



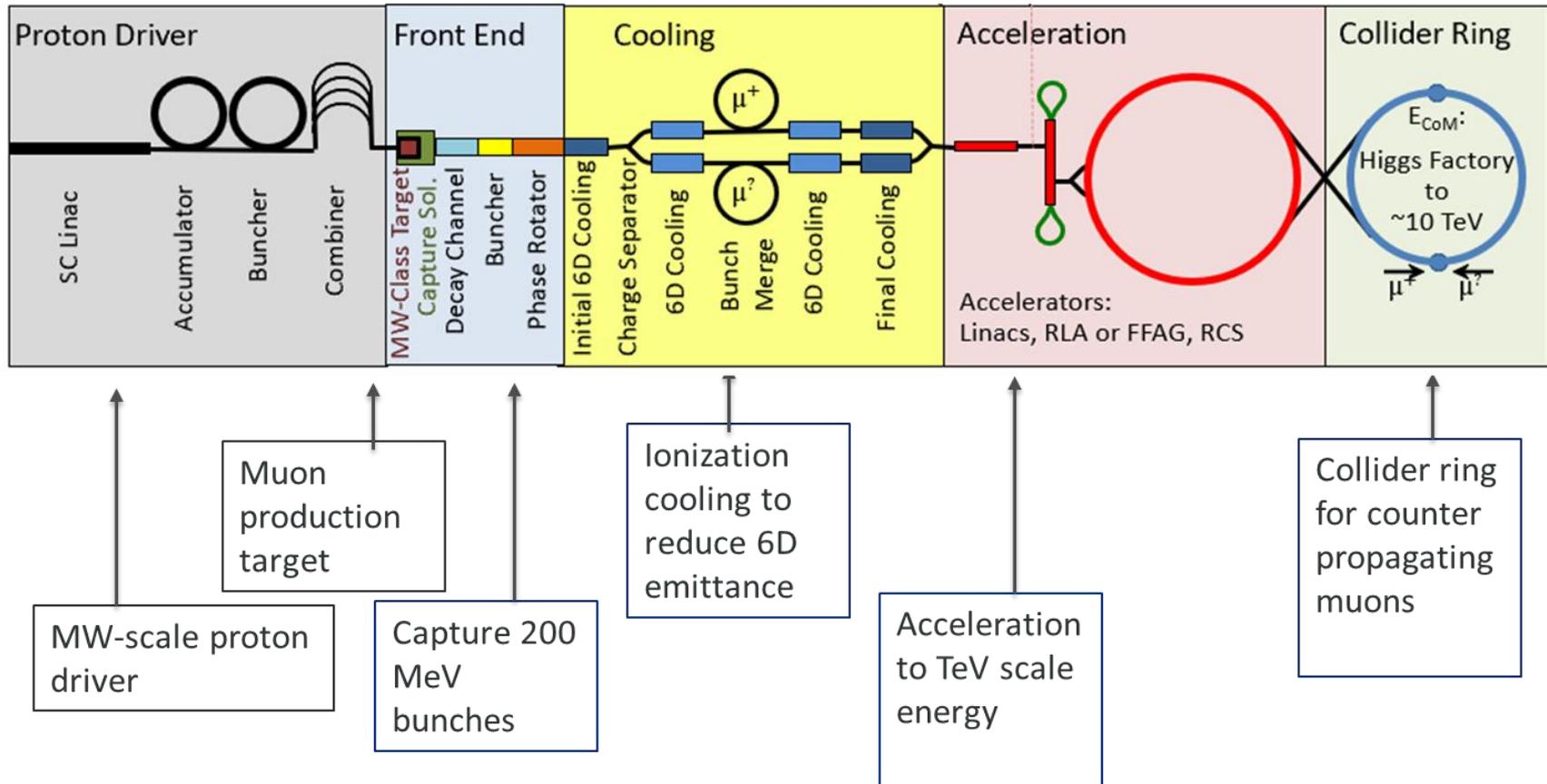
Muon Cooling Demonstrator Program for the Muon Collider

Diktys Stratakis (Fermilab)

National Study Group Meeting

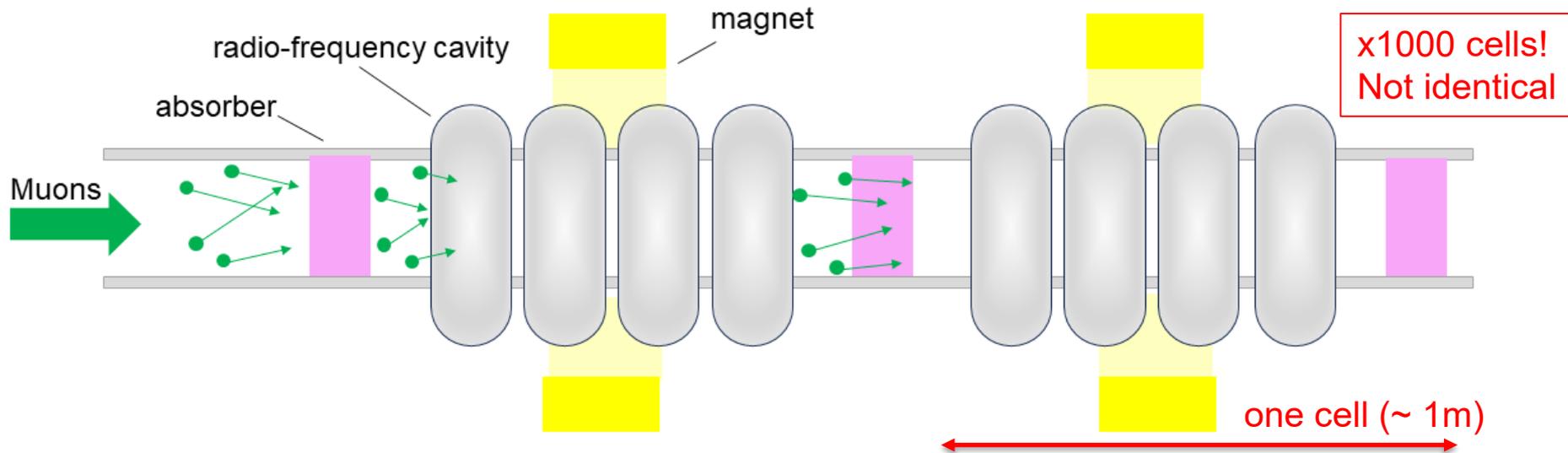
February 16, 2026

Muon Collider overview



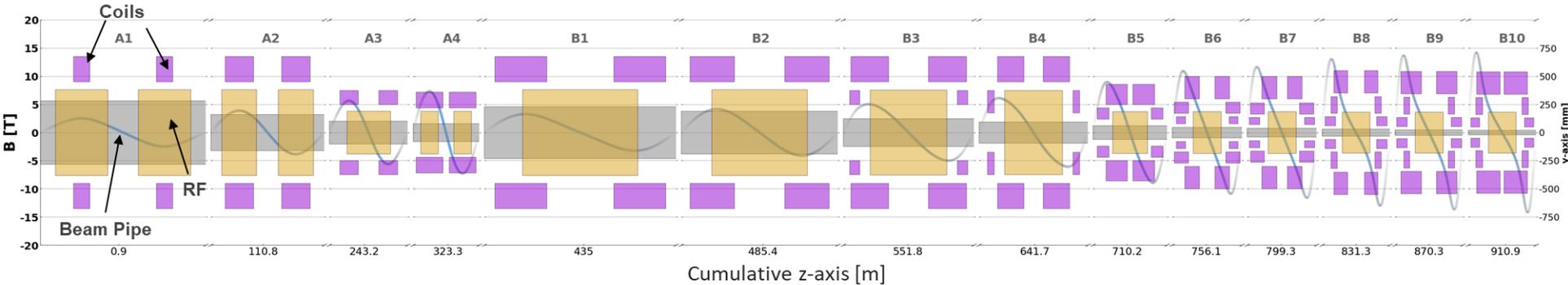
- Cooling has huge leverage on the overall machine design
 - What proton power is required? What target technology to choose?
 - What luminosities can be envisioned?

Concept of ionization cooling



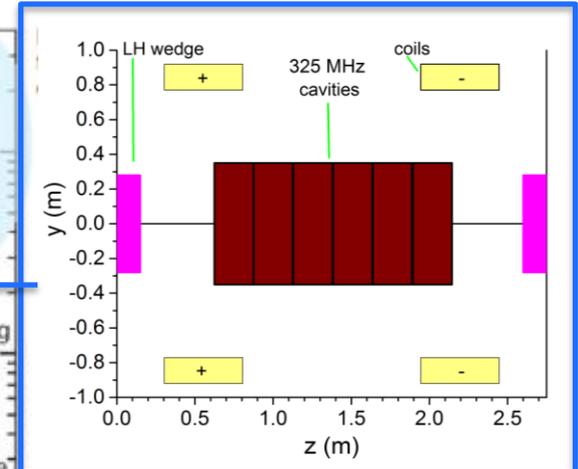
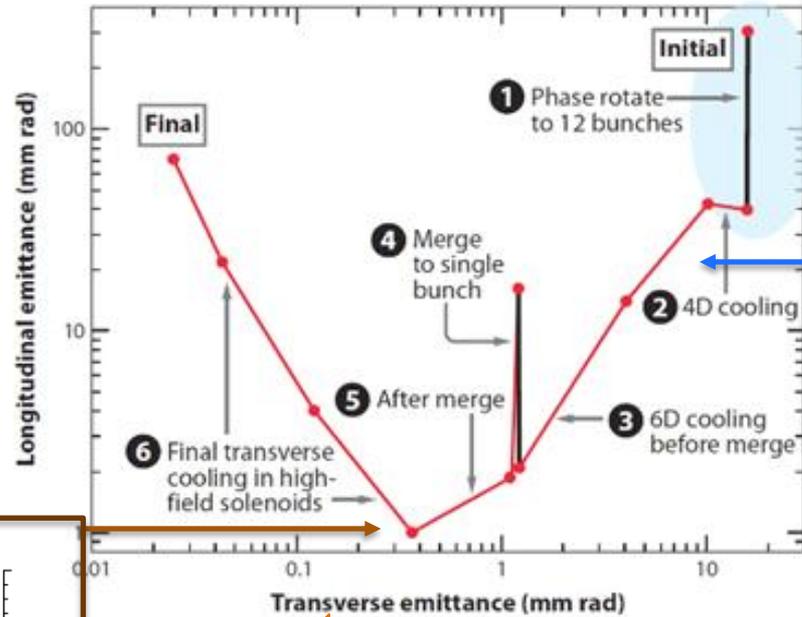
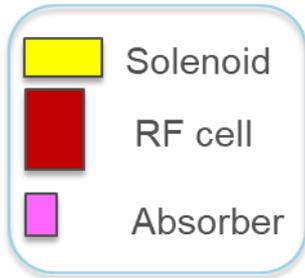
- Considerations for MuC cooling:
 - Beam size must be small at the absorber to reduce scattering
 - Absorbers with low Z and large energy loss must be selected
 - Magnetic field has to increase in strength over distance to keep cooling
 - The magnetic field, makes normal conducting (NC) cavities the only option

6D cooling for the MuC (requirements)

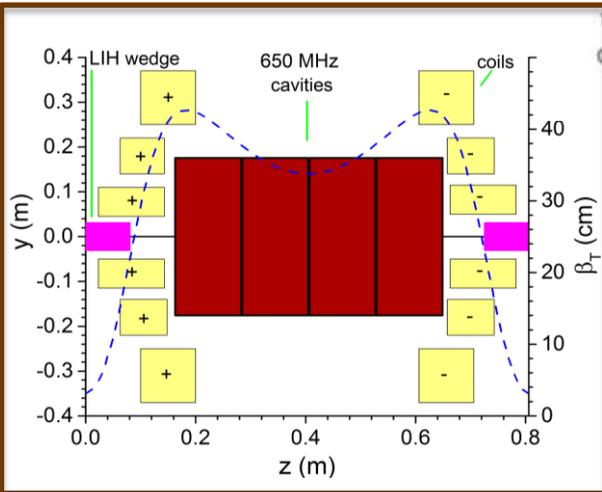


- Magnets (~3000 per sign)
 - On axis field: 2.5 T to 14.3 T over ~ 1 km length
 - Bore radius: 50 mm to 450 mm
- RF cavities (~2000 per sign)
 - 300-800 MHz exposed to magnetic fields up to ~ 10 T
 - Need to operate at 25-30 MV/m, with 4 MW peak power/cavity
- Absorbers
 - Made out of LH or LiH or a combination of the two

6D cooling for the MuC (challenges)



Early cell ("easy") – 2 T peak



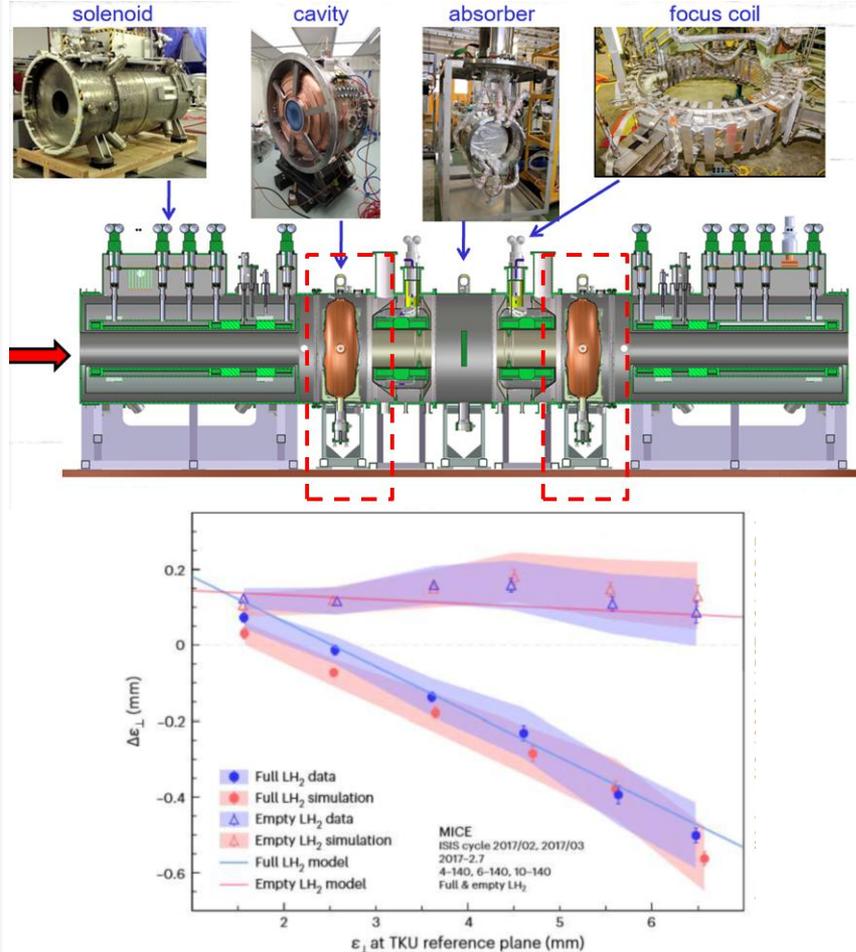
Late cell ("hard") – 14 T peak

Several **multi-T** solenoidal coils
Very tight space between rf and coils
Very tight space between coils
 rf cavities exposed to **multi-T** fields

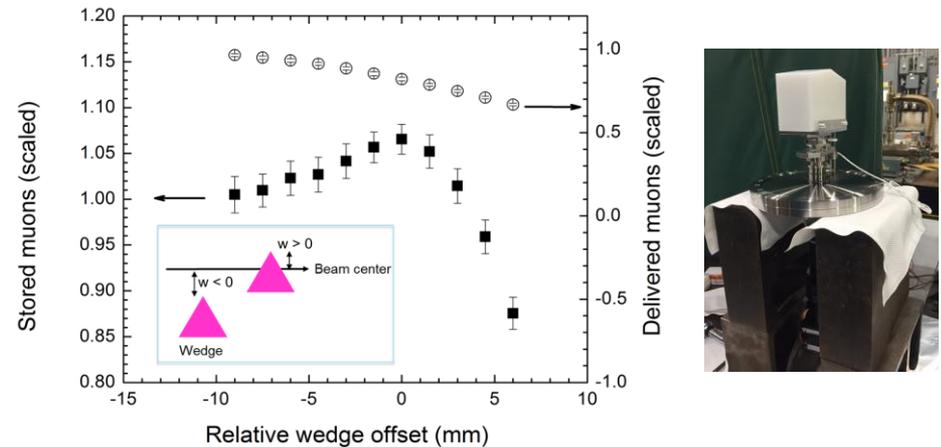
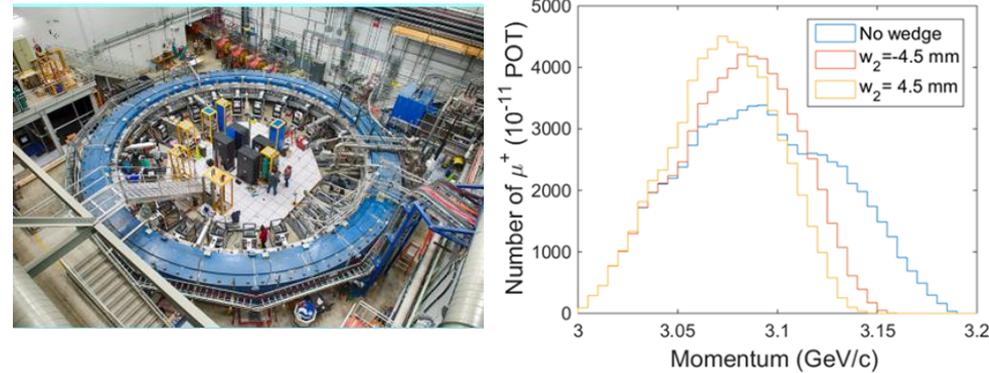
Cooling Demonstration – past experience

- Physics of ionization cooling has been demonstrated in two occasions

MICE Experiment



Fermilab Muon g-2 Experiment

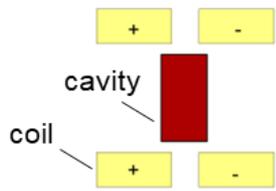


Cooling demonstration (new) program goals

- Demonstrate operation of NC RF cavities under conditions relevant to a muon cooling channel
 - Developing the technology for rf-cavities to sustain high-gradients in multi-T fields
- Develop solenoids capable of operating in realistic cooling-channel environments
 - Developing the technology towards multi-Tesla solenoids capable to withstand forces/stresses from nearby magnets
- Demonstrate integration of cooling-cell components
 - Validate operation of closely spaced magnets, RF cavities, and absorbers
- Benchmark a realistic cooling channel
 - Gain operational experience with cooling-channel systems
 - Develop capability to measure and characterize muon beams
 - Benchmark simulation tools and investigate potential new physics effects

Muon cooling demonstrator program staging

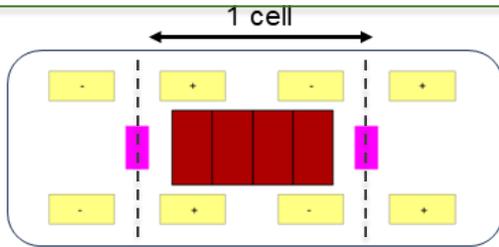
Phase-I



RF studies in B-fields

Material studies & cryogenic Cu

Phase-II

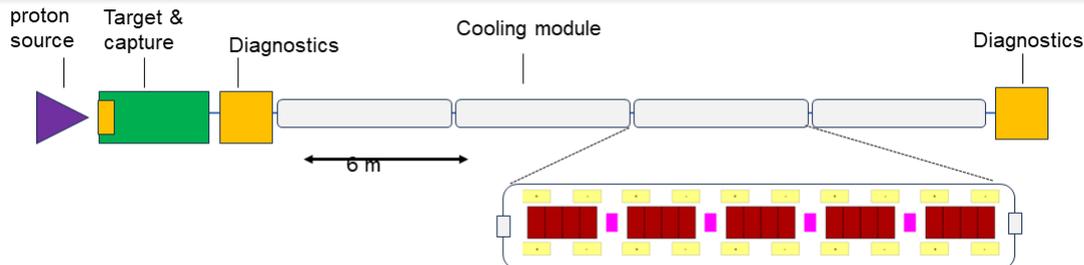


Cell integration studies

Cell resembles late 6D cooling stages

Reuse components from Phase I

Phase-III



Full demonstrator with beam

Many cells from phase-II

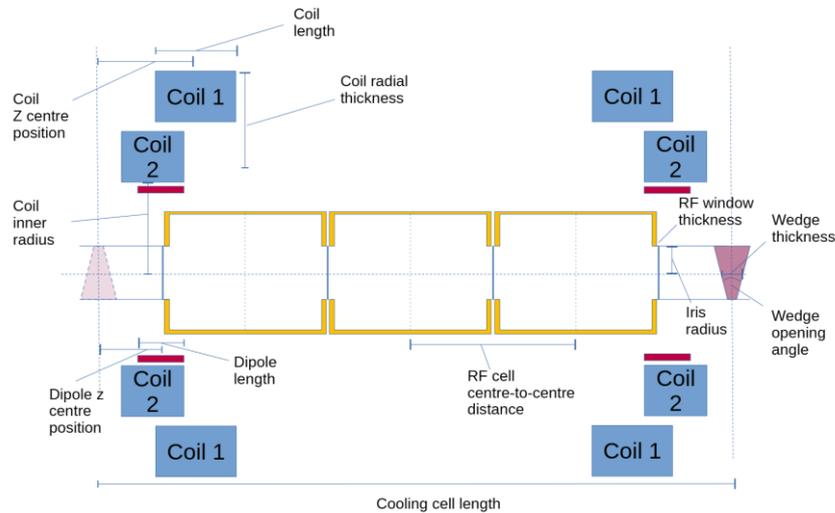
Test various components with the beam

Cooling cell for demo (IMCC)

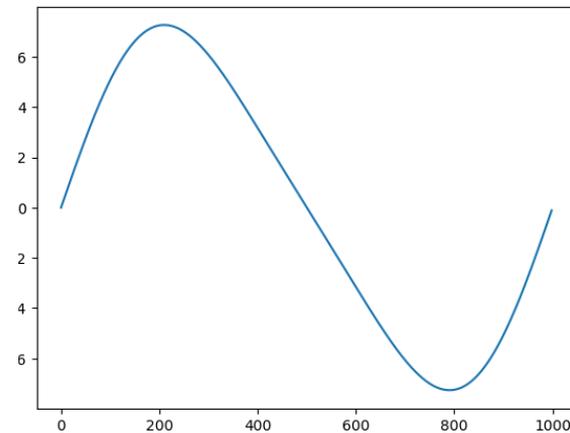
Stage	Cell length (m)	Stage length (m)	Pipe radius (cm)	Max. on-axis B_z (T)	Integrated B_y (T·m)	Transverse beta (cm)	Dispersion (mm)	On-axis wedge length (cm)	Wedge apex angle (deg)	RF frequency (MHz)	Number of RF cells	RF cell length (cm)	Max. RF gradient (MV/m)	RF phase (deg)
A1	1.8	104.4	28	2.5	0.102	70	-60	14.5	45	352	6	19	27.4	18.5
A2	1.2	106.8	16	3.7	0.147	45	-57	10.5	60	352	4	19	26.4	23.2
A3	0.8	64.8	10	5.7	0.154	30	-40	15	100	704	5	9.5	31.5	23.7
A4	0.7	86.8	8	7.2	0.186	23	-30	6.5	70	704	4	9.5	31.7	25.7
B1	2.3	50.6	23	3.1	0.106	35	-51.8	37	110	352	6	25	21.2	29.9
B2	1.8	66.6	19	3.9	0.138	30	-52.4	28	120	352	5	22	21.7	27.2
B3	1.4	84	12.5	5.1	0.144	20	-40.6	24	115	352	4	19	24.9	29.8
B4	1.2	66	9.5	6.6	0.163	15	-35.1	20	110	352	3	22	24.3	31.3
B5	0.8	44	6	9.1	0.116	10	-17.7	12.5	120	704	5	9.5	22.5	24.3
B6	0.7	38.5	4.5	11.5	0.0868	6	-10.6	11	130	704	4	9.5	28	22.1
B7	0.7	28	3.75	13	0.0882	5	-9.8	10	130	704	4	9.5	28.5	18.4
B8	0.65	46.15	2.85	15.8	0.0726	3.8	-7.0	7	140	704	4	9.5	27.1	14.5
B9	0.65	33.8	2.3	16.6	0.0694	3	-6.1	7.5	140	704	4	9.5	29.7	11.9
B10	0.63	29.61	2	17.2	0.0691	2.7	-5.7	6.8	140	704	4	9.5	24.9	12.2

ti

Stage 5



Target field on axis for a 1 m cell



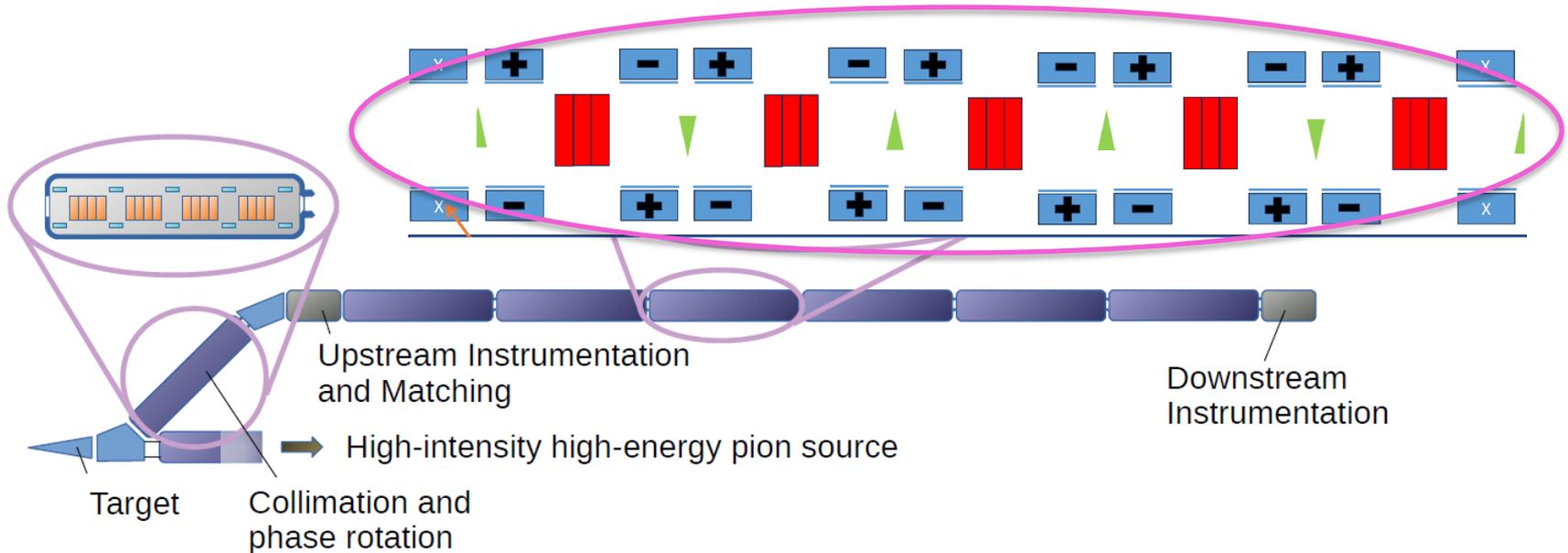
Cooling demo facility (baseline)

- Key elements

- Target & capture (~15 m)
- Beam transport (~35 m)
- Cooling channel (~50 m)

	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	$\times 1/10^5$	~70%
Demonstrator	200	48	24	0.5-7	$\times 1/2$	4-6%

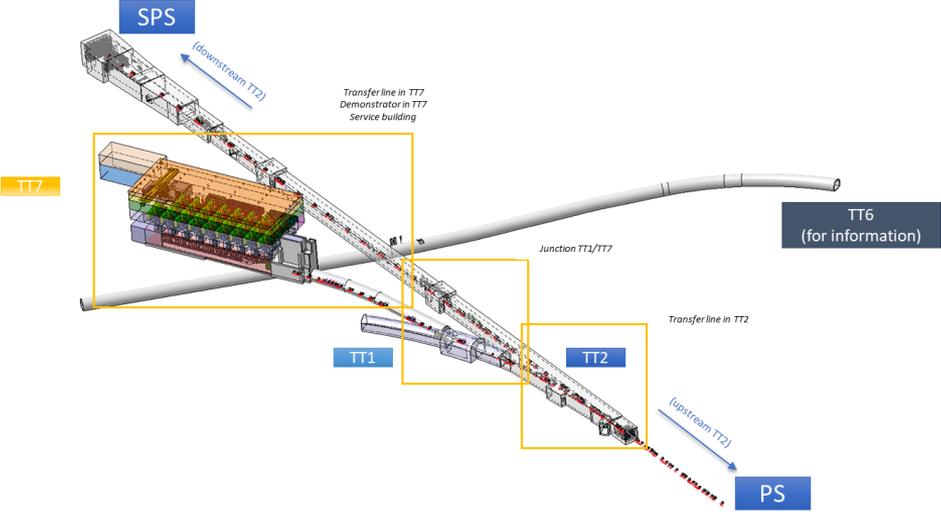
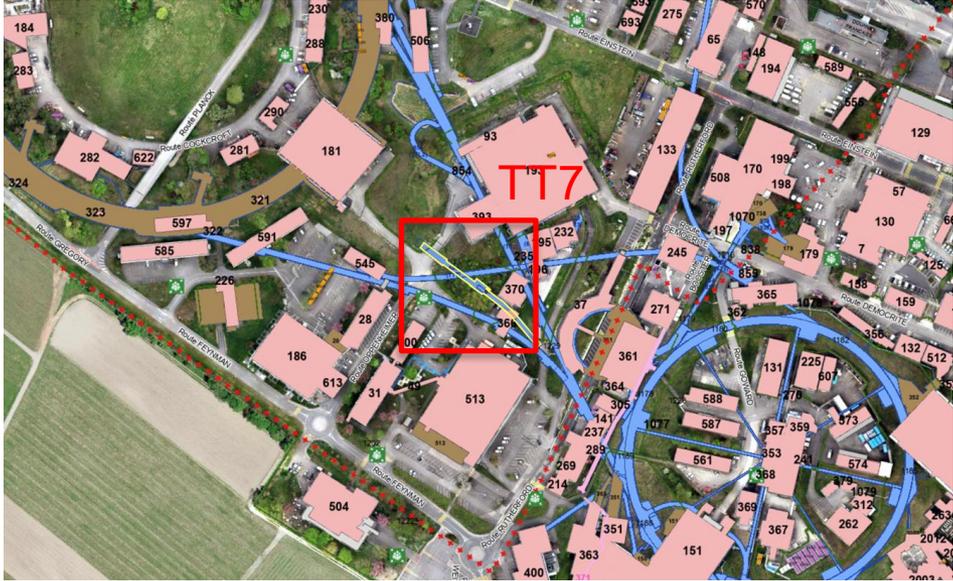
- Parameters to be refined



C. Rogers, Phys. Sci. Forum 2023, 8(1), 37

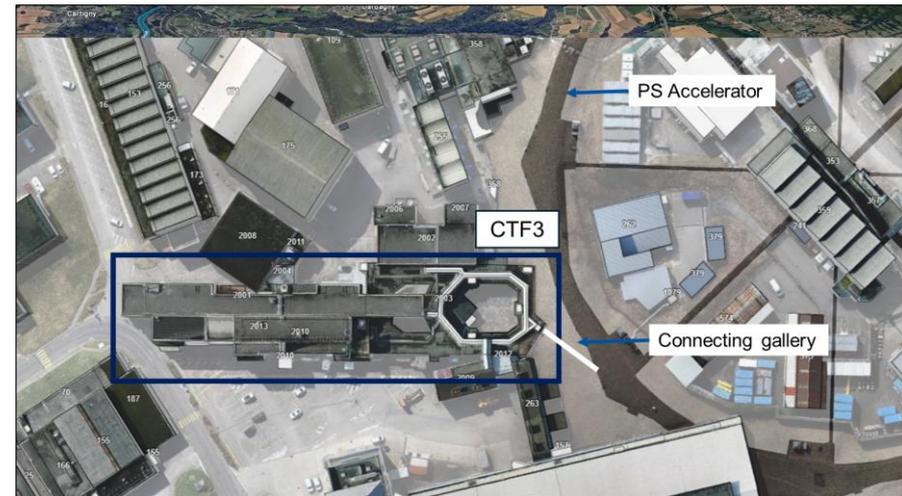
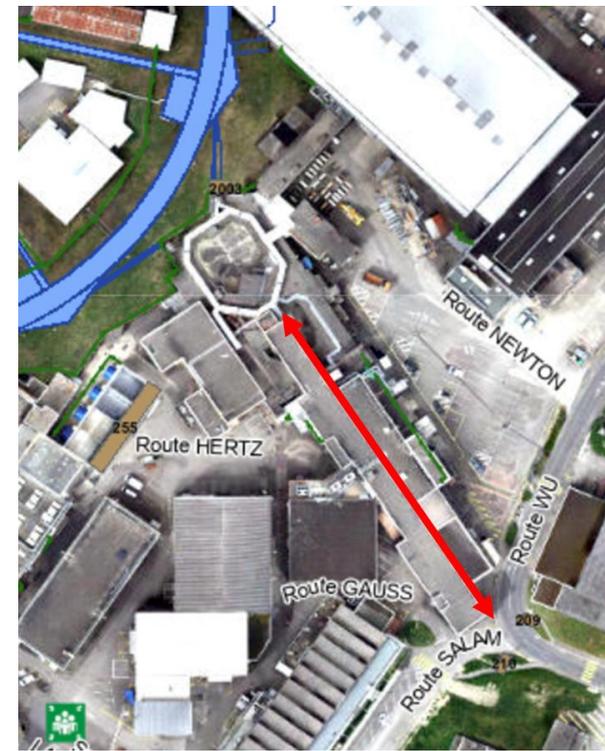
TT7 facility at CERN

- Advantages
 - Does not require a new beam extraction in the PS
 - Existing tunnel (~50 m)
- Disadvantages:
 - No surface buildings
 - Limited beam power (10 kW)

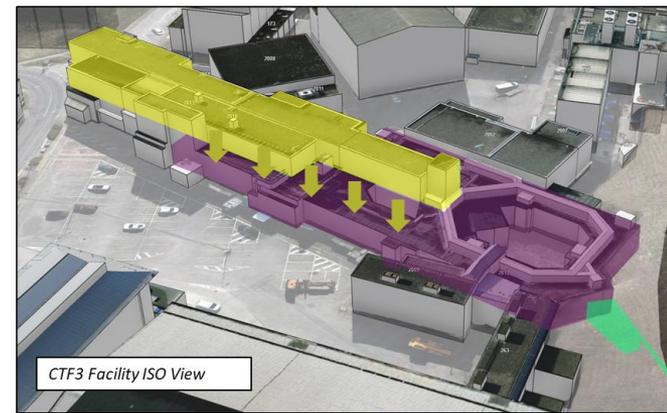
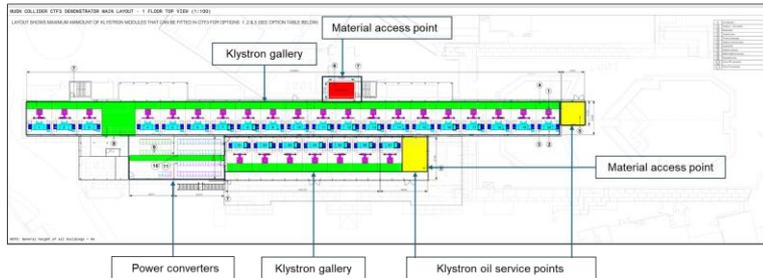


CTF3 Facility at CERN (1)

- Advantages
 - Existing tunnel (~80 m) and surface building available
 - Klystron gallery available
 - Space available to build a proper target area and decay tube
 - Combatable with high-power beam (>10 kW)
- Disadvantages
 - No extraction in the PS



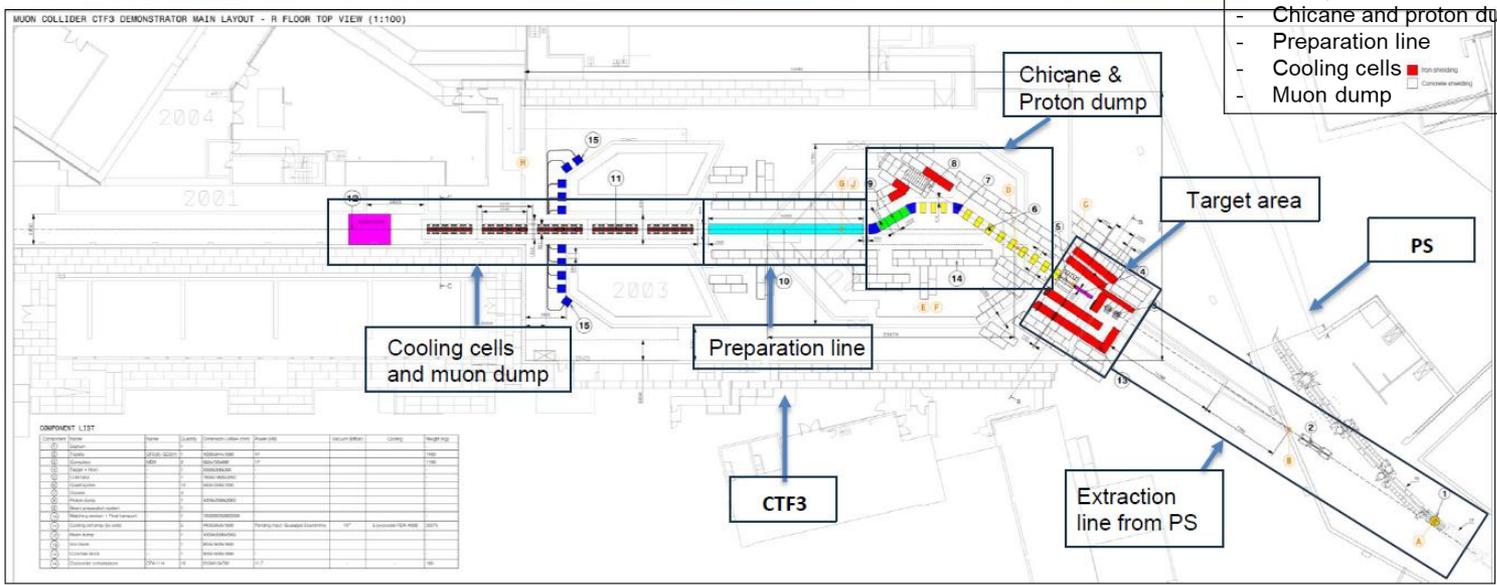
CTF3 Facility at CERN (2)



- R-Floor**
- Transfer line
 - Target area
 - Decay channel
 - Chicane and proton dump
 - Preparation line
 - Cooling cells
 - Muon dump

- 1st - Floor**
- Klystron gallery
 - Power converters

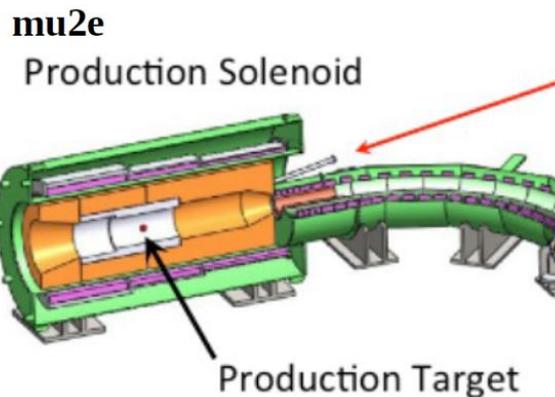
- R-Floor**
- Connecting gallery with PS



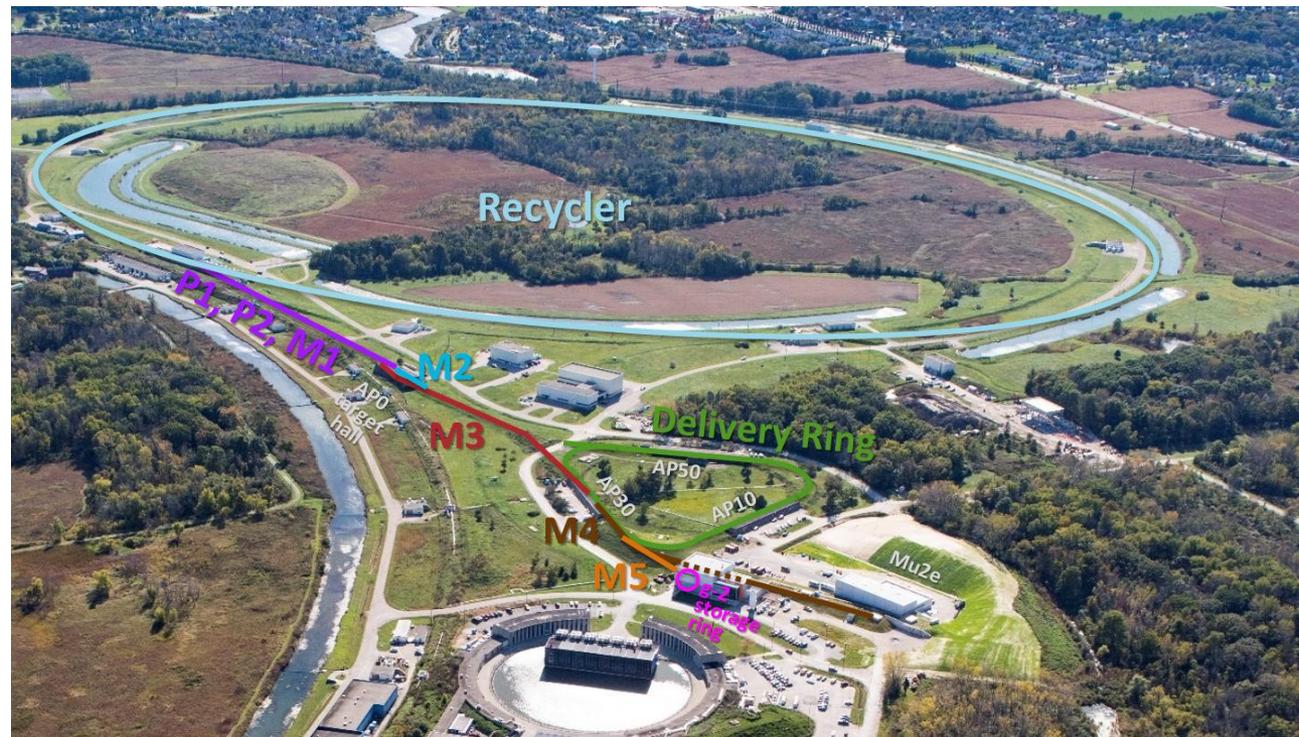
- A preliminary feasibility study for the usage of CTF3 facility as a cooling demo facility has been done by the IMCC (link)

Muon Campus at Fermilab (1)

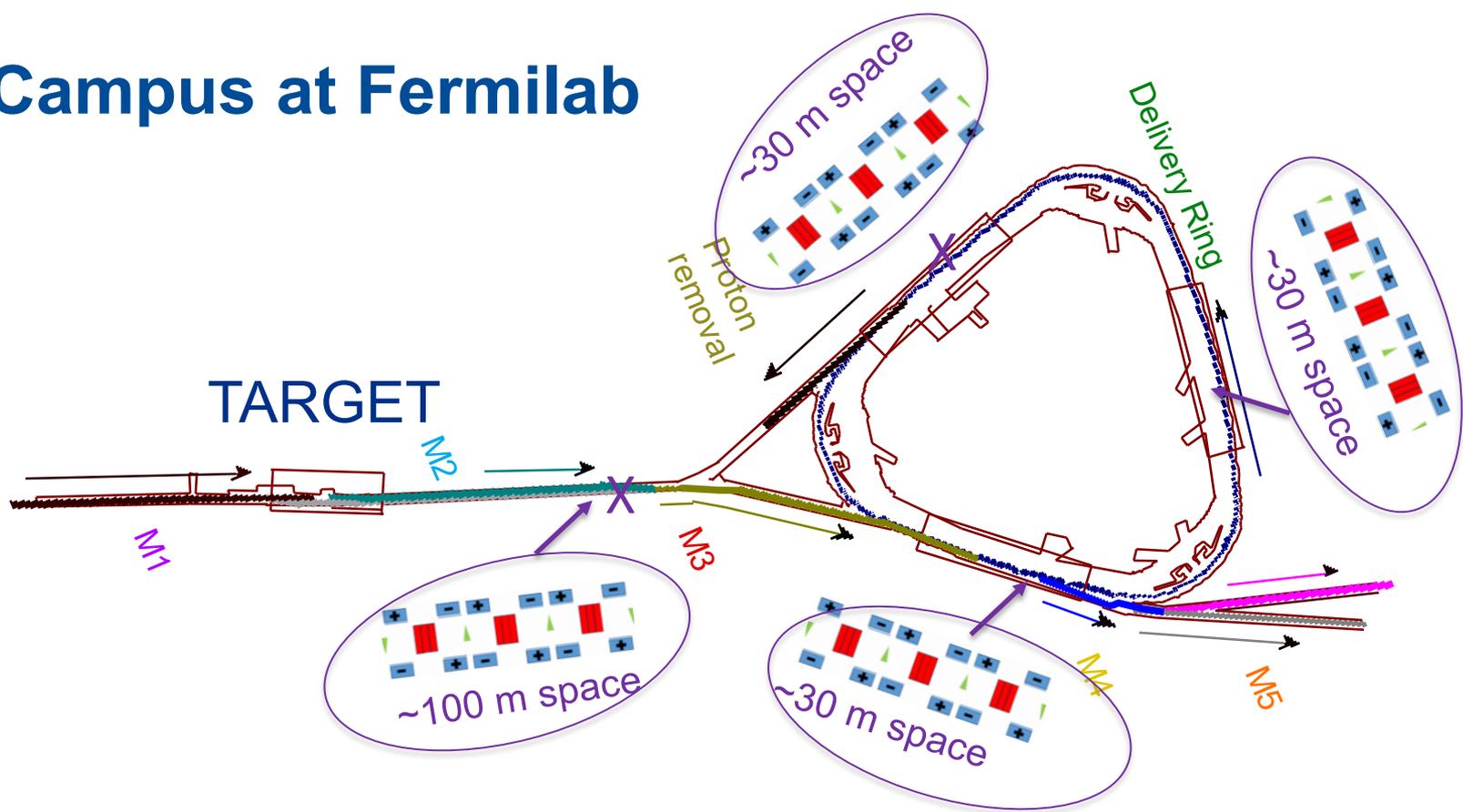
- Designed to provide beam for the Muon g-2 and Mu2e experiments
 - Capable to deliver **8 kW** beam at **8 GeV** to the Mu2e production target
 - Available tunnel space to run the demonstrator without interfering with Mu2e
 - Production target is similar to the MuC target



Excellent opportunity to examine targets under 5 T field



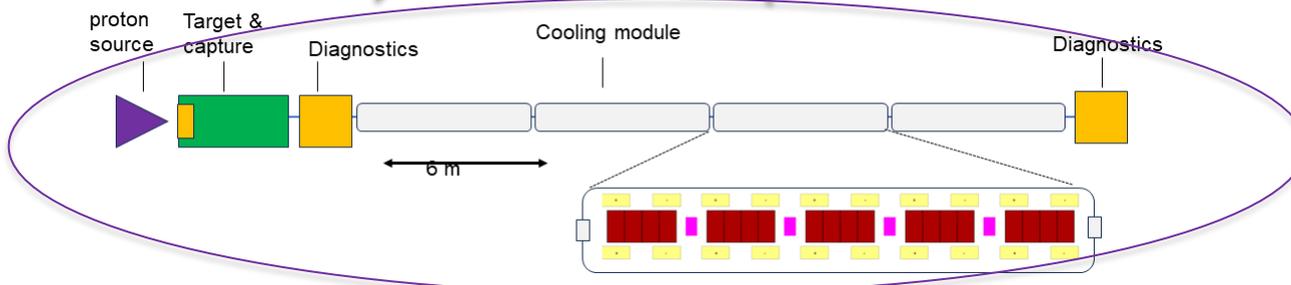
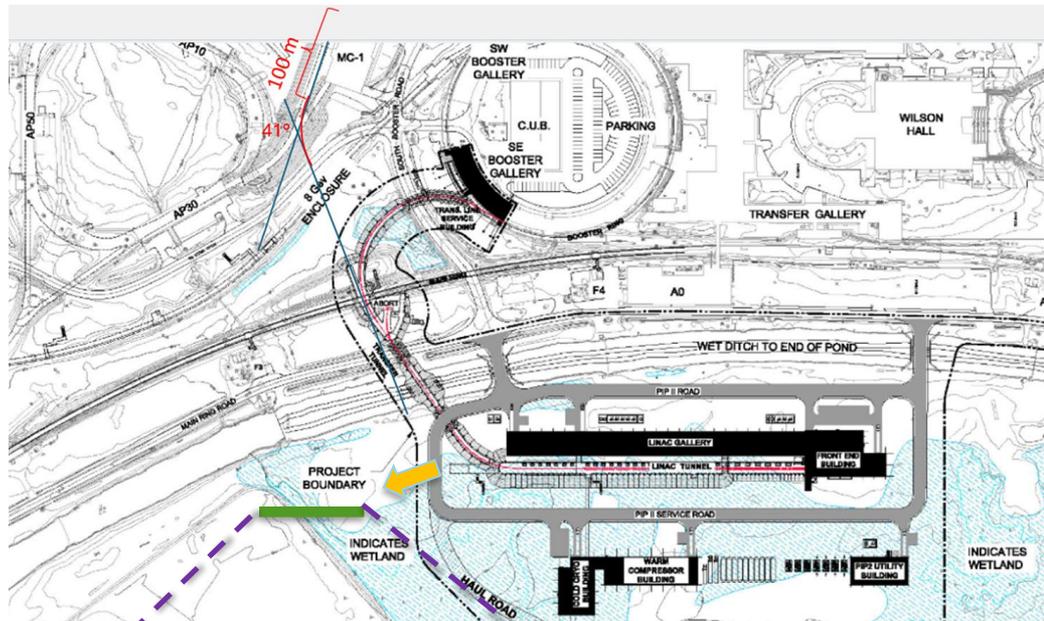
Muon Campus at Fermilab



- Array of cells can be installed over many straight sections
- Ability to pass the beam multiple times around the cells if needed
- Ability to extract beam to other users if needed
- Tunnels, target station and some infrastructure is already in place

Post PIP-II beam at Fermilab

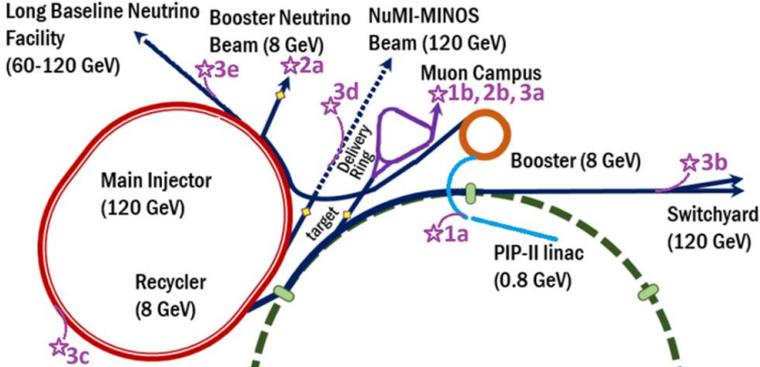
- PIP-II proton accelerator will deliver intense proton beam at 800 MeV
 - only 1% which is used for the Fermilab booster (the rest is potentially available)



Funded LDRD at Fermilab (2025-2027)

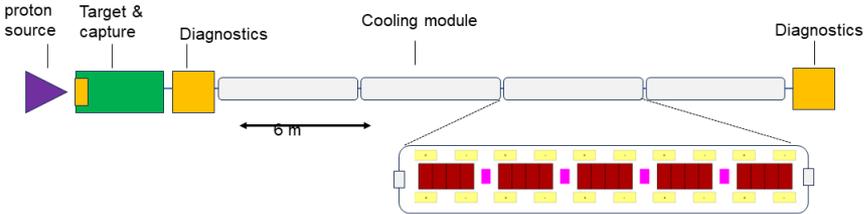
- Task # 1

- Explore candidate sites for a Cooling Demonstrator within Fermilab



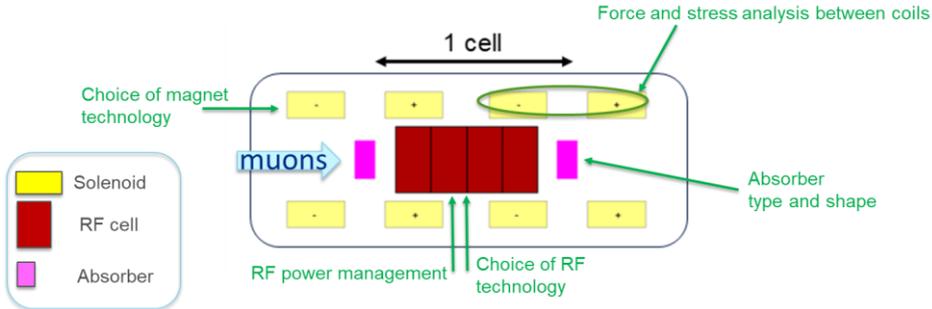
- Task # 2

- Produce a conceptual design of a Demonstrator within Fermilab



- Task # 3

- Preliminary technical risk evaluation for the cooling cells



Feasibility at the SNS (1)

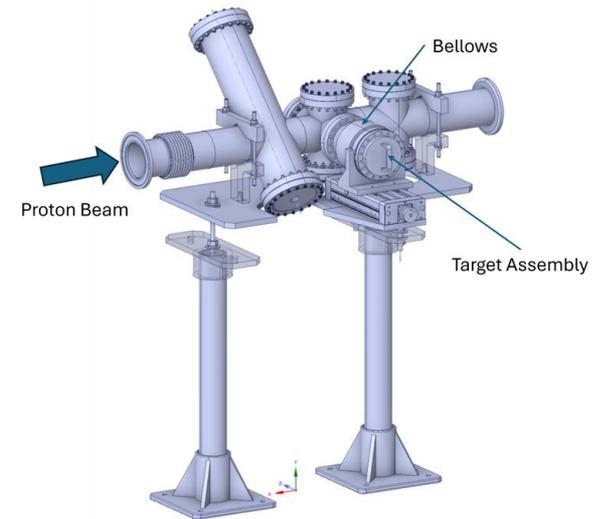
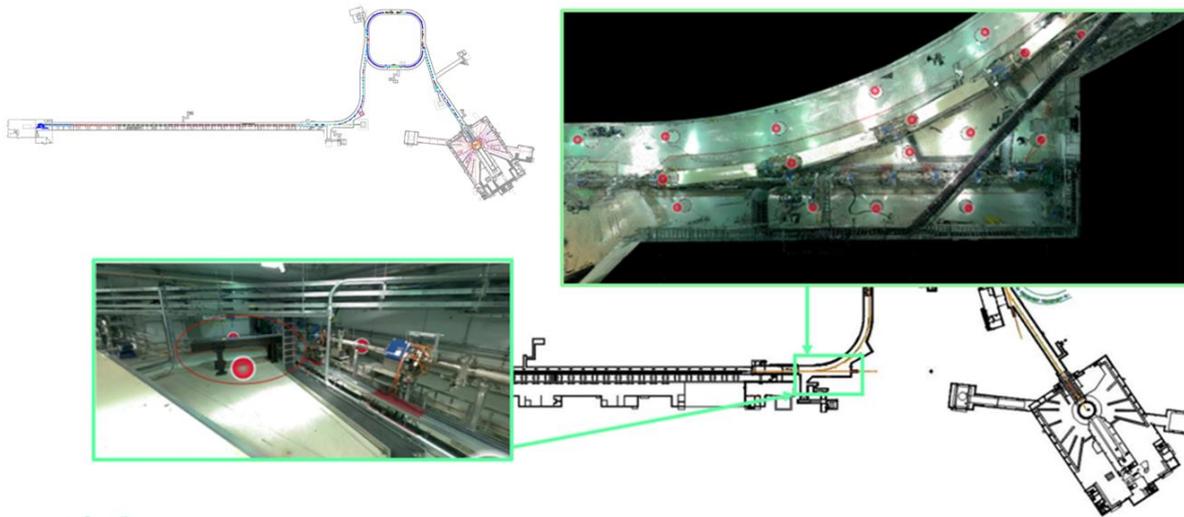
- In view of access beam power availability, SNS started exploration of its potential applications.

Era	Beam Power Capability	Beam Power to FTS	Beam Power to STS	Available Beam Power
2026 Capability	2.8 MW	2.0 MW	N/A	800 kW
STS Project Baseline	2.8 MW	2.0 MW	0.7 MW	100 kW
Ultimate Capability	3.0 MW	2.0 MW	0.7 MW	300 kW

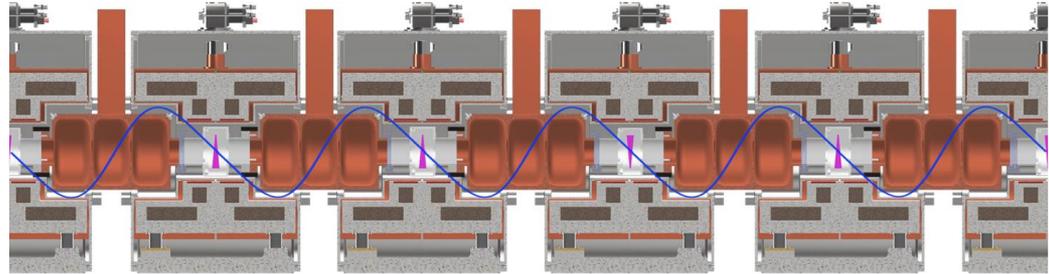
- A three-year LDRD has been proposed; first year has been funded to
 - Evaluate possible future applications.
 - Design and install a prototype target station in the existing beam line without major infrastructure modifications.
- Evaluating using the SNS excess power to support a volumetric neutron source to test fusion materials. A muon cooling channel is one of its critical components. A pre-conceptual design and a follow up test are being prepared.
 - User workshop on June 10-12 will collect user input and prioritize applications.

Feasibility at the SNS (2)

- Plan install a prototype target in the “linac dump line” of the SNS.
- Must consider space limitations
- Beam power is limited by the dump to ~ 7 kW
- An isotope production target has been designed for this location in an earlier LDRD

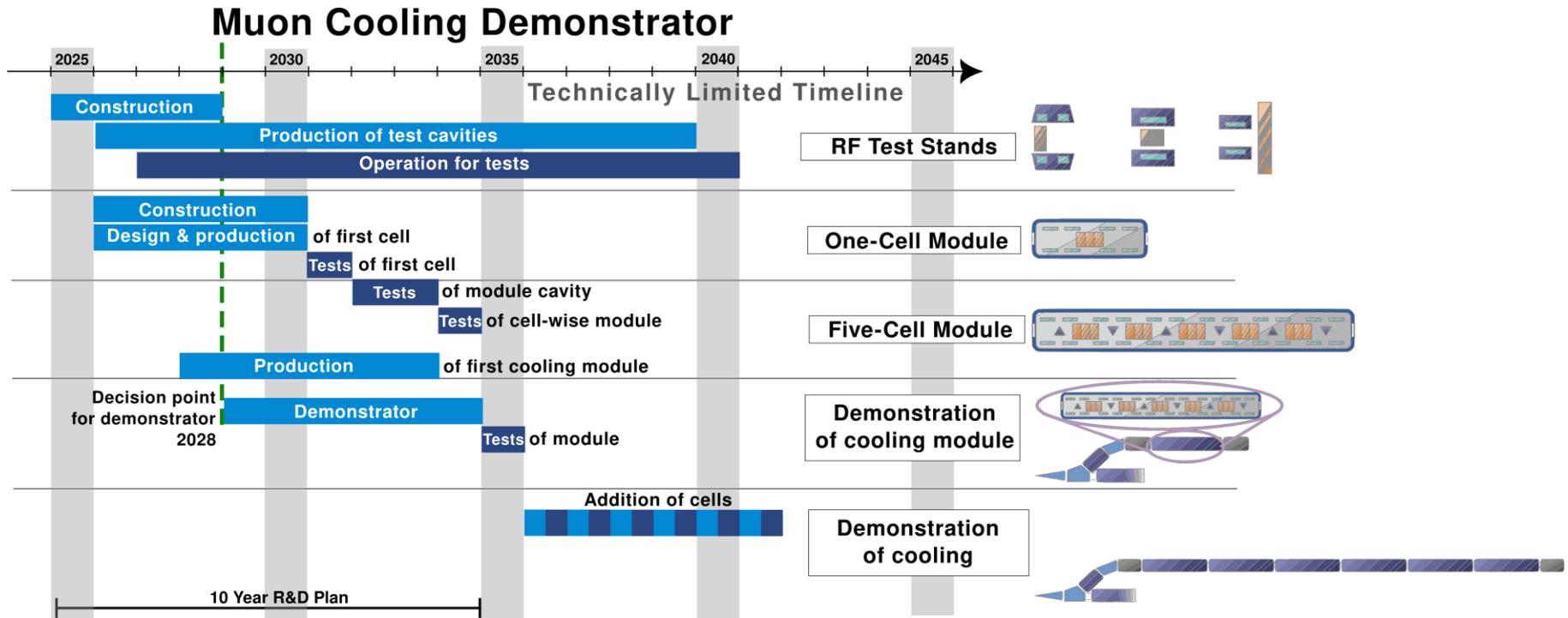


R&D towards a cooling demonstrator



- RF cavities R&D
 - Design muon cooling pillbox cavities (including associated foils)
 - Develop power sources for these cavities
 - Test rf cavities in high-magnetic fields (test-stands)
- Magnet R&D
 - Develop magnet concepts for the rf test stand and the cooling demonstrator
 - Cryostat concept, protection for quench and force unbalance, structure support
- Absorbers R&D
 - Manufacturing procedure, prototype, and handling of LiH absorbers
- Assembly process, accessibility issues, upgrade concepts

Cooling demonstrator roadmap (IMCC)



- It's a multi-year program that can be staged
- Work can be done collaboratively in different places, institutions, countries,...

Relevant workshops

- We organized workshops relevant to the demonstrator
- 2024 IMCC Demonstrator Workshop at Fermilab
 - ~110 participants, strong US participation
 - Link: <https://indico.fnal.gov/event/64984/>
- 2025 IMCC Demonstrator Workshop at INFN
 - ~90 participants, strong US participation
 - Link: <https://indico.cern.ch/event/1569430/overview>
- 2026 IMCC Demonstrator Workshop at SLAC (in preparation)

International Muon Collider Collaboration: Demonstrator Workshop

October 30, 2024 to November 1, 2024
Fermilab - Wilson Hall
US/Central timezone

Enter your search term

OVERVIEW

Surveys

SCIENTIFIC PROGRAM

I. Committees

ZOOM DETAILS

TIMETABLE

PARTICIPANT LIST

REGISTRATION & FEES

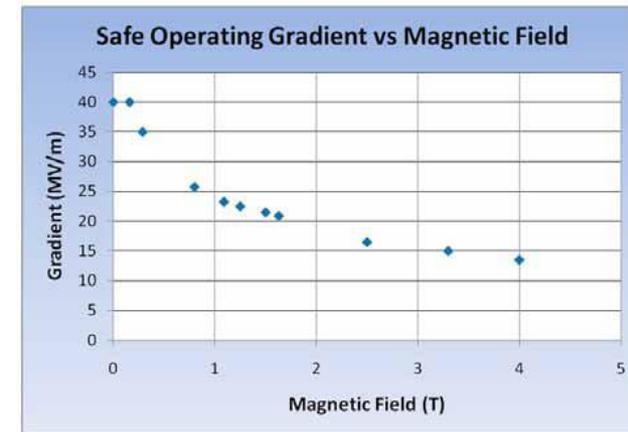
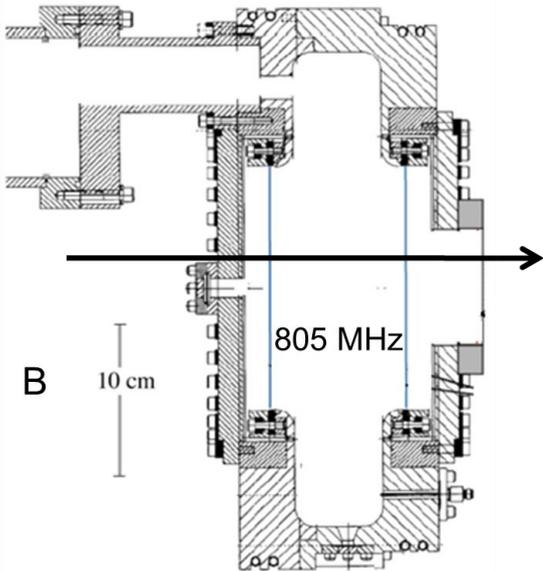
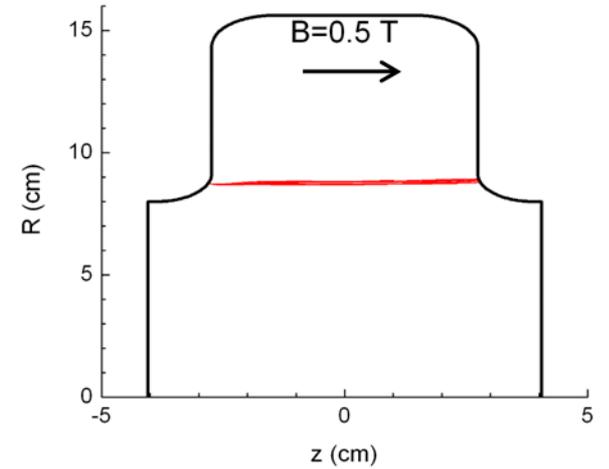
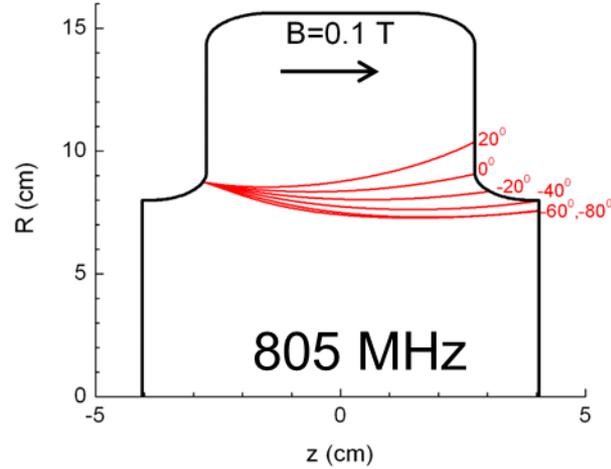
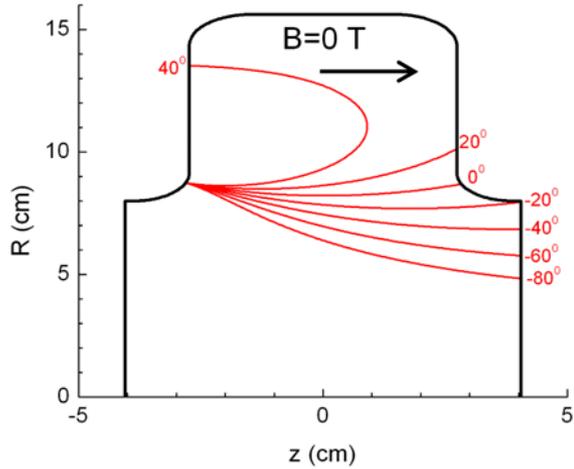


International Muon Collider Collaboration Cooling Demonstrator Workshop

Nov 5 – 7, 2025
Europe/Zurich timezone

Enter your search term

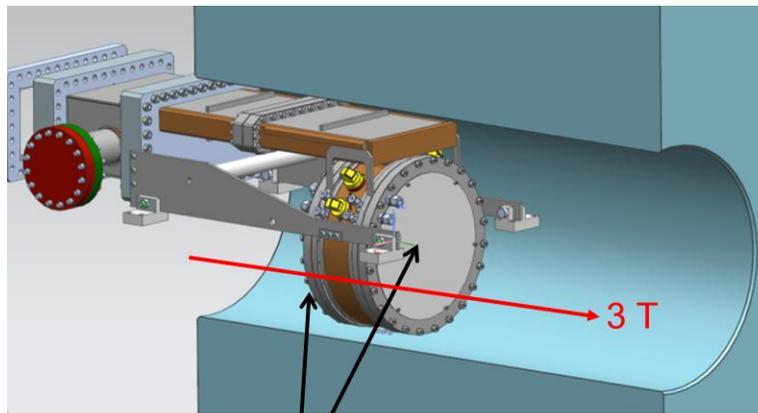
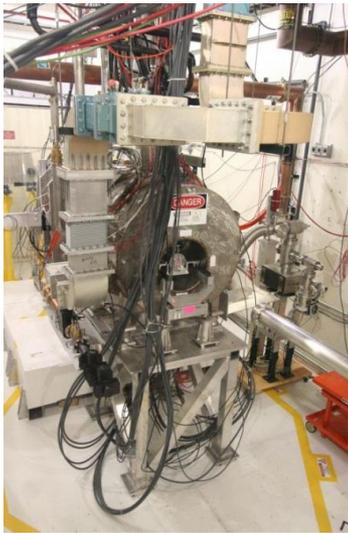
NC cavities in B-fields (findings)



NC cavities in B-fields (solutions?)

- RF breakdown depend on the **thermo-mechanical properties** of the build material
 - We need an R&D program to test rf materials and rf technologies (cold-Cu)
 - We need facilities to test rf cavities in multi-T fields

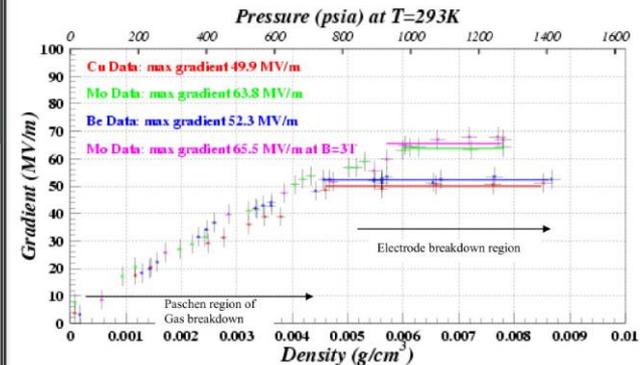
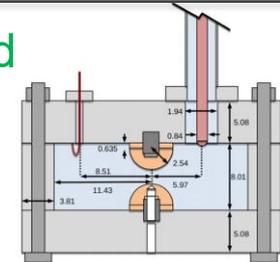
Vacuum cavities



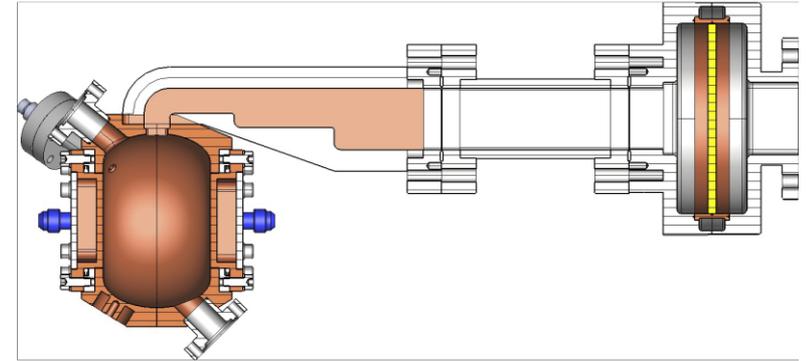
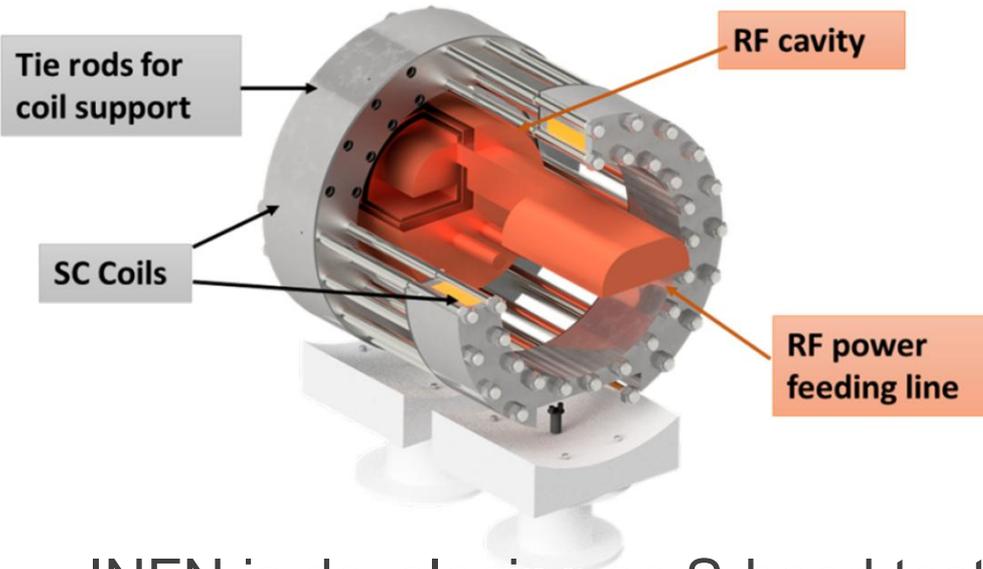
removable plates (Cu, Al, Be)

Material	B-field (T)	SOG (MV/m)	BDP ($\times 10^{-5}$)
Cu	0	24.4 ± 0.7	1.8 ± 0.4
Cu	3	12.9 ± 0.4	0.8 ± 0.2
Be	0	41.1 ± 2.1	1.1 ± 0.3
Be	3	$> 49.8 \pm 2.5$	0.2 ± 0.07
Be/Cu	0	43.9 ± 0.5	1.18 ± 1.18
Be/Cu	3	10.1 ± 0.1	0.48 ± 0.14

Gas-filled cavities



RF test-stand at INFN-LASA

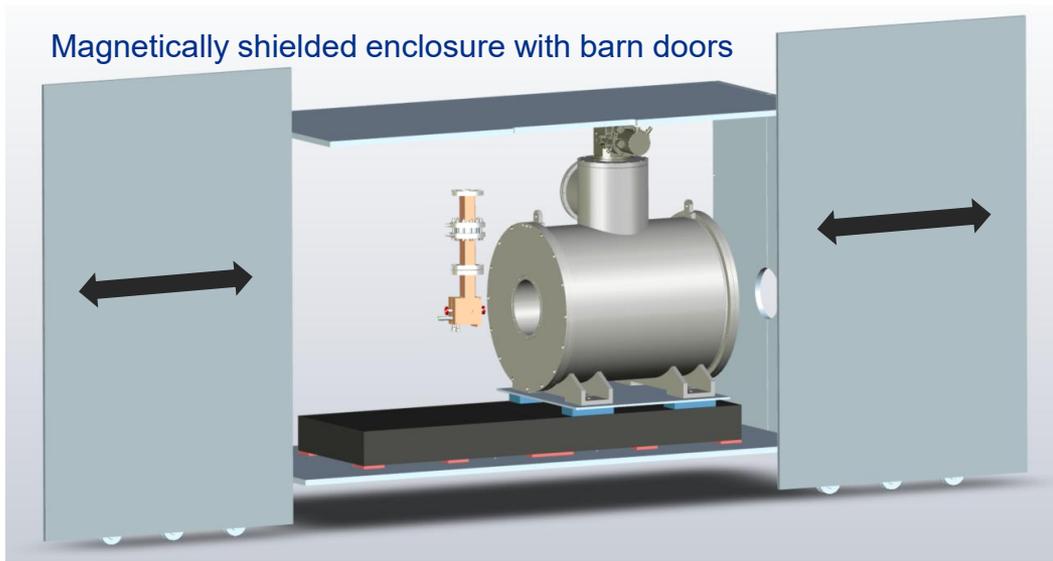


- INFN is developing an S-band test stand
 - Cavity-test with a single or two-coil arrangement
 - HTS magnets with a 250 mm bore at 7 T
 - Thermal and mechanical designs in place
 - **Opportunity** to test material technologies for cooling rf cavities

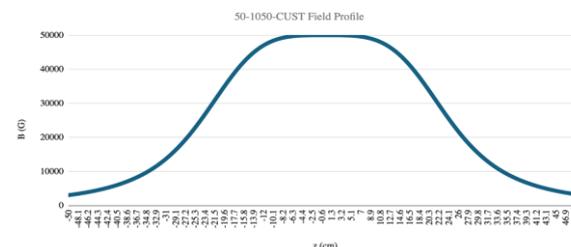
More details [here](#)



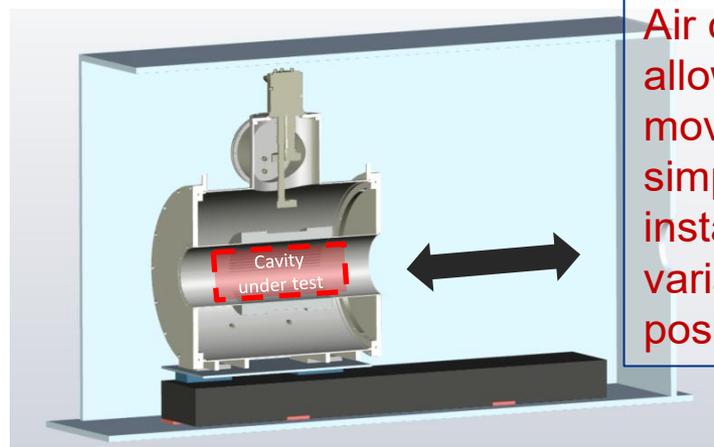
RF test-stand at SLAC



- 5 T Solenoid from Cryomagnetics with $\pm 1\%$ over >10 cm DSV Homogenous Region
- 9.5" diameter horizontal bore at room temperature



- Test cavity geometries and materials relevant to muon cooling channel
 - First measurements planned with a single-cell S-band cavity in the fringe field (schematic above)
- Benchmark high gradient results for frequency scaling with measurements at S-band and L-band



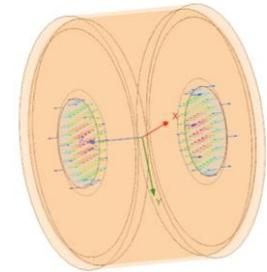
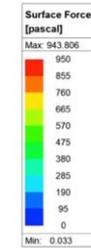
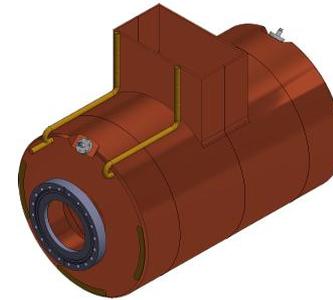
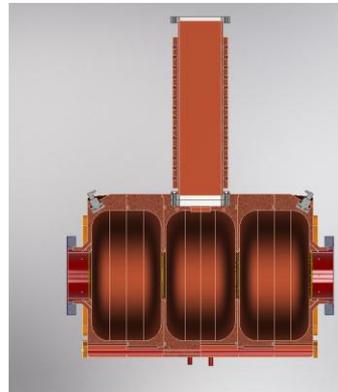
Air casters will allow magnet to move linearly, simplifying cavity installation and variable positioning

For more information and testing availability contact Emma Snively (esnively@slac.stanford.edu)

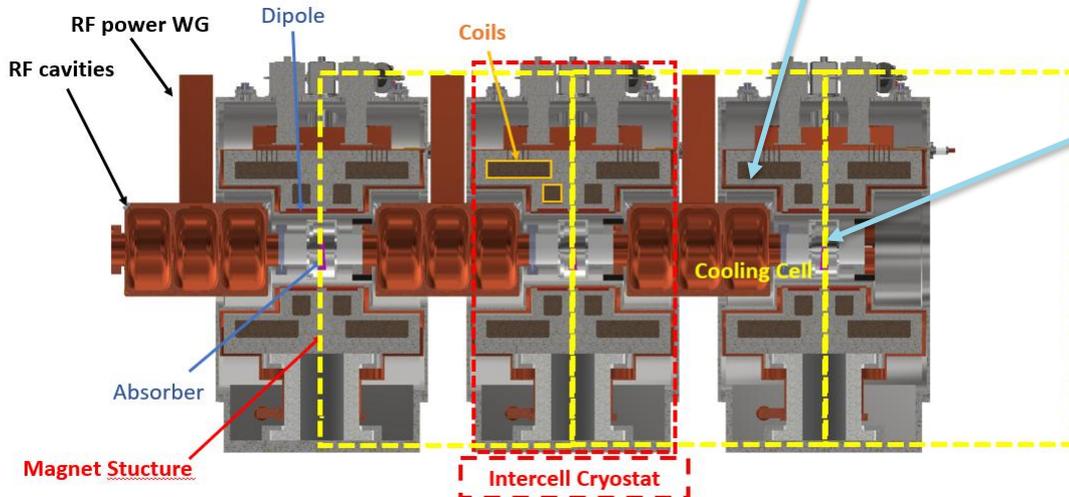
More details [here](#)

R&D for cooling cell: rf cavities & absorbers

- RF cavities
 - Baseline design developed
 - Al foils seem ok
 - Details [here](#)



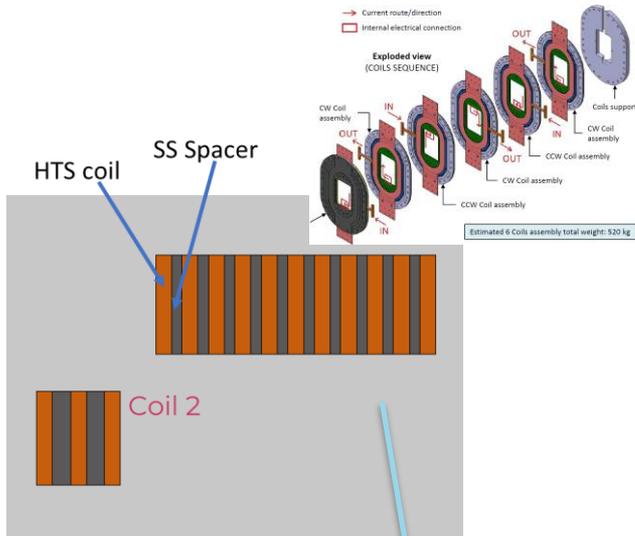
Copper weight: 180 kg
8 water channels
Max. external diameter: less than 500



- LiH absorber
 - Uncommon material & reactive
 - Experience from MICE; R&D is needed for manufacturing, operation and integration
 - Details [here](#)

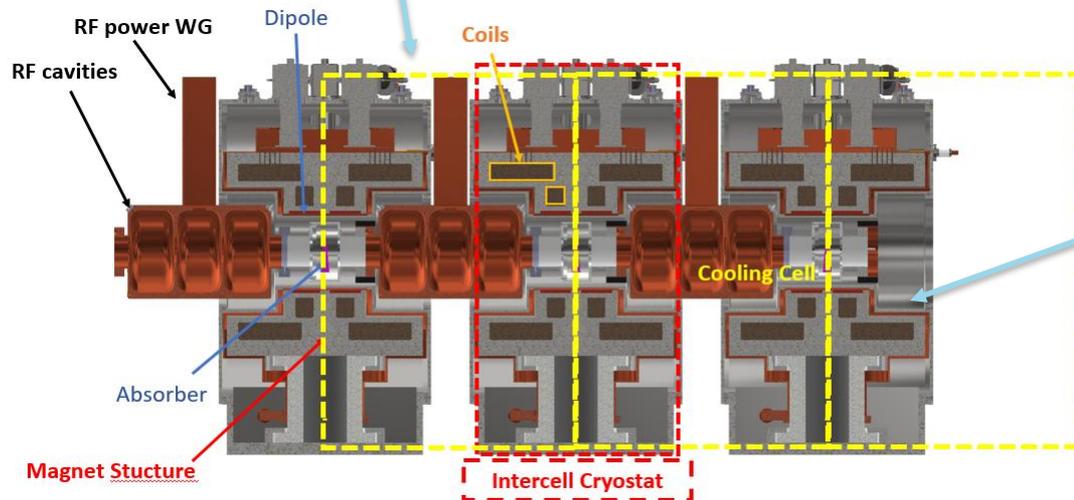


R&D for cooling cell: magnets & surroundings



• Magnets:

- HTS technology, non insulation coils at 20 K
- Magnet design has been optimized given engineering and spatial constraints
- An overall path has been prepared but more R&D is needed
- Details [here](#)



Cryostat concept



Future Steps

- Demonstration of cooling is a key technology requirement for the Muon Collider
- IMCC has done significant progress on the facility design and its associated components
- Per P5, a **targeted panel** in the US is expected to review demonstrator facilities in the collider R&D portfolios later this decade
 - In preparation for this, we need to prepare a Demonstrator conceptual design AND a detailed study on possible US sitting locations
- In the US efforts have been ramping up towards a cooling Demo
 - Key contributions from SLAC, Oak Ridge and Fermilab
 - Hopefully more to come

Benefits of a cooling demonstrator program

- Benchmark a realistic cooling lattice
 - This will give us the input, knowledge, and experience to design a real, operational cooling channel for a MuC
- It will advance magnet technology since we will design, prototype and test solenoids similar to those needed for a MuC
 - Synergistic with fusion reactors and axion dark matter searches
- It will advance rf cavity technology since we will design, prototype and test NC cavities similar to those need for a MuC
 - Opportunity to develop efficient klystrons that can be useful for future colliders
 - Opportunity to develop technology towards very high-gradient rf cavities for future colliders