A rectilinear channel for muon cooling towards micron scale emittances

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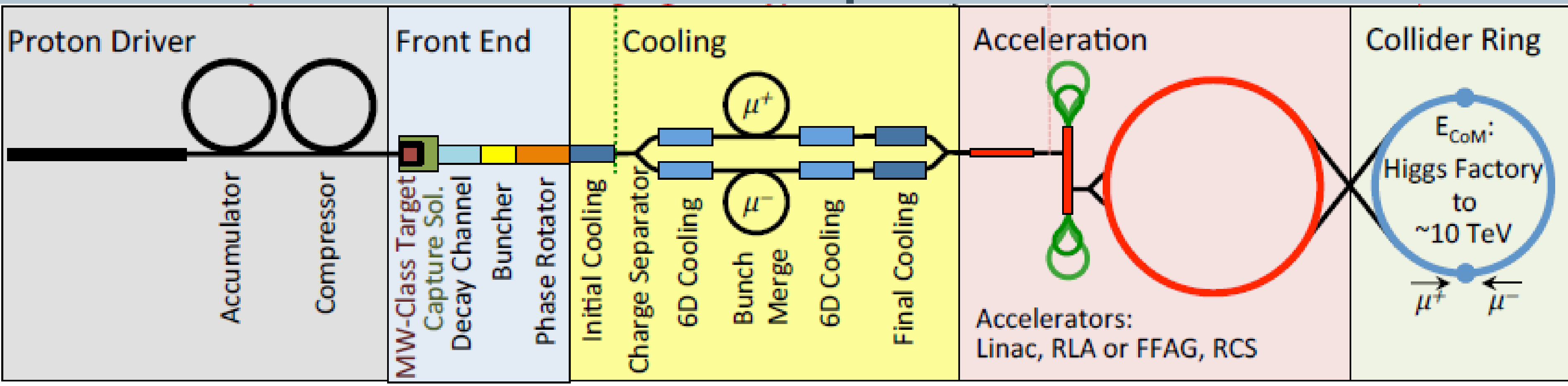
Outline

- Introduction to muon accelerators
- Challenges
- Cooling solution for a muon accelerator
  - Introduction to ionization cooling
  - Lattice design features
  - End-to-End simulation
  - Challenges & feasibility issues
- Summary

Muon Collider parameters



Muon Collider Parameters								
		Higgs Factory		**Top Threshold Options**		**Multi-TeV Baselines**		
Parameter	***Units***	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top^{+} Production/10^7sec		3,500*	13,500*	7,000^{+}	60,000^{+}	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	4$^{\#}$	4	4	4	4	4	1.6

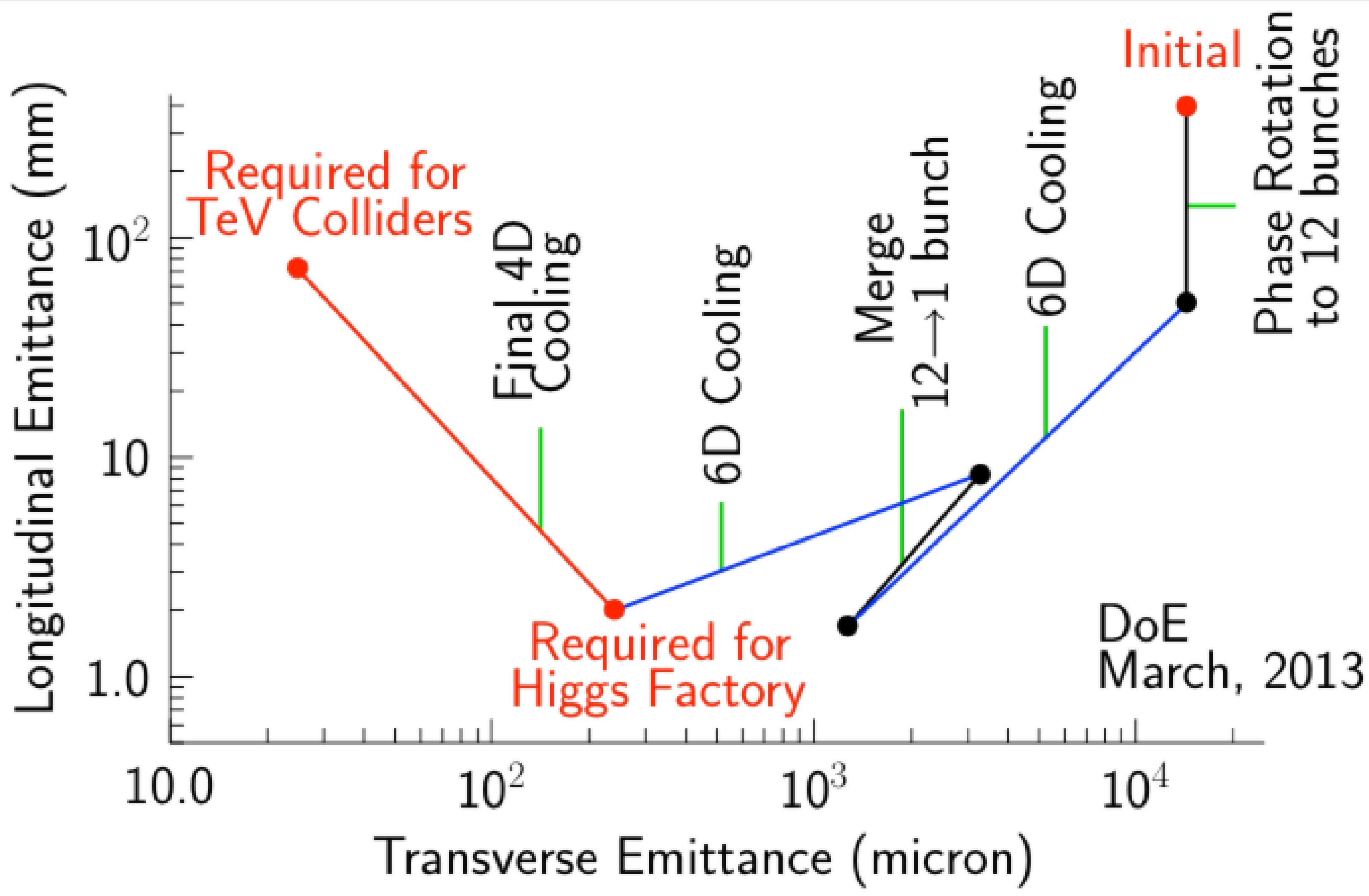
Dealing with muons: Challenges

- Muon beams are born as tertiary beams
  - Protons → pions → muons
  - Challenge: How to capture & transport muons efficiently?
- Muons are born within a large phase-space
  - To obtain luminosities O(10^{34}) $cm^{-2}s^{-1}$ need to reduce the initial phase-space by 6 orders of magnitude
  - Challenge: How to cool the muon beam?

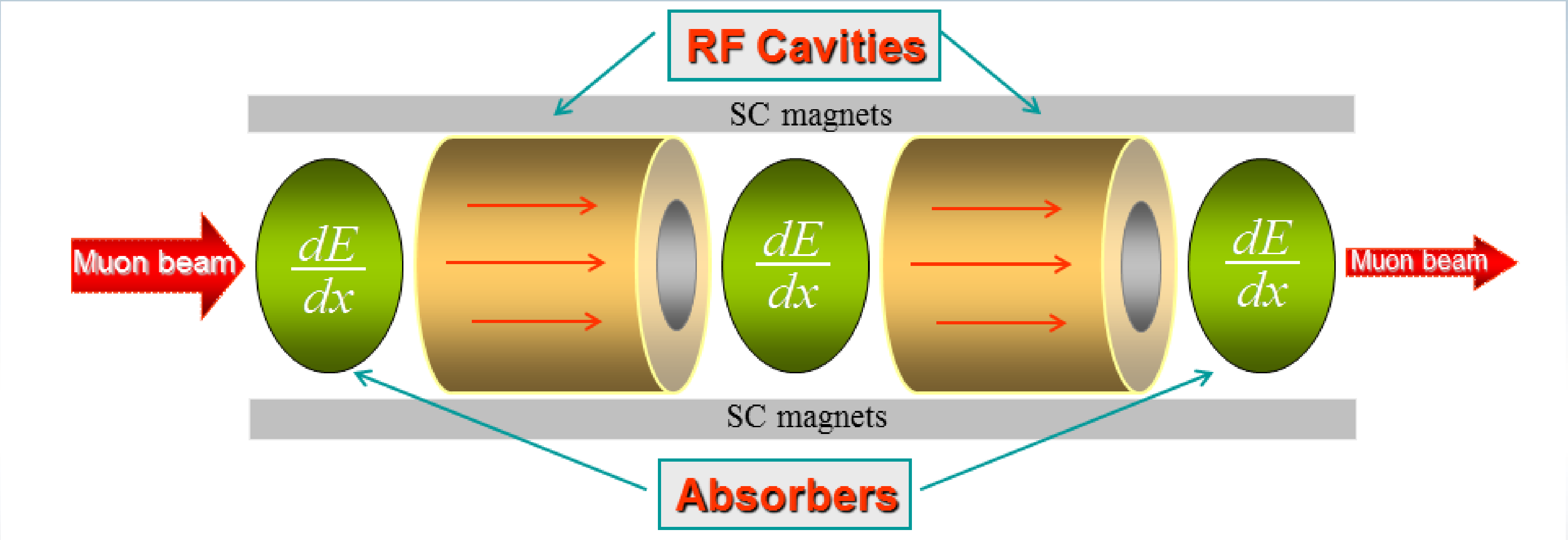
This talk

- Muons decay fast (~ 2 µs at rest)
  - At the same time, deal with high momentum protons, electrons…
  - Challenge: How to accelerate fast the beam? Collider ring design?

The cooling challenge

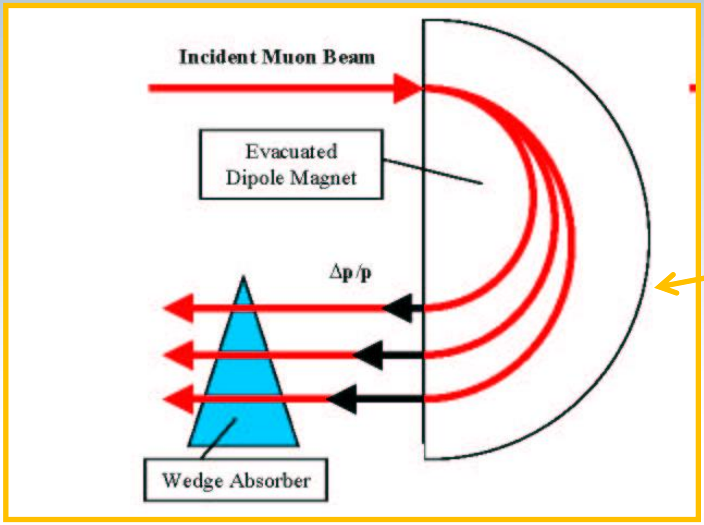


Ionization cooling concept



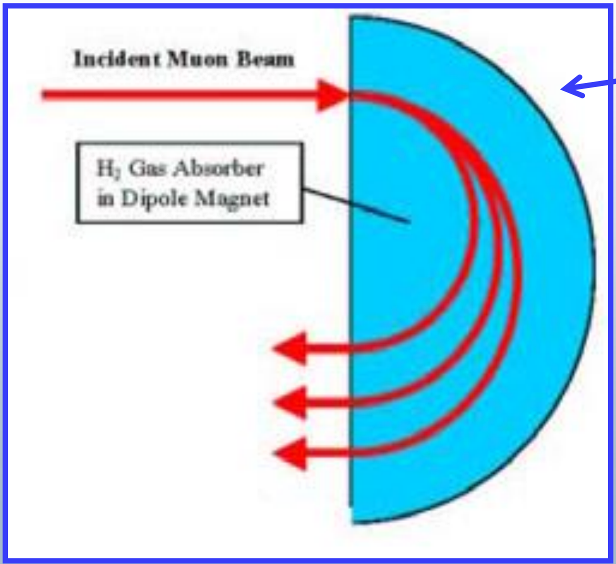
- Given the short muon lifetime, ionization cooling is the only practical method that can be realized
- Energy loss in discrete absorbers
- rf cavities to compensate for lost longitudinal energy
- Multi-tesla magnetic field to confine muon beams

Emittance exchange for 6D cooling



Concept 1: Generate dispersion and cool via emittance exchange in a wedge absorber

Concept 2: Energy loss dependence on path length in a continuous absorber



- Two concepts, same principle
- Dispersion is introduced to spatially separate muons of different momenta
- This study focuses on channels with discrete absorbers only!

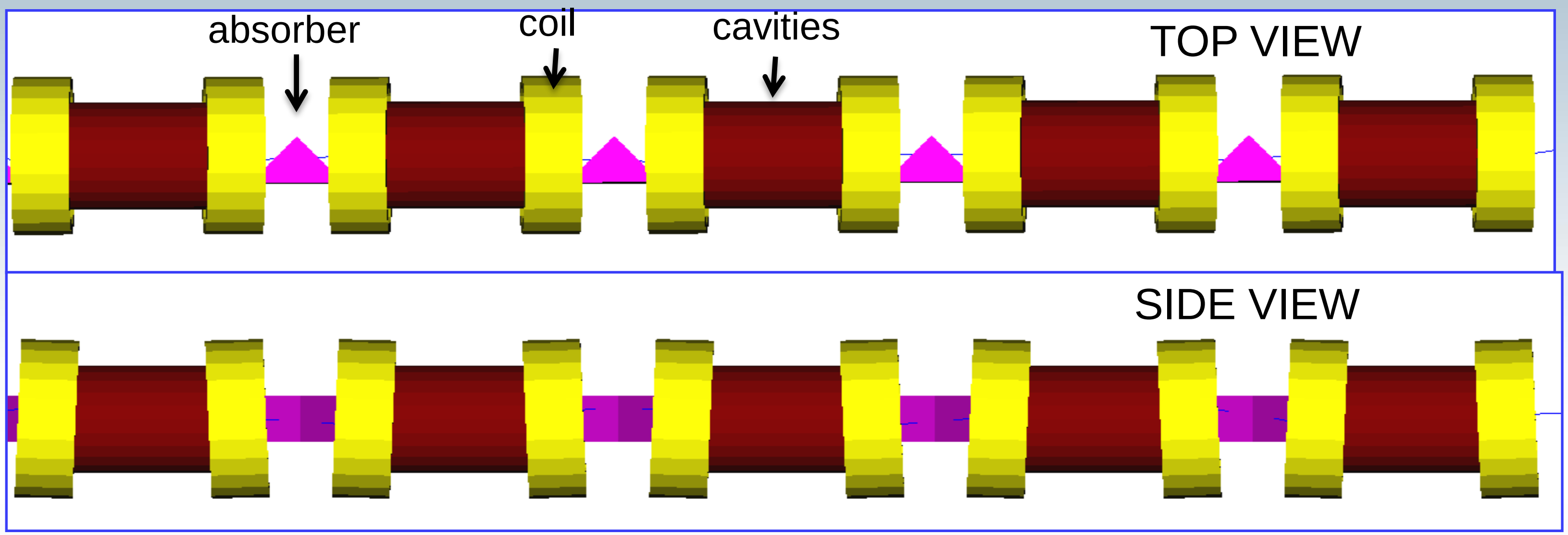
Ionization cooling theory

- Transverse cooling: $$\frac{d\varepsilon_\perp}{ds} = -\frac{\varepsilon_\perp}{\beta^2 E}\frac{dE}{ds} + \frac{\beta_\perp (13.6\ \mathrm{MeV})^2}{2\beta^3 E_\mu X_0 E}$$

Cooling term → scattering term

- Minimum emittance: $$\varepsilon_\perp^{eq} = \left(\frac{dE}{ds}\right)^{-1} \frac{\beta_\perp (13.6\ \mathrm{MeV})^2}{2\beta E_\mu X_0}$$
- Emittance evolution: $$\varepsilon_\perp(s) = \varepsilon_\perp^{eq} + (\varepsilon_\perp^i - \varepsilon_\perp^{eq}) \exp(-s/s_\perp^c)$$ $$s_\perp^c = \beta^2 E/(dE/ds)$$
- Emittance can be controlled by:
  - Material: Product of radiation length X_0 and energy loss rate dE/ds large. Best choices are LiH & H
  - Magnet strength: Transverse beta function β_T must be small. Thus, we progressively taper the magnetic field towards higher values

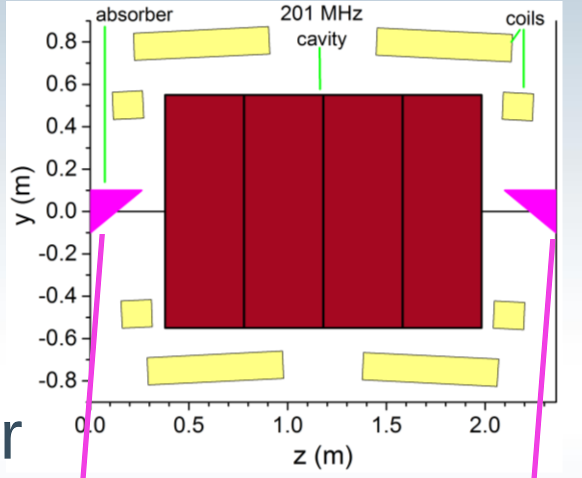
Cooling channel solution

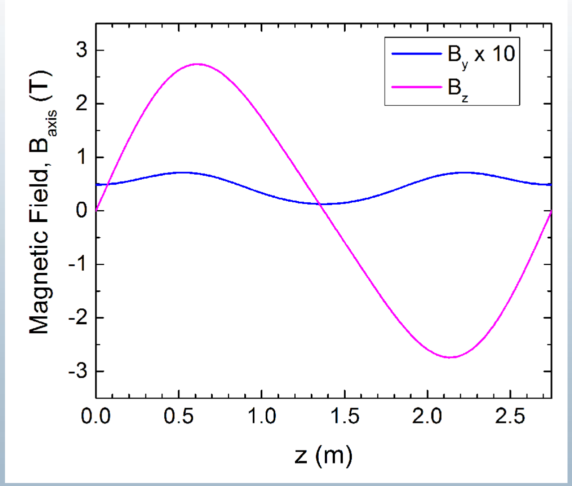


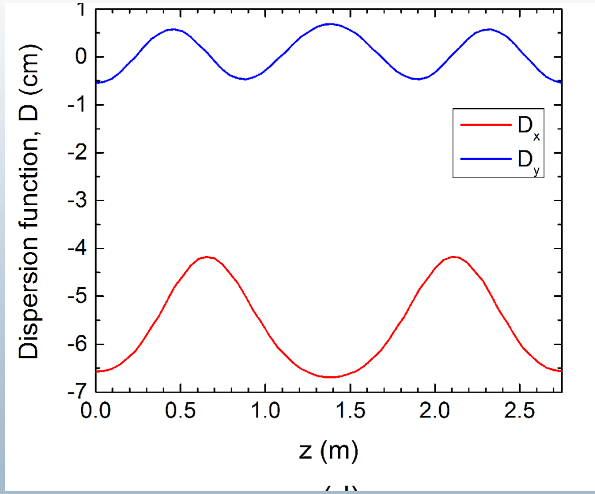
- We considered a rectilinear cooling scheme for a MC. Idea first proposed by V. Balbekov (Fermilab).
- Its simple geometry avoids several engineering challenges of previously considered schemes (rings or helix)

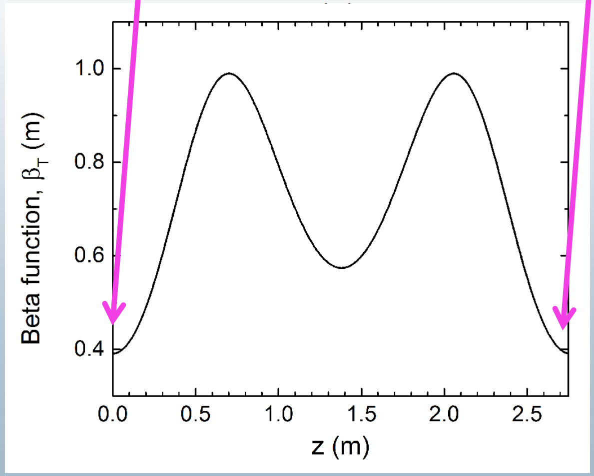
Cooling channel: How it works

- Coils are slightly tilted to generate a B_y field component
- This leads to dispersion, primarily in x.
- 6D cooling on wedge absorber
- Better, if beta is minimum at the absorber

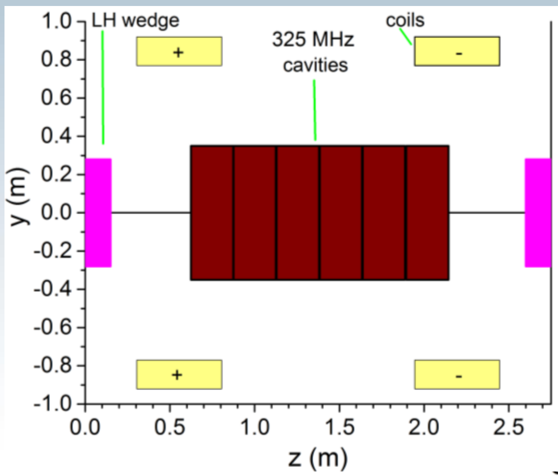


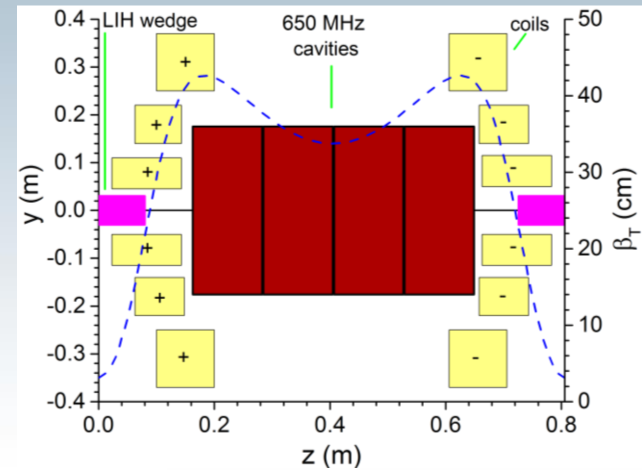






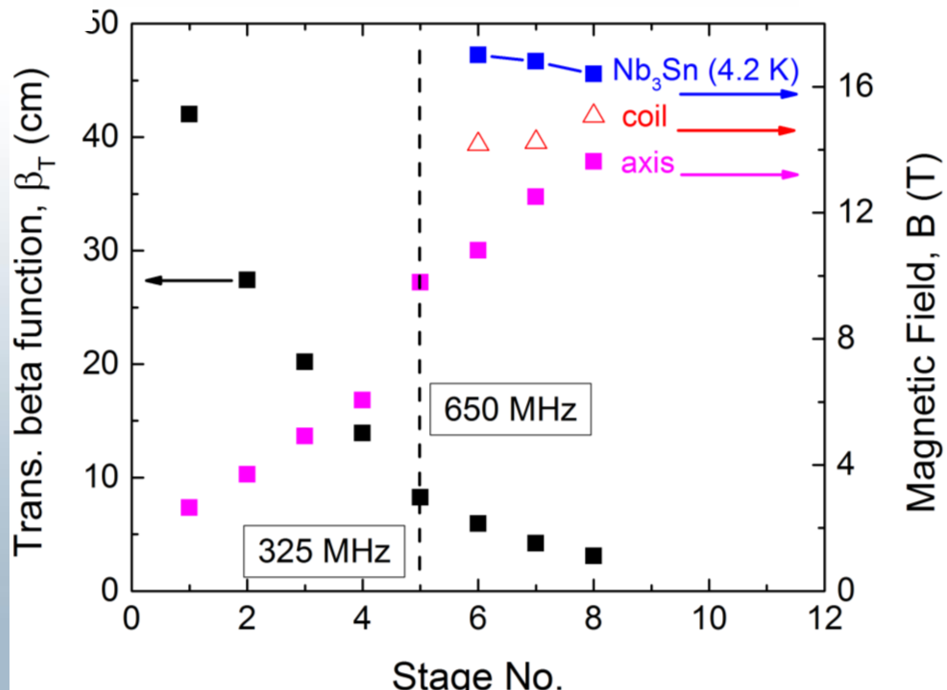
Tapered lattice design





EARLY STAGE COOLING

- 275 cm long
- Coils far
- 325 MHz
- Axial B ~ 3 T
- Beta ~ 40 cm

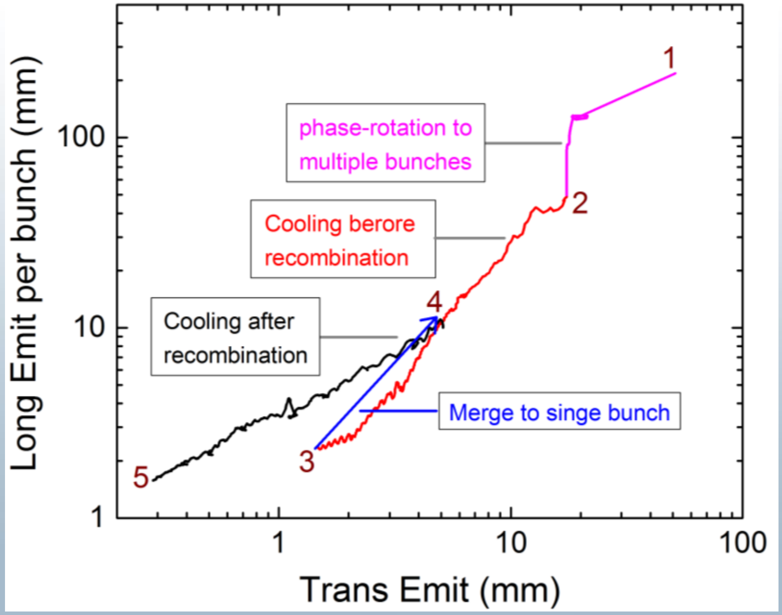


LATE STAGE COOLING

- 80 cm long
- Coils near axis
- 650 MHz
- Axial B ~ 12 T
- Beta ~ 3 cm

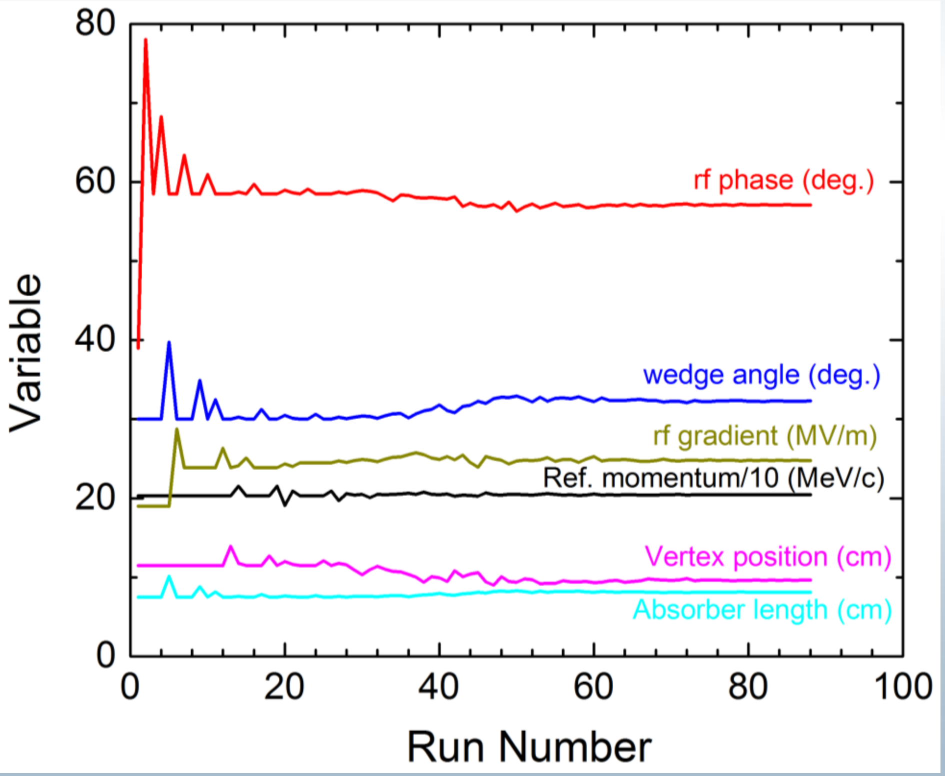
Numerical study with ICOOL

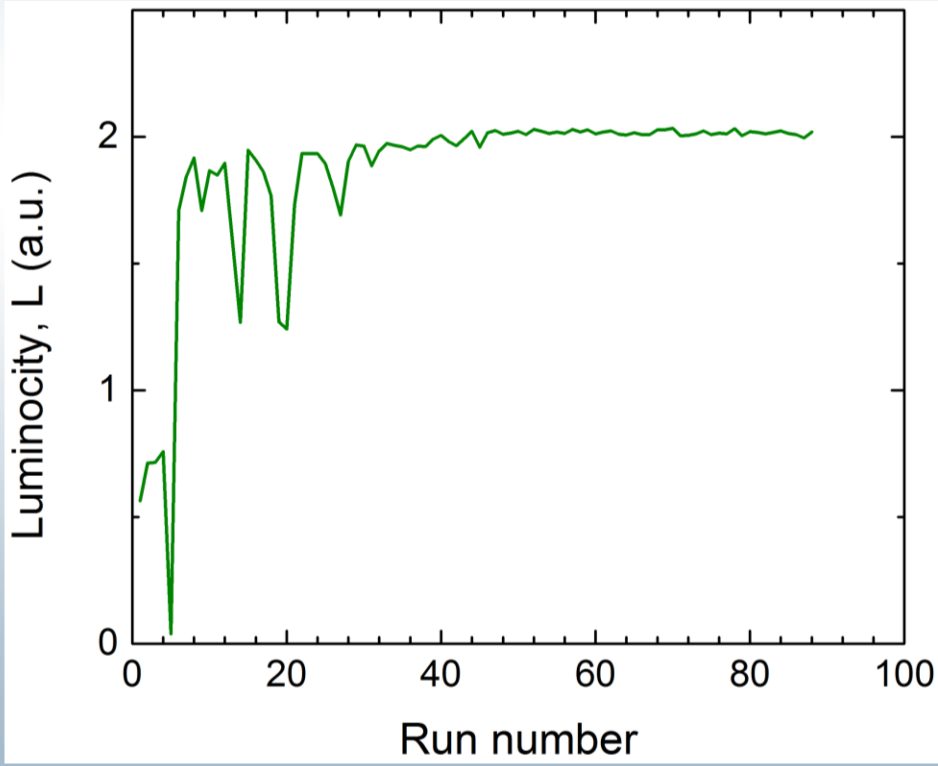
- End-to-end simulation starting from the muon beam birth place (point 1)
- Notable reduction of 6D-emittance a factor of 10^5
- Desired emittances for Higgs factory delivered!



Multivariable optimization

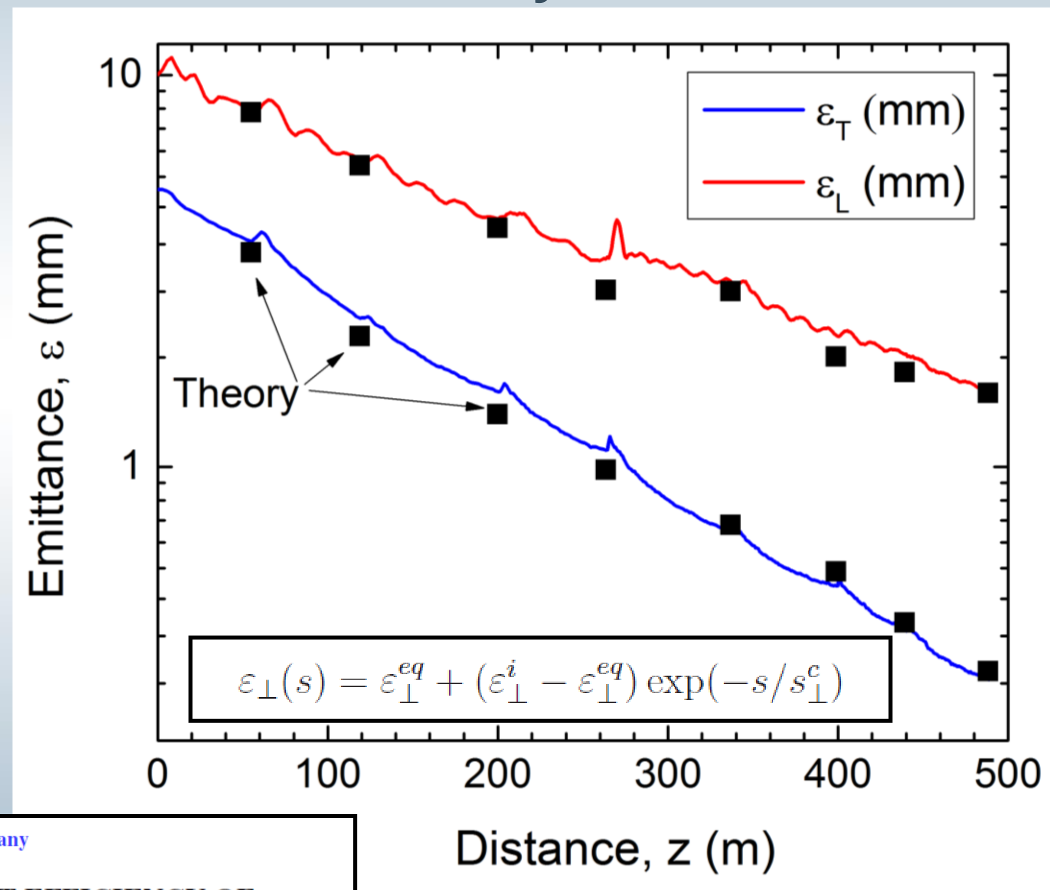
- 6 beam & lattice parameters were scanned with the goal to maximize the luminosity using the Nelder-Mead algorithm





Theory and simulation

- Found good agreement between theory and simulation



$$\varepsilon_\perp^{eq} = \left(\frac{\mathrm{d}E}{\mathrm{d}s}\right)^{-1} \frac{\beta_\perp (13.6\ \mathrm{MeV})^2}{2\beta E_\mu X_0}$$

$$s_\perp^{c} = \beta^2 E / (\mathrm{d}E/\mathrm{d}s)$$

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THEORETICAL FRAMEWORK TO PREDICT EFFICIENCY OF IONIZATION COOLING LATTICES*

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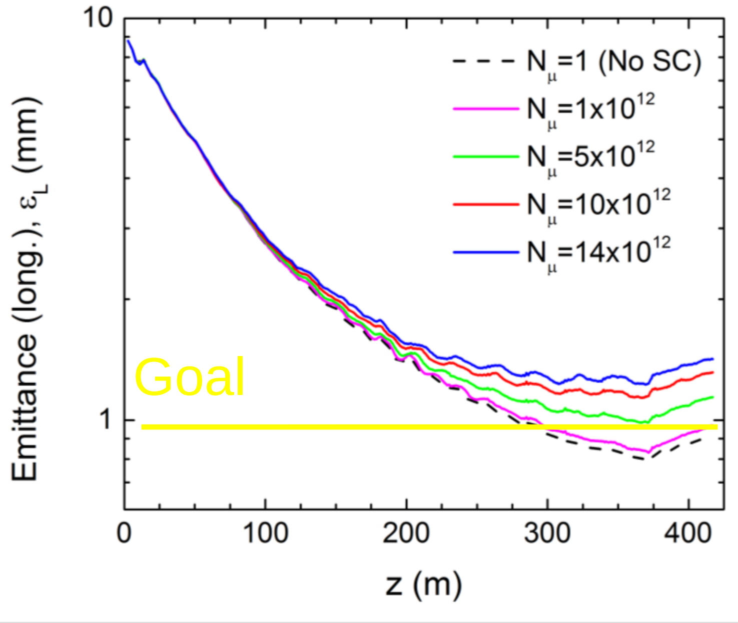
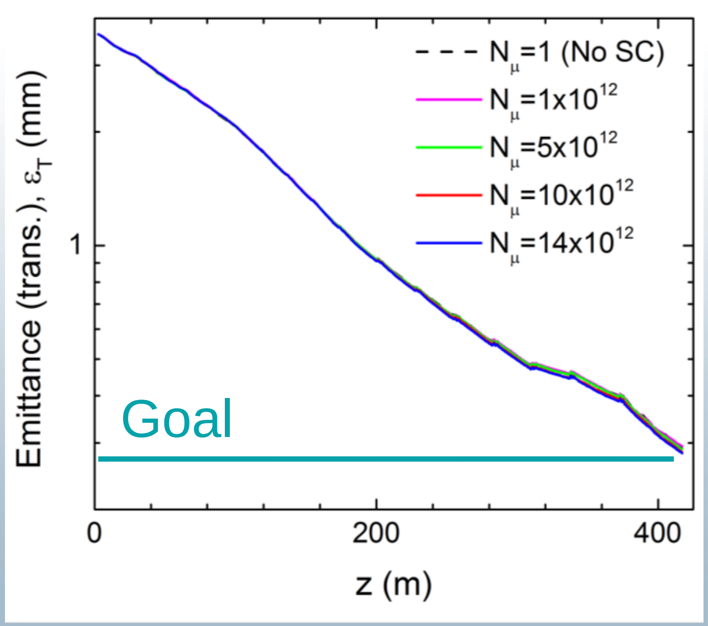
Influence of space-charge

- At the end of the cooling, the bunch is 2 cm long, has 5×10^{12} muons with a peak current of 5 kA at 200 MeV/c!
- We examined the influence of SC fields on cooling.
- SC causes particle loss and longitudinal emittance growth



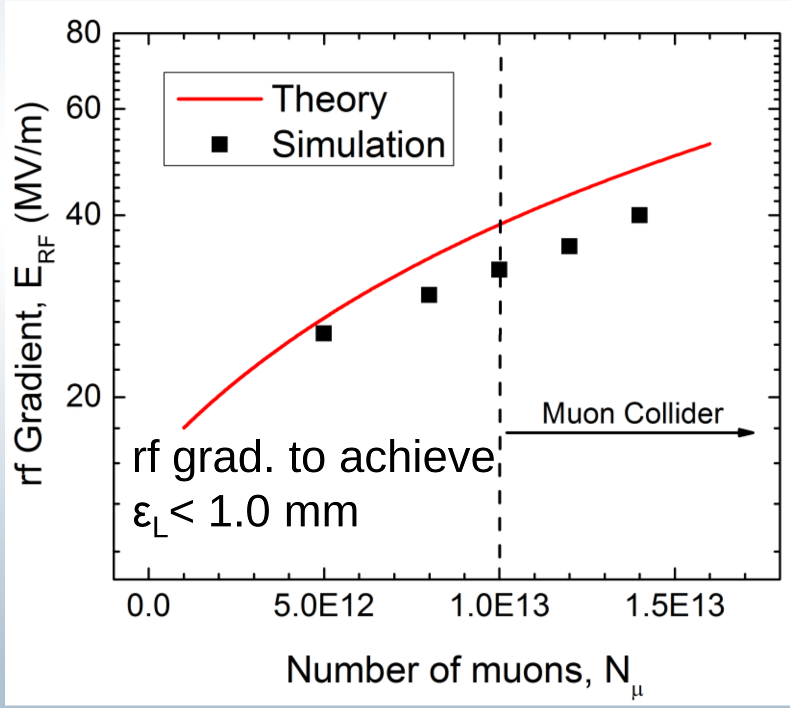
WARP Simulation



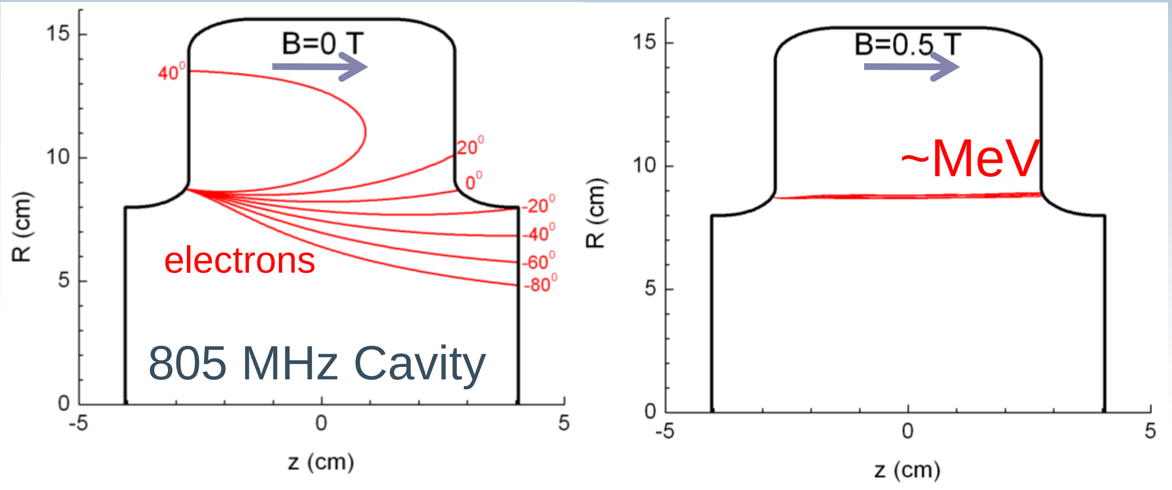
Space-charge compensation (2)

- For a Muon Collider to obtain a longitudinal emittance < 1.0 mm the rf gradient of a 805 MHz cavity needs to surpass 32.5 MV/m
- Avoid longitudinal cooling to < 1.3 mm
- Required compensation gradient from theory:

$$E_{rf,c} = \frac{eN_0 g_0 c}{4\pi\varepsilon_0\sqrt{2\pi}\gamma^2\sigma_z^3(2\pi f n \cos\varphi)^2}$$



rf operation in B-fields



- Numerical simulations predict that the copper surfaces of a rf cavity may damaged when B> 1T

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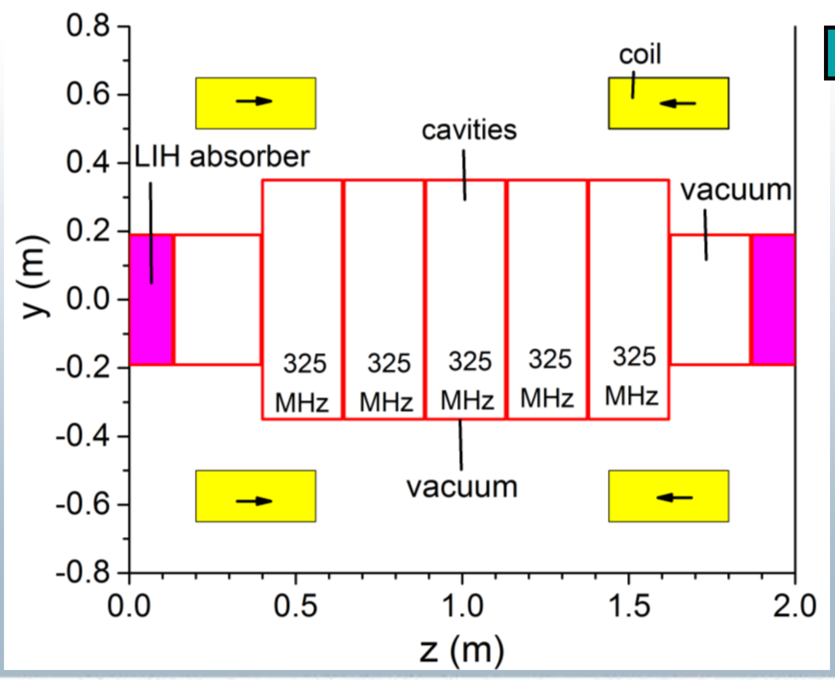
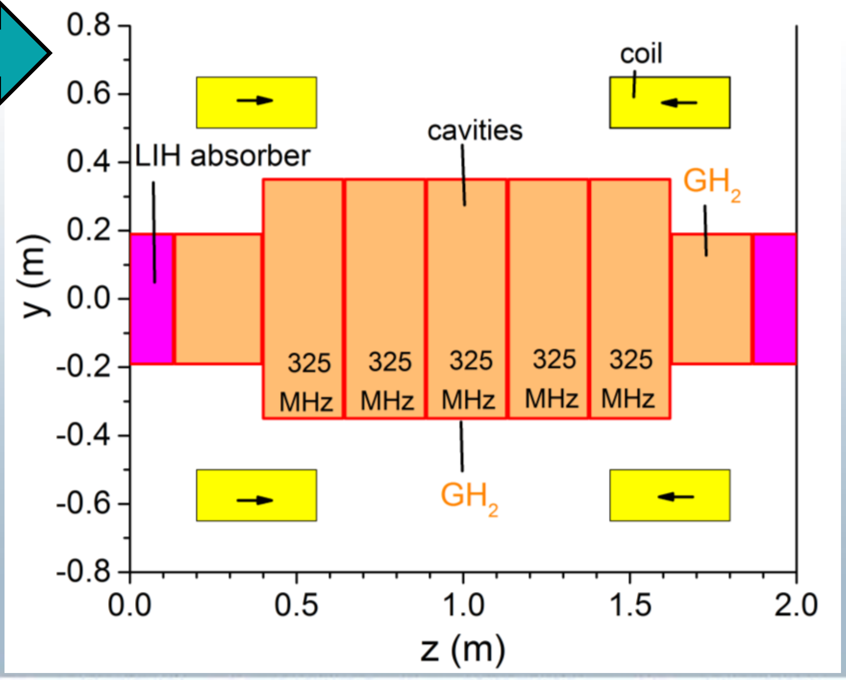
Effects of external magnetic fields on the operation of high-gradient accelerating structures

Diktys Stratakis *, Juan C. Gallardo, Robert B. Palmer

Hybrid solution

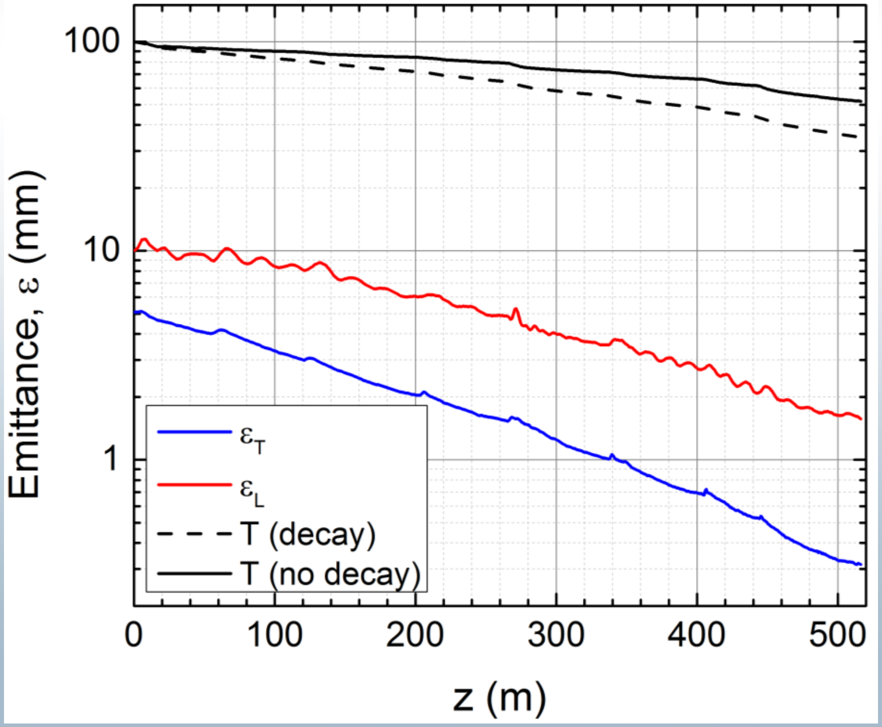
- Key Idea: Utilize gas filled cavities in a rectilinear channel
- Majority of cooling will be done in LiH and use gas only to protect the cavity from the high-field. Similar idea was used in the past for 4D cooling (Gallardo & Zisman, Nufact09)





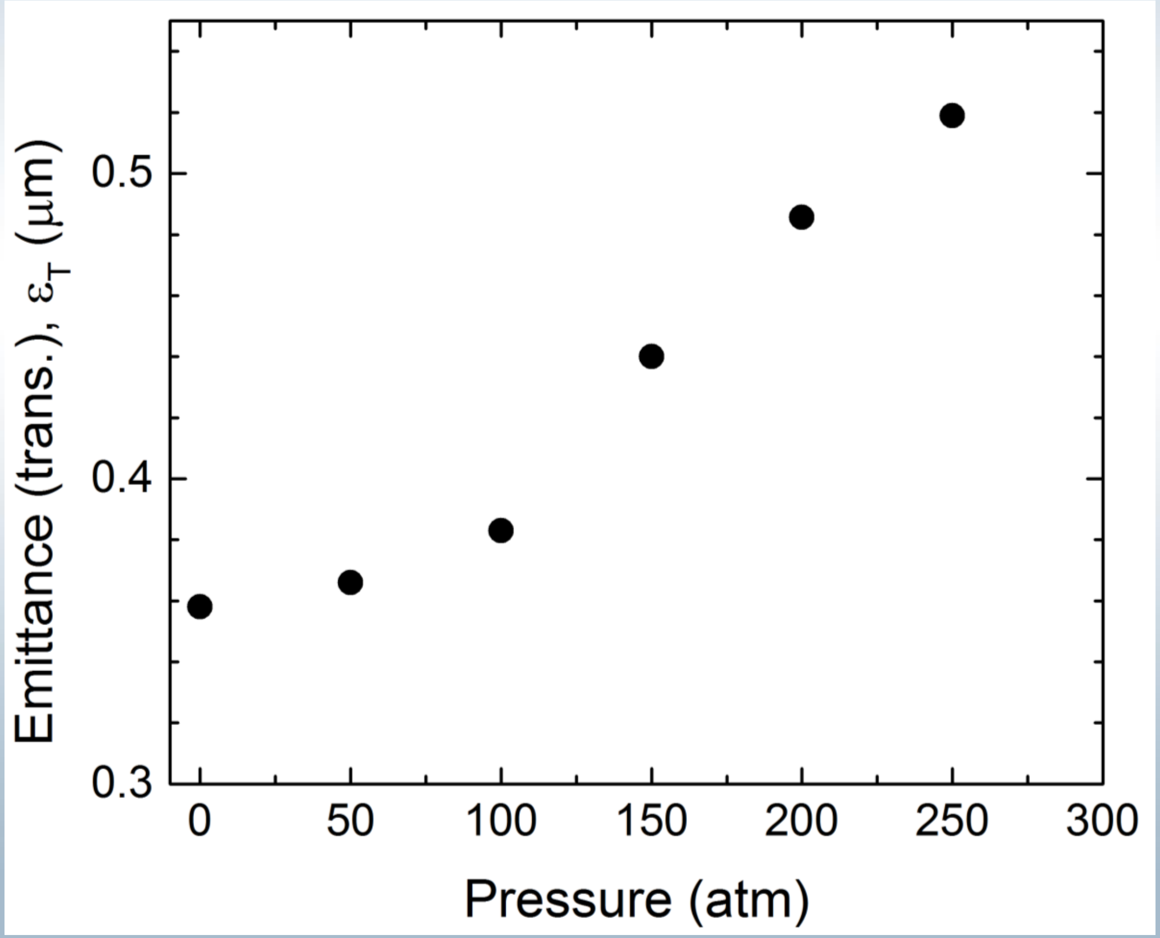
Lattice performance

- Essentially, the same performance as the conventional channel with vacuum cavities
- BUT there remains considerable work to do before a hybrid channel can be considered a validated cooling channel option.

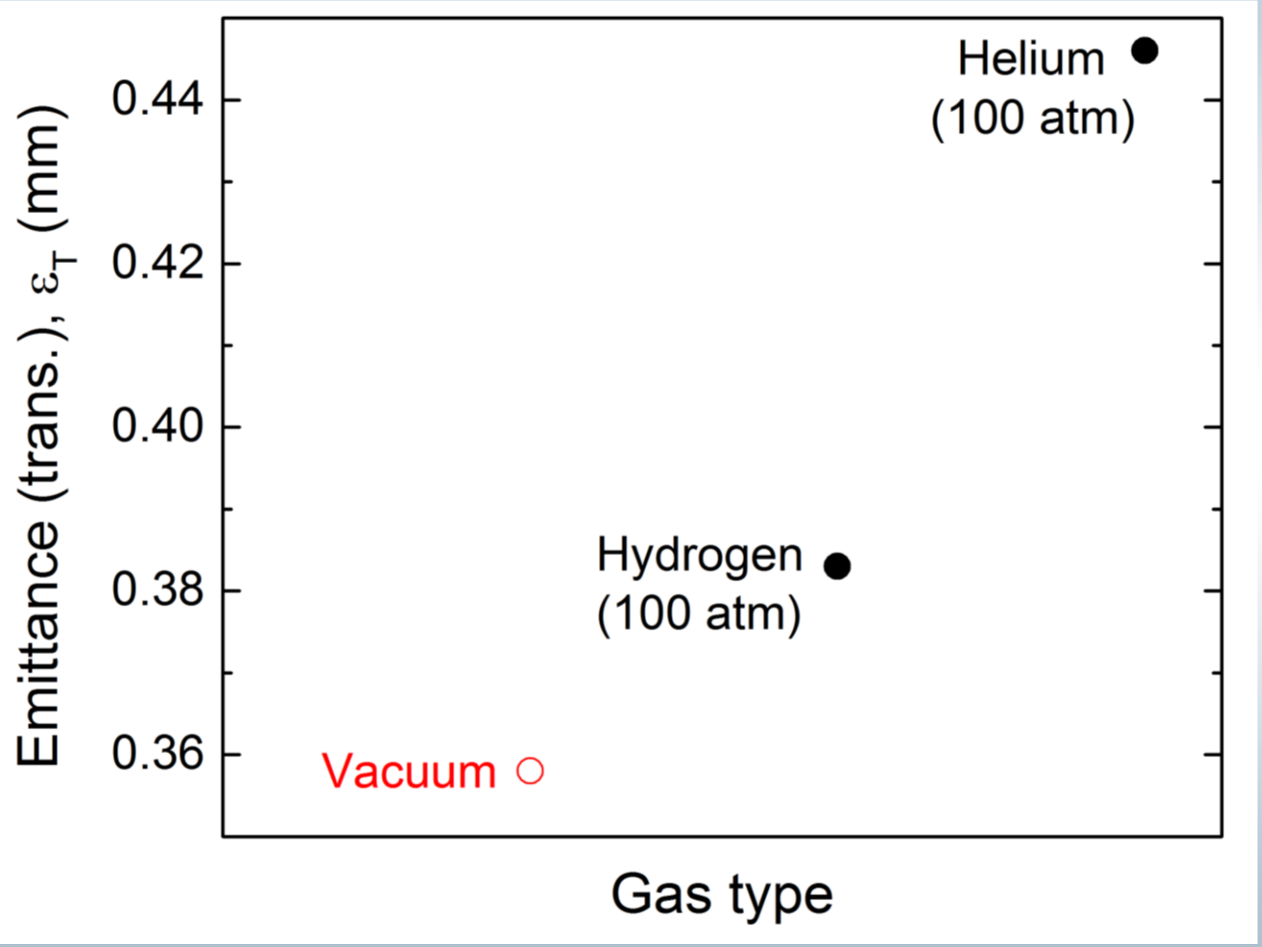


Sensitivity to pressure

- Final transverse emittance is correlated to gas pressure



Sensitivity to gas type



Summary

- We have presented a conceptual design of a rectilinear channel that in view its simple geometry may offer several technological advantages (compared to a helix or a ring)
- Showed reduction of 6D by at least 5 orders of magnitude.
- The influence of space-charge fields on the cooling process was thoroughly examined
- Nb_3Sn magnets can be used for late stage cooling
- A hybrid solution with gas filled cavities was presented