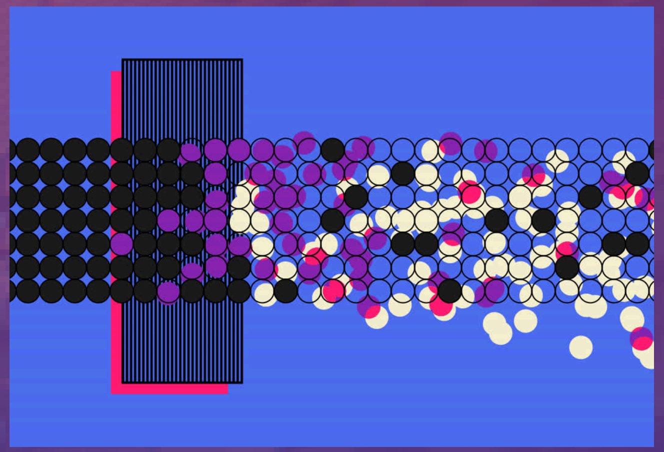


# Muon Collider Machine Overview

**Inaugural US Muon Collider Accelerator School**

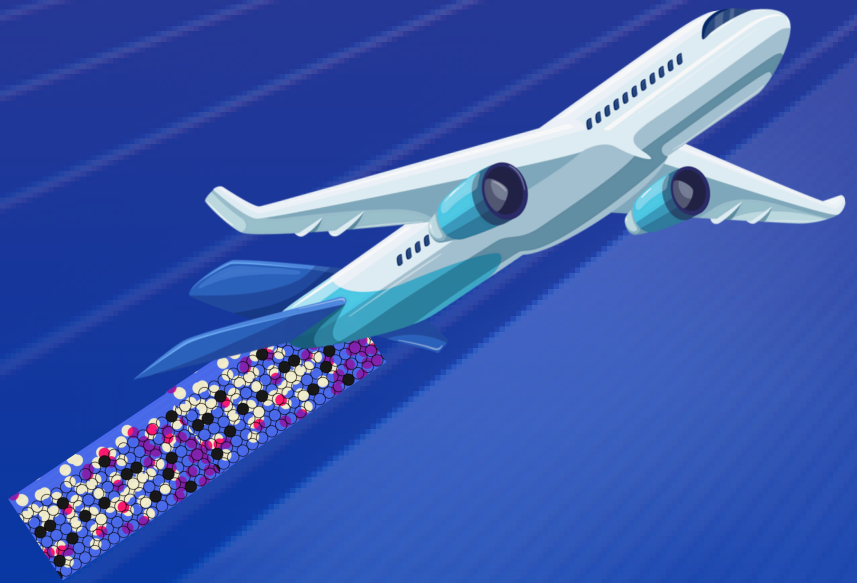
University of Chicago

Invited Evening Plenary Talk

Monday 4th August

**R. Taylor**

*Featuring work from 450 members of the International Muon Collider Collaboration*



# Content

1) What we deliver to the experiments and **why**

2) Muon collider **overview** and challenges

3) Muon Collider beam **optics**

4) Why is the [ ▼ ] **challenging**

```
a. Proton driver
b. Target & front-end
c. Cooling
d. High energy acceleration
e. Collider ring
f. Decay
```

Goals:
- Connect morning's beam dynamics to Muon Collider
- Describes IMCC progress
- Contextualises to USMCC lectures

# Content

1) What we deliver to the experiments and **why**

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3) Muon Collider beam **optics**

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b. Target & front-end
c. Cooling
d. High energy acceleration
e. Collider ring
f. Decay

Stickers for good questions, now and during tutorials!


Goals:

- Connect morning's beam dynamics to Muon Collider
- Describes IMCC progress
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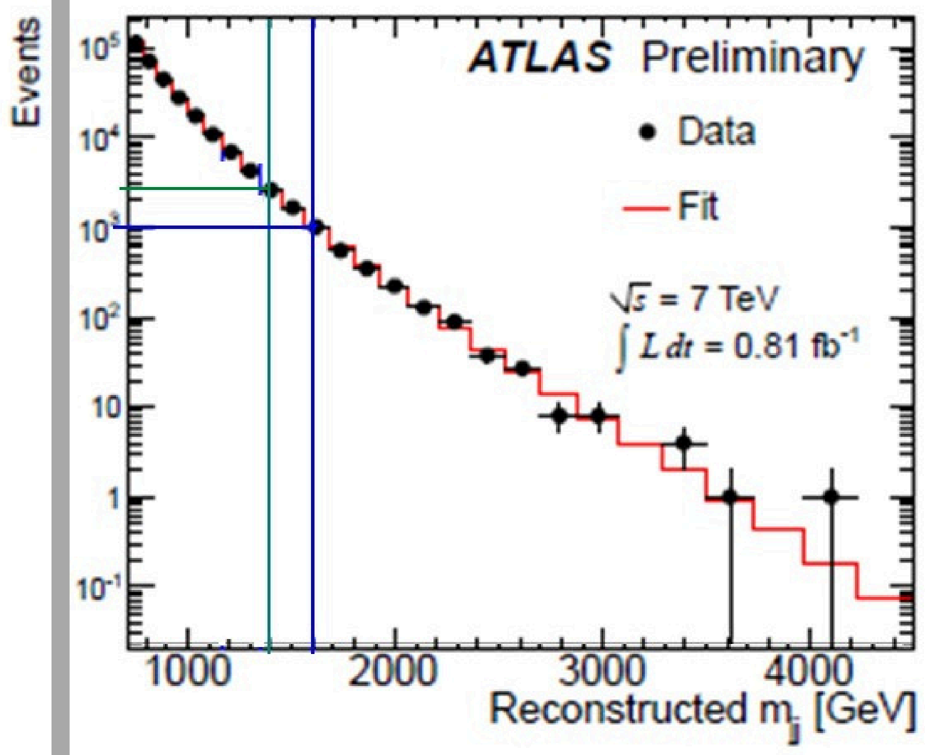
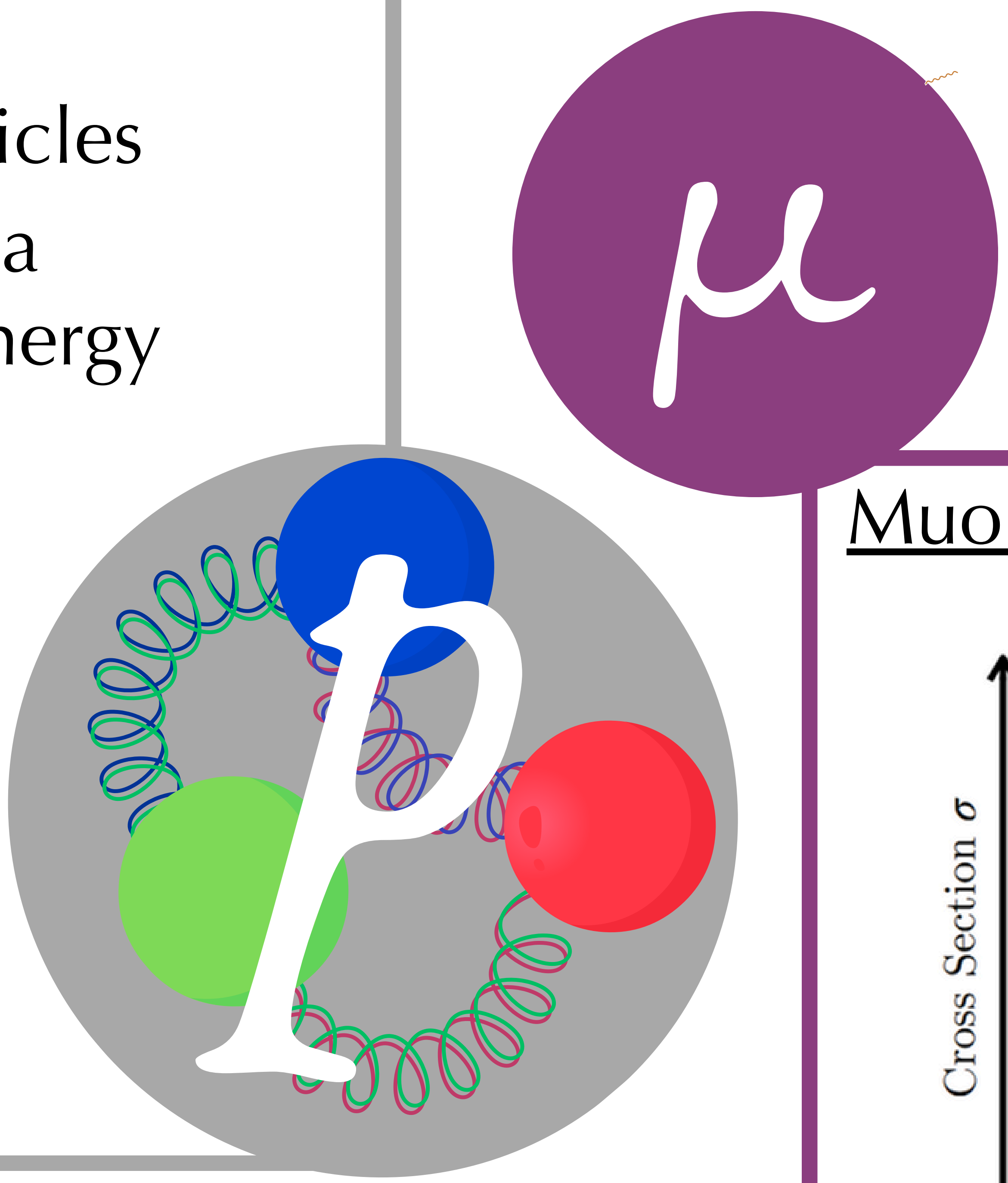
# WHY should we collide muons?

## Muons are:

- Fundamental particles

**Hadrons** collide with a fraction of their full energy




## Muons are:

- 200x heavier than **electrons**

Emit $6\times10^{-10}$ less bremsstrahlung / turn

$$\Delta E \propto \frac{E^4}{m^4 r}$$

## Muon colliders are:

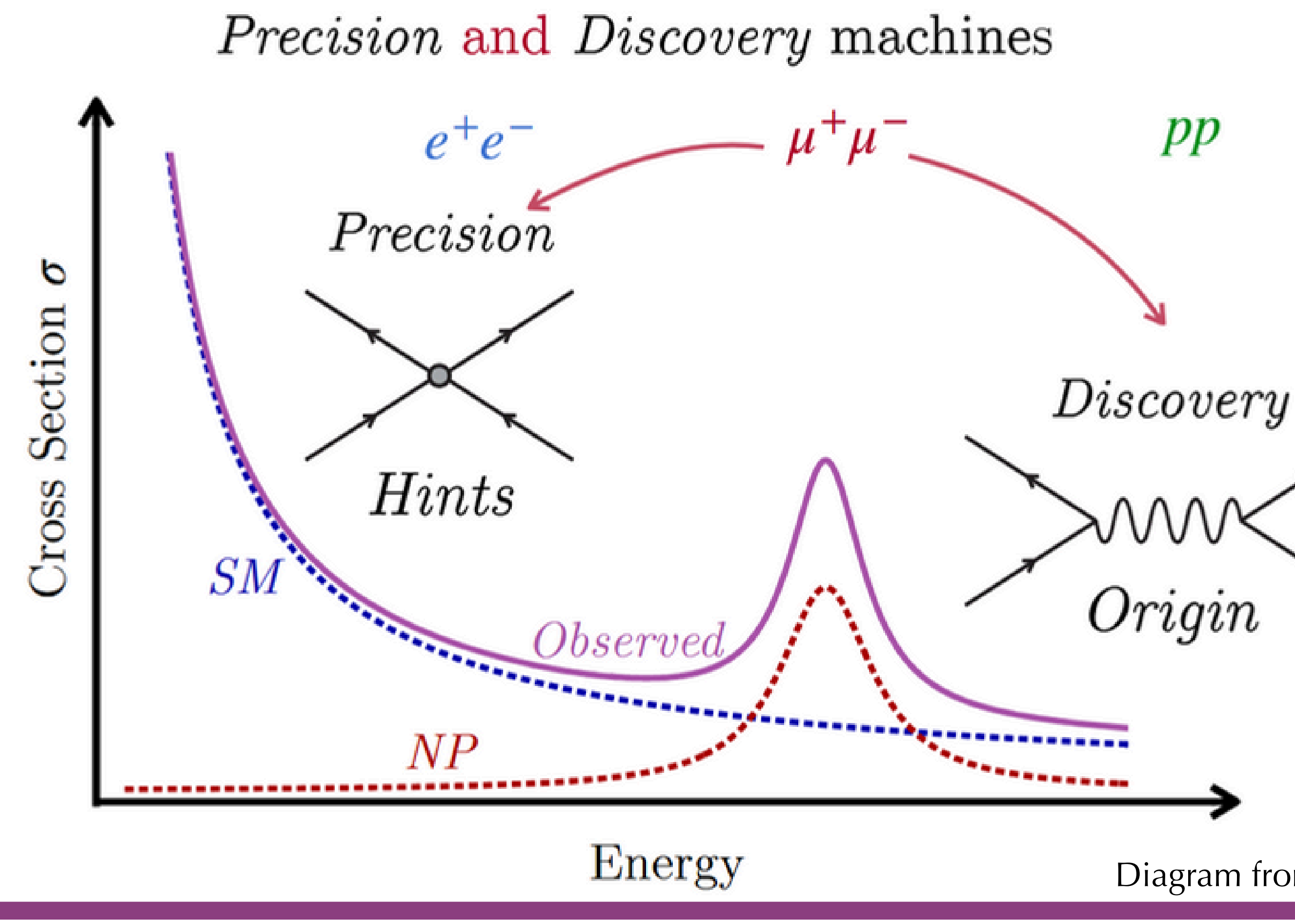
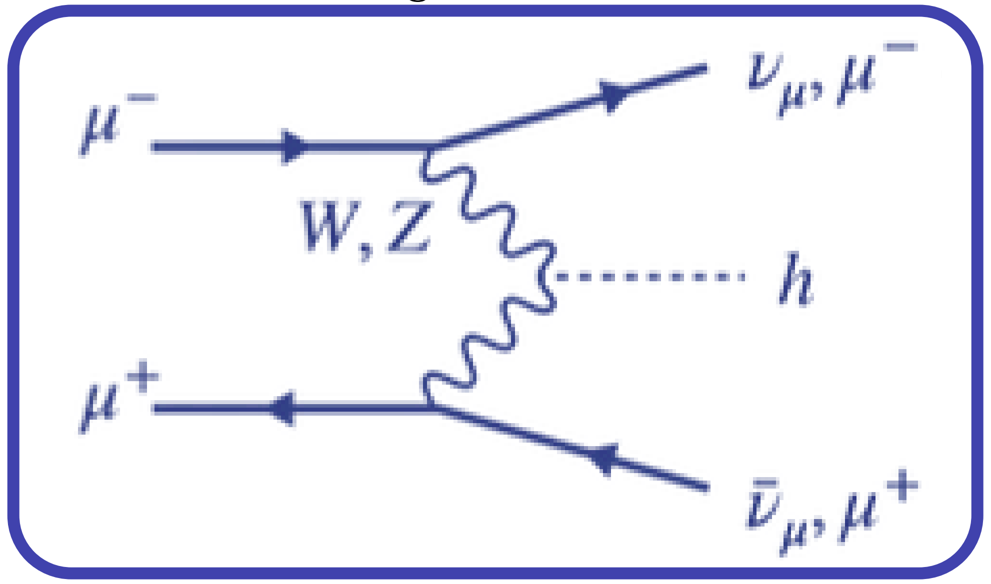


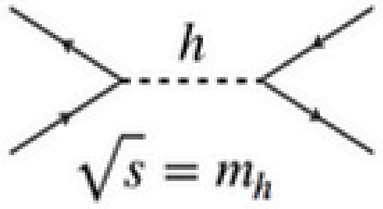

Diagram from C. Cesarotti

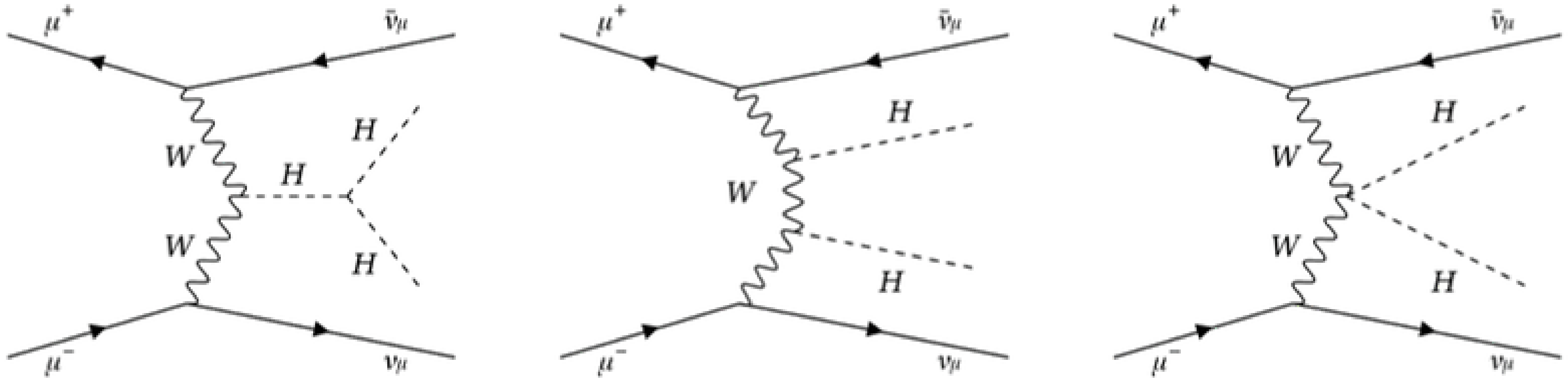
Info/Diagrams from C. Cesarotti

# WHY should we collide muons?

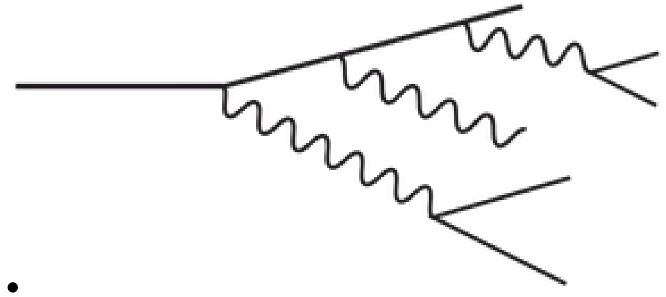



Muons at high energies are **vector boson fusion (VBF)** factories.
S-channel directly has lower cross-sections.
Environment to probe di-higgs / tri-higgs coupling.

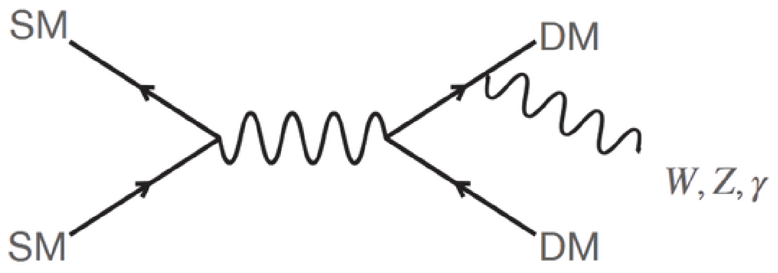



At high energies, muons radiate gauge bosons like photons.



Ideal environment for **electroweak** studies, including WIMPS.



# What will we deliver to the detector?

| | | | | | |
|---|---|---|---|---|---|
| **Energy!** | Either | 3 TeV | or | 10 TeV | Center-of-mass |
| **Luminosity!** | | $2 \times 10^{34}$ | or | $20 \times 10^{34}$ for 16 T<br>$15 \times 10^{34}$ for 11 T | $cm^{-2}s^{-1}$ luminosity |
| **Muons!** | | $2.2 \times 10^{12}$ | or | $1.8 \times 10^{12}$ | |

Luminosity also depends on:

- Transverse Emittance - 25 um
- Longitudinal Emittance - 0.025 eVs
- Beta at IP: 1.5 mm
- Repetition rate: 5 Hz

$$\mathcal{L} = \frac{\gamma^3 \tau_0 c}{2C} \frac{N_0^2 \sigma_\delta}{4\pi \epsilon_{\perp,\mathrm{N}} \epsilon_{\mathrm{L,N}}} f_{\mathrm{r}}$$

# What will we deliver to the detector?

| | | | | | |
|---|---|---|---|---|---|
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**First published muon collider concepts**
G.I. Budker & A.N. Skirnsky at Novosibirsk
~1969

**Muon Collider Workshops**
Annual workshops, mostly in the US
~1992 - 1999

**The Neutrino Factory and Muon Collider Collaboration (NFMCC)**
Produced a NuFact design at CERN
1999 - 2011

**Muon Acceleration Programme (MAP)**
Fermilab based programme
2011 - 2017

**Muon Ionization Cooling Experiment (MICE)**
UK-based cooling experiment
2004 - 2019

**IMCC and USMCC**
Following ESPPU 2022
2023 --->

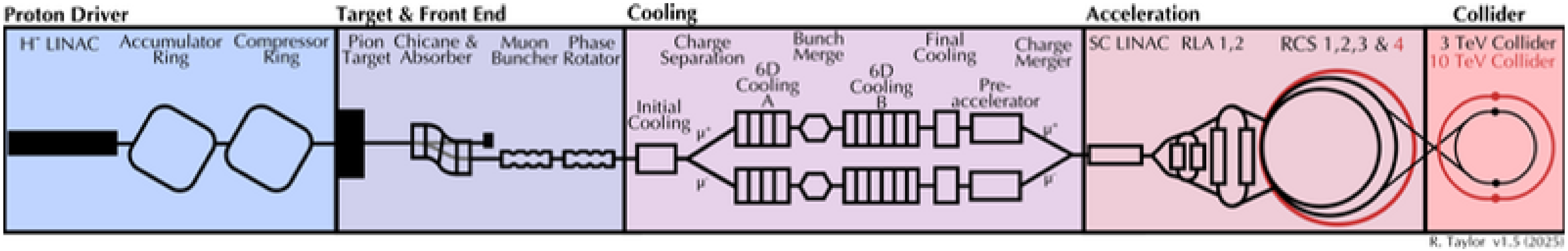
# WHY is this challenging?

**Challenge 1:**
Need to produce the muons

- Produce a high power proton beam
- Target material to withstand high-power

**Challenge 2:**
The muons decay

- Rapidly reduce the beam size
- Rapidly Accelerate
- Collide tight beams




**Challenge 3:**
Need to adjust for collective effects due to high intensity beam across the complex.

# WHY is this challenging?

## Challenge 1:
## Need to produce the muons

Produce a high power proton beam

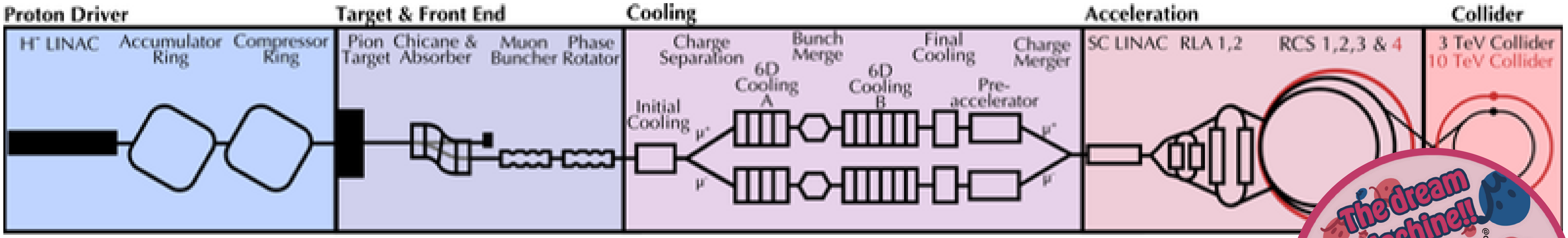
Target material to withstand high-power

## Challenge 2:
## The muons decay

Rapidly reduce the beam size

Rapidly Accelerate

Collide tight beams





## Challenge 3:
## Need to adjust for collective effects due to high intensity beam across the complex.

# Alternative: LEMMA Scheme

Generate electron-positron pair at muon mass resonance.
Complicated due to ~TW positron source and intersecting beamlines at target.

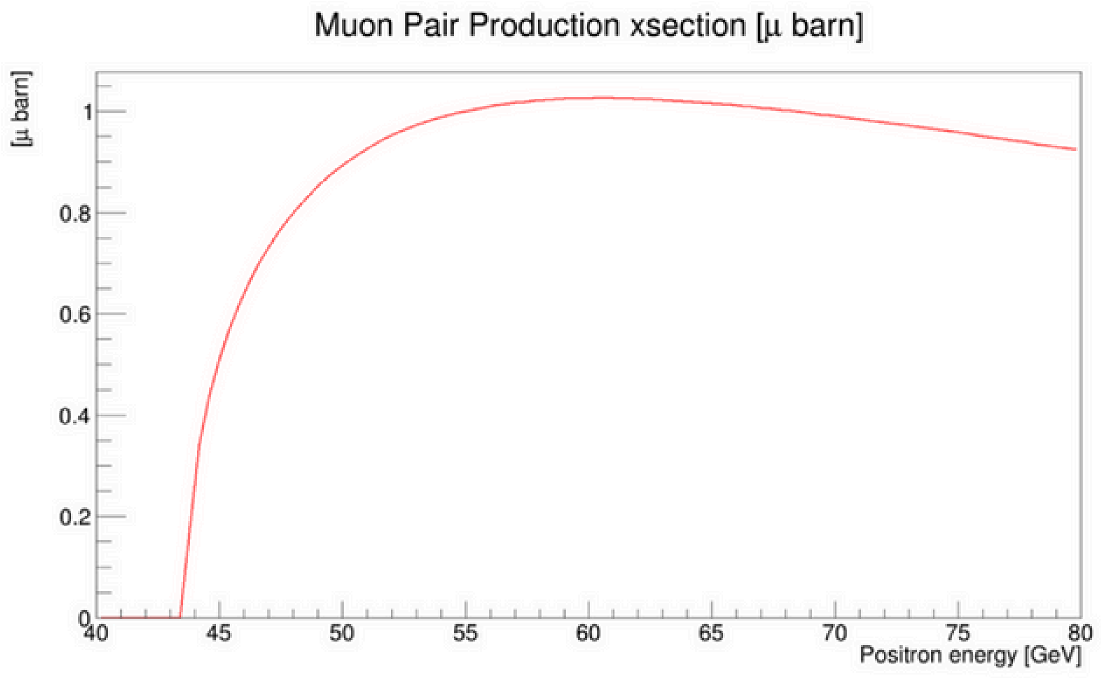
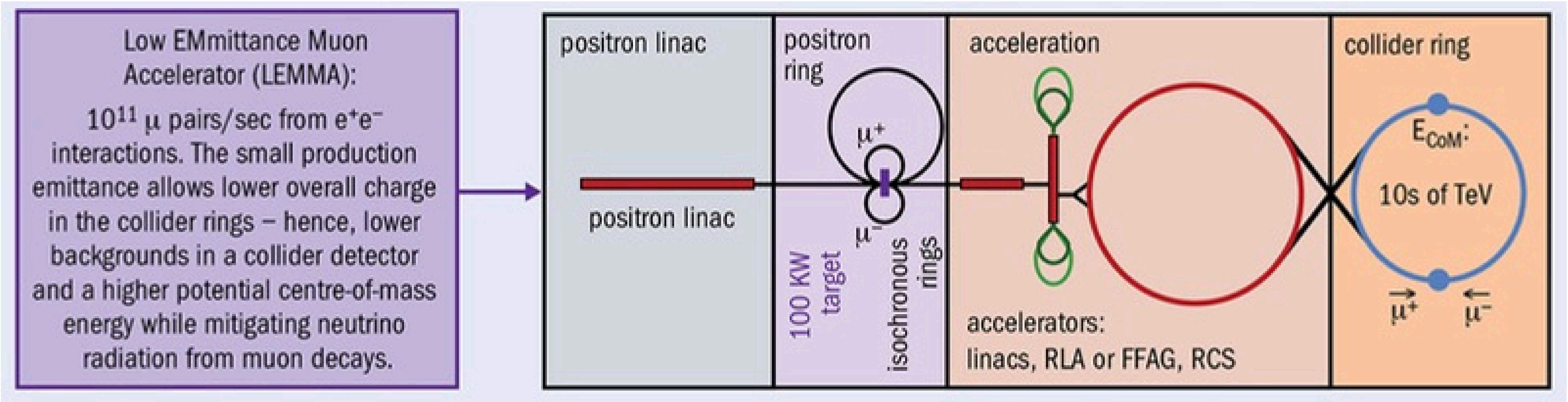


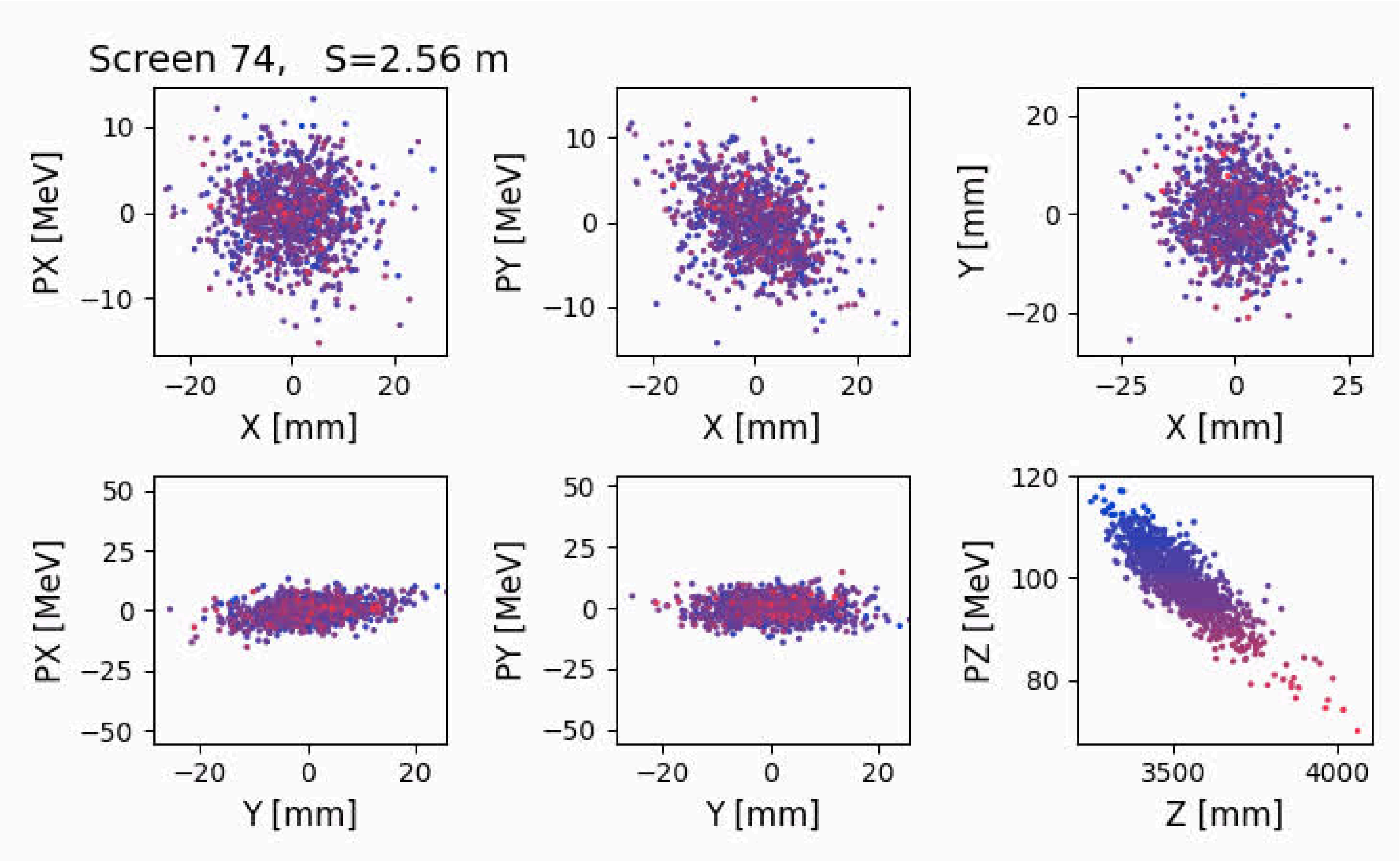

Figure 1: $e^+e^- \rightarrow \mu^+\mu^-$ cross section as a function of the positron beam energy ($\sqrt{s}$ ~0.23 GeV = 53 GeV positron beam).

POSITRON DRIVEN MUON SOURCE FOR A MUON COLLIDER (2019)



# How do we simulate beam optics

We describe a beam as a *collection of single particles* with 6 coordinates:




**x**: Horizontal position

**px**: Horizontal momentum

**y**: Vertical position

**py**: Vertical momentum

(x, px, y, py: Transverse)

**z** or **t** : Longitudinal position *or* time

**pz:** Longitudinal momentum

# How do we simulate beam optics

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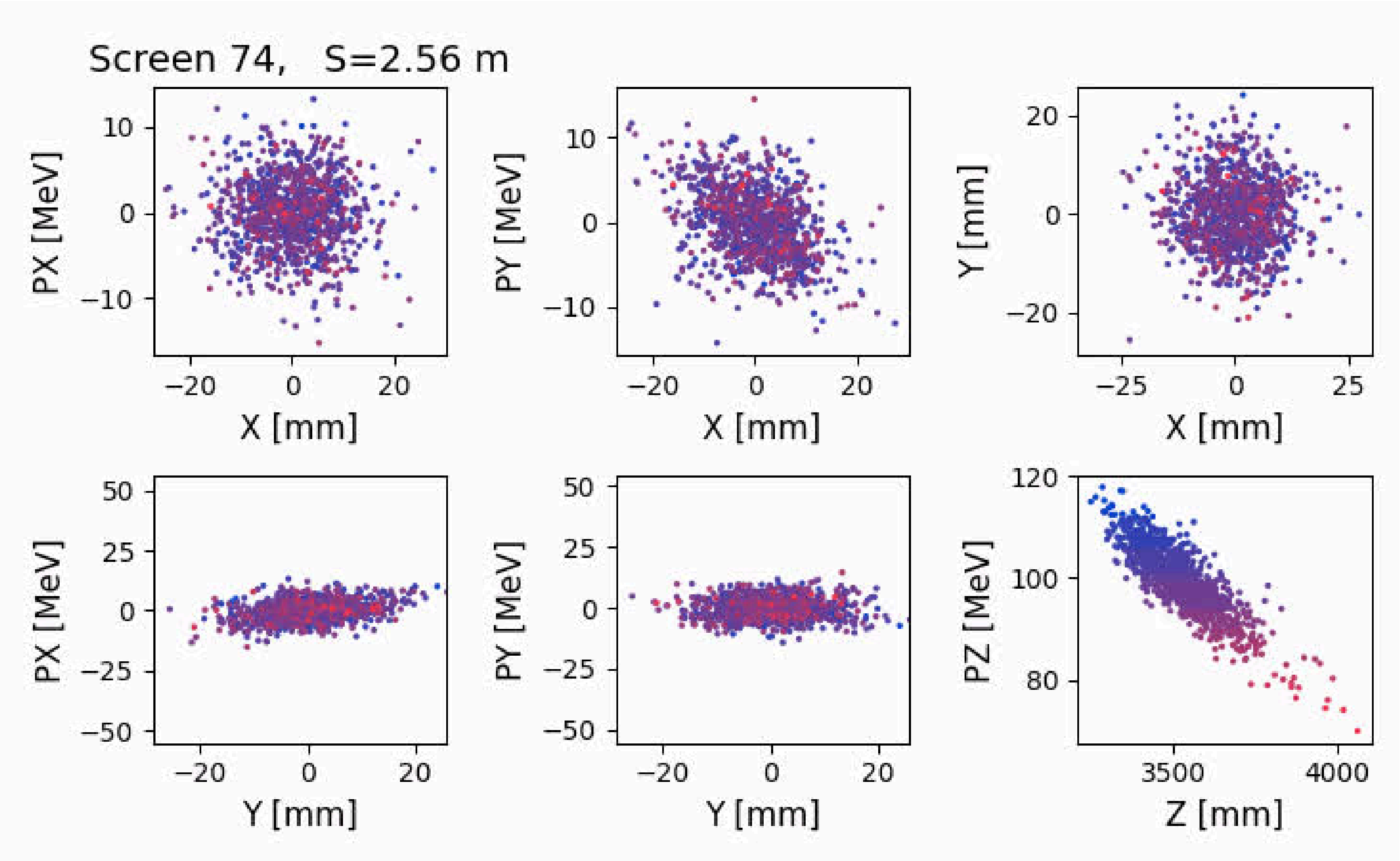


**x**: Horizontal position
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} Transverse

**z** or **t** : Longitudinal position *or* time
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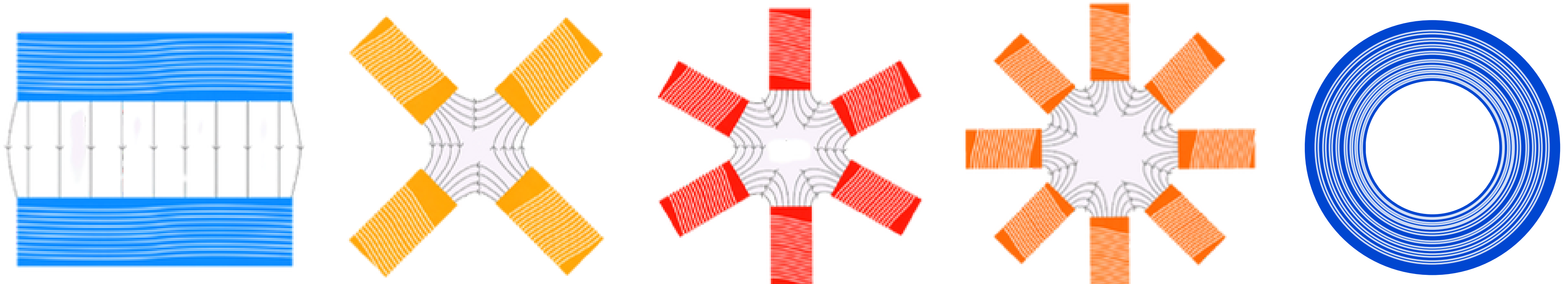
Two* philosophies to simulations:

-Either model magnets as a **matrix**, applied to the 6D phase-space vector.
-Or model magnets as a **fieldmap** (Bx, By, Bz), and interpolate forces in steps.



Dipoles Quadrupoles Sextupoles Octupoles Solenoids

*at least two

# Why are simulations challenging?

Simulation code wish-list includes...

**Particle interactions with matter**
Target, Cooling, MDI

**Radiation effects on surrounding materials**
Target, Collider

**Overlapping elements in high $B_z$ fields**
Target, Front-End, Cooling

**Muon decay and tracking secondaries**
Everywhere

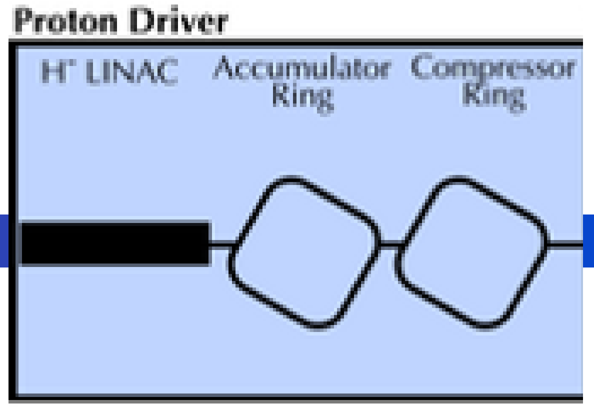
**Low-energy linear acceleration of a long beam**
Cooling, Acceleration

**Matching beam conditions between synchrotrons**
Accelerator, Collider, (Everywhere)

**Non-linear effects**
Collider

**Collective effects including space-charge, beam-beam and wakefields**
Everywhere

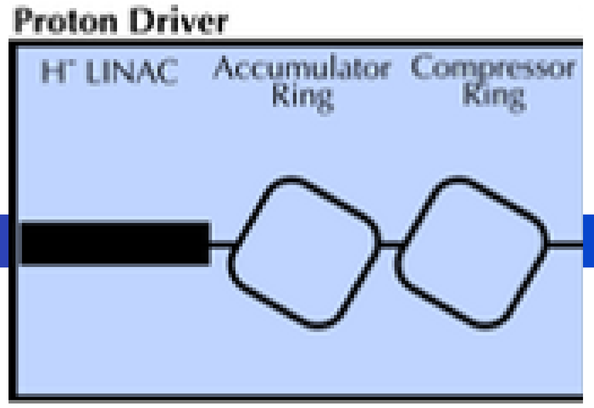
# Why is the **proton driver** challenging?




Short answer: Needs an intense, short beam.

**Plenary: Tuesday Morning**

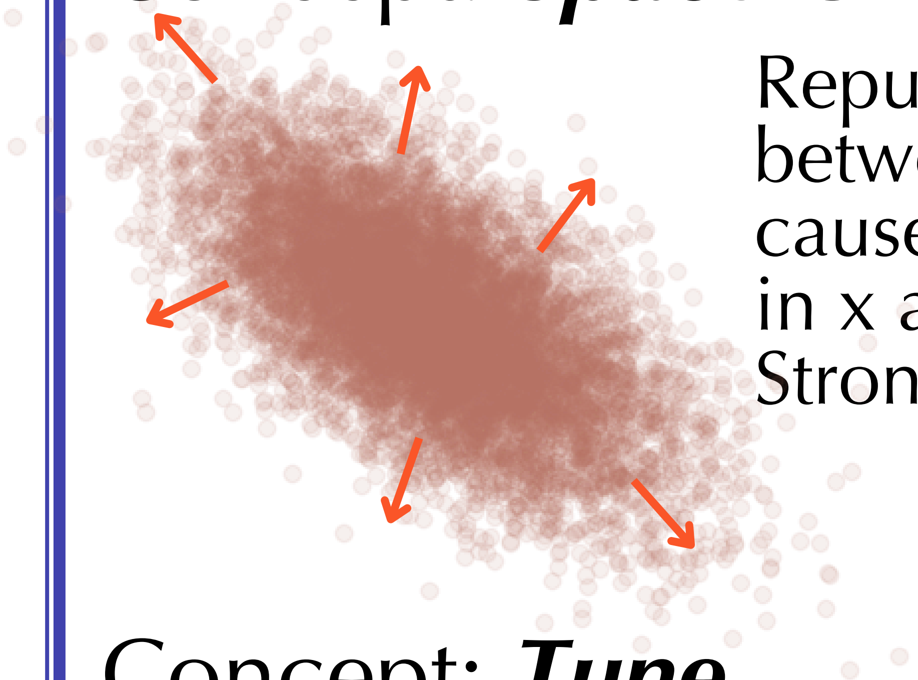
09:00 Proton Driver and Beam Delivery for a MuC
**Speaker**: Jeff Eldred (Fermilab)




# Why is the **proton driver** challenging?

Short answer: Needs an intense, short beam.

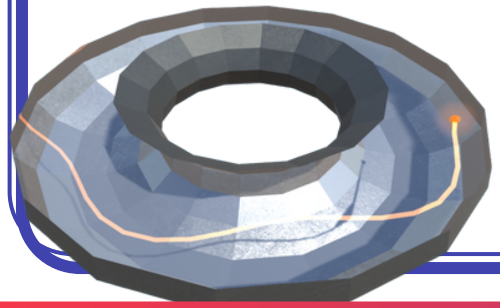
## Concept: ***Space Charge***

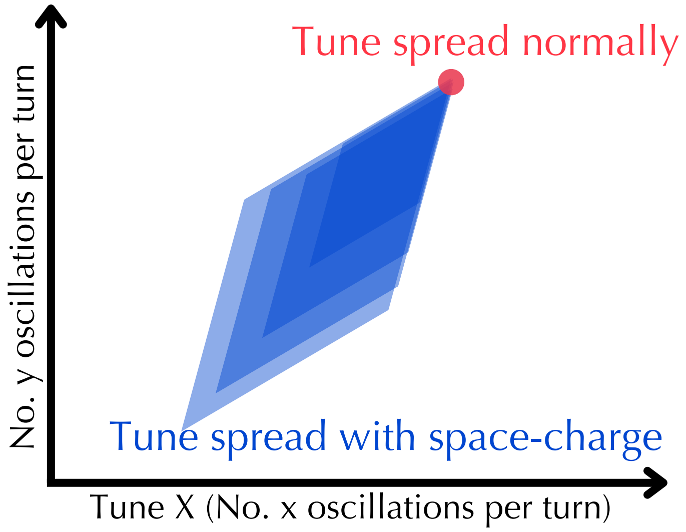


Repulsive forces between particles causes de-focusing in x and y and z. Stronger at low E.

## Concept: ***Tune***

Particles oscillate throughout the ring. Frequency of this oscillation is called the **tune**



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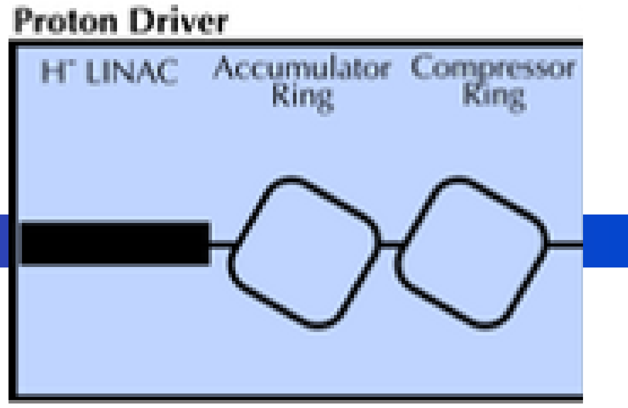


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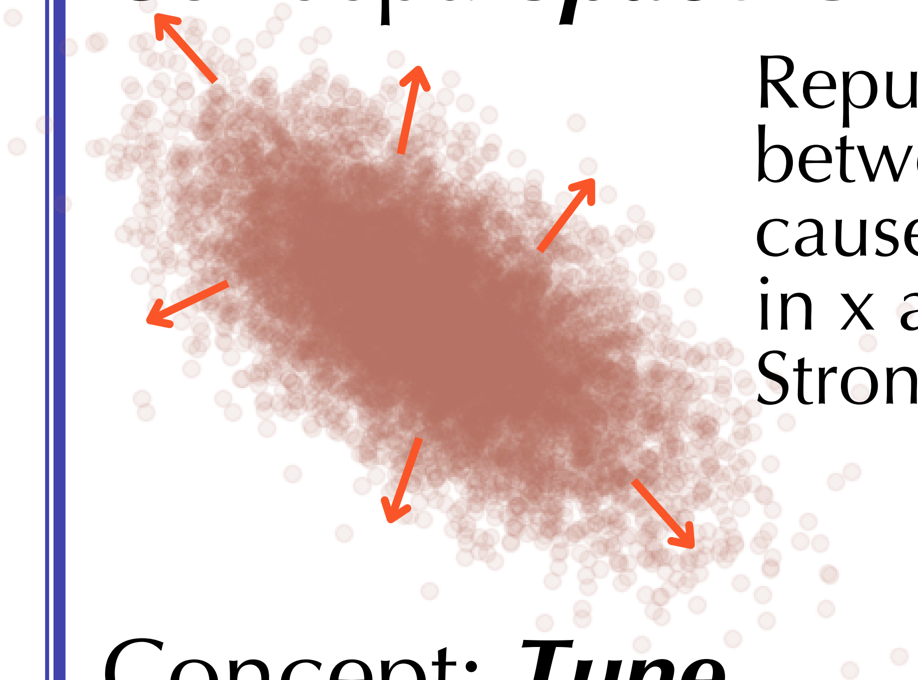

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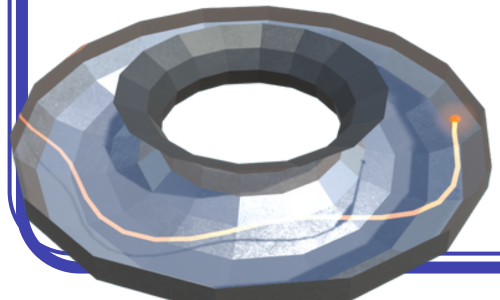
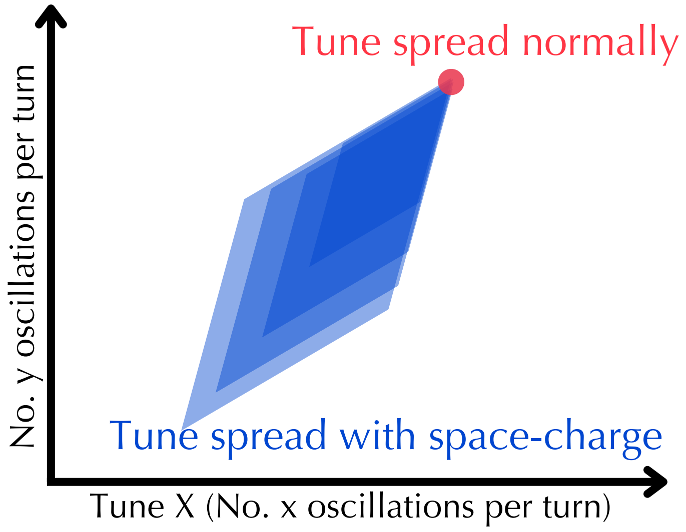





Parameters request a **2 MW** beam at **5 GeV** or a **4 MW** beam at **10 GeV**.

Very short pulse rms of ~2 ns

High Intensity + Short pulse + Lower Energy = Significant Space- Charge

Designing beam optics throughout:

- A LINAC to 5 or 10 GeV
- A ring to accumulate to one pulse
- A compressor ring to shorten the pulse

All while having a wide tune spread.

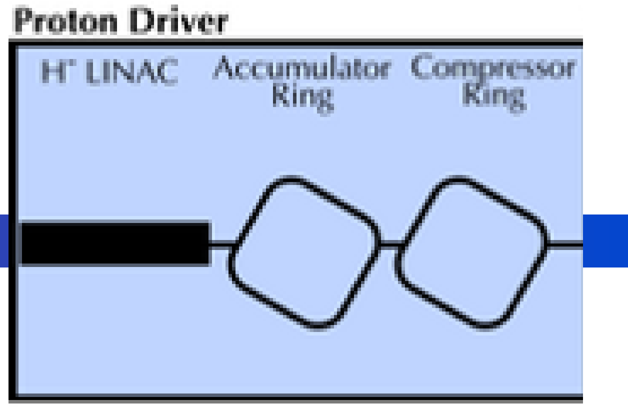
*Thanks to S. Johannesson*

Plenary: Tuesday Morning

09:00 Proton Driver and Beam Delivery for a MuC

**Speaker**: Jeff Eldred (Fermilab)

# **Proton Driver** progress

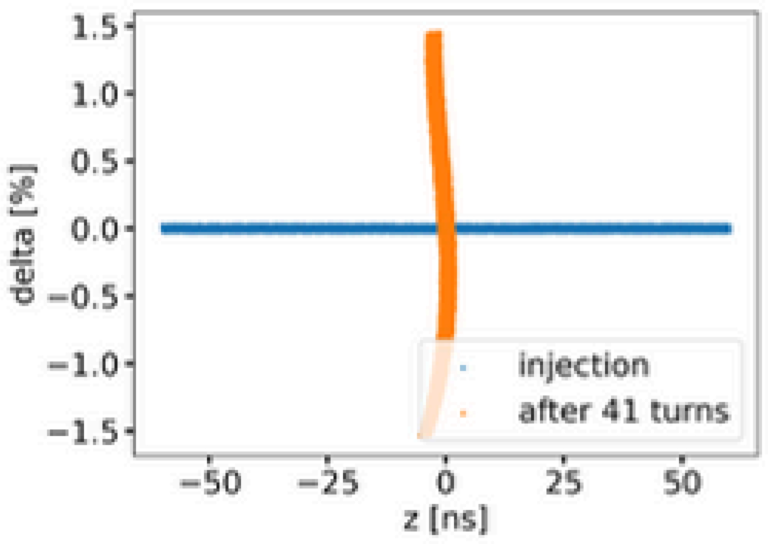


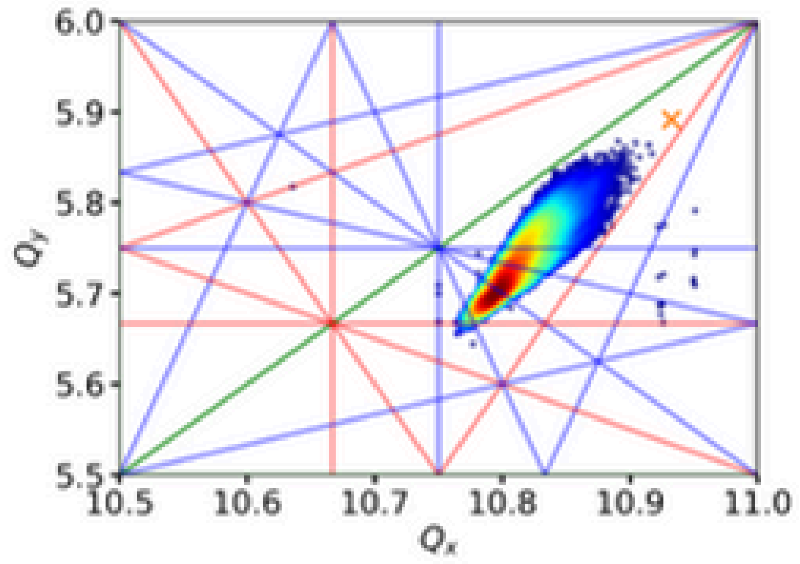

**Challenges:**

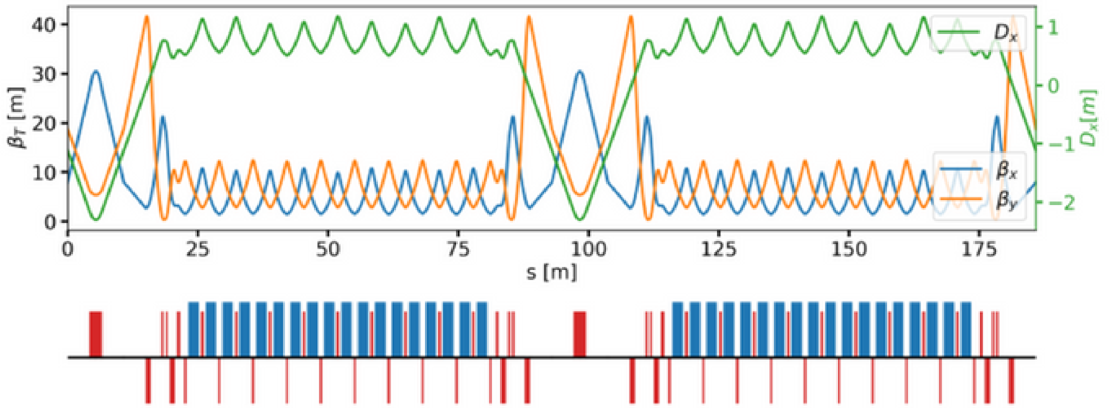
- High intensity proton beam
- 2 MW, 5 GeV or 4 MW, 10 GeV
- Accumulate 5x10$^{14}$ p$^{+}$/pulse
- Compress to 2 ns

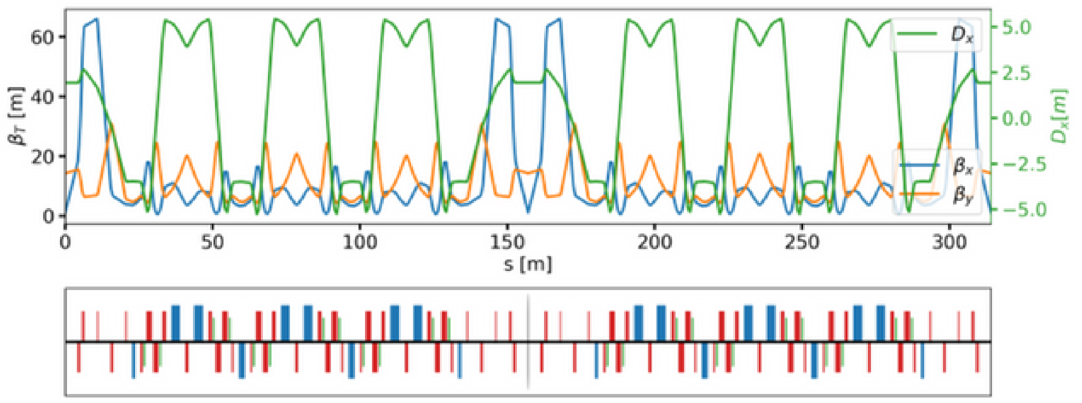
**Achievements:**

- Lattice designs for accumulator and compressor rings
- Collective effects studies




**Future R&D:**

- In parallel with other **high-intensity p$^{+}$** facilities (SNS, ESS, CERN, JPARC, ISIS)
- High intensity, large-aperture **H$^{-}$ sources** and **laser-assisted charge exchange** injection
- High transmission, high current RFQs
- Limitation of high intensity compression schemes with high space-charge

14:40 Proton Driver for the Demonstrator and Muon Collider
**Speaker**: Dr Austin Hoover (ORNL)

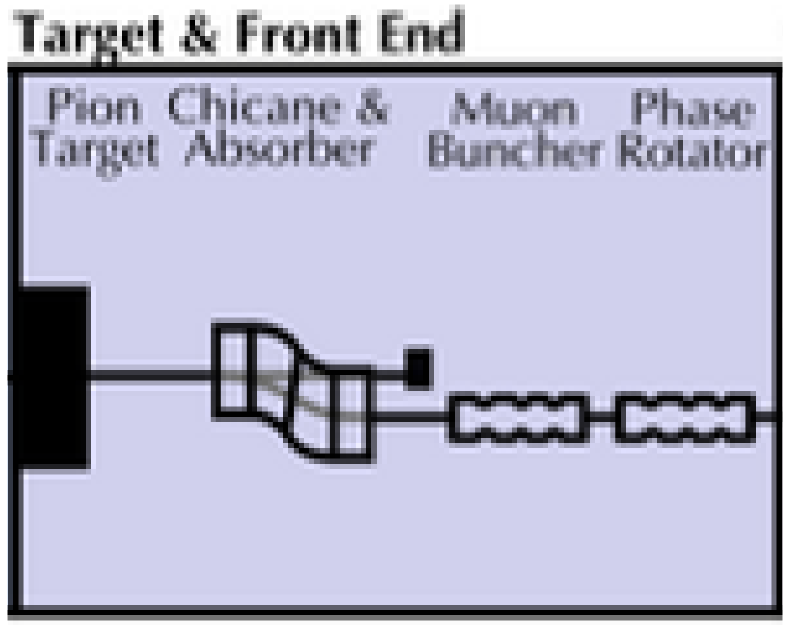
# Why is the **target & front-end** challenging?

Short answer: Not damaging your equipment.

$$p^+ + p^+ \rightarrow \pi^+ (+ p^+) \rightarrow \mu^+ + \nu_\mu$$
$$p^+ + n^0 \rightarrow \pi^- (+ p^+) \rightarrow \mu^- + \bar{\nu}_\mu$$

**Input** | **Target**

A 2 MW or 4 MW p+ beam → Graphite or liquid metal → $\pi^{+/-}$ decaying to $\mu^{+/-}$




*Thanks to P. Jurj*

**Plenary: Tuesday Morning**

11:00 Muon Capture and Transport
**Speaker**: Dr David Neuffer (Fermilab)

**Plenary: Wednesday Afternoon**

13:30 Target Technology
**Speaker**: Robert Zwaska (Fermila

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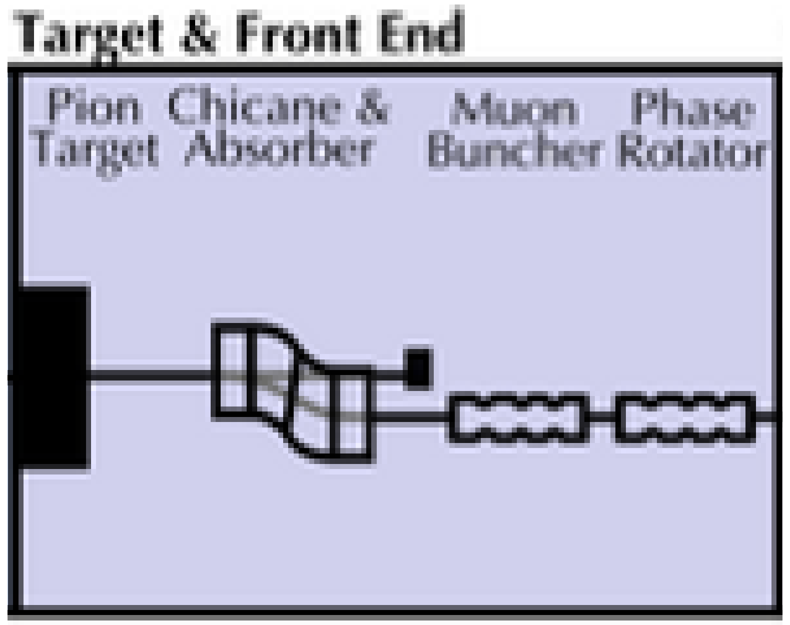
**Input** — A 2 MW or 4 MW p+ beam

**Target** — Graphite or liquid metal

$\pi^{+/-}$ decaying to $\mu^{+/-}$

A 'horn' of strong tapered solenoids

500 p+ produces 45 mu- and 60 mu+

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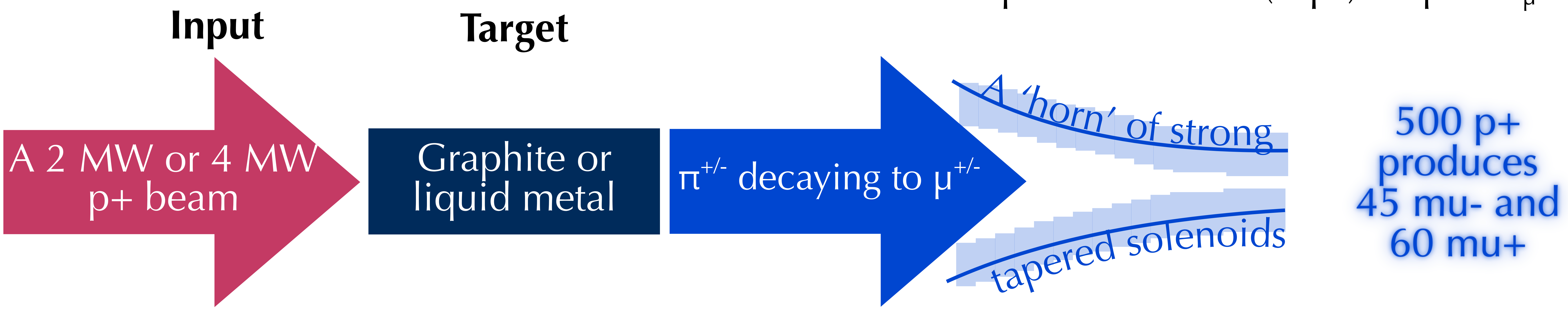


<u>Open questions:</u>
- From what point do we define yield?
- What to do with the high-power protons after the target?
- How can we prevent the particles damaging the SC solenoids?
- How often do we need to replace the target?

*Thanks to P. Jurj*

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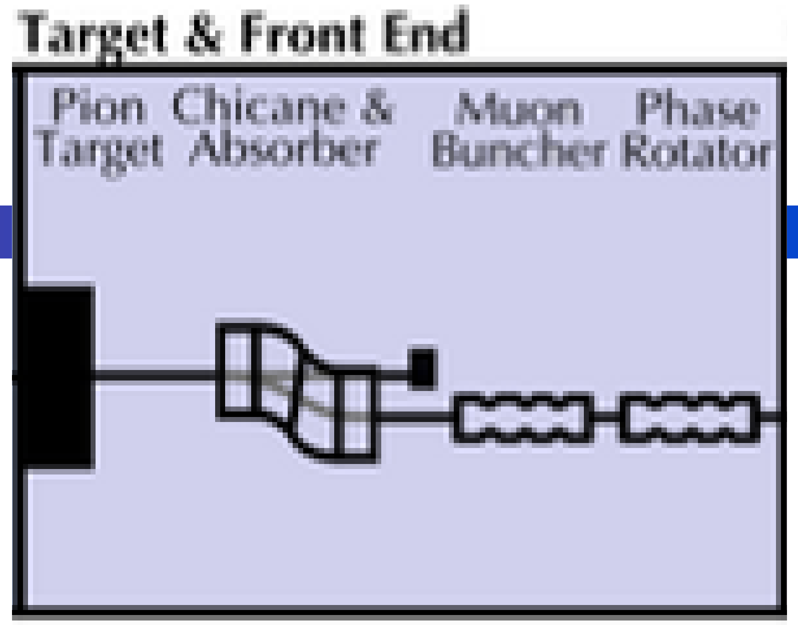
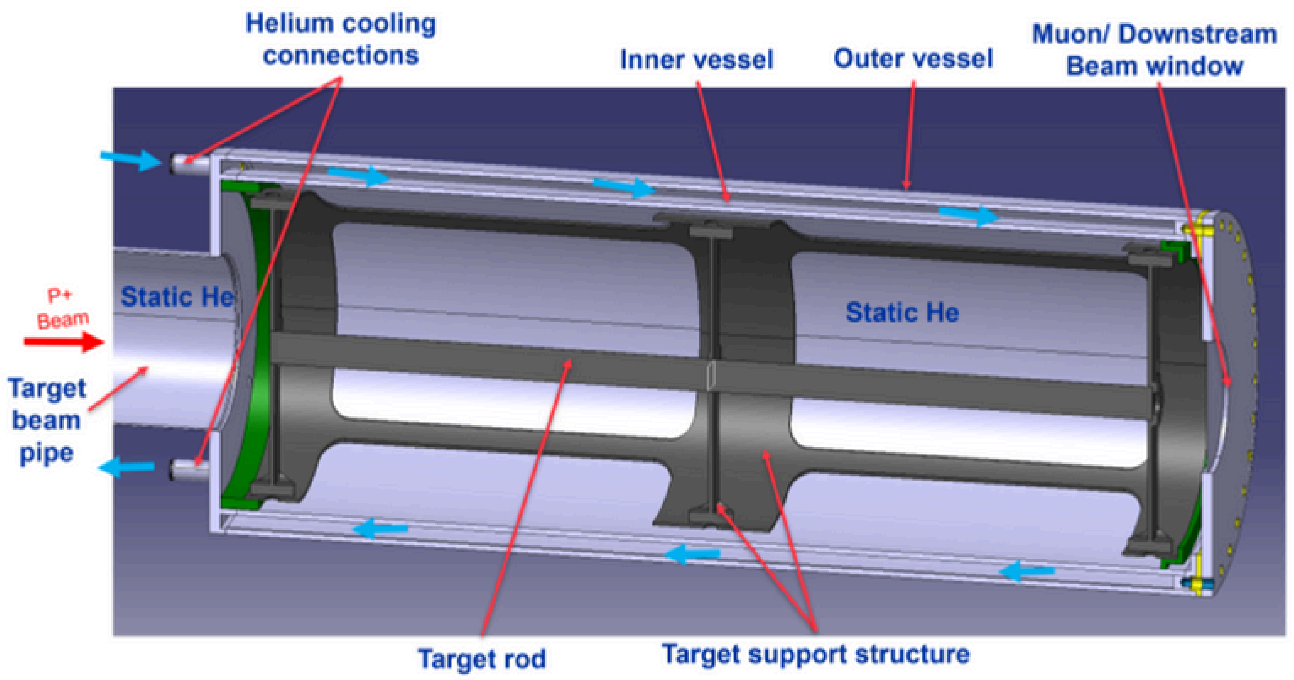
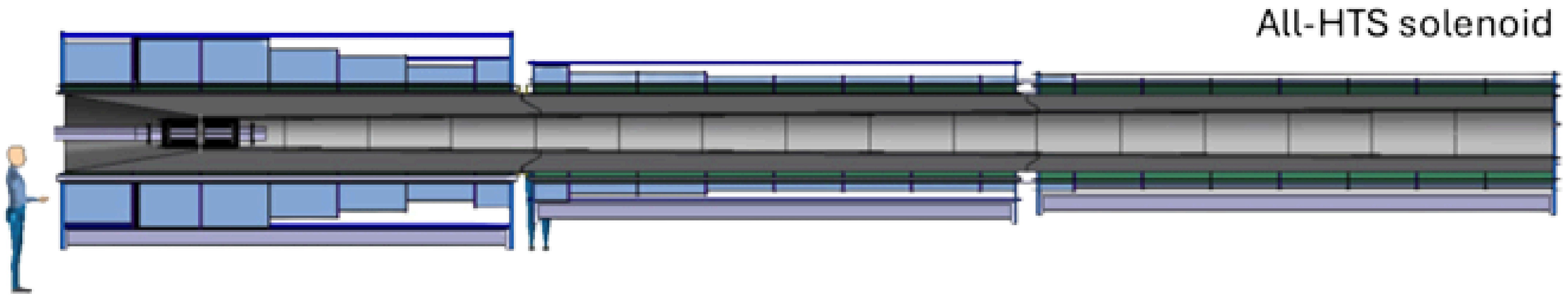
# Target & capture progress




**Challenges:**
- 2 MW, 400 MJ/pulse on target
- Optimising for pion yield
- HTS solenoid capture system
- Extraction of spent proton beam

**Achievements:**
- Radial build of graphite target
- Studied radiation load on HTS
- Begin 4 MW targets, e.g. liquid Pb, fluidized W

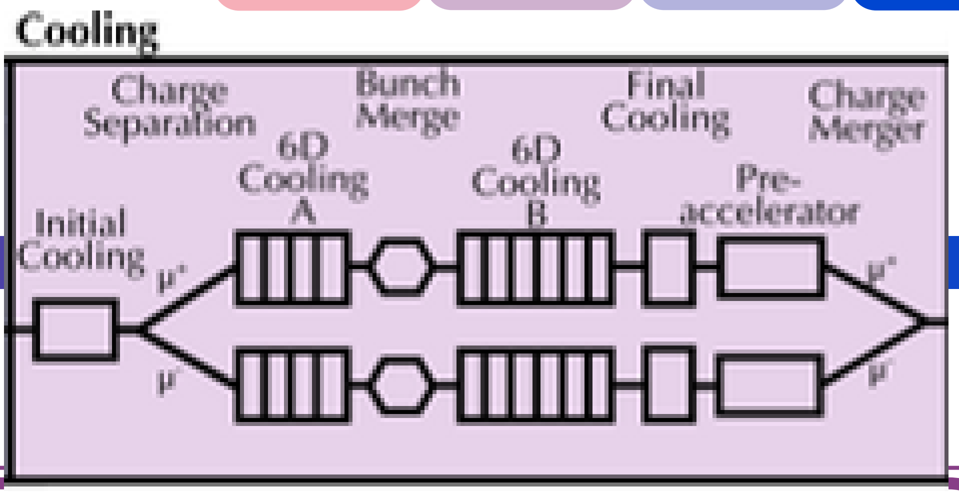



**Future R&D:**
- 1400 mm, 20 K, 20 T HTS solenoids with 80 MGy radiation. Synergies with fusion magnets.
- 20 MV/m RF cavities within 3 T, over large range of frequencies.
- Beam loading and collective effects in Front-End.

| 15:00 | **Progress on High Power Targetry**<br>**Speaker**: Dr Katsuya Yonehara (Fermilab) |
|---|---|

# Why is the **cooling** challenging?




Short answer: Needing to be encased in solenoids

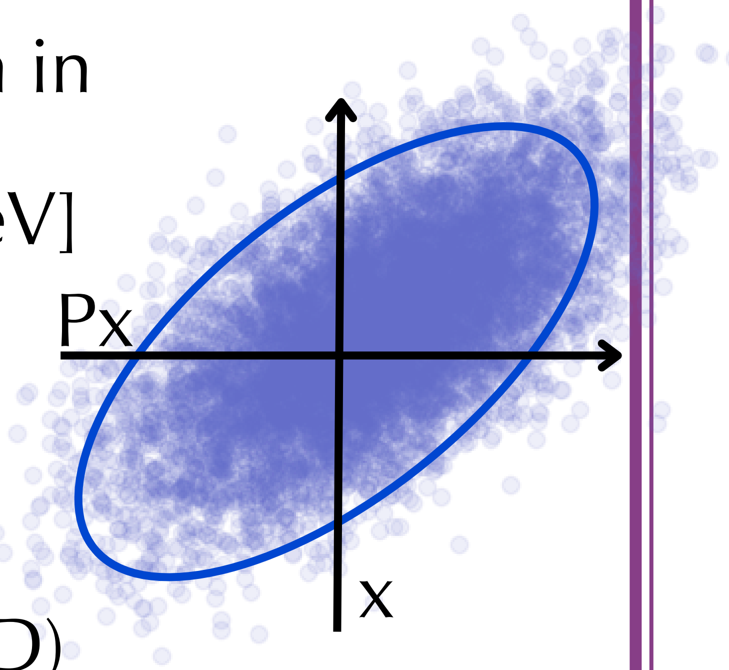
Cooling refers to reducing the **emittance** (size) of the beam:

- Allows the beam to fit within a reasonable magnet size

## Concept: ***Emittance***

The area of the beam in phase-space.
Expressed as Ɛ[m MeV]

Calculated as the **covariance** to include correlations between the planes

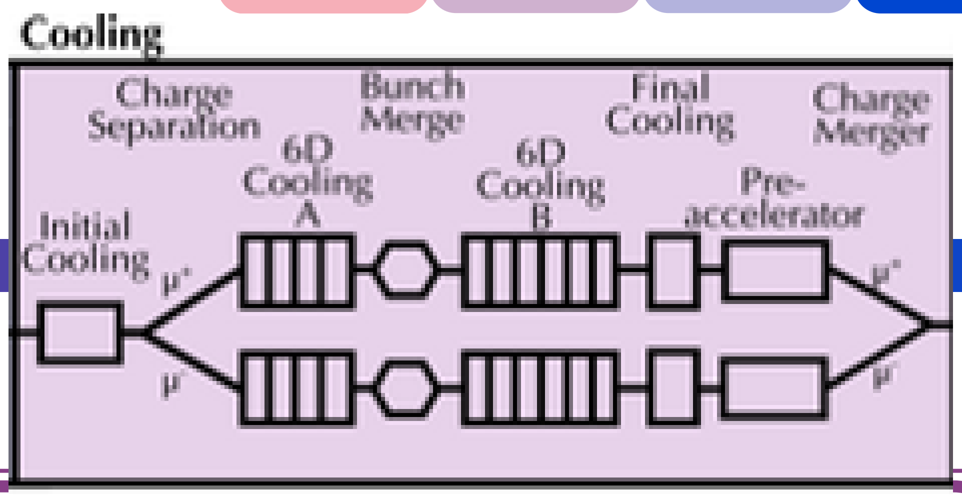



Ɛx = area in X, Px (2D)
Ɛy = area in Y, Py (2D)
ƐL = area in Z, Pz *or* T, E (2D)
ƐT = area in X, Px, Y, Py (4D)
Ɛ = area in X, Px, Y, Py, T, Pz (6D)


**Plenary: Tuesday Afternoon**

13:30 **Muon Collider Ionization Cooling Channel**
**Speaker**: Katsuya Yonehara (Fermilab)

# Why is the **cooling** challenging?



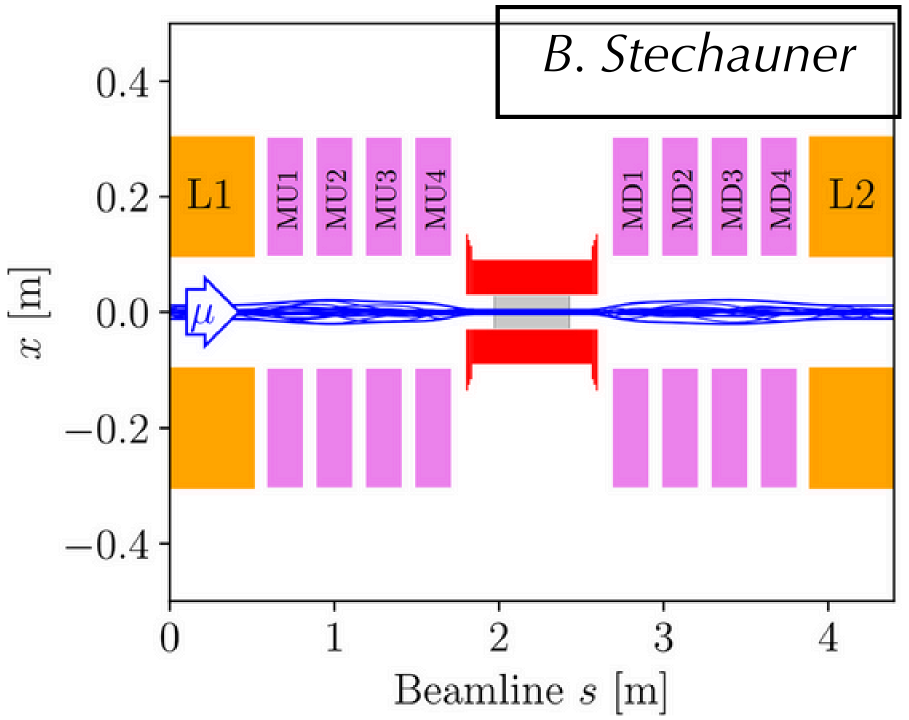

**Short answer: Needing to be encased in solenoids**

Cooling refers to reducing the **emittance** (size) of the beam:

- Allows the beam to fit within a reasonable magnet size

**After target, beam is non-relativistic:**

- Energy = 5 – 200 MeV = 30 – 80% speed of light




Beam must be constantly focused to keep their size. Lack of solenoid fields causes emittance increase.

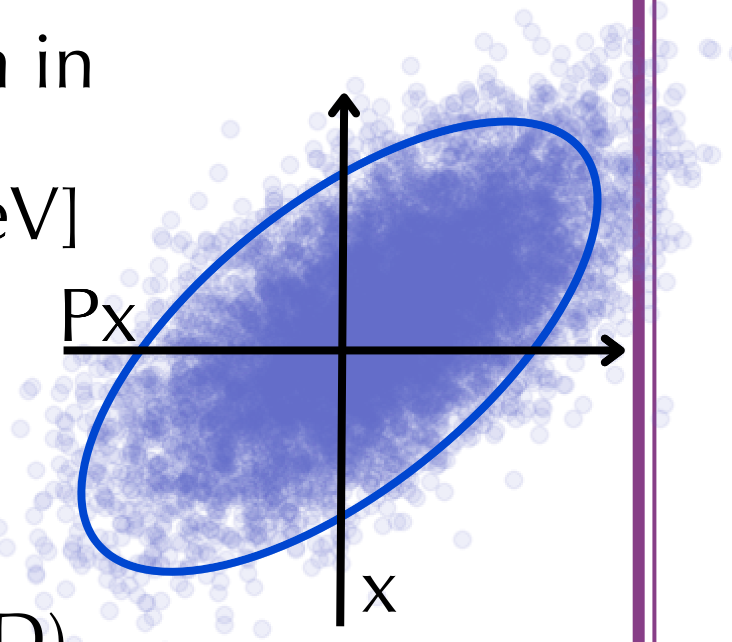
Need to ensure smooth fields between solenoids, to avoid emittance increase (see, matching).

## Concept: ***Emittance***

The area of the beam in phase-space.

Expressed as Ɛ[m MeV]

Calculated as the **covariance** to include correlations between the planes



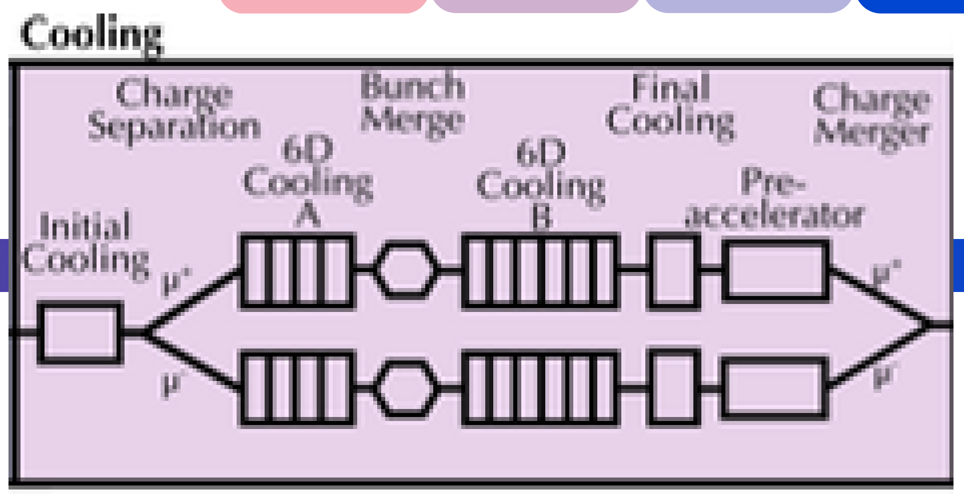

Ɛx = area in X, Px (2D)
Ɛy = area in Y, Py (2D)
ƐL = area in Z, Pz *or* T, E (2D)
ƐT = area in X, Px, Y, Py (4D)
Ɛ = area in X, Px, Y, Py, T, Pz (6D)

**Plenary: Tuesday Afternoon**

13:30 Muon Collider Ionization Cooling Channel

**Speaker**: Katsuya Yonehara (Fermilab)

# Why is the **cooling** challenging?




Short answer: Needing to be encased in solenoids

| IONIZATION COOLING | |
|---|---|
| Elastic Electron Scattering | Nuclear Multiple Scattering |
| Cooling | Heating |
| Favour low-A materials<br>E.g. Hydrogen, Lithium Hydride | |

There are other cooling methods, but often require significantly more time than the muon lifetime.

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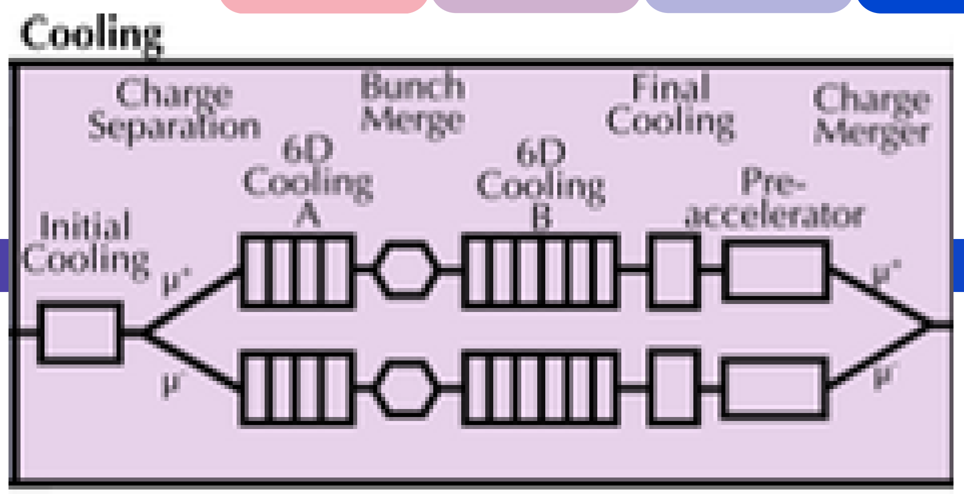


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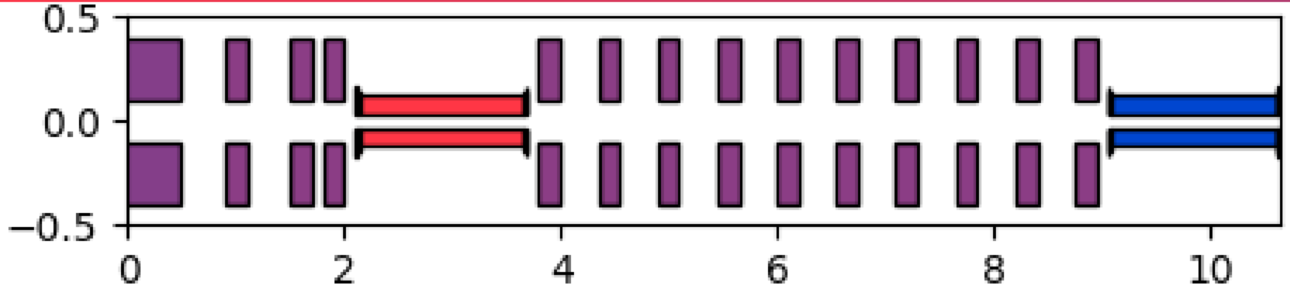
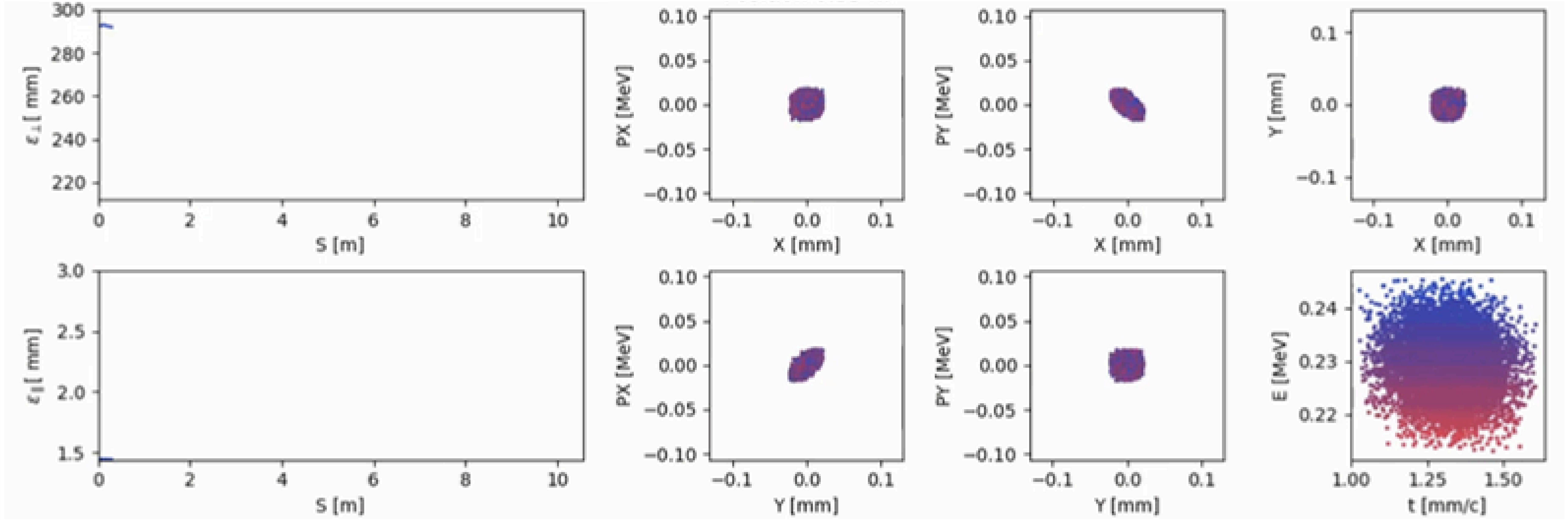



## Final Cooling 6D Beam Dynamics



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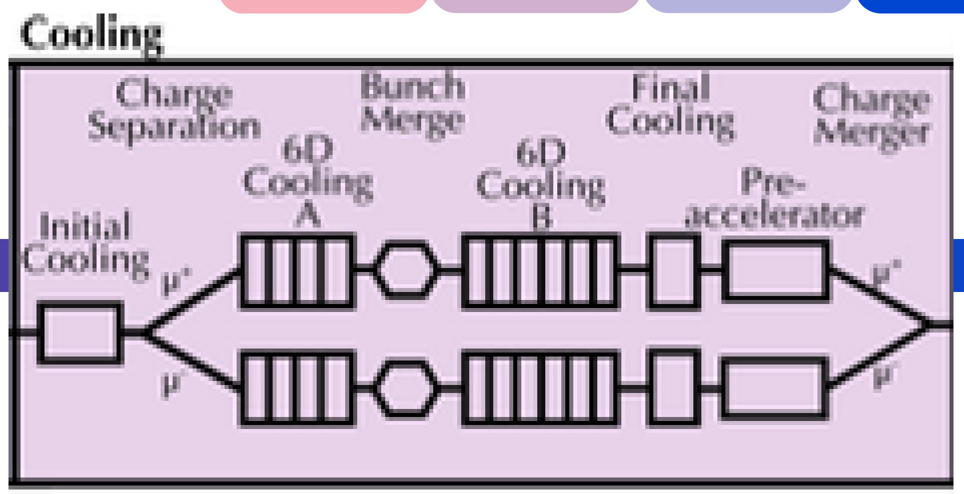


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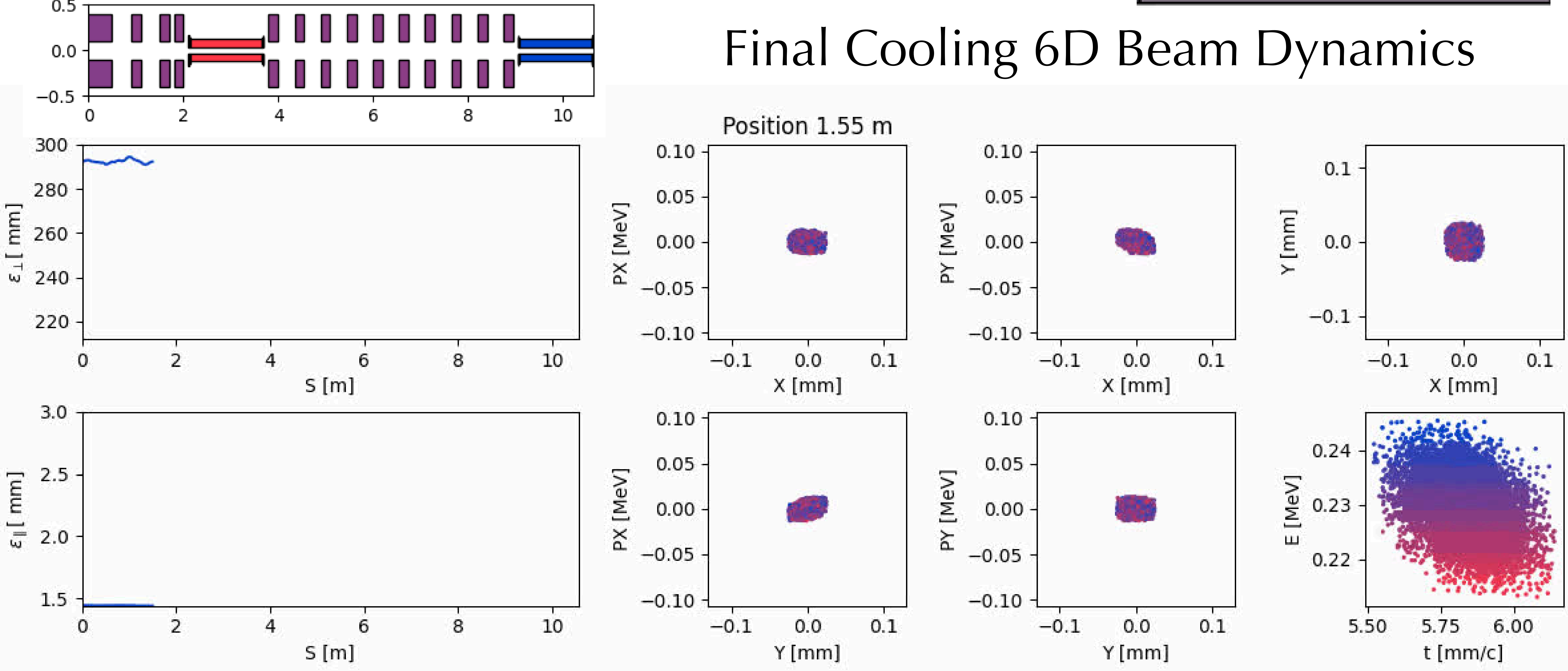

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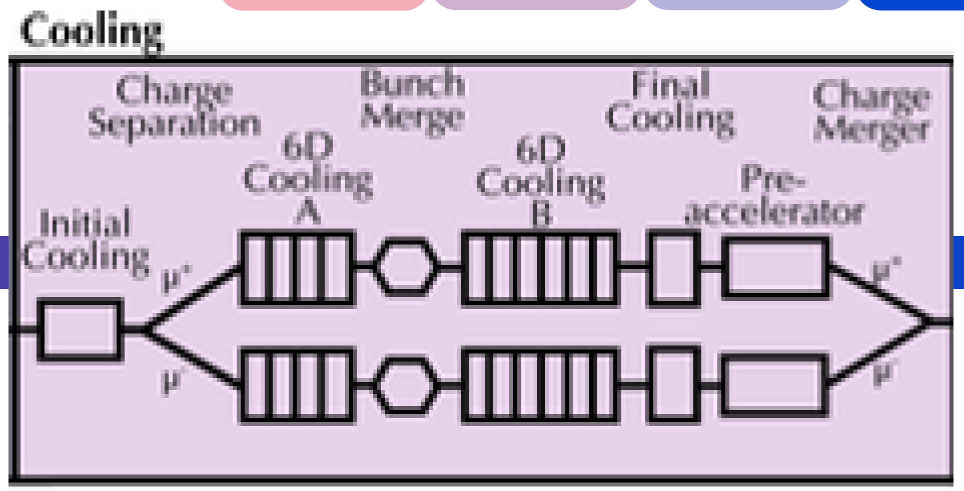


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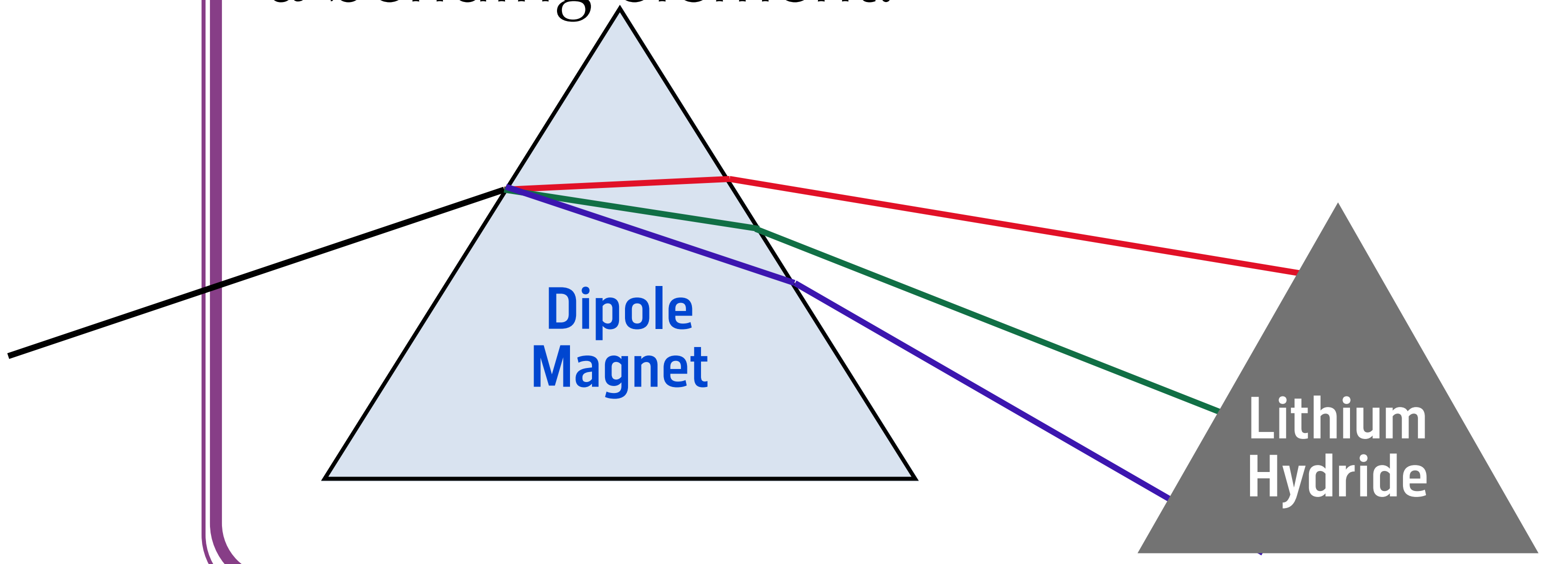
There are other cooling methods, but often require significantly more time than the muon lifetime.

However this only cools **transversely**. Can ensure longitudinal cooling by introducing *dispersion* and a wedge absorber, so higher-energy particles travel through more material than lower-energy particles.

## Concept: ***Dispersion***

Particles with higher momentum are harder to bend.
*Dispersion* is the correlation between position and momentum, introduce by a bending element.



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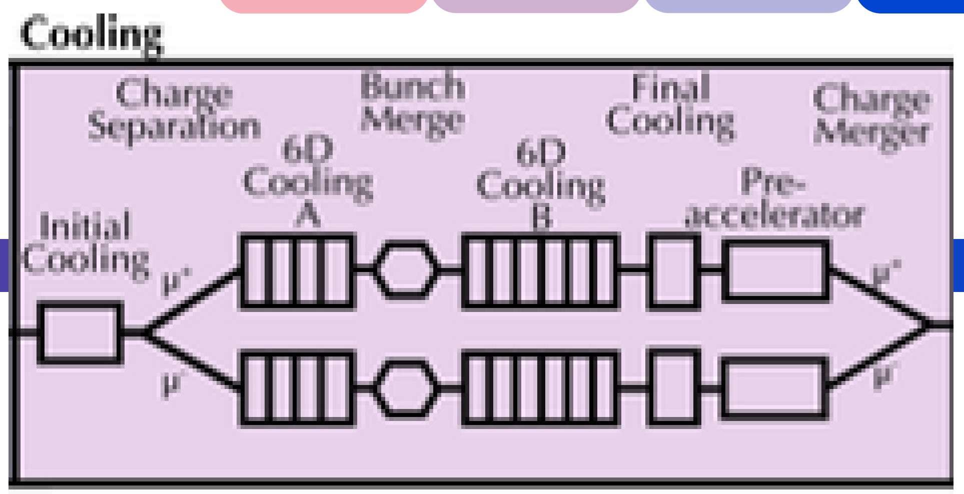


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There are other cooling methods, but often require significantly more time than the muon lifetime.

However this only cools **transversely**. Can ensure longitudinal cooling by introducing *dispersion* and a wedge absorber, so higher-energy particles travel through more material than lower-energy particles.

For both forms of cooling, we need to restore the energy lost, or else the muons will slow down to a stop.
So after our absorbers we need an *RF cavity* to re-accelerate the beam.

**Absorbers and RF Cavities need to constantly be in high solenoidal fields!**
Don't forget waveguides, power cables, cryogenics, instrumentation!

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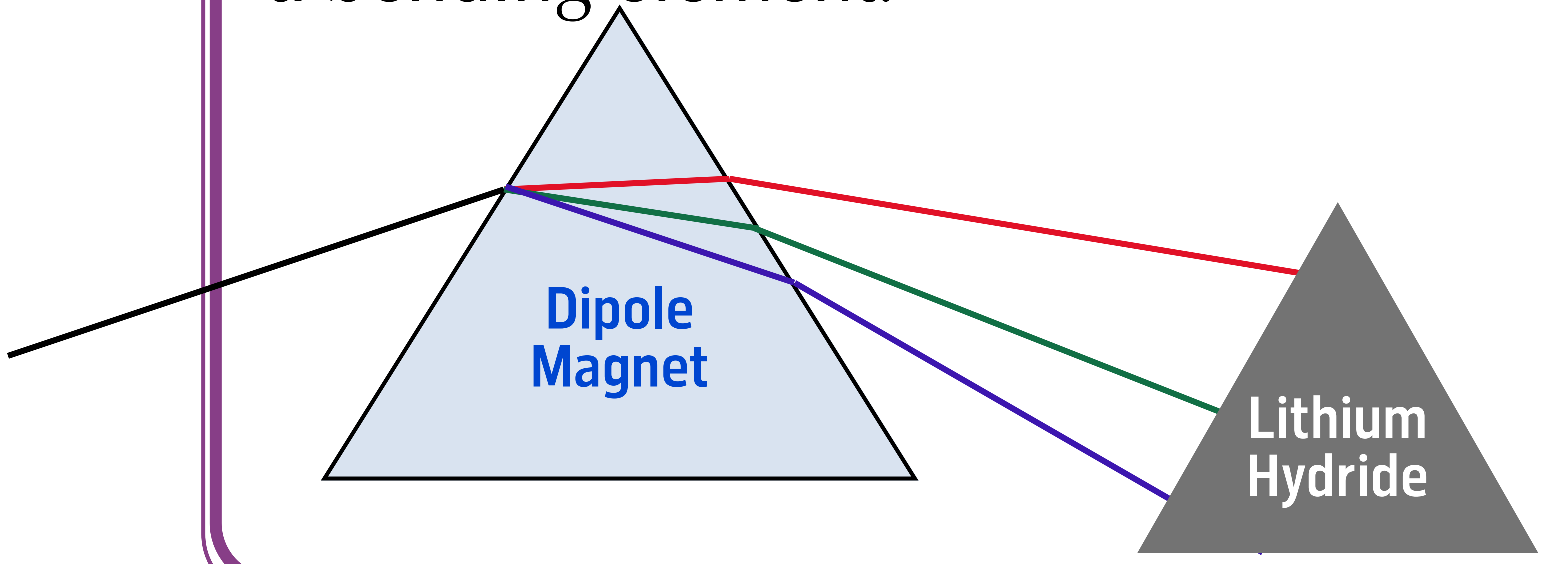
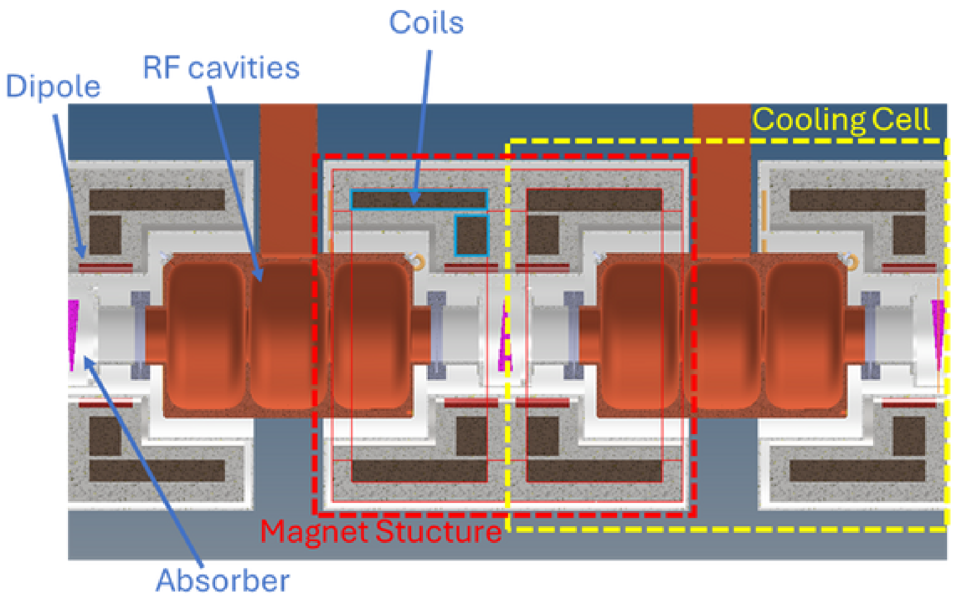
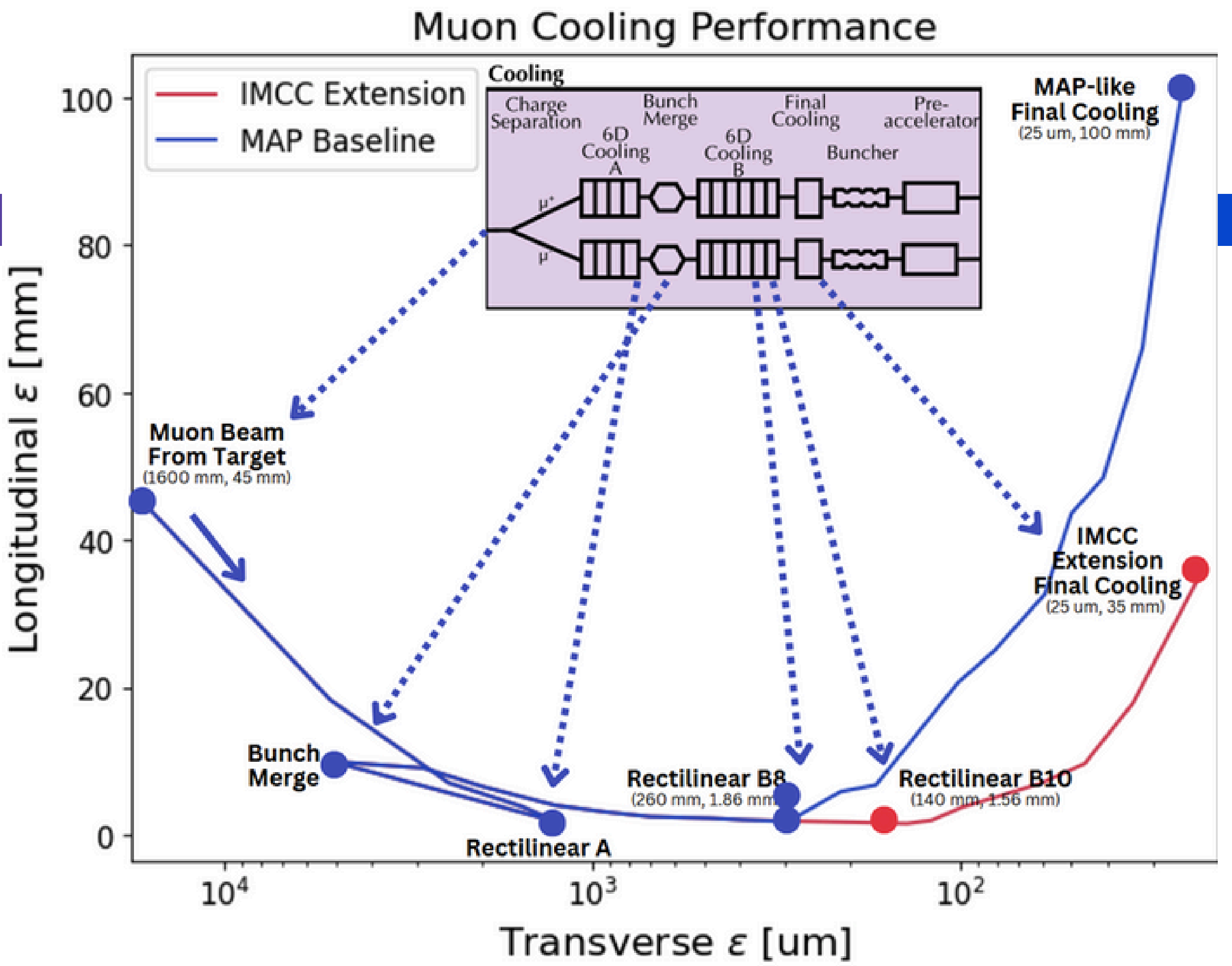


# Cooling progress

## Challenges:

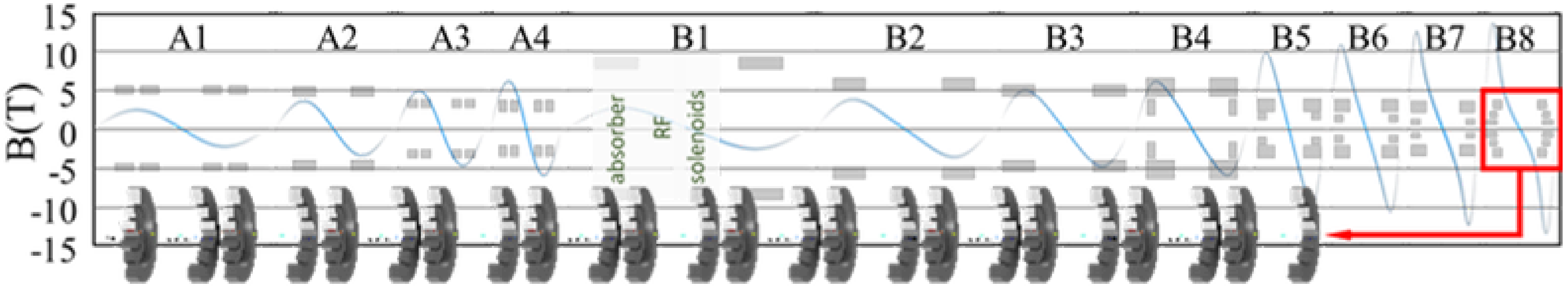
- Overlapping dipoles, absorbers and RF cavities within solenoids.
- Bright beam on liquid hydrogen
- Beam loading and space charge




## Achievements:

- Benchmarked codes, RF Track, BDSIM, G4Beamline, ICOOL
- Improved 6D cooling design




## 6D Future R&D:

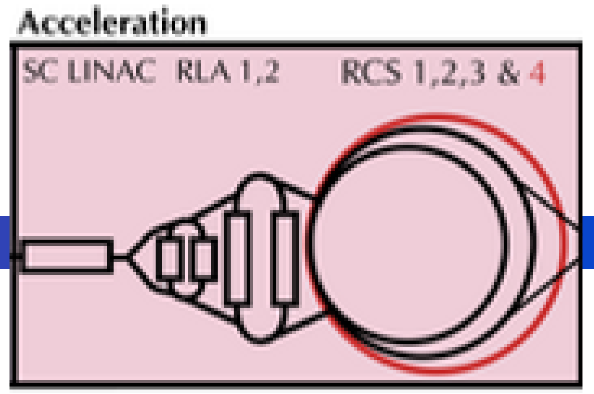
- 2.6 - 17.9 T solenoids with 800 - 60 mm bore.
- >30 MV/m in fields >10 T.
- Develop **cooling demonstrator** to verify integration.

## Final Cooling Future R&D:

- 40 T, 50 mm solenoids for final cooling.
- ~20 MV/m in 4 T fields from 200 - 5 MHz
- $LH_2$ pressure and windows

14:00 Progress on the HFOFO snake channel for 6D Muon Cooling
**Speaker**: Caroline Riggall (University of Tennessee)

# Why is the **acceleration** challenging?

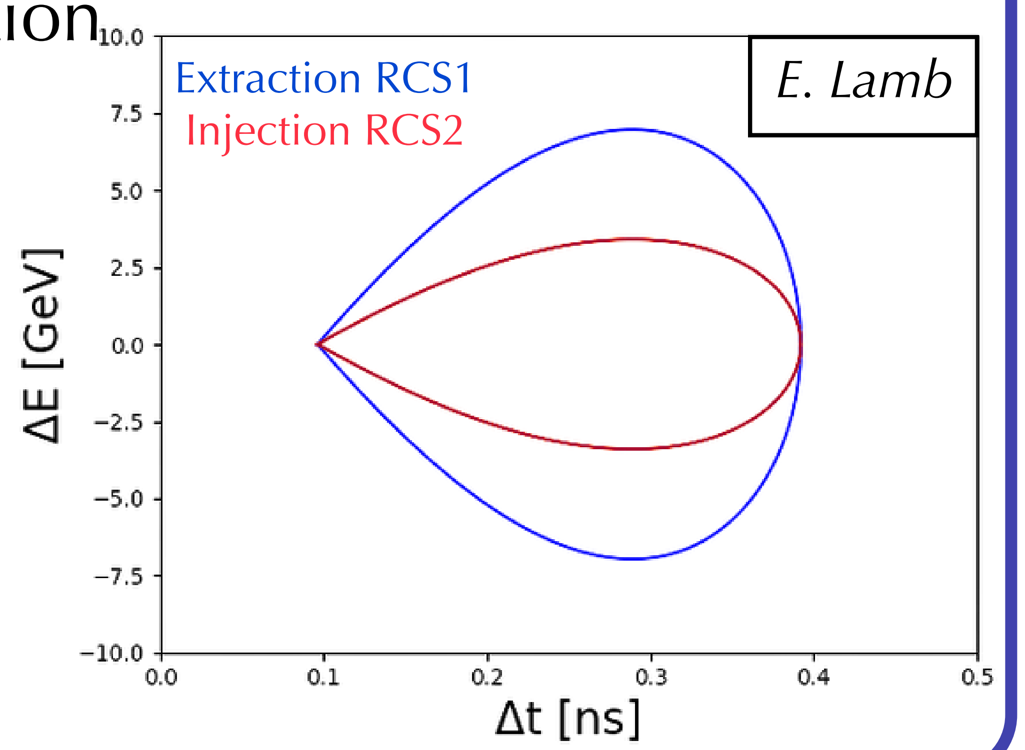



Short answer: Primarily due to **fast-acceleration** rate.

Need a set RF gradient per accelerator length to get reasonable transmission (90%).
10 RF stations throughout synchrotron.
**4506 cavites, 138 GV total**

## Concept: **Matching**

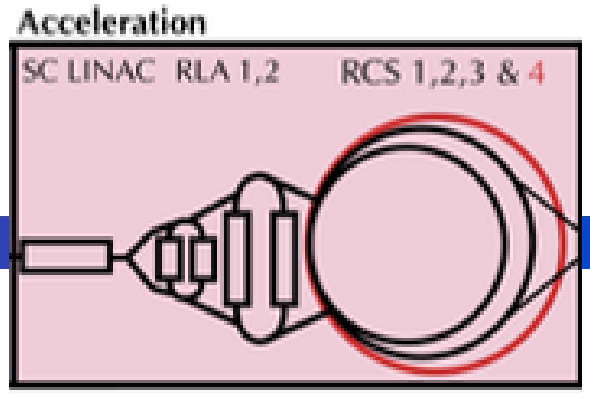
The beam oscillates within a stable area (called RF bucket). Differences in bucket sizes causes emittance increase and filamentation




**Plenary: Tuesday Afternoon**

15:30 **Acceleration Complex**

**Speaker**: Dr Rebecca Taylor (CERN)

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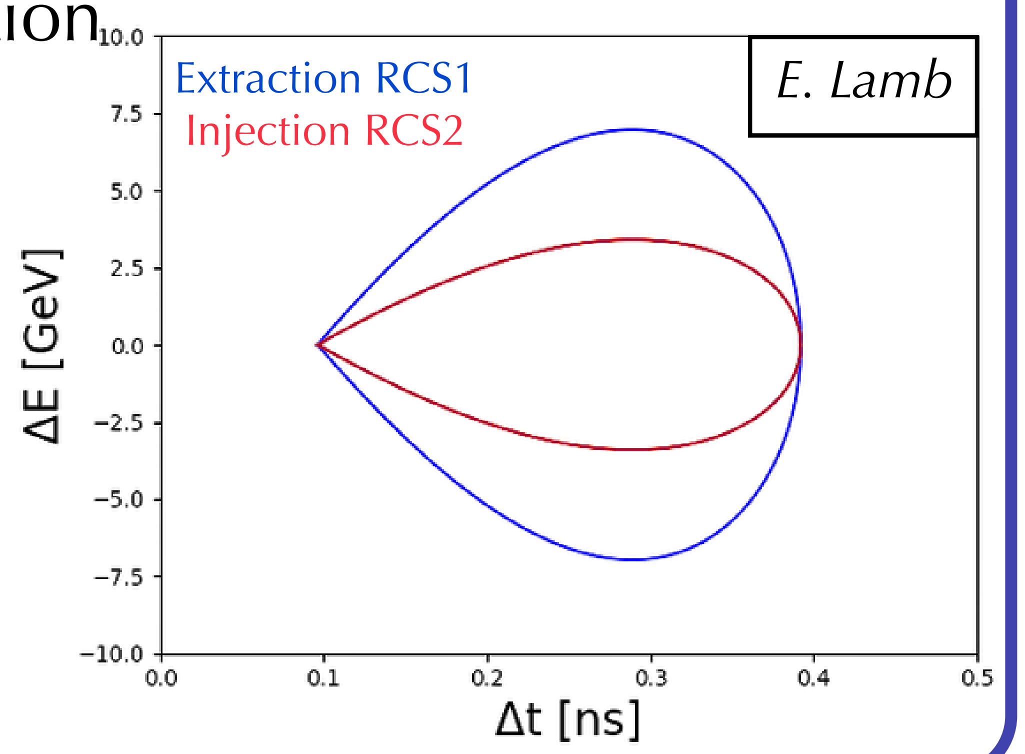
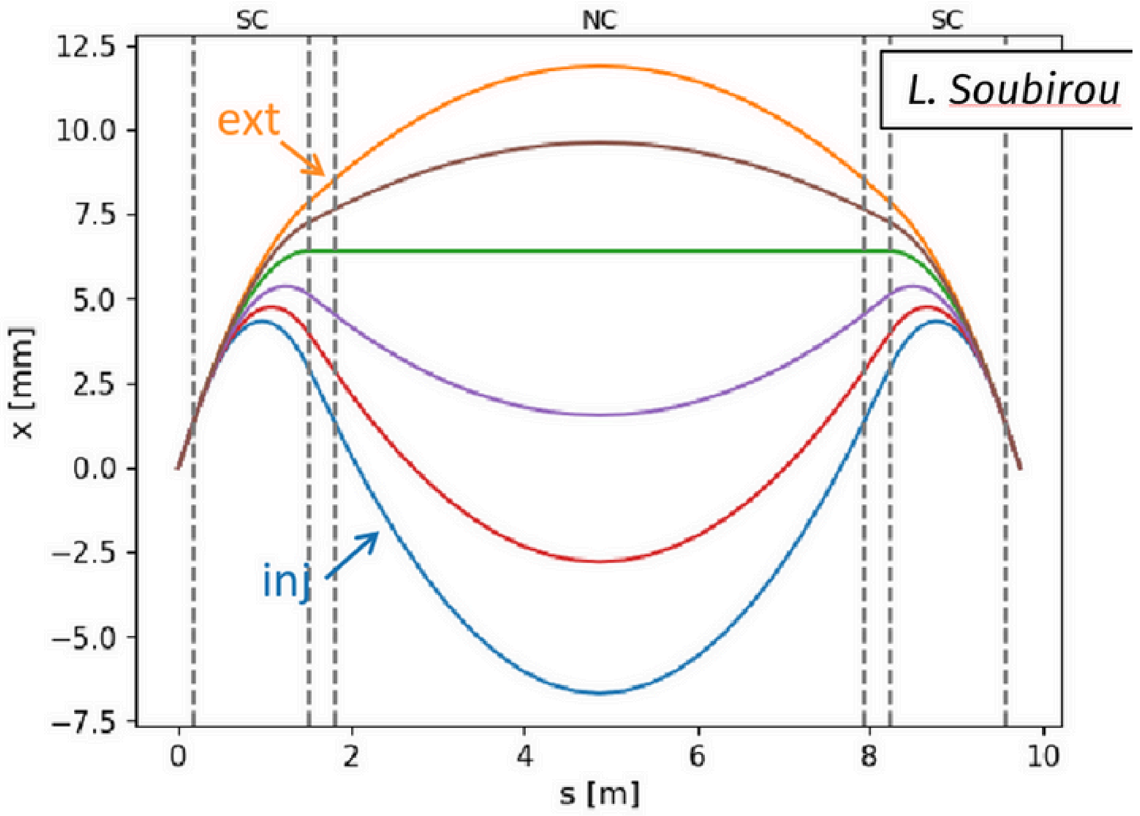



Hybrid RCS includes both *fast-ramping normal-conducting* magnets and *static superconducting* magnets:
This gives large orbits, and large magnet sizes

See Lisa's talk




**Plenary: Tuesday Afternoon**

15:30 **Acceleration Complex**

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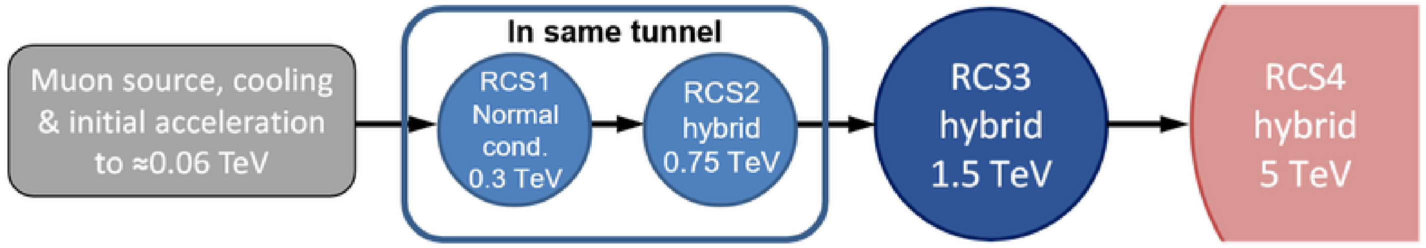
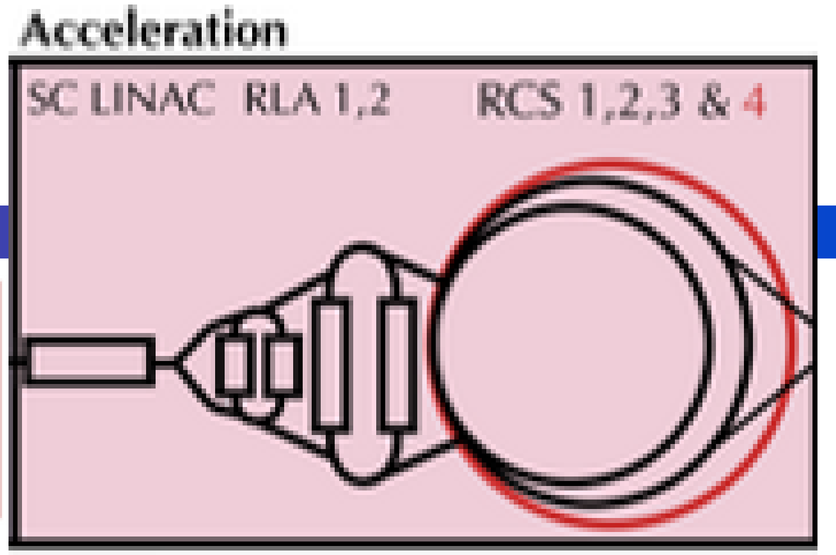
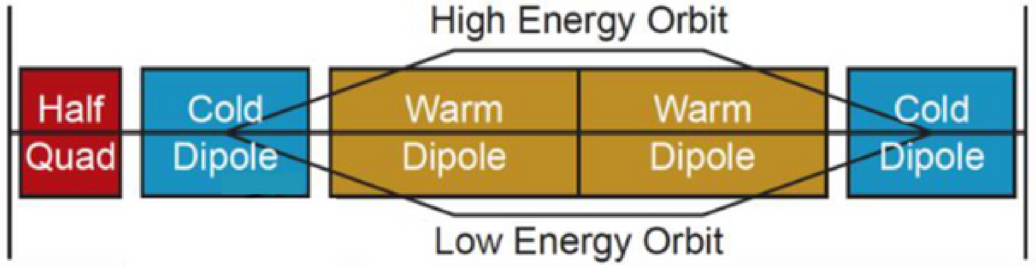
# **Acceleration** progress

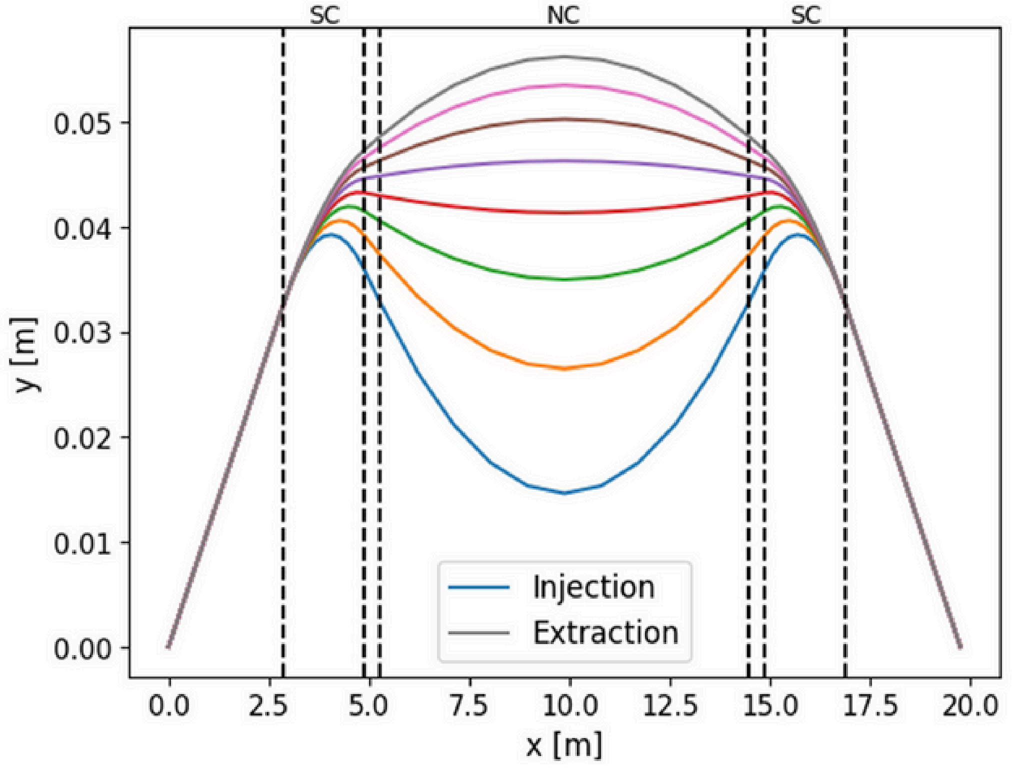
**Challenges:**
- Fast-Ramping NC magnets hybrid with static SC magnets
- Multiple RF stations throughout
- Large aperture from orbit

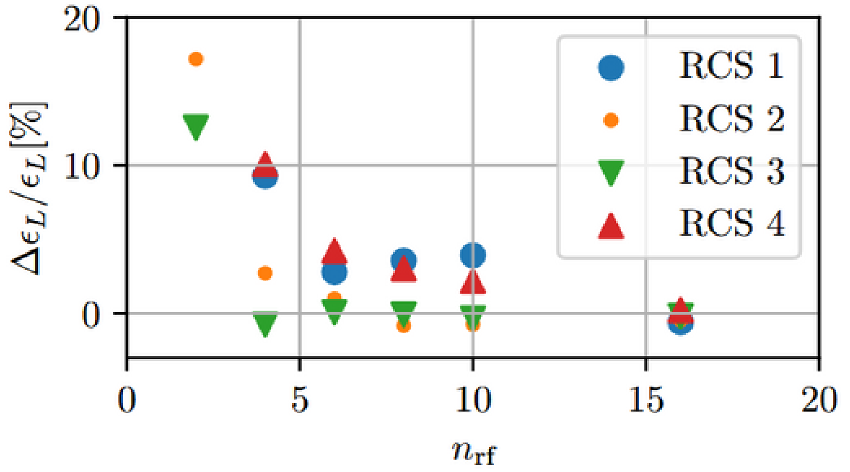
**Achievements:**
- Lattice designs & matching for greenfield and CERN RCS
- 1.3 GHz Tesla Cavities
- Impedance studies of RCSs

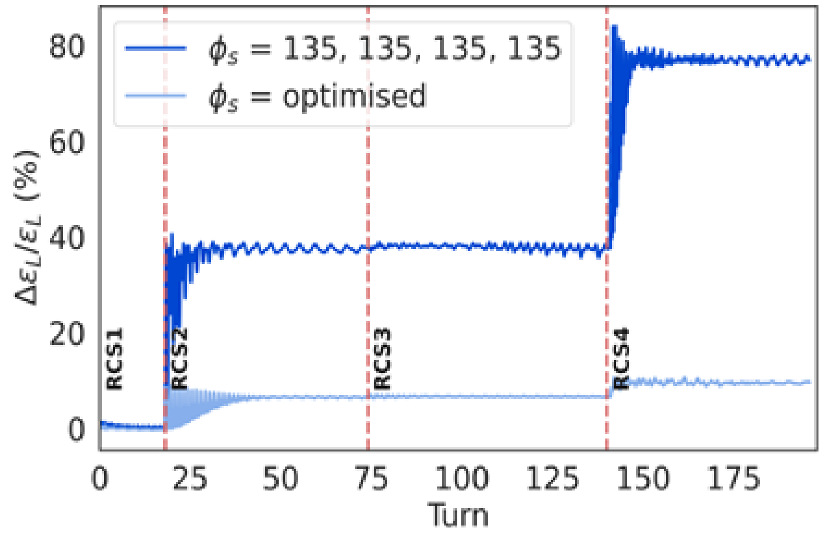


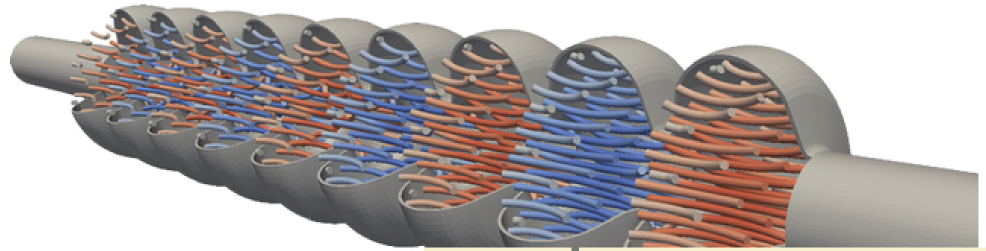



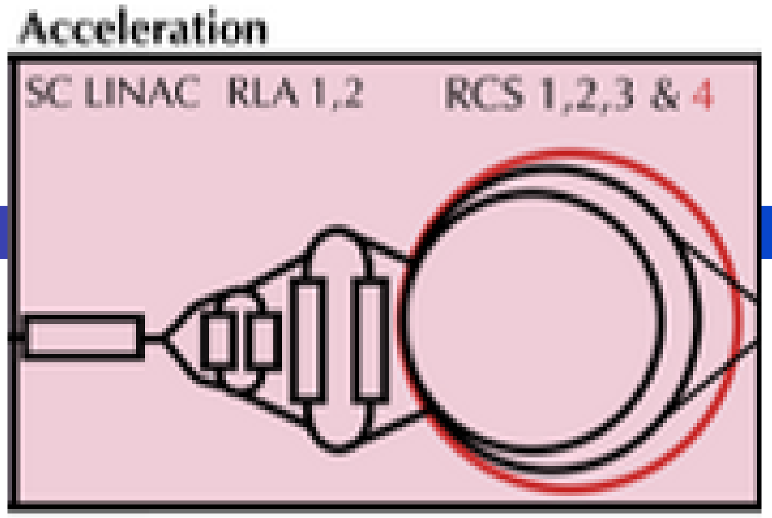




**Future R&D:**
- Designs of SC LINAC and Recirculating LINACS
- Validate power sources for 1.3 GHz
- Higher order mode damping schemes



14:20 **Progress on TeV acceleration for the Fermilab Muon Collider**
**Speaker**: Kyle Capobianco-Hogan (Stony Brook University)

# **Acceleration** progress

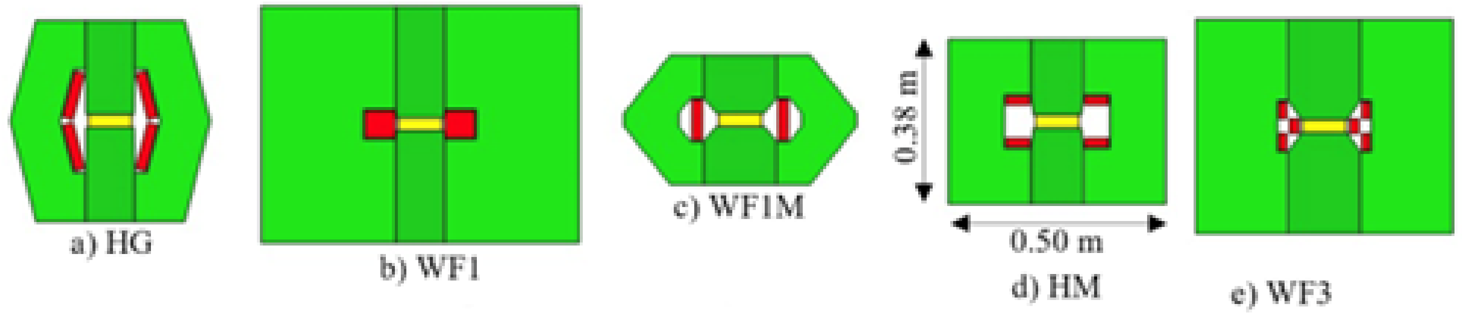



## Challenges:

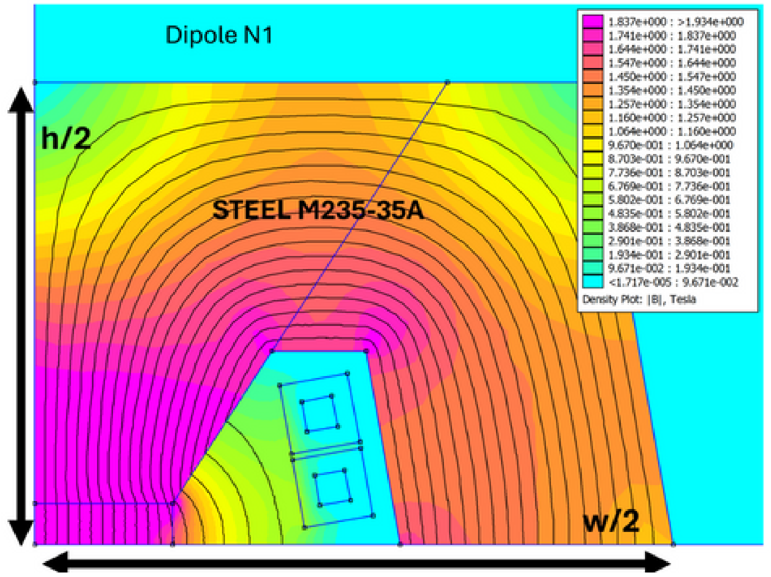
- 1-10 ms ramping NC magnets with 98-99% energy recovery of 200 MJ stored in magnets

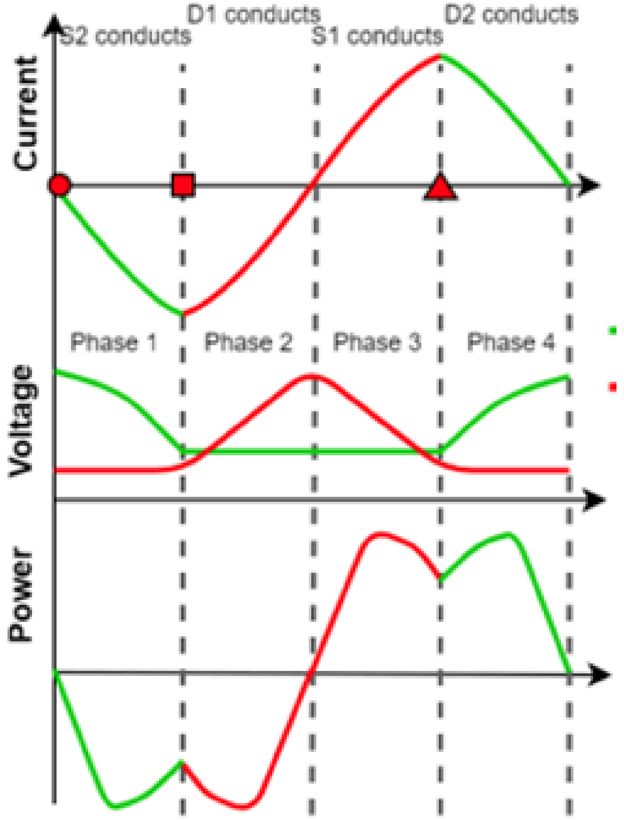
## Achievements:

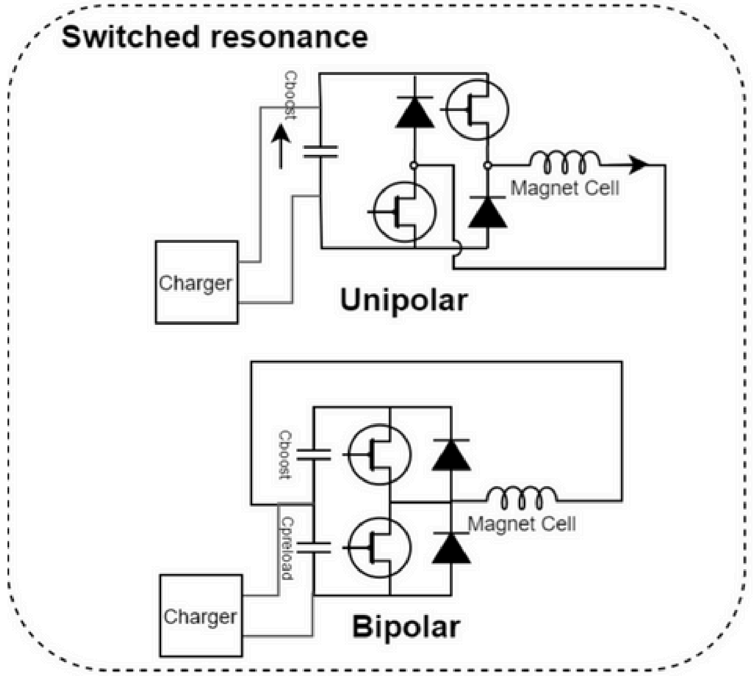
- Design of magnets, power converters, optimised together with RF
- Power converters switching magnet sign magnets without changing voltage direction




| RCS | E [J/m] | E_iron [J/m] | E_copper [J/m] | Loss [%] | P [MW] |
|---|---|---|---|---|---|
| SPS 1 | 5447 | 10 | 52 | **1.1** | 1.9 |
| LHC 1 | 5678 | 9.2 | 80.6 | **1.6** | 12.8 |
| LHC 2 | 5752 | 63.4 | 298 | **6.3/2** | 26.6 |




## Future R&D:

- 4 kT/s ramp rate
- Synergies with infineon for sustainable energy sources

# Why is the **collider ring** challenging?

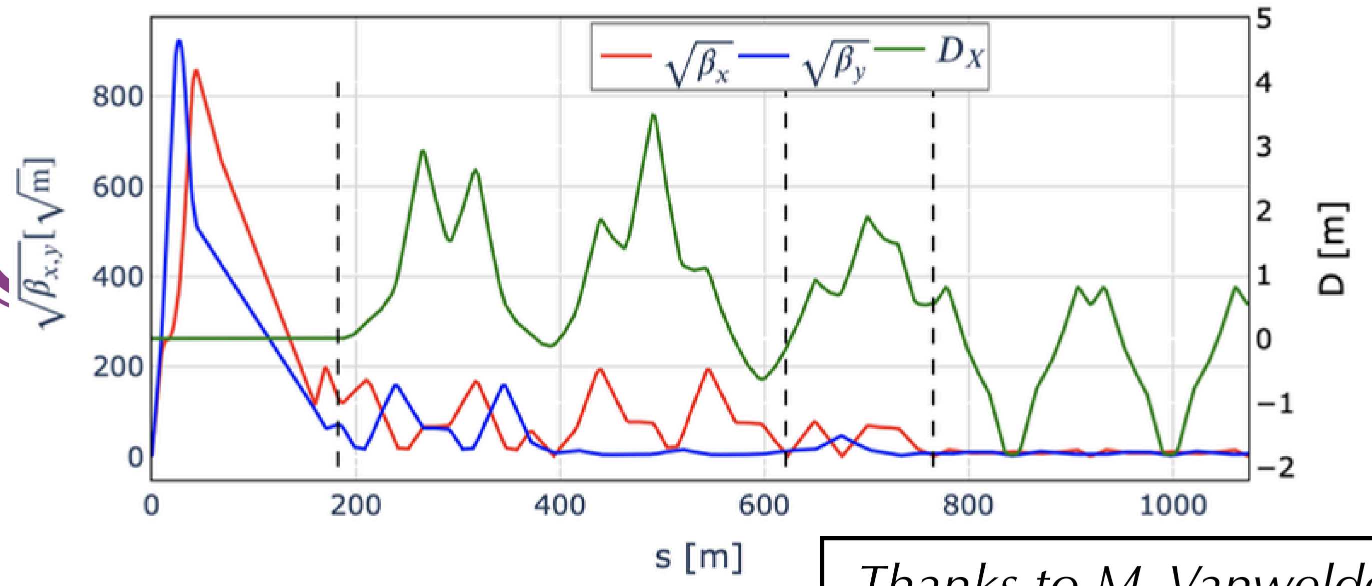
Short answer: The very small beta*

To get highly-focused beams at collision, the beta must first increase as much as possible (~700 km).

High beta means large beam sizes means high-amplitude effects, especially with momentum spreads. Requires large magnet sizes.

## Concept: ***Beta function***

Emittance is constant, but the beam size changes according to focusing. $\sigma(s) = \sqrt{\epsilon \cdot \beta(s)}$ Known as *beta*, this parameter is periodic throughout a synchrotron.




*Thanks to M. Vanwelde*

**Plenary: Wednesday Morning**

09:00 **Collider Ring**

**Speaker**: Dr Eliana Gianfelice-Wendt (Fermilab)

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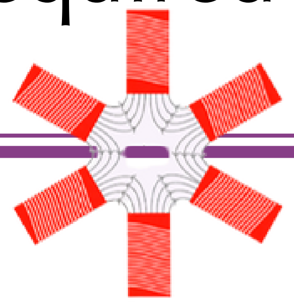
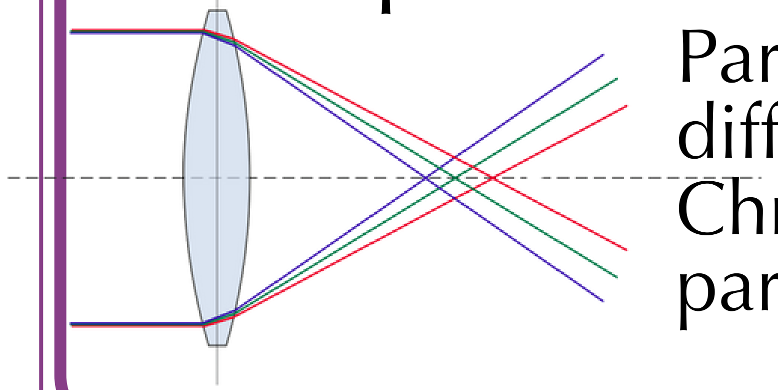
Large beta causes strong *chromatic effects*, especially to prior to the interaction point. Required dedicated correction via *sextupole* magnets.



### Concept: ***Chromaticity***



Particles with different energy will focus at different points. This affects their *tune*. Chromaticity is the linear correlation between particle momentum and tune.

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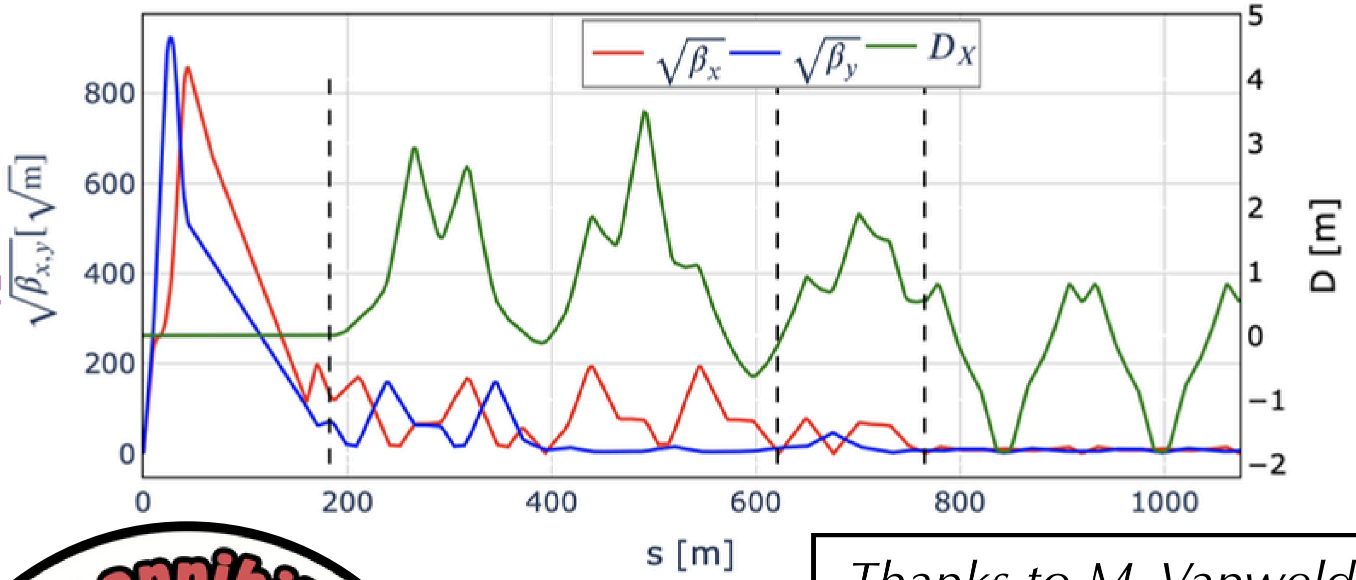



*Thanks to M. Vanwelde*


**Plenary: Wednesday Morning**

09:00 **Collider Ring**

**Speaker**: Dr Eliana Gianfelice-Wendt (Fermilab)

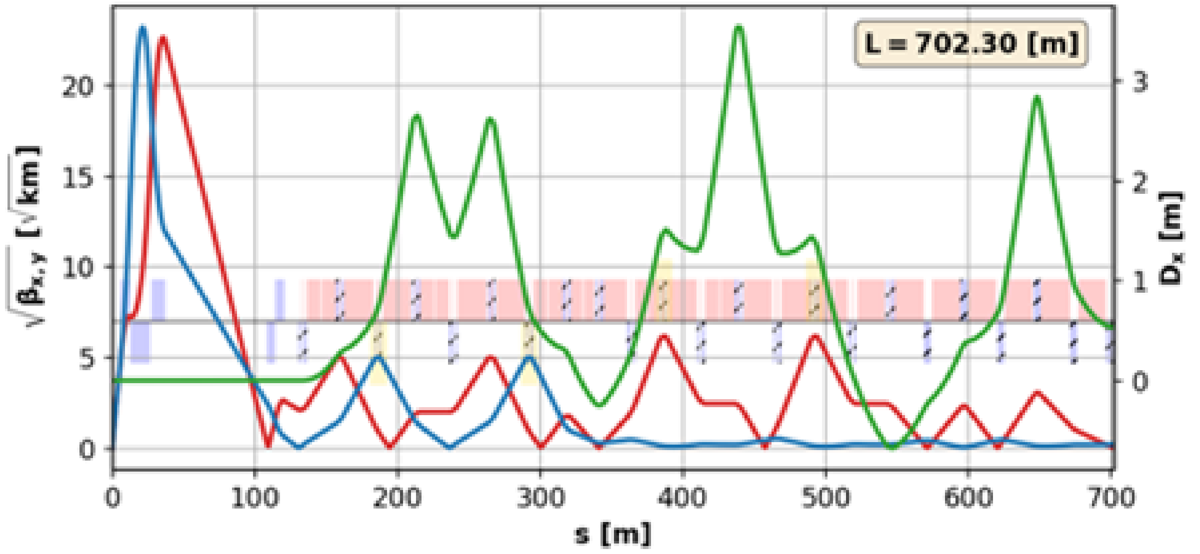
# Collider progress

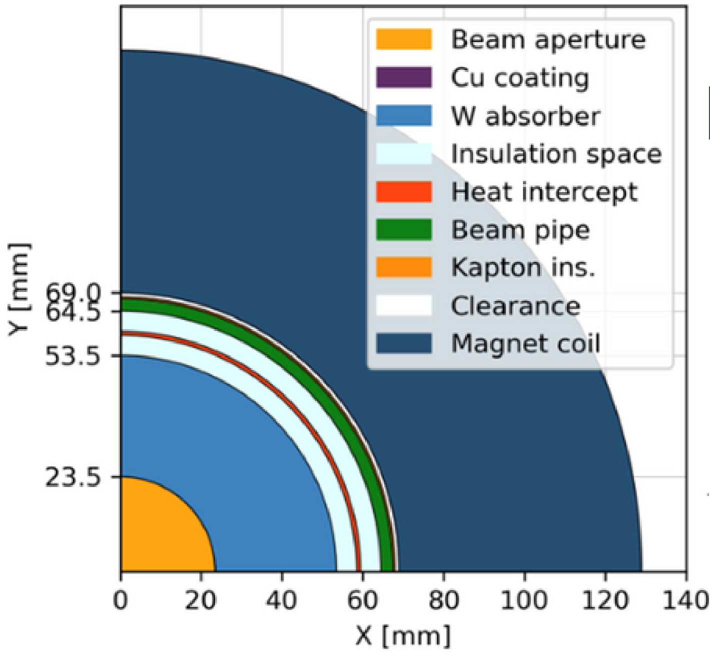
**Challenges:**

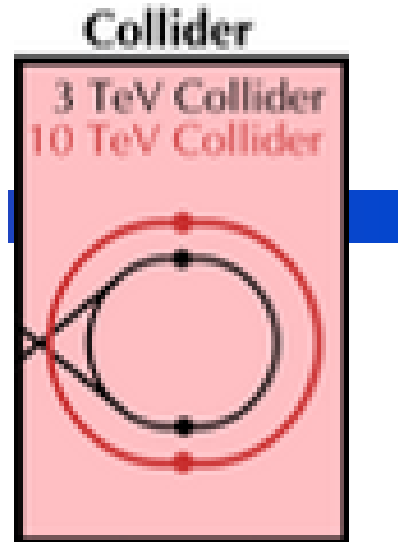
- Lattice design with $\beta^*$ 1.5 – 5 mm
- 0.1% beam energy spread
- High radiation, 500 W/m loss
- High magnetic field / aperture

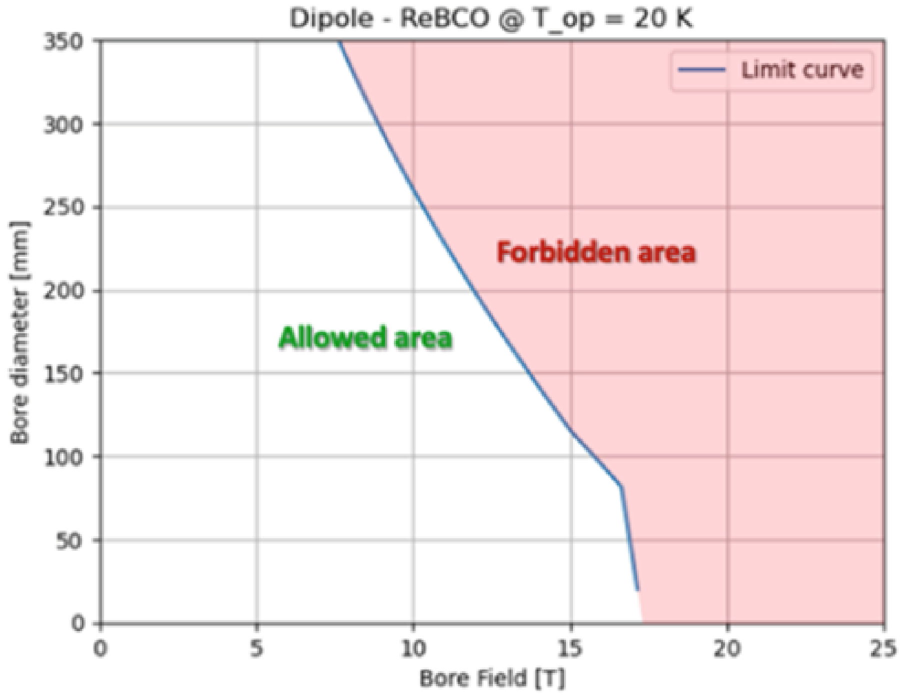
**Achievements:**

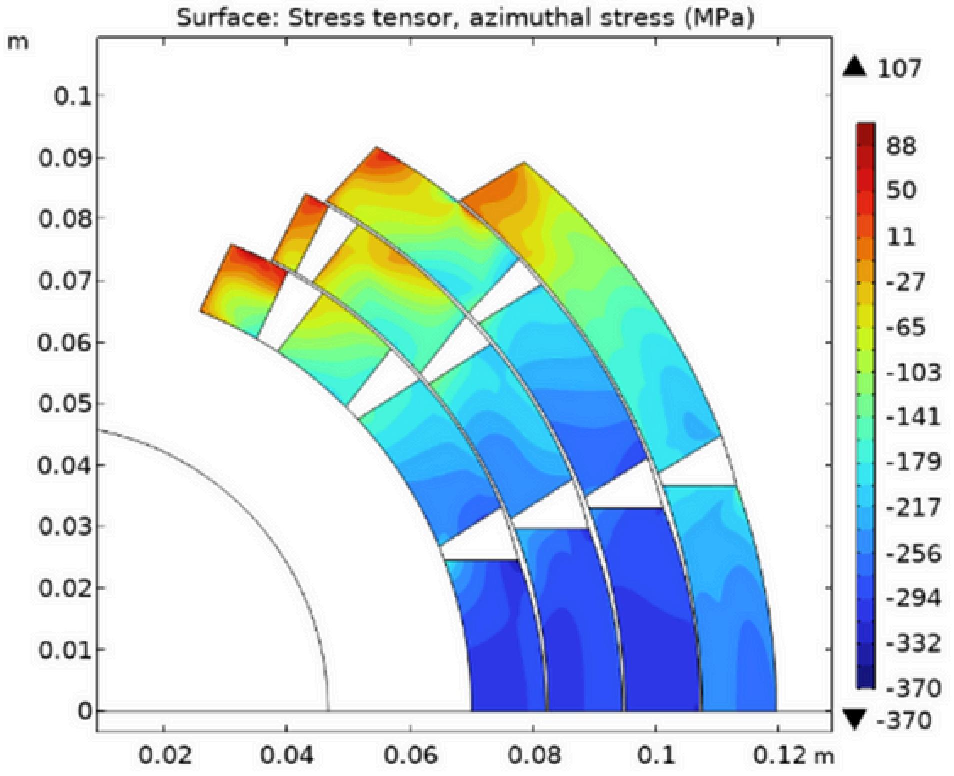
- Magnetic shielding design
- Cryogenic concept
- Impedance models




**Future R&D:**

- Studies on machine imperfections and misalignment
- Improve energy acceptance compensating chromatic effects
- *NbTi*: 4.8 T, 16 cm / *Nb3Sn*: 11 T, 16 cm / *HTS*: 14 T, 14 cm

Experimental programme is now essential

# Why is **decay** challenging?

Short answer: Time

Muons have a rest lifetime of *2.2 us*.

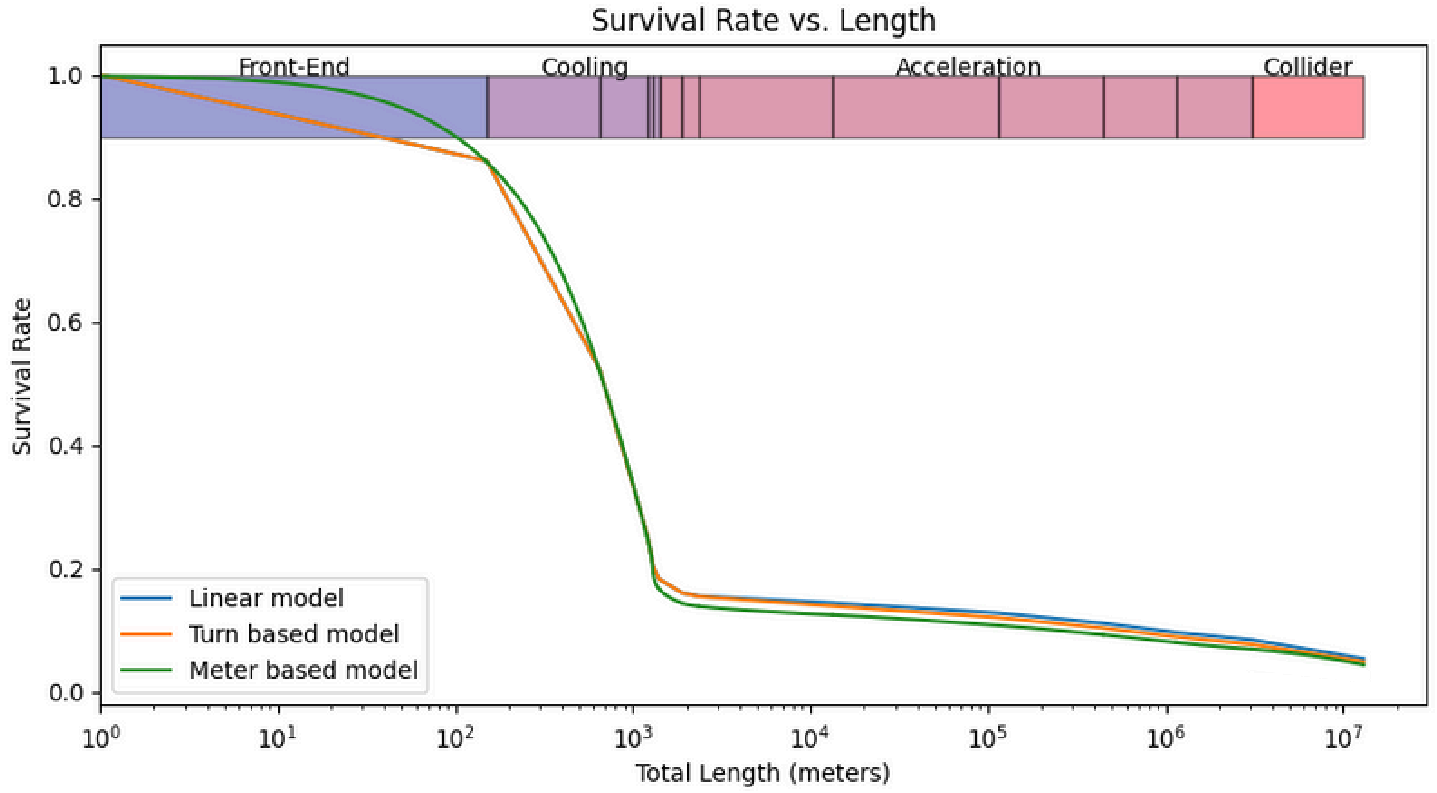
At 5 TeV, this would be 110 ms.
At 1.5 TeV, this would be 30 ms.

The speed throughout the muon collider *changes*.

- Have a decay 'budget', based on energy and length
  - Earlier stages are shorter but have non-relativistic energies
  - Later stages are longer, have multiple passes, but relativistic energies

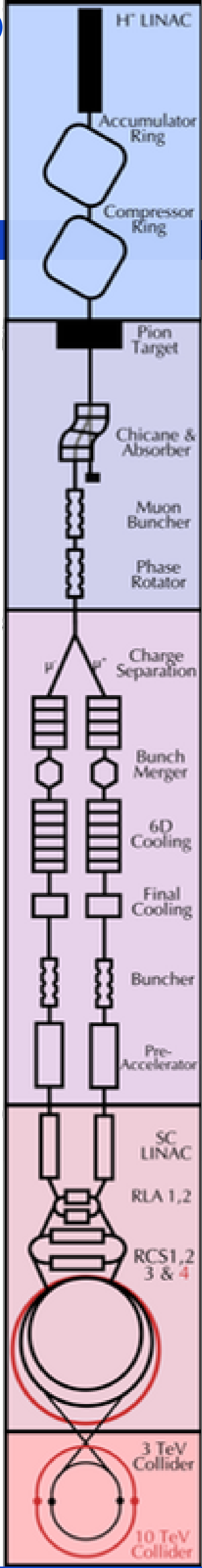
| System: | RLA1 | RLA2 | RCS1 | RCS2 | RCS3 | RCS4 |
|---|---|---|---|---|---|---|
| Passes: | 4.5 | 4.5 | 17 | 55 | 66 | 55 |

Currently estimate 5% of muons survive.
But full start-to-end simulation required.

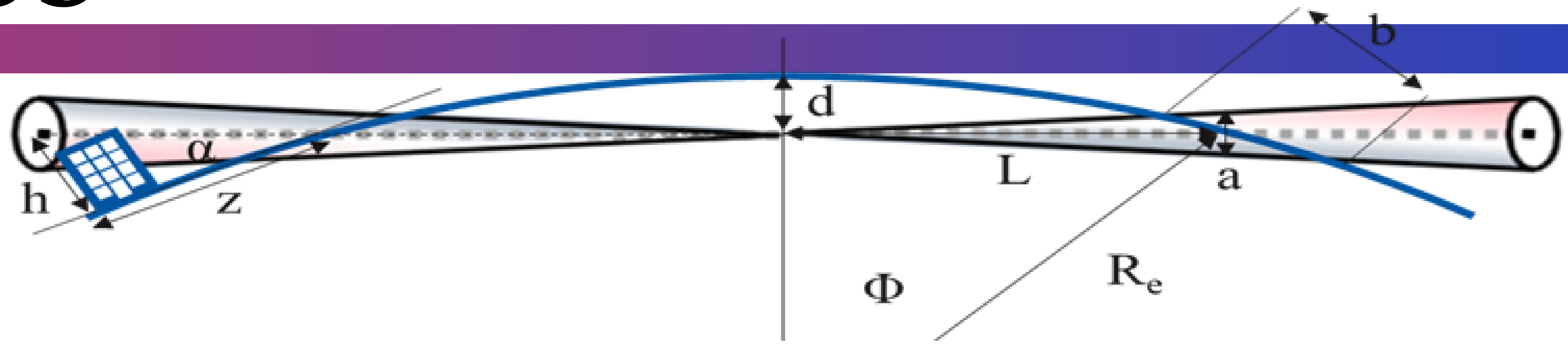


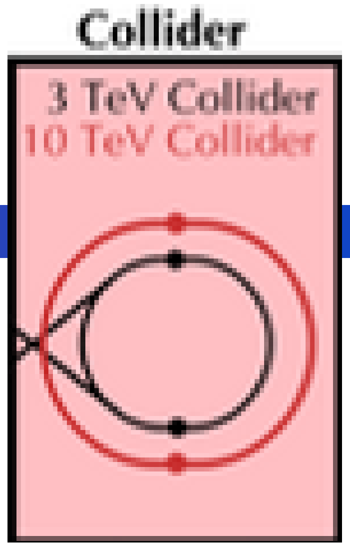

Short answer: Neutrinos

Neutrino radiation at the collider must remain negligible at the earths' surface. Affects design of the straight sections to prevent build-up of muon decay in one direction.



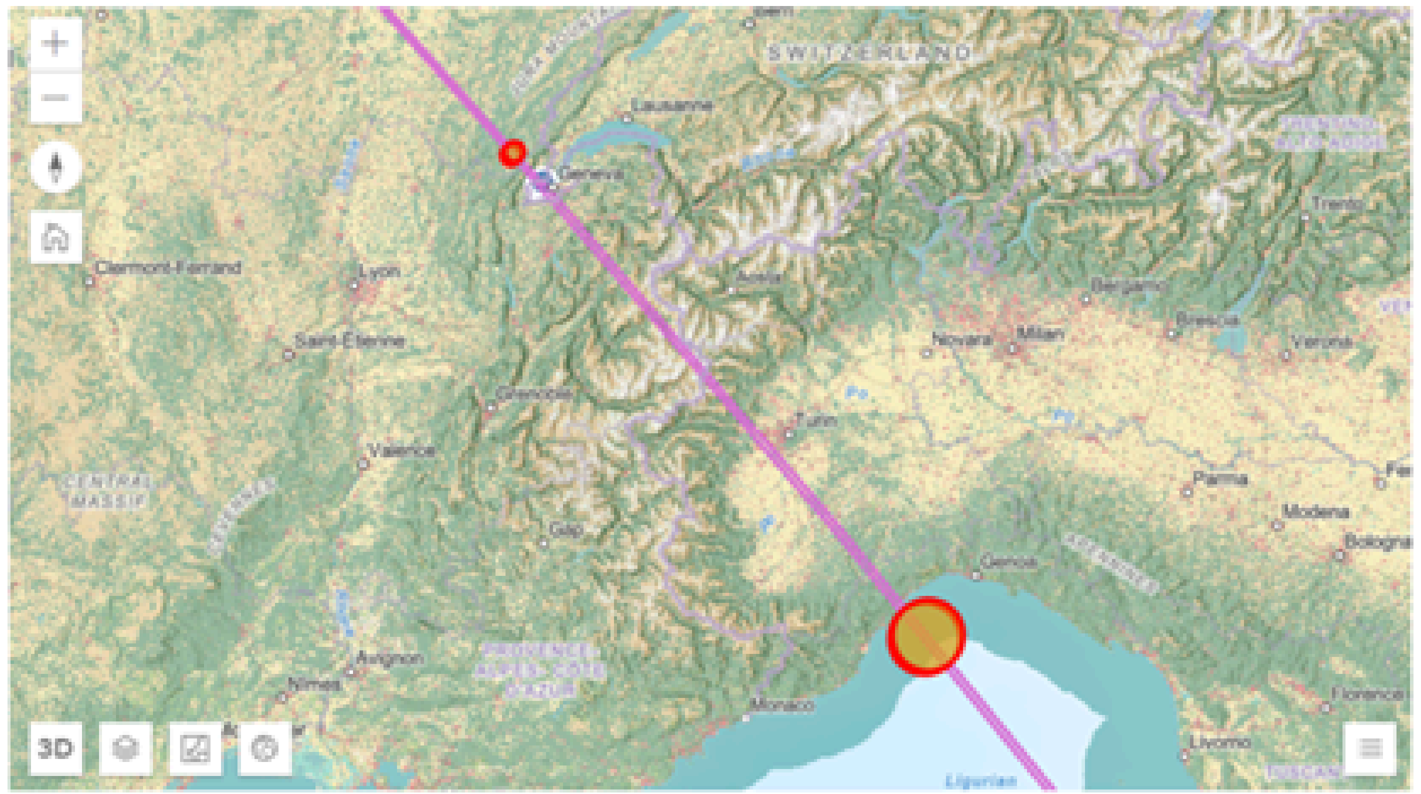
# **Collider** progress

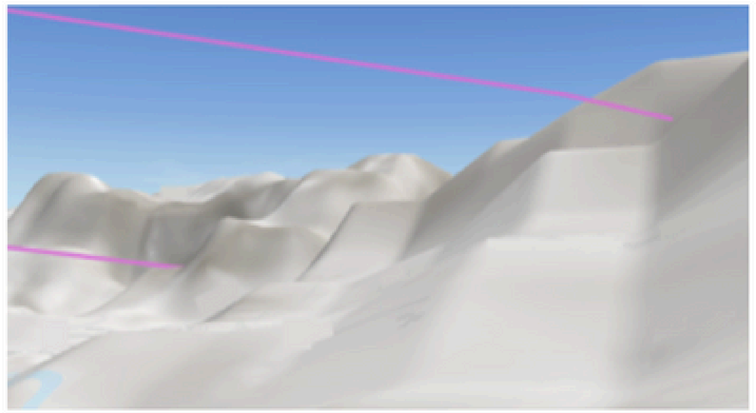


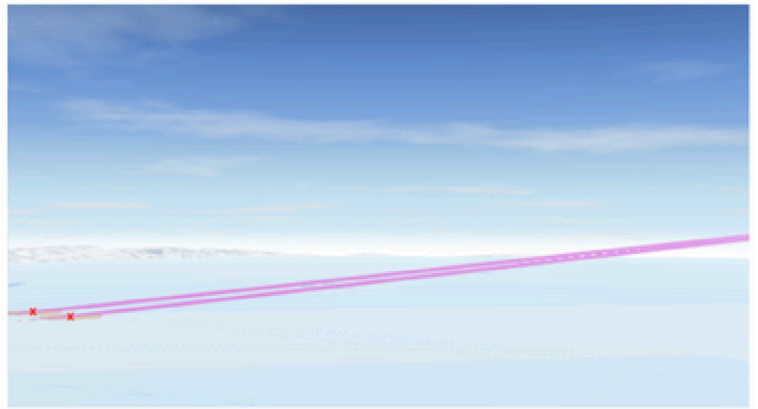



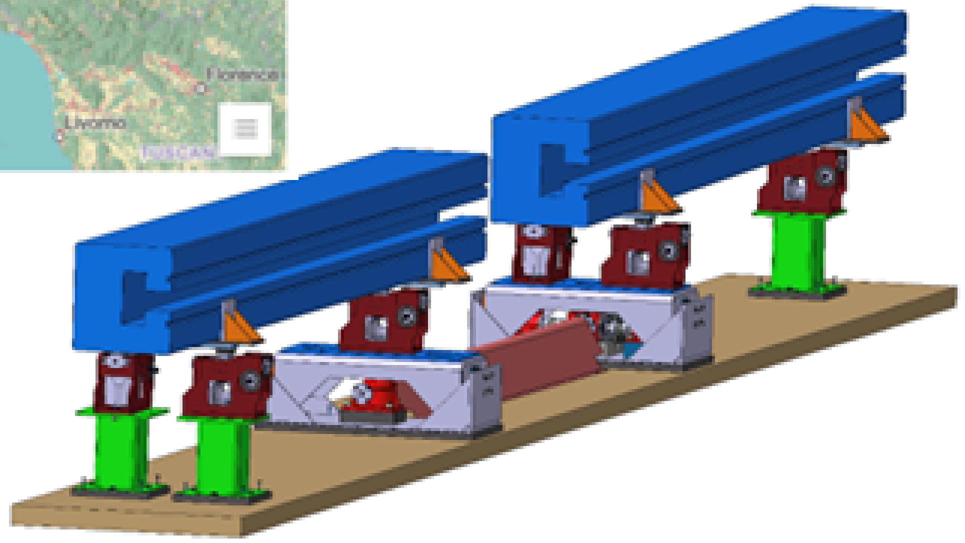

**Challenges:**
- Negiliable neutrino flux
- Orient collider to benefit neutrino detector studies

**Achievements:**
- Geoprofiler for detailed modelling
- Orientation options found
- Conceptualised mover system



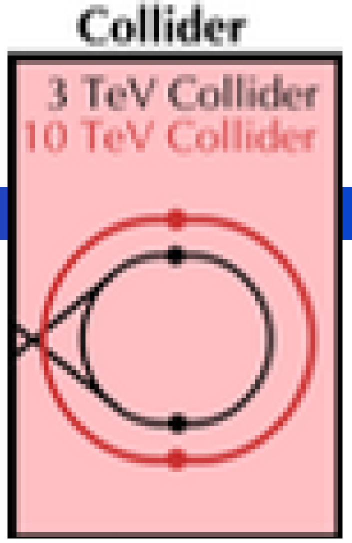







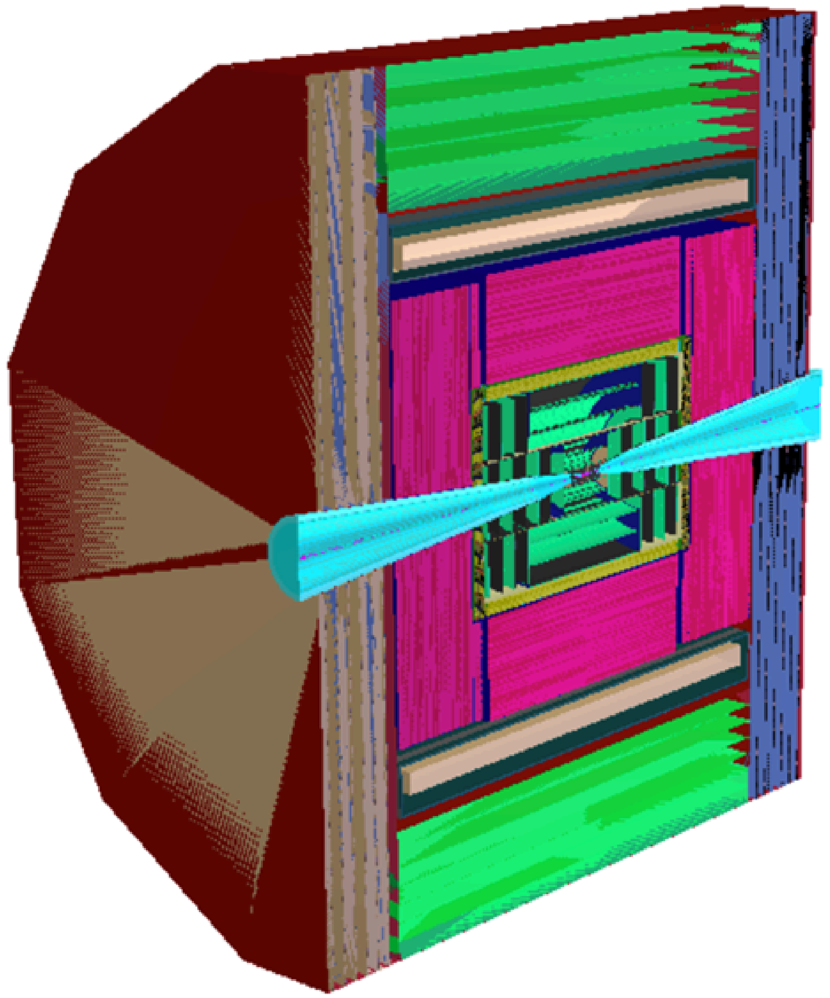
**Future R&D:**
- Jack development programme to reach 1 mrad with 0.004 mrad tolerance
- Further iteration with collider lattice

# Detector progress

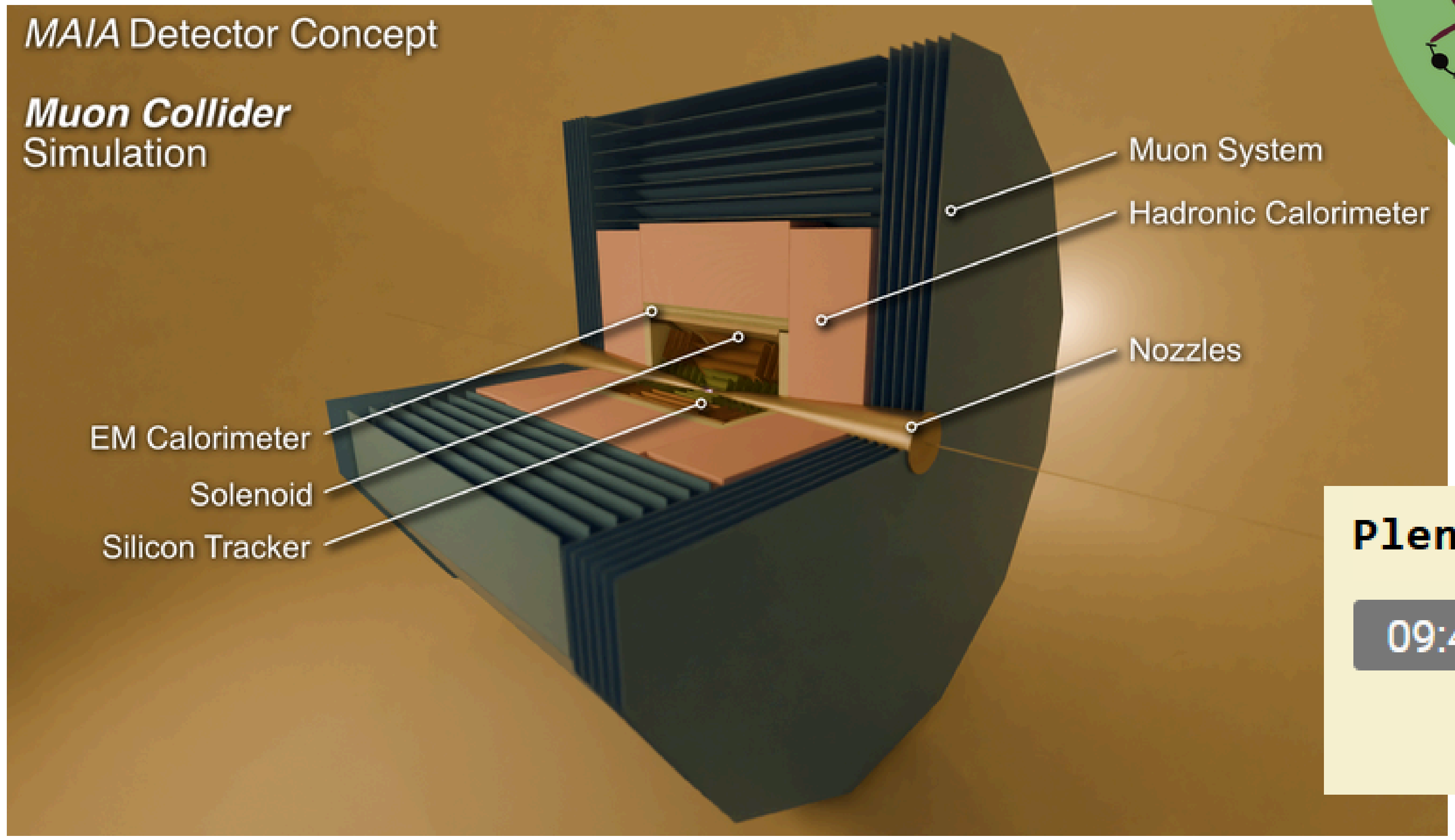

## MUSIC

Muon Smasher for Interesting Collisions



## MAIA

Muon Accelerator Instrumented Apparatus



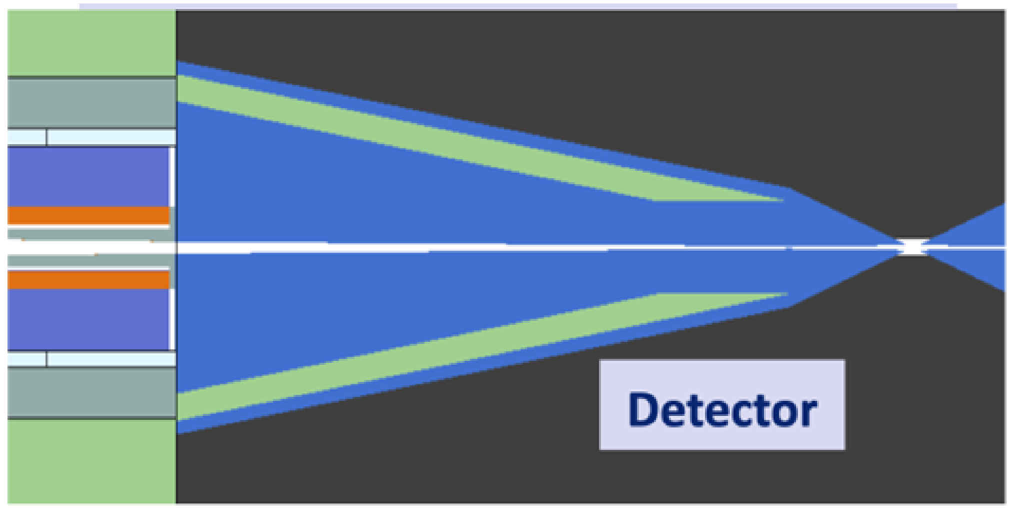

**Plenary: Wednesday Morning**

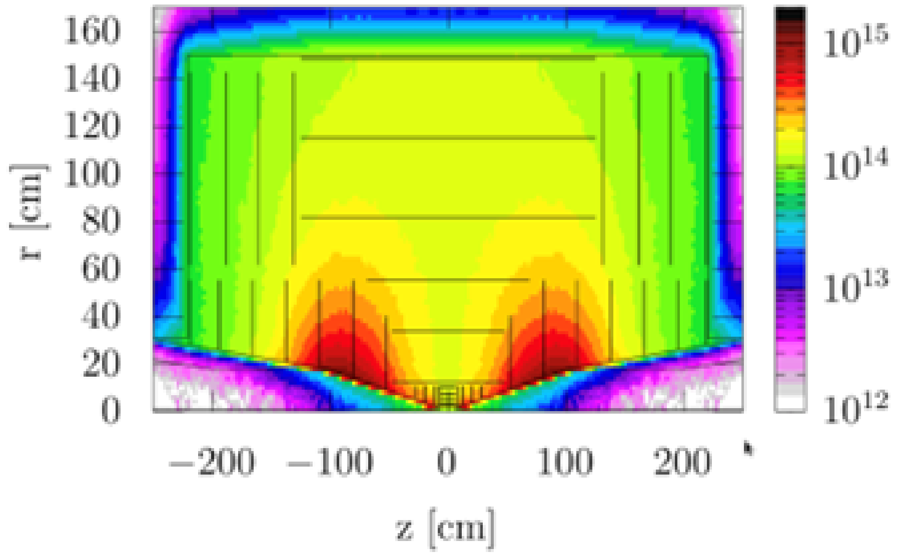
09:45 **MDI Design**

**Speaker**: Dr Donatella Lucchesi (INFN)

**Future R&D:**

- Reconstructing events with high BIB
- Tungsten nozzle configuration
- State-of-the-art detector technologies



# Useful Links

**IMCC Mattermost:**

- Can be accessed with a guest account
- Channels for each section
- Direct communication to members of the IMCC active community
  - (Don't need to know who you're messaging)

**Early Career Mailing List:**

- Informal, open to those external to USMCC/IMCC interested in muons
- Workshops, job openings can be advertised here

**MuonCollider-Facilities Mailing List:**

- The main Muon Collider mailing list in IMCC. Best way to stay in touch.

Other mailing lists can be subscribed on e-groups.cern.ch
Search for "*muoncollider*". (Some may be less active):

- detector, cooling, magnets, mdi, rf, test facilities, coffee meeting

# Conclusion



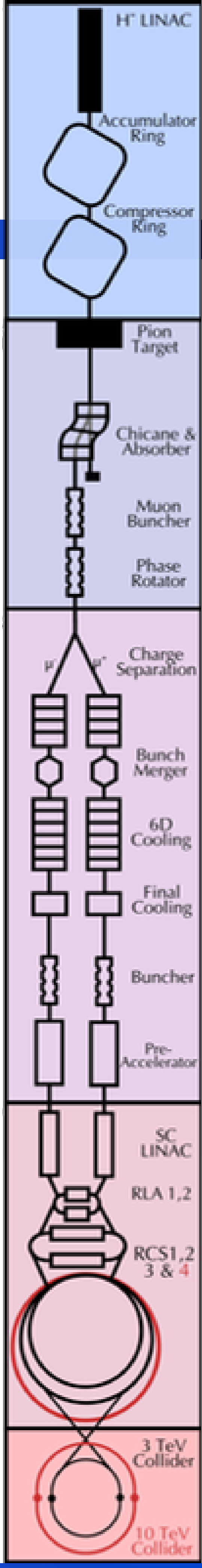
The beam physics challenges change across the muon collider.

Each system requires a different combination of simulation codes to accurately model their effects.

Modelling these systems is essential to begin the design process and guide magnet/RF/technological limits.

A start-to-end simulation would ensure matching between systems and model rate of muon decay.

Overall aim is to provide a design which meets the goals of energy, intensity and luminosity, at interaction points.

# Thank you

International MUON Collider Collaboration

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