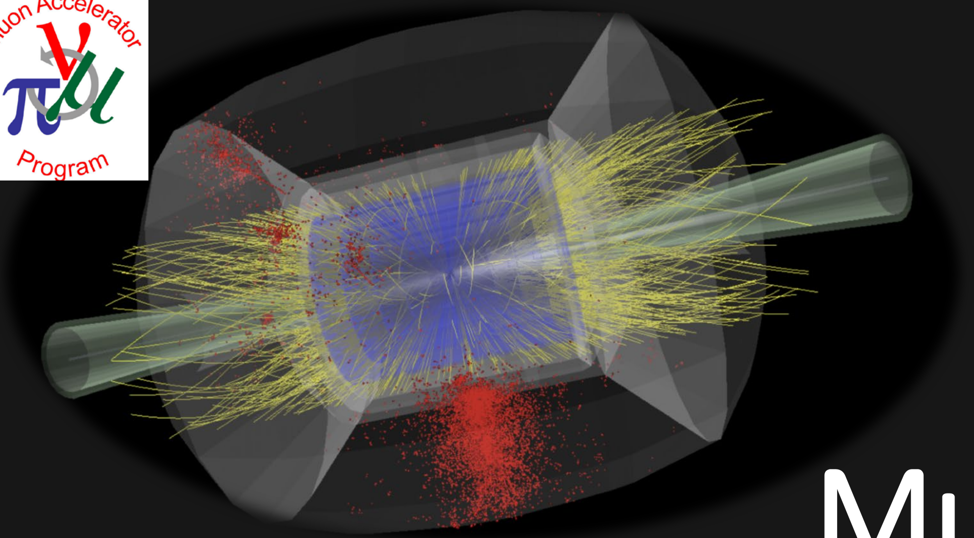


Muon Colliders: Perspectives from the Muon Accelerator Program (MAP)

Mark Palmer

Brookhaven National Laboratory

Presented to the Committee on Elementary Particle Physics: Progress and Promise

Meeting No. 4

December 13, 2024

Question Posed by the Committee

What can we learn from the previous US Muon Collider Collaboration and how can we frame a new collaboration?

Acknowledgements

US Muon Accelerator Program (MAP)

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

International Muon Ionization Cooling Experiment (MICE)

International Muon Collider Collaboration

European Laboratory Directors Group – Accelerator R&D Roadmap

Snowmass Muon Collider Forum

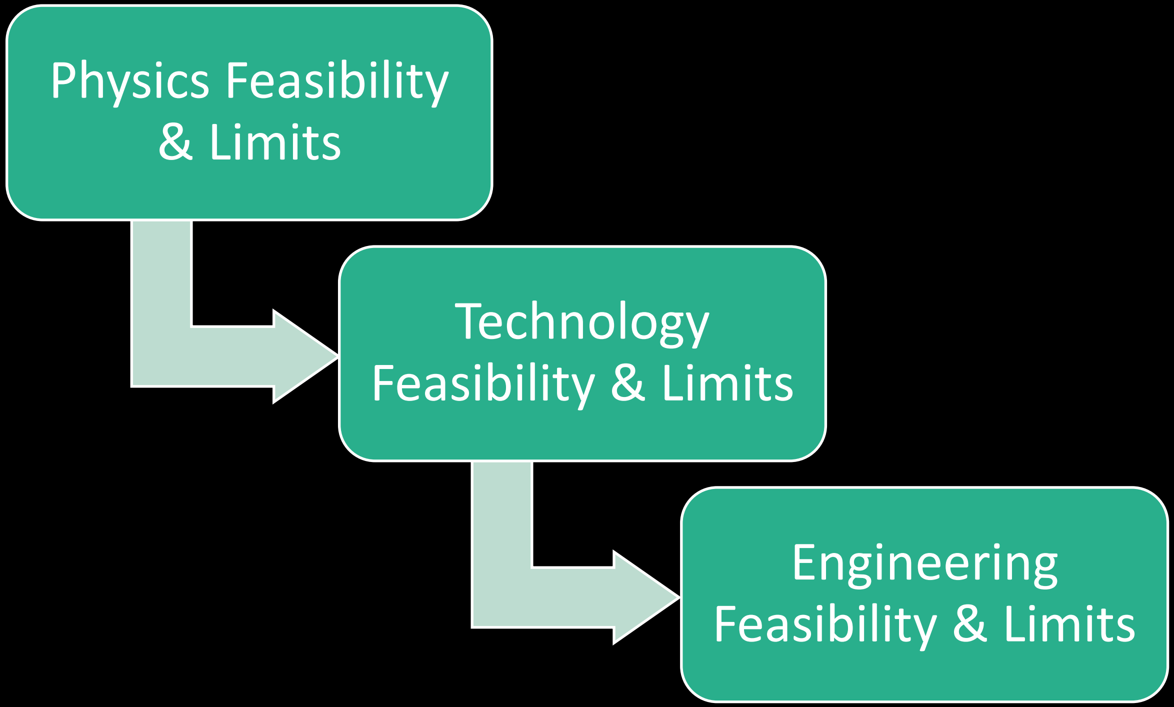
Introduction: Assessing Feasibility

The US Muon Accelerator Program (2011-2014)

Charged with: *Assessing the Feasibility of Muon Accelerator Concepts*

What was that interpreted to mean?

MAP interpreted this charge to require a multi-phase assessment supporting *clear decision points*



Introduction: The MAP Approach

The US Muon Accelerator Program (2011-2014)

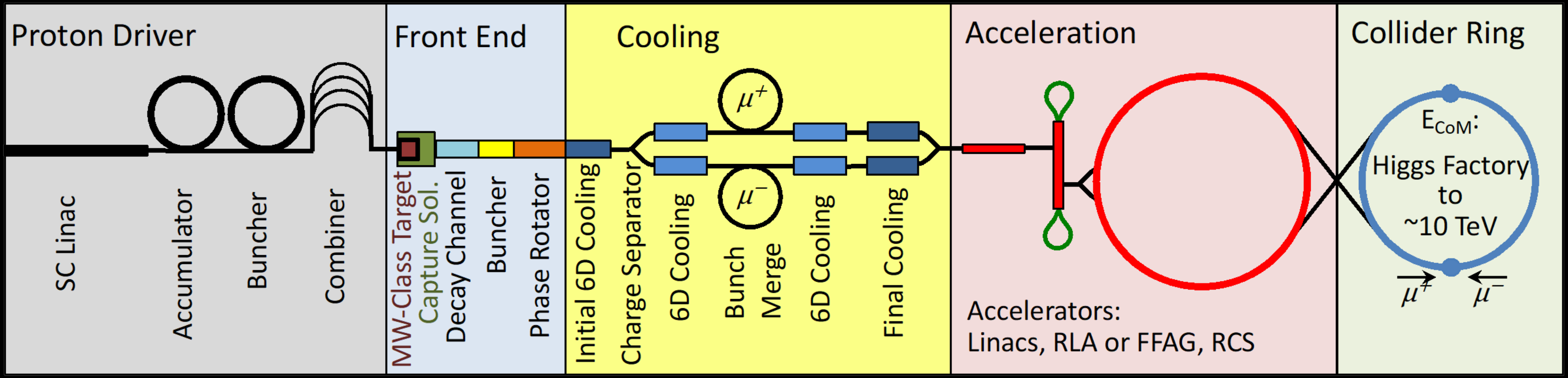
- *Phase 1:*
  - *Evaluate the physics limits of the beams required (intensity, lifetime, emittance, decay impacts...)*
  - *Establish a preliminary set of operating parameters for each accelerator sub-system*
  - *Develop technology concepts with the potential to deliver the necessary operating parameters*
- *Phase 2:*
  - *Define a baseline design and execute a program of technology R&D*
  - *Prepare preliminary engineering concepts for each sub-system*
  - *Deliver a reference design suitable for developing detailed system specifications*
- *Phase 3:*
  - *Develop physics and engineering demonstrators based on detailed machine targets*
  - *Optimize operating parameters and machine configurations*
  - *Deliver a Conceptual Design Report*

2013-2014:
MAP concluded while executing Phase 1

Provide community with ***informed decision points***

Introduction III: Proton-Driven MC Concept

Muon Collider



Short & intense proton bunches to deliver hadronic showers

p→π→μ → bunched beams

Ionization cooling reduces the transverse & longitudinal emittance

Rapid acceleration to high energy to avoid μ losses. Multi-pass acceleration offers energy efficiency.

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

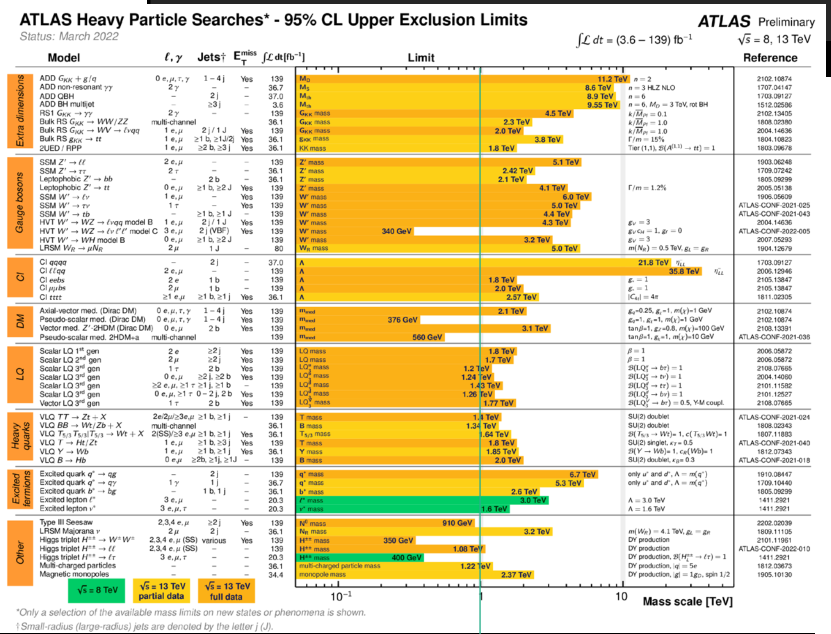
Accelerator design is driven by the short muon lifetime

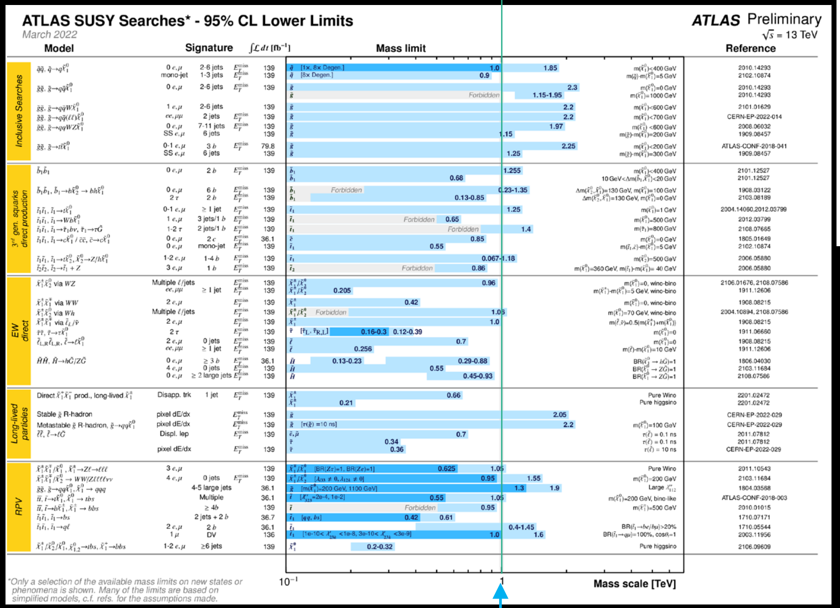
What has changed?

The physics landscape

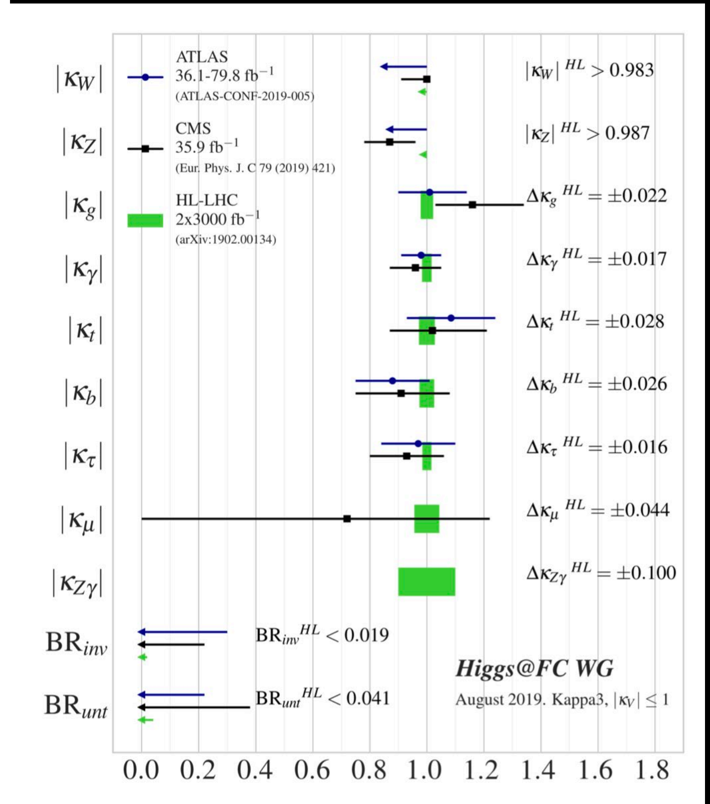
Muon Collider R&D progress

What has changed? The Physics Landscape – *Generic Lessons from the LHC*





1 TeV



~1% tests on the Higgs

Implies roughly the ~ TeV scale for New Physics which could cause such a deviation

There *could* still be New Physics at LHC/HL-LHC…

However, data suggests generically there is a gap from EW scale to scale of New Physics

We need to be able to probe **>>1 TeV**

10 TeV is interesting as a step into the unknown but also for ***physics targets***

Courtesy Patrick Meade (SBU)

Physics Reach of a 10 TeV Muon Collider

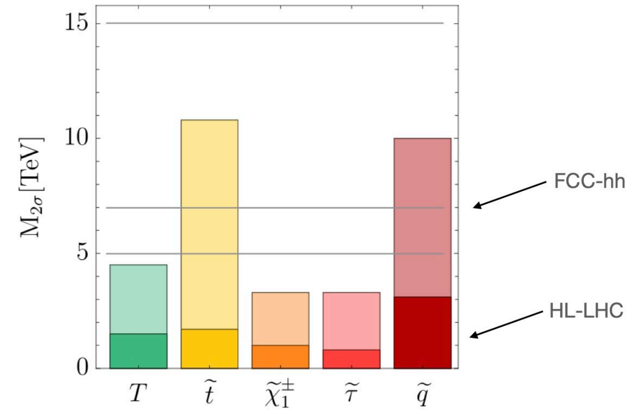
	HL-LHC	HL-LHC +10 TeV	HL-LHC +10 TeV + ee
κ_W	1.7	0.1	0.1
κ_Z	1.5	0.4	0.1
κ_g	2.3	0.7	0.6
κ_γ	1.9	0.8	0.8
κ_c	-	2.3	1.1
κ_b	3.6	0.4	0.4
κ_μ	4.6	3.4	3.2
κ_τ	1.9	0.6	0.4
$\kappa_{Z\gamma}^*$	10	10	10
κ_t^*	3.3	3.1	3.1

10 TeV MC → (HL-LHC +10 TeV)

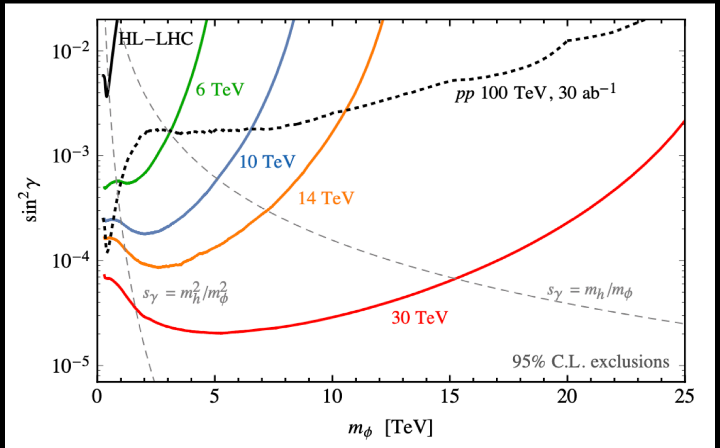
* No input used for μ collider

Order of magnitude in Higgs precision
and
can directly probe the scale implied in same machine!

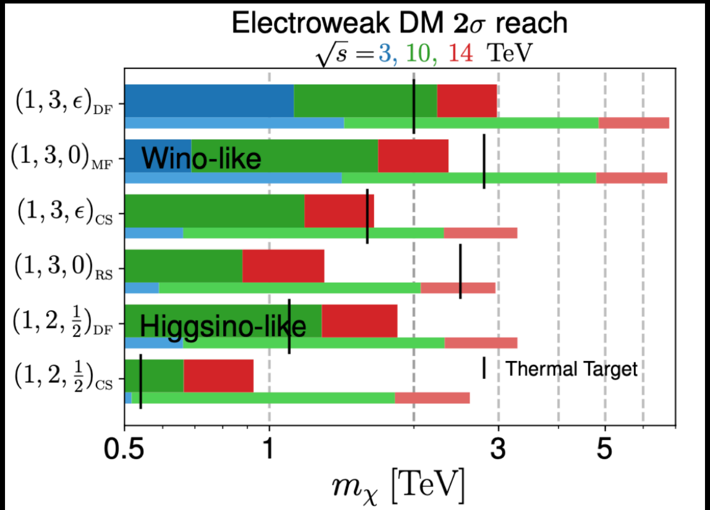
Courtesy Patrick Meade (SBU)



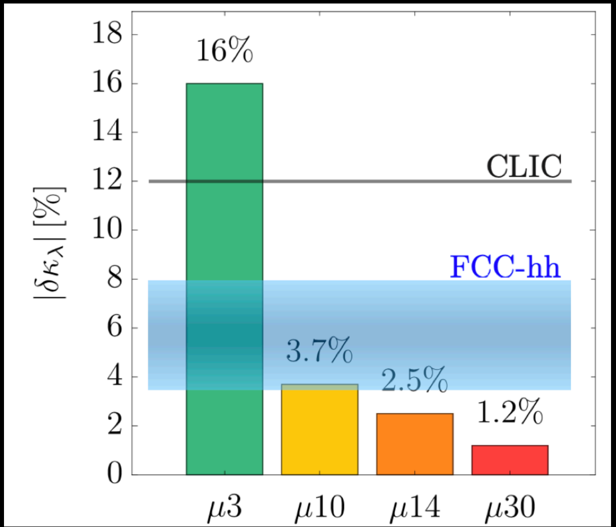
Direct production at higher scales – strongly motivated targets up to 10 TeV



Qualitatively improved reach into Higgs Portal



Covers *simplest* WIMP candidates – hard or impossible with next generation DM direct detection



Turn Higgs potential into precision science (e.g., needed for EW phase transition)

What has changed? Strong US Interest

MC Forum Report: https://arxiv.org/pdf/2209.01318.pdf

Offering a combination of unprecedented energy collisions in a comparatively clean leptonic environment, a high energy muon collider has the unique potential to provide both precision measurements and the highest energy reach in one machine that cannot be paralleled by any currently available technology.

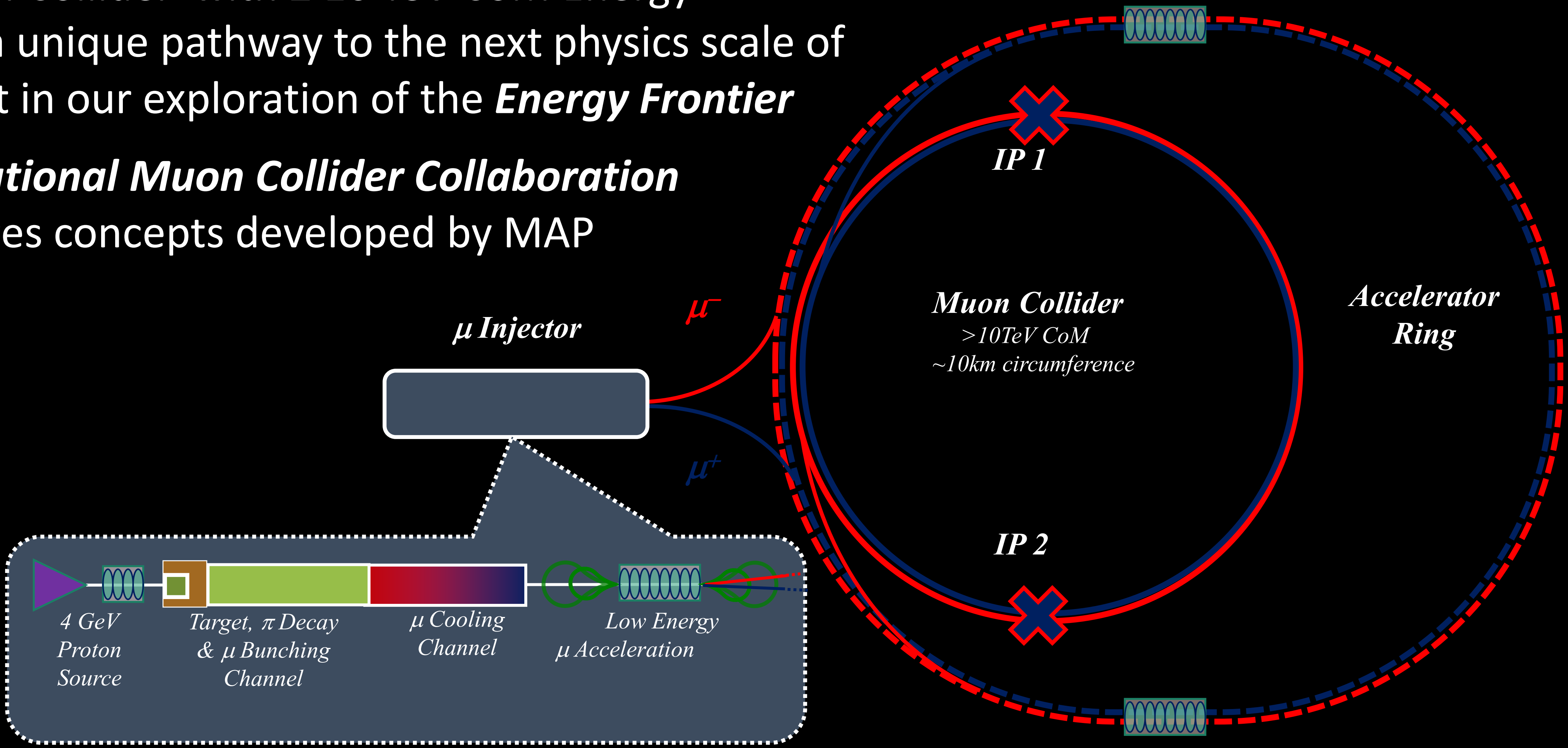
No fundamental show-stoppers have been identified. Nevertheless, engineering challenges exist in many aspects of the design and targeted R&D is necessary in order to make further engineering and design progress.

Engaging in the development of a muon collider will reinvigorate the U.S. HEP community and provide benefit to the field across multiple frontiers.

IMCC Efforts for a 10-TeV Class Muon Collider

A Muon Collider with ≥ 10 TeV CoM Energy offers a unique pathway to the next physics scale of interest in our exploration of the ***Energy Frontier***

International Muon Collider Collaboration leverages concepts developed by MAP



The muon injector chain provides cooled muons with roughly 100 GeV/c for acceleration to the multi-TeV scale

Parameter Sets for the International MC Collaboration

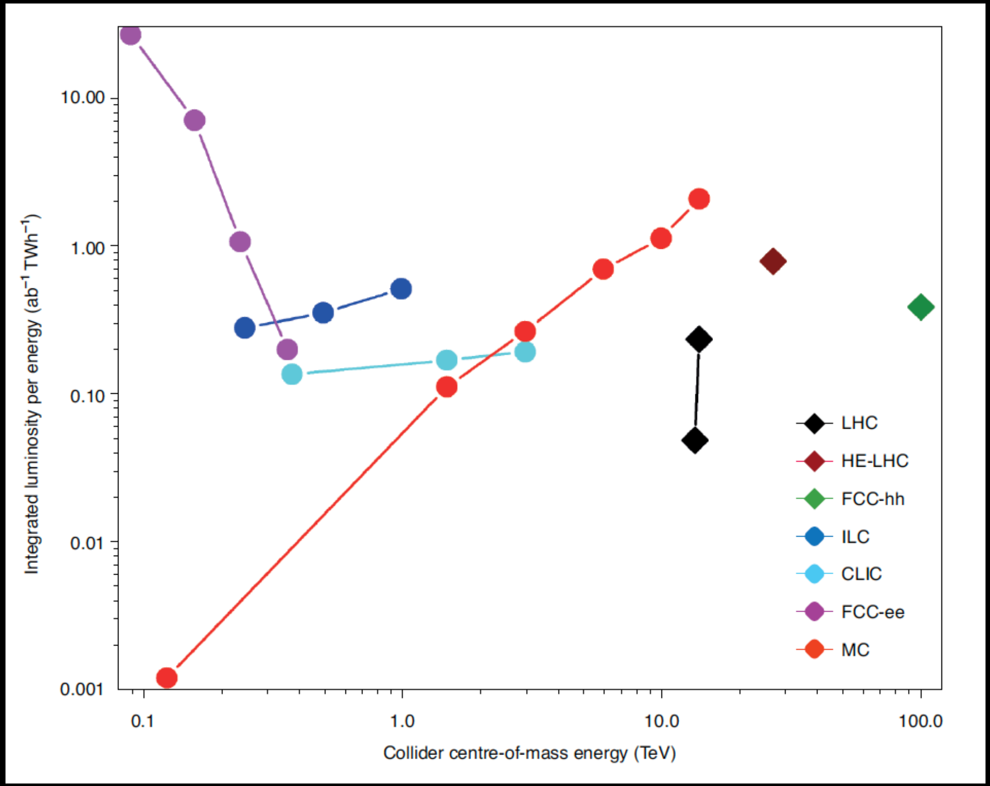
- Performance Aims:
  - Achieve the target integrated luminosity in ~5 years of running

$\sqrt{s}$	$\int \mathcal{L} dt$
3 TeV	$1\ ab^{-1}$
10 TeV	$10\ ab^{-1}$
14 TeV	$20\ ab^{-1}$

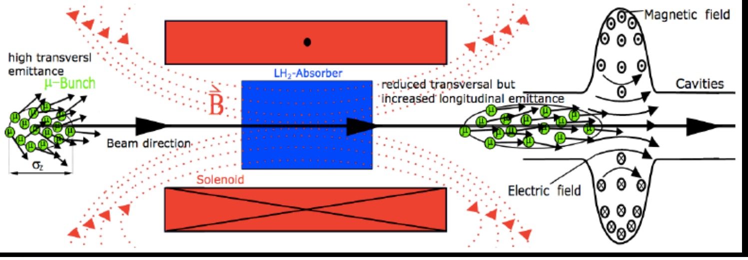
Parameter	Unit	3 TeV	10 TeV	14 TeV
L	$10^{34}\ cm^{-2}s^{-1}$	1.8	20	40
N	10^{12}	2.2	1.8	1.8
f_r	Hz	5	5	5
P_{beam}	MW	5.3	14.4	20
C	km	4.5	10	14
<B>	T	7	10.5	10.5
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Compare: 28 MW for 3 TeV CLIC

Energy Efficiency



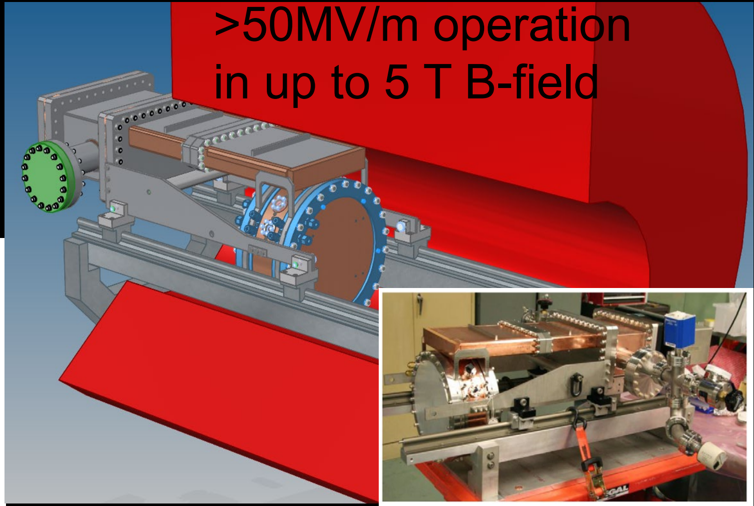
What has changed? *Concept Maturity*

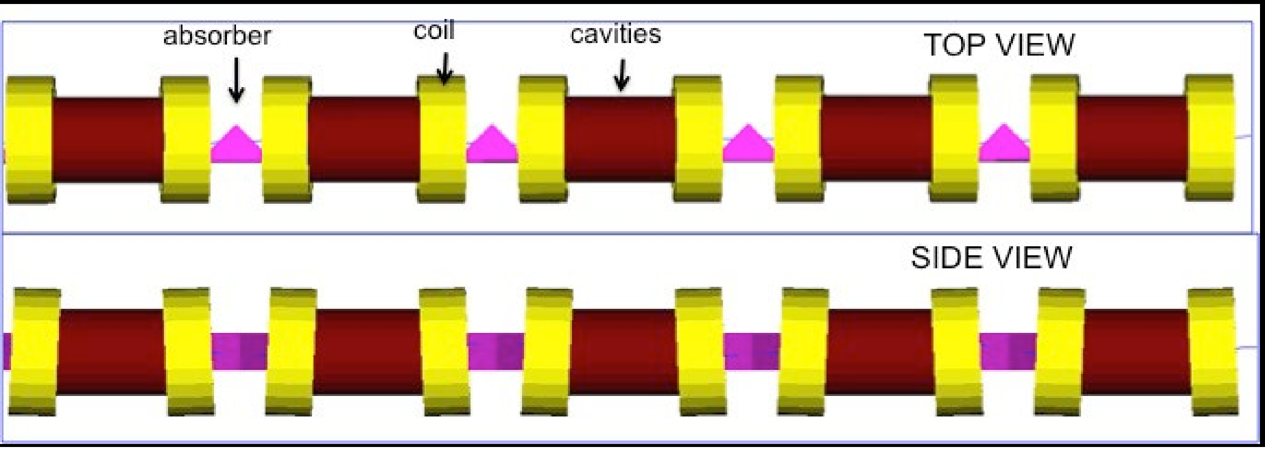


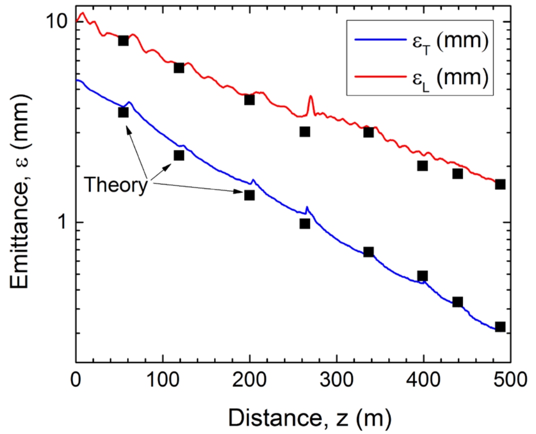
One Example: Ionization Cooling

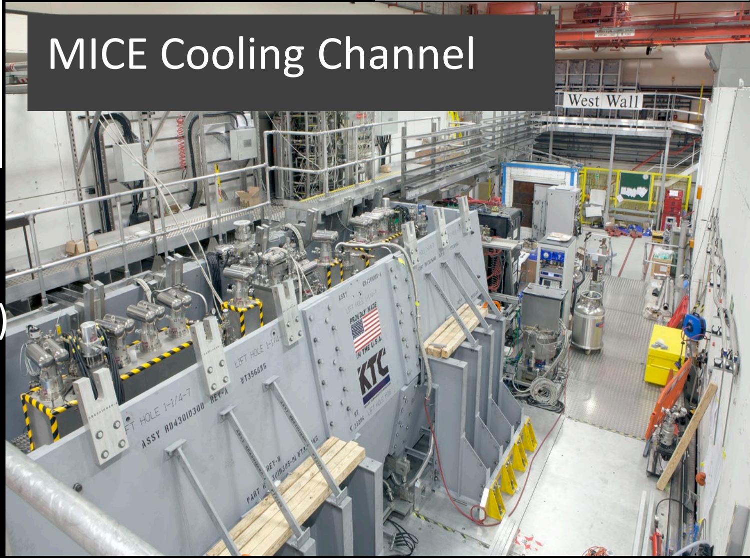
Cooling designs with good performance and significant room for improvement based on recent R&D

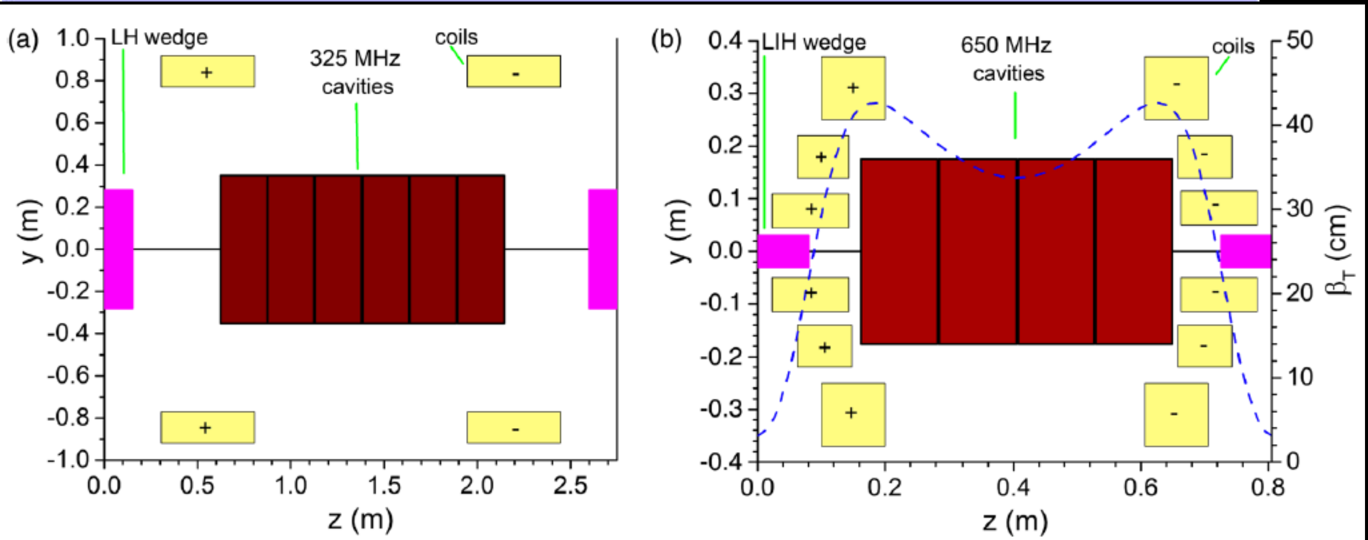
Rectilinear Cooling Channel – PRSTAB 18, 031003 (2015)











MICE Demo of Ionization Cooling
Nature **578,** 53–59 (2020)

RF in Magnetic Fields
~2.5x improvement over current designs

- Phys. Rev. Accel. Beams 23, 072001
- 2018 JINST 13 P01029

What has changed? *MC R&D Progress*

	Issues	Status
Target	• Multi-MW Targets • High Field, Large Bore Capture Solenoid	Ongoing >1 MW target development Solenoid specs similar to ITER Central Solenoid
Front End	• Energy Deposition in FE Components • RF in Magnetic Fields (see Cooling)	Current designs handle energy deposition
Cooling	• RF in Magnetic Field • High and Very High Field SC Magnets • Overall Ionization Cooling Performance	MAP designs use ~20 MV/m → 50 MV/m demo >30 T solenoid demonstrated for Final Cooling Cooling design that achieves most goals
Acceleration	• Acceptance • Ramping System • Complete design concept to all energies	Designs in place for accel to 125 GeV CoM Magnet system development needed for TeV-scale Additional design work needed for TeV-scale
Collider Ring	• Magnet Strengths, Apertures, & Shielding • High Energy Neutrino Radiation	Lattices with magnet conceptual design to 3 TeV ν radiation at 10 TeV requires further study
MDI/Detector	• Backgrounds from μ Decays • IR Shielding	Physics studies show good performance (2020 *JINST* **15** P05001) Further design work required for multi-TeV

The Path Forward

Successful development of key MC concepts provides a foundation to continue a machine design that can deliver discovery physics for the particle physics community

A new International Muon Collider Collaboration (IMCC) has been formed

An R&D roadmap has been delivered as an outcome of the European Strategy process

How can the US engage with this process?

Addressing the Committee's Question

What can we learn from the previous US Muon Collider Collaboration and how can we frame a new collaboration?

Some Lessons and Questions:

1. MAP was focused on accelerator feasibility
   - The HEP community is interested in physics capability
   - A transformation has come with a more detailed evaluation of the physics potential initiated by our European colleagues as supported by MAP output

⇨ **An integrated physics/detector/accelerator approach is an absolute necessity**

2. A commitment to milestones that support informed decisions is critical for community planning
   - This requires a sustained commitment
3. A high brightness muon source has more applications than just an energy frontier collider
   - Neutrinos
   - Rare processes
   - **How do we drive a broader assessment that includes more than just the Energy Frontier machine? Including areas beyond HEP?**

Addressing the Committee's Question

What can we learn from the previous US Muon Collider Collaboration and how can we frame a new collaboration?

arXiv:2201.07895 [physics.acc-ph]

- Further work in the context of an international collaboration is highly desirable
  - Shared resources
  - Shared commitment
  - Draw on the broadest reservoir of accelerator and detector expertise to enable a successful conclusion
  - The Energy Frontier, and more broadly high energy physics, is a global effort
- Any plan must provide clear decision points to evaluate progress towards "concept maturity"
  - See slide after next

Timeline to a
Multi-TeV Collider

European Accelerator R&D
Roadmap

This roadmap picks up at ~Phase 2 of the MAP Approach with clear "decision points" over the next decade

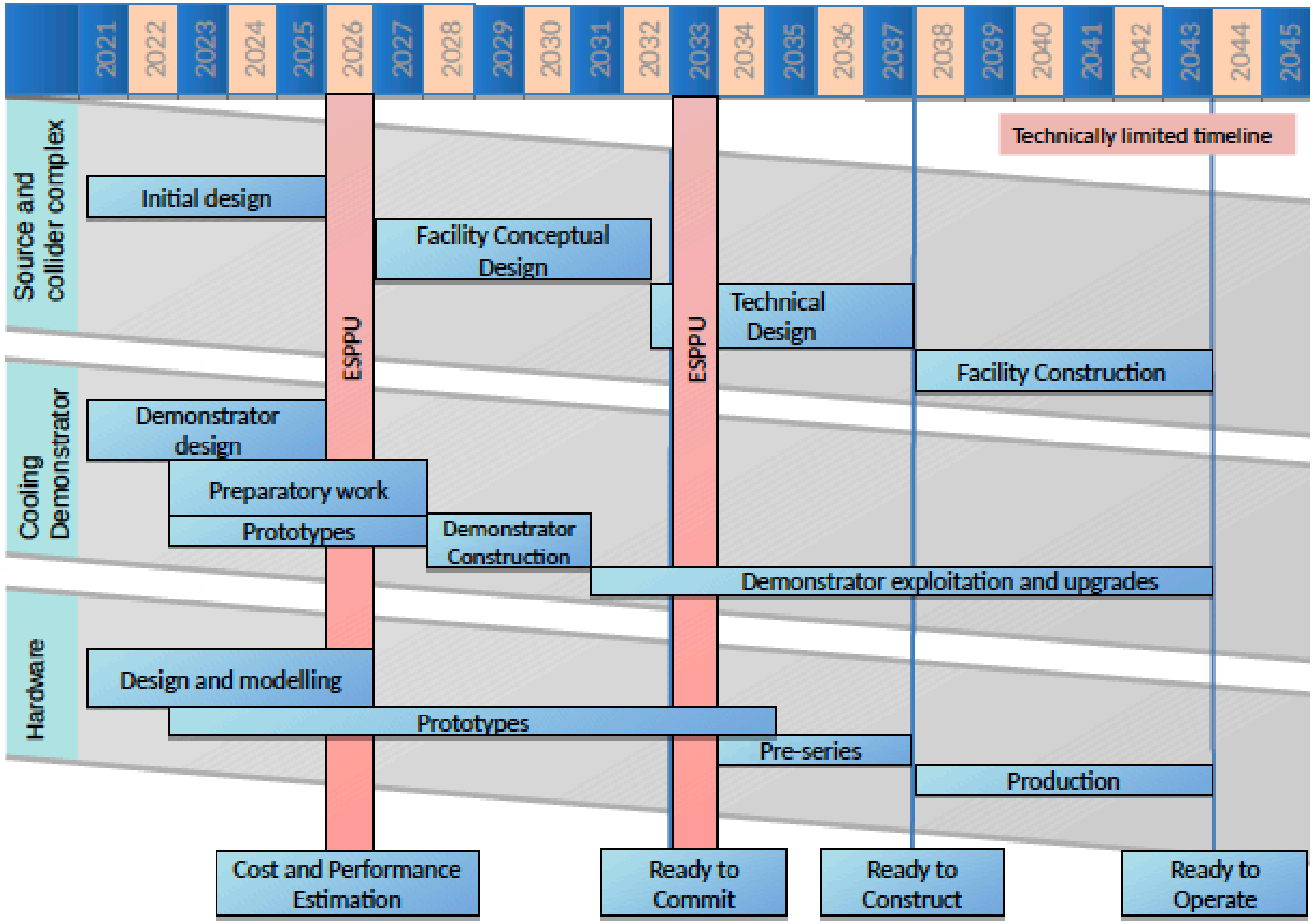


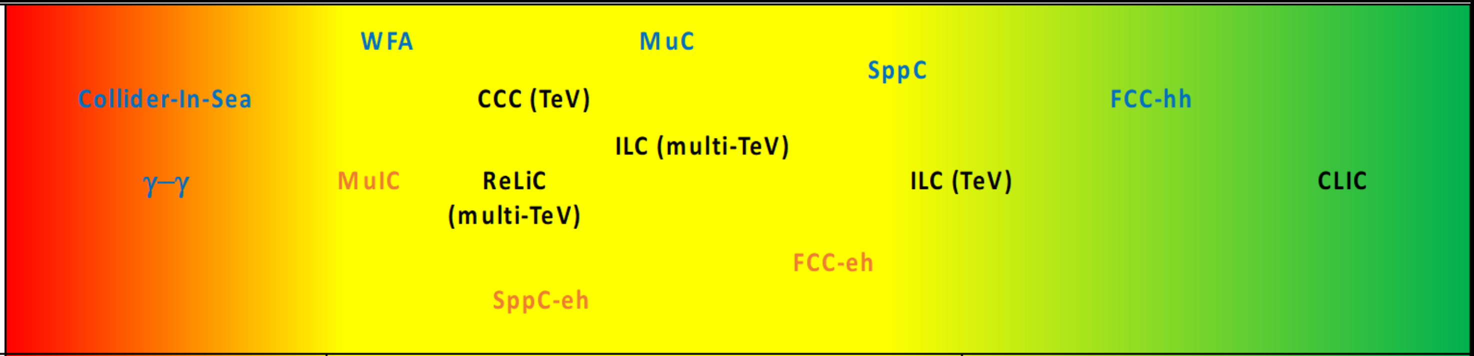
Fig. 5.3: A technically limited timeline for the muon collider R&D programme.

Addressing the Committee's Question

What can we learn from the previous US Muon Collider Collaboration and how can we frame a new collaboration?

- A key element for "emerging" accelerator technologies is to execute a program that can provide ***mature concepts*** that enable ***informed choices*** by the HEP community

Collider Concepts



Technical Maturity	• Low maturity conceptual development. • Proof-of-principle R&D required. • Concepts not ready for facility consideration.	• Emerging accelerator concepts requiring significant basic R&D and design effort to bring to maturity.	• Designs have achieved a level of maturity to have reliable performance evaluations based on prior R&D and design efforts. • Critical project risks have been identified and sub-system focused R&D is underway where necessary.
Funding Approach	• Funding for basic R&D required. • Availability of "generic" accelerator test facility access often necessary.	• Efforts would benefit from directed R&D funding to mature collider concepts. • Availability of test facilities to demonstrate a broad range of technology concepts required. • Some large-ticket demonstrators are generally necessary before a detailed "reference" design can be completed.	• Funding approach typically transitions to "project-style" efforts with significant dedicated investment required.

Maturity evaluation from the Accelerator Frontier Topical Group on Multi-TeV Colliders (AF4)

- It is crucial to take concepts to the green range in the graphic to provide reliable performance and risk evaluations
- This is a requirement to enable informed HEP community decisions

Implications for the US Planning Process

Some thoughts on the US Timeline:

- FY25 (post-P5): US accelerator physicists funded to engage directly with the International Muon Collider Collaboration
  - Engage in R&D, simulation, and planning to deliver a **Reference Design**
  - Lay the groundwork for deploying required **demonstration facilities** over the course of the next decade
  - Execute US efforts in the framework of an integrated **US Future Collider R&D Program**
- ~2028: Deliver MC Reference Design Report for the next US Planning Process
  - Basis for subsequent **site-specific** efforts – e.g., HF & site-filler options at Fermilab
  - Enables a serious discussion of the ***ultimate limits*** that may be reached with this technology
- Early 2030s: Deliver a full Conceptual Design Report
  - Supported by:
    - Detailed end-to-end design
    - Significant component prototyping
    - First results from Demonstrator Facility operations
  - Sets the stage for **fully informed decisions by the community** on pursuit of this collider technology

Conclusion

Engagement with the International Muon Collider Collaboration is of great interest to many members of the US HEP Community

- Provides a structured approach to evaluating this novel technology approach
  - Supports informed decision points by the HEP community
  - Timescales are consistent with key decision points for the US community
- Allows US expertise to re-engage with a great deal of IP that was developed in MAP and its predecessor collaborations
  - US expertise is important to the overall success of this collaboration!!
  - Will help drive growth of a new generation of collider experts
- Path for considering a potential future US facility

A US MC Effort fits in a National Future Collider R&D Program

- As part of a general approach to ensure continued US engagement in delivering Energy Frontier capabilities

Thank you for your attention!

Some Useful References

- A Muon Collider Facility for Physics Discovery, arXiv:2203.08033
- Boscolo, Delahaye, Palmer, RAST, Vol 10, No. 01, pp. 189-214 (2019)
- The JINST dedicated volume on Muon Collider Research and Technology: Muon Accelerators for Particle Physics https://iopscience.iop.org/journal/1748-0221/page/extraproc46
- Demonstration of cooling by the Muon Ionization Cooling Experiment, Nature 578, 53-59(2020).
- Long, K.R., Lucchesi, D., Palmer, M.A. *et al*, "Muon colliders to expand frontiers of particle physics," *Nat. Phys.* (2021), https://doi.org/10.1038/s41567-020-01130-x
- The Muon Smashers Guide, arXiv:2103.14043

Current Muon Collider Activities

- US Snowmass Process
  - Muon Collider Forum
    - Slack channel: "muon-collider-forum"
    - Mailing list: SNOWMASS-MUON-COLLIDER-FORUM@FNAL.GOV
  - Accelerator Frontier Topical Group 4 (AF4) – Multi-TeV Colliders
    - multitev-snowmass21@listserv.fnal.gov
- International Muon Collider Collaboration
  - http://muoncollider.web.cern.ch
  - Working groups and contacts:
    - Accelerator design – daniel.schulte@cern.ch
    - Physics & Detectors – nadia.pastrone@cern.ch
    - Physics potential – andrea.wulzer@cern.ch
    - Detector simulations – donatella.llucchesi@pd.infn.it
    - Muon Cooling – chris.rogers@stfc.ac.uk, klaus.hanke@cern.ch
- Detector Performance Baseline Efforts
  - DELPHES card (methodology utilized for FCC-hh and CLIC evaluations)
  - https//muoncollider.web.cern.ch/node/14
- Detector Impacts of Beam Induced Backgrounds
  - Studies led by Donatella Lucchesi (Padova) and Sergo Jindariani (FNAL)

Backup Slides

Why Muons?

Physics Frontiers

- **Intense and cold muon beams ⇨ unique physics reach**
  - Tests of Lepton Flavor Violation
  - Anomalous Magnetic Moment (g-2)
  - Precision sources of neutrinos
  - Next generation lepton collider

$$m_\mu = 105.7\,MeV/c^2$$
$$\tau_\mu = 2.2\,\mu s$$

Colliders

- **Opportunities**
  - s-channel production of scalar objects
  - Strong coupling to particles like the Higgs →
  - Reduced synchrotron radiation ⇨ multi-pass acceleration feasible
  - Beams can be produced with small energy spread
  - Beamstrahlung effects suppressed at the collider IP
- ***BUT*** **the accelerator complex and detector must be able to handle the impacts of μ decays**

$$\Box \left(\frac{m_\mu^2}{m_e^2}\right) \cong 4\times10^4$$

Collider Synergies

- High intensity beams required for a long-baseline Neutrino Factory are readily provided in conjunction with a Muon Collider Front End
- Such overlaps offer unique staging strategies to guarantee physics output while developing a muon accelerator complex capable of supporting collider operations

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

Collider Luminosity

Detector and Physics Performance at a Muon Collider
N. Bartosik et al 2020 JINST 15 P05001

- For a muon collider, we can write the luminosity as:

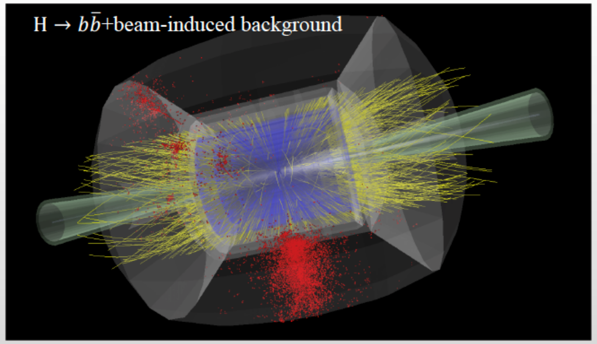
$$\mathcal{L} = \frac{N^2 f_{coll}}{4\pi\sigma_x\sigma_y} = \frac{\langle N^2 \rangle_{n_{turns}} n_{turns} f_{bunch}}{4\pi\sigma_\perp^2}$$

- For the 1.5 TeV muon collider design, we have
  - N = 2×10^{12} particles/bunch
  - $\sigma_{x,y}$ ~ 5.9 μm, β^* = 10 mm, $\varepsilon_{x,y}(norm)$ = 25 μm-rad
  - N_{turns}>1000
  - f_{bunch}=15 Hz (rate at which new bunches are injected)

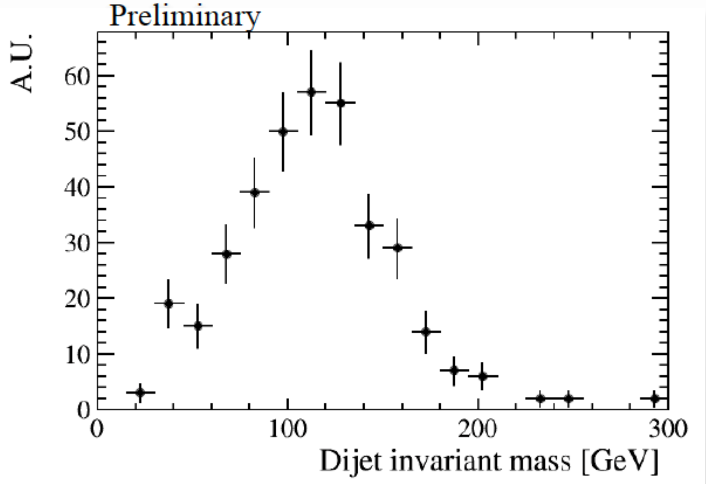
$$\mathcal{L} \approx \frac{N_0^2 n_{turns} f_{bunch}}{4\pi\sigma_\perp^2} \approx 1.4\times10^{34}\, cm^{-2}s^{-1}$$

$b\bar{b}$ Studies at $\sqrt{s}$ =1.5 TeV

Process	cross section [pb]	
$\mu^+\mu^- \to \gamma^*/Z \to b\bar{b}$	0.046	
$\mu^+\mu^- \to \gamma^*/Z\gamma^*/Z \to b\bar{b}$ +X	0.029	
$\mu^+\mu^- \to \gamma^*/Z\gamma \to bb\gamma$	0.12	
$\mu^+\mu^- \to HZ \to b\bar{b}$ +X	0.004	
$\mu^+\mu^- \to \mu^+\mu^- H\,H \to b\bar{b}$ (ZZ fusion)	0.018	
$\mu^+\mu^- \to \nu_\mu\nu_\mu H\,H \to bb$ (WW fusion)	0.18	Signal



$\mu^+\mu^- \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + beam-induced background fully simulated



MC Parameters as Developed by MAP

RAST, Vol 10, No. 01, pp. 189-214 (2019)

Table 3. Main parameters of the various phases of an MC as developed by the MAP effort.

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/10^7 sec		13,500	7000	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

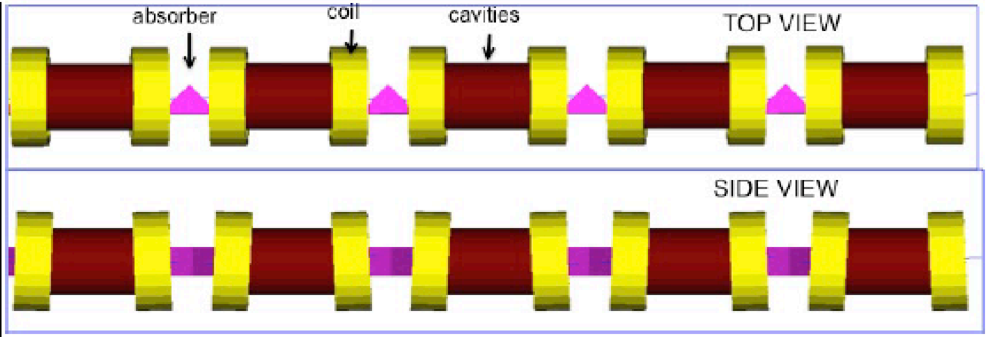
* Accounts for off-site neutrino radiation

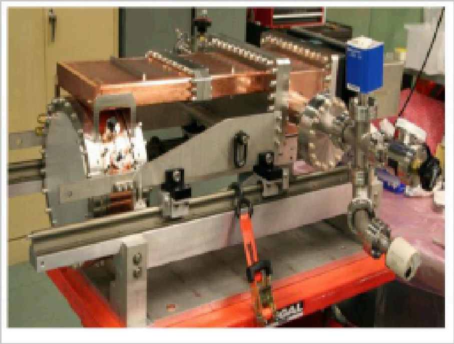
Feasibility Status

- Critical concepts now demonstrated (at the TRL 1-3 level)
  - Target Solenoid
    - Similar LTS parameters to ITER Central Solenoid
    - Performance can be improved with a radiation resistant HTS or Cu insert
  - Muon 6D Cooling
    - MICE Demonstration of Emittance Cooling
    - High gradient demonstration of RF operating in Tesla-class magnetic fields
    - Cooling channel concepts and detailed simulation consistent with operational targets
  - Muon Final Cooling
    - Advances in HTS conductor/cable/magnet technology
    - High Field User Magnet program operationally demonstrating magnet parameters that are rapidly approaching the MC requirements
  - Muon Acceleration
    - Significant recent advancement in HTS-based fast-ramping magnets
    - Focused effort on studying the integrated magnet/power supply efficiency issues for TeV-scale acceleration
  - Collider and Detector
    - Detailed studies of backgrounds that may impact physics
    - Detector performance studies now demonstrate the ability to successfully measure key processes
    - Concepts in development to manage off-site neutrino radiation issues

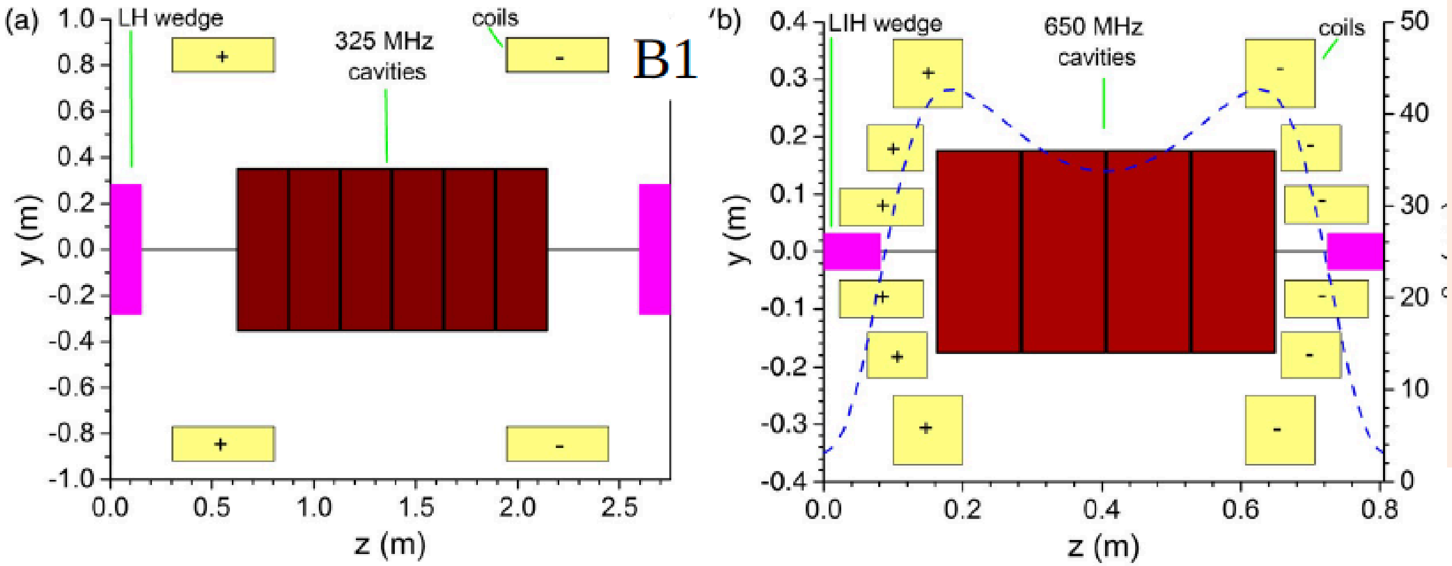
See dedicated JINST Volume for key references:
Muon Accelerators for Particle Physics (MUON)

The Ionization Cooling Cell





MuCool: >50 MV/m in 5 T
Two solutions
- H2-filled copper cavities
- Cavities with Be end caps



High-gradient cavities in high magnetic field
tests much better than design values but need to develop

Design can achieve target emittance

D. Schulte

Will aim for further optimisation
This is the **unique** and **novel** system of the muon collider
Will need a **test facility**

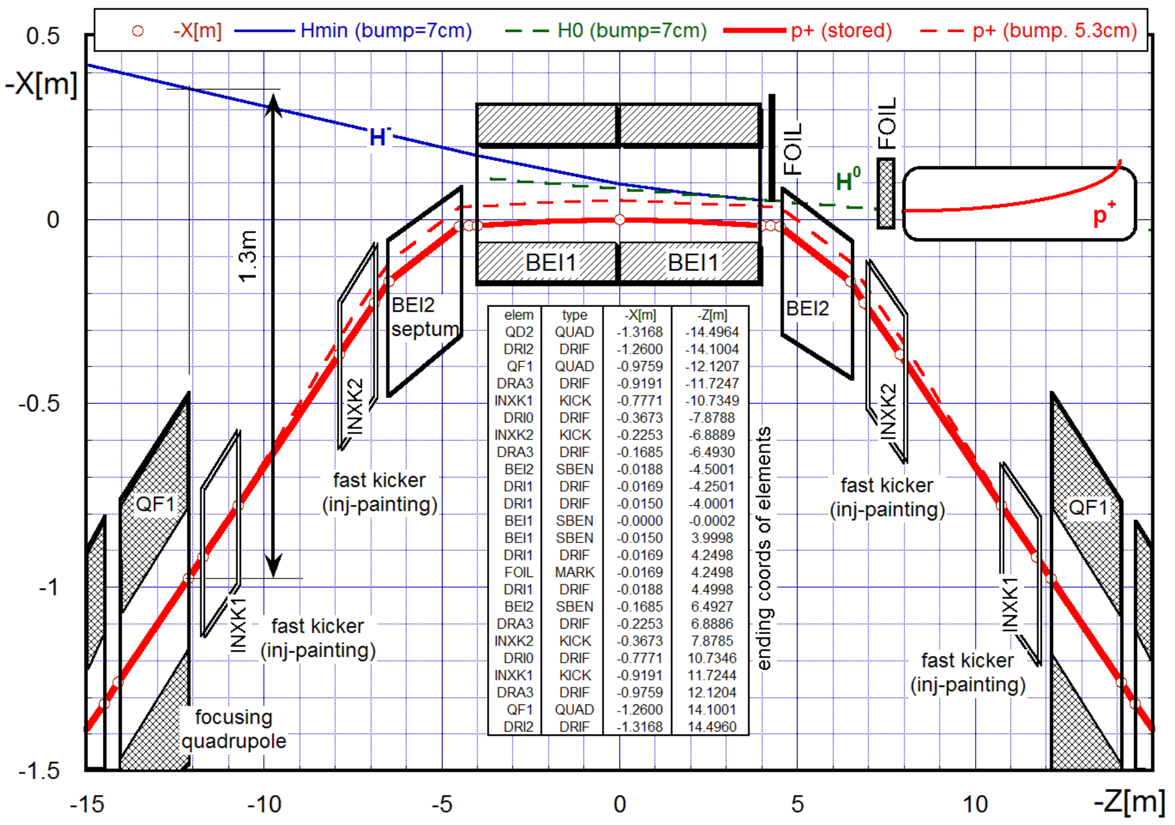
Design Status

- Preliminary design concepts exist for all key systems
- Next steps:
  - Integrate most recent R&D results into the accelerator designs
    - Deliver updated sub-system performance evaluations
  - Evaluate all required technologies
    - Move from conceptual feasibility to detailed technical designs and evaluations
  - Set the stage for the first integrated end-to-end performance evaluations
  - Identify any technology limitations and explore mitigations
  - Set the stage for a complete Conceptual Design Report

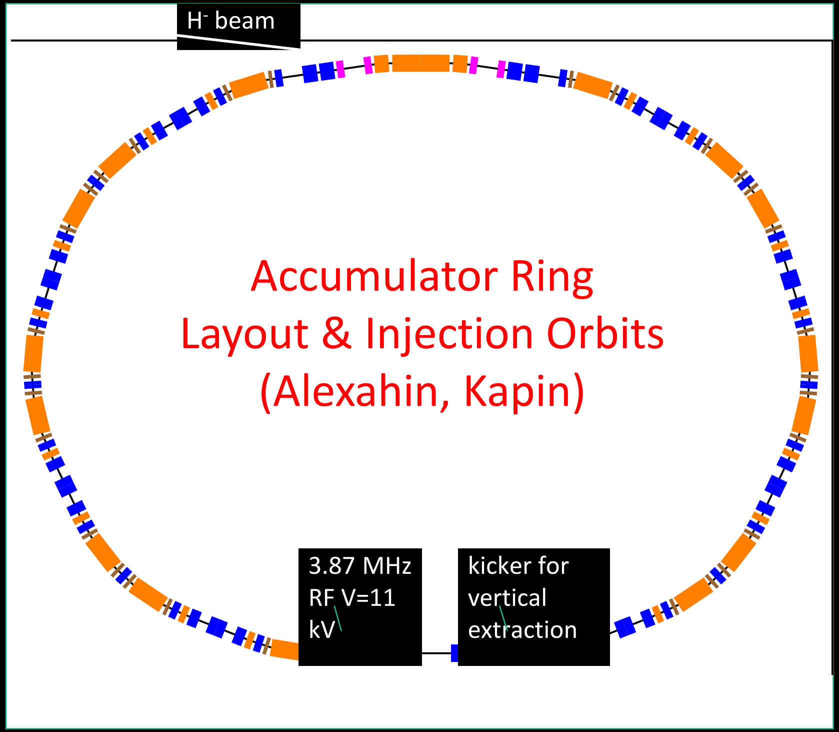
In summary: ***mature the design*** with the goal of delivering a full CDR within the next decade

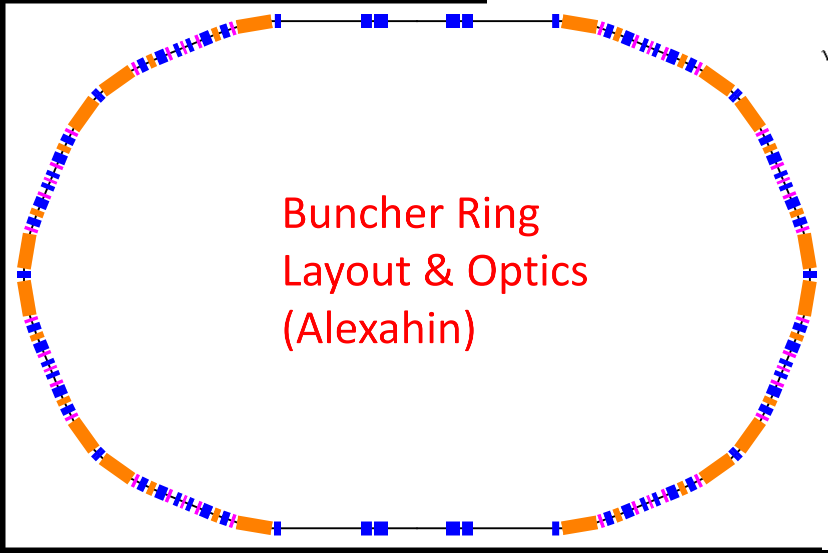
Proton Driver

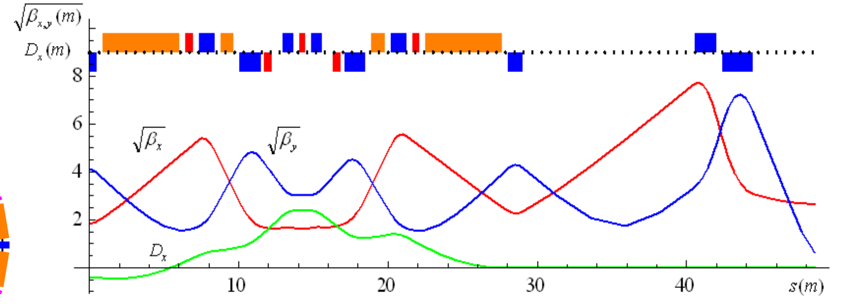
- ✓ Based on 6-8 GeV Linac Source
- ✓ Accumulator & Buncher Ring Designs in hand
- ✓ H- stripping requirements same as those originally established for Fermilab's Project X



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







Optics:
½ staight +
1 arc cell

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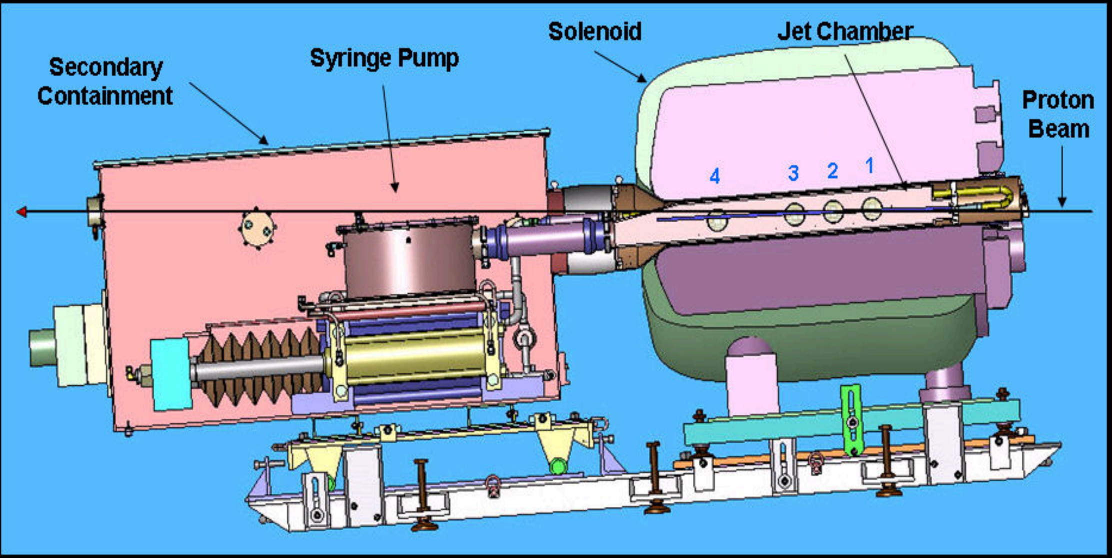
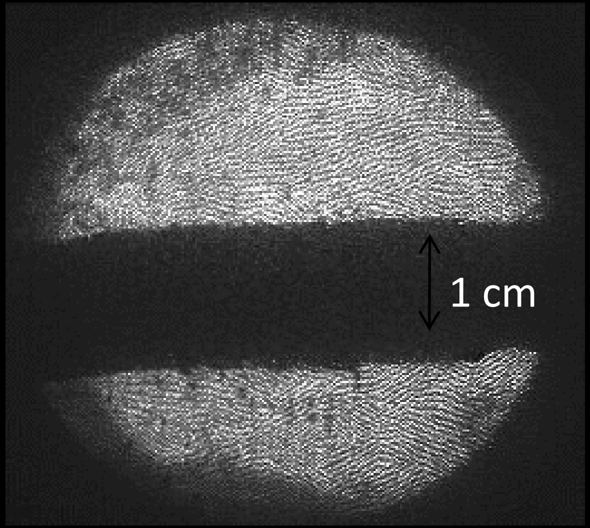
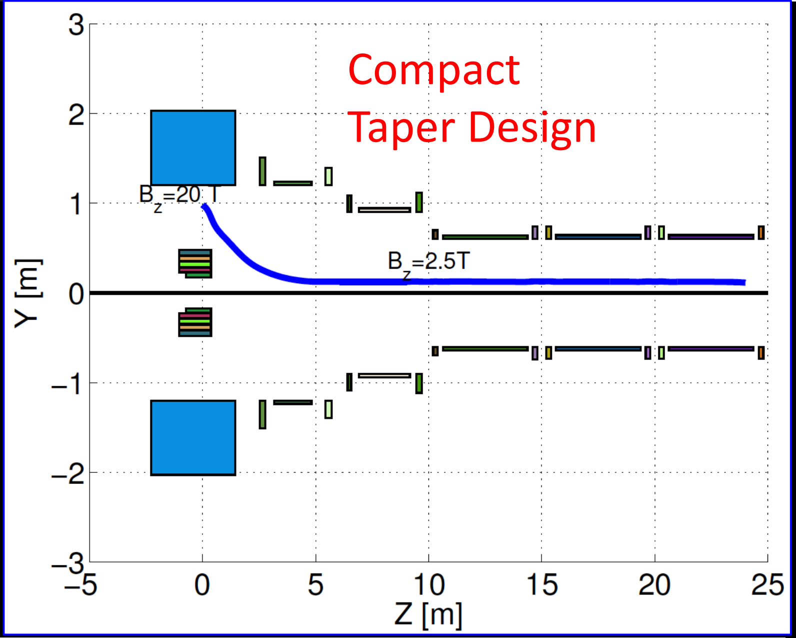
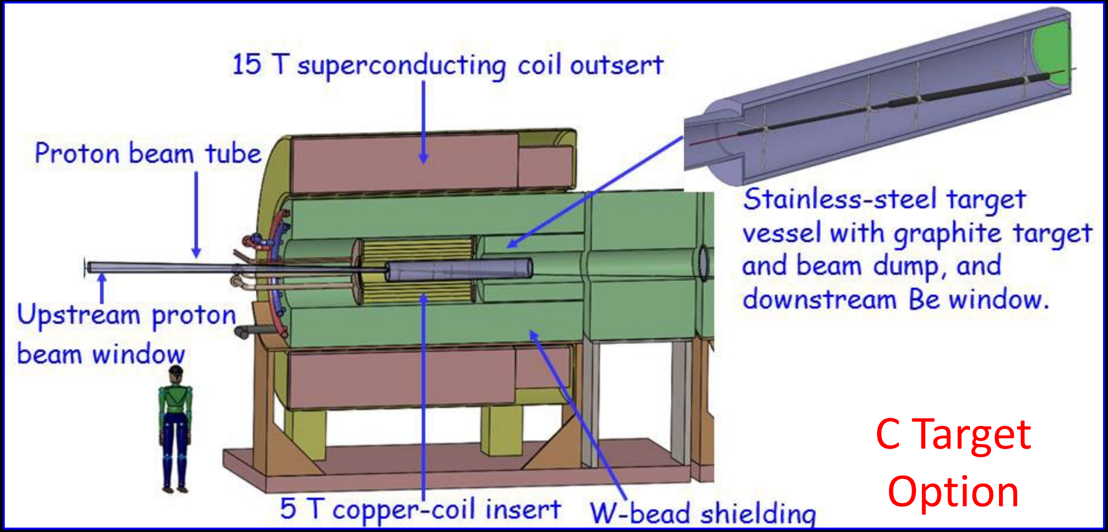
Target & Capture System



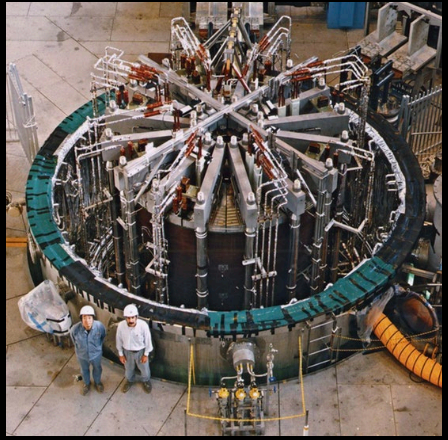
MERIT Experiment (CERN)

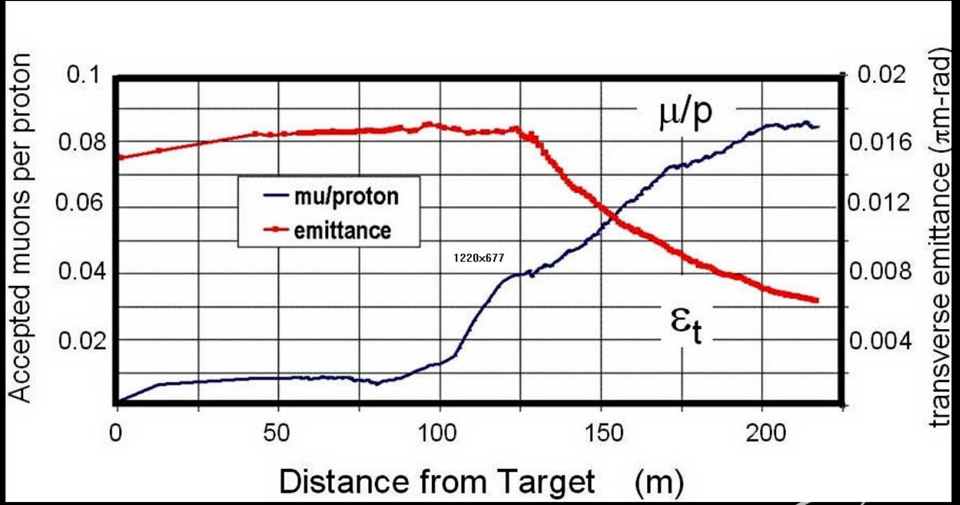




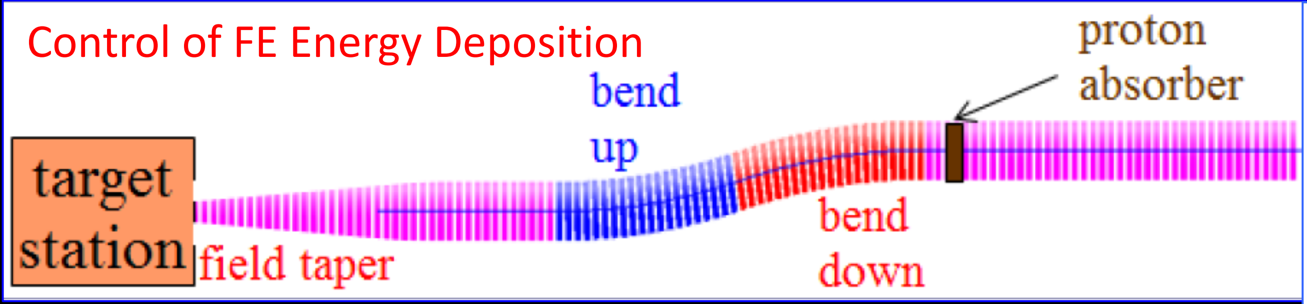


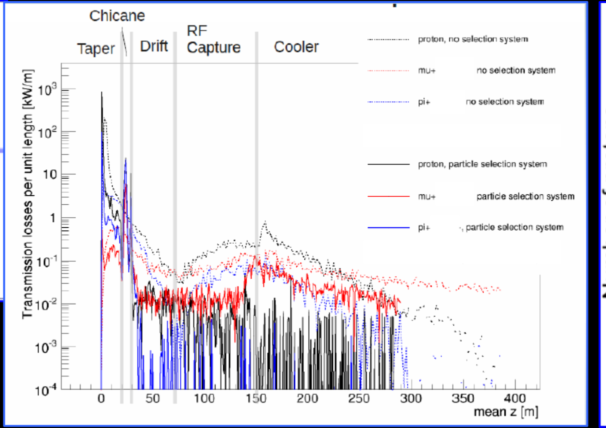
ITER Central Solenoid 13T LTS w/1.7m bore

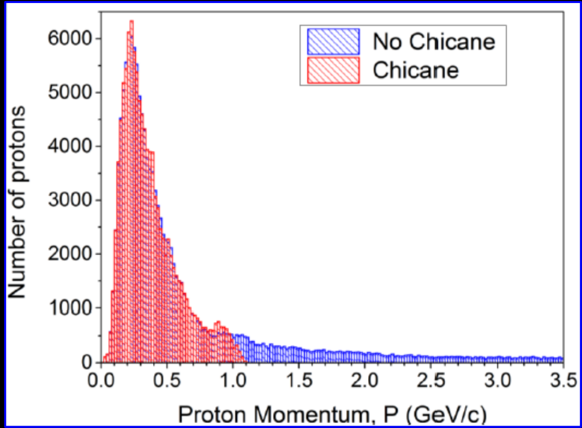


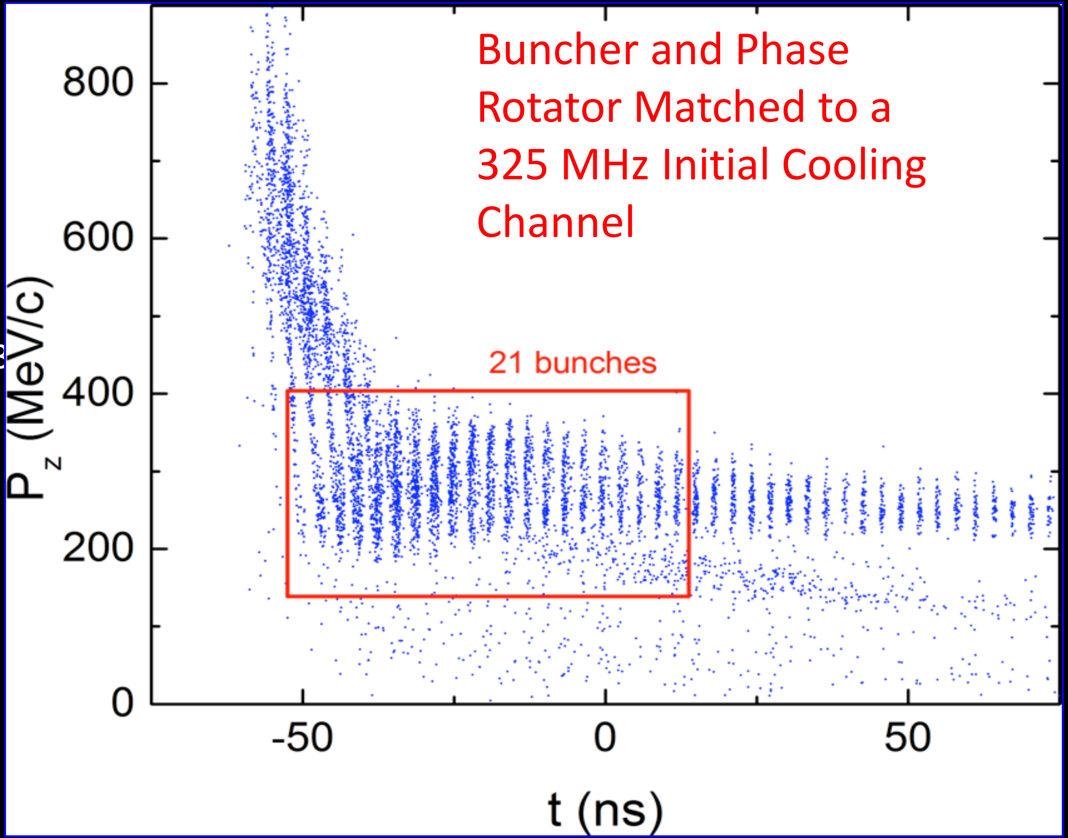


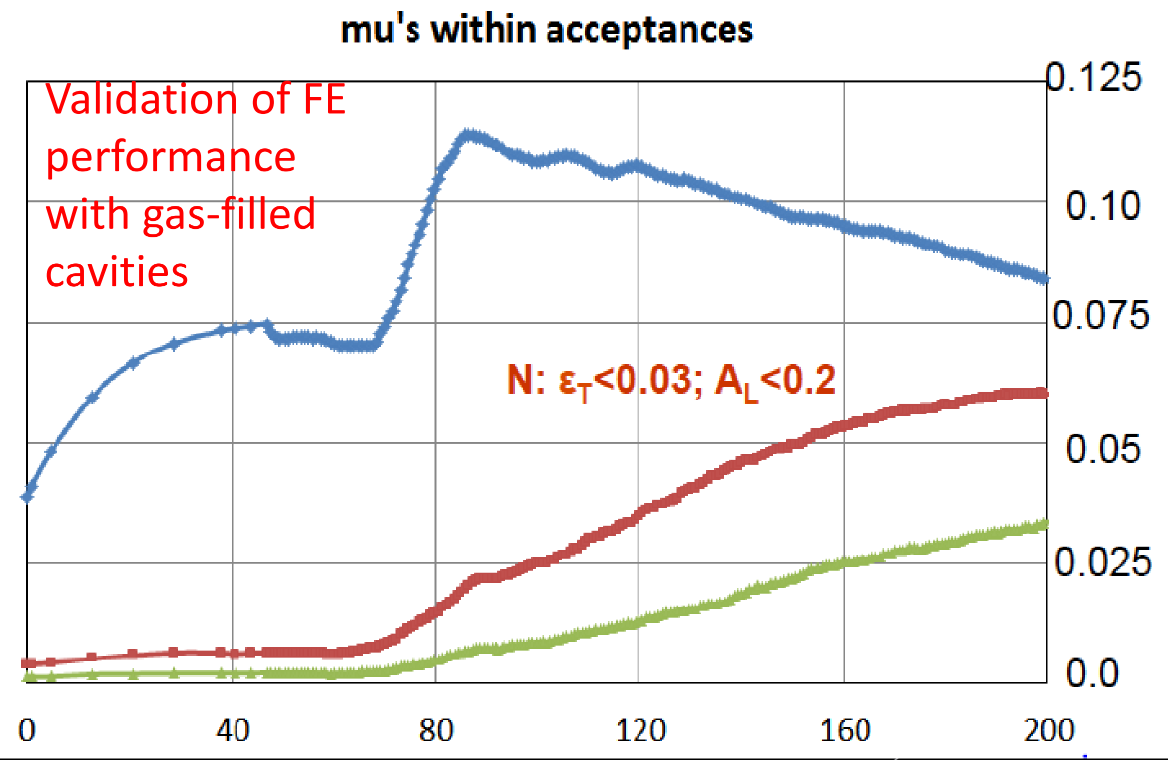
Front End and Energy Deposition











Cooling Methods

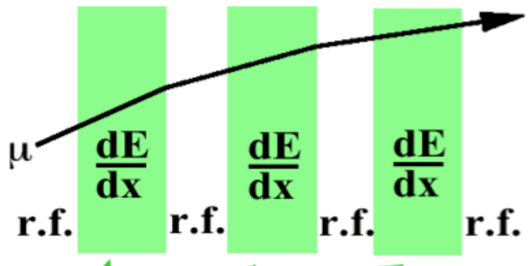
- The unique challenge of muon cooling is its short lifetime
  - Cooling must take place very quickly
  - More quickly than any of the cooling methods presently in use

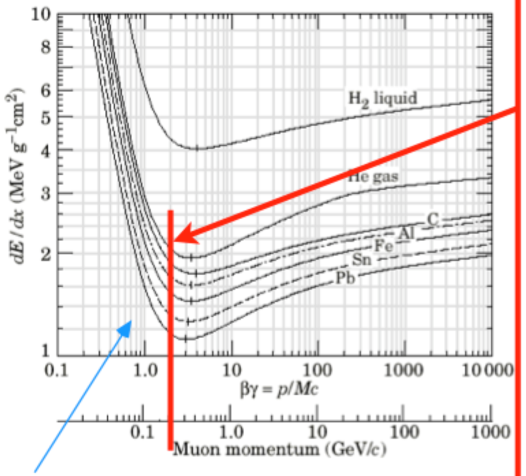
⇨ Utilize energy loss in materials with RF re-acceleration

- MAP R&D Efforts:
  - RF in High Magnetic Fields: MuCool Test Area (MTA) at Fermilab
  - High Field Magnet Design and Development
  - The International Muon Ionization Cooling Experiment (MICE)

- ε_N(equilib.) ∝ β_∞ ∝ B_{max}

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





– Absorbers:

$$E \to E - \left\langle \frac{dE}{dx} \right\rangle \Delta s$$ ← ionization energy loss

$$\theta \to \theta + \theta^{rms}_{space}$$ ← multiple Coulomb scattering

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

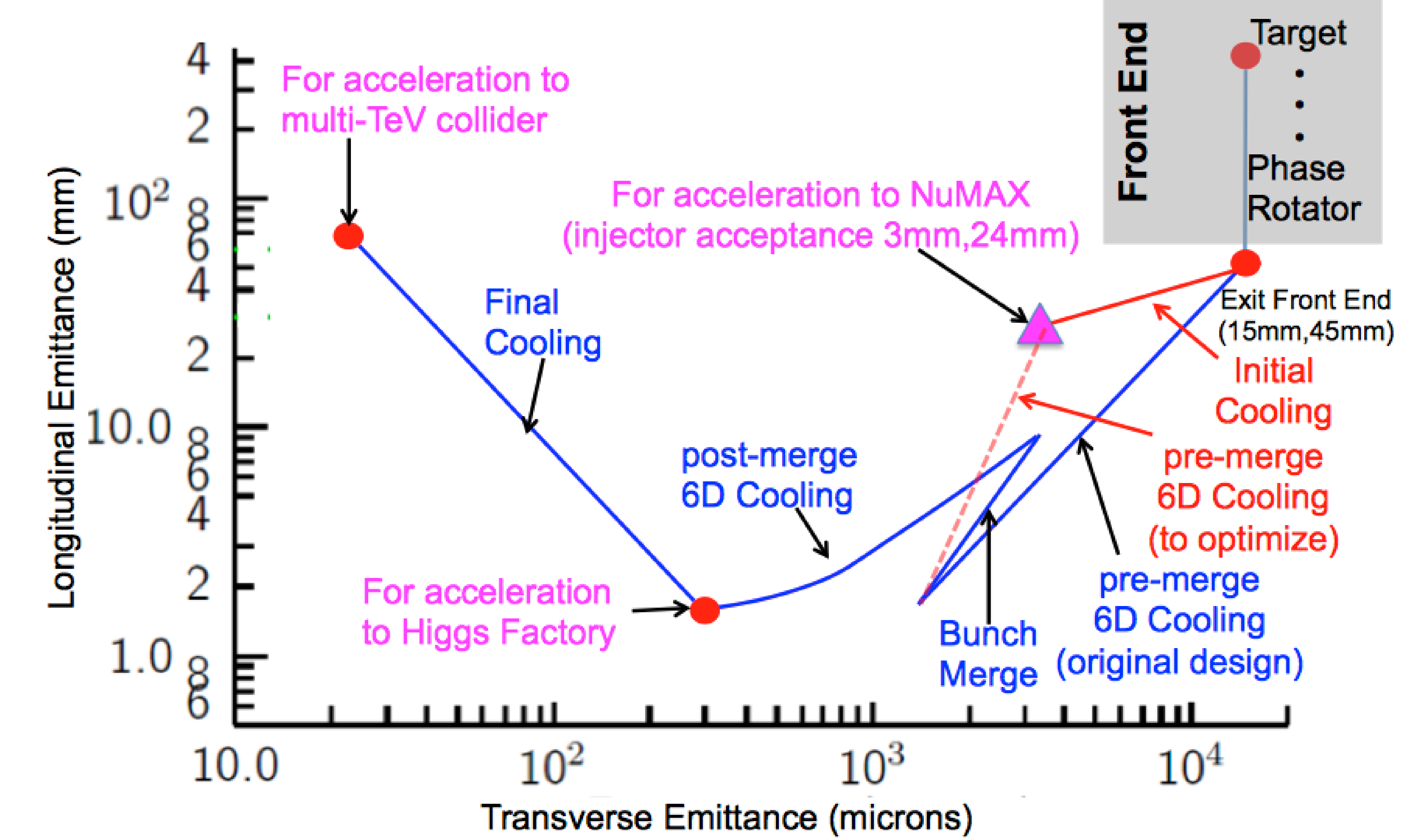
- 2 competing effects ⇒ ∃ equilibrium emittance

– RF cavities between absorbers replace ΔE

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

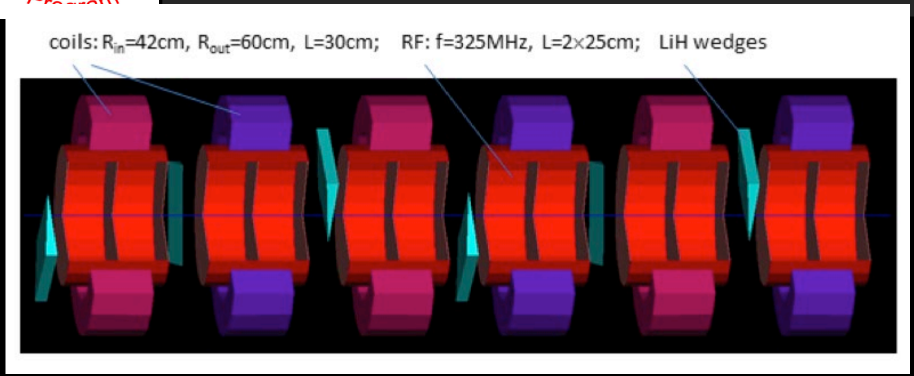
$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2}\left\langle\frac{dE_\mu}{ds}\right\rangle\frac{\epsilon_N}{E_\mu} + \frac{\beta_\perp (0.014\ \mathrm{GeV})^2}{2\beta^3 E_\mu m_\mu X_0}$$ (emittance change per unit length)

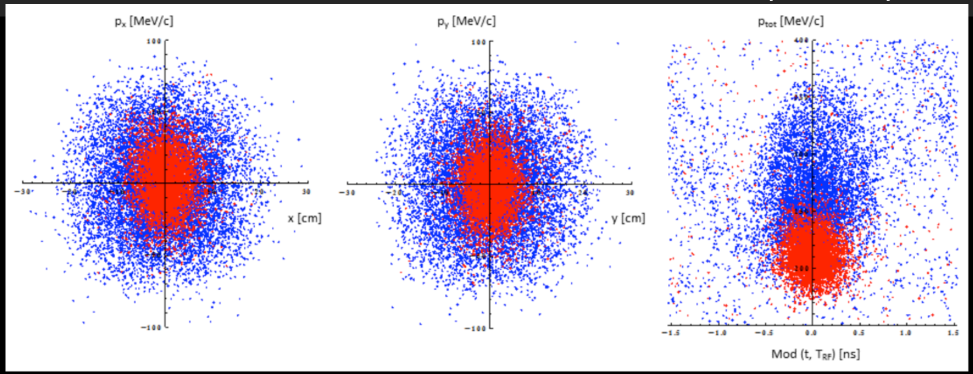
MAP Cooling Targets

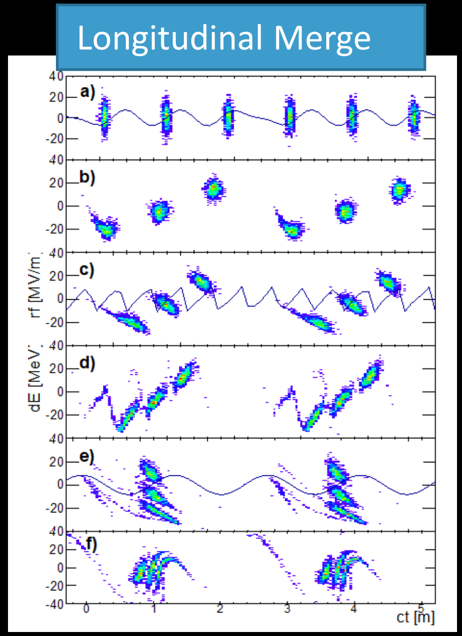


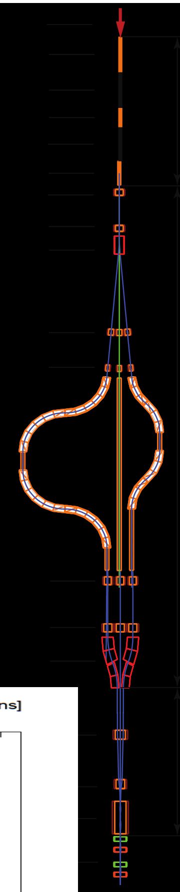
Muon Ionization Cooling (Design)

D. Stratakis, *et al.*, *PRSTAB* **18** 031003, 2015
D. Stratakis *JINST* **12** P09027, 2017
Y. Bao, *et al.*, *PRAB* **19** 031001, 2016

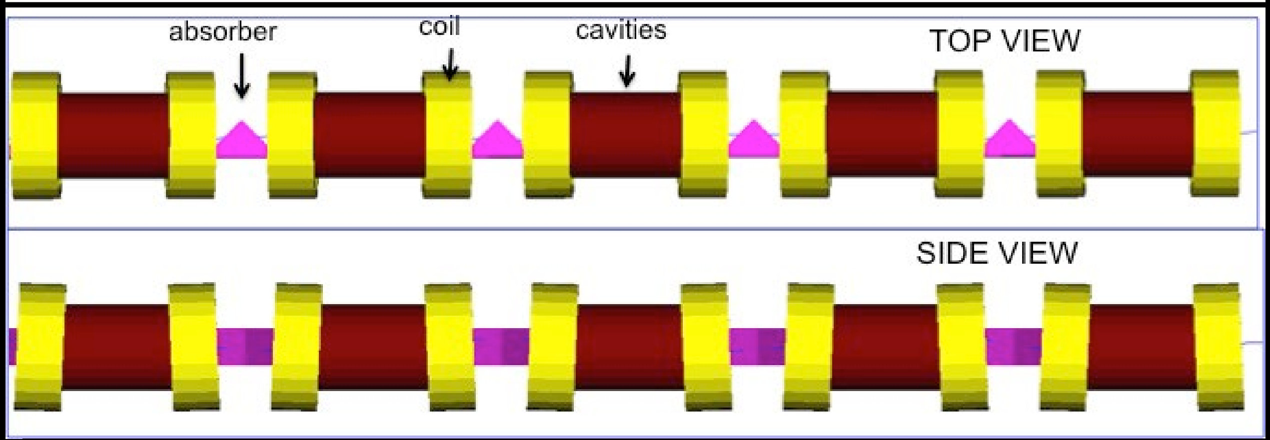


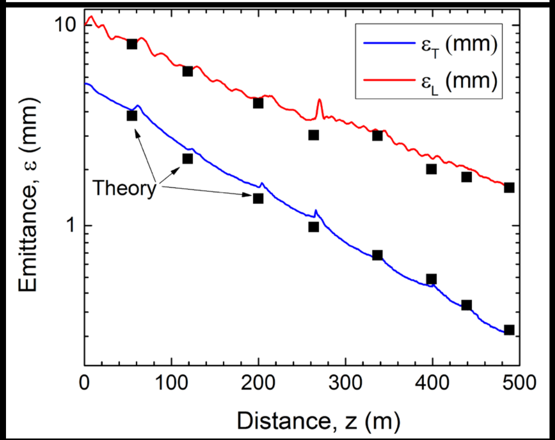


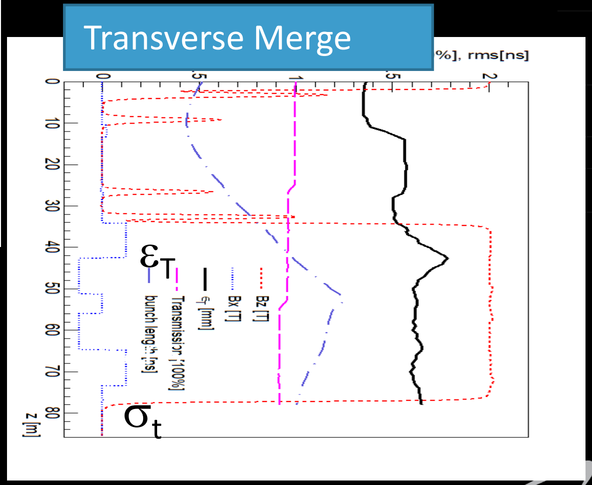




Initial 6D Cooling: ε_{6D} 60 cm^3 ⇨ ~50 mm^3; Trans = 67%





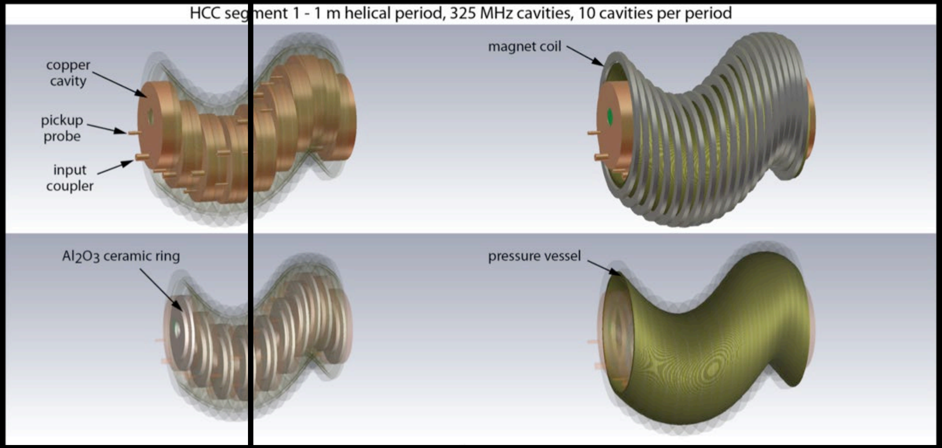


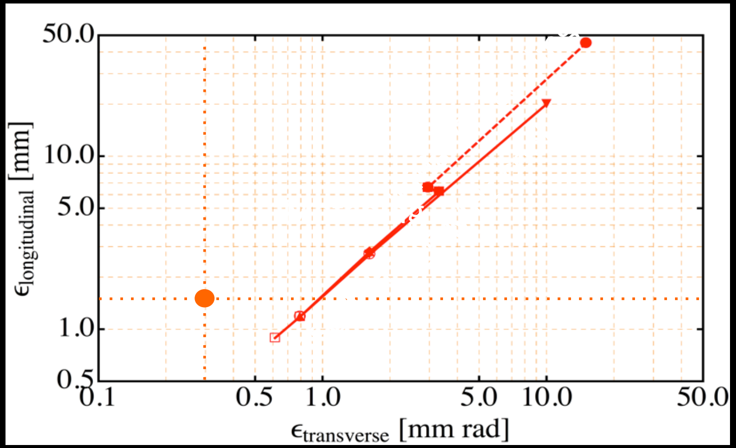
6D Rectilinear Vacuum Cooling Channel:

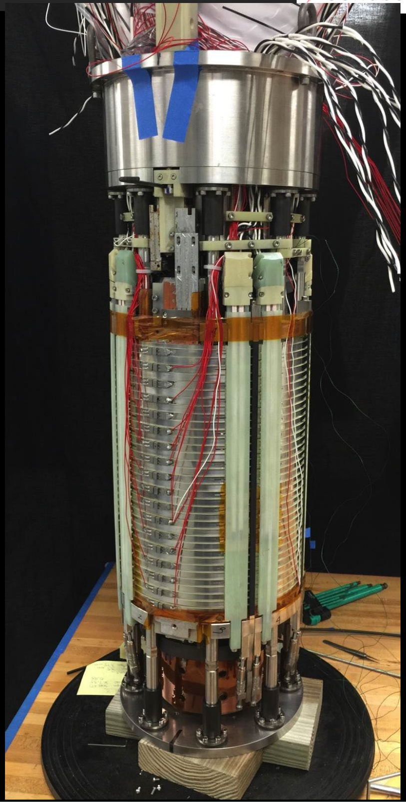
ε_T = 0.28mm, ε_L = 1.57mm @488m
Transmission = 55%(40%) without(with) bunch recombination

Hybrid Design: Equivalent performance with gas-filled cavity variant

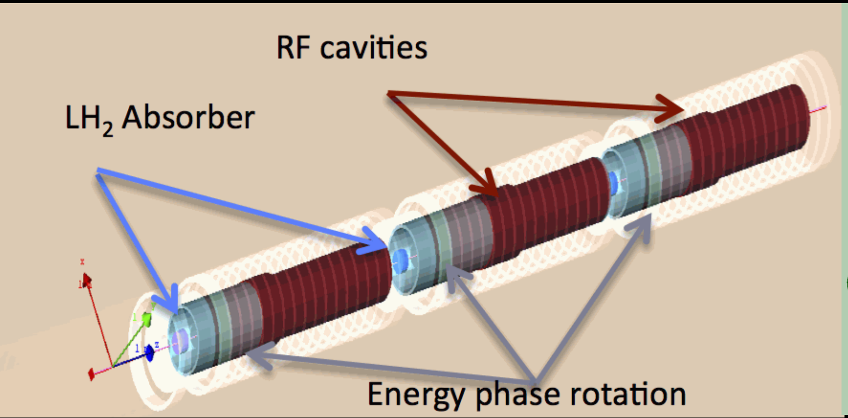
Muon Ionization Cooling (Design)

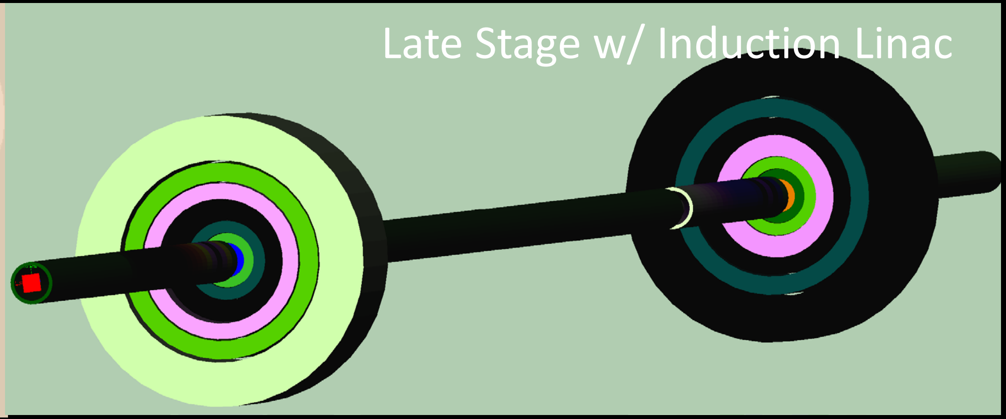






- Helical Cooling Channel (Gas-filled RF Cavities): $\varepsilon_T = 0.6$mm, $\varepsilon_L = 0.3$mm

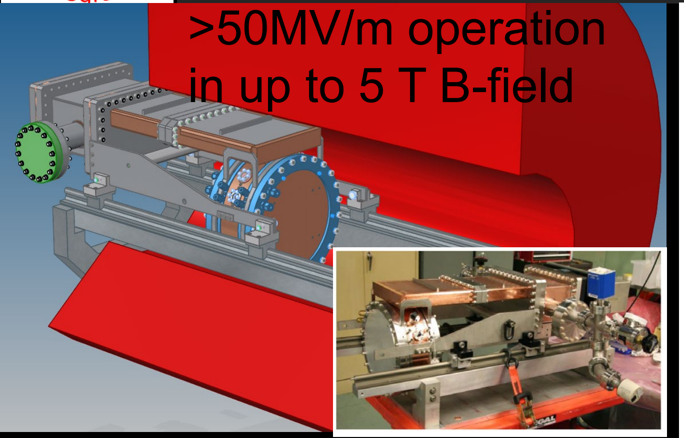


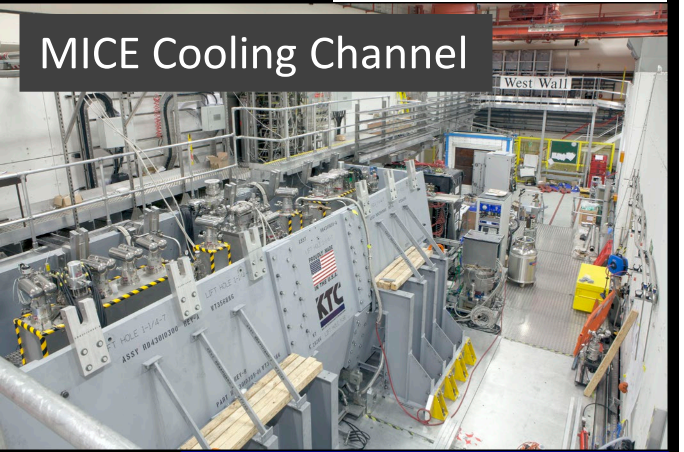


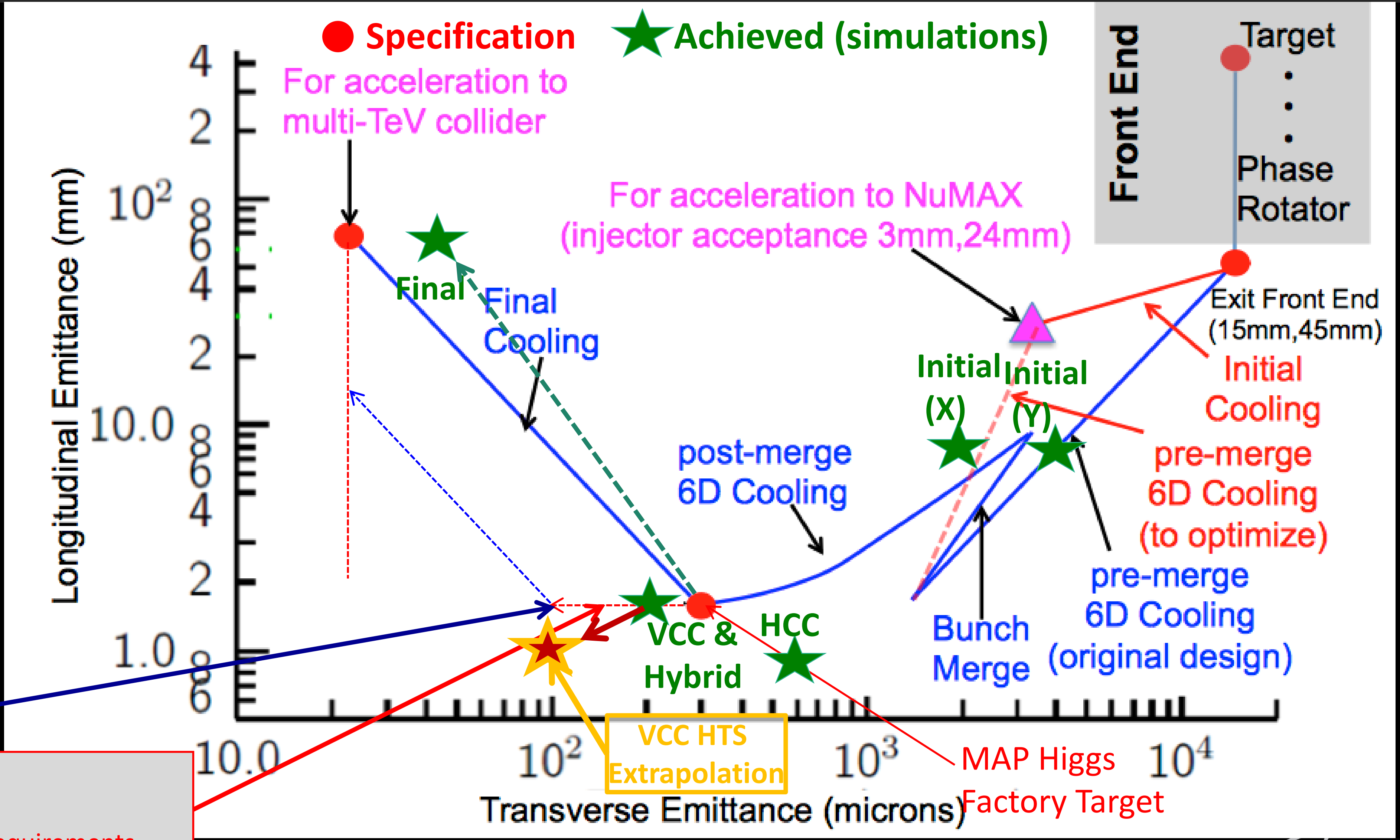
World Record LTS-HTS Hybrid Magnet
32T on-axis field
NHFML

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

Ionization Cooling







PIC assumed in Carlo Rubbia's Proposal

Advanced techniques ⇨
- Improved HF Luminosity
- Simplified Final Cooling requirements

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Some Cooling Comments

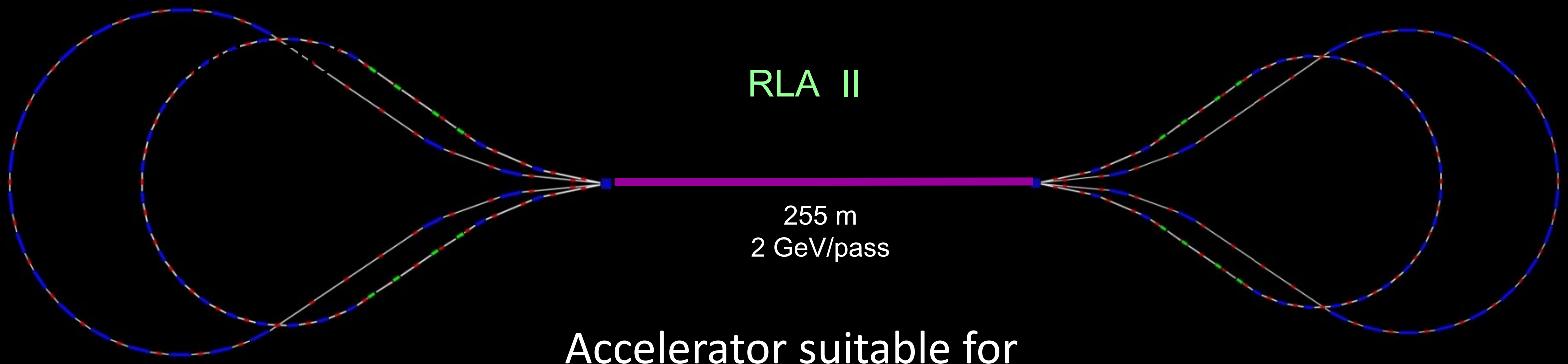
- MICE confirms our understanding of the ionization cooling process for muons
- MAP design studies and R&D provide a basis for the technologies in a complete cooling channel
  - But only piece-wise studies completed
  - Technology deliverables were achieved
    ⇨ now need to move to next-generation design effort
- Cooling has huge leverage on the overall machine design
  - What proton power is required on target?
  - What luminosities can be envisioned?
- A fully integrated design study is now warranted
- A technology demonstrator would enable performance studies of the cooling concepts at high beam intensities

Acceleration

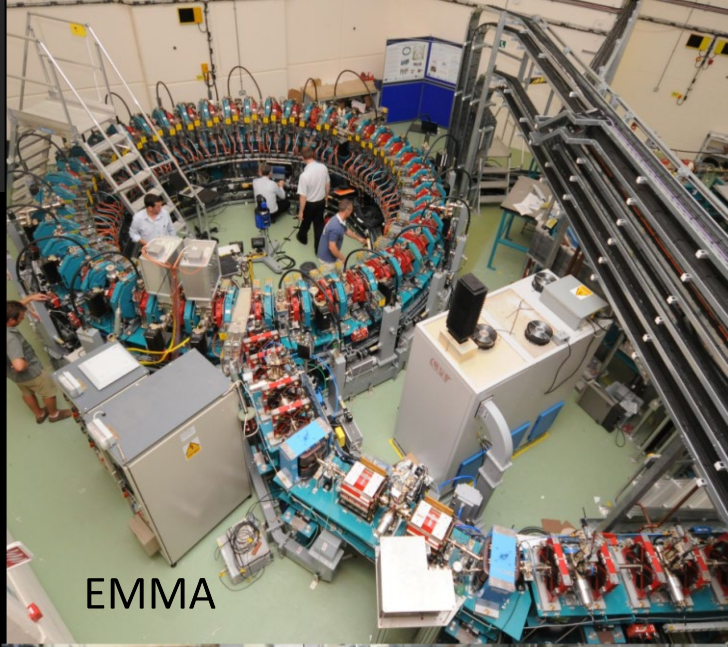
- Technologies Include:
  - Superconducting Linacs
  - Recirculating Linear Accelerators (RLAs)
  - Fixed-Field Alternating-Gradient Rings (FFAs)
  - Hybrid Rapid Cycling Synchrotrons

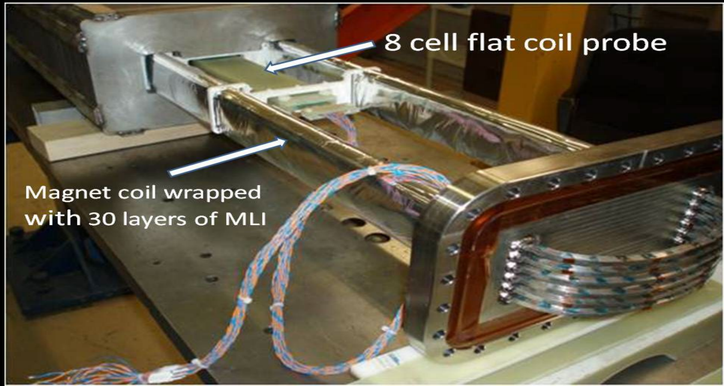
Designs to 125 GeV CoM (Superconducting Linacs, RLAs)

Needed for Multi-TeV Scale (FFAs, Hybrid Rapid Cycling Synchrotrons)

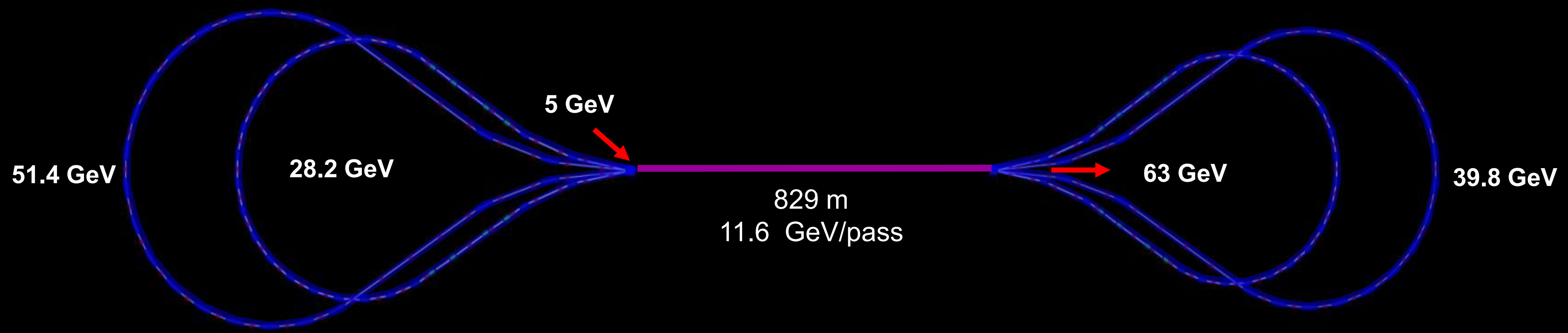


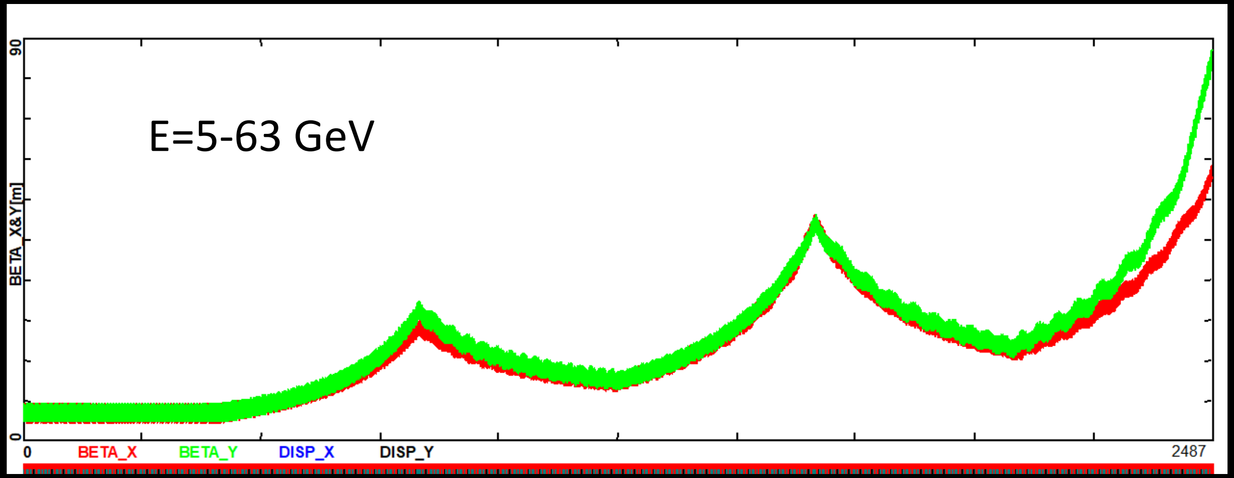
Accelerator suitable for Neutrino Factory Applications

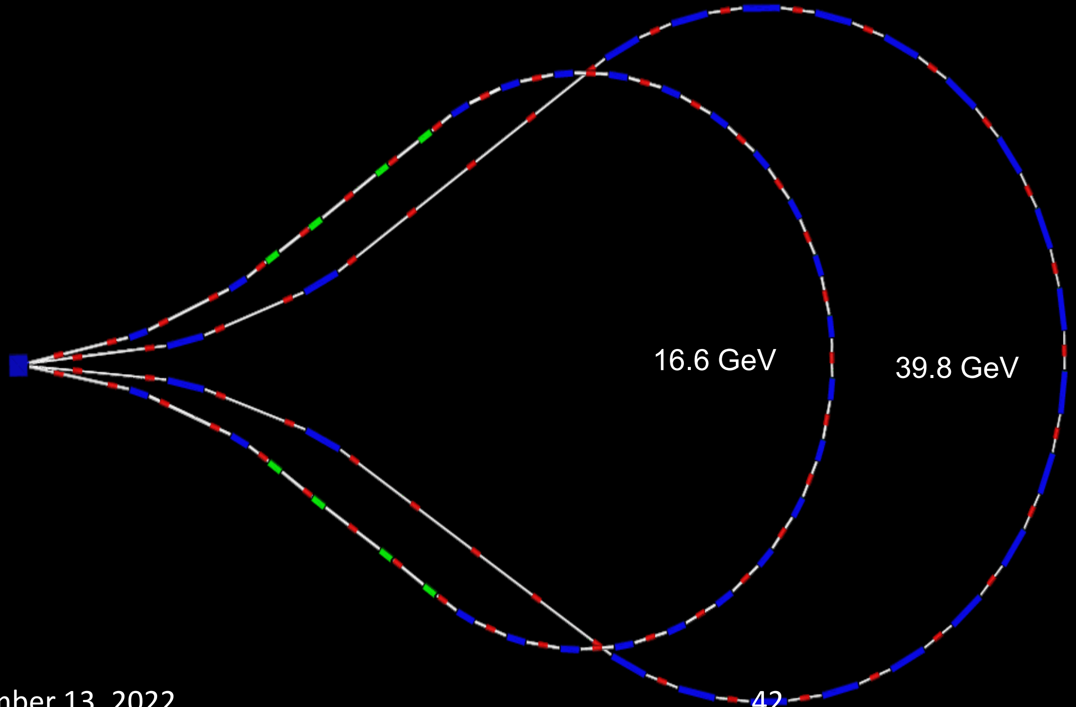




Acceleration to 125 GeV Center-of-Mass





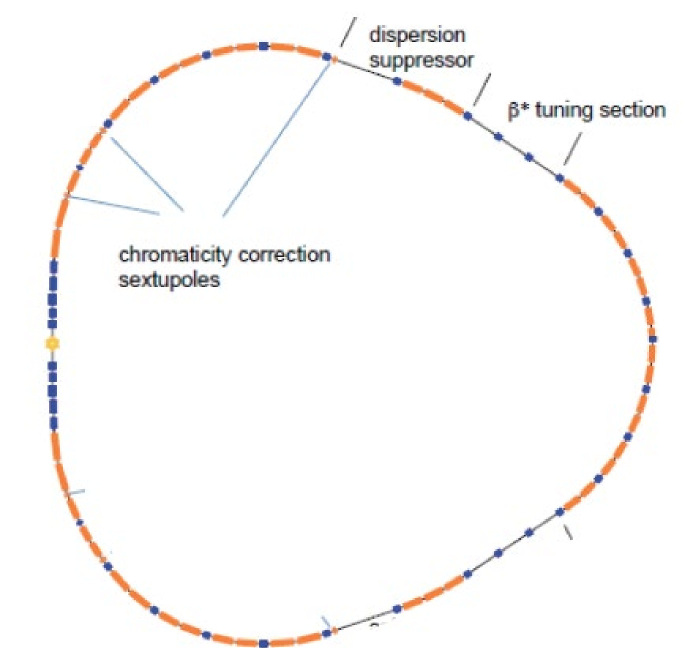


RF: f = 650 MHz cells/cavity = 5 Gradient = 25 MV/m phase = 22°

Higgs Factory (125 GeV) Lattice Design

Alexahin, et al., JINST 13 P11002

MC Higgs Factory:
MAP design
with a single IP



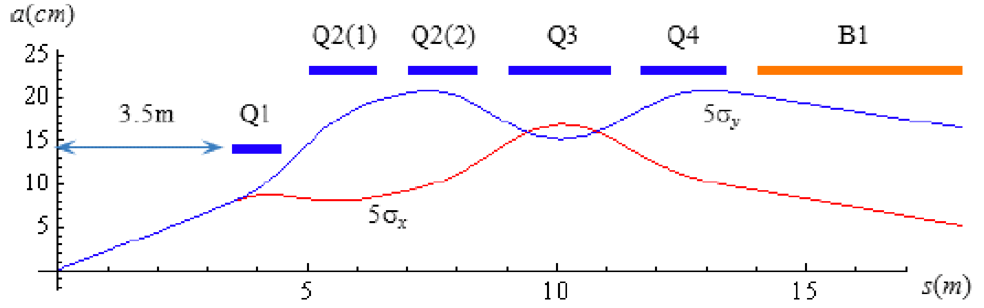


Figure 12. Higgs factory IR quadrupoles aperture and 5σ beam envelopes for $\beta^* = 2.5$ cm. Beam parameters are given in table 3.

Table 4. Higgs Factory IR Magnet Specifications

Parameter	Q1	Q2	Q3	Q4	B1
Aperture (mm)	270	450	450	450	450
Gradient (T/m)	74	−36	44	−25	0
Dipole field (T)	0	2	0	2	8
Magnetic length (m)	1.00	1.40	2.05	1.70	4.10

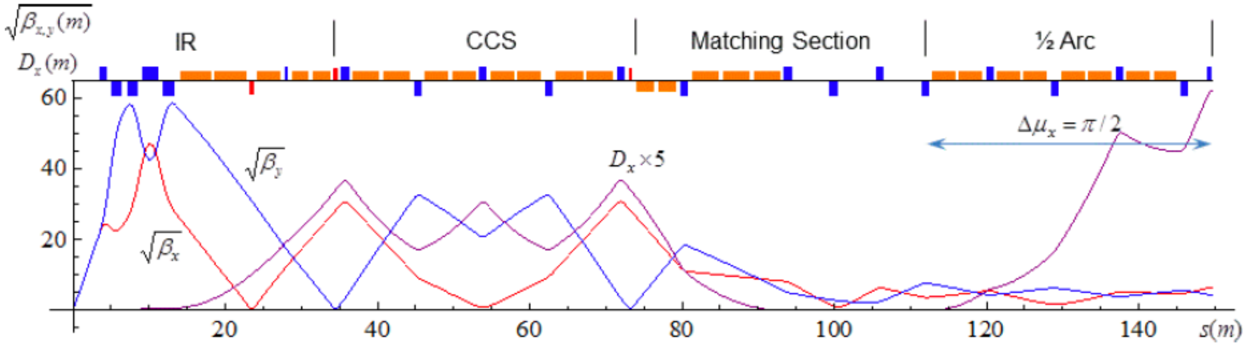
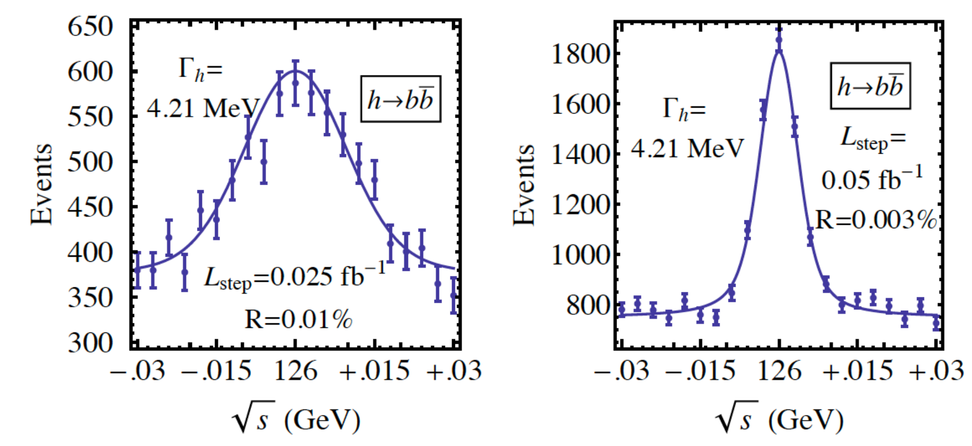


Figure 13. Layout and optics functions in half ring of the Higgs factory.

Key Features/Challenges of MC Higgs Factory



Han & Liu, arXiv:1210.7803 [hep-ph]

- Features:
  - s-channel production
  - Exquisite energy spread ($\delta E_b/E_b \sim 4\times10^{-5}$) allows direct probe of Higgs line shape
  - Spin precession of μ allows precise E calibration (Raja & Tollestrup, arXiv:hep-ex/9801004)
- Challenges
  - Higgs production rate with preliminary MAP assumptions (~13,500/Snowmass year) hasn't been considered competitive
    - However, VCC simulations already suggest we can do better than this
    - Introduction of alternative techniques such as Parametric Ionization Cooling (PIC) offer the potential of further rate improvements
  - Machine-Detector interface
    - IR magnet aperture requirements
    - Shielding detector from machine backgrounds

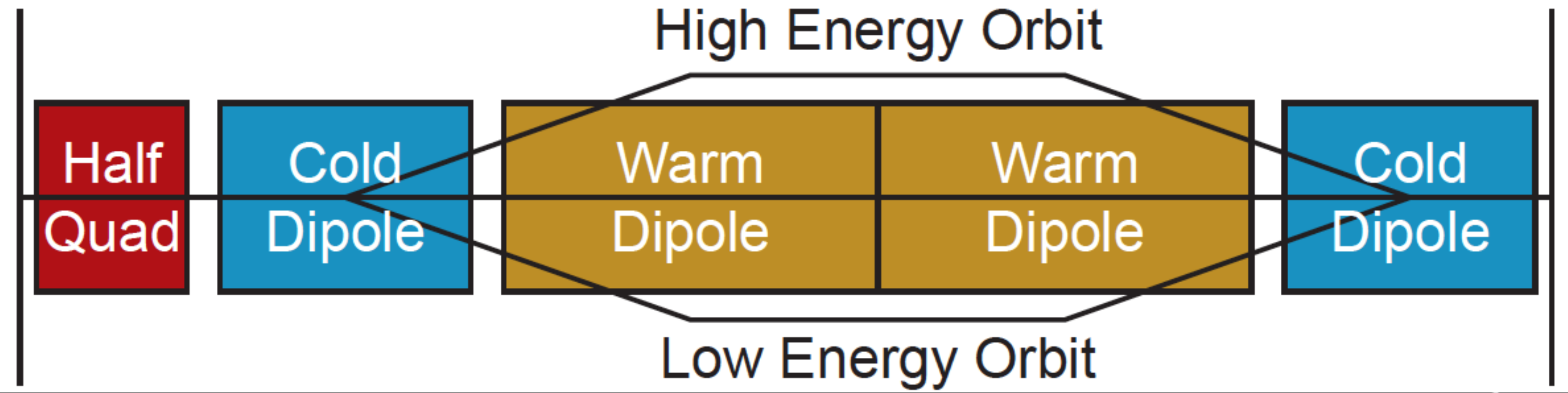
Based on MAP R&D results, an updated design study is required to fully evaluate potential performance

TeV-Scale Acceleration

H. Piekarz *et al.*, Record fast-cycling accelerator magnet based on HTS
NIM A, Vol 943, 2019, 162490, https://doi.org/10.1016/j.nima.2019.162490

FNAL
290 T/s
HTS
0.6 T max

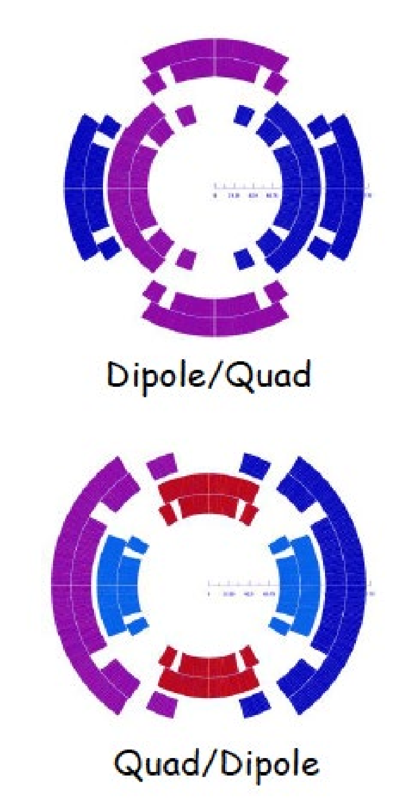
- MAP identified concepts
  - Final designs are not in hand
- Challenges:
  - Large energy bandwidth lattice at high energies
  - Fast-ramping magnets
    - Grain-oriented silicon steel?
    - HTS?
  - Power supply system and efficiency will determine the viability and energy efficiency of the accelerator systems

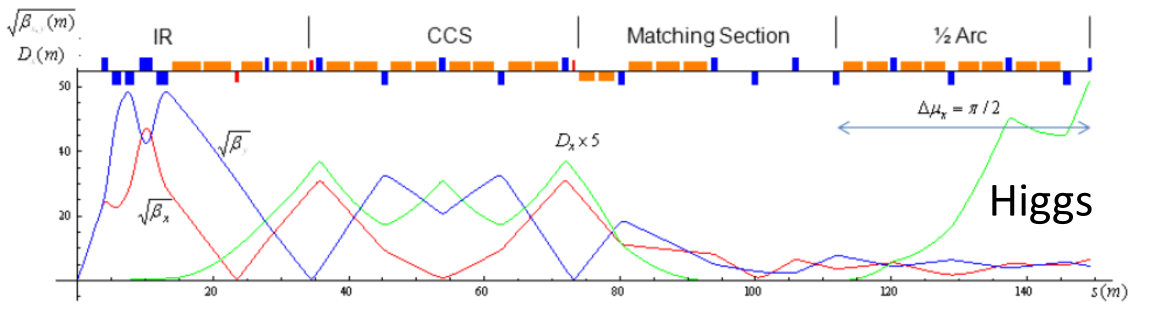


Hybrid Rapid Cycling Synchrotron Cell Concept

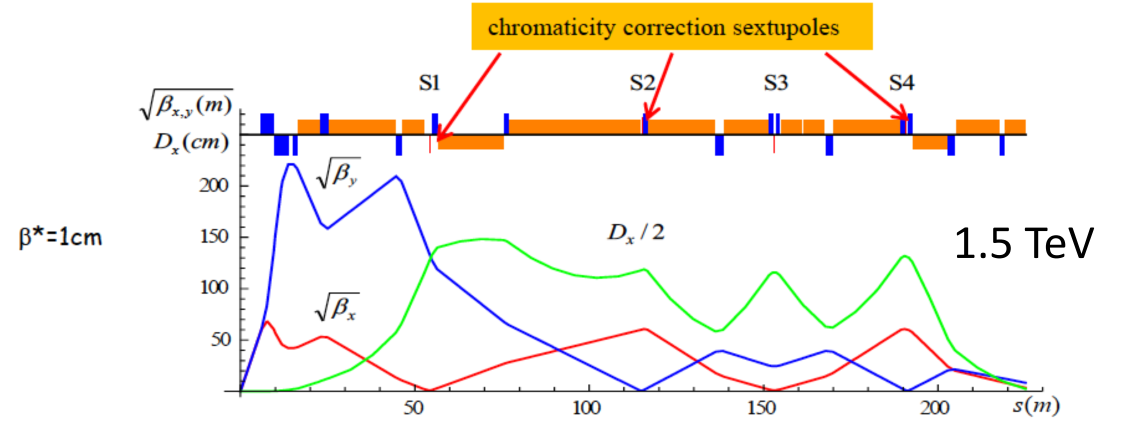
Collider Ring & Detector

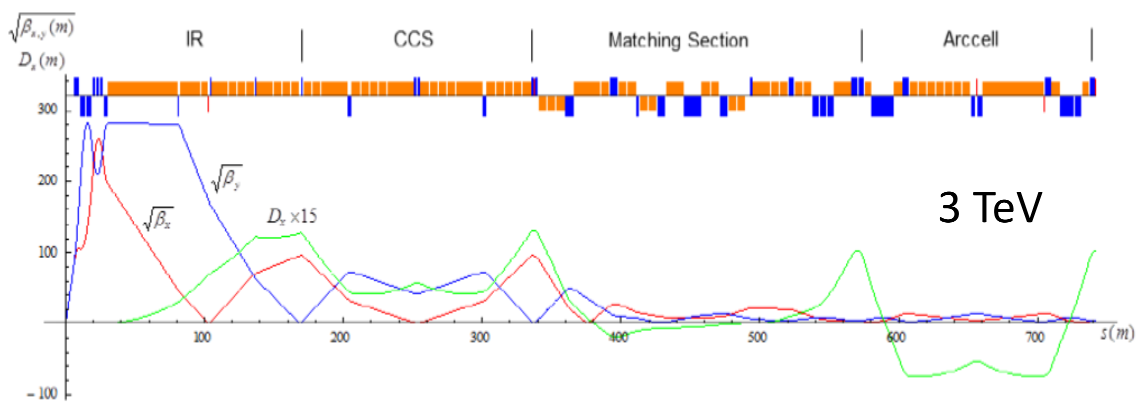
- MAP Optics Designs for
  - Higgs Factory (125 GeV)
  - 1.5 TeV CoM
  - 3.0 TeV CoM
  - 6.0 TeV CoM [extrapolation]
- Ring Magnet Designs
- IR Design



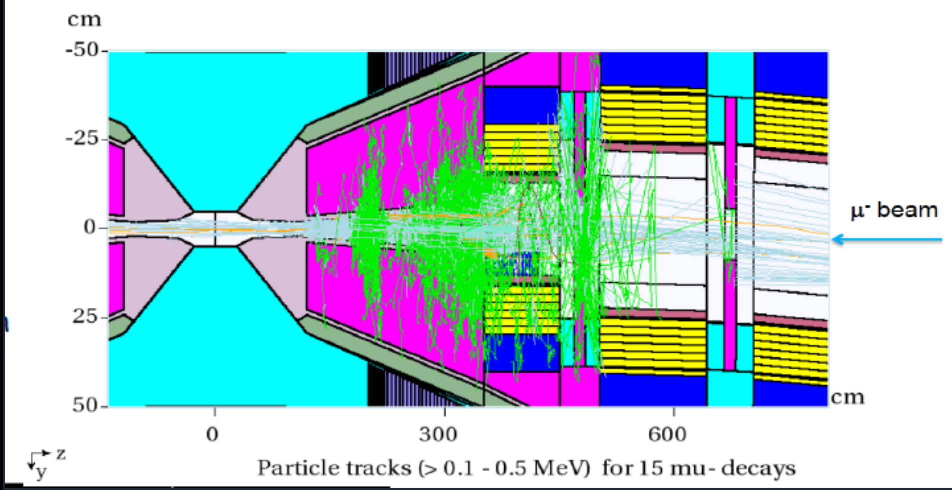


Higgs Factory lattice and optics functions for β*=2.5cm in a half-ring starting from IP





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

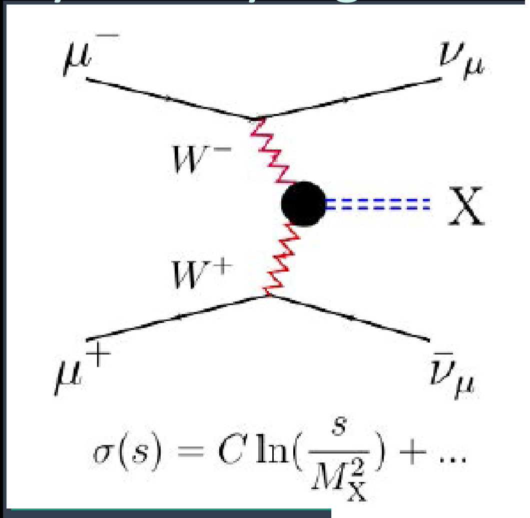


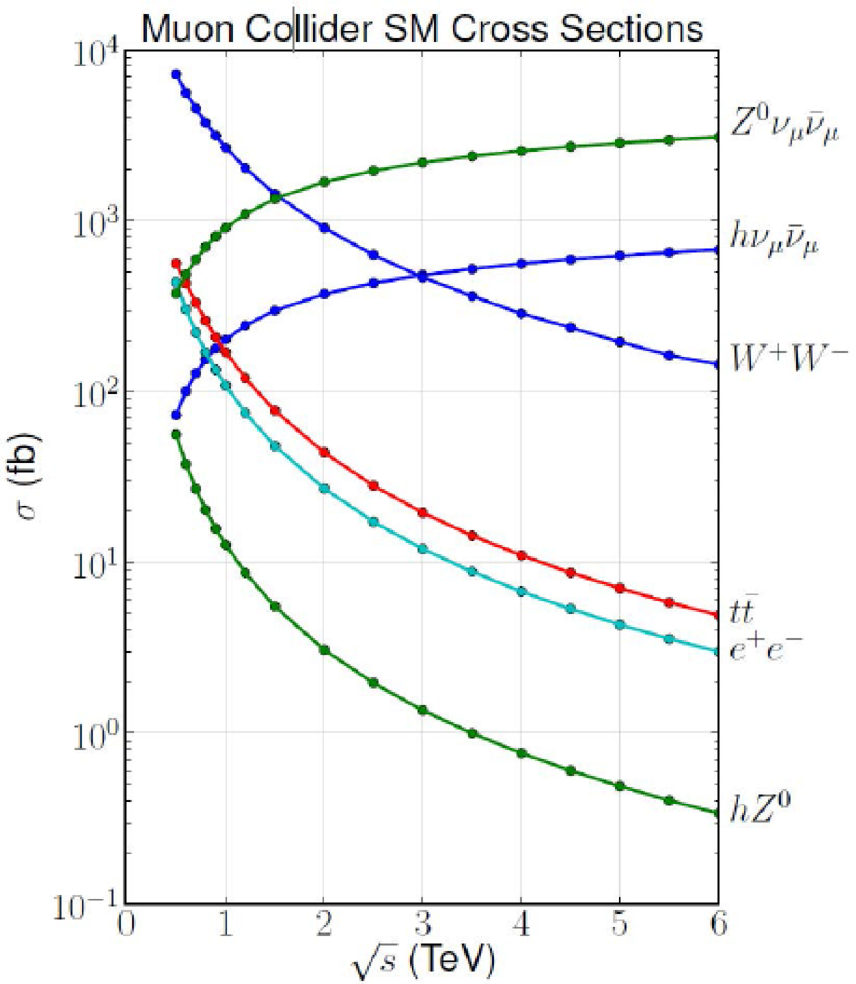
High Energy Muon Colliders

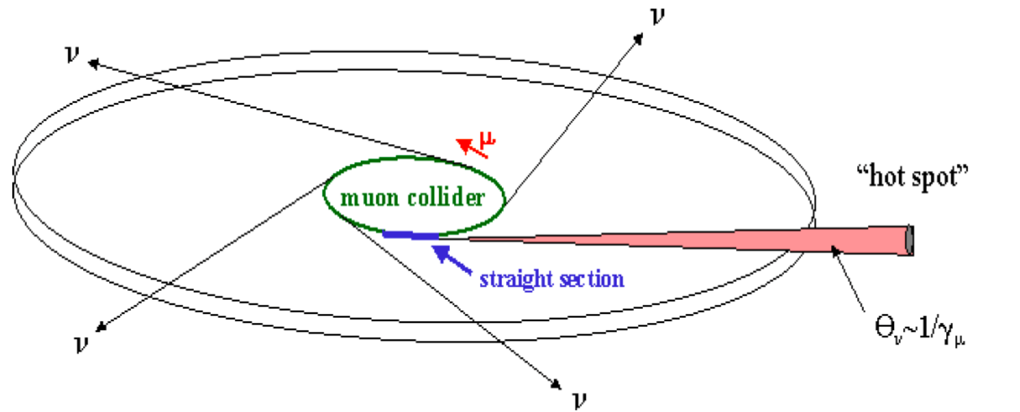
- Physics Reach
  - At √s > 1 TeV: Fusion processes dominate
  - An Electroweak Boson Collider
  - A discovery machine complementary to very high energy pp collider
  - At >5TeV: Higgs self-coupling resolution <10%
- Limitations
  - Beam-induced Backgrounds
  - Neutrino radiation -

Dose at earth's surface $\propto E_{\mu}^{3}$

B. King - https://arxiv.org/abs/hep-ex/0005006v1







Looking Forward…

- Muon Colliders offer an energy-efficient path to multi-TeV CoM energies
- Recent physics studies indicate that important collider physics is accessible
- The MAP R&D Program has successfully demonstrated critical technologies for the cooling channel ⇨ Now ready for:
  - Updated Cooling Channel Conceptual Design
  - Demonstrator of a high intensity cooling cell
- Other key developments to pursue for a TeV-class collider (move beyond the parameters and scope of MAP)
  - Ongoing physics studies
  - Detailed designs for TeV-class acceleration
  - Full end-to-end conceptual design
  - Mitigation approaches to minimize "ν Radiation" issues at the exit point on the surface

A new international design effort is timely and ready to evaluate an important option for the HEP community

Key Challenges – IMCC Efforts

10+ TeV is NEW Territory ⇨ Key Challenges:

- Evaluation of physics potential (including detector concept and technology)
  - Impacts of beam induced background across all physics analyses
- Neutrino Flux Mitigation
  - Straight accelerator sections at high energy produce an intense ν beam
- High Energy Systems
  - Acceleration sections can impact the energy reach due to cost, power, technical risk, and impact on beam quality ⇨ requires more detailed evaluation
  - 10+ TeV Collider designs must be developed and fully evaluated
- Cooling string demonstration to verify high brightness muon beam delivery

Neutrino Flux – IMCC Efforts

Team of RP experts, civil engineers, beam physicist and FLUKA experts

Goal to be **similar to LHC**: i.e. **negligible**, "fully optimised" (10 x better than MAP goal, 100 x better than legal requirements)

- With indirect effects (air, ground water, …)

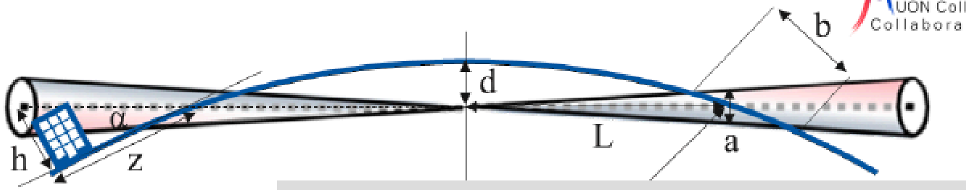
Addressed by:

Site choice in direction of experiments

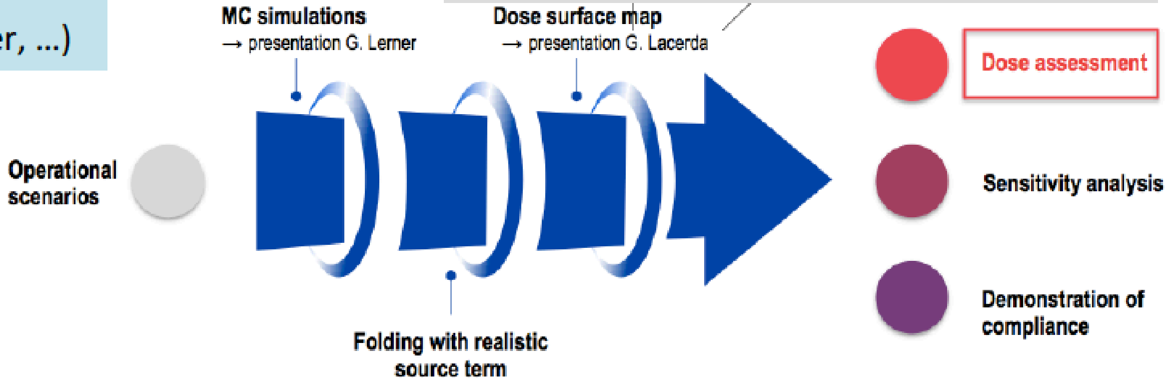
- tools in preparation

Mechanical mover system in arcs

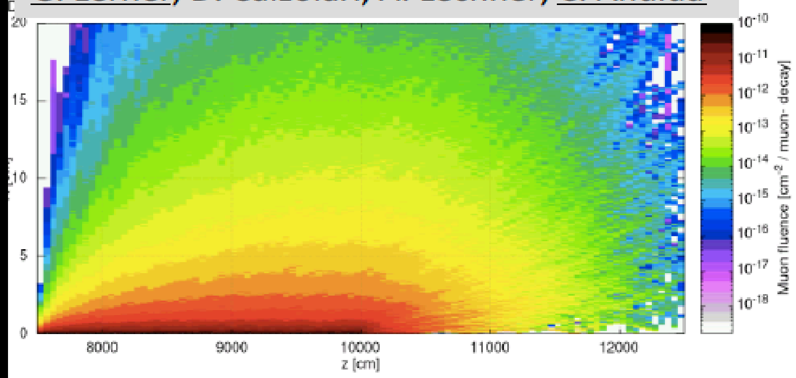
- allows 14 TeV in 200 m deep tunnel



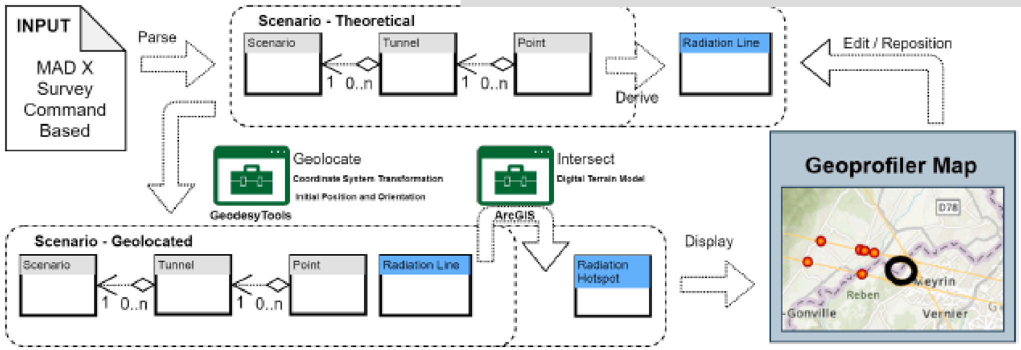
C. Ahdida, P. Vojtyla, M. Widorski, H. Vincke



G. Lerner, D. Calzolari, A. Lechner, C. Ahdida



G. Lacerda, Y. Robert, N. Guilhaudin



Mover system and impact on beam will be addressed in the coming years before end if 2025

D. Schulte