Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

Challenging of muon acceleration for muon colliders

Story based on Fermilab Accelerator Complex Evolution

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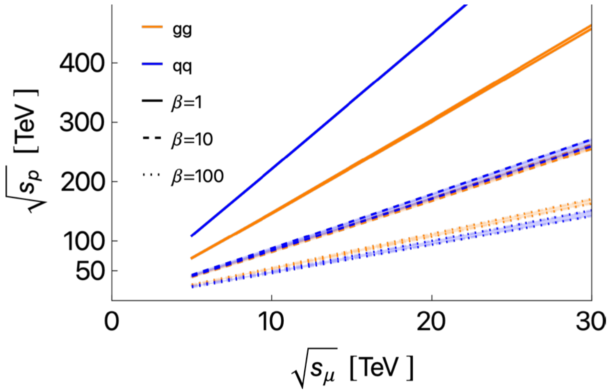
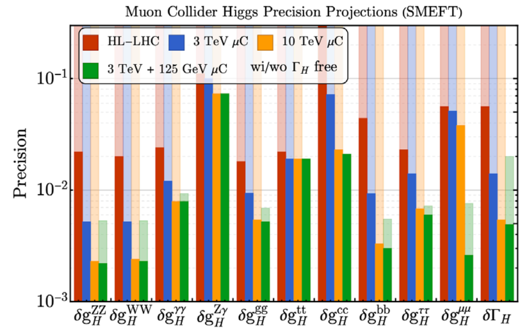
Discovery Machine MuC Design Parameter

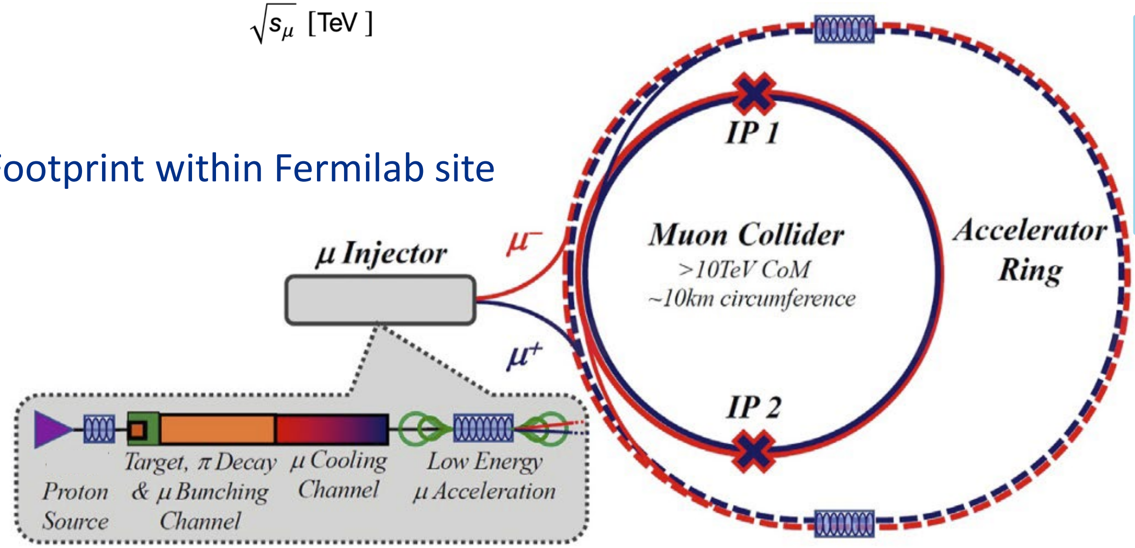




- MuC COM can be fully utilized for physics events
- Clean lepton collision event allows for precise measurements

@ 3 TeV	~ 1 ab^{-1}	5 years
@ 10 TeV	~ 10 ab^{-1}	5 years

Footprint within Fermilab site



$$\mathcal{L} = \frac{N_{\mu^+} N_{\mu^-} \cdot f N_{IP} R}{4\pi\sigma_x \cdot \sigma_y}$$

f: Revolution of beam in the ring
N_{IP}: Number of interaction points
R: Beam repetition rate

Muon Acceleration Requirement

- Make muon beam phase space as small as possible (small σ_x, σ_y)
- Maintain muon beam intensity as much as possible (large N_{μ^+}, N_{μ^-})

Challenge in Initial Stage Muon Acceleration

- Proton Driver (Find extra slides in “Backup”)
  - Intense proton beam (~10^{14} protons per bunch, small spot size ~5 mm, bunch length 1~3 ns, and repetition is 5~10 Hz) with kinetic energy range 5-20 GeV
  - Beam parameter is limited by the **space charge effect**
- Pion Production Target and Pion/Muon Capture Channel
  - Target must stand for the impact of extremely intense proton beam
  - Heat deposition system, beam dump, and beam absorbers are needed without losing production and capture efficiencies
  - Capture magnet (baseline design is a solenoid magnet) must survive in extremely high radiation environments
- Muon Ionization Cooling (Find extra slides in “Backup”)
  - Maximize cooling decrement and minimize particle loss

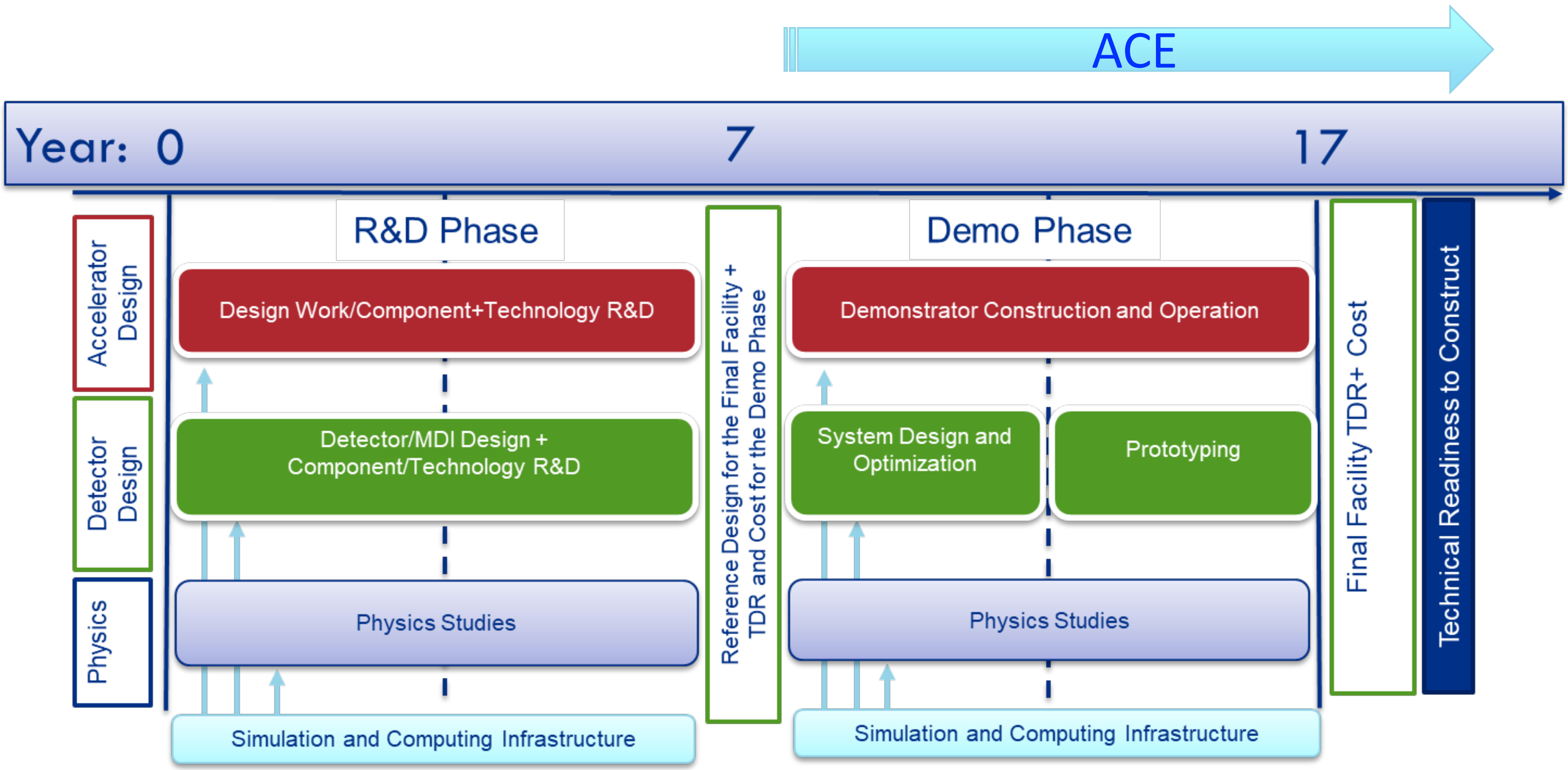
R&D are necessary to tackle these challenges

Accelerator Complex Evolution (ACE) plan

- Increase protons on target to DUNE Phase I detector by
  - Shortening the Main Injector cycle time to increase beam power
  - Upgrading target systems for up to 2.4 MW
  - Improving reliability of the Complex
- Establish a project to build a Booster replacement to
  - Provide a robust and **reliable** platform for the future of the Accelerator Complex
  - Ensure high intensity for DUNE Phase II CP-Violation measurement
  - Enable the **capability** of the complex to serve precision experiments and searches for new physics with beams from 1-120 GeV
  - Create the **capacity** to adapt to new discoveries
  - Supply the high-intensity proton source necessary for future multi-TeV accelerator research

Courtesy of M. Convery, ACE workshop 2023 at Fermilab
J. Eldred also presents in HB2023

Suggested US Muon Collider R&D timeline to P5



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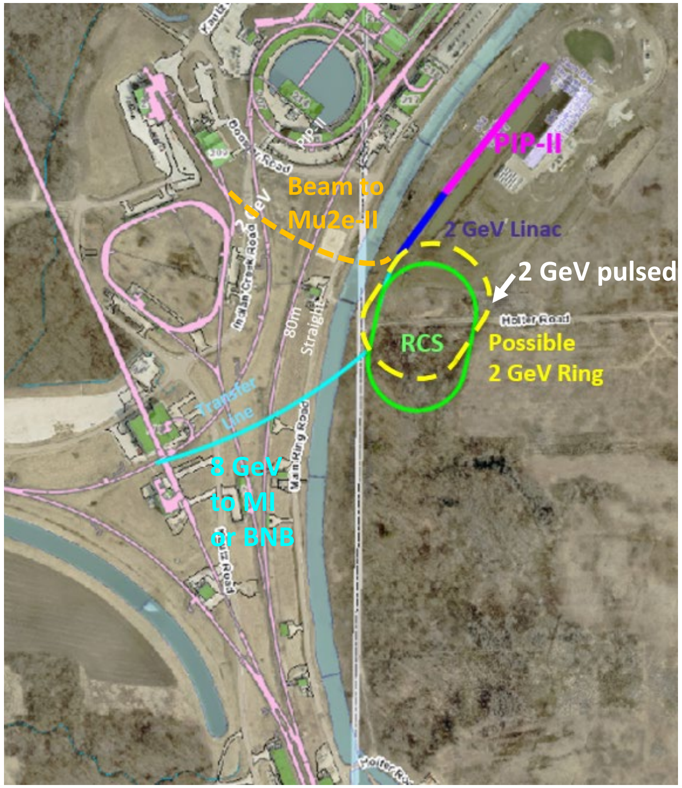
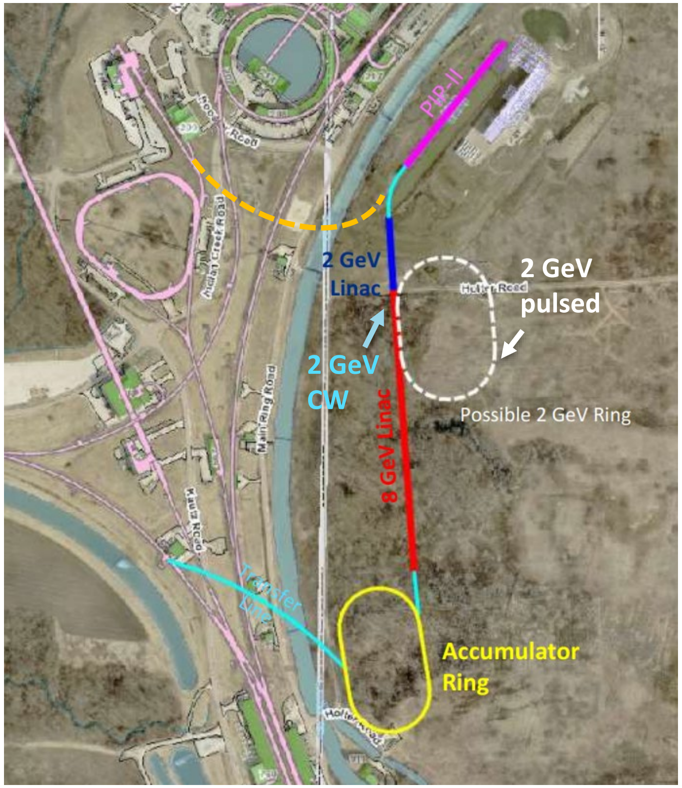
Example Booster replacement options and possible add-ons





Courtesy of M. Convery, ACE workshop 2023 at Fermilab

Possible 8 GeV Booster Beam parameter in Demo Phase

- Share beam with BNB and LBNF programs
- Booster provides 1.8μs pulses every 20 Hz of 6.5e12 protons at 8 GeV
- Impacted by MI cycle rate, but at least as high as present

		PIP-II Booster		
Operation scenario	**Present**	**PIP-II**	**A**	**B**
MI 120 GeV ramp rate	**1.333**	**1.2**	0.9	**0.7**
Booster intensity	**4.5**			**6.5**
Booster ramp rate	15			**20**
Number of batches	12		12	
MI power	0.865	**1.2**	1.7	**2.14**
cycles for 8 GeV	6	12	6	2
Available 8 GeV power	29	**83**	56	**24**

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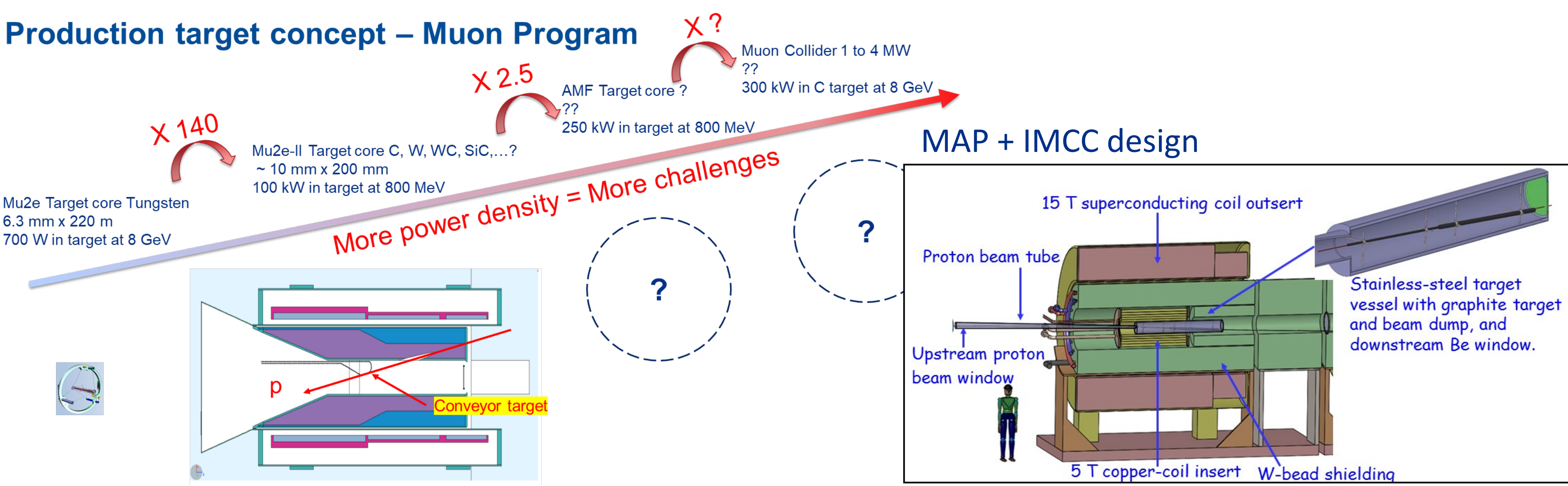
Milestone of Targetry R&D for Future Projects

- High Power Target technology has been developed for neutrino program
  - Established 1.2 MW graphite target for LBNF
  - ACE plan pushes the target R&D to produce 2+ MW target
- ACE plan opens more high power target applications
  - Target R&D roadmap to support Mu2e+, AMF and MuC



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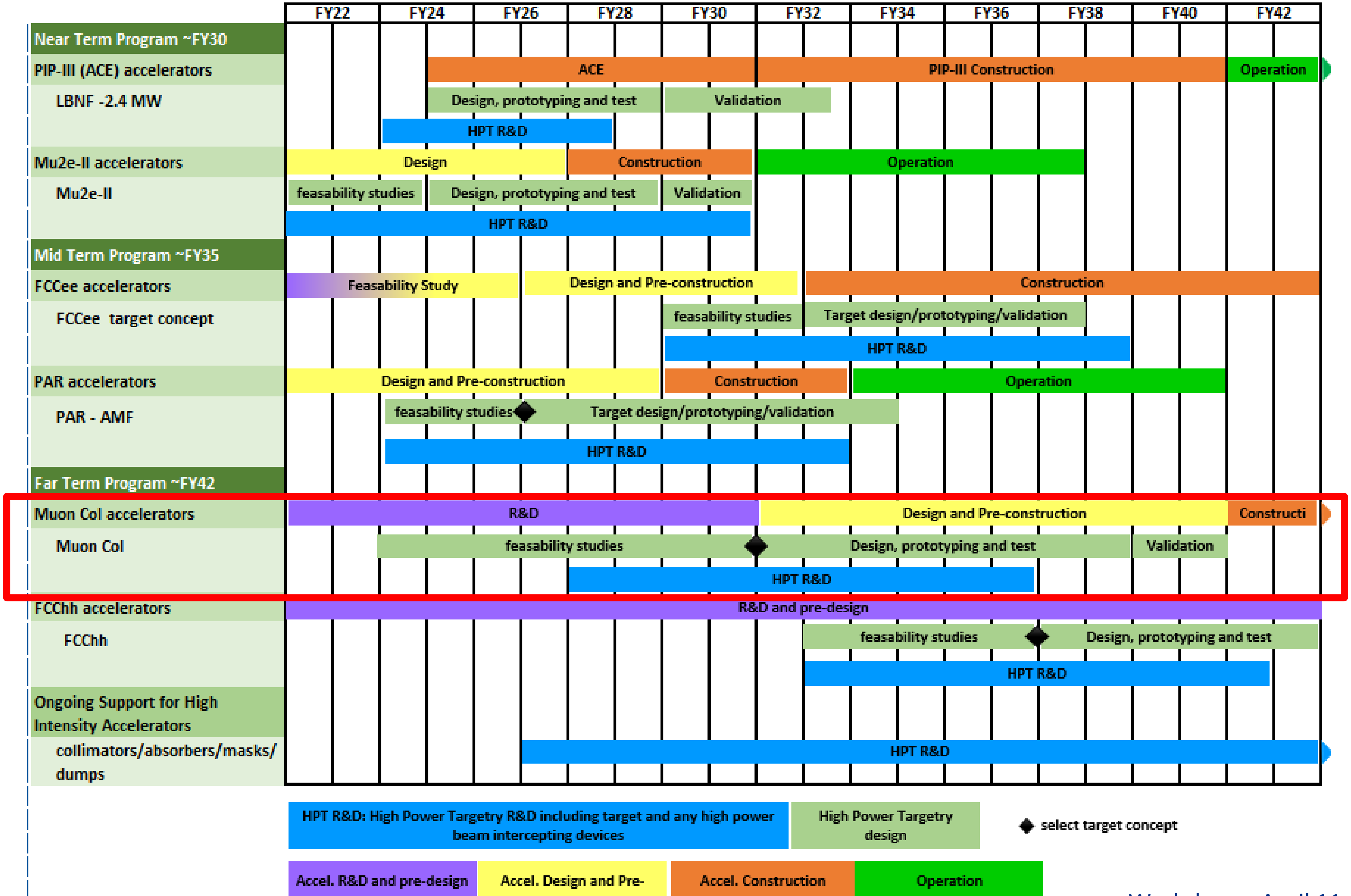
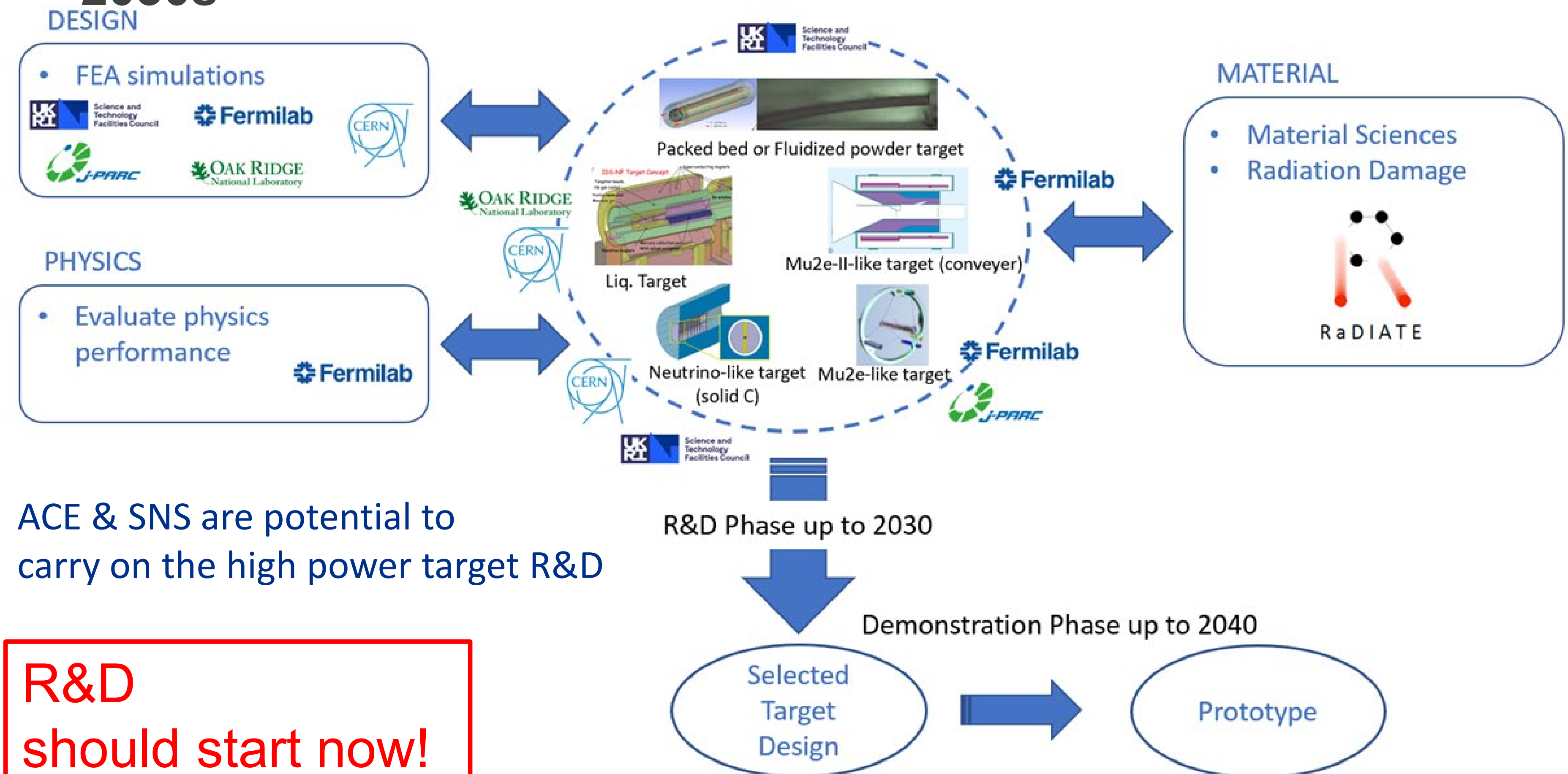
Proposed Roadmap of Targetry R&D



Workshop – April 11-12 2023

International Targetry R&D programs

- MuC targetry is included in the proposed GARD High Power Targetry Roadmap with a plan to have a prototype in the **late 2030s**



ACE & SNS are potential to carry on the high power target R&D

R&D should start now!

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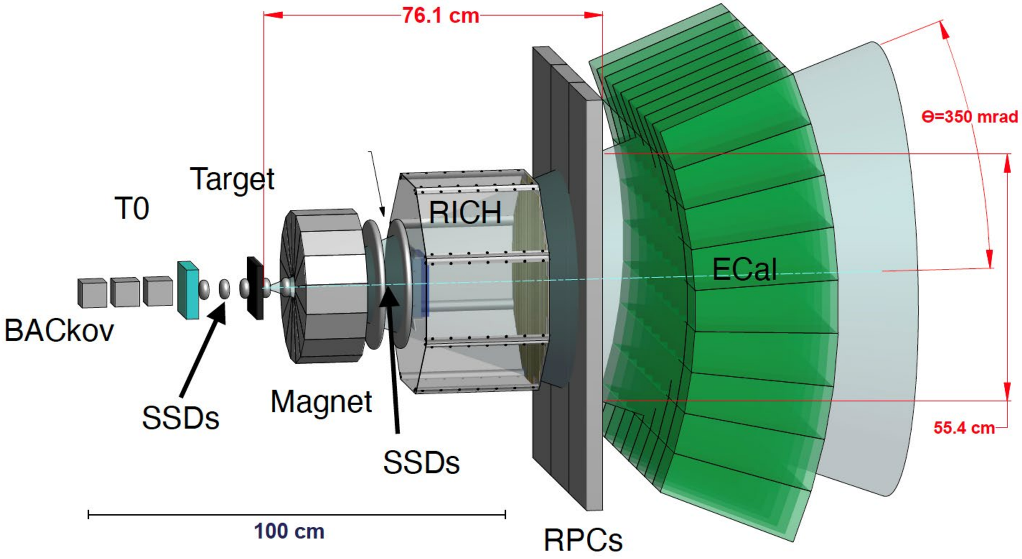
Optimize MuC Target performance

- Select the building material including shielding block, beam window based on the material study
  - Study radiation & thermal stresses of building materials (RaDIATE)
- Design dimensions of target system from engineering and physics point views
  - Pion yield study
    - Angular distribution
    - Target Z dependence
    - Energy dependence
    - Hadronic shower

EMPHATIC
for yield study

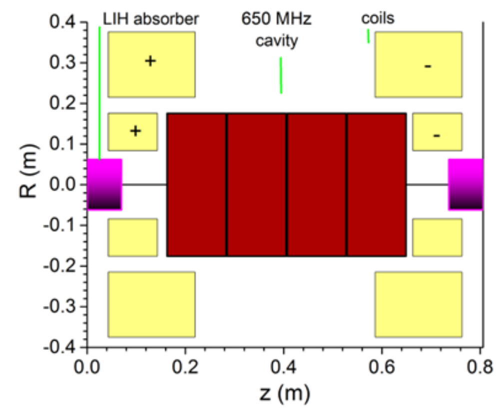


Muon Cooling Channel Hardware R&D

Collaborate with International Muon Collider Collaboration (IMCC)

- High gradient RF cavity in strong magnetic fields
  - Study cold RF cavity with various wall materials (Cu, Be, Al)
  - Beam window
  - Power coupler
  - High power RF source
  - Gas-plasma process in gas-filled cavities (beam needed)
- Prototype cooling cell
  - Integrate high field magnet coils
  - Infrastructure
    - LN2
    - RF waveguide
    - Beam instrumentation

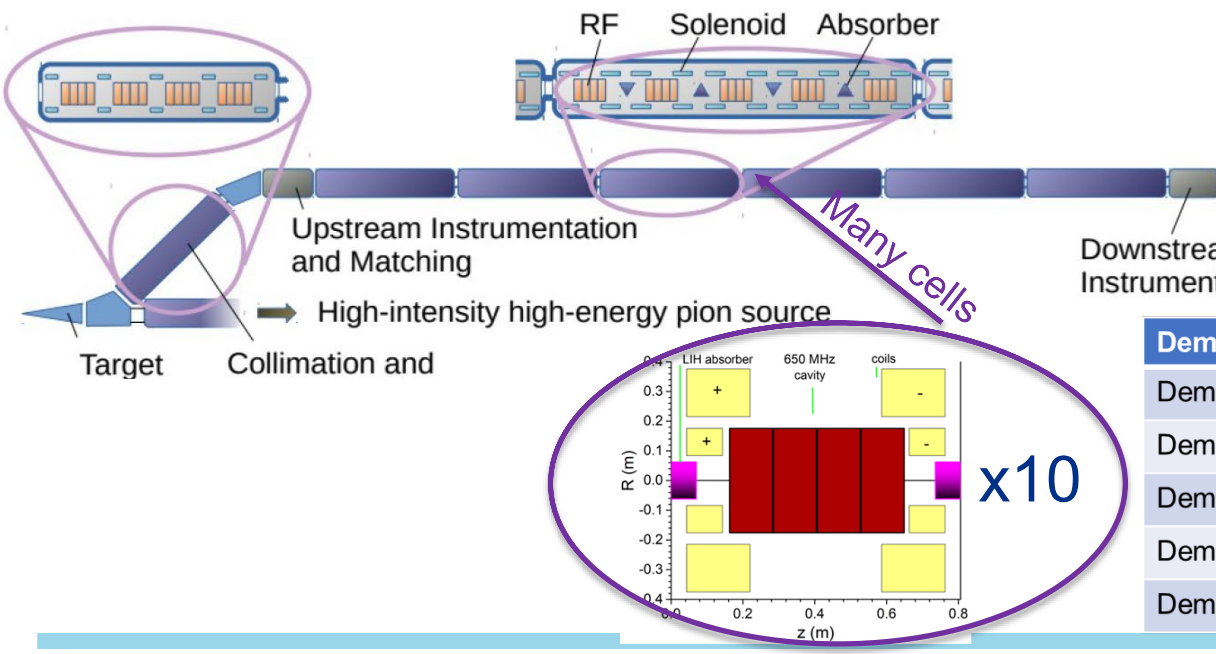
Example cooling cell



Muon Collider cooling: Path forward (demonstrator)

Collaborate with International Muon Collider Collaboration (IMCC)

- While the physics of ionization cooling has been shown it is **critical** to benchmark a **realistic** MuC cooling lattice
  - This will give us the input, knowledge, and experience to design a real, buildable cooling channel for a MuC
  - Next **5 years:** (1) A conceptual design of a demonstrator facility that allows testing the technology for cooling (2) Site exploration & cost estimate of a demo facility (3) Engineering design & start fabrication of a 1.5 prototype cooling cell



Demonstrator concept proposed by IMCC

Demonstrator plan
Demonstrate operation of NC rf in B-field environment
Demonstrate forces between coils are manageable
Demonstrate performance of absorbers
Demonstrate performance of instrumentation system
Demonstrate 6D cooling with a realistic set-up

Summary

- Concepts of Muon Colliders were reviewed by the HEP community in the US Snowmass and the P5 townhall meetings
  - White paper contains comprehensive narratives of the concepts which includes ACE and Booster replacement plan
  - P5 will release the report in December
- R&D for challenging of muon acceleration was presented in the meetings
  - Muon Cooling Channel Hardware R&D and Demonstrator will be a critical path; These concepts are shared with IMCC
  - Target R&D will utilize 8 and 120 GeV ACE beam in synergy with the Fermilab physics program; SNS shows an interest in conducting the R&D related with target and proton driver as well