The Neutrino Factory

The Final Frontier in Neutrino Physics?

Alan Bross

PAC09

Fermilab

Outline

- In order to demonstrate the power of the Neutrino Factory, I will first briefly discuss the physics of neutrino oscillations
- Describe the Baseline Neutrino Factory Design
  - International Design Study for a Neutrino Factory
- Show the Neutrino Factory Sensitivity for the neutrino oscillation parameters in comparison to other State-of-the-art facilities – *"Final Frontier"*
- Outline the Technical ingredients of the Neutrino Factory
- Outline the R&D Program and give the proposed Timeline
- Beyond the Neutrino Factory?
  - "A Journey of a thousand miles, begins with a single step"

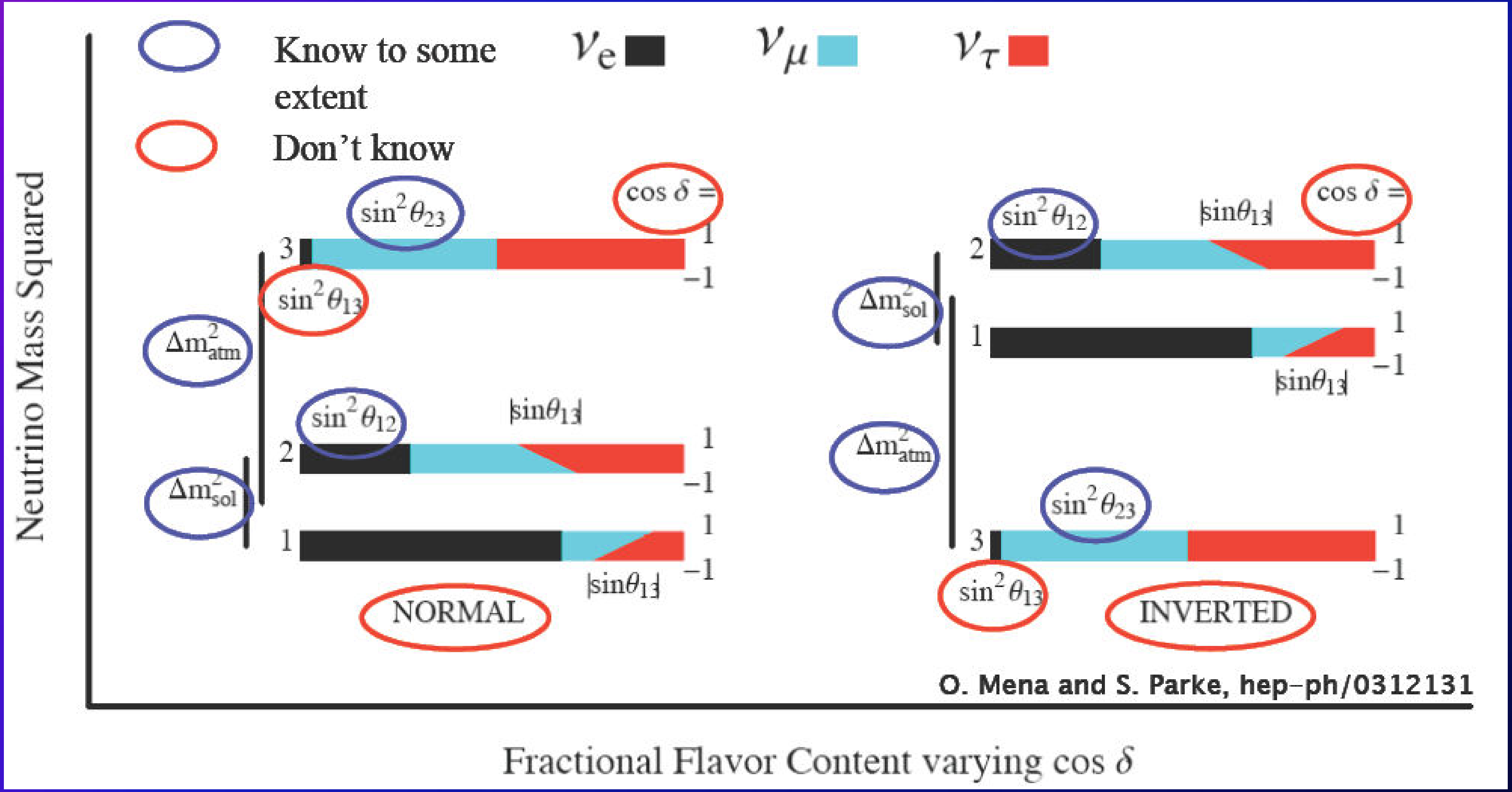
The "Standard" Neutrino Model:

- It has now been over 10 Years since the discovery of ν oscillations/mixing
- Neutrino oscillations can be described within the following framework:
  - Mixing between three mass eigenstates (SνM)
  - Existence of Right-handed neutrino states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\sin^2 2\theta_{12} = 0.82 \pm 0.055$$
$$\sin^2 2\theta_{23} > 0.95$$
$$\sin^2 2\theta_{13} < 14^\circ$$
$$\Delta m^2_{21} = (7.9 \pm 0.7) \times 10^{-5}\ \mathrm{eV}^2$$
$$|\Delta m^2_{31}| = (7.9 \pm 0.7) \times 10^{-5}\ \mathrm{eV}^2$$

3ν Mixing Model



- How are the unknown parameters determined?

Oscillation Probability

The "Golden" Channel: $\nu_e \rightarrow \nu_\mu$

$$P_{e\mu} \simeq \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

$$\pm\ \alpha \sin 2\theta_{13}\, \xi \sin \delta_{CP} \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

$$+\ \alpha \sin 2\theta_{13}\, \xi \cos \delta_{CP} \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})}$$

$$+\ \alpha^2 \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}. \qquad (1)$$

$\nu_e \rightarrow \nu_\mu$ (+) or $\nu_\mu \rightarrow \nu_e$ (-)

P. Huber and W. Winter, Phys. Rev. D68, (2003)

- **Where**
  - $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$
  - $\Delta = \Delta m^2_{31} L/4E$ {E is the ν energy and L the baseline (distance from source}
  - $\xi = \cos\theta_{13}\sin2\theta_{12}\sin2\theta_{23}$
  - $A = \pm(2\sqrt{2}G_F n_e E)/\Delta m^2_{31}$ (G_F, the Fermi coupling constant n_e the electron density in matter)
  - To second order in $\sin2\theta_{13}$ and α

Magic Baseline, L_{magic}

- In the previous equation if $\sqrt{2}G_F n_e L = 2\pi$, $\sin A\Delta = 0$, and all but the first term disappear

$$\sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}$$

- This allows for a clean measurement (no dengeneries) of $\sin^2 2\theta_{13}$ and the sign of Δm^2_{31} (Hierarchy)
- For a constant matter density, ρ, (approximately 2 e^- per nucleon)
  - L_{magic} [km] $\approx 32{,}726/\rho \approx$ 7630 km (with ρ in g/cm^3)
- Then $\Rightarrow$ Add a Second baseline for CP violation sensitivity

ν Oscillations Experiments are counting Experiments

- What you have are 2 counting experiments
  - Measuring the # evts of all neutrino flavors that you are sensitive to as a function of neutrino energy @ 2 Ls
- But, of course, you must know your source
  - Neutrino energy spectrum
  - Neutrino flavors in the beam
- A very precise determination of the neutrino source provides the opportunity to measure the neutrino mixing parameters very precisely
  - The detector Must be Up to the Job
  - Must have sufficient statistics
  - Good handle on All systematic uncertainties

How Do We Accomplish This?

ν Oscillations Experiments are counting Experiments

- What you have are 2 counting experiments
  - Measuring the # evts of all neutrino flavors that you are sensitive to as a function of neutrino energy @ 2 Ls
- But, of course, you must know your source
  - Neutrin
  - Neutrin

Neutrino Factory

- A very precise determination of the neutrino source provides the opportunity to measure the neutrino mixing parameters very precisely
  - The detector Must be Up to the Job
  - Must have sufficient statistics
  - Good handle on All systematic uncertainties

How Do We Accomplish This?

The Neutrino Factory

Well-understood neutrino source:

μ Decay Ring:

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

S. Geer, Phys. Rev. **D57** (1998) 6989

- **Flavor content fully known**
- **"*Absolute*" Flux Determination is possible**
  - **Beam current, polarization, Near Detector semi & purely leptonic event rates**
- **Tremendous control of systematic uncertainties with well designed near detector(s)**

Neutrino Factory – μ Decay Rings

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	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

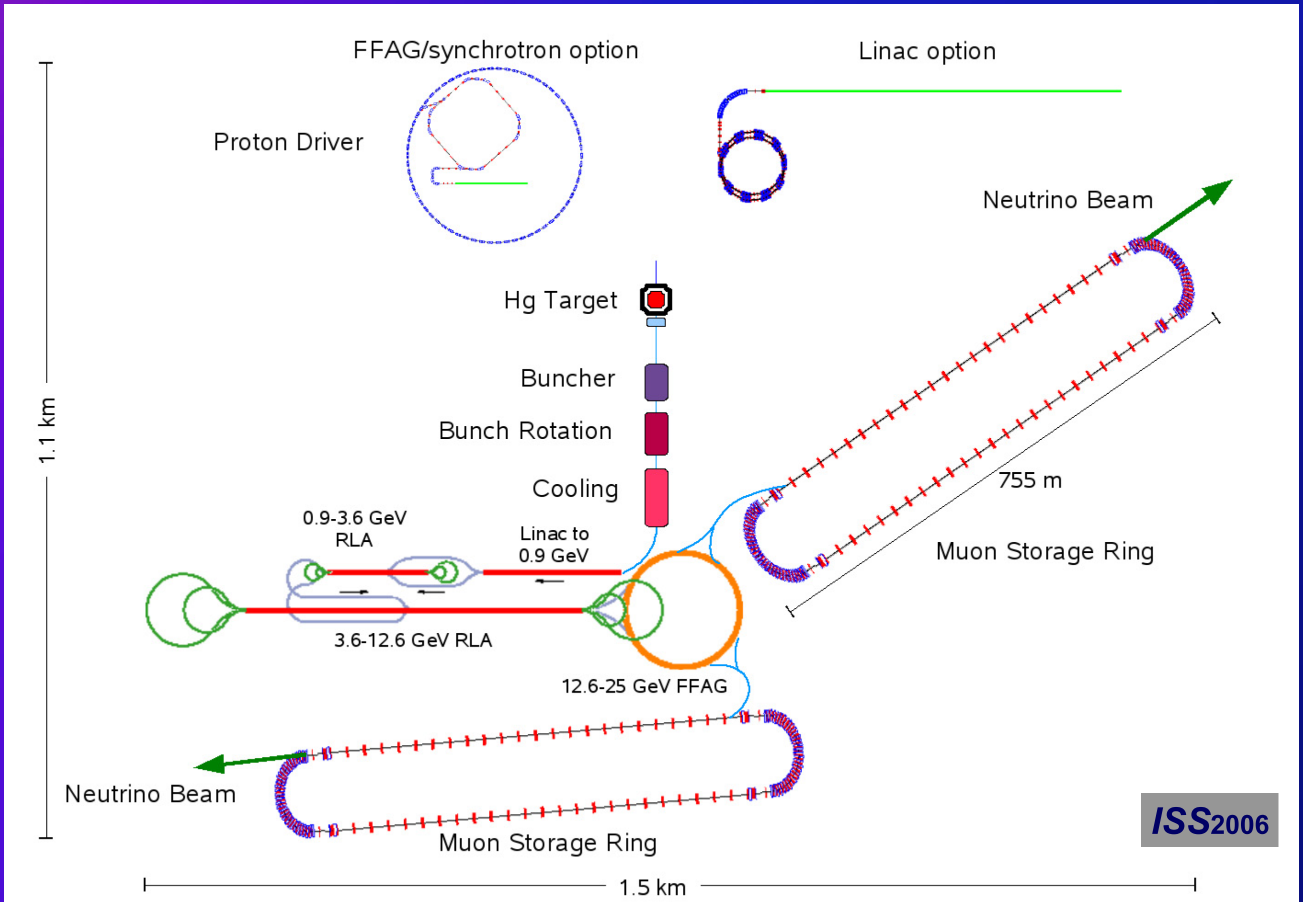
- 'Reference' Neutrino Factory:
  - $\geq 10^{21}$ useful decays/yr; exposure '5 plus 5' years
- Two baselines (≈7500 km & ≈4000 km)
  - 50 kT magnetised iron detector (MIND) with MINOS performance – Golden Channel Detector
  - Backgrounds (for golden channel):
    - Sign of μ mis-ID'd
    - Charm decays
  - $E_{res} \sim 0.15 * E_\nu$

"Golden" → Sign of μ observed in detector opposite to that stored in decay ring

$\mu^+ \to \nu_e \Rightarrow \nu_\mu n \to \mu^- p$

Neutrino Factory Accelerator Facility

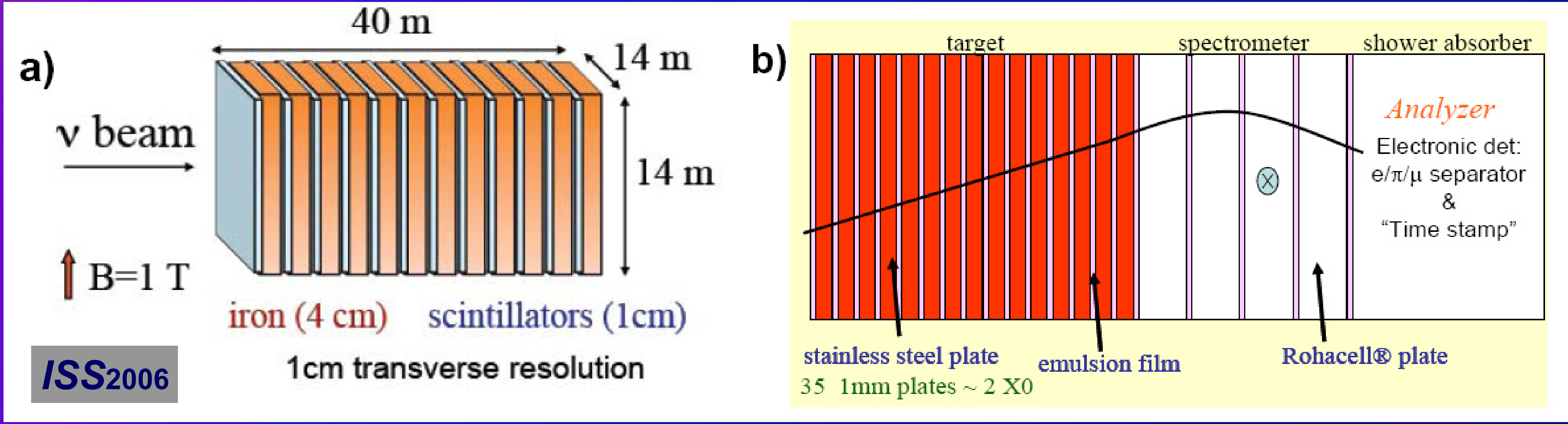
Baseline out of International Scoping Study

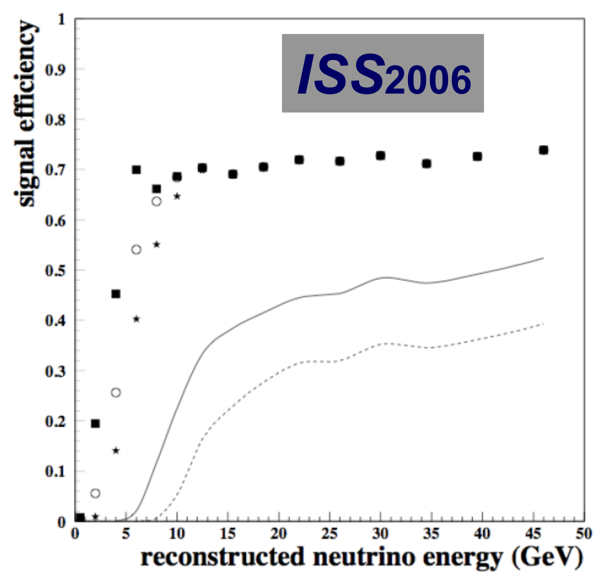


- **Proton Driver**
  - 4 MW, 2 ns bunch
- **Target, Capture, Drift ($\pi \rightarrow \mu$) & Phase Rotation**
  - Hg Jet
  - 200 MHz train
- **Cooling**
  - 30 πmm ($\perp$)
  - 150 πmm (L)
- **Acceleration**
  - 103 MeV $\rightarrow$ 25 GeV
- **Decay rings**
  - 7500 km L
  - 4000 km L
    - Baseline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

ISS Accelerator WG report: RAL-2007-023

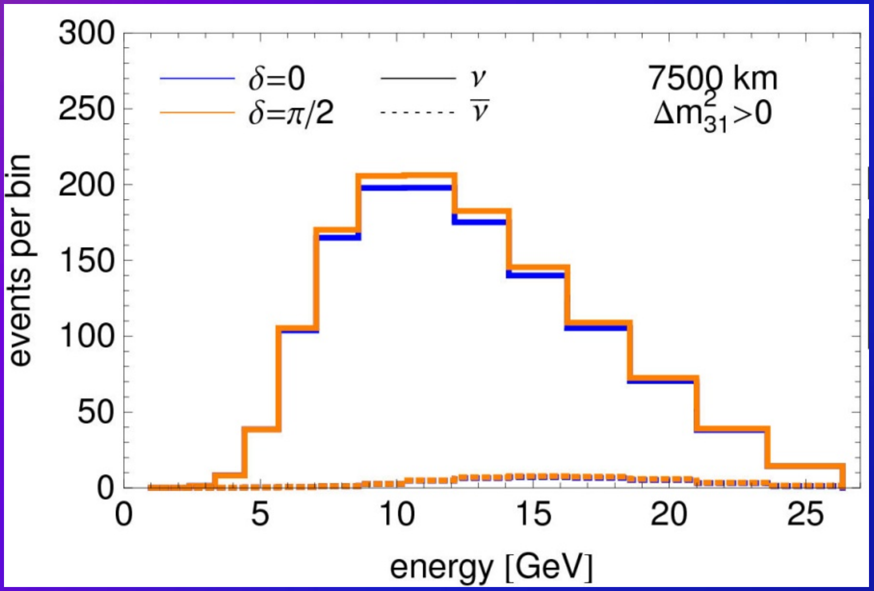
ISS baseline: Detectors

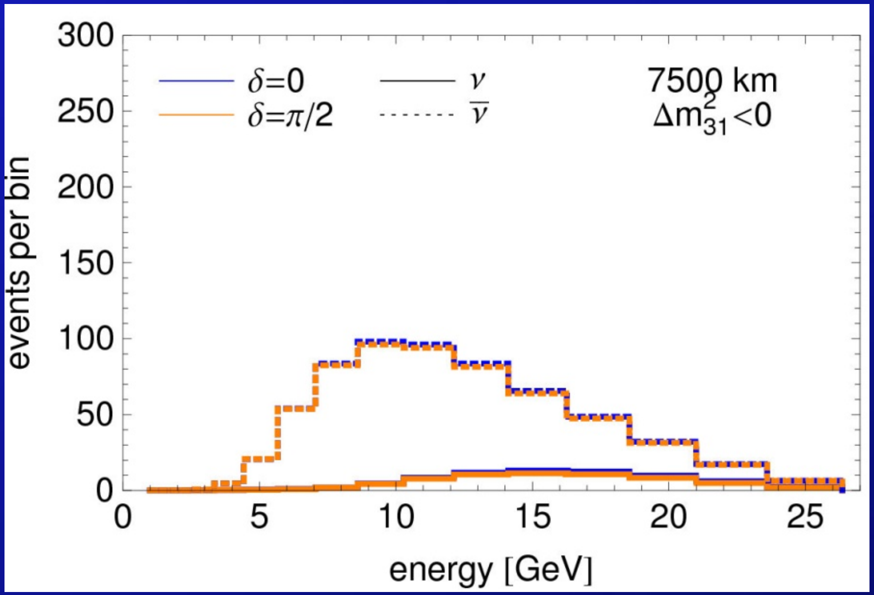




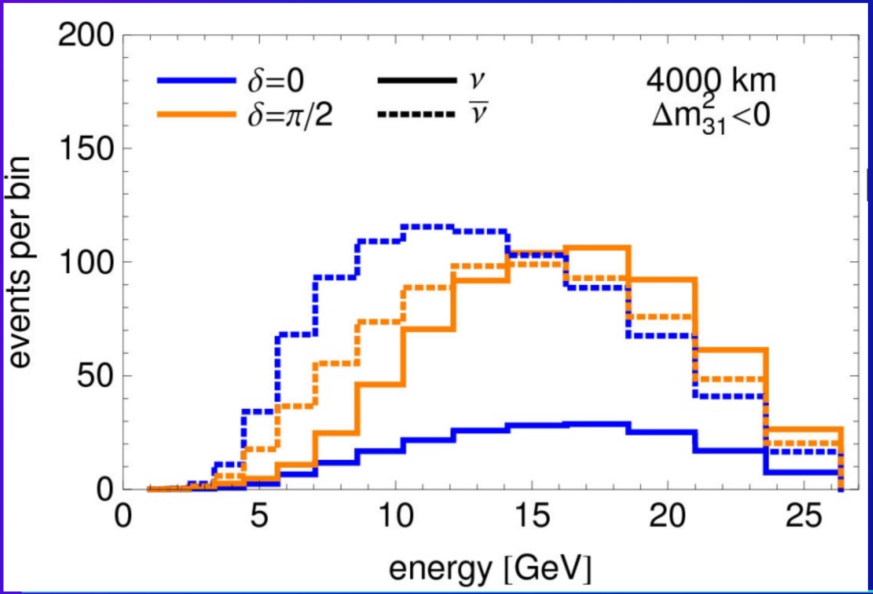
- **Two baselines:**
  - 3000 – 5000 km
  - 7000 – 8000 km
- ***Magnetised Iron Neutrino Detector (MIND) at each location***
- ***Magnetised Emulsion Cloud Chamber at intermediate baseline for tau detection***

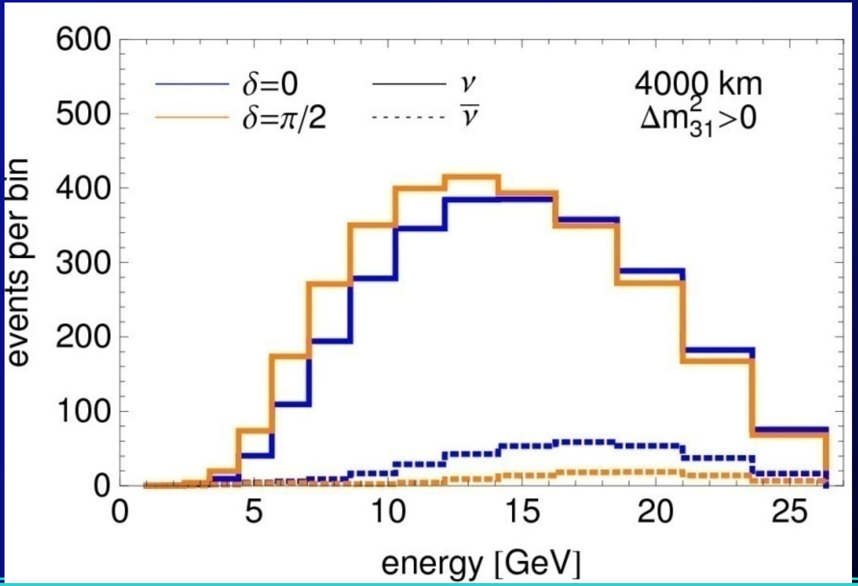
"Golden Channel" What you Actually Measure
evts/Energy Bin





$\sin^2 2\theta_{13}$
$\Delta m^2{}_{31}$





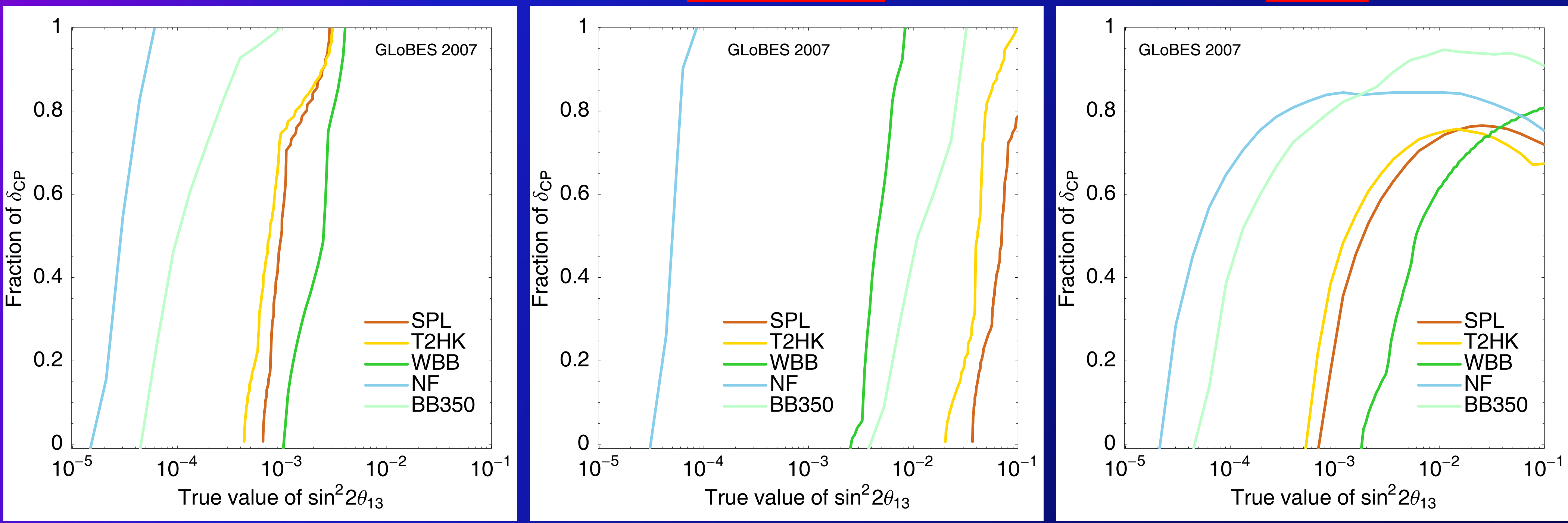
CPV phase
δ

International Scoping Study – Physics Reach

3σ contours shown

ISS Physics Group Report: arXiv:0710.4947v2

Sin$^2 2\theta_{13}$ | Hierarchy | δ *CP*

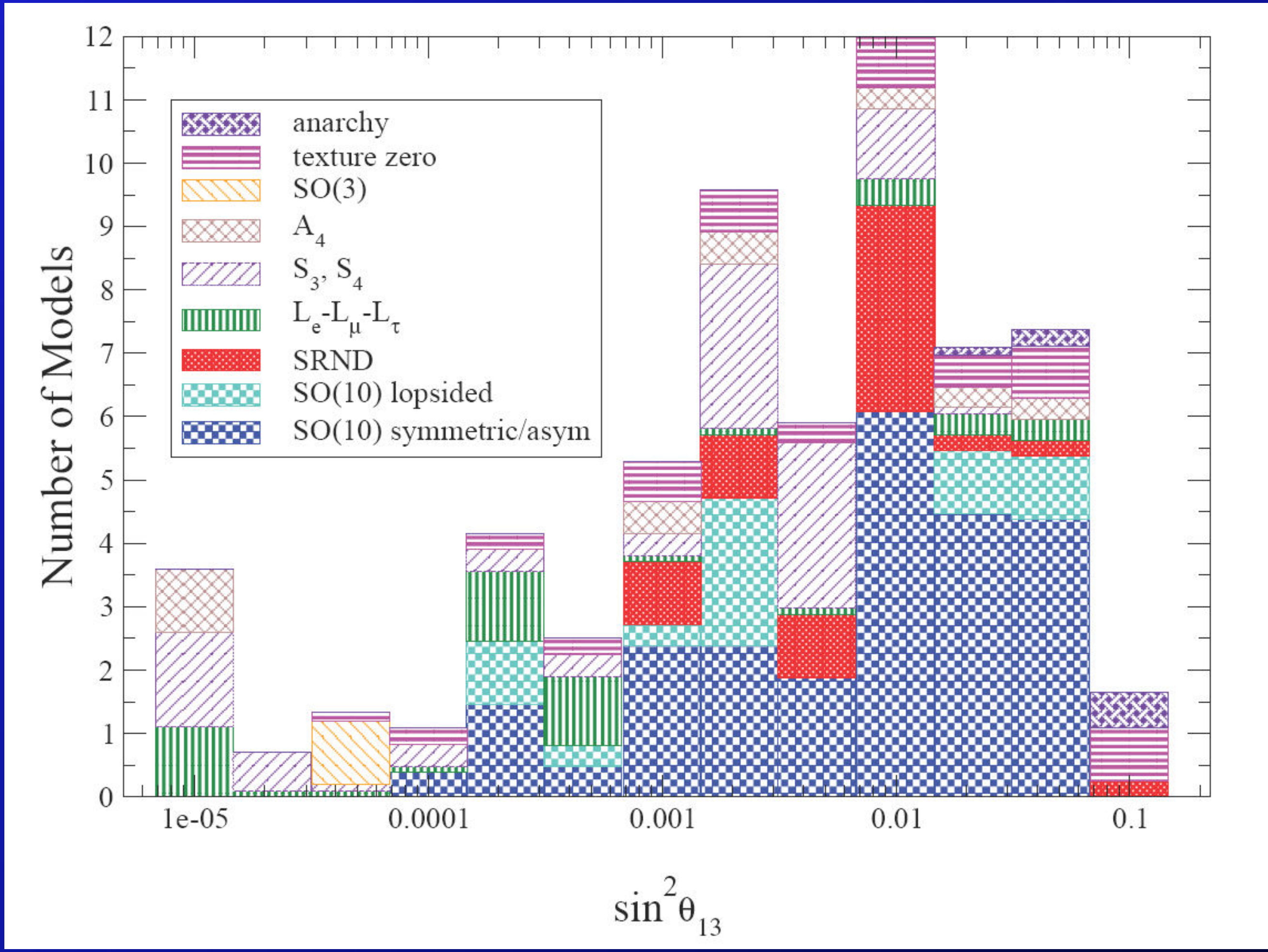


SPL: 4MW, 1MT H_2OC, 130 km BL
T2HK: 4 MW, 1MT H_2OC, 295 km BL
WBB: 2MW, 1MT H_2OC, 1300 km BL

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

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)



Carl Albright – arXiv:0803.4176v1

Now that I have Convinced You we Must Build a Neutrino Factory

How do we go about it?

Key Technical Ingredients of The Neutrino Factory

- Proton Driver
  - Primary beam on production target
- Target, Capture, and Decay
  - Create π's; decay into μ's
- Phase Rotation
  - Reduce ΔE of bunch
- Cooling
  - Reduce emittance of the muons
    - Ionization Cooling (transverse)
- Acceleration
  - Accelerate the Muons
- Decay Rings
  - Store for ~1000 turns

Production of $O(10^{21})$ μ/yr

R&D Program Overview II

- High Power Targetry *(MERIT Experiment)*
- Ionization Cooling – *(MICE (4D Cooling))*
- 200 (& 805) MHz RF *(MuCool and Muons Inc)*
  - Investigate RF cavities in presence of high magnetic fields
  - Obtain high accelerating gradients (~15MV/m)
  - Investigate Gas-Filled RF cavities
- Acceleration– A cost driver for NF
  - Linac for initial acceleration
  - Multi-turn RLA's
  - FFAG's – *(EMMA Demonstration)*
- Decay Ring(s)

Prior, C. R. WE6PFP099, (these proceedings)

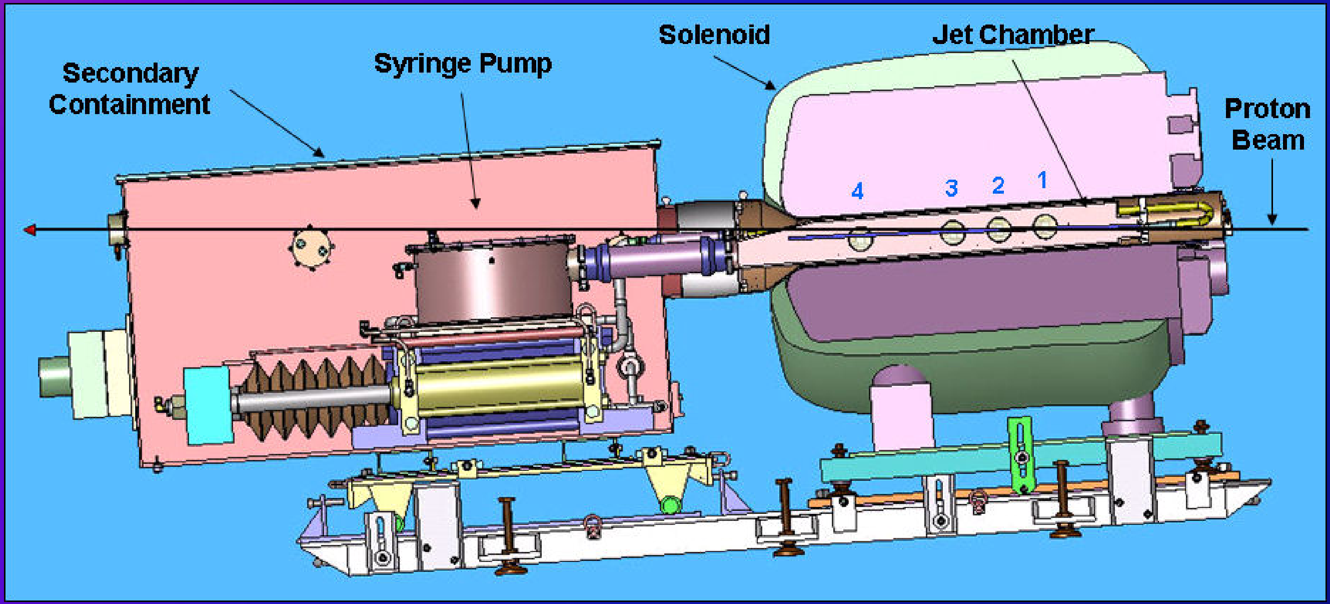
- Theoretical Studies
  - Analytic Calculations
  - Lattice Designs
  - Numeric Simulations

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

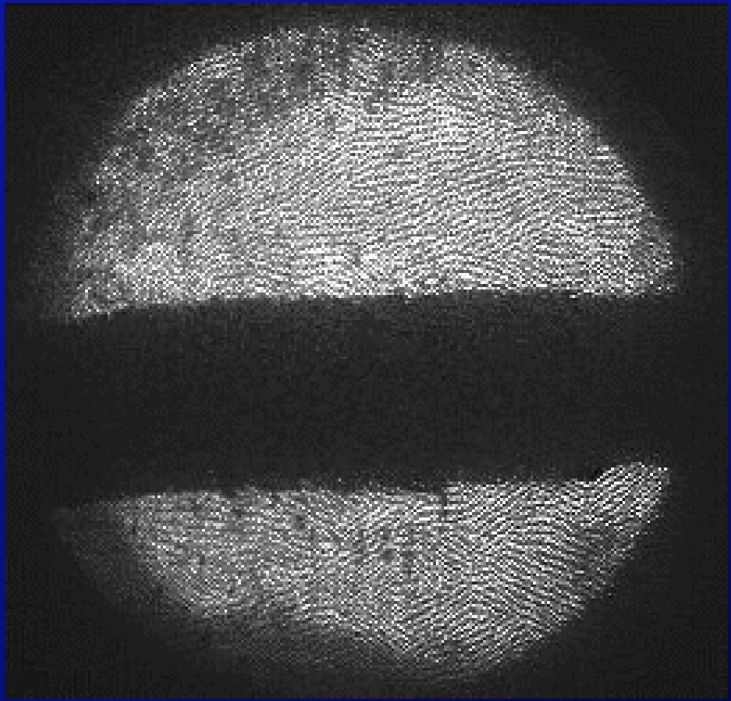
MERIT

Mercury Intense Target
Liquid-Hg Jet

MERIT
The Experiment Reached 30TP @ 24 GeV

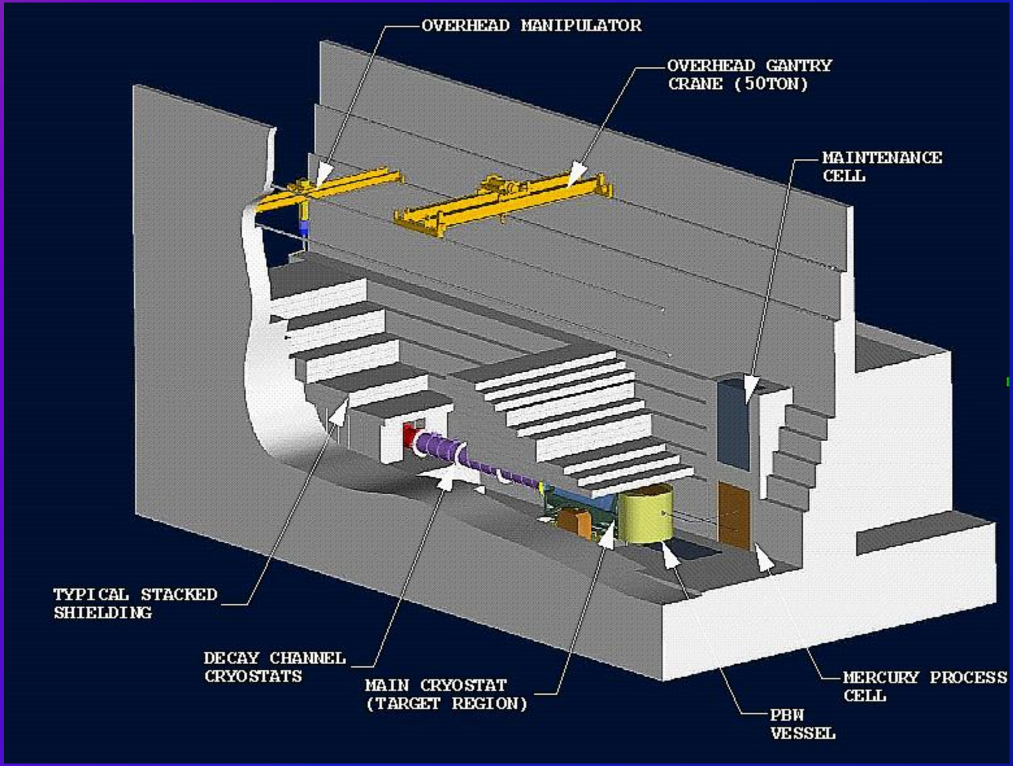


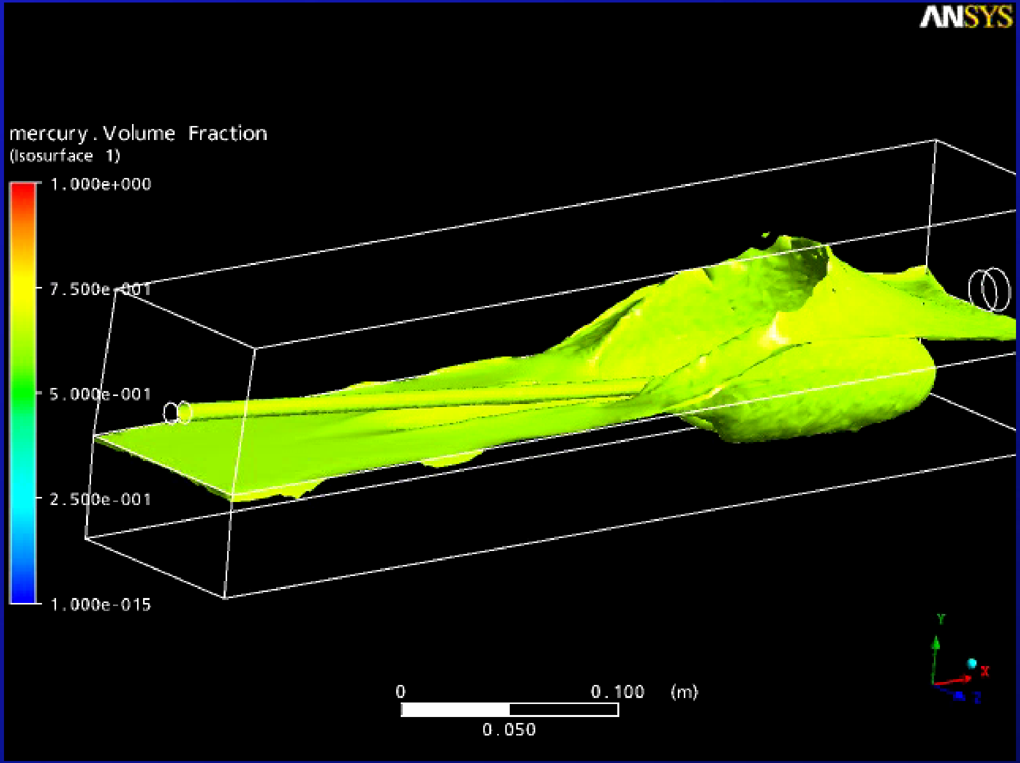
K. McDonald, TU4GRI03 (these proceedings



- 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

Target Station R&D





The Target Hall Infrastructure

V. Graves, ORNL

Proton Hg Beam Dump

T. Davonne, RAL

Muon Ionization Cooling

MuCool and MICE

Absorber R&D - Fundamentals

- 2D Transverse Cooling

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

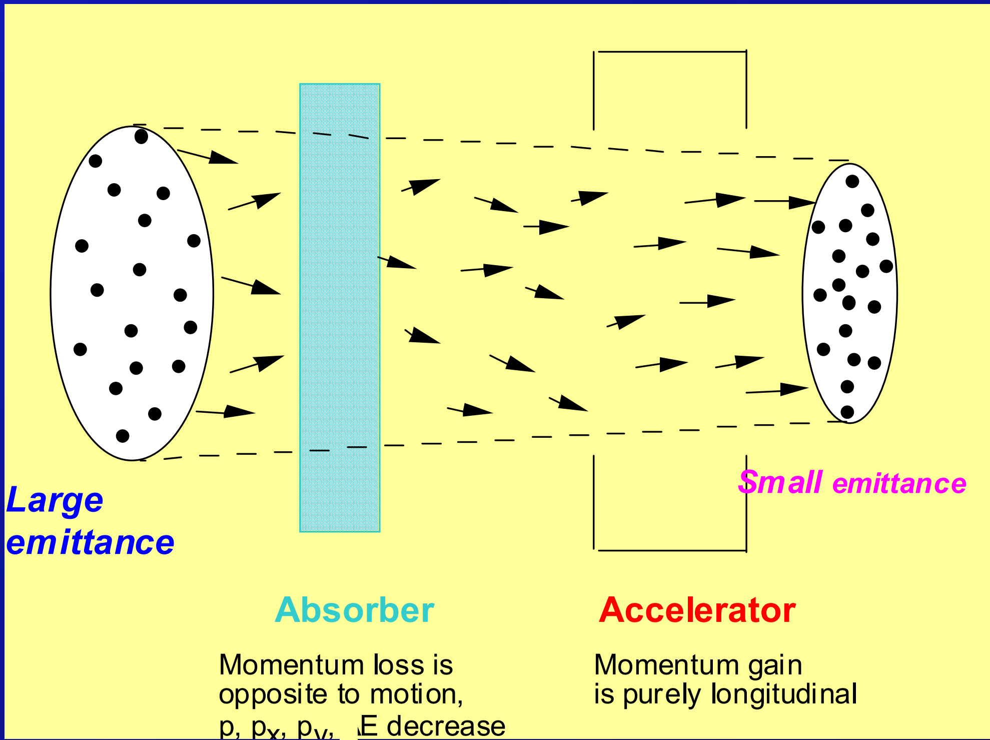
and

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

- 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

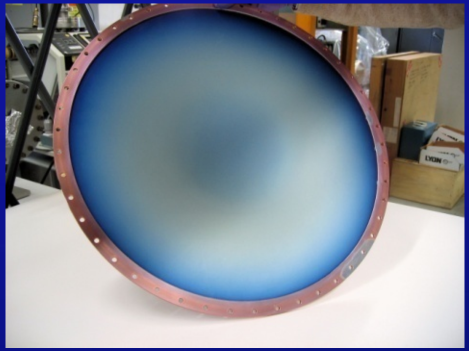


H_2 is clearly Best -
Neglecting Engineering Issues
Windows, Safety

MuCool

Component R&D and Cooling Experiment

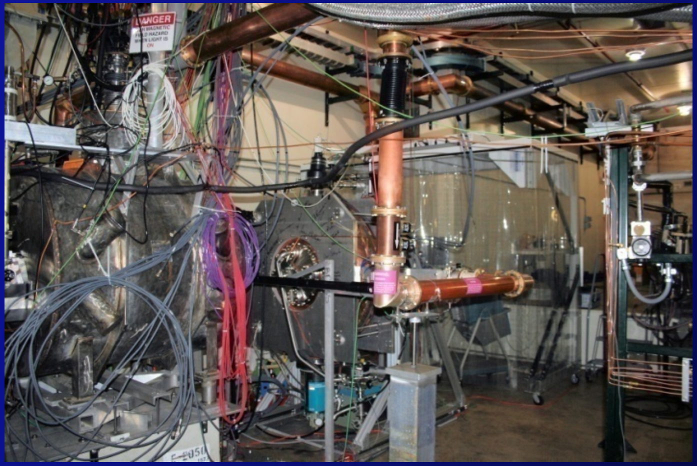
- **MuCool**
  - Component testing: RF, Absorbers, Solenoids
    - With High-Intensity Proton Beam
  - Uses Facility @Fermilab (MuCool Test Area –MTA)
  - Supports Muon Ionization Cooling Experiment (MICE)



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

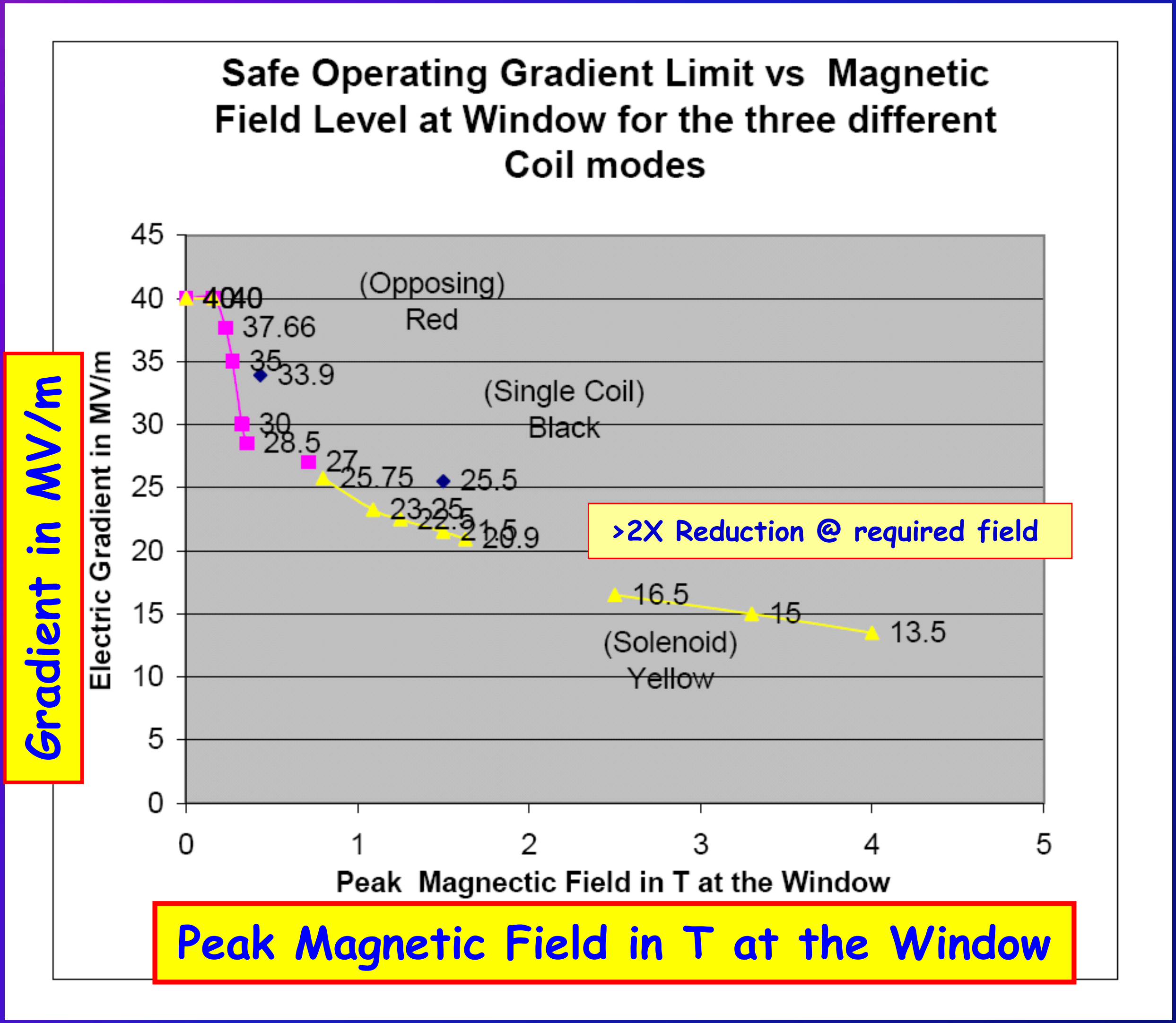
- Study the limits on Accelerating Gradient in NCRF cavities in magnetic field
- Understand, in detail, the interaction of field emission currents with applied external magnetic field
- Fundamental Importance to both NF and MC – RF needed in
  - Muon capture, bunching, phase rotation
  - Muon Cooling
  - Acceleration

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

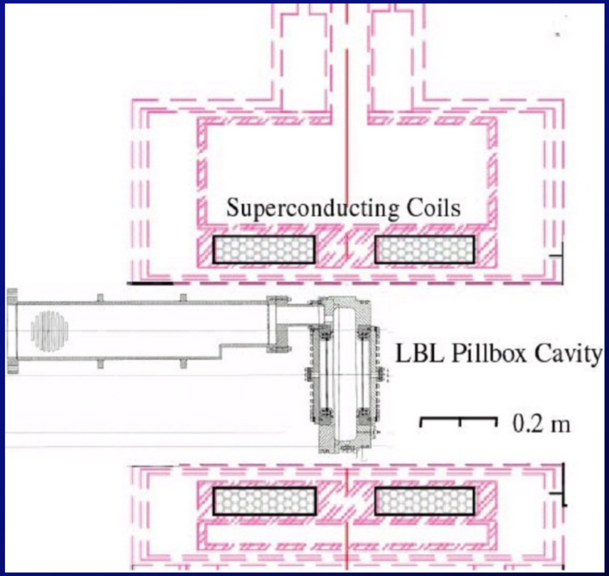
The Basic Problem – B Field Effect

805 MHz Studies

D. Huang, TU5PFP032, these proceedings.



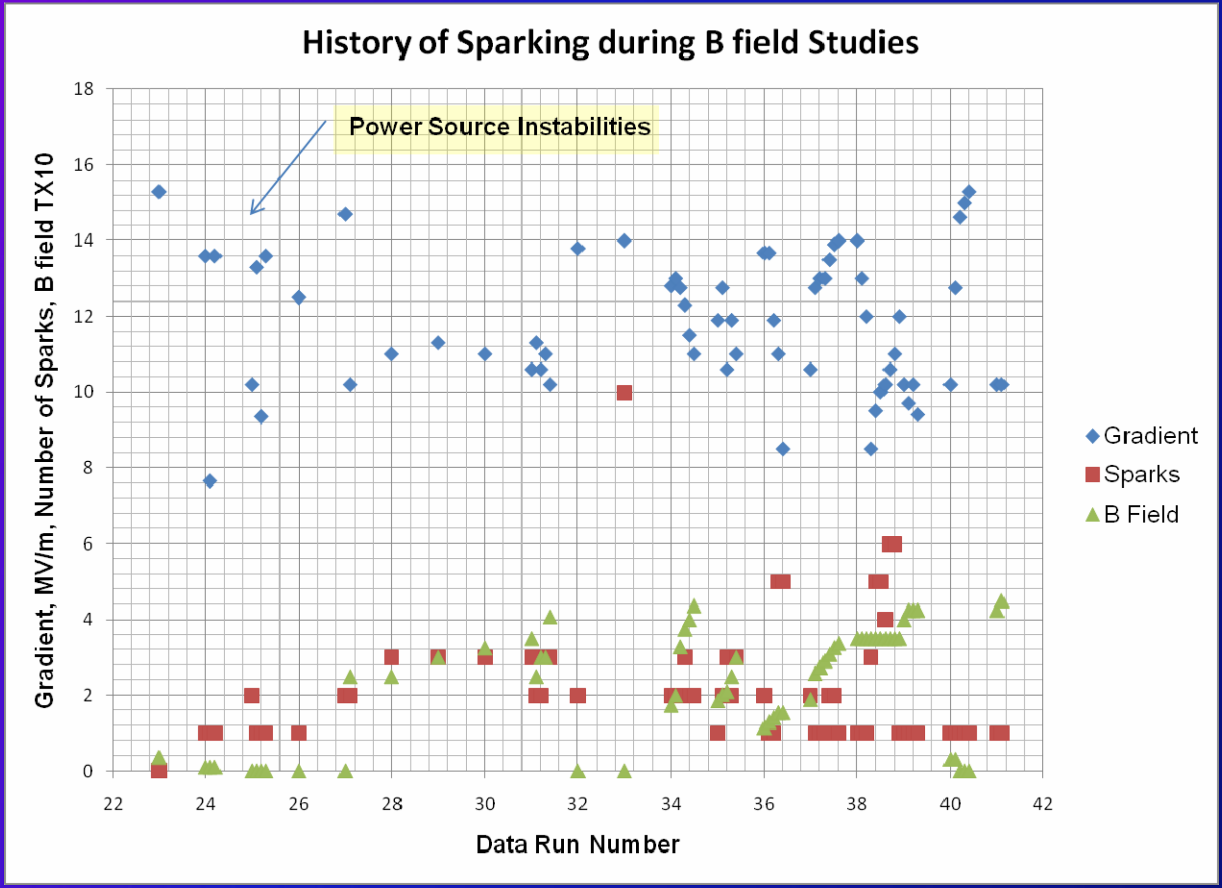
- **Data seem to follow universal curve**
  - Max stable gradient degrades quickly with B field
- **Re-measured**
  - Same results

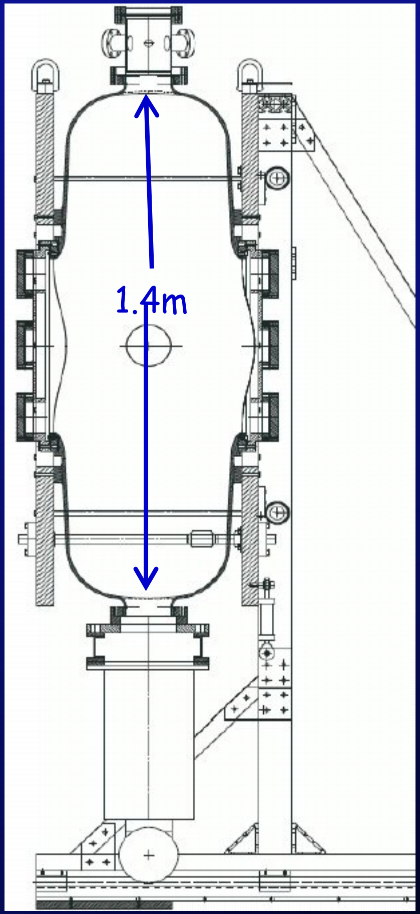


RF R&D – 201 MHz Cavity Test

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*
- But exhibited Gradient fall-off with applied B





Facing the RF B Field Challenge

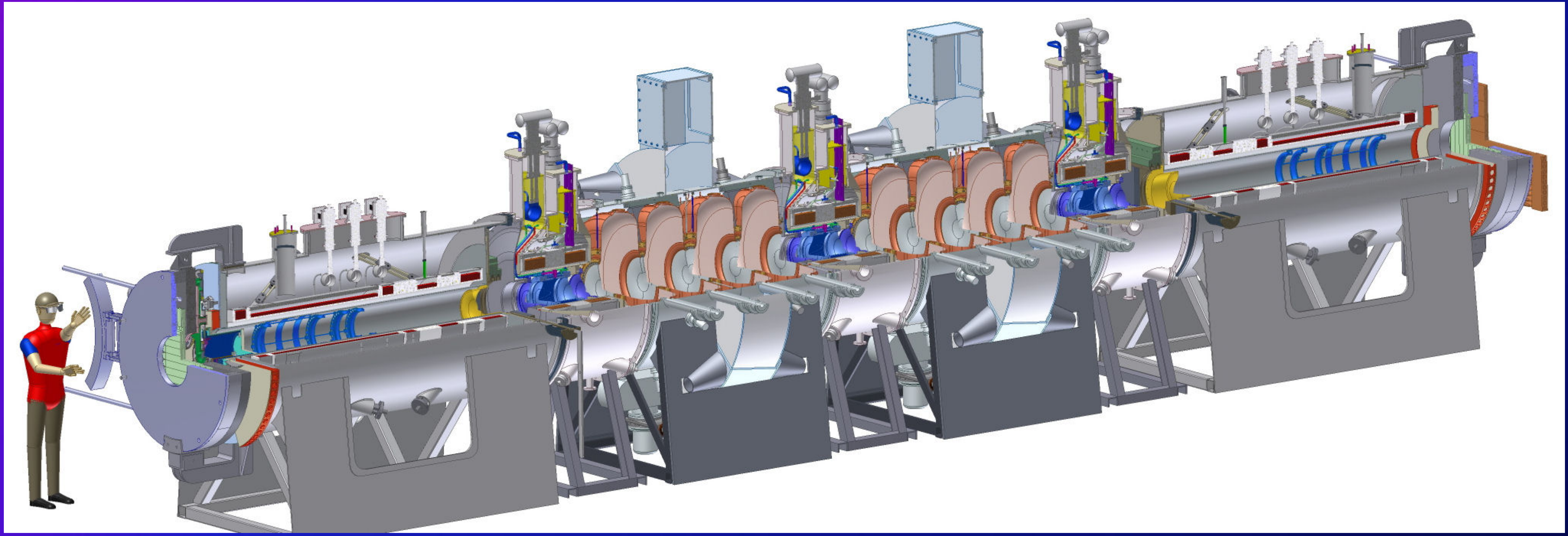
- Approaches to a Solution
  - Reduce/eliminate field emission
    - Process cavities utilizing SCRF techniques
    - Surface coatings
      - Atomic Layer Deposition

        Norem, J., TU5PFP002, (these proceedings)
  - Material Studies
      - Non-Cu bodies (Al, Be?)

        R. Palmer, TU1GRI03, (these proceedings)
        - Mitigate the effect of B field interaction on field emission currents ⇒ Breakdown
  - RF cavities filled with High-Pressure gas (H_2)
    - Utilize Paschen effect to stop breakdown

      K. Yonehara, TU5PFP020, (these proceedings)
  - Magnetic Insulation
    - Eliminate magnetic focusing
      - Not Yet Tested

Muon Ionization Cooling Experiment (MICE)

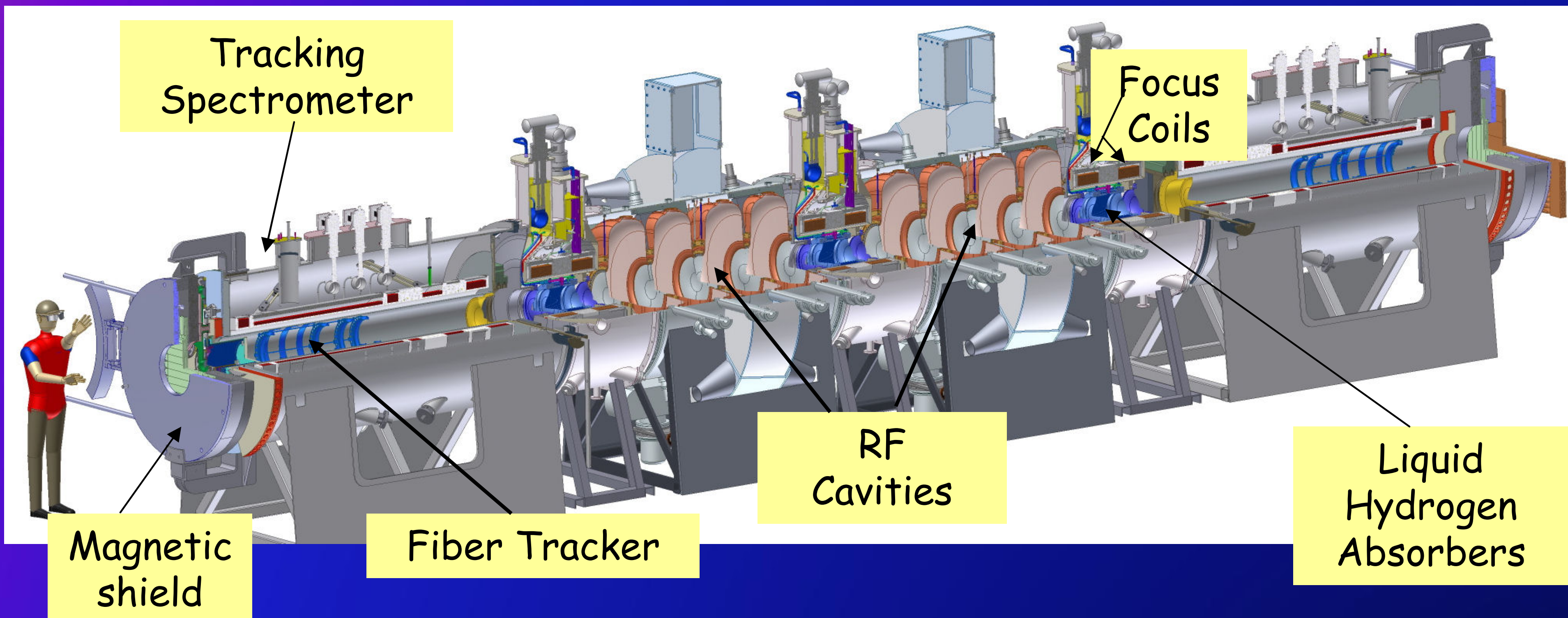


http://mice.iit.edu/

Fermilab

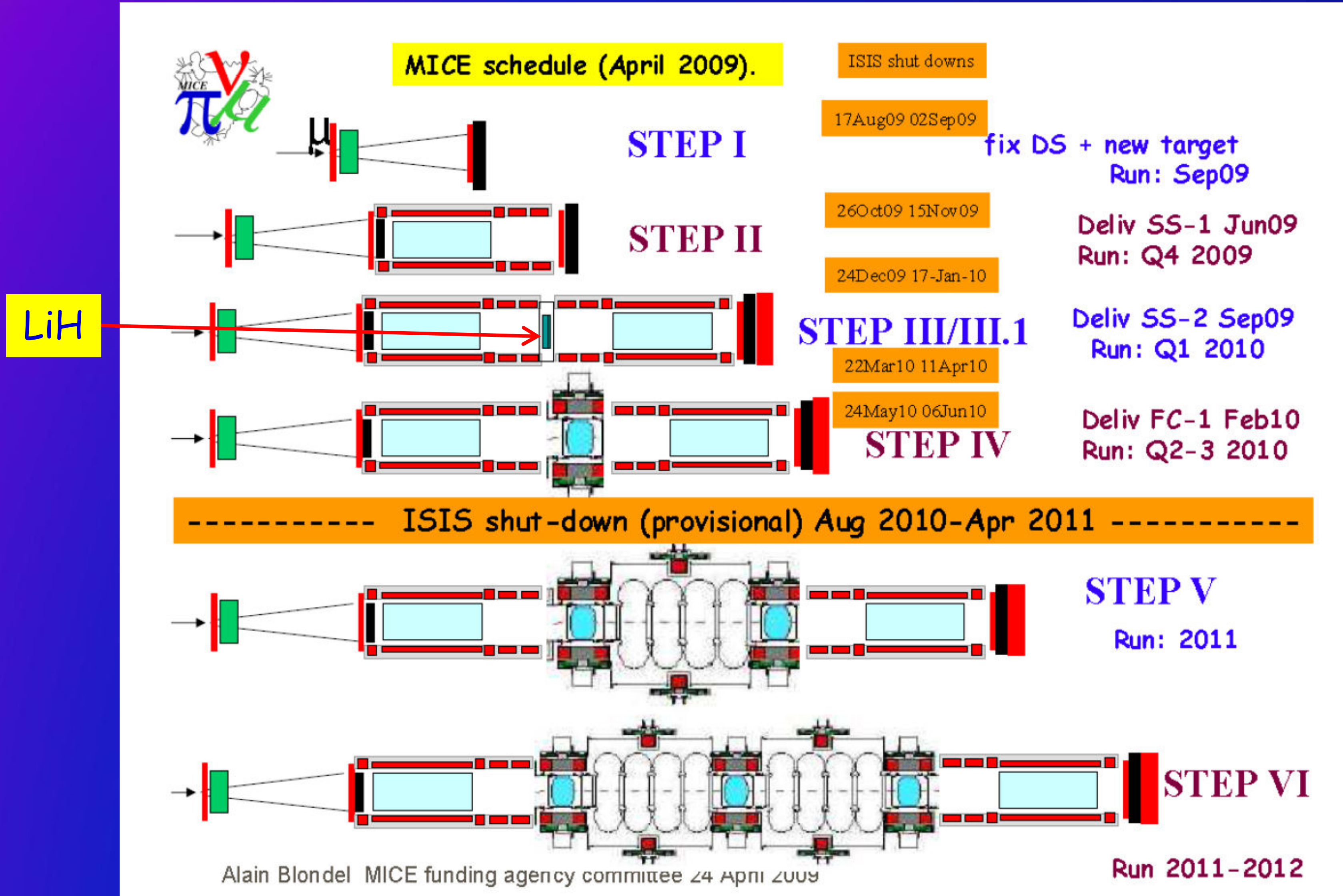
Muon Ionization Cooling Experiment

L. Coney, TU6RFP057, (these proceedings)

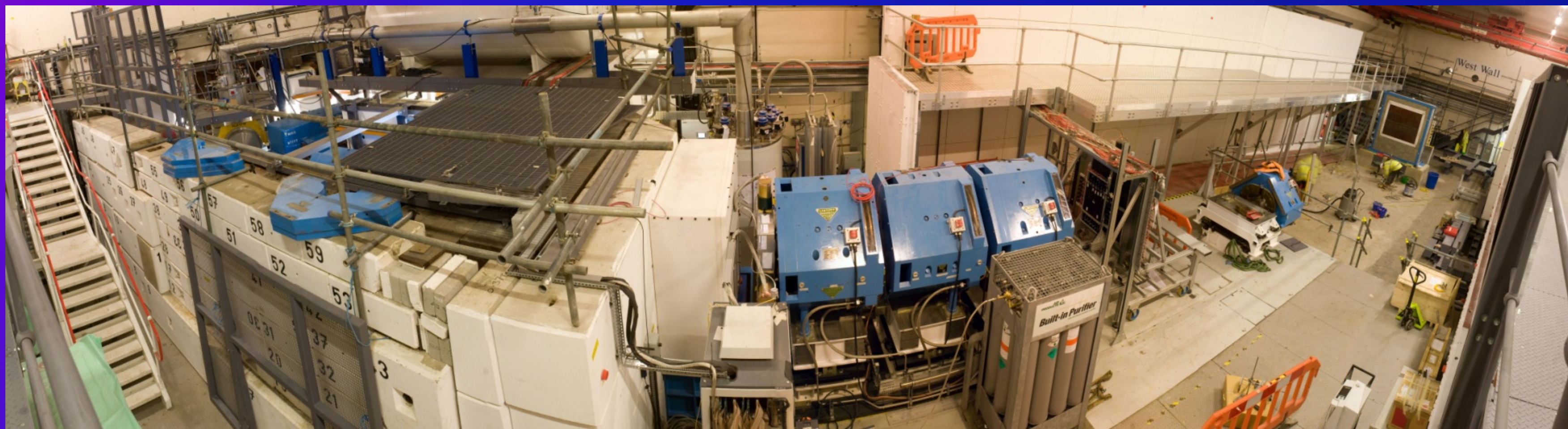


- **Measure transverse (4D) Muon Ionization Cooling**
  - 10% cooling – measure to 1% (10^{-3})
- **Single-Particle Experiment**
  - Build input & output emmittance from μ ensemble

MICE Schedule

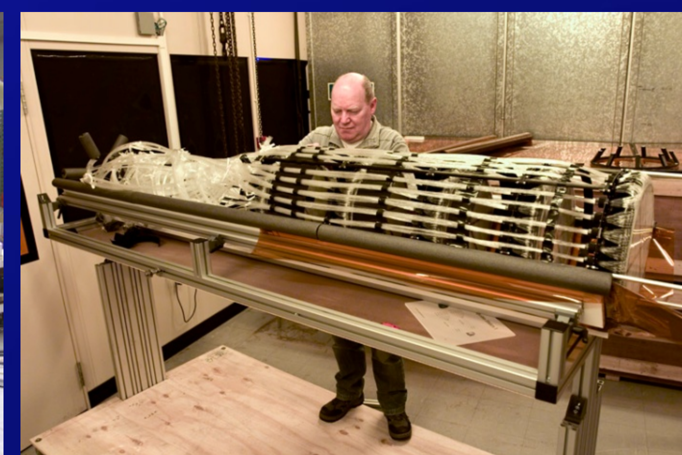


Progress on MICE



- Beam Line Complete
  - First Beam 3/08
- PID Installed
  - CKOV
  - TOF
  - EM Cal
- First Spectrometer
  - Summer 09

Spectrometer Solenoid being assembled



Fiber Tracker

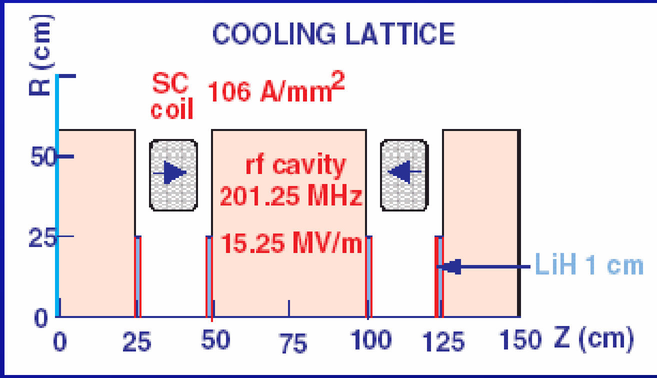
Neutrino Factory Front-End and Acceleration

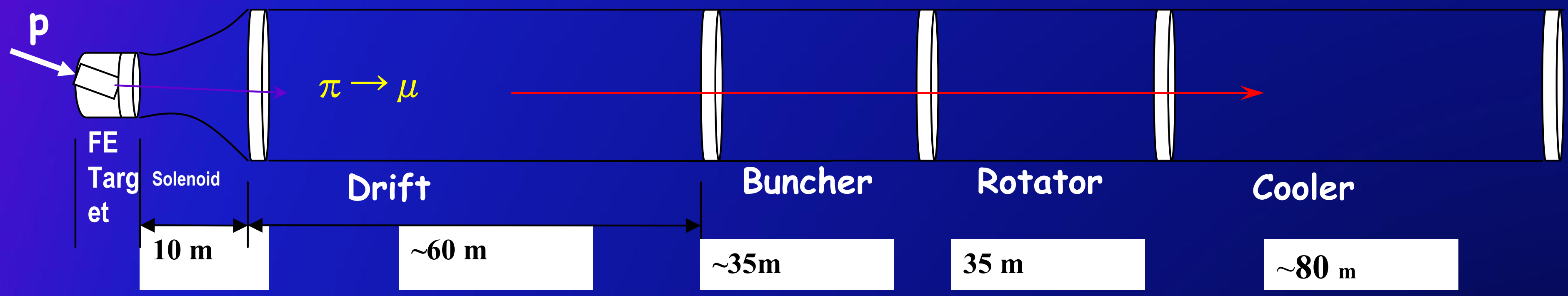
Fermilab

High-frequency Buncher and φ-E Rotator

D. Neuffer, TU1GRC05, (these proceedings)

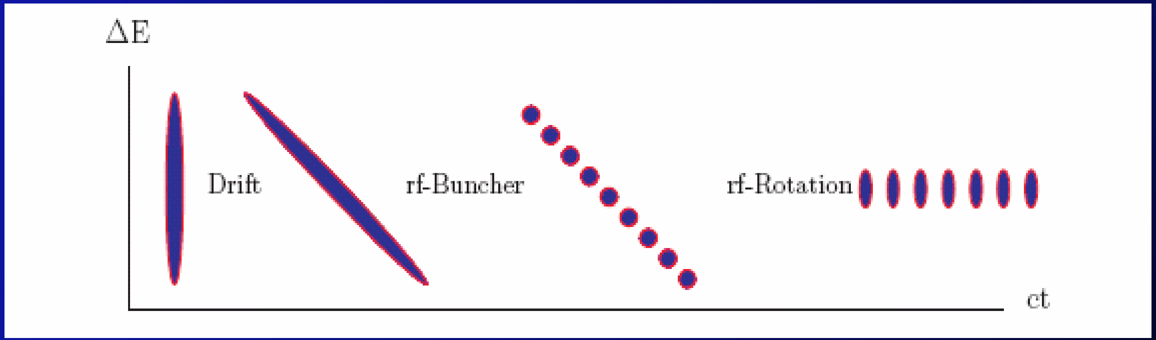
- Drift (π→μ)
- "Adiabatically" bunch beam first (weak 320 to 240 MHz rf)
- Φ-E rotate bunches – align bunches to ~equal energies
  - 240 to 202 MHz, 12MV/m
- Cool beam 201.25MHz



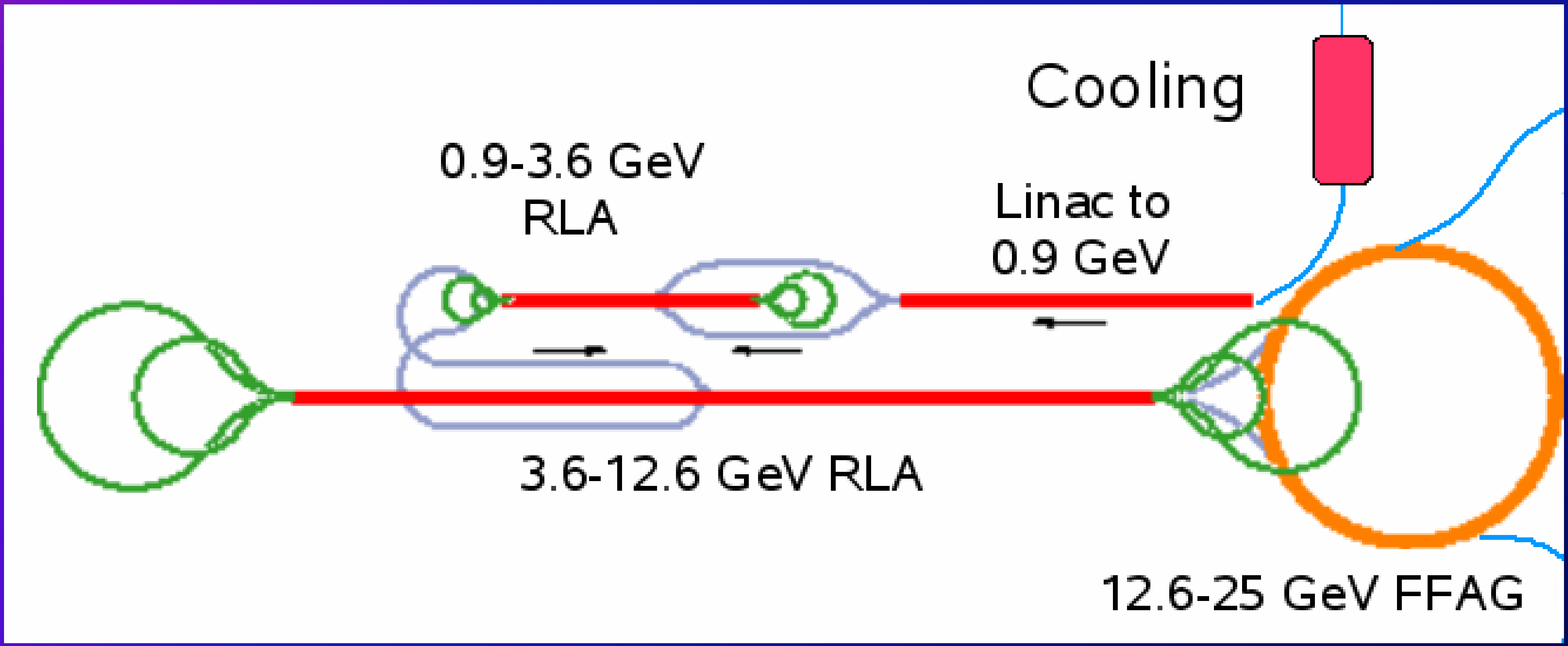


Obtains ~0.085 μ/ 8 GeV p

≈ 1.5 10^{21} μ/year



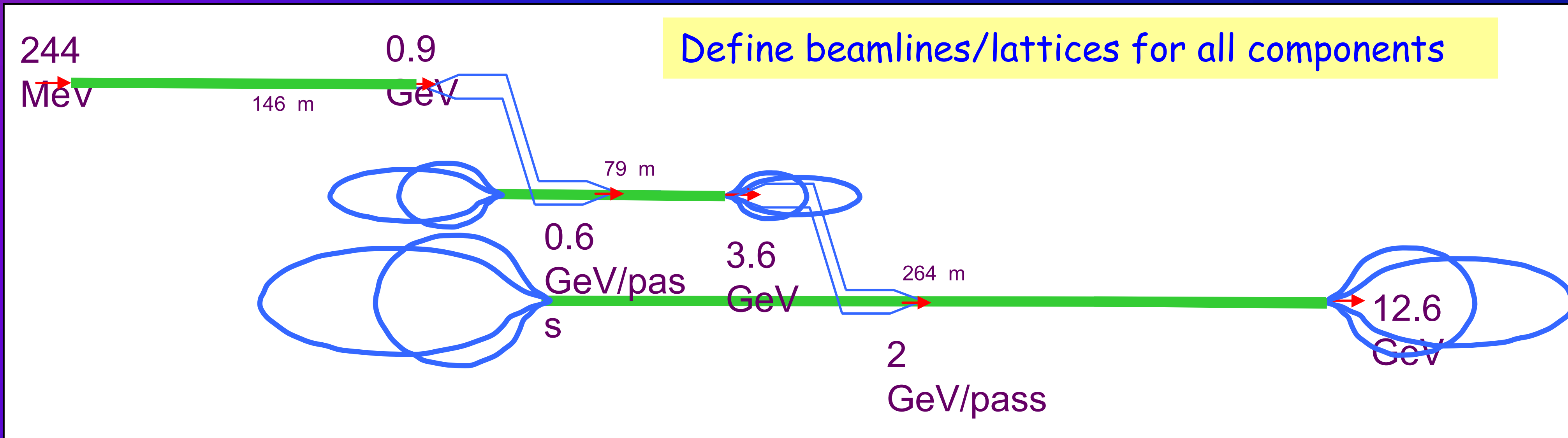
R&D on Neutrino Factory Subsystems

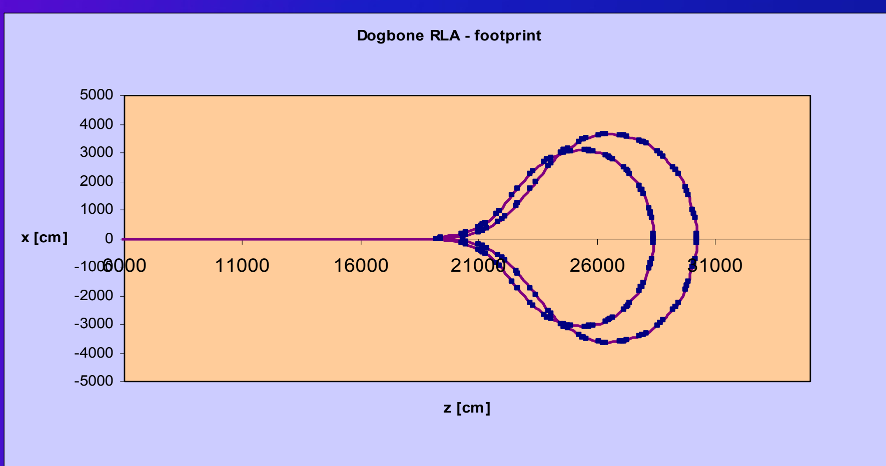


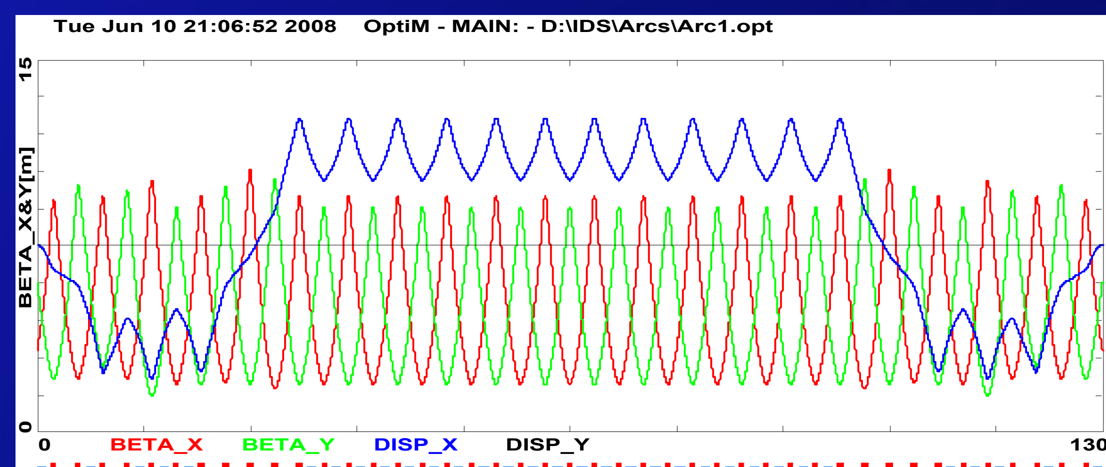
Acceleration Systems

Develop Engineering Design Foundation

A. Bogacz, WE6PFP100, (these proceedings)







FFAGs → EMMA

S. Smith, WE4PBI01, (these proceedings)

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

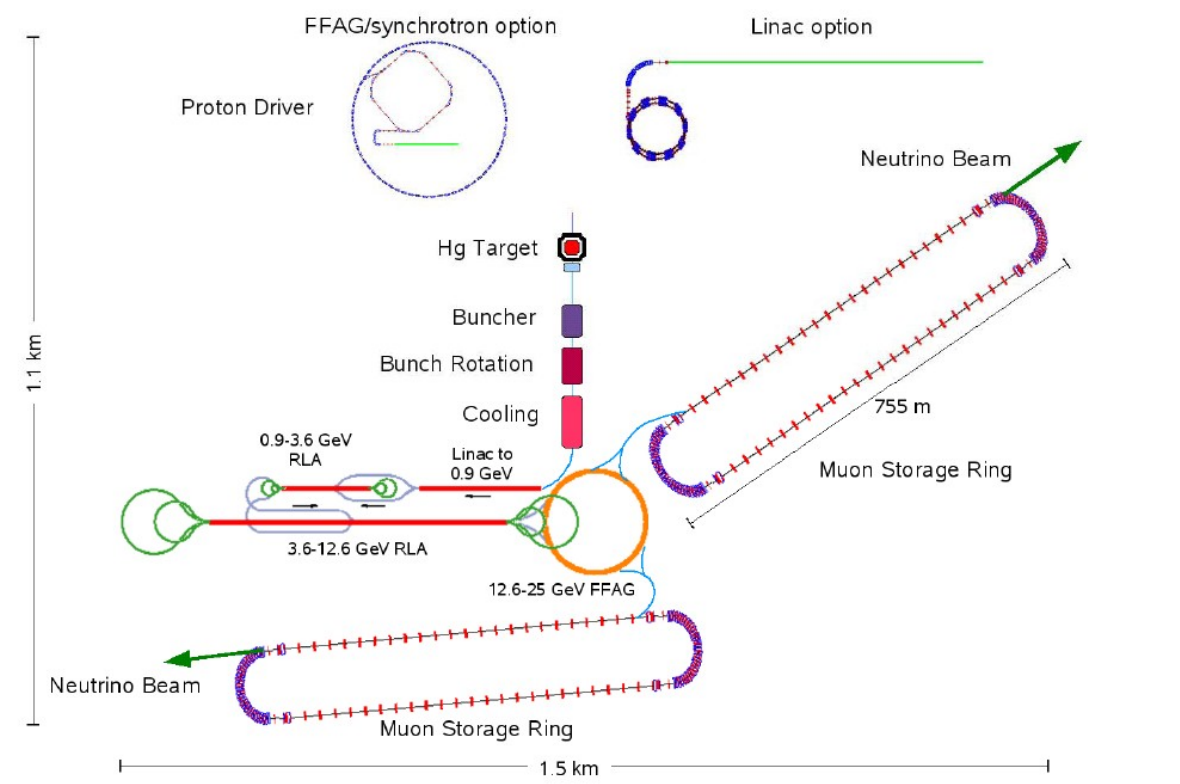


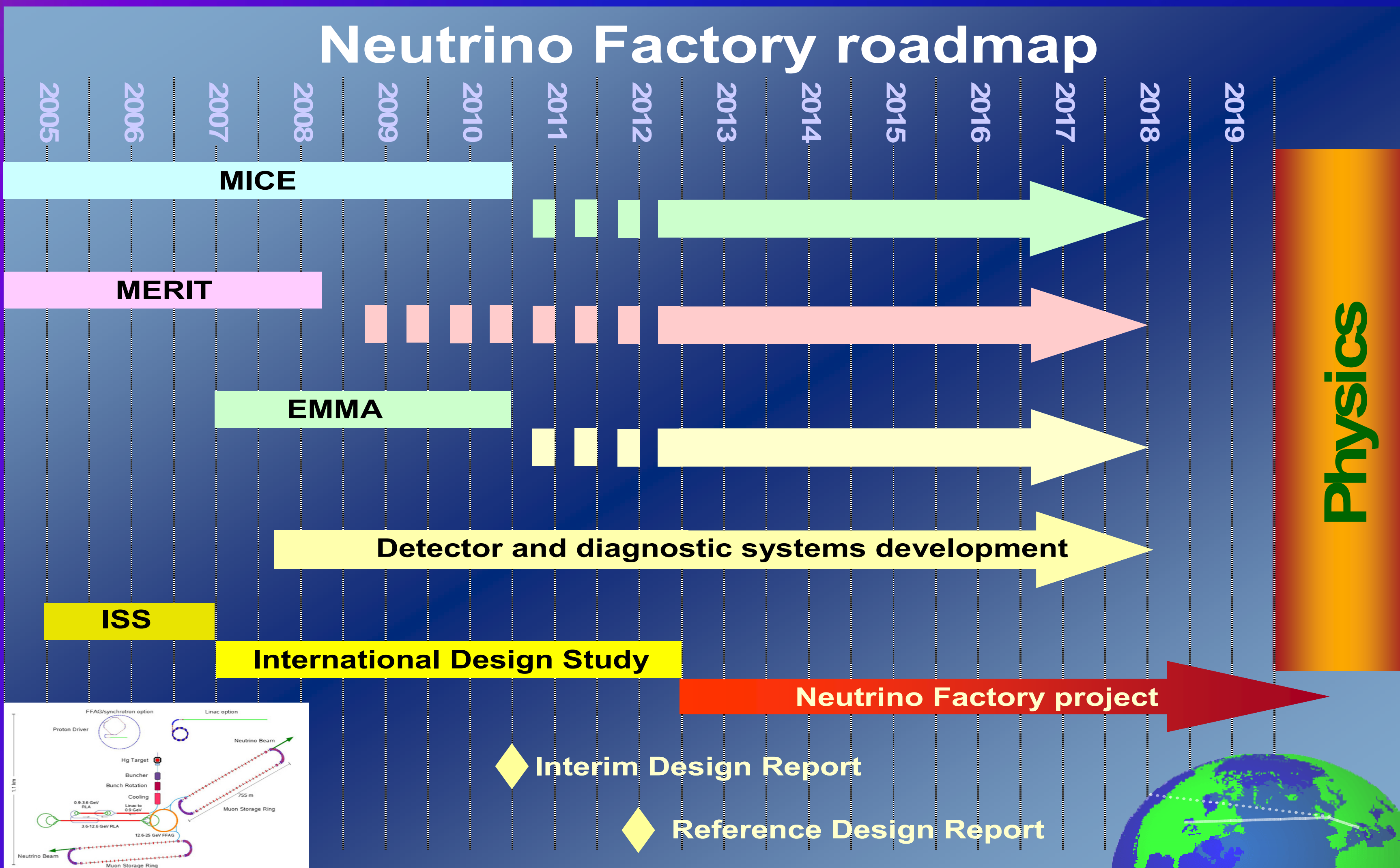
Figure 1: Schematic drawing of the ISS baseline for the Neutrino Factory accelerator complex. The various systems have been drawn to scale.

IDS-NF

Kurup and Long, WE6RFP067 (these proceedings)

- Takes as starting point - International Scoping Study ν-Factory parameters
  - ~4MW proton source producing muons, accelerate to 25 GeV, Two baselines: 2500km & 7500km
- IDS Goals
  - Specify/compute physics performance of neutrino factory
  - Define accelerator and detector systems
  - Compute cost and schedule
    - Understand the cost at the ≈ 50% level
  - 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 a "request for resources" to get serious about building a neutrino factory

Timeline - NF



Aspirational NF timeline presented in at NuFact07

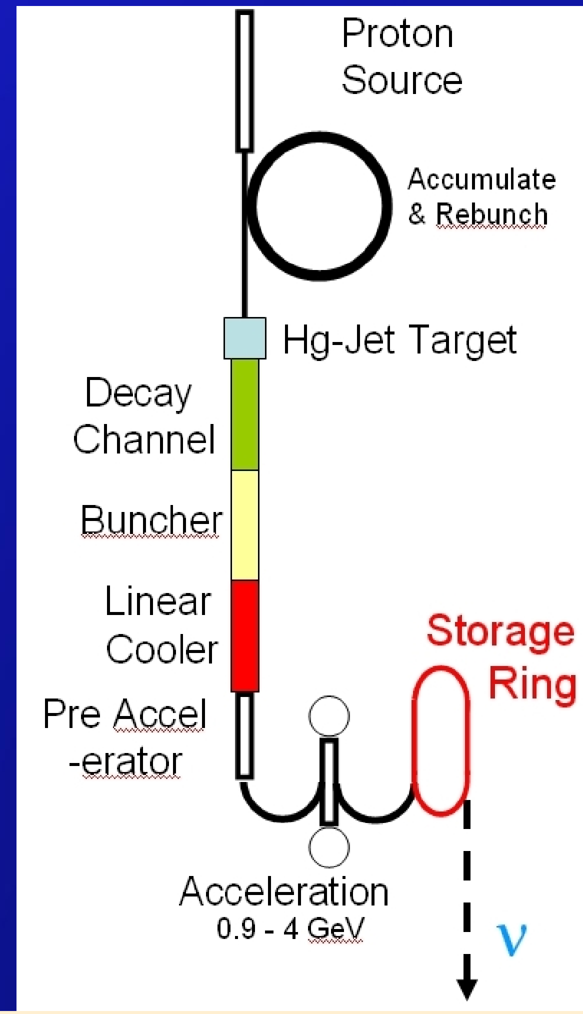
Status of IDS-NF with Respect to θ_{13}

- Must Consider the case for a Neutrino Factory for the scenario where θ_{13} is large(ish)
  - Possibly measured before report is delivered
- Low-energy Neutrino Factory:
  - Interesting option, especially in this scenario and as a step in a possible staging scenario, but:
    - Physics reach for oscillation parameters for small θ_{13} not as competitive as for baseline

IDS 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)



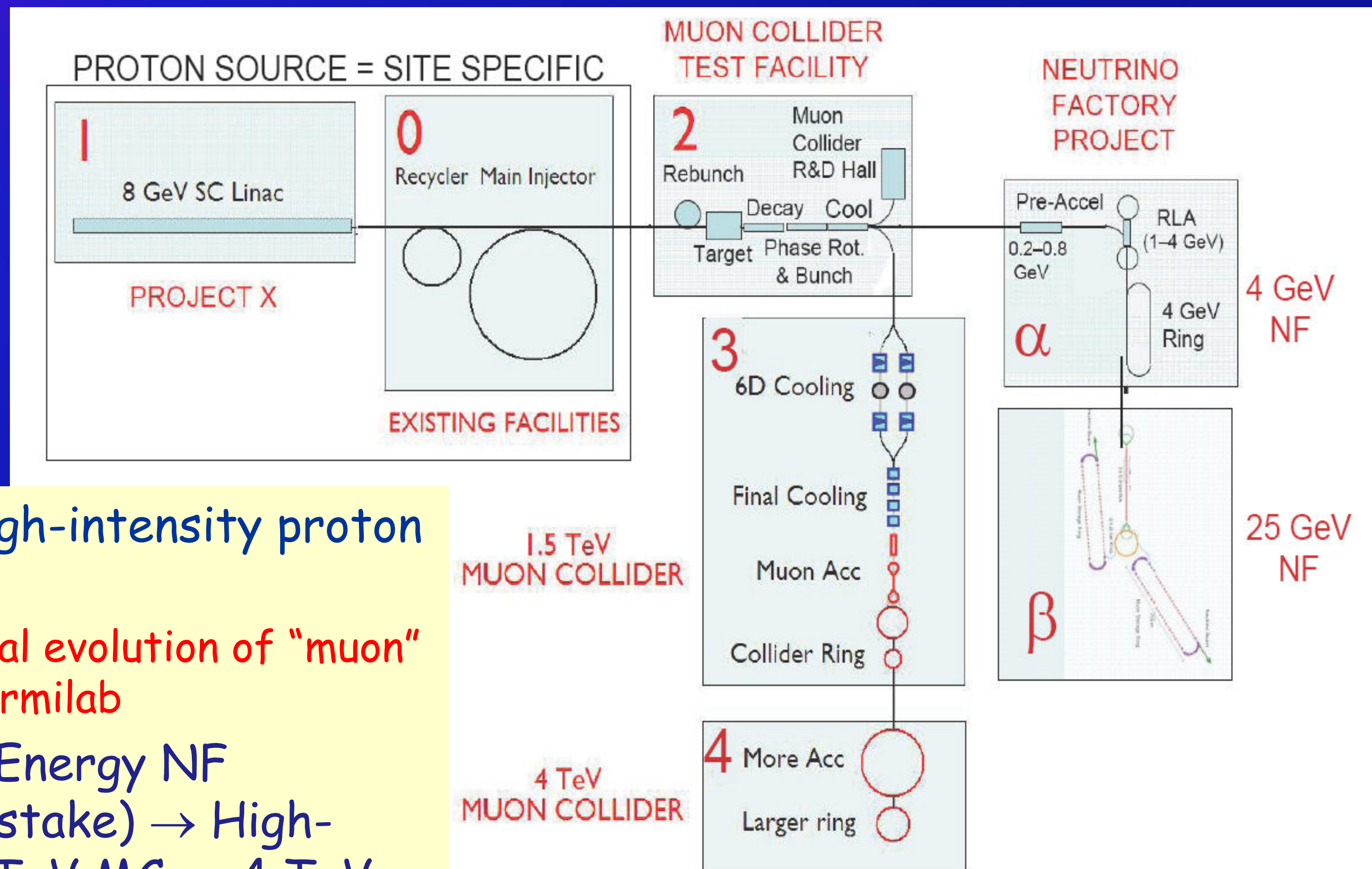
Potentially X10 increase in Sensitivity Over Super-Beam

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

Searching beyond Neutrino Physics

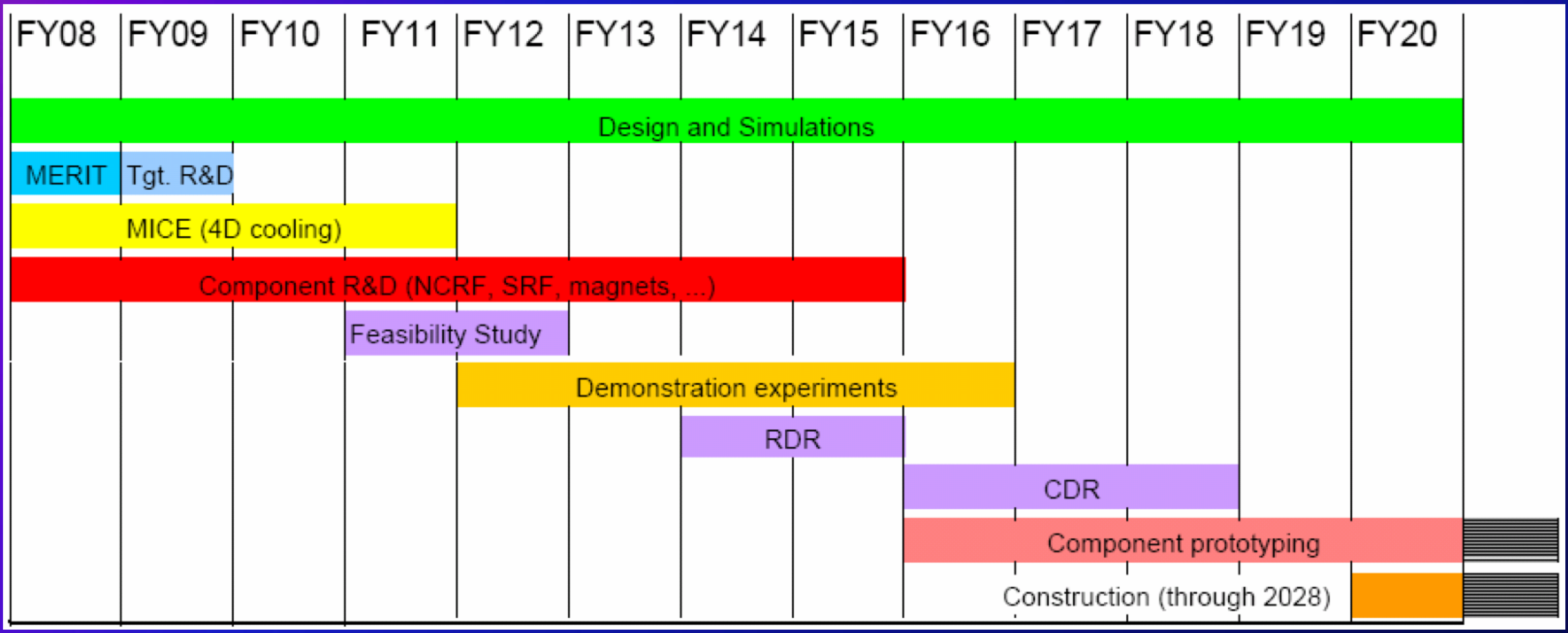
Exploring the Energy Frontier with a
Muon Accelerator Facility

Muon Complex Evolution At Fermilab



- 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

Timeline - MC



Illustrative MC timeline presented to P5 (Palmer)

Closing Remarks

The Neutrino Factory
The Final Frontier in Neutrino Physics

- Neutrino Factory
  - There is a Very Compelling Physics case for a precision neutrino program
    - With present assumptions Neutrino Factory out-performs all other options. However, more is needed before concluding this is the right path – size of θ_{13}
      - What the on-going Neutrino Physics program tells us
  - With our present understanding the NF looks to be Technically Feasible
    - IDS-NF will set the Engineering Benchmark and Cost
- We believe ~2013 will be a pivotal time in HEP
  - Neutrino Data from Reactor and Accelerator Experiments
    - Double Chooz Daya Bay
    - MINOS, T2K ,NOνA
  - LHC Physics Results (may impact ν sector)
  - RDR for a Neutrino factory available from IDS-NF
- The Neutrino Factory may become the Final Frontier in Neutrino Physics (no other facility can do better)
  - But it may also be the first step along the way to a New Energy Frontier in HEP

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Thank You

Fermilab