Hybrid channel for 6D muon 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)
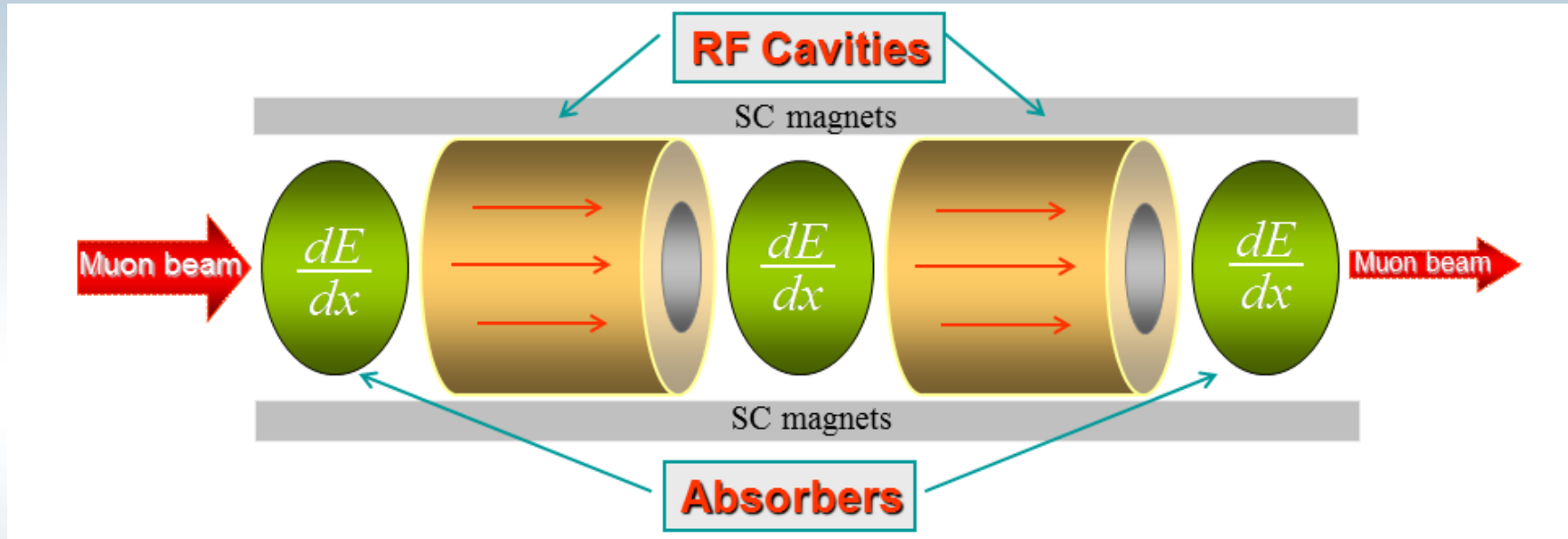
  - Cooling (beneficial for some applications)

Muon production

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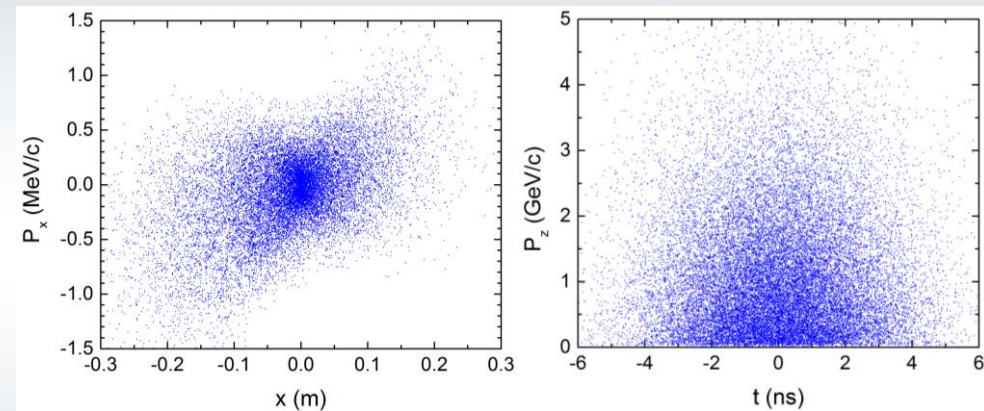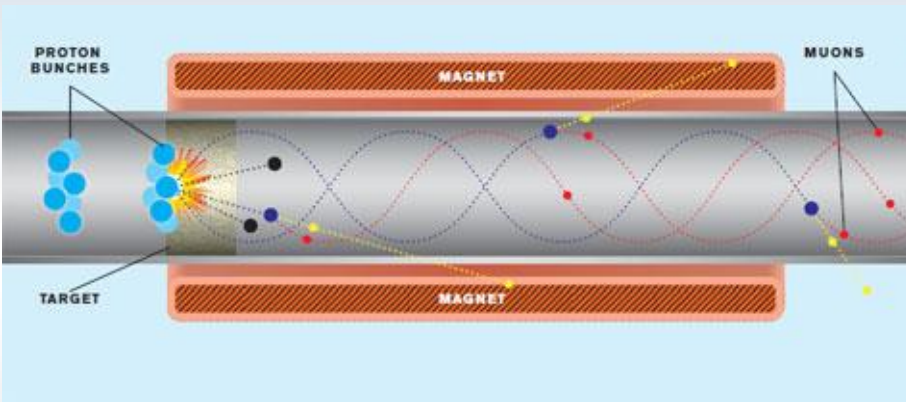

- The initial muon beam is huge: enormous 6D emittance and very large momentum spread.

- Beam cooling (i.e. reduction of phase-space volume) can improve beam quality

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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
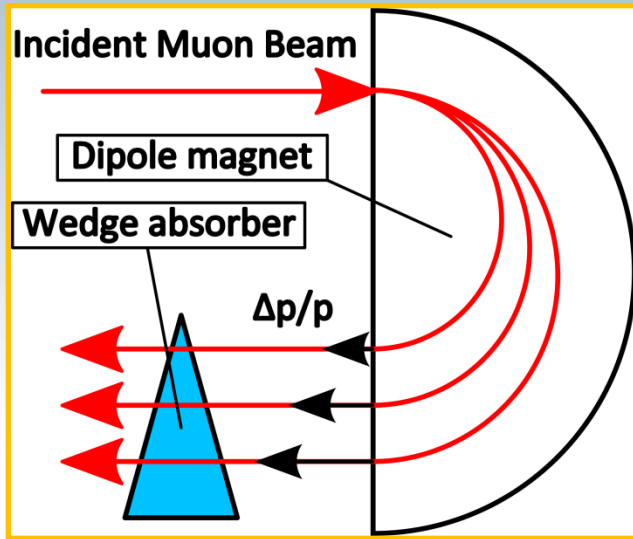
Concept 1: Generate dispersion and cool via emittance exchange in a wedge absorber
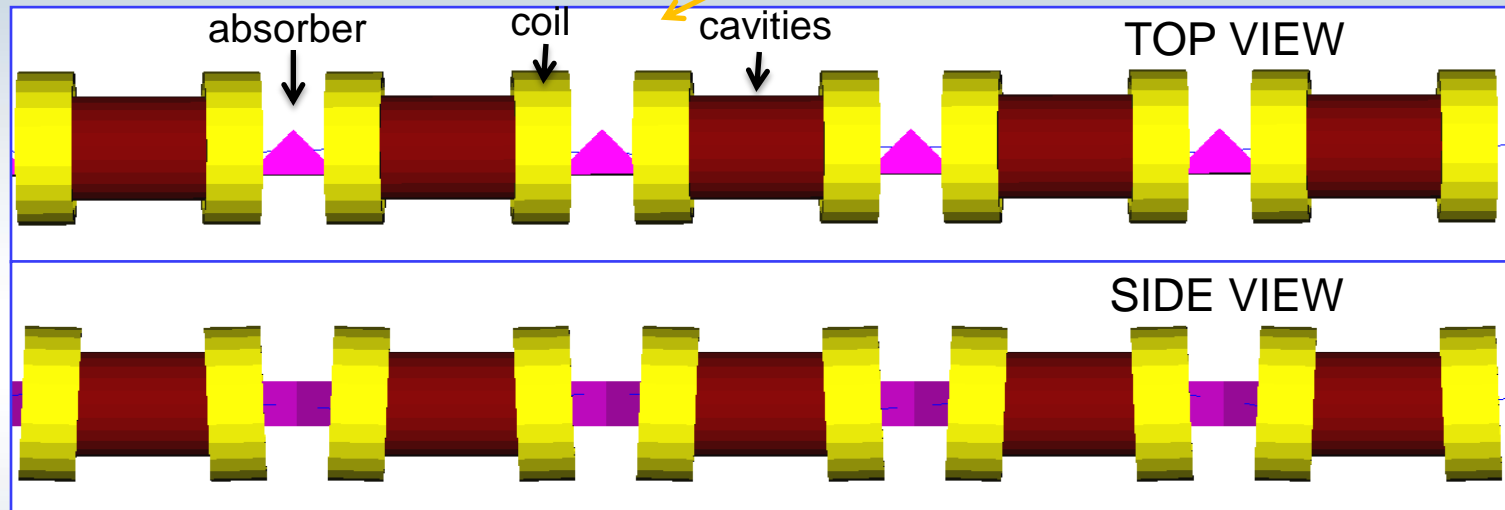
Concept 2: Energy loss dependence on path length in a continuous absorber
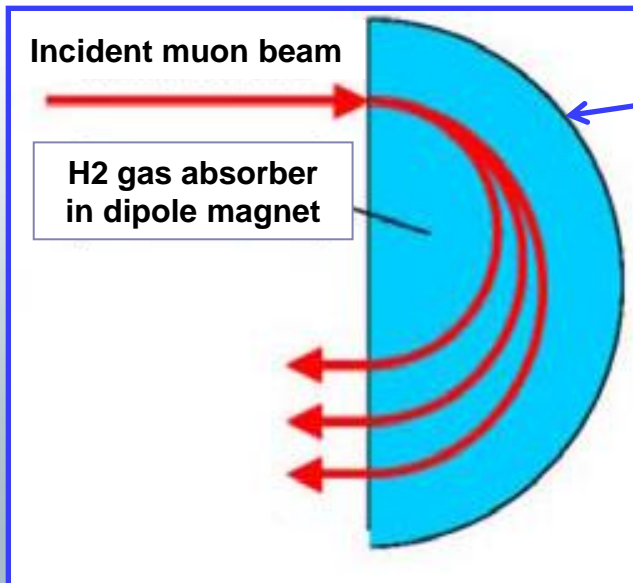
- Two concepts, same principle

- Dispersion is introduced to spatially separate muons of different momenta

Incident Muon Beam

Dipole magnet

Wedge absorber

$\Delta p/p$

Incident muon beam

H2 gas absorber in dipole magnet

6-Ionization cooling lattices

Lattice 1: Vacuum cooling channel (VCC)

absorber   coil   cavities   TOP VIEW

SIDE VIEW

Lattice 2: Helical cooling channel (HCC)
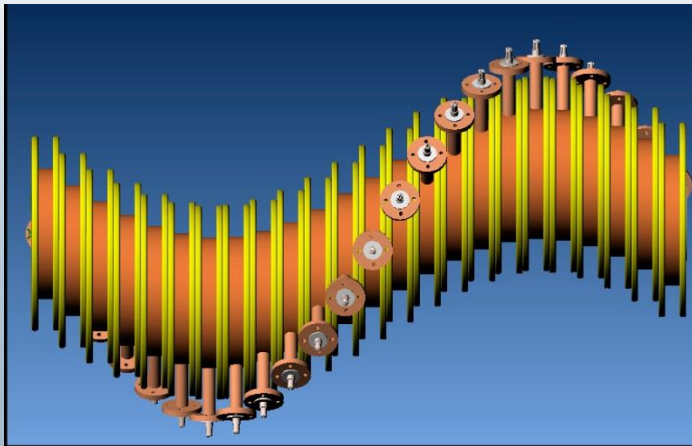
History of VCC Concept

- We replaced the helical (Guggenheim) channel to the less-challenging Rectilinear channel (2013)

- Designed a complete 6D cooling channel. Can cool to < 0.30 mm emit. (trans.) as required for a Muon Collider (2014)

- PRST-AB paper in preparation...

End-To-End Simulation!

Theory to predict performance. Agrees with simulation!
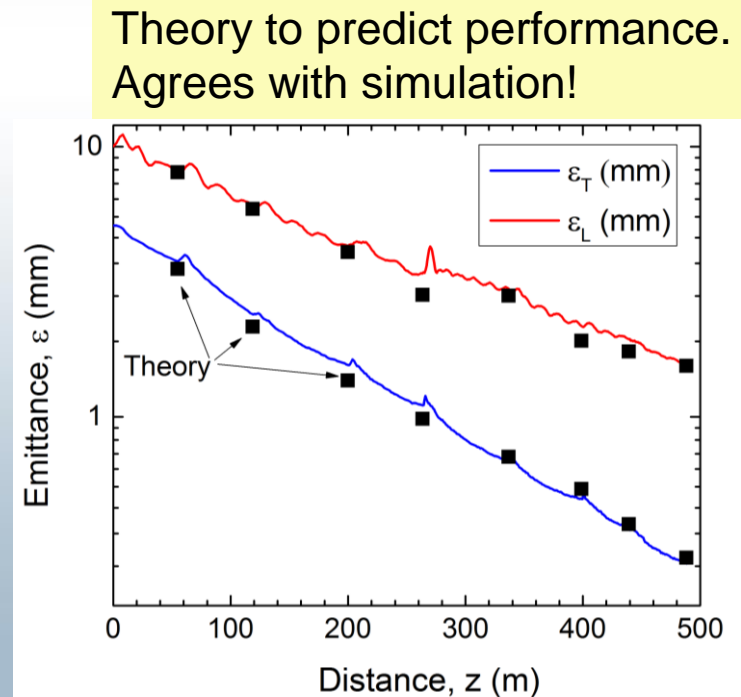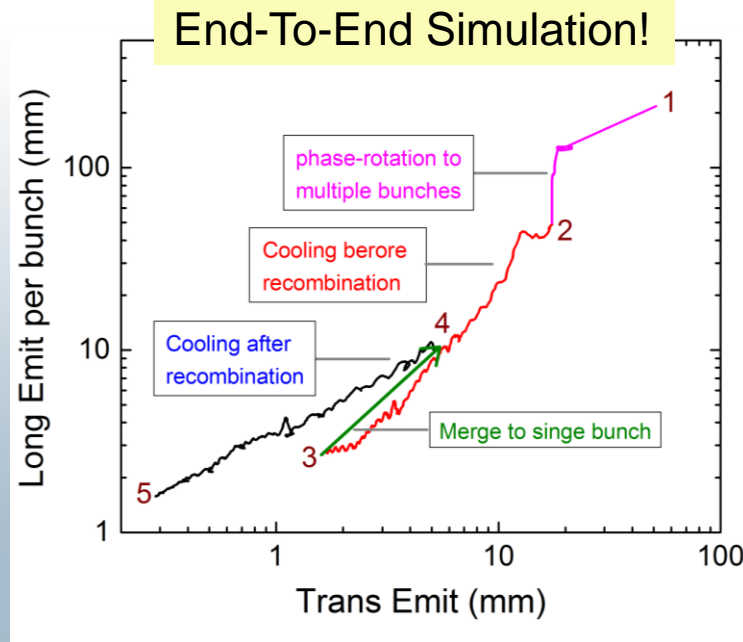
Challenges for the VCC

- Both schemes require the operation of high-gradient rf cavities within multi-Tesla fields
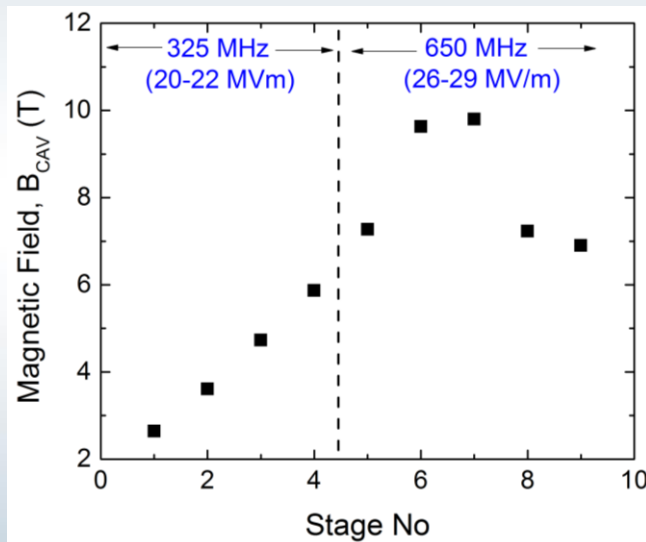
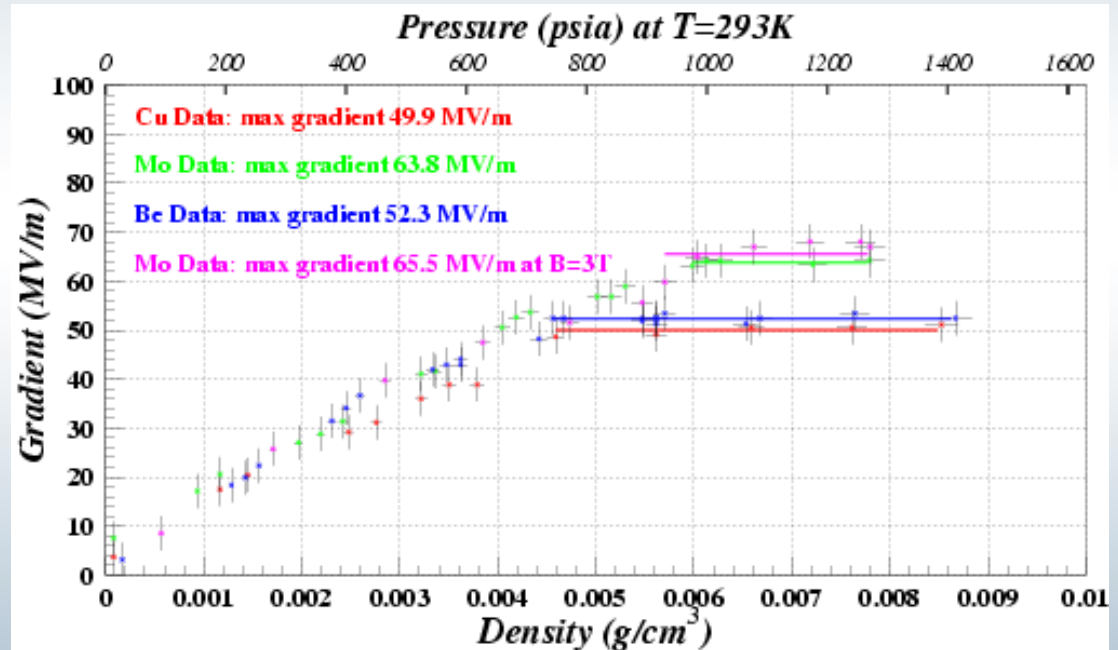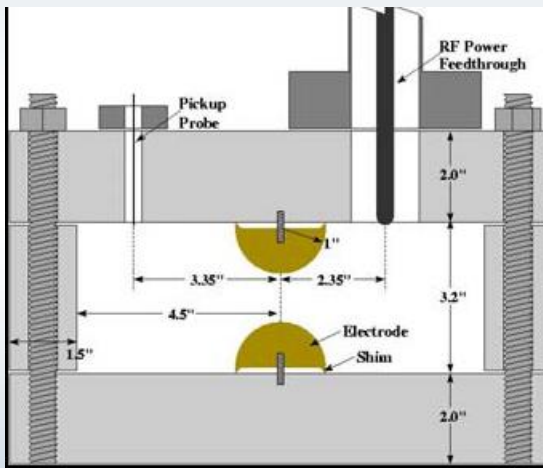Magnetic field & rfrequirement for a Muon Collider

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

- VCC Challenge:

  - While recent results are encouraging, there are still some questions about operating rf in multi-Tesla fields.

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 (< 500 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

References: Gallardo & Zisman, AIP Conf. Proceedings 1222, 308 (2010)
Stratakis, Proc. of IPAC 2014, Dresden, Germany, p. 1402 (2014)

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
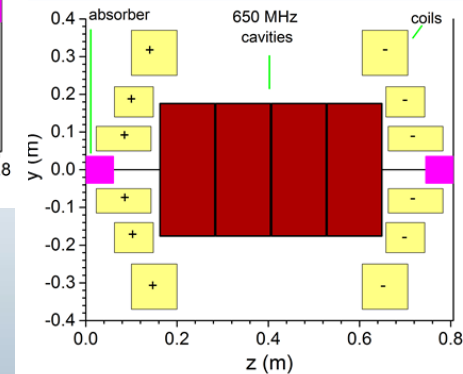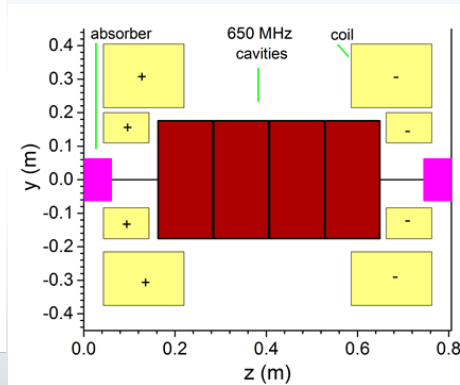
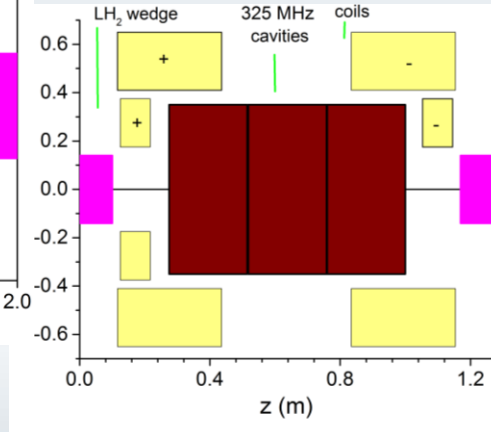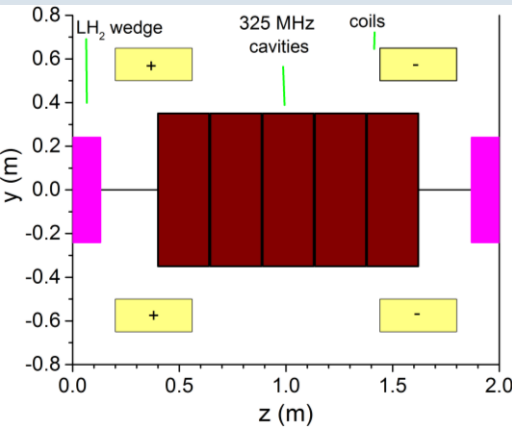- LIH absorber length is slightly reduced
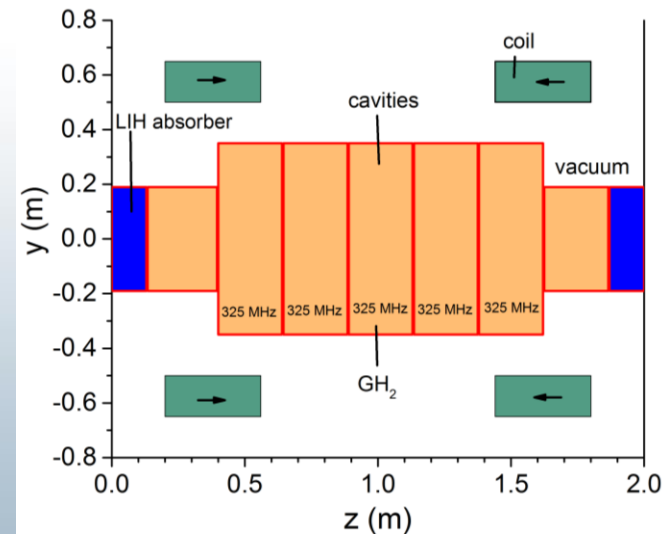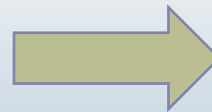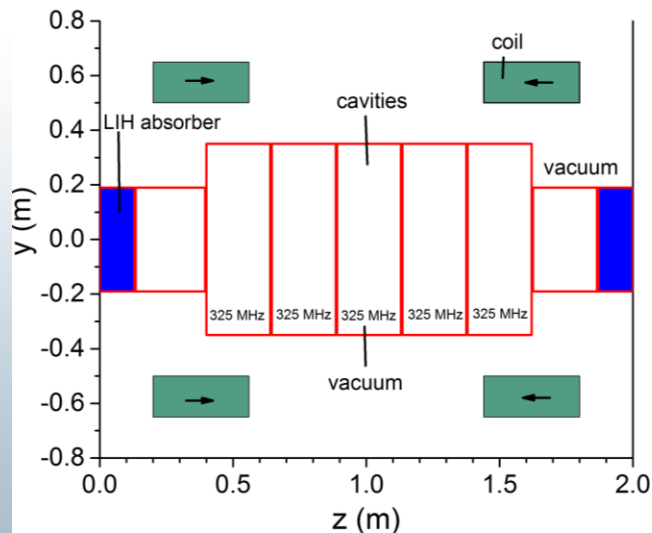
Cooling application: Muon Collider

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

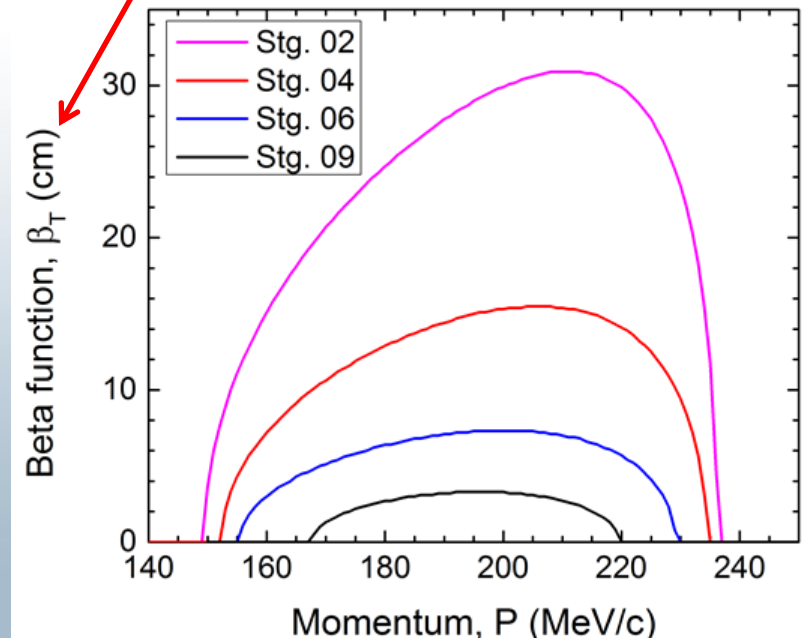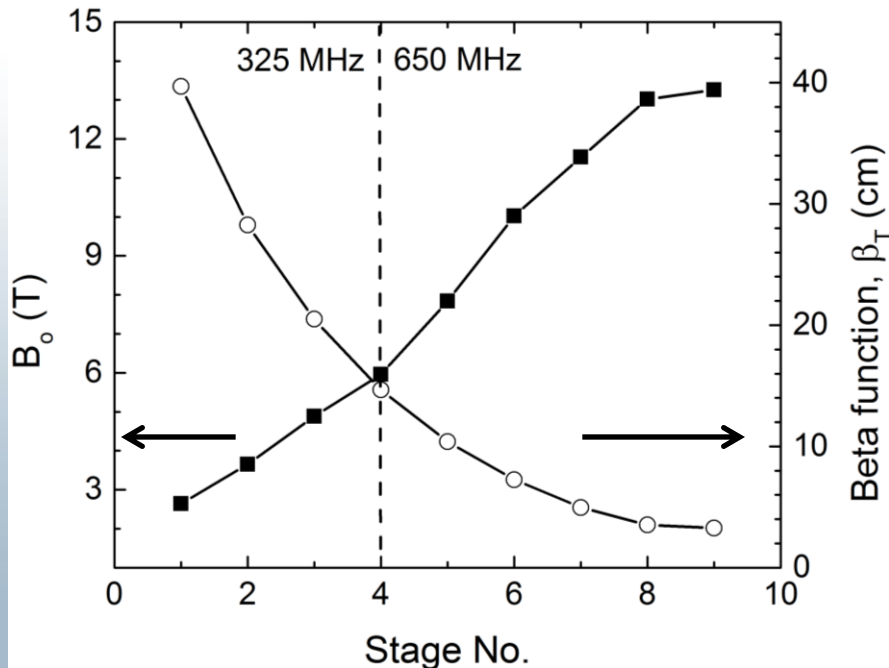3.7 T (8.4 T)   6.0 T (9.2 T)   10.8 T (14.2 T)   13.6 T (15.0 T)

MAGNETIC FIELD   axis (coil)

Lattice properties

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

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

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)

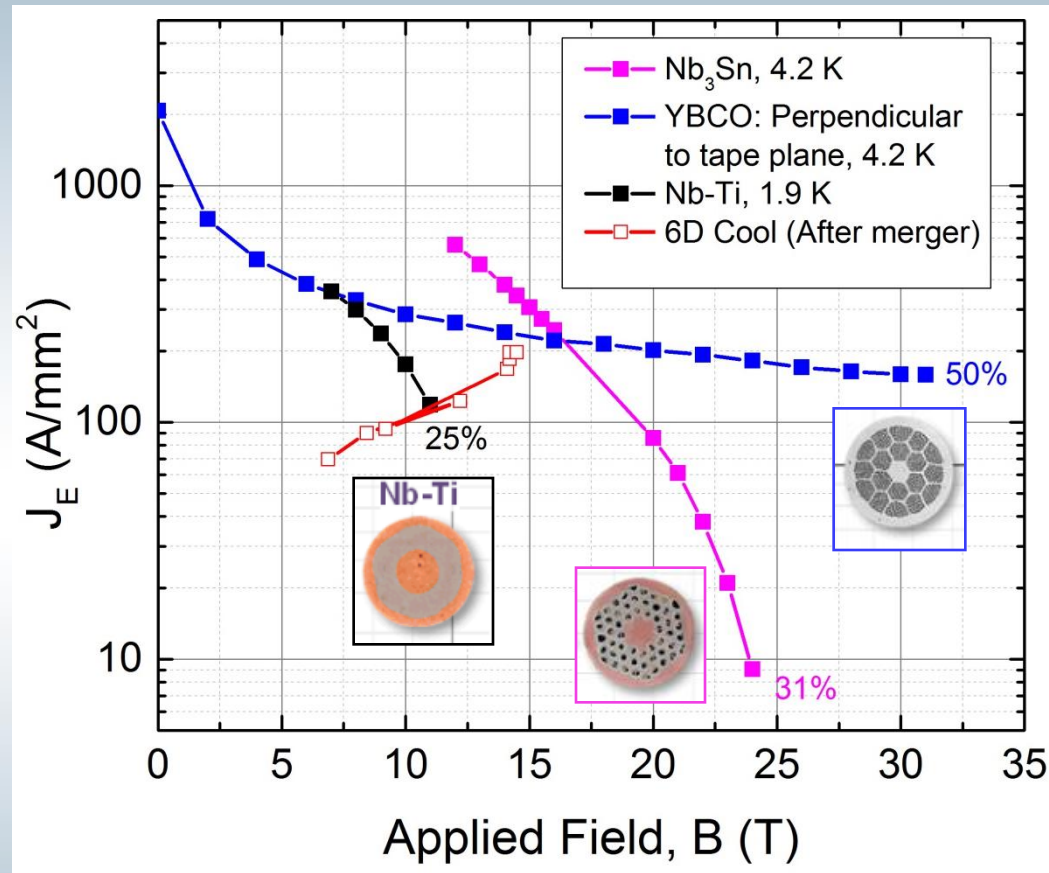- Same result obtained with a conventional VCC channel
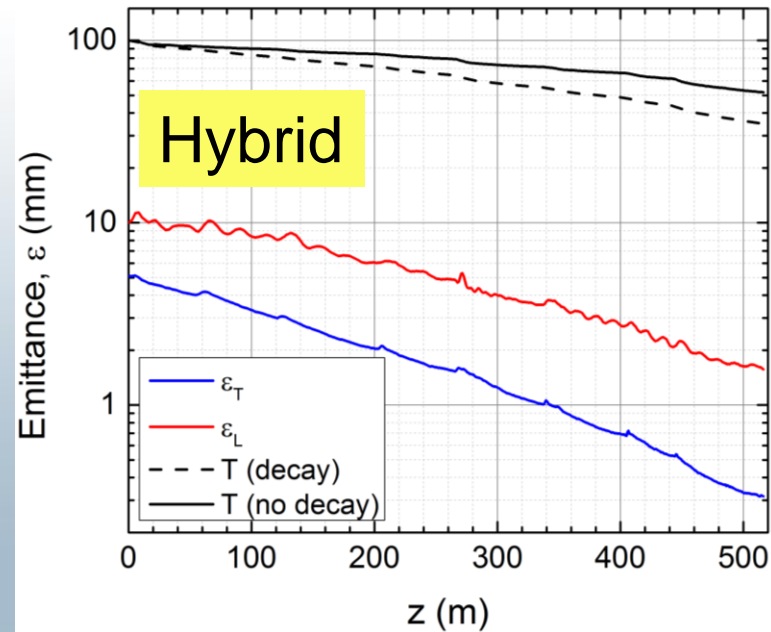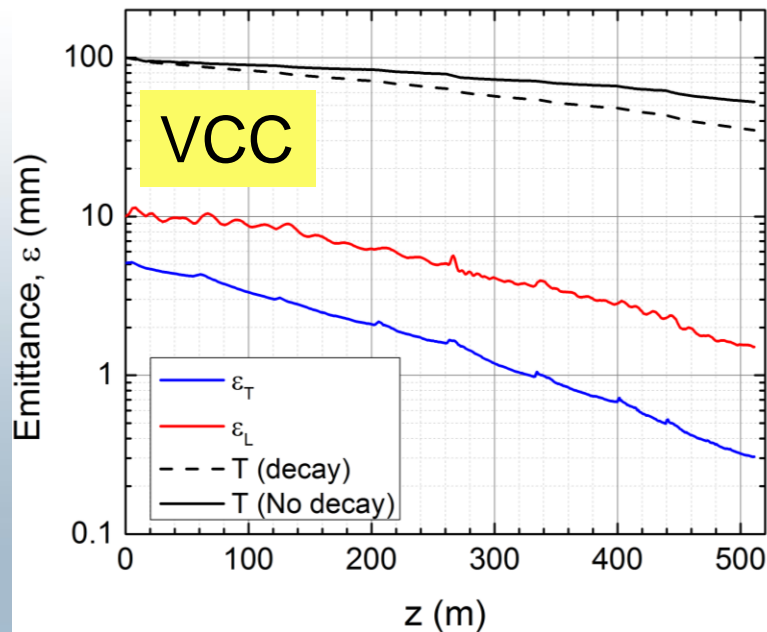
Quality factor (Q-Factor)

- 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.

$$Q = \frac{\mathrm{d}\varepsilon_{6D}^{N}/\mathrm{d}s}{\mathrm{d}N/\mathrm{d}s}\frac{N(s)}{\varepsilon_{6D}^{N}(s)}$$
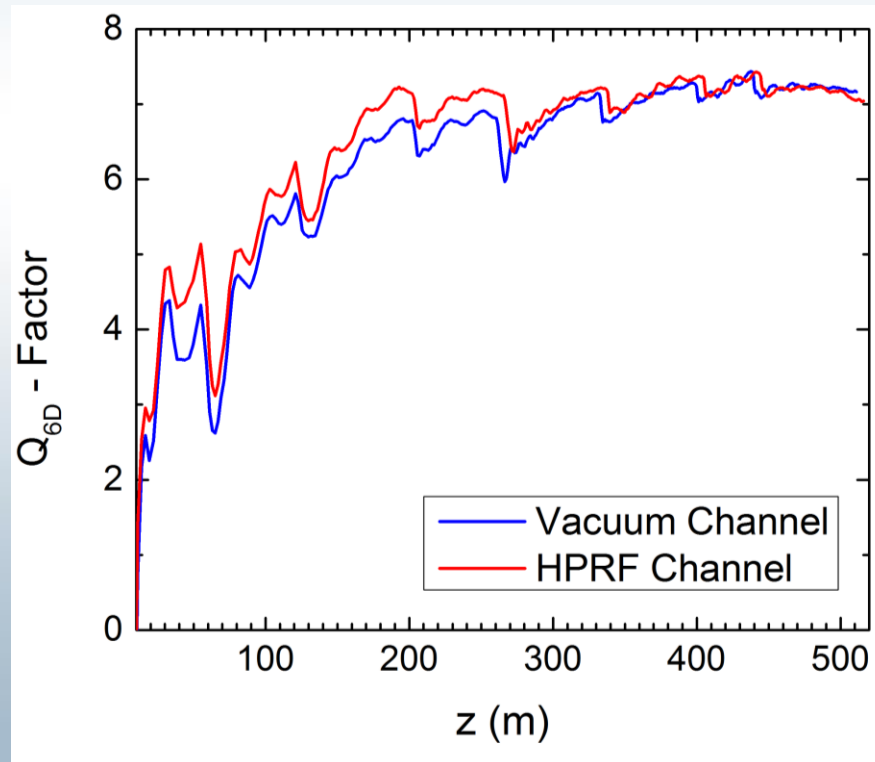
Magnet feasibility

- Magnet requirements appear to be within the critical engineering limits for Nb_3Sn

- Last stages are challenging

Summary

- We discussed a possible implementation of high-pressure (HP) gas-filled RF cavities in a 6D cooling channel

- Our solution is a hybrid approach that uses HP hydrogen gas to avoid cavity breakdown, along with discrete LiH wedge absorbers to provide the majority of the energy loss.

- Without loss in performance, we 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.