International MUON Collider Collaboration

MuCol

Demonstrator

Lucio Rossi
Università di Milano & INFN-Milano LASA

Funded by the European Union (EU). Views and opinions expressed are however those of the author only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

(long) session on Wednesday afternoon

Day 3: Cooling Demonstrator (21 Jun 2023, 14:00 - 15:30)

-Conveners: Rossi, Lucio (Università degli Studi e INFN Milano (IT)); Losito, Roberto (CERN)

[120] Demonstrator layout - requirements from beam optics (14:00)

Presenter: ROGERS, Chris (RAL)

[121] Perspective for the demonstrator from the Target point of view (14:20)

Presenter: FRANQUEIRA XIMENES, Rui (CERN)

[122] Perspective from the magnet point of view (14:30)

Presenter: Dr STATERA, Marco (INFN Milano - LASA)

[123] Perspective from the RF point of view (14:40)

Presenter: GRUDIEV, Alexej (CERN)

[124] Possible Implementation at CERN (14:50)

Presenter: LOSITO, Roberto (CERN)

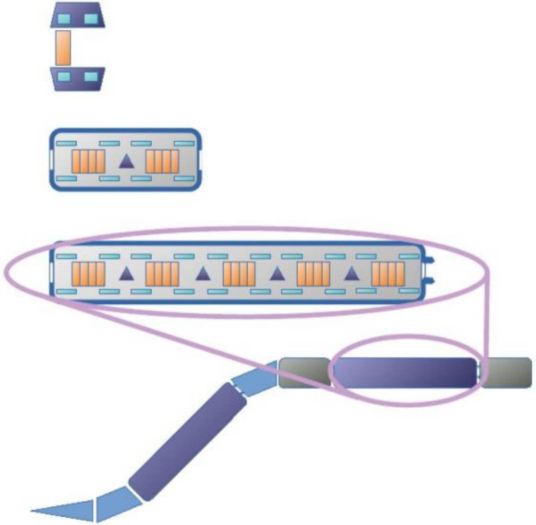
[126] Possible implementation in the US (15:00)

Presenter: STRATAKIS, Diktys

Demostrator … of what?

- Ionisation cooling is a key technology for the Muon Collider
  - It is entirely novel
  - Proof of principle “MICE” in 2020
  - But only a single cooling element
- Now need to deliver a demonstration of 6D ionisation cooling
  - Demonstrate full capability
  - Sufficient emittance reduction to convince that we can deliver the full cooling channel

C. Rogers

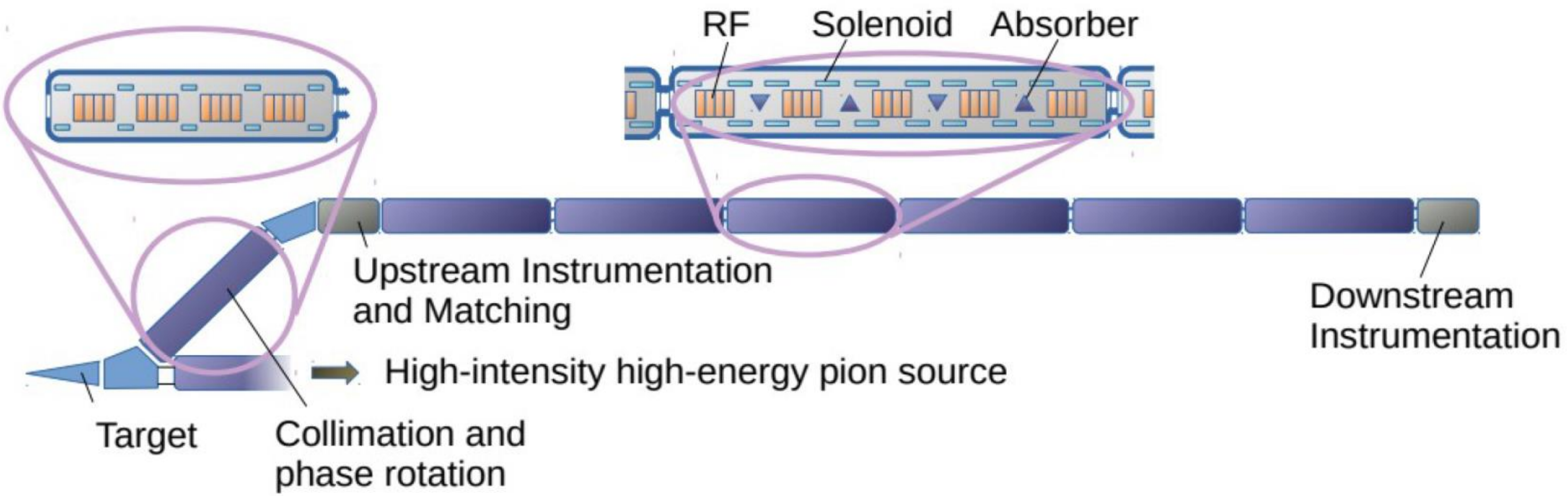


RF Test programme, with upgradeable magnet configuration, to test novel RF technologies

Prototype of a cooling vacuum vessel to test magnet, absorber and RF integration

Full cooling vacuum vessel with beam

Final stage of the demonstrator

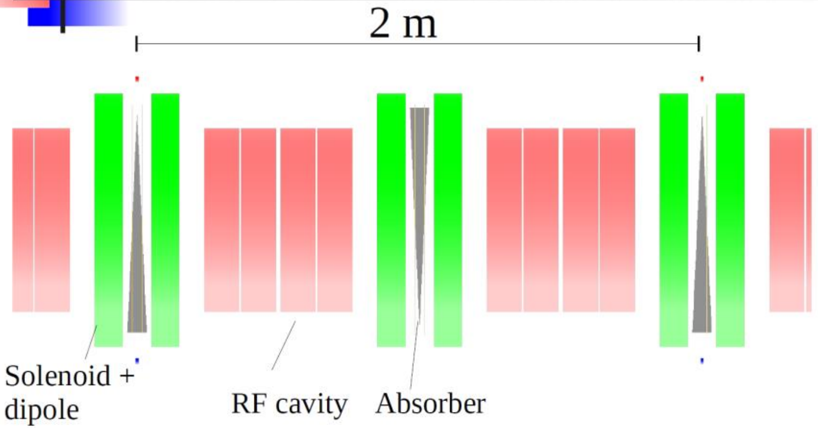


	MICE	Demonstrator
Cooling type	4D cooling	6D cooling
Absorber #	Single absorber	Many absorbers
Cooling cell	Cooling cell section	Many cooling cells
Acceleration	No reacceleration	Reacceleration
Beam	Single particle	Bunched beam
Instrumentation	HEP-style	Multiparticle-style

Going well beyond Mice…

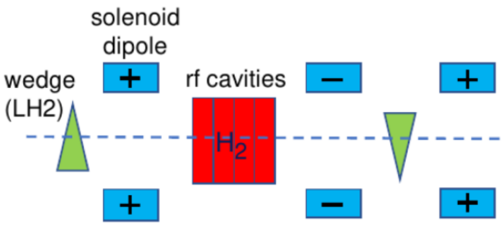
C. Rogers

Preliminary Cooling Cell Concept



Cooling System	
Cell length	2 m
Peak solenoid field on-axis	7.2 T
Dipole field	0.2 T
Dipole length	0.1 m
RF real estate gradient	22 MV/m
RF nominal phase	20°
RF frequency	704 MHz
Wedge thickness on-axis	0.0342 m
Wedge apex angle	5°
Wedge material	LiH

lH2 Performance (Zhu Riuhu, IMP CAS)



Losses	8%
Trans ε in	1.3 mm
Trans ε out	0.8 mm
Long ε in	3.3 mm
Long ε out	2.5 mm
6D ε in	5.3 mm³
6D ε out	1.5 mm³

- Look at lH_2
  - Improved performance
- Considering both Be/vacuum or High Pressure gas insulation
- Next
  - Consider spreading H2 in whole lattice
  - Consider effect of pressure windows at start/end

C. Rogers

First look at tolerance at solenoidal fields
Looks feasible no show stopper. Hints at elimanting systematic effect via mechanical construction of vac vessel

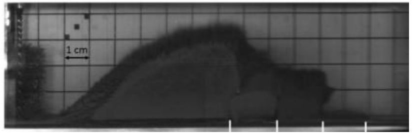
- Demonstration of cooling is a key technology requirement for Muon Collider
  - Improved demonstrator lattice studied
  - Beam preparation system looks okay
  - Looking at layout from target to cooling system for CERN site
    - Happy to look at non-CERN sites!
  - Working on initial transport line and integration with nuSTORM
- Aim is to deliver a design by 2026
  - In time for next European strategy update

C. Rogers

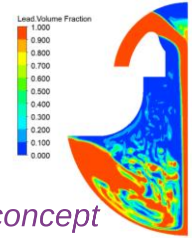
Targetry at the demonstrator

by Rui Franqueira Ximenes (CERN-SY-STI-TCD)

- **Demonstrator can(shall ?) be a multi-target test facility**. Either in parallel with cooling experiment or ad-hoc. Feasibility of the different concepts can be pursued
  - C-Target
  - Fluidized W &/or static W powder target
  - (HLM) Pb curtain target &/or liquid lead pool



W powder tests.



Pb curtain concept

- **Possibility to (re)test spent targets.**
  - CNGS? (probe dpa + MuC pulse conditions)
  - Other (e.g. RADIATE samples ?)

CNGS Target

AD-T Horn at CERN

- **Test beam window materials & designs**
- **Design/integration/remote handling proof of concept.**
- **Opportunity to develop magnetic horns and test them at CERN.**
- **Test the SC solenoid around the target and alike**
- CERN sitting allows direct access to services and capabilities

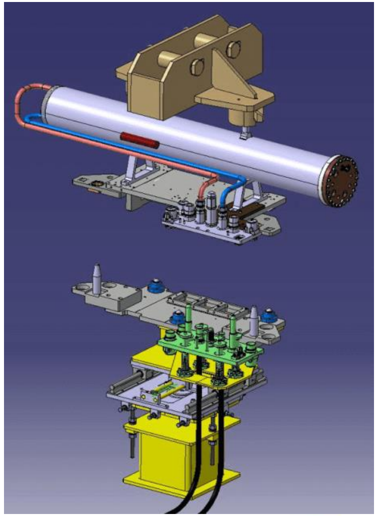
Targetry at the demonstrator

by Rui Franqueira Ximenes (CERN-SY-STI-TCD)

	Protons	^{208}Pb Ions
Beam Momentum	440 GeV/c	173.5 GeV/n (36.1 TeV per ion)
Pulse Energy	up to 2.4 MJ	up to 21 kJ
Minimum Bunch Intensity	$5 \cdot 10^{9}$ protons	$3 \cdot 10^{7}$ ions
Maximum Bunch Intensity	$1.2 \cdot 10^{11}$ protons	$7 \cdot 10^{7}$ ions
Number of Bunches	1 to 288	52
Maximum Pulse Intensity	$3.46 \cdot 10^{13}$ protons	$3.64 \cdot 10^{9}$ ions
Bunch Length	11.24 cm	11.24 cm
Bunch Spacing	25 ns	100 ns
Pulse length	7.95 us	5.2 us
Cycle length	22.9 or 40.8 s	13.2 s
Beam Size at Target	variable around 1mm^2	variable around 1 mm^2

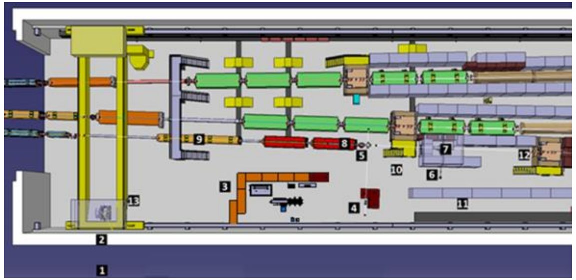
What other testing platforms can we already use @ CERN ?

- The HiRadMat facility (https://hiradmat.web.cern.ch/hiradmat-facility)



- Slow Extraction (SX) TCC2 testing area @ CERN's North Area

NA SX TCC2 Testbench
- 400 GeV/c p+
- Up to 4e13 ppp
- SX (1s) but maybe fast SX (~20ms) is possible.
- Plugin-in table. Thought for fully remote interventions



https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.22.123001

Conclusions for targetry

by Rui Franqueira Ximenes (CERN-SY-STI-TCD)

- If tailored as such, Demonstrator can be a strategic platform for proof-of-concept target designs for the final collider, material testing, benchmarking studies.

Targetry

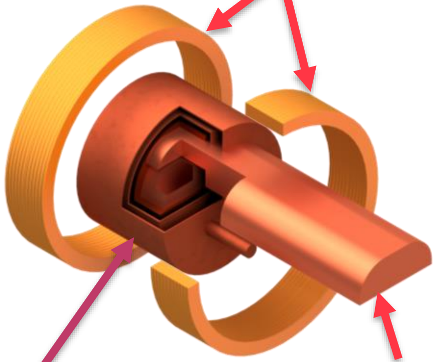
- At first sight, no major showstopper nor critical pre-experimental program required for the demonstrator.
- **Possible challenges ?** → multi target, particularly if considering C, fluidized W, HLM – may be challenging to integrate and include all in the Demo program. Services (cooling, HLM & fluidized W circuits pumping circuits) can likely be eased for a Demo. To what extent ?
- **Pre-experimental program ?** → Will depend on the maturity and likely offline testing & characterization of the Targetry options.
- **What can we learn ?** → Full suite assessment of pulse response, operational conditions, integration constrains, simulation benchmark, etc

Windows & absorbers: Readiness of the Cooling absorber & beam windows strongly dependant on ongoing studies. → Possibly requiring a dedicated experimental program ?

Other: Possibly Horn design/testing in synergies with target developments ?

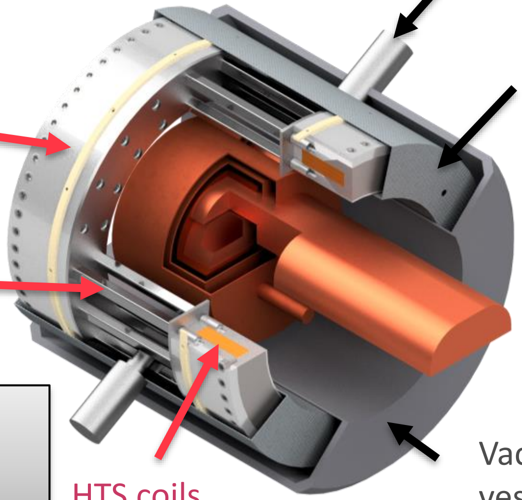
First sketch of RFMF test stand (scheme split coils in single cryostat)

Bare coils and RF cavity



M. Statera
INFN-Lasa

With cryostat



Sc magnet/cryostat sketch by M. Castoldi & Stefano Sorti, UMIL & INFN-LASA

(RF drawing by Guillaume Ferrand –CEA)

B1 as aspect ratio of the cross section
B3 and A2 similar inner diameter
A4 similar field 6T, but smaller diameter

The construction of a test bed is an important push toward the definition of a baseline technology.
An intermediate construction can be the commisisonig of first design choices

International MUON Collider Collaboration

MuCol

Schedule for discussion

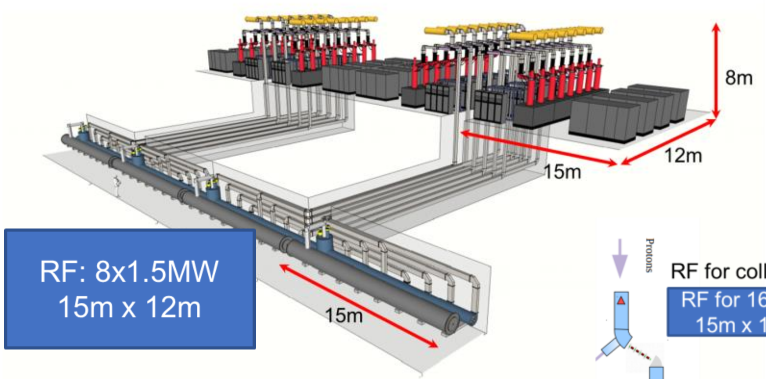
Tentative schedule with no contingency and assuming the task is approved and financed today
By now, no funding and no dedicated manpower for the executive design and construction

Design studies for single cryostat and double cryostat scheme	Nov 2023
Design evaluations for higher frequencies RF and smaller diameters	Dec 2023
Design choices (conductor configuration, mechanics, cryogenics)	May 2024
Coil demonstrator (about half size) design	Jun 2024
Demo coil production and test	Apr 2025
Production of the test bench (coils, mechanics, cryostat)	May 2025
Commissioning of the test bech	Oct 2025

M. Statera
INFN-Lasa

RF for cooling demo
Alexej Grudiev (CERN)

Stub Concept



RF: 8x1.5MW
15m x 12m

RF for collimation
20 MV/m

RF for 8 cavities
15m x 12m

RF for 8 cavities
15m x 12m

Protons

RF for 4 cavities
15m x 12m

RF for 4 cavities
15m x 12m

RF for 4 cavities
15m x 12m

RF for 4 cavities
15m x 12m

RF for 4 cavities
15m x 12m

5m

RF for cooling
gradient 30MV/m

modulator
klystron
klystron
WG
WG
WG
cavity

Protons

RF for collimation: Max 20MV/m

RF for 16 cavities
15m x 12m x 2

RF for cooling: Max. gradient 30 MV/m

180m

30m

RF for 120 cavities at ~30 MV/m
15m x 12m x 5 x 6 = 30m x 180m

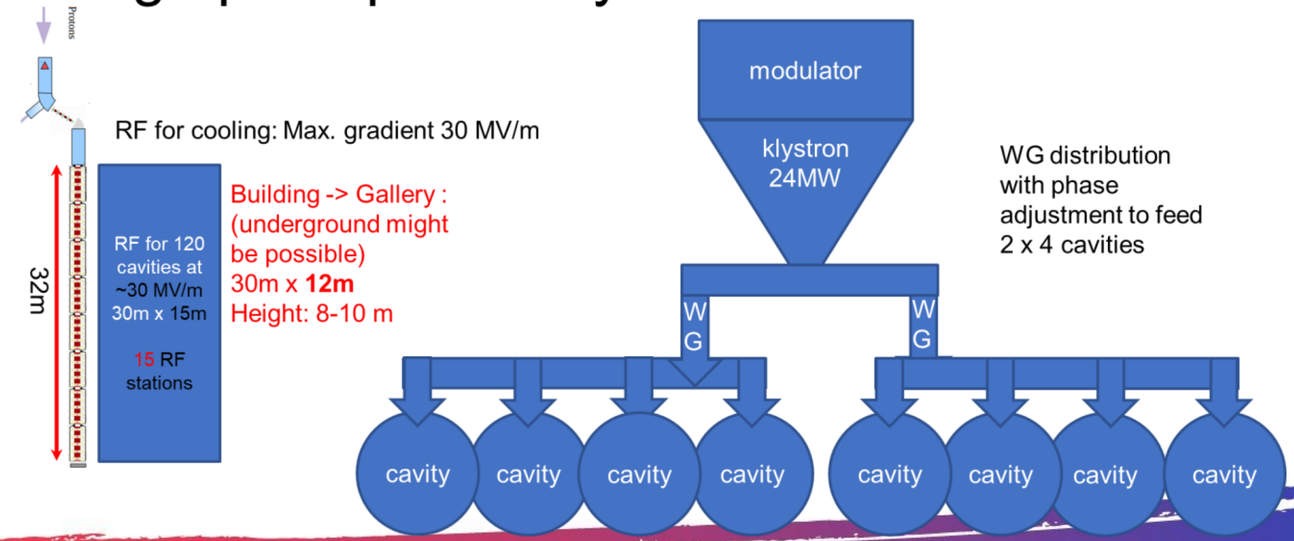
Big building:
(surface)
30m x 200m
Height: 8-10 m

Large number of very long waveguides
100m surface
+50m shaft
~15% losses

RF for cooling demo
Alexej Grudiev (CERN) – cont.

- Pulse compressors
- **Higher peak power RF sources**
- **Feeding several cavities from one source**

Muon cooling demonstrator layout
High peak power klystron: 24 MW



RF final cosideration

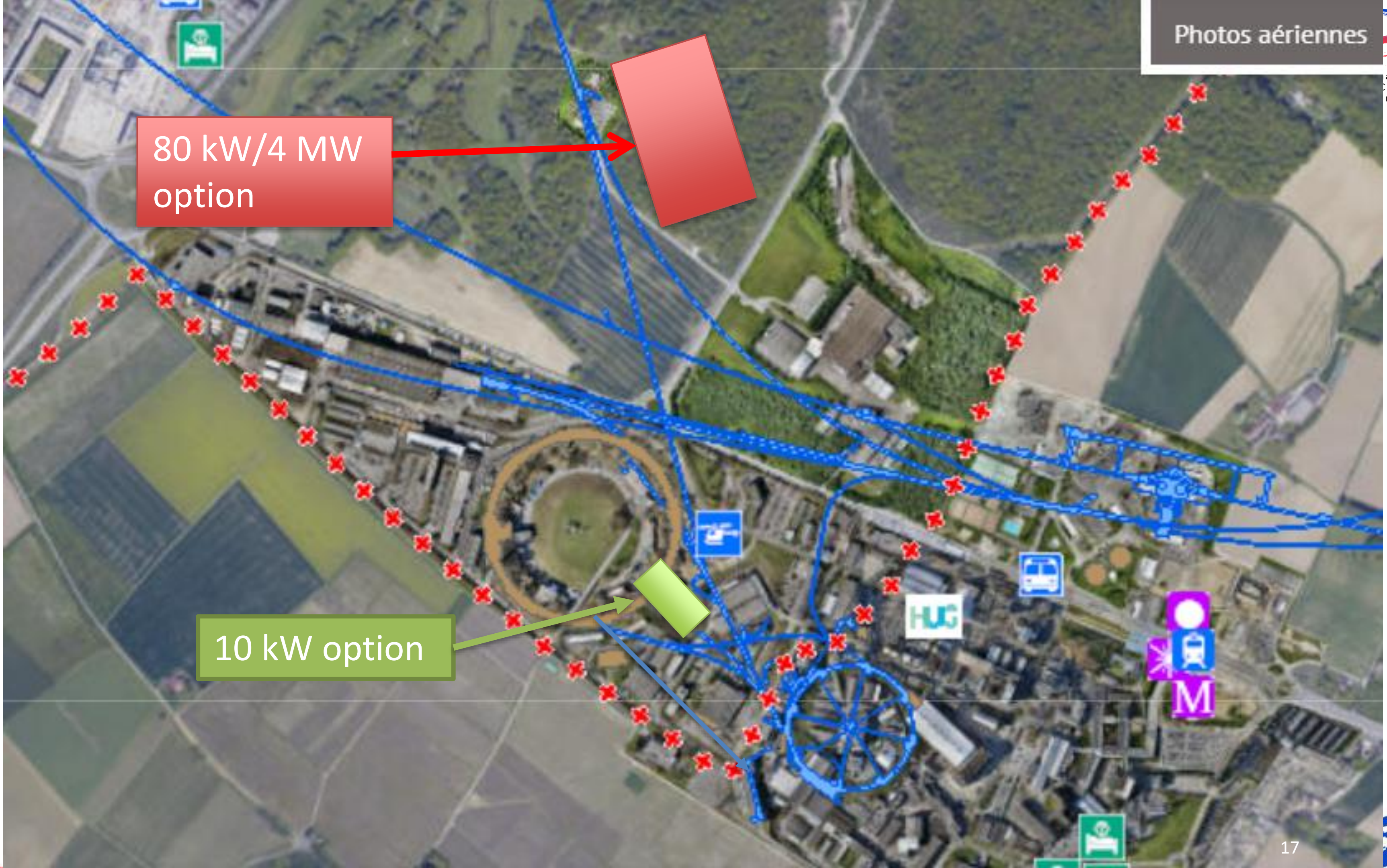
- Cavity performance difference: only 10% (the nice side of non-SRF…) → power in parallel is possible.
- The power equipment is not a big deal : *only time and money* (Alexej dixit…)
- Performance of each cavity would need to be validated in real condition → RFMF test stand is not only a tool for study but also a necessary QA tool…

Implementation at CERN by R. Losito

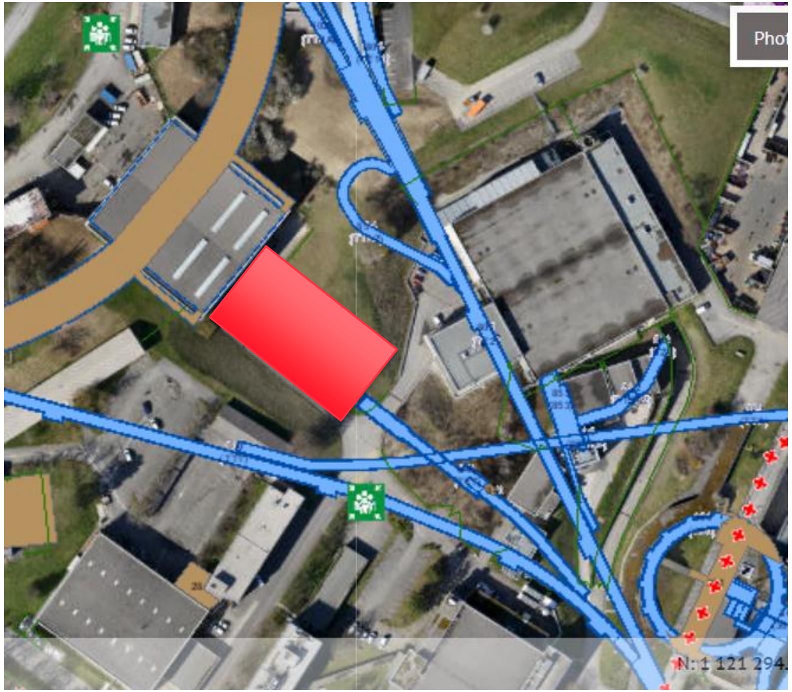
- …
- **CERN needs to have a project of a size that is sufficiently large to provide a platform for training of new arrivals, but not too big to jeopardise the main activities (HL-LHC commissioning and operation, FCC).**
- **The Demonstrator can therefore be organised to be complementary** and in support of the FCC-ee. Level of resources involved should be modulated in this respect.
- The Demonstrator can play the role that the various CTF facilities have played in the past: a nice framework for the development of new technologies as well as a place where young people can take relevant scientific and technical responsibilities, in a less stressful environment than LHC or FCC. It can be a fantastic gymnasium for part of the 1000+people that will be hired

Demonstrator Options at CERN

- Two options are being studied at CERN for the implementation of the Muon Cooling Demonstrator
- Both options allow using the maximum intensity per pulse 10^{13} ppp (or more) in pulses of few ns at 20+ GeV.
- The difference is in the repetition rate:
  - Up to one pulse every few seconds on the high-power site
  - One or two per minute on the low-power site.
- Cost and timeline are different as we will see in the next slides


Photos aériennes
80 kW/4 MW option
10 kW option
HUG
M

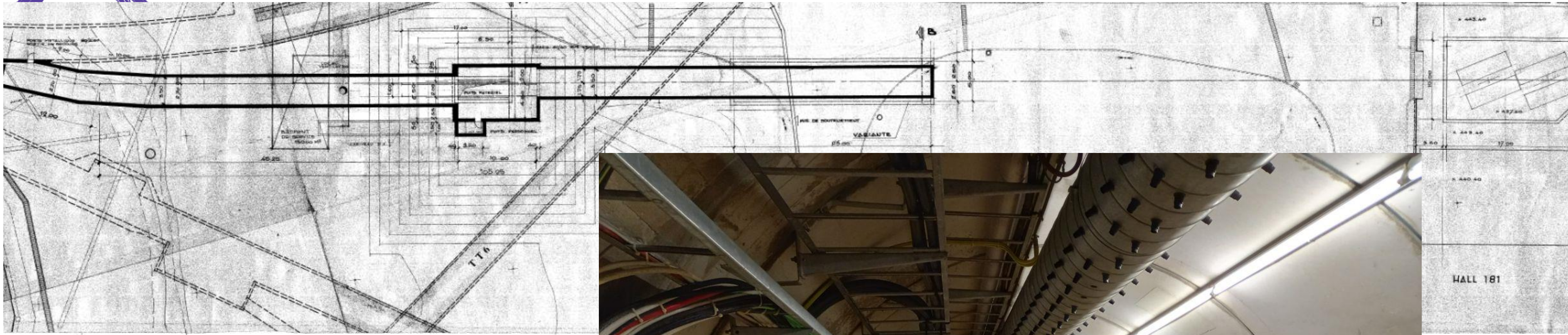
TT7 Low Power option

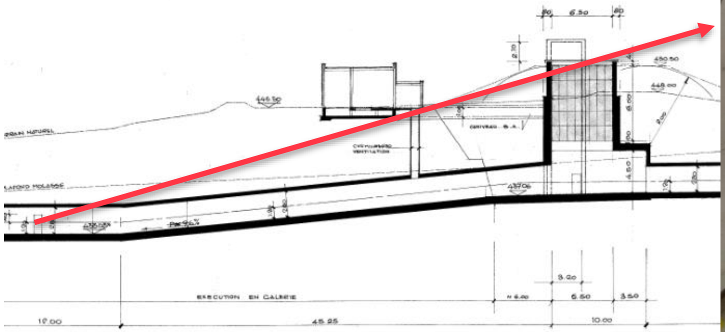


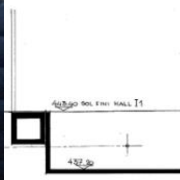
- Reusing the line of the BEBC-PS180 Collaboration, presently decommissioned.
- Extending it towards B181 (presently used as magnet factory)
- Shallow tunnel (10m underground)

TT7 low power option

- Average power limited to 10 kW
- Peak intensity ~10^{13} ppp.
  - One pulse every ~ 20÷30 seconds instead of every 5 seconds
- Controls, power and services on surface
- Tunnel already existing, used as repository of very low activity waste to be released before use
- Present tunnel not accessible easily. Maybe not large enough for the chicane.

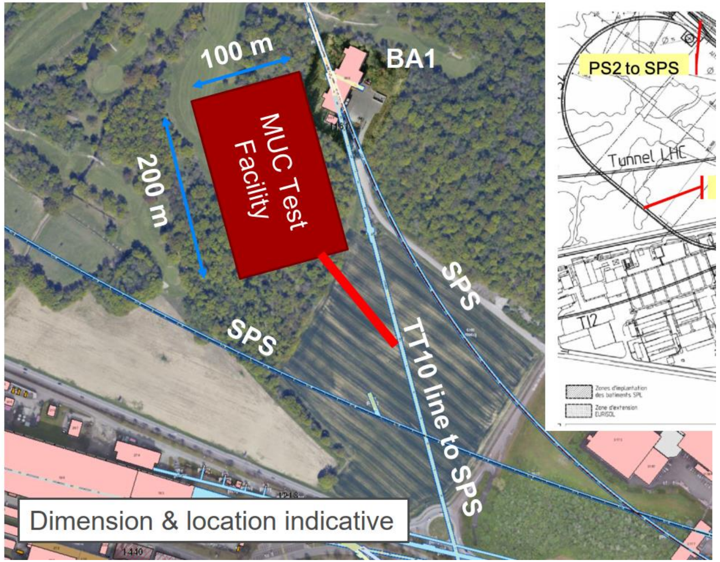

TT6
VARIANTE
HALL 181


EXECUTION EN GALERIE

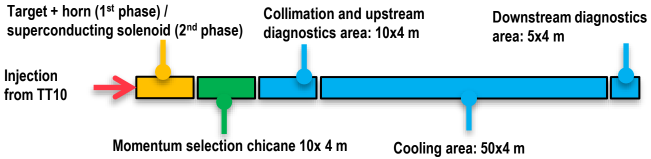


TT10 line High Power option

- TT10 is the transfer line from the CERN PS (≤26 GeV) to the CERN SPS.
  - O(80kW) on target can easily be achieved.
  - $>10^{13}$ protons can be sent on a target at 20GeV+ in pulses of few nsec (n_TOF beam).
  - 4 MW does not appear to be a showstopper in this layout with beam at a depth of 40 m (detailed studies will have to be performed).
  - Future upgrades towards a collider and HP-SPL are in principle compatible with this layout.

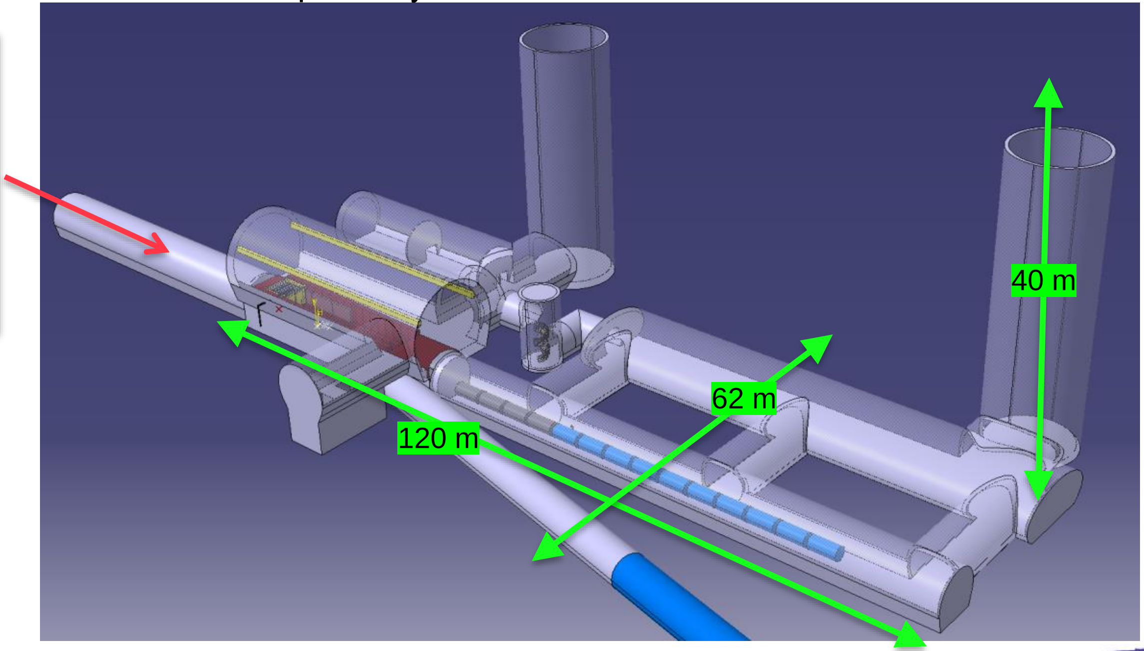


Conceptual layout



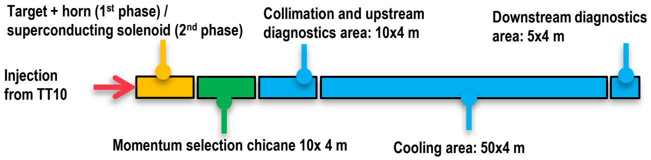
MUC Demonstrator VERY Conceptual layout

CERN TT10 branch



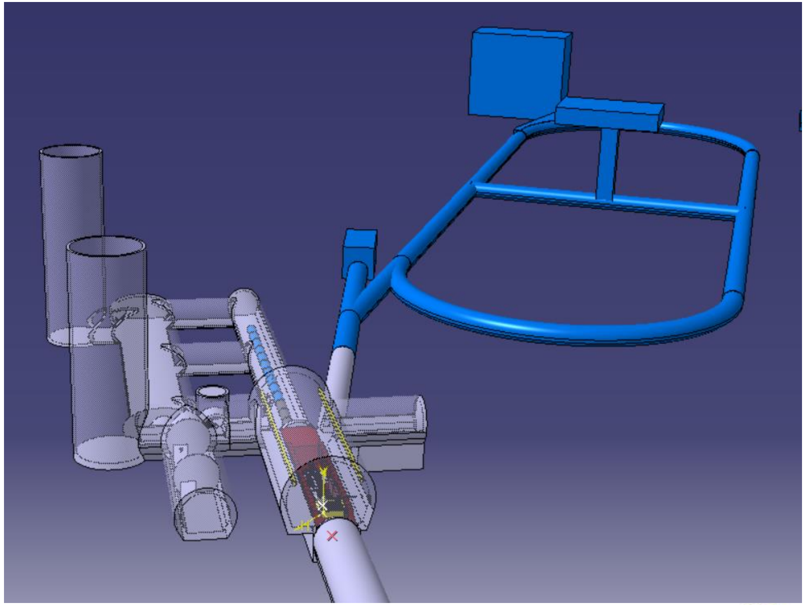
Indicative dimensions. Model is very flexible at this stage

Conceptual layout



MUC Demonstrator VERY Conceptual layout

- The Facility is flexible enough to accommodate other experiments.
- nuSTORM and potentially ENUBET could be branched from the MUC Demonstrator Facility.
- The same target complex would be used profiting from its shielding and general target systems infrastructure, utilities, and accesses.
- The double deflection of the beamline could reduce radiation streaming towards the nuSTORM ring.
- Synergies between experiments would reduce costs on both sides.
- 26 GeV/c beam from the PS is appropriate for nuSTORM



Implementation at CERN: a possible roadmap

- If we assume approval of the European Strategy Update in 2028 by CERN council, we have the following scenario scenarios:
- *Period from **today until 2028***
  - Need to increase our budget in order to build a few prototypes: Cooling cell, RF test stand, Mover system mock up etc…
  - Advance the design in order to have execution drawings available for construction
  - Build prototypes, test them before 2027/28
  - Funds to clean up TT7, evacuate radioactive waste, install a fast extraction in the PS and the beam transfer line to TT7
  - Preliminary test of some material with Protons.

Implementation at CERN: a possible roadmap

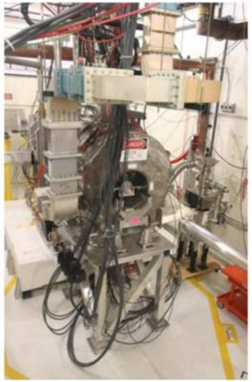
- 2028-2035
  - FCC is approved:
    - We (already have) convinced the management that the demonstrator is essential
    - We continue on the low power side, at a pace compatible with running HL-LHC and the FCC programme, still aiming at a reasonable facility by 2035.
  - FCC is further delayed or not clearly approved
    - We request the full budget for the high-power option
    - We speed up in order to start installation in TT10 by 2033, first beam 2035.

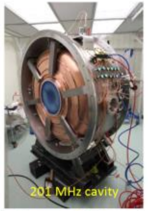
US Option & Potential
by Diktys Stratakis

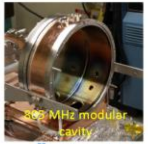
Past US experience: NC RF in B-fields tests

- Muon Test Area (MTA): a dedicated facility at Fermilab for muon accelerator components testing – RF and absorbers
- Experimental NCRF R&D conducted at 805 MHz cavities for vacuum and high pressure cavities, and MICE prototype cavity at 201 MHz

- High pressure cavity reached 60 MV/m without B dependence
- Modular cavity reached 50 MV/m in 3 Tesla magnetic field.
- MICE cavity with Be windows and module with vacuum protection reached to the design goals.







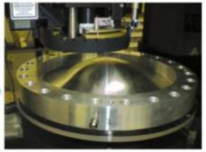
Fermilab

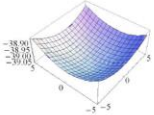
Past US experience: cooling channel elements

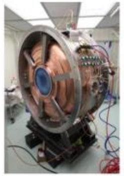
- Many elements for a cooling channel was fabricated in the US
- As a result significant experience gained **and still exists**!

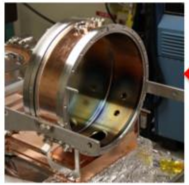
spectrometer solenoid

Absorber window









NC 201 MHz and 805 MHz cavities

RF Module design for MICE

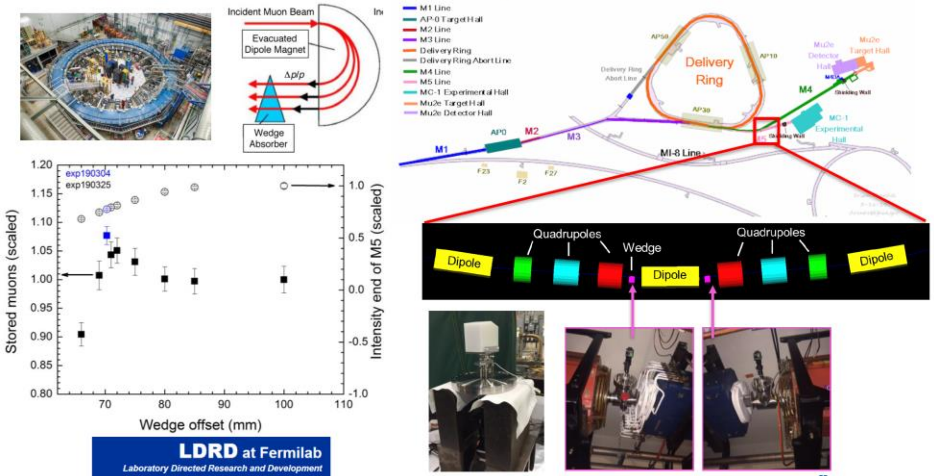
Fermilab

US Option & Potential by Diktys Stratakis –cont.

RF in 0.5T field @ SLAC…

Muon campus experience with cooling

- Proof-of-principle for emittance-exchange carried out. Resulted to MORE muons for the Muon g-2 Experiment

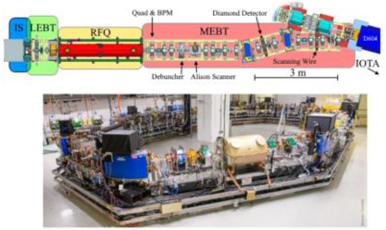


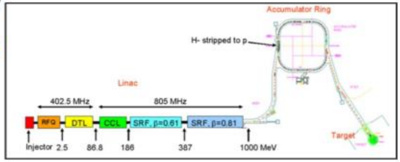
LDRD at Fermilab
Laboratory Directed Research and Development

Fermilab

MuC proton driver tests

- Goal: carry a proton compression R&D program in existing facilities
- IOTA/FAST @ Fermilab
  - Intense space-charge 2.5 MeV p beam, may have unique opportunities for expanded diagnostics or lattice modification studies
  - Aid our understanding on how space-charge can affect the process
- SNS @ Oak Ridge National Laboratory
  - 1.8 MW facility with painted H- injection of 1-1.3 GeV beam
  - Allows testing of laser stripping





Fermilab

International
MUON Collider
Collaboration

Thank you for your attention