# Towards a Muon Collider *accelerator*

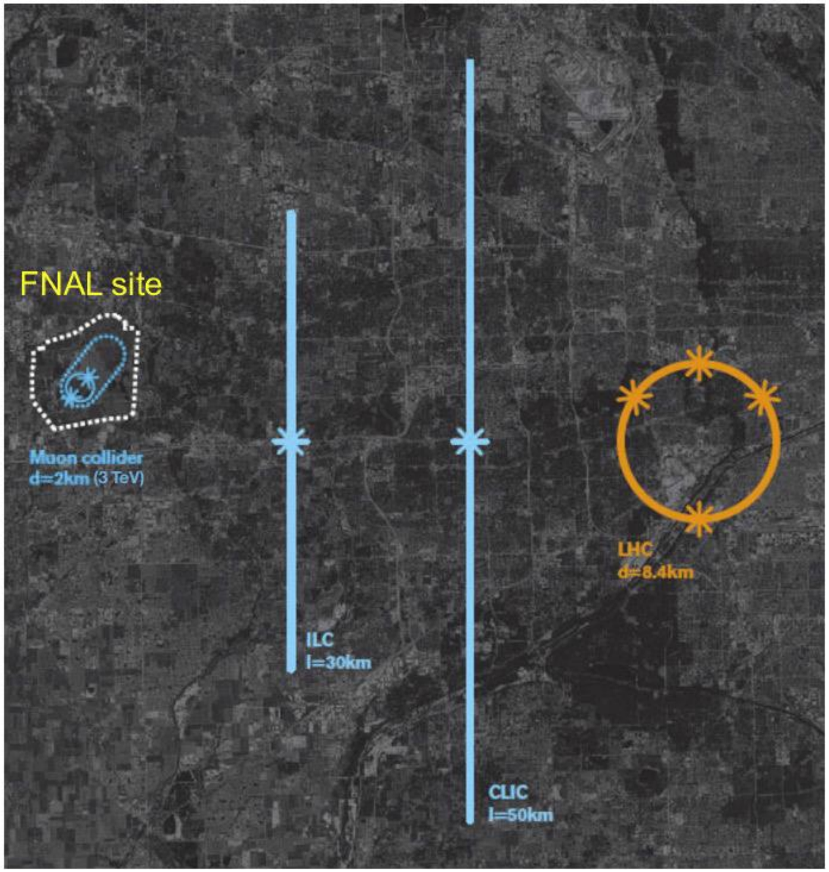
Diktys Stratakis (Fermilab)

P5 Town Hall at SLAC

May 3rd, 2023

On behalf of US Muon Collider Community,
International Muon Collider Collaboration, and
Snowmass Muon Collider Forum

# Muon Collider in comparison with other machines




- A Muon Collider would offer a precision probe of fundamental interactions, in a <u>smaller</u> footprint and <u>good</u> power efficiency as compared to other colliders

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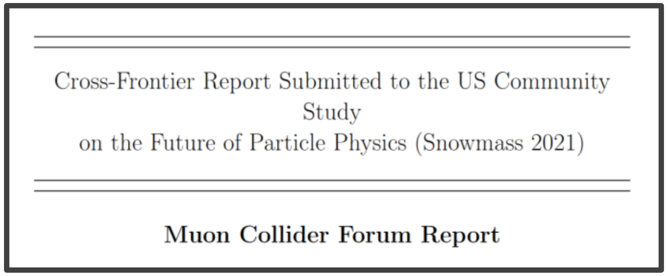
# Snowmass Muon Collider Forum

- The forum established a strong collaboration between the AF+EF+TF frontiers for Muon Collider (MuC) research
  - Monthly meetings and dedicated workshops for 18+ months before Snowmass: 160 e-mail subscribers, 50-100 regular participants
  - MuC Forum report is now public: ~180 authors, 50+% are early career scientists
- Forum conclusions:
  - Significant progress on MuC work recently
  - BUT engineering challenges exist
  - Requires significant R&D for making a Muon Collider a credible option

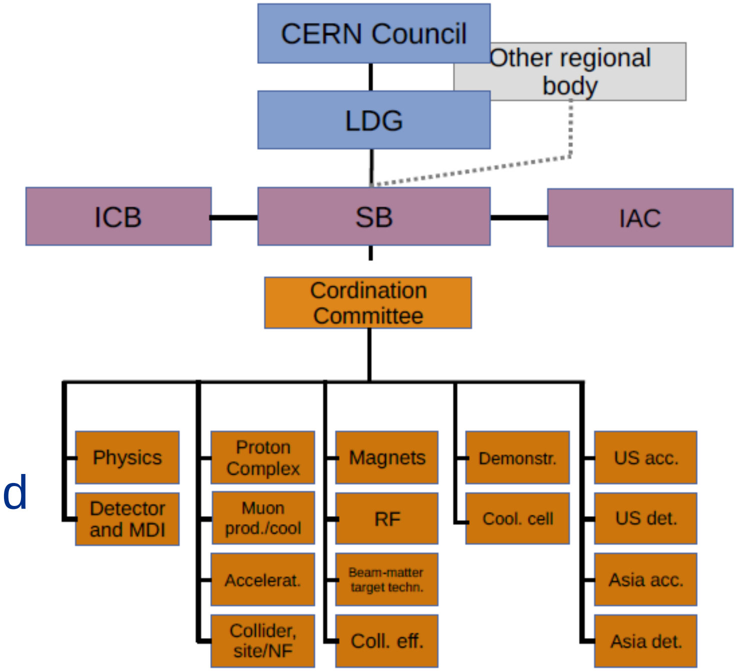

Cross-Frontier Report Submitted to the US Community Study
on the Future of Particle Physics (Snowmass 2021)

**Muon Collider Forum Report**

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

# International Effort

- 2020: Following the 2018 European Strategy process, Laboratory Director's Group initiated a Muon Collider feasibility study
- 2022: Formation of the International Muon Collaboration (IMCC)
  - US universities started to join, many more expressed interest
  - IMCC planning assumes a significant US participation to develop the baseline project and the best siting option (including US siting)



# Target parameters

**Target integrated luminosities**

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

**Note: currently focus on 10 TeV, also explore 3 TeV**

- Tentative parameters based on MAP study, might add margins
- Achieve goal in 5 years
- FCC-hh to operate for 25 years
- Aim to have two detectors

**Feasiblity addressed,** will evaluate luminosity performance, cost and power consumption

| 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 |
| $\varepsilon_L$ | MeV m | 7.5 | 7.5 | 7.5 |
| $\sigma_E / E$ | % | 0.1 | 0.1 | 0.1 |
| $\sigma_z$ | mm | 5 | 1.5 | 1.07 |
| $\beta$ | mm | 5 | 1.5 | 1.07 |
| $\varepsilon$ | µm | 25 | 25 | 25 |
| $\sigma_{x,y}$ | µm | 3.0 | 0.9 | 0.63 |

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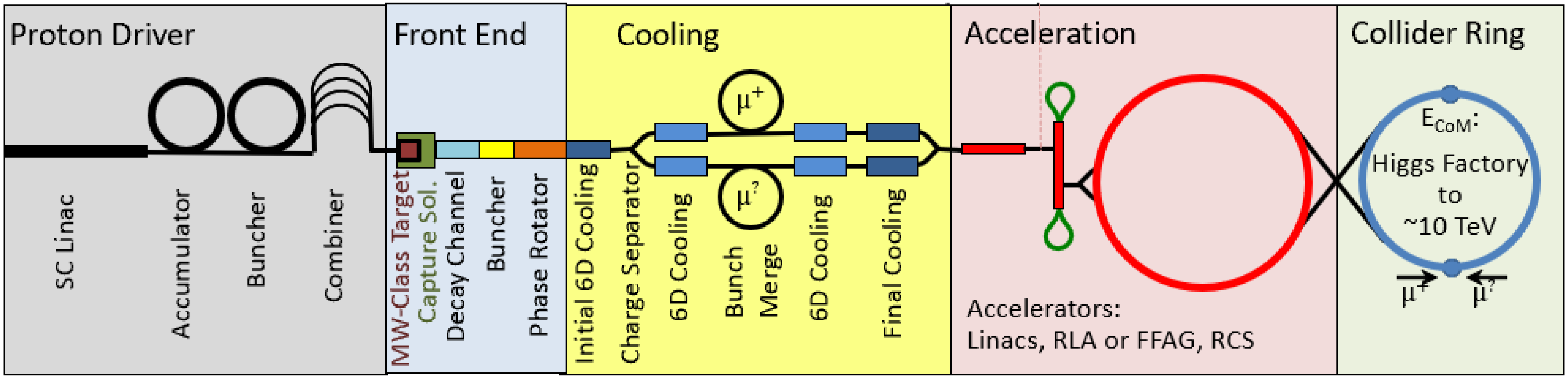
# Machine overview




Muon production target

MW-scale proton driver

Capture 200 MeV bunches

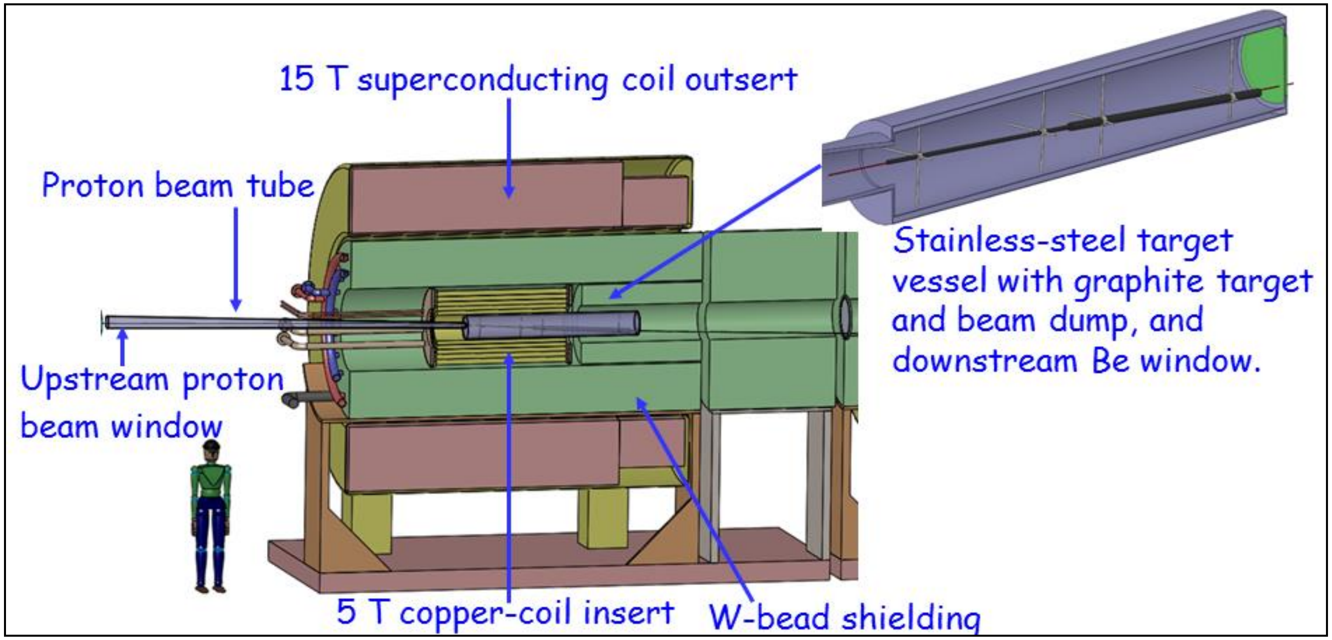
Ionization cooling to reduce 6D emittance

Acceleration to TeV scale energy

Collider ring for counter propagating muons

- Requires a **1-4 MW** proton beam @ **5-20 GeV**, compressed to **1-3 ns** bunches at a **5-10 Hz** frequency

# Muon Collider target: Concept & technology needs




- Technology requirements for MuC targets:
  - Target materials that produce high muon yield; This requires their placement in a high-field solenoid (15-20T)
  - Tolerant materials to thermal shock and fatigue from MW-scale beams
  - Shielding system that protects the capture magnet and surrounds
  - Large solenoidal aperture to allow for shielding

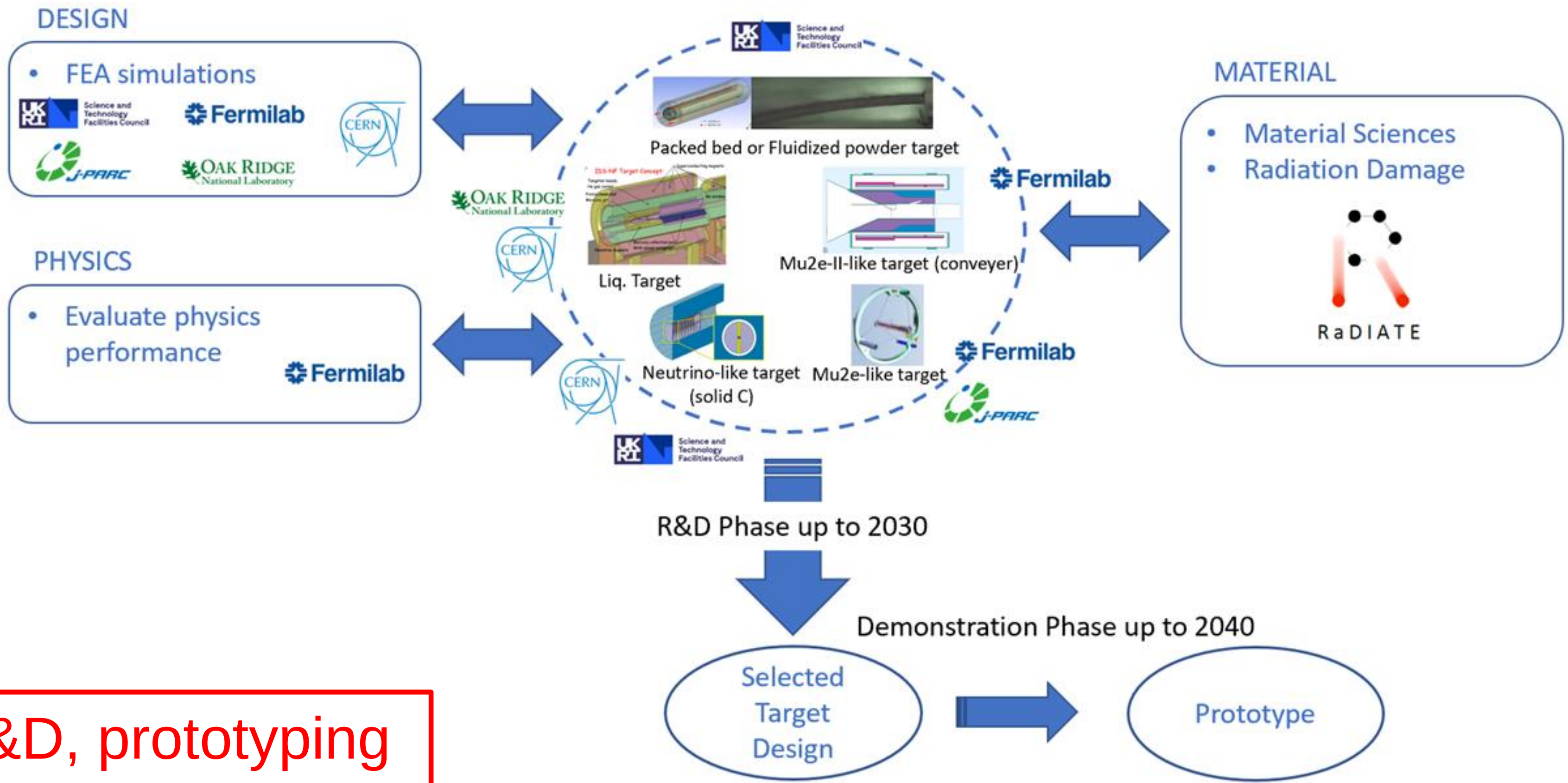
# Muon Collider target: Path forward (1)

- In 2007, a proof-of principle test validated the concept with a liquid Hg target. Technology was OK but some safety concerns
- Recent work shows promising results with C or W but still significant R&D is needed to confirm that the target can withstand 2+ MW
- This fact, combined with the strong demand of high-power targets puts the MuC in a synergistic path with many future experiments:

| Experiment | Material | Energy | Target in Sol | Synergy with Muon Colliders |
|---|---|---|---|---|
| LBNF Phase-1 | C | 120 GeV | No | Material test, physics performance |
| Mu2e | W | 8 GeV | YES | Material test, physics performance, magnet integration |
| Mu2e-II (proposed) | C, W,… | 800 MeV | YES | Same, but **higher** power density of Mu2e |
| AMF (proposed) | C, W, … | 800 MeV | YES | Same, **even higher** power density of Mu2e-II |

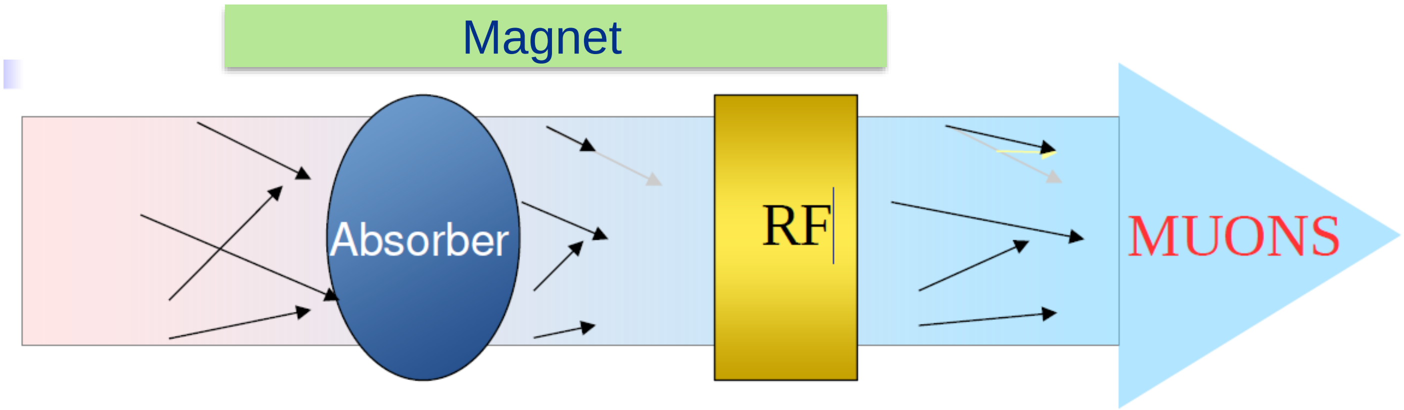
# Muon Collider target: Path forward (2)

- MuC targetry is included in the proposed HPT roadmap (GARD) with a plan to have a prototype in the **late 2030s**




R&D, prototyping should start now!

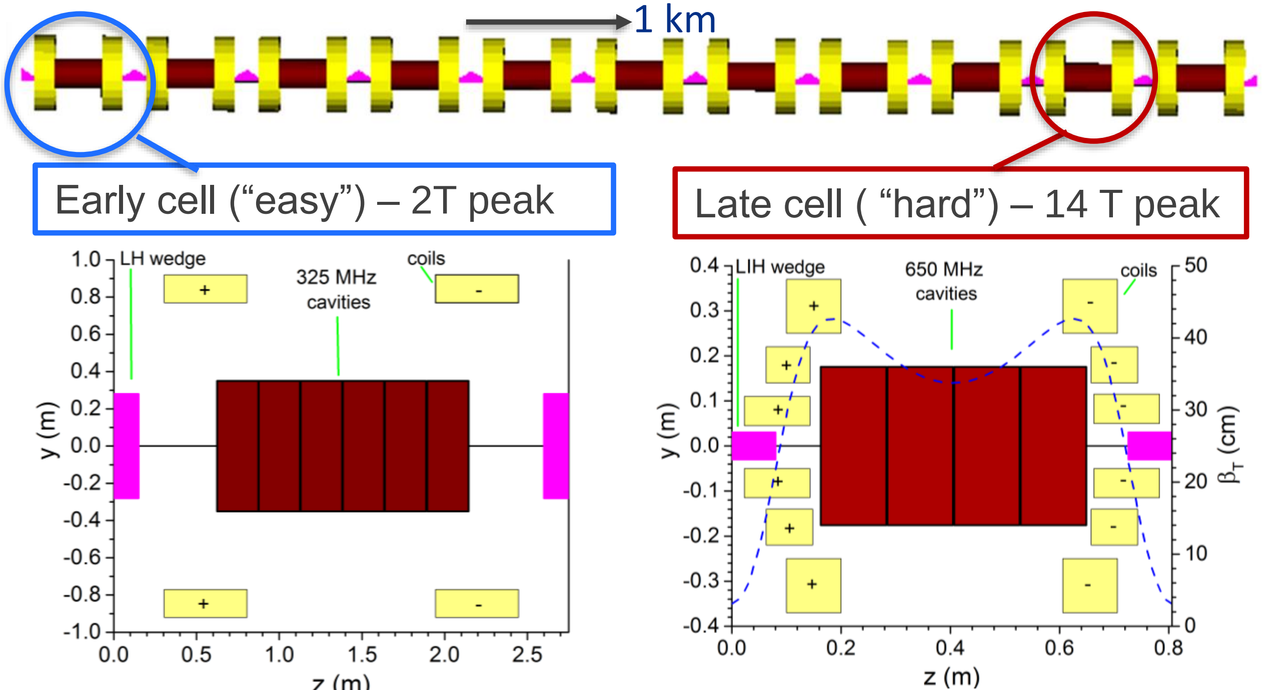
# Muon Collider cooling – Concept & technology needs

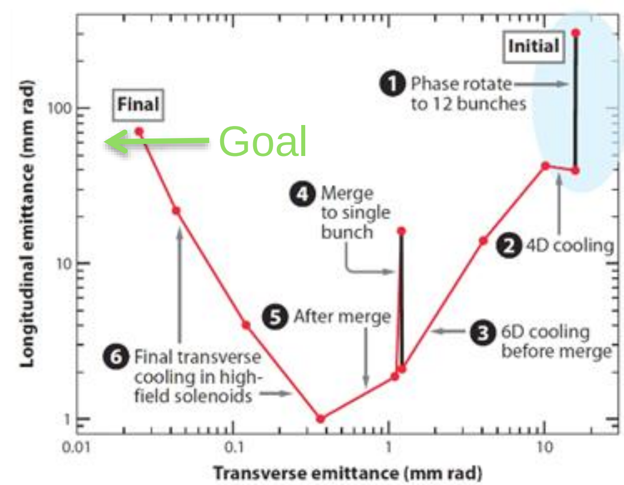



- Technology requirements for MuC cooling:
  - Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
  - Normal conducting rf that can provide high-gradients within a multi-T fields
  - Absorbers that can tolerate large muon intensities
  - Integration: Solenoids coupled to each other, near high power rf & absorbers)

# Muon Collider cooling: Path forward (design)

- Good progress in all cooling section designs over the last year. **BUT**, the final cooling **did not** achieve our goals [ref]
- Goals for next **5 years**:
  - (1) Deliver a realistic end-to-end design that meets the MuC criteria (2) take into account engineering aspects of the design and (3) improve performance with AI/ML methods and latest technology advancements



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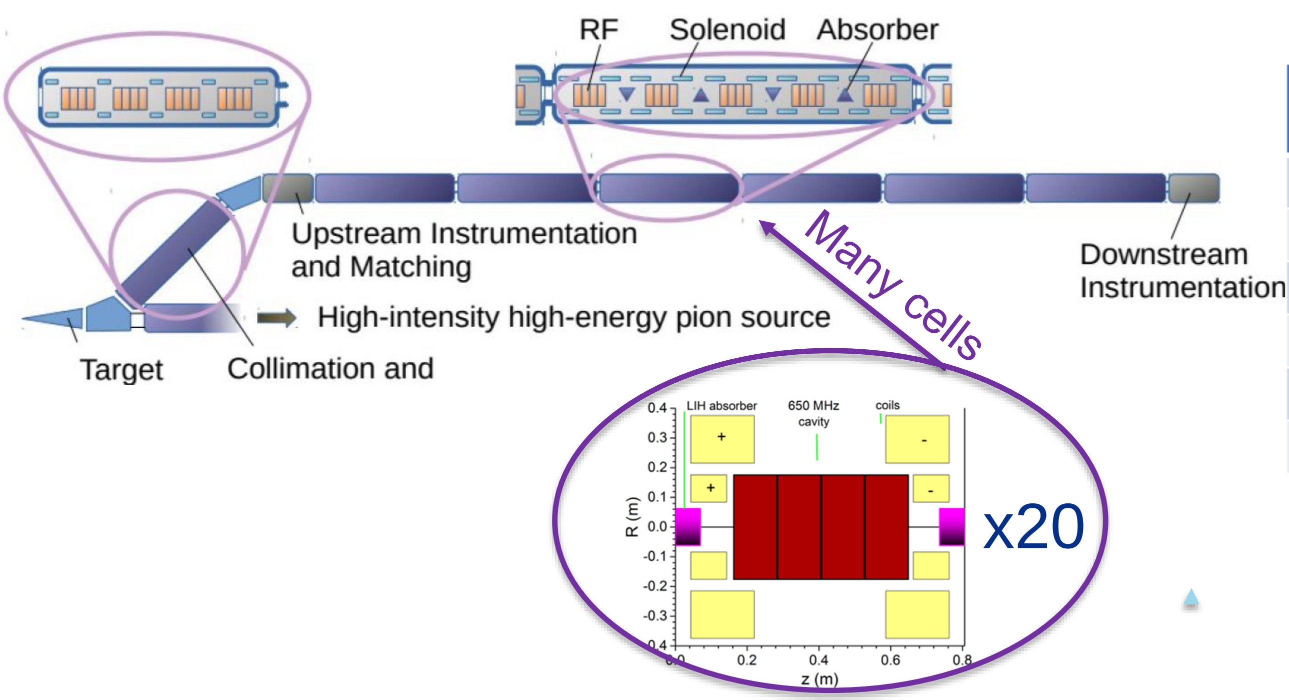
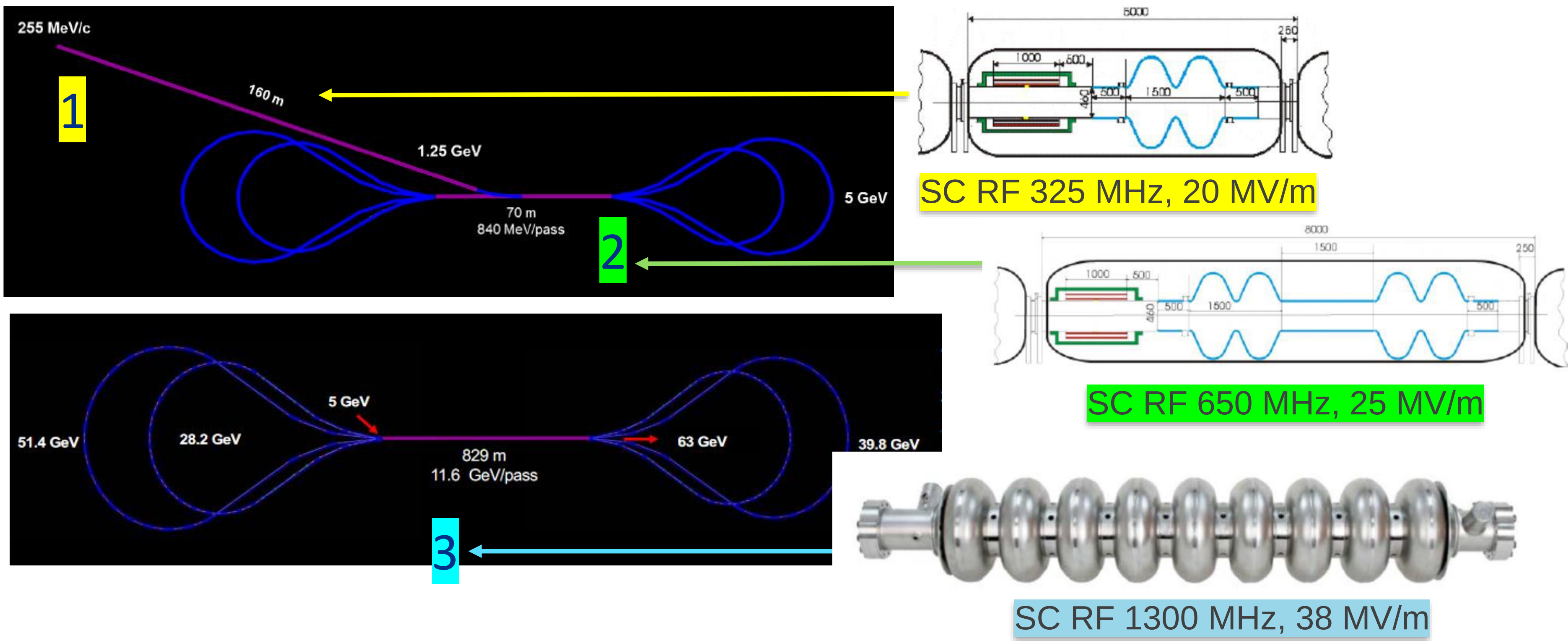
# Muon Collider cooling: Path forward (demonstrator)

- While the physics of ionization cooling has been demonstrated [ref] it is **critical** to develop a cooling demonstrator using a **realistic** lattice
  - Requires significant effort on the facility design & site exploration
  - Goal for the next **5 years:** Deliver demonstrator TDR with cost estimates & site selection (including US options)




| Concepts to be validated AND improved under realistic conditions | YES or NO |
|---|---|
| Target performance | YES |
| NC rf performance | YES |
| Magnetic lattice | YES |
| Absorber performance | YES |
| 6D cooling performance | YES |
| Instrumentation performance | YES |

# Acceleration to GeV – Concept & technology needs




- Technologies requirements for a Muon Collider:
  - Superconducting linacs and Recirculating linear accelerators (RLAs)
  - SC RF that: (1) starts at a low frequency ~ 325 MHz, (2) operate at high-gradients

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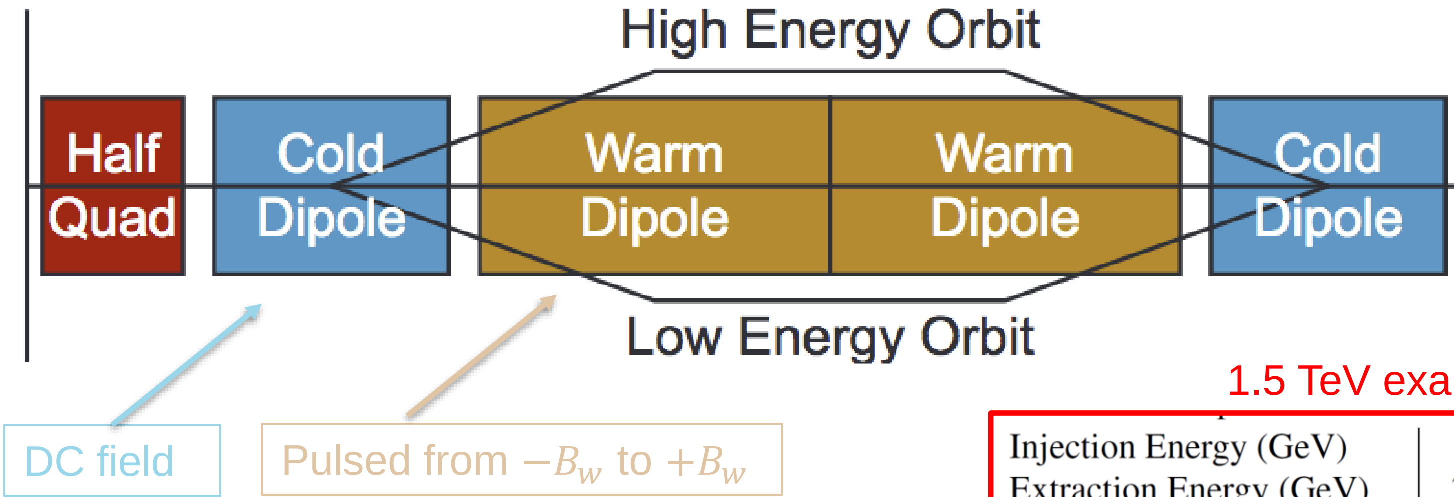
# Acceleration to TeV – Concept & technology needs



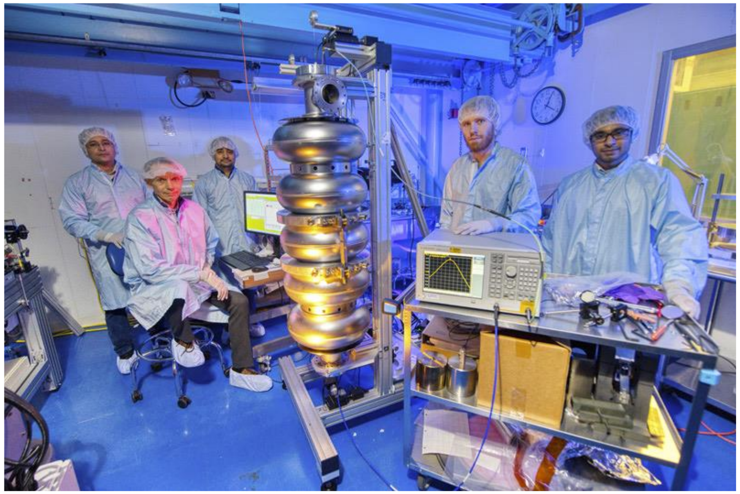


1.5 TeV example

| | | | |
|---|---|---|---|
| Injection Energy (GeV) | 63 | 303 | 750 |
| Extraction Energy (GeV) | 303 | 750 | 1500 |
| Circumference (m) | 5210 | 5210 | 9361 |
| Fixed Dipole Length (m) | — | 1103 | 2358 |
| Ramped Dipole Length (m) | 4229 | 3126 | 5240 |
| Turns | 13 | 25 | 23 |
| Time (ms) | 0.23 | 0.43 | 0.72 |
| Cavity Power (kW) | 950 | 950 | 530 |

- Technologies needs for a Muon Collider
  - Hybrid Rapid Cycling Synchrotron accelerators
  - Fast ramping magnets (<0.5 ms) accompanied with a 8-10 T DC magnet
  - Energy storage and power management with high quality factor

# Muon Acceleration: Path forward

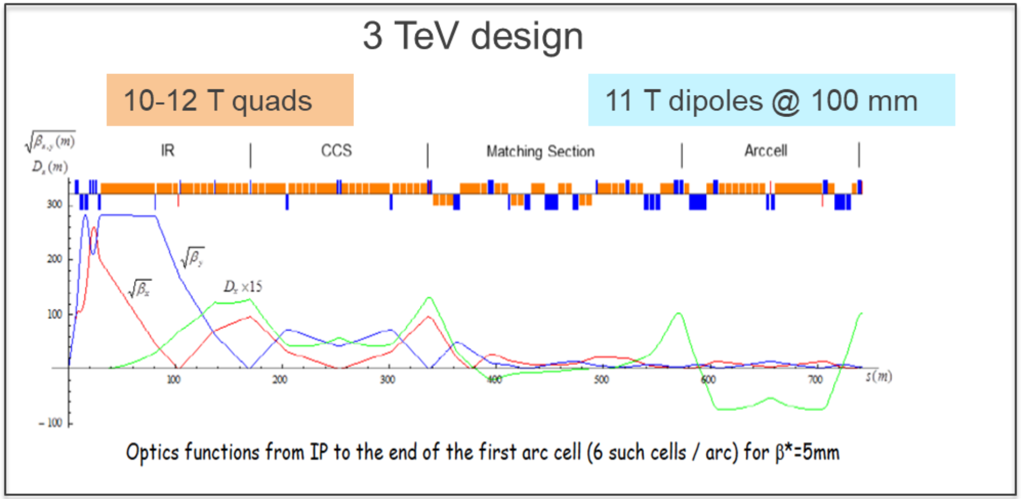


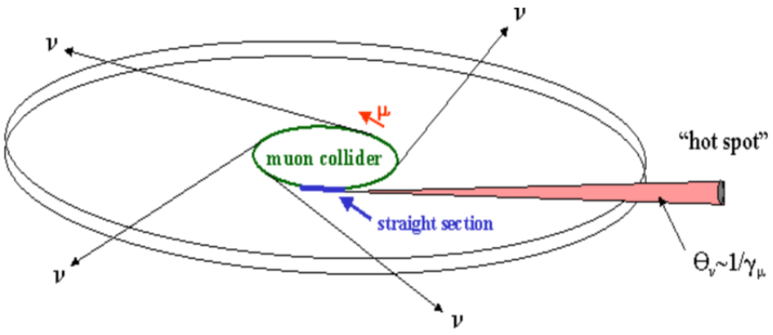
5 cell elliptical cavities @ 650 MHz for PIP-II

Cryomodule @ 1300 MHz for LCLS-II

- In the next **5 years** develop self-consistent accelerator lattice designs towards a 10 TeV collider
  - Investigate the beam-cavity interactions in all parts of the accelerator
- Utilize the extensive experience of the US on SRF for:
  - Design and testing SRF cavities for a MuC (325, 650, 1300 MHz)
  - Investigate alternative superconductors for pushing the gradient
  - Significant synergy with other programs (ILC, FCC-ee, GARD)

# Muon Collider ring – Concept & technology needs

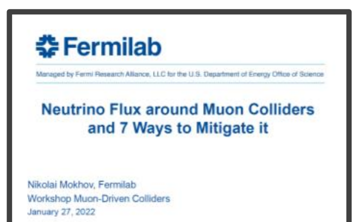



- Technology requirements for a 10 TeV ring
  - Strong quad focusing (> 12 T at IR)
  - High-field dipoles (12-16 T) with large aperture (~150 mm) for shielding
  - Mitigation system for the dense neutrino flux from muon decays

# Muon Collider ring – Path forward

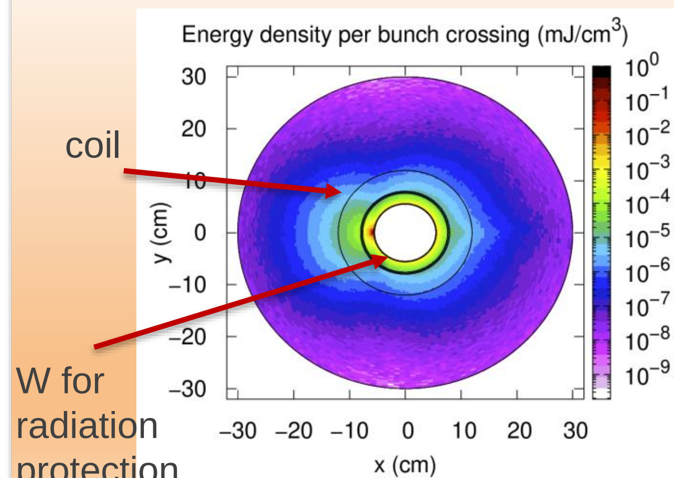
- Lattice design in place for a 3 TeV collider with optics and magnet parameters within existing technology limits
- In the next 5-years: Develop concepts for a 10 TeV collider
  - The shielding required is roughly the same for 3 TeV and 10 TeV [ref]: Good!
  - Preliminary concepts for 10 TeV published [ref] but more work is needed
  - Develop conceptual magnet designs with shielding from beam decay
- Several solution for Neutrino flux mitigation proposed and need to be evaluated
  - Examples include situating the collider ~200 m underground [ref] or move lattice overtime [ref] or a combination of the two
  - Promising example to follow (next slide)


Fermilab
Managed by Fermi Research Alliance, LLC for the U.S. Department of Energy Office of Science

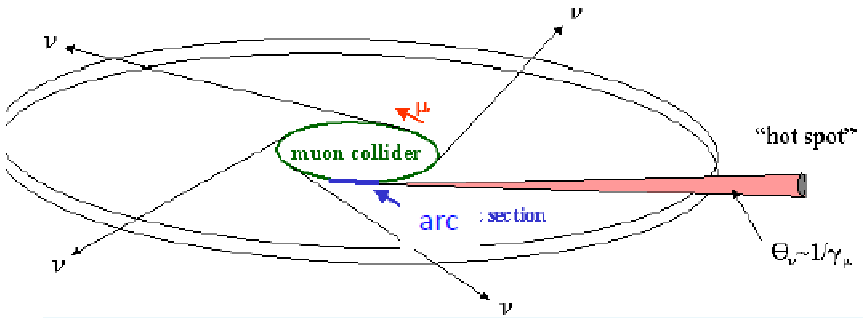
**Neutrino Flux around Muon Colliders and 7 Ways to Mitigate it**

Nikolai Mokhov, Fermilab
Workshop Muon-Driven Colliders
January 27, 2022

10 TeV radiation studies

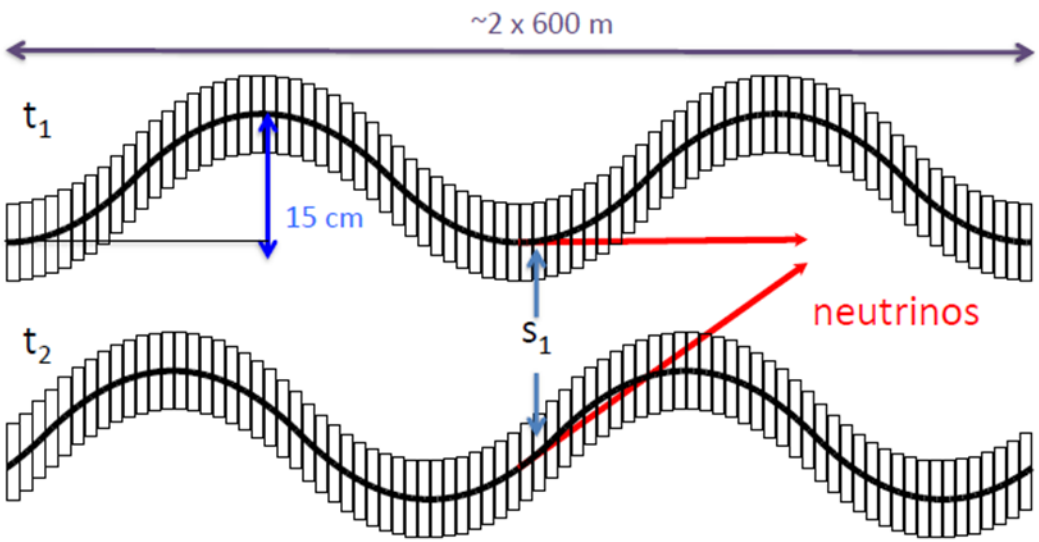


# Neutrino flux mitigation (IMCC scheme)




Legal limit: 1 mSv/year
MAP goal: <0.1 mSv/year
IMCC goal: <10 µSv/year
LHC : <5 µSv/year

Solution: A mechanical system that will disperse the neutrino flux by periodically deforming the collider ring arcs vertically with remote movers; (Schulte, IPAC 22)




Could work even for 14 TeV collider at 200 m

Need to study mover system, magnet, connections and impact on beam

Working on different approaches for experimental insertion

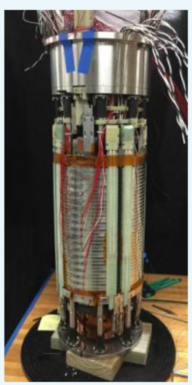
Requires significant R&D and proof-of principle tests

# Muon Collider Magnets: Path Forward

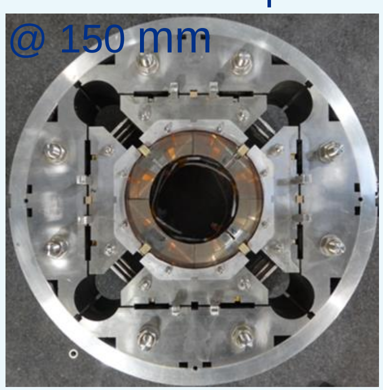
| MuC section | Type | 10 TeV MuC needs | Status |
|---|---|---|---|
| Cooling | Solenoid | 30-50 T @ 50 mm | 32 T @ 50 mm |
| Acceleration | Rapid cycling mag. | 1.8 T @ 5 kT/s (30 mm x 100 mm) | 1.8 T @ >5 kT/s (1.5 mm x 36 mm) |
| Collider Ring | Dipole | 12-16 T @ 150 mm | 11-12 T @ 120 mm |
| IR | Quadrupole | 15-20 T @ 150 mm | 11-12 T @ 150 mm |

- ~15% improvement by 2030 may be possible
- Many synergies with other programs. BUT RCS is unique for MuC!

32T @ NHMFL



LHC-HL 12 T quad @ 150 mm



| | Synergies | | | | |
|---|---|---|---|---|---|
| | US-MDP | Future Colliders | Fusion | ARDAP/Industry | NSF (NMR) |
| Target Solenoid | | | ■ | | ■ |
| Cooling Channel Solenoids | ■ | | | | ■ |
| High Ramp Rate for RCS | | | | | |
| Collider Dipoles | ■ | ■ | | | |
| IR Quads | | ■ | | | |
| | | | | | |
| **Alternatives R&D** | | | | | |
| HTS for collider magnets | ■ | | ■ | ■ | ■ |
| Acceleration | | | | | |
| FFA | | | | | |
| RLA | | | | | |
| Conventional | | | | | |

# ACE and Muon Collider

- Muon Collider proton driver needs are beyond existing facilities
- Fermilab ACE program offers several synergies with Muon Collider R&D
- The ACE booster replacement plan may provide a path for a MuC front-end
  - ACE parameters are being defined. Workshop in June will investigate synergies and options, including front-end for a MuC

| Muon Collider Proton Driver Parameters | |
|---|---|
| Energy | 5-15 GeV |
| Rep. rate | 5-10 Hz |
| Ave. Beam Power | 1-4 MW |
| Proton structure | 1-3 ns bunch with ~$10^{14}$ |

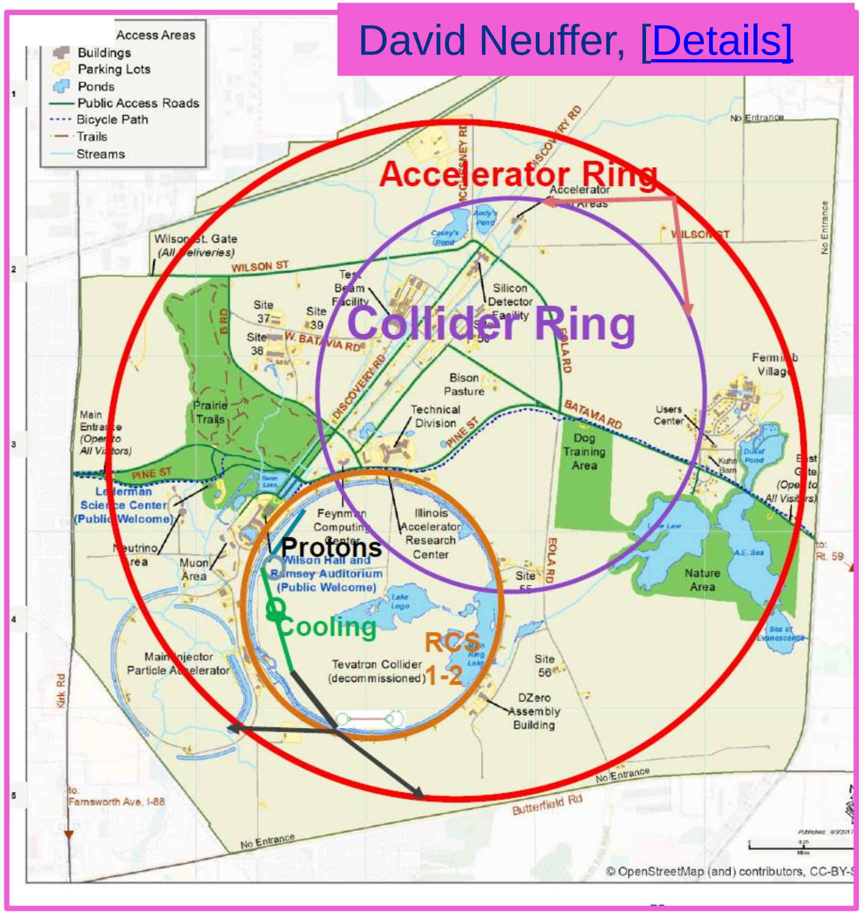
Synergies with ACE program

| ACE | Target | SRF | Proton Driver |
|---|---|---|---|
| Main injector upgrade | YES | | |
| Booster replacement | YES | YES | YES |

# Muon Collider @ Fermilab

- A conceptual for Fermilab 6-10 TeV MC site-filler 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 → **5 TeV (site filler)**
- 10 TeV collider
  - Collider radius: 1.65 km

David Neuffer, [Details]




- In the next **5 years**, have a baseline design including the neutrino flux mitigation system, establish operating parameters and develop technology concepts with potential to meet these parameters

# US Muon Collider R&D coordination group

- 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 (Wisconsin), Sergo Jindariani, Diktys Stratakis (Fermilab)

**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)

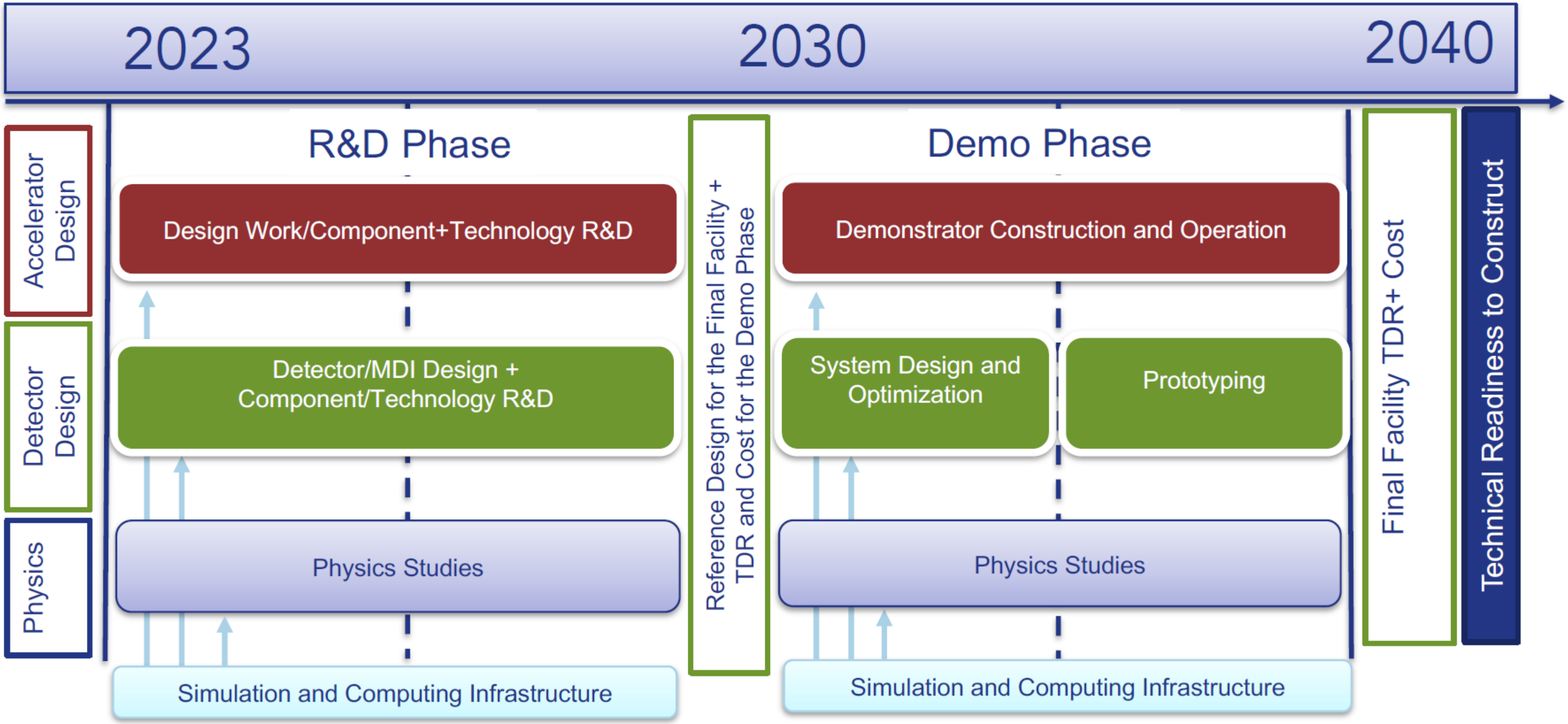
Electronics/TDAQ
Darin Acosta (Rice), Isobel Ojalvo (Princeton), Michael Begel (BNL)

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)

# US Muon Collider timeline



# A possible R&D roadmap

2024-2030

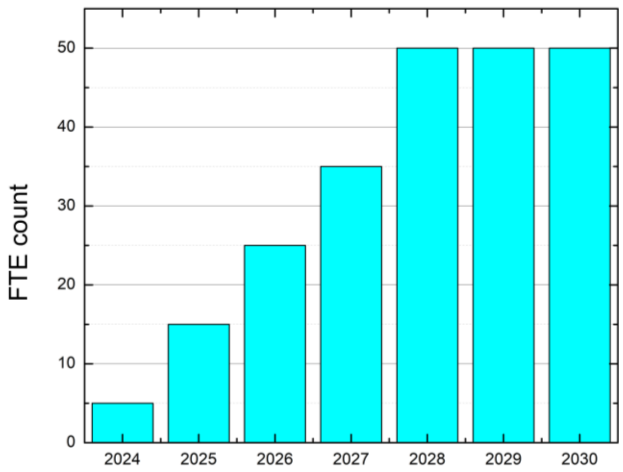
- Complete design & simulation of the whole MuC complex, including a neutrino flux mitigation system (include designs for a Fermilab MuC option)
  - Take into account engineering aspects of the design, establish operating parameters and develop technology concepts with potential to meet these parameters
- Proceed with prototyping & technology R&D
  - Rapid cycling magnets: magnet prototype, including its power deliver system
  - Proton driver tests: bunch compression and laser stripping at existing facilities
  - Target: material study & pion yield measurement at existing facilities
  - Conceptual design for magnets and cavities along the complex with some prototyping
  - Engineering design of the cooling demonstrator

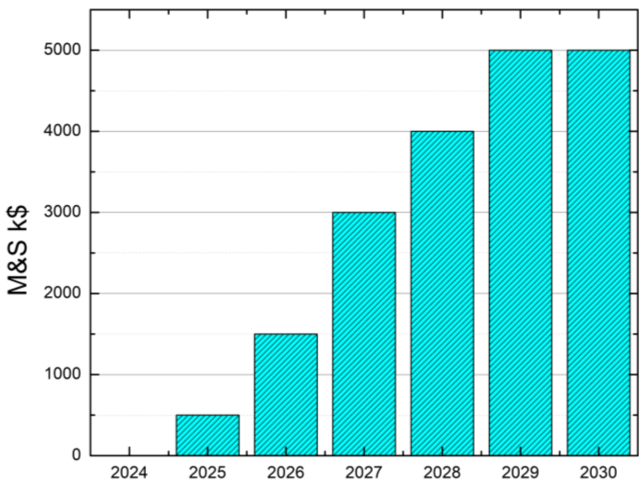
Synergistic with other programs

- Define what we like to test, how and where after 2030
- **By the next Snowmass study, have enough information to illustrate that a MuC has received enough maturity to be the next machine in the 2040s**

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

# US R&D budget estimate (Accelerator)




- **2024+**: US accelerator experts funded to engage with the IMCC
  - Ramp-up cost profile towards **equal-partnership** with the European effort.
- **~2030**: Deliver a MuC **reference design report** and a **TDR report** for the demonstrator facility with **cost** estimates
- **2031+**: Develop technology to be ready to commit, verify performance of all components
  - Cooling channel demonstrator is expected to be the cost driver. EU accounting **~$300M**

# Summary

- MC offers a unique opportunity for energy frontier collider with high luminosity
- Physics & technology landscape has significantly changed recently
- We have established a highly motivated group to address challenges for a Muon Collider
- As also presented at BNL, we are asking P5 to:
  - 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 base program proposals
  - Support the formation of a US Muon Collider effort to coordinate US impact while engaging in the international effort
  - Enable US to compete for hosting a Muon Collider

# Extra

# Demonstrator facility consideration

- Finding demonstrator sites is a key component of the effort
  - Demonstration of radiation and shock resistance of materials
  - Demonstration of high field muti-Tesla magnets for muon production, cooling, acceleration and collision
  - Demonstration of high gradient, normal conducting rf cavities for cooling and power-efficient superconducting rf for acceleration
  - Demo of an integrated ionization cooling module as an engineering prototype
- Other challenges exist but can be addressed with prototypes and beam tests (e.g. collider & fast cycling magnets, magnet movement system for neutrino flux mitigation,  H- stripping, bunch compression)

# Muon Collider Synergies

| Facility/Experiment | Physics Goals | Synergy |
|---|---|---|
| nuStorm | Short baseline neutrino program, including searches for sterile neutrino and cross section measurements | 100kW proton source, muon production and collection, storage ring operation |
| Neutrino Factory (e.g. nuMax) | Better CP, mixing angles, mass splitting, non-standard interactions | MW class proton source, muon production and collection, 6D partial cooling and muon acceleration (up to ~5 GeV) |
| Dark Sector searches | Searches for particles from Dark Sectors produced in fixed target experiments using high intensity proton beam | MW class high-intensity proton beams |
| Charged Lepton Flavor Violation (e.g. AMF) | Searches for rare lepton flavor violating processing (mu2e, mu2eg, mu3e, etc) | MW class proton source, muon production and collection, storage ring |
| Beam dump experiments | Searches for exotic particles (dark photons, Lmu-Ltau, etc) in muon beam dump experiments | 100kW – MW proton source, muon production and collection, partial cooling and acceleration |
| Neutrinos from collider beam muon decays | DIS in neutrino-nucleus interactions, better nuclear PDF, atmospheric neutrinos<br>FASERv like experiment with smaller flux uncertainties | Everything up to multi-TeV energy collider beams |
| Muon Ion Collider | A broad program addressing many fundamental questions in nuclear and particle physics | Everything up to multi-TeV energy collider beams |

# Muon Collider Challenges

| Challenge | Progress | Future work |
|---|---|---|
| Multi MW proton sources with short bunches | Multi-MW proton sources have been and are being produced for spallation neutron sources and neutrino sources (SNS, ESS, J-PARC, Fermilab) | Refine design parameters, including proton acceleration to 5-10 GeV. Accumulation and compression of bunches. |
| Multi MW targets | Neutrino targets have matured to 1+MW. RADIATE studies of novel target materials and designs aim at 2.4MW. | Develop target design for 2 MW and short muon collider bunches. Produce a prototype in 2030s. |
| Production solenoid | ITER Nb3Sn central solenoid with similar specifications and rad levels produced | Study cryogenically stabilized superconducting cables and validate magnet cooling design. Investigate possibility of HTS cables. |
| Cooling channel solenoids | Solenoid with 30+T field now exists at NHMFL. Plans to design 40+T solenoids in place. | Extend designs to the specs of the 6D cooling channel, fabrication for the demo experiment |
| Ionization cooling | MICE transverse cooling results published. Long.cooling via emittance exchange demonstrated at g-2. | Optimize with higher fields and gradients. Demonstrate 6D cooling with re-acceleration and focusing |
| RF in magnetic field | Operation of up to 50 MV/m cavity in magnetic field demonstrated, results published | Design to the specs of the 6D demo, experimen; fabrication |

# Muon Collider Challenges

| Challenge | Progress | Future work |
| --- | --- | --- |
| Fast Ramping Magnets | Demonstrated 5000+ T/s  with 1. 8T | We need to design a efficient power supply system for these magnets |
| Neutrino Flux Effects | Mitigation strategies based on placing the collider ring at 200m and introducing beam wobble has been shown to achieve necessary reduction up to 10-14 TeV | Study mechanical feasibility, stability and robustness of the mover's system and impact on the accelerator and the beams |
| Detector shielding and rates | Demonstrated to be manageable in simulation with next generation detector technologies | Further develop and optimize 3 and 10 TeV detector concepts and MDI. Perform detector technology R&D and demonstration. |
| Open aperture storage ring magnets | 12-15T Nb3Sn magnets have been demonstrated | Design and develop larger aperture magnets 12-16T dipoles |
| Low-beta IR collider design and dynamic aperture | Lattice design in place for a 3 TeV collider with optics and magnet parameters within existing technology limits | Develop lattice design for a 10 TeV collider |