Next steps
Intensity → Energy Frontier

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Fermilab graduate (2024)

July 2025

Over view

- ➢ **Future**
  - **~Fermilab-centric perspective ?**
    - **Post Tevatron Energy Frontier**
    - **LHC is energy frontier now**

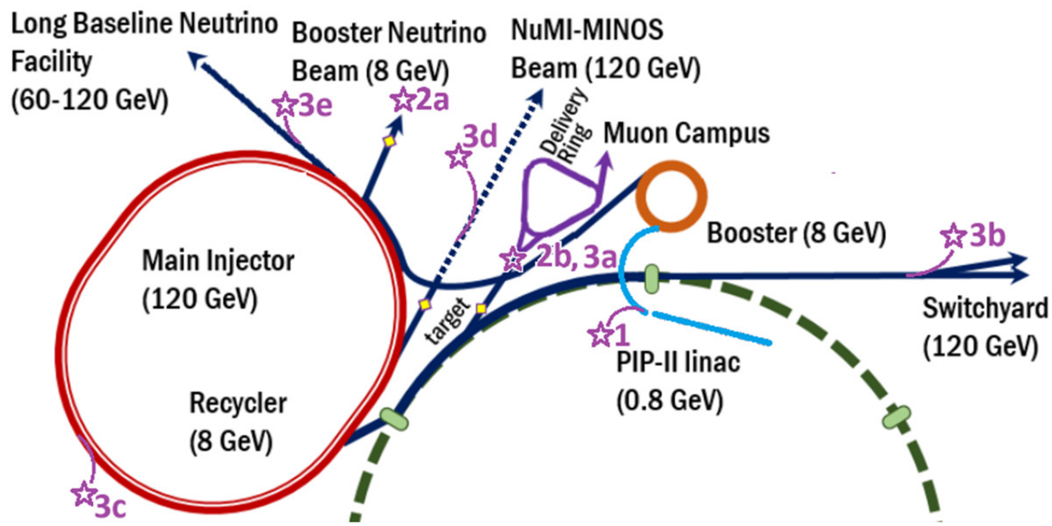
2014 P-5 US HEP focus on Intensity frontier

Energy frontier is too expensive

- ➢ **Intensity frontier**
  - **g-2, Mu2e**
  - **Neutrinos**
  - **PIP-2 → DUNE**
    - **FCC-ee**

- ➢ **Energy Frontier**
- **Muon Collider -IMCC**
- **FCC-hh**

Intensity Frontier at Fermilab

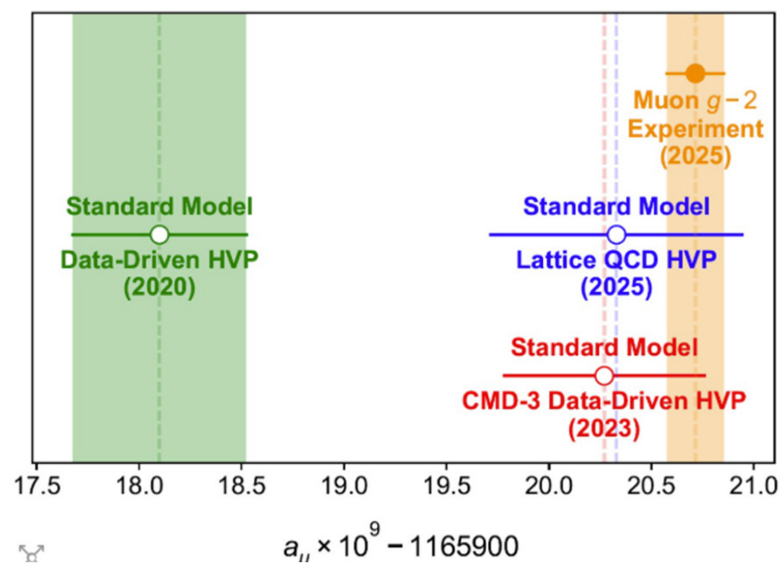


- **Proton beams**
  - **Booster**
    - 8 GeV – up to ~ 100 kW
  - **Main Injector**
    - 120 GeV – up to 1MW

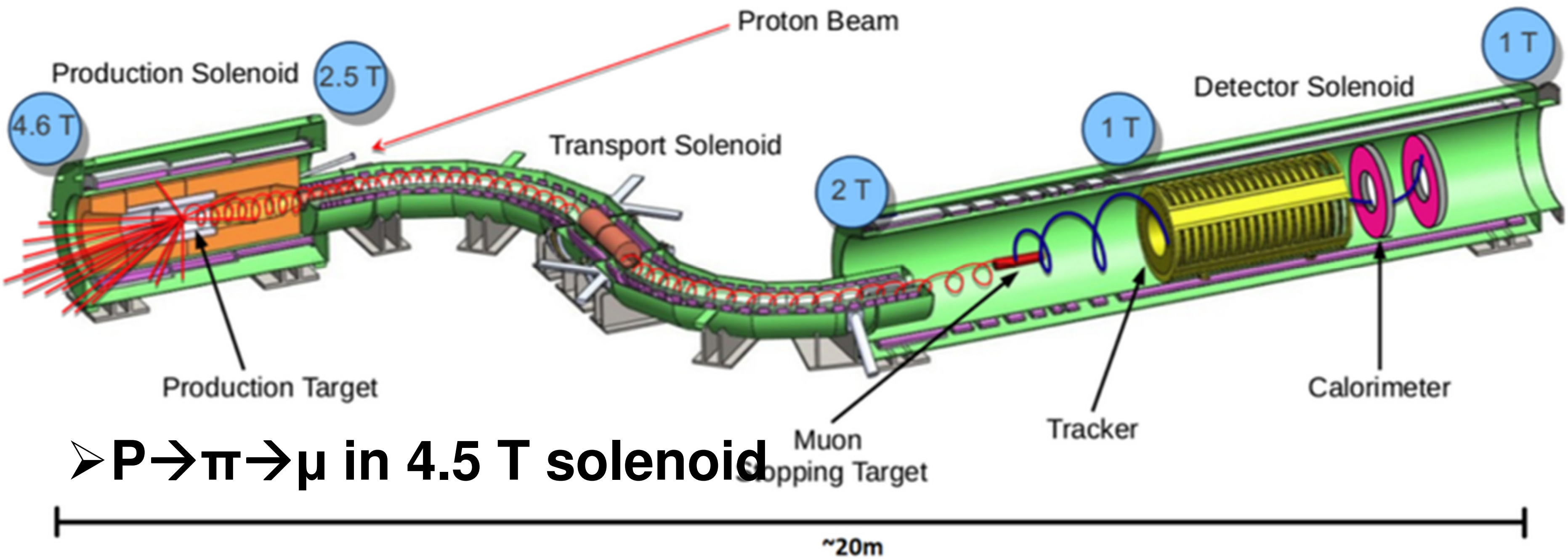
- **Neutrino beams**
  - **NuMI**
    - Measurements of neutrino properties
  - **BNB**
    - Search for "sterile neutrinos"
  - **Muon beams**
    - g-2
    - Mu2e

Current Muon Beams at Fermilab

- **g-2 Experiment**
  - **Uses Tevatron production target to produce π→ μ**
  - **3.1 GeV μ ~10^{12} μ**
  - **Measured g-2**
    - **Resolved (?) g-2 anomaly**
- **Mu2e experiment**
  - **~ 10^{18} μ**



Mu2e experiment



➢ **P→π→μ in 4.5 T solenoid**

- **Backward capture of low-E μ**
- 0→0.1 GeV
- > ~10^{-3} stopped μ/p 10^{18} μ^-

- **Complementary to PSI, J-Parc, etc. experiments**

PIP-II Linac upgrade

PIP-II Project at Fermilab

Raimondi – Talk WEYA003

Proton Improvement Plan II (PIP-II) is currently in the construction phase and is planned for completion in 2029 with substantial in-kind contributions from international partners.

PIP-II Scope

- 800 MeV, 2mA H^- SRF linac, CW RF Operations
- Linac-to-Booster transfer line
- Accelerator Complex Upgrades
  Booster
  Main Injector
- Conventional Facilities

PIP-II Beam Power

- 1.2 MW H^+ beam
- Upgradeable to multi-MW

Project cost

- Approximately $1B

➢ **1MW + at ~1 GeV**
  - **> 200 kW   from Booster 8 GeV**
  - **> 2 MW 60-120 GeV for DUNE, …**

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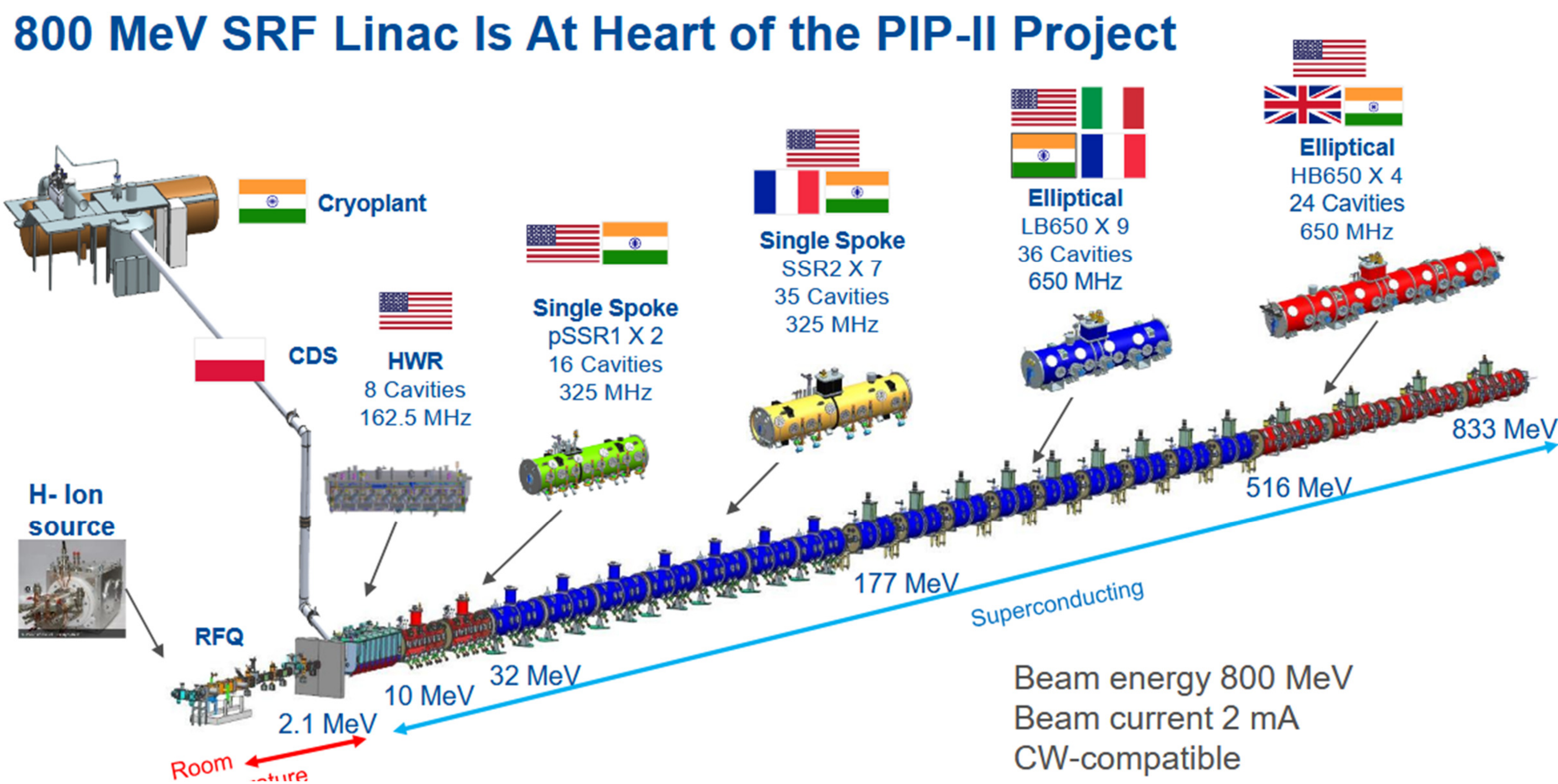
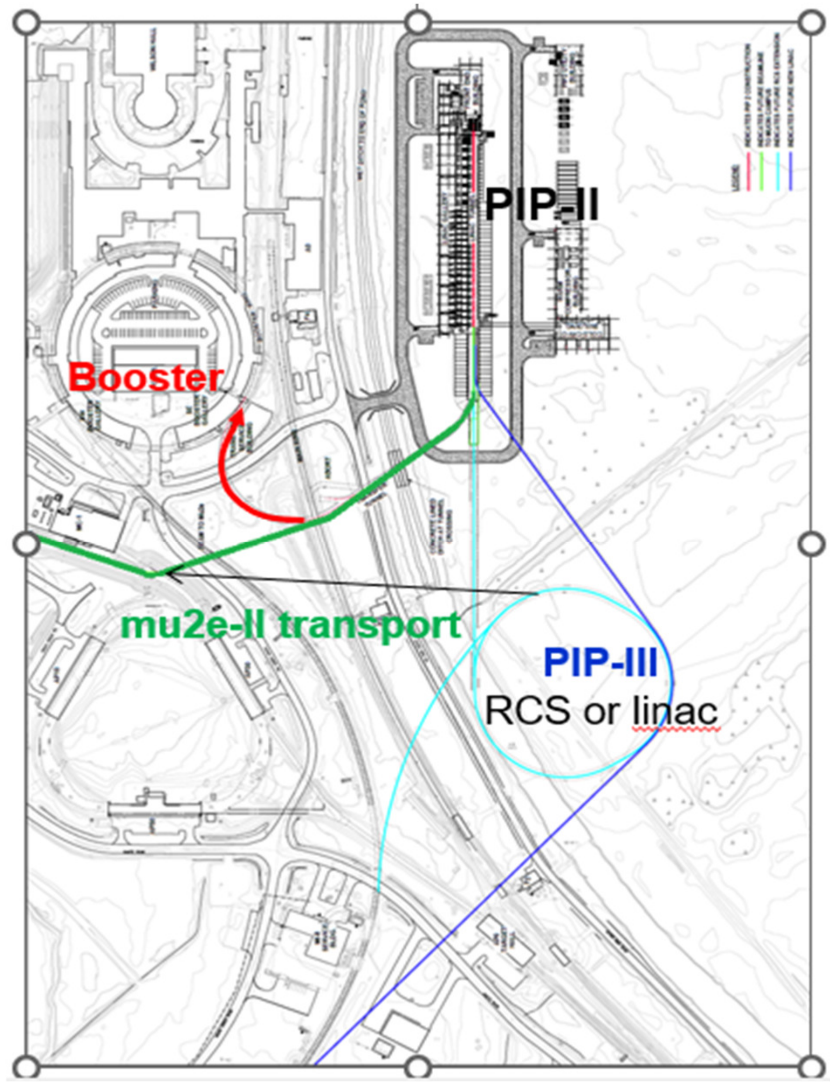
SRF Linac 162.5 →325→650 MHz



PIP-II → new beam possibilites

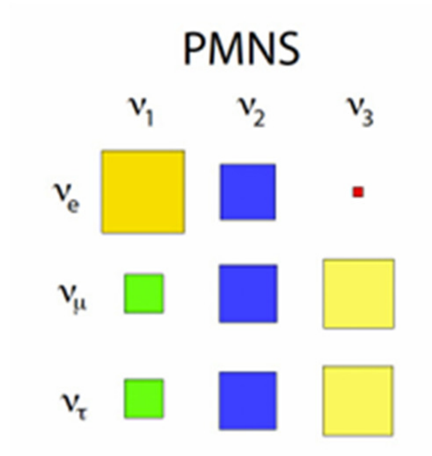
- Up to ~1 MW, ~1 GeV p
  - Only need ~20 kW for DUNE

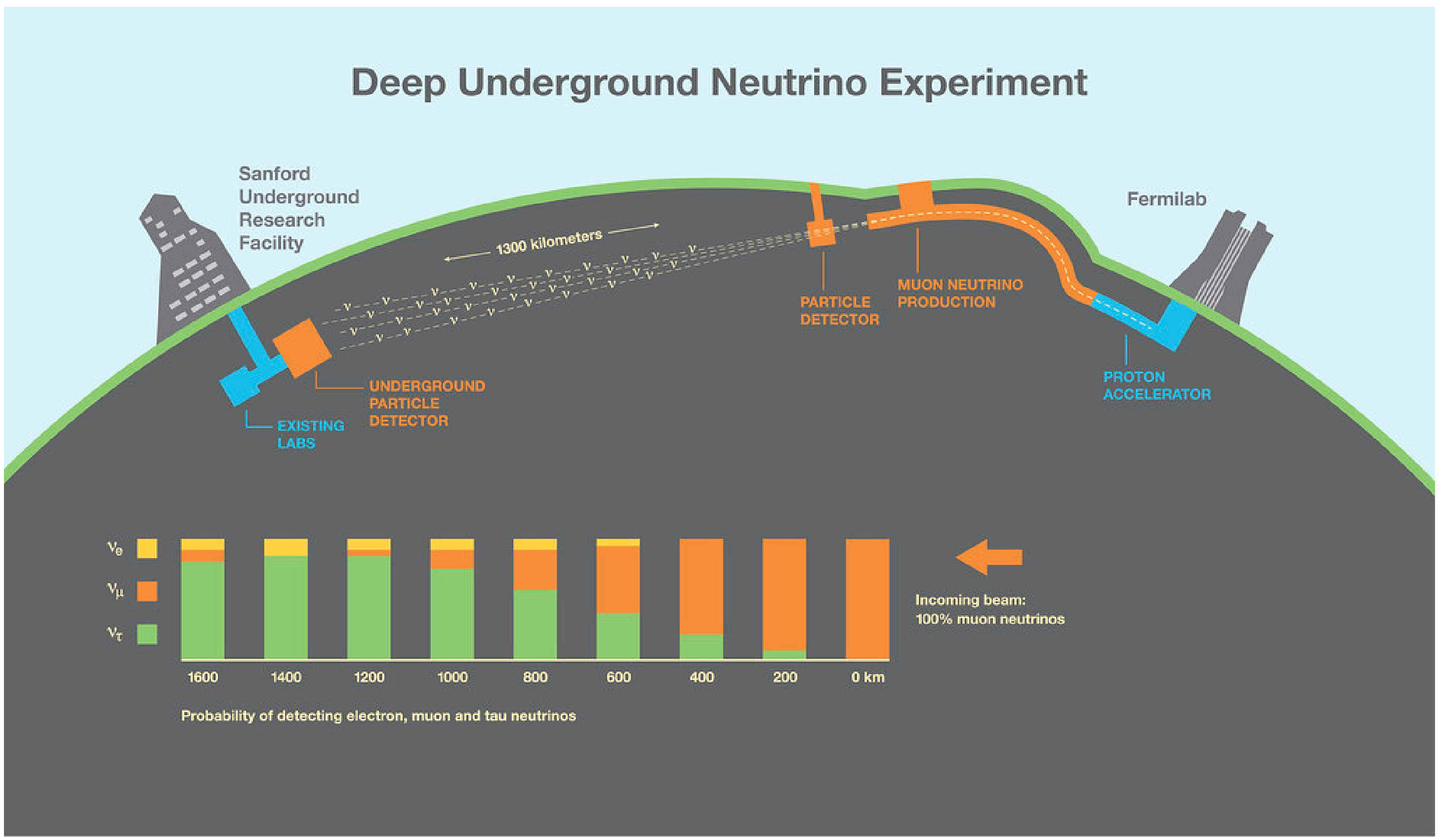
- π, μ, ν beams
  - lepton number conservation
    - μ→e , μ→ 3e, μ→ eγ
  - μSR, π, μ low E physics
  - Eventually, “Booster replacement”
    - ~8 GeV RCS/Linac



Physics program (~2030—2040)

- **Neutrino Physics at DUNE**
  - **Intensity 1→2.5 MW 120 GeV p**
    - **Measure SM neutrino parameters**
    - **PMNS matrix**
    - **Mass-order, CP phase**
  - **Other physics ?**
    - **Mu2e(-II)**

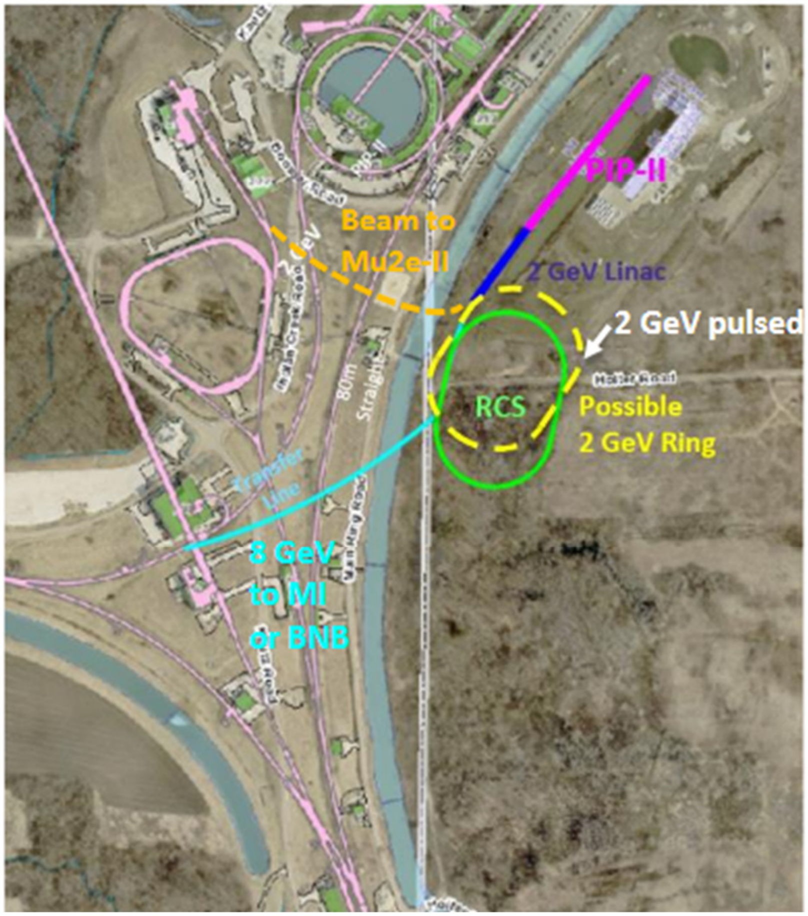


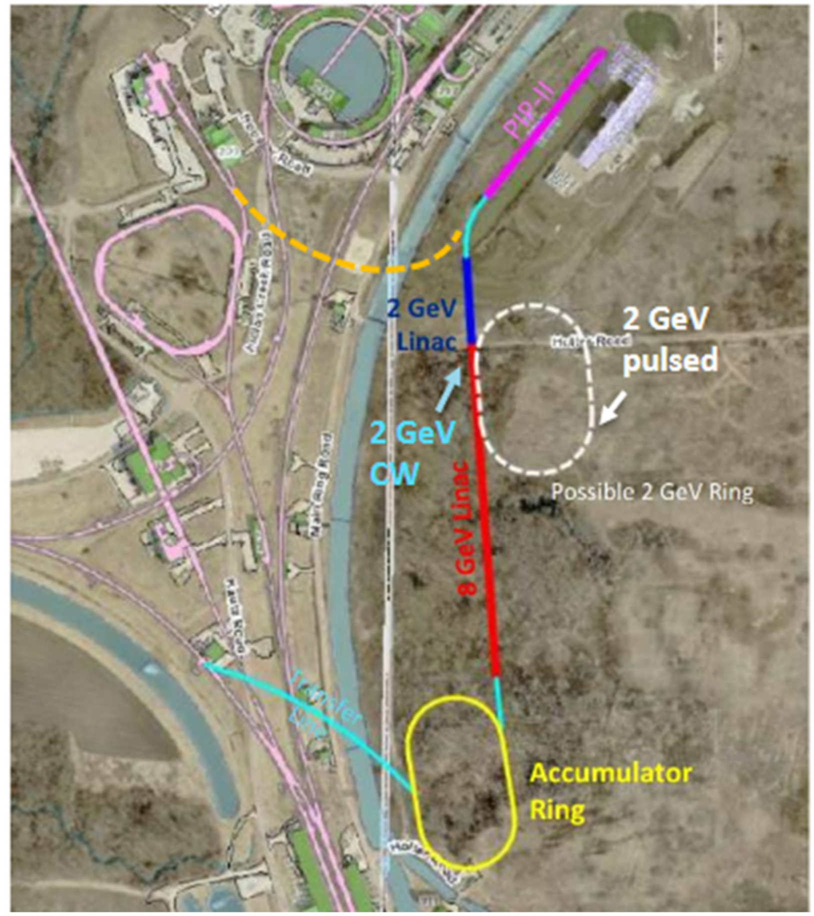


After PIP-II, upgrade Booster

Example Booster replacement options and possible add-ons

2GeV Linac + 2-8GeV RCS **or** 8GeV Linac + 8GeV AR





- ~2 MW at ~8 GeV
- 2-4 MW at 60—120 GeV

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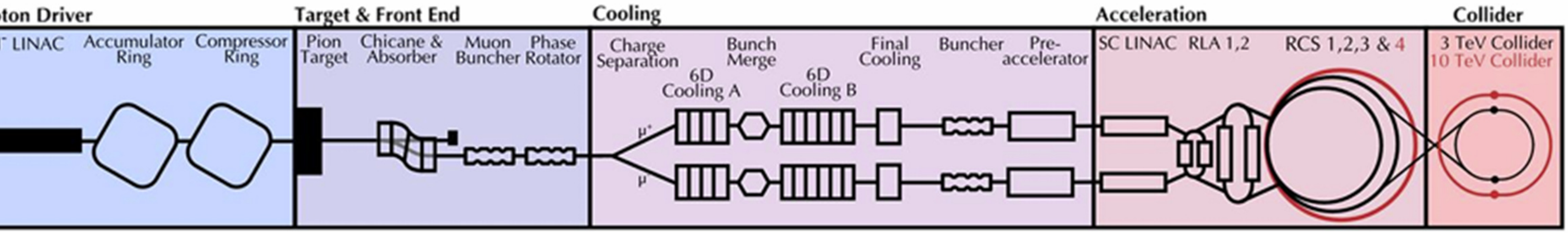
Energy Frontier or Intensity Frontier??

- LHC ~14 TeV (since ~2010)
  - Intensity upgrades

- "Higgs Factory"
  - 250 GeV ee
    - Intensity Frontier

- Higher- Energy ??
    - European strategy/ US P5

  - 100 km ring to 100TeV?
  - Muon Collider →
    - MAP → International Muon Collider Collaboration



Short, intense proton bunch

Protons produce pions which decay into muons which are captured

Ionisation cooling of muon in matter

Acceleration to collision energy

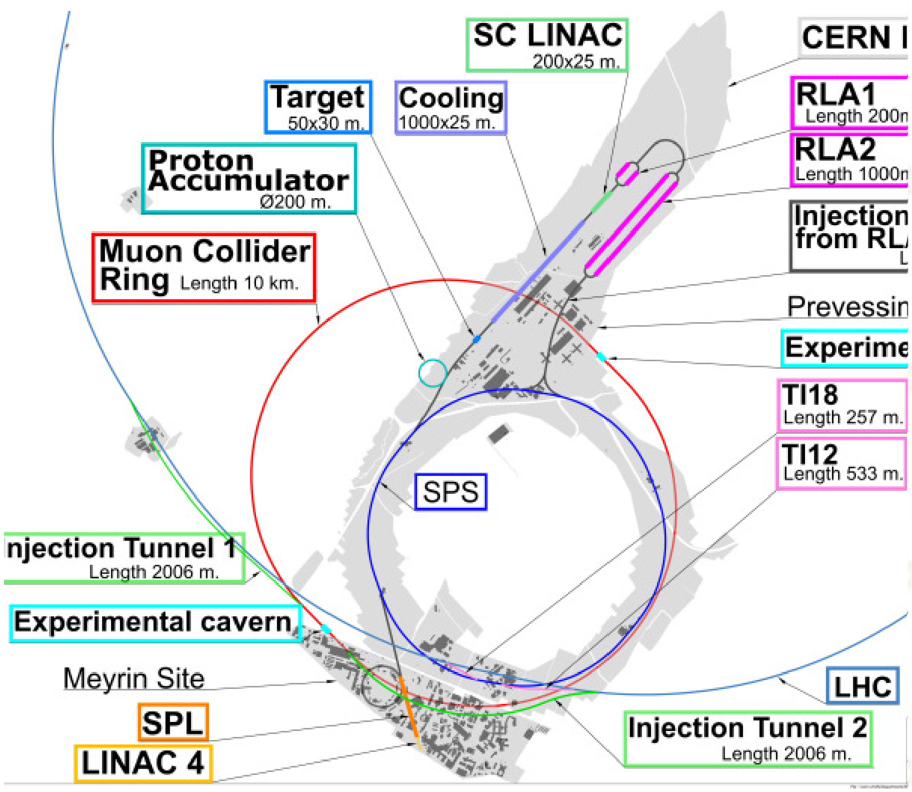
Collision

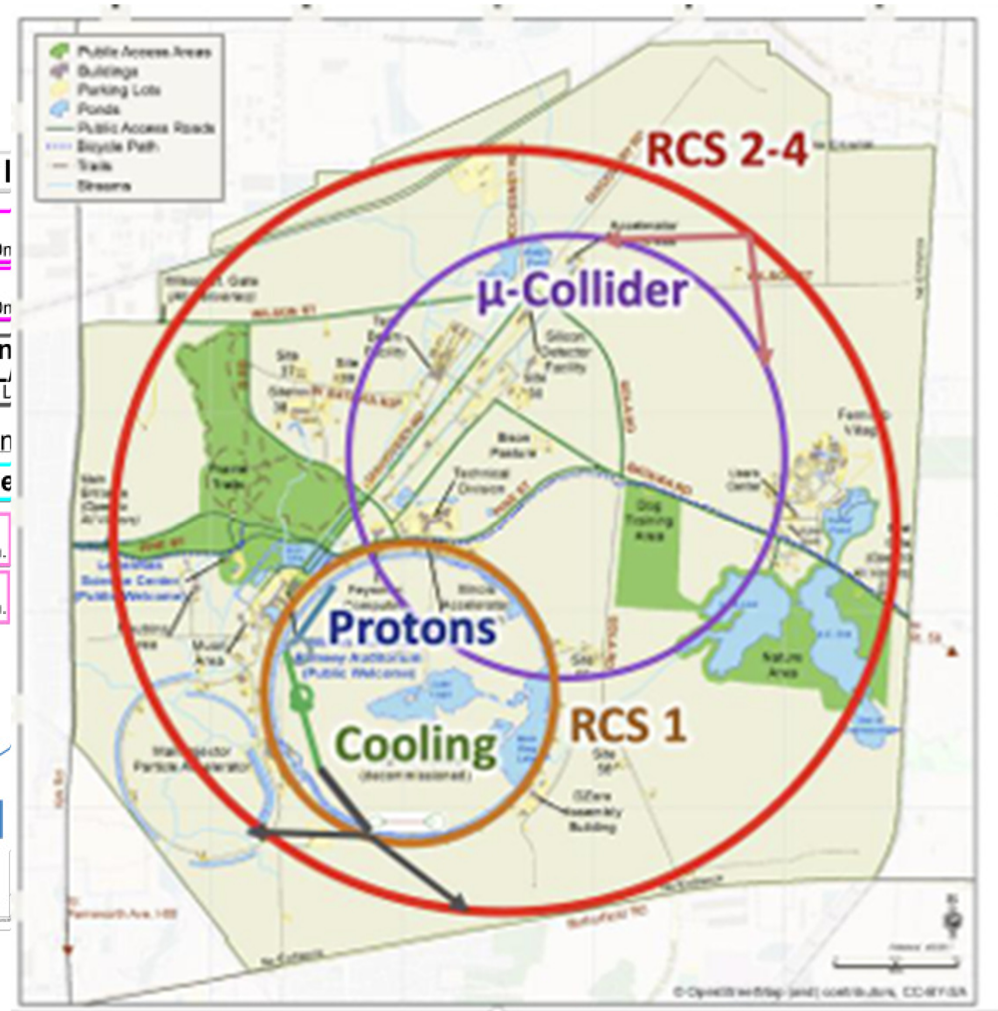
- $L = \frac{N^- N^+ f_0 \gamma n_{store}}{4\pi \beta_t \epsilon_T}$
- $n_{store} = 150\ B_{ave}$
  - Luminosity lifetime
- $\beta_T = \frac{m_\mu}{\delta E} \epsilon_L$
- $\beta_T = \frac{1000}{\gamma} \epsilon_L$ for $\frac{\delta E}{E} = 0.001$

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
ε_L	MeV m	7.5	7.5	7.5
σ_E / E	%	0.1	0.1	0.1
σ_z	mm	5	1.5	1.07
β	mm	5	1.5	1.07
ε	µm	25	25	25
$\sigma_{x,y}$	µm	3.0	0.9	0.63

Muon Collider Layouts

~3—10 TeV





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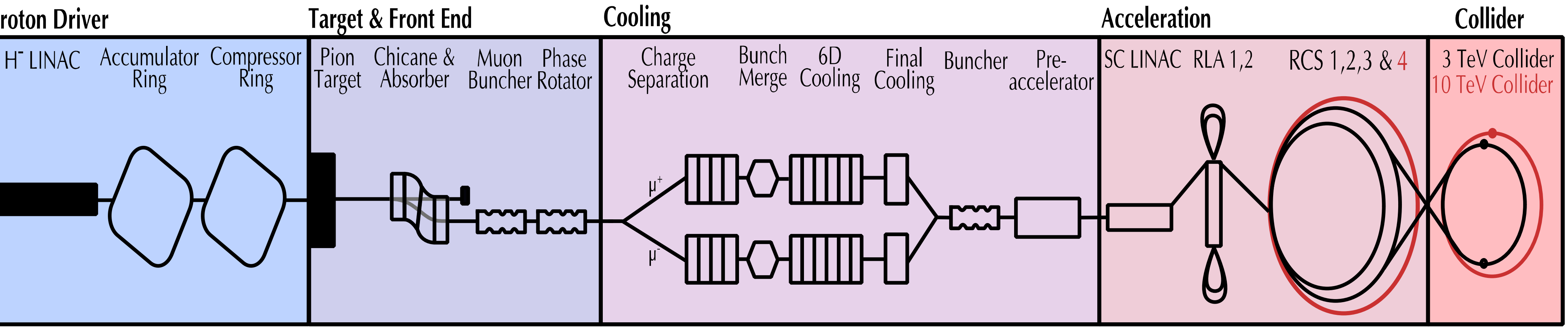
IMCC Scenario (2025)



- **Demos needed**
  - **Ionization cooling**
    - **Can components be built?**
      - **Rf within B-fields and with beam**
    - **Cool by large factor? >2?**
  - **Target**
    - **Can be built?**
    - **Target production/heating ?**
    - **π/μ capture?**
  - **Acceleration**
    - **Rf/magnets can be built?**
    - **Operate in desired mode?**

- **Demos needed**
  - **Final Cooling**
    - **B=40?T, low-frequency rf ?**
    - **Operate with beam ?**
    - **Wedge alternative ?**
  - **Front End**
    - **Optimize, demonstrate ???**
  - **Magnets**
    - **Build, test, operate**
    - **High field,**
      - RCS ramp ?

Intensity upgrade PIP-II → ???

20-Year Roadmap for Accelerator Complex Upgrades

Raimondi – Talk WEYA003

DEEP UNDERGROUND NEUTRINO EXPERIMENT

2024

~1 MW proton beam

- In the last 10 years, the beam power increased from 0.3MW to approximately 1 MW.

2029

1.2 MW proton beam

- **PIP-II Project:**
  - LINAC upgrade to provide beam for injection into Booster at energy of 800 MeV from present 400 MeV.
  - Booster cycle rate is upgraded to 20 Hz from 15 Hz.
  - **Proton flux at 8 GeV increases 2 times** resulting in beam power from Main Injector up to 1.2 MW

~2032

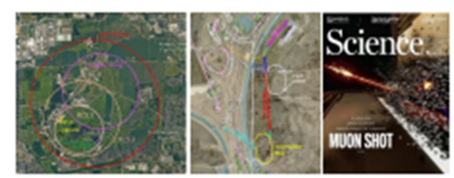
~2 MW proton beam

- **ACE- MIRT**
  - Main Injector Reliability Improvements, cycle time shortening, and target systems upgrade
  - Will accelerate the achievement of the DUNE science goals with respect to the original PIP-II plan
  - Improve reliability and safety of the key machines for the future of accelerator complex

~2040

>2 MW proton beam

- **ACE-BR**
- A project would be established to build **Booster Replacement**
- Considerably enhance beam capabilities for a broader physics program
- Also, it could eventually pave the way for new muon facilities, such as a **10 TeV Muon Collider (MuC)** at Fermilab.



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2023 P5 Report – 2025 NAS recommendation

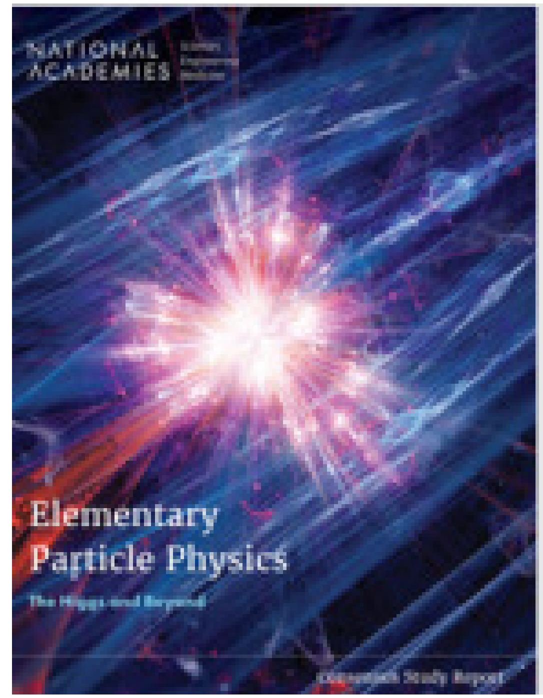
NEWS | 08 August 2022 | Correction 11 August 2022

Particle physicists want to build the world's first muon collider

The accelerator would smash together this heavier version of the electron and, researchers hope, discover new particles.

By Elizabeth Gibney

symmetry



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.

Recommendation 2: The United States should participate in the international Future Circular Collider Higgs factory currently under study at CERN to unravel the physics of the Higgs boson.

Recommendation 3: The United States should continue to pursue and develop new approaches to questions ranging from neutrino physics and tests of fundamental symmetries to the mysteries of dark matter, dark energy, cosmic inflation, and the excess of matter over antimatter in the universe.

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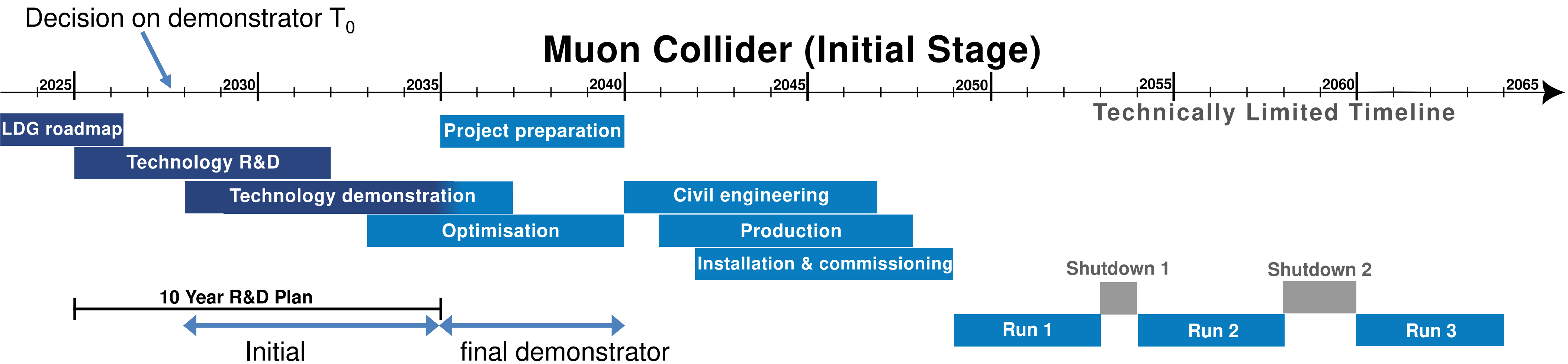
IMCC plans/ time lines

D. Schulte

Timeline and R&D Programme Proposal



Timeline is **driven by R&D**

Most ambitious example to define R&D programme priorities

- Assumes firm commitment to enable the muon collider as next flagship after HL-LHC
- R&D is fully successful
- No delays due to decision making

Other options

- In Europe after a higgs factory
- In the US to become leader at the energy frontier

Milestone	Muon Collider
Construction of RF test stands	2025 – 2028
Production of test cavities	2026 – 2039
Operation of test stands	2027 – 2040
Demonstration Phase	$T_0 - (T_0 + 7)$
Demonstrator technical design	
Construction of initial demonstrator	
Construction of muon cooling module (5 cells)	
Definition of the placement scenario for the collider	
Project Preparation Phase	$T_1 - (T_1 + 5)$
Final demonstrator	
Implementation studies with the Host states	
Environmental evaluation & project authorisation processes	
Main technologies R&D completion	
Industrialisation of key components	
Engineering Design completion	
Construction Phase (from ground breaking)	$T_2 - (T_2 + 9)$
Civil engineering	
TI installation	
Component construction	
Accelerator HW installation	
HW commissioning	
Beam commissioning	
Physics operation start	$T_2 + 10$

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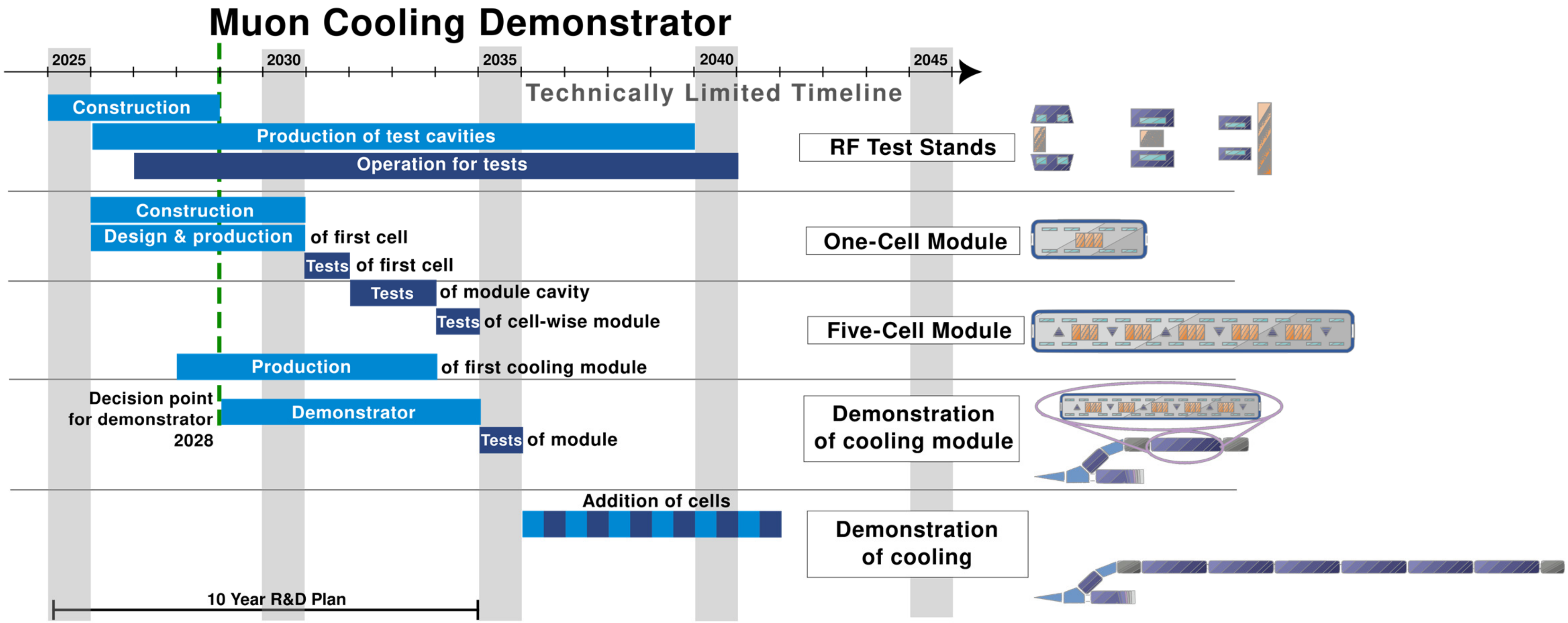
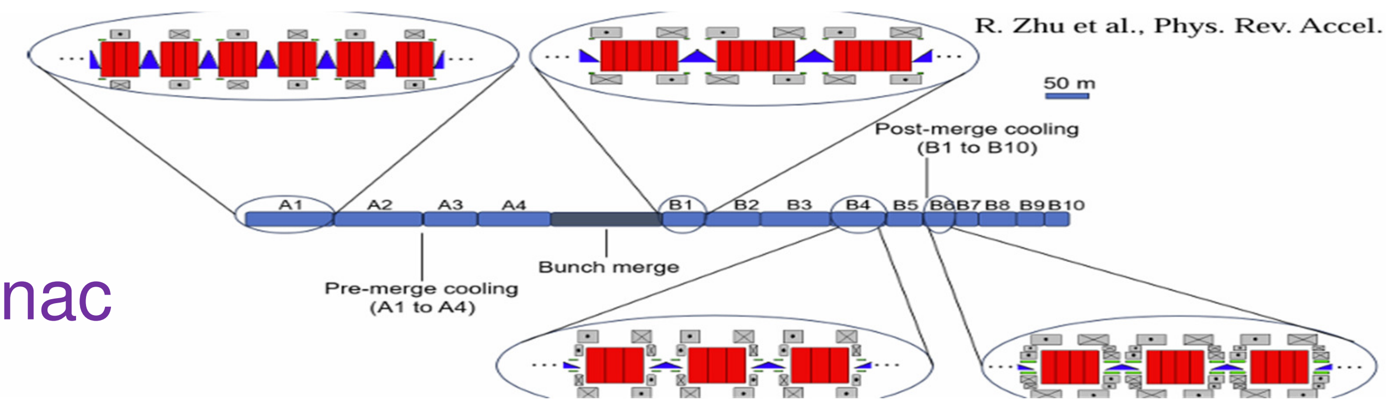
https://indico.cern.ch/event/1439855/contributions/6542430/

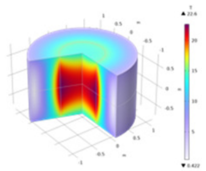
Cooling Demonstrator timeline



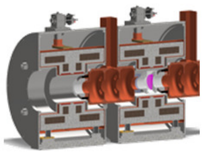


Cooling Linac

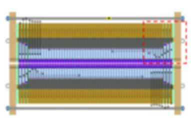
Technology Demonstrators- Magnets



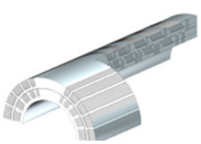
Target solenoid model coil (20@20)
Objectives: Generate a bore field of 20 T, and operating at a temperature of 20 K.
Time: 2033



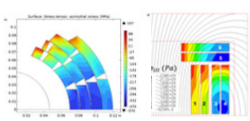
Split Solenoid integration for 6D cooling cell (SOLID)
Objectives: Demonstrator of HTS split solenoid representative of a 6D cooling cell.
Time: 2032



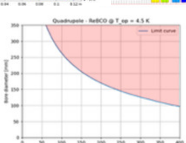
Final cooling UHF solenoid (UHF-Demo)
Objectives: HTS final cooling solenoid, 40 T in a 50 mm bore, 150 mm length.
Time: 2034



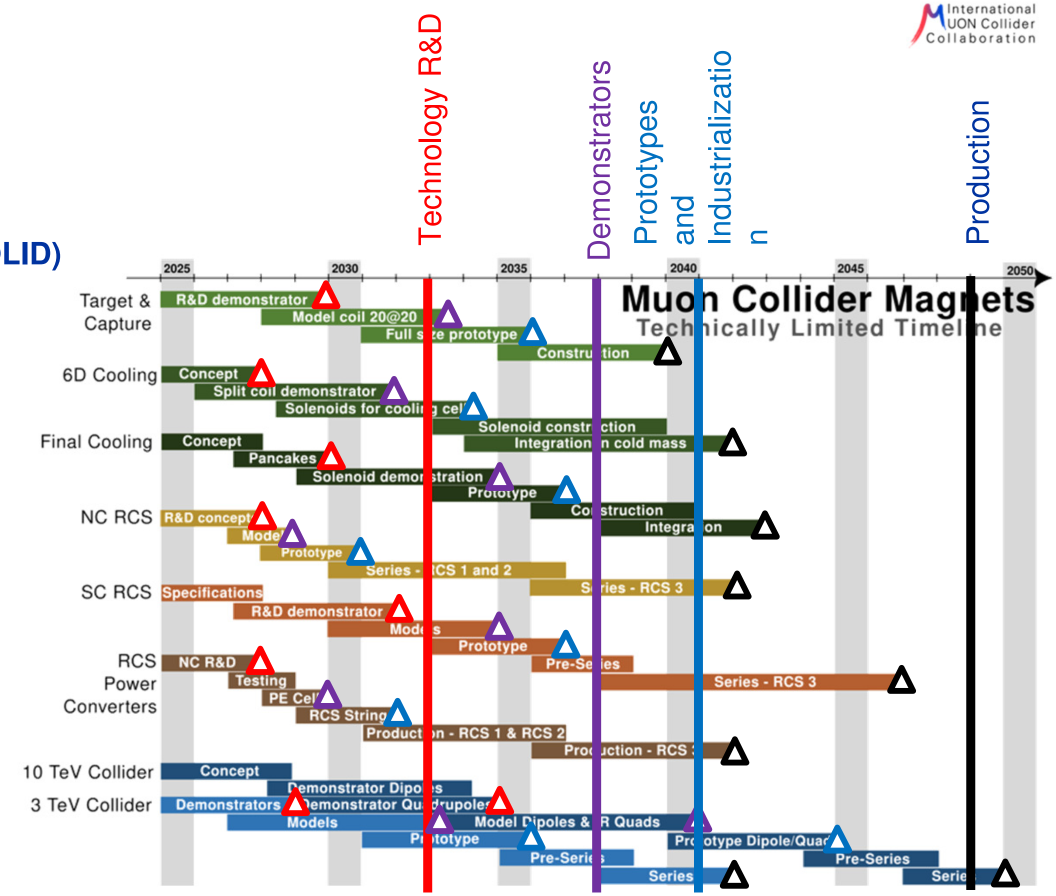
Wide-aperture, DC Nb_3Sn dipole (MBHY)
Objectives: Demonstrate wide-ap. LTS dipole
Time: 2036



Wide-aperture DC HTS dipole (MBHTSY)
Objectives: Demonstrate wide-ap. HTS dipole
Time: (2045)



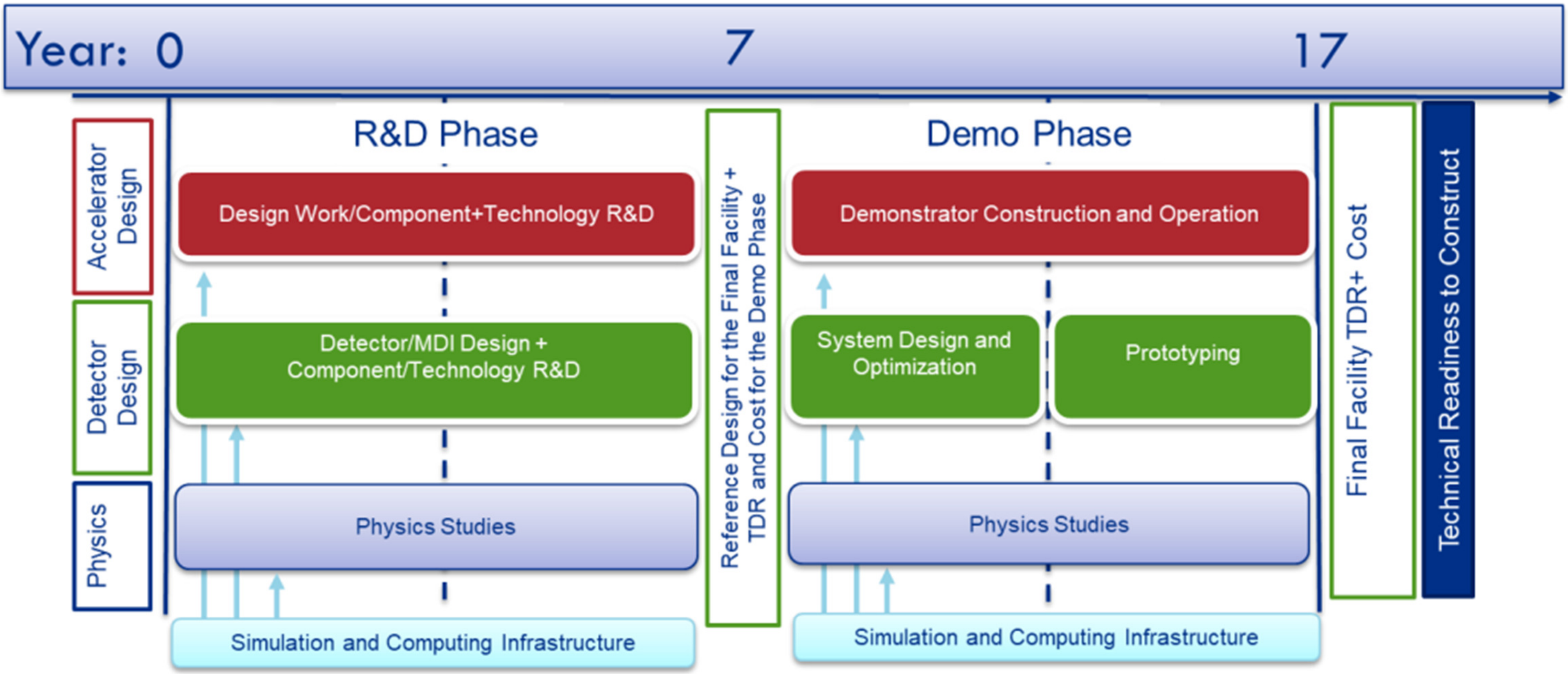
Wide aperture HTS IR quadrupole (MQHTSY)
Objectives: Demonstrate wide-ap. HTS quadrupole for the collider IR.
Time: (2045)



B. Auchmann

US MCC collaboration

US Muon Collider timeline



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

Initial R&D research

US R&D accelerator roadmap (~5 year plan)

Design
- Integrated design of all MuC subsystems
- Physics processes (space-charge, beam loading, radiation, HOM)

Proton Driver
- Study needed beam manipulations at existing facilities (SNS, IOTA)
- Define additions to Fermilab accel. complex to support MuC

Targets
- Extend R&D program for high-power targetry & irradiated materials
- Synergistic with Fermilab ACE-MIRT and SNS

Magnets
- Design and modeling studies of late stage cooling solenoids
- Design and prototyping of demonstrator solenoids
- Design & prototyping of fast-ramping magnets & power supply

RF Cavities
- R&D on high-gradient NC cavity designs
- Design and prototype cavities for the demonstrator
- Conceptual designs of SRF for accelerator lattices

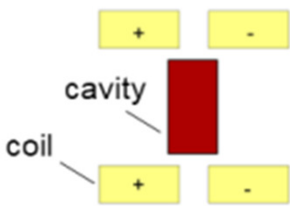
Demonstrator
- Conceptual design of a demonstrator for cooling technology
- Site exploration (CERN, Fermilab) & begin Phase-I of testing

Muon Collider: Muon cooling demonstrator facility

- Ionization cooling demonstrated by MICE in 2020 (10% emit. reduction)
- Next step is to study **integration** by building ionization cooling cells that resemble a realistic channel

J. S. Berg et al. WEPR34
T. Luo et al., TUPR12
R. Kamath, MOPR03
C. Barbagallo, WEPR25

Phase-I

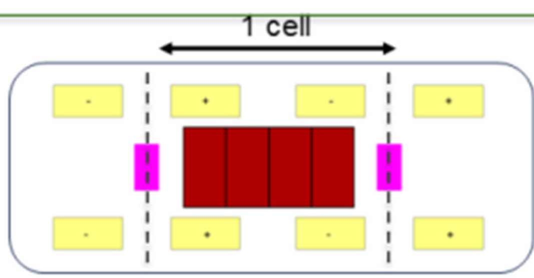


RF studies in B-fields

Material studies & cryogenic Cu

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

Phase-II

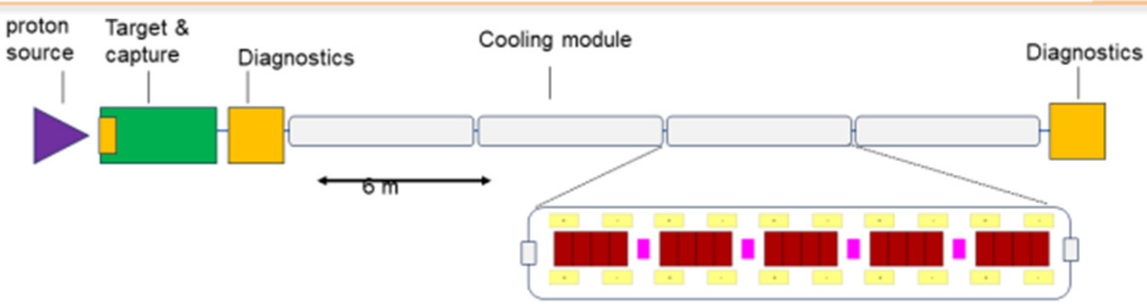


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III



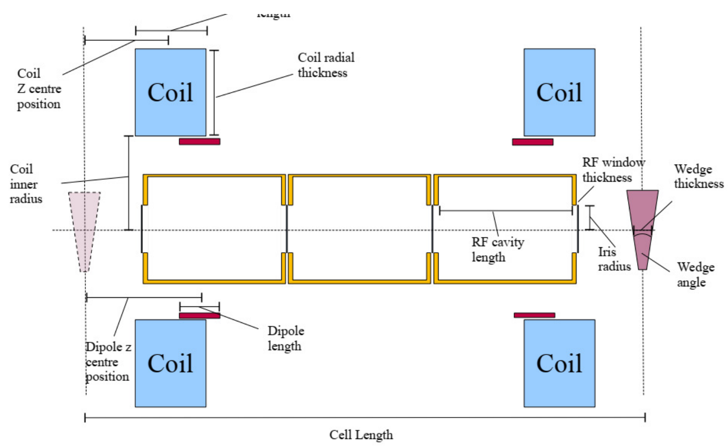
Full demonstrator with beam

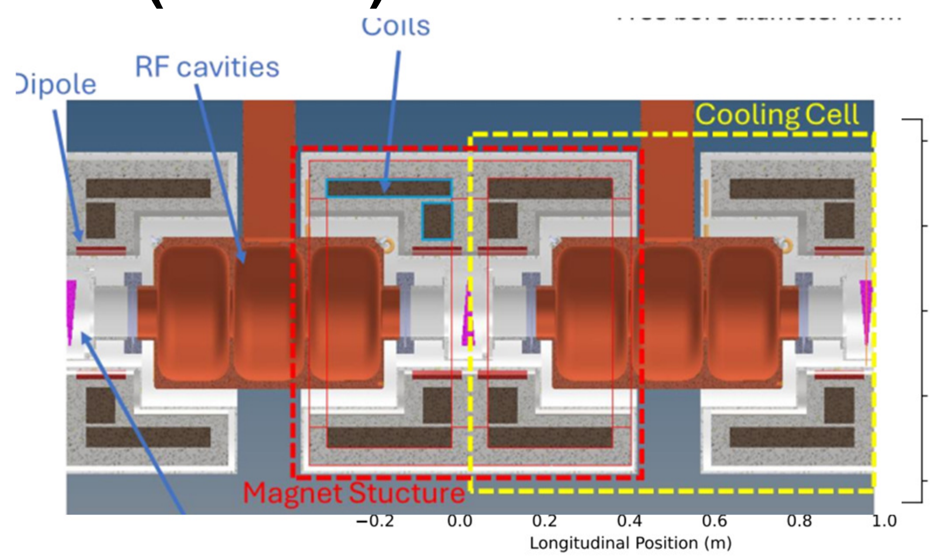
Coils producing 7-10 T axial fields

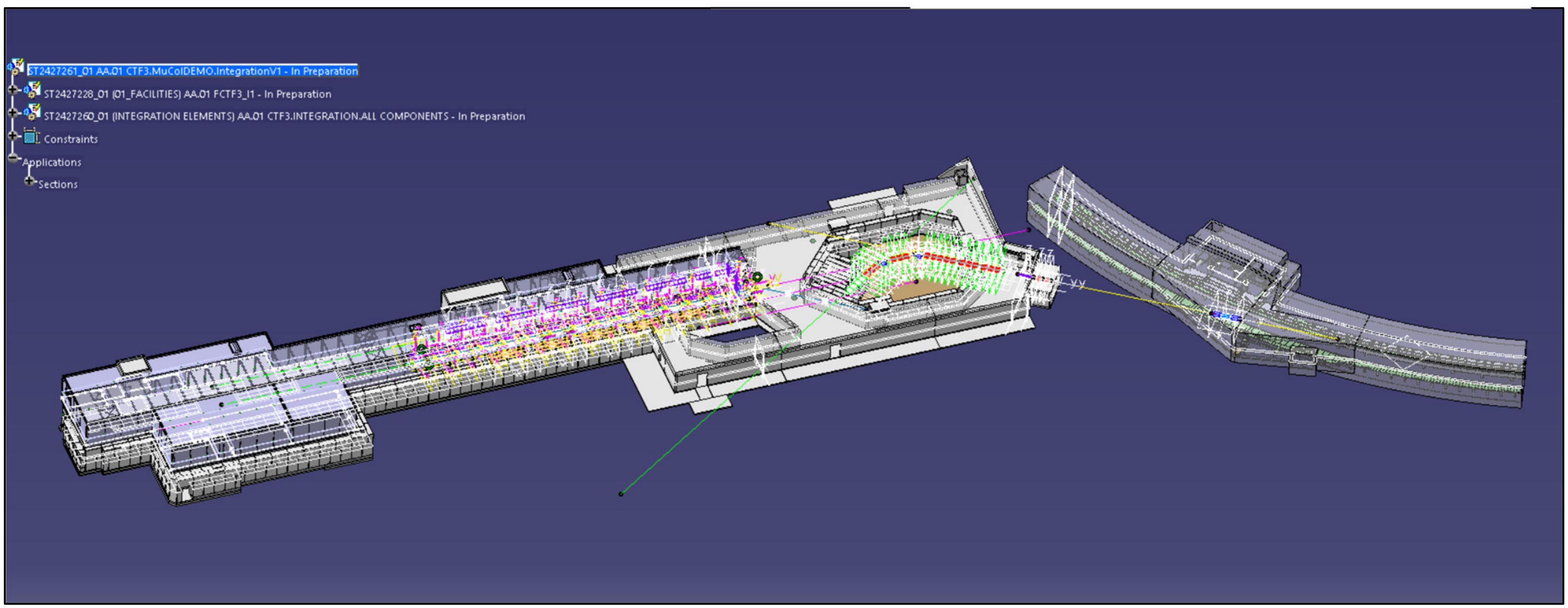
Potential to achieve 50% 6D cooling

Demonstrator Design (CERN)

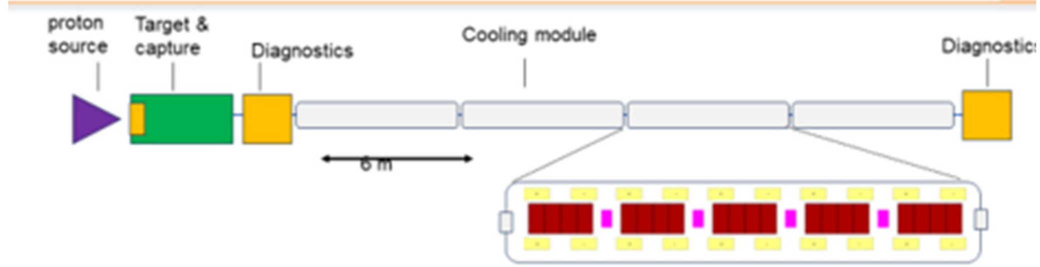
➢ **CT3 Facility could demonstrate cooling in a Multicell/multicavity scenario (~ 50 m)**

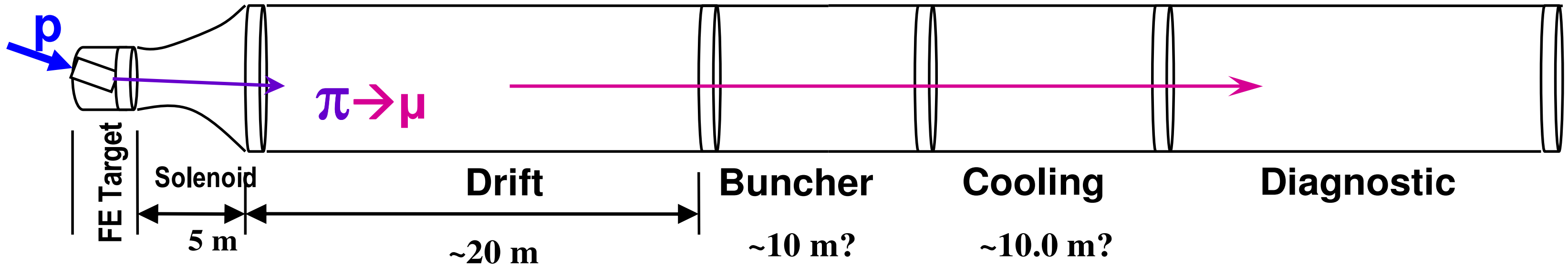


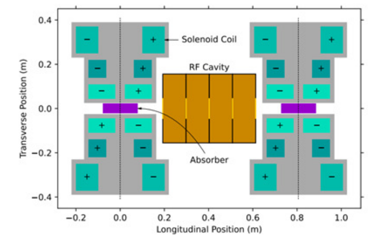




A demo idea







- ➢ **Scaled-back version of MC Front end**
  - **8 GeV p, use BNB line**
    - **Or M1-AP0 line**
  - **FE – 5 → 1 T , C target**
  - **Buncher to shape beam**
  - **Cooling device to be tested**
    - **Cooling section from scenario(325 MHz ?**
    - **Example: inject into cooling ring ??**
    - **Example: stopping target for low-energy πμν neutrino beams?**

2nd Annual
US Muon Collider
Meeting

University of Chicago, 7-8 August 2025 indico.uchicago.edu/e/usmc2025

- **Next Event:**
  - **US Muon Collider collaboration meeting**
    - **August 7—8 (U of Chicago)**