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International MUON Collider Collaboration

Brookhaven National Laboratory

U.S. Department of ENERGY

Muon Collider R&D Perspectives

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@BrookhavenLab

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Presentation Outline

Preface:

- Perspectives from MAP
- Basis for Prioritization
- Some Comments

Structure of Each R&D Item

Review of “Key” R&D Items

- As informed by experience with MAP and IMCC

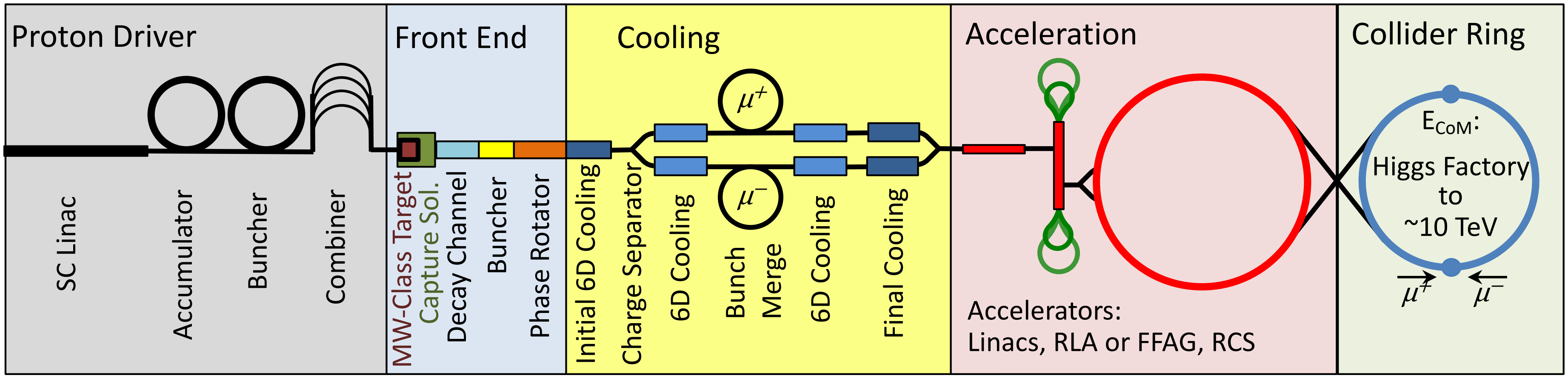
Overall Prioritization based on:

- TRL
- Fermilab planning
- Timeliness
- Community Perceptions

Conclusion: Some Priorities

Preface: Perspectives from MAP

Muon Collider



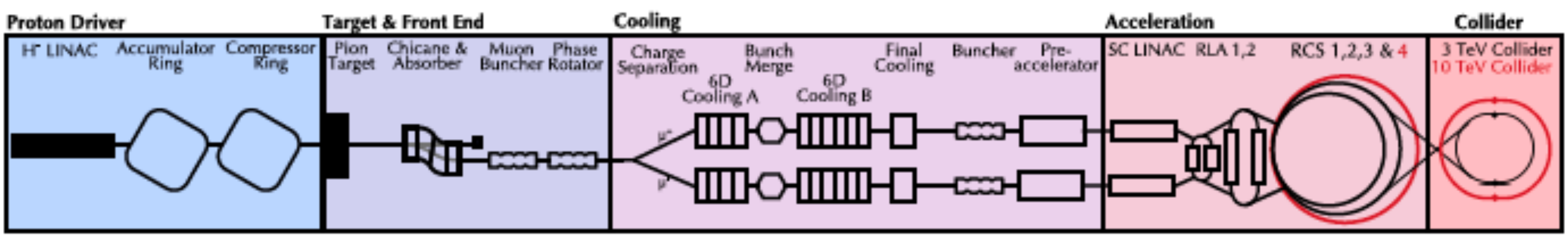


Figure 1.1.1: Conceptual layout of the muon collider.

Preface: Basis for Prioritization

- What is needed to:
  - Bring each collider sub-system to a reasonable TRL
    - Provide a reference design report with a clearly defined R&D program
  - Make the Muon Collider case to the community
    - Establish a clear Reference Design
    - Provide a validated set of operating parameters
    - Evaluate the realistic reach of any facility that we could deploy
    - Address basic concerns - such as:
      - Cooling performance
      - The impacts of off-site ionizing radiation
  - Ensure that we understand the performance trade-offs required to build a Muon Collider
    - End-to-End versus Piece-Wise understanding of the machine
    - Enable useful performance validations and multi-system optimization
    - Develop a viable pathway for Fermilab

Preface: Comments

This presentation is inherently a very short high-level overview focusing on the accelerator complex

Will try to highlight items that this panel should prioritize in its requests for further information

Not meant to be truly comprehensive ⇨ rather to identify items that should be US priorities

Structure

- Scope for R&D (Facility, Sub-system, Technology, Beam Physics,…)
- Description
- R&D Required
- Issues specific to potential Fermilab siting
- Potential Synergies
- Useful Materials

Proton Driver (1)

- Scope for R&D: Proton Driver
- Providing a conceptual design for a proton driver meeting the requirements for muon production – MAP parameters (nominal):
  - H⁻ LINAC
  - 2-4 MW
  - 5-15 Hz (50-60 Hz for ν Factory)
  - 6-8 GeV (5-15 GeV plausible) [IMCC focus on 5 and 10 GeV]
  - Accumulator/Compressor System
    - ~3-6 bunches combined on target
    - 1-3 ns bunch length on target (nom. 2 ns)
- R&D Required
  - PIP-II LINAC as presently implemented cannot achieve the required MC parameters ⇨ upgrade concept
    - Project X: Provide a straightforward upgrade path for a 4 MW, low-duty-factor source of protons at energies between 5 and 15 GeV.
  - MAP chose to consider PIP-II+ + PIP-III to provide a plausible staging scenario (proton upgrades followed by further improvements mated to MC/NF front end implementation)
    - 3 GeV H⁻ LINAC, *followed by a*
    - 3.75 GeV Dual Use LINAC
  - Demonstration of a multi-GeV laser stripping system
  - Design of fixed energy, large aperture, ~1-3×10^2 m circumference Buncher and Accumulator rings
  - More mature design of the “compressor” stage to deliver POT

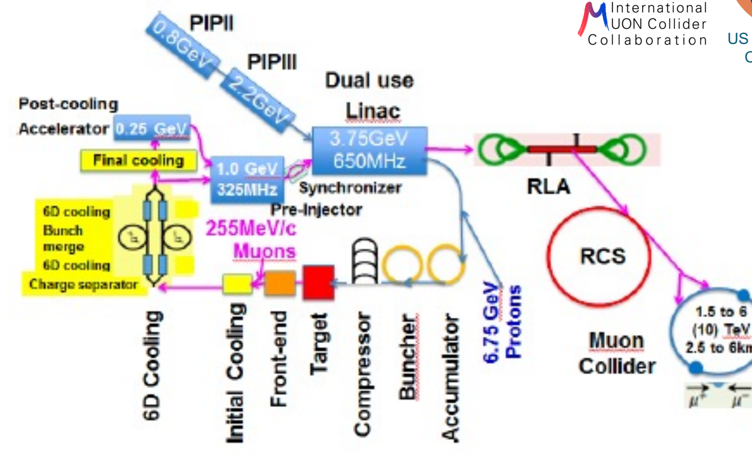


Fig. 13. Layout of a muon-based multi-TeV MC.

TABLE I. Proton-driver requirements. A proton kinetic energy in the range 5 to 15 GeV has been shown to provide adequate performance. The number of protons, beam radius, β^*, and geometric emittance correspond to the values for an 8 GeV proton beam.

Parameter	Value
Kinetic energy	5–15 GeV
Average beam power	4 MW
	(3.125×10^{15} protons/s)
Repetition rate	50 Hz
Bunches per train	3
Total time for bunches	240 μs
Bunch length (rms)	1–3 ns
Beam radius	1.2 mm (rms)
Rms geometric emittance	<5 μm
β^* at target	≥ 30 cm

Proton Driver (2)

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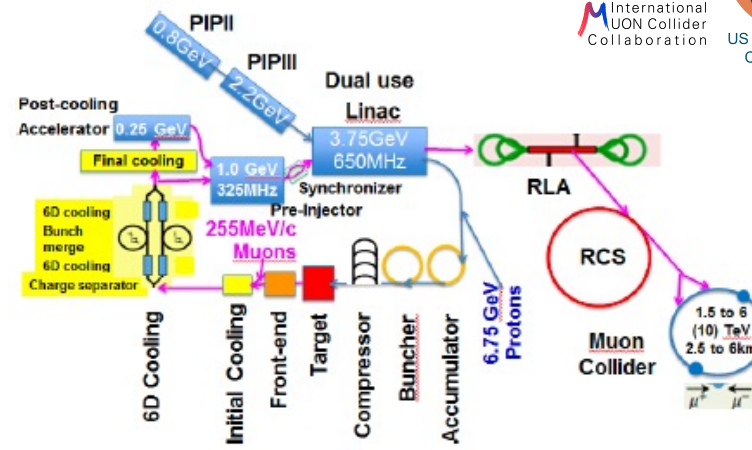
- Issues specific to potential Fermilab siting
  - Requires a robust analysis of the Fermilab Accelerator Complex Evolution (ACE) options
  - Needs significant focus to provide a plan to DOE (upcoming review panel?)
- Potential Synergies
  - Would a ~2 GeV PIP-n implementation with space for buncher and accumulator rings allow a staging option for science:
    - Via an Advanced Muon Facility?
    - For MC R&D?
    - Followed by deployment of a dual-use LINAC to achieve optimized target parameters?
  - Delivery of ≳5 GeV would support a range of ν factory possibilities
- Useful Materials
  - Project X Design Study
    - Presentation by S. Nagaitsev at ACE Science Workshop
  - MAP Concepts
  - IMCC Concepts:
    - "Towards a Muon Collider"
    - "The Muon Collider – Supplementary report to the European Strategy for Particle Physics - 2026 update"



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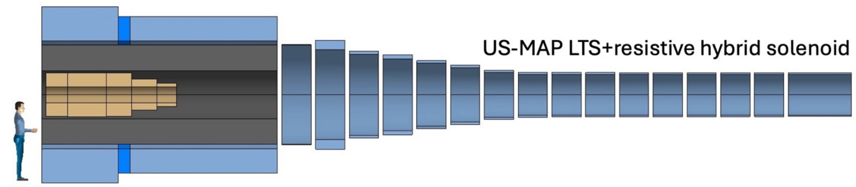
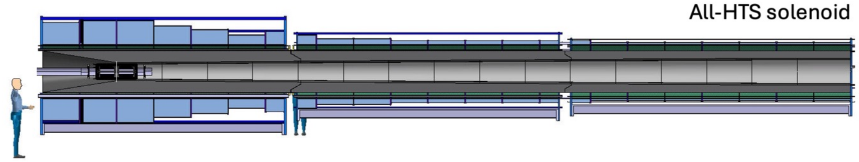
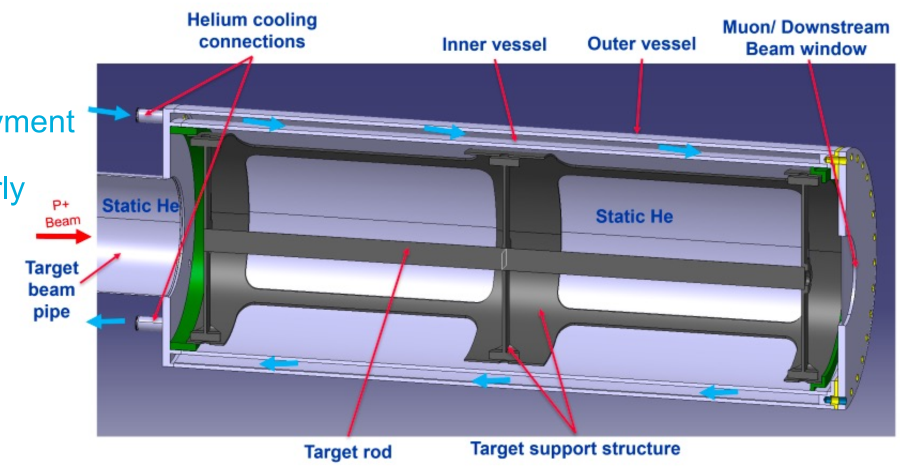
Target Systems

- Scope for R&D: Target Solenoid and High-Power Target
- Description: High field capture solenoid and multi-MW target options
- R&D Required
  - Magnet Design
    - MAP studies showed that ~15T would allow acceptable performance
    - All HTS appears plausible – but need to balance readiness versus R&D (i.e., identify the most acceptable baseline design)
  - Proton beam delivery scheme
    - Downstream proton beam filtering in front end
    - On- versus off-axis beam delivery
    - Primary proton beam dump
  - Target Technologies
    - Initial solid target (C)
    - Ultimate liquid metal target?
    - Modular concept to support target upgrades
- Issues specific to potential Fermilab siting
  - Can a relevant target demonstration be integrated with deployment of a Cooling Demonstrator?
  - Stronger engagement with the RADIATE collaboration is clearly necessary to deliver target concepts
- Potential Synergies
  - Target development for an Advanced Muon Facility?
- Useful Materials
  - HTS Target Solenoid and references therein
  - "The Muon Collider – Supplementary report to the European Strategy for Particle Physics - 2026 update"







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Initial Cooling and Charge Separator

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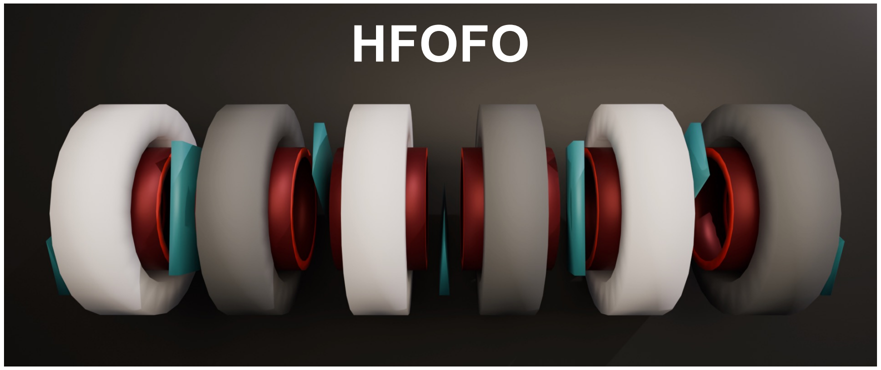
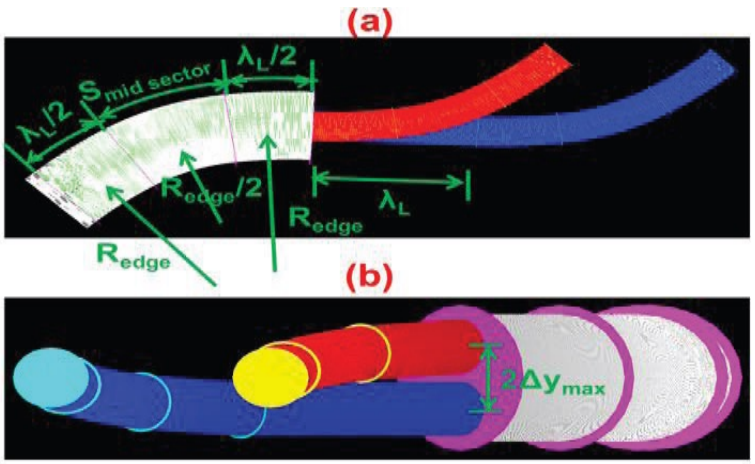
- Scope: Preparation of muon beams for the 6D cooling channel
- Description: Charge separation challenging given the large beam sizes a Initial Cooling section needs to be retained at the start of the cooling system
- R&D Required
  - Dual-charge cooling can be provided by the MAP HFOFO snake design
  - Potential to do either gas-filled or discrete absorber scheme
- Issues specific to potential Fermilab siting
  - Effective demonstration of a 6D cooling cell may require preliminary beam preparation. A modest initial cooling stage to provide better beam parameters and matching?
- Potential Synergies
  - Improved beams for muon experiments
- Useful Materials
  - [HFOFO]
  - [MAP Charge Separation Study]





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6D Cooling

- Scope: 6D Cooling Channel Design and Demonstration
- Develop preliminary engineering designs for a 6D cooling cell and
- R&D Required
  - Establish acceptable design parameters and operating limits
    - Options for absorber materials and configurations
    - Solenoid fields and conductors
    - RF in magnetic fields
    - Validation of proposed cooling channel performance parameters
    - Initial evaluation of instrumentation requirement and techniques
    - Evaluation of matching issues
  - Ensure that we can reliably evaluate the full physics performance of the cooling channel
- Issues specific to potential Fermilab siting
  - Proton-based beam testing of hardware in addition to demonstrator testing with muons
  - Opportunity to explore an alternative design strategy to the IMCC proposal
    - US program well-suited to model gaseous absorber and plasma-driven beam dynamics
    - Potentially more readily engineered implementation?
- Potential Synergies
  - Strong coupling to US MDP program
  - Exploits US modeling capabilities for RF in magnetic fields
  - Potential delivery of improved beams for a range of muon-based experiments
- Useful Materials
  - Rectilinear Cooling Channel
  - Gas-filled Rectilinear Cooling
  - IMCC 6D Cooling Concept (ESPPU Submission)

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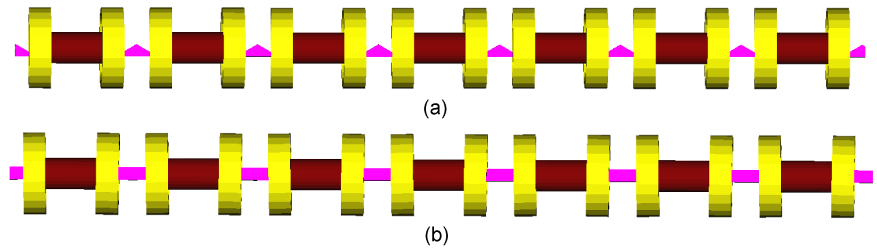

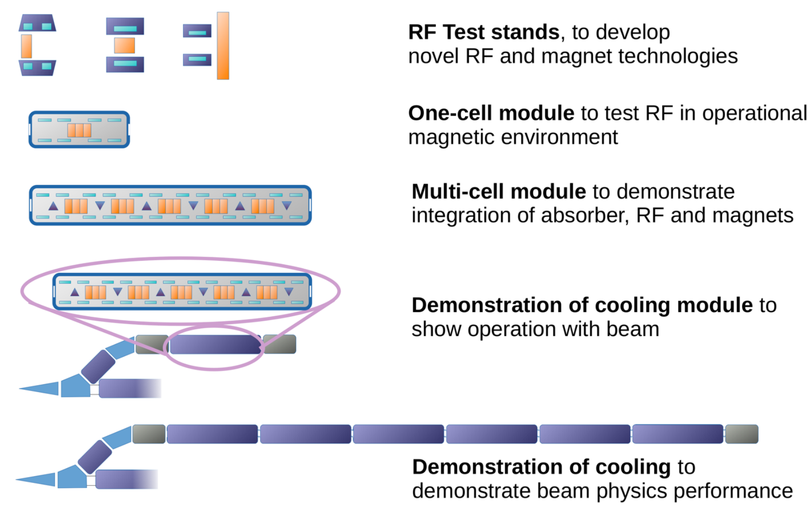

Final Cooling

- Scope for R&D: Final Cooling and high field solenoid demonstrations
- Description: Moderate aperture (r ~ 25 mm) very high field solenoids (>40 T) of meter-scale length represent the default design concept.
- R&D Required
  - High field solenoid parameters
  - Potential RF configurations
  - Detailed design with full matching criteria to better evaluate performance
- Issues specific to potential Fermilab siting
  - Not significant in near term
- Potential Synergies
  - Strong coupling to high-field solenoid user magnet program at MagLab
- Useful Materials
  - MAP Baseline
  - IMCC Final Cooling Concept (ESPPU Submission)

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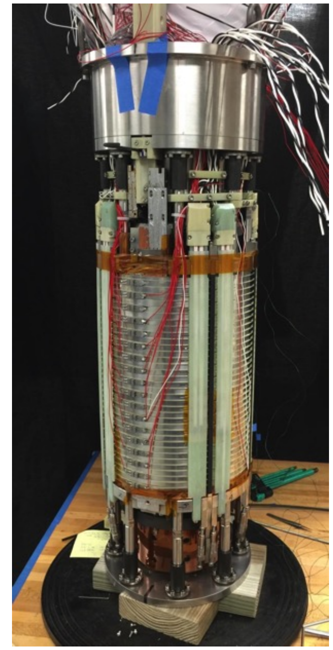
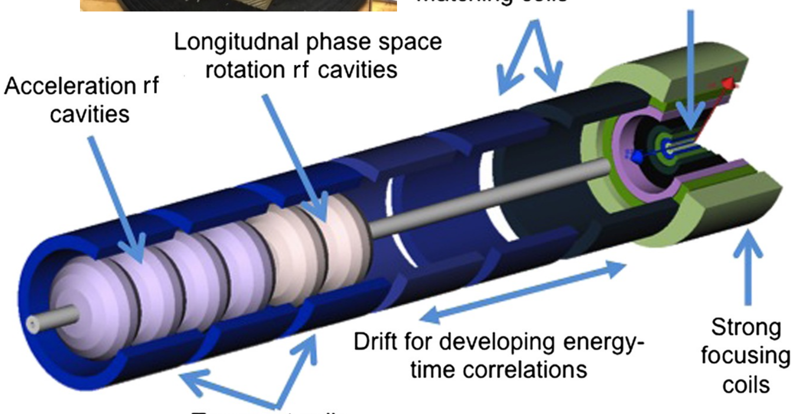


MagLab 32T HTS User Magnet



Acceleration

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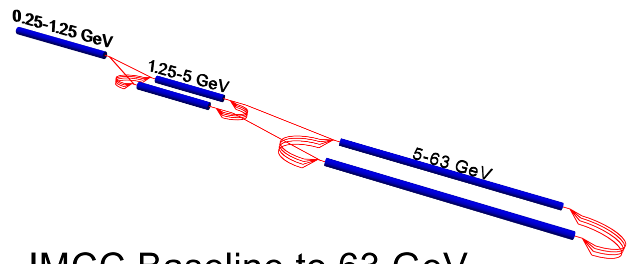
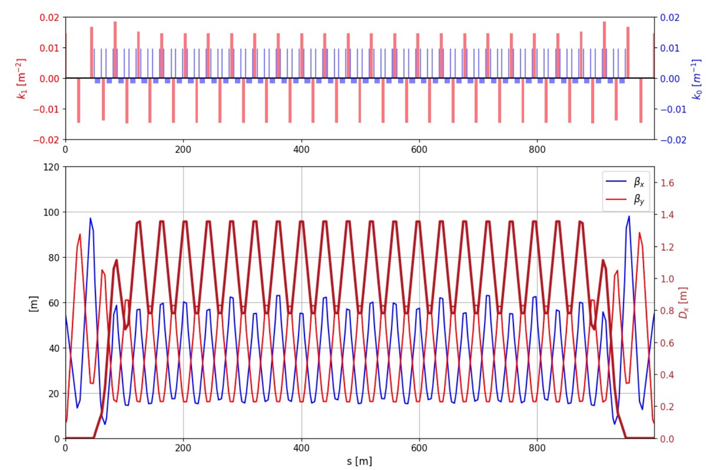
- Scope: Accelerator Systems for the MC
- Description: Accelerator design studies, with an emphasis on Fermilab siting
- R&D Required:
  - Design issues:
    - Update acceleration stage parameters (low, medium, and high energy ranges) and optimal transition points
    - Evaluate potential of dual LINAC scheme
    - Standardize RCS design tools
    - Evaluate potential energy limits for final ring
  - Injection/Extraction/Matching issues
  - Evaluate magnet designs – increasing the peak useful field has tremendous leverage
  - Full accelerator system beam modeling
- Issues specific to potential Fermilab siting
  - Establishing a realistic collider CoM energy limit is critical
- Potential Synergies
  - HTS-based fast ramping magnets at FNAL offer significant potential
  - Evaluate implications for the fast-ramping power supply system
- Useful Materials
    - "The Muon Collider – Supplementary report to the European Strategy for Particle Physics - 2026 update" summarizes current state of accelerator design and modeling
    - HTS Magnet Feasibility



IMCC Baseline to 63 GeV



RCS2 in IMCC Baseline

Collider

- Scope: Collider and Interaction Region
- Description: IR, BIB impacts, νs in straights
- R&D Required
  - Interaction region design concepts
  - Identify acceptable trade-offs for collider design
    - Luminosity impacts of conservative magnet assumptions (distinguish from FCC-hh needs)
    - Optimization of straight section lengths
  - Evaluate detector and physics performance
- Issues specific to potential Fermilab siting
  - Evaluate site options for ν exit locations
- Potential Synergies
  - Can Fermilab become the world leader in delivery of high quality and high intensity muon beams for a broad range of science?
- Useful Materials
  - "The Muon Collider – Supplementary report to the European Strategy for Particle Physics - 2026 update"

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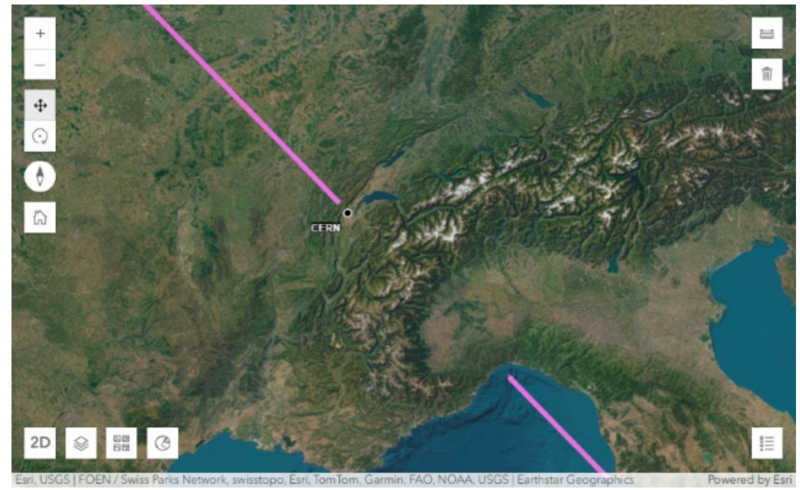

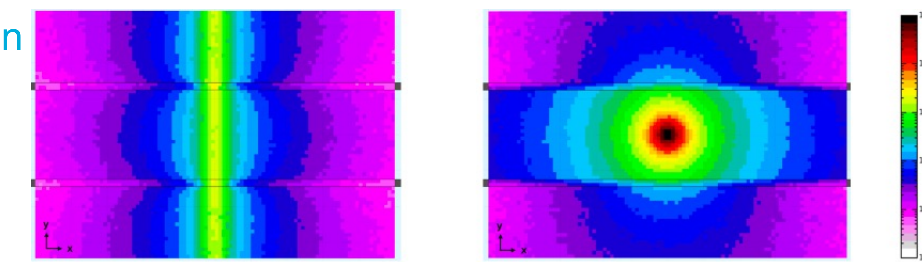

Mitigated

Unmitigated

Collider Straight Section ν-induced Ionizing Radiation

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End-to-End Design and Beam Simulation

- Scope: Reference Design Report and End-to-End Simulation
- Description: A reliable end-to-end performance simulation based on an approved baseline configuration is needed.
- R&D (and other) Required:
  - Continued improvement to design tools
  - Effort to address matching within and between all key systems
- Issues specific to potential Fermilab siting
  - Proton driver configuration and performance
  - Establish an integrated design team that can interface closely with the IMCC effort and provide site-specific options
  - Energy reach
  - Off-site radiation
  - Luminosity performance
  - Cost implications
- Potential Synergies
  - Clarify options for future μ and ν sources at various stages of the complex
  - Create a full scientific basis for a US-based facility

Conclusion: Some Priorities

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- Fermilab Complex
  a. Proton Driver parameters
  b. Acceleration concepts and staging options
  c. Synergies for staging
  d. Evaluating the collider energy limits for the Fermilab site
- Reference Design Development
  a. Limits of acceleration stage energy reach at Fermilab
  b. Site layout options to manage ν radiation
  c. Matching studies throughout complex
  d. First end-to-end beam modeling
- Ionization Cooling
  a. Engineering evaluation of a late-stage 6D cell
  b. Technology evaluations and simulations
     i. RF in magnetic field design and materials R&D
     ii. Realistic solenoid design parameters (Initial, 6D, and Final Cooling)
     iii. Cryomodule integration concepts
     iv. Iterate with 6D Cooling Channel design studies
  c. Continued effort on Initial through full 6D cooling design
  d. Gas-filled channel option
- Interaction Region Design
  a. Implications for physics
  b. Implications for off-site impacts