Muon Accelerators:
Accelerator Science Challenges

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November 18, 2015

with acknowledgments to the MAP, MICE and IDS-NF Collaborations

Why Muons?

Muon Accelerator Program

Physics Frontiers

- **Intense & cold muon beams ⇨ unique high-energy physics reach**
  - μ→e conversion (cLFV)
  - g-2 (a_μ)
  - Neutrino Factory (NF) – precision neutrino source
  - Muon Collider (MC) – next generation lepton collider

$$m_\mu = 105.7\, MeV/c^2$$

$$\tau_\mu = 2.2\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalars
  - Strong coupling to Higgs
  - Reduced synchrotron radiation ⇨ ***multi-pass acceleration***
  - Beams with small energy spread
  - Beamstrahlung effects suppressed at IP
- ***BUT*** **accelerator complex/detector must be able to handle the impacts of μ decay**

$$\sim \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4 \times 10^4$$

NF/MC Synergies

- **A high intensity muon front end can serve both NF and MC**
- **Unique staging strategies combining physics and accelerator development ⇨ Muon Accelerator Staging Study (MASS)**

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

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

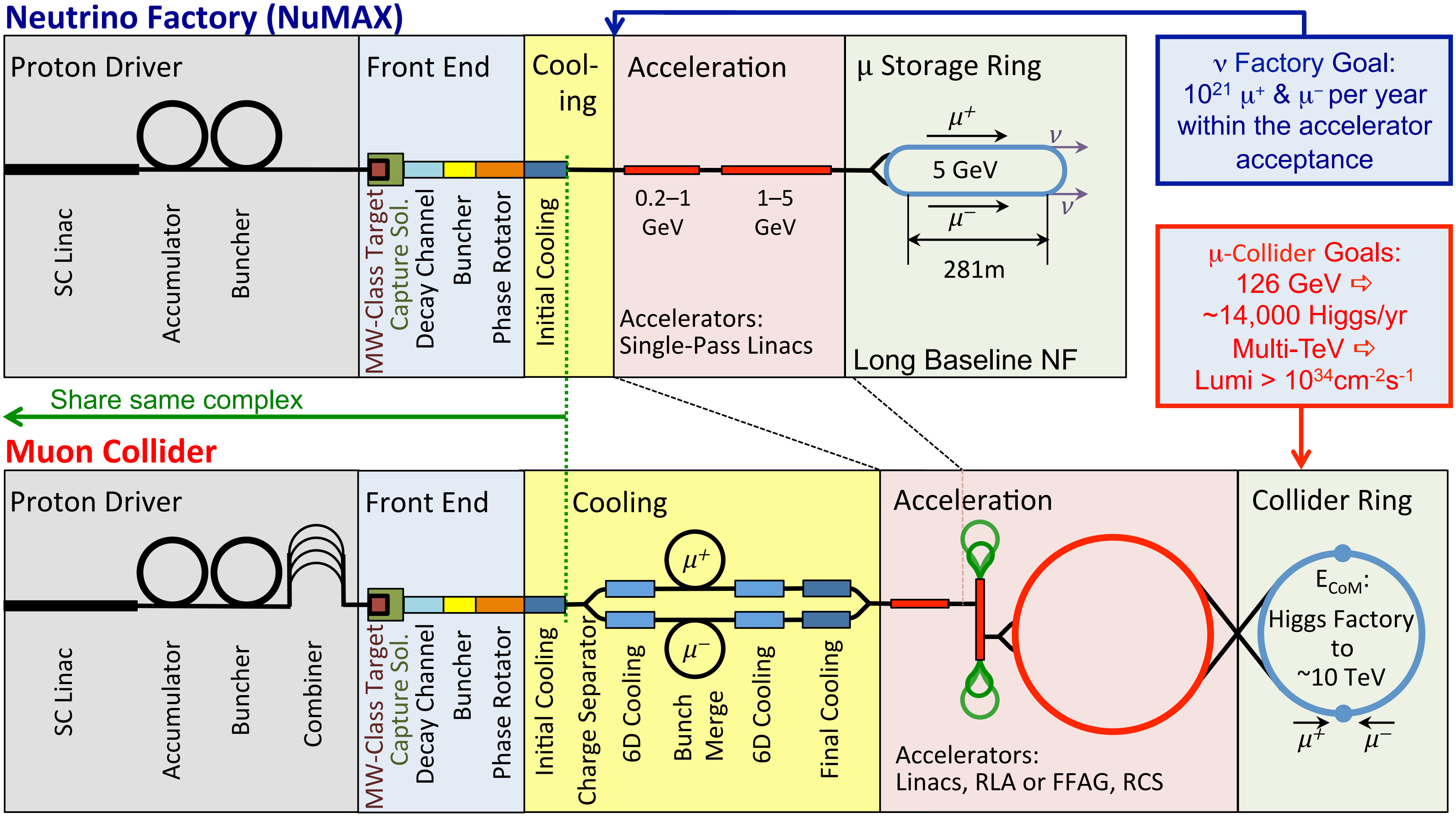
Introduction

- Charge is to discuss "Accelerator Science Challenges"
- Approach: Look at progress over the last several years
  - RD&D and Muon Accelerator Staging Study (MASS) concepts

Initial concepts for Neutrino Factory and Muon Collider

- ⇨ Evaluation of anticipated performance
  - ✧ Supported by extensive development of muon codes
- ⇨ Optimization of the concepts
  - ✧ Enabled by the introduction of high performance computing tools
- ⇨ Concepts that are ready for detailed engineering studies
- ⇨ Preparation for the next *Muon Demonstrator Facility*

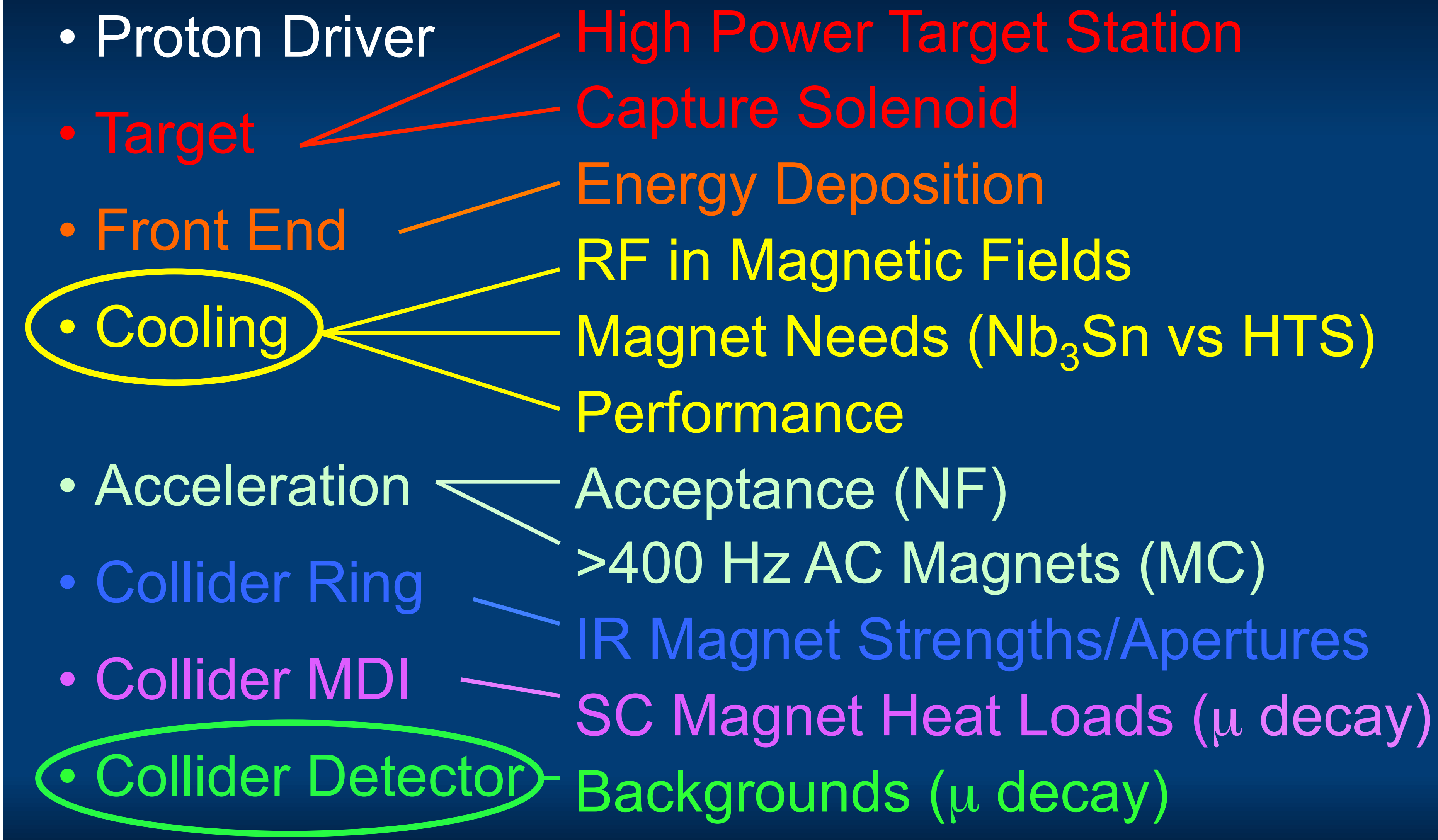
High Energy Muon Accelerator Capabilities



ν Factory Goal:
10^{21} μ^+ & μ^- per year
within the accelerator
acceptance

μ-Collider Goals:
126 GeV ⇨
~14,000 Higgs/yr
Multi-TeV ⇨
Lumi > 10^{34}cm^{-2}s^{-1}

Key Feasibility Issues



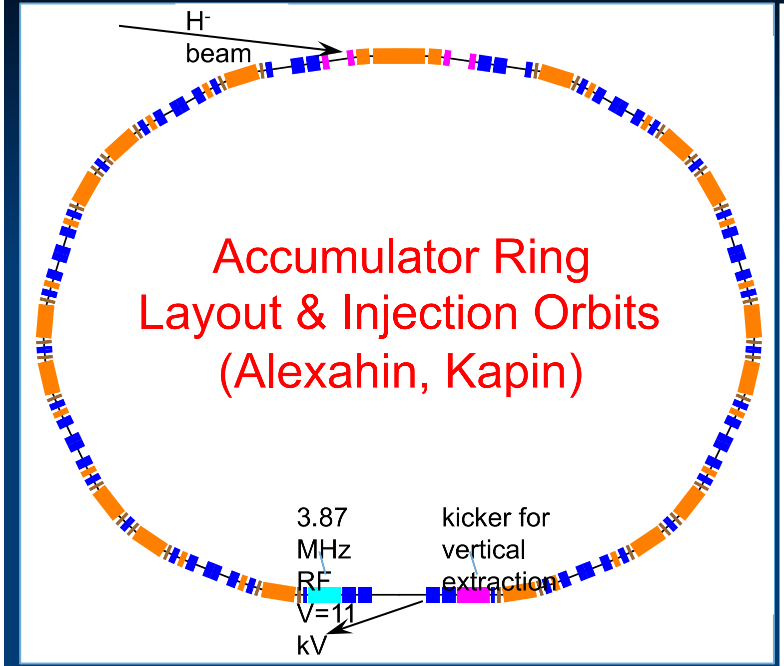
- Proton Driver
- Target
- Front End
- Cooling
- Acceleration
- Collider Ring
- Collider MDI
- Collider Detector

High Power Target Station
Capture Solenoid
Energy Deposition
RF in Magnetic Fields
Magnet Needs (Nb_3Sn vs HTS)
Performance
Acceptance (NF)
>400 Hz AC Magnets (MC)
IR Magnet Strengths/Apertures
SC Magnet Heat Loads (μ decay)
Backgrounds (μ decay)

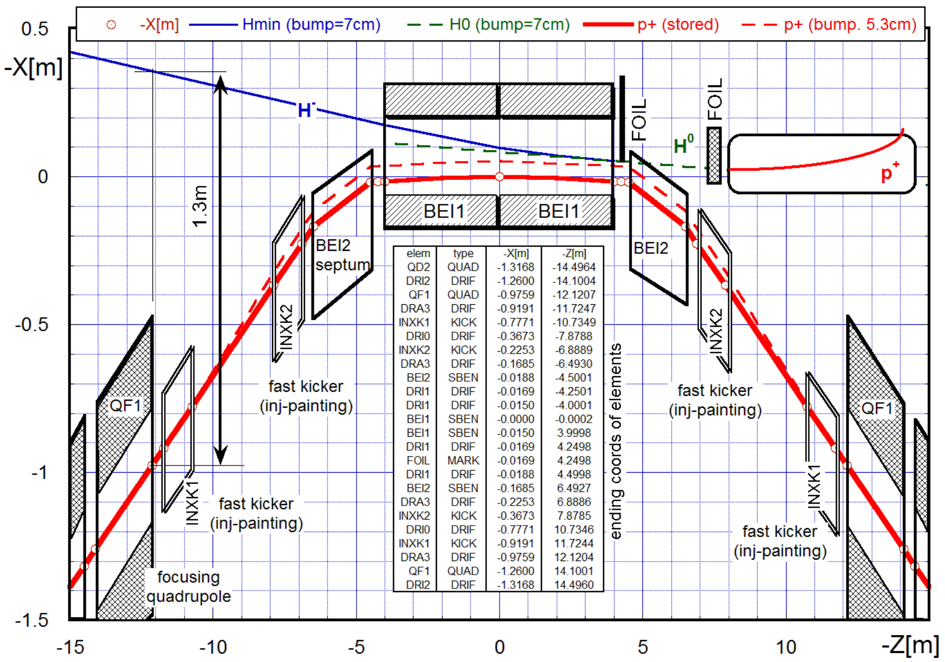
Characteristics of the Muon Source

- Overarching goals
  - NF: Provide O(10^{21}) μ/yr within the acceptance of a μ ring
  - MC: Provide luminosities >10^{34}/cm^{-2}s^{-1} at TeV-scale (~n_b^2)
    Enable precision probe of particles like the Higgs
- Options (see comparisons from AAC2014, WG7)
  - Tertiary production through proton on target (and then cool)
    Rate > 10^{13}/sec $n_b = 2\times10^{12}$
  - Production of low emittance (and potentially highly polarized) beams
    - e^+e^- annihilation: positron beam on plasma or solid target
      Rate ~ 10^8/sec $n_b \sim 10^7$
    - μ-pair production with GeV-scale compton γs
      Pulsed Linac: Rate ~ 5×10^{10}/sec $n_b \sim 10^6$
      High Current ERL: Rate > 10^{13}/sec $n_b \sim$ few$\times10^4$
- n_b^2 dependence makes collider luminosity goal difficult for the non-proton sources (by a few orders of magnitude)
  ⇨ Will focus on the proton-based source

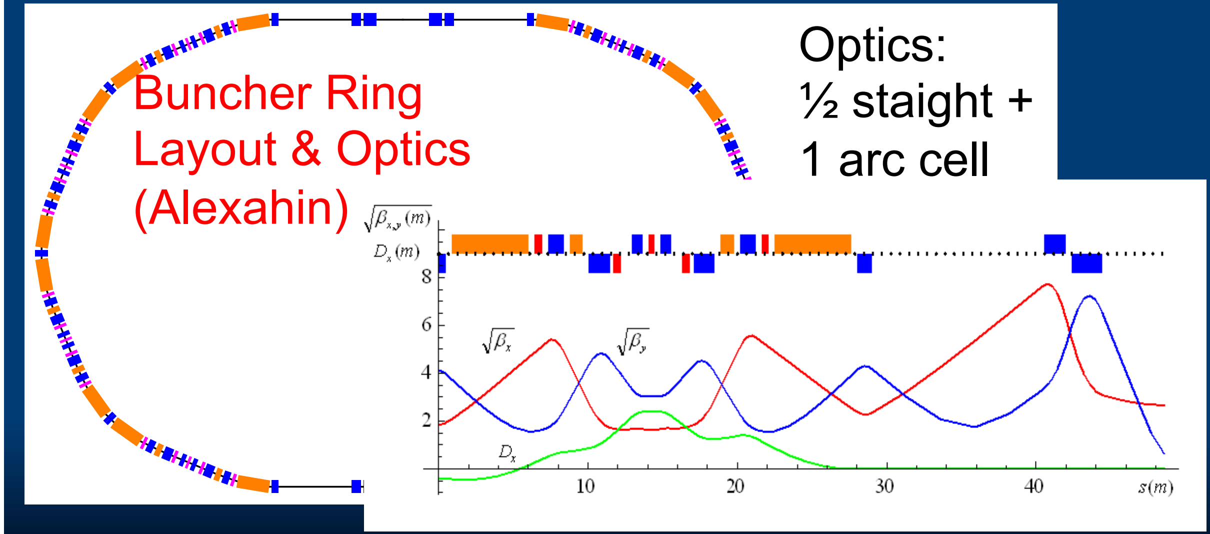
Proton Driver



Accumulator Ring
Layout & Injection Orbits
(Alexahin, Kapin)



elem	type	-X[m]	-Z[m]
QD2	QUAD	-1.3168	-14.4964
DRI2	DRIF	-1.2600	-14.1004
QF1	QUAD	-0.9759	-12.1207
DRA3	DRIF	-0.9191	-11.7247
INXK1	KICK	-0.7771	-10.7349
DRI0	DRIF	-0.3673	-7.8788
INXK2	KICK	-0.2253	-6.8889
DRA3	DRIF	-0.1685	-6.4930
BEI2	SBEN	-0.0188	-4.5001
DRI1	DRIF	-0.0169	-4.2501
DRI1	DRIF	-0.0150	-4.0001
BEI1	SBEN	-0.0000	-0.0002
BEI1	SBEN	-0.0150	3.9998
DRI1	DRIF	-0.0169	4.2498
FOIL	MARK	-0.0169	4.2498
DRI1	DRIF	-0.0188	4.4998
BEI2	SBEN	-0.1685	6.4927
DRA3	DRIF	-0.2253	6.8886
INXK2	KICK	-0.3673	7.8785
DRI0	DRIF	-0.7771	10.7346
INXK1	KICK	-0.9191	11.7244
DRA3	DRIF	-0.9759	12.1204
QF1	QUAD	-1.2600	14.1001
DRI2	DRIF	-1.3168	14.4960

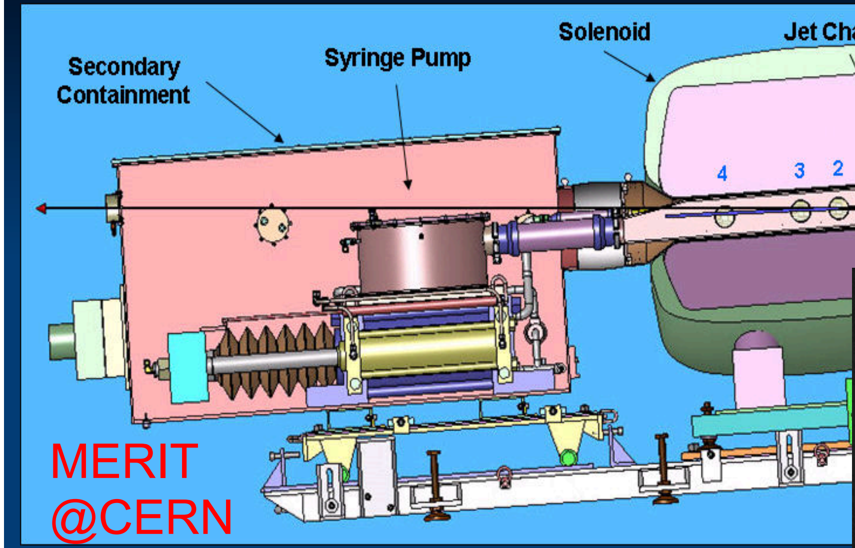


Buncher Ring
Layout & Optics
(Alexahin)

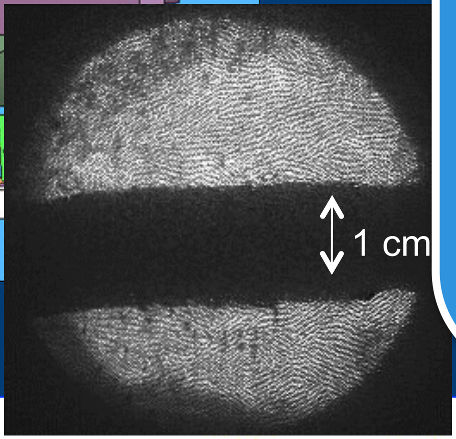
Optics:
½ staight +
1 arc cell

- ✓ Based on 6-8 GeV Linac Source
- ✓ Accumulator & Buncher Ring Designs in hand
- ✓ H- stripping requirements same as those established for Fermilab's Project X

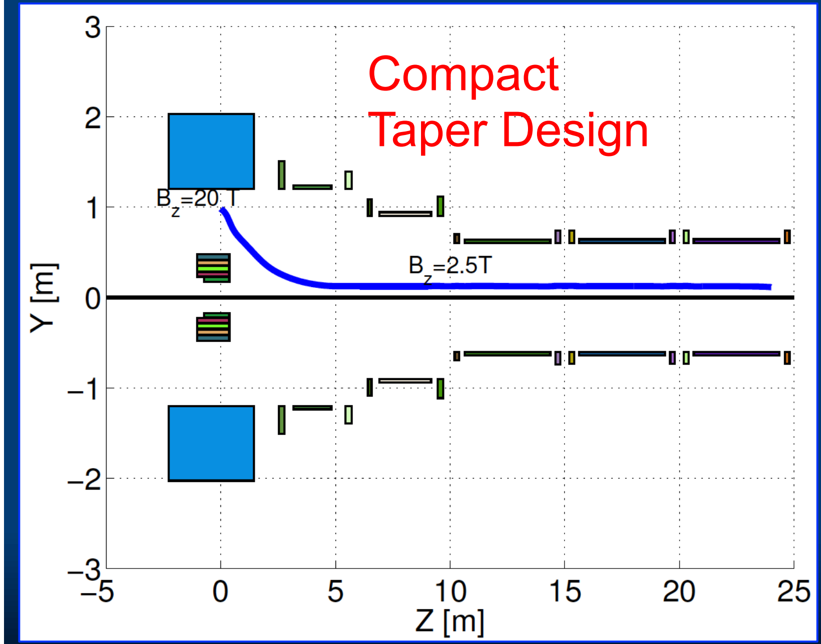
High Power Target



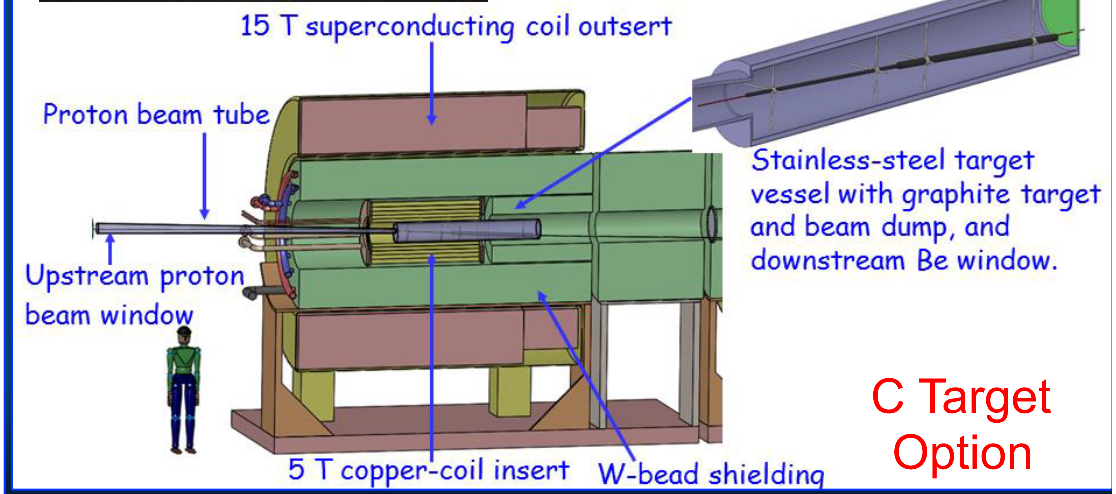
MERIT @CERN



- ✓ MERIT Expt:
  - LHg Jet in 15T
  - Capability: 8MW @70Hz
- ✓ MAP Staging aims at 1-2 MW ⇨ C Target
- ✓ Improved Compact Taper Design
  - Performance & Cost

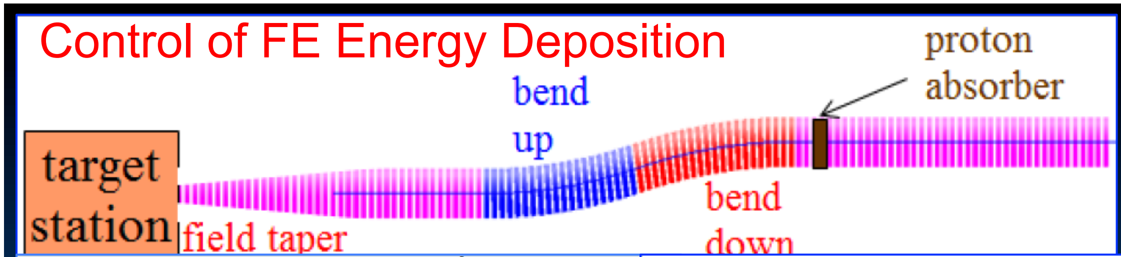


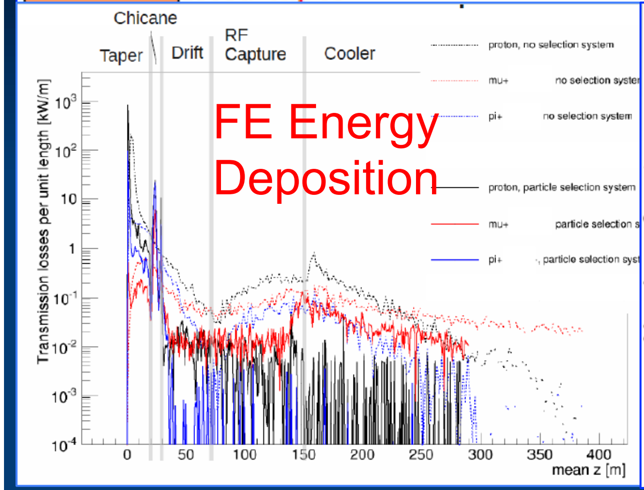
Compact Taper Design

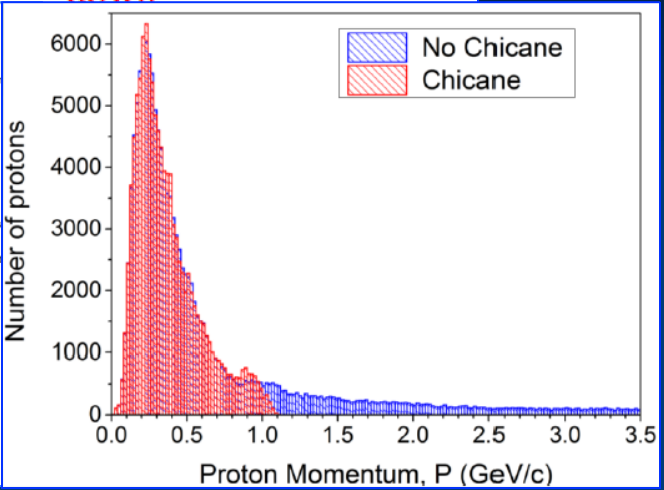


C Target Option

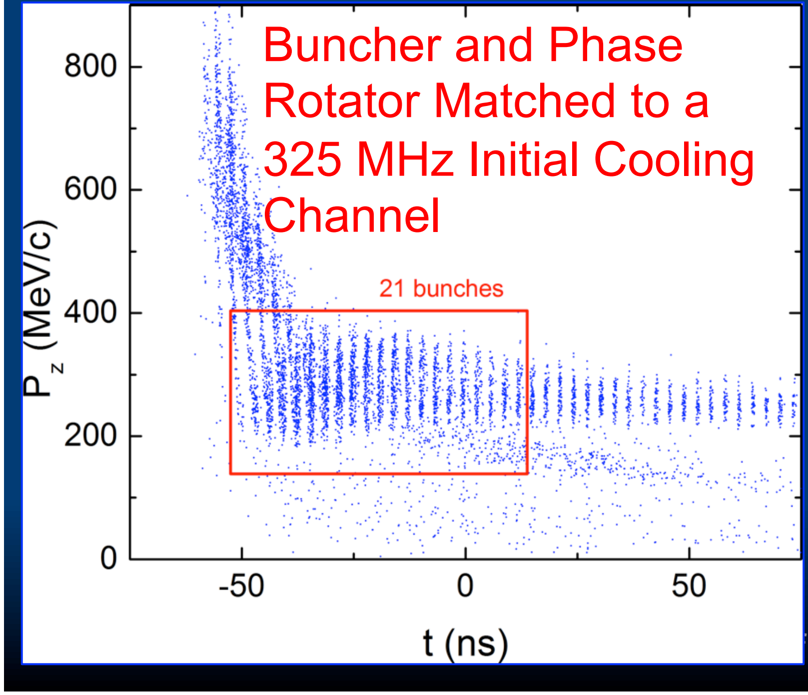
Front End

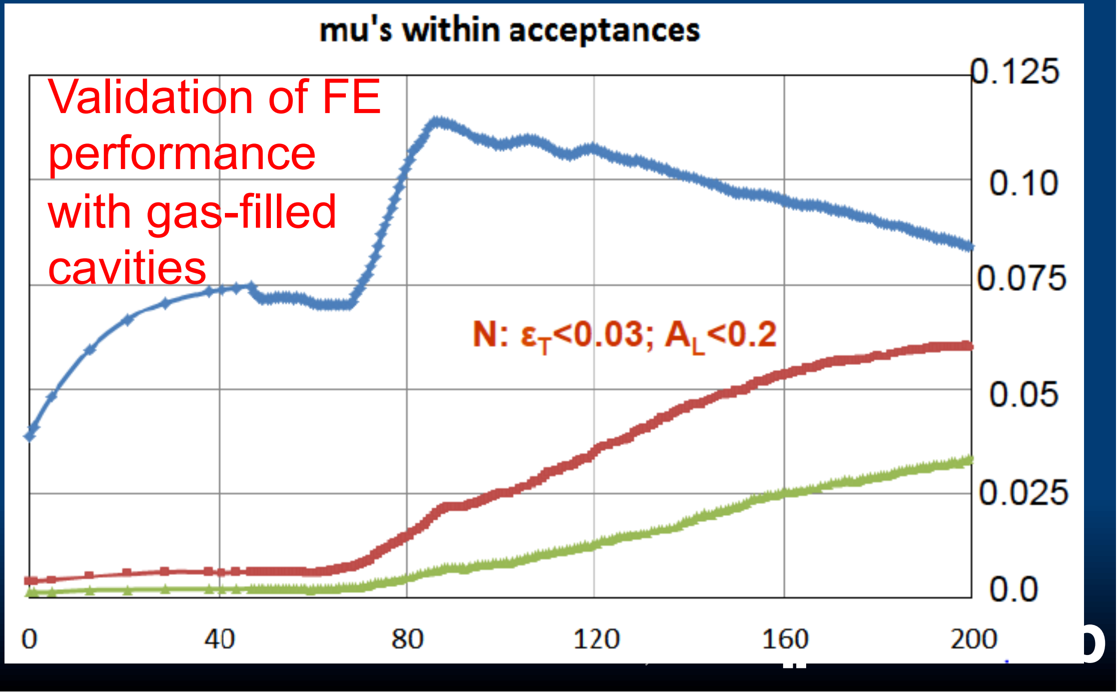

Control of FE Energy Deposition


FE Energy Deposition



- ✓ Energy Deposition
- ✓ Full 325 MHz RF Design
- ✓ Validation of gas-filled RF cavity performance

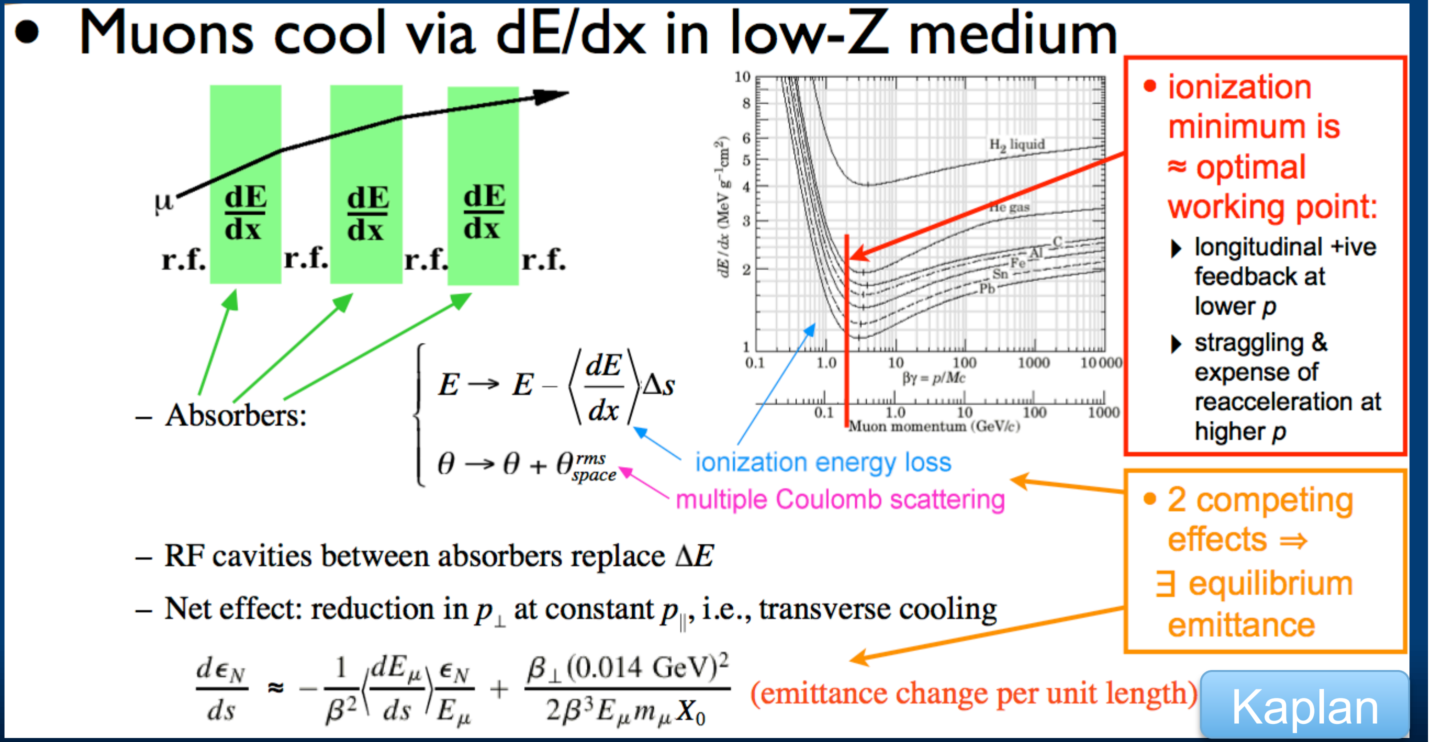

Buncher and Phase Rotator Matched to a 325 MHz Initial Cooling Channel


Validation of FE performance with gas-filled cavities

Cooling Methods

- The particular challenge of muon cooling is its short lifetime
  - – Cooling must take place very quickly
  - – More quickly than any of the cooling methods presently in use
  - ⇨ Utilize energy loss in materials with RF re-acceleration

Muon Ionization Cooling



- Muons cool via dE/dx in low-Z medium

– Absorbers:

$$\begin{cases} E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \to \theta + \theta^{rms}_{space} \end{cases}$$

ionization energy loss

multiple Coulomb scattering

- ionization minimum is ≈ optimal working point:
  - longitudinal +ive feedback at lower *p*
  - straggling & expense of reacceleration at higher *p*

- 2 competing effects ⇒ ∃ equilibrium emittance

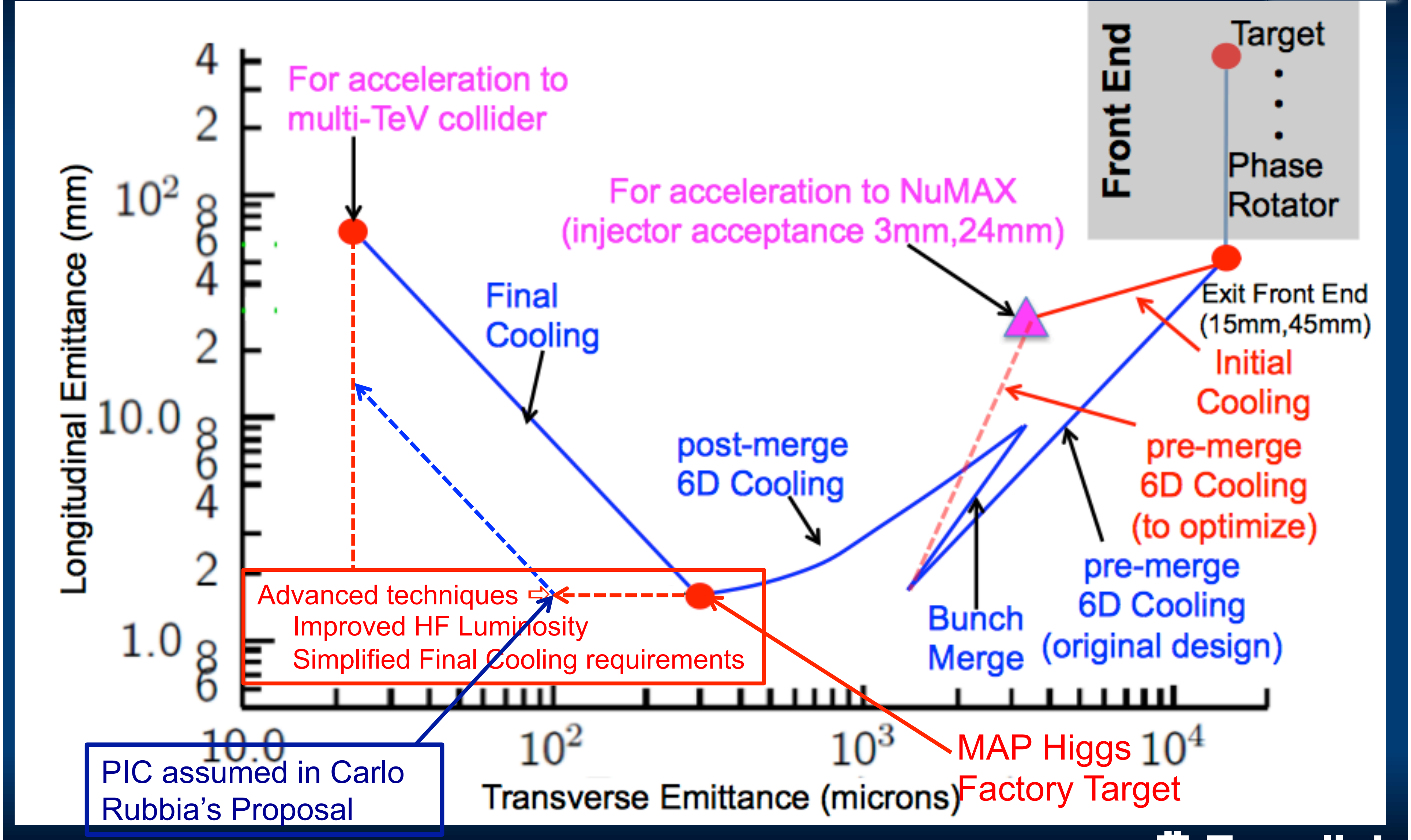
– RF cavities between absorbers replace ΔE

– Net effect: reduction in $p_\perp$ at constant $p_\parallel$, i.e., transverse cooling

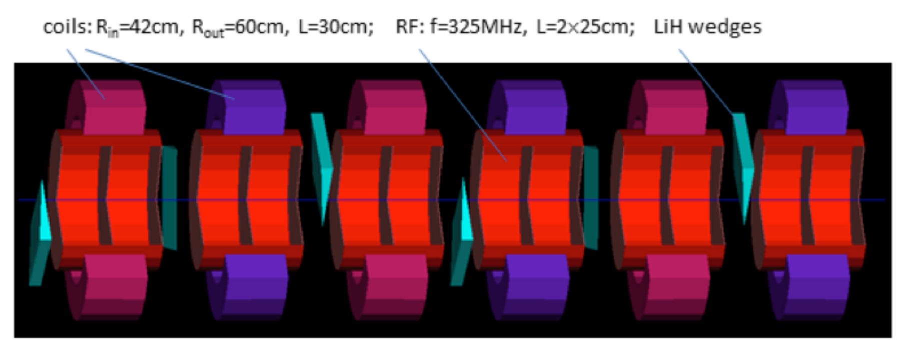
$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$ (emittance change per unit length)

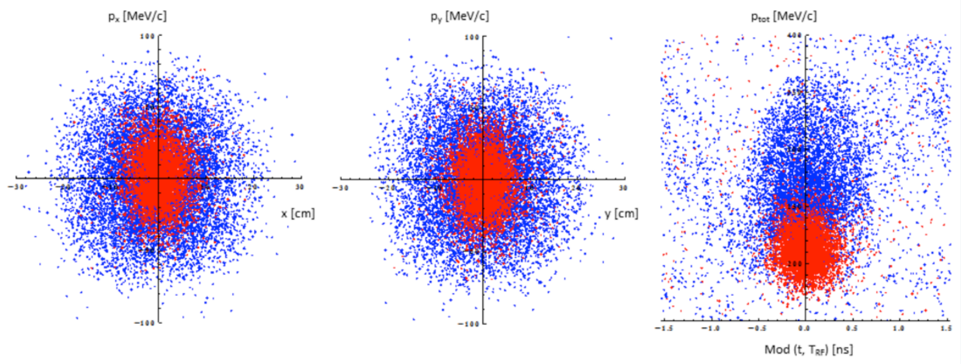
Kaplan

Muon Ionization Cooling

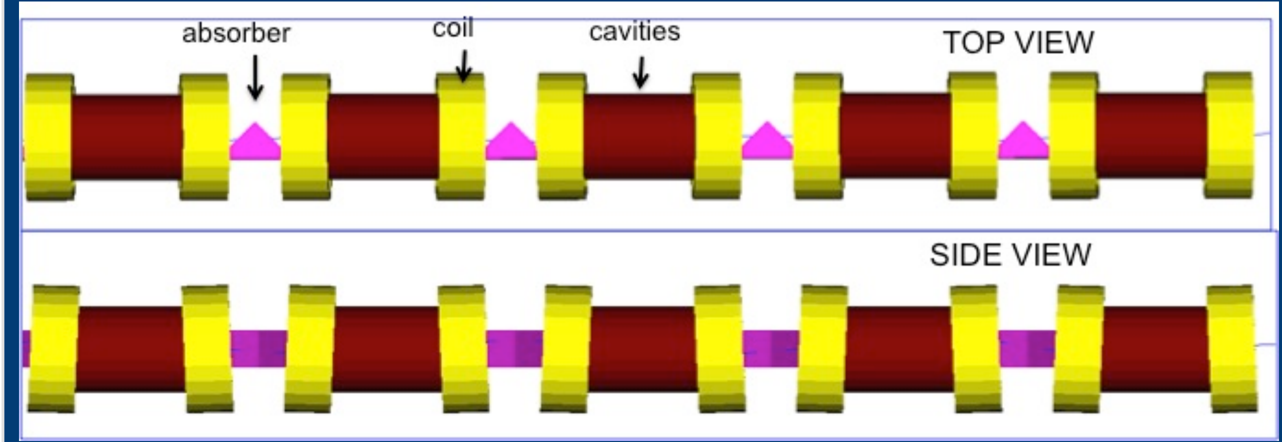


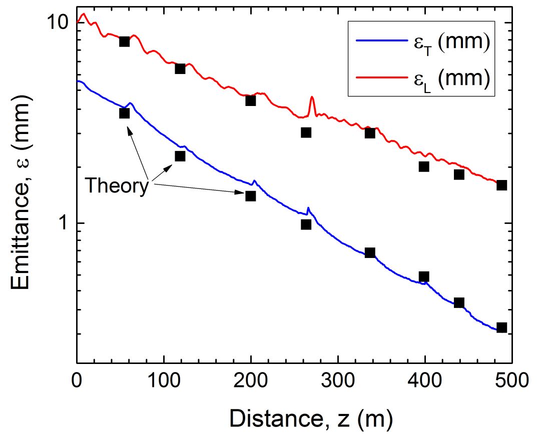
Muon Ionization Cooling (Design)





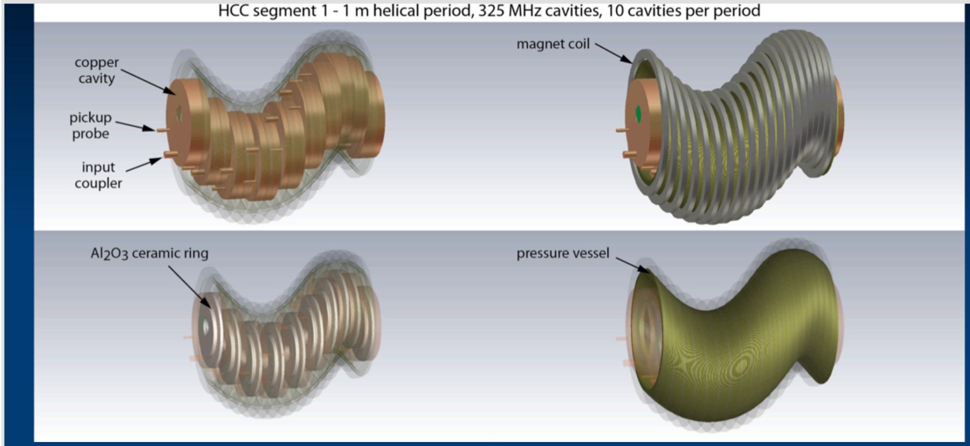
Initial 6D Cooling: ε_{6D} 60 cm^3 ⇨ ~50 mm^3; Trans = 67%

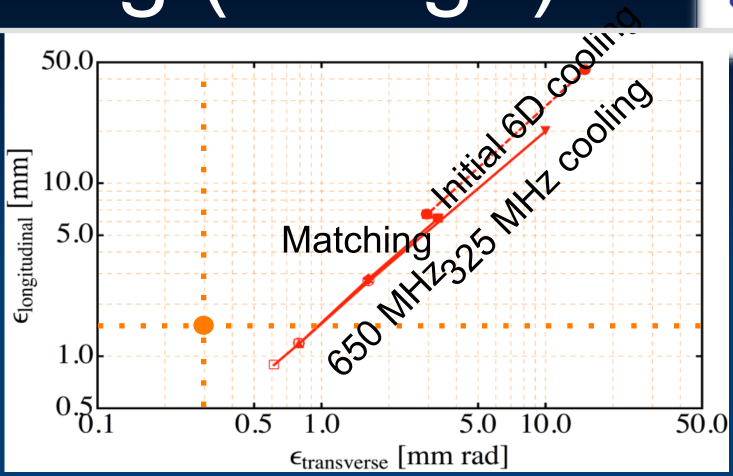




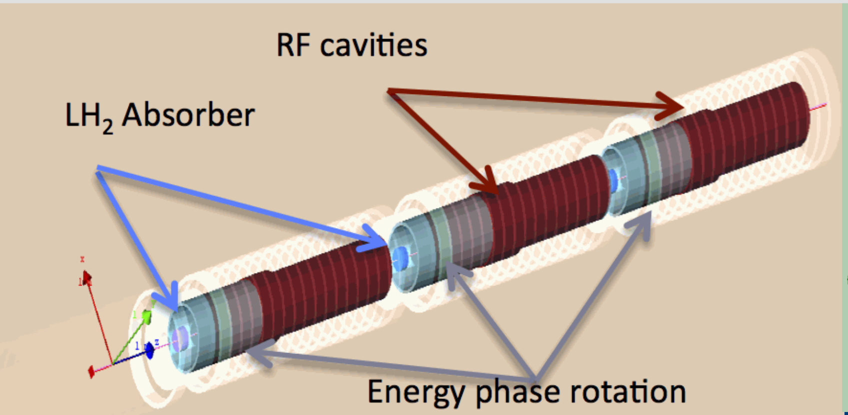
6D Rectilinear Vacuum Cooling Channel (replaces Guggenheim concept):
ε_T = 0.28mm, ε_L = 1.57mm @488m
Transmission = 55%(40%) without(with) bunch recombination

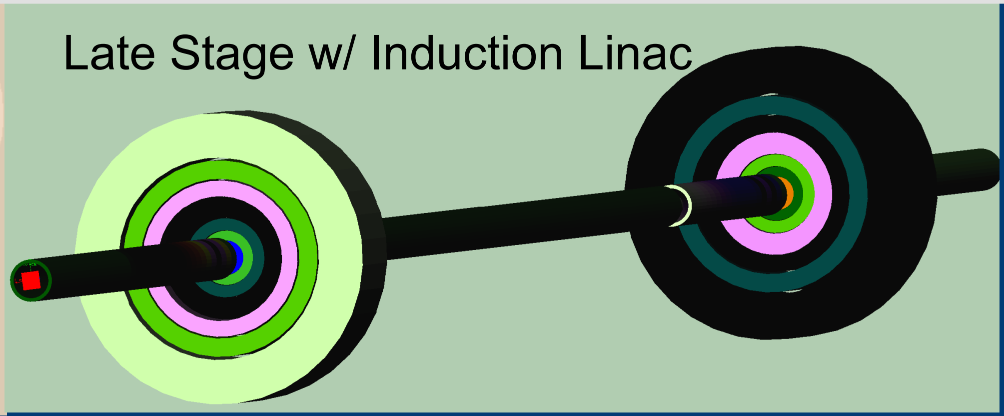
Muon Ionization Cooling (Design)





- Helical Cooling Channel (Gas-filled RF Cavities): $\varepsilon_T = 0.6$mm, $\varepsilon_L = 0.3$mm

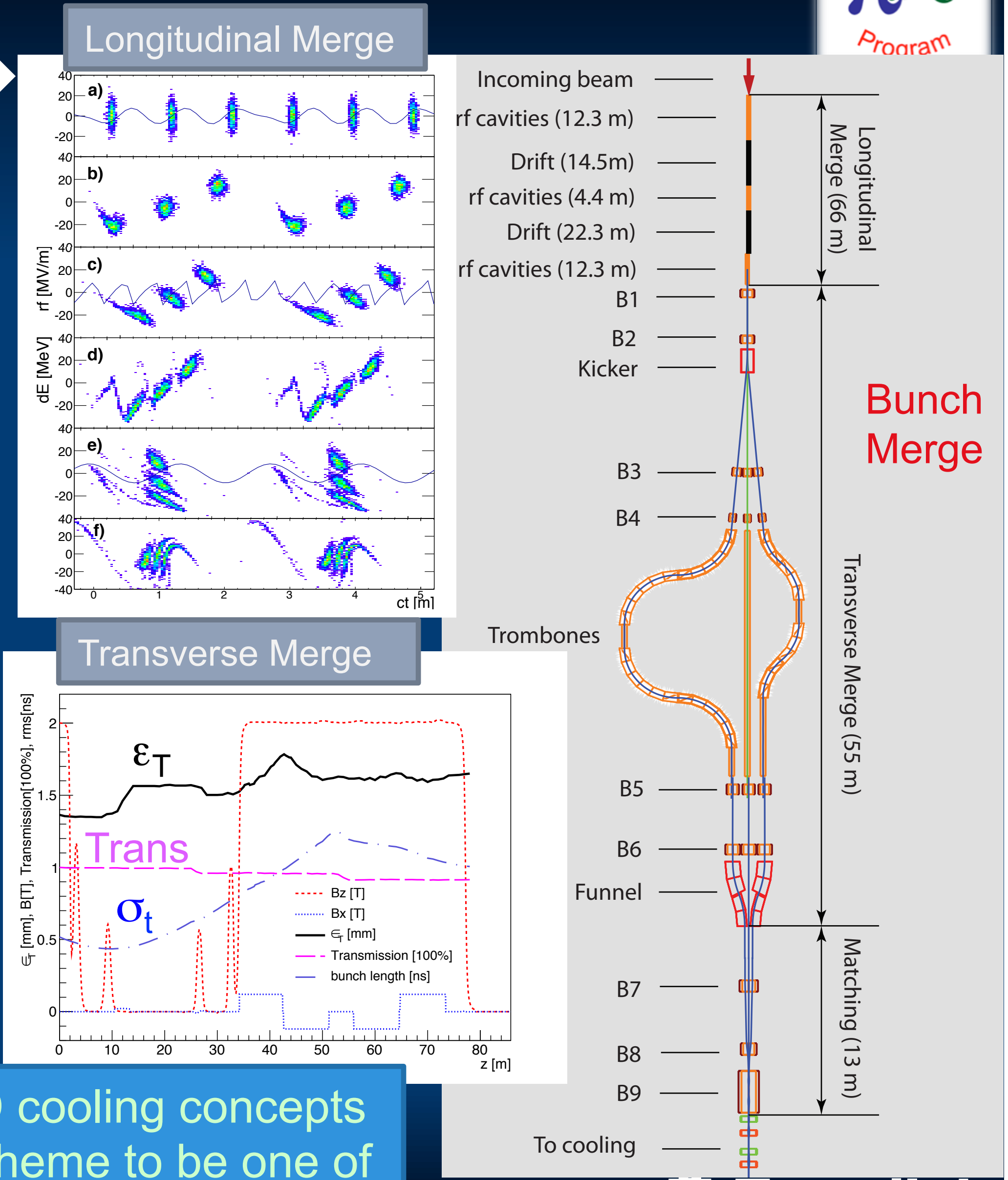




- Final Cooling with 25-30T solenoids (emittance exchange): $\varepsilon_T = 55\mu$m, $\varepsilon_L = 75$mm

Muon Ionization Cooling (Design)

Bunch Merge



- MAP Baseline Designs offer
  - Factor >10^5 in emittance reduction
- Alternative and Advanced Concepts

Higgs Factory

  - Hybrid Rectilinear Channel (gas-filled structures)
  - Parametric Ionization Cooling
  - Alternative Final Cooling

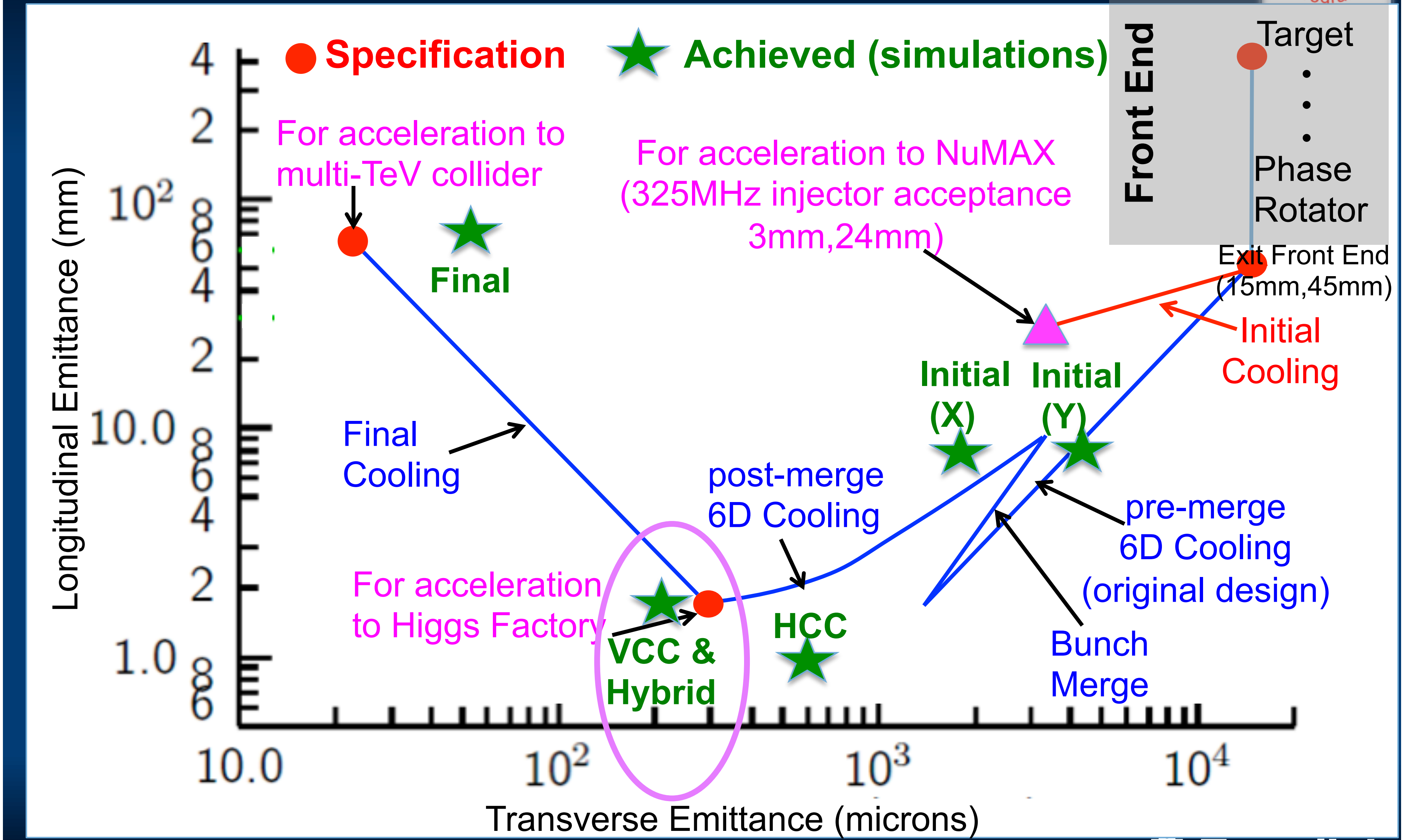
One example:

⇨ Early stages of existing scheme
⇨ Round-to-flat Beam Transform
⇨ Transverse Bunch Slicing
⇨ Longitudinal Coalescing
(at ~10s of GeV)

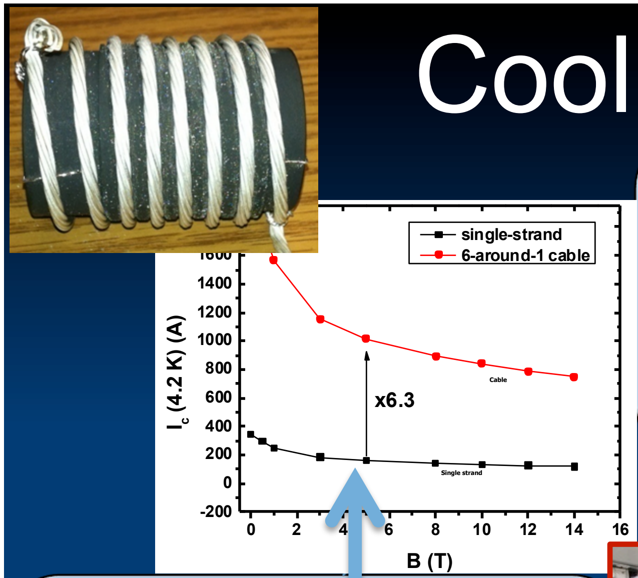
⇨ *Considerable promise to exceed our original target parameters*

MASS identified extension of the 6D cooling concepts and modification of Final Cooling scheme to be one of most likely areas of performance improvement

Cooling: The Emittance Path

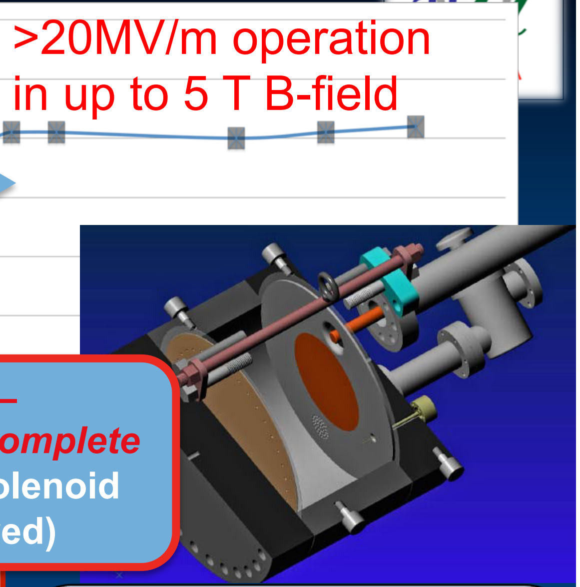


Cooling Technology R&D



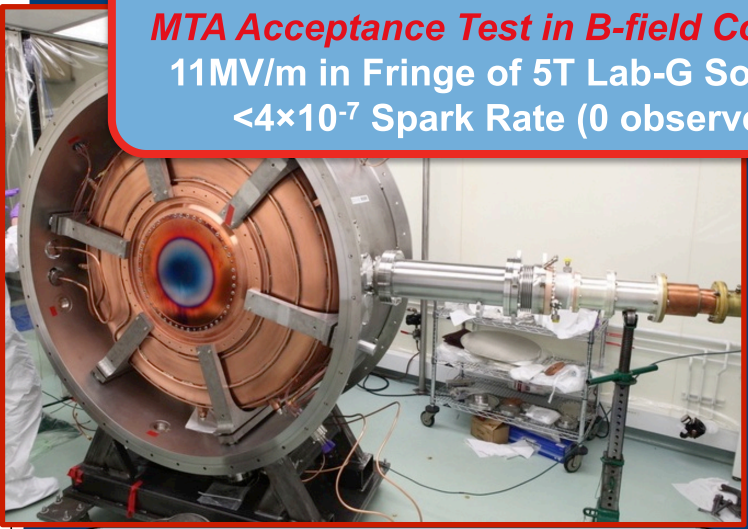
Successful Operation of 805 MHz "All Seasons" Cavity in 5T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc



>20MV/m operation in up to 5 T B-field

MICE 201 MHz RF Module –
MTA Acceptance Test in B-field Complete
11MV/m in Fringe of 5T Lab-G Solenoid
$<4\times10^{-7}$ Spark Rate (0 observed)

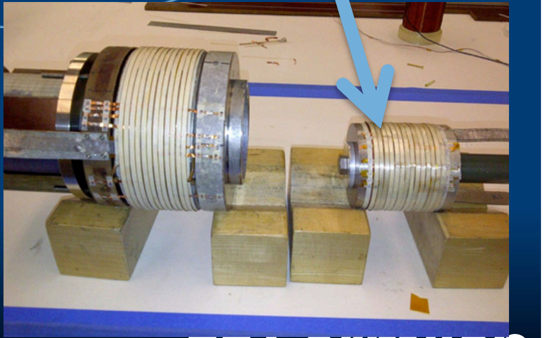


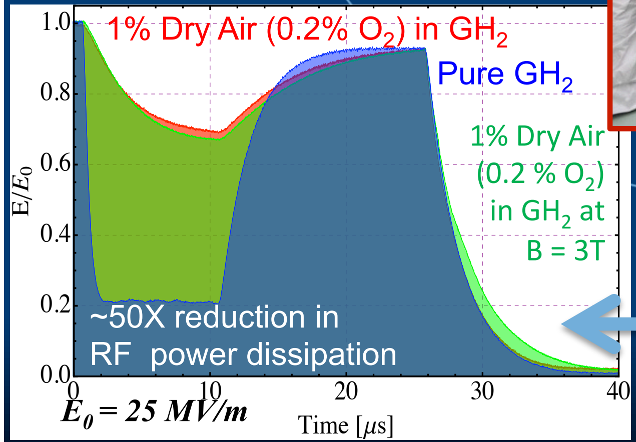
Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

FNAL-Tech Div
T. Shen-Early Career Award

World Record HTS-only Coil
15T on-axis field (16T on coil)

R. Gupta
PBL/BNL





~50X reduction in RF power dissipation

$E_0 = 25$ MV/m

Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to required μ-Collider Parameters

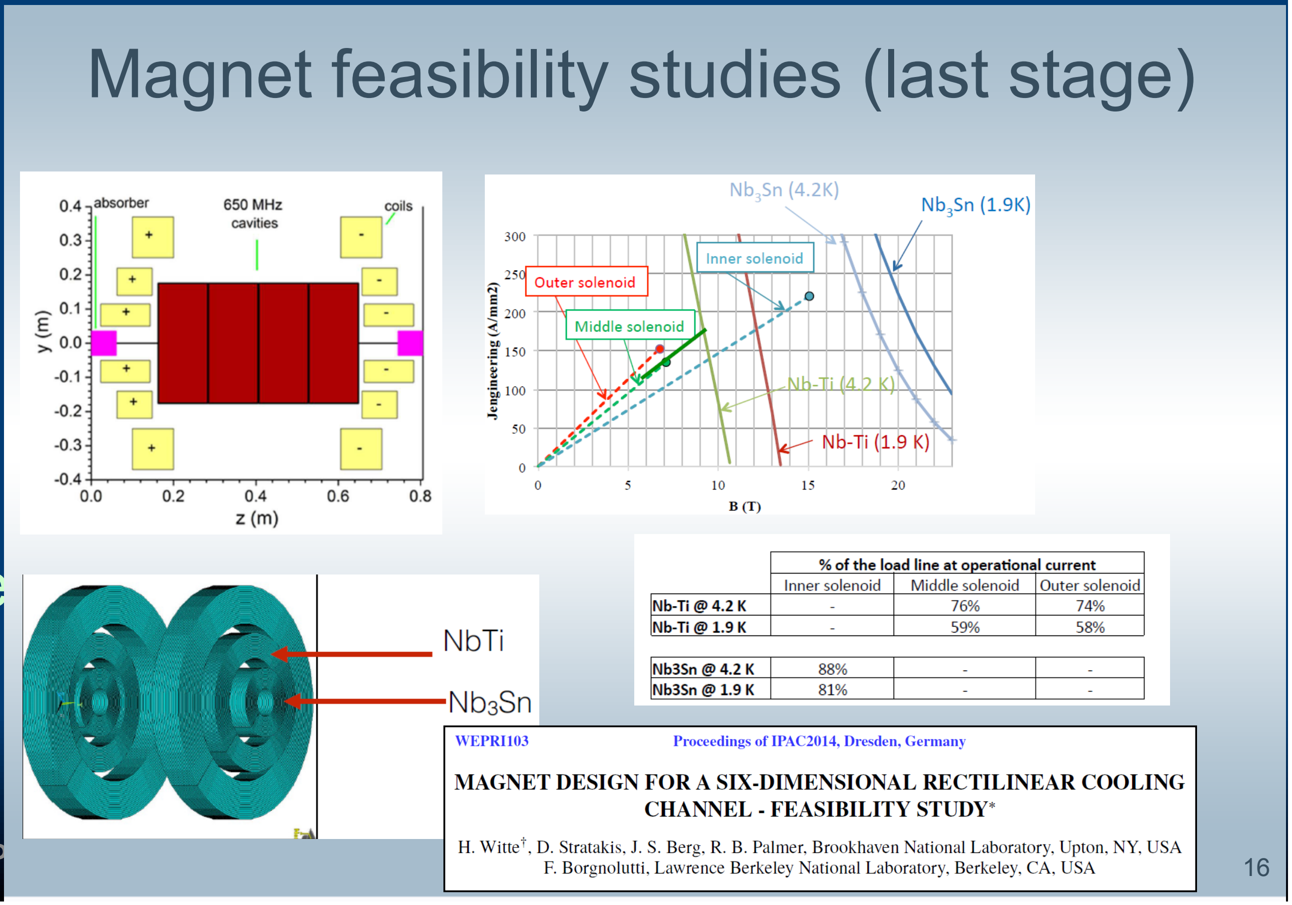
MuCool Test Area

Muon Ionization Cooling Experiment

Cooling Channel Commissioning Underway for MICE Step IV

Cooling Technology Status I

- Magnets
  - MAP Initial Baseline Selection (IBS) process
    ⇨ 6D cooling baselines that do ***not*** require HTS magnets
    - Concepts now ready to move to detailed engineering and prototype development
  - HTS Solenoids could be part of a higher performance 6D Cooling Channel
  - HTS solenoids are the baseline for the Final Cooling Channel



Magnet feasibility studies (last stage)

	% of the load line at operational current		
	Inner solenoid	Middle solenoid	Outer solenoid
Nb-Ti @ 4.2 K	-	76%	74%
Nb-Ti @ 1.9 K	-	59%	58%
Nb3Sn @ 4.2 K	88%	-	-
Nb3Sn @ 1.9 K	81%	-	-

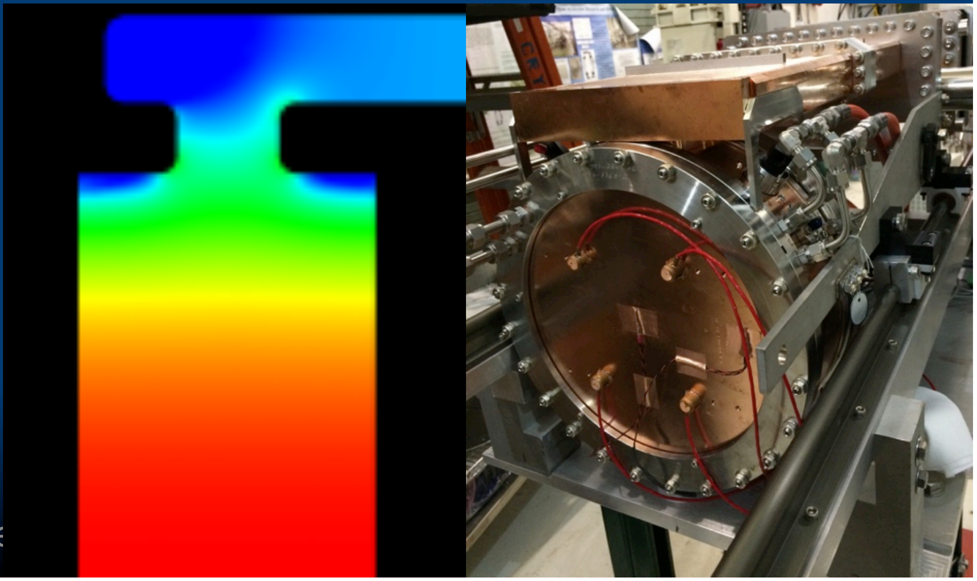
WEPRI103 Proceedings of IPAC2014, Dresden, Germany

MAGNET DESIGN FOR A SIX-DIMENSIONAL RECTILINEAR COOLING CHANNEL - FEASIBILITY STUDY*

H. Witte†, D. Stratakis, J. S. Berg, R. B. Palmer, Brookhaven National Laboratory, Upton, NY, USA
F. Borgnolutti, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Cooling Technology Status II

- RF Cavities
  - *Successful test in magnetic field* of the MICE RF Module shows
    - The importance of cavity surface preparation
    - The importance of designs incorporating detailed magnetic simulation
  - High Pressure Gas-Filled RF Cavities provide a *demonstrated route to the required gradients with high intensity beams*
  - Vacuum RF: recent B-field tests consistent with our physical models
    - **805 MHz "Modular" Cavity:** *A test vehicle to characterize breakdown effects in vacuum cavities (in operation now)*



Ionization Cooling Summary

✓ 6D Ionization Cooling Designs
  - Designs in hand that meet performance targets in simulations with stochastic effects
  - Ready to move to engineering design and prototyping
  - Able to reach target performance with Nb_3Sn conductors (NO HTS)

✓ RF operation in magnetic field (MTA program)
  - Gas-filled cavity solution successful and performance extrapolates to the requirements of the NF and MC
  - Vacuum cavity performance now consistent with models
  - MICE Test Cavity significantly exceeds specified operating requirements in magnetic field

✓ MICE Experiment now in commissioning phase

~ Final Cooling Designs
  - Baseline design meets Higgs Factory specification and performs within factor of 2.2× of required transverse emittance for high energy MC (while keeping magnets within parameters to be demonstrated within the next year at NHMFL).
  - Alternative options under study

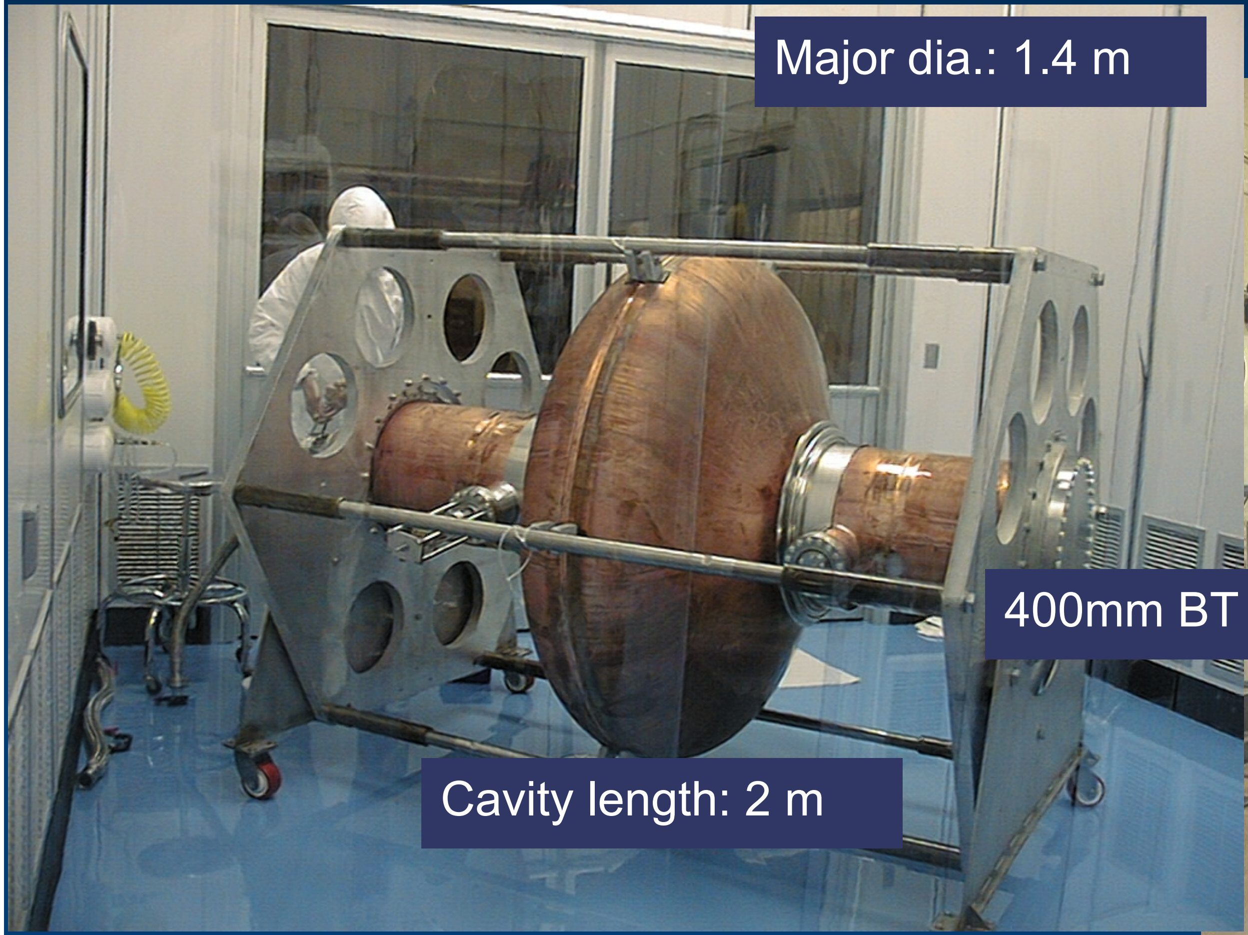
Acceleration Requirements

- Key Issues:
  - Muon lifetime ⇨ ultrafast acceleration chain
  - NF with modest cooling ⇨ accelerator acceptance
  - Total charge ⇨ cavity beam-loading (stored energy)
  - TeV-scale acceleration focuses on hybrid Rapid Cycling Synchrotron ⇨ requires rapid cycling magnets

    $B_{peak} \sim 2T$ $f > 400Hz$

Superconducting RF Development

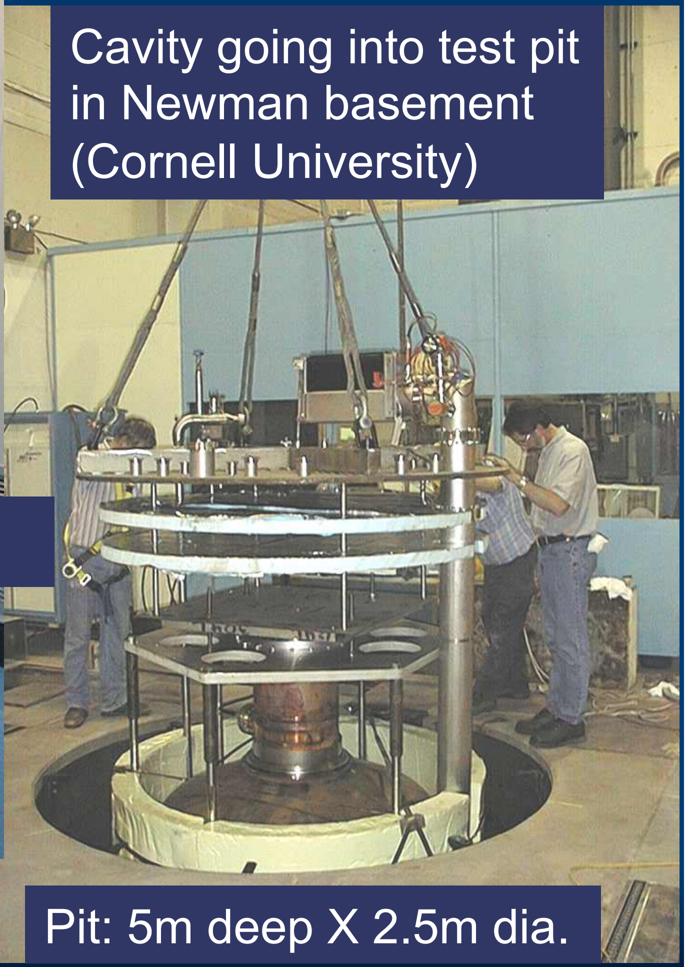
201 MHz SCRF R&D



Major dia.: 1.4 m

400mm BT

Cavity length: 2 m



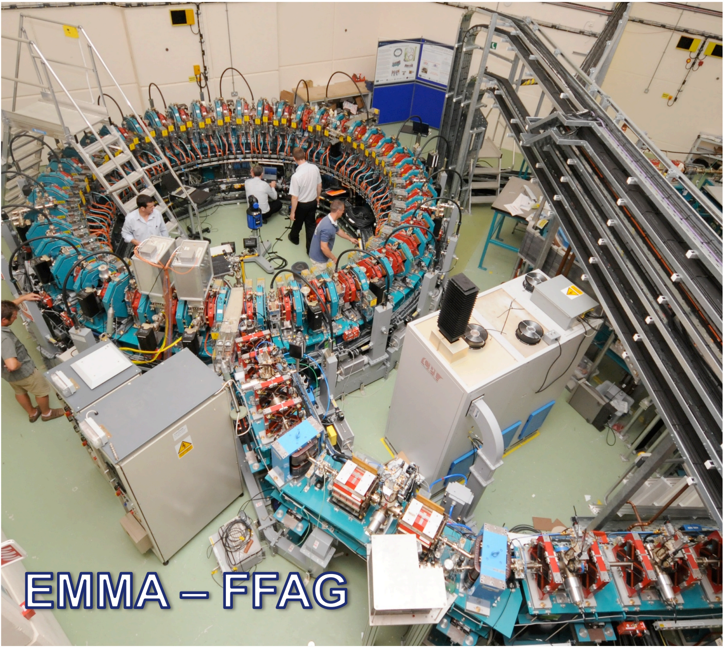
Cavity going into test pit in Newman basement (Cornell University)

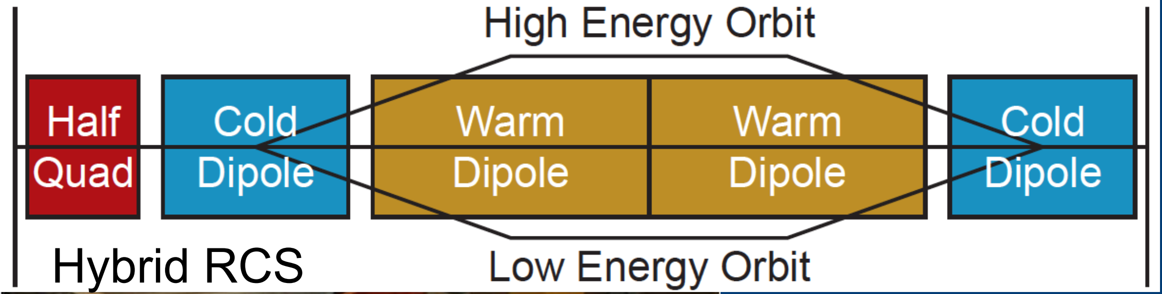
Pit: 5m deep X 2.5m dia.

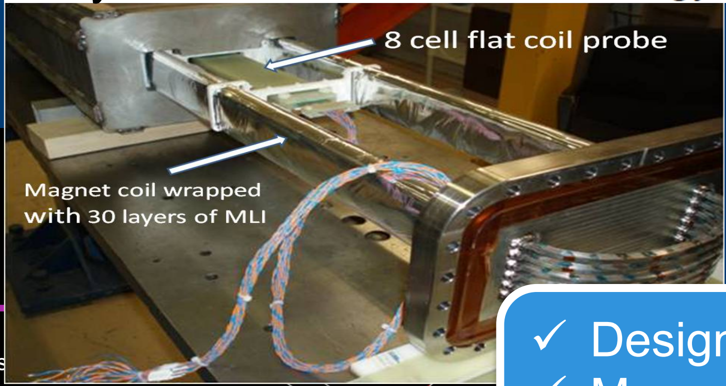
Acceleration

Technologies include:

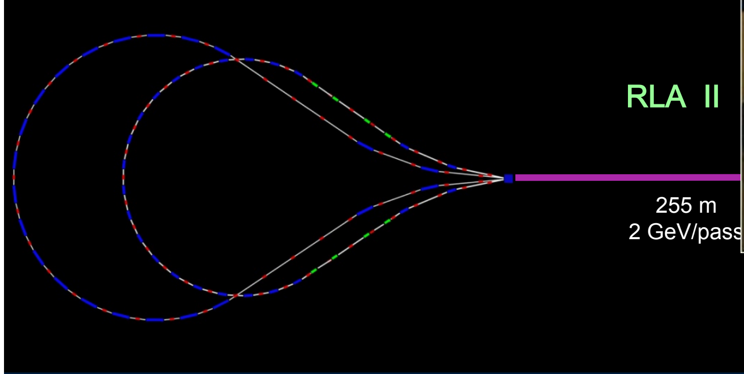
- Superconducting Linacs (NuMAX choice)
- Recirculating Linear Accelerators (RLAs)
- Fixed-Field Alternating-Gradient (FFAG) Rings
- (Hybrid) Rapid Cycling Synchrotrons (RCS) for TeV energies





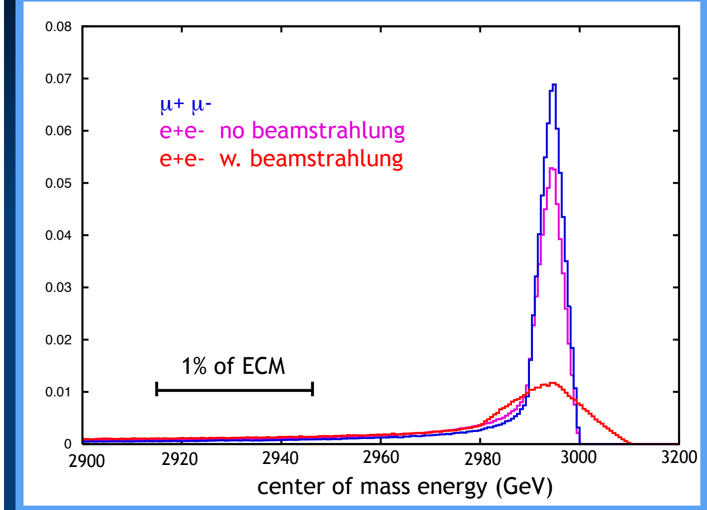


RCS requires 2 T p-p magnets at f > 400 Hz (U Miss & FNAL)

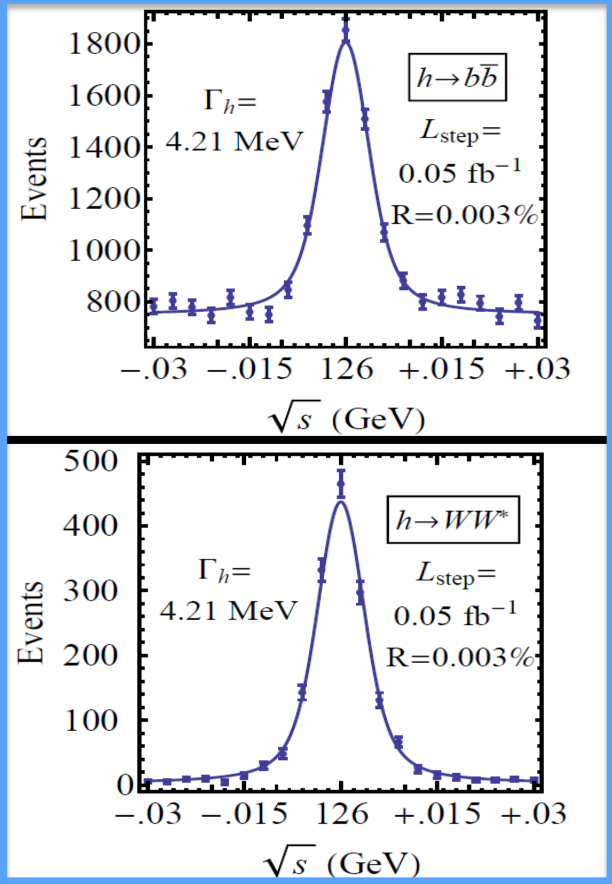


- ✓ Design concepts in hand
- ✓ Magnet R&D indicates parameters achievable

Collider Physics with $\mu^+\mu^-$



Effect of Beamstrahlung on CoM Energy Distribution at 3 TeV

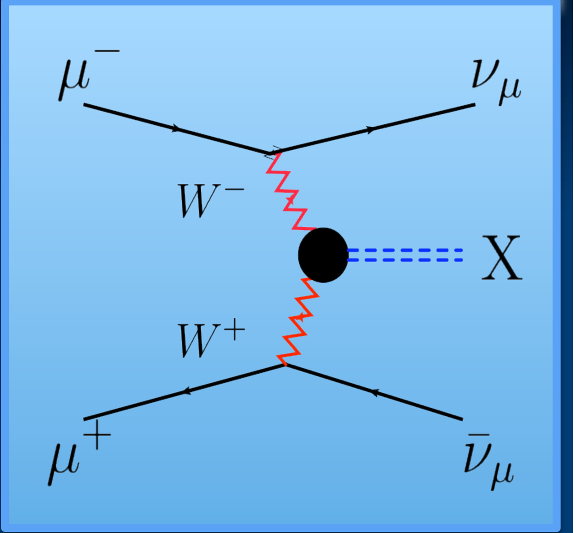


Energy Resolution:

$\delta E_b/E_b \sim 4\times10^{-5}$ @ Higgs

$\delta E_b/E_b \sim 10^{-4}$ to 10^{-3} @ Top

$\delta E_b/E_b \sim 1\times10^{-3}$ @ TeV-scale

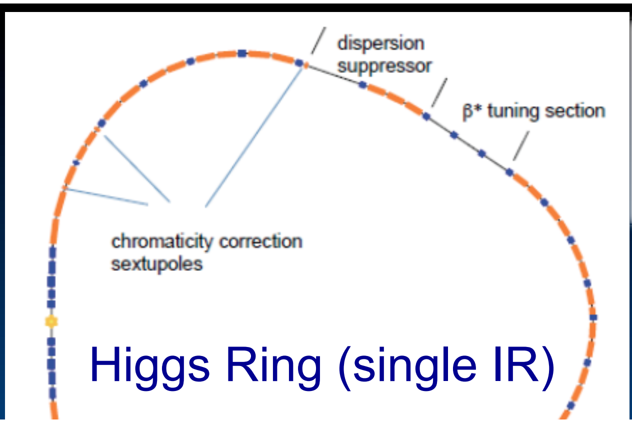


√s > 1 TeV: Fusion processes dominate

- EW Boson Collider
- Discovery machine complementary to very high energy pp
- At >5TeV: Higgs self-coupling resolution <10%

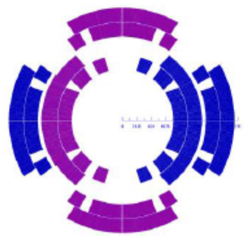
Collider Rings

- Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM
  - With supporting magnet designs and background studies

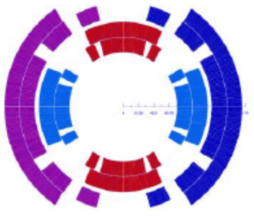


Higgs Ring (single IR)

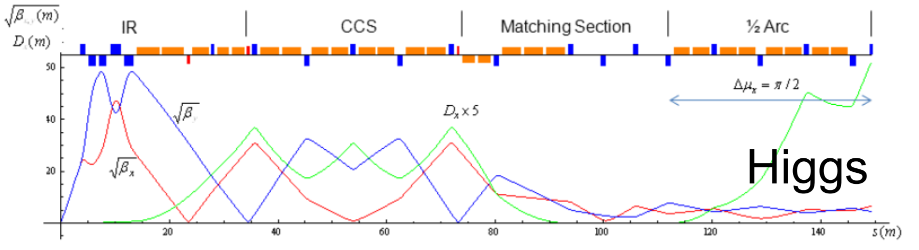
- ✓ Higgs, 1.5 TeV CoM and 3 TeV CoM Designs
  - With magnet concepts
  - Achieve target parameters
- ✓ Preliminary 6 TeV CoM design
  - Key issue is IR design and impact on luminosity
  - Utilizes lower power on target



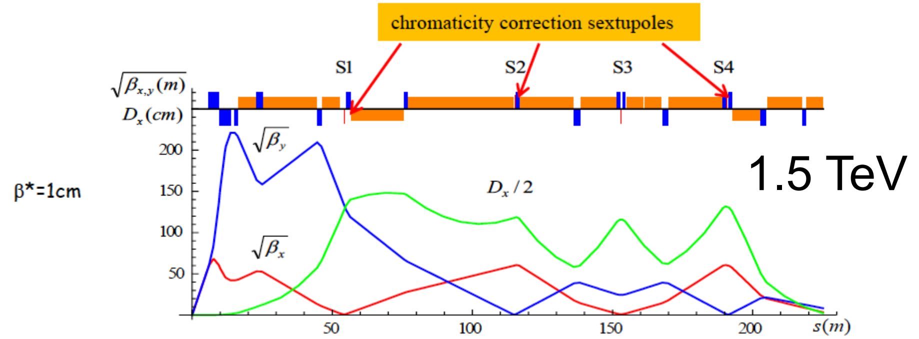
Dipole/Quad

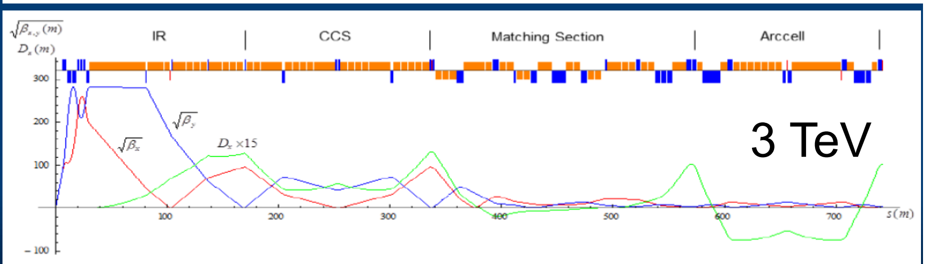


Quad/Dipole



Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP

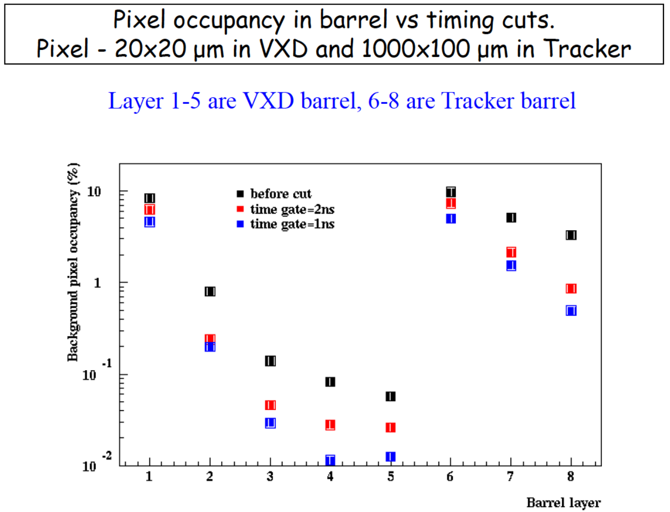




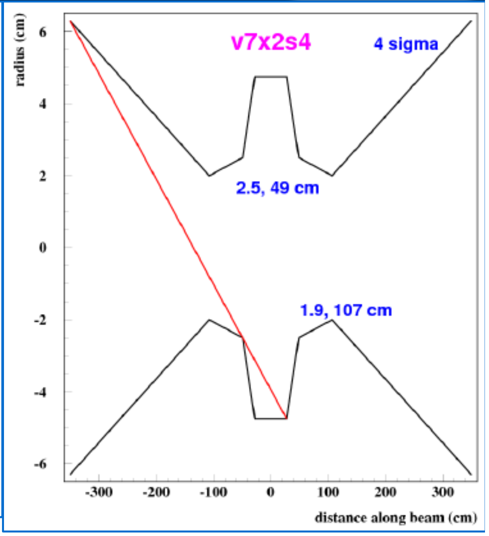
Optics functions from IP to the end of the first arc cell (6 such cells / arc) for β*=5mm

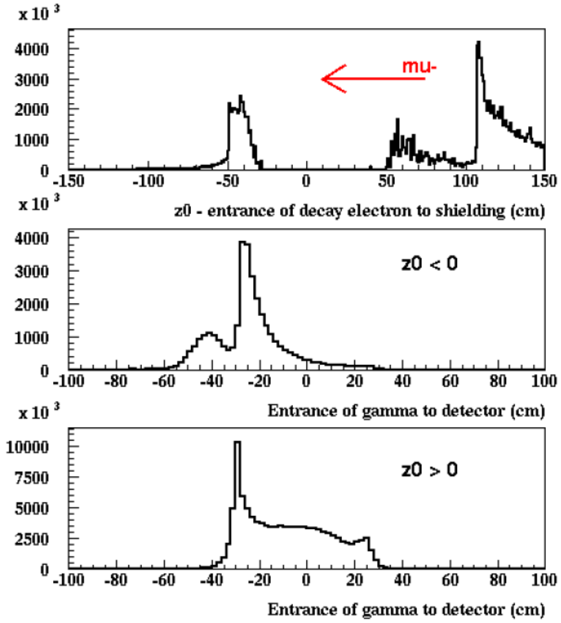
Machine Detector Interface

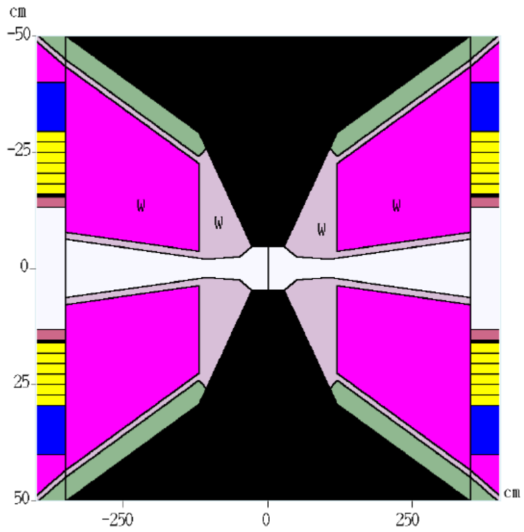
- ✓ Backgrounds appear manageable with suitable detector pixelation and timing rejection
- ✓ Recent study of hit rates comparing MARS, EGS and FLUKA appear consistent to within factors of <2
  - ⇨ Significant improvement in our confidence of detector performance

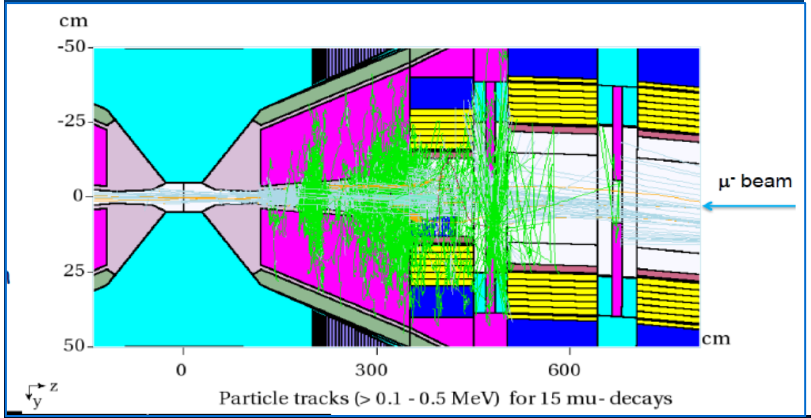

Pixel occupancy in barrel vs timing cuts.
Pixel - 20x20 μm in VXD and 1000x100 μm in Tracker

Layer 1-5 are VXD barrel, 6-8 are Tracker barrel





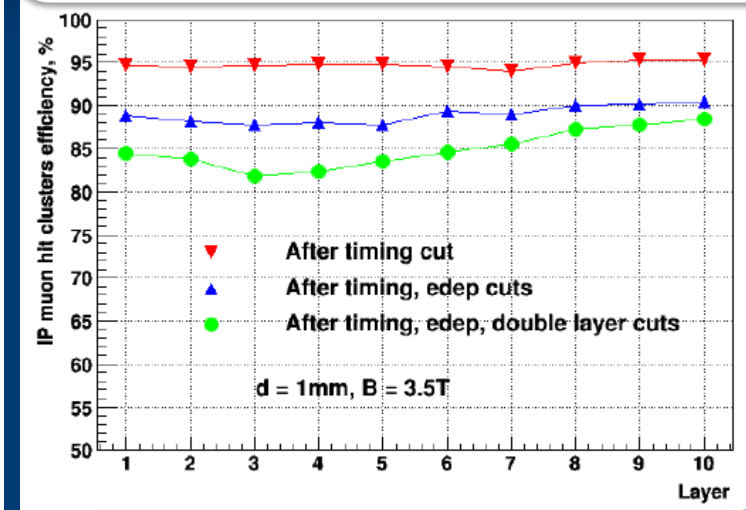


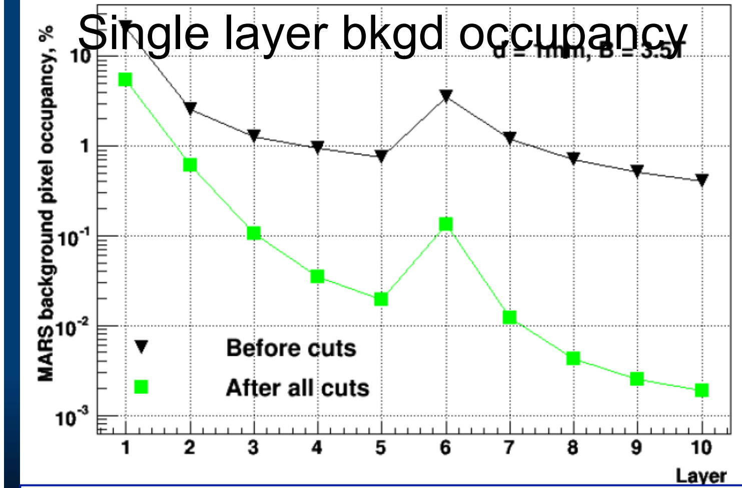


Particle tracks (> 0.1 - 0.5 MeV) for 15 mu- decays

Detector Backgrounds & Mitigation

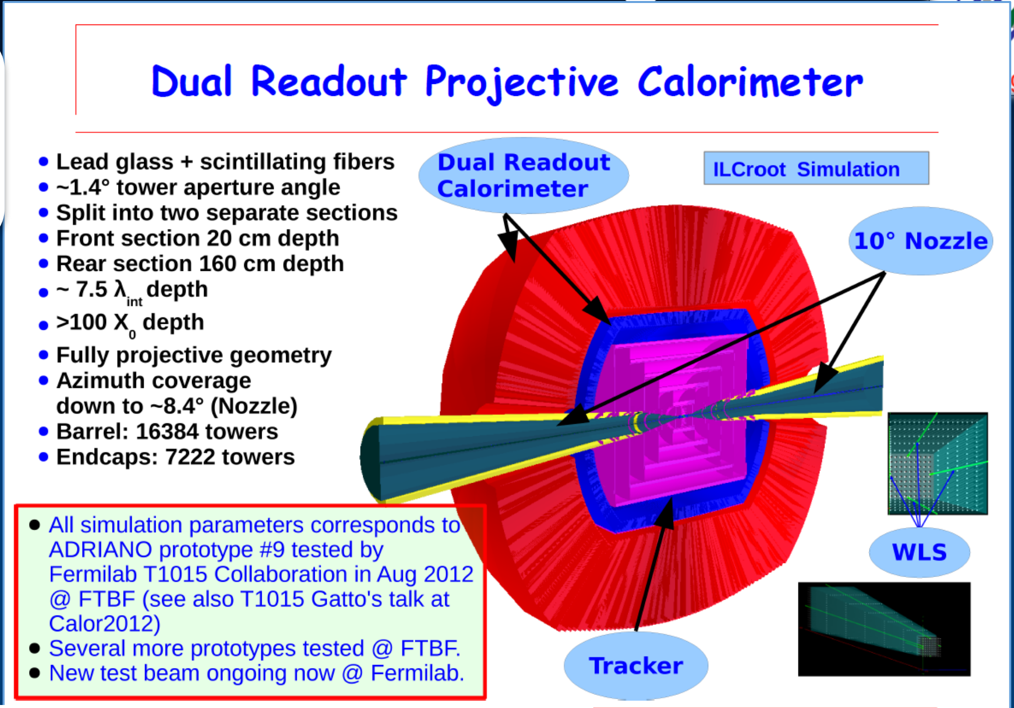
Trackers: Employ double-layer structure with 1mm separation for neutral background suppression





Single layer bkgd occupancy

MARS Bkgds ⇨ ILCRoot Det Model



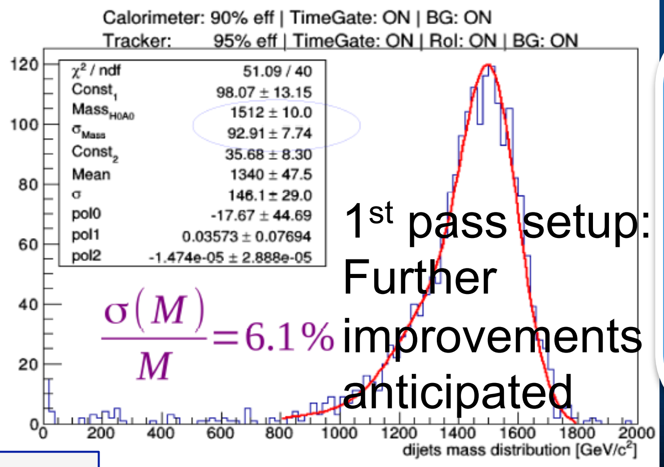
Dual Readout Projective Calorimeter

- Lead glass + scintillating fibers
- ~1.4° tower aperture angle
- Split into two separate sections
- Front section 20 cm depth
- Rear section 160 cm depth
- ~ 7.5 λ_{int} depth
- >100 X_0 depth
- Fully projective geometry
- Azimuth coverage down to ~8.4° (Nozzle)
- Barrel: 16384 towers
- Endcaps: 7222 towers

- All simulation parameters corresponds to ADRIANO prototype #9 tested by Fermilab T1015 Collaboration in Aug 2012 @ FTBF (see also T1015 Gatto's talk at Calor2012)
- Several more prototypes tested @ FTBF.
- New test beam ongoing now @ Fermilab.

- Fermilab 7

Time gate & RoI ON – BG ON



Calorimeter: 90% eff | TimeGate: ON | BG: ON
Tracker: 95% eff | TimeGate: ON | RoI: ON | BG: ON

χ^2 / ndf	51.09 / 40
$Const_1$	98.07 ± 13.15
$Mass_{H0A0}$	1512 ± 10.0
σ_{Mass}	92.91 ± 7.74
$Const_2$	35.68 ± 8.30
Mean	1340 ± 47.5
σ	146.1 ± 29.0
pol0	-17.67 ± 44.69
pol1	0.03573 ± 0.07694
pol2	-1.474e-05 ± 2.888e-05

$$\frac{\sigma(M)}{M}=6.1\%$$

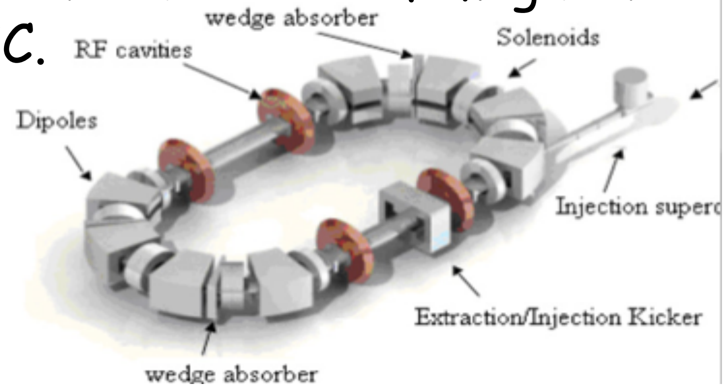
1st pass setup: Further improvements anticipated

- ✓ Preliminary detector study promising
  - Real progress requires dedicated effort, which MAP was not allowed to fund

A tentative proposal for a Higgs factory at CERN

- The muon cooled Higgs factory can be easily housed within CERN
- The new 5 GeV Linac will provide at 50 c/s a multi MWatt H^- beam with enough pions/muons to supply the muon factory.
- The basic additional accelerator structure will be the following:
  - Two additional small storage rings with R ≈ 50 m will strip H^- to a tight p bunch and compress the LP-SPL beam to a few ns.
  - Muons of both signs are focused in a axially symmetric B = 20 T field, reducing progressively p_t with a horn and B = 2 T
  - A buncher and a rotator compresses muons to ≈ 250 MeV/c
  - Muon Cooling in 3D compresses emittances by a factor $>10^6$.
- Bunches 1-2 x 10^{12} $\mu\pm$ are accelerated to 62.5 GeV with an unconventional, bi-directional recirculating LINAC ≈200 m long.
- Muons are colliding in a SC storage ring of R ≈ 60 m (about one half of the CERN-PS , 1/100 of LHC) where > 10^4 Higgs events/y are recorded for each of the experiments.

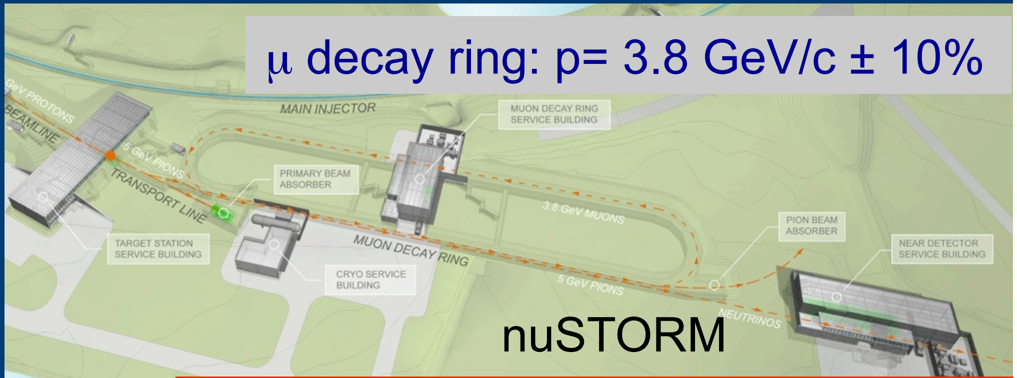
- The first muon cooling ring should present no unexpected behaviour and good agreement between calculations and experiment is expected both transversely and longitudinally
- The novel Parametric Resonance Cooling (PIC) involves instead the balance between a strong resonance growth and ionization cooling and it may involve significant and unexpected conditions which are hard to predict.
- Therefore the experimental demonstration of the cooling must be concentrated on such a resonant behaviour.
- On the other hand the success of the novel Parametric Resonance Cooling is a necessary premise for a viable luminosity of the initial proton parameters of the future CERN accelerators since the expected Higgs luminosity is proportional to the inverse of the transverse emittance, hence about one order of magnitude of increment is expected from PIC.



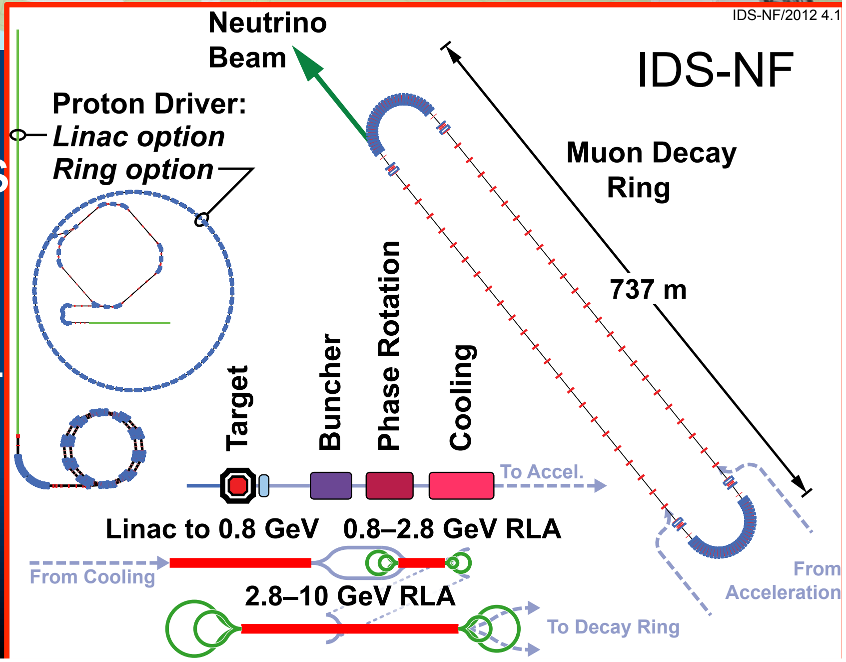
Carlo Rubbia – FNAL May 2015

Muon Accelerator Staging Study

- Is there a facility path that supports both physics output and the required accelerator development?
  - nuSTORM
    - Short baseline NF
    - No new technology
  - IDS-NF concept ⇨ 5 GeV NuMAX optimized for SURF
  - NF effort can lay the groundwork for subsequent collider capabilities
    - Demonstrate operational 6D cooling concepts as a performance
    - Performance improvement path for NF

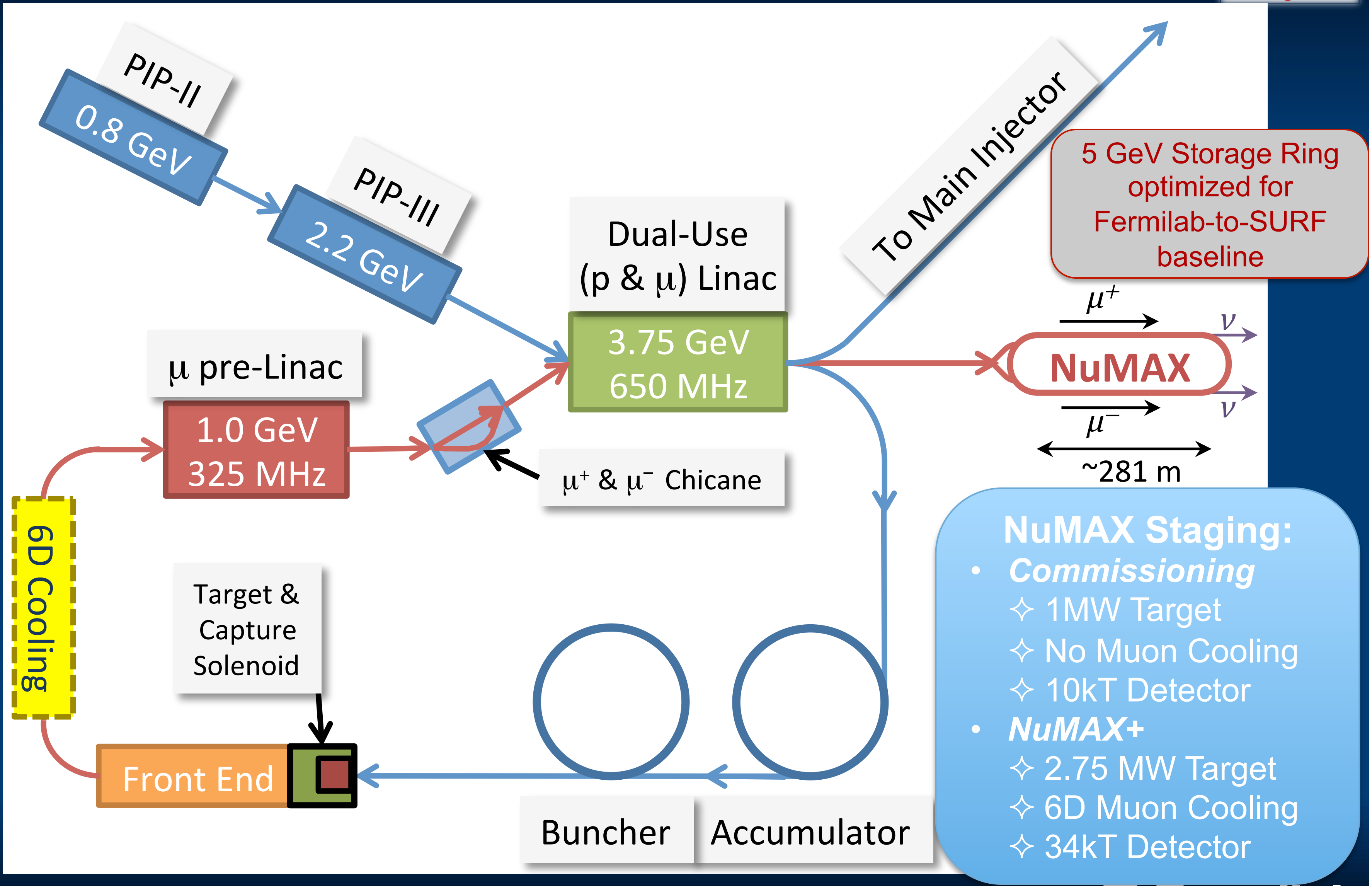

μ decay ring: p= 3.8 GeV/c ± 10%

nuSTORM



IDS-NF

The MAP Muon Accelerator Staging Study ⇨ NuMAX



PIP-II

0.8 GeV

PIP-III

2.2 GeV

Dual-Use (p & μ) Linac

3.75 GeV
650 MHz

To Main Injector

5 GeV Storage Ring optimized for Fermilab-to-SURF baseline

μ^+

ν

NuMAX

ν

μ^-

~281 m

μ pre-Linac

1.0 GeV
325 MHz

μ⁺ & μ⁻ Chicane

6D Cooling

Target & Capture Solenoid

Front End

Buncher

Accumulator

NuMAX Staging:

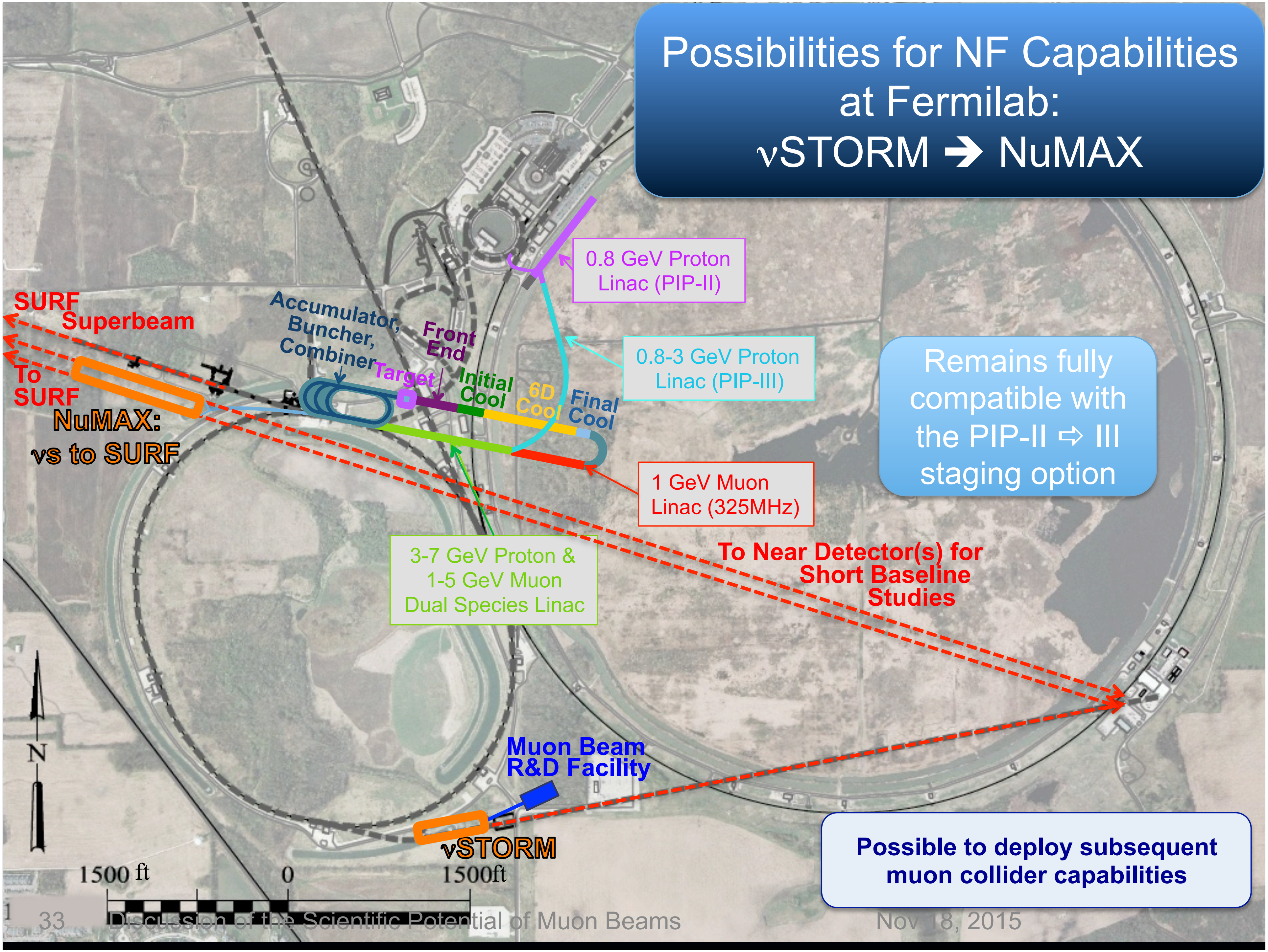
- ***Commissioning***
  - ✧ 1MW Target
  - ✧ No Muon Cooling
  - ✧ 10kT Detector
- ***NuMAX+***
  - ✧ 2.75 MW Target
  - ✧ 6D Muon Cooling
  - ✧ 34kT Detector

MASS NF Parameters

Neutrino Factory Parameters

Parameters	**Unit**	**nuSTORM**	**NuMAX Commissioning**	**NuMAX**	**NuMAX+**
ν_e or ν_μ to detectors/year	-	3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
Stored μ+ or μ-/year	-	8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
Far Detector:	Type	SuperBIND	MIND / Mag LAr	MIND / Mag LAr	MIND / Mag LAr
Distance from Ring	km	1.9	1300	1300	1300
Mass	kT	1.3	100 / 30	100 / 30	100 / 30
Magnetic Field	T	2	0.5-2	0.5-2	0.5-2
Near Detector:	Type	SuperBIND	Suite	Suite	Suite
Distance from Ring	m	50	100	100	100
Mass	kT	0.1	1	1	2.7
Magnetic Field	T	Yes	Yes	Yes	Yes
Accelerator: Ring Momentum (P_μ)	GeV/c	3.8	5	5	5
Circumference (C)	m	480	737	737	737
Ionization Cooling	-	No	No	**6D Initial**	**6D Initial**
Proton Beam Power	MW	0.2	1	1	2.75

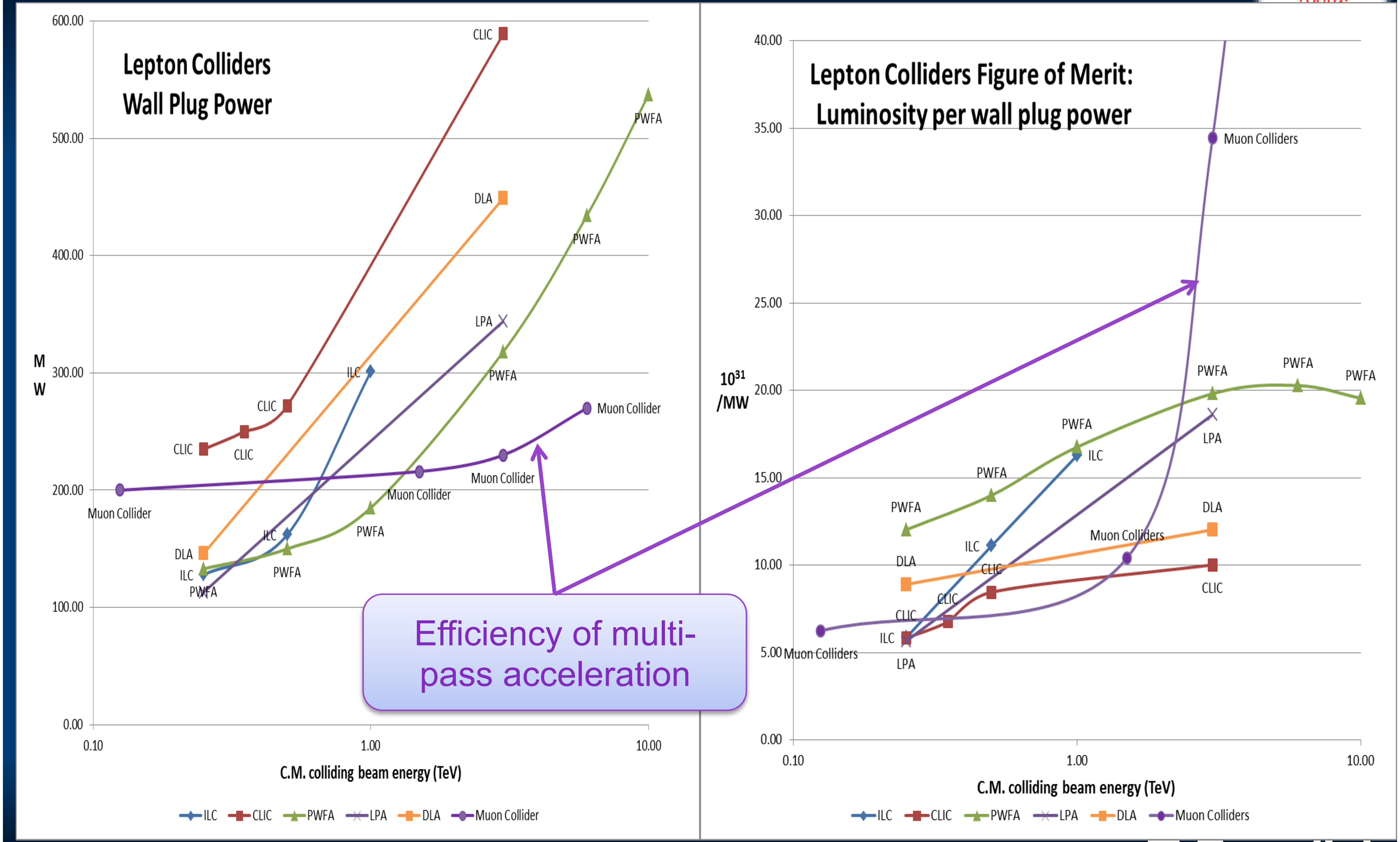
Possibilities for NF Capabilities at Fermilab: νSTORM ➔ NuMAX



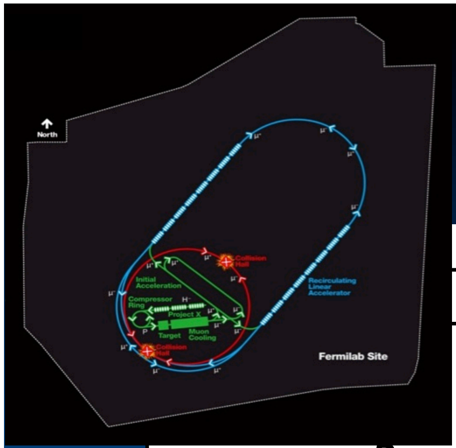
Remains fully compatible with the PIP-II ⇨ III staging option

Possible to deploy subsequent muon collider capabilities

Muon Colliders – Efficiency at the multi-TeV scale



Efficiency of multi-pass acceleration



Muon Collider Parameters

Muon Collider Parameters

		Higgs	**Multi-TeV**		
Parameter	***Units***	*Production Operation*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	**0.126**	**1.5**	**3.0**	**6.0**
Avg. Luminosity	10^{34}cm^{-2}s^{-1}	0.008	1.25	4.4	12
Beam Energy Spread	%	0.004	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	37,500	200,000	820,000
Circumference	km	0.3	2.5	4.5	6
No. of IPs		1	2	2	2
Repetition Rate	Hz	15	15	12	6
β^*	cm	1.7	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	2	2	2
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.2	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1.5	70	70	70
Bunch Length, σ_s	cm	6.3	1	0.5	0.2
Proton Driver Power	MW	4	4	4	1.6
Wall Plug Power	MW	200	216	230	270

Exquisite Energy Resolution Allows Direct Measurement of Higgs Width

Success of advanced cooling concepts
⇨ several × 10^{32} [Rubbia proposal: 5×10^{32}]

Conclusion

- NF ⇨ precision ν microscopes
- Multi-TeV MC ⇨ potentially only cost-effective route to lepton collider capabilities with $E_{CM} > 5$ TeV
- Key technical hurdles have been addressed:
  - High power target demo (MERIT)
  - Realizable cooling channel designs with acceptable performance
  - Breakthroughs in cooling channel technology
  - Significant progress in collider & detector design concepts

Accelerator	Energy Scale	Performance
Cooling Channel	**~200 MeV**	**Emittance Reduction**
MICE	*160-240 MeV*	*5%*
Muon Storage Ring	**3-4 GeV**	**Useable μ decays/yr***
νSTORM	*3.8 GeV*	*$3x10^{17}$*
Intensity Frontier ν Factory	**4-10 GeV**	**Useable μ decays/yr***
NuMAX (Initial)	*4-6 GeV*	*$8x10^{19}$*
NuMAX+	*4-6 GeV*	*$5x10^{20}$*
IDS-NF Design	*10 GeV*	*$5x10^{20}$*
Higgs Factory	**~126 GeV CoM**	**Higgs/10^7s**
s-Channel μ Collider	~126 GeV CoM	3,500-13,500
Energy Frontier μ Collider	**> 1 TeV CoM**	**Avg. Luminosity**
Opt. 1	*1.5 TeV CoM*	*$1.2x10^{34}cm^{-2}s^{-1}$*
Opt. 2	*3 TeV CoM*	*$4.4x10^{34}cm^{-2}s^{-1}$*
Opt. 3	*6 TeV CoM*	*$12x10^{34}cm^{-2}s^{-1}$*

* Decays of an individual species (ie, μ^+ or μ^-)

Muon accelerator capabilities offer unique potential for the future of high energy physics research