Hybrid channel for fast 6D cooling using gas-filled cavities

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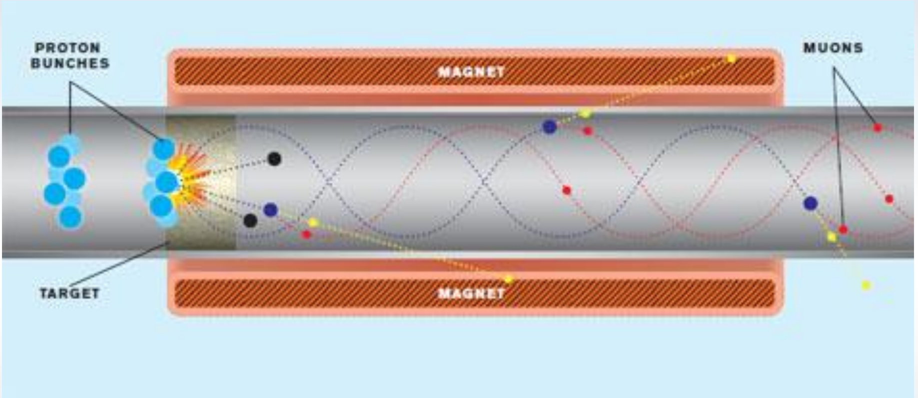
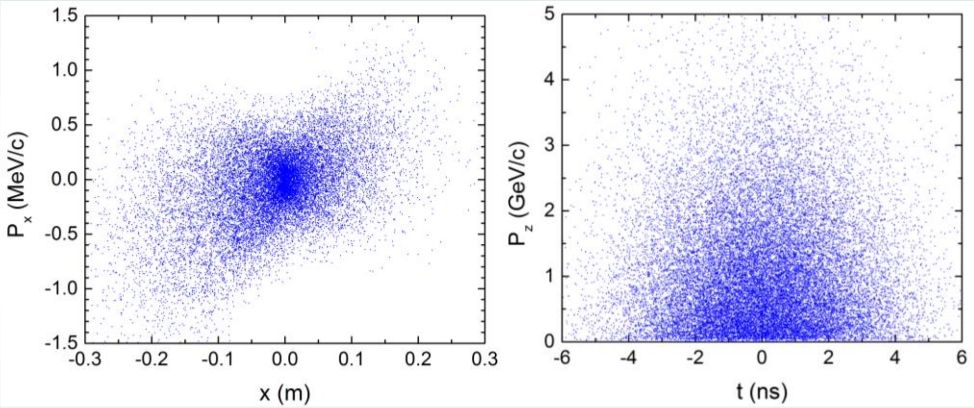
Introduction

- Muons have relative immunity to synchrotron radiation due to their large rest mass
- Have been reported to have applications to fundamental research as well as to various industrial applications:
  - Muon radiography
  - Medical and material detection applications
  - Neutrino Factory and Muon Collider
- But there are some challenges:
  - Muon production and capture
  - Short lifetime (~2 μs in rest)
  - Cooling (beneficial for some applications)

Muon production

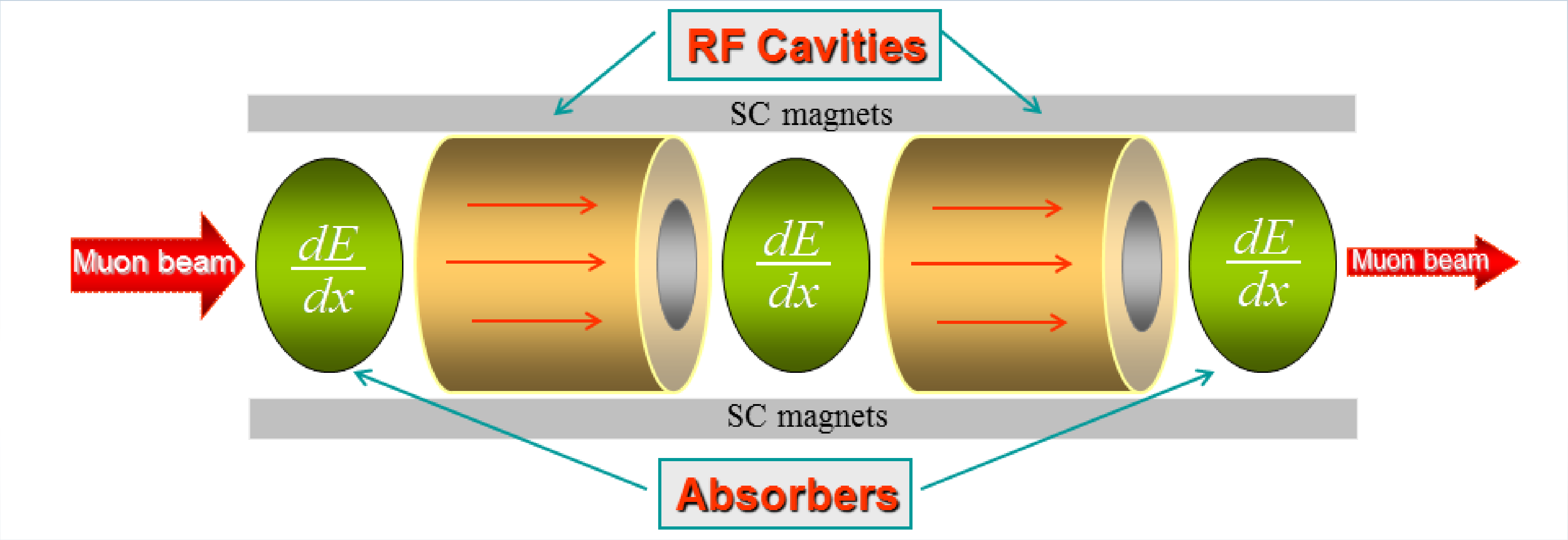
- Muons can be produced indirectly through pion decay by interaction of charged particle beam with a stationary target





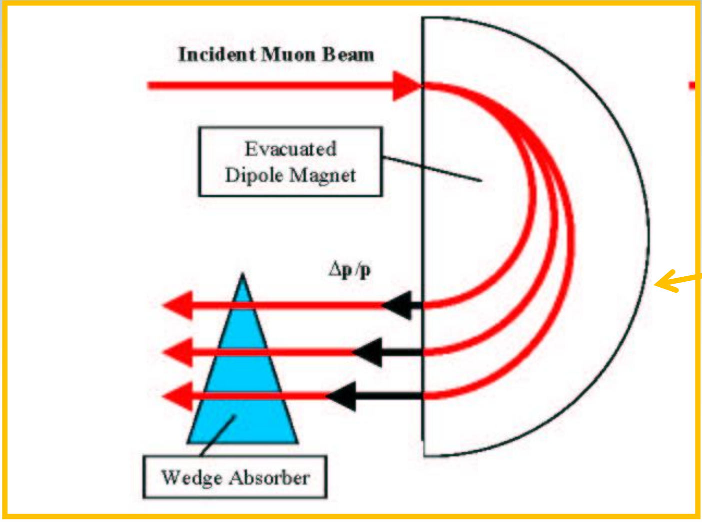
- The initial muon beam is huge: enormous 6D emittance and very large momentum spread.
- Beam cooling (i.e. reduction of phase-space volume) can improve beam quality

Ionization cooling



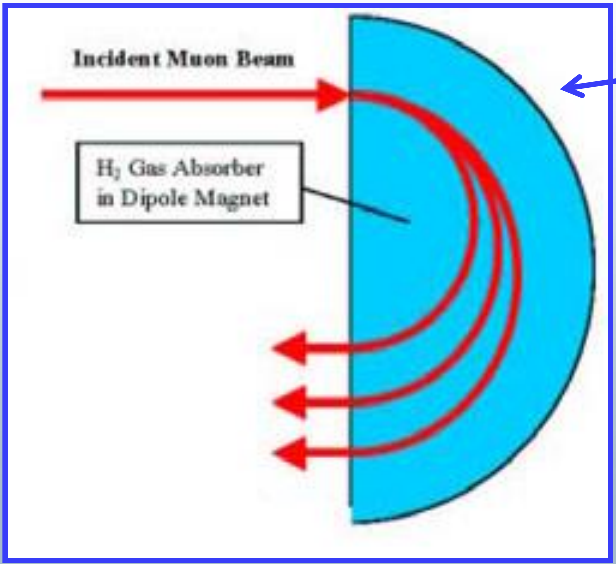
- Energy loss in discrete absorbers
- rf cavities to compensate for lost longitudinal energy
- Multi-tesla magnetic field to confine muon beams
- This method cools only in 4D

Emittance exchange for 6D cooling



<u>Concept 1:</u> Generate dispersion and cool via emittance exchange in a wedge absorber

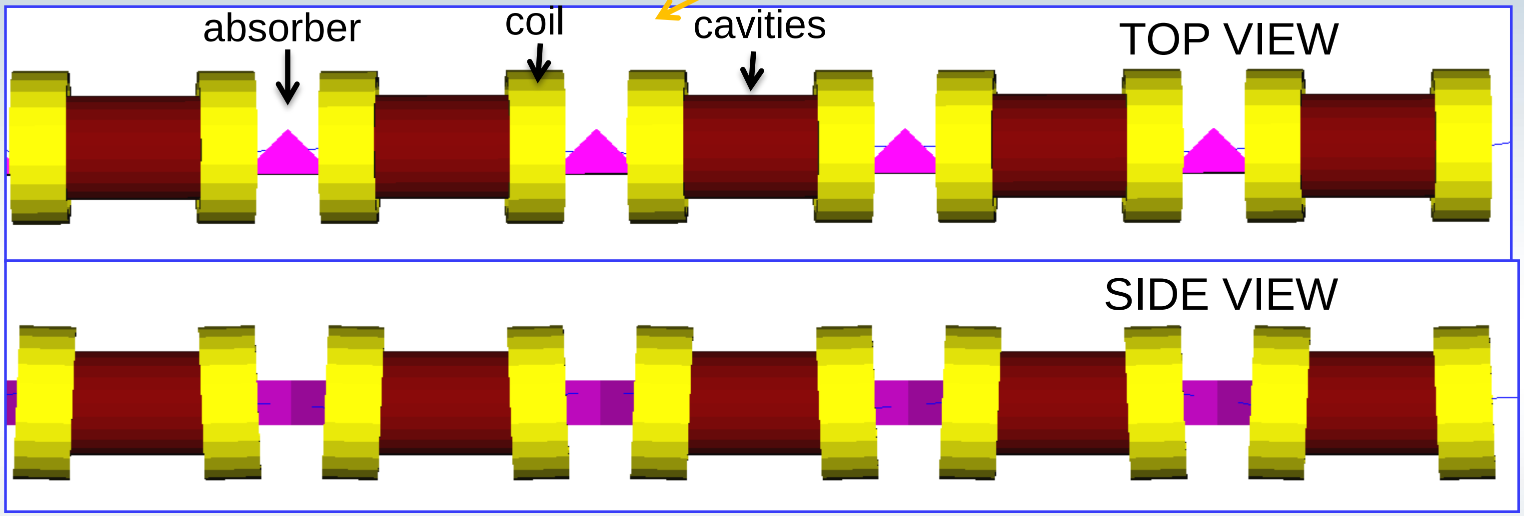
<u>Concept 2:</u> Energy loss dependence on path length in a continuous absorber

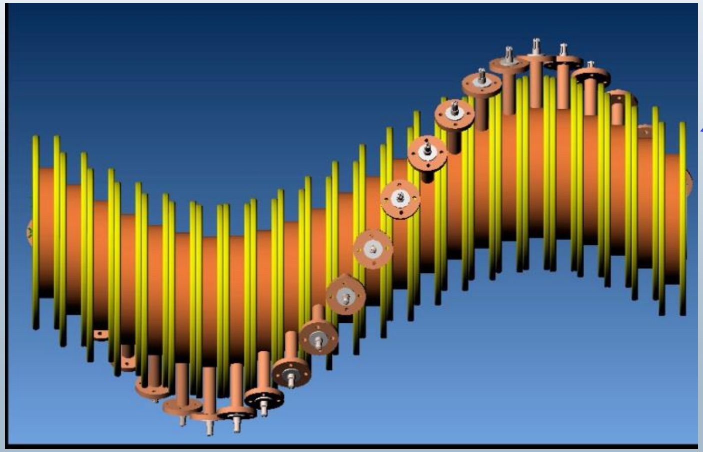


- Two concepts, same principle
- Dispersion is introduced to spatially separate muons of different momenta

6-Ionization cooling lattices

Lattice 1: Vacuum cooling channel (VCC)

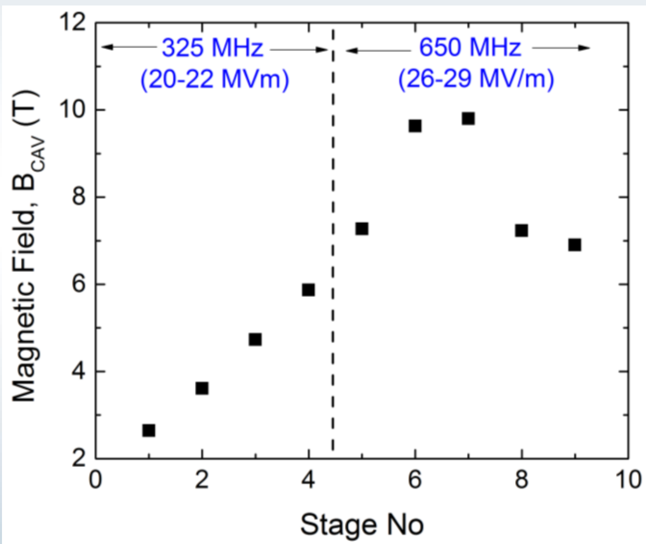




Lattice 2: Helical cooling channel (HCC)

Challenges for the VCC

- Both schemes require the operation of high-gradient rf cavities within multi-Tesla fields



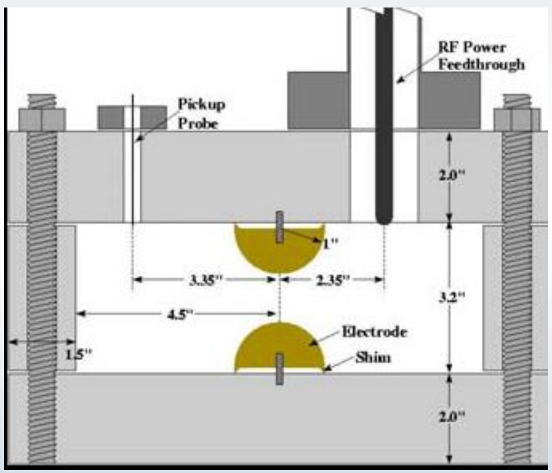
Magnetic field requirement for a Muon Collider

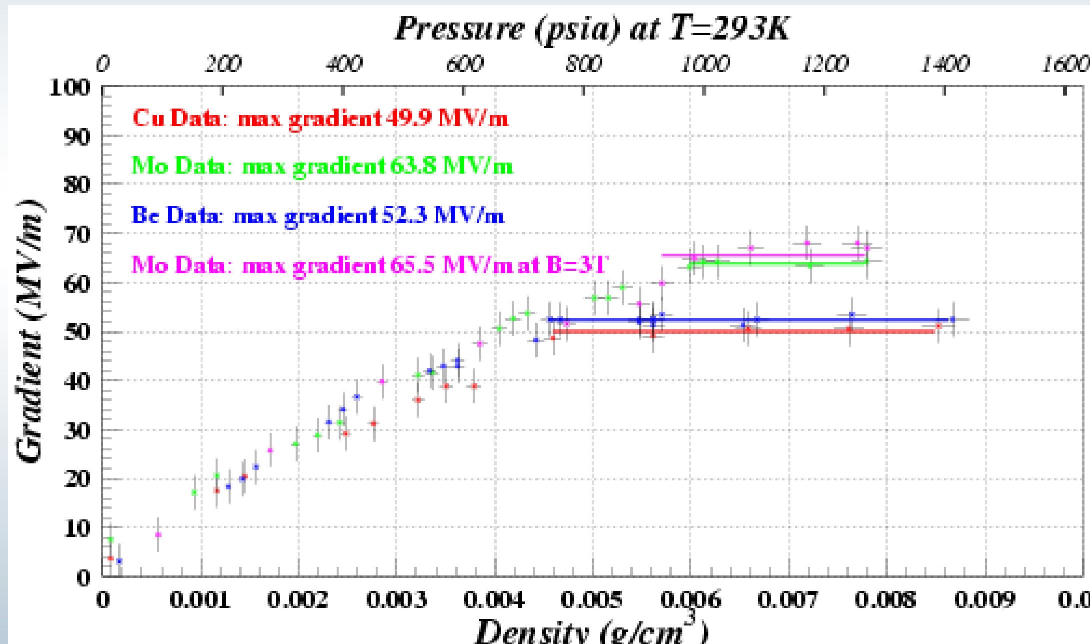
Damage on a 805 MHz rf cavity immersed in a 3 T magnetic field.

- VCC Challenge:
  - Operation of vacuum rf cavities in a magnetic field is still a big challenge

Challenges for the HCC

- The gradient of a gas filled cavity showed no magnetic field dependence in a solenoidal field up to 3 T.





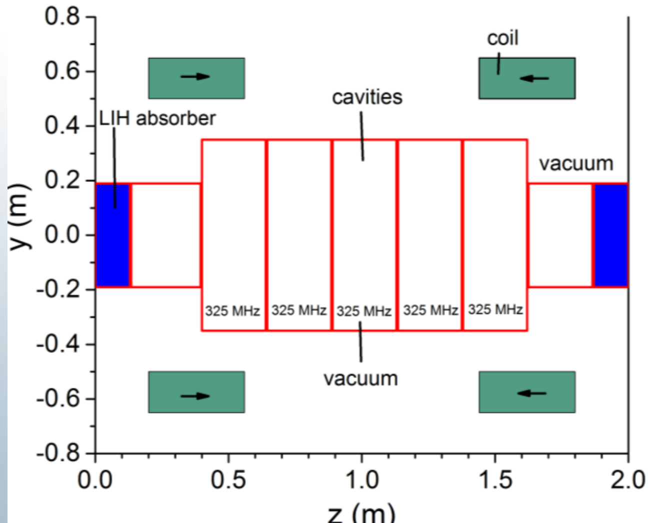
- HCC Challenge:
  - High pressure (160 atm at room Temperature)
  - Cooling to micron-scale emittances (< 400 µm) is a challenge

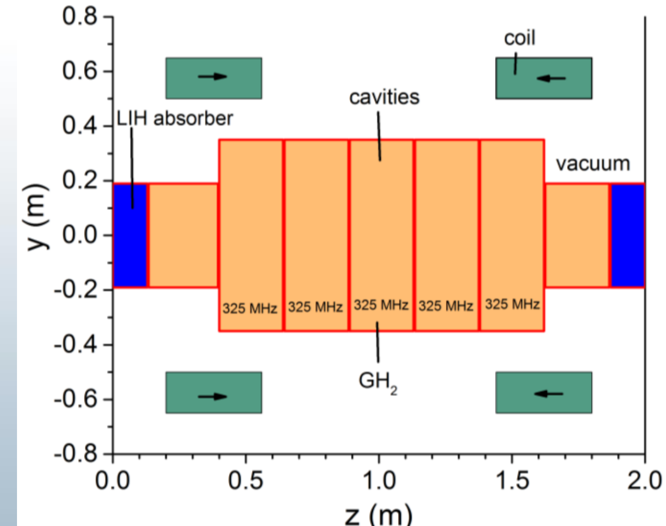
Hybrid solution

- Key Idea: Take most benefits from VCC and HCC concepts and design a new channel!
- Result: Integrate low-gas filled cavities into a rectilinear VCC channel
- Majority of cooling will be still with in LiH absorber
- Use gas only to protect rf cavity from the high-field
- For a Muon Collider we need 26-28 MV/m at 650 MHz
- Based on the experimental data, 34 atm gas, at room temperature, should be satisfactory

Hybrid rectilinear channel

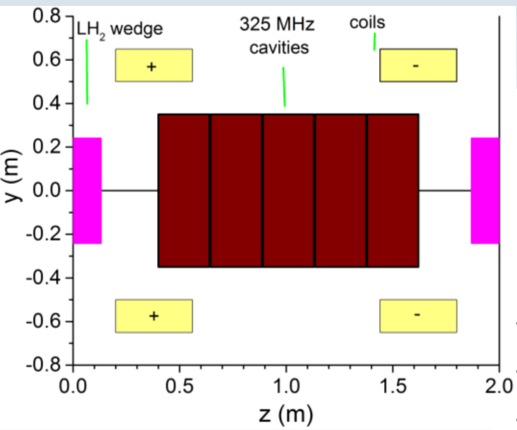
- The lattice cell of a hybrid channel is essentially the same as the VCC. The only difference is that it is filled with low pressure hydrogen gas
- LIH absorber length is slightly reduced

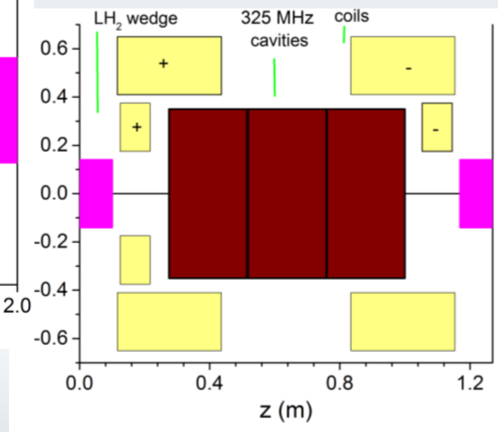


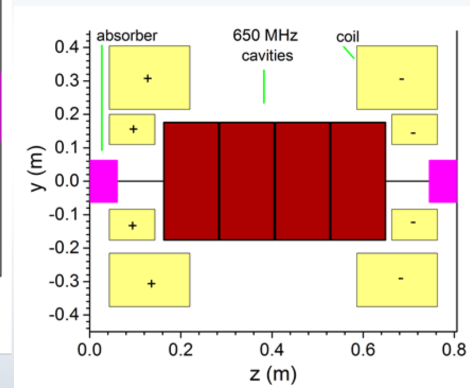


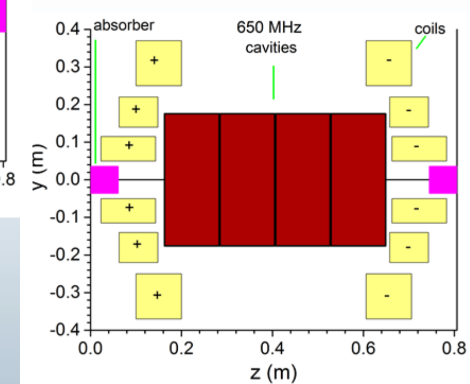
Cooling application: Muon Collider

STAGE 2	STAGE 4	STAGE 6	STAGE 9
66 m (33 cells)	63.5 m (50 cells)	66.9 m (83 cells)	30.6 m (38 cells)









Absorber
TOP VIEW
LIH

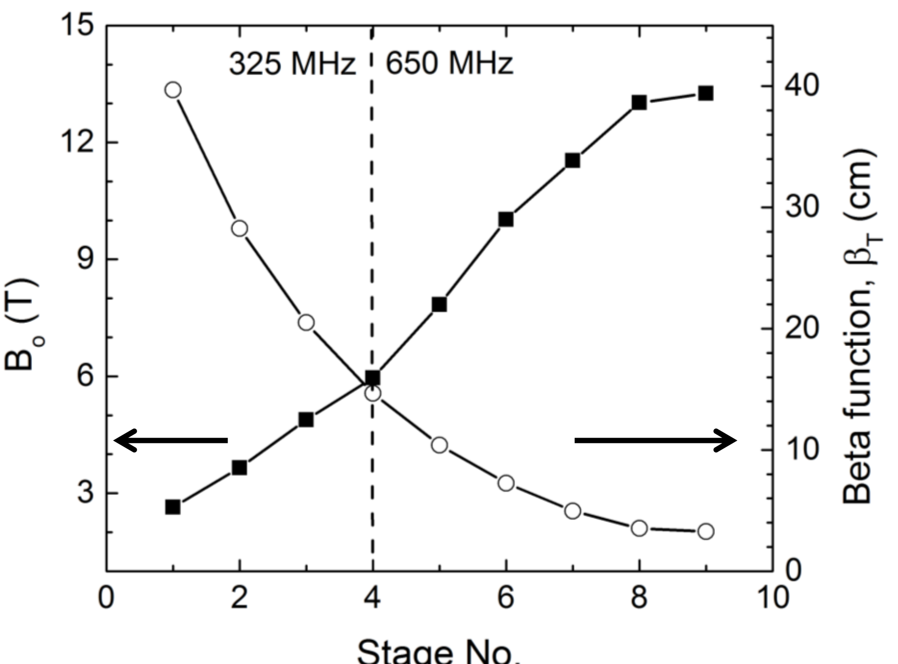
3.7 T (8.4 T) | 6.0 T (9.2 T) | 10.8 T (14.2 T) | 13.6 T (15.0 T)

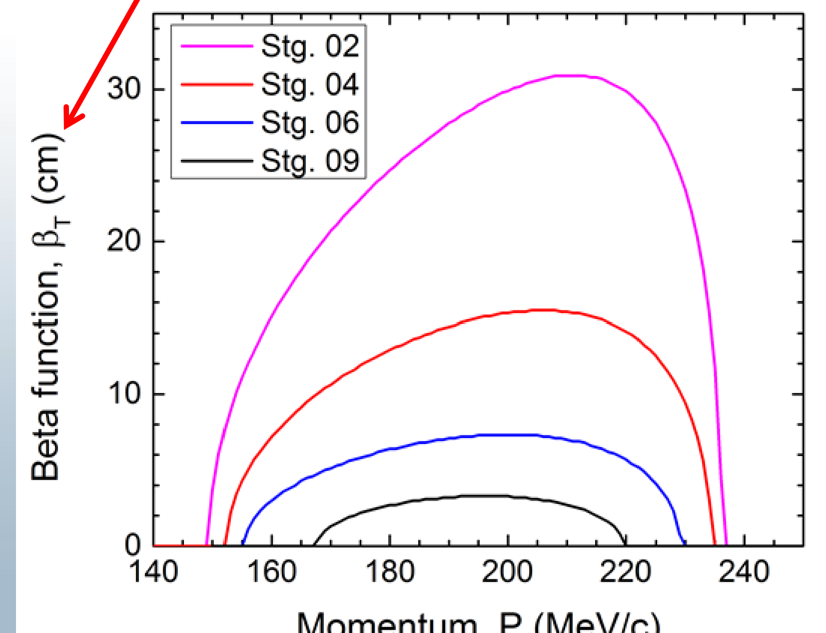
MAGNETIC FIELD axis (coil)

Lattice properties

- Tapered channel: The focusing field becomes progressively stronger to reduce the equilibrium emittance.

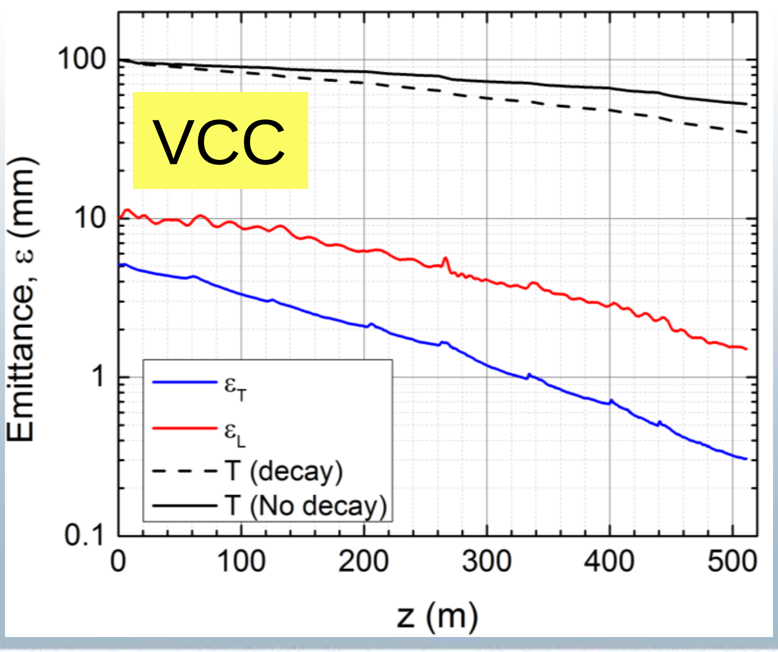
Equilibrium Emittance: $$\varepsilon_{N,\min} = \frac{\beta_T (E_s)^2}{2\beta m_\mu c^2 L_R \left| \frac{dE_\mu}{ds} \right|}$$

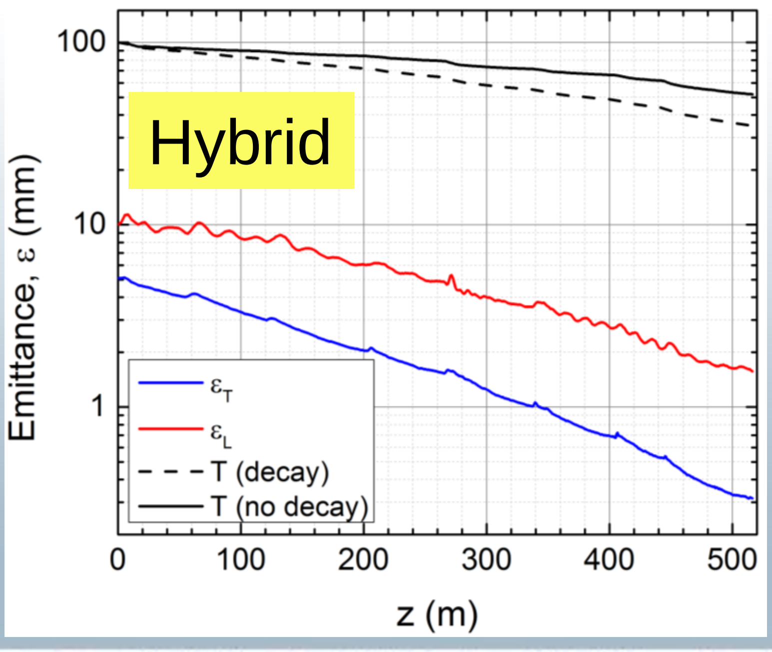




Lattice performance

- Channel performance was simulated with the ICOOL code
- Final emittances are 0.30 mm (trans.) and 1.5 mm (long.) with a transmission of 50 % (no decays)
- Same result obtained with a conventional VCC channel

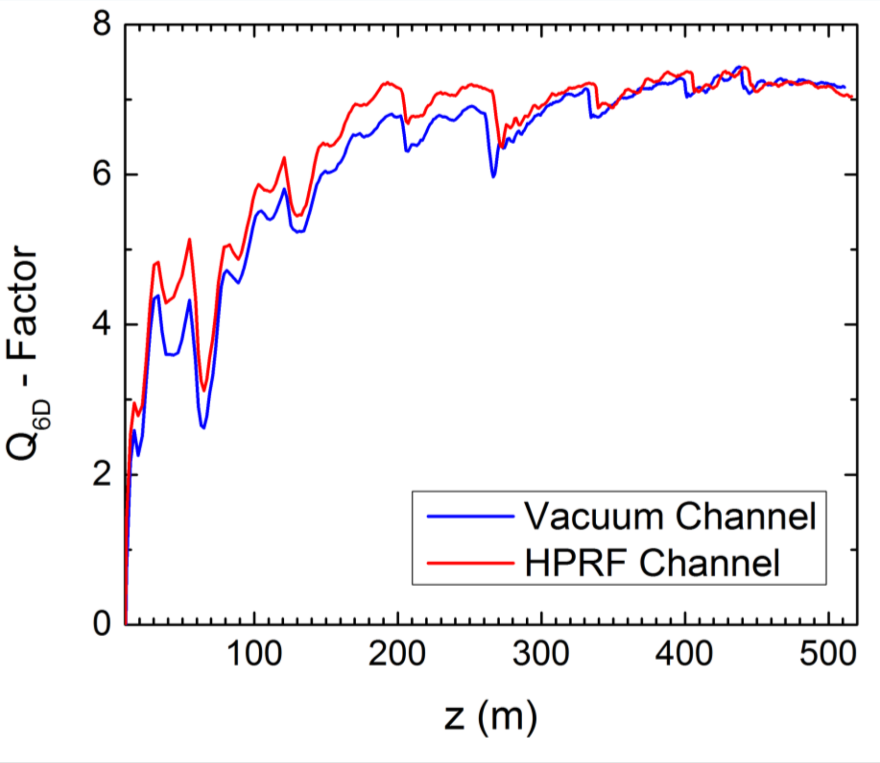




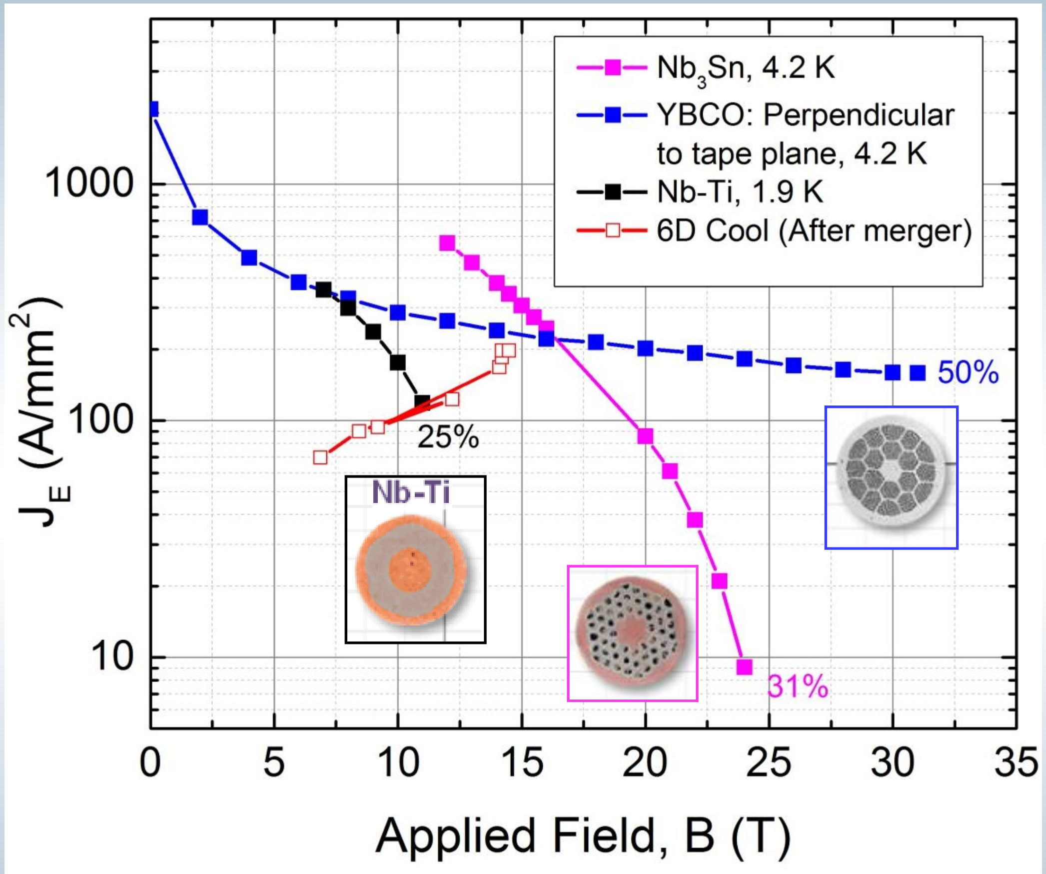
Quality factor (Q-Factor)

- The Q factor compares the rate of change of emittance to the particle loss and under ideal conditions should remain the same (constant) through the lattice.

$$Q = \frac{d\varepsilon_{6D}^{N}/ds}{dN/ds}\frac{N(s)}{\varepsilon_{6D}^{N}(s)}$$



Magnet feasibility



- Magnet requirements appear to be within the critical engineering limits for Nb_3Sn
- Last stages are challenging

Issues to consider

- Cavity walls must be thick enough to withstand pressure
- rf window must be pressurized on both sides for 34 atm gas
- A storage system is needed to accommodate the evacuation of the channel for maintenance
- Isolation windows to separate different sections
- The RF input couplers must also be pressurized equally on both sides, unless the coupler can be made strong enough to handle the pressure.

Summary

- We discussed a possible implementation of high-pressure (HP) gas-filled RF cavities in a rectilinear cooling channel
- Our solution is a hybrid approach that uses HP hydrogen gas to avoid cavity breakdown, along with discrete LiH absorbers to provide the majority of the energy loss.
- Without loss in performance, can cool towards micron-scale emittances making it a very promising approach
- This work was a “proof-of-principle” numeric study only!
- There remains considerable work to do before a hybrid channel can be considered a validated cooling channel option.