IMCC and MuCol Annual Meeting 2025

Cross-Pollination Crash Course
Muon Collider Beam Physics

12th May 2025

R. Taylor

International MUON Collider Collaboration

MuCol

Funded by the European Union

CLUSTER OF EXCELLENCE QUANTUM UNIVERSE

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

CERN

Content

1) What do we need to deliver to the experiments

2) Why is this challenging

3) Muon collider overview

4) Brief Introduction to beam optics

5) Why is the [▼] challenging

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

One example per system

What is the Muon Collider?

A **particle accelerator** which produces, accelerates and collides **muons**.

What is an accelerator?
A machine for accelerating **charged particles** to **high energies** using **electric** or **magnetic** fields.

What is a muon?
A fundamental particle, a lepton, 'heavier' electron, 2.2us lifetime, 105MeV mass

Further details in
Muon Collider Theory

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The muon collider has:

- **High energy** reach of protons, due to high mass / low bremsstrahlung
- **High precision** of electrons, as the muon is fundamental

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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 MuCol
Following ESPPU 2022
2023 --->

Let's Shoot For The Muon!

Further details in
Muon Collider Theory

What will we deliver to the detector?

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

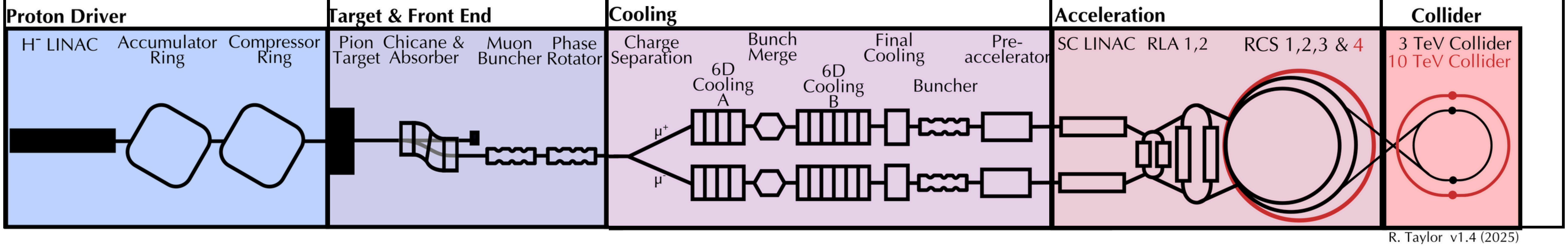
Luminosity also depends on:

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

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

Why is this challenging?

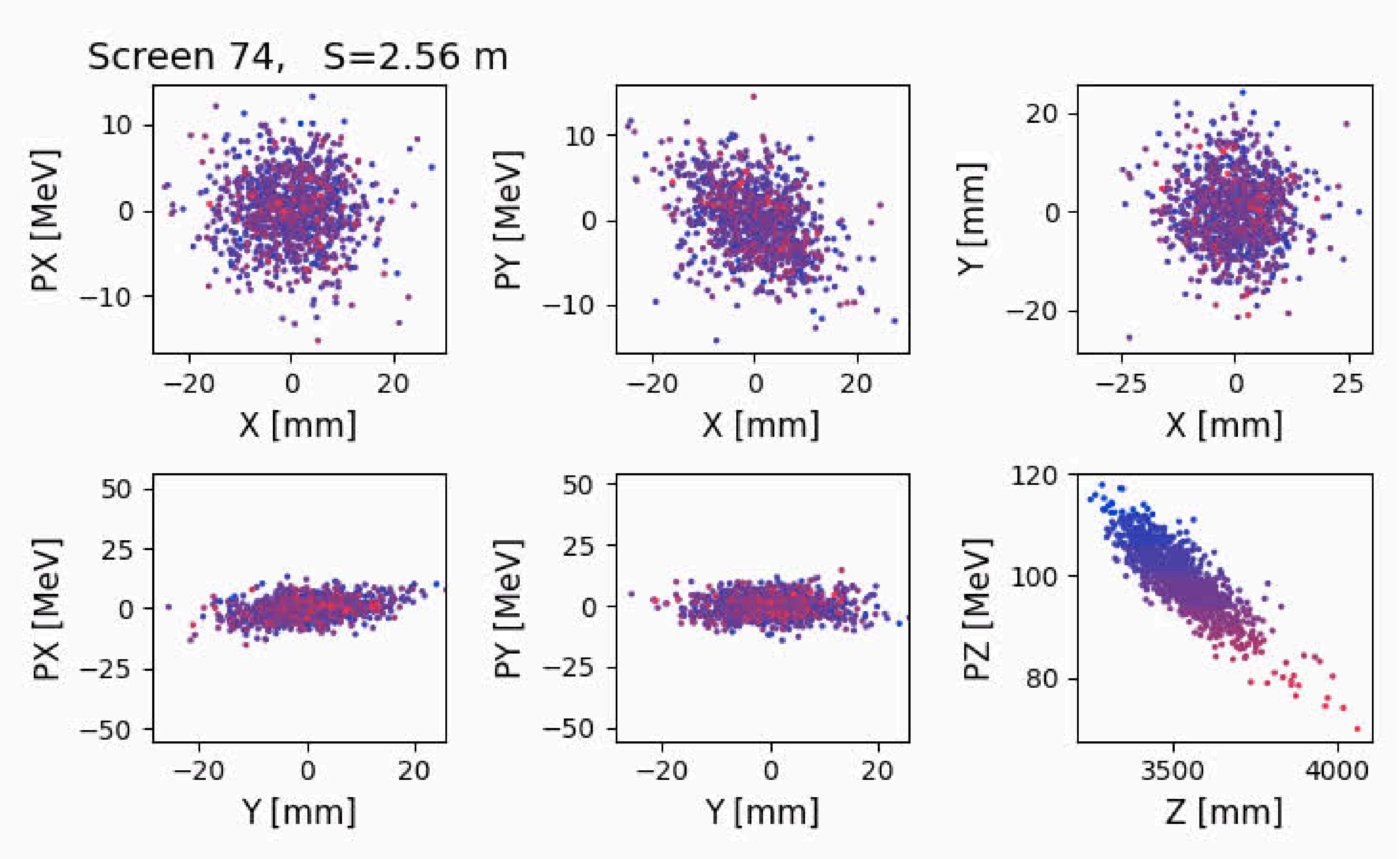
1) Need to produce the muons		2) The muons decay		
A) Produce a high power proton beam	B) Target material to withstand high-power	A) Quickly reduce the beam size	B) Quickly Accelerate	C) Collide small beams



3) Need to adjust for collective effects due to high intensity beam across the complex.

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

Transverse

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

pz: Longitudinal momentum

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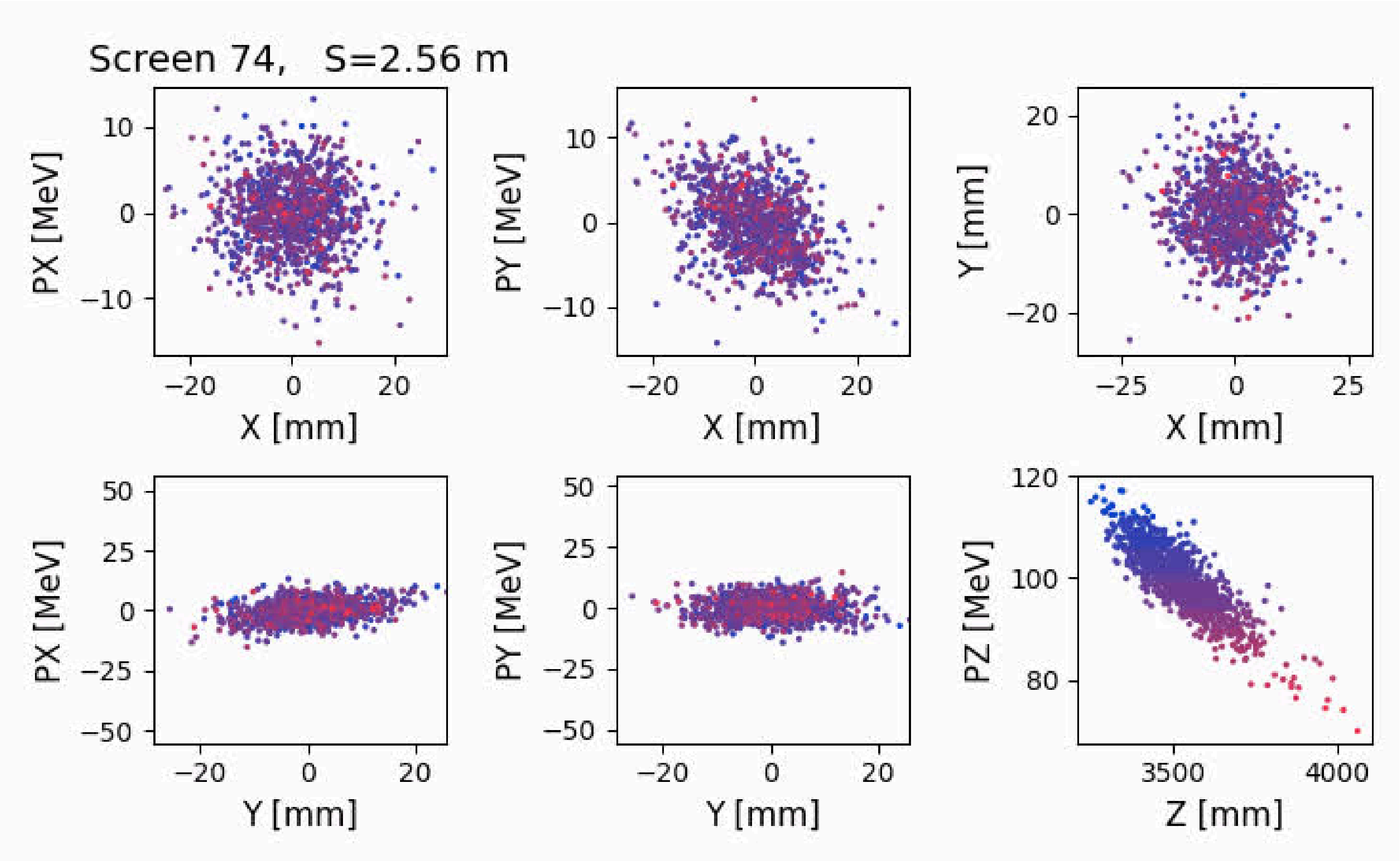

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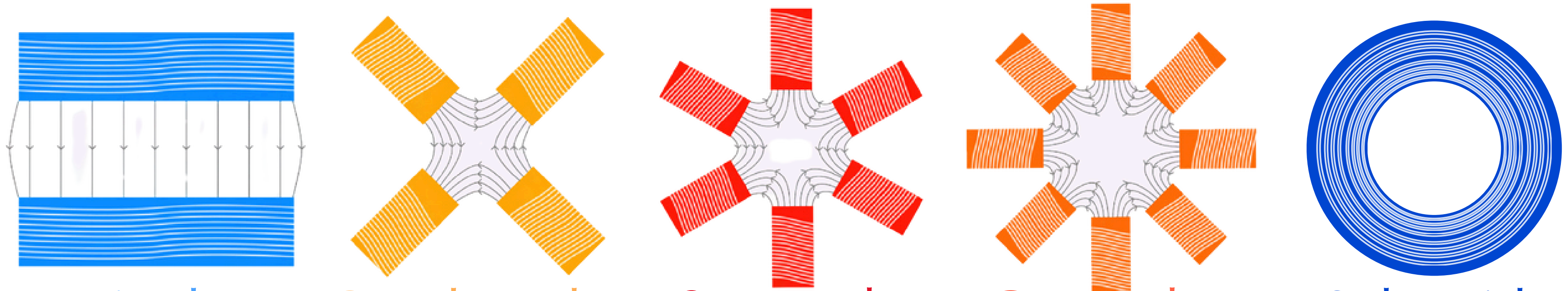
Two* philosophies to simulations:

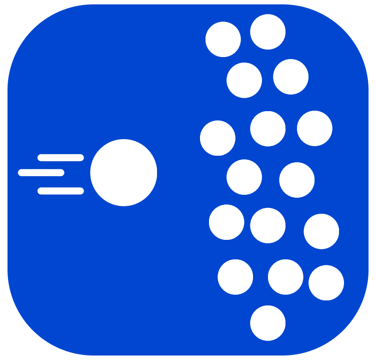
-Either model magnets as a **matrix**, applied to the 6D phase-space vector.
-Or model magnets as a **fieldmap** (Bx, By, Bz), and interpolate forces in steps.



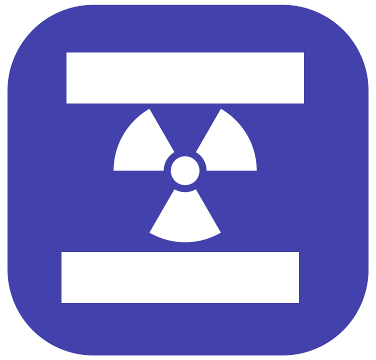
*at least two

Why are simulations challenging?

Simulation code wish-list includes...

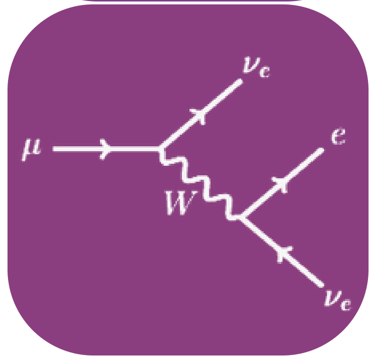


Particle interactions with matter
Target, Cooling, MDI

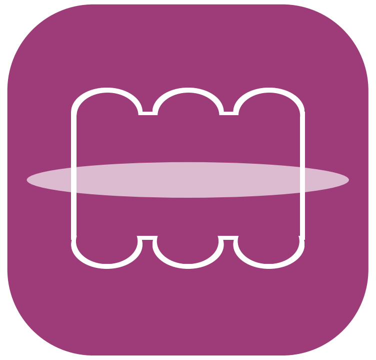


Radiation effects on surrounding materials
Target, Collider

Overlapping elements in high Bz fields
Target, Front-End, Cooling



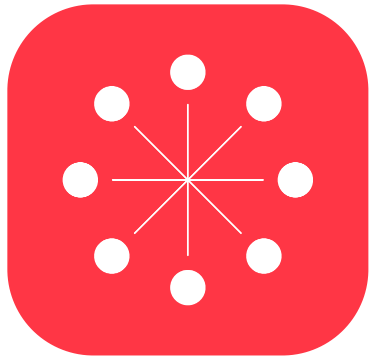
Muon decay and tracking secondaries
Everywhere



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

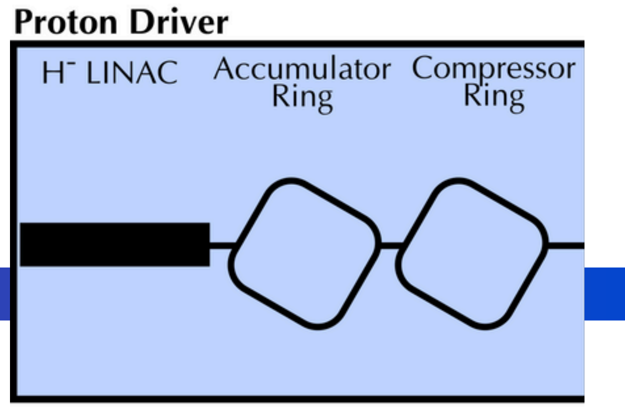
Matching beam conditions between synchrotrons
Accelerator, Collider, (Everywhere)

Non-linear effects
Collider



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

Why is the **proton driver** challenging?

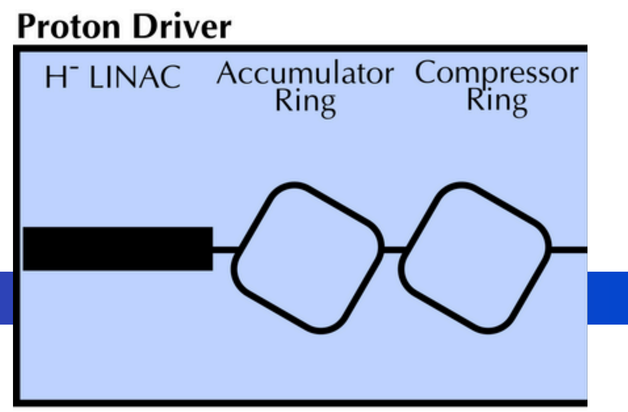


Short answer: Needs an intense, short beam.

For more information, tomorrow

Accelerator parallel: Proton Driver

DESY 08:30 - 10:15



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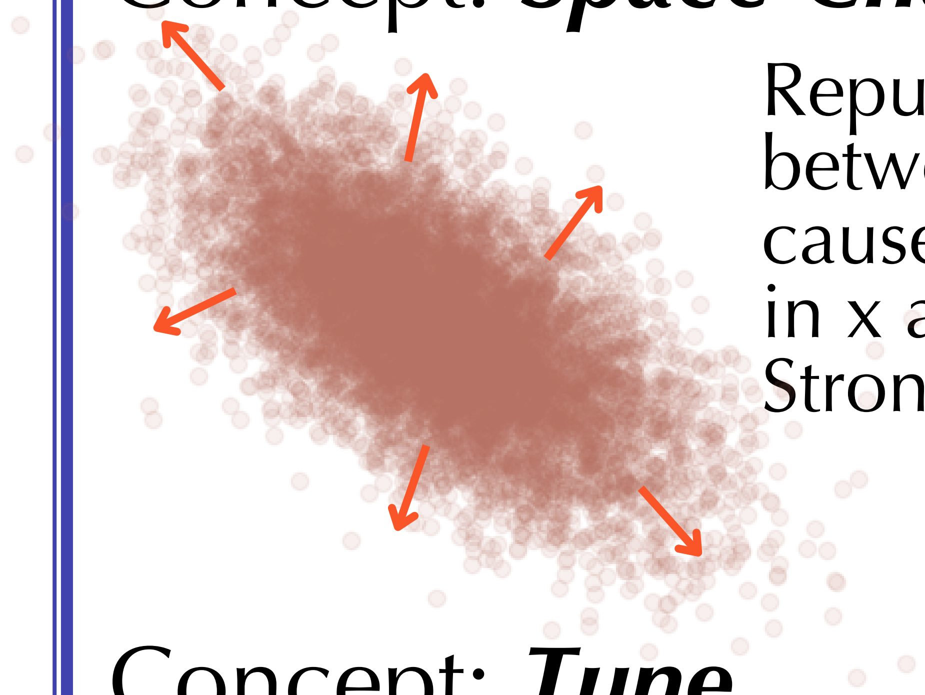
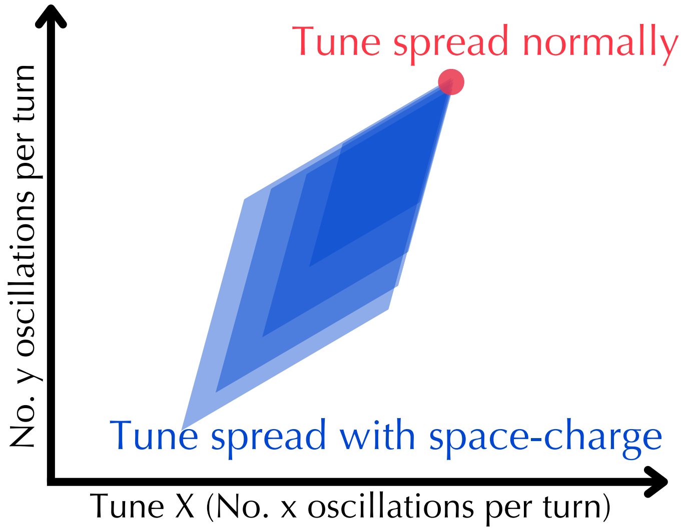
Concept: ***Space Charge***

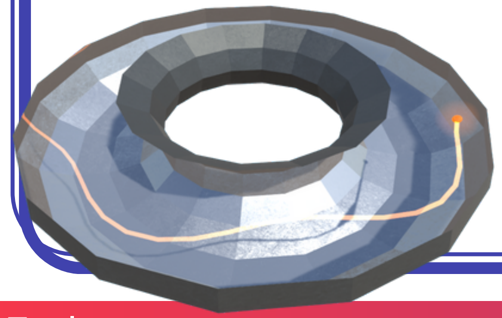


Repulsive forces between particles causes de-focusing in x and y and z. Stronger at low E.

Concept: ***Tune***

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





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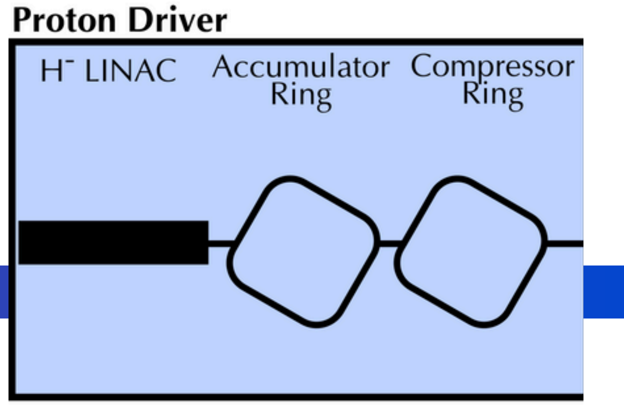

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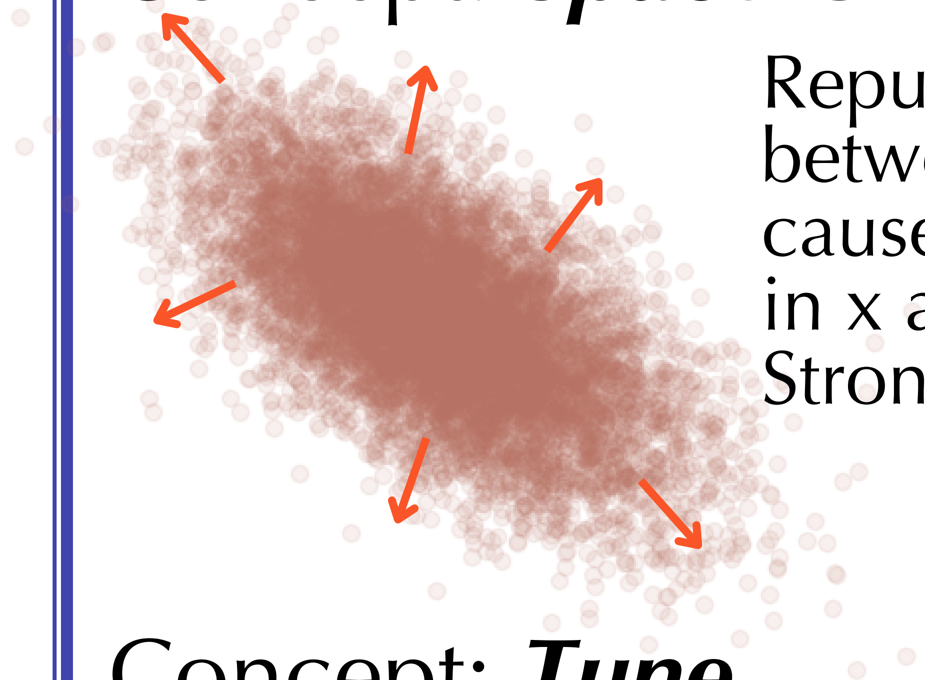

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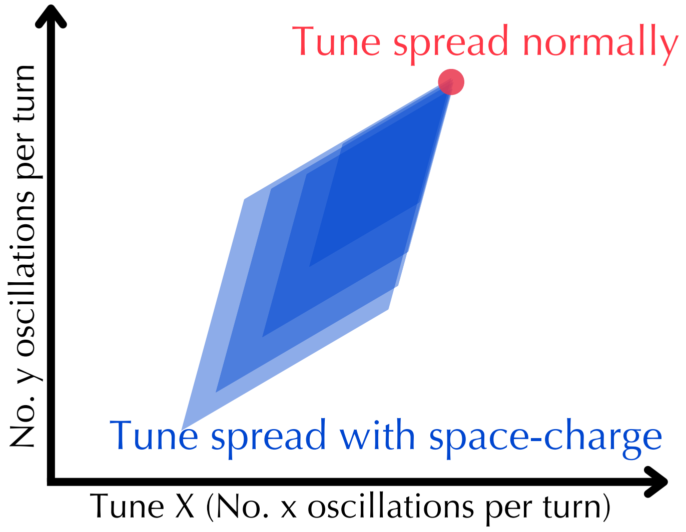

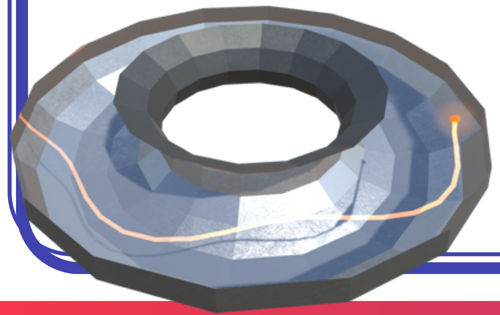

Parameters request a **2 MW** beam at **5 GeV** or a **4 MW** beam at **10 GeV**.

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.

For more information, tomorrow

Accelerator parallel: Proton Driver

DESY 08:30 - 10:15

Thanks to S. Johannesson

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

A 2 MW or 4 MW p+ beam

Target

Graphite or liquid metal

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

For more information, tomorrow

Thanks to P. Jurj

Accelerator technology parallel: Target technologies
DESY 10:45 - 12:30

Accelerator parallel: Muon Production, Radiation & Magnets
DESY 16:15 - 18:00

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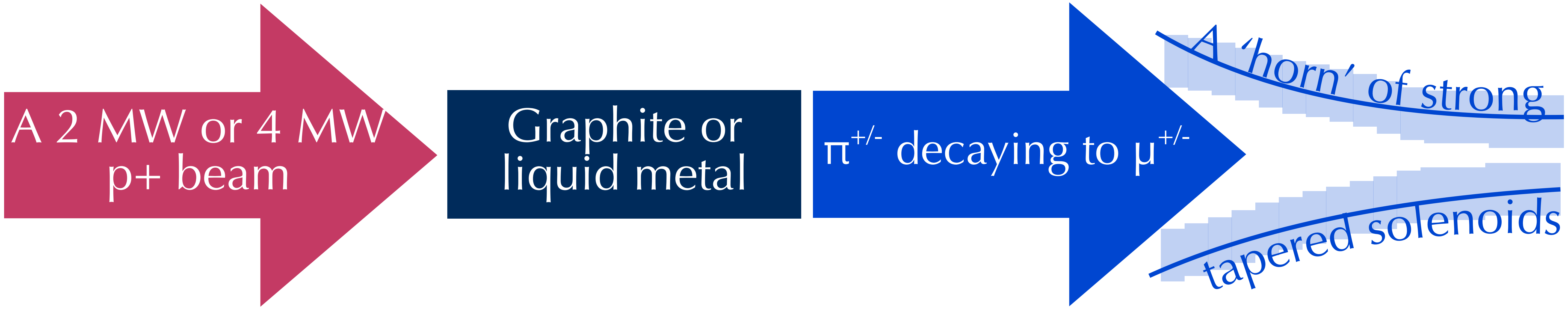

500 p+ produces 45 mu- and 60 mu+

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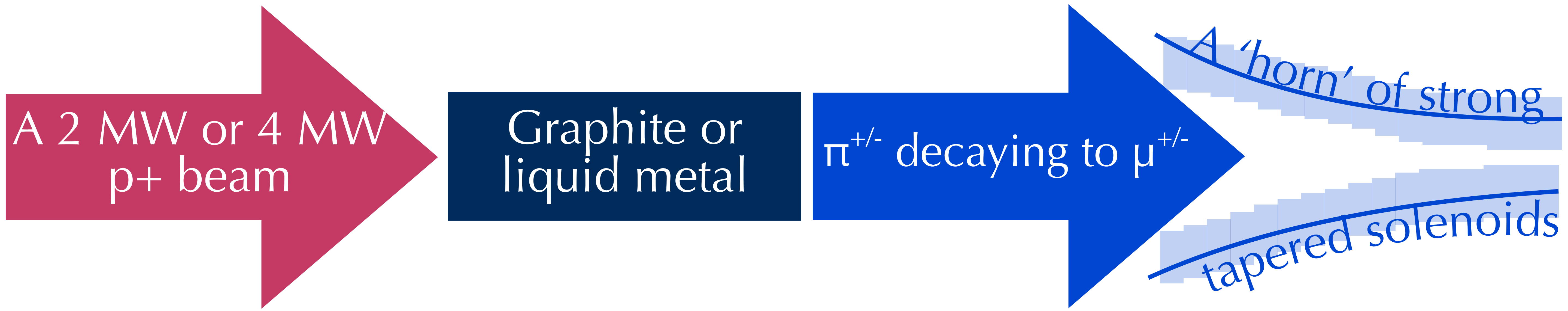

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<u>Open questions:</u>

- 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?

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Accelerator parallel: Muon Production, Radiation & Magnets
DESY 16:15 - 18:00

Why is the **cooling** challenging?

Short answer: Needing to be encased in solenoids

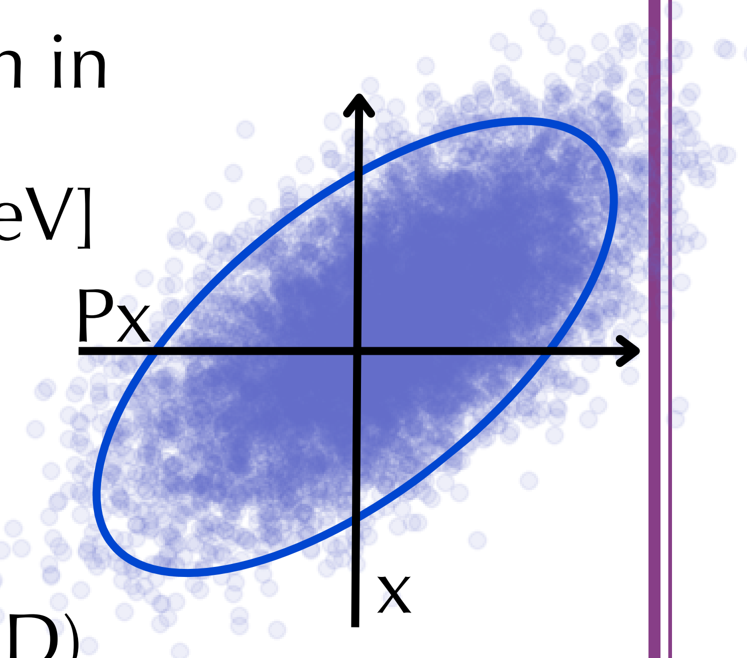
Cooling refers to reducing the **emittance** (size) of the beam:

- Allows the beam to fit within a reasonable magnet size

Concept: ***Emittance***

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

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



εx = area in X, Px (2D)
εy = area in Y, Py (2D)
εL = area in Z, Pz *or* T, E (2D)
εT = area in X, Px, Y, Py (4D)
ε = area in X, Px, Y, Py, T, Pz (6D)

For more information, Thursday

Accelerator parallel: 6D Cooling, Magnets & RF
Seminar Room 4a+b, DESY
08:30 - 10:15

Accelerator parallel: Final Cooling, Magnets & RF
Seminar Room 4a+b, DESY
10:45 - 12:30

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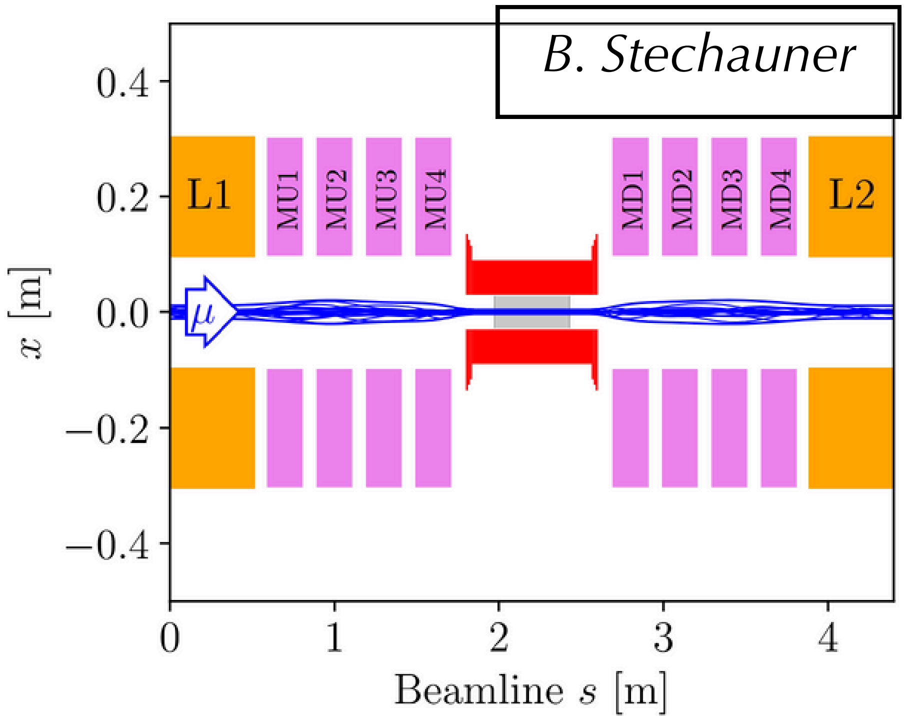
After target, beam is non-relativistic:

- 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).

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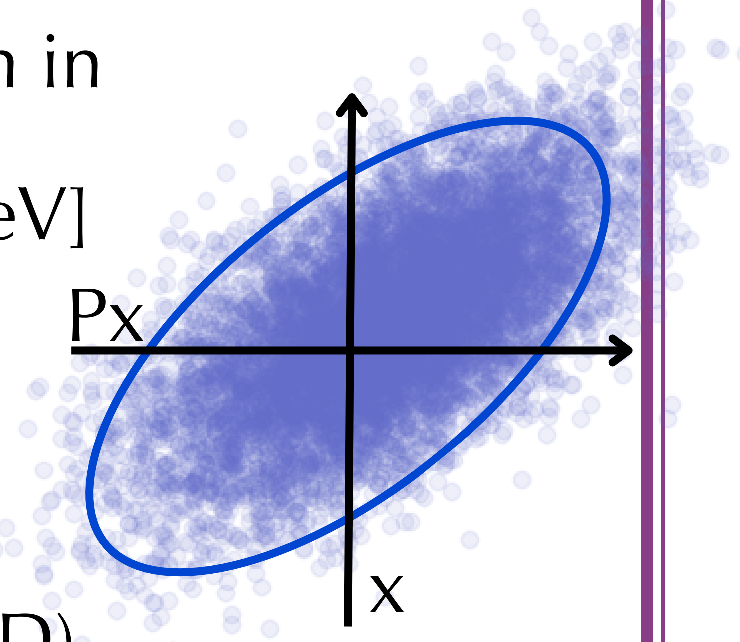

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IONIZATION COOLING	
Elastic Electron Scattering	**Nuclear Multiple Scattering**
Cooling	Heating
Favour low-A materials E.g. Hydrogen, Lithium Hydride	

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

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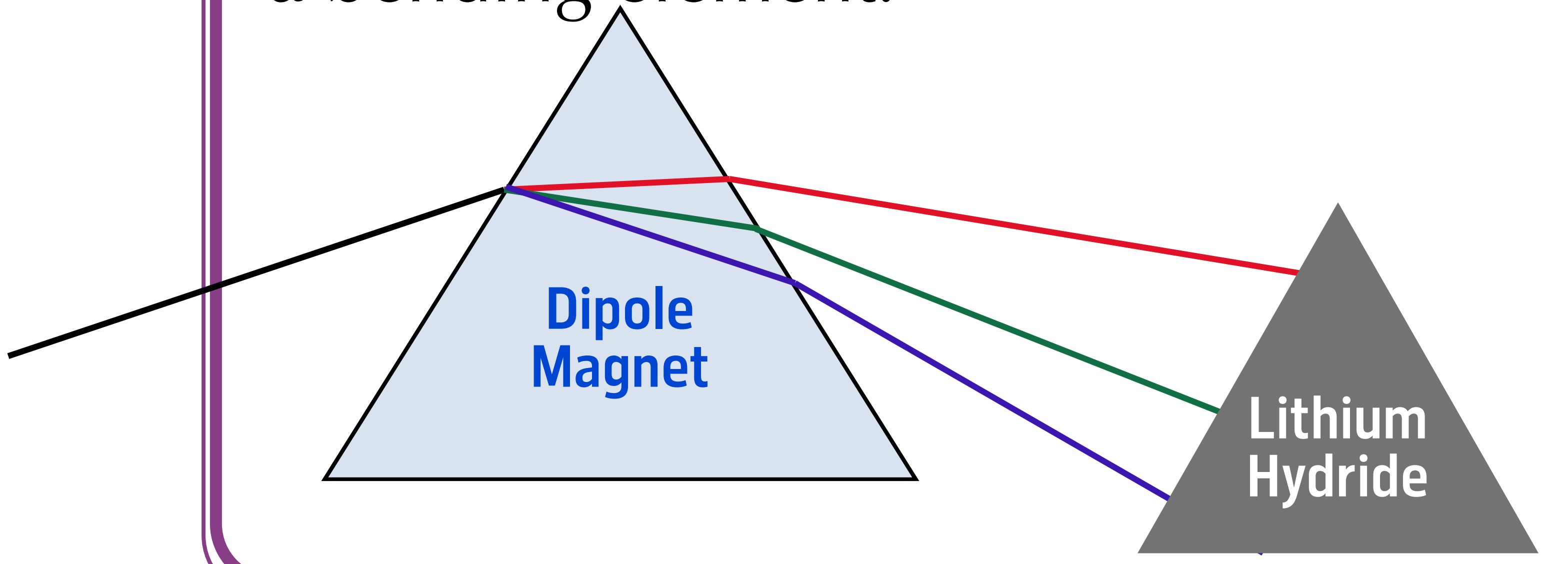
However this only cools **transversely**. Can ensure longitudinal cooling by introducing *dispersion* and a wedge absorber, so higher-energy particles travel through more material than lower-energy particles.

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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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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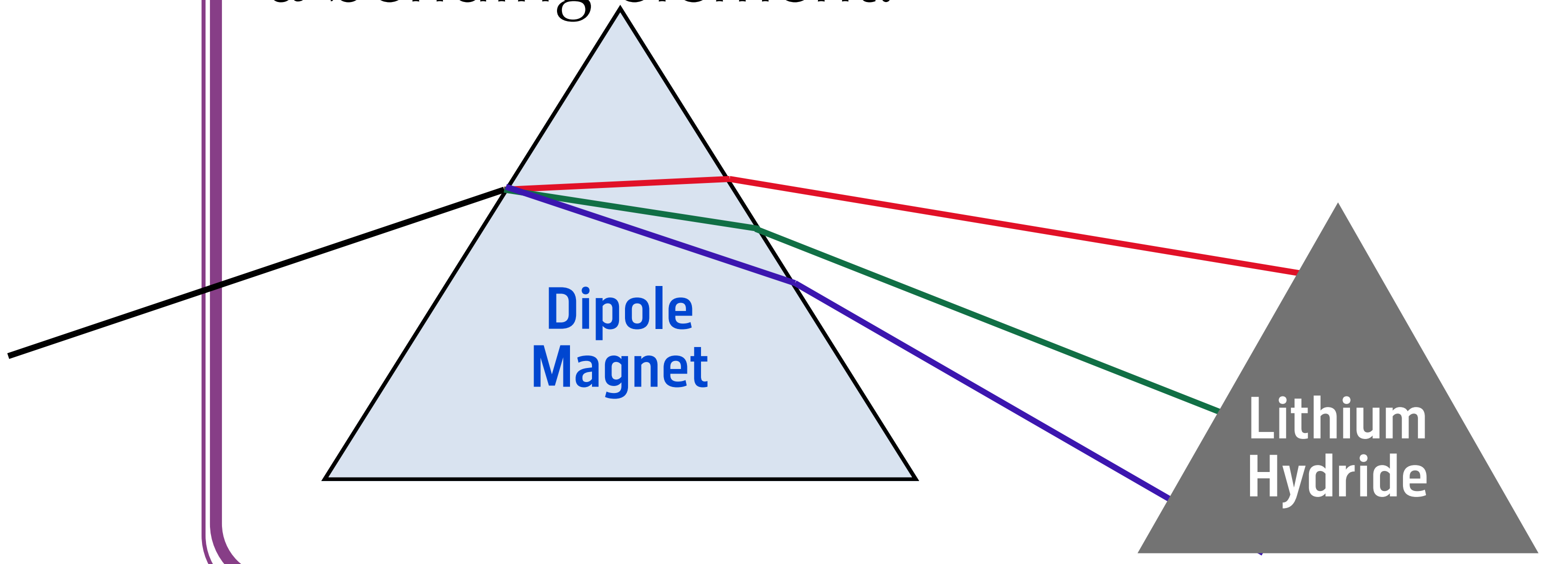


Why is the **acceleration** challenging?

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

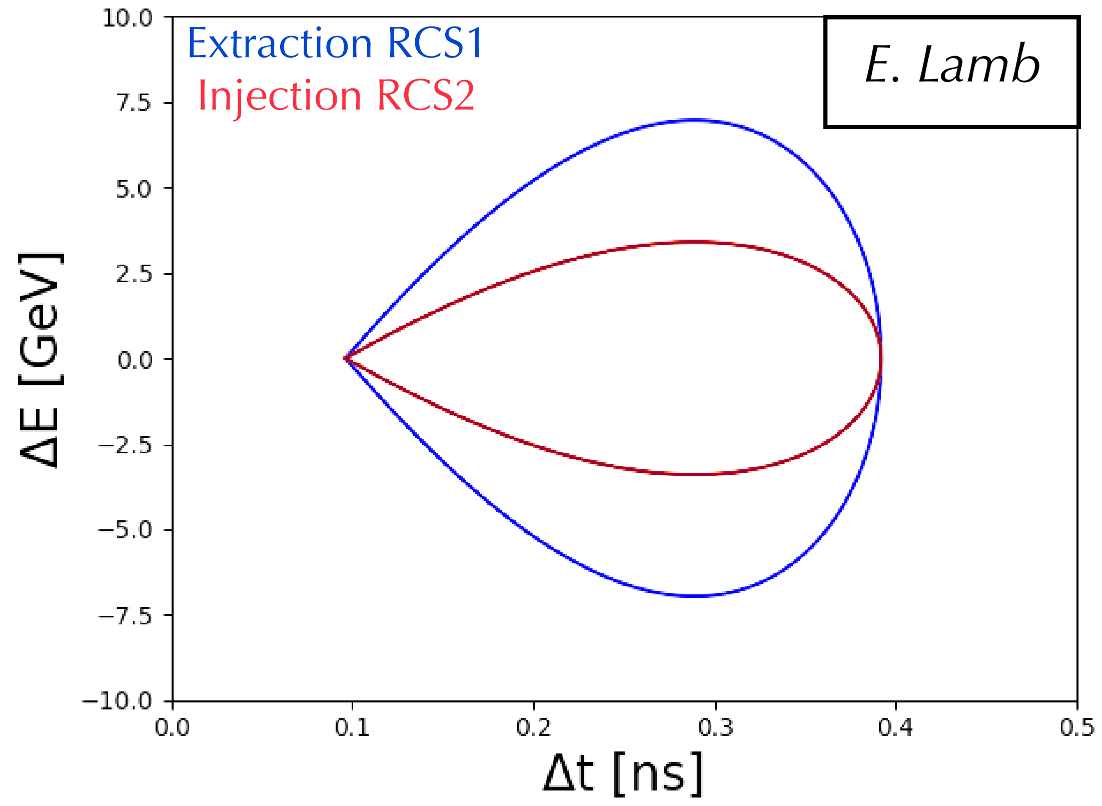
Need a set RF gradient per accelerator length to get reasonable transmission (90%).
10 RF stations throughout synchrotron.

4506 cavites, 138 GV total

More RF details from Simon

Concept: **Matching**

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



For more information, tomorrow

Accelerator parallel: Acceleration, Magnets & RF

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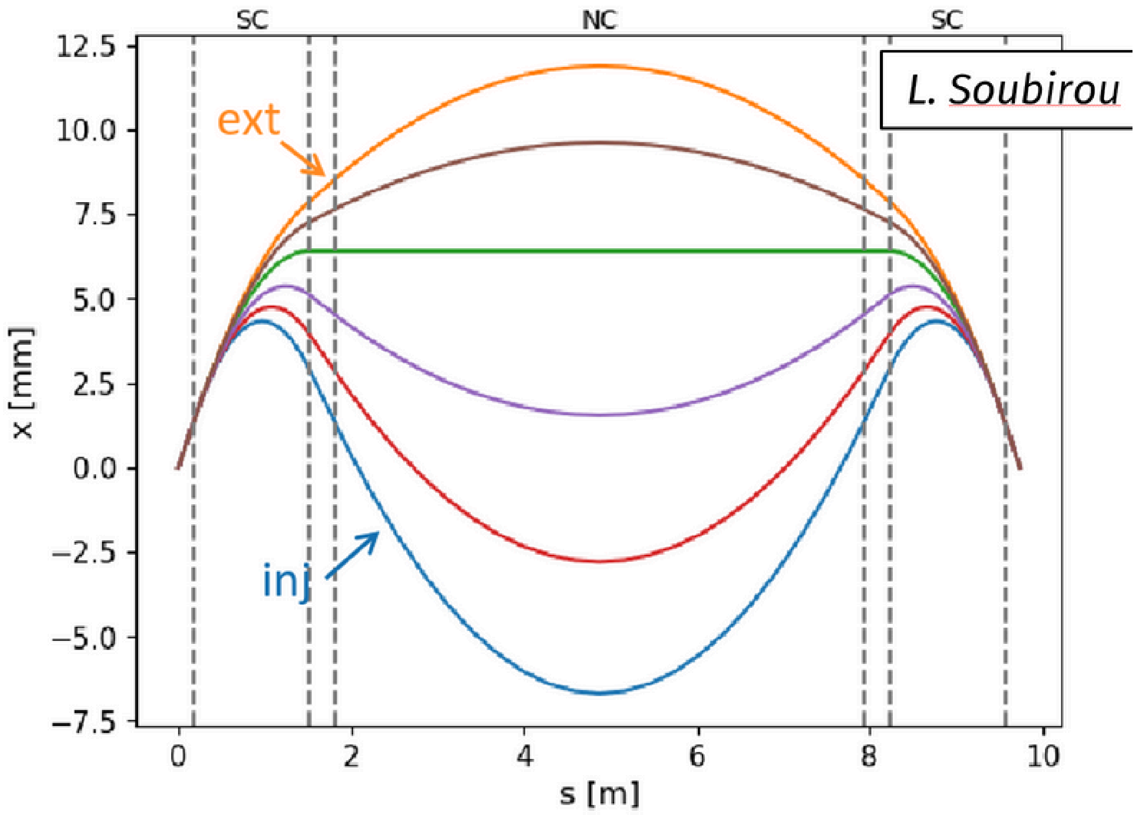
Hybrid RCS includes both *fast-ramping normal-conducting* magnets and *static superconducting* magnets:
This gives large orbits, and large magnet sizes

See Lisa's talk



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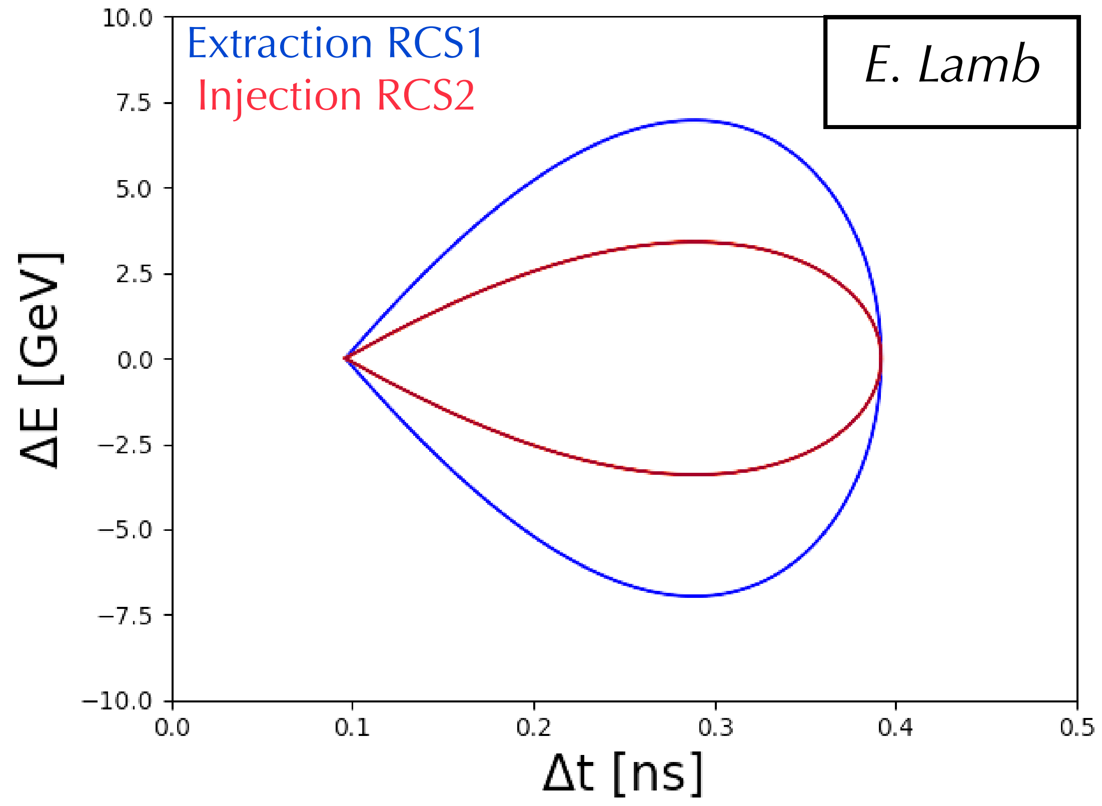

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Accelerator parallel: Acceleration, Magnets & RF

Why is the **collider ring** challenging?

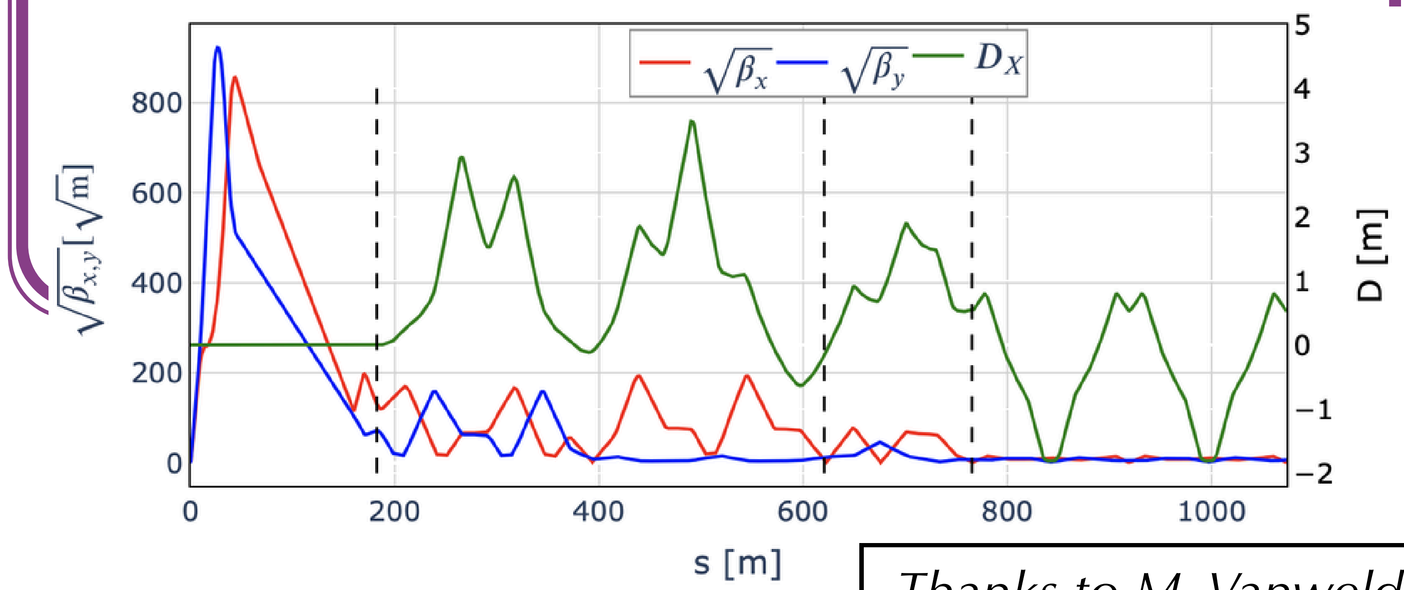
Short answer: The very small beta*

To get highly-focused beams at collision, the beta must first increase as much as possible.

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

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

For more information, Thursday

Accelerator parallel: Collider Design & Magnets

Main Auditorium, DESY 08:30 - 10:15

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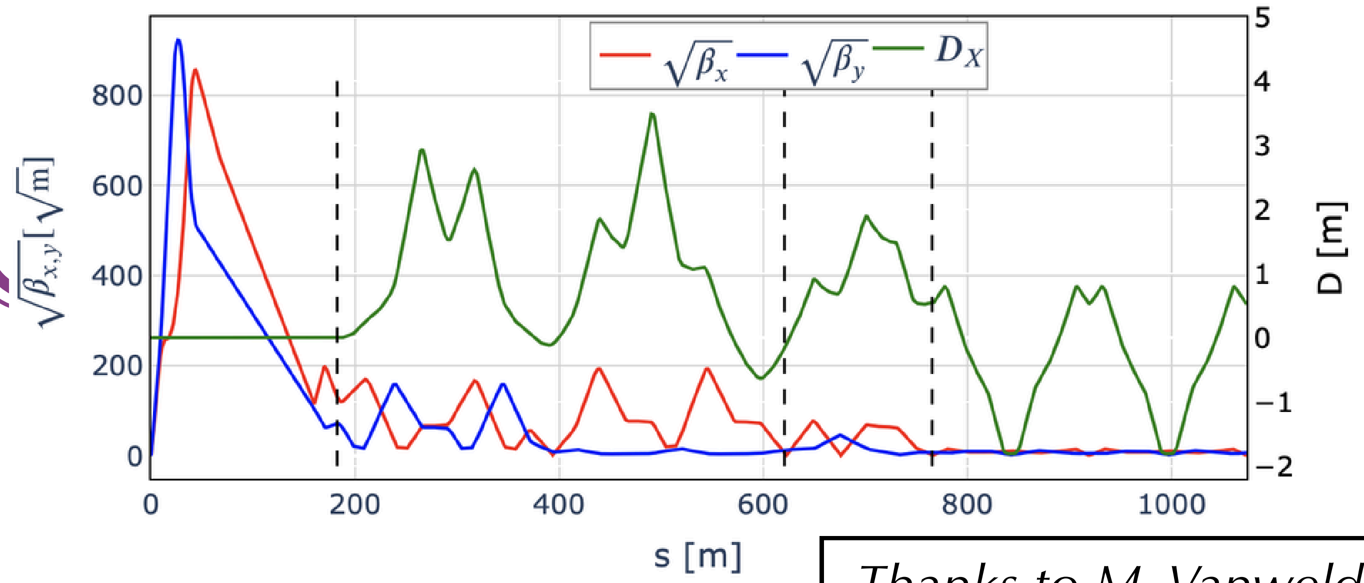

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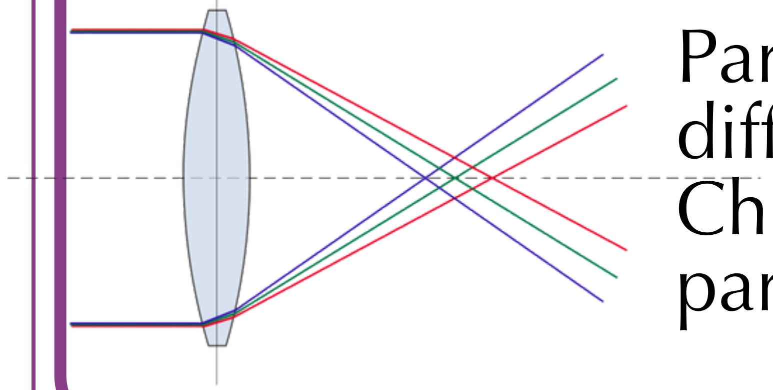
Definition: ***Chromaticity***



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

For more information, Thursday

Accelerator parallel: Collider Design & Magnets

Main Auditorium, DESY 08:30 - 10:15

Why is **decay** challenging?

Short answer: <u>Time</u>

Please see poster during Tuesday reception

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.

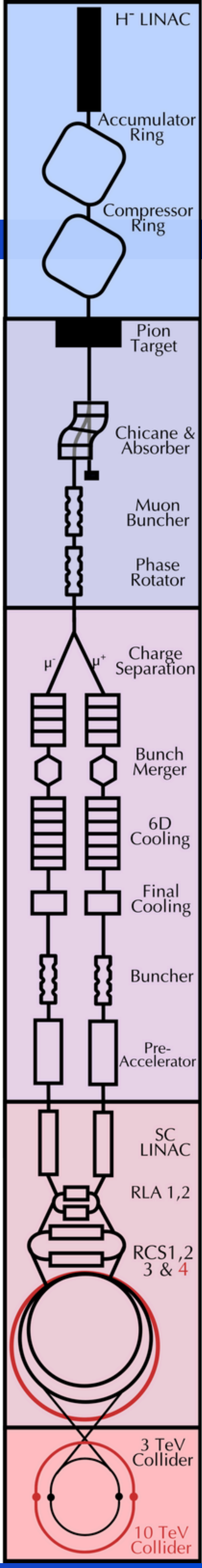
The speed throughout the muon collider *changes*.

- 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

Acceleration may not be linear. I.e. accelerated boosted frames.

Currently estimate 30% of muons survive. But full start-to-end simulation required.



Conclusion

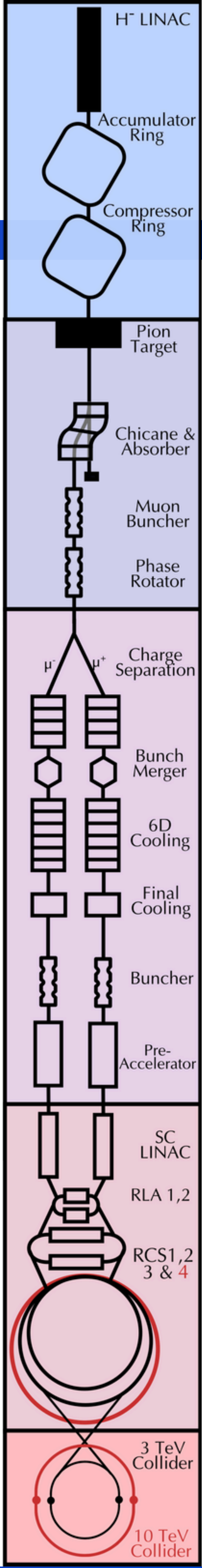
The beam physics challenges change across the muon collider.

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.

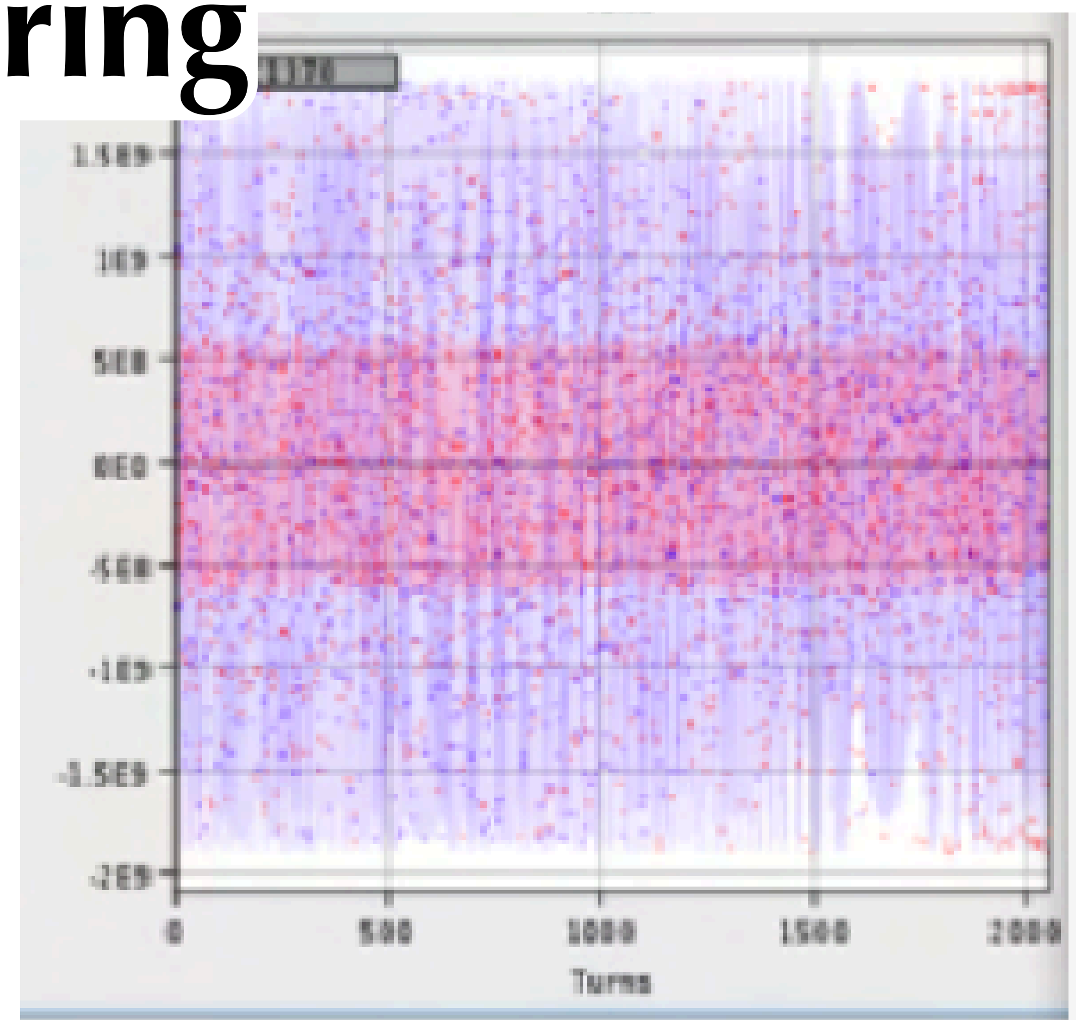
A start-to-end simulation would ensure matching between systems and model rate of muon decay.

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

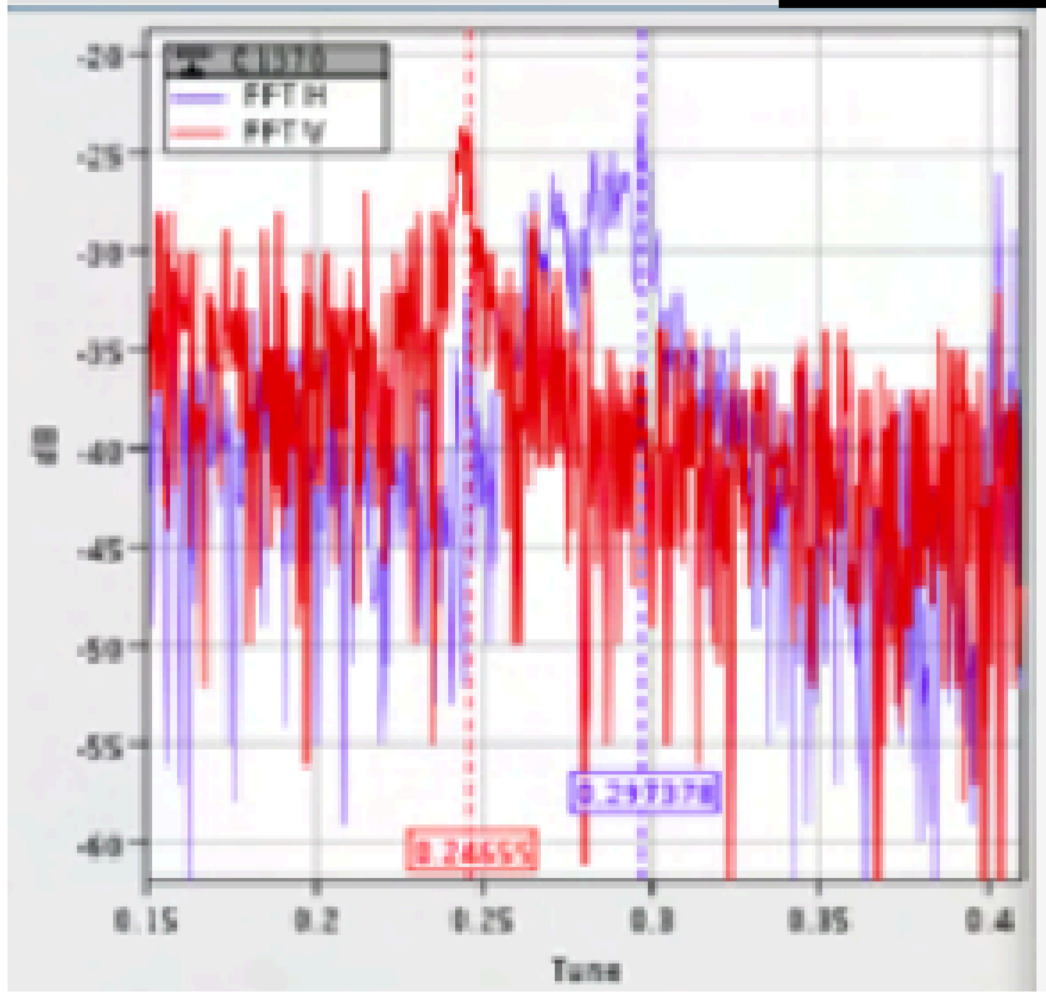


Measuring Tune!

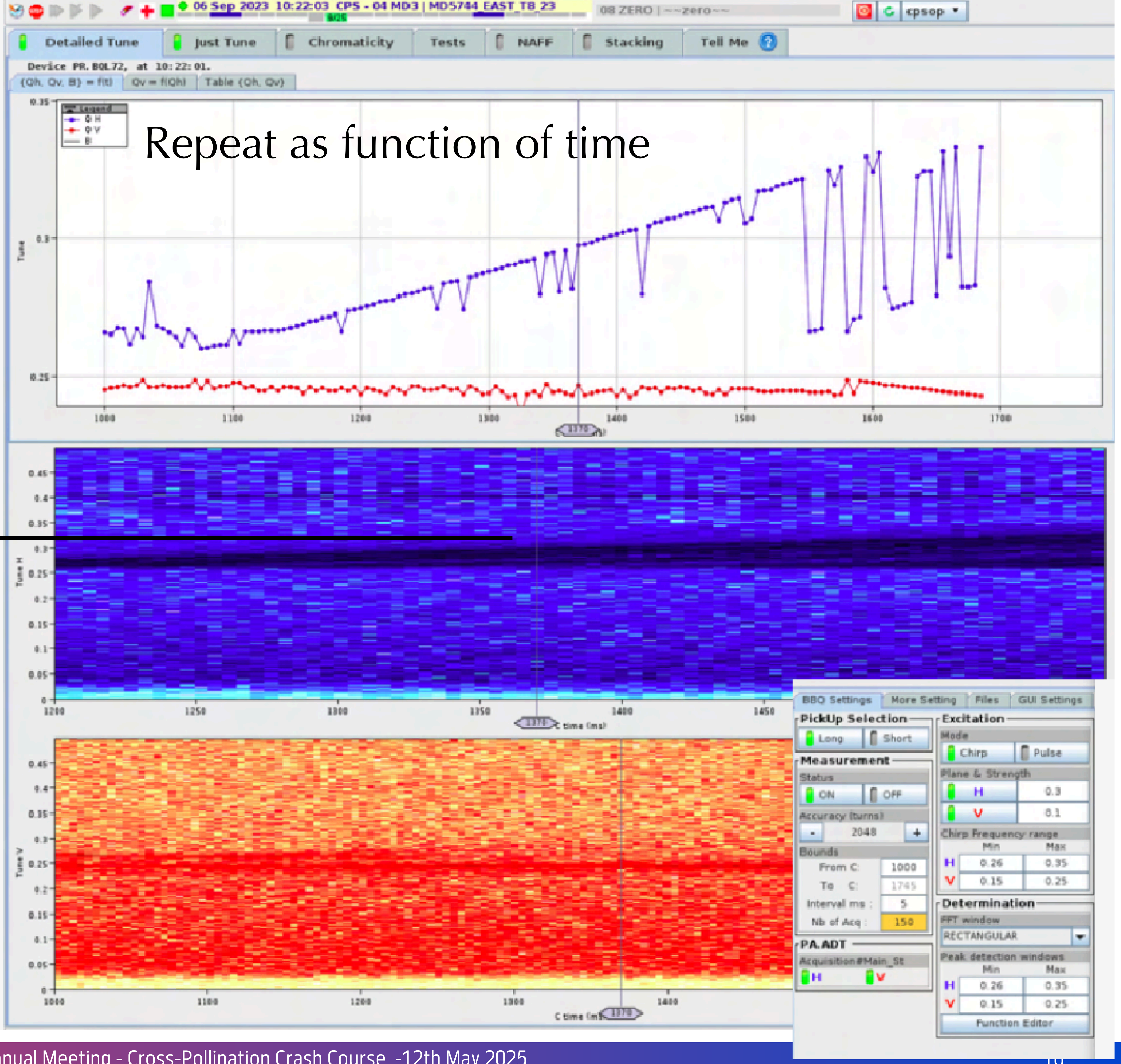
Apply excited kick + measure beam position



Apply FFT on signal



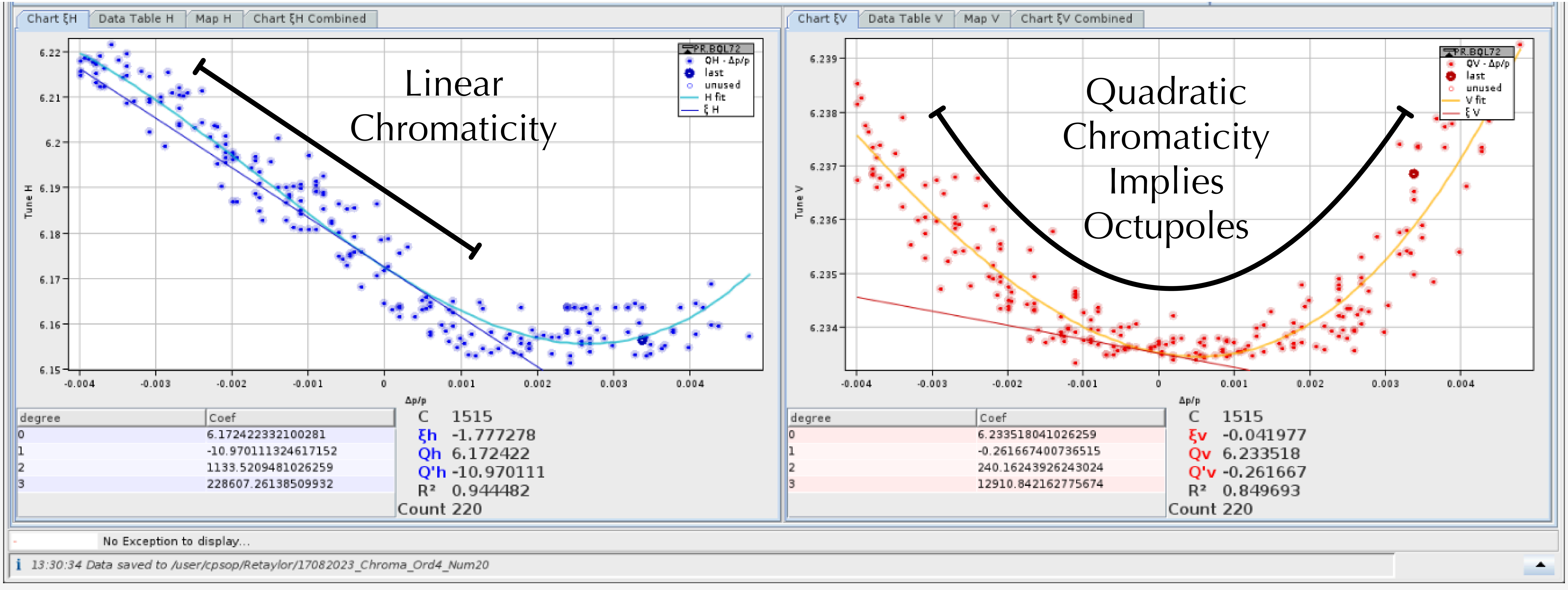
Repeat as function of time



Measuring Chromaticity!

$$f_{RF} \longrightarrow \frac{\Delta f}{f_{rev}} \xrightarrow{\frac{1}{\eta}} \frac{\Delta p}{p} \xrightarrow{D_x} x$$

Change the momentum and repeat!



Measuring Chromaticity!