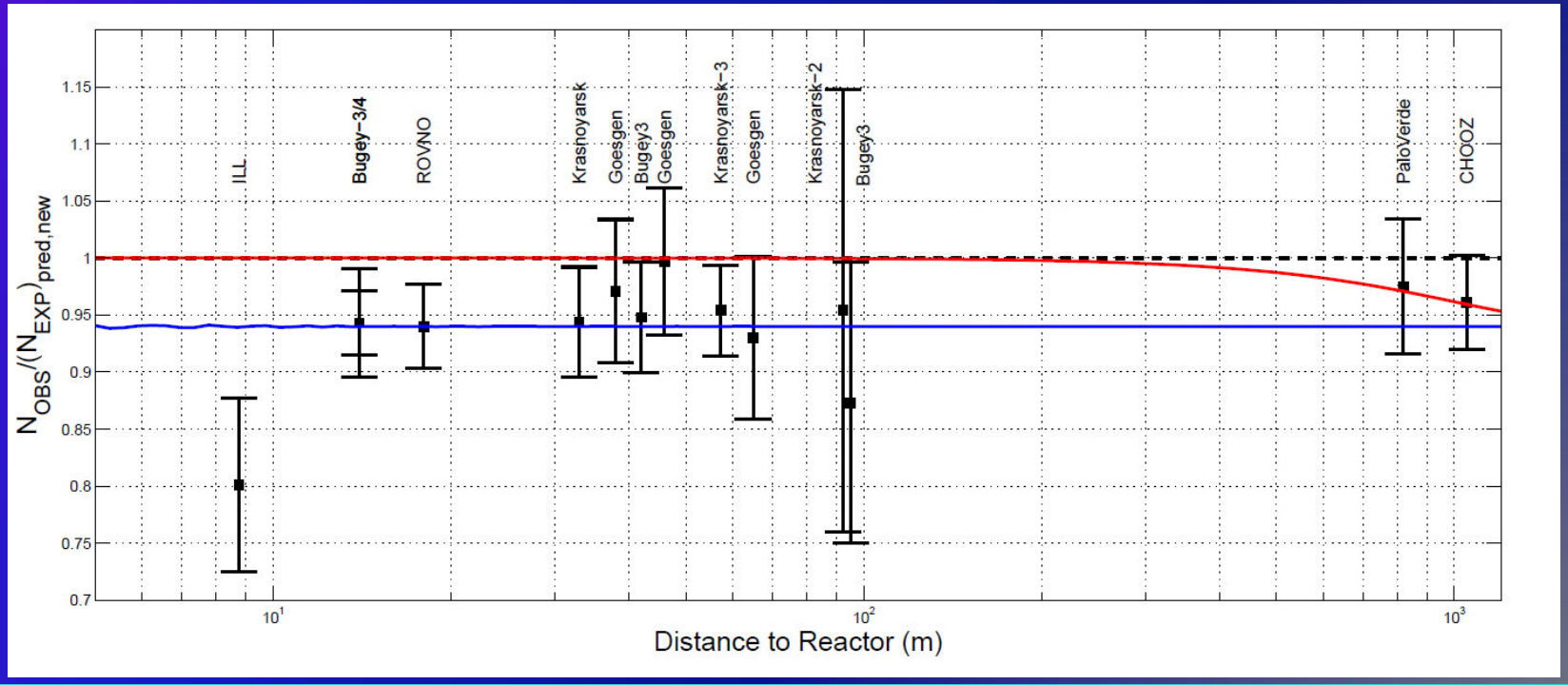
$\mu^+ \to e^+\nu_e\overline{\nu}_\mu$	$\mu^- \to e^-\overline{\nu}_e\nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel



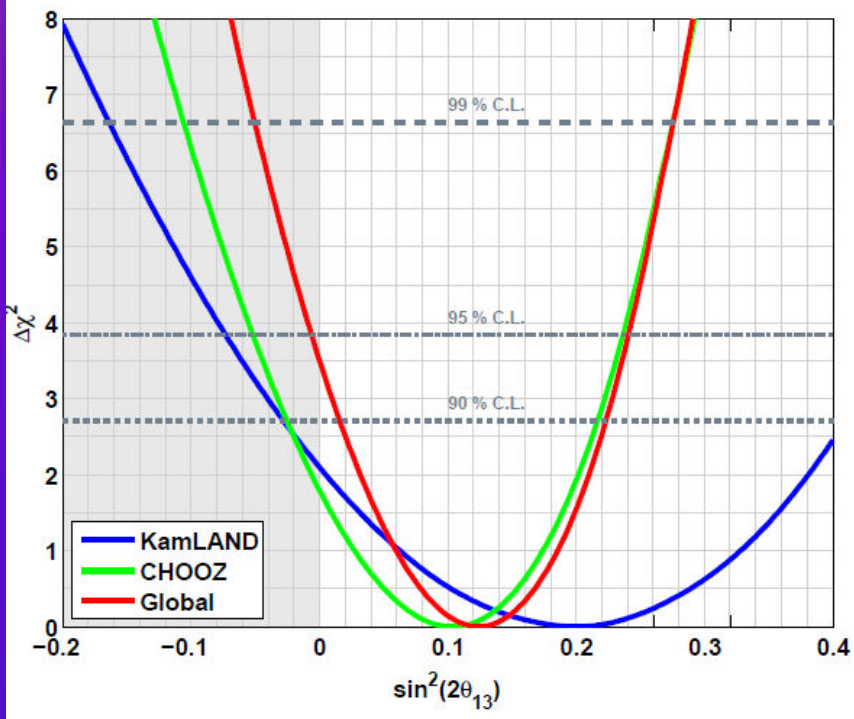
Carl Albright – arXiv:0803.4176v1

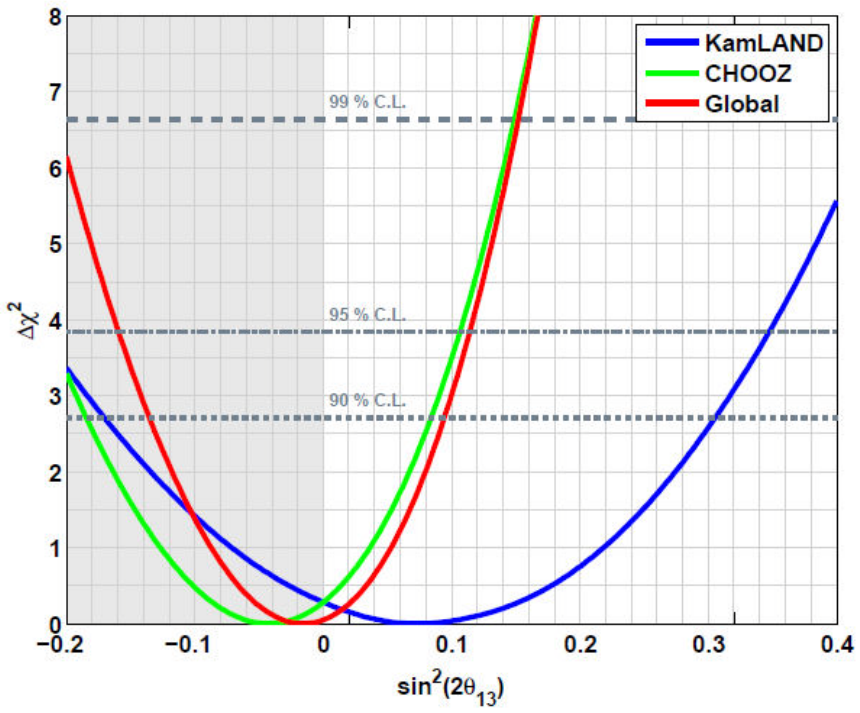
Sterile ν and Reactor Experiments

- The Reactor Antineutrino Anomaly (Mention et al. arXiv:1101.2755)
  - Re-evaluation of nuclide decay rates leads to an increase in neutrino flux at reactors
- Observed rate/predicted rate @ near detectors → 0.937 from 0.979



Global Fit
Impact on θ_{13}



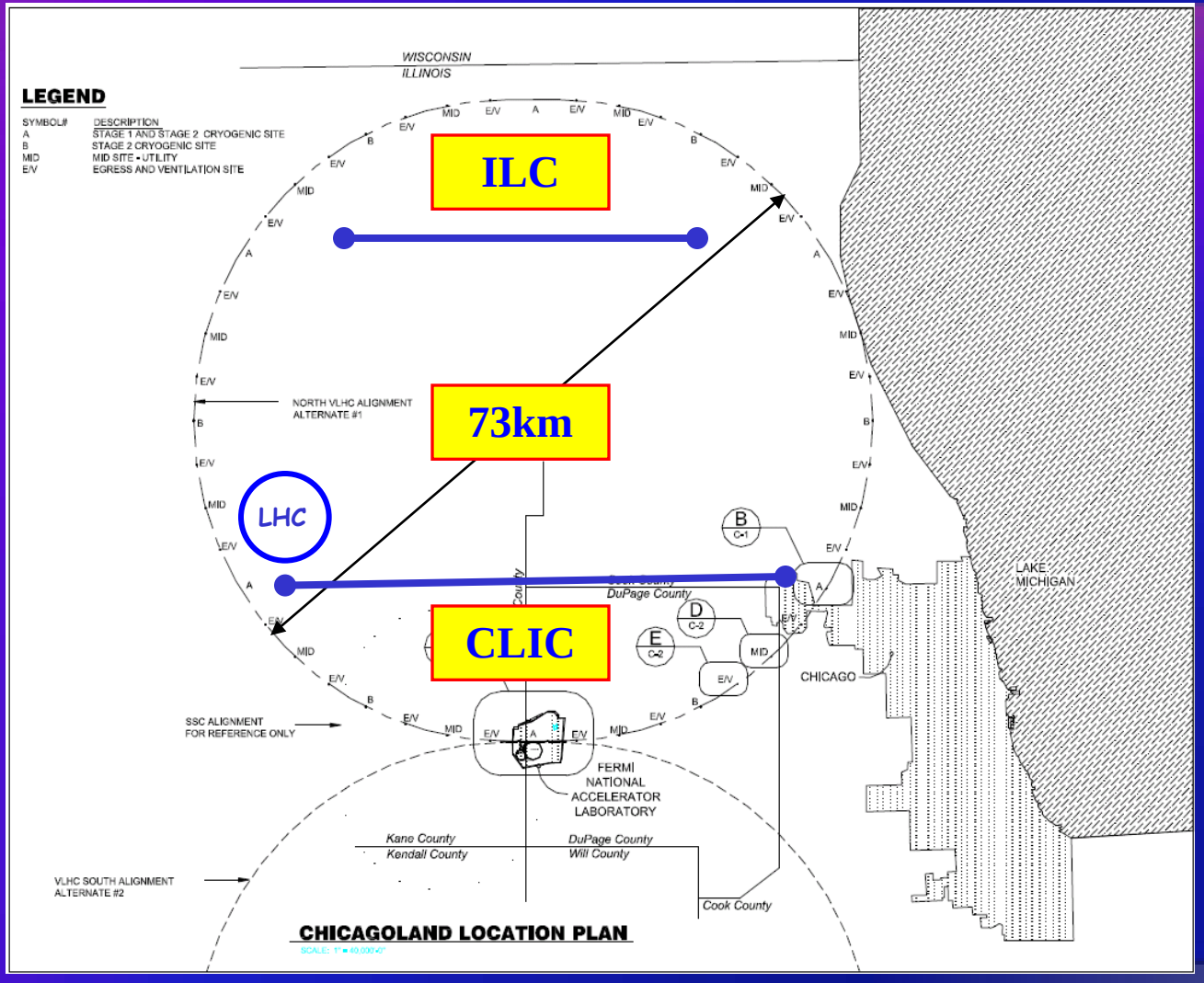


ν_e disappearance experiment using stored μ beam

Looking into ways to do this Soon(ish)

The Energy Frontier

Footprint and the Energy Frontier



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

- Stage 1 – 40 TeV
  - > 2 TeV
- Stage 2 – 200 TeV
  - 3 -> 10 TeV

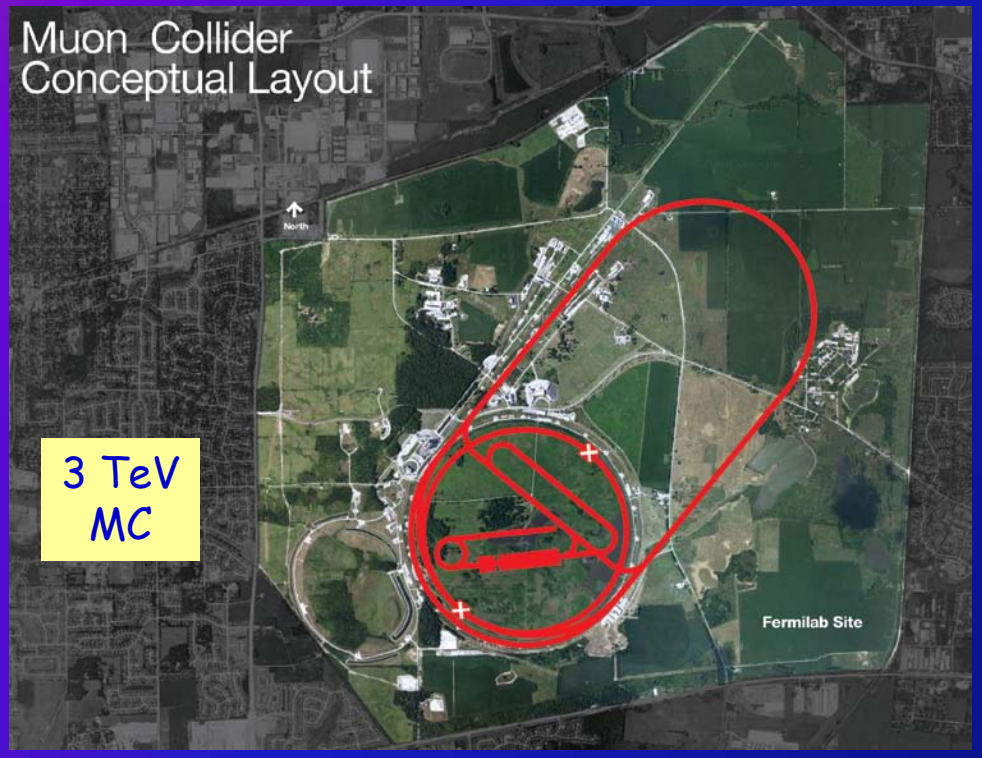
Muon Facilities are different

ILC

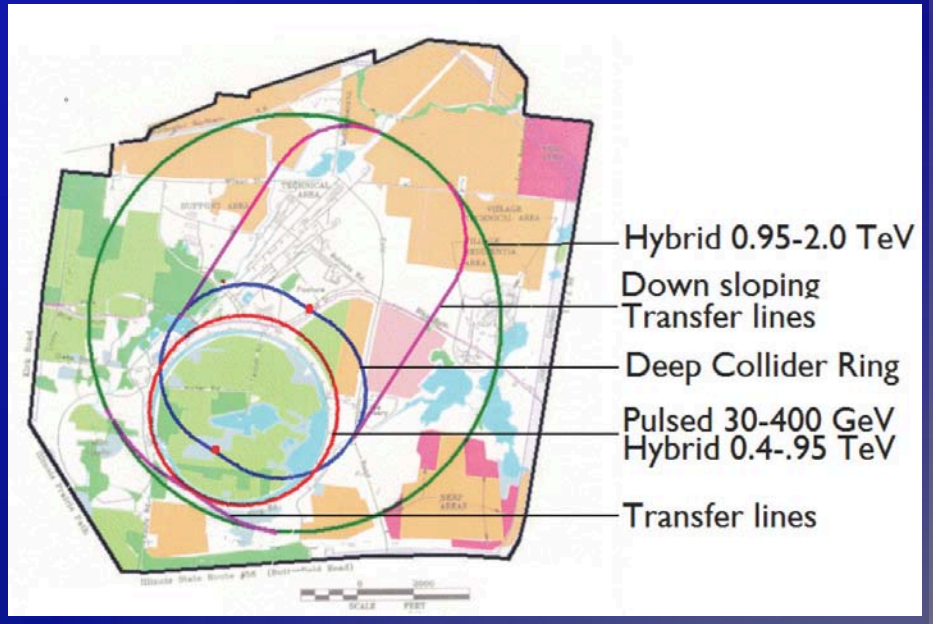
CLIC

0.5 TeV

The Energy Frontier via $\mu^+ \mu^-$ Collisions



3 TeV MC



3 TeV Machine based on Recirculating Linear Accelerators & ILC SC RF

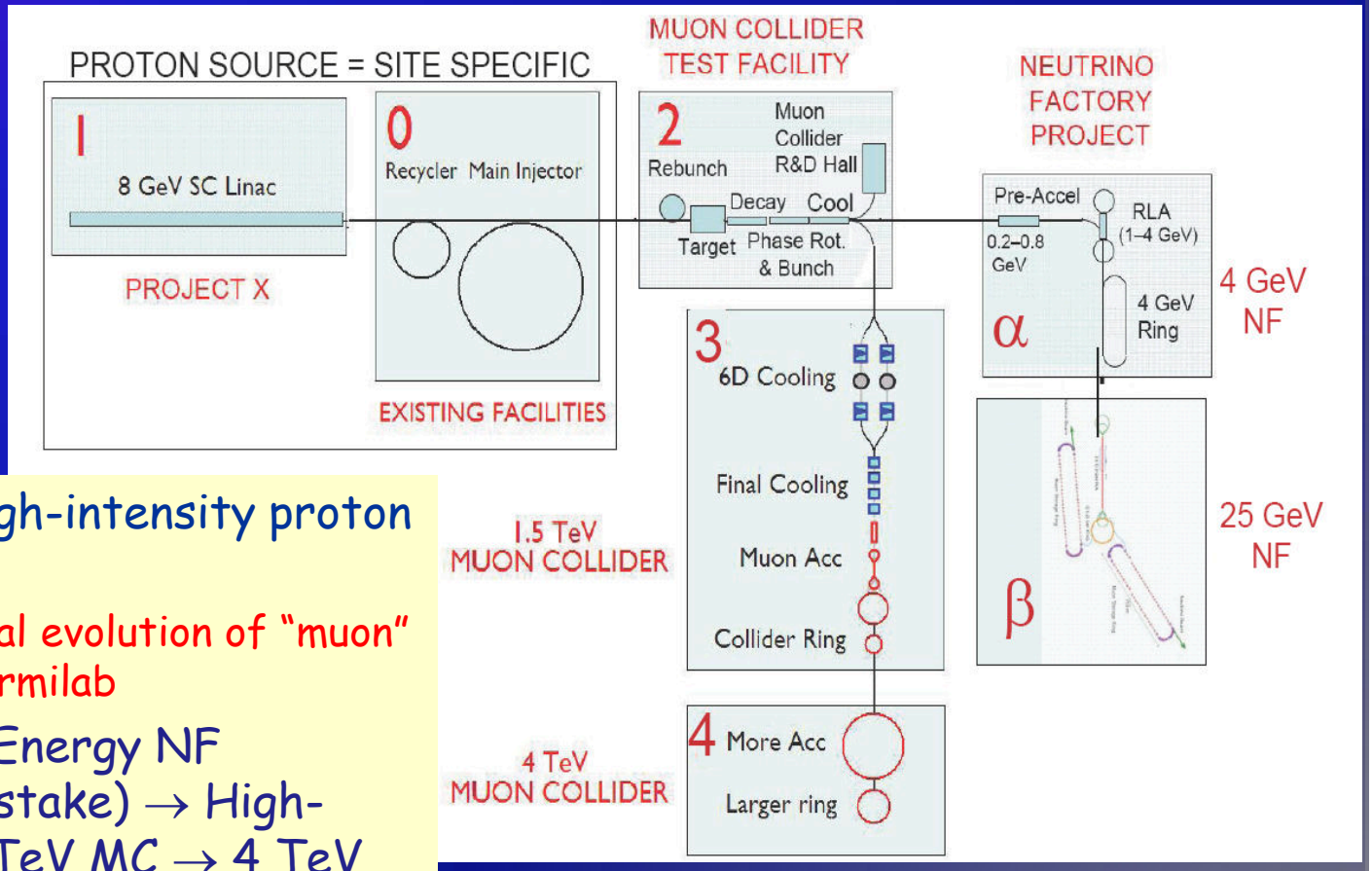
4 TeV Machine based on Rapid Cycling Synchrotron

Complexity of Colliders

	LHC	MC	CLIC
state of the art magnets	√	√	-
state of the art RF system	-	√	√
state of the art beam dynamics	-	√	√
Total # of elements	~4000	~4000	~200,000
Luminosity	>1e34	>1e34	>1e34

Muon Complex Evolution At Fermilab

Snowmass Update



- Starting with a high-intensity proton source: Project X
  - We see a natural evolution of "muon" program for Fermilab
- Project X → Low-Energy NF (pointing to Homestake) → High-Energy NF → 1.5 TeV MC → 4 TeV MC

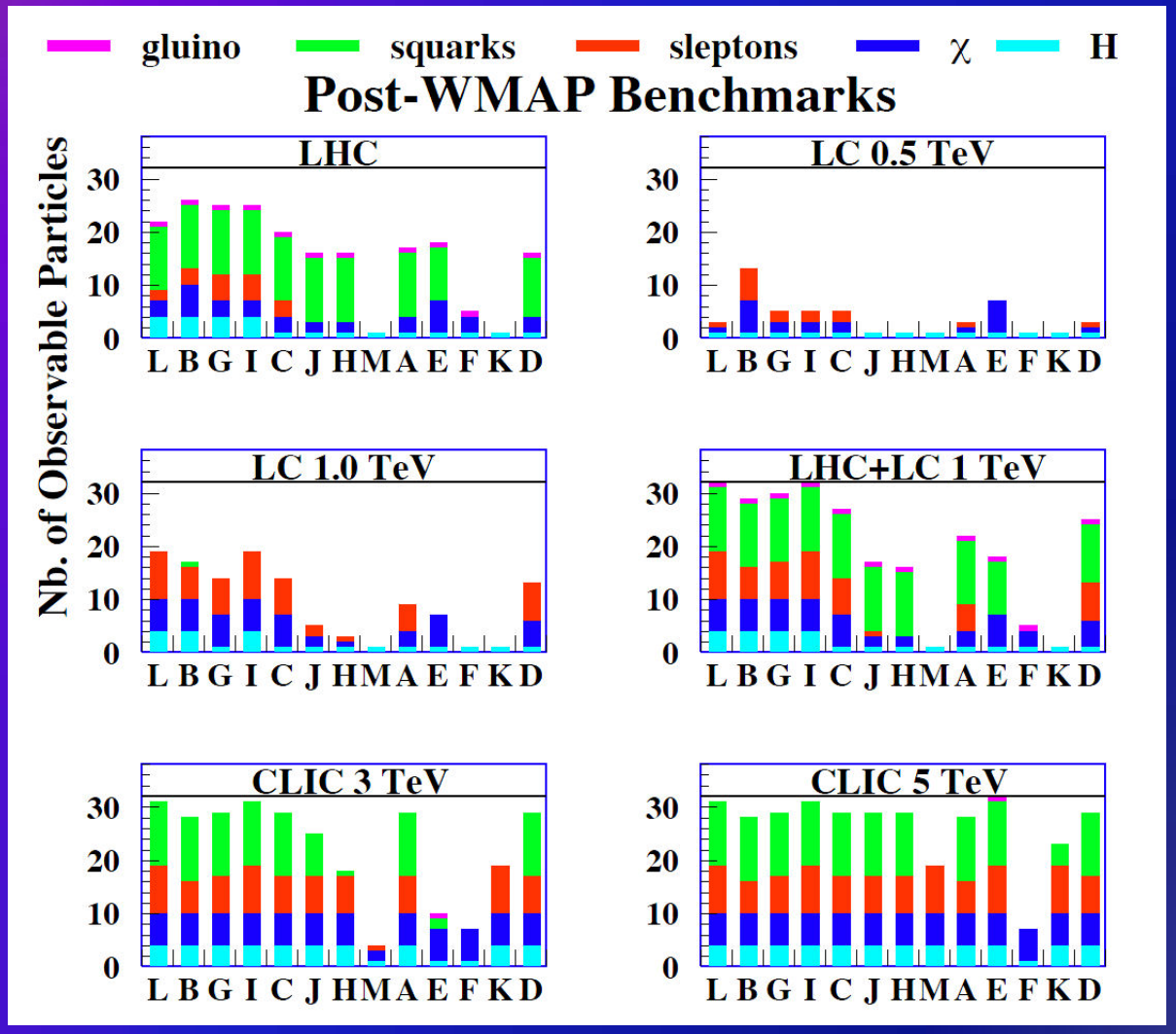
Muon Collider - Motivation

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

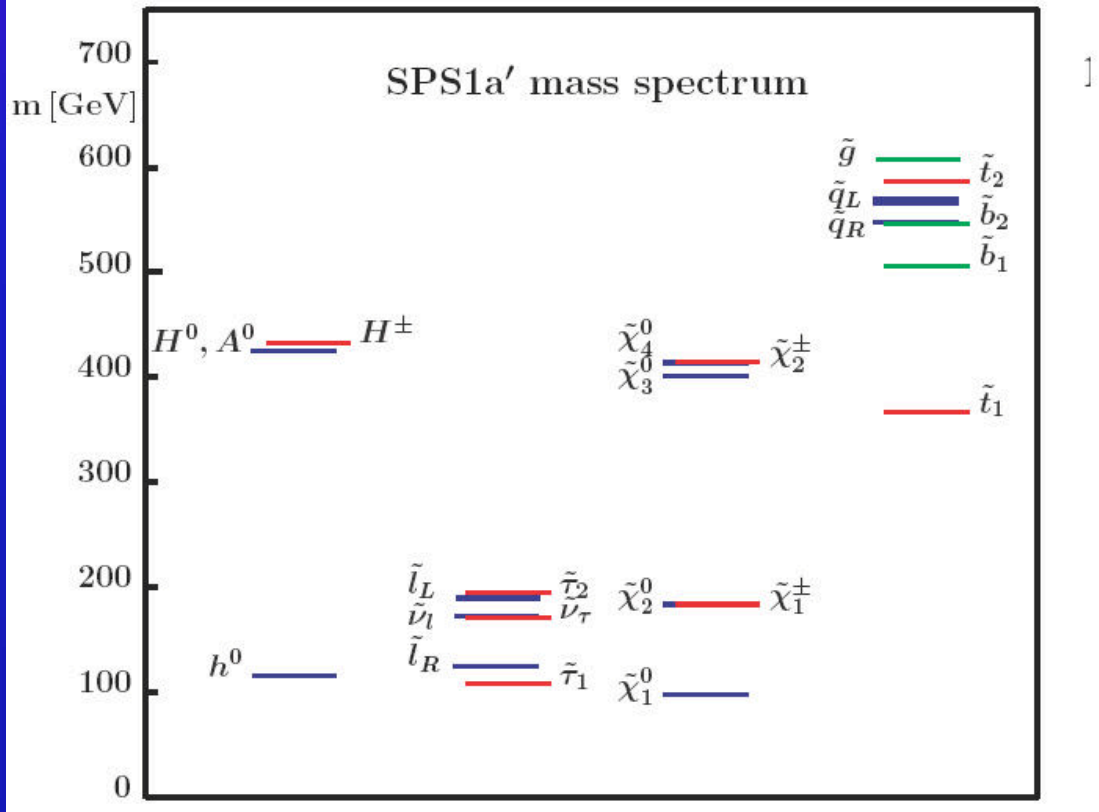
Why consider a Muon Collider?
The Supersymmetric Particle Zoo



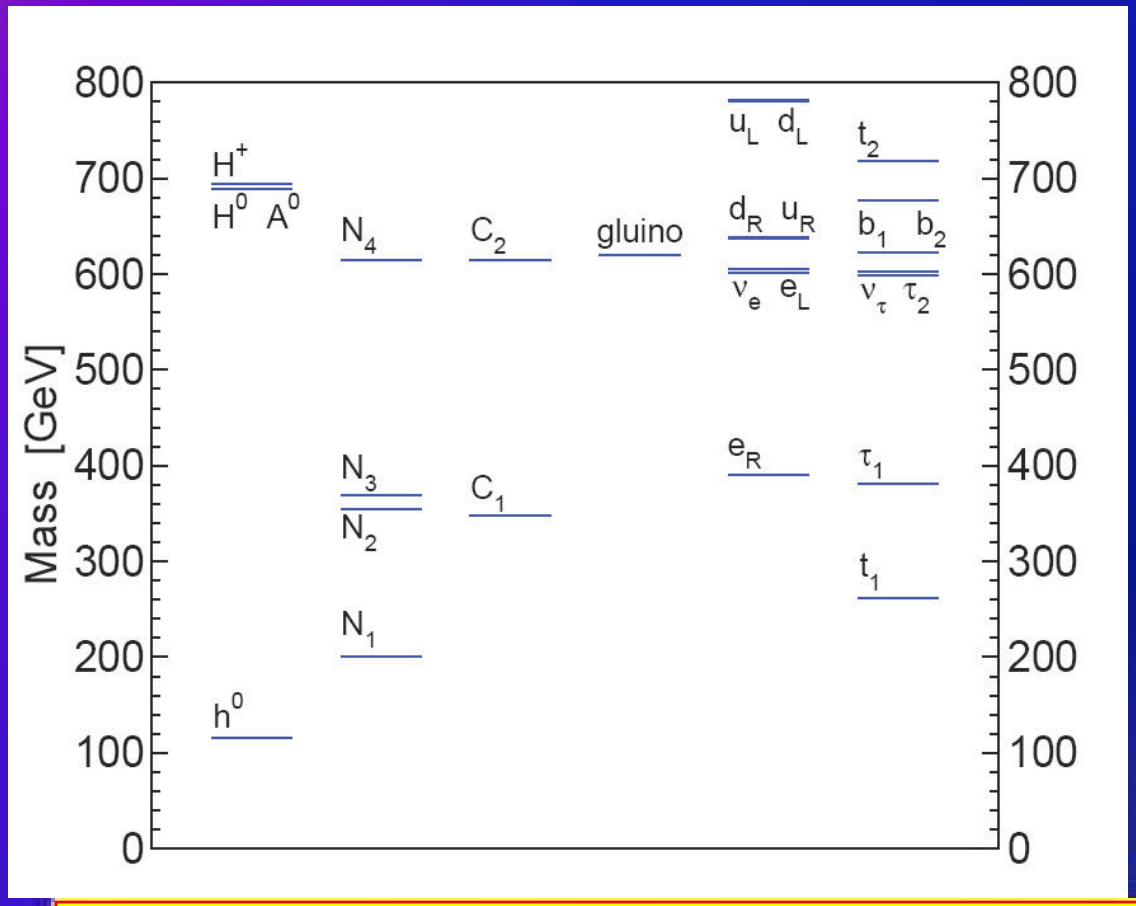
- Independent of actual supersymmetric mass scale and the reach of the ILC, the 2004 CLIC Study conclusions are still valid
  - "A Multi-TeV machine is needed for extended coverage of the mass range

Snowmass Supersymmetric Benchmark

cMSSM ILC Benchmark



But the Physics Landscape has New Features since 2001



Also New results from $e^+e^- \to \pi\pi(\gamma)$ (TAU08) Puts further pressure on Low-mass SS

Strong(er?) Case for considering Multi-TeV Lepton Collider

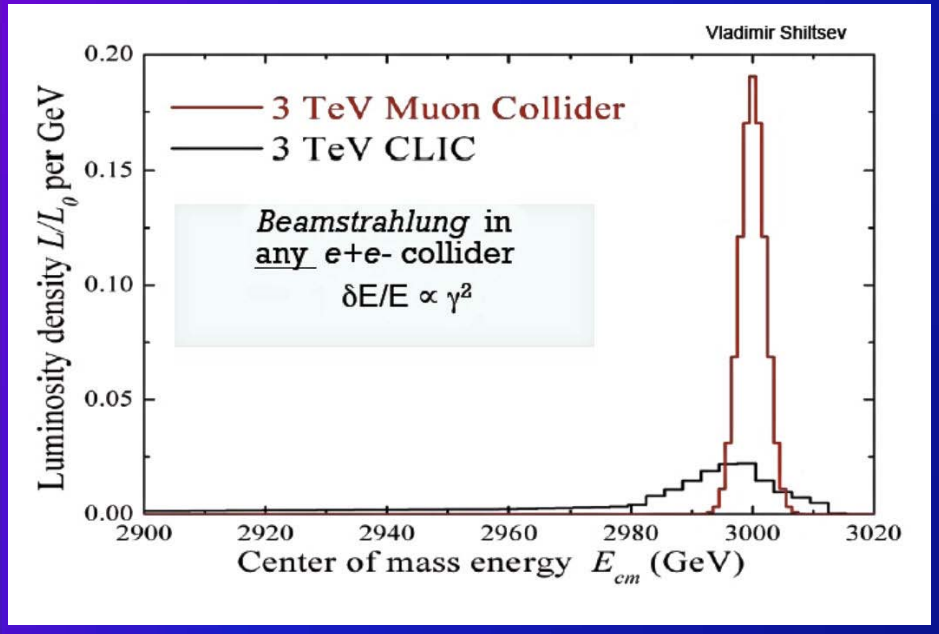
Stephen Martin
hep-ph/0703097
March, 2007

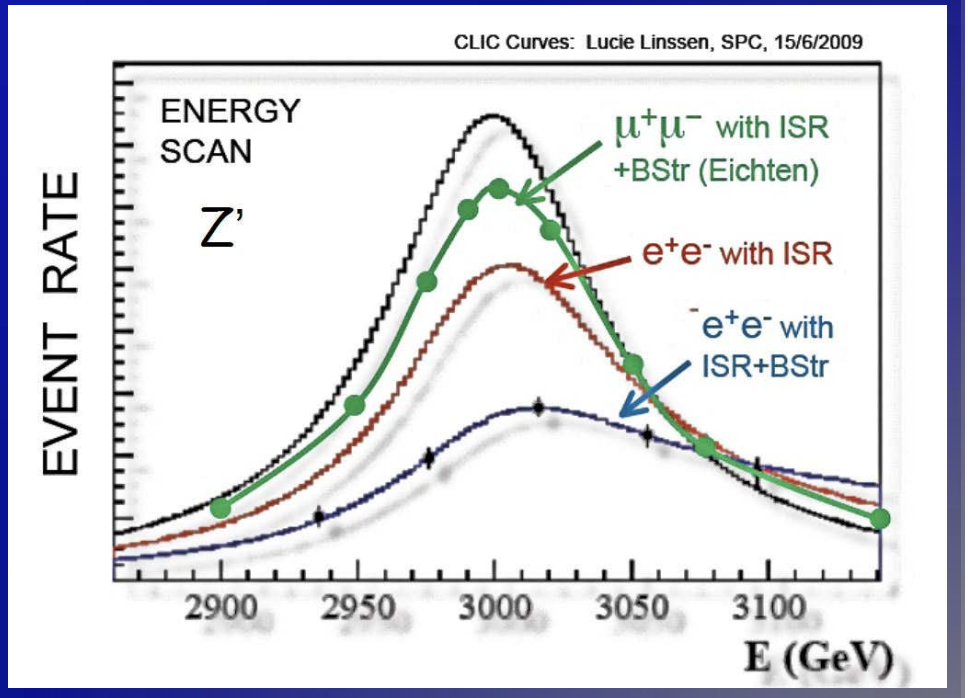
A typical sample "compressed" Higgs and superpartner mass spectrum with $\Omega_{DM}h^2 = 0.11$
An unfortunate feature, quite common to this scenario for dark matter, is that no visible superpartners would be within reach of a linear collider with $\sqrt{s}$ = 500 GeV

Why consider a Muon Collider?

Precision Energy Scans

- **Excellent energy resolution**
  - MC: 95% luminosity in $\Delta E/E \sim 0.1\%$
  - CLIC: 35% luminosity in $\Delta E/E \sim 1\%$





U.S. Muon Acceleration R&D Community

History

- NFMCC (Neutrino Factory & Muon Collider Collab.)
  - National collaboration funded since 1999.
  - Pursues Neutrino Factory & Muon Collider R&D.
  - NF R&D pursued with international partners
- MCTF (Muon Collider Task Force)
  - Task Force established at Fermilab in 2006
  - Pursues Muon Collider R&D, utilizing FNAL assets and extends & complements the NFMCC program
- MCCC (Muon Collider Coordinating Committee)
  - Leadership of NFMCC (Bross, Kirk, Zisman) and MCTF (Geer, Shiltsev)
  - Co-ordinates NFMCC & MCTF plans to optimize the overall program … has worked well and resulted in a joint 5 year plan for future activities.

THE MAP INITIATIVE IN THE U.S.

- Oct 1, 2009 letter from Denis Kovar 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 a new organization for a national Muon Collider & Neutrino Factory R&D program, hosted at FNAL. Muon Accelerator Program Organization is now in place & functioning: 214 participants at birth from 14 institutions:
  - ANL, BNL, FNAL, Jlab, LBNL, ORNL, SLAC, Cornell, IIT, Princeton, UCB, UCLA, UCR, U-Miss
- MAP R&D proposal reviewed August 2010 … committee concluded that the *"proposed work was very important to the field of high energy physics."*

ORGANIZATION/FUNDING EVOLUTION

First ~10 years	FY07 – FY09	Now (FY10/11)	≥FY11
NFMCC	NFMCC + MCTF	Interim MAP	MAP
~4 M$	~9 M$	~10 M$	~15 M$ (requested)

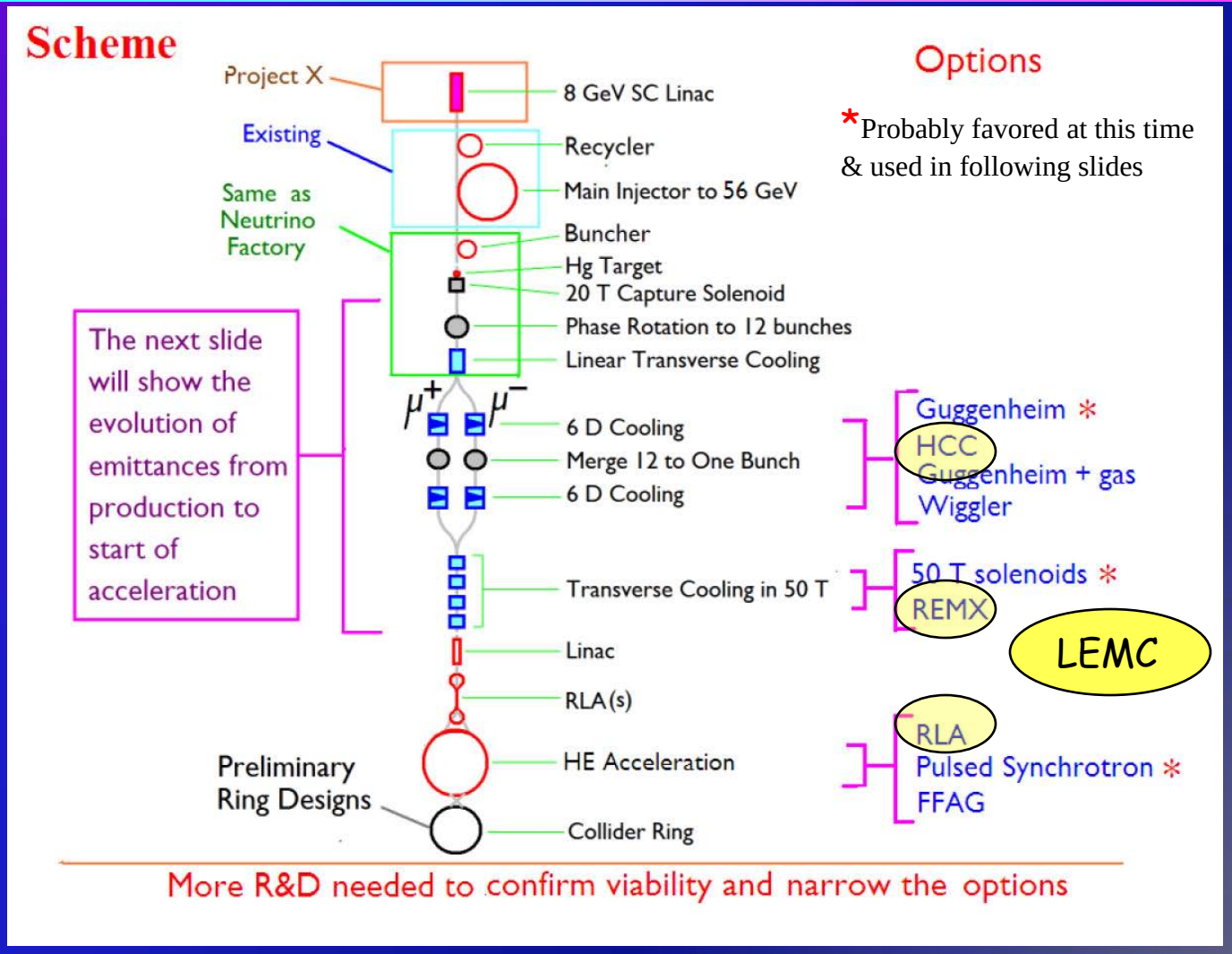
Muon Collider Design

Emphasis on Cooling

Parameters of Different MC options

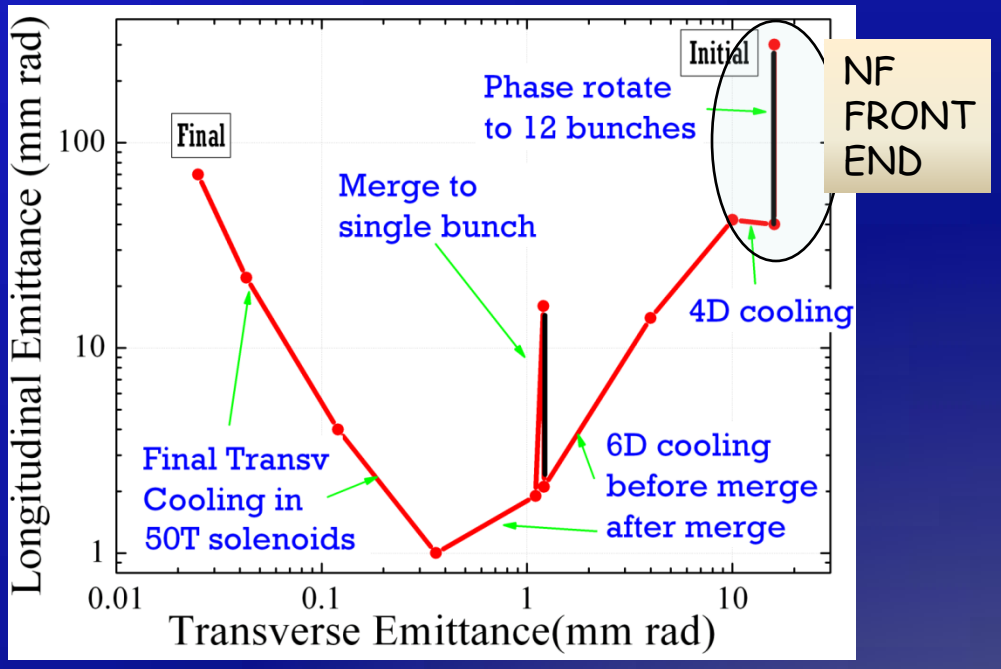
	Low Emit.	High Emit.	MCTF07	MCTF08	
$\sqrt{s}$ (TeV)		1.5			
Av. Luminosity ($10^{34}/cm^2/s$) *	2.7	1	1.33-2		
Av. Bending field (T)	10	6	6		
Mean radius (m)	361.4	500	500 ⇒	495	
No. of IPs	4	2	2		
Proton Driver Rep Rate (Hz)	65	13	40-60		
Beam-beam parameter/IP	0.052	0.087	0.1		
β^* (cm)	0.5	1	1		
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** ⇒	$0.3^\dagger$
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	?	

Muon Collider Facility



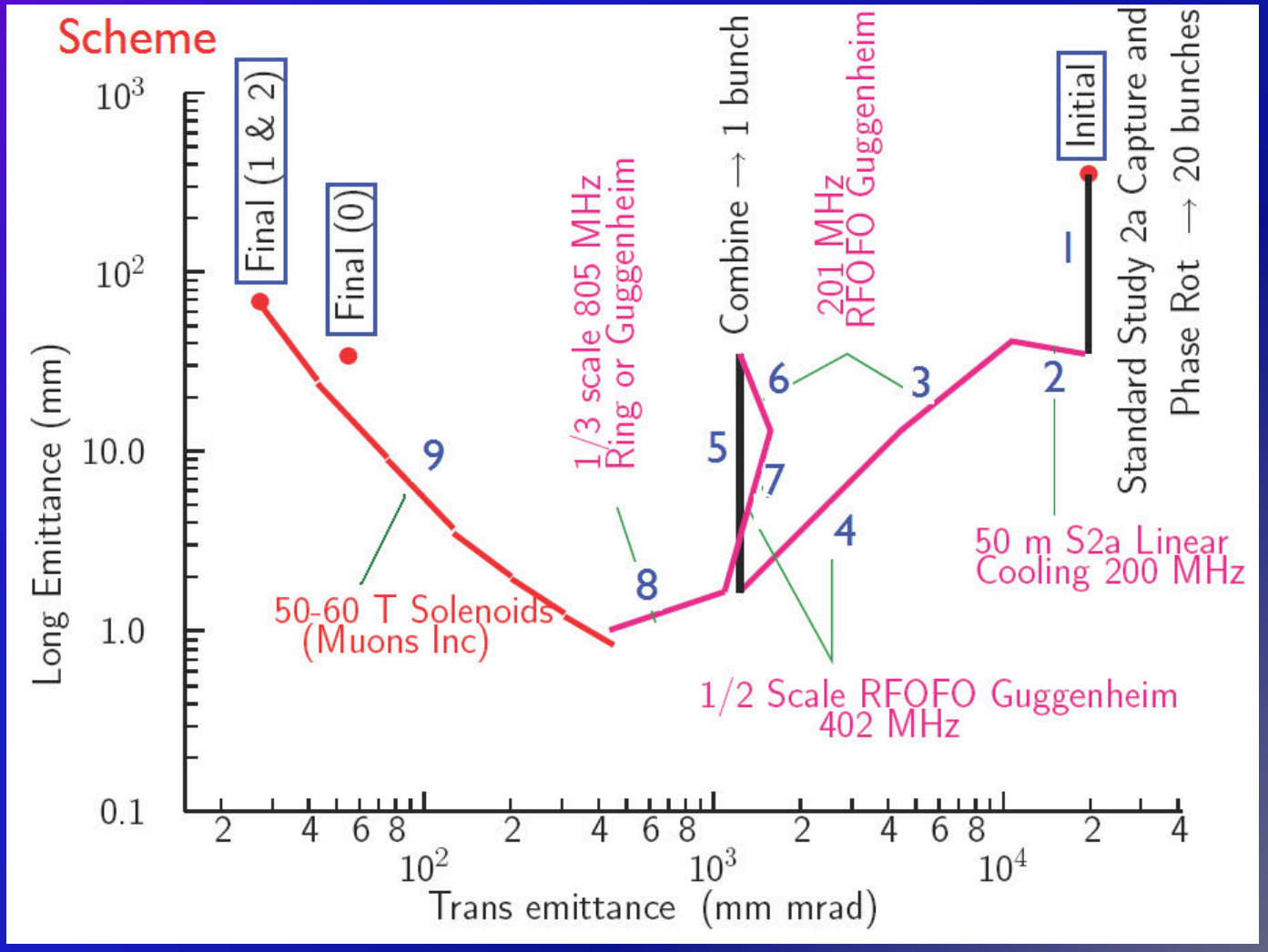
Muon Collider Design Progress

- 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



Muon Ionization Cooling

Basic Concepts

Muon Ionization Cooling - Transverse

- 2D Transverse Cooling

$$\frac{d\epsilon_N}{ds} = -\frac{1}{\beta^2}\frac{dE_\mu}{ds}\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu L_R}$$

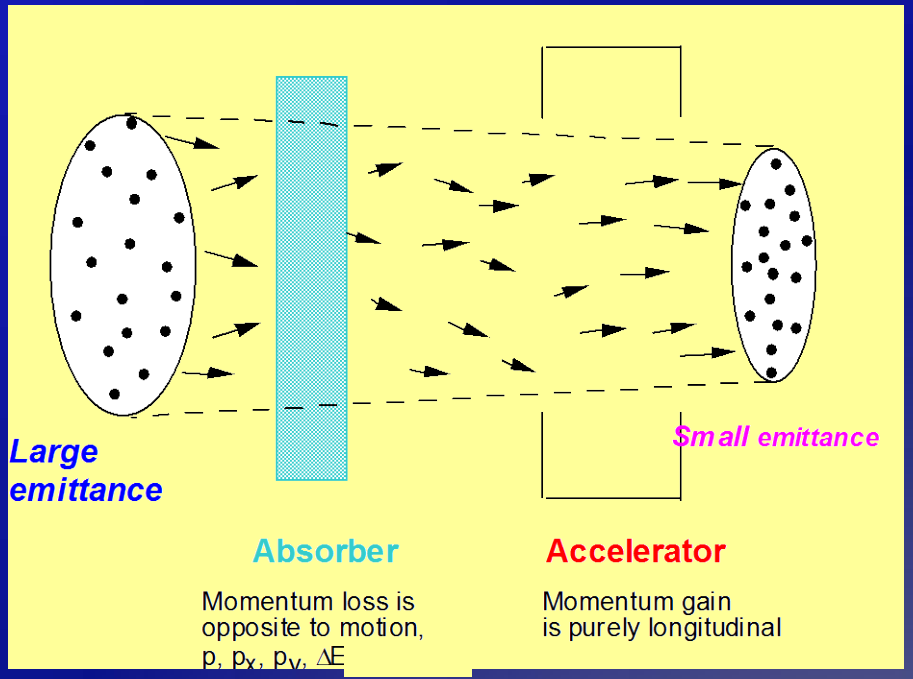
and

$$\epsilon_{N,\min} = \frac{\beta_\perp (14\ \mathrm{MeV})^2}{2\beta m_\mu \frac{dE_\mu}{ds} L_R}$$

- Figure of merit: $M = L_R dE_\mu/ds$

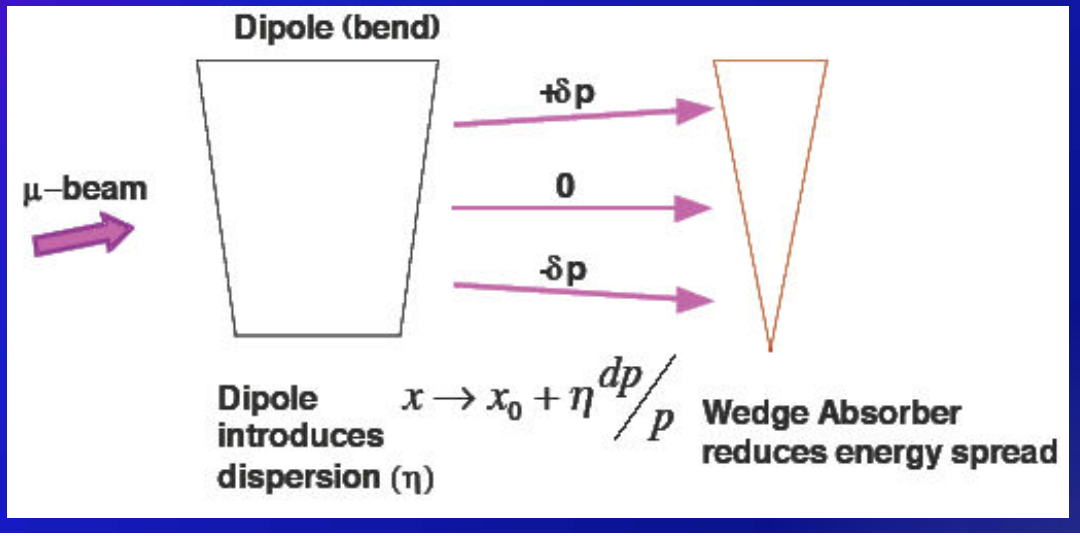
M^2 (4D cooling) for different absorbers

Material	$\langle dE/ds \rangle_{\min}$ (MeV g^{-1}cm^2)	L_R (g cm^{-2})	Merit
GH_2	4.103	61.28	1.03
LH_2	4.034	61.28	1
He	1.937	94.32	0.55
LiH	1.94	86.9	0.47
Li	1.639	82.76	0.30
CH_4	2.417	46.22	0.20
Be	1.594	65.19	0.18



H_2 is clearly Best -
Neglecting Engineering Issues
Windows, Safety

Muon Ionization Cooling – Longitudinal *Emittance Exchange*



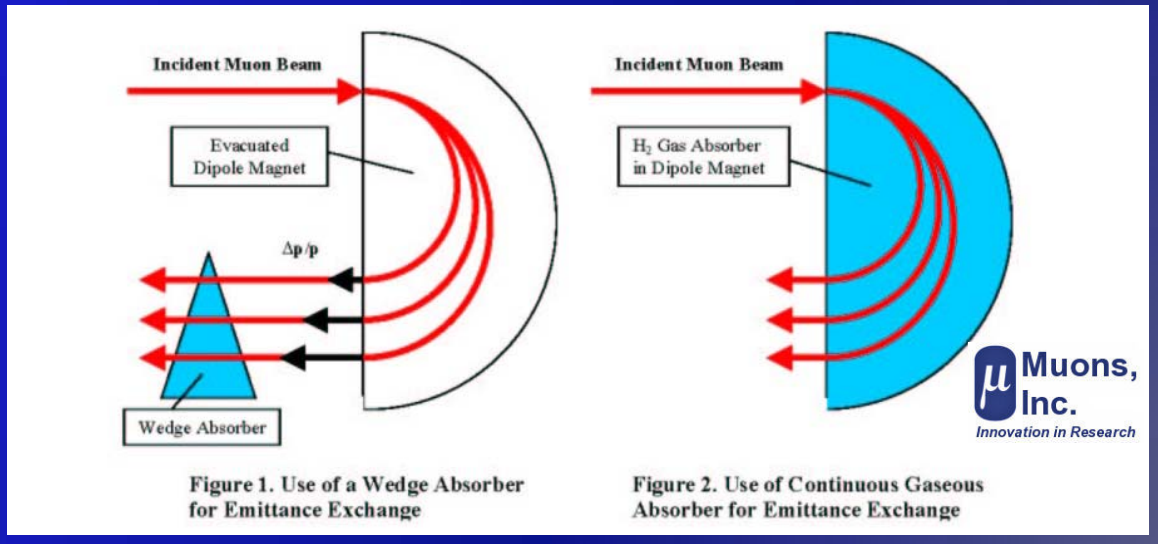
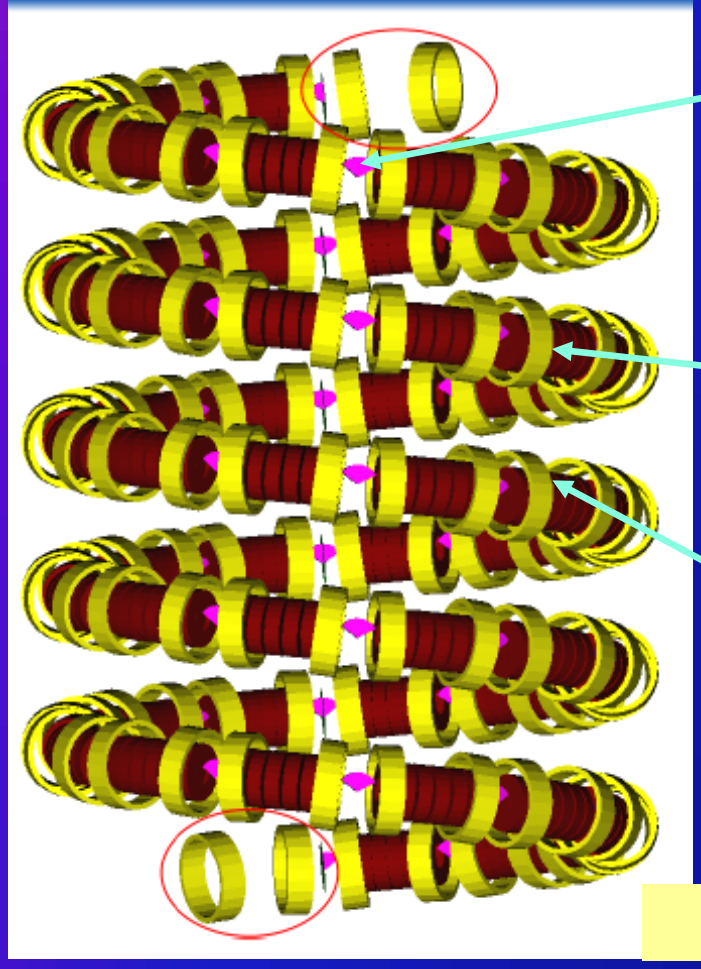


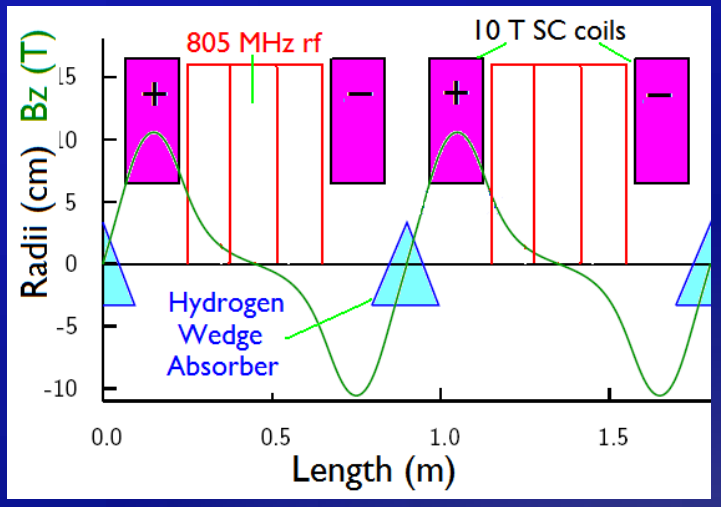
Figure 1. Use of a Wedge Absorber for Emittance Exchange

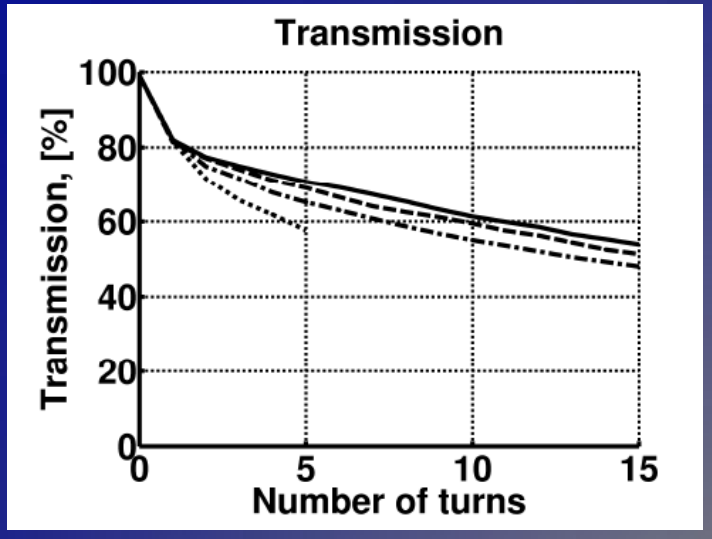
Figure 2. Use of Continuous Gaseous Absorber for Emittance Exchange

Guggenheim RFOFO - Simulations

Multilayer scheme



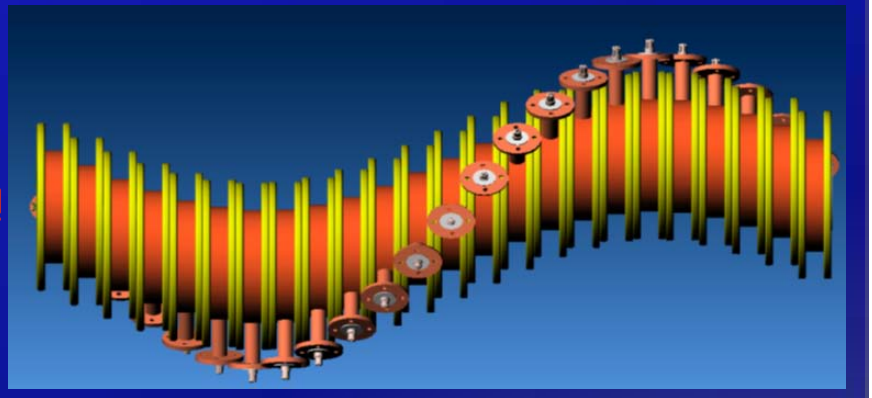


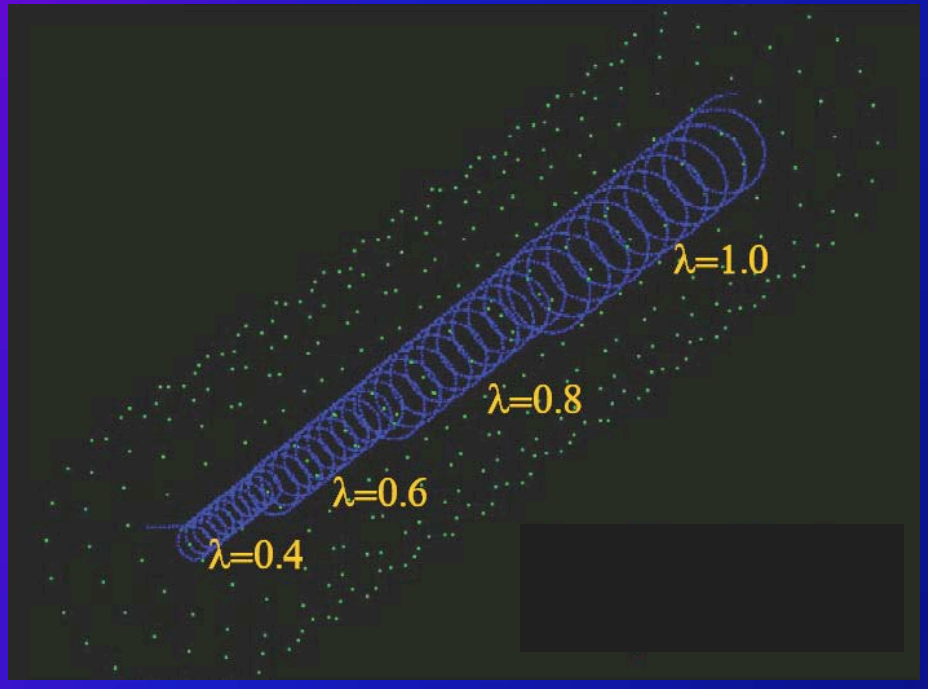


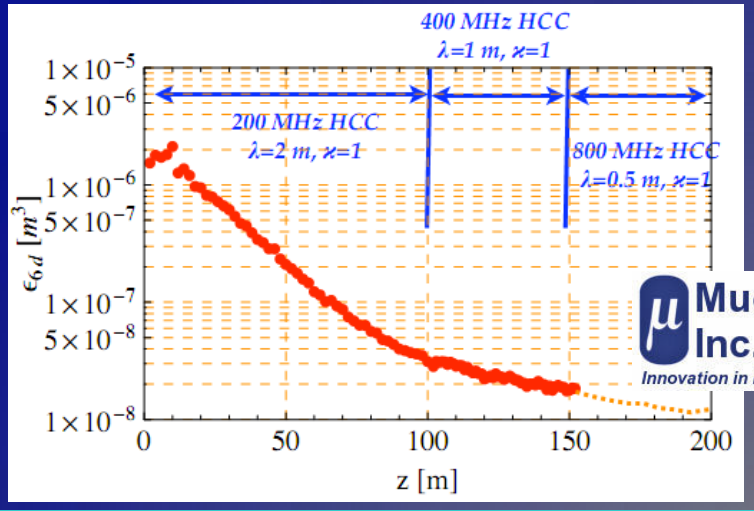
Pavel Snopok

Helical Cooling Channel

- Magnetic field is solenoid B0+ dipole + quad
- System is filled with H_2 gas, includes rf cavities
- Cools 6-D (large E means longer path length)
- But, incorporating RF is Engineering challenge!

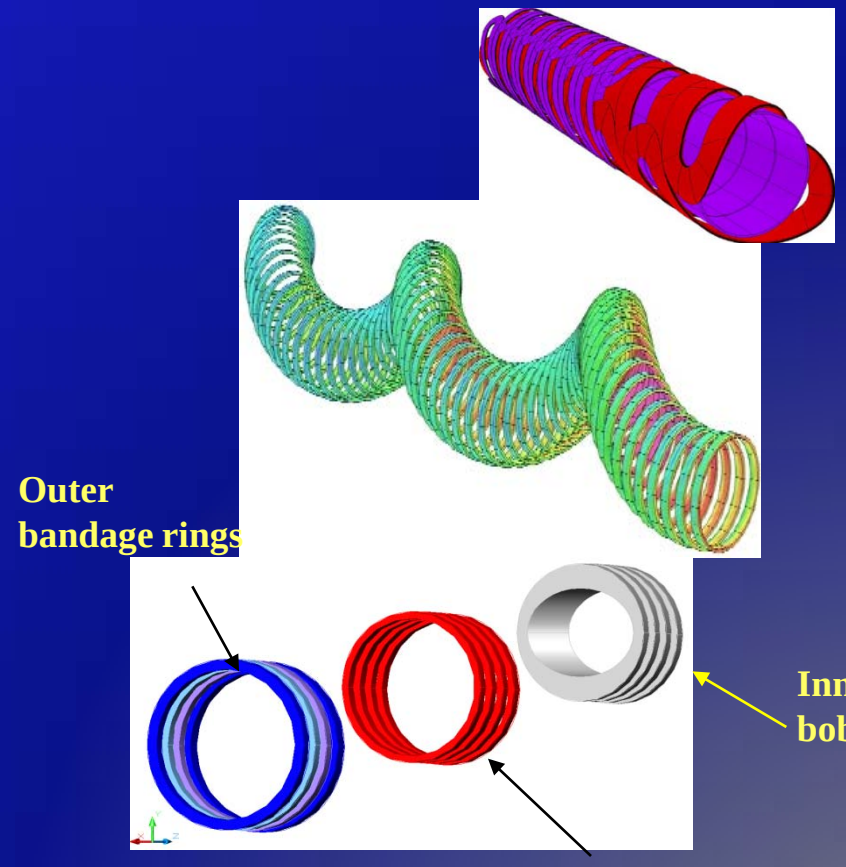




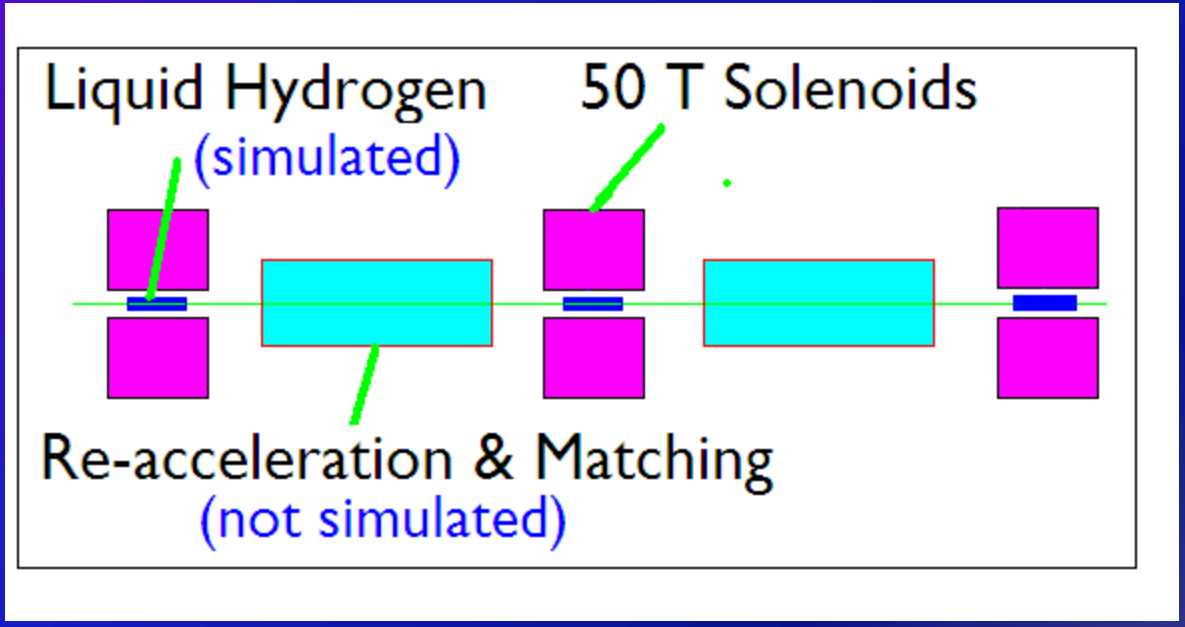


HCC Magnet Design & Prototyping

- Helical solenoid (HS): Smaller coils than in a "snake" design
  - Smaller peak field
  - Lower cost
- Field components in HS determined by geometry
  - Over constrained
  - Coil radius is not free parameter
- 4 Coil Demonstration Model
  - Validate mechanical structure and fabrication methods
  - Study quench performance and margins, field quality, quench protection
  - Use SSC conductor



Final Cooling



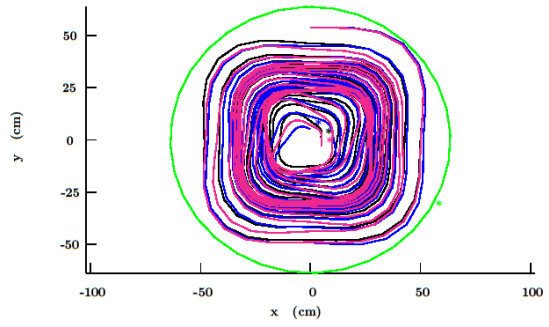
- LH_2 absorbers tested in MICE
- 50 T Solenoids
  - The *"National Very High Field Superconducting Magnet Collaboration"* was formed in the US
    - 2 Year $4M program to study HTS conductor and cable

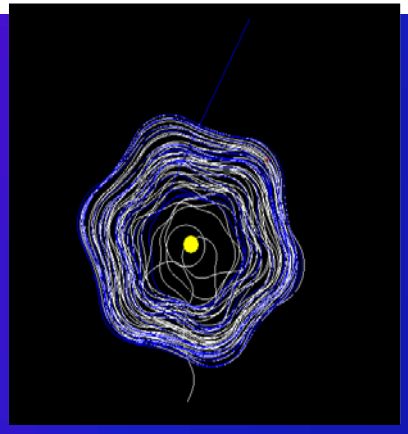
Alternate Cooling Concepts

"Frictional Cooling"

Muon Cooling With an Inverse Cyclotron

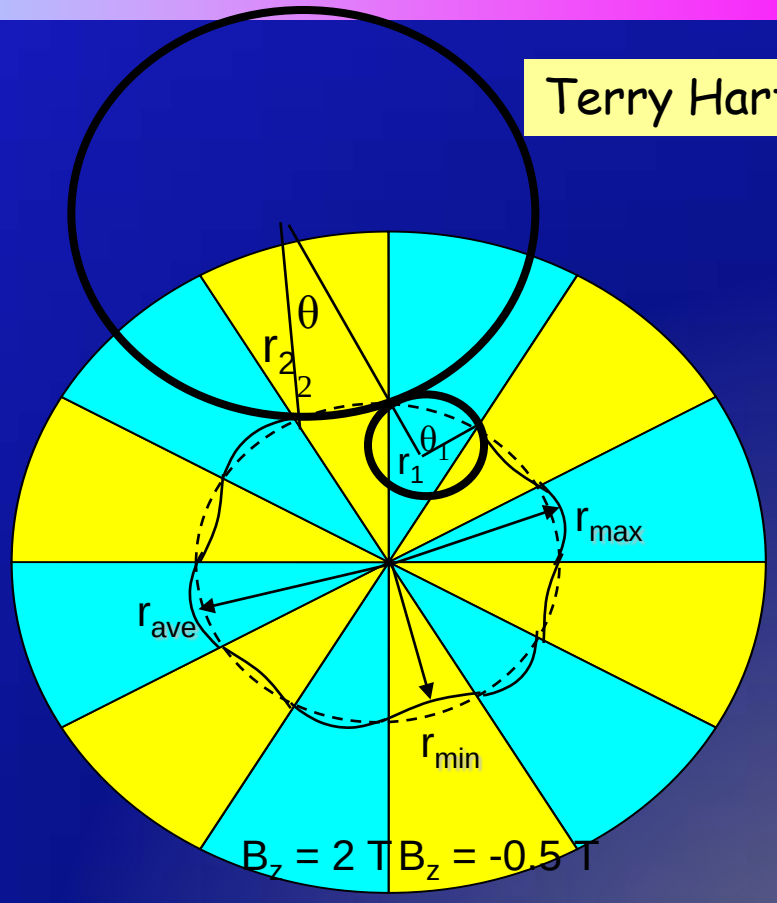
R. Palmer's ICOOL model





G4beamline model

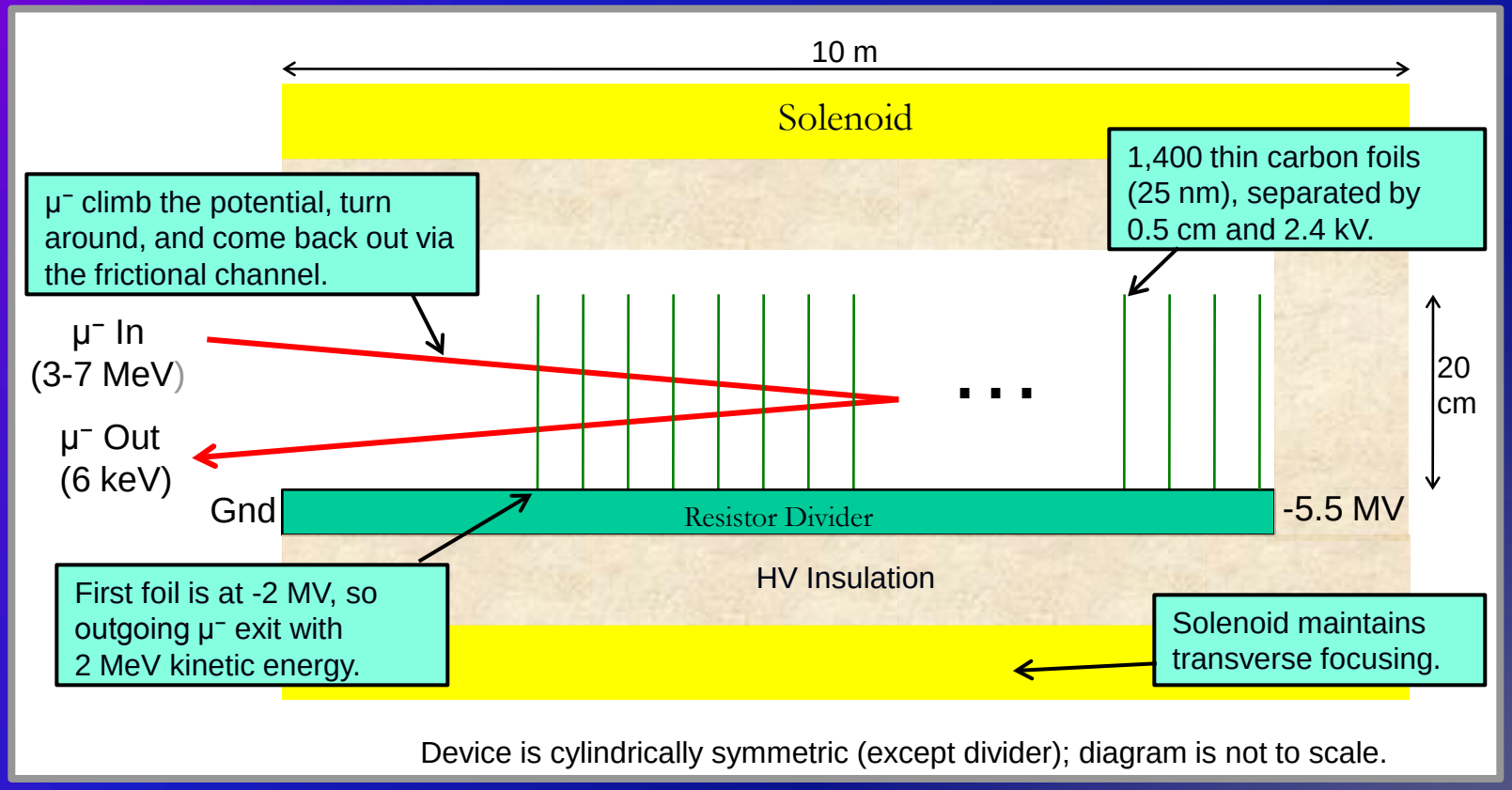
Terry Hart



VORPAL 3D Simulations with space-charge

Kevin Paul

Frictional Cooling



Tom Roberts

Remember that 1/e transverse cooling occurs by losing and re-gaining the particle energy. That occurs every 2 or 3 foils in the frictional channel.

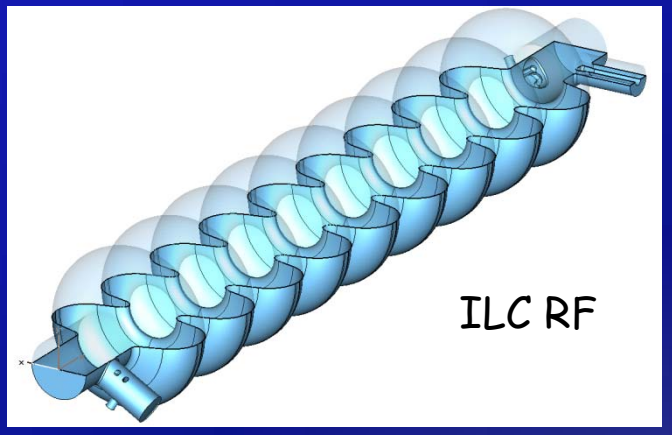
Acceleration

Acceleration - Overview

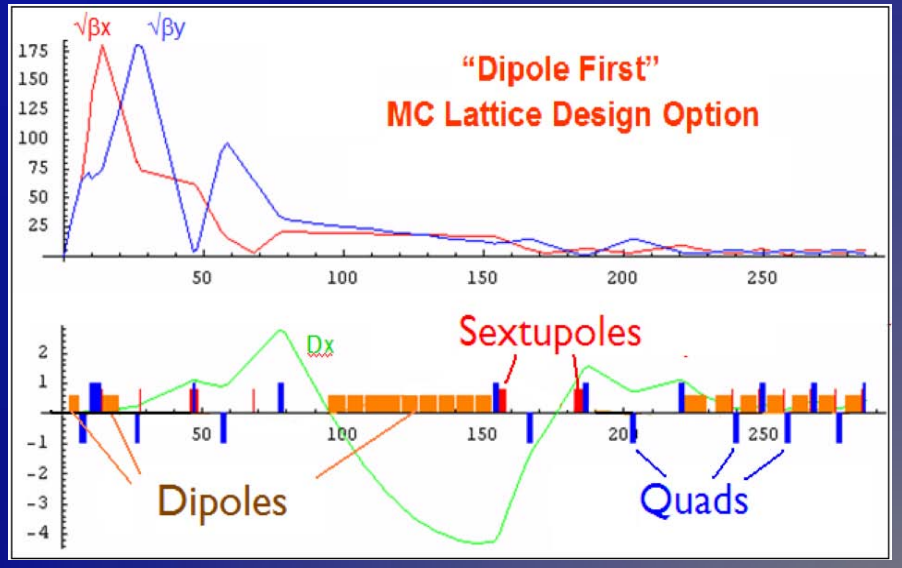
- RLA: get more passes
  - Ramp linac magnets, get more passes (12)
  - Non-scaling FFAG arcs: get 2 passes per arc, maybe more
- Fast ramping synchrotron (RCS)
  - Potential for many more passes
- FFAG: not studied much as yet for Muon Collider

Acceleration and Collider

- Acceleration
- Rapid acceleration in linacs and RLAs, <90MW wall plug for 3TeV
- Lower cost option – pulsed synchrotrons
- FFAGs might also play a role

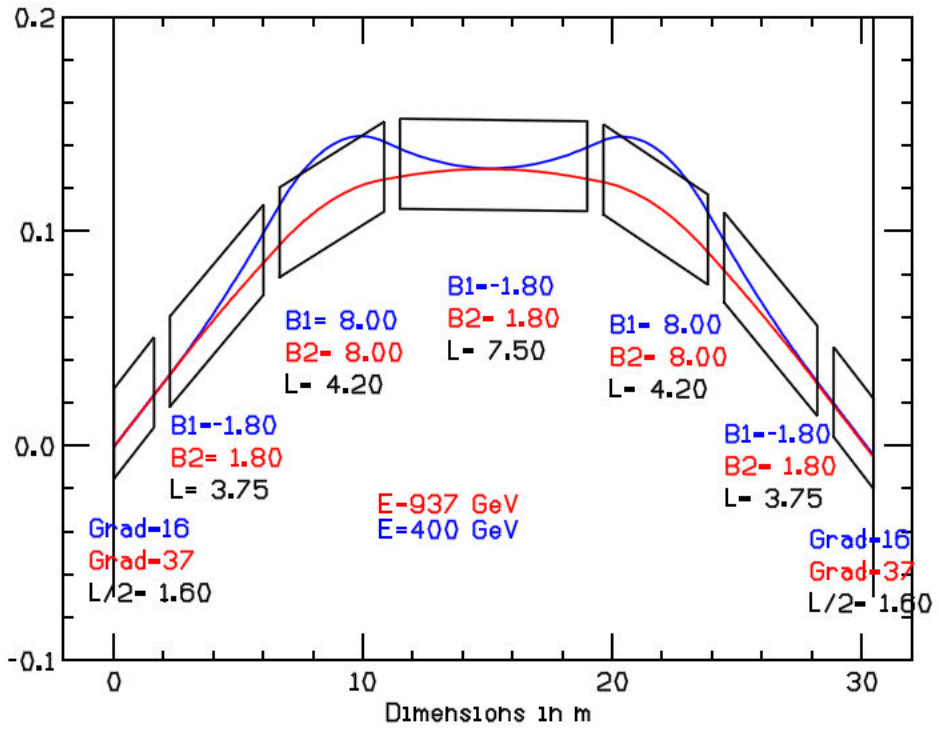


- Collider Ring
  - 1.5 TeV designed
- To be studied: Detector background with early dipole scheme



Acceleration –Rapid Cycling Synchrotron

Particle Paths in a 400 to 750 GeV Hybrid Half Cell



- Dipoles oppose at injection, then act in unison at extraction. Edge focusing changes during the cycle. Can quads correct? Try to simulate focusing with OPTIM.

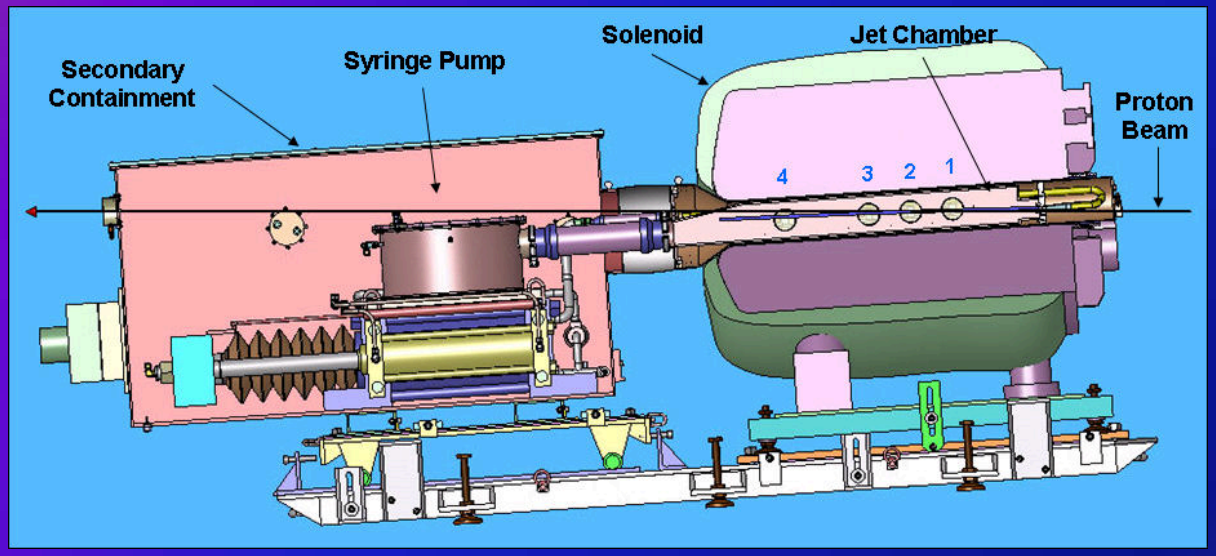
Addressing the Technological Challenges of
The Muon Collider

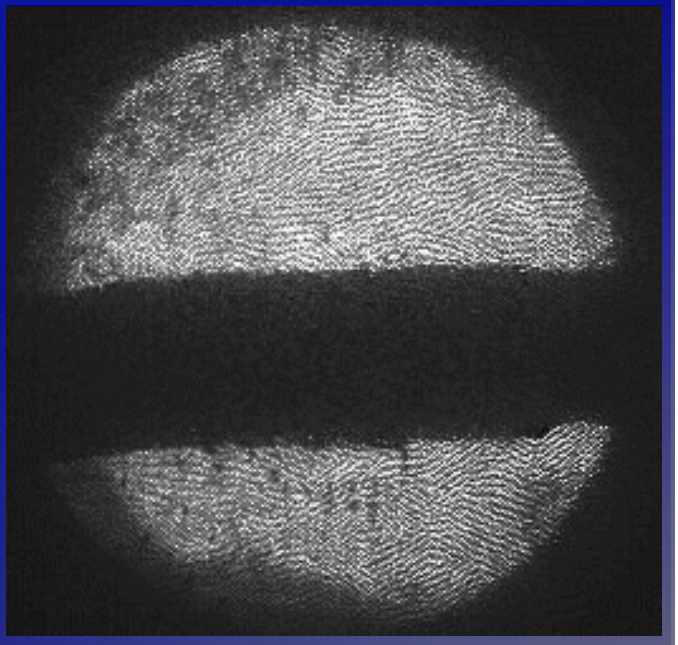
R&D Program Overview

Indicating some areas common to NF

- High Power Targetry – NF & MC *(MERIT Experiment)*
- Initial Cooling – NF & MC *(MICE (4D Cooling))*
- 200 (& 805) MHz RF - NF & MC *(MuCool and Muon's Inc)*
  - Investigate RF cavities in presence of high magnetic fields
  - Obtain high accelerating gradients (~15MV/m)
  - Investigate Gas-Filled RF cavities
- Intense 6D Cooling – MC
  - RFOFO "Guggenheim"
  - Helical Channel Cooling
  - Parametric Resonance Ionization Cooling
- Bunch Recombination - MC
- Acceleration– A cost driver for both NF & MC, but in very different ways
  - Multi-turn RLA's – a BIG cost reducer
  - RCS for MC
  - FFAG's – *(EMMA Demonstration)*
- Storage Ring(s) – NF & MC
- Theoretical Studies NF & MC
  - Analytic Calculations
  - Lattice Designs
  - Numeric Simulations

MERIT
The Experiment Reached 30TP @ 24 GeV



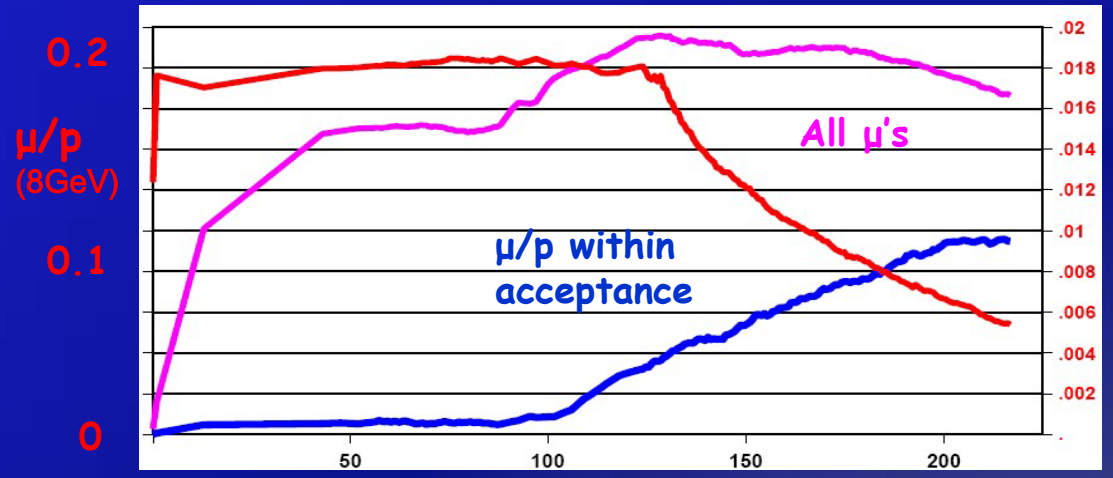


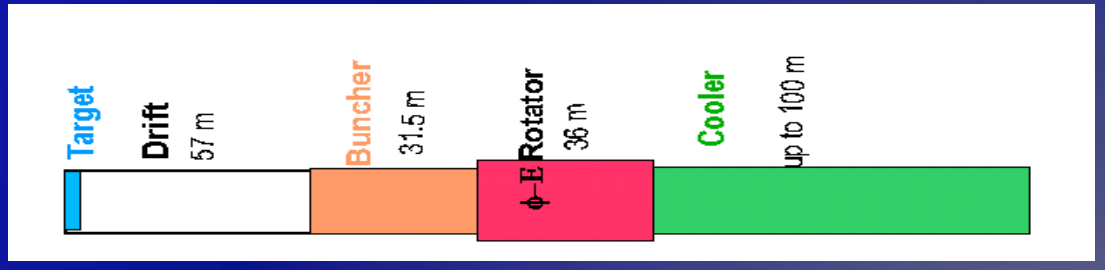
- Experiment Completed (CERN)
  - Beam pulse energy = 115kJ
  - B-field = 15T
  - Jet Velocity = 20 m/s
  - Measured Disruption Length = 28 cm
  - Required "Refill" time is then 28cm/20m/s = 14ms
    - → Rep rate of 70Hz
  - → Proton beam power at that rate is 115kJ *70 = 8MW

Fermilab ν-factory (MC) Front End baseline

- **Drift– 56.4m**
  - B=2T
- **Bunch– 31.5m**
  - P_1=280MeV/c, P_2 =154 MeV/c, δn_{rf} = 10; V_{rf}= 0 to 15 MV/m
- **ϕ-E Rotate – 36m –**
  - V_{rf} = 15MV/m, B =2T
  - **(240 -> 201.5 MHz)**
- **Match and cool (80m)**
  - Alternating solenoid (2.8T)
  - LiH or H_2 absorbers
  - V_{rf}=16, 201.25 MHz

Transverse emittance





- **Obtains ~0.085 μ/ 8 GeV p**

1.4 10^{21} μ/year

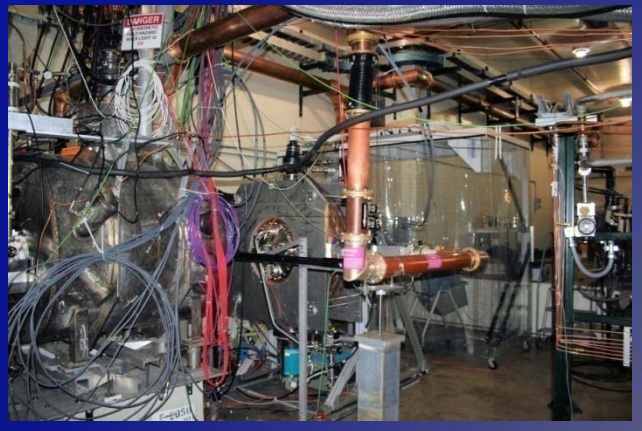
MuCool
Component R&D and Cooling Experiment

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

50 cm ∅ Be RF window

MuCool Test Area

MuCool
201 MHz RF Testing



MuCool
LH_2 Absorber
Body

RF Test Program

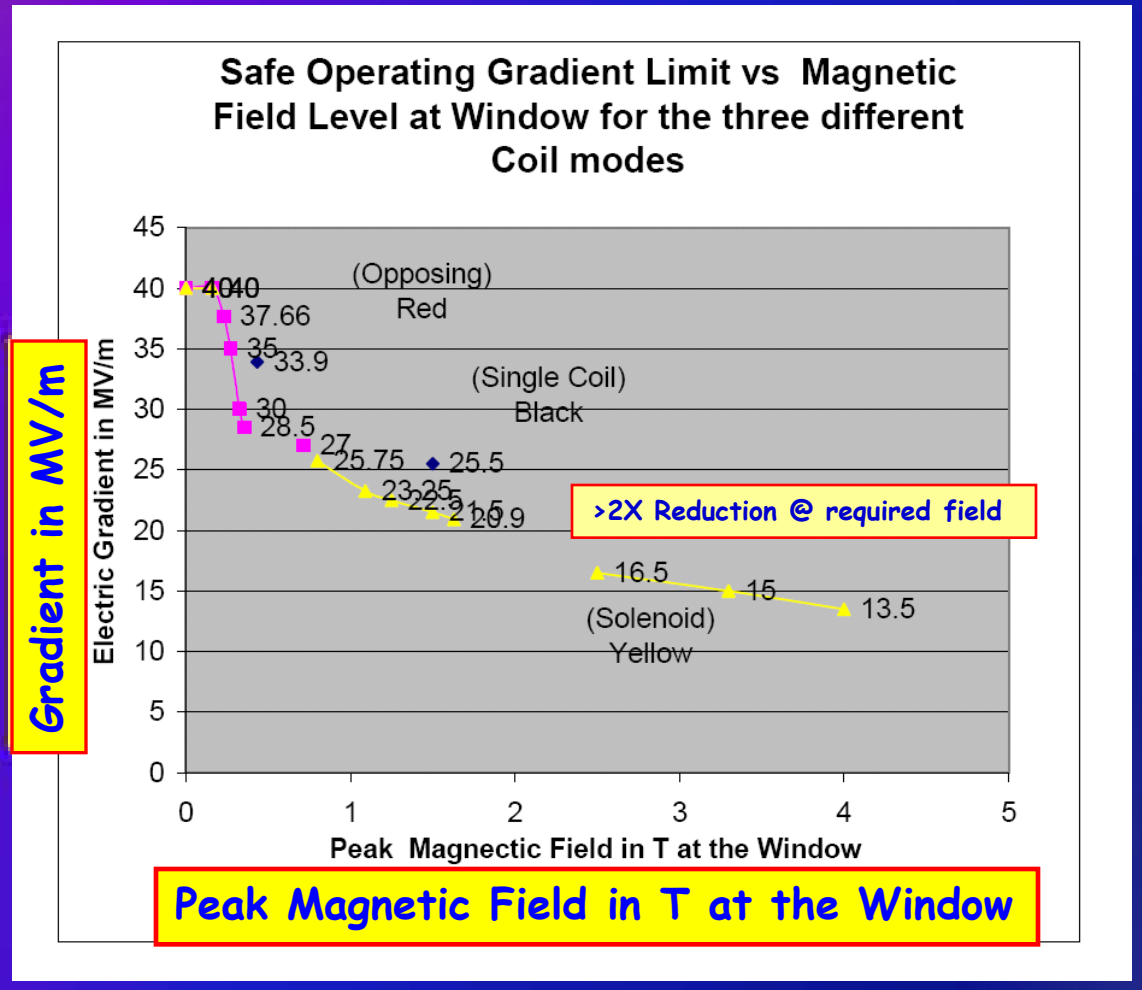
MuCool has the primary responsibility to carry out the RF Test Program

- Study the limits on Accelerating Gradient in NCRF cavities in magnetic field
- Fundamental Importance to both NF and MC – RF needed in
  - Muon capture, bunching, phase rotation
  - Muon Cooling
  - Acceleration

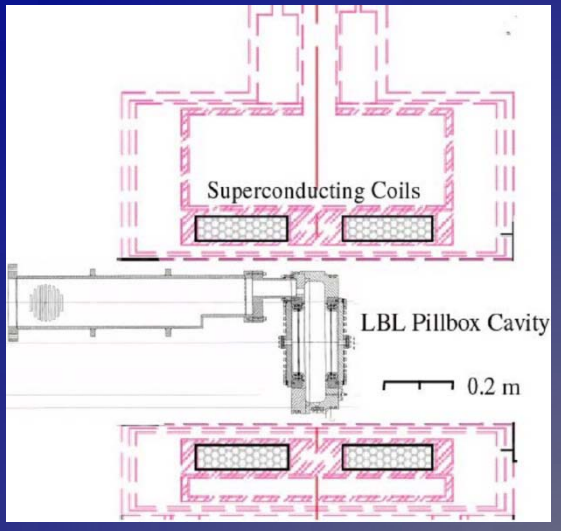
Arguably the single most critical Technical challenge for the NF & MC

The Basic Problem – B Field Effect

805 MHz Studies



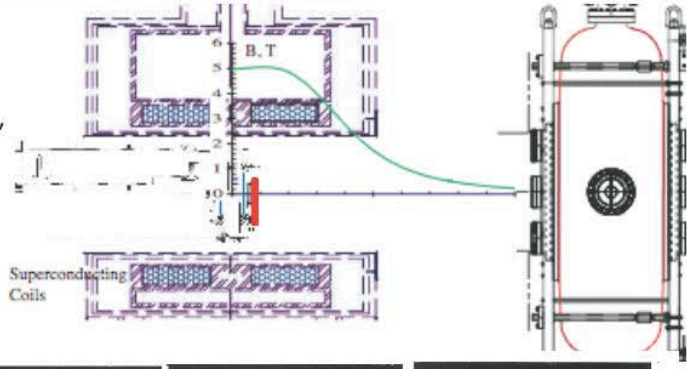
- Data seem to follow universal curve
  - Max stable gradient degrades quickly with B field
- Re-measured
  - Same results



805 MHz Imaging

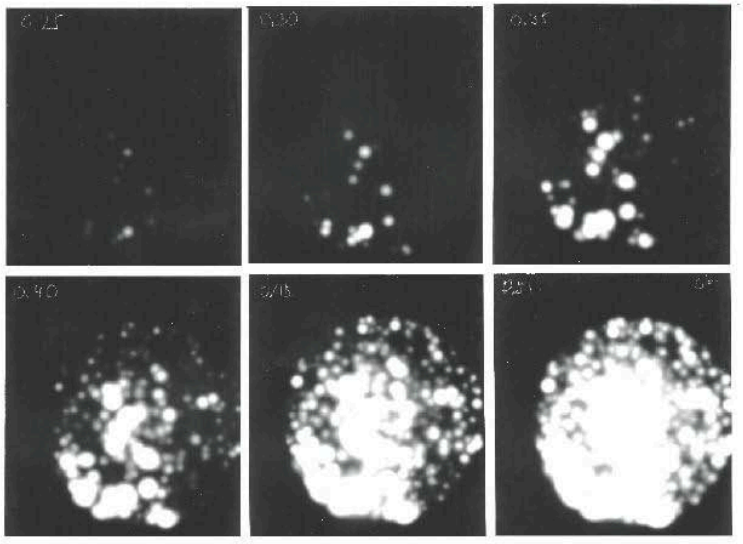
Polaroid Pictures of Field emitters

- Inserting polaroids near the window,



- Gives a picture of how the field emitters change with rf field.

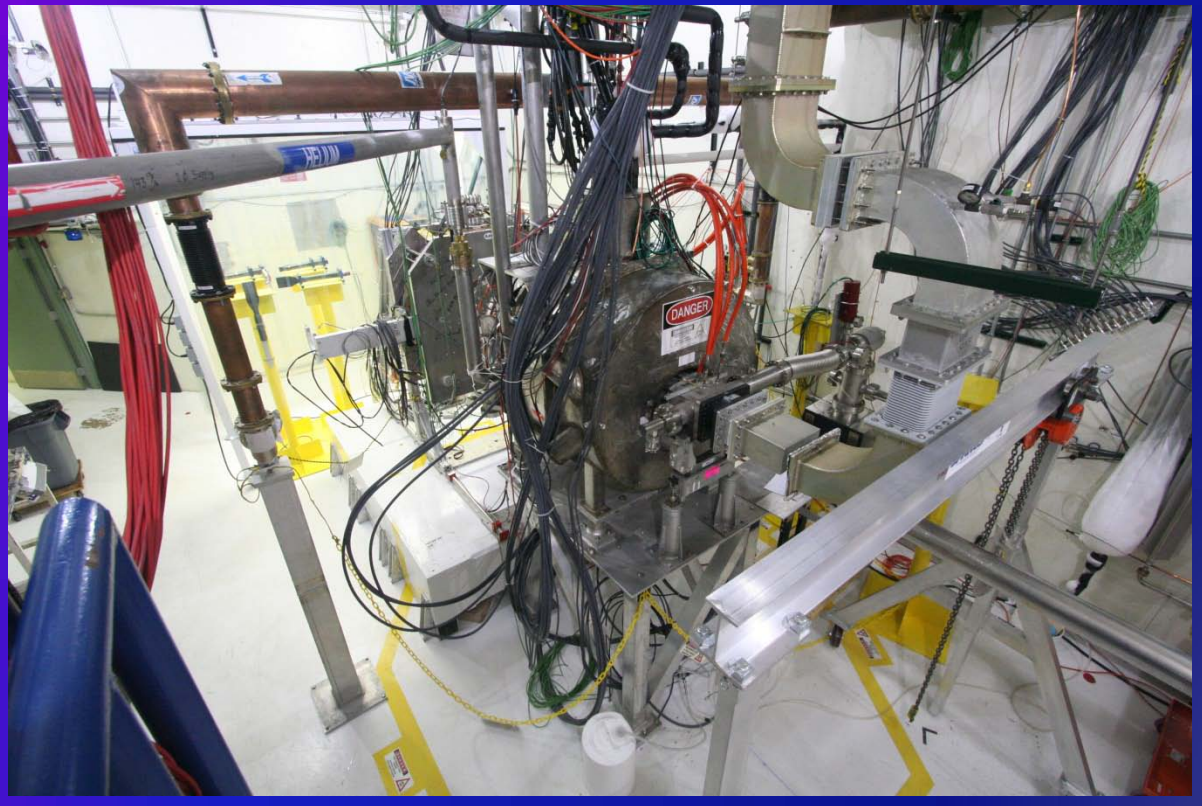
  8.8 – 17.6 MV/m

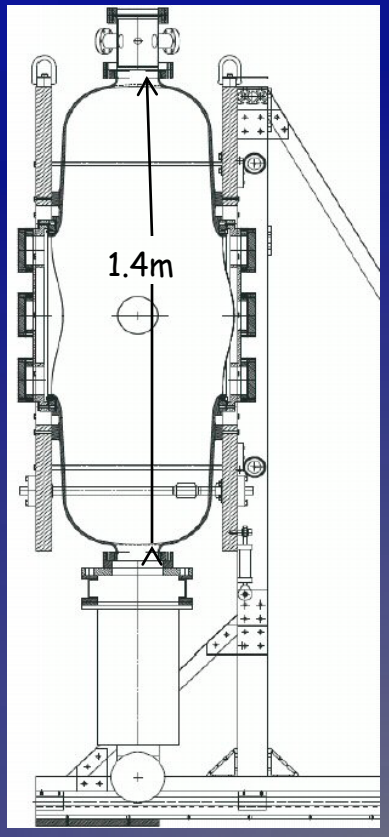


RF R&D – 201 MHz Cavity Test

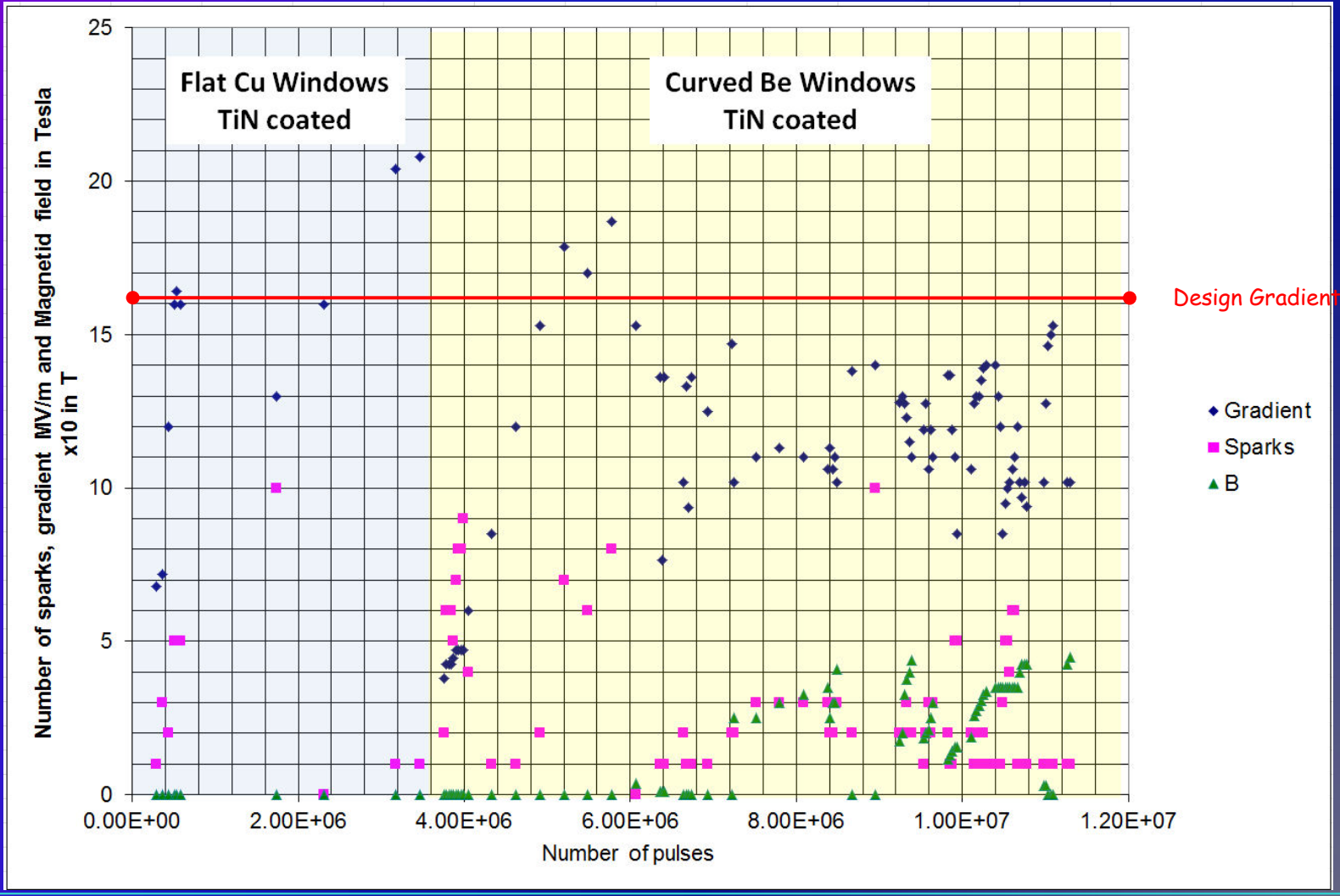
Treating NCRF cavities with SCRF processes

- **The 201 MHz Cavity – *21 MV/m* *Gradient Achieved* (Design – 16MV/m)**
  - *Treated at TNJLAB with SCRF processes – Did Not Condition*





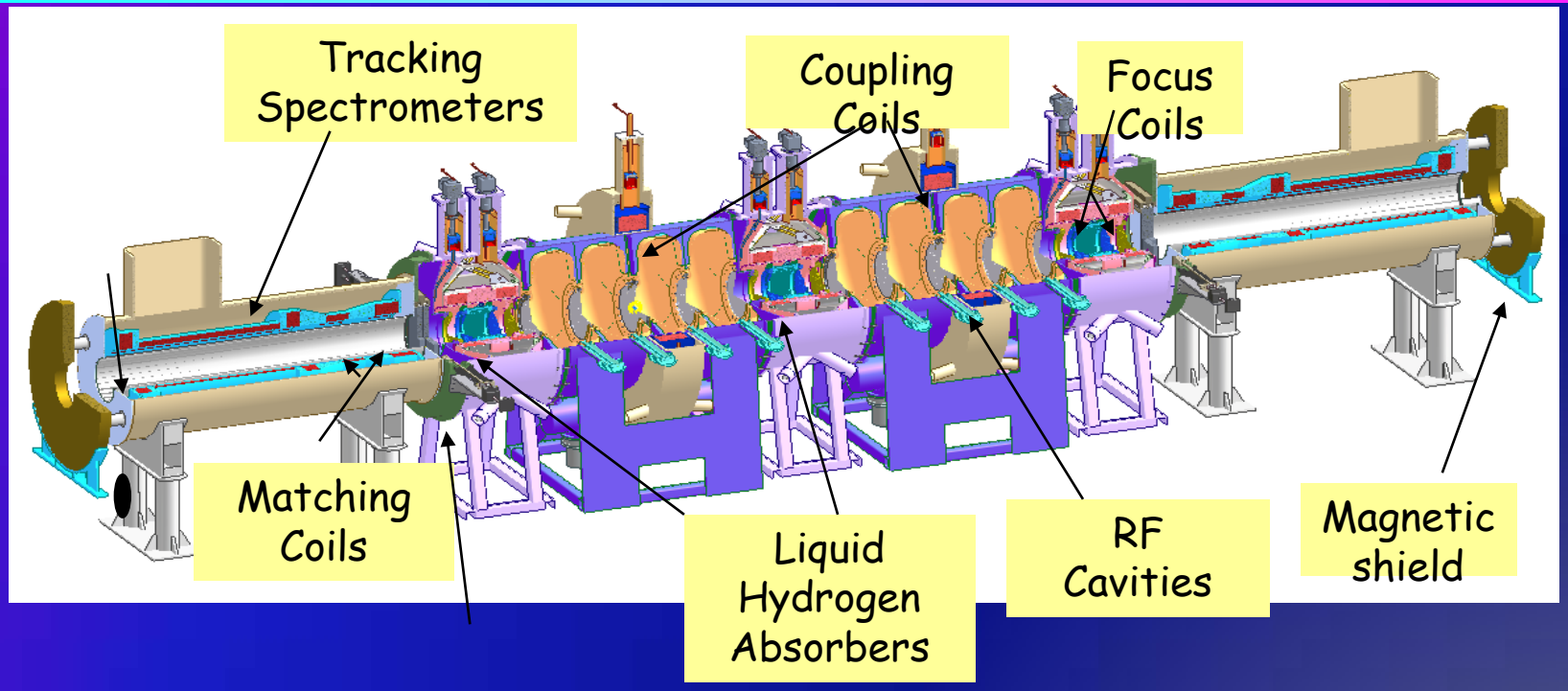
201 MHz Cavity Running



The MAP NCRF Program
R&D Strategy

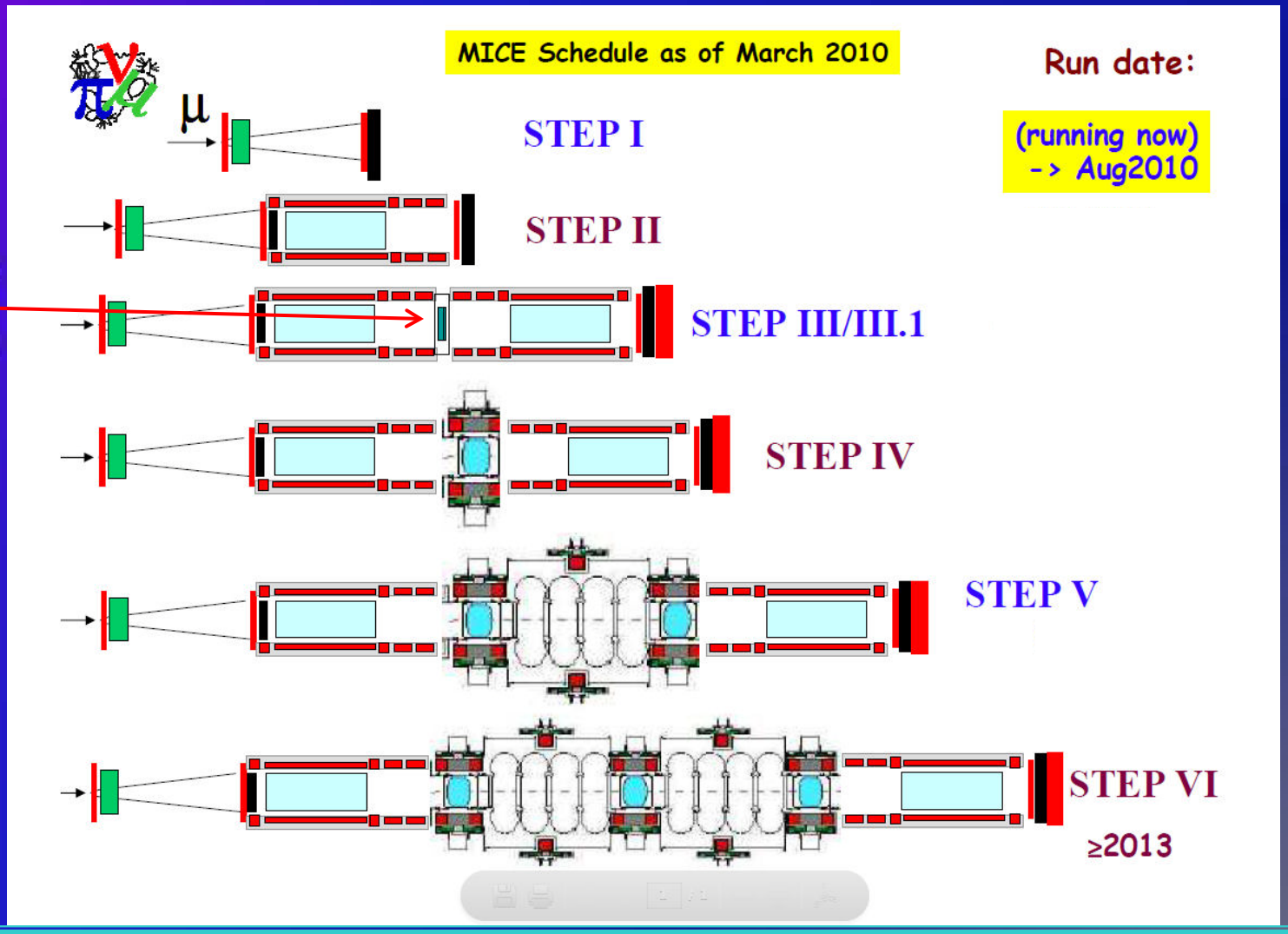
- *Technology Assessment (continuation of existing multi-pronged program & explore new ideas)*
  - Surface Processing
    - Reduce (eliminate?) surface field enhancements
      - SCRF processing techniques
        - Electro-polishing (smooth by removing) + HP H_2O rinse
      - More advanced techniques (Atomic-Layer-Deposition (ALD))
        - Smooth by adding to surface (conformal coating @ molecular level)
  - Materials studies: Use base materials that are more robust to the focusing effects of the magnetic field
    - Cavity bodies made from Be or possibly Mo
  - Magnetic Insulation
    - Inhibit focusing due to applied B
  - High-Pressure Gas-filled (H_2) cavities

Muon Ionization Cooling Experiment

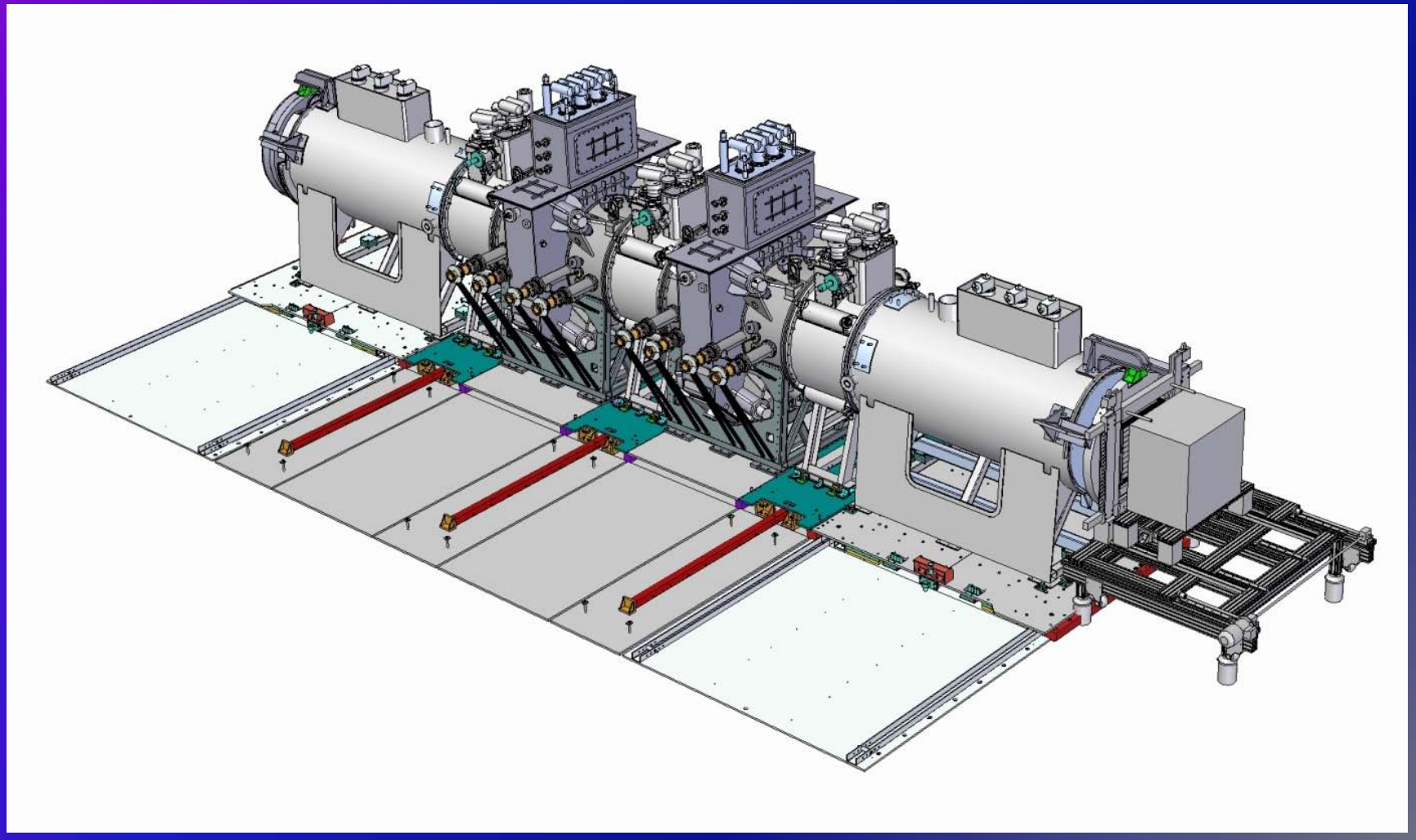


- **Measure transverse (4D) Muon Ionization Cooling**
  - 10% cooling – measure to 1% (10^{-3})
- **Single-Particle Experiment**
  - Build input & output emmittance from μ ensemble

MICE Schedule



STEP VI



Progress on MICE

- **Beam Line Complete**
  - First Beam 3/08
  - Running now
- **PID Installed**
  - CKOV
  - TOF
  - EM Cal
- **First Spectrometer**
  - Jan 2012

Fiber Tracker

Muon Collider Machine-Detector Interface

If a Multi-TeV Muon Collider is built

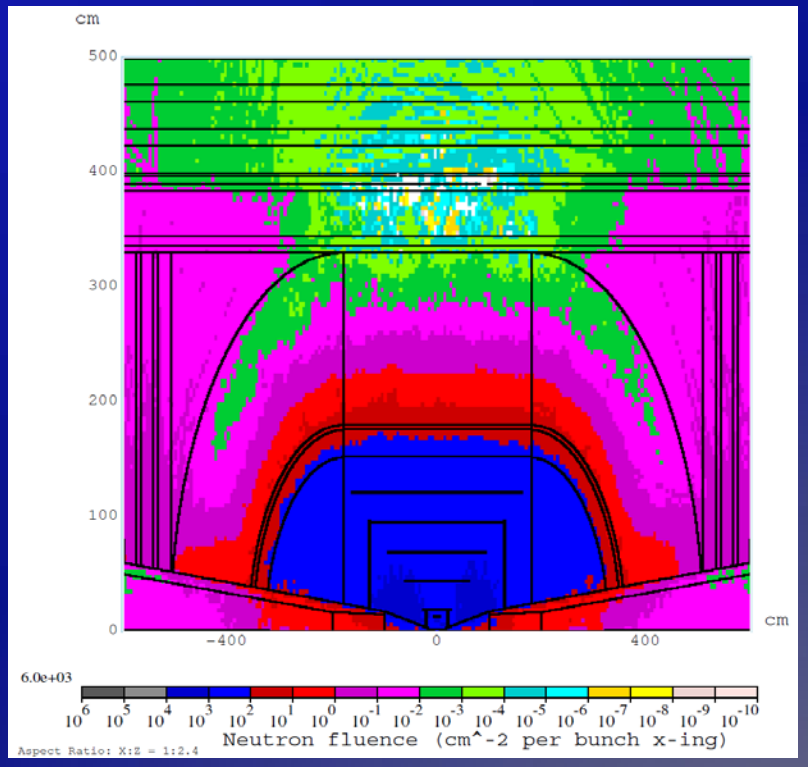
Can a detector be designed that will do the physics?

Muon Collider Detector Issues

Shielding Backgrounds

- **MC detector backgrounds studied actively 10 years ago (1996-1997).**
  - Large background from decay electrons
- **Shielding strategy**
  - Electron "sweeping" & IP shielding high-Z cone
- **New studies have advanced our understanding and show that this strategy can work extremely well.**
  - Note: Tungsten cone in forward direction with angle 10°
    - CLIC detector uses 7° cone

MARS simulation - 1.5 TeV MC

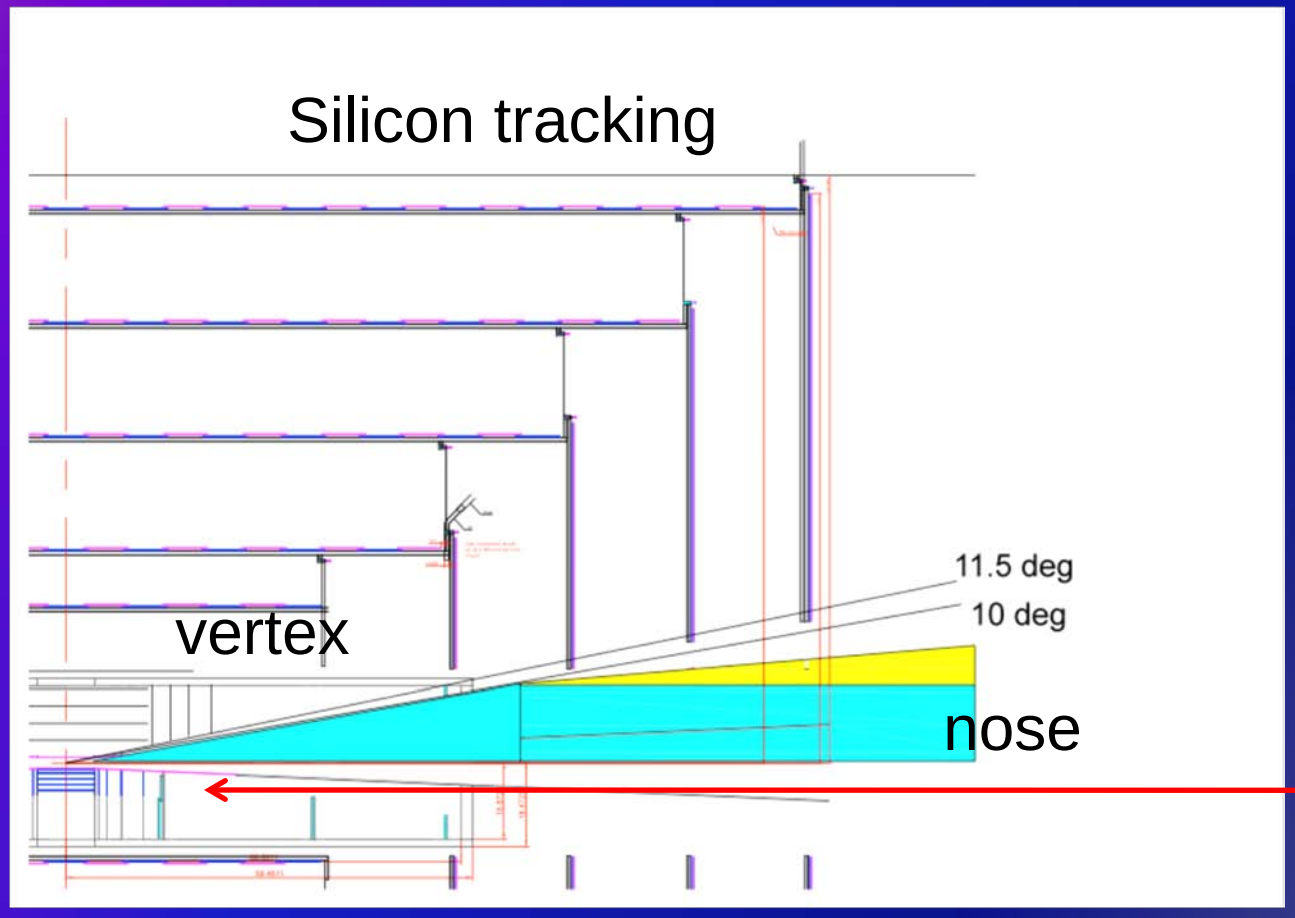


Total dose in Si detector $\approx \frac{1}{2}$ that at LHC @ $L=10^{34}$

Background Levels

- Detailed shielding design done plus background simulations using two codes (MARS & GEANT) → consistent results. Tungsten cone in forward direction with angle 20° (c.f. CLIC = 7°).
  - With modern detector technologies, perhaps angle can be reduced & tungsten can be instrumented.
- Hit densities at, r=5cm are 0.2 hits/mm2. Comparable to CLIC estimates. Also, ideas on how to further reduce hits by x100.
- SYNERGY with CLIC Detector R&D and design studies.
  - LHC Detector Technologies

Detector Simulation
4th Concept + SiD



- **SiD ILC detector in the muon collider framework**

ADVERTISEMENT

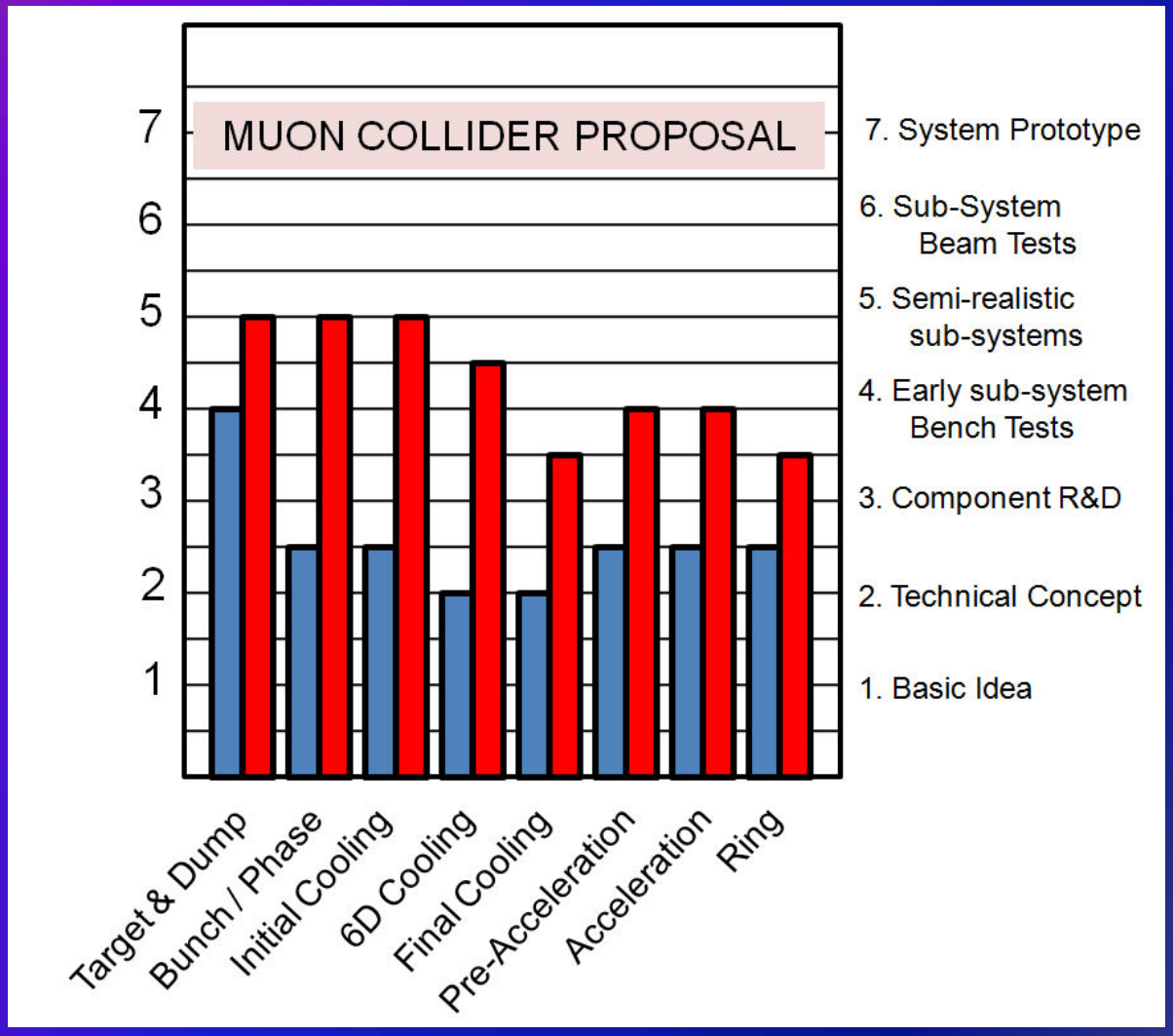
The Way Forward

Road "MAP"

MAP 6 Year Program

- US Program
  - A measured program based on the solid muon accelerator R&D achievements of the last decade
  - Sufficiently ambitious to make substantial progress before the next round of long-term decisions by the particle physics community
  - Includes accelerator, physics & detector studies –The physics & detector studies will be in a separate proposal.
- Meets our existing commitments (NF-RDR, MICE) and in addition will deliver:
  - MC performance requirements based on physics
  - A first end-to-end MC simulation
  - Critical component development & proof-of-principle experiments
  - A first MC cost estimate

Muon Collider Design Feasibility Study

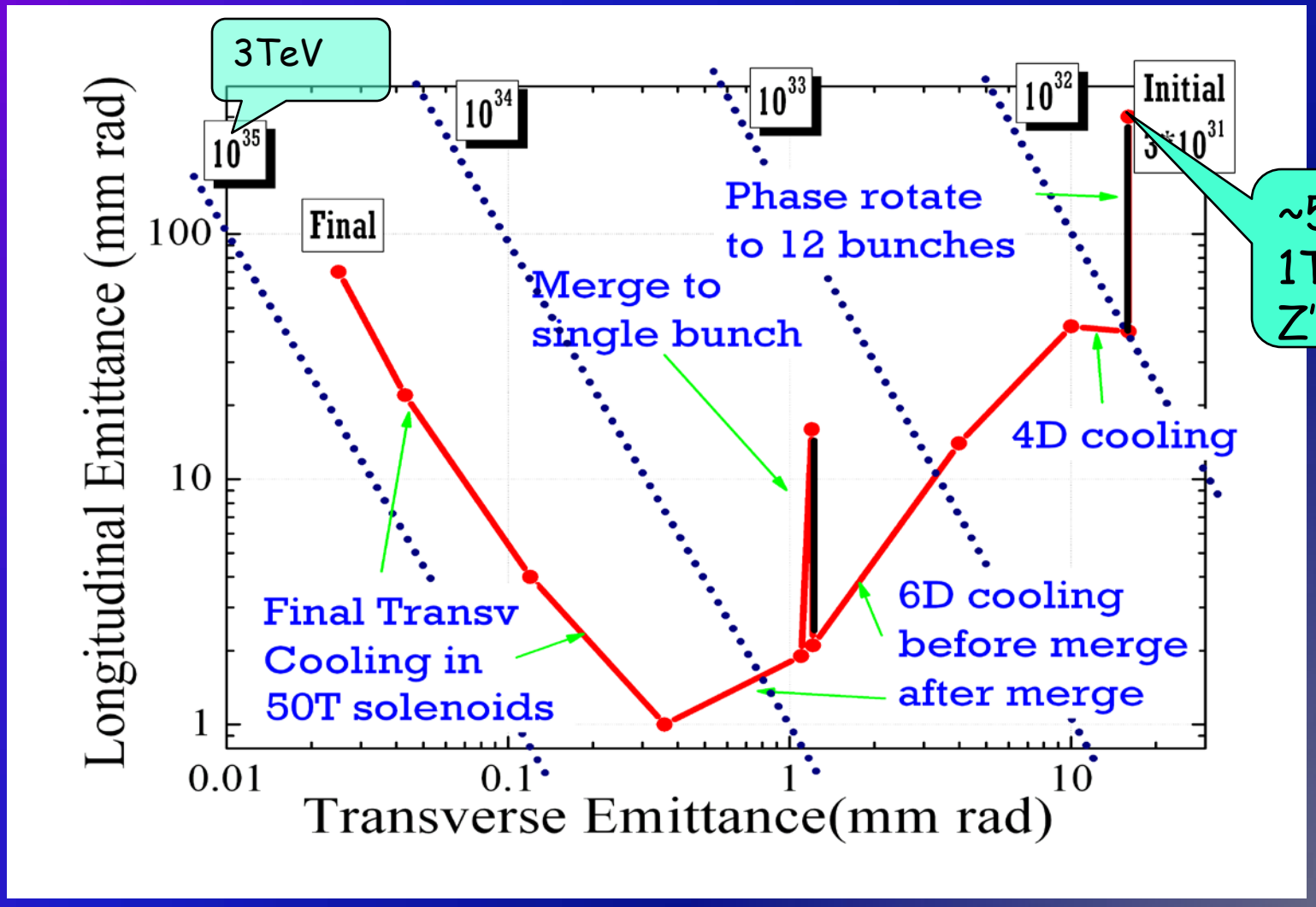


NOW

PROPOSED MC-DFS

End of 6 Year Program

Not Quite Getting There
Luminosity vs. Cooling



Participation

MAP has a diverse and very rich R&D Program

- Technology Development
  - High gradient RF - MuCool
    - SC also for the accelerators
  - Very-high field magnets – HTS development
  - High-power targetry
- System Tests
  - MICE
    - Much more scientific effort is needed on MICE
      - Hardware
        - RF, Magnet systems
      - Online systems
        - Monitoring/data quality
      - Software development
        - Reconstruction
        - Data Analysis
  - Planning for follow-on experiment to MICE
    - High-power 6D cooling demonstration
- Accelerator systems simulation work
  - Capture, Cooling, Acceleration, Collider
- Machine-Detector Interface
- Detector simulations

Where are we headed?

- 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 – Will point us in *Some* Direction
  - We Don't Know Which One Yet, But the NF and/or the MC may be part of our future

END

Acknowledgments

I want to thank all my colleagues in the Neutrino Factory and Muon Collider Collaboration and the Fermilab Muon Collider Task force for all the hard work and for the many conversations I have had with them on this subject.

In Particular I want to thank Bob Palmer, Steve, Geer, Vladimir Shiltsev and Mike Zisman