The US efforts towards a Muon Collider

Diktys Stratakis (Fermilab)

IMCC Annual Meeting

June 19, 2023

History (1)

- **1960s:** First mention of Muon Colliders in the literature
- **1990s-2010:** Design studies through US institutional collaborations
- **2011-2016:** Muon Accelerator Program (MAP) was approved and supported by DOE to address key feasibility issues of a MC
  - Focused on a proton-driver based solution
  - End-to-end design for a Neutrino Factory & a 125 GeV Higgs Factory. Considered colliders at 1.5, 3 and 6 TeV
- **2021:** CERN Council has charged the EU Laboratory Directors Group to develop the Accelerator R&D Roadmap for next decade
  - Formation of a Muon Panel that assessed MuC challenges and defined prioritized work with resource estimates through a series of community meetings with input from the global community.

History (2)

- **2022:** Muon Colliders become part of the European Accel. R&D Roadmap:
  - CERN asked for implementation of the plan
  - International Muon Collider Collaboration (IMCC) has formed
- **2022:** US Snowmass study reveal strong interest on Muon Colliders:
  - Presented the Muon Collider Forum Report: a coherent vision for Muon Colliders from the US perspective
  - Proposed and presented a National Collider Initiative
  - **Received strong support from the global community**
- **2023:** Formation of the US Muon Collider R&D coordination group:
  - Initiated and supported by the Fermilab directorate
  - It's goal is to provide input to the P5 panel on Muon Collider research
  - Its ASK was presented at two P5 town-hall meetings (BNL and SLAC)

What has changed since over the last decade?

- Lattice design
  - Developed designs for all MuC subsystems, including a promising solution for a neutrino flux mitigation system
- Targets
  - Significant developments on MW-class target concepts due to the strong demand by many experiments.
- Magnet technology
  - Development of high-field solenoids & dipoles with specs close to the MuC needs
- RF technology
  - Demonstrated high-gradient operation of NC cavities in B-fields (50 MV/m @ 3T)
  - SCRF cavity gradients for a MuC are within reach of current technology
- Ionization cooling concept demonstration
  - Physics of ionization cooling has been demonstrated and results are published

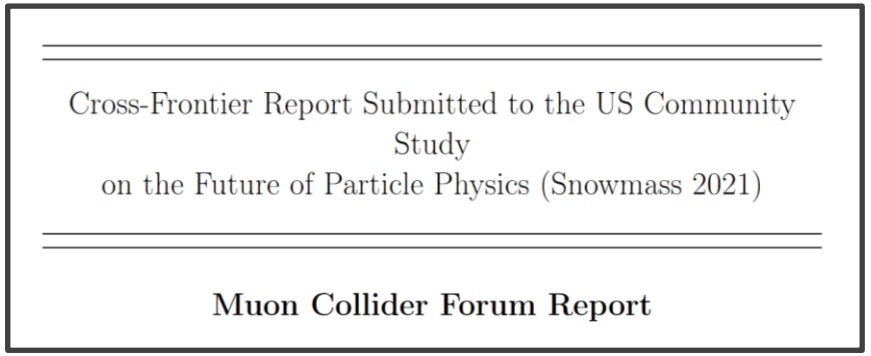
2021 Snowmass Process in the US

- Happens roughly once a decade
- A two year long scientific study process to determine future directions for the particle physics in US, together with international partners
- Work done in 10 frontiers + several cross-frontier groups
- Final reports available:
  - Snowmass report: arXiv:2301.06581
  - EF report: arXiv:2211.11084, AF report: arXiv:2209.14136
  - Muon Collider Forum Report: arXiv:2209.01318
- Had several townhall meetings along several institutions in the US
- Next step is the Particle Physics Project Prioritization Panel (P5) deliberation
  - We expect report later this year

Snowmass 2021

Snowmass Muon Collider Forum

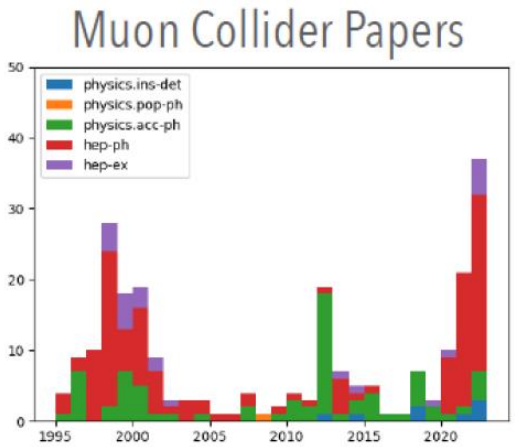
- The forum established a strong collaboration between the AF+EF+TF frontiers for Muon Collider (MuC) research
  - Goal was to make a strong physics case for MuC and inform the community
  - Monthly meetings and dedicated workshops for 18+ months before Snowmass
  - Lined-up a plan for Muon Collider R&D in the US
  - Identified synergies with other programs
  - Published all findings as a **"MuC Forum report"** and presented it in the Snowmass meeting: ~180 authors, 50+% are early career scientists
- Forum conclusions:
  - No fundamental showstoppers identified
  - BUT engineering challenges exist
  - R&D is needed to improve a MuC risk profile
  - **This R&D should start now!**

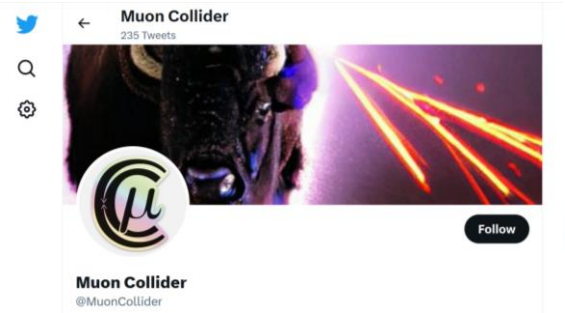

Cross-Frontier Report Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

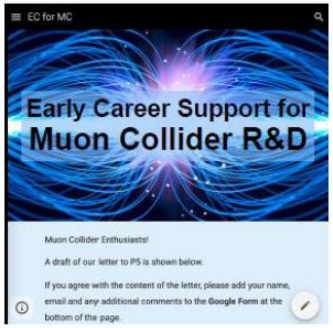
Muon Collider Forum Report

Enthusiasm about Muon Colliders is surging in US

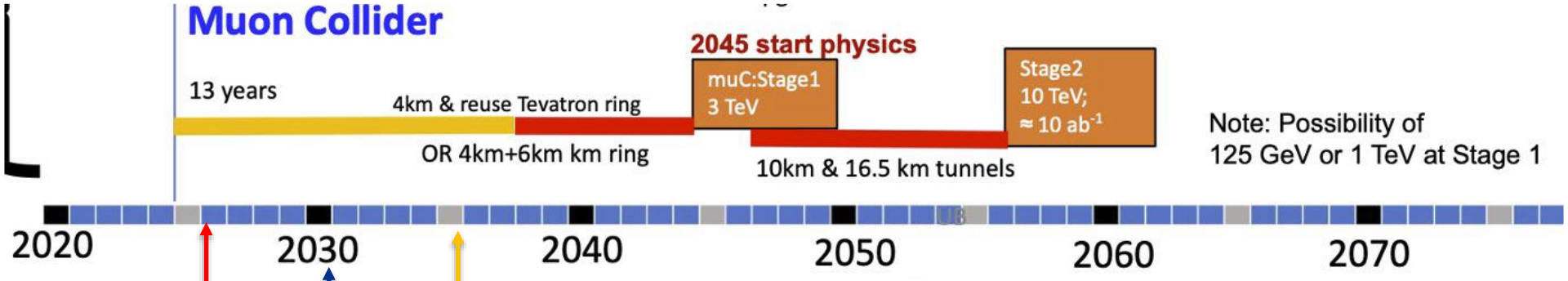
- MuC was the most studied machine during Snowmass. Many new results & papers, propagated to the EF vision.







US timeline & vison as presented at Snowmass



Develop an initial design for a first stage TeV-scale MC in the US (pre CDR)+ Support relevant detector R&D (2025-2030)

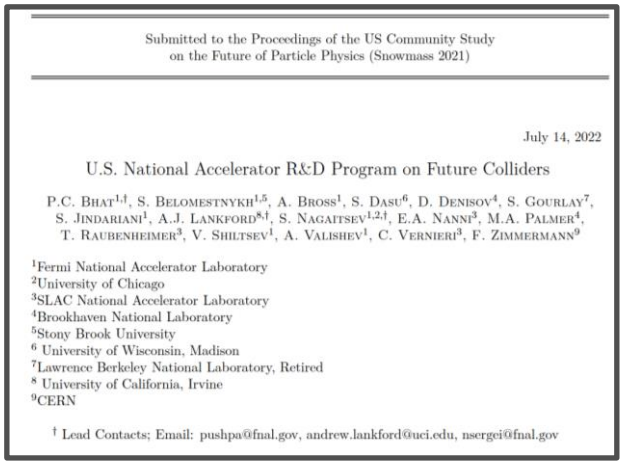
Demonstrate principal risk mitigation and deliver CDR for a first stage TeV-scale MC (2030-2035)

Demonstrate readiness to construct and deliver TDR for a first TeV-scale MuC. Ramp up funding support for relevant detector R&D (2035-2040)

- The actual project start time is subject to:
- Successful outcome of the proposed extensive R&D program
- Availability of funding + resources, host laboratory, and international agreements
- **Development will take a long time – need to start now**

National Collider Initiative

- The U.S. HEP accelerator R&D program has no support for targeted development of collider concepts for strategic planning
  - An integrated national accelerator R&D program on future colliders **was proposed at Snowmass** to address this shortcoming
- Goal is to address, in an integrated fashion, the technical challenges of promising future collider concepts
  - Focus on aspects of accelerator design, technology, and beam physics that are not covered by the existing DOE General Accelerator R&D (GARD) program.
- The proposed national future colliders R&D program gained **strong support** by the community at the last Snowmass



Submitted to the Proceedings of the US Community Study
on the Future of Particle Physics (Snowmass 2021)

July 14, 2022

U.S. National Accelerator R&D Program on Future Colliders

P.C. Bhat[1,†], S. Belomestnykh[1,5], A. Bross[1], S. Dasu[6], D. Denisov[4], S. Gourlay[7], S. Jindariani[1], A.J. Lankford[8,†], S. Nagaitsev[1,2,†], E.A. Nanni[3], M.A. Palmer[4], T. Raubenheimer[3], V. Shiltsev[1], A. Valishev[1], C. Vernieri[3], F. Zimmermann[9]

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Post-Snowmass: US Muon Collider R&D coordination group formation

- In March, R&D coordination group formed to provide input to P5
- Focus on key elements of **10 TeV accelerator & detector design**
  - Develop R&D plan, activities, budget and deliverables
  - Chairs: Sridhara Dasu, Sergo Jindariani, and Diktys Stratakis

Physics Case Development:
Patrick Meade (Stony Brook), Nathaniel Craig (UCSB)

Accelerator R&D Focus Areas:
Muon source:
Mary Convery (Fermilab), Jeff Eldred (Fermilab), Sergei Nagaitsev (JLAB), Eric Prebys (UC Davis)

Machine design:
Frederique Pellemoine (Fermilab), Scott Berg (BNL), Katsuya Yonehara (Fermilab)

Magnet systems:
Steve Gourlay (Fermilab), Giorgio Apollinari (Fermilab), Soren Prestemon (LBNL)

RF systems:
Sergey Belomestnykh (Fermilab), Spencer Gessner (SLAC), Tianhuan Luo (LBNL)

Detector R&D Focus Areas:
Tracking Detectors:
Maurice Garcia-Sciveres (LBNL), Tova Holmes (Tennessee)

Calorimeter Systems
Chris Tully (Princeton), Rachel Yohay (FSU)

Muon Detectors
Melissa Franklin (Harvard), Darien Wood (Northeastern)

Electronics/TDAQ
Darin Acosta (Rice), Isobel Ojalvo (Princeton), Michael Begel (BNL)

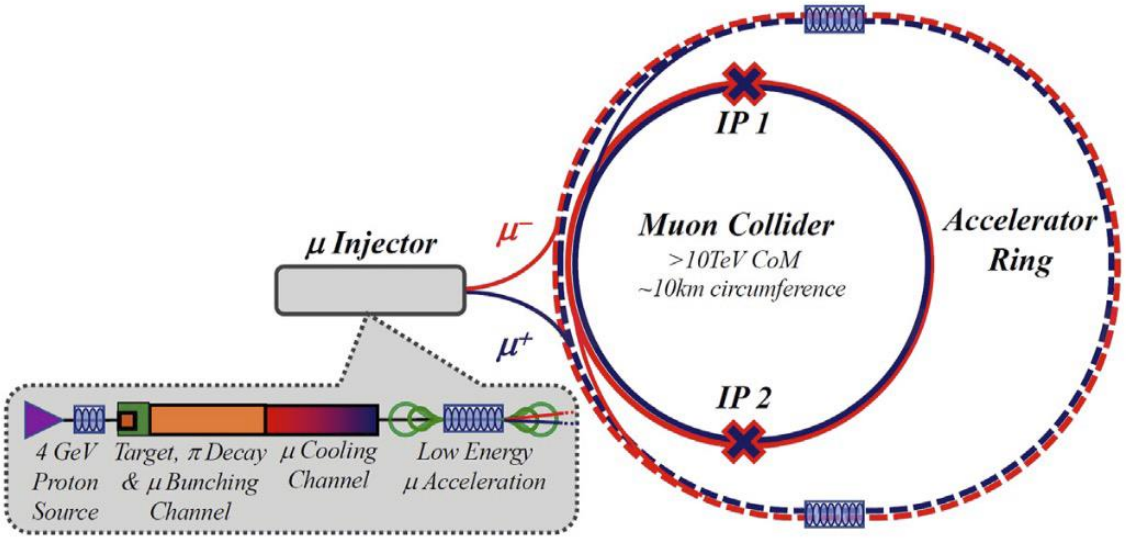
MDI+Forward Detectors:
Kevin Black (Wisconsin), Karri DiPetrillo (Chicago), Nikolai Mokhov (Fermilab)

Detector Software and Simulations:
Liz Sexton-Kennedy (Fermilab), Simone Pagan Griso (LBNL)

International Liaisons:
Daniel Schulte (CERN), Chris Rogers (RAL), Donatella Lucchesi (INFN), Federico Meloni (DESY)

Target parameters

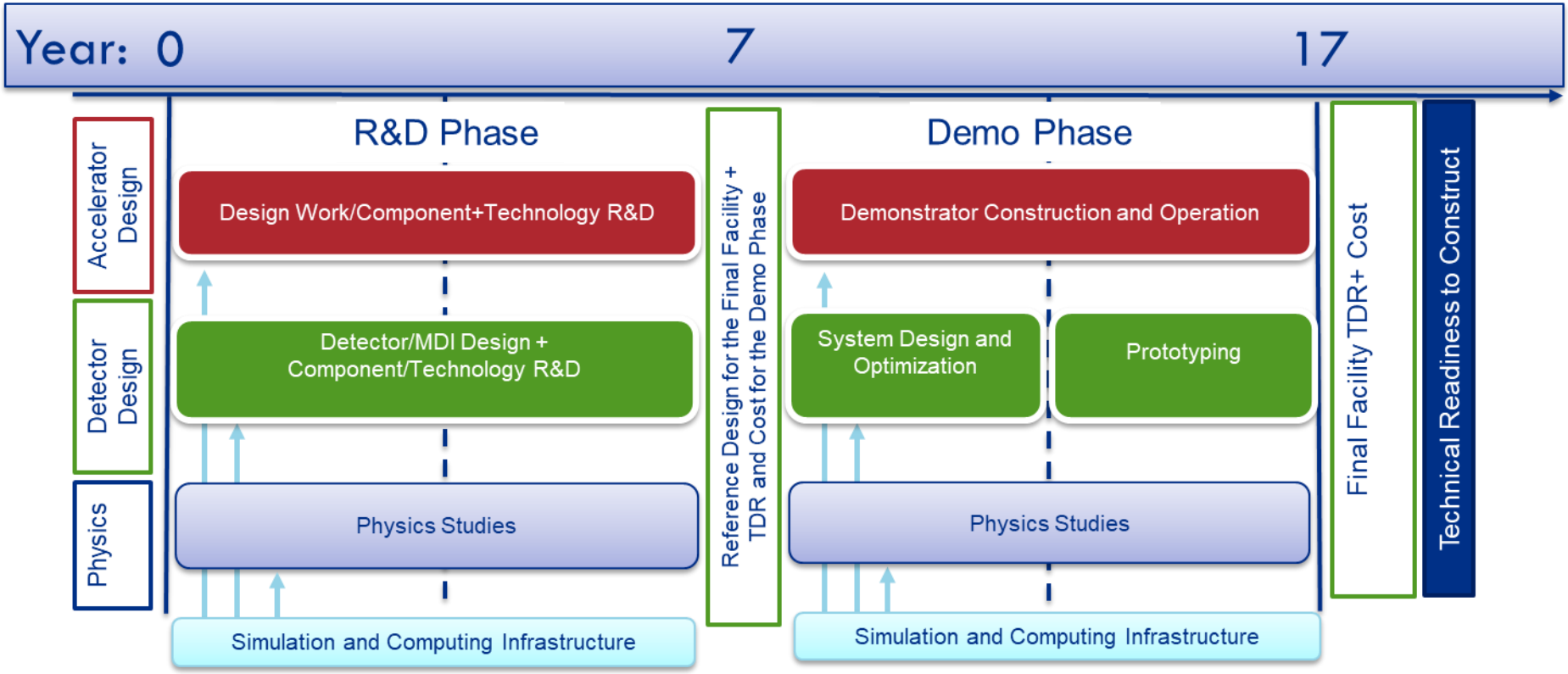
- The goal is to get to **10 TeV center-of-mass energy**
- Consider proton driver based Muon Collider
- Staging at 3 TeV is the current baseline
- Aim to have two detectors but only experiment assumed now



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

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

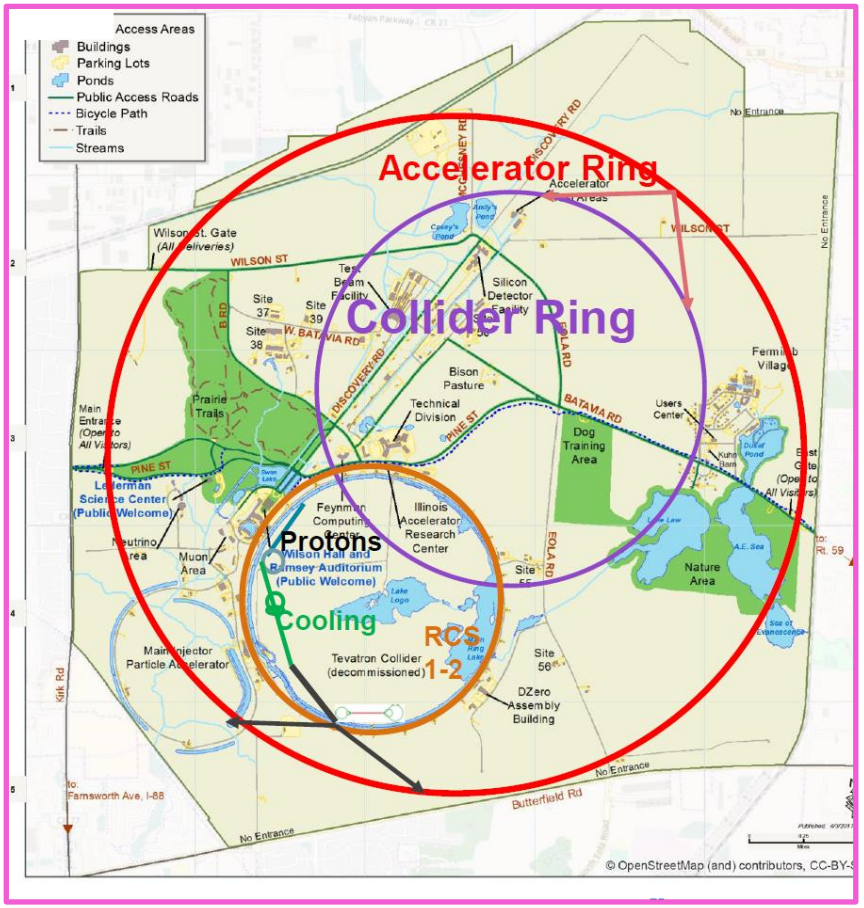
US Muon Collider timeline



It is crucial for the US to engage **NOW** if we want an MC as a future option!

Muon Collider @ Fermilab

- A concept design for a Fermilab **6-10 TeV MuC** is in place
- Proton source
  - Post-ACE driver -> Target
- Ionization cooling channel
- Acceleration (3 stages)
  - Linac + RLA → **65 GeV**
  - RCS #1, #2 → **1 TeV (Tevatron size)**
  - RCS #3 → **3-5 TeV (site filler)**
- 6-10 TeV collider
  - Collider radius: 1.65 km



- In the next **5 years**, have a baseline design including the neutrino flux mitigation system

Elements of a MuC US R&D program (2024-2030)

Some examples

Design and Simulation work

- Optimize ACE for MuC proton driver needs
- Accelerator & collider designs for a FNAL MuC
- Neutrino flux mitigation for a FNAL MuC
- Ionization cooling design work

Some examples

Prototyping & tests

- Bunch compression & proton stripping
- Target material & performance studies
- Fast ramping magnet prototypes
- Low-frequency SRF cavity prototyping & testing

Some examples

Demonstrator

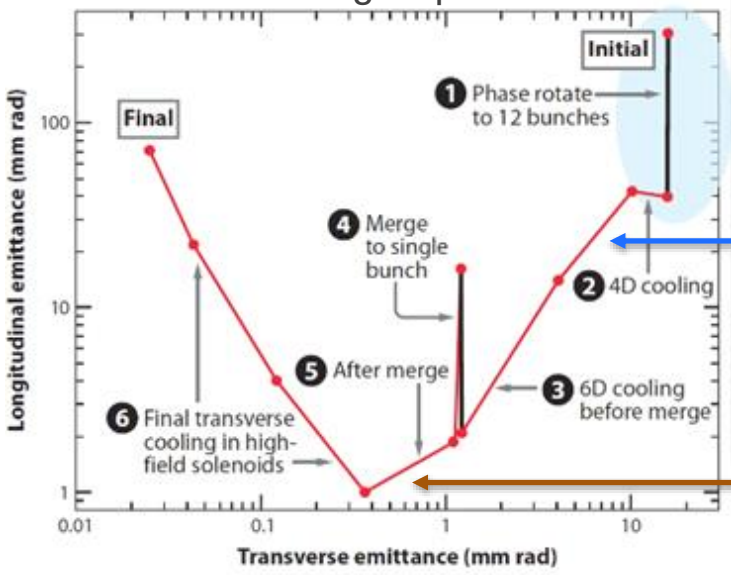
- Explore facility options for a full demo
- Design & prototype (if possible) 1.5 cooling cell
- Deliver a TDR for a demo facility with costs

- **This plan is pending P5 decision and will be modified after consultation with the IMCC AND knowledge of the US funding profile**

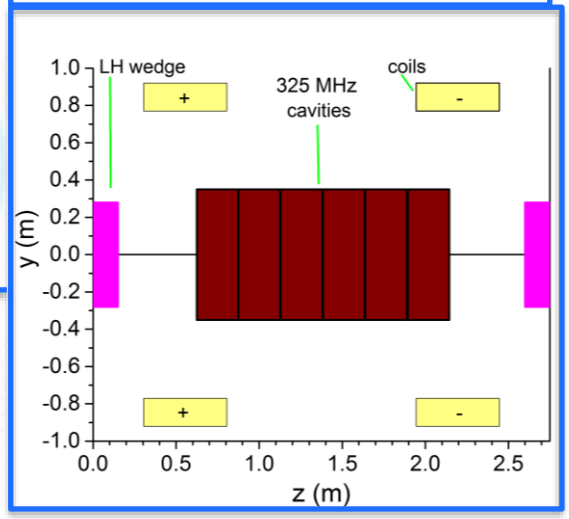
Why we need a demonstrator?

- Muon cooling is one the most important pieces of a MuC. **It will determine the TECHNOLOGY SPECS of the machine!**
  - Example: Good cooling, less demand on proton driver and targetry
- MuCs, uniquely, utilize ionization cooling channels. These channels require **special attention**, especially the late stages which closely pack high field magnets, absorbers, and rf cavities

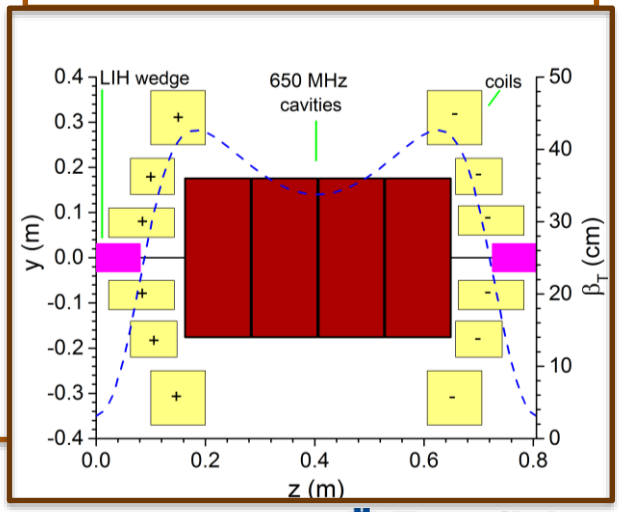
MuC cooling requirement



Early cell ("easy") – 2T peak



Late cell ("hard") – 14 T peak



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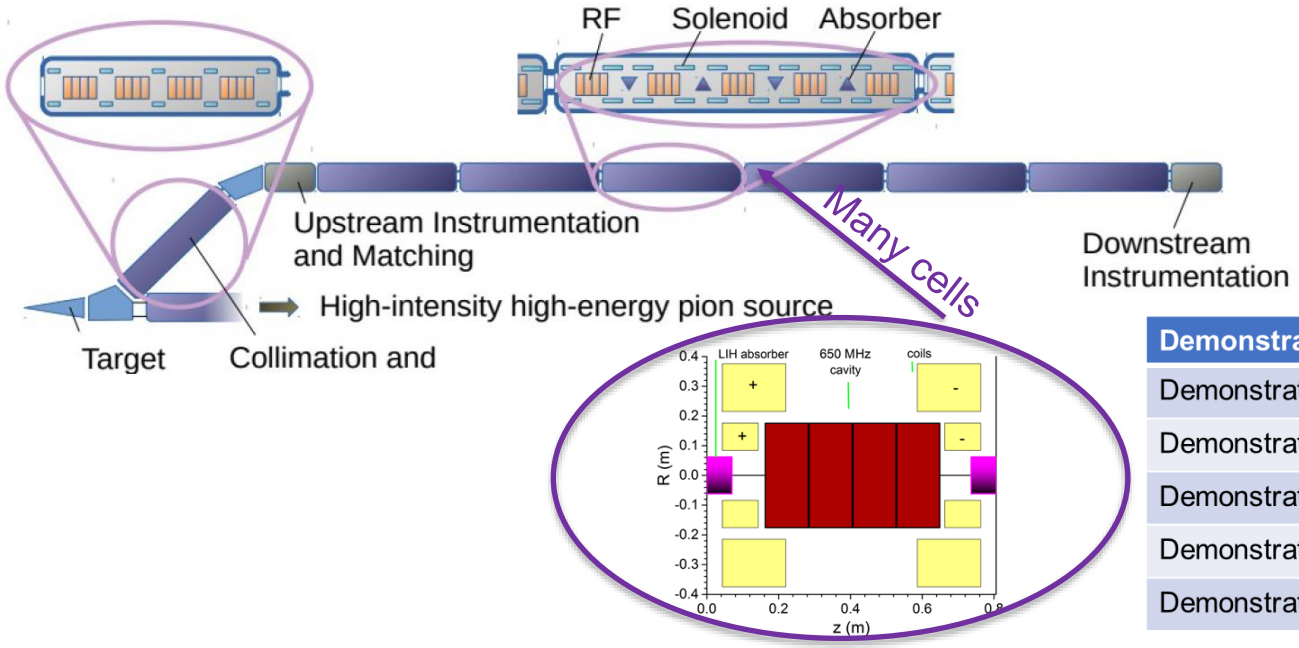
Cooling demonstrator (2030+)

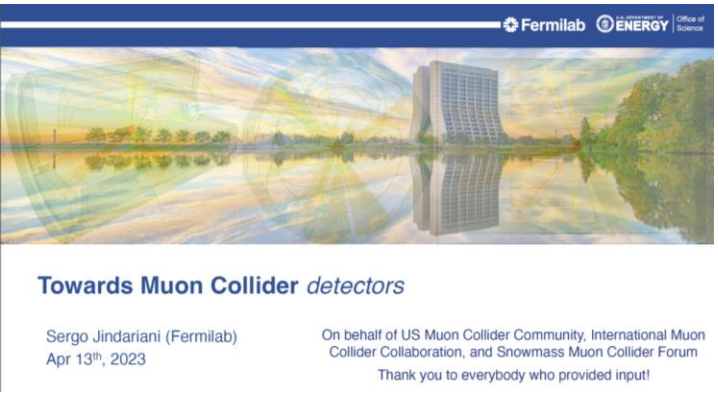
- While the physics of ionization cooling has been shown [ref] it is **critical** to benchmark a **realistic** MuC cooling lattice
  - This will give us the input, knowledge, and experience to design a real, buildable cooling channel for a MuC
  - **Possibilities for hosting such a facility in the US exist** (see Stratakis talk on Wednesday)



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

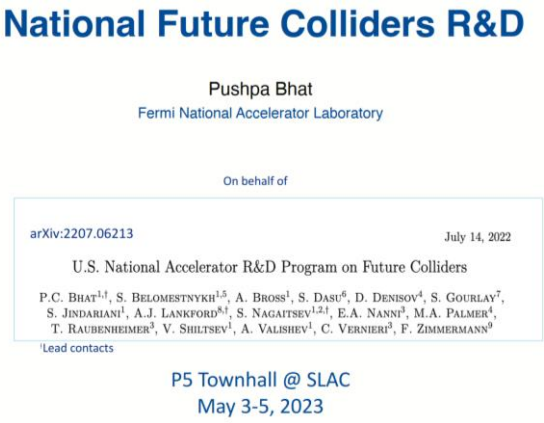
Post-Snowmass P5 Townhall Meetings

- Findings of the coordination groups were presented at two P5 Town-hall meetings



[Detector R&D plans and budget request]

[Accelerator R&D plans and budget request]

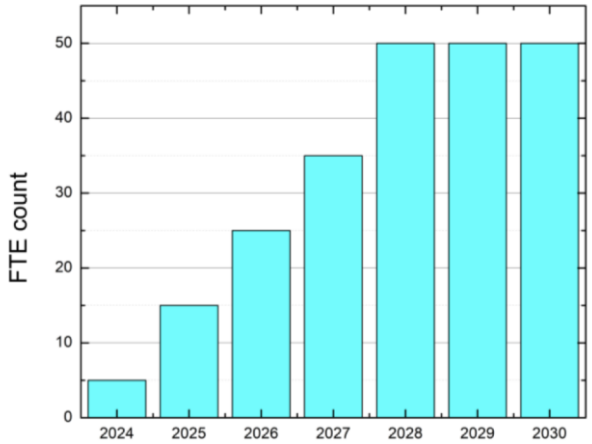


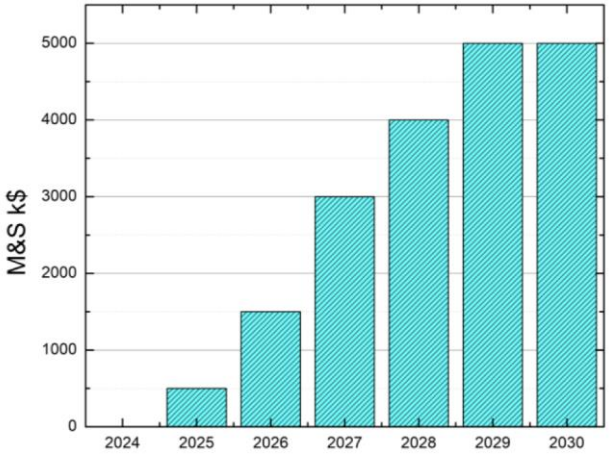
[National Collider R&D]

Our ASK for P5

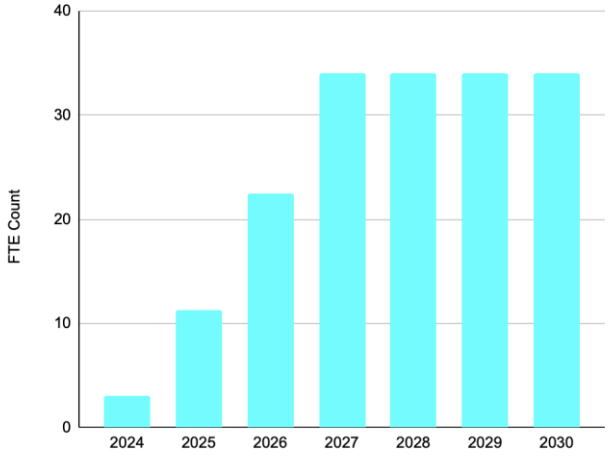
- The Detector and Accelerator ASK at the P5 townhalls was:
  - Recommend establishing a Muon Collider R&D program with the aim for delivering a RDR report for the final facility & TDR report for the demo facility by 2030 AND with an overall goal of having a TDR for the final facility by 2040
  - Recommend that DOE and NSF recognize Muon Collider work within the AF and EF base program proposals
  - Support the formation of a US Muon Collider effort to coordinate US impact while engaging in the international effort
  - Support the National Collider Initiative R&D program
  - Enable US to compete for hosting a Muon Collider

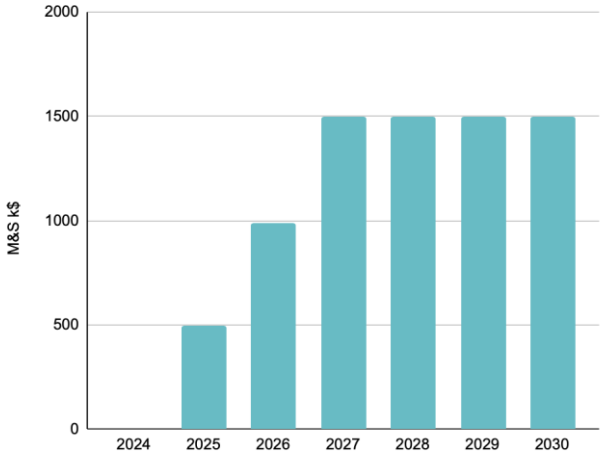
Muon Collider budget profile (2024-2030)





Accelerator

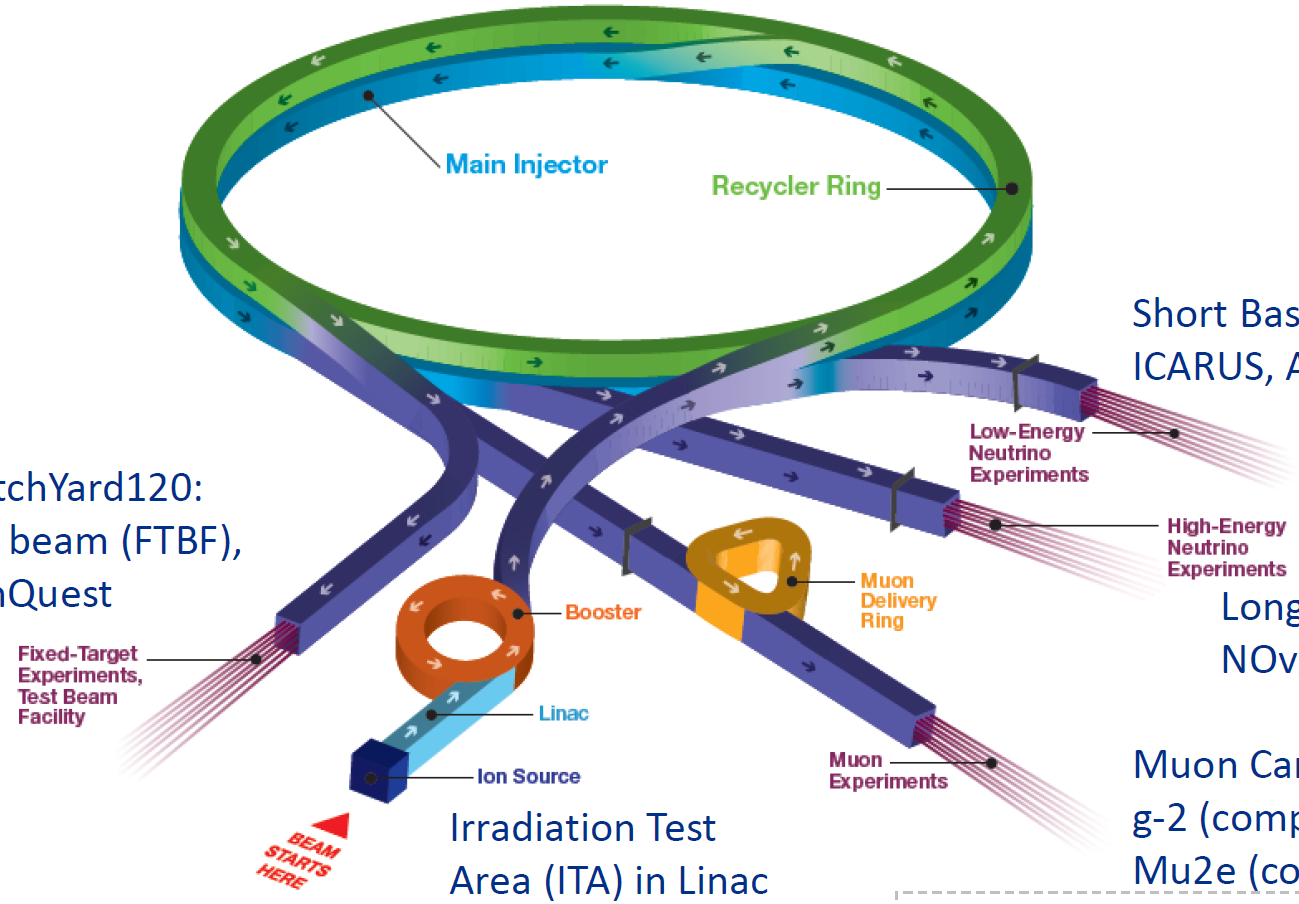




Detector

- **GOAL:** By 2030, achieve enough technical maturity for the construction of the demo facility in 2030s and potential construction of the collider facility in the 2040s.

Fermilab Accelerator Complex



Short Baseline Neutrino:
ICARUS, ANNIE, SBND

SwitchYard120:
test beam (FTBF),
SpinQuest

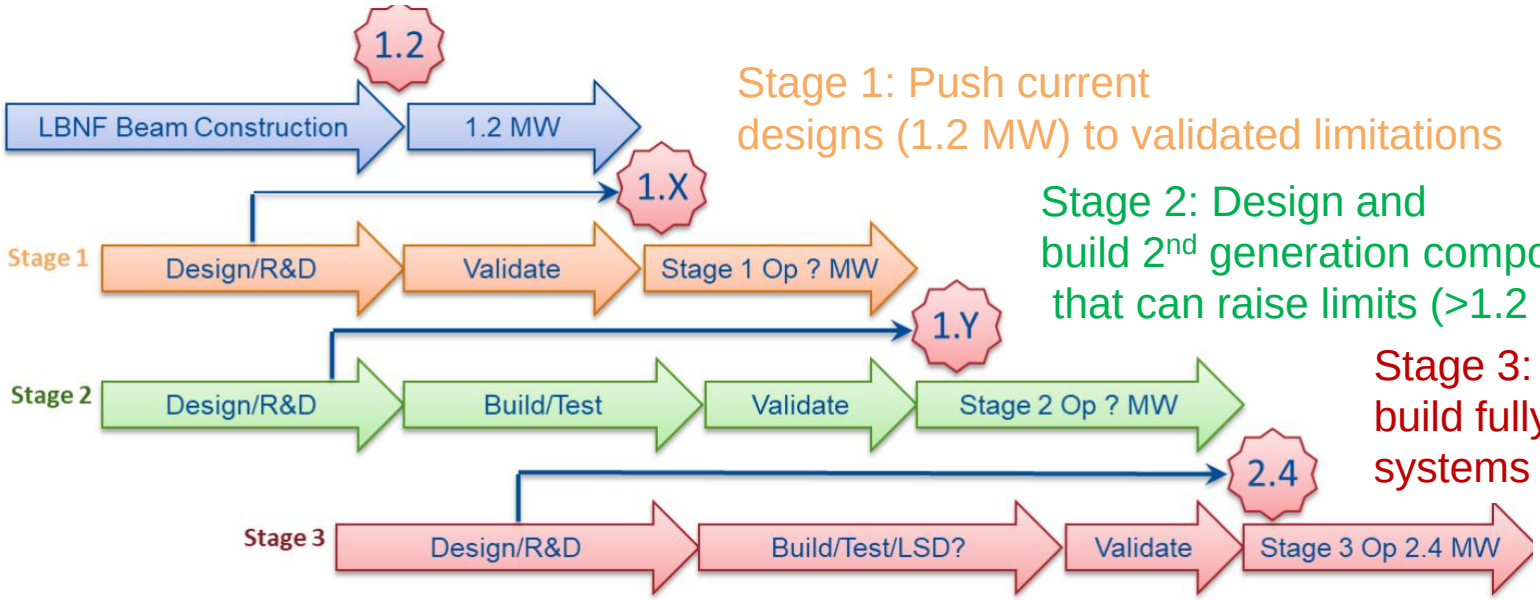
Long Baseline Neutrino:
NOvA

Muon Campus:
g-2 (completes this year),
Mu2e (commissioning)

Irradiation Test
Area (ITA) in Linac

Fermilab ACE program – Phase I (proposed to P5)

- In the next decade, LBNF plans to use protons which will operate at 1.2 MW to start and will be upgradable to 2.4 MW
- Accelerator Complex Evolution (ACE) aims a Main Injector upgrade to deliver >1.2 MW by 2032
  - Will include a rigorous **target R&D program for 2+ MW** beam powers
  - This program will **extremely benefit** the R&D for a MuC!



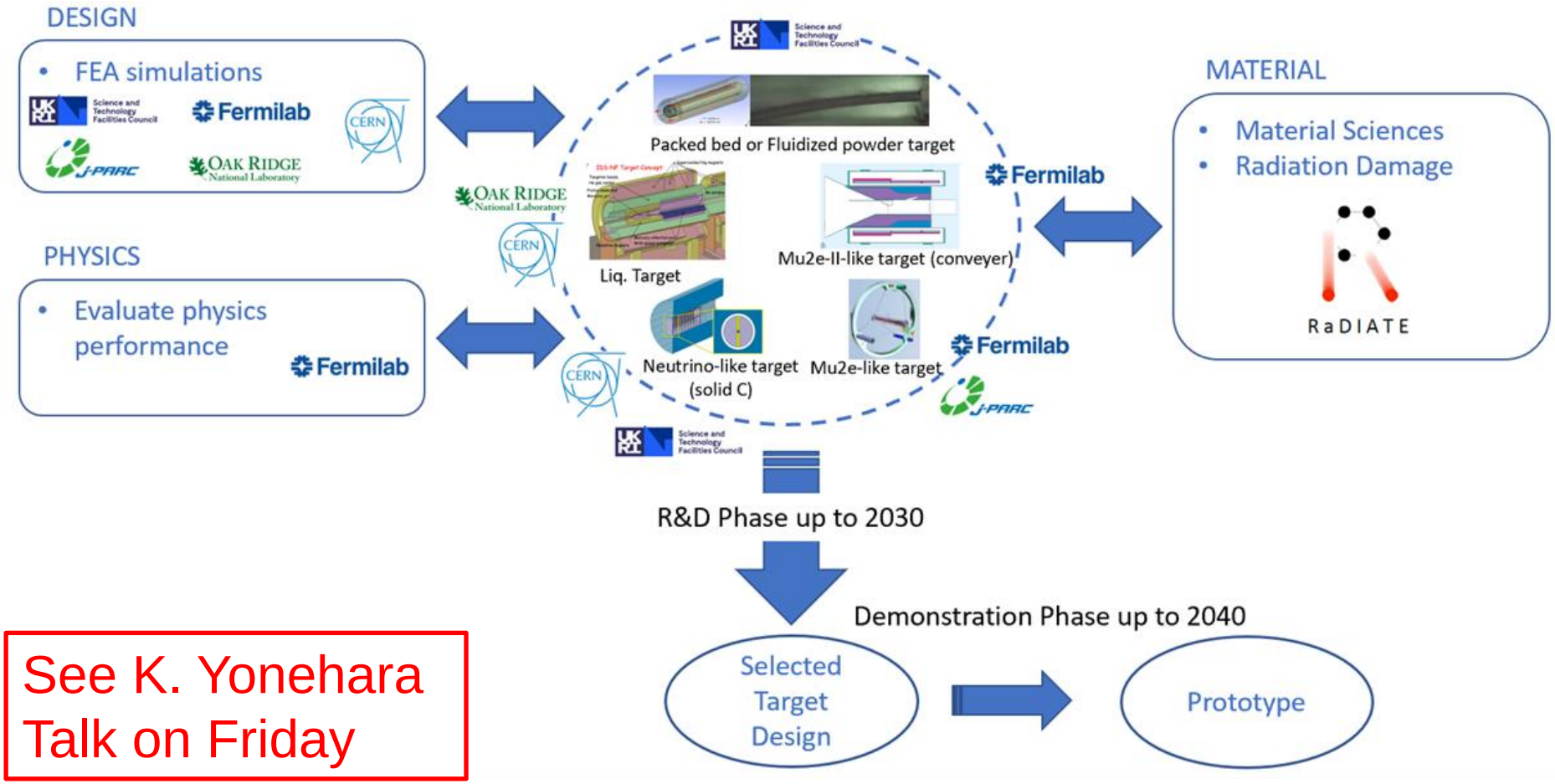
Stage 1: Push current designs (1.2 MW) to validated limitations

Stage 2: Design and build 2nd generation components that can raise limits (>1.2 MW)

Stage 3: Design and build fully optimized systems (2.4 MW)

DOE High-Power Targetry roadmap proposal

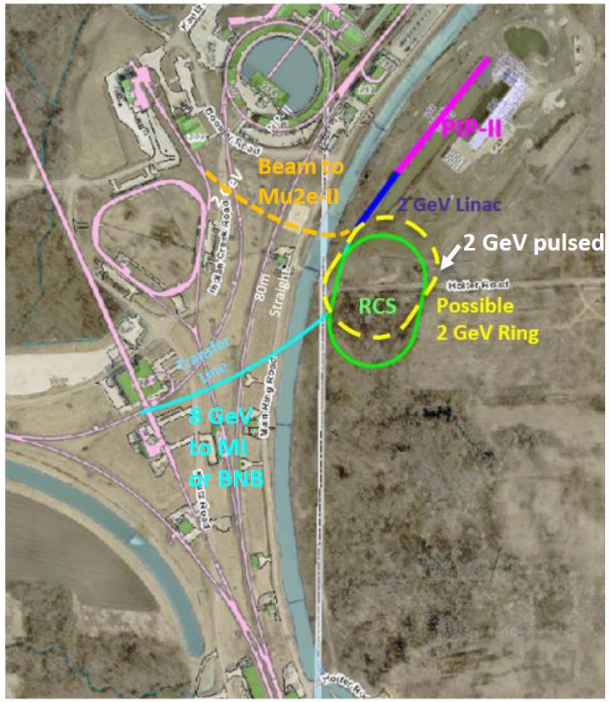
- MuC targetry is included in the proposed GARD High-Power Targetry Roadmap with a plan to have a prototype in the **late 2030s**

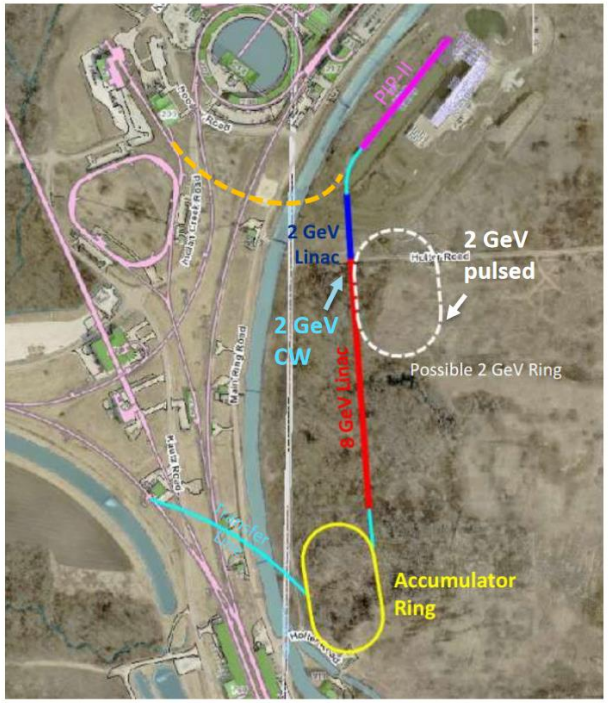


See K. Yonehara Talk on Friday

Fermilab ACE – Phase II (proposed to P5, > 2032)

- PIP-II linac extension: 0.8 to 2 GeV (may happen earlier)
- Then: (1) Linac further extension to 8 GeV OR (2) RCS to 8 GeV
  - Both scenarios may provide a path for a MuC proton driver **but will require significant R&D**





Fermilab ACE Science Workshop

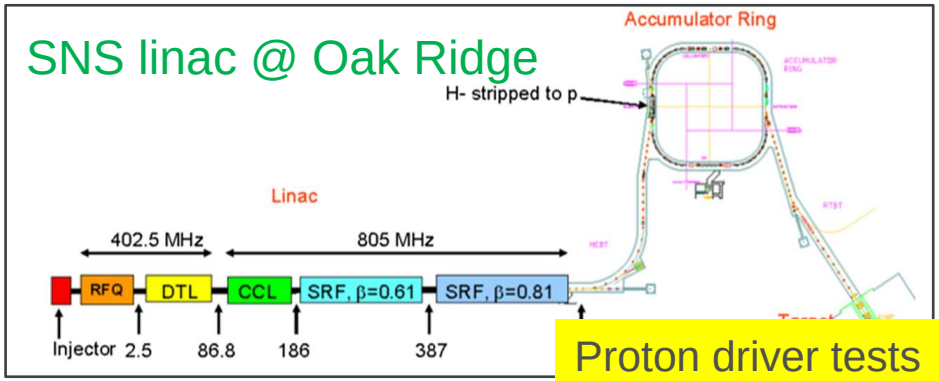
Jun 14 – 15, 2023
America/Chicago timezone

More details

Further possibilities within the US

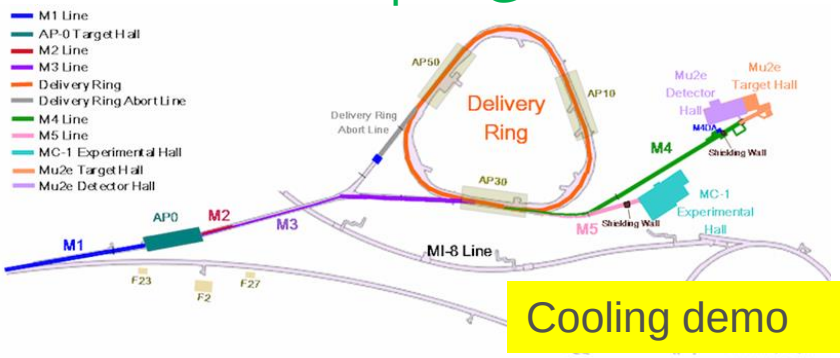
- Several **existing US based facilities** can aid the MuC R&D program: **they expressed interest** and are currently explored
  - **More discussions at the Synergies workshop on Friday**

SNS linac @ Oak Ridge



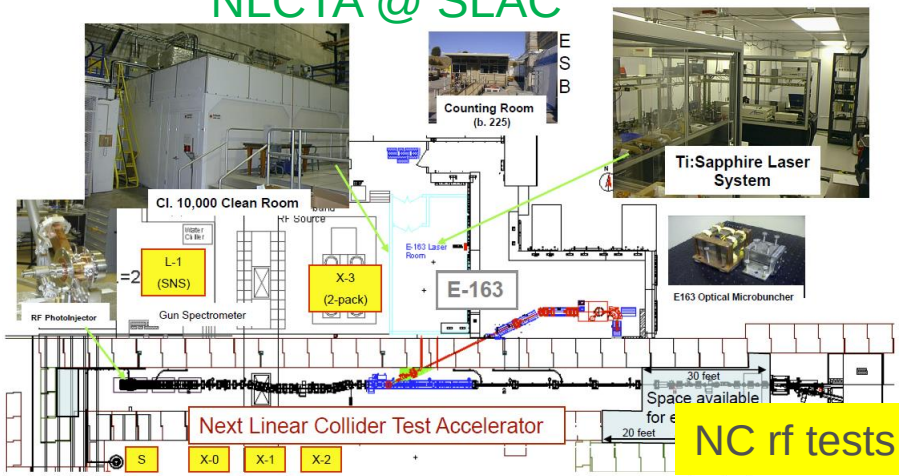
Proton driver tests

Muon Campus @ Fermilab



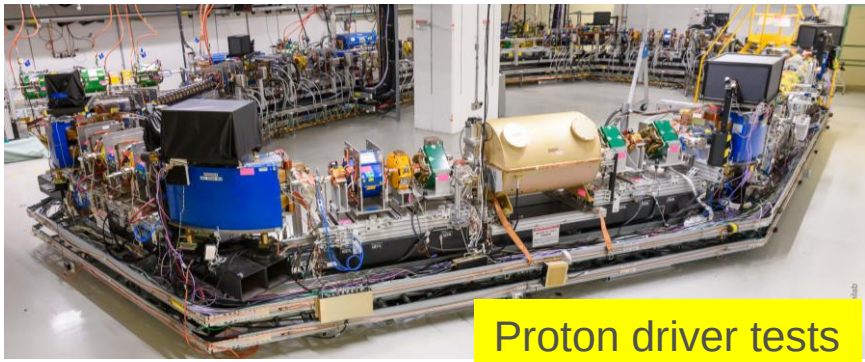
Cooling demo

NLCTA @ SLAC



NC rf tests

FAST/ IOTA @ Fermilab



Proton driver tests

Fermilab

Summary

- MC offers a unique opportunity for energy frontier collider with high luminosity
- Physics & technology landscape has significantly changed recently
  - Explosion of physics interest in muon colliders as indicated by the number of publications, activities in IMCC, Muon Collider Forum, and Snowmass white papers
- No fundamental show-stoppers in physics and technology 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
- We have established a highly motivated group to address challenges for a Muon Collider

It is crucial for the US to engage **NOW** if we want an MC as a future option!