
# *Towards a 10 TeV Muon Collider*

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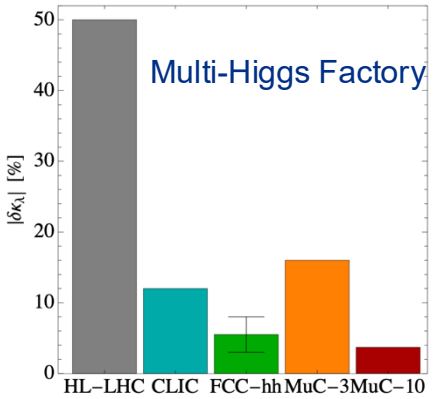
on behalf of International Muon Collider Collaboration (IMCC) and US Muon Collider Collaboration

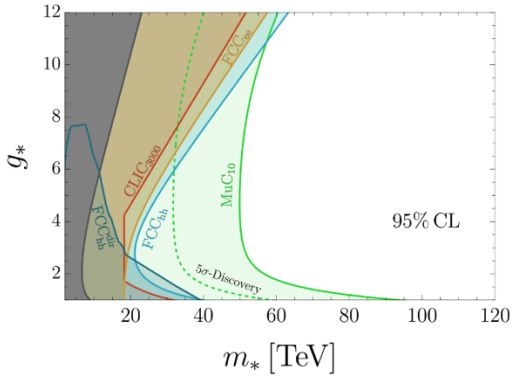
Lepton-Photon'2025, Madison, Wisconsin

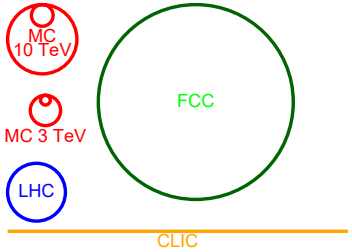
# Why Muon Collider?

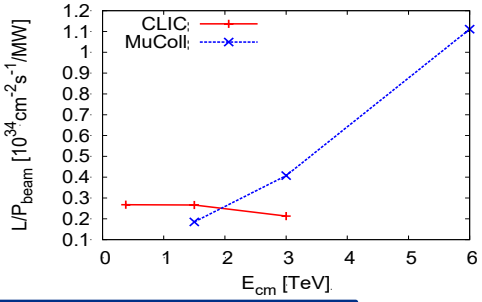
- Amazing physics opportunities through combination of energy and precision
- Small footprint
- Good Luminosity/Power scaling
- Initial studies indicate favorable cost wrt comparable machines

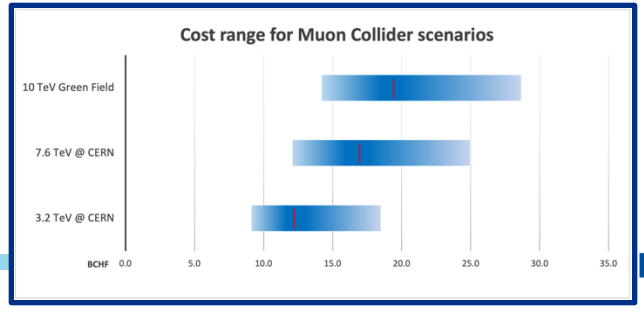



Compositeness reach



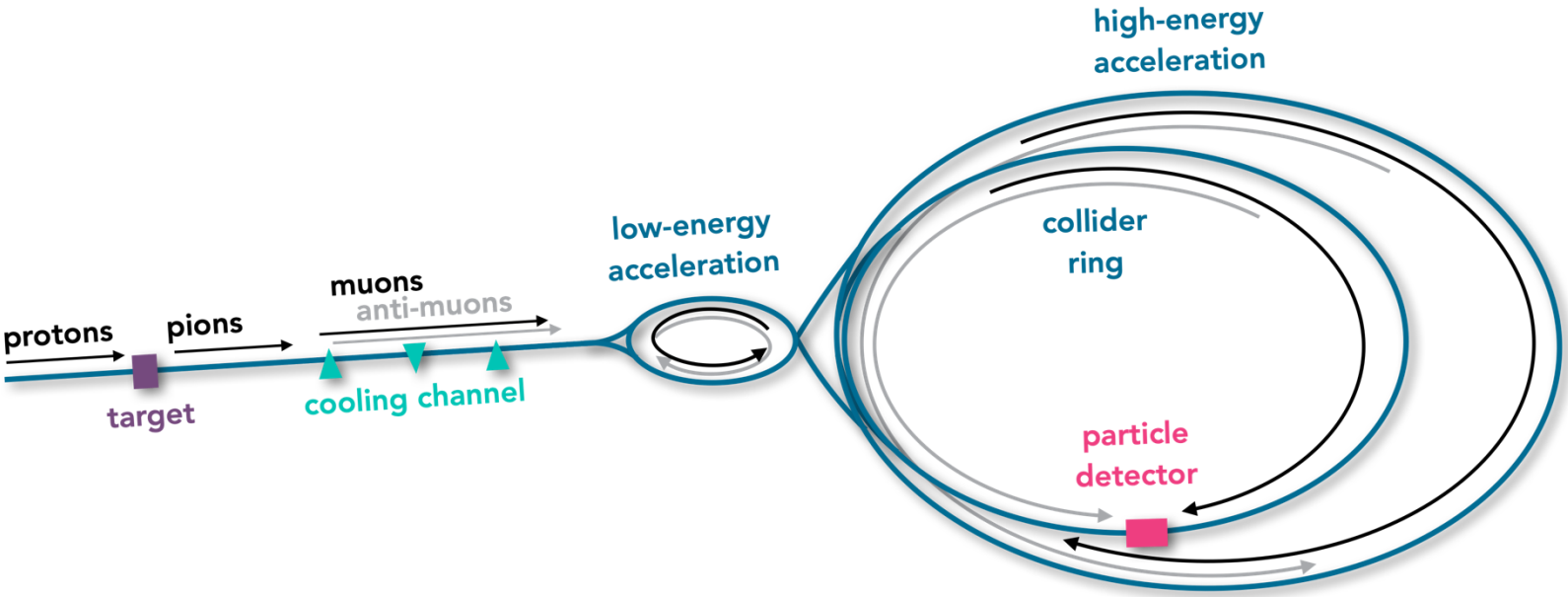
# Statements from the P5 and NAS panel reports

**P5:** Although **we do not know if a muon collider is ultimately feasible**, the road toward it leads from current Fermilab strengths and capabilities to **a series of proton beam improvements and neutrino beam facilities**, . . . . At the end of the path is an unparalleled global facility on US soil… ***This is our muon shot***

**NAS EPP Recommendation 1: The United States should host the world's highest-energy elementary particle collider around the middle of the century.** This requires **the immediate creation of a national muon collider research and development program** to enable the construction of a demonstrator of the key new technologies and their integration.

# The Machine Concept at ~10 TeV

- The goal is to get to **10 TeV center-of-mass** energy with L ~ $10^{35}$ $cm^{-2}$ $s^{-1}$
- **Staging in energy** (e.g. 3→10 TeV) or **in luminosity** are possible and being studied

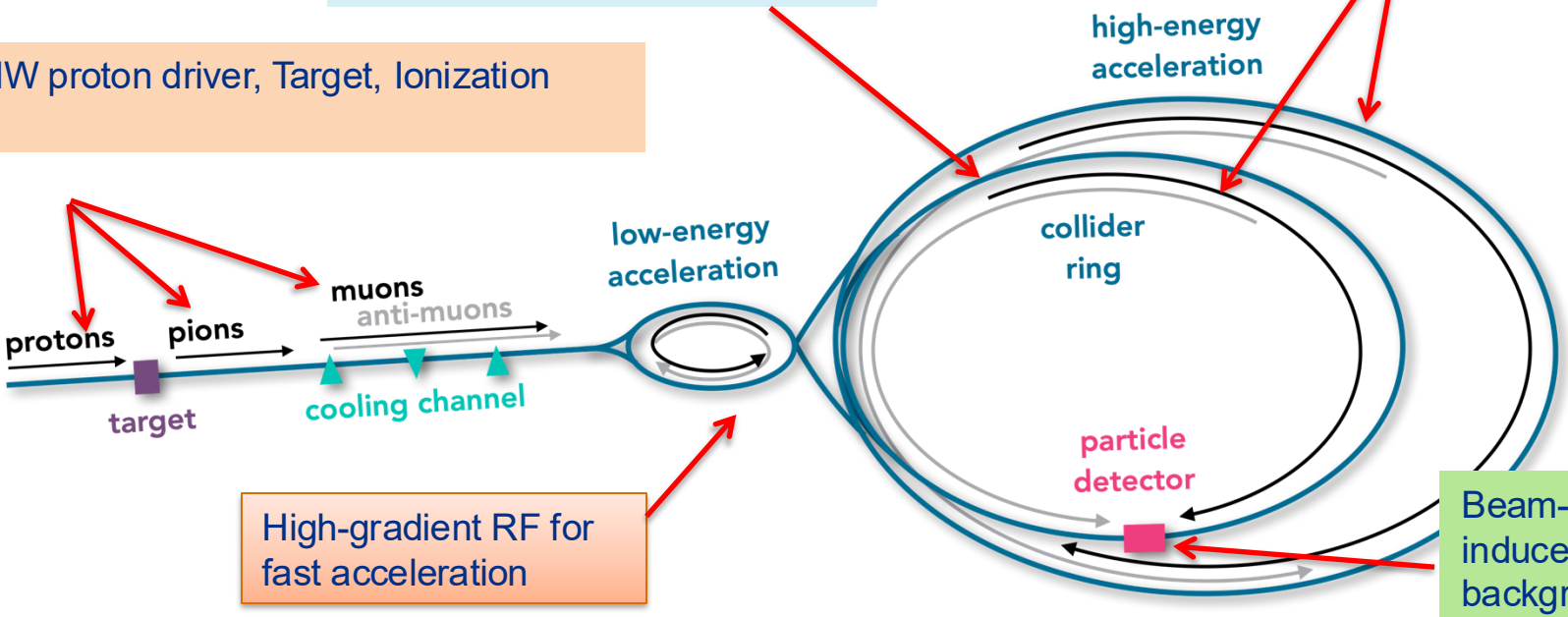


# Muon Accelerator Challenges

Challenging magnets in many places

Dense neutrino flux needs to be mitigated

Multi-MW proton driver, Target, Ionization cooling




High-gradient RF for fast acceleration

Beam-induced background in the detectors

These challenges should not be seen as show-stoppers but rather luminosity and cost risks



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# Global Muon Collider Efforts

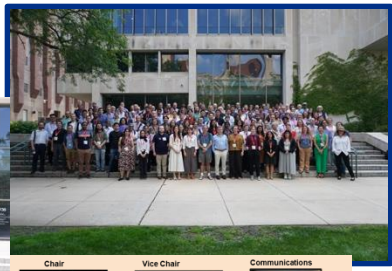
- International Muon Collider R&D activities are coordinated by IMCC
  - Very active community since 2020
  - Over 50 institutions signed MoC
  - Strong contributions from the US
  - Comprehensive 500 page report submitted to ESPPU - [arXiv: 2504.21417]

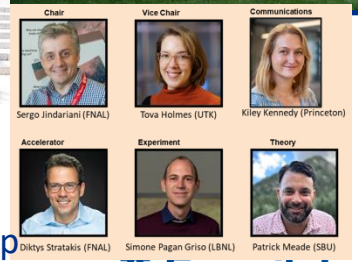
- US community recently formed a *national organization* (USMCC) and elected leadership
  - USMCC enhances the ability to tailor strategies and resources to meet the unique funding requirements and community priorities within the United States.

- DOE-CERN collaborative agreement addendum on Muon Colliders is in preparation

IMCC Annual Meeting at DESY

US Meeting+School at UChicago






Elected USMCC Leadership



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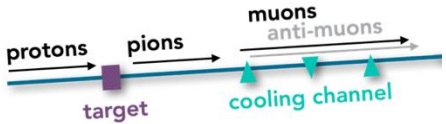
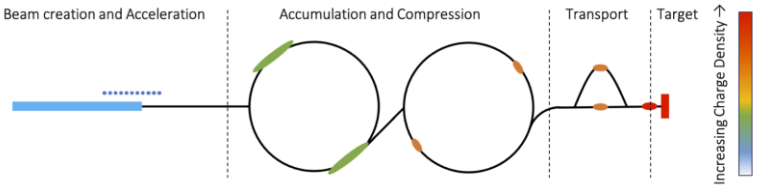
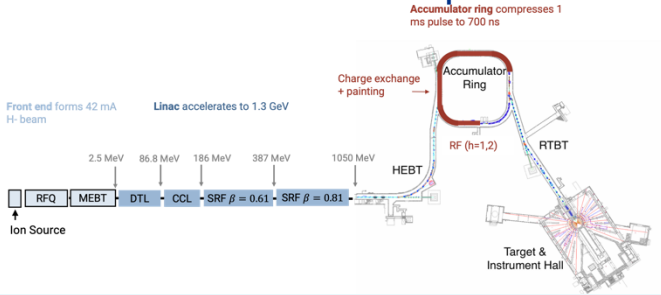
# Muon Production and Capture




Challenge: **2-4 MW** at **5-20 GeV**, compressed at **1-3 ns @ 5-10 Hz**

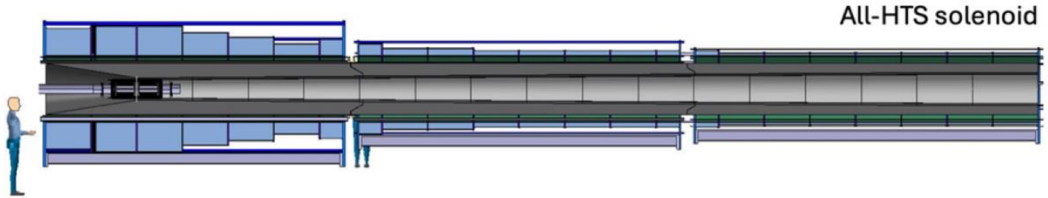
- ORNL SNS resembles proton driver and could probe relevant space charge regime.
- Experiments will test hardware limits, explore modifications for bunch compression.

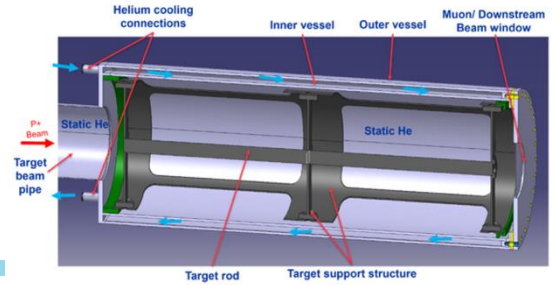



- Initial 2 MW graphite target and HTS solenoid conceptual design done
- Study of proton removal ongoing

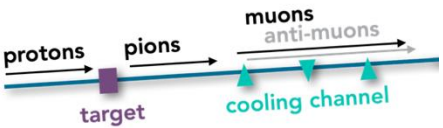
Challenge: 2 MW, 5 Hz, 400 MJ/pulse target and High –B HTS solenoid in extreme environment

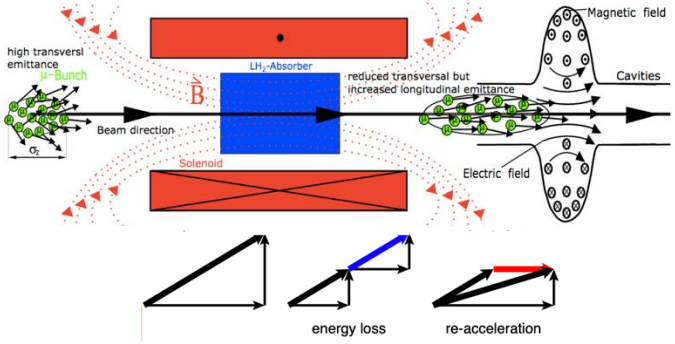


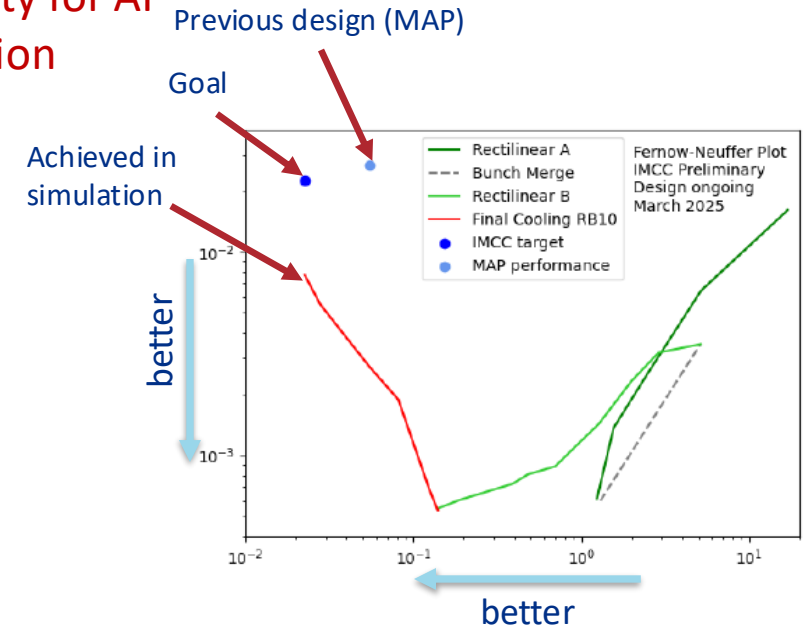



# Ionization Cooling

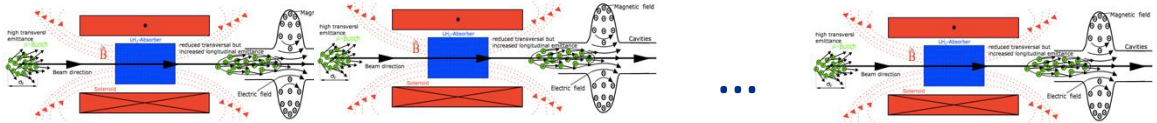
Great opportunity for AI based optimization




Each cell reduces emittance by few %. **Repeat O(100) times = $10^6$ reduction**




Not all cells identical



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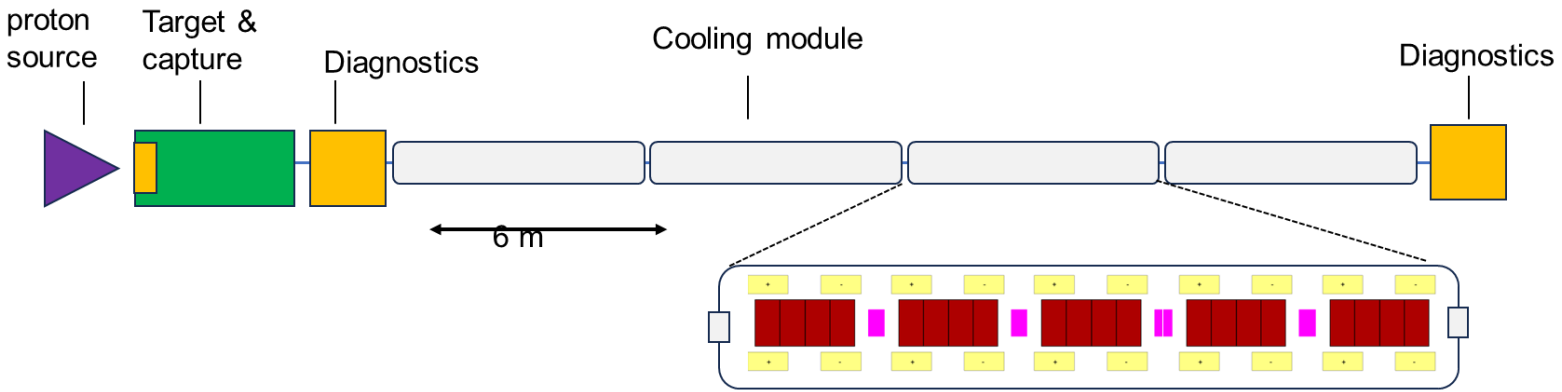
# Ionization Cooling Demonstrator

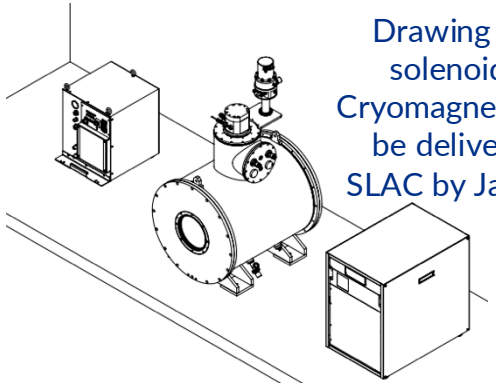



## Demonstrator, example configuration:

| | Muon energy, MeV | Total length, m | Total # of cells | B_max, T | 6D emm. reduction | Beam loss, % |
|---|---|---|---|---|---|---|
| Full scale MC | 200 | ~980 | ~820 | 2-14 | x $1/10^5$ | ~70% |
| Demonstrator | 200 | 48 | 24 | 0.5-7 | x 1/2 | 4-6% |

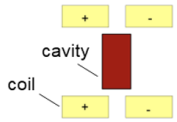
# Staging the Demonstrator

Extending SLAC's high power RF testing capabilities to include external magnetic fields



Drawing of 5 T solenoid from Cryomagnetics to be delivered to SLAC by January 2026

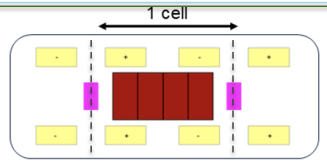
**Phase-I**




**Verify RF performance in B-fields**

Test materials and RF concepts

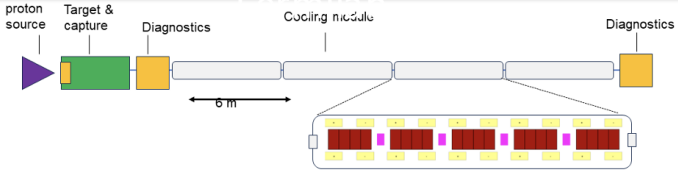
**Phase-II**




**Address integration issues**

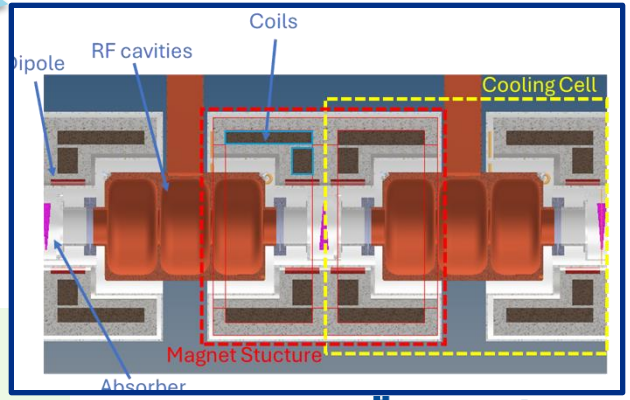
Test engineering

**Phase-III**




**Full demonstrator with beam**

Test operation and instrumentation




Mid-complexity 6D cooling cell engineering design almost ready



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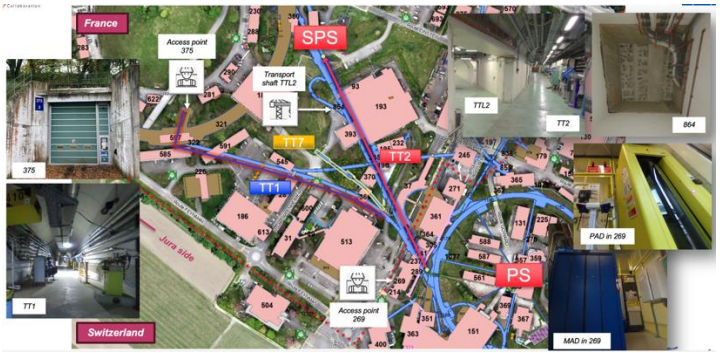
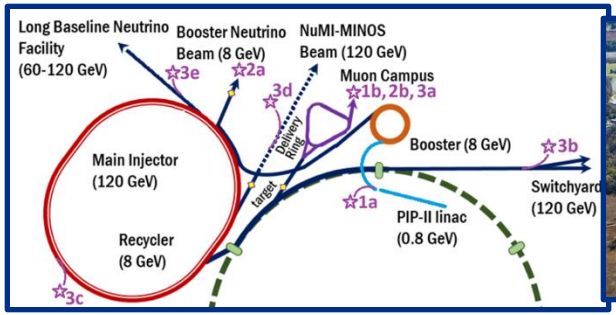
# Demonstrator Site exploration

- Both Fermilab and CERN with access to high-power proton beams and technological expertise, have excellent potential to host a Cooling Demonstrator
- At CERN study is ongoing: TT7 and CTF3 as candidates (each with pros and cons)
- At Fermilab, two-year LDRD approved to develop initial design of a demonstrator on Fermilab site

TT7 beamline




Potential demo locations at FNAL







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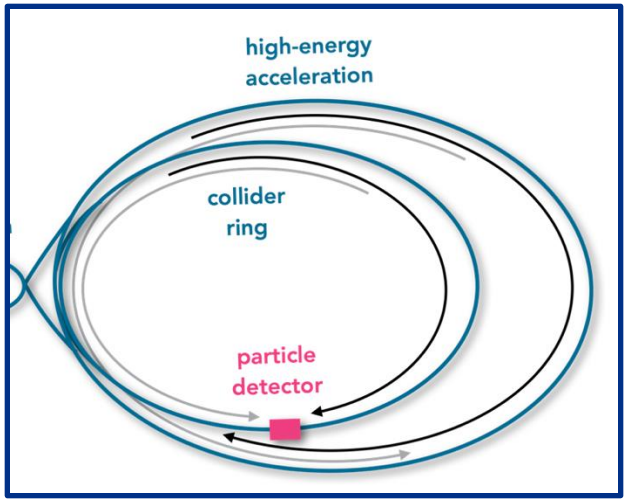
# Magnets for Accelerator and Collider Rings

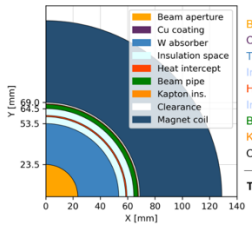
More in Steve's and Kyle's talks on Monday




**Accelerator + Collider ring Challenges:**

Acceleration: Fast-ramping magnets, power management

Collider: High field magnets with large aperture, 500W/m heat load




| | Δr |
|---|---|
| Beam aperture (5σ) | 23.49 mm |
| Cu layer beam screen | 0.01 mm |
| Tungsten absorber | 20-40 mm |
| Insulation space | 5 mm |
| Heat intercept | 1 mm |
| Insulation space | 5 mm |
| Beam pipe | 3 mm |
| Kapton insulation | 0.5 mm |
| Clearance to coils | 1 mm |
| **Total magnet aperture** | **118-158 mm (diameter)** |

- Accelerator RCSs need a combination of fixed field SC magnets (12-15 T) and fast ramping magnets (up 1000T/s). Power supply design developed, need to build prototype.
- Interaction region has very challenging lattice design due to small ß* : momentum acceptance, alignment requirements for IR magnets, IR magnet apertures vs achievable field strength
- Magnet developments within MDP and in Europe are entering Muon Collider territory: 3 TeV collider magnets are withing HL-LHC range , 10 TeV requires HTS with up 15 T dipoles and ~20T IR Quads.



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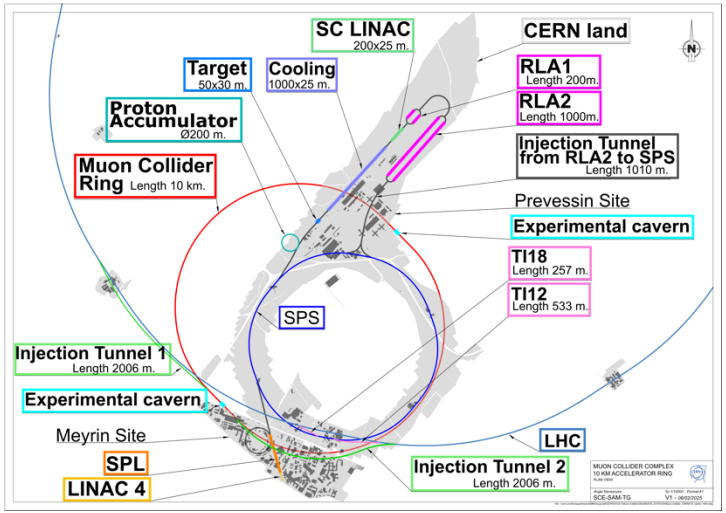
# Site Specific Designs

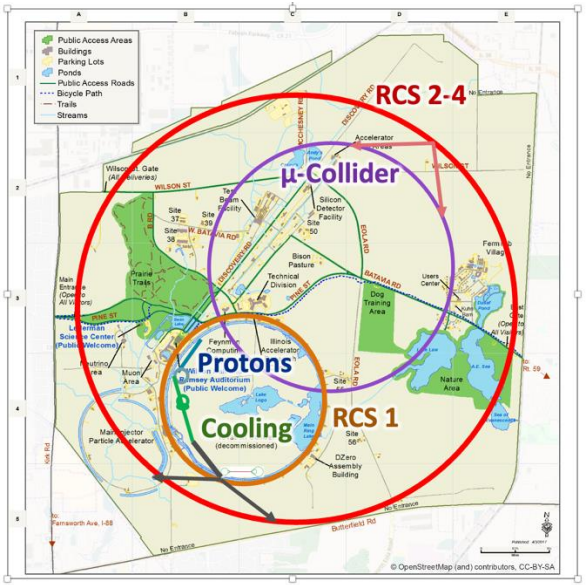
**CERN:**
One RCS in SPS and two in LHC
Construct facility on CERN land

- Adjusted parameters
  (3.2 and 7.6 TeV, 10 TeV maybe possible)




**Fermilab study in progress:**

- One RCS in Tevatron tunnel,
- Three RCSs in one site-filler tunnel



# Experimental Challenge

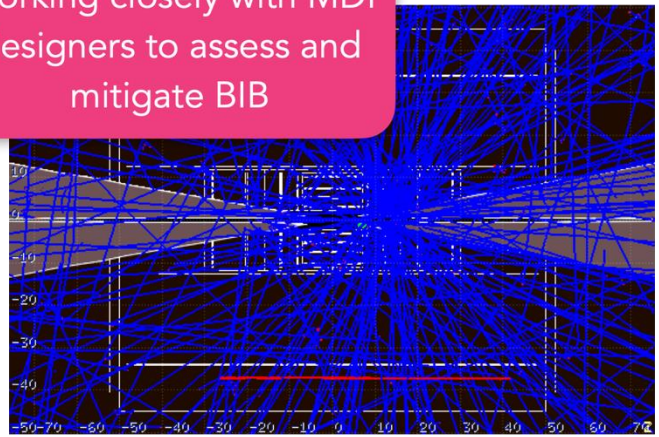
More in Karri's talk on Thursday

- **Beam-Induced Backgrounds** dictate detector design and technologies

- Major progress in **suppressing** the backgrounds:
  - Improving the Interaction Region design
  - Optimizing shielding nozzles in forward region
  - 4D detector technologies and developing novel algorithms

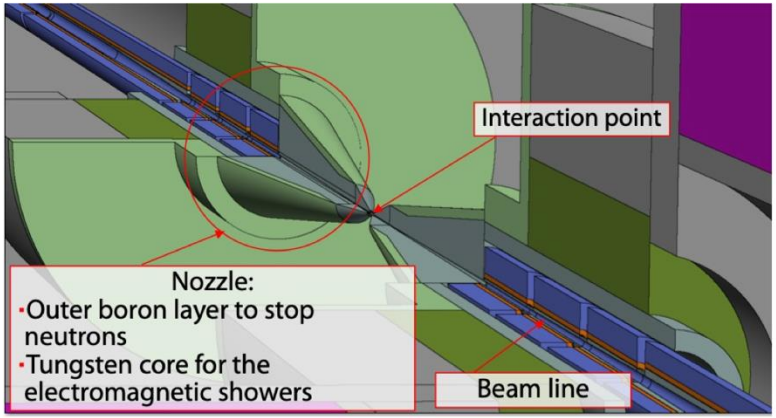
- **Fundamentally reducible:** unlike *pp* the backgrounds are out-of-time and largely not from the IP
  - Can be mitigated with precision spatial and timing detectors and advanced algorithms

Working closely with MDI designers to assess and mitigate BIB



photons, electrons, positrons

(0.0003% of a BIB event)



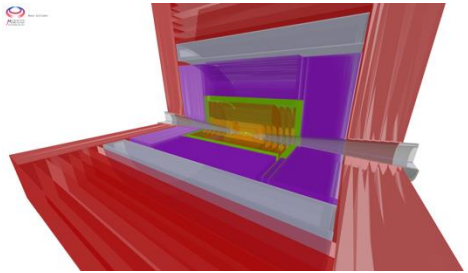
# Detector Development

- Two design concepts (MAIA and MUSIC) for a 10 TeV detector:
  - Good physics performance achievable with both
  - Now turning towards identifying promising detector technologies
  - Design, assembly, support, integration and alignment of the nozzles and central beam chamber is needed
  - Detector magnet (5T) is a challenge

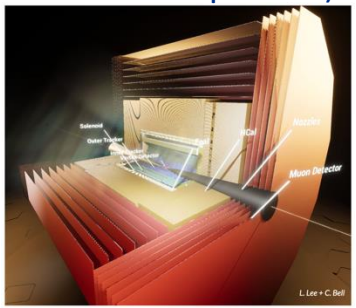
- ***With investment***, should be ready to maximize physics potential by the time accelerator technology is ready

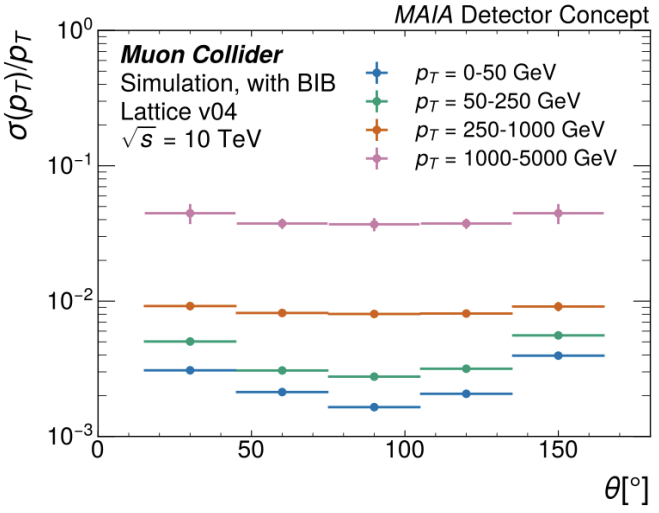
Massimo's talk

**MUSIC**
(MUon System for Interesting Collisions)

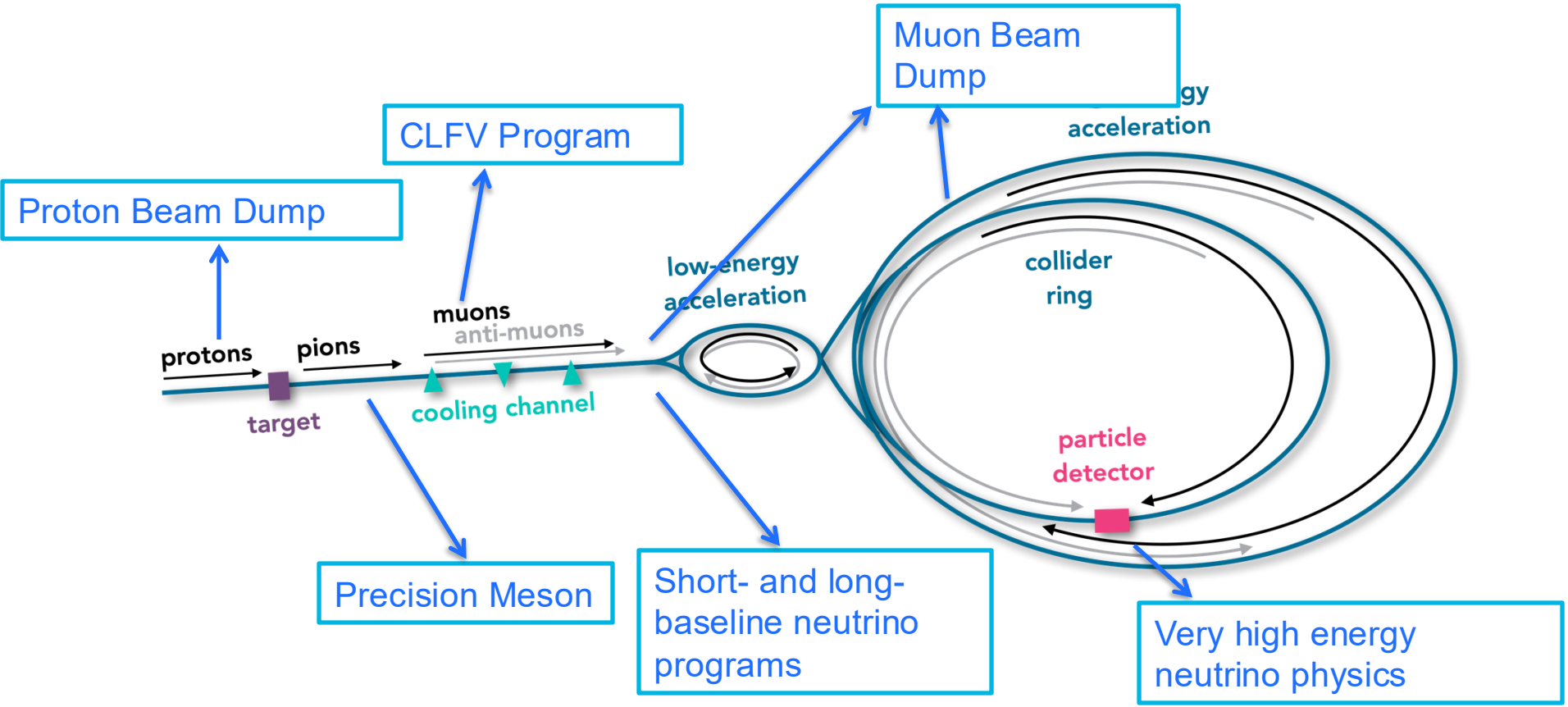


**MAIA**
(Muon Accelerator Instrumented Aperatus)



# A lot more than collider…



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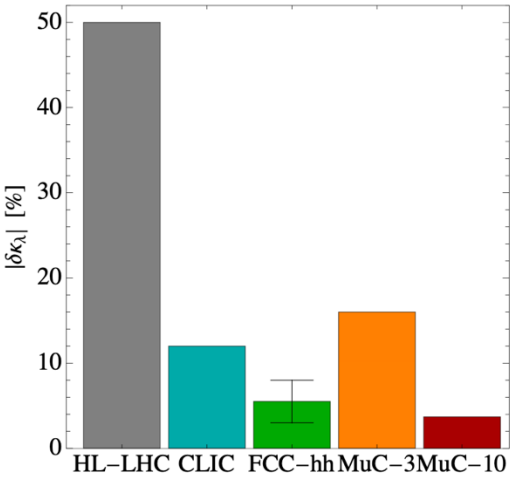
# Summary

- Muon Collider is a future machine with outstanding physics potential
- Realization of a Muon Collider requires significant R&D and a demonstrator/ prototyping program
- Design for most sub-systems now exists, need resources to start building hardware prototypes
- Cutting edge R&D across accelerator/theory/experiment - need people, resources, creative ideas, AI – please consider joining the effort

# Backup

# Highlights of Muon Collider Physics

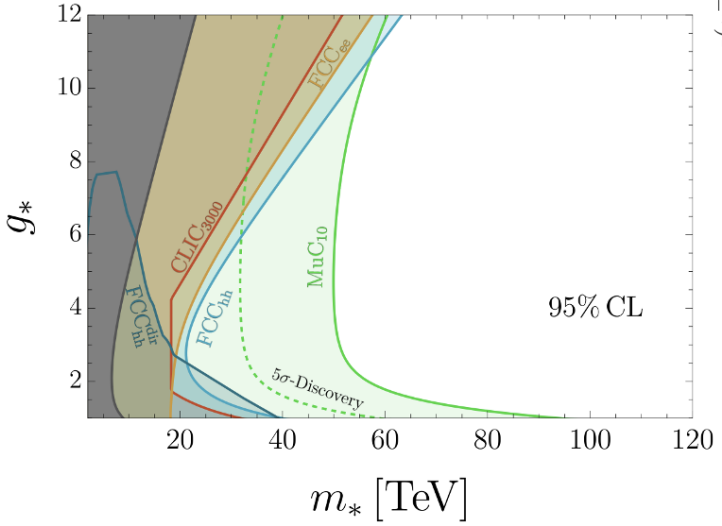


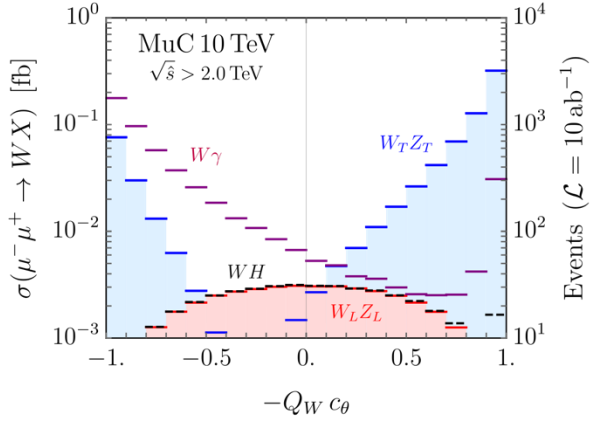

Multi-Higgs Factory

ESPPU Muon Collider Report
Arxiv: 2504.21417

Unprecedented reach for New Physics due to combination of energy+precision

ESPPU Muon Collider Report
Arxiv: 2504.21417




Opens door for studies of new SM phenomena such EWK symmetry restoration

R. Capdevilla, T. Han
Arxiv: 2412.12336



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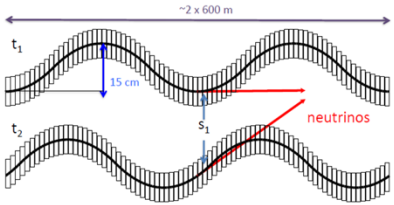
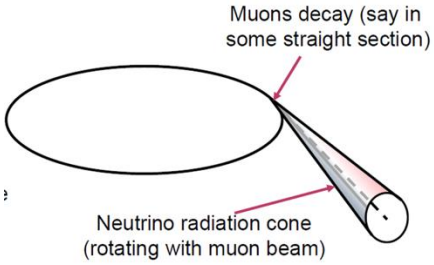
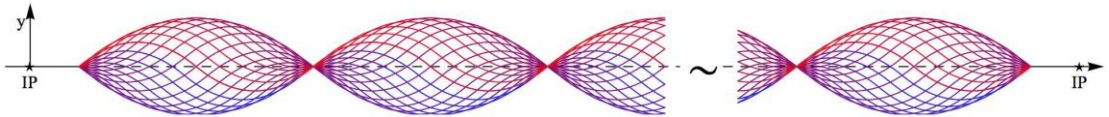
# Neutrino radiation + mitigation

Solution: A mechanical system that will disperse the neutrino flux by periodically deforming the collider ring arcs vertically with remote movers;




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

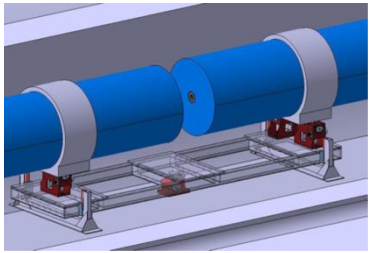



Vertical slope modulation ~ 1 mrad

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

Working on different approaches for experimental insertion



14th International Particle Accelerator Conference,Venezia JACoW Publishing
450-231-8 ISSN: 2673-5490 doi: doi/jacow-ipac2023-mopl166/index.html

**NEUTRINO GENERATED RADIATION FROM A HIGH ENERGY MUON COLLIDER**

C. Carli, C. Ahdida, D. Calzolari, G. Lacerda, G. Lerner, A. Lechner, D. Schulte, K. Skoufaris, Y. Robert, CERN, Geneva, Switzerland

Requires significant R&D and proof-of principle tests



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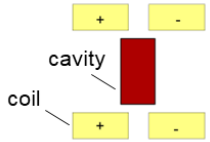
# Demonstrator staging

Phase-I

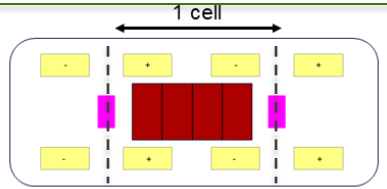



**RF studies in B-fields**

Material studies & cryogenics

600-800 MHz NC cavity, with coils making 10-14 T on axis

Phase-II

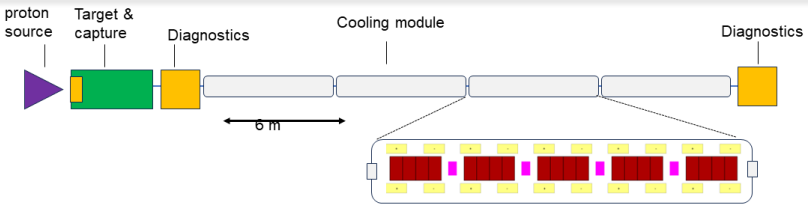



**Cell integration studies**

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III




**Full demonstrator with beam**

Coils producing 7-10 T axial fields

Potential to achieve 50% 6D cooling

- Parameters may need to be adjusted
- Needs design studies for HTS coils under extreme forces (BNL LDRD, M.Palmer et al)
- Design of specialized RF cavities for the cooling channel – **more in talk by Dillon**



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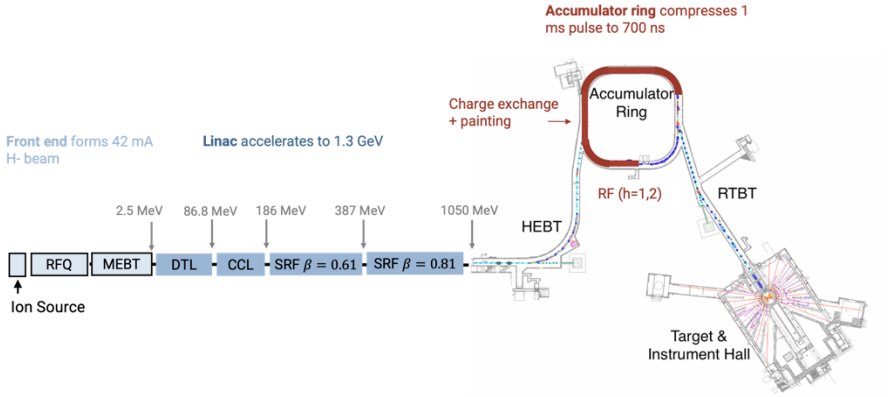
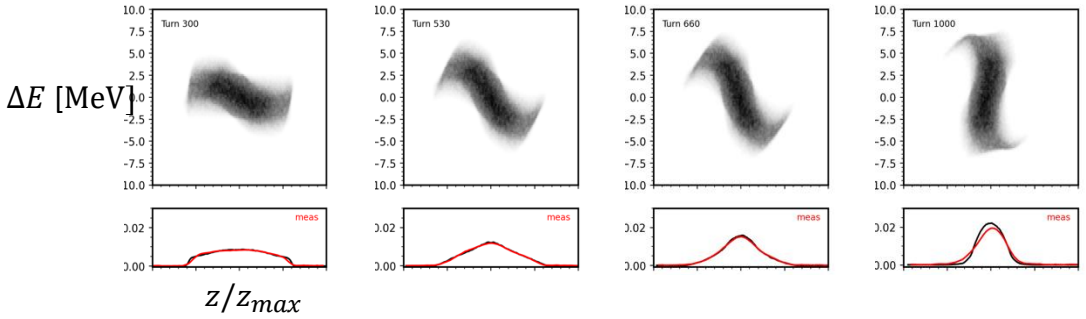
# Bunch Compression Studies at SNS

More in talk by Austin

- ORNL SNS resembles proton driver and could probe relevant space charge regime.
- Experiments will test hardware limits, explore modifications for bunch compression.
- Initial experiment at low charge + simulation benchmark are shown on the slide.



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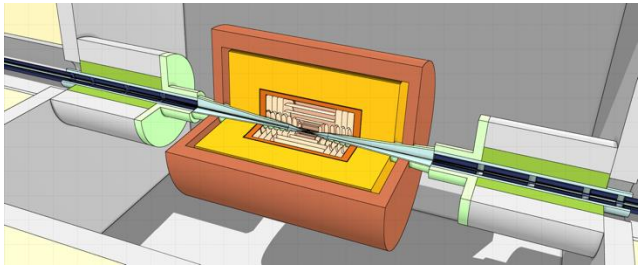
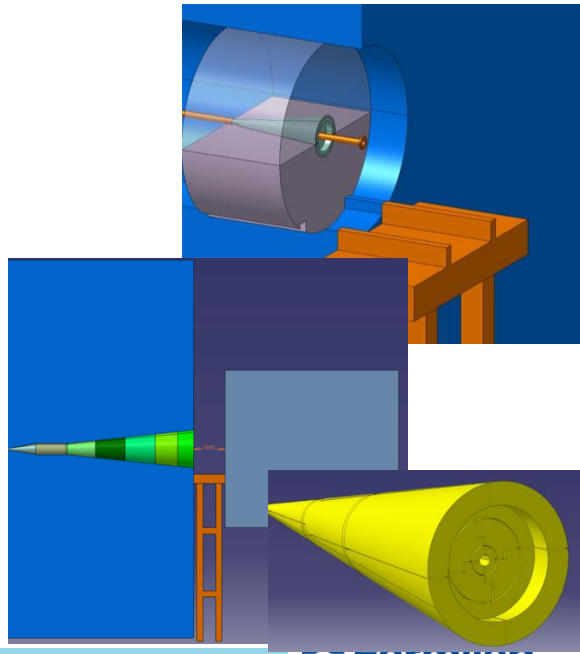
# MDI Challenges

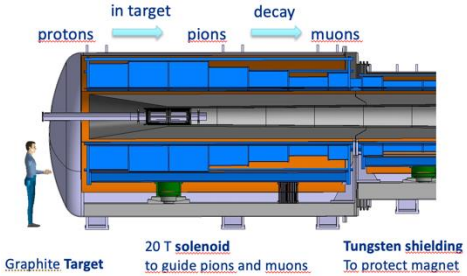
- Very challenging lattice design:
  - Key points: momentum acceptance, alignment requirements for IR magnets, IR magnet apertures vs achievable field strength
- Combined optimization of the interaction region, the nozzles and the detector
- Design, assembly, support, integration and alignment of the nozzles and central beam chamber
- Important to start with global MDI integration studies in order to define space requirements and interfaces

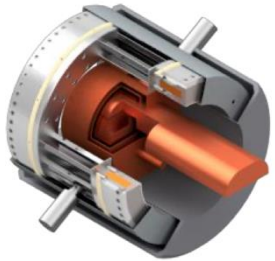


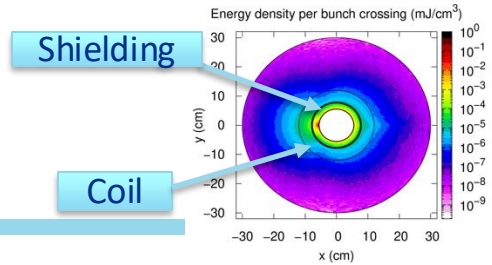


# Muon Collider Needs: Accelerator Technology

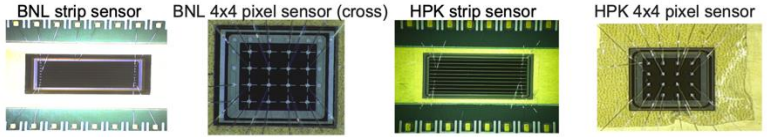
- Optimal performance of a Muon Collider requires significant development in several areas of accelerator technology, including:
  - High Power Targets and Capture systems
    - Ability to withstand large thermal and structural shock
    - Large B superconducting magnets in high radiation environment
  - RF cavities:
    - High gradient NC cavities for cooling that have to operate in multi-T fields
    - High gradient SC cavities for acceleration that tolerate muon decay products
  - A variety of different Magnets:
    - High-field solenoids for the Cooling channel
    - Fast ramping dipoles for the muon acceleration
    - High-aperture and field dipoles and quadrupoles in the collider ring



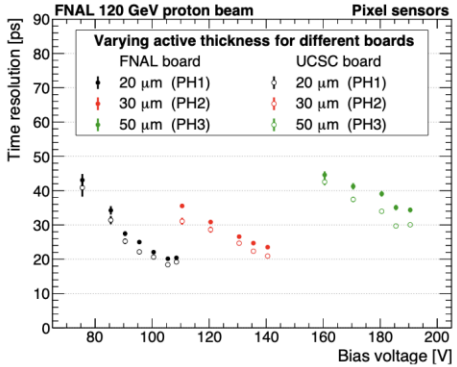


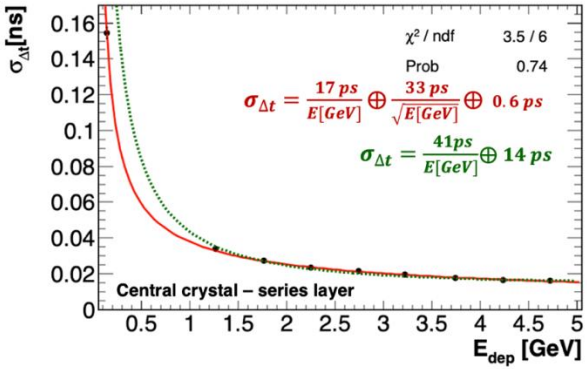
# Detector Technologies



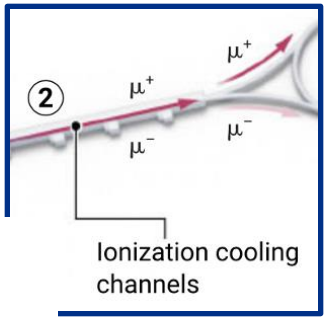

- Identify promising technologies
- Silicon based Sensor Technologies - very rapidly developing area – from LGADs to Quantum detectors
- PF and Dual Readout Calorimetry
- Novel DAQ architectures

- Many opportunities for contributions:
  - ASIC and Magnet need long lead time
  - Power Distribution
  - Readout
  - Mechanics and Assembly
  - Forward detector, Luminosity, PID

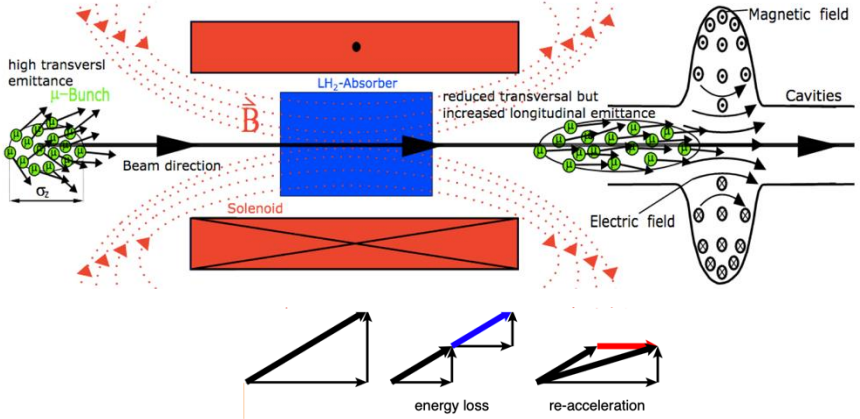


# Muon Collider Needs: Ionization Cooling

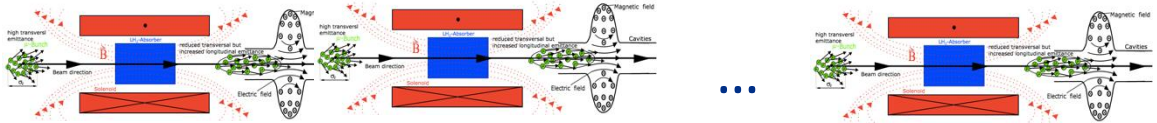



$$L = \frac{N_+ N_- n_c f}{4\pi\sigma_x\sigma_y}$$




Need to cool muons to achieve target luminosity!

Each cell reduces emittance by ~10%. **Repeat O(100) times = cooling channel**



...

Not all cells identical



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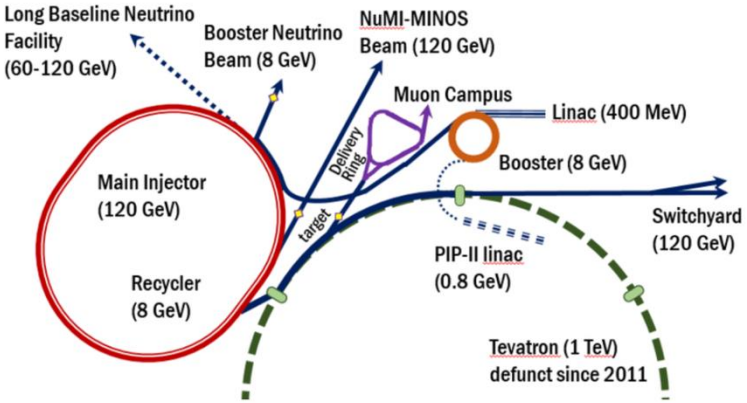
# Fermilab Accelerator Complex Evolution (ACE)

- Fermilab accelerator provides a variety of different beams to the user experiments
- Modernization and upgrades of the complex are ongoing or planned ***(more in Sasha's talk)***




ACE

1.2 MW
- PIP-II Project replaces Linac
- Modernization/upgrades of complex

2 MW
- Reliability upgrades
- Main Injector capabilities (cycle time)

**ACE-MIRT Upgrades to existing machines**

- Target Systems capability improvements

2.4 MW
- Booster replacement
- New physics capabilities

**ACE-BR New machine**



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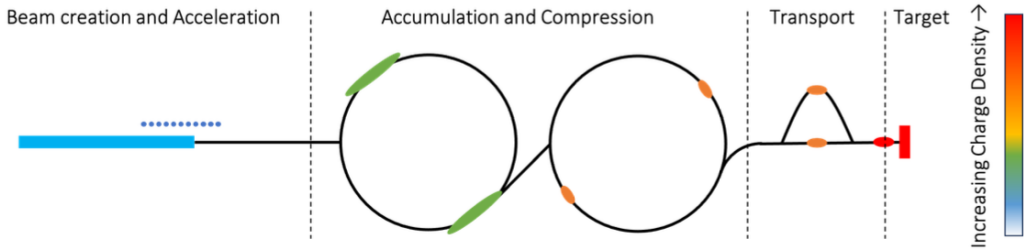
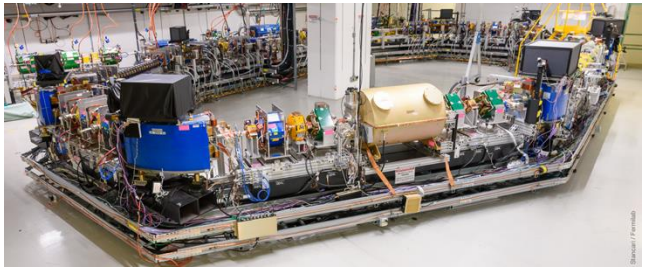
# Can ACE provide the Proton Source?




- Proton beam ranges for optimal performance :
  - **1-4 MW @ 5-20 GeV**,
  - Narrow bunches **1-3 ns**
  - **5-10 Hz** frequency

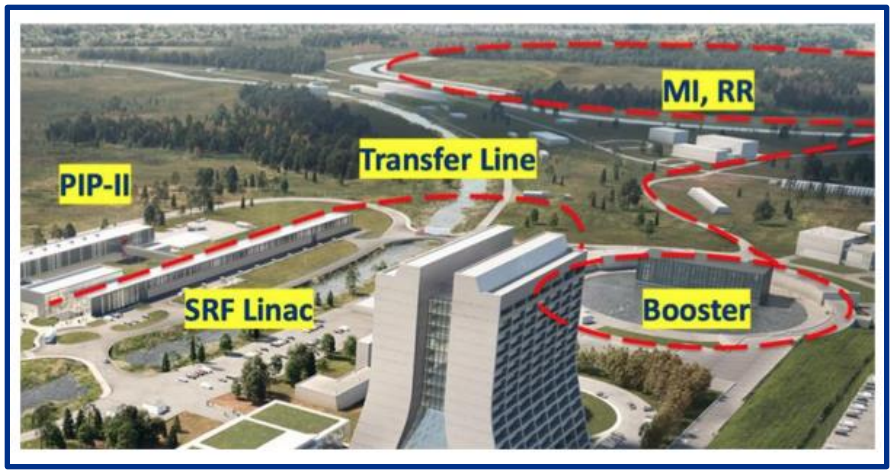


- Requires work to study bunch accumulation, compression and collective effects to convert ranges into specific set of parameters

# PIP-II as part of the Muon Collider Proton Driver

## PIP-II Project provides

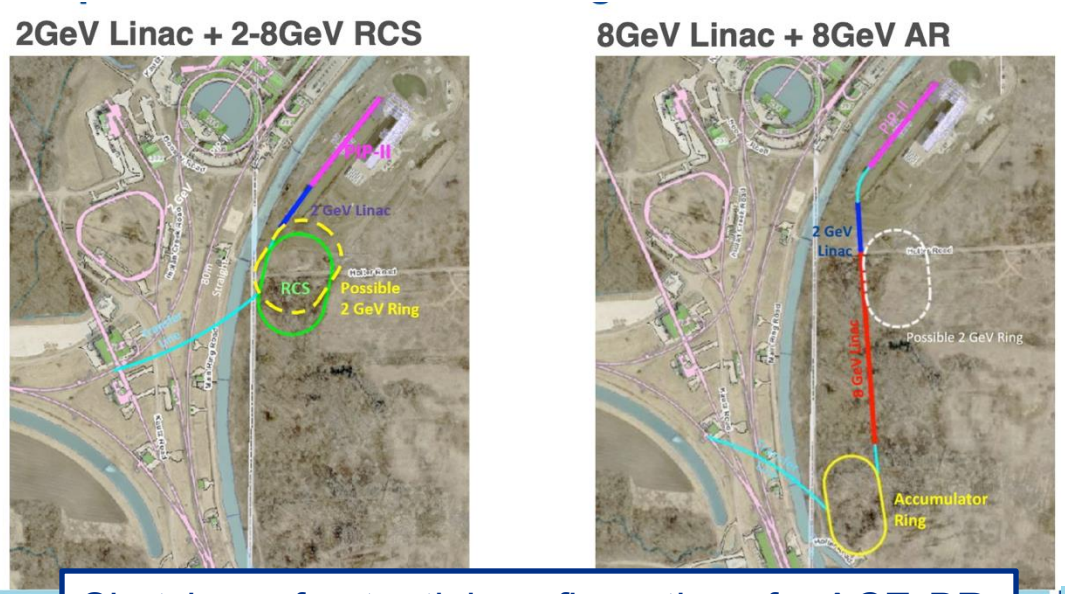
- New SRF linac for injection into Booster at 800 MeV (present 400 MeV)
- New Beam Transfer Line (BTL) from Linac to 8 GeV Booster,
- Booster cycle rate upgraded to 20 Hz from 15 Hz
- Increased proton beam intensity at 8 GeV for 1.2 MW beam power from MI




- The present PIP-II linac current appears too low for the MC Proton Driver
- There are ideas on how to adopt/adjust the PIP-II linac design, but requires a detailed study

# New Booster as part of the Muon Collider Proton Driver

- Past Booster Replacement designs focused almost entirely on DUNE needs
- Muon Collider adds a new goal for the ACE-BR design choices
- Need to evaluate compatibility with potential modifications for the PIP-II linac




Sketches of potential configurations for ACE-BR



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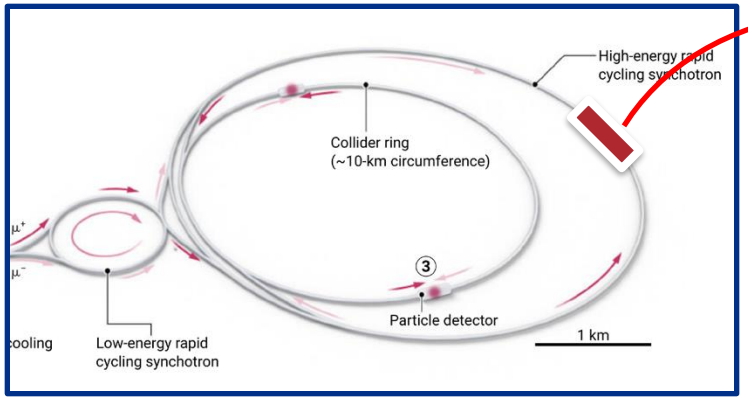
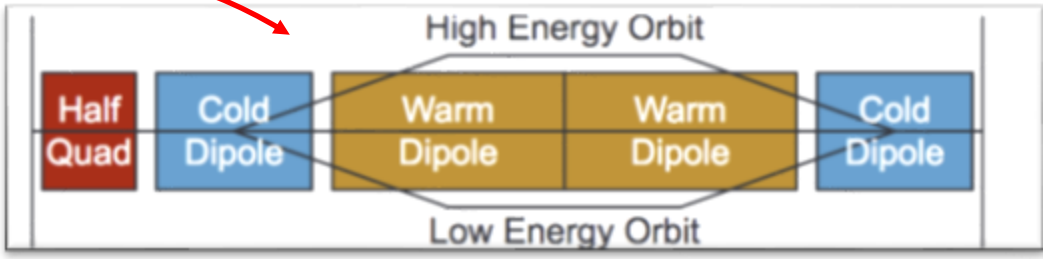
# Acceleration of Muons

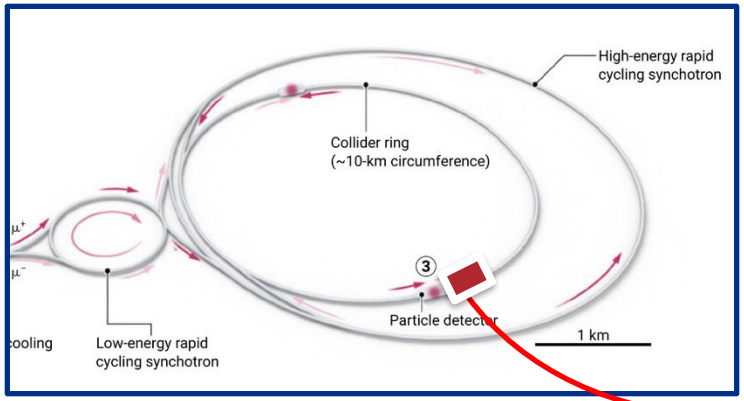



DC field  Pulsed from $-B_w$ to $+B_w$

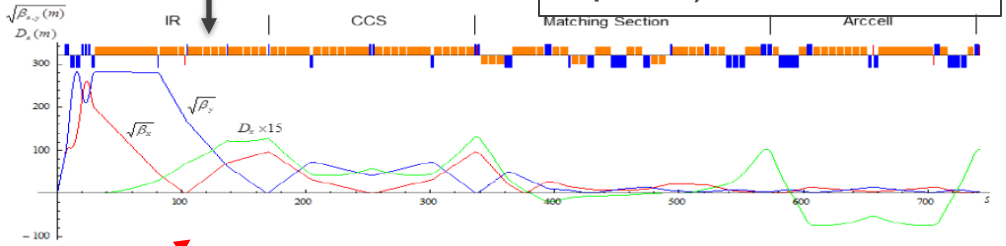
- Rapid Cycling Synchrotron accelerators
- Fast ramping magnets (up to 1000 T/s) accompanied with 16 T  DC magnet
- Design of efficient energy sources with good power management (10s of GW) for pulsed magnets is the key

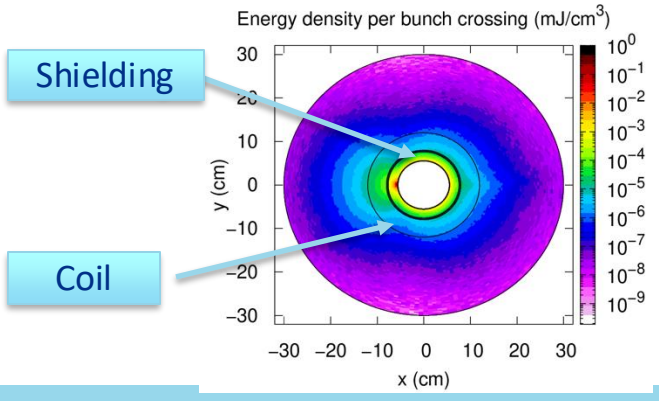
# Collider Ring Needs




IR region (high-B quads)

bend region (high-B dipoles)




- Dipoles with strong field (12-16 T for 10 TeV) and large aperture
- Quadrupoles with strong fields for the IR (15-20 T for 10 TeV)
- Power loss due to muon decay 500 W/m → requires tungsten shielding + cooling



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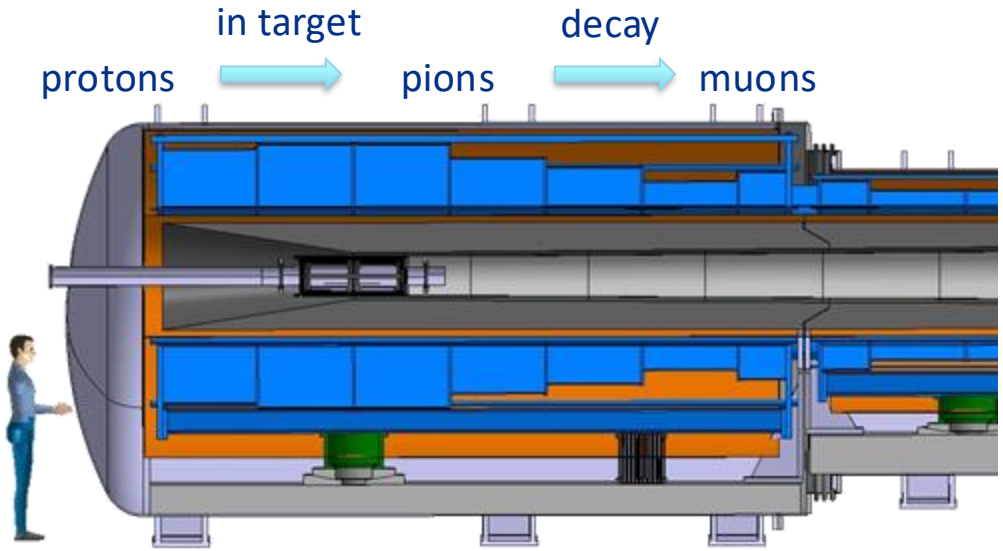
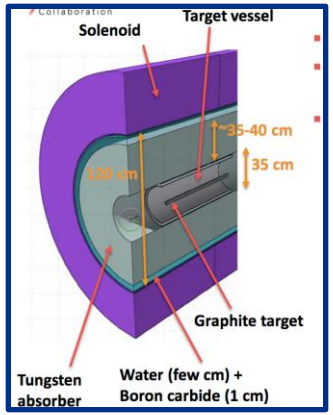



Graphite **Target**

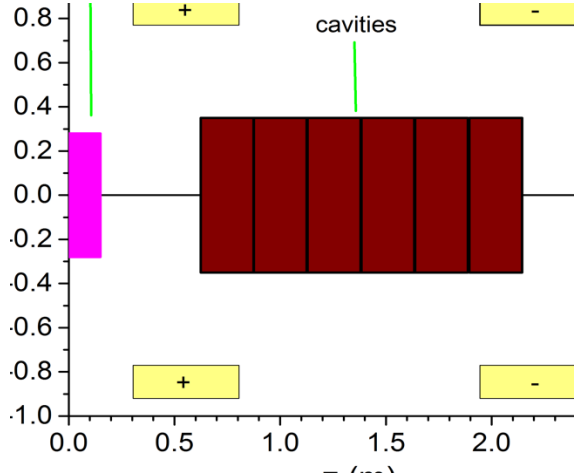
20 T **solenoid**
to guide pions and muons

**Tungsten shielding**
To protect magnet

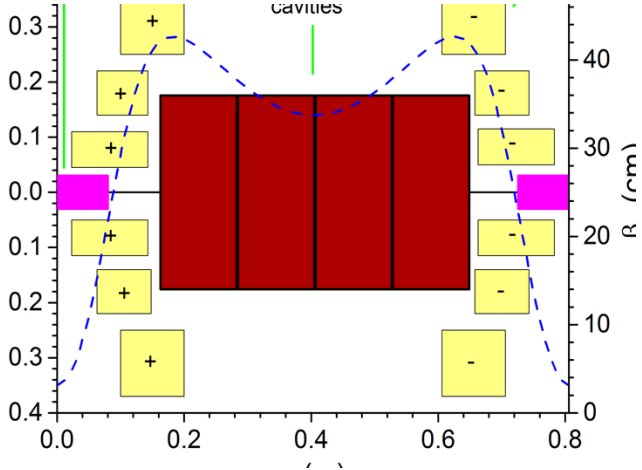
- Thermal and structural shock on the target due 2-4 MW and short proton bunches
- Study different materials, shapes, size optimization, advanced target concepts
- Focusing magnet is challenging due to field strength, size and radiation load

# Cooling Cells

Early cell (“easy”) – 2T peak



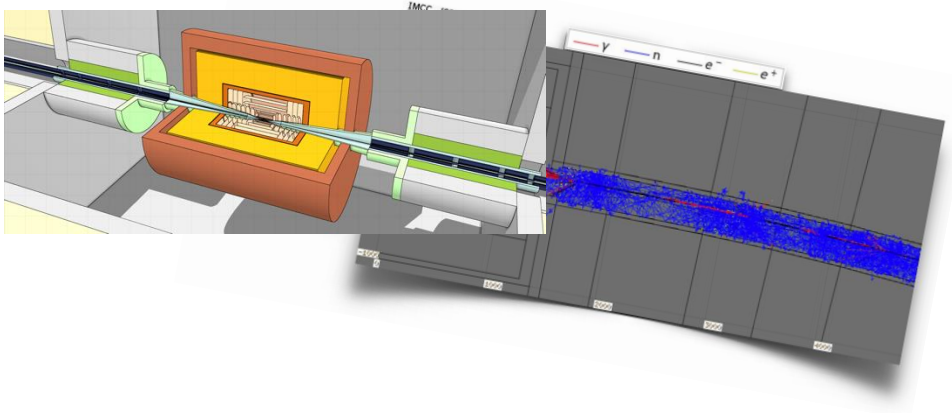

Late cell ( “hard”) – 14 T peak

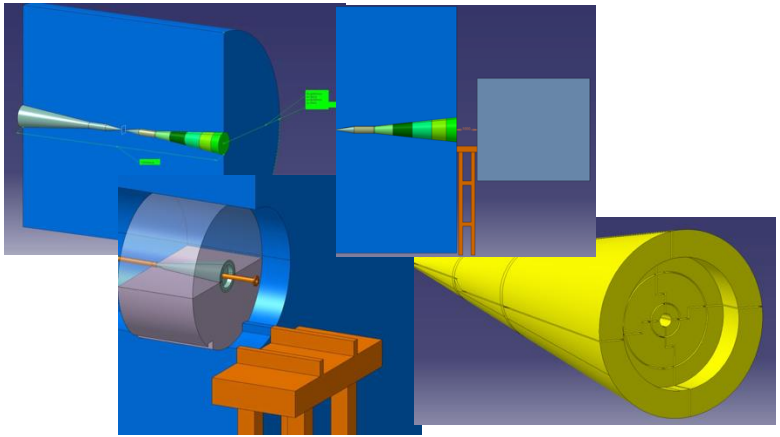



- Large bore solenoidal magnets: From 2 T (500 mm IR), to 14 T (50 mm IR)
- Normal conducting RF that can provide high-gradients within a multi-T fields
- Absorbers that can tolerate large muon intensities
- Need to further optimize the design considering engineering constraints

# BIB Challenges

- Beam background is one of the unique features/challenges of Muon Colliders
  - $10^6$ muon decays per meter Simulating the BIB is a computational challenge



- Machine-Detector Interface requires careful design optimization and engineering studies
- Next step in evolution of detectors, hybrid of LHC and Higgs Factory needs. Requires novel detectors - opportunities for innovative detector designs and technology!



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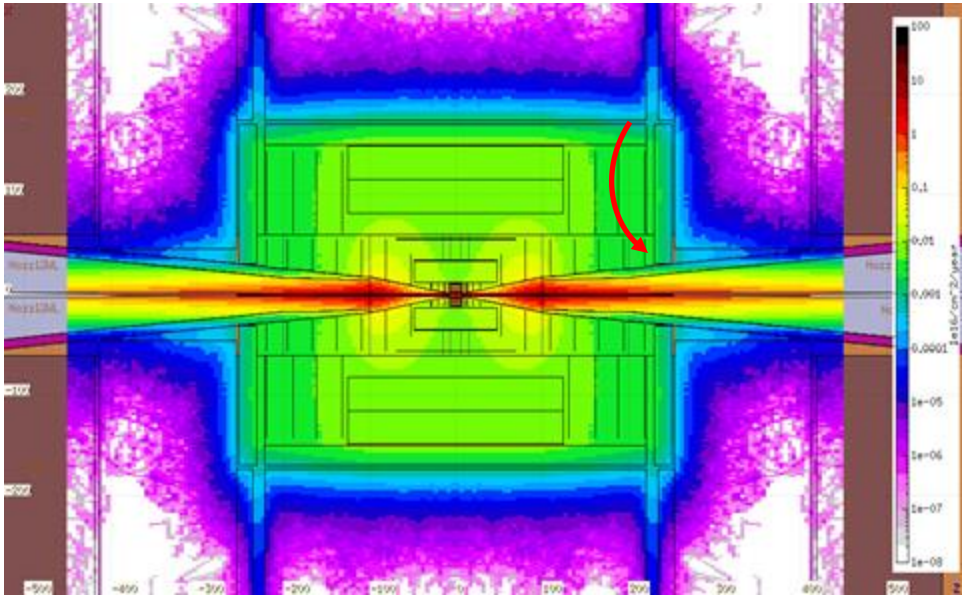
# Detector Design – radiation environment



| | Maximum Dose (Mrad) | | Maximum Fluence (1 MeV-neq/cm$^2$) | |
|---|---|---|---|---|
| | R= 22 mm | R= 1500 mm | R= 22 mm | R= 1500 mm |
| Muon Collider (3 TeV) | 10 | 0.1 | $10^{15}$ | $10^{14}$ |
| HL-LHC | 100 | 0.1 | $10^{15}$ | $10^{13}$ |
| Muon Collider (10 TeV) | 20 | 0.2 | $3 \times 10^{14}$ | $10^{14}$ |

# Training new Generation of Experts

- Successful 3+ day Accelerator school this week with 70+ students
- Training clusters of new students in muon collider accelerator R&D, e.g.:
  - ~10 Summer Students (undergrad and graduate) based at Fermilab and BNL
- Interested in expanding summer program in future years — needs funding for student and expert time!

Muon Collider is an excellent motivator attracting
new generation to accelerator

# Muon Collider Challenges and Progress

| 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. Longitudinal 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, experiment; fabrication |

# Muon Collider Challenges and Progress

| Challenge | Progress | Future work |
|---|---|---|
| Fast Ramping Magnets | Demonstrated with 290 T/s up to 0.5T peak field at FNAL. Ramps up to 5000 T/s demonstrated with small magnets. | Design and demonstration work to achieve higher ramp rates (up to 1000 T/s) and peak fields of ~2T with large magnets |
| Very Rapid Cycling Synchrotron Dynamics | Lattice design in place for a 3 TeV accelerator ring | Develop lattice design for a 5 TeV accelerator ring |
| 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 and HTS quads |
| 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 |

# 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 proceses (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 |