US Strategy for Muon Collider Targetry R&D Based on Fermilab Accelerator Complex Evolution Plan

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Muon Collider Synergies Workshop

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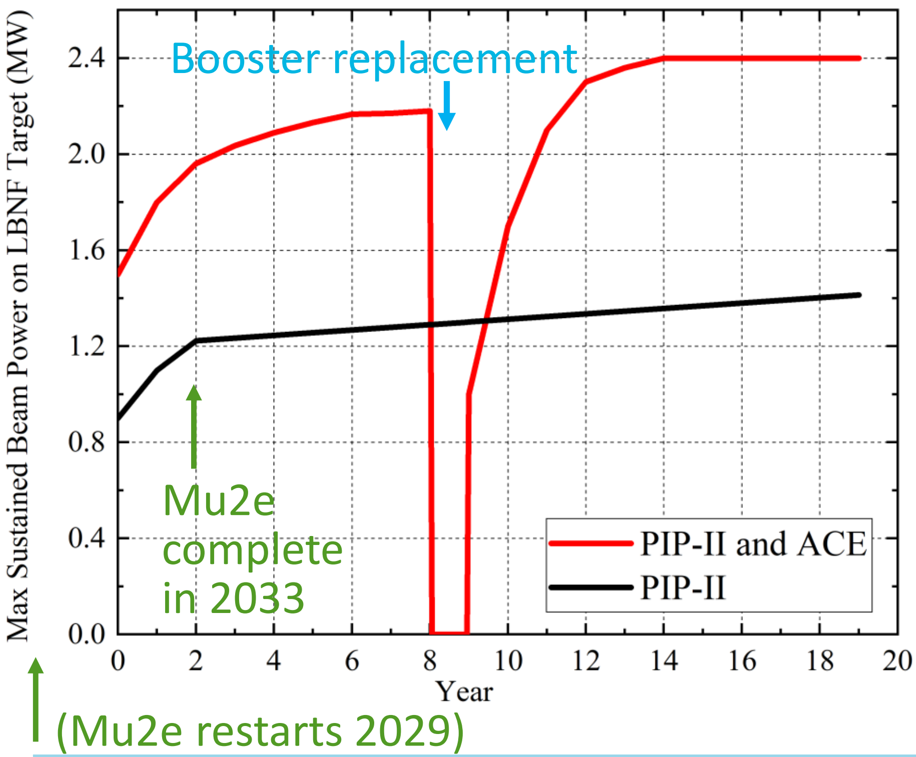
Targetry R&D for Fermilab future accelerator upgrade plan

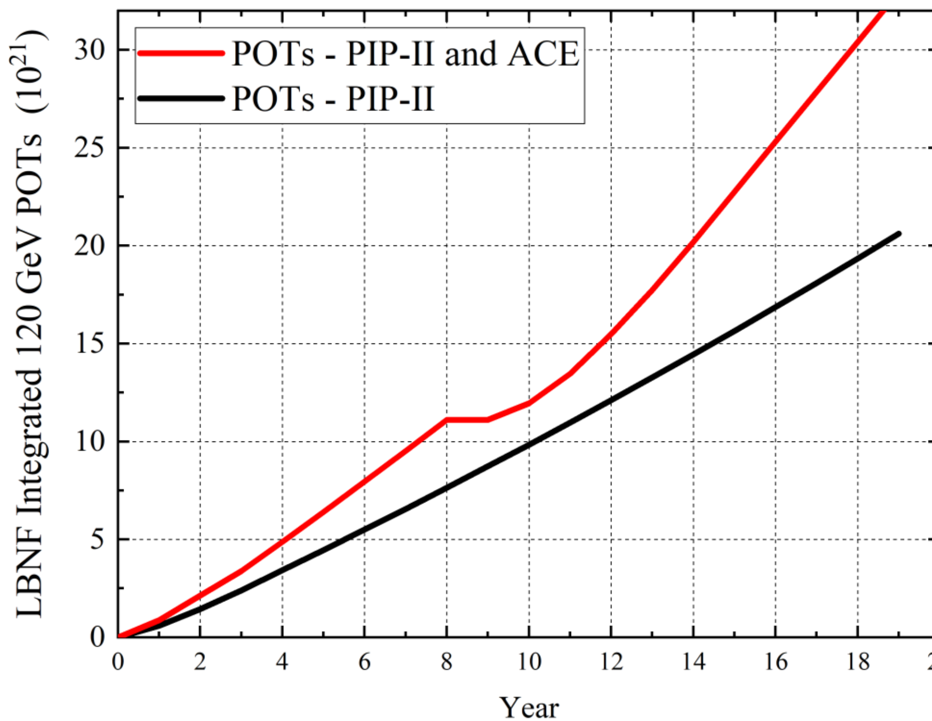
- Fermilab propose Accelerator Complex Evolution (ACE) plan in the last P5 townhall meeting at Fermilab in 2023
- High Power Target technology has been developed for neutrino program
  - Established 1.2 MW graphite target for LBNF
  - **ACE plan pushes the target R&D schedule to produce 2+ MW target**
- ACE plan opens more high power target applications
  - Target R&D roadmap to support Mu2e+, AMF and MuC

Fermilab Accelerator Complex Evolution (ACE) plan

M. Convery, ACE Workshop'23

- 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





Booster replacement options

M. Convery, ACE Workshop'23

- Extend SRF Linac to higher energy or construct new Rapid-Cycling Synchrotron
- Looked at 3 representative options of each type
- All six configurations require an extension of the SRF Linac to 2 GeV
  - The RCS option will benefit from the reduced space charge at the increased energy
  - The high-energy linac option will need the beam with an approximate energy of 2 GeV to take advantage of higher frequency, $\beta = 1$, high-gradient cavities that can be grouped and fed from a single, high-power klystron.
- Parameters can be optimized based on outcome of this workshop

RCS

C1a) 10 Hz: Metallic vacuum chamber

C1b) 20 Hz: Ceramic vacuum chamber, larger aperture magnets, accumulator ring

C1c) 20 Hz: (C1b) with high-current linac, no accumulator ring

SRF Linac and Accumulator Ring

C2a) Basic: small increase in PIP-II current, using demonstrated XFEL RF

C2b) High current (5mA) and some RF R&D

C2c) High current and significant RF R&D

Example Booster replacement options and possible add-ons

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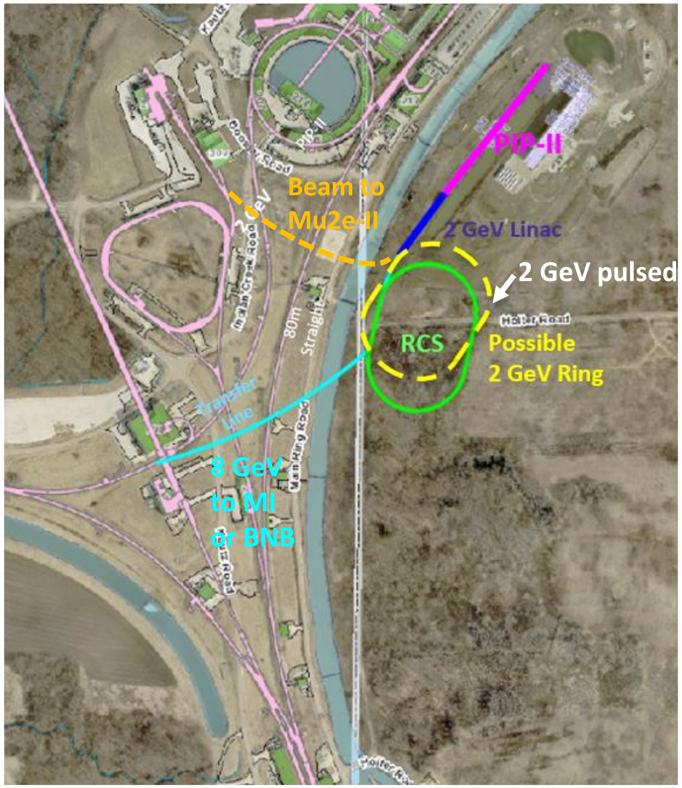
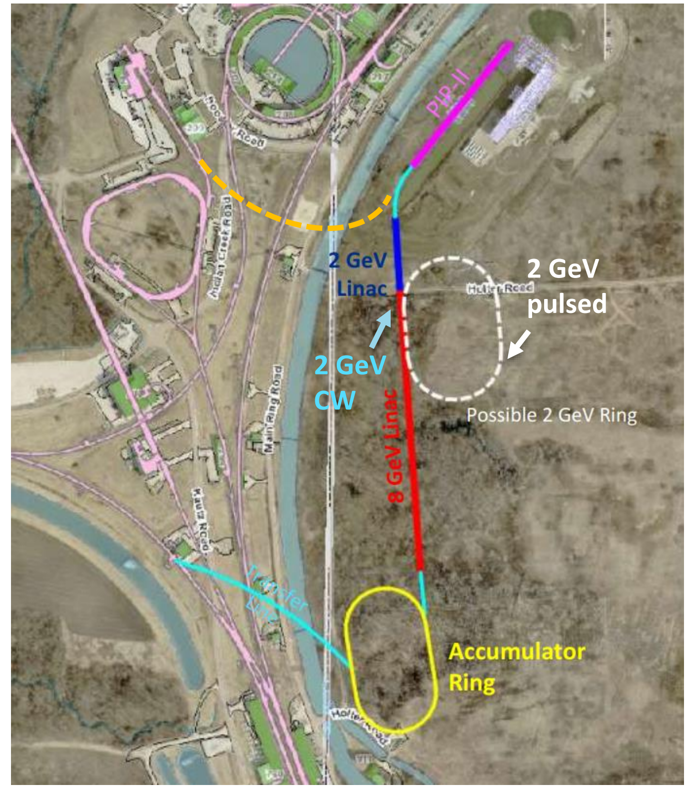
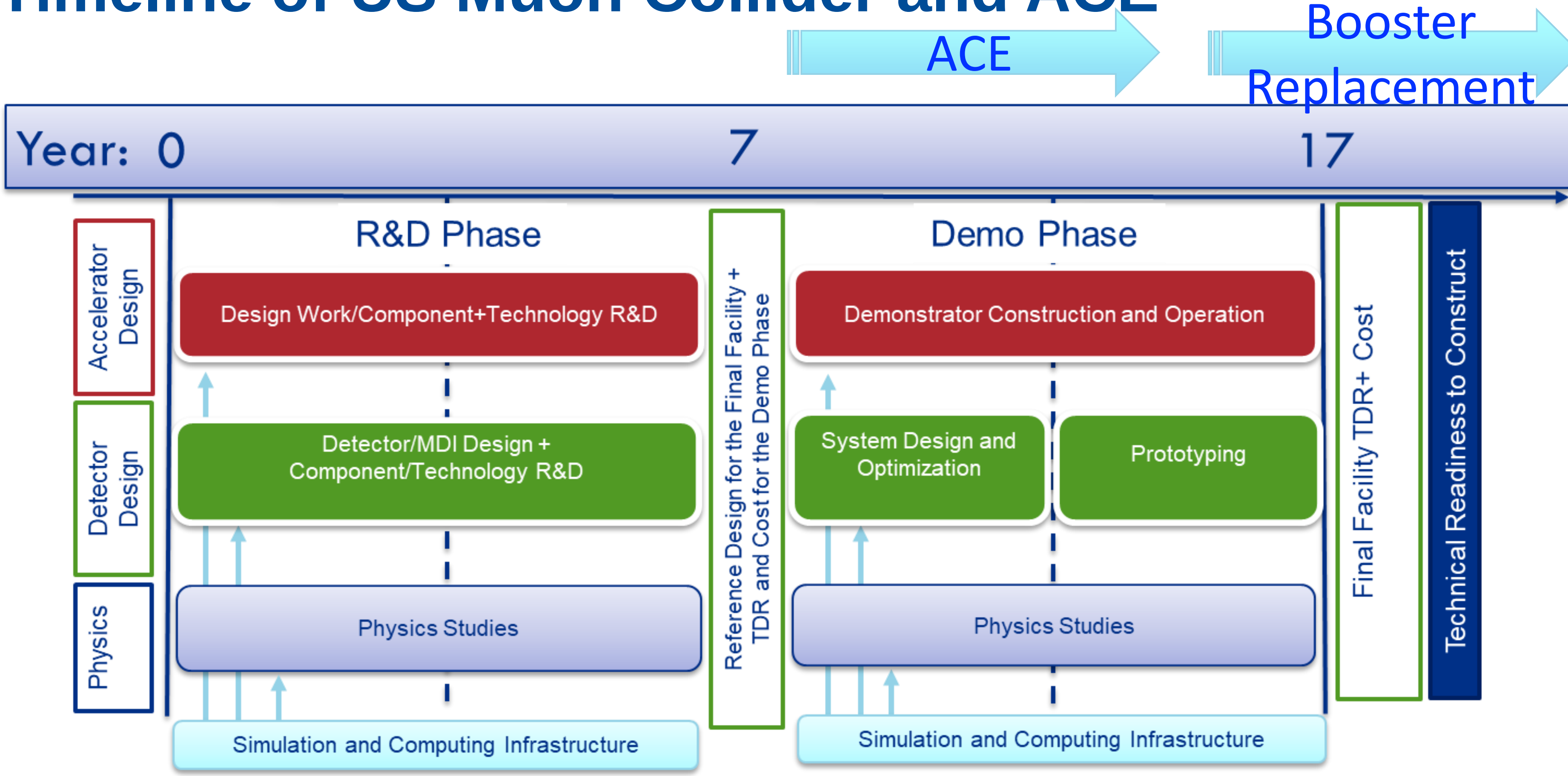




- Proton beam parameters in the present ACE Booster Replacement plan are preliminary and should be optimized specifically as Muon collider proton driver.

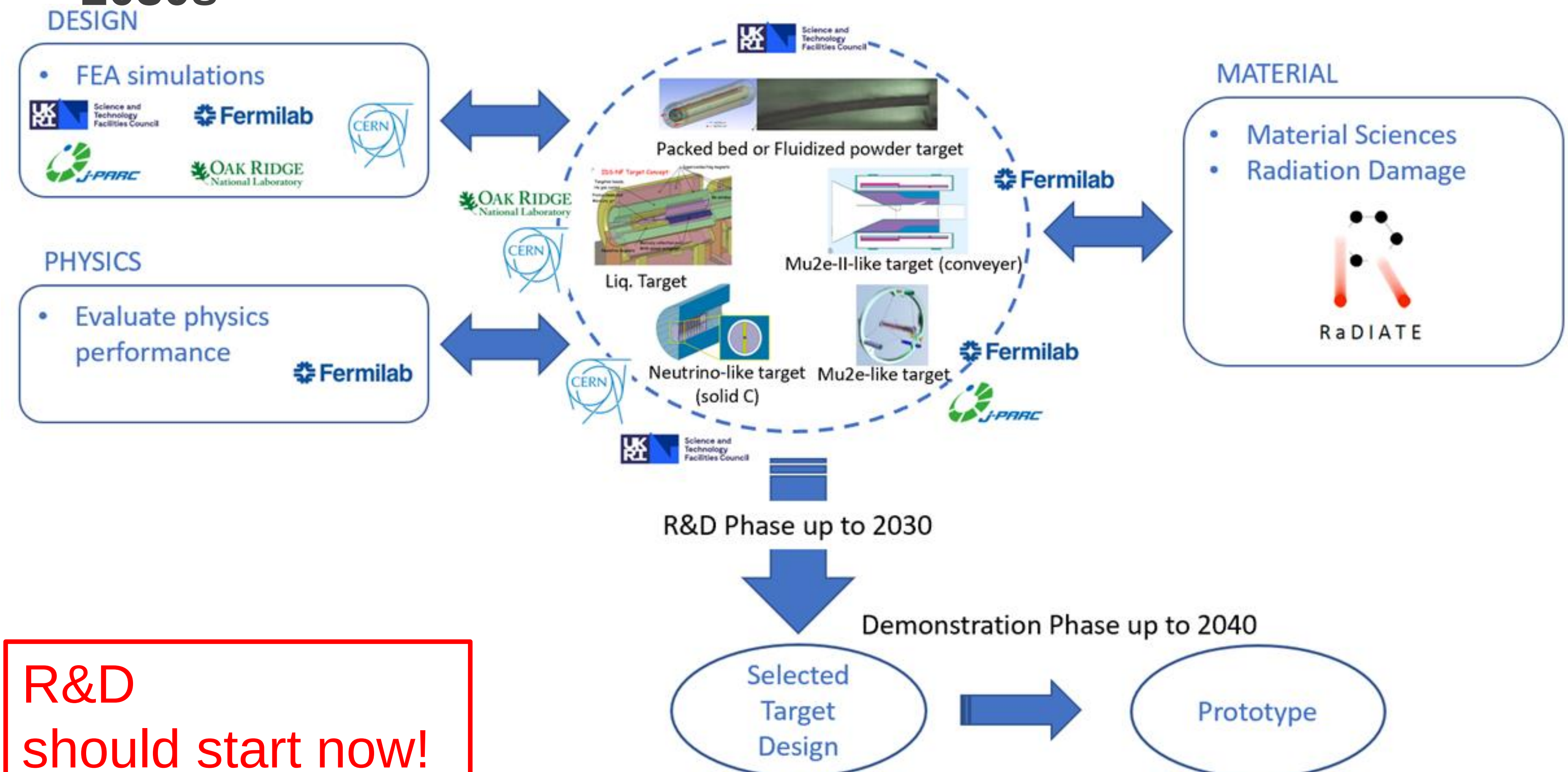
Timeline of US Muon Collider and ACE



- ACE + Booster Replacement will be expected around the year 17 where the Muon Collider facility design will be done

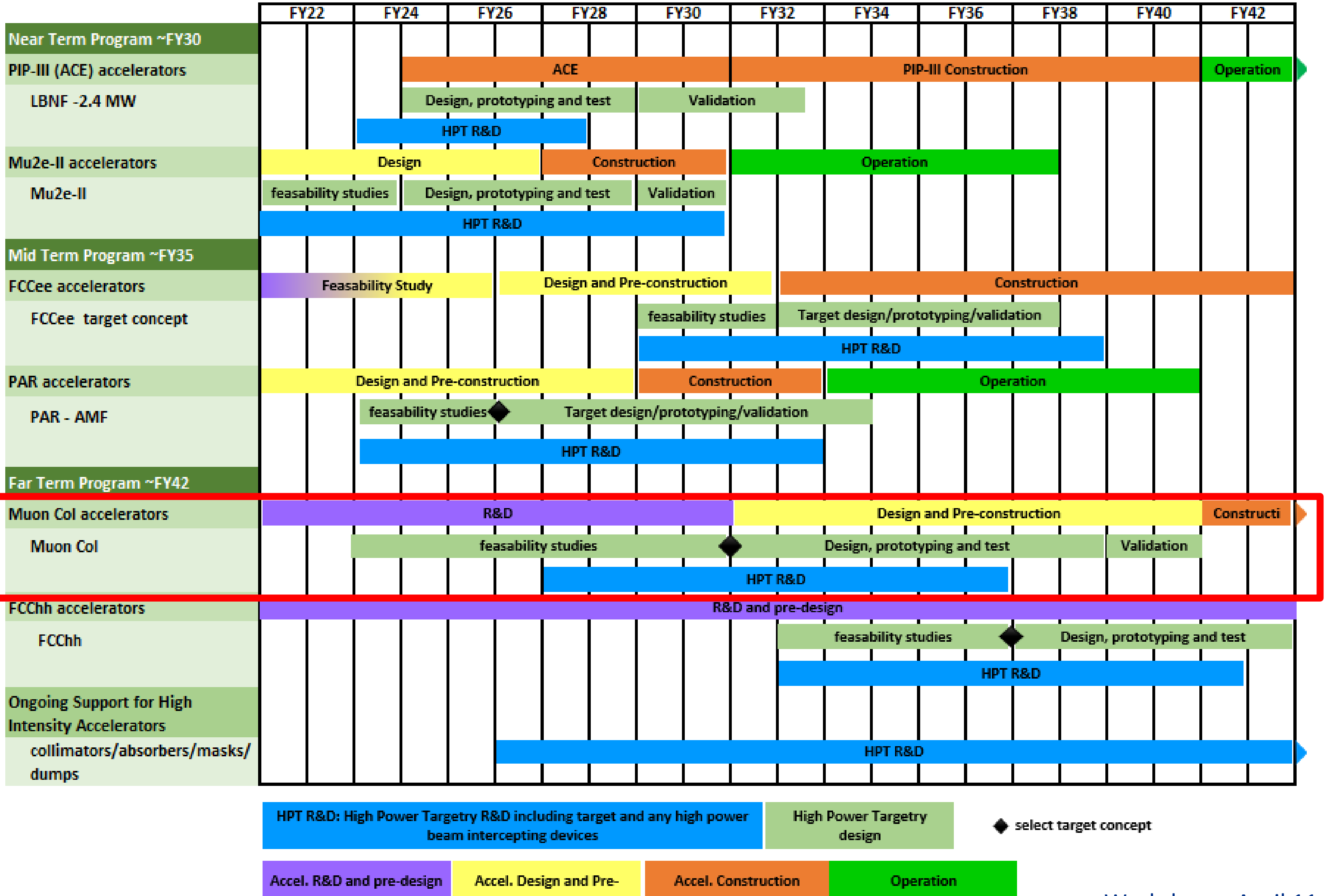
Collaborate Targetry R&D for MuC target study

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



R&D
should start now!

Proposed Roadmap of Targetry R&D



Workshop – April 11-12 2023

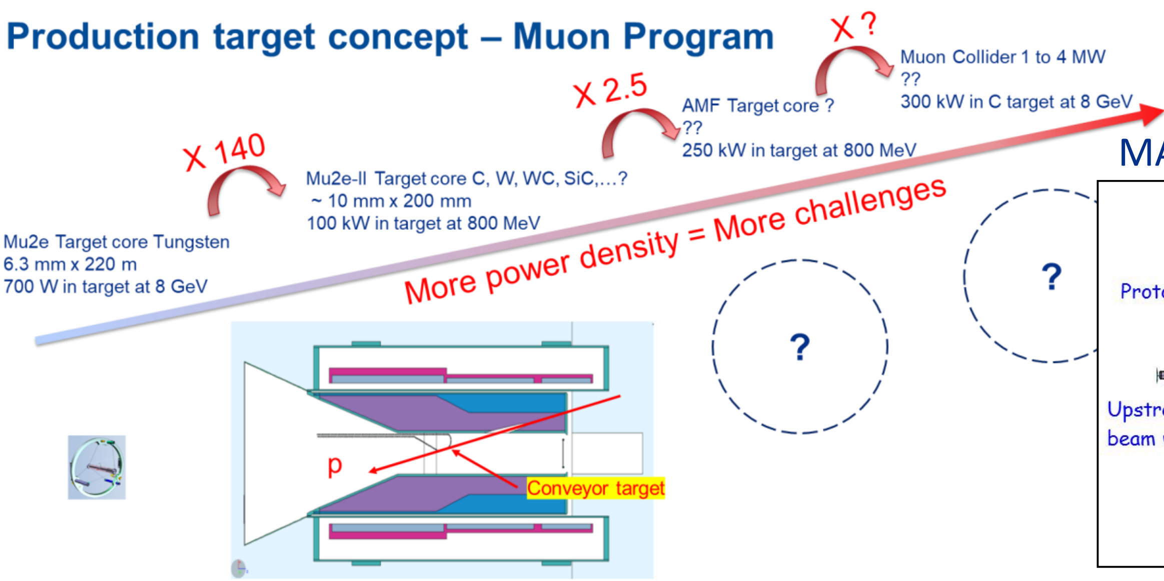
Fermilab

Strategic plan of Targetry for Fermilab accelerator program

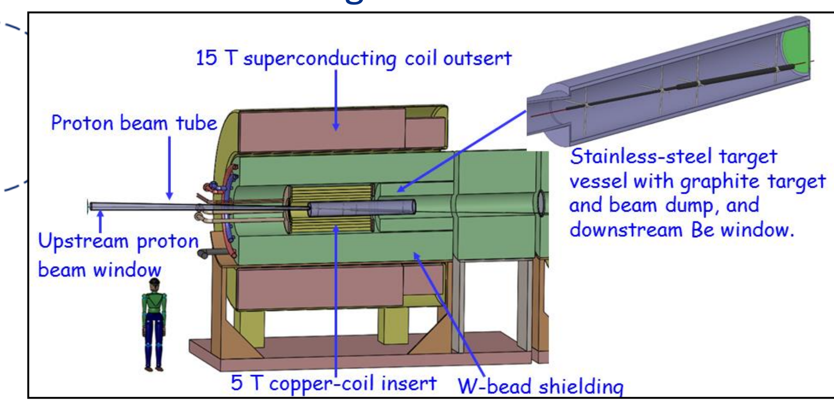
- LBNF 1.2 MW and Mu2e 700 W are the first upcoming experiments at Fermilab
  - Targets have already been designed
- Design and prototyping LBNF 2+ MW and Mu2e-II 100 kW targets will be done around 2030
  - Graphite will be the baseline material for LBNF 2+ MW target
  - **However, no conventional material is utilized for Mu2e-II target**
    - Extremely dense proton beam which has never been operated

R&D of Targetry for Fermilab accelerator program

- Mu2e-II target has similar feature as a muon collider target
  - Target immersed in a high field magnet
  - Short bunch length and 0.8-8 GeV energy proton beams are needed (5-20 GeV for muon collider)
- Developing Mu2e-II target technology will be beneficial for muon collider



MAP + IMCC design



Advance Muon Facility

S. Middleton, ACE Workshop'23

Targetry: 1MW Targeting

- Mu2e uses a cooled tungsten rod target with a 8GeV, 8kW beam.
- AMF has a much more intense environment: ~1GeV, 1MW beam.
  - We will need to re-think our production target design!

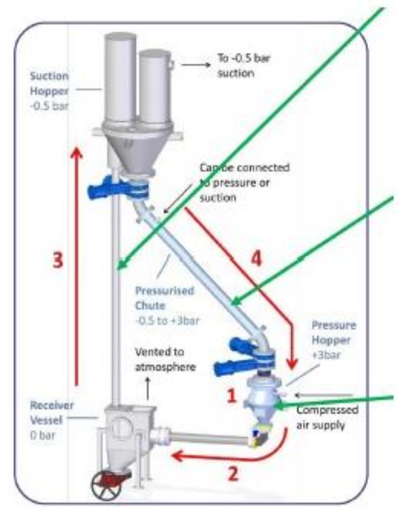
- Previous designs for similar complex envisioned a liquid target:
  - MERIT experiment (possible proof of principle?):
    - Liquid mercury - (not an option due to environmental issues);
    - Rep. rates only about 70 Hz, limited by disruption of the jet.

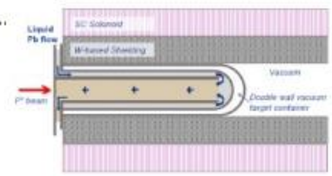
Recent Results from the MERIT Experiment
https://aip.scitation.org/doi/pdf/10.1063/1.3399332

- Mu2e-II: rotating carbon spheres on conveyor (100kW, 800MeV).
- Muon collider at MW: fluidized tungsten, other possibilities…

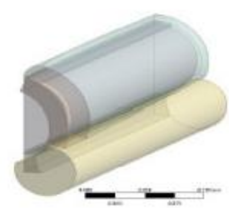
- **R&D required to design target for the AMF target!**
  - **Exciting synergies with muon collider R&D here.**

Fluidized Tungsten





Liquid Lead Flow



Lead Curtain

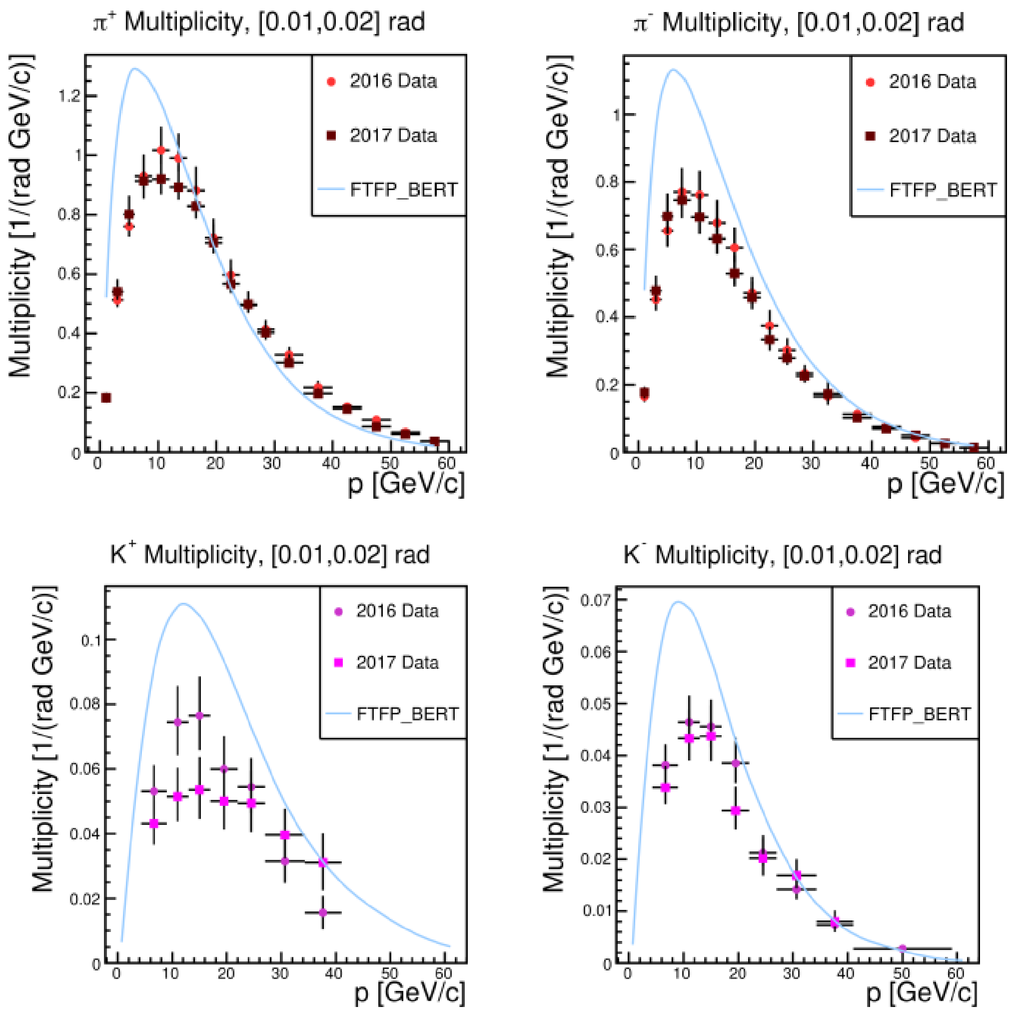
FIG. 3. The mercury jet target geometry. The proton beam and mercury jet cross at $z = -37.5$ cm.

Liquid jet

Study pion production physics

- Physics model in simulations has a large systematic uncertainty on the estimation of pion/kaon productions
  - Prediction becomes harder for longer target
  - Hard to model hadronic cascades

NA61/SHINE arXiv:2306.02961

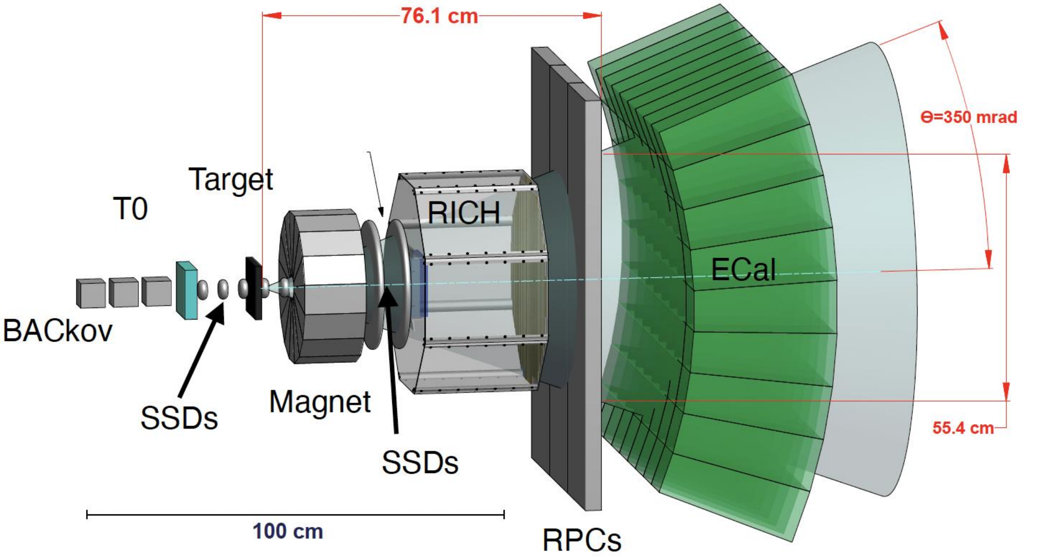


Fermilab

Measure MuC Target physics parameter

- Pion yield measurement by using the modern spectrometer particle detector (EMPHATIC)
  - Compact but large solid angle 350 mrad
  - High-rate DAQ system, precision tracking and timing
- Measurement at Fermilab Test Beam Facility (FTBF)
  - Angular distribution
  - Target Z dependence
  - Energy dependence
  - Hadronic shower

EMPHATIC
for yield study



Summary and Final remark

- Fermilab propose the ACE plan
  - It can speed up the neutrino program
  - Booster Replacement plan will be extended as muon collider proton driver (more design study needed)
- Targetry R&D is crucial for future HEP programs
  - All future HEP programs require high power target
  - We submitted the roadmap of US targetry R&D to the P5 committee
    - Covers LBNF 2+ MW, Mu2e-II, AMF, and MuC target R&Ds
  - **Once the R&D will be officially funded, the US MuC target group will immediately join IMCC to boost the activity!**

Extra slide

Possible demonstrator facility at Fermilab based on ACE plan

Caution:

- Candidate of demo facility is very preliminary and conceptual
- No design work done

S0D: 8 GeV Booster Experiments

J. Eldred, ACE Workshop'23

Example: Current BNB Program.

Booster provides 1.8μs pulses every 20 Hz of 6.5e12 protns 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**

Evaluate ACE beam parameter for MuC R&D scenario

- Scenario A
  - Capable to deliver 8 GeV ACE beam to Recycler Ring
  - AP0 could be potential to utilize for Target R&D and Muon Cooling demo
- Scenario B
  - Share 8 GeV ACE beam with SBN