A Muon Collider Based on a Proton Source

Muon Collider – Preparatory Meeting, April 10-11, 2019

Mark Palmer

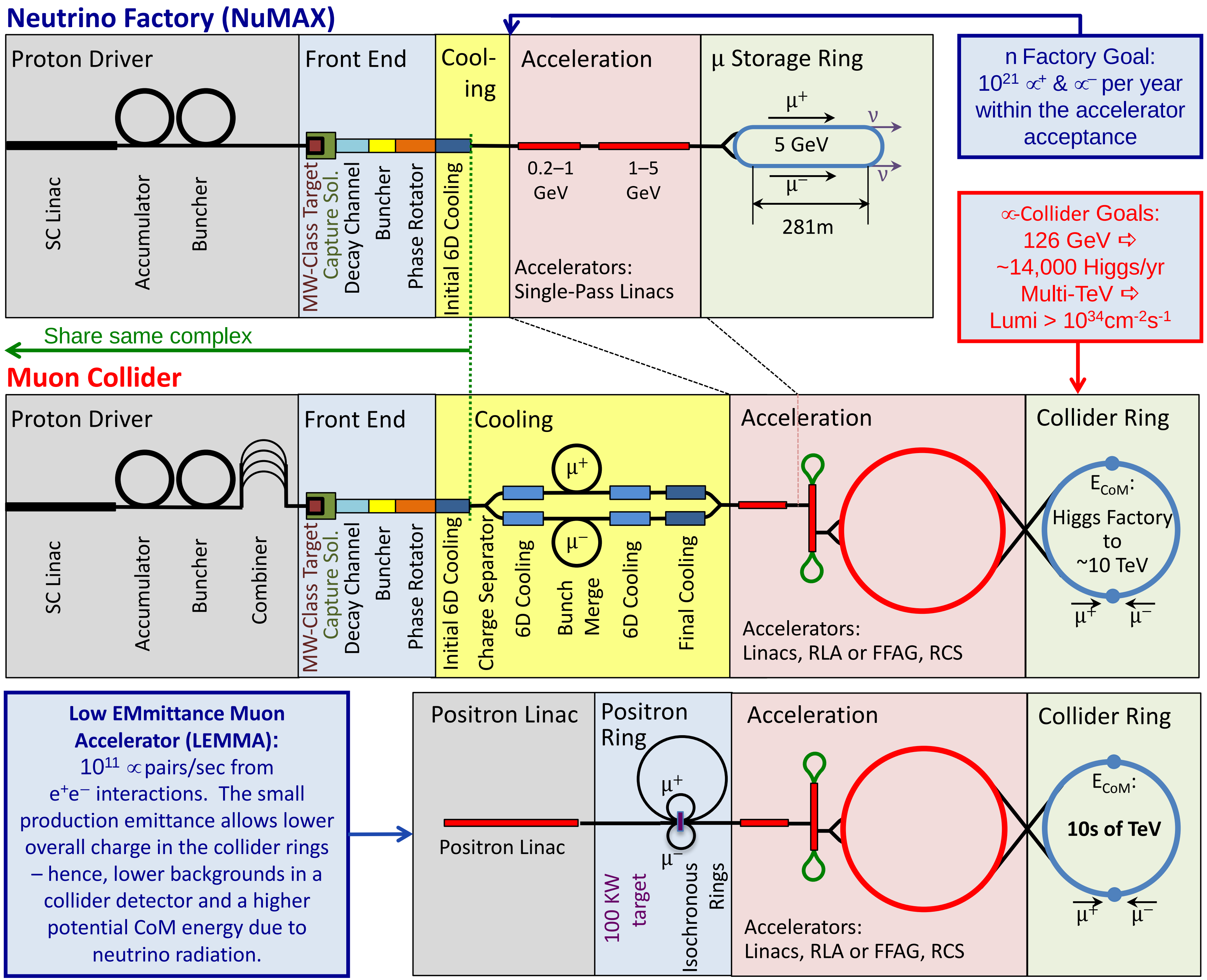
Muon Accelerator Program

BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

Acknowledgements

- MAP Collaboration
- IDS-NF Collaboration
- MICE Collaboration



Broad Applications:

- Neutrino Factories
- Colliders from ~100 GeV to 10s of TeV scale
- Secondary Beams

Potential Sources:

- Proton-driver with ionization cooling
- Positron-driver with low emittance

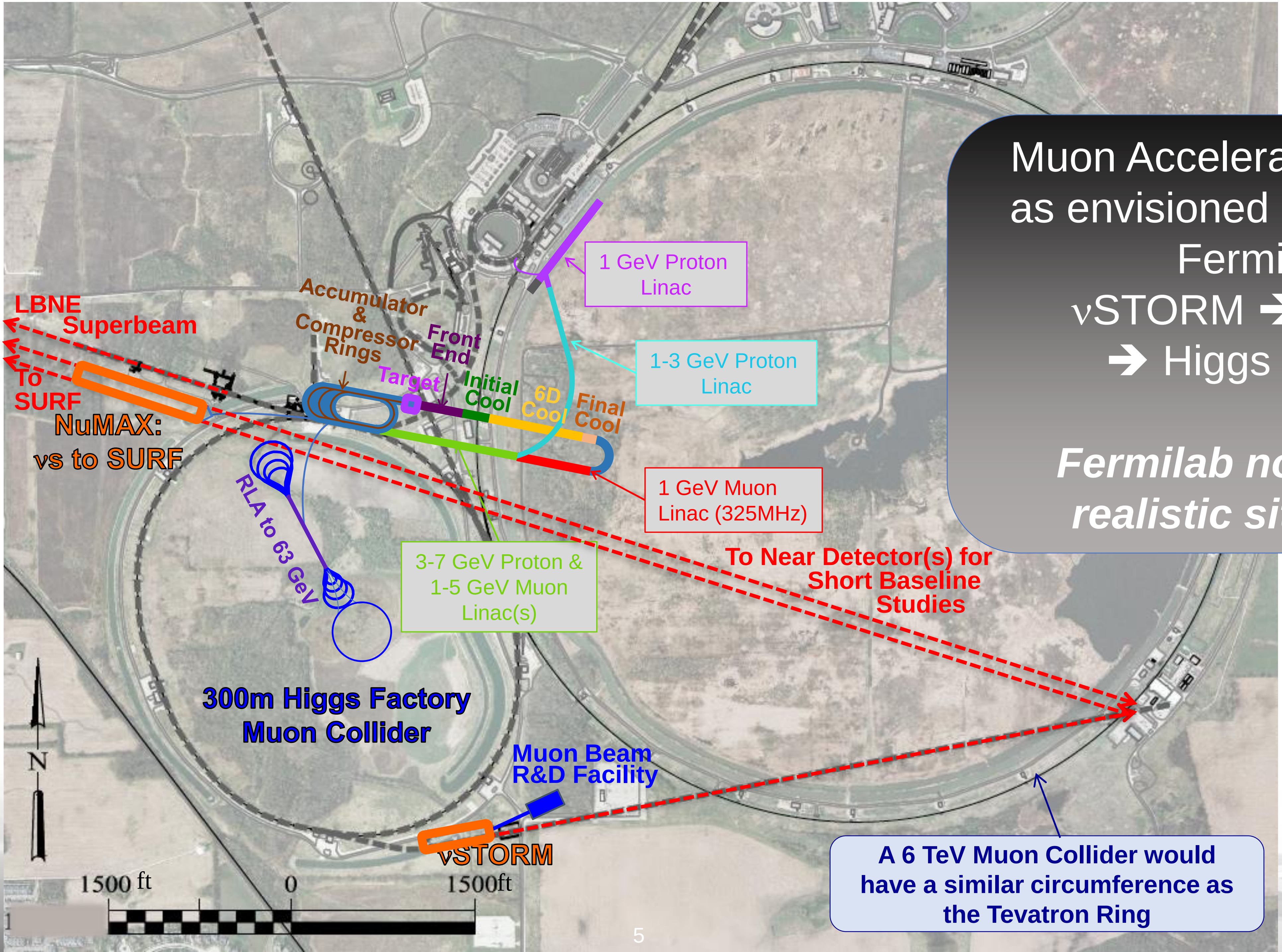
Muon Accelerator Design Status

- Full conceptual designs for NFs
- Collider effort (US) focused on key R&D elements as opposed to a full conceptual design
  - In 2012, justified by the facts that
    - Proposed parameters for some systems appeared extremely challenging
    - Some concepts could not be "easily" demonstrated
- R&D and design progress since 2012 arguably changes this picture

MAP Approach

- Conceptual design of individual accelerator sub-systems
  - Identify performance parameter targets and limitations
  - Identify R&D requirements
  - Provide realistic sub-system conceptual designs
- Muon Accelerator Staging Study
  - Explored potential staging options and estimated overall performance
- R&D Program
  - Identify potential showstoppers
  - Provide targeted effort to identify viable paths forward
- Next step planned
  - Full conceptual design
  - Sub-system prototypes
  - Detector & physics analysis

Support from the European Strategy process would allow these steps to be pursued

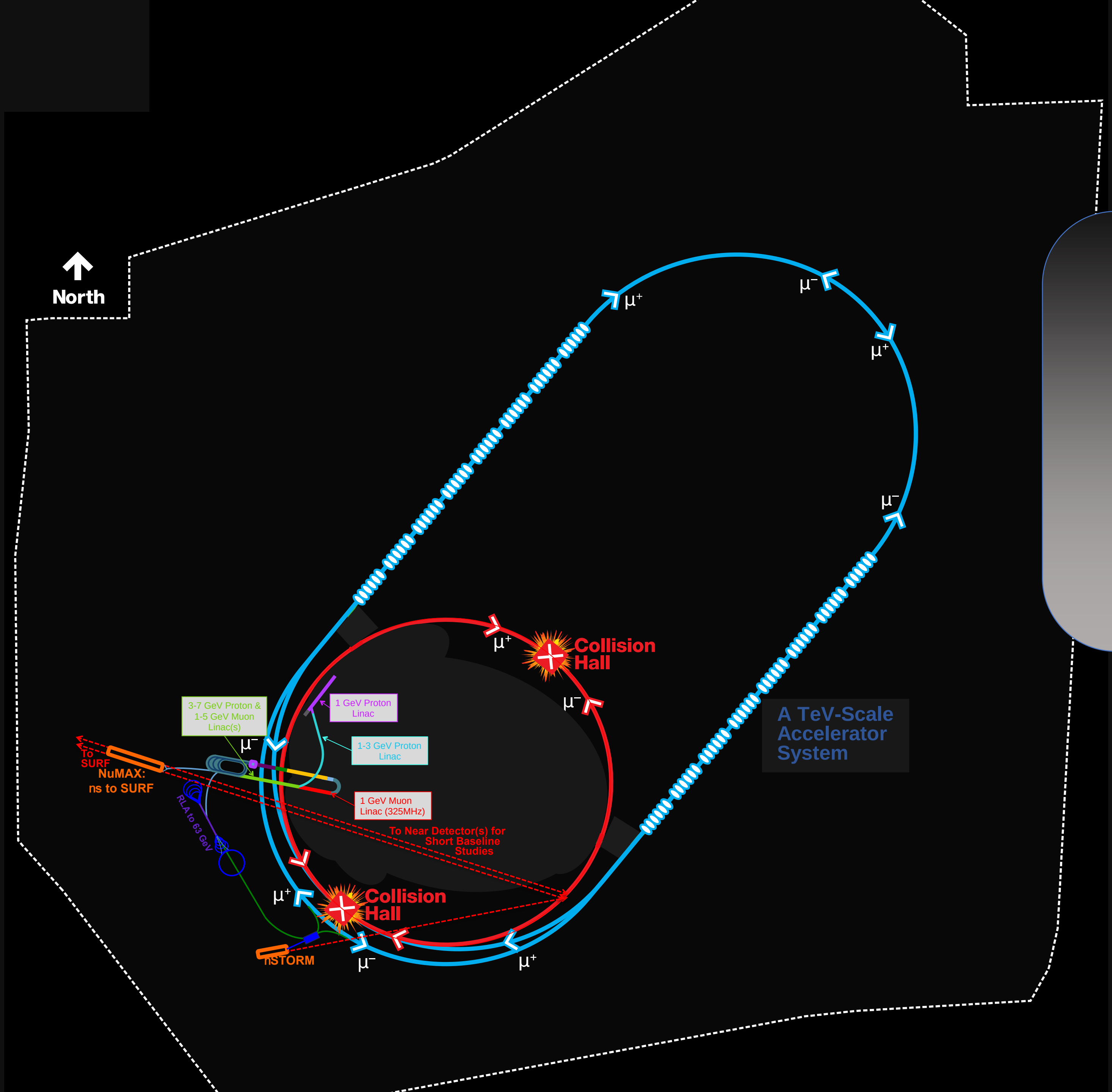


Muon Accelerator Complex as envisioned by MASS for Fermilab:
νSTORM ➔ NuMAX
➔ Higgs Factory

Fermilab no longer a realistic site option

A Multi-TeV Collider
Collider Footprint with FNAL site outline

Fermilab no longer a realistic site option



MAP Neutrino Factory Parameters

System	Parameters	Unit	nuSTORM	NuMAX Commissioning	NuMAX	NuMAX+
Performance	Stored μ+ or μ-/year		8×10^{17}	1.25×10^{20}	4.65×10^{20}	1.3×10^{21}
	ν_e or ν_μ to detectors/yr		3×10^{17}	4.9×10^{19}	1.8×10^{20}	5.0×10^{20}
Detectors	**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
Neutrino Ring	Ring Momentum (P_μ)	GeV/c	3.8	5	5	5
	Circumference (C)	m	480	737	737	737
	Straight Section	m	184	281	281	281
	Number of Bunches	-	-	60	60	60
	Charge per Bunch	1×10^{9}	-	6.9	26	35
Acceleration	Initial Momentum	GeV/c	-	0.25	0.25	0.25
	Single-pass Linacs	GeV/c	-	1.0, 3.75	1.0, 3.75	1.0, 3.75
	SRF Frequencies	MHz	-	325, 650	325, 650	325, 650
	Repetition Frequency	Hz	-	30	30	60
Cooling	Horizontal/Vertical/Longitudinal		None	None	5/5/2	5/5/2
Proton Source	Proton Beam Power	MW	0.2	1	1	2.75
	Proton Beam Energy	GeV	120	6.75	6.75	6.75
	protons/year	1×10^{21}	0.1	9.2	9.2	25.4
	Repetition Rate	Hz	0.75	15	15	15

MAP Collider Parameters

Parameter	*Units*	*Higgs*	*Top - High Resolution*	*Top - High Luminosity*	*Multi-TeV*		
CoM Energy	TeV	0.126	0.35	0.35	1.5	3.0	6.0*
Avg. Luminosity	$10^{34} cm^{-2} s^{-1}$	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.004	0.01	0.1	0.1	0.1	0.1
Higgs Production/10^7sec		13,500	7,000	60,000	37,500	200,000	820,000
Circumference	km	0.3	0.7	0.7	2.5	4.5	6
Ring Depth [1]	m	135	135	135	135	135	540
No. of IPs		1	1	1	2	2	2
Repetition Rate	Hz	15	15	15	15	12	6
$\beta^*_{x,y}$	cm	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	4	4	3	2	2	2
Norm. Trans. Emittance, ε_T	π mm-rad	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_L	π mm-rad	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4	4	4	4	4	1.6
Wall Plug Power	MW	200	203	203	216	230	270

*Accounts for off-site neutrino radiation

MAP References

- *The future prospects of muon colliders and neutrino factories,* Boscolo, Delahaye, Palmer, to appear in RAST volume 10, arXiv:1808.01858v2 [physics.acc-ph].
- *Muon Accelerators for Particle Physics (MUON),* special volume in the Journal of Instrumentation
  - *https://iopscience.iop.org/journal/1748-0221/page/extraproc46*
  - *20 articles presently posted, with a few more to come…*

Slides to follow:

- Will provide an overview of the status of the MAP concepts
  - Sub-system by sub-system

Challenges for a $\mu^{+}\mu^{-}$ Collider

- MW-class proton beam on target ⇨ pions ⇨ muons
- Efficient capture of the produced pions
  - Capture of both forward and backward produced pions loses polarization
- Phase space of the created pions is ***very large!***
  - Transverse: 20π mm-rad
  - Longitudinal: 2π m-rad
- Emittances must be cooled by factors of ~10^{6}-10^{7} to be suitable for multi-TeV collider operation

  ~1000x in the transverse dimensions
  ~40x in the longitudinal dimension
- The muon lifetime is 2.2 μs lifetime at rest

Characteristics of the Proton Driver Muon Source

- Overarching goals

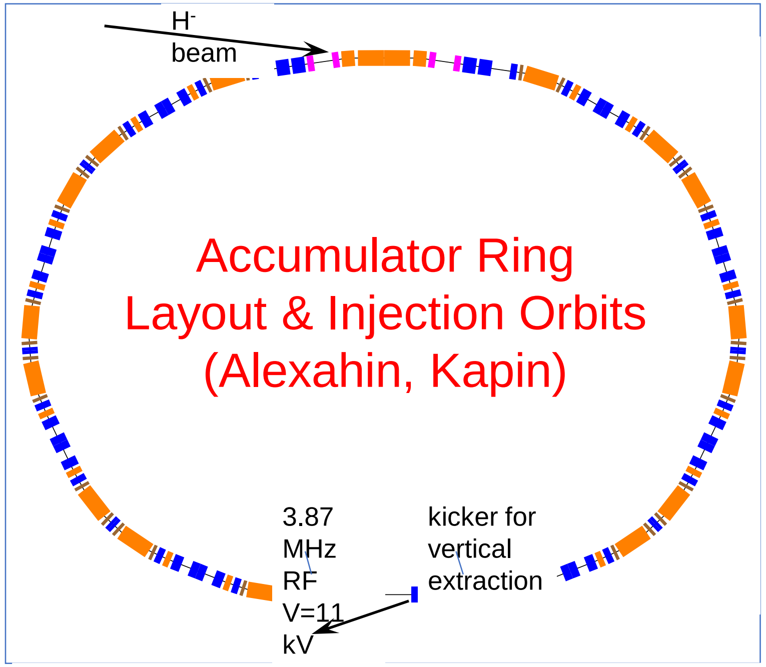
- NF: Provide $O(10^{21})$ μ/yr within the acceptance of a μ ring
- MC: Provide luminosities $>10^{34}$ $cm^{-2}s^{-1}$ at TeV-scale ($\sim n_b^2$)
  Enable precision probe of particles like the Higgs

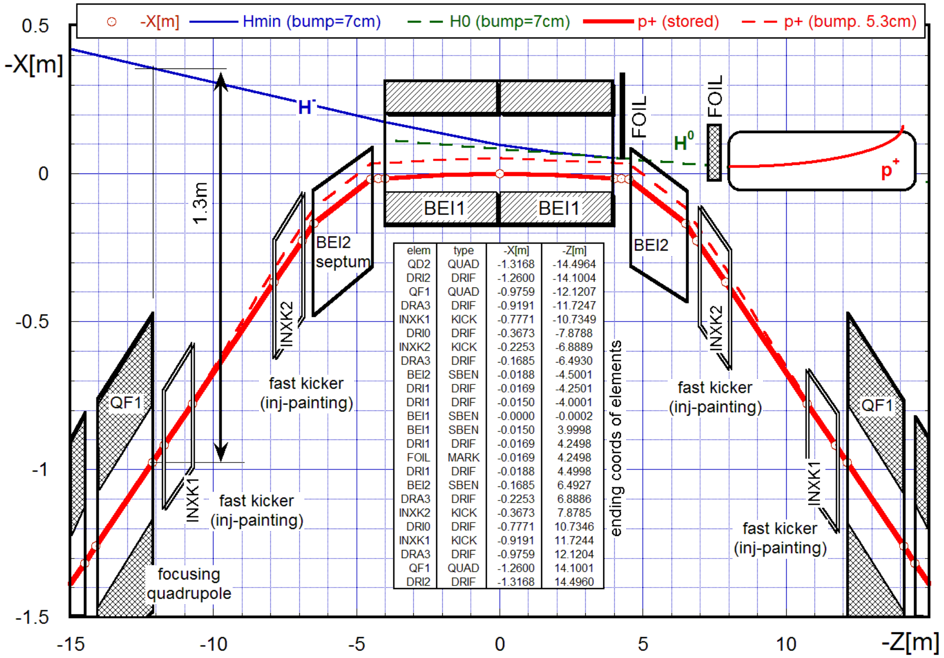
- How do we do this?
  - Tertiary muon production through protons on target (followed by capture and cooling)
  - **Rate > 10^{13}/sec** **$n_b = 2\times10^{12}$**

MAP Feasibility Issues

- Proton Driver
- Target — High Power Target Station; Capture Solenoid
- Front End — Energy Deposition
- Cooling — RF in Magnetic Fields; Magnet Needs (Nb_3Sn vs HTS); Performance
- Acceleration — Acceptance (NF); Rapid cycling magnets or FFA lattices for high E
- Collider Ring — IR Magnet Strengths/Apertures
- Collider MDI — SC Magnet Heat Loads (μ decay)
- Collider Detector — Backgrounds (μ decay)

Proton Driver

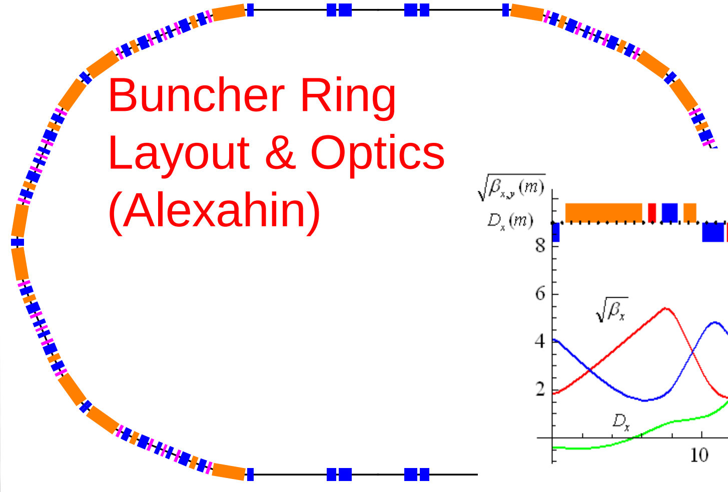




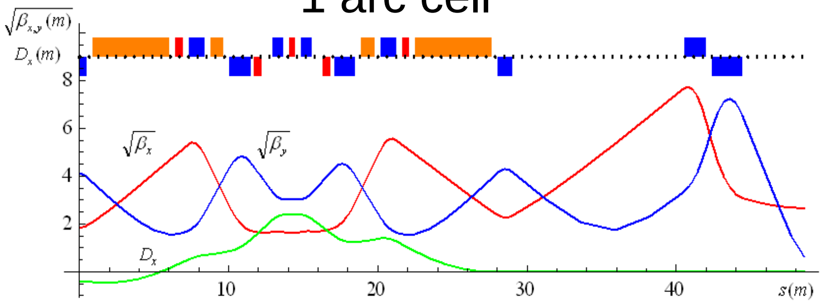
elem	type	-X[m]	-Z[m]
QD2	QUAD	-1.3168	-14.4964
DRI2	DRIF	-1.2600	-14.1004
QF1	QUAD	-0.9759	-12.1207
DRA3	DRIF	-0.9191	-11.7247
INXK1	KICK	-0.7771	-10.7349
DRI0	DRIF	-0.3673	-7.8788
INXK2	KICK	-0.2253	-6.8889
DRA3	DRIF	-0.1685	-6.4930
BEI2	SBEN	-0.0188	-4.5001
DRI1	DRIF	-0.0169	-4.2501
DRI1	DRIF	-0.0150	-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

Recommendations:

- *No showstoppers identified*
- *Adapt concept for likely proton source*

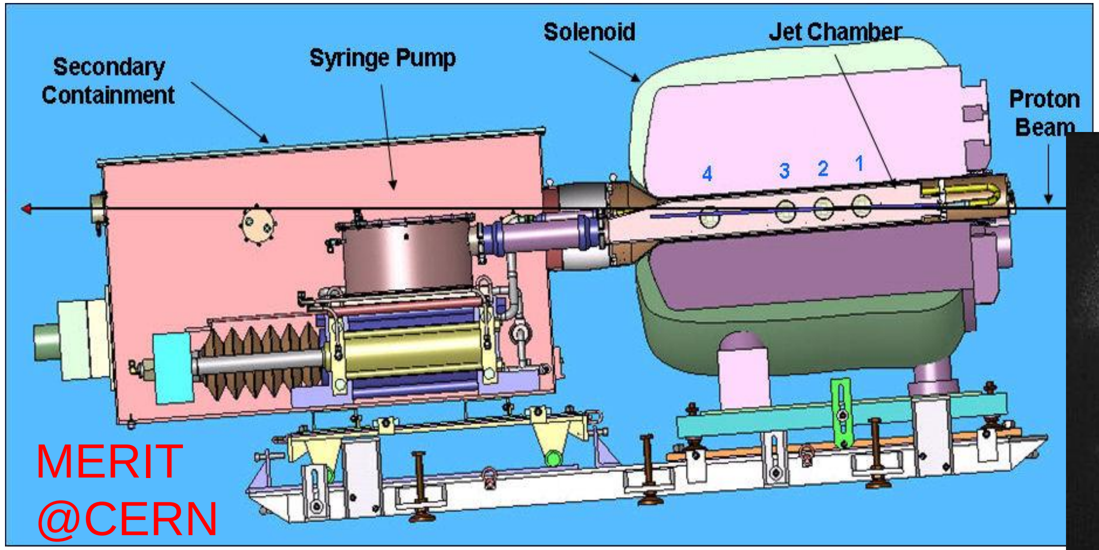


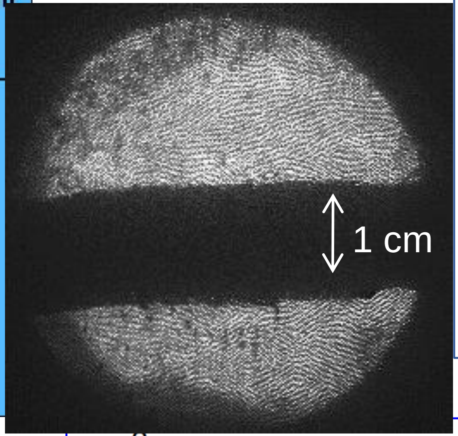
Optics:
½ straight +
1 arc cell



- ✓ 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

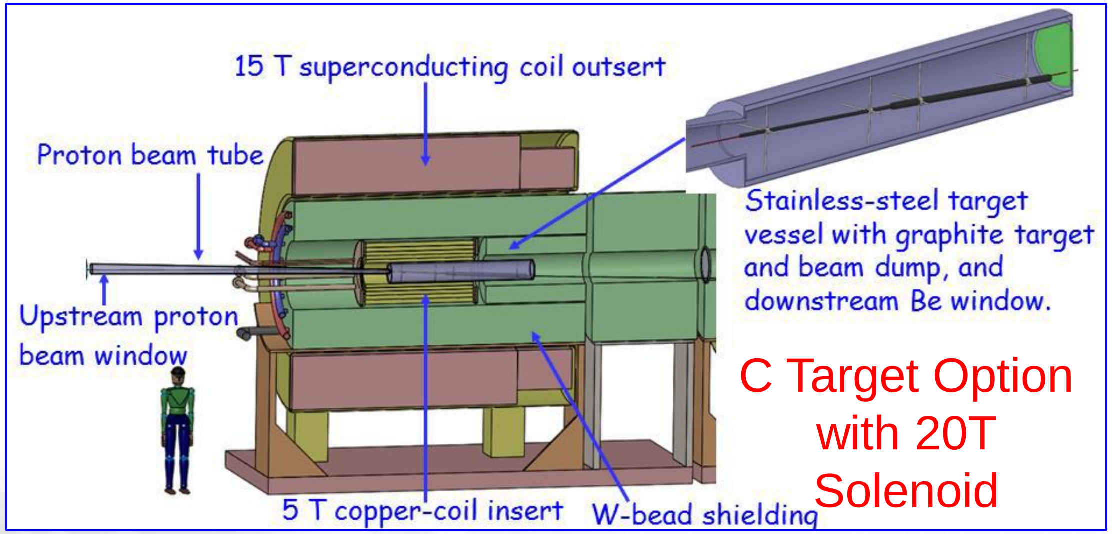
High Power Target

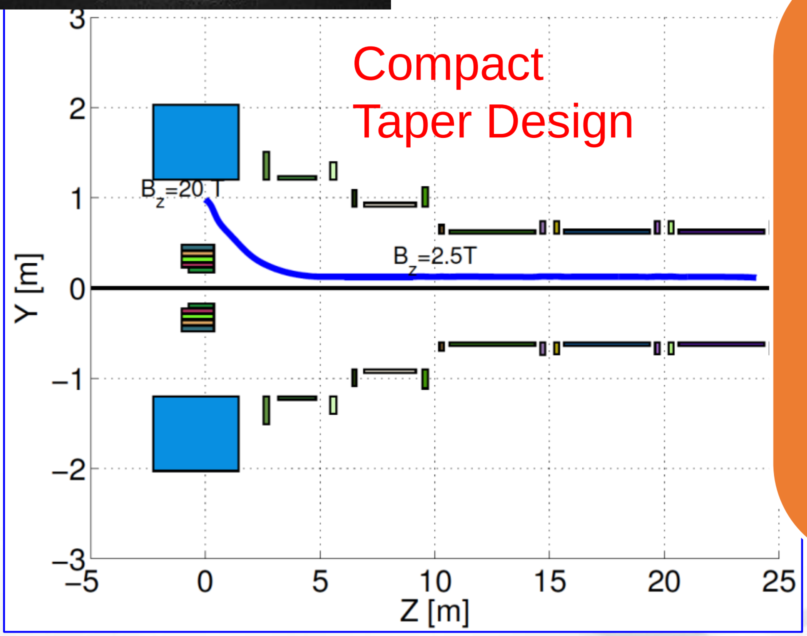




Recommendations:

- *No showstoppers identified*
- *Challenging engineering required*
  - *Optimized capture solenoid*
  - *Target module*
  - *Remote handling design*
- *Leverage neutrino program target development efforts*





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

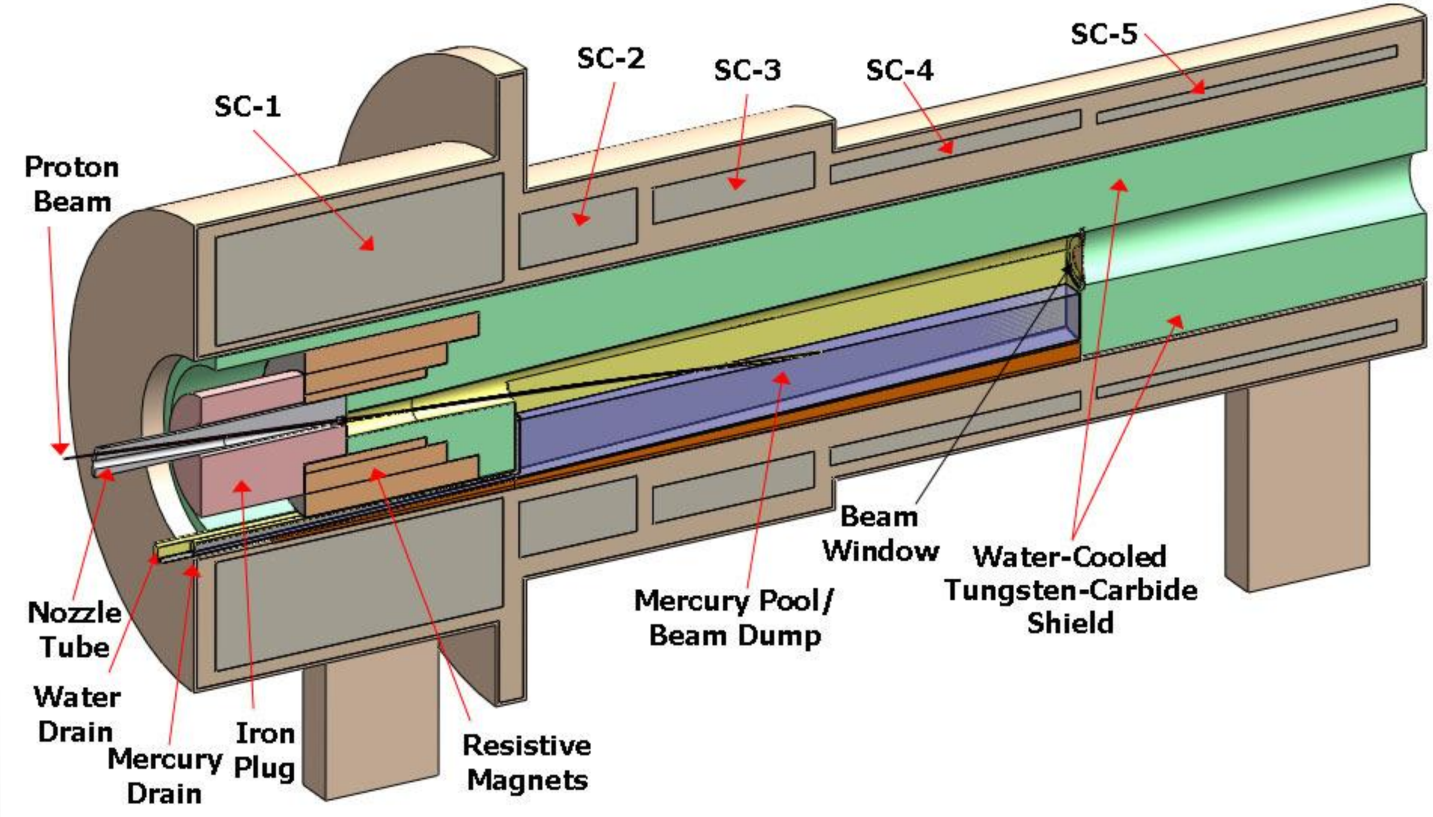
Capture Solenoid

- A Neutrino Factory and/or Muon Collider Facility requires challenging magnet design in several areas:
  - Target Capture Solenoid (15-20T with large aperture)

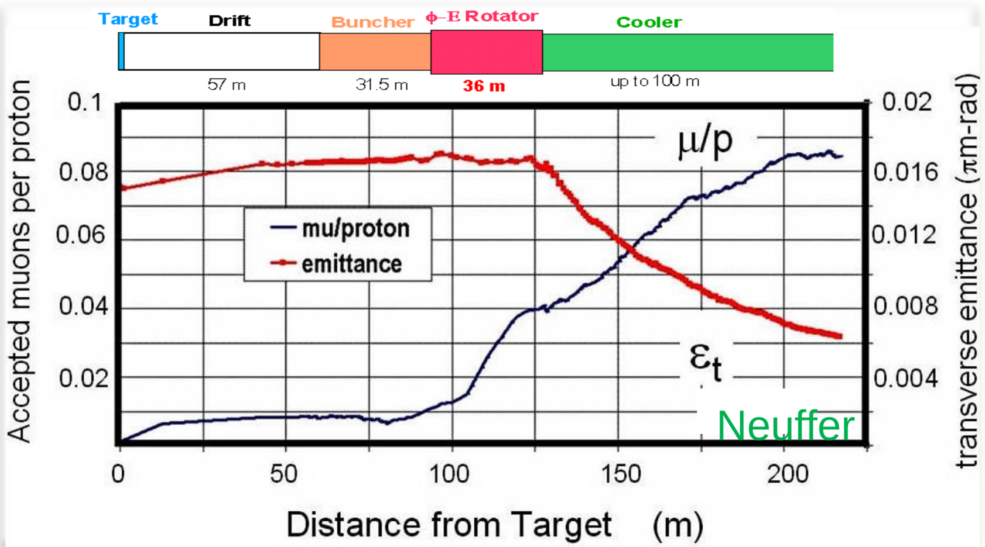
E_{stored} ~ 3 GJ

O(10MW) resistive coil in high radiation environment

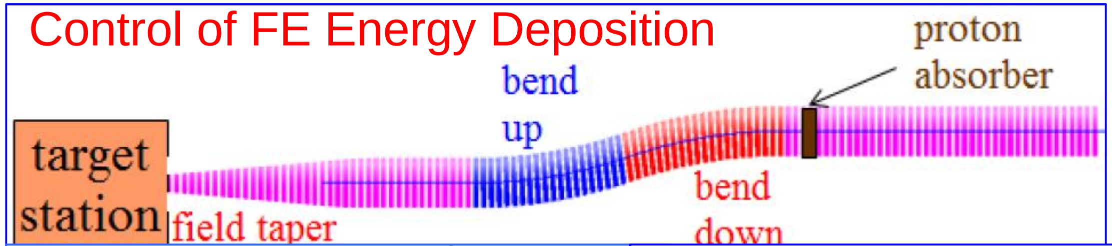
Possible application for High Temperature Superconducting magnet technology

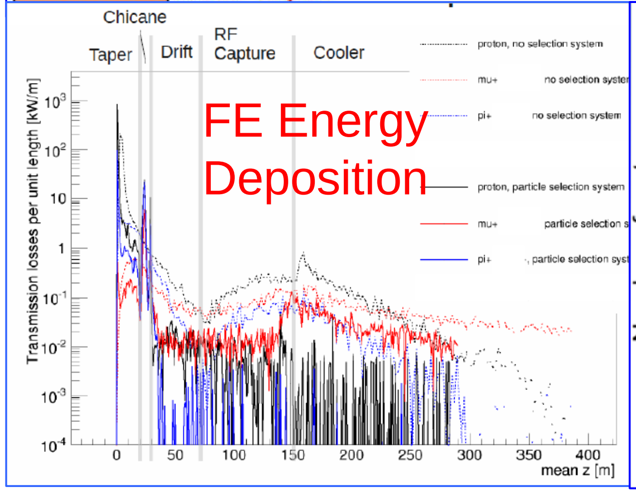


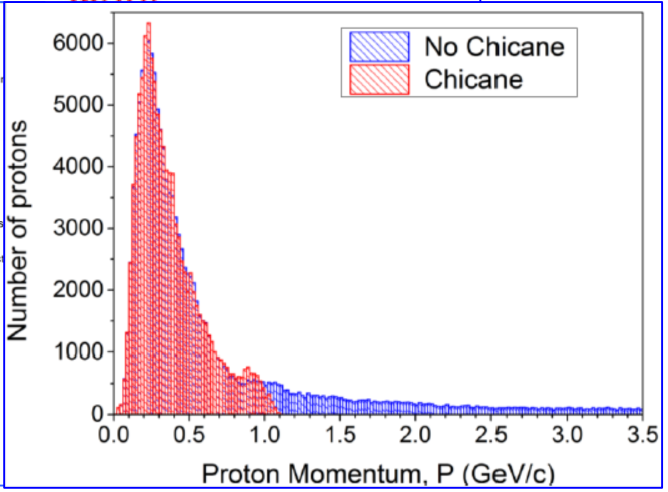
Front End

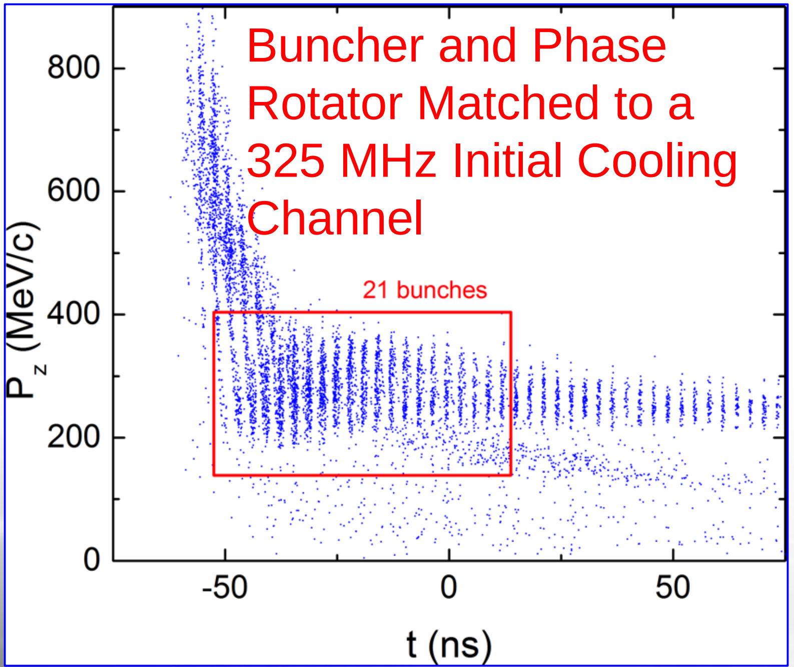


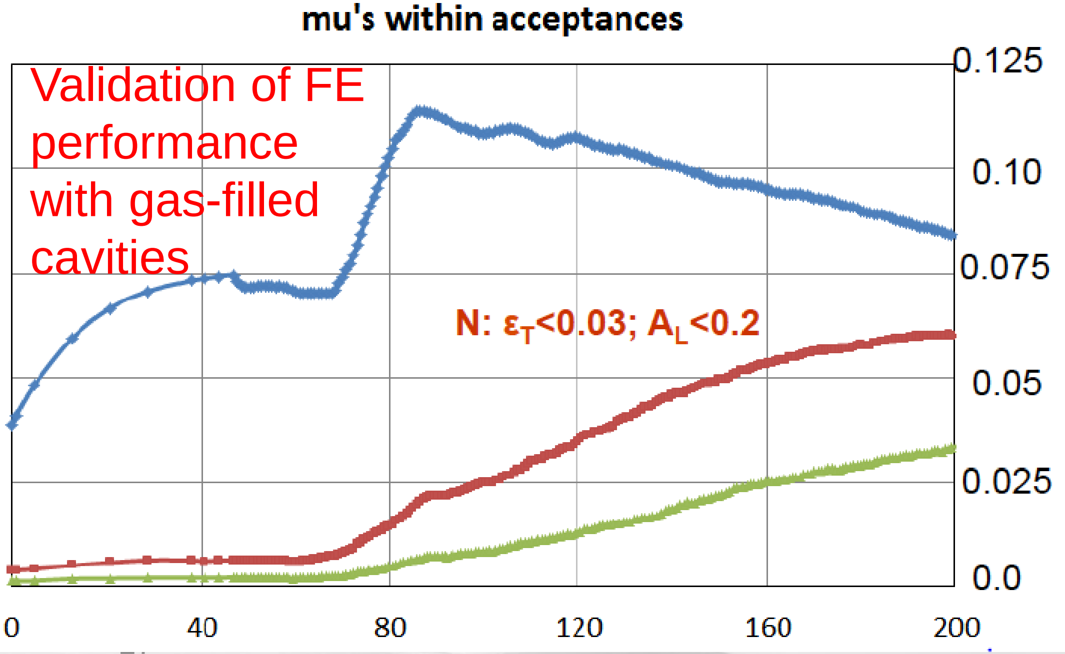
Control of FE Energy Deposition











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

Recommendations:

- *Ready for updates leading to full conceptual design*

Cooling Options

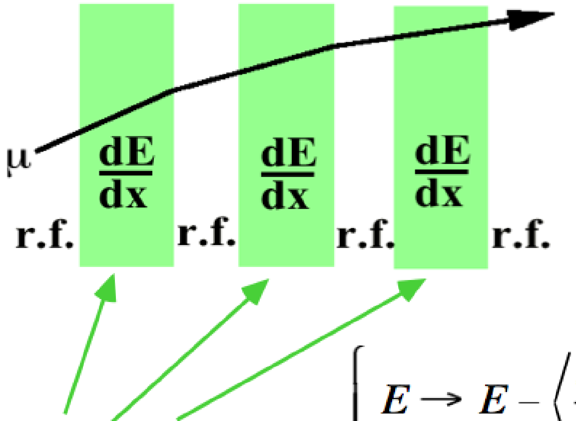
- Electron/Positron cooling: use synchrotron radiation
  ➪ For muons $\Delta E \sim 1/m^3$ (*too small!*)
- Proton Cooling: use
  - A co-moving cold e- beam
  ➪ For muons this is too slow
  - Stochastic cooling
  ➪ For muons this is also too slow
- Muon Cooling: use
  - Use Ionization Cooling
  ➪ Likely the only viable option
  - Optical stochastic cooling
  ➪ Maybe, but far from clear

Cooling Methods

- The unique 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

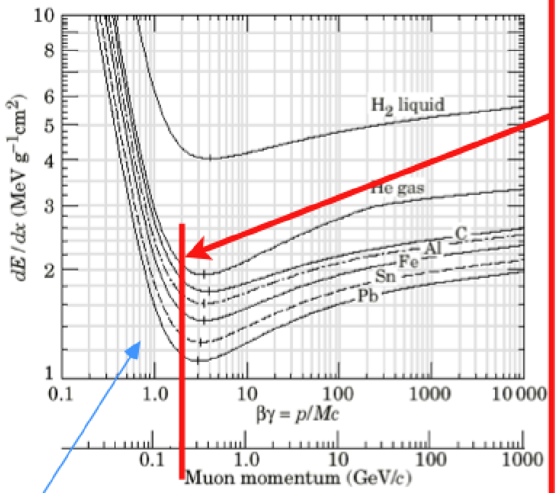
Muon Ionization Cooling

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



– Absorbers:

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



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 $p_{||}$, 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

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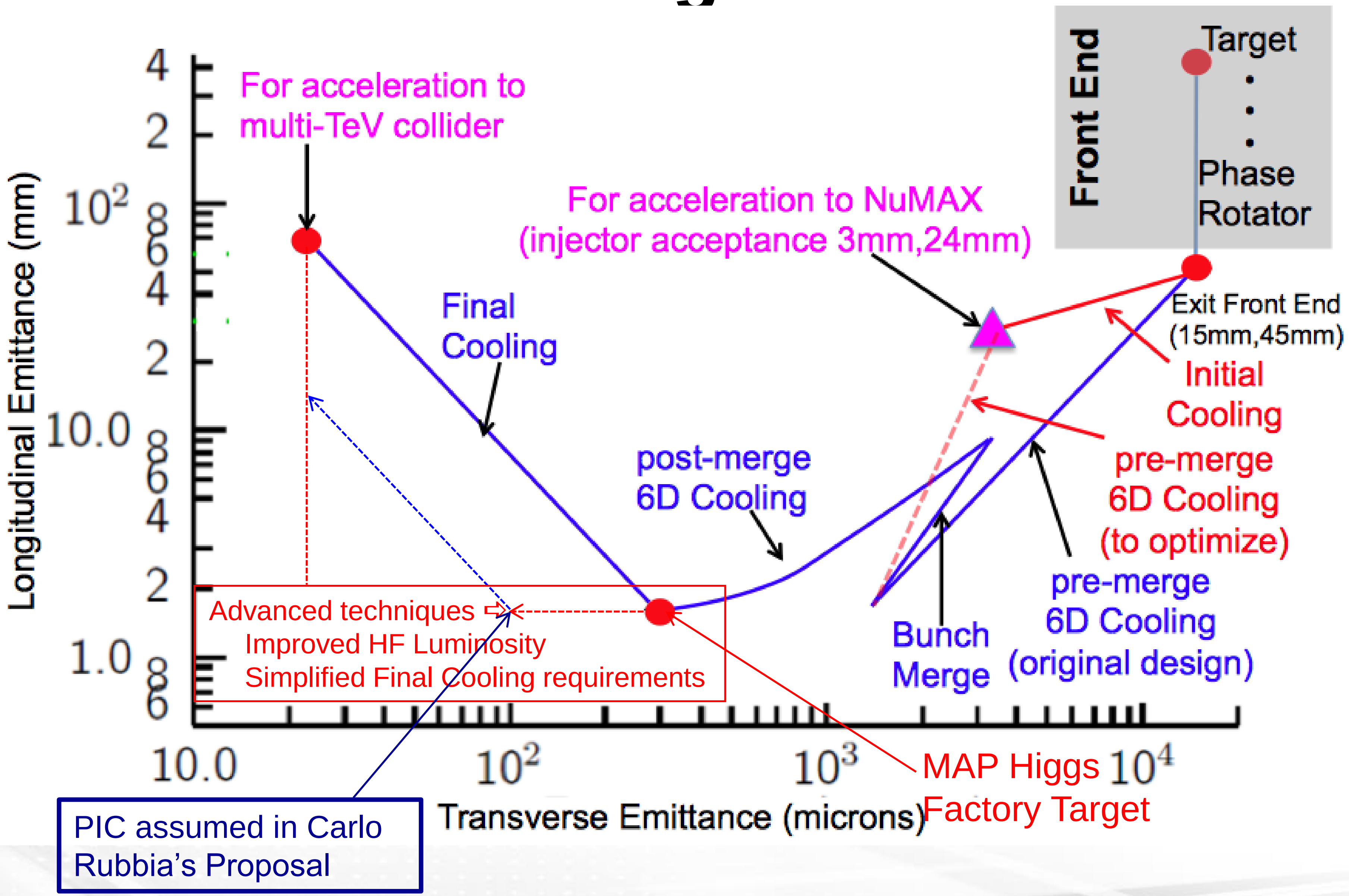
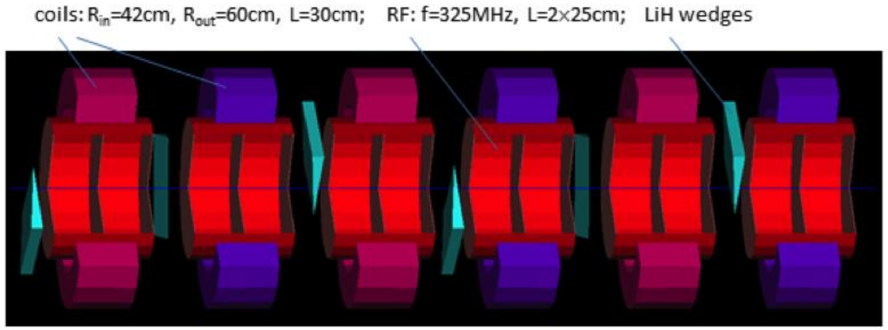
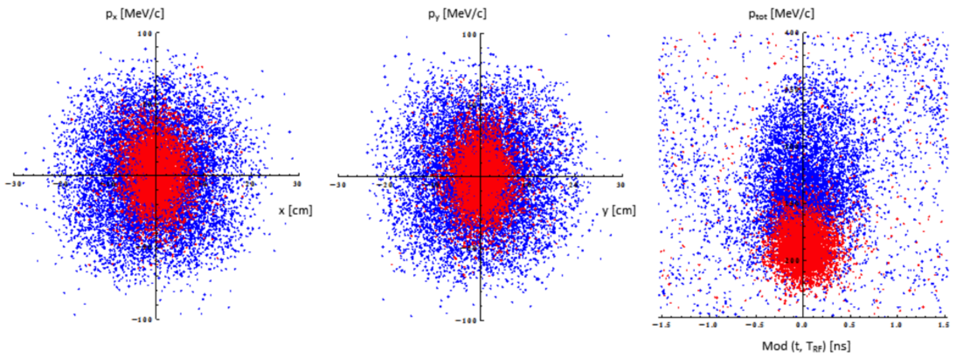
Muon Ionization Cooling

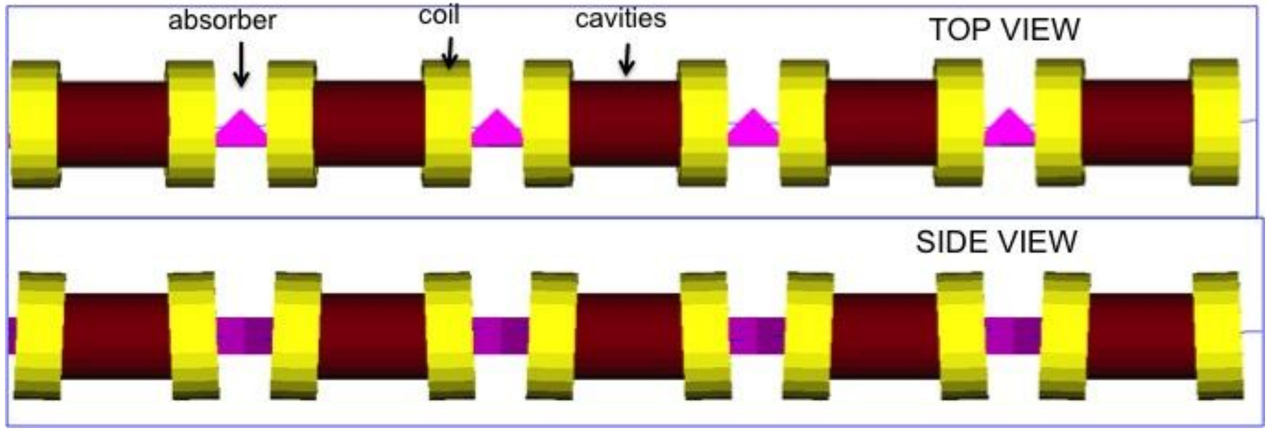


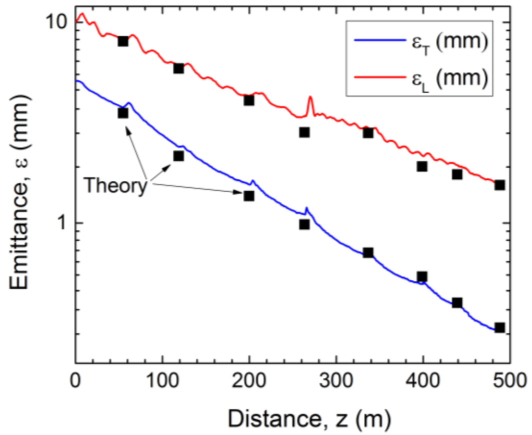
Muon Ionization Cooling (Design)





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





6D Rectilinear Vacuum Cooling Channel (replaces Guggenheim concept):

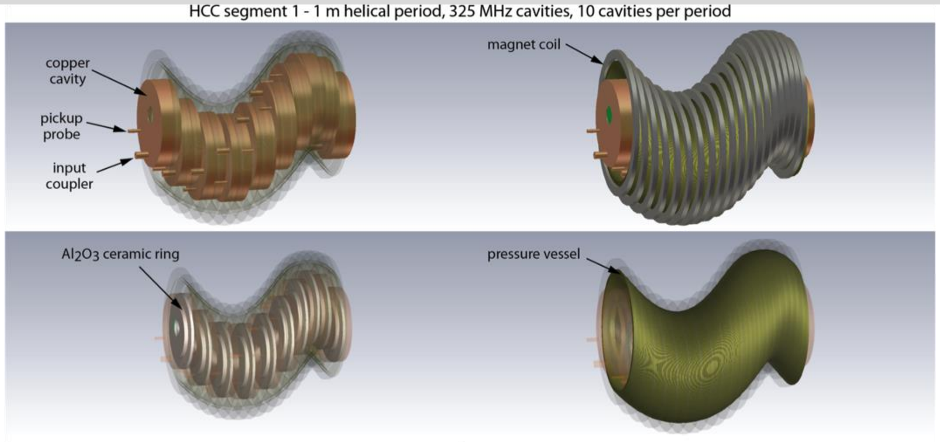
ε_T = 0.28mm, ε_L = 1.57mm @488m

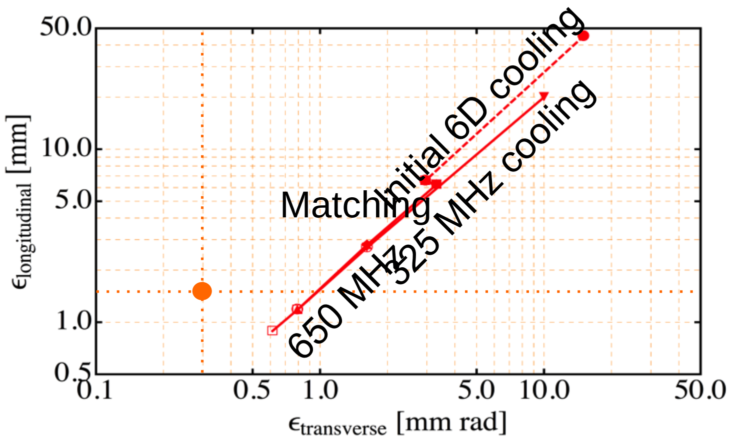
Transmission = 55%(40%) without(with) bunch recombination

Recommendations:

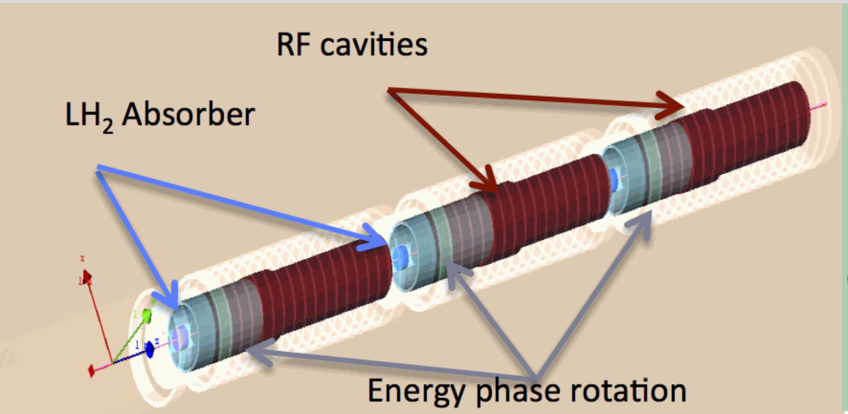
- *Designs assumed 20 MV/m RF in magnetic field*
- *Demonstration of 50 MV/m in magnetic field means that a new optimization study is required!!*

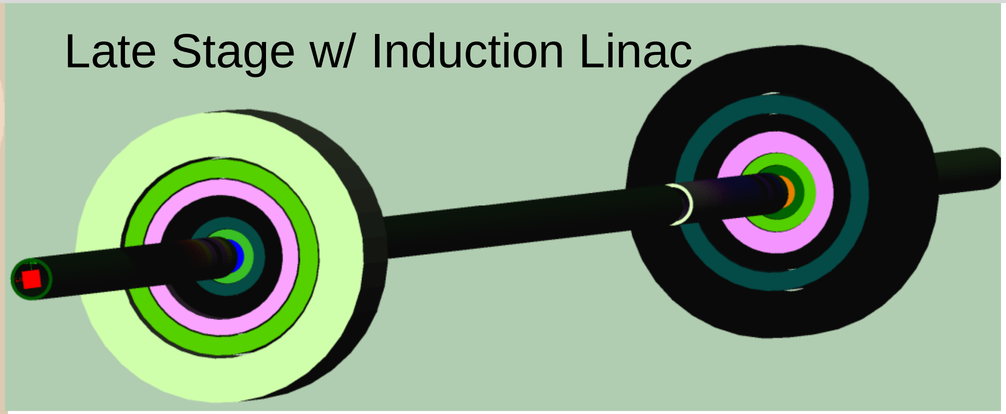
Muon Ionization Cooling (Design)





- 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)

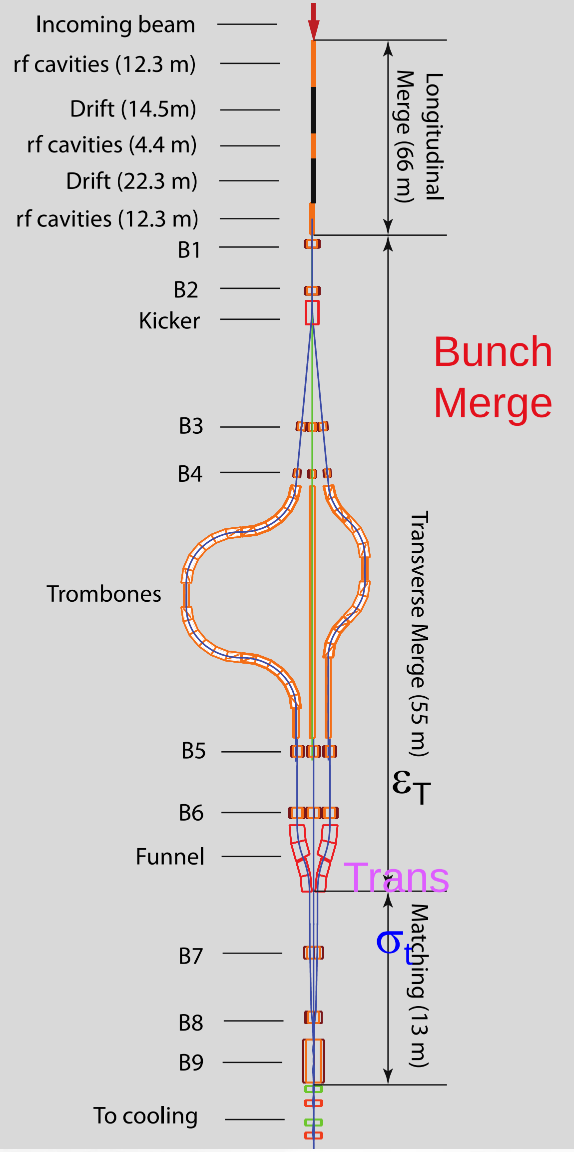
- MAP Baseline Designs offer
  - Factor >10^5 in emittance reduction
- Alternative and Advanced Concepts
  Higgs Factory
  - Hybrid Rectilinear Channel (gas-filled structures)
  - Parametric Ionization Cooling
  - Alternative Final Cooling

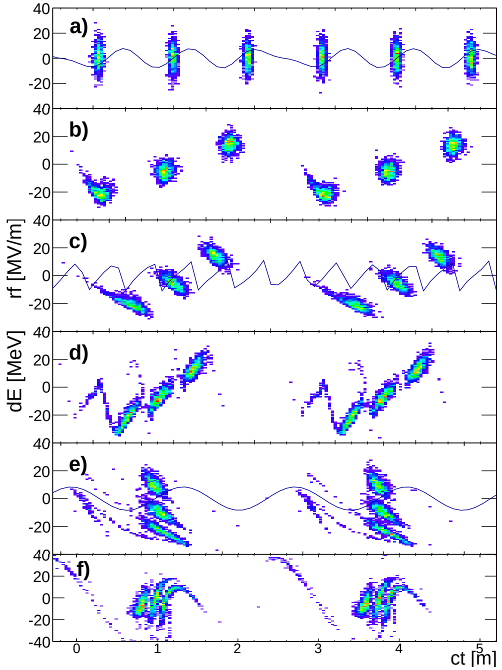
One example:
⇨ Early stages of existing scheme
⇨ Round-to-flat Beam Transform
⇨ Transverse Bunch Slicing
⇨ Longitudinal Coalescing
(at ~10s of GeV)

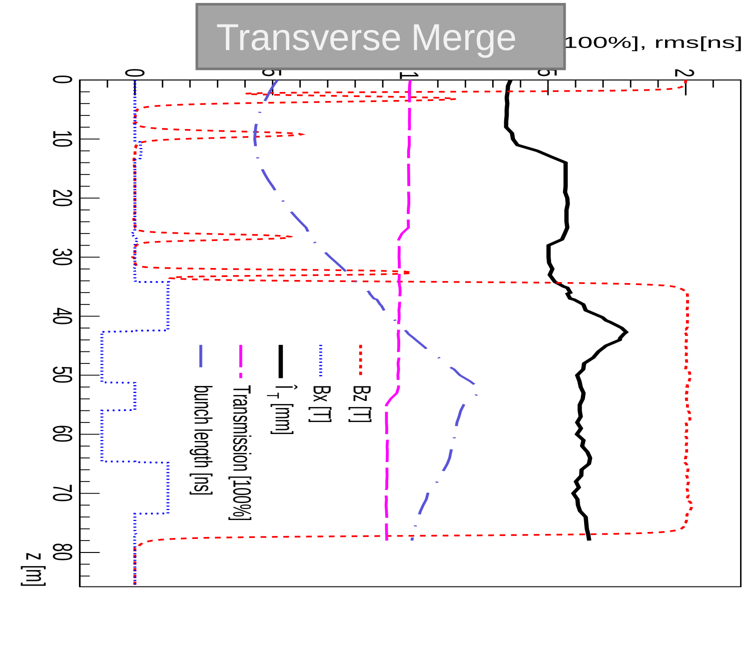
⇨ *Considerable promise to exceed our original target parameters*

⇨ *Every improvement in emittance makes the collider designs more readily achievable*

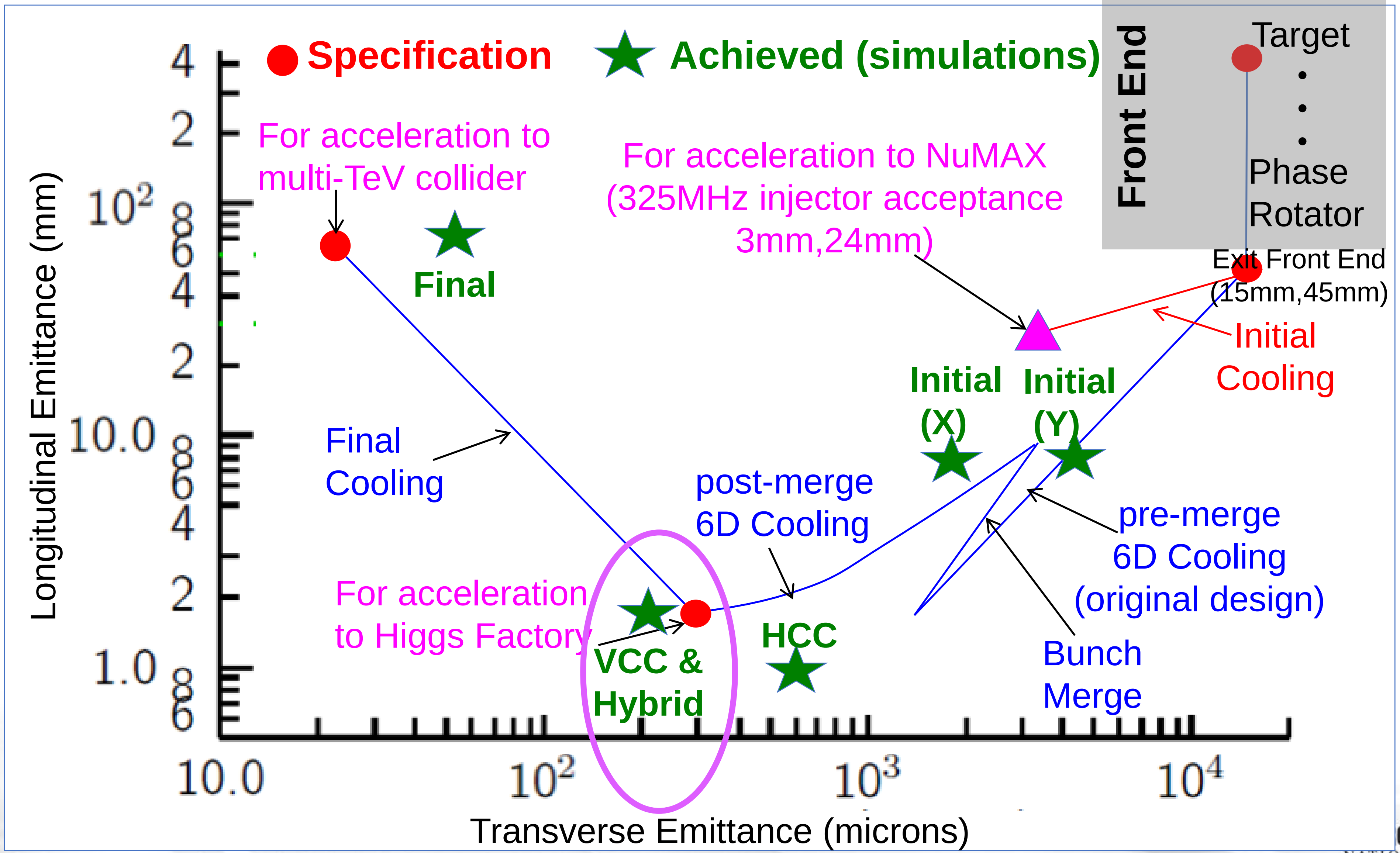
Bunch Merge



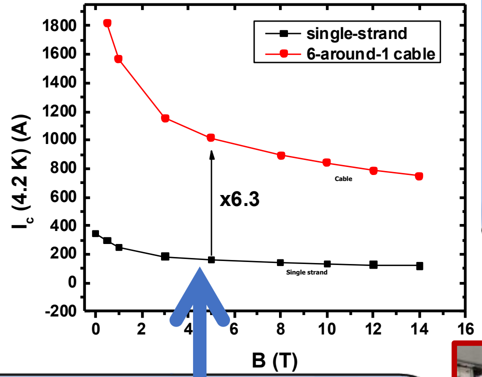




Cooling: The Emittance Path



Cooling Technology R&D

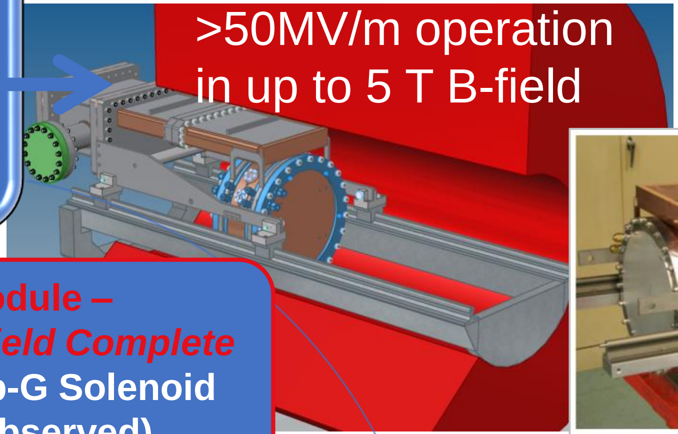


Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

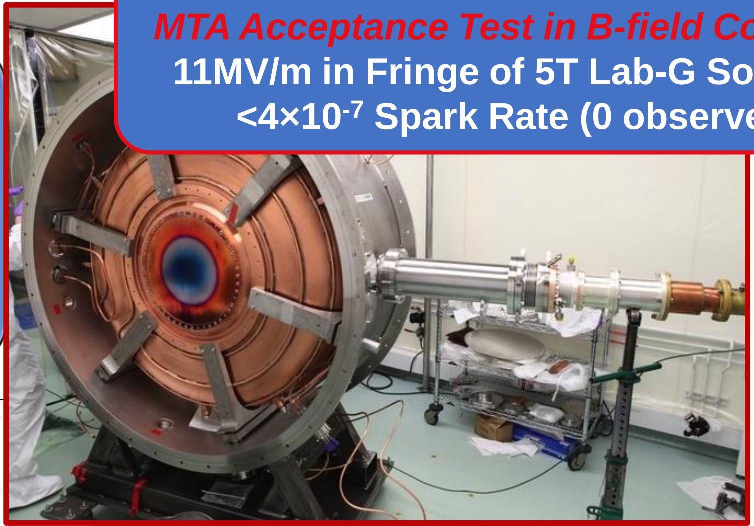
FNAL-Tech Div
T. Shen-Early Career Award

Successful Operation of 805 MHz Modular Cavity in 5T Magnetic Field under Vacuum

MuCool Test Area
Paper in preparation

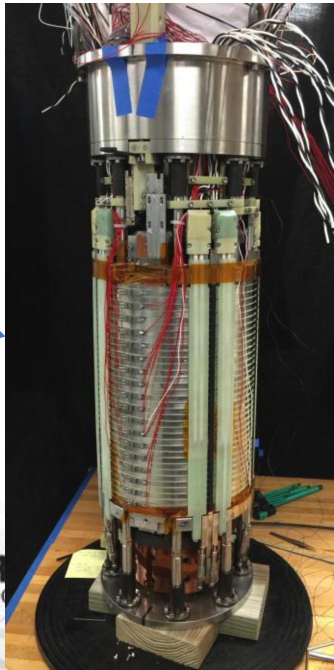


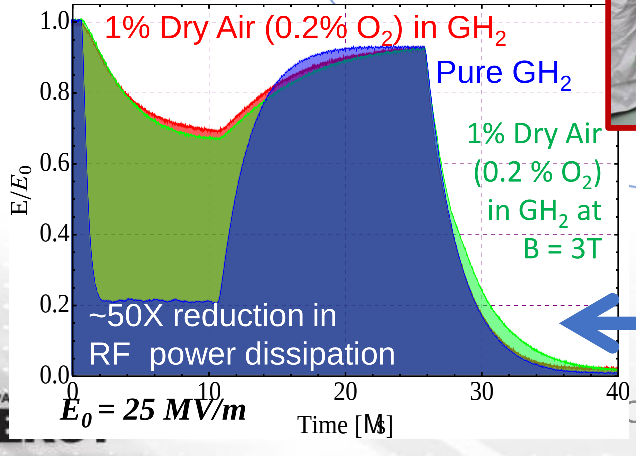
MICE 201 MHz RF Module –
MTA Acceptance Test in B-field Complete
11MV/m in Fringe of 5T Lab-G Solenoid
$<4\times10^{-7}$ Spark Rate (0 observed)



World Record LTS-HTS Hybrid Magnet
32T on-axis field

NHFML



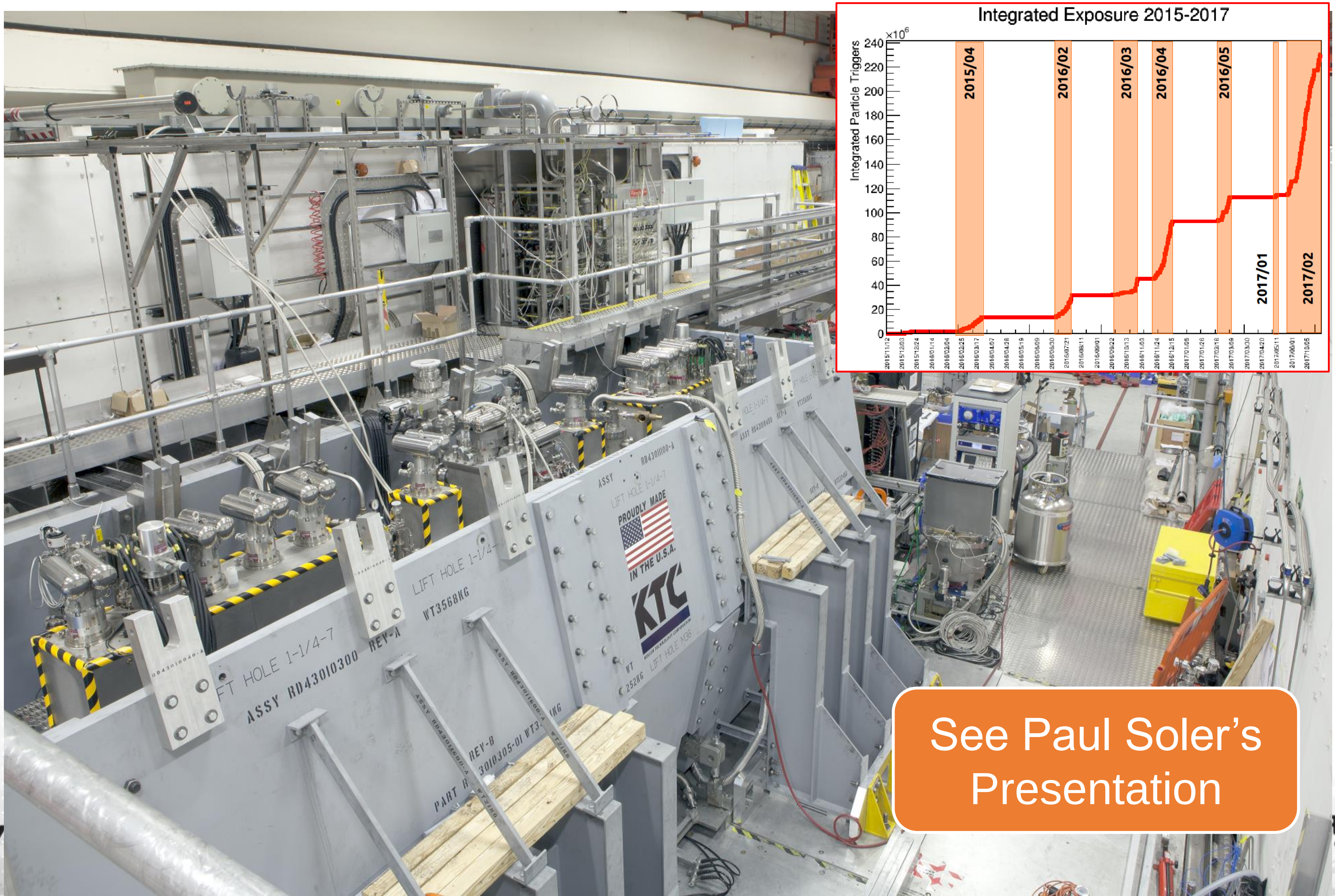


Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to required μ-Collider Parameters

MuCool Test Area

Muon Ionization Cooling Experiment



See Paul Soler's Presentation

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 data now in hand
- ✓ 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

Recommendations:

- *Designs and performance should be updatd for 50 MV/m RF*
- *Followed by engineering design of 6D Cooling Cell Prototypec*

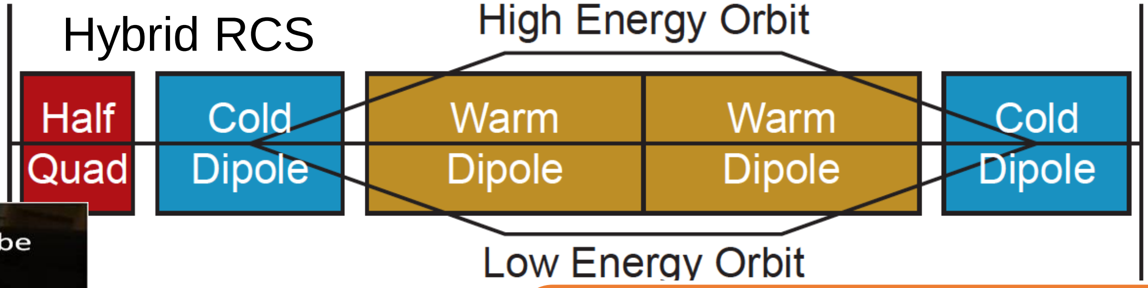
Acceleration Requirements

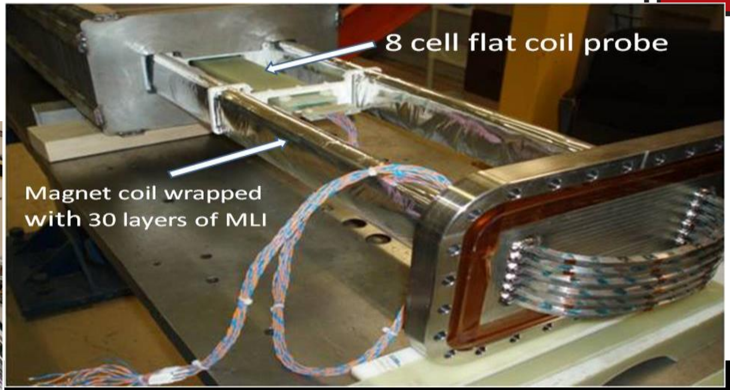
- Key Issues:
  - Muon lifetime ⇨ ultrafast acceleration chain
  - NF with modest cooling ⇨ accelerator acceptance
  - Total charge ⇨ cavity beam-loading (stored energy)
  - TeV-scale acceleration focuses on hybrid Rapid Cycling Synchrotron ⇨ requires rapid cycling magnets

    B_{peak} ~ 2T **f > 400Hz**

Technologies include:

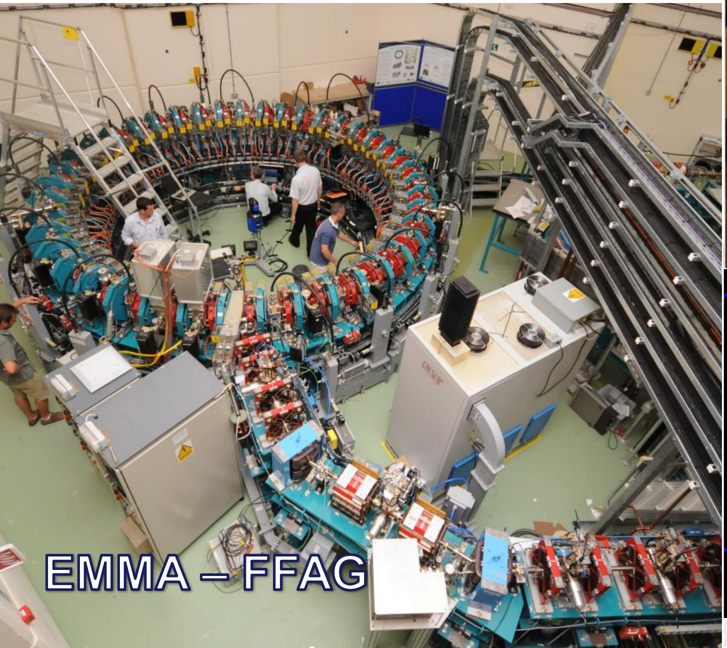
- Superconducting Linacs (NuMAX choice)
- Recirculating Linear Accelerators (RLAs)
- Fixed-Field Alternating-Gradient (FFAG) Rings
- (Hybrid) Rapid Cycling Synchrotrons (RCS) for TeV energies

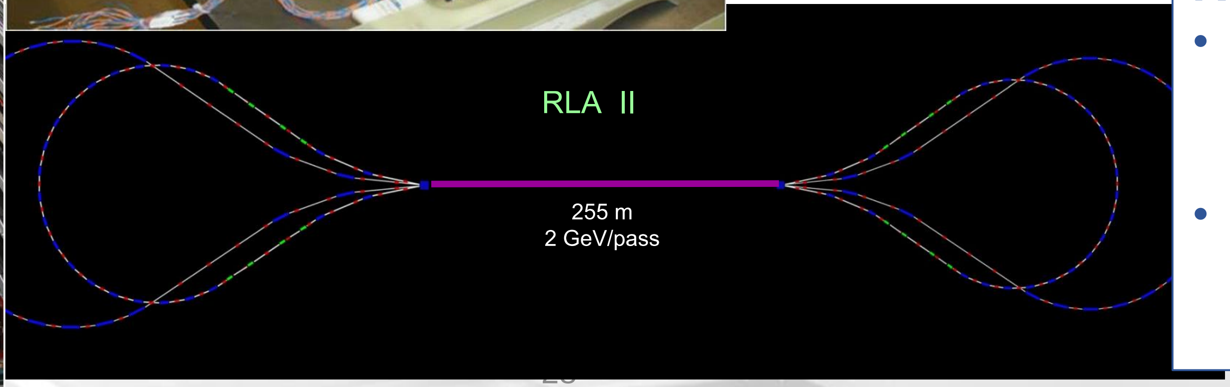




RCS requires 2 T p-p magnets at f > 400 Hz (U Miss & FNAL)

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



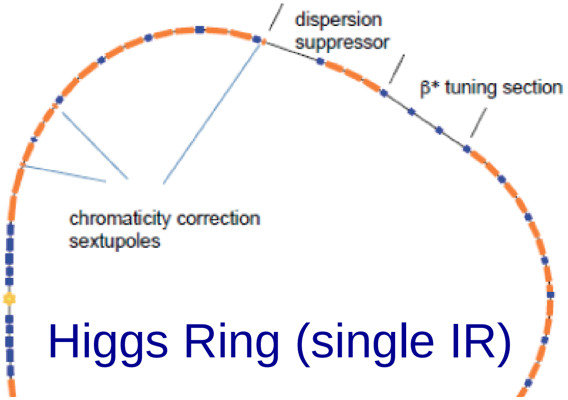


Recommendations:

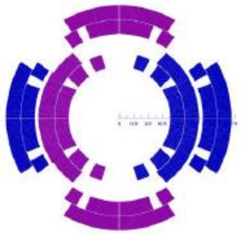
- *Recent FFA results should be incorporated into designs*
- *Detailed look at requirements for multi-TeV acceleration needed*

Collider Rings

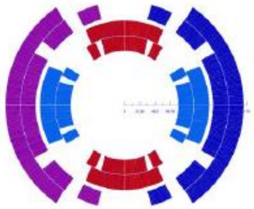
- Detailed optics studies for Higgs, 1.5 TeV, 3 TeV and now 6 TeV CoM
  - With supporting magnet designs and background studies



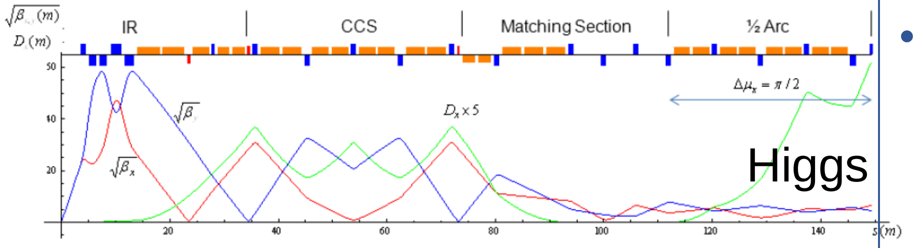
- ✓ Higgs, 1.5 TeV CoM and 3 TeV CoM Designs
  - With magnet concepts
  - Achieve target parameters
- ✓ Preliminary 6 TeV CoM design
  - Key issue is IR design and impact on luminosity
  - Utilizes lower power on target



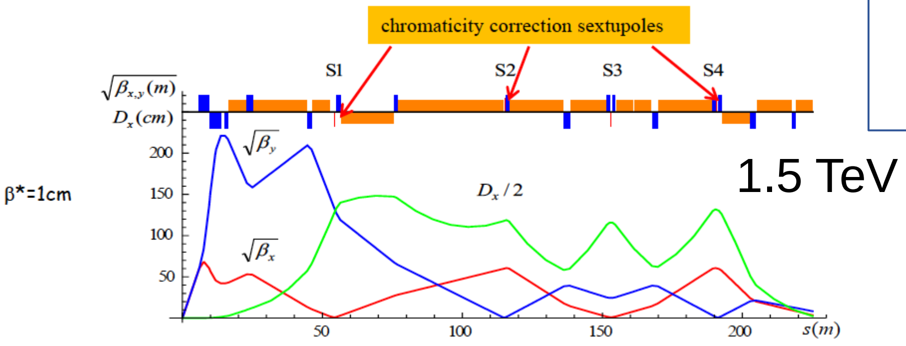
Dipole/Quad

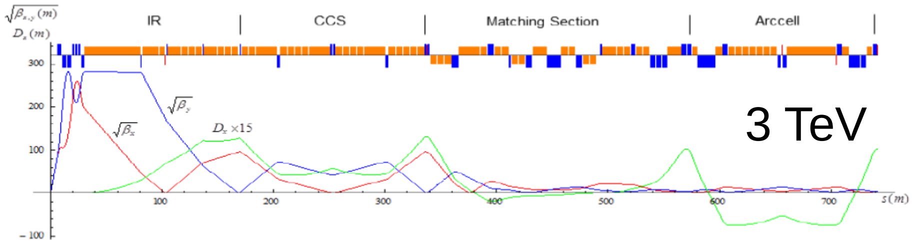


Quad/Dipole



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

Recommendations:
- *3 TeV collider design is the most refined of the MAP designs*
- *Evaluate MDI and backgrounds with 3 TeV design next*

Summary

- MDI and detector discussed extensively in yesterday's session
  - Have skipped over those topics here
- Critical issue is that the MC design is *fully coupled* from source to detailed collider and background performance
- Priorities (my thoughts at this meeting):
  - Re-optimization of the cooling channel based on current technology limits
  - Detector, MDI and physics studies
  - A thorough review of acceleration designs and options
  - Make the first full conceptual design