Challenges of final cooling

National Labs Muon Collider Study Group Seminar Series

Monday 5th January 2026

R. Taylor & B. Stechauner

Featuring work from B. Bordini, J. Ferreira, A. Grudiev, T. Mulder, C. Rogers, R. Zhu

and *450 members of the International Muon Collider Collaboration*

International MUON Collider Collaboration

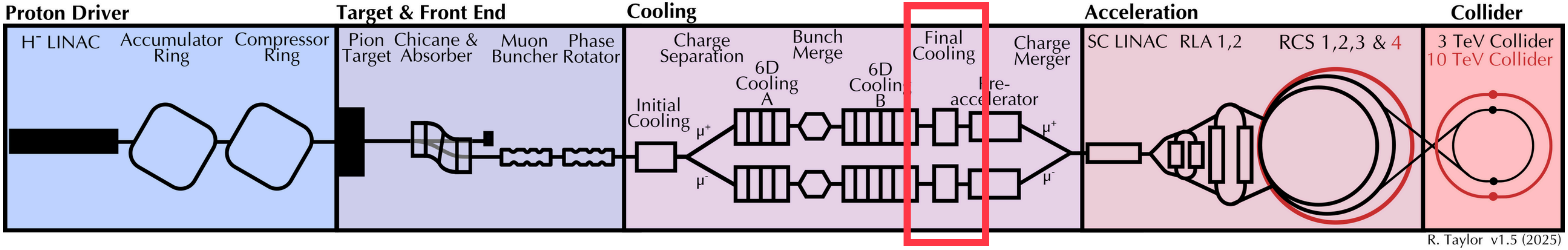
MuCol

Funded by the European Union

CERN

Overview

A small cooling system (~100 m) with a big impact on downstream performance.



This Talk

1) Introduction to final cooling

2) How to design a final cooling lattice

3) System overview

4) Summary of final cooling lattices

5) Solenoid, RF and absorber R&D

6) Conclusions and next steps

Final Cooling & The Muon Collider

Further reduce transverse beam emittance

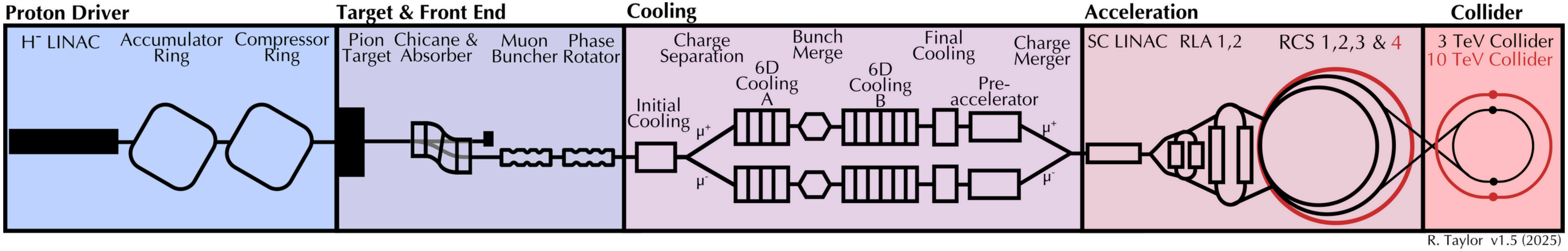
300 um ⟶ 25 um

by allowing longitudinal emittance to increase

1.5 mm ⟶ 75 mm

and still retain reasonable transmission.

~80%



Final Cooling & The Muon Collider

Further reduce transverse beam emittance → Affects **magnet aperture** downstream and **luminosity** at the collider

300 um ⟶ 25 um

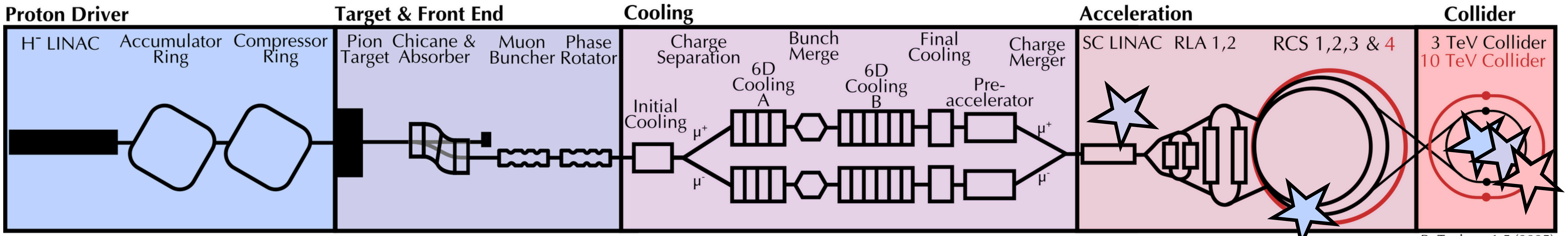
$$\mathcal{L} = \frac{\gamma^2 \tau_0 c}{2C_{\text{coll}}} \frac{N^2}{4\pi\varepsilon_\perp \beta^*} f_r F_{hg} H_D$$

by allowing longitudinal emittance to increase → Affects **RF cavity** frequency downstream, and the **beta*** at the collider (hourglass effect)

1.5 mm ⟶ 75 mm

and still retain reasonable transmission. → Affects **luminosity** as factor of N^2.

~80%



Final Cooling & The Muon Collider

Dependence of muon collider luminosity on ionization cooling performance

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Dr Rebecca Taylor (CERN)

Collider IPAC26

Description

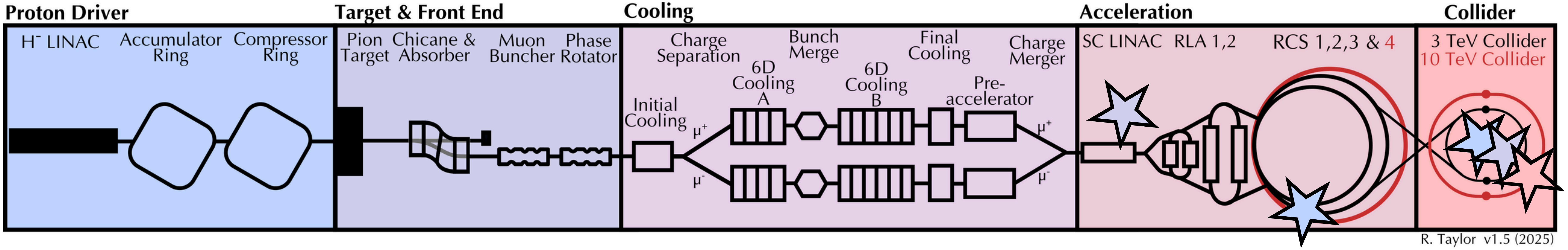
A 10 TeV center-of-mass muon collider is a high-energy lepton collider that has the potential to achieve physics reach comparable to much larger hadron colliders. The final luminosity depends on the performance of the entire complex, from muon beam production to the collider ring, including the rapid cooling and acceleration stages. Achieving the target luminosity imposes stringent constraints on the ionization cooling and the collider optics, such as extremely small betatron functions at the interaction points, which induce strong chromatic effects that ultimately limit the machine momentum acceptance. To meet the momentum acceptance requirements without significant luminosity loss, one possible strategy is to end the muon cooling stage earlier, since a reduction of the longitudinal emittance can be traded against larger transverse emittances with a shorter cooling system. The design and performance of the ionization cooling channel thus have a strong impact on the achievable luminosity. A study of a common optimization of the ionization cooling and the collider ring design to maximize the luminosity is presented in this work.

magnet aperture downstream
minosity at the collider

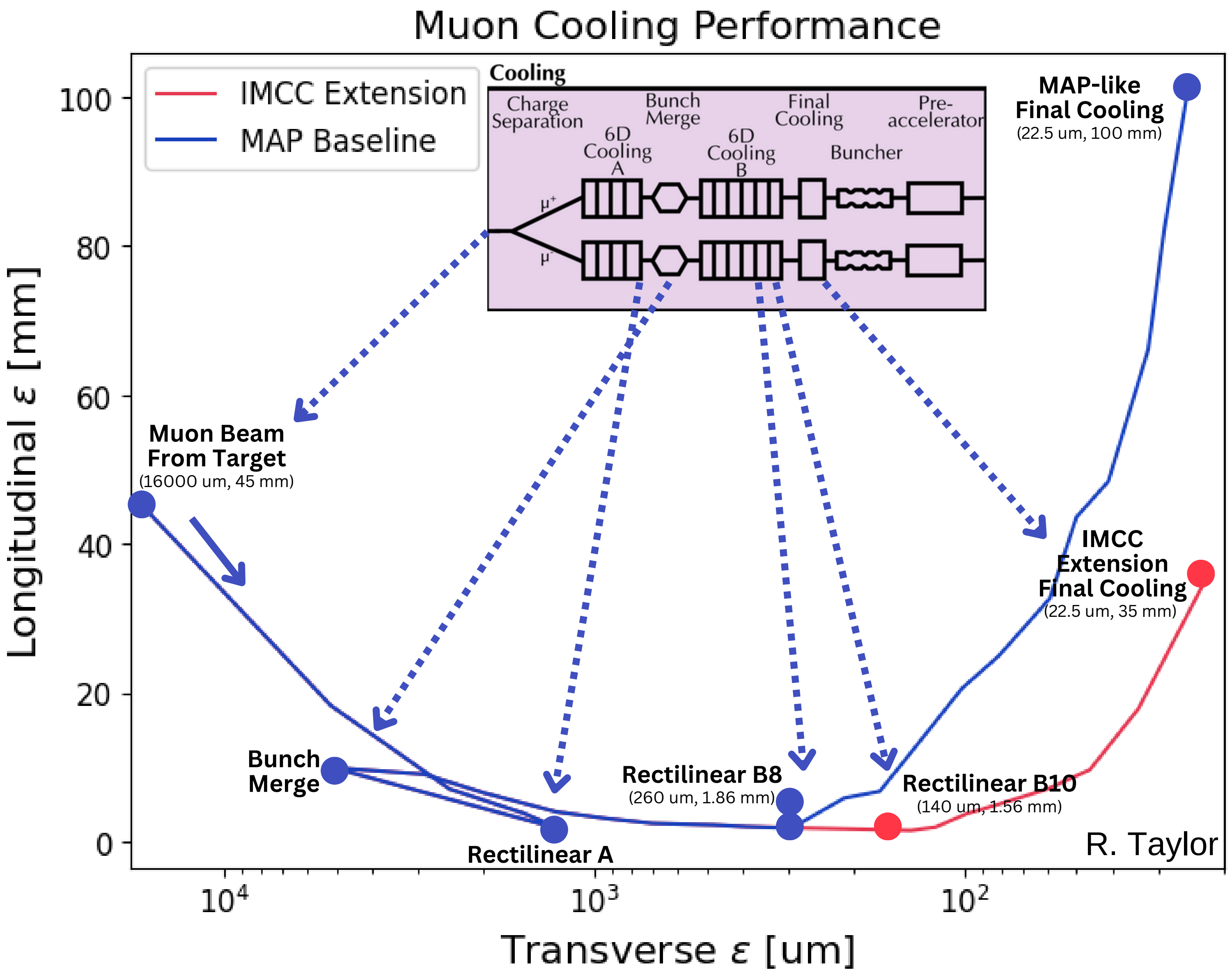
$$\mathcal{L} = \frac{\gamma^2 \tau_0 c}{2C_{\text{coll}}} \frac{N^2}{4\pi\varepsilon_\perp \beta^*} f_r F_{hg} H_D$$

s **RF cavity** frequency downstream,
e **beta*** at the collider (hourglass effect)

luminosity as factor of N^2.



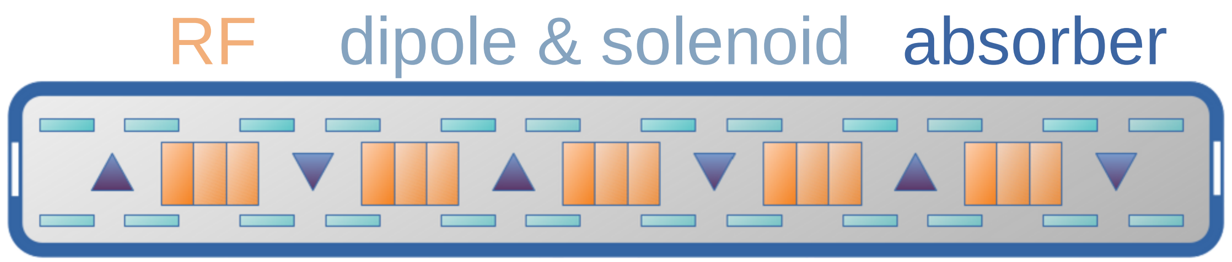
Final Cooling In An Integrated Cooling System



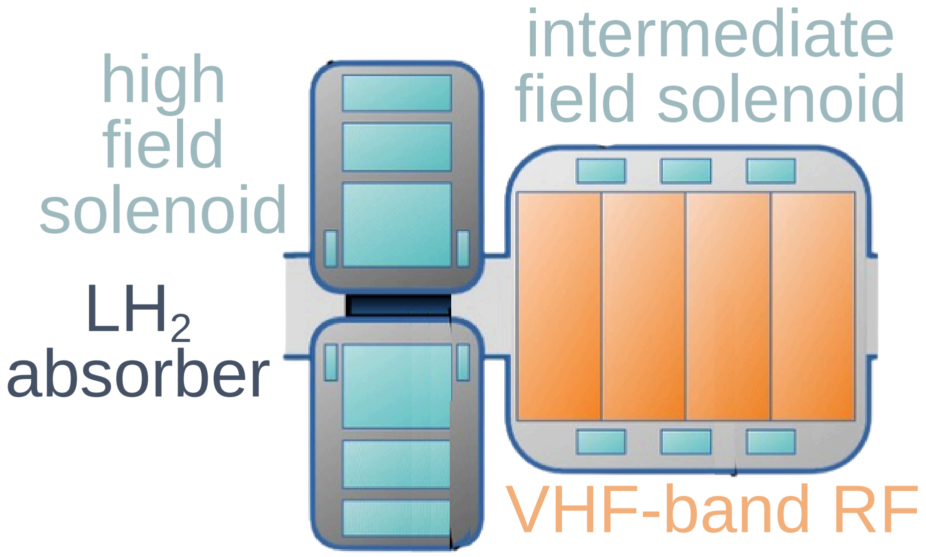
Depends strongly on initial beam from the 6D cooling lattice.

See talk from C. Rogers 08/12/25
https://indico.muoncollider.us/event/7/

<u>Rectilinear Cooling</u>:
- Cools in **6D**
- Uses **wedge**-shaped lithium hydride absorbers
- Uses a **periodic** lattice

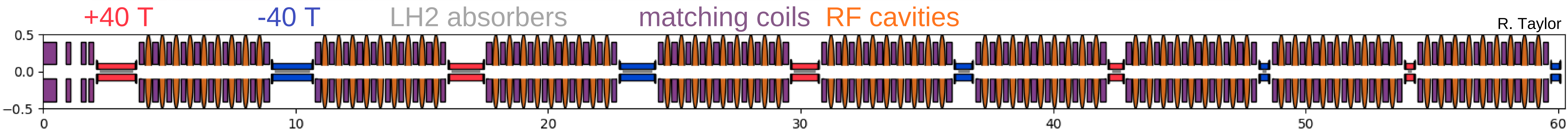


<u>Final Cooling</u>:
- Cools in **4D**
- Uses **block** liquid hydrogen absorbers
- Is non-periodic

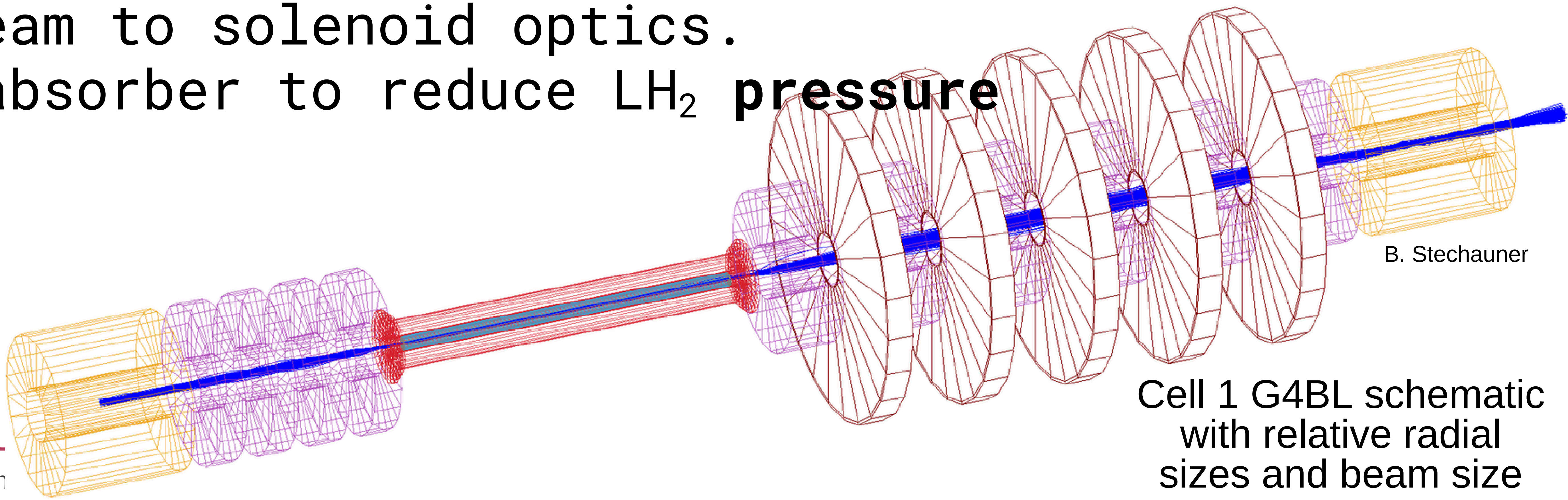


Beam leaves 6D cooling with **pz = 200 MeV/c**
Energy decreases throughout final cooling and leaves with **pz = 20 MeV/c**

How to Design a Final Cooling Lattice



Step 0) Choose your **simulation code**
Step 1) Implement a **high-field solenoid** design
Step 2) Optimise **LH_2 absorbers** for performance.
Step 3) Apply **RF gradient** to obtain required kinetic energy.
Step 4) **Match** beam to solenoid optics.
Step 5) Adjust absorber to reduce LH_2 **pressure**

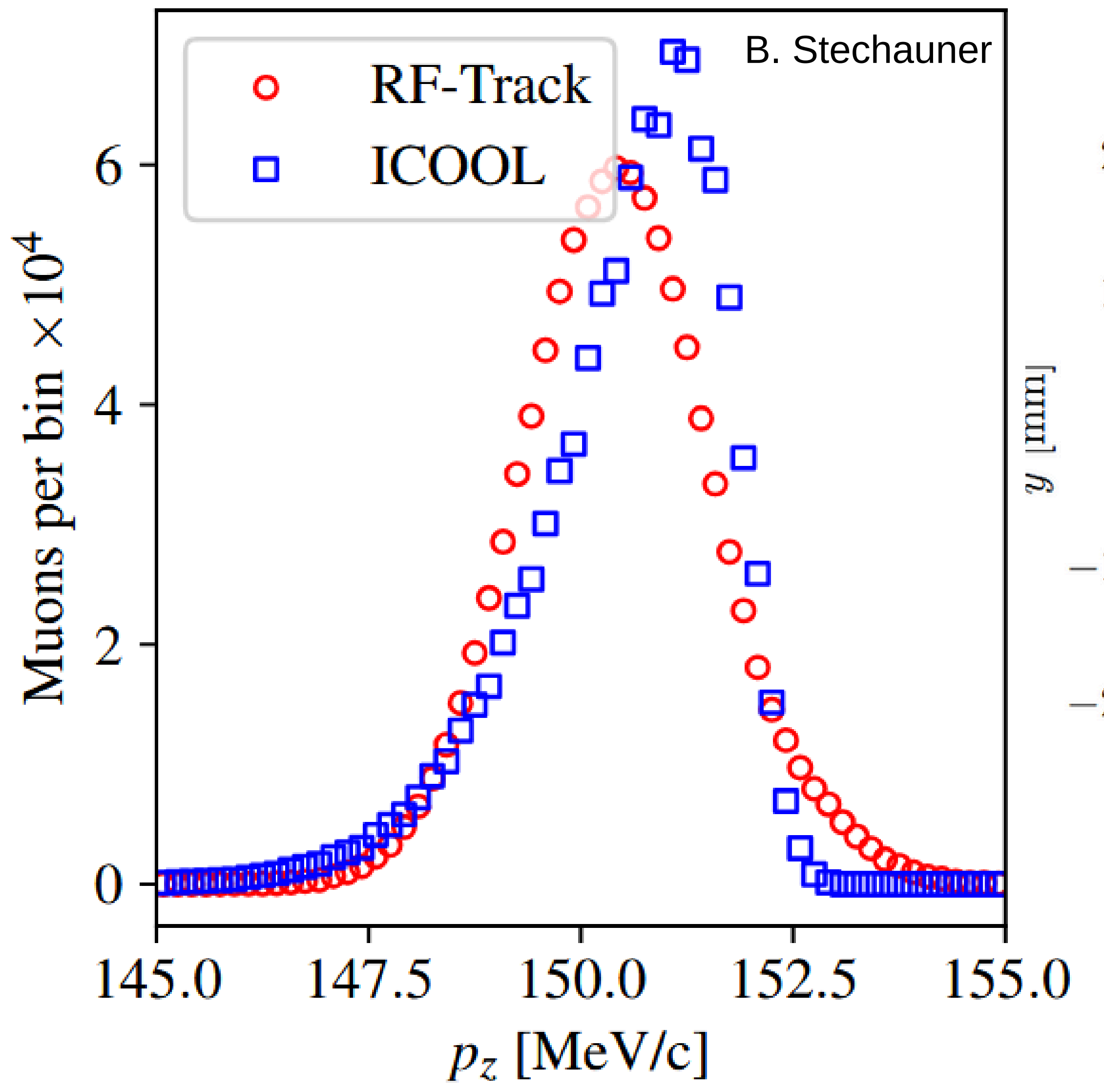


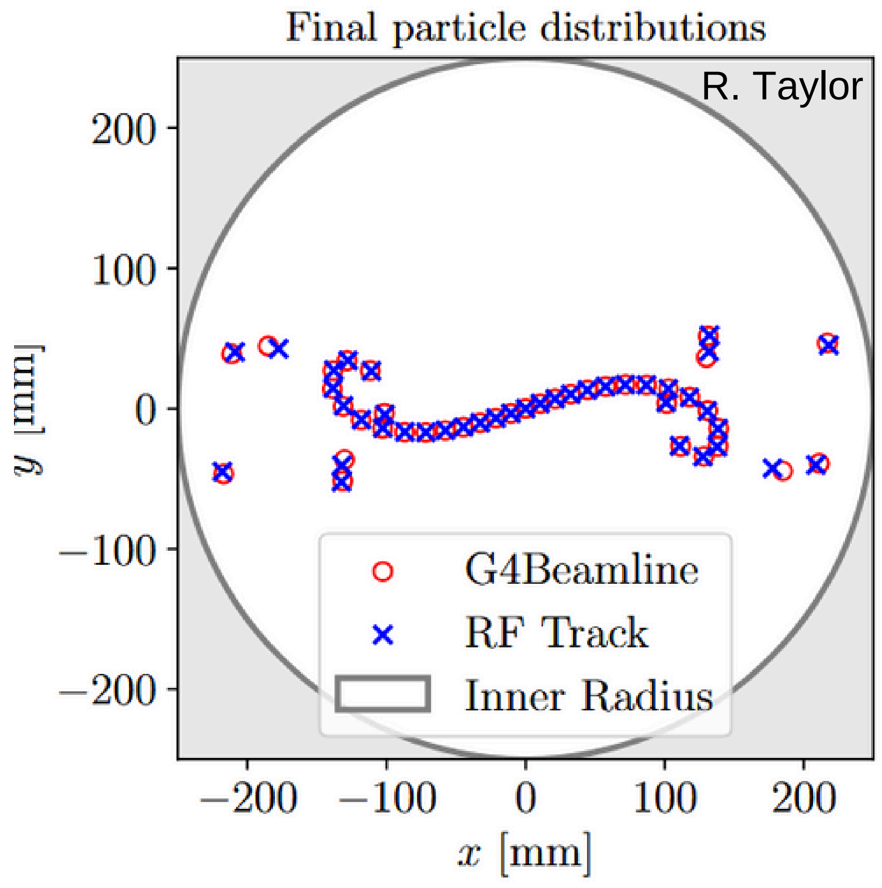
Cell 1 G4BL schematic with relative radial sizes and beam size

Step 0) Simulation Code

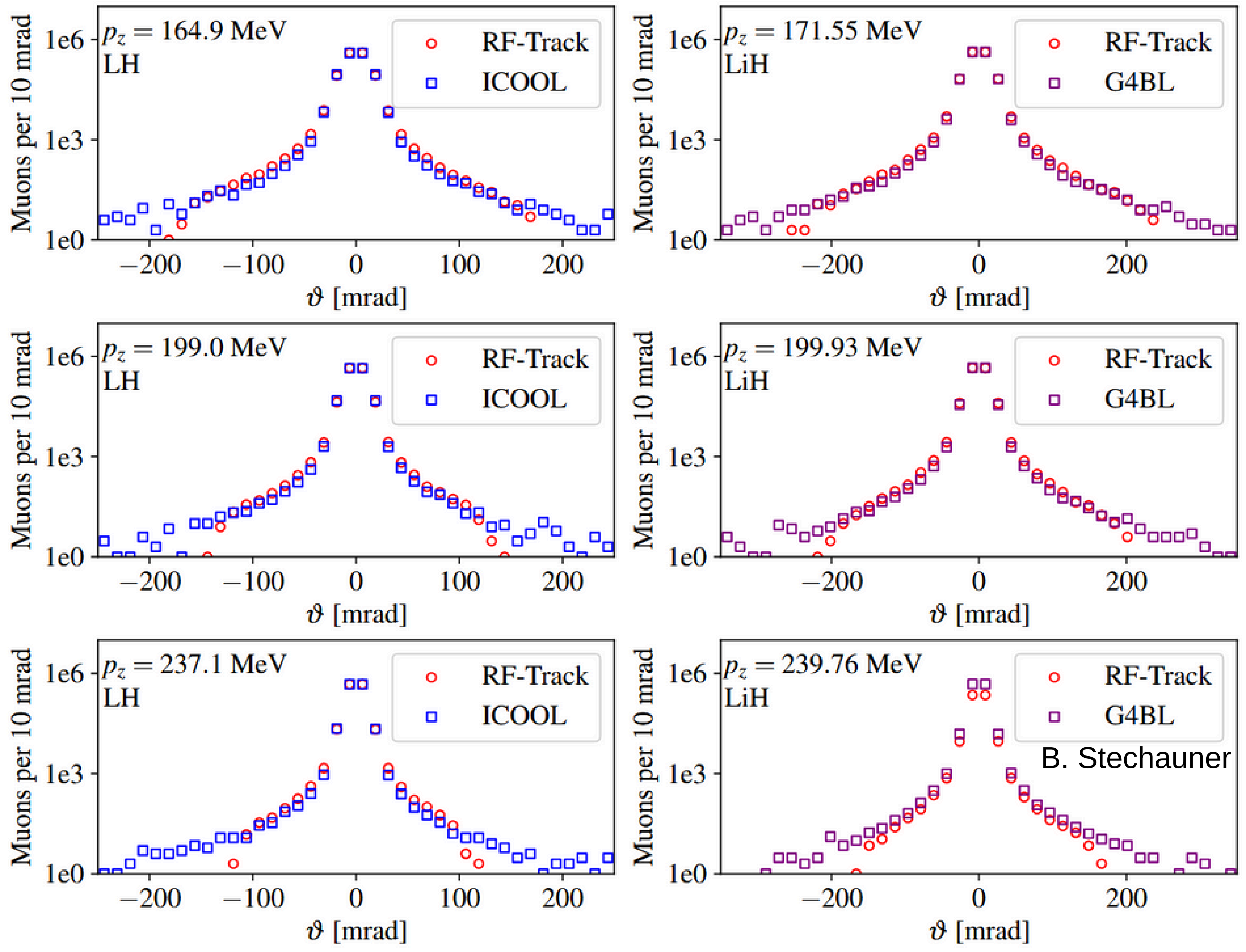
- **ICOOL** - from *BNL*
- **G4Beamline** - from *Muons Inc.*
- **RF Track** - from *CERN*
- **BDSIM** - from *RHUL / Imperial*

G4BL is current standard. RFT and BDSIM are in active development. RFT required for collective effects.

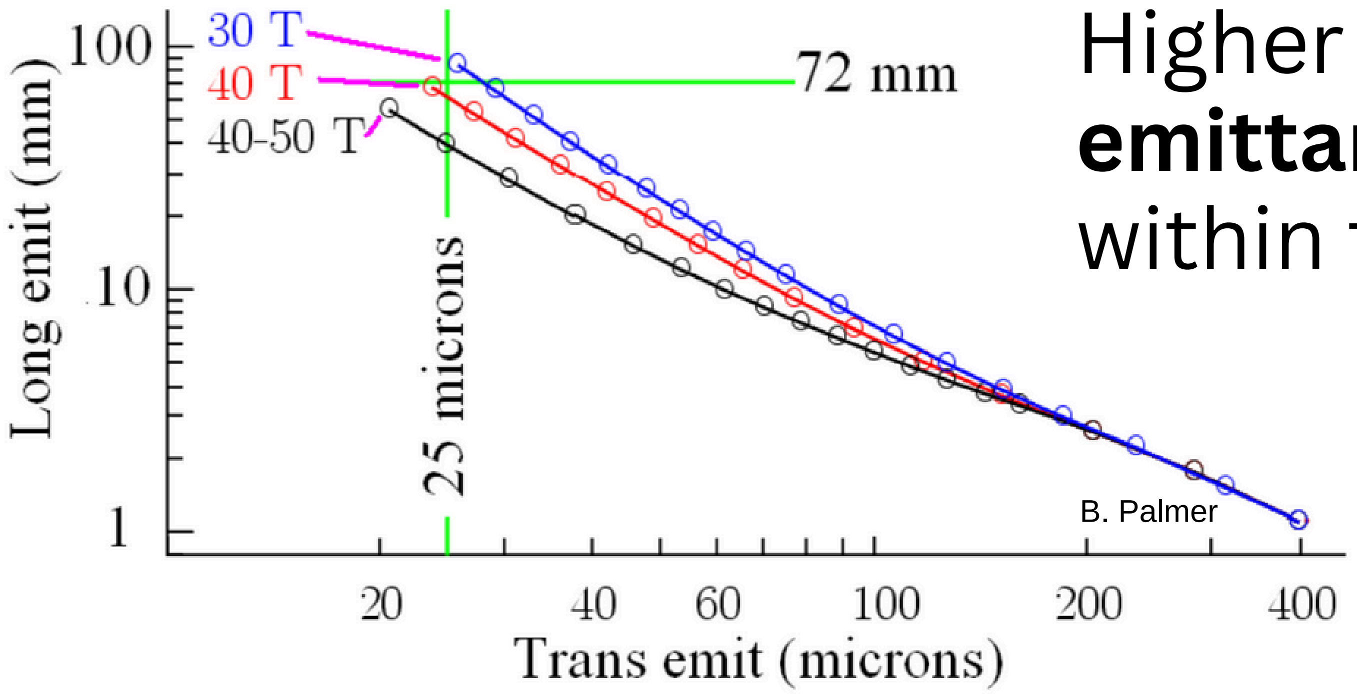




R. Taylor

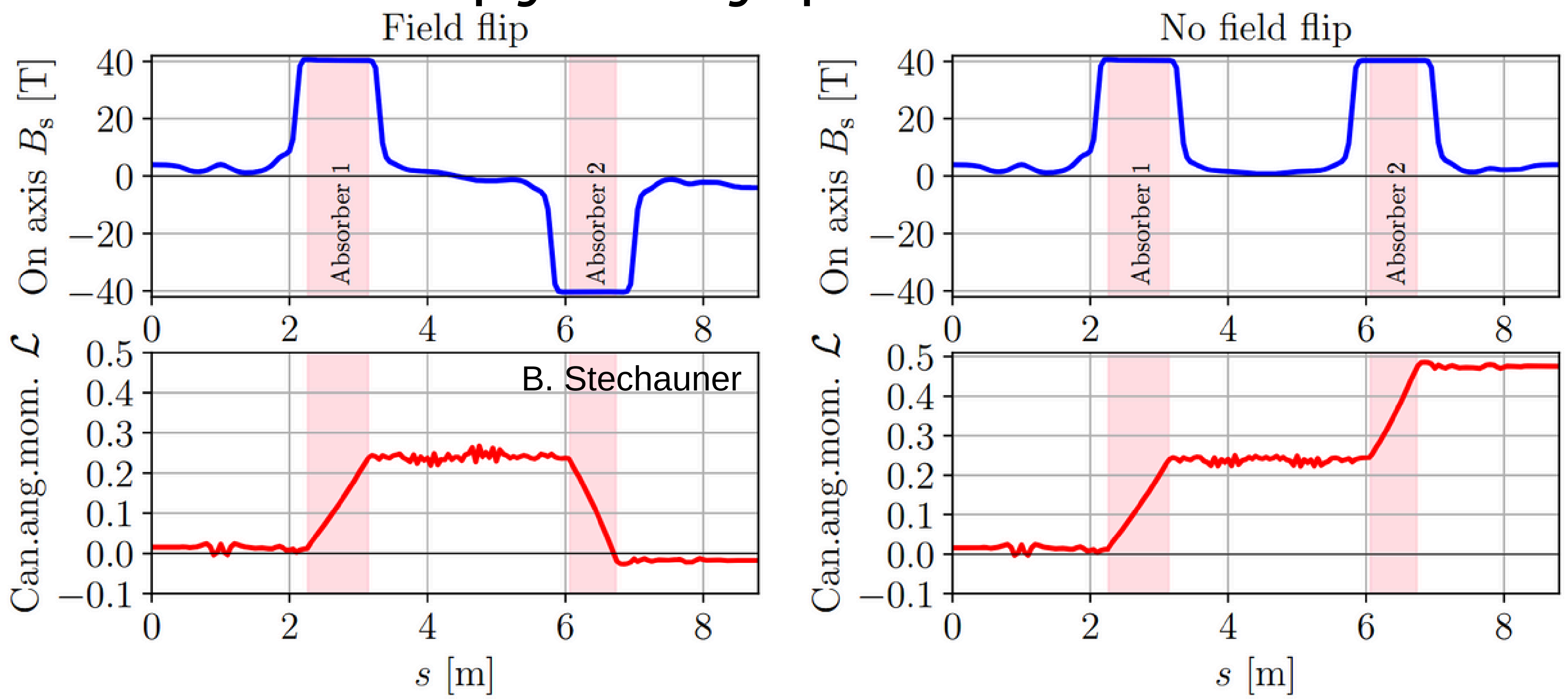


Step 1) High-Field Solenoids

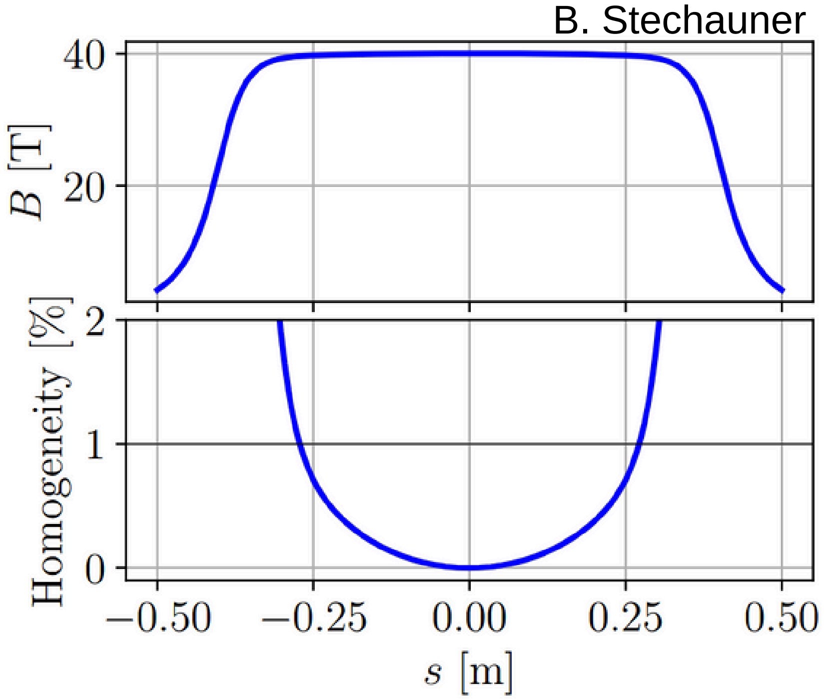


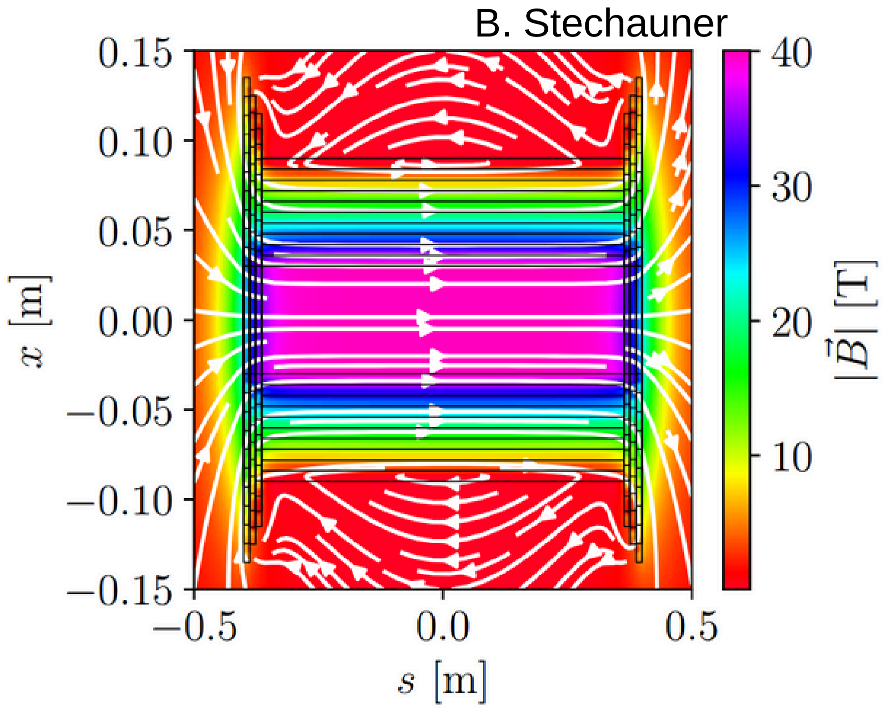
Higher on-axis solenoid field reduces **equilibrium emittance** and provides additional cooling rate within the absorbers. Recommend 40 T.

Field must be flipped in polarity to return canonical angular momentum (correlation between x-py and y-px) to zero.



Must have **homogeneous** field within absorber





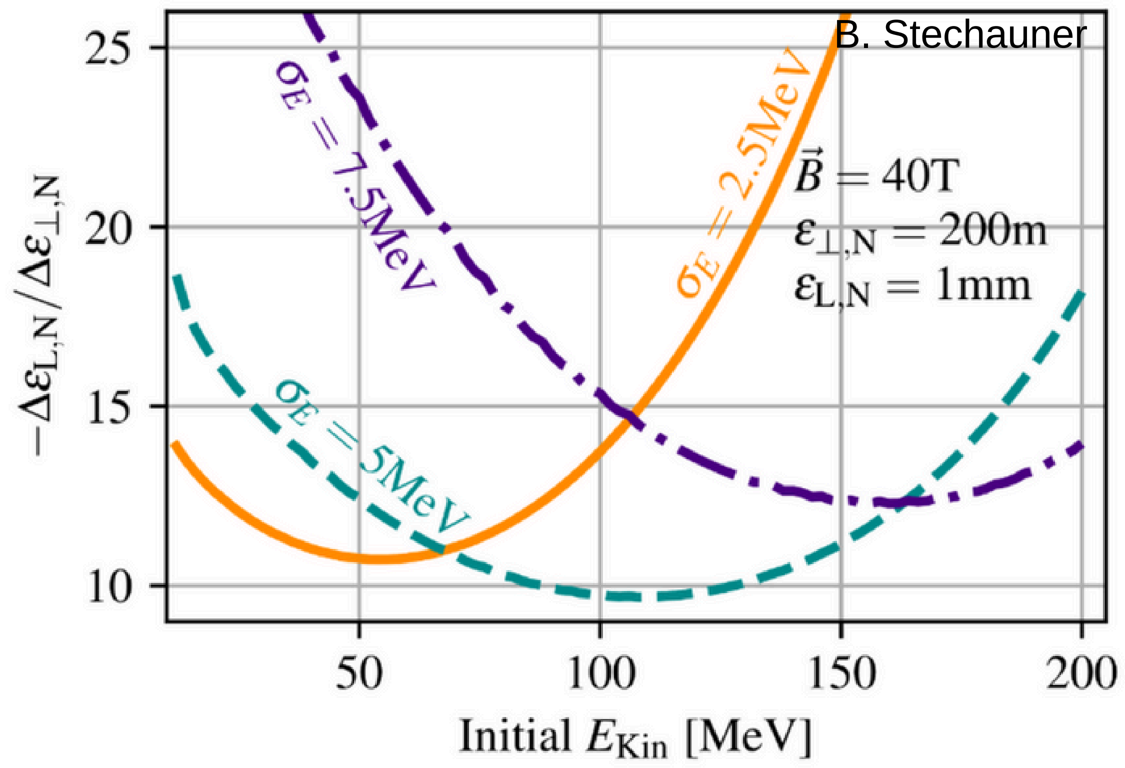
Step 2) Optimise LH_2 absorbers for performance

Steps of Bernd's analytical model:

Semi-gaussian scattering through Liquid Hydrogen material. Heating and cooling terms.

Longitudinal straggling of energy distribution

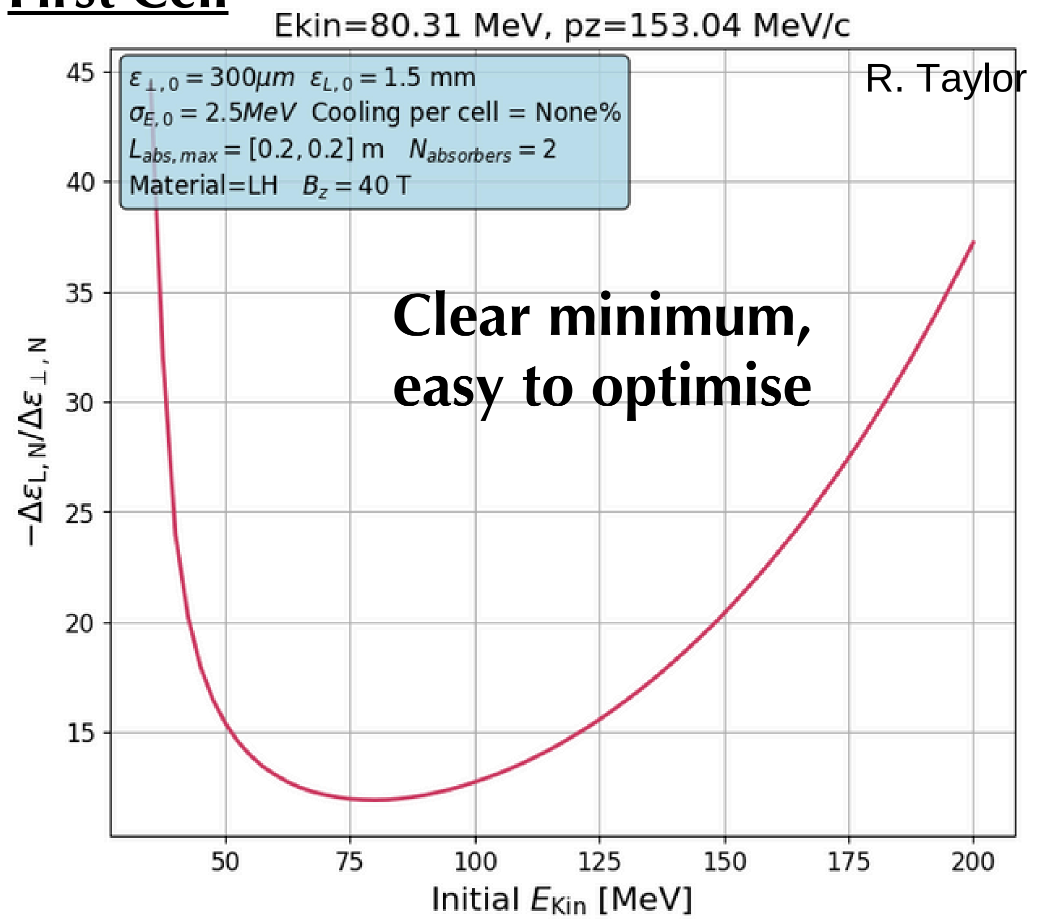
Longitudinal rotation due to drift



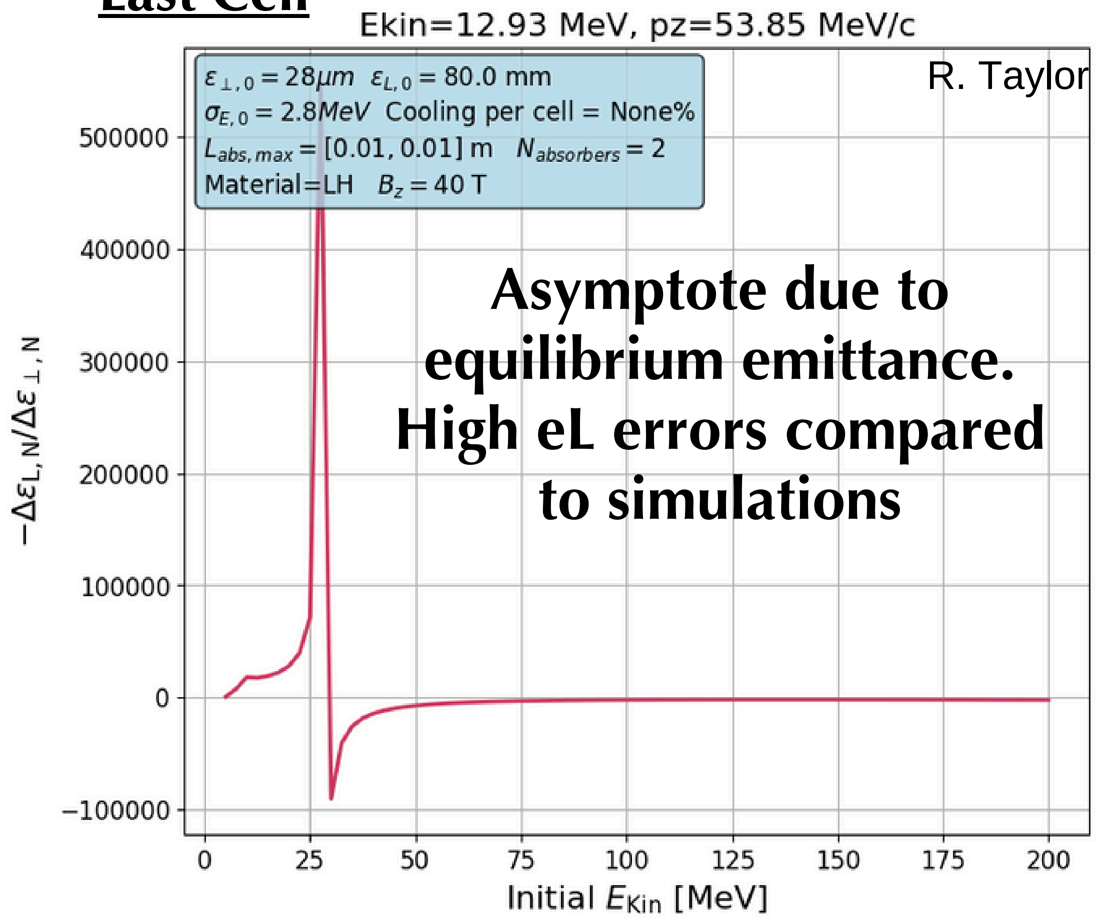
"SEARCHING FOR THE BEST INITIAL BEAM PARAMETERS FOR EFFICIENT MUON IONIZATION COOLING" **B. Stechauner *2024***

For constant absorber length and a given energy spread, happen to find a parabolic distribution between initial kinetic energy and cooling ratio.

First Cell



Last Cell

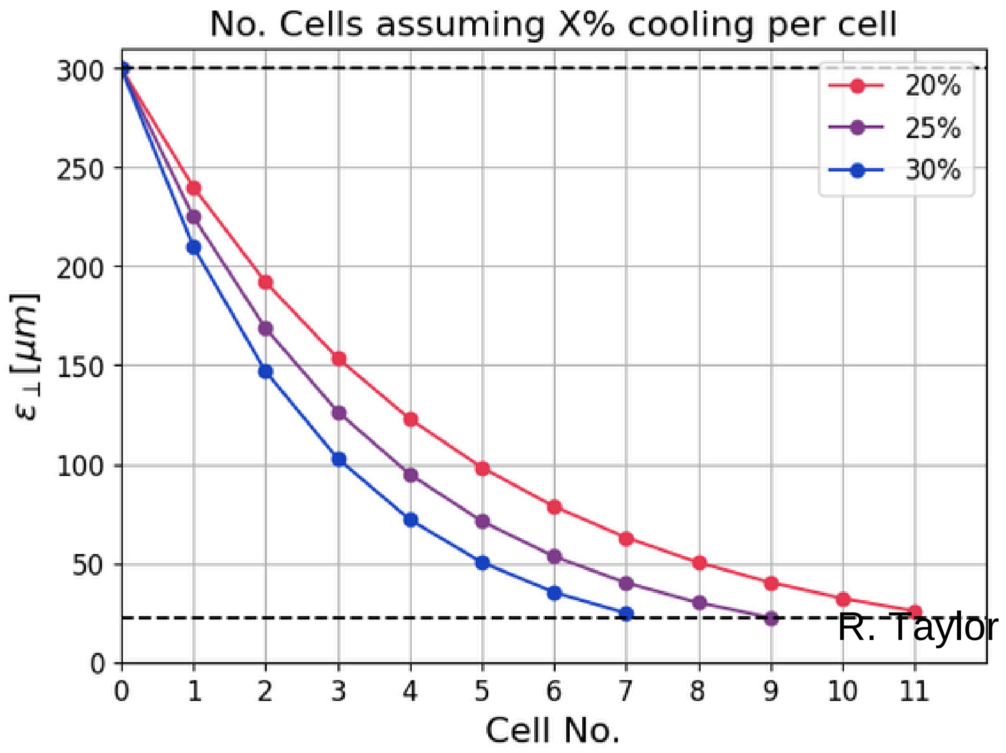


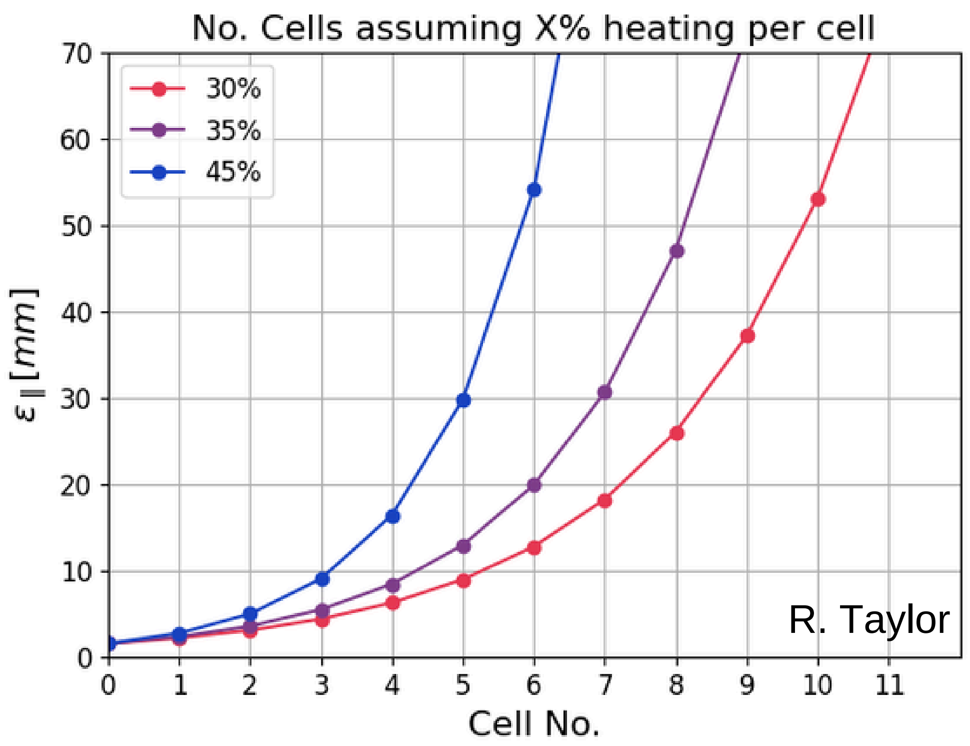
Right-side of parabola has too high energy to scatter.
Left-side of parabola is affected by equilibrium emittance (i.e. if emittance is too low, heating effect dominates)

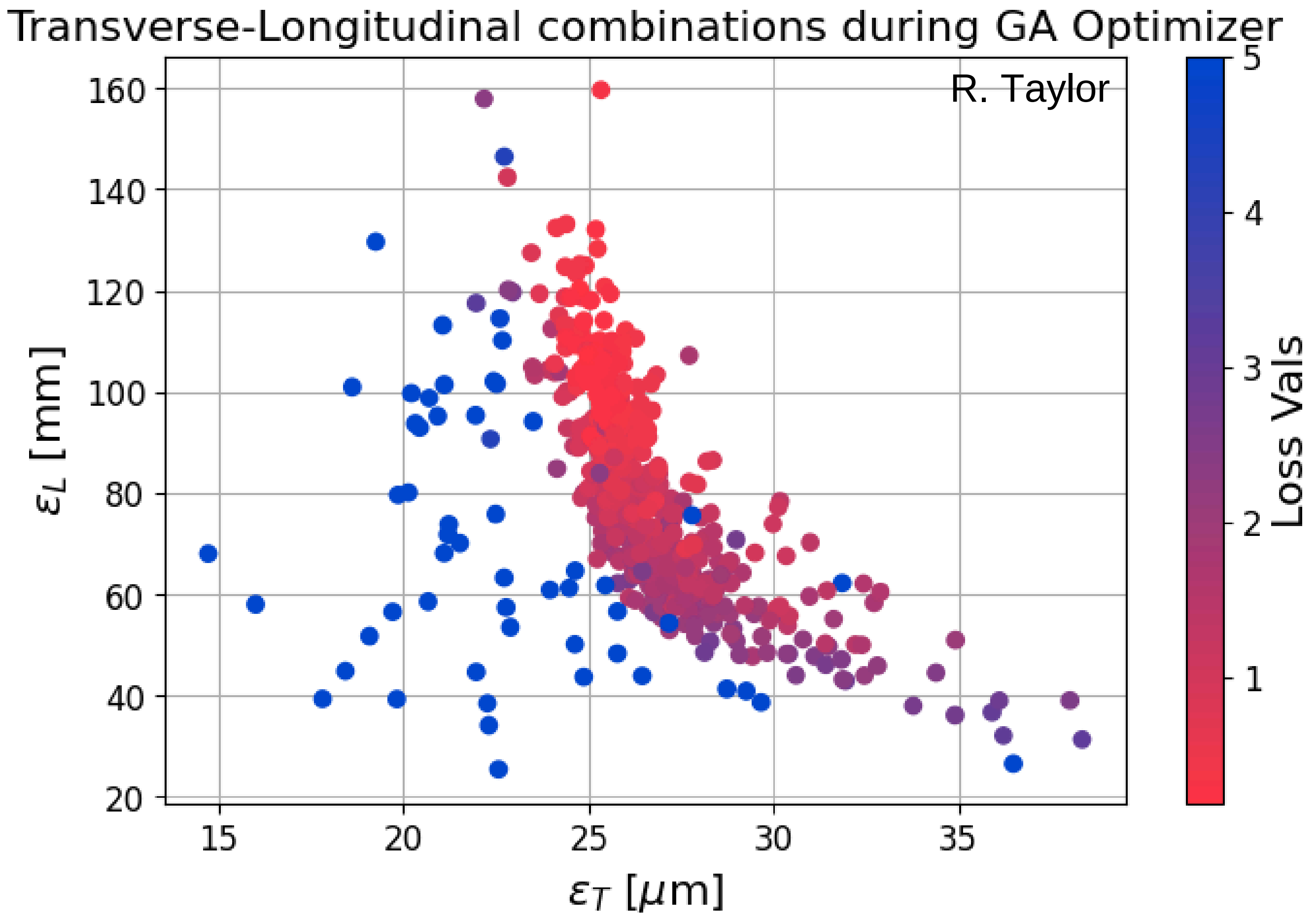
Step 2) Optimise LH_2 absorbers for performance

Optimising <u>cell-by-cell</u> may not guarantee a **global minimum**. Exponentially decreasing transverse cooling results in exponentially increasing longitudinal heating. This accumulation is most significant at the last few cells. Lowest gain in transverse, highest loss longitudinally.

Small changes in early cells can have an **exponential** impact on the resulting longitudinal emittance. Highly recommend a **global optimiser** to improve the parameters of the whole lattice, rather than optimising cell-by-cell. For this exercise, used a **Genetic Algorithm**. Optimised absorber length, energy and energy spread.

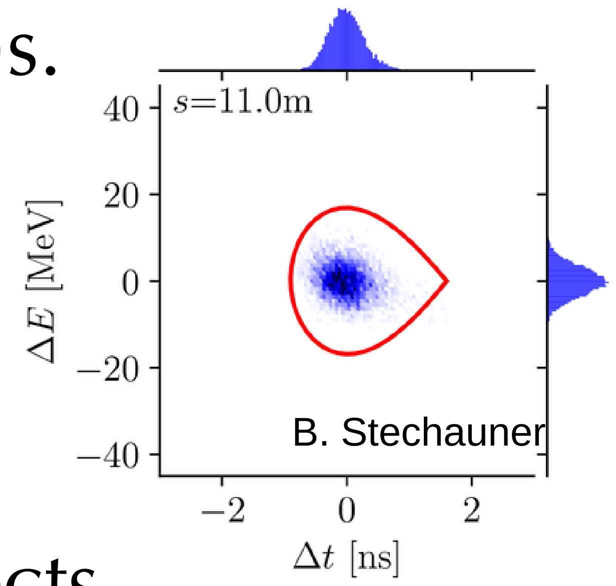


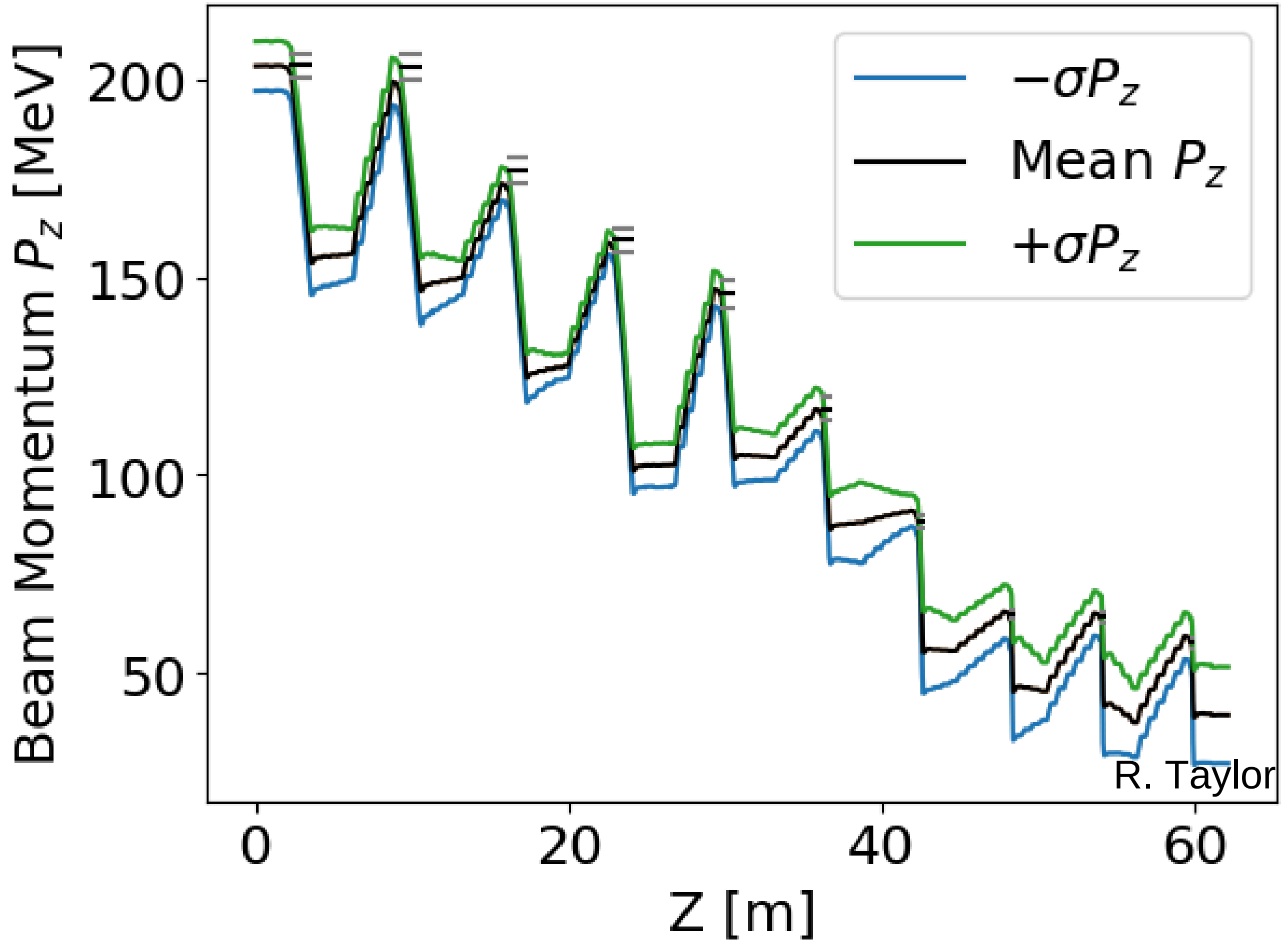




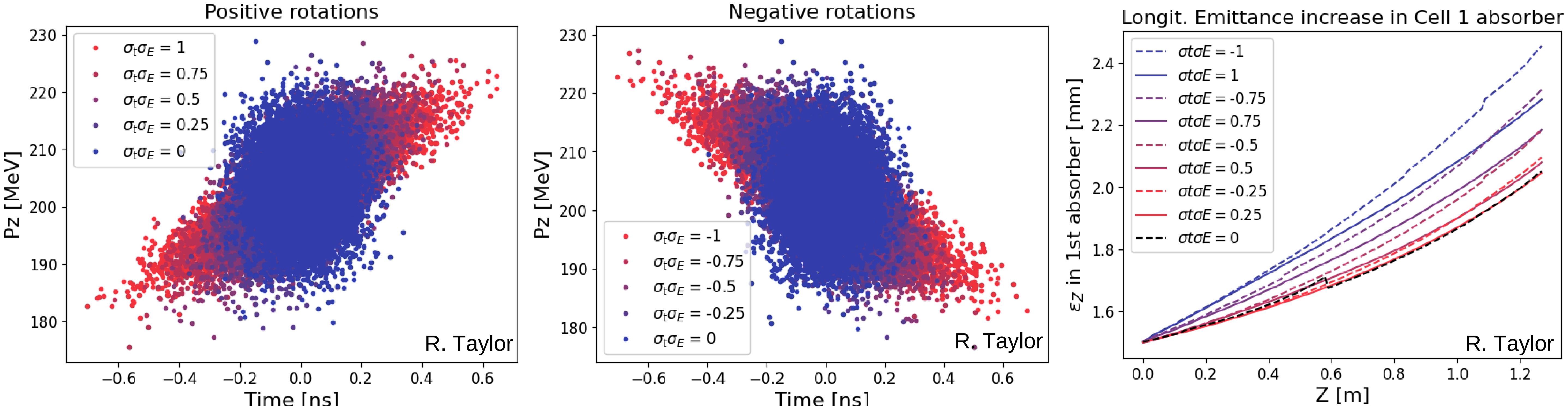
Step 3) RF cavities and kinetic energy

For a given absorber length and pressure, there is an **ideal energy and energy spread** to minimize cooling ratio.
Need to set RF cavities to match these conditions.





Longitudinal correlation of beam distribution affects longitudinal emittance growth within the absorber.

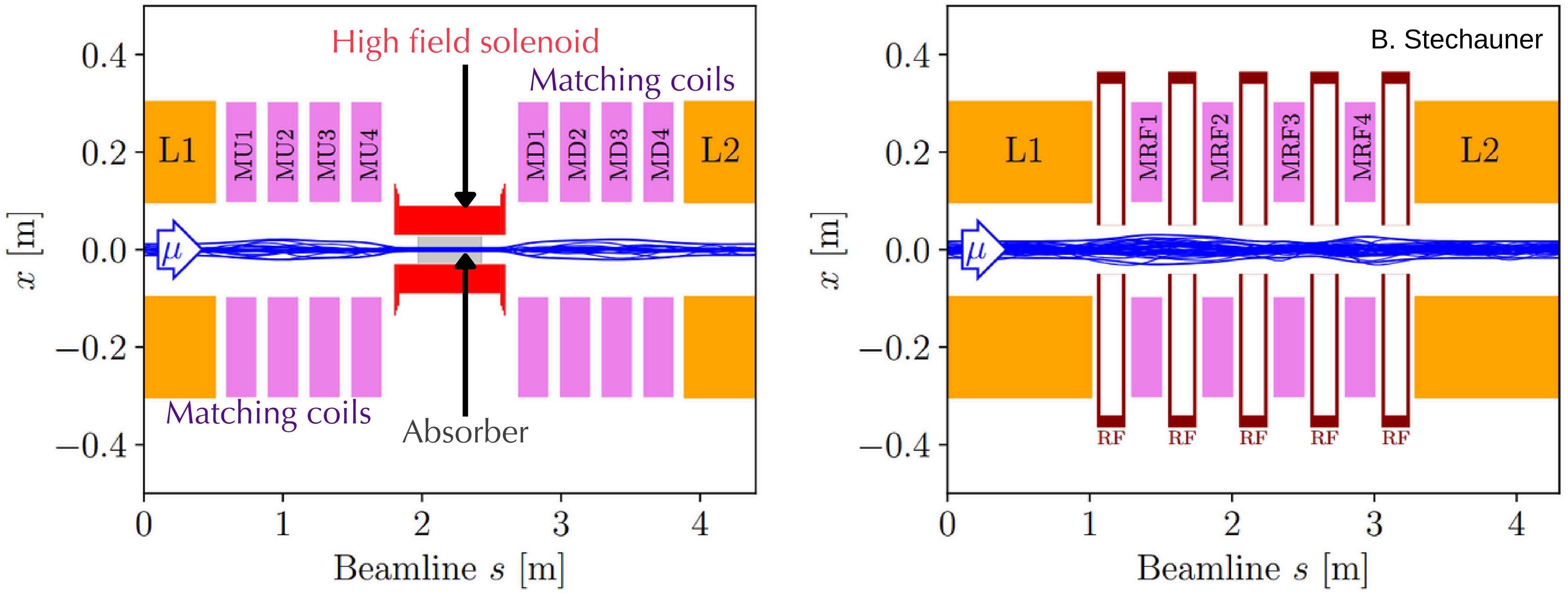


$$\varepsilon_{LN} = \frac{c}{m}\sqrt{M^L_{1,1}M^L_{2,2} - \left(M^L_{1,2}\right)^2}$$

Step 4) Solenoid Matching

Proper beam matching is a key requirement for maintaining low emittance in final cooling.

Mismatches primarily cause emittance growth in the high-field and RF sequence.



Matched conditions for the final cooling stage can be obtained analytically.

Cylindrically symmetric Twiss parameters are optimized by propagating multiple reference particles.

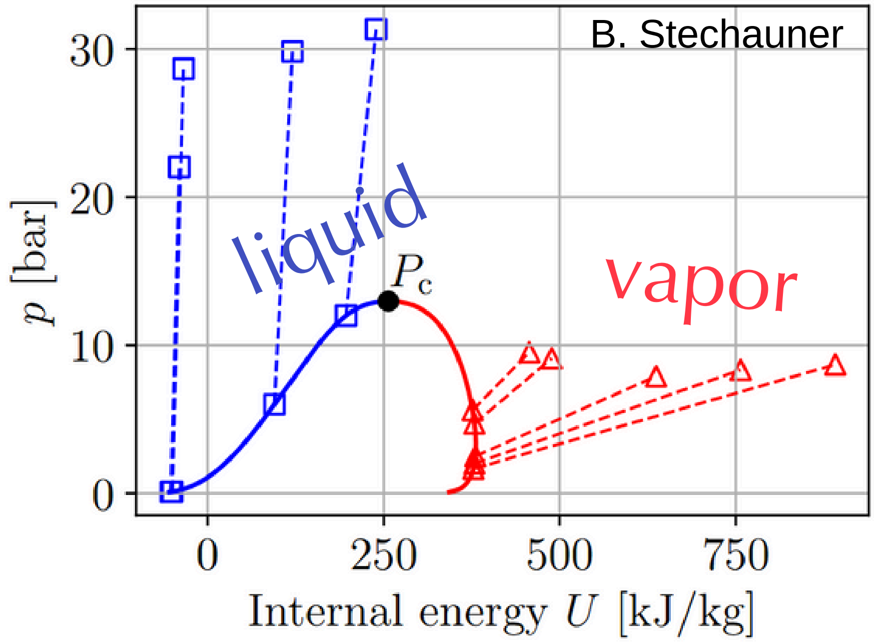
Beam envelope equation in solenoids:

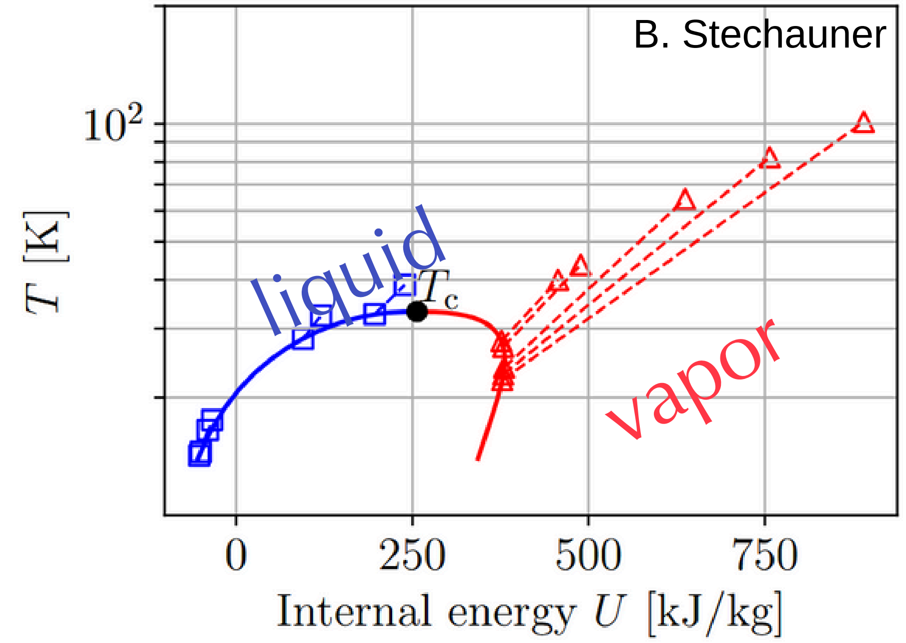
$$2\beta_\perp \beta_\perp'' - (\beta_\perp')^2 + 4\kappa^2 \beta_\perp^2 - 4(1 + \mathcal{L}^2) = 0$$

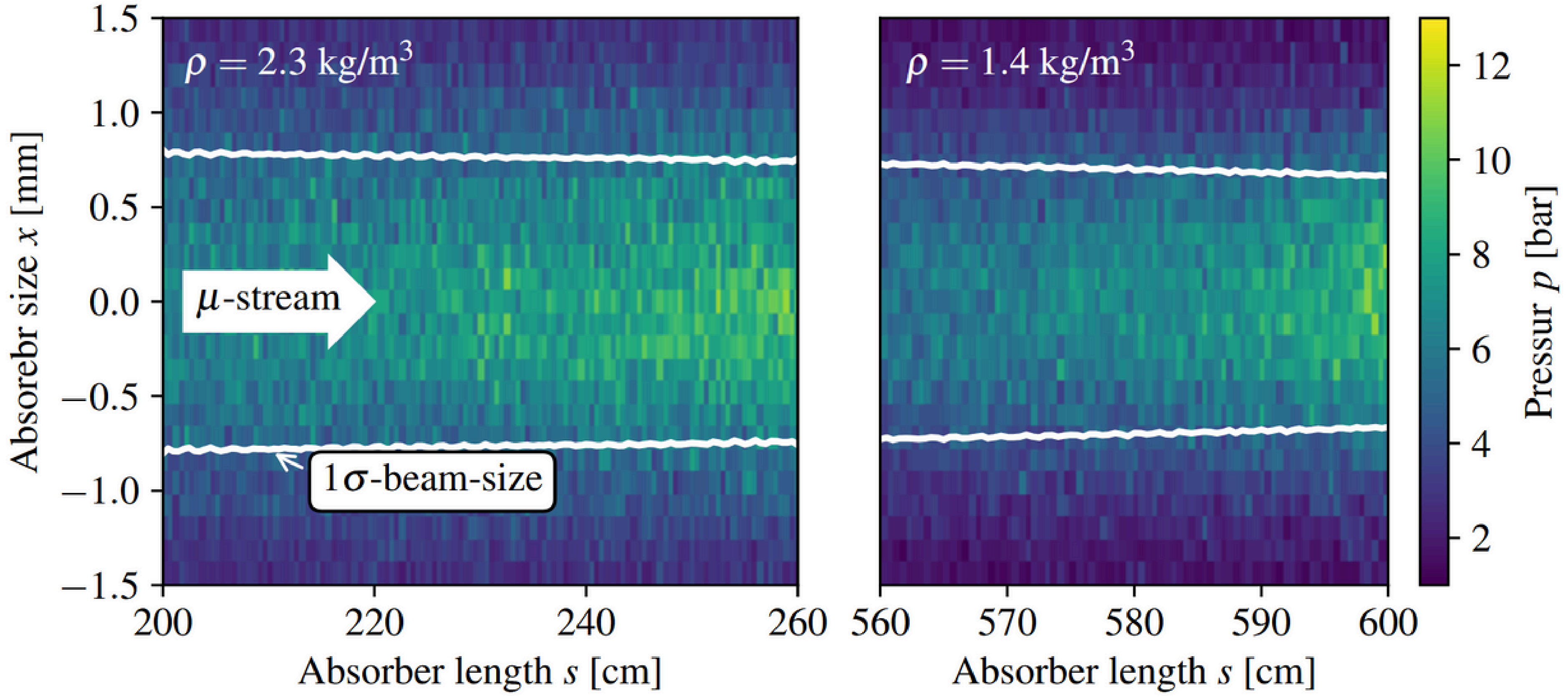
G. Penn et al.: Phys. Rev. Lett. 85, 764

Step 5) Adjust absorber to reduce LH2 pressure

Low-energy, low–transverse-emittance beams deposit energy in hydrogen.
The initial hydrogen pressure and temperature must be tuned prior to muon beam passage.
Hydrogen absorbers operate in either saturated liquid or vapor states.





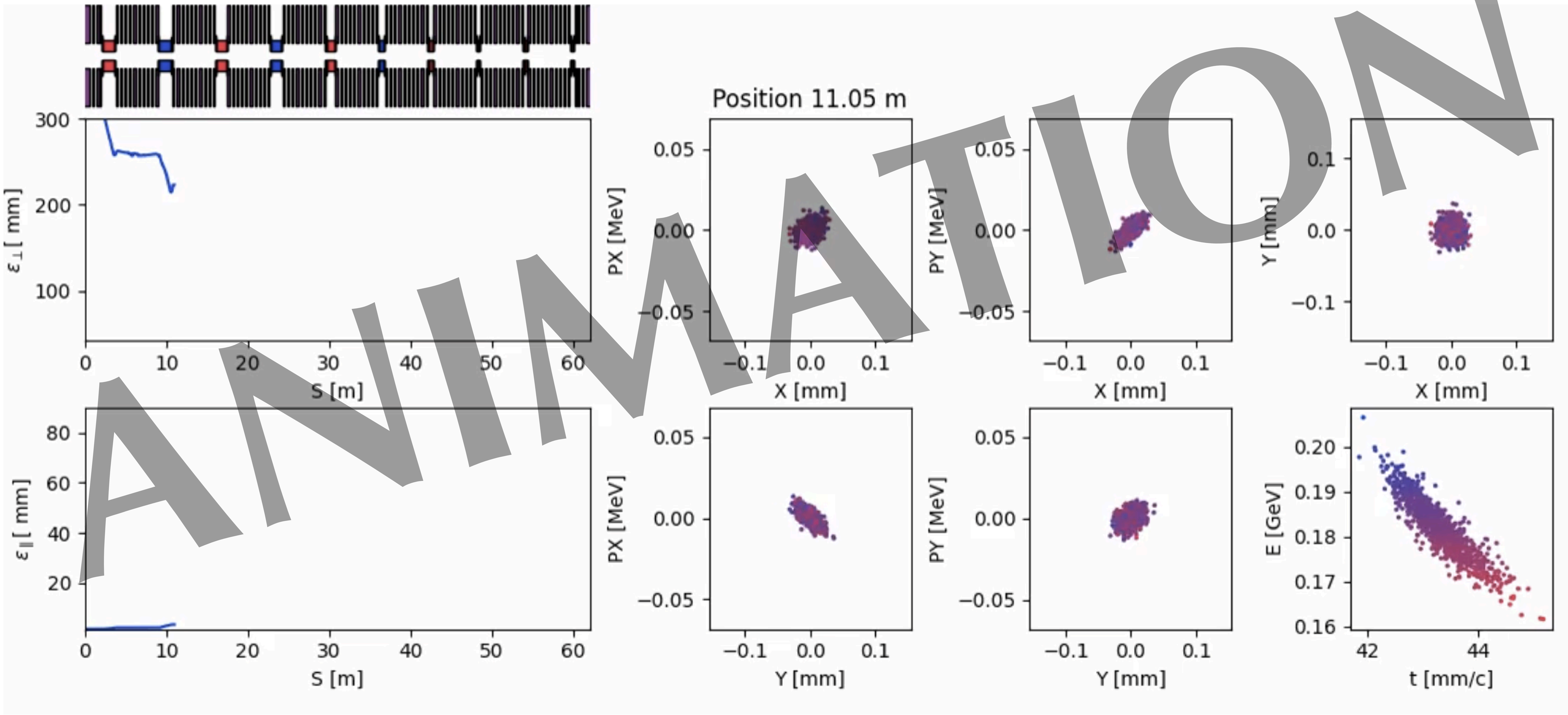


B. Stechauner

Goal:
Prevent preasure increasae and beam window demage.

Strategy:
Optimization of the initial hydrogen phase at the saturation line.

Putting it all together:



Final Cooling Lattice History

2011 - B. Palmer

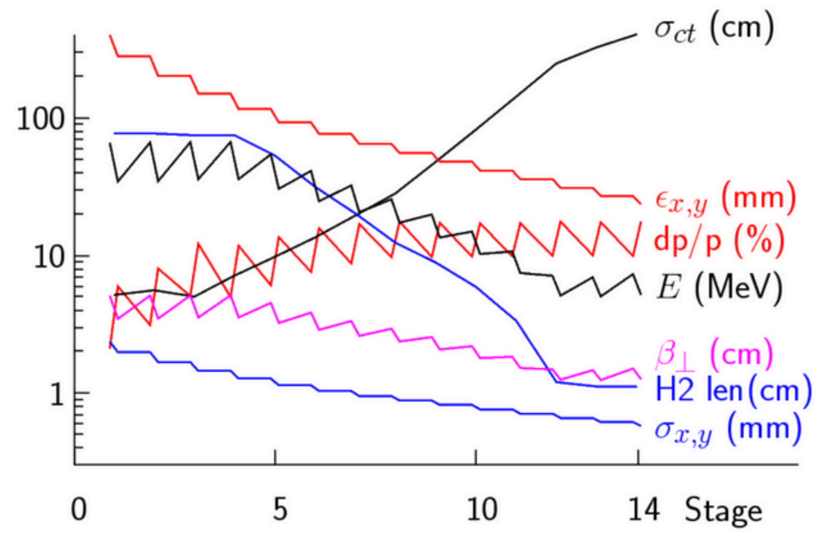
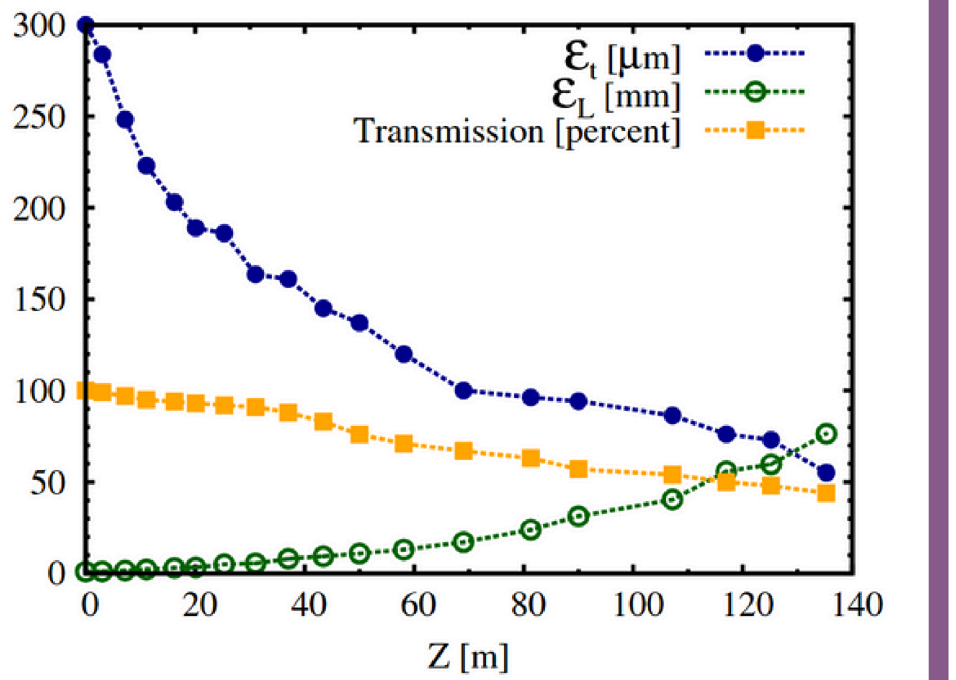


Figure 6: Some parameters vs. stage for the 40 T sequence.

25 um and 72 mm ~67% transmission (With 50 T solenoids)

G4BL - just 40T + absorbers.

2015 - H. Sayed et al.



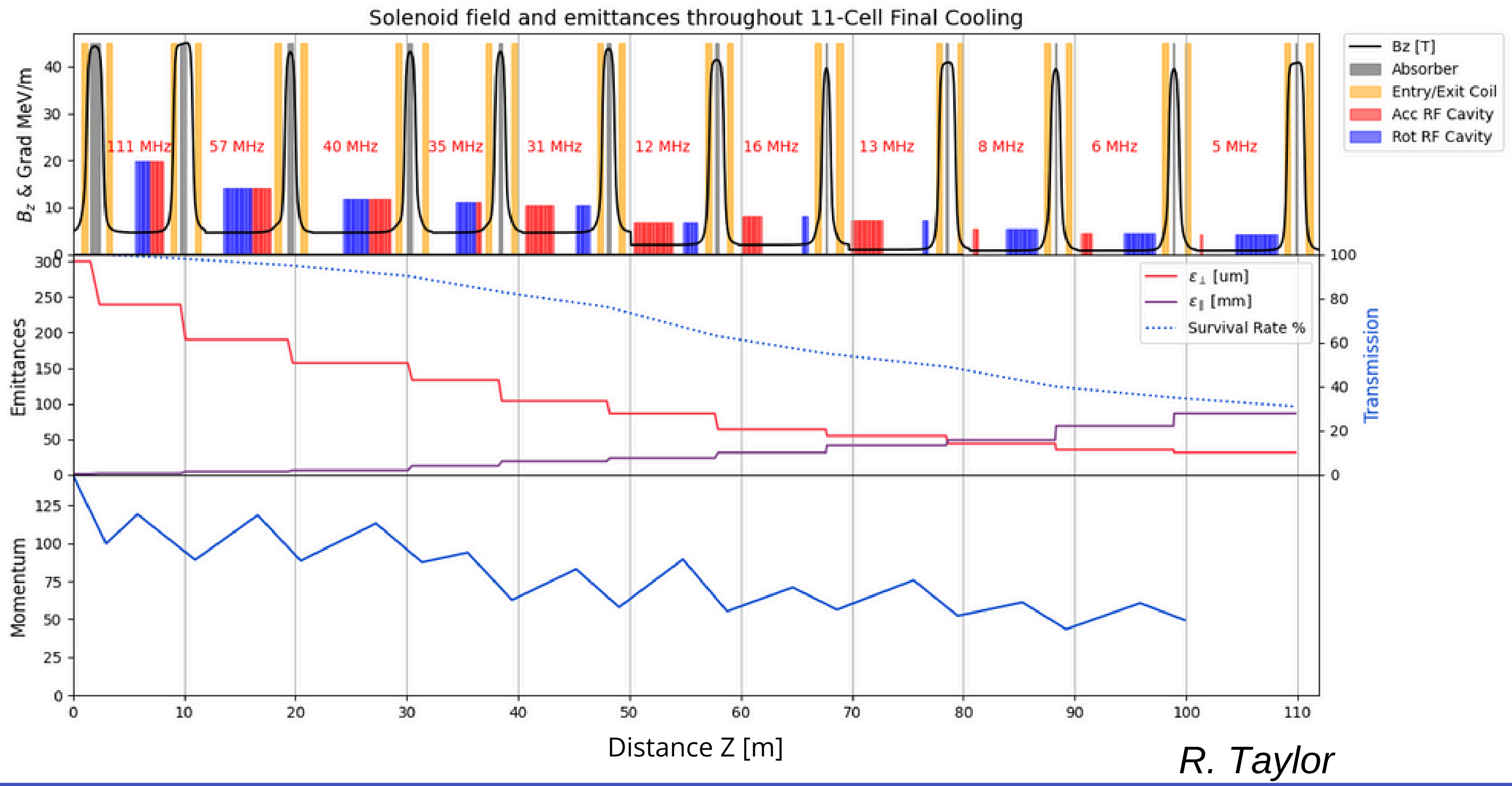
55 um and 76 mm ~45% transmission

G4BL - 30T solenoids

2024 - E. Fol

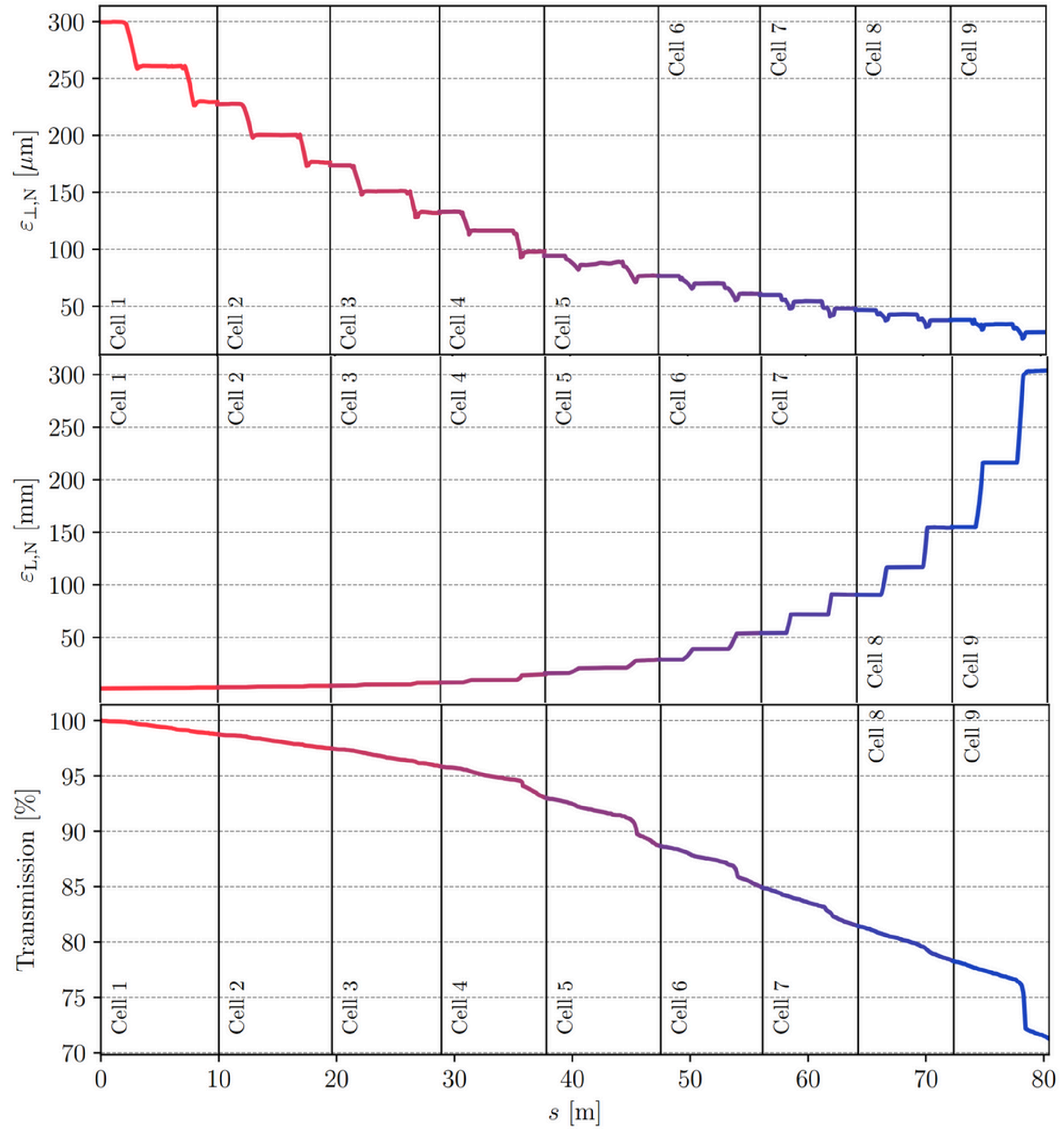
RFT from Bayesian Optimisation Cell-by-cell

Cell no.	ε_T μm	ε_L mm	ε_{6D} μm	Cumulative transmission %
Start	300	1.5		100
10	32.9	66.1	414.6	31.7
11	29.5	82	414.5	28.5



R. Taylor

Final Cooling Lattice History



2025 - B. Stechauner

25 um and 300 mm ~70% transm.
G4BL, cell-by-cell

2025 - R. Zhu

G4BL from Dif Ev
Cell-by-cell

From B8

Stage	ε_T mm	ε_L mm	ε_{6D} mm^3	Cumulative transmission %
Start	0.26	1.8	0.12	100
Stage 0	0.21	2.5	0.11	99.6
Stage 1	0.16	5.2	0.14	90.1
Stage 2	0.12	8.7	0.13	79.8
Stage 3	0.095	10.3	0.098	72.5
Stage 4	0.063	15.1	0.064	65.5
Stage 5	0.041	22.7	0.039	55.5
Stage 6	0.032	32	0.035	52
Stage 7	**0.0224**	**42.68**	**0.022**	**42.7**

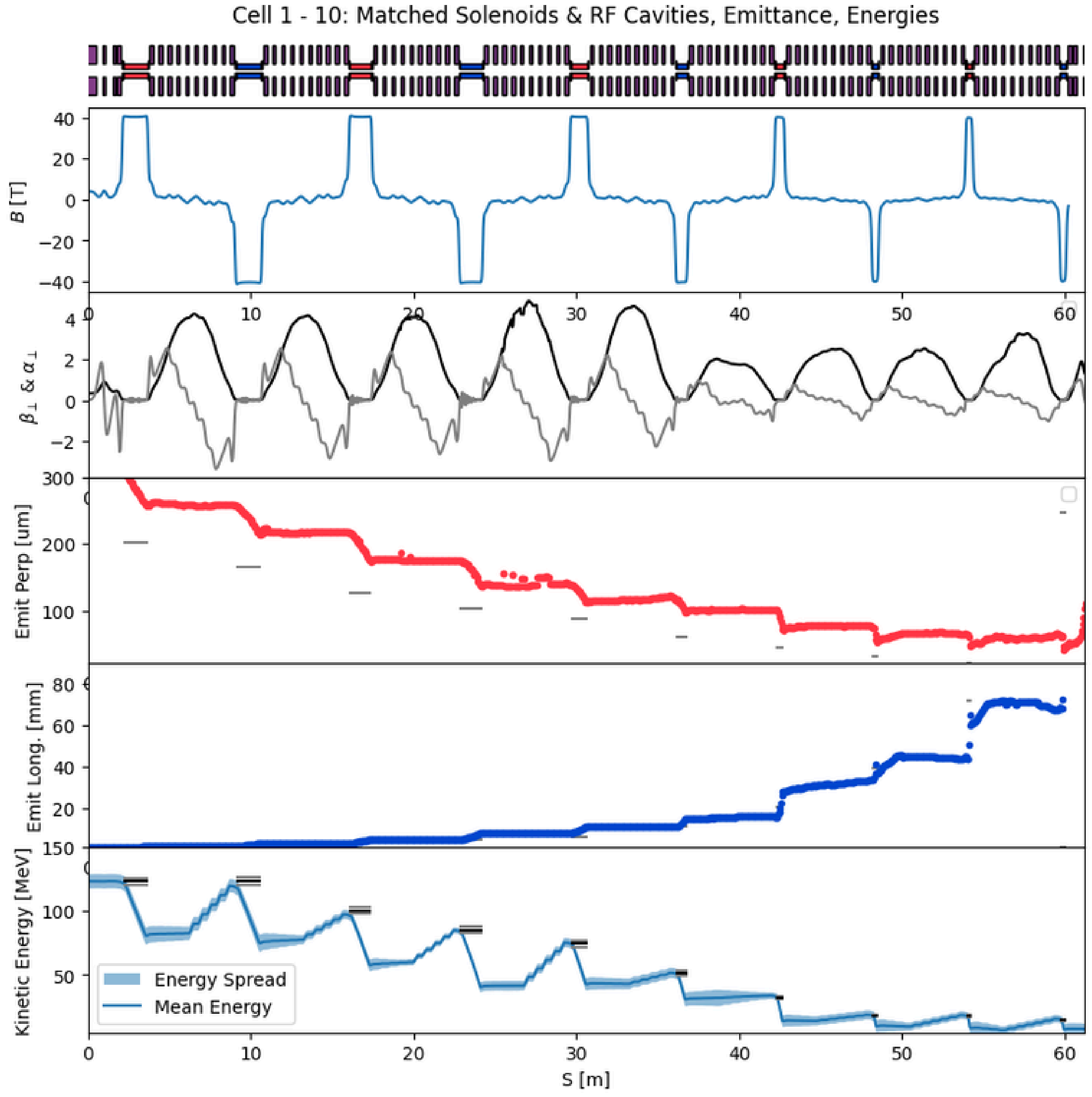
From B10

Stage	ε_T mm	ε_L mm	ε_{6D} mm^3	Cumulative transmission %
Start	0.14	1.5	0.03	100
Stage 0	0.12	1.9	0.03	99.5
Stage 1	0.08	5.2	0.034	90.6
Stage 2	0.053	7.7	0.023	77.9
Stage 3	0.041	10.9	0.019	71.9
Stage 4	0.029	15.7	0.014	66.8
Stage 5	**0.023**	**22.1**	0.012	**61.4**

2025 - R. Taylor

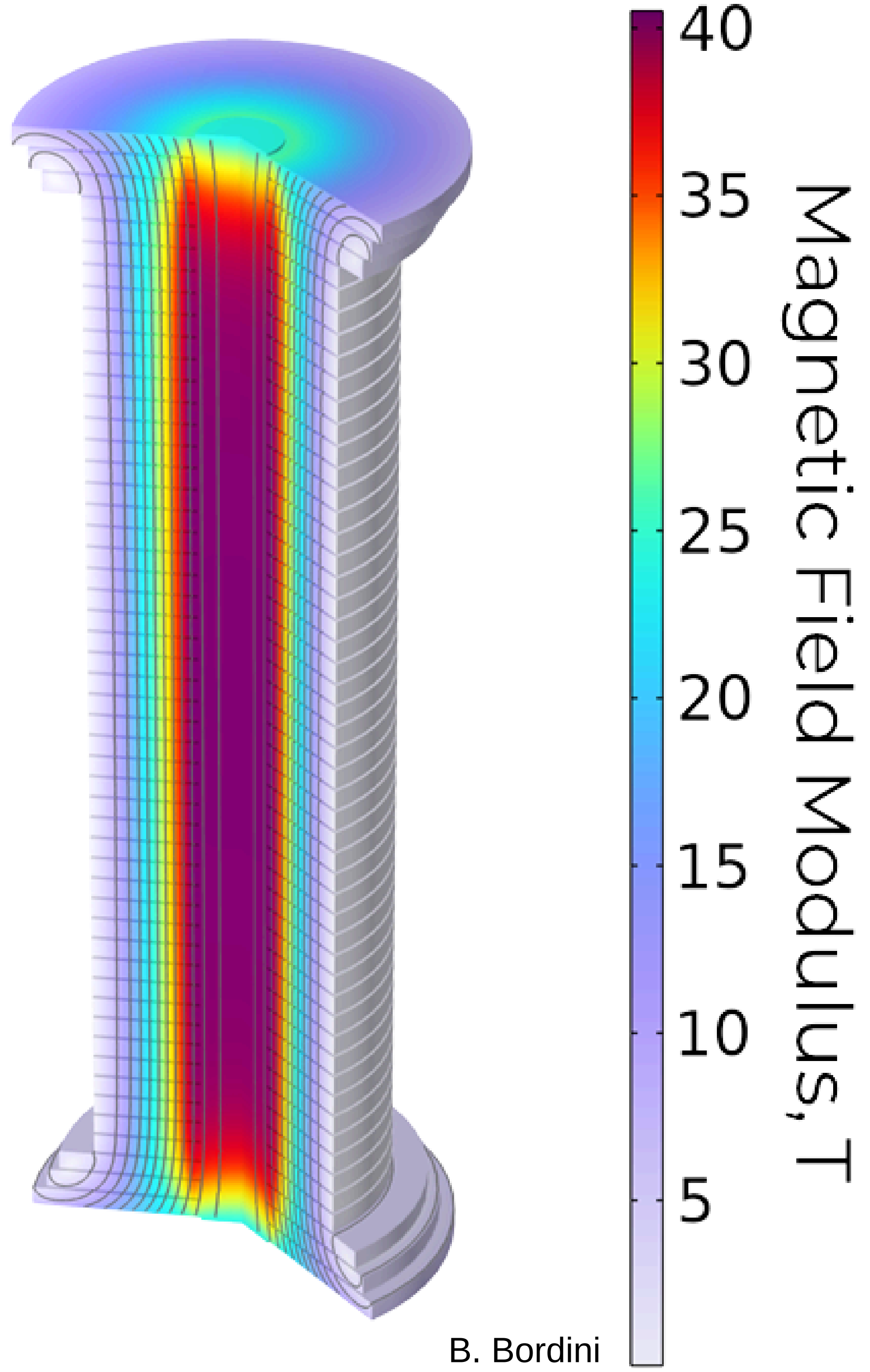
G4BL, start-to-end

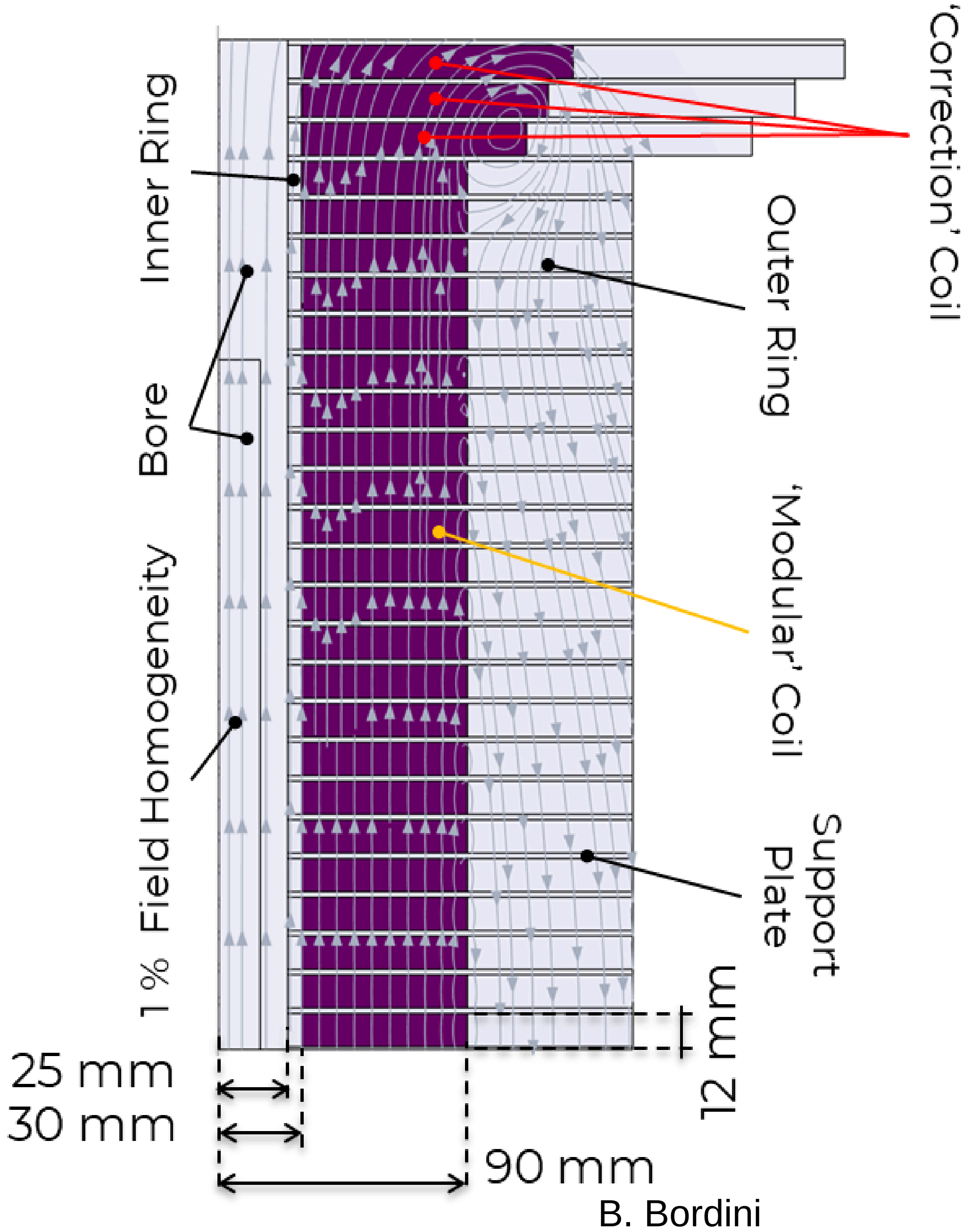
Currently 47 um and 91 mm ~44% transmission



Final Cooling & High Field Solenoid R&D

- 40 T pancake design, with outer windings of higher radius.
- Mechanical bracing with radial pre-compression desks





Main Dimensions, mm	Free Bore	50
	Winding ID	60
	Winding OD	180
	1st Radial Disk OD	~ 300
	2nd Radial Disk OD	~ 540
	Solenoid Height	~ 220
Precompression, MPa	Radial on the outermost layer	~200
Field, T	Peak	40
Current Density, A/mm^2	Overall	~ 650
Current, A	Conductor	~ 650
Magnetic Energy, MJ	Overall	1.8
Temperature, K	Conductor Innermost layer	4.5
Current Margin, %	Current, B//a-b	> 100

B. Bordini

High Field Solenoid R&D & Quench Protection Studies

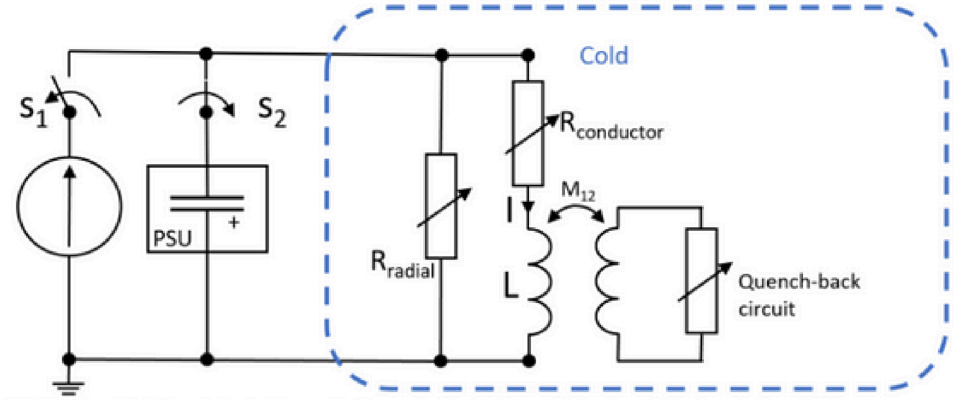
Magnet protection is a serious challenge as:

T. Mulder

- The stored energy density of UHF solenoids is commonly large, in the order of 30 kJ/kg.
- NI-coil layout has the risk of large induced currents during a quench, potentially resulting in large Lorentz forces and thus mechanical stress.

Several quench protection solutions are being investigated, such as resistive heaters and a novel quench protection technique using a capacitor discharge[1].

- Capacitor Discharge (CD) offers a robust and elegant quench protection solution, as it can transition the full magnet to normal state within milliseconds without the need of additional electrical infrastructure.
- Combination of opening the breaker and injecting additional current to heat the magnet using its internal turn-to-turn resistance.

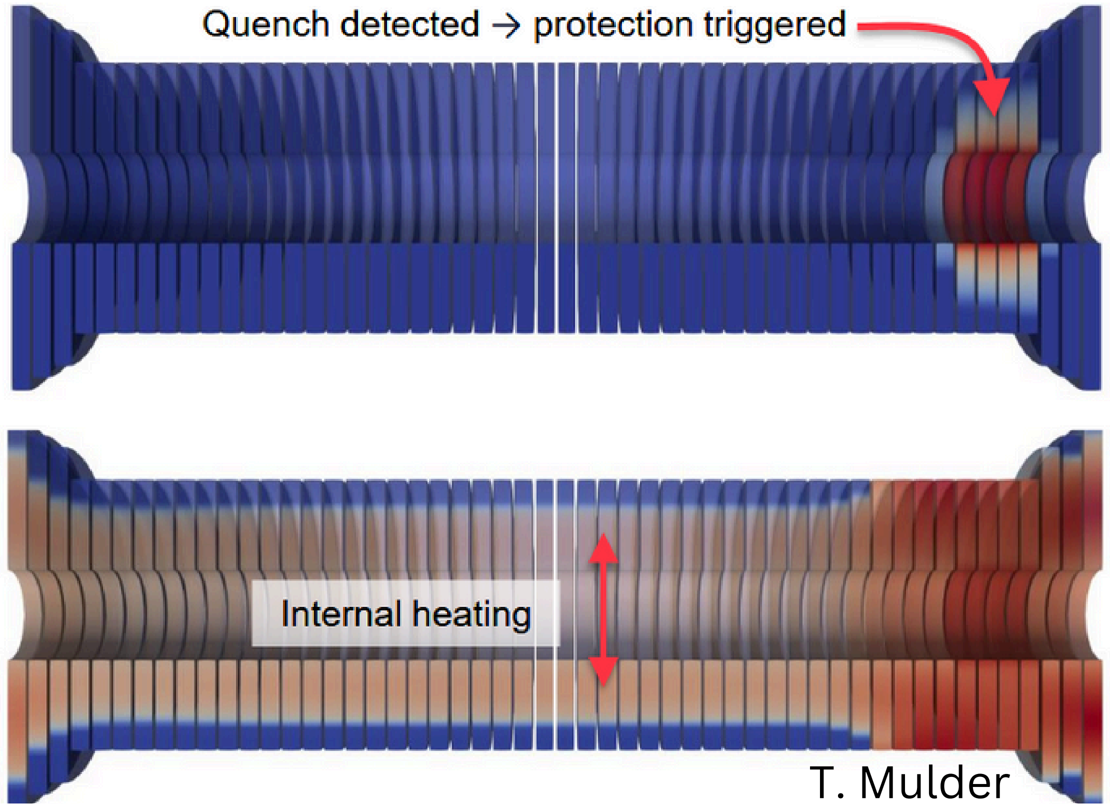


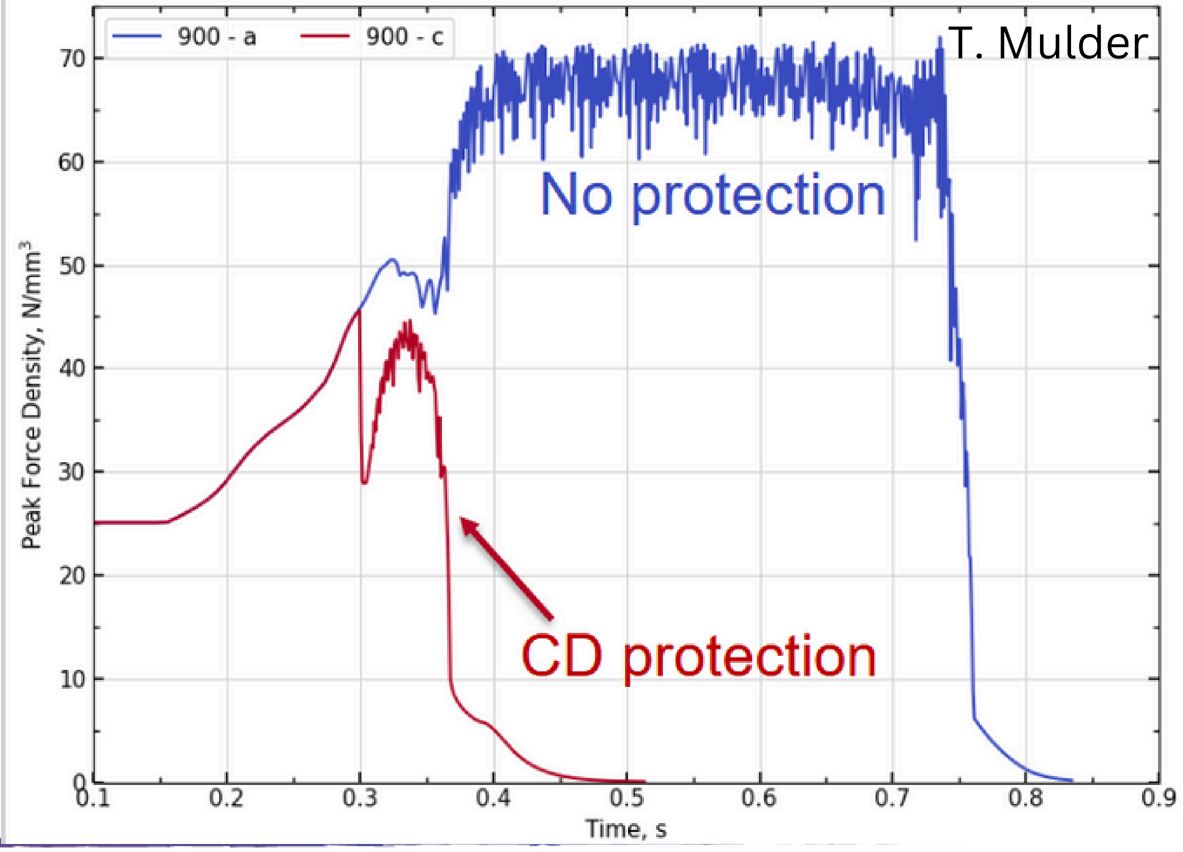
[1]T. Mulder, M. Wozniak, A. Verweij, Quench Protection of Stacks of No-Insulation HTS Pancake Coils by Capacitor Discharge, IEEE Trans. Appl. Supercond., Vol 34, Nr 5, 2024.

- The **Capacitor Discharge** (CD) quenches the full magnet to **normal state** within **milliseconds** without the need of additional electrical infrastructure.
  - **opening the breaker** and **injecting** additional **current** to **heat the magnet**

Benefits:
✓ Controlled **predictable quench**.
✓ **Reduces** the radial and axial **forces**.
✓ **Reduces** the **hot-spot temperature**.

T. Mulder, UHF Solenoids Workshop, CERN, 26.11.2025

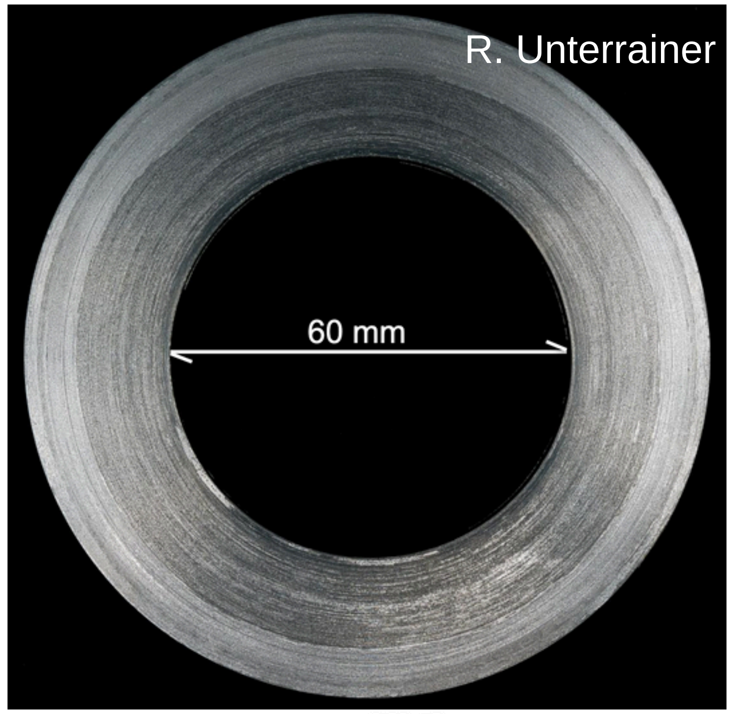




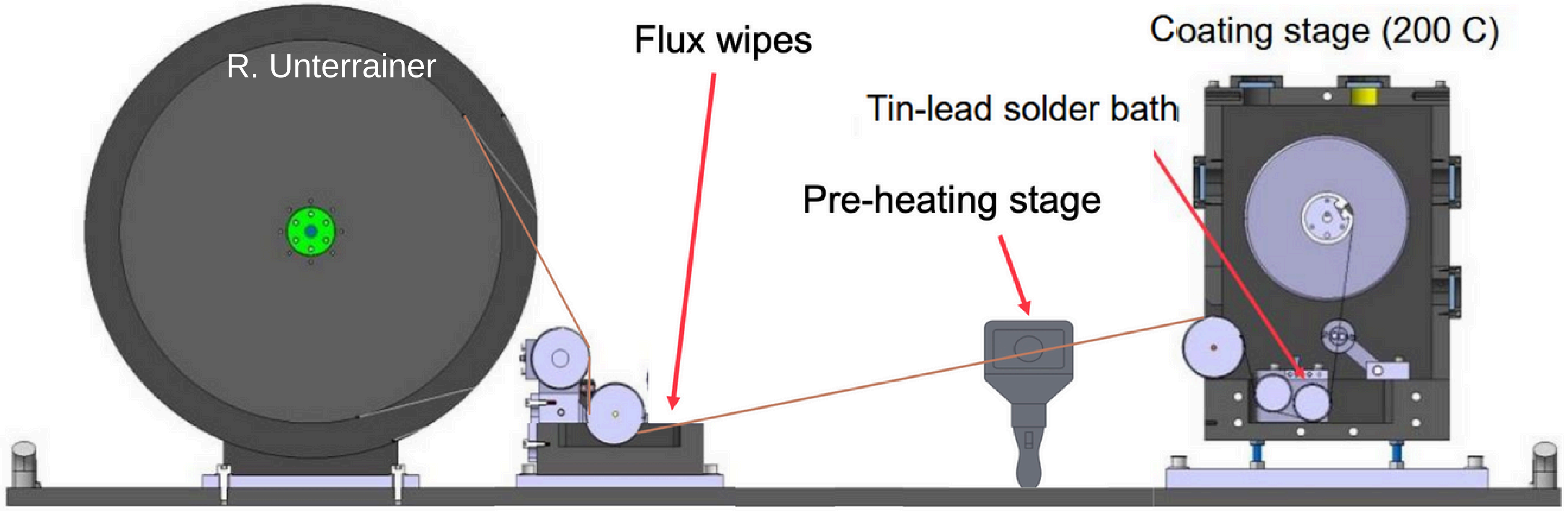
"Final Cooling Solenoid of the Muon Collider located in a good resistance to mass ratio range for CD quench protection to work."
Detection is key

Final Cooling & High Field Solenoid R&D

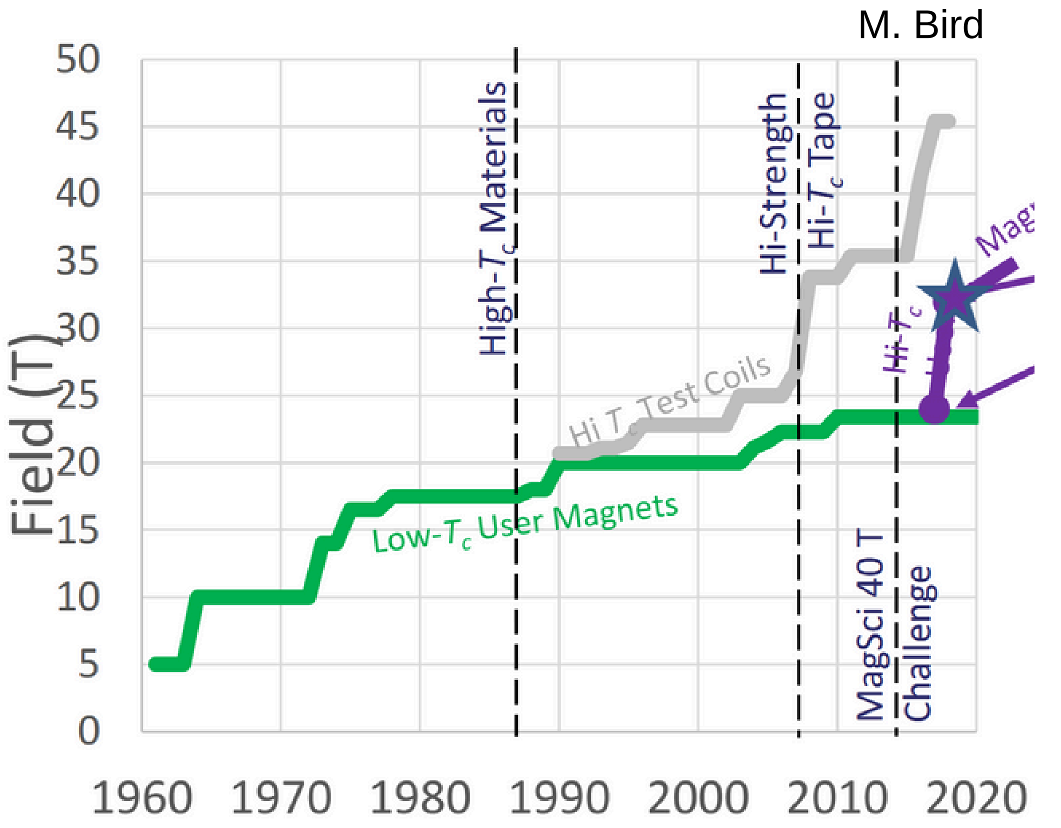
In November, IMCC and CERN hosted the workshop on ultra-high-field solenoids

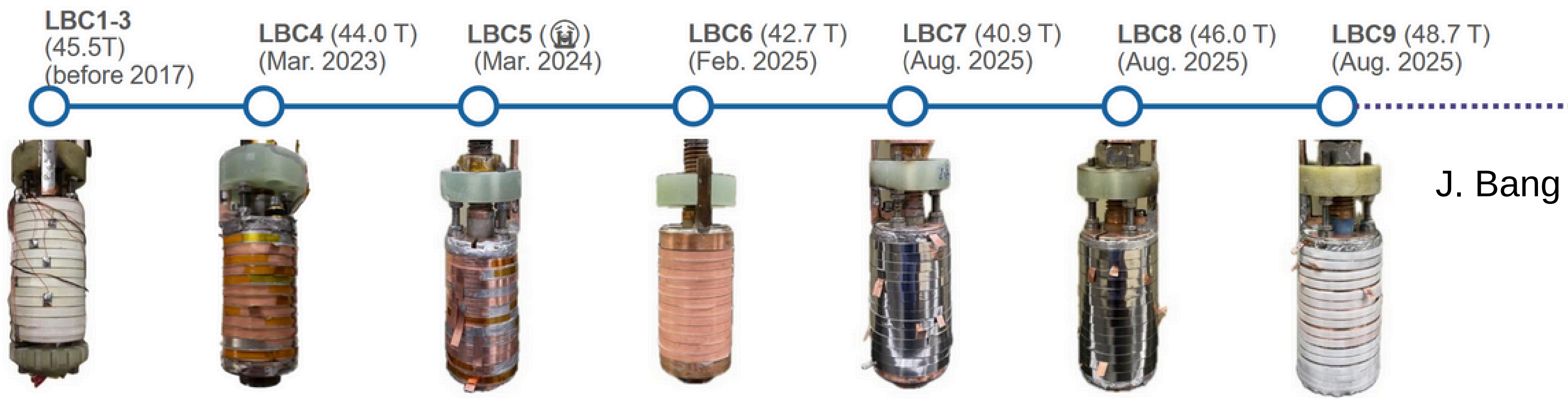


High field solenoid prototype at CERN.
Manufacturing of the first HTS pancake.



Active US participation from NHMFL (National High Magnetic Field Laboratory), Bruker and CFS





Final Cooling & RF Cavity R&D

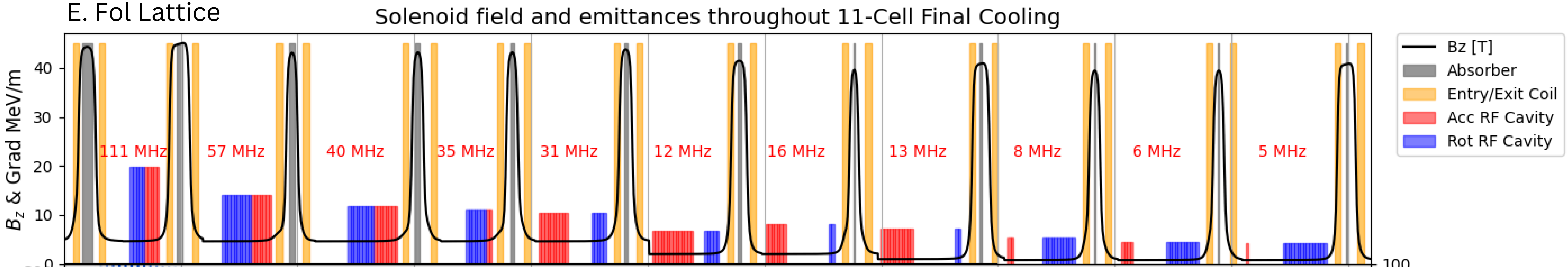
Final cooling requires:

- Range of frequencies (~150 → 5 MHz)
- Range of RF gradients
- Dedicated rotating and accelerating cavities
- Spacing between matching solenoids
- RF gap to fit beam size

R. Zhu Lattice

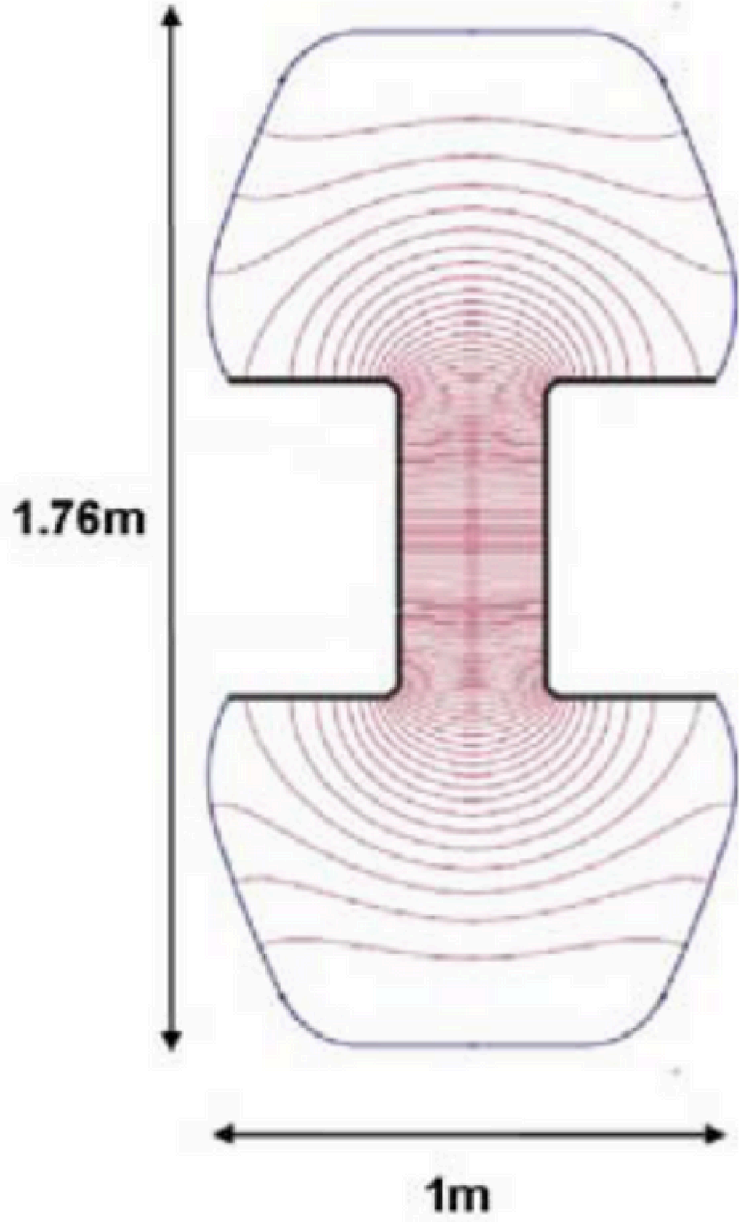
Stage	Frequency MHz	Maximum gradient MV/m
stage 0		
stage 1	142.9	9.2
stage 2	67.3	5
stage 3	52.7	4.9
stage 4	29.8	1.7
stage 5	15.3	1.5
stage 6	10	1.3
stage 7	8	1.2

E. Fol Lattice



Final Cooling & RF Cavity R&D

88 MHz, 4 MV/m cavity in test from muon cooling for a neutrino factory. Constructed from lepton accelerating cavities from the PS.

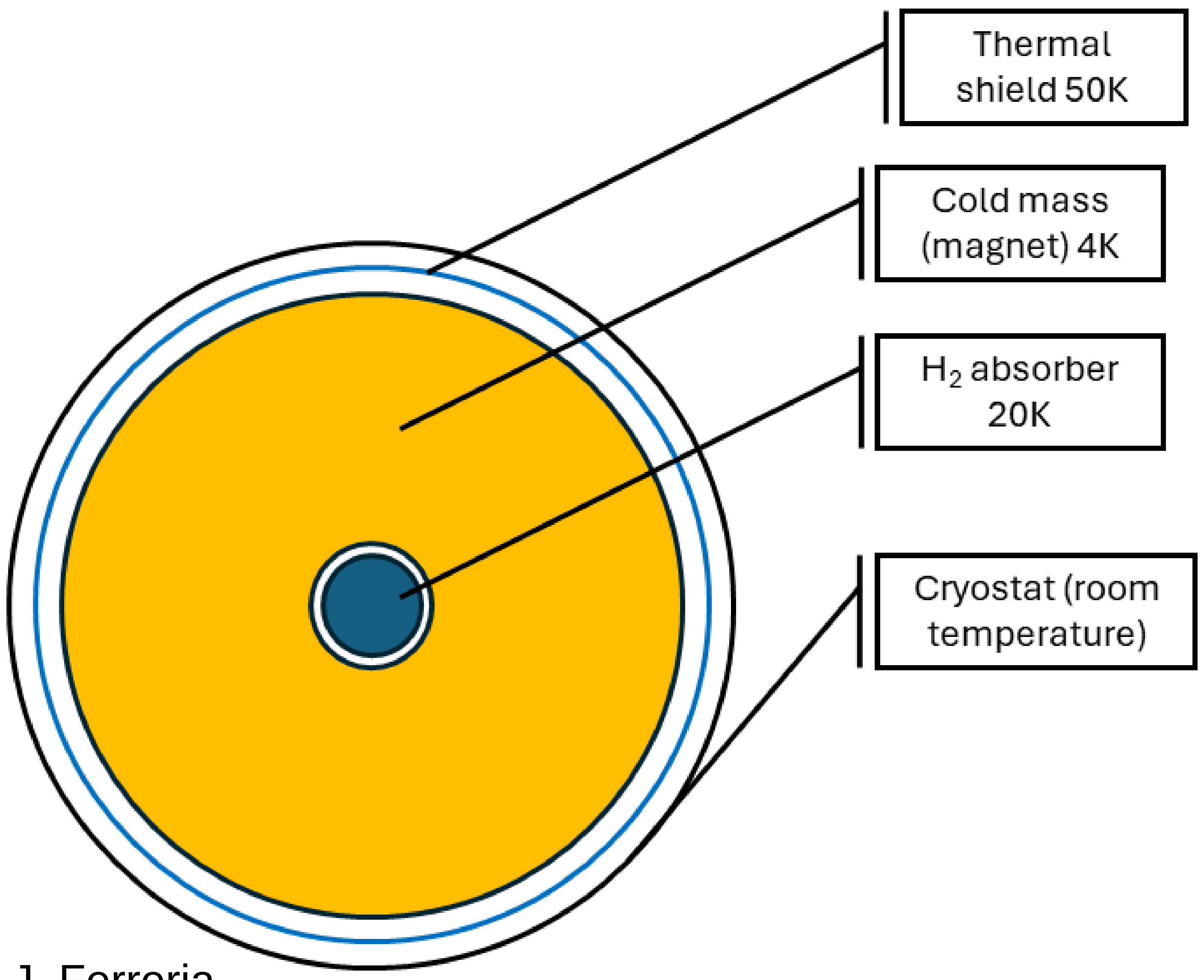


Below 50 MHz:
- Ferrite-loaded
- Magnetic alloy cavities

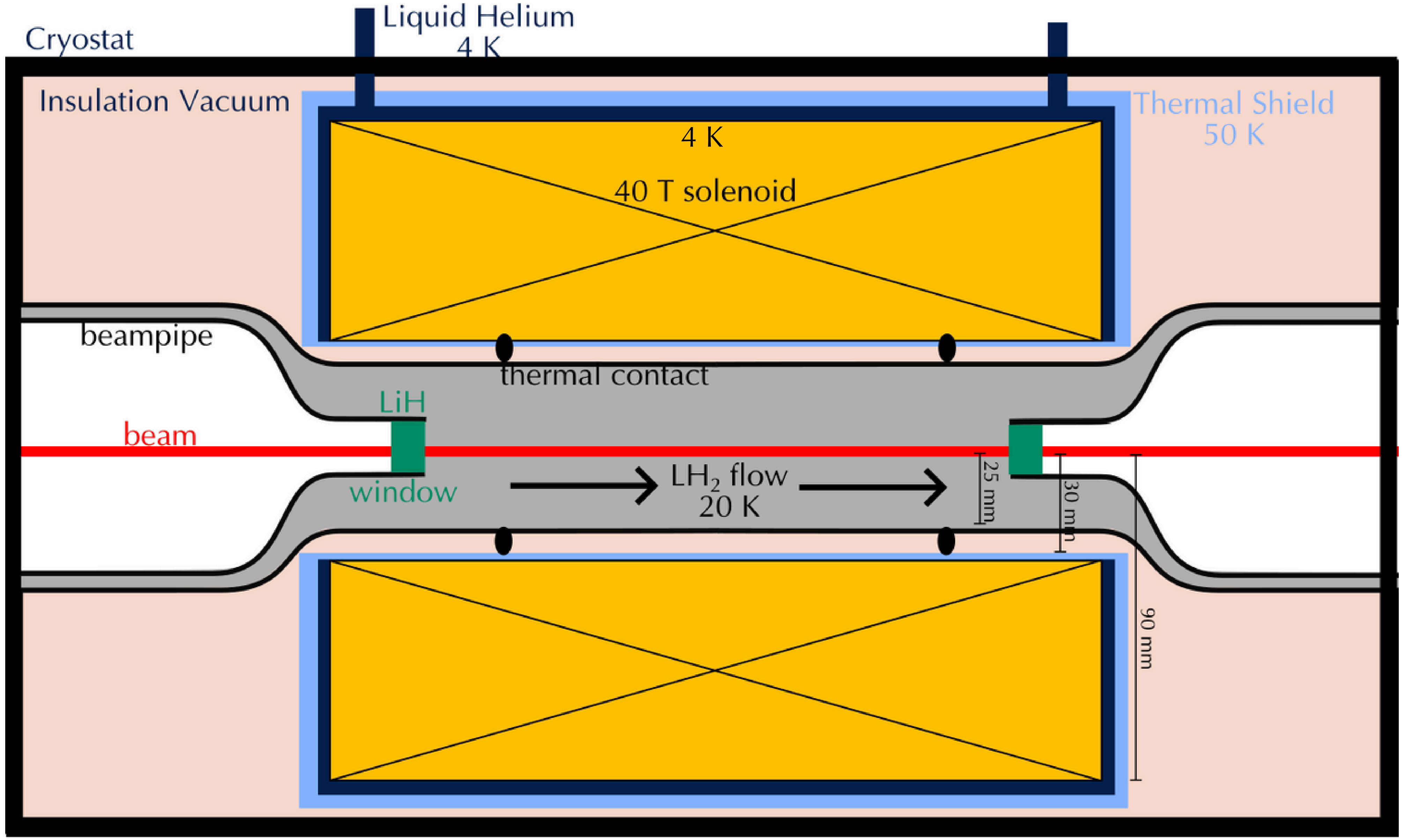
Few MHz RF:
- Widely used in p+ synchrotrons
  - Semi-relativistic momentum
  - Voltages are typically low for final cooling needs
    - MA can probably get to higher voltages.
- Option of ceramic loading
  - Would be dedicated R&D task.

Final Cooling & Hydrogen Absorber R&D

No cryostat design exists of LH_2 absorber. Below images predict what a liquid hydrogen absorber may look like with respect to the high field solenoid and the beampipe.



J. Ferreria



R. Taylor

Final Cooling & Demonstrators?

Demonstrating final cooling with muons requires an already cooled muon beam.
Instead can test high field solenoids, liquid and gaseous hydrogen absorbers, and explore R&D with intense proton beams.

Muons Inc planned absorber prototypes with beam.

RESEARCH ARTICLE | MARCH 20 2006

Mucool Hydrogen Absorber R & D

Mary Anne Cummings; Muon Collaboration

+ Author & Article Information

AIP Conf. Proc. 821, 442–447 (2006)

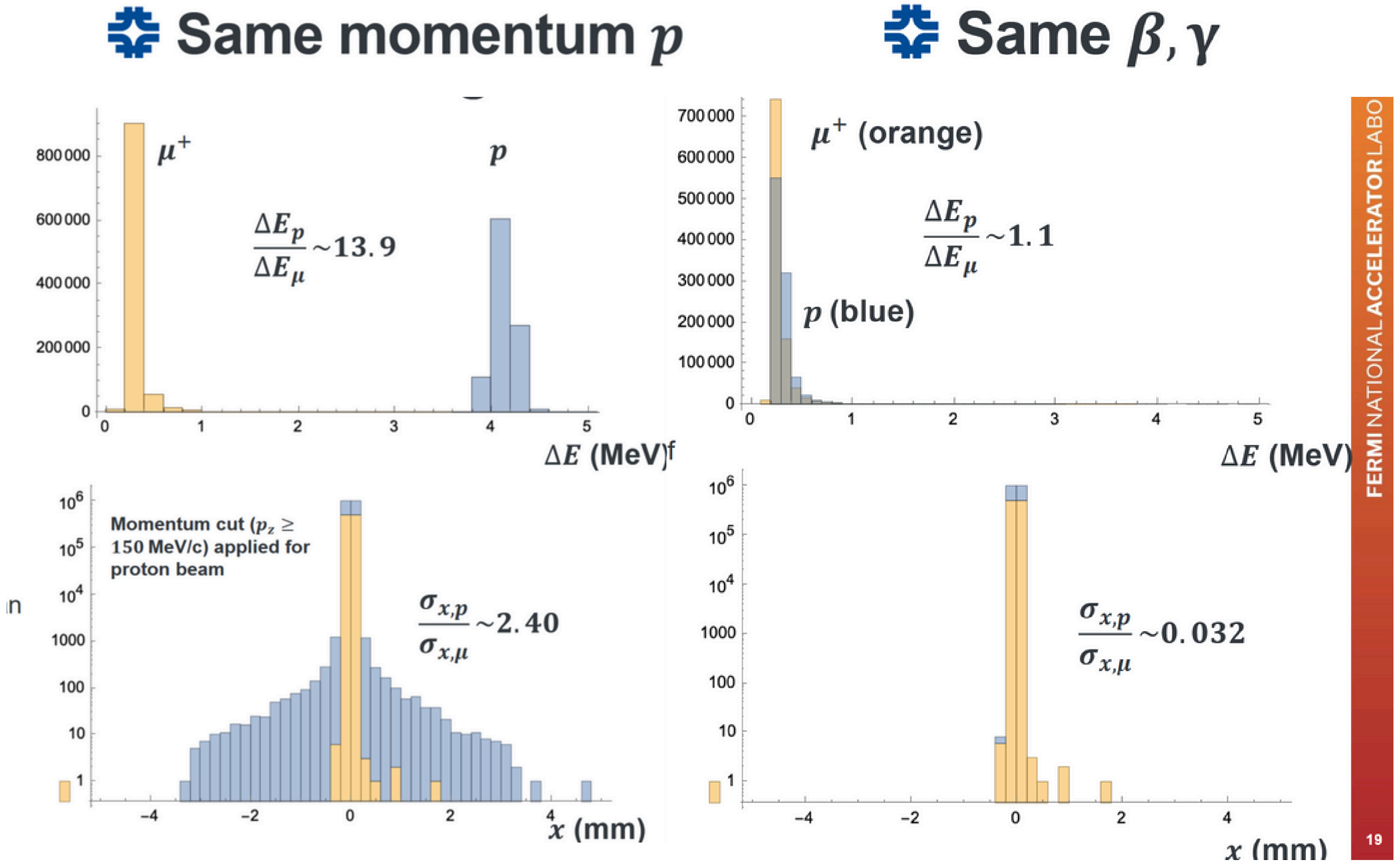
https://doi.org/10.1063/1.2190149

Share Tools

The Mucool hydrogen absorber program will be presented. An update of current projects will be described, and the next year's plan will be reviewed, along with efforts in collaboration with the Muon International Cooling Experiment.

been adapted for the 201 MHz RF cell. An operational beamline is on schedule to run as early as 2006 in the MTA for tests on LH_2 and GH_2 absorber prototypes.

K. Yohenara and *C. Riggall* comparing proton and muon beams for in a 1 cm thick LH_2 target.



Conclusion of Challenges

Simulation Codes

- Implementing collective effects, inc. space-charge and IBS.

Analytical Models

- Break down near the equilibrium emittance.

Lattice and Beam Optics

- Ensuring adiabatic matching between solenoids and cavities.

Solenoid R&D

- 40 T pancake prototypes. Strong radial stresses. Quench protection.

RF Cavity R&D

- Low frequency, high gradient cavities in magnetic fields.

Absorber R&D

- LH_2 pressure from intense beam. Developing cryogenic model.

International MUON Collider Collaboration

MuCol

Thank you for your attention.

I look forward to hearing how USMCC would like to engage with Final Cooling activities

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Resources

TECHNISCHE UNIVERSITÄT WIEN
Vienna University of Technology
Technische Universität Wien

Investigations and technology developments for a final cooling scheme in muon colliders

Bernd Stechauner
Matrikelnummer: 1426914
Großau, am 11. September 2025

Workshop on ultra-high-field solenoids

This 1.5-day workshop will bring together experts in the design, development, and application of ultra-high-field...

Indico / Nov 25, 2025

MuCol Milestone Report No. 7: Consolidated Parameters

This document is comprised of a collection of consolidated parameters for the key parts of the muon collider. These consolidated parameters follow on from the October 2024 Preliminary Parameters...

arXiv.org

IMCC and MuCol annual meeting 2025

The 4th Annual Meeting of the International Muon Collider Collaboration and the 2nd MuCol Annual Meeting will take...

DESY-Konferenzverwaltung (Indico) / May 12, 2025

Final cooling beam physics	*Bernd Stechauner*	*Seminar Room 4a+b, DESY*	10:45 - 11:05
Absorbers and Windows for 6D and Final Cooling	*Jose Antonio Ferreira Somoza et al.*	*Seminar Room 4a+b, DESY*	11:05 - 11:25
Final cooling magnets	*Bernardo Bordini*	*Seminar Room 4a+b, DESY*	11:25 - 11:45
Final cooling lattice design	*Rebecca Taylor*	*Seminar Room 4a+b, DESY*	11:45 - 12:05
Lattice with Longer 6D option	*Ruihu Zhu*	*Seminar Room 4a+b, DESY*	12:05 - 12:25

MuonCollider-WG4/
muon_final_cooling

2 Contributors · 0 Issues · 0 Stars · 0 Forks

MuonCollider-WG4/muon_final_cooling

Contribute to MuonCollider-WG4/muon_final_cooling development by creating an account on GitHub.

GitHub