DESIGN AND SIMULATION OF A HIGH FIELD COOLING CHANNEL

H. KAMAL SAYED – R. B. PALMER – J. S. BERG

BROOKHAVEN NATIONAL LABORATORY

Muon Accelerator Program

BROOKHAVEN NATIONAL LABORATORY

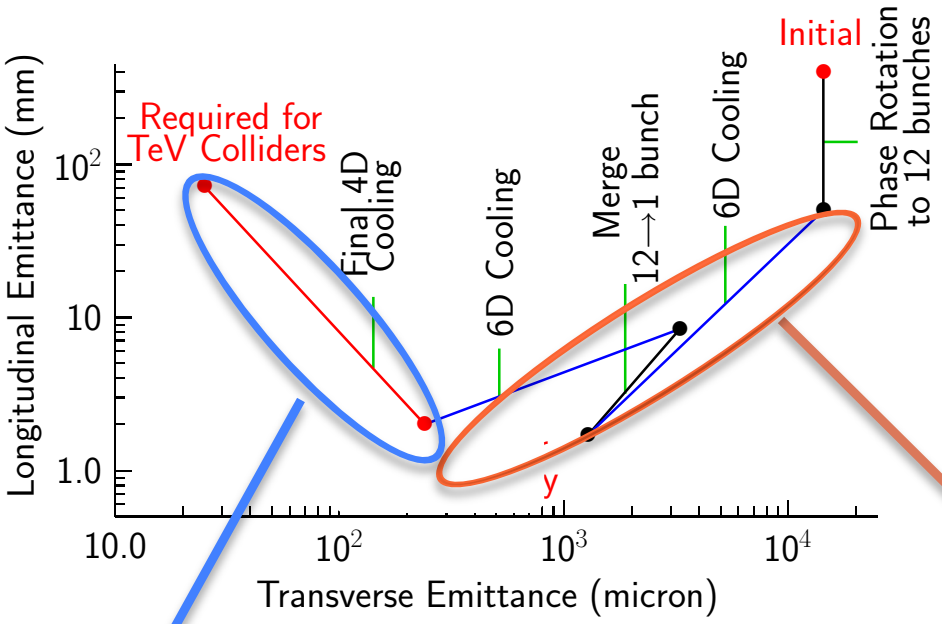
LAYOUT & INTRODUCTION

- Muon Collider cooling concept & Final cooling starting point and goals

- High field cooling channel concept
- High field cooling channel design
  - Focusing coils + transport coils
  - Asymmetric match in & out of the focuing coils
  - Field flip design
  - Absorber parameters
  - Control of energy spread & energy phase rotation

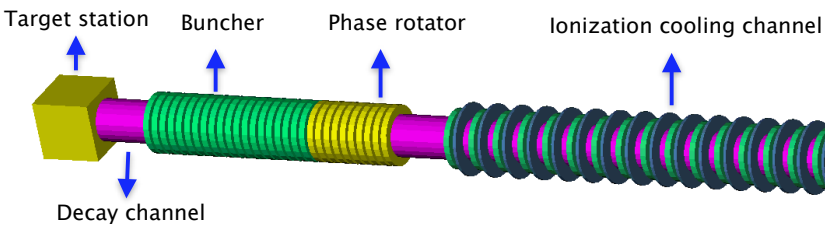
- Simulation results for 30 – 25 T cooling channels
- Conclusion

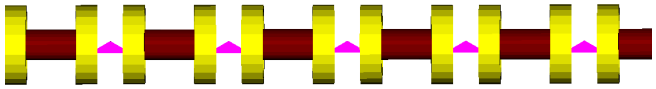
Muon Collider cooling Concept



R. Palmer *et. al* 2007

- Muon production
- Muon Capture
- Bunching into 12 microbunches
- Energy phase rotation of microbunches to a common centeral energy

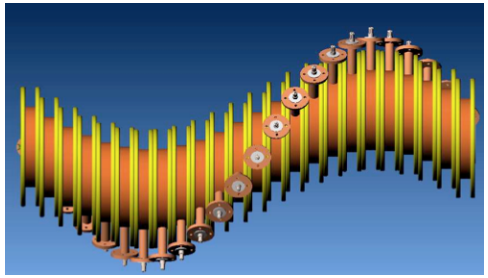




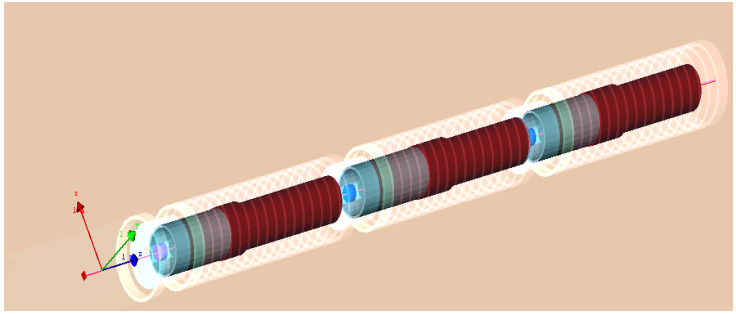
6D cooling Channels:

Target :ε_T= 300 μm ε_L= 1.5 mm

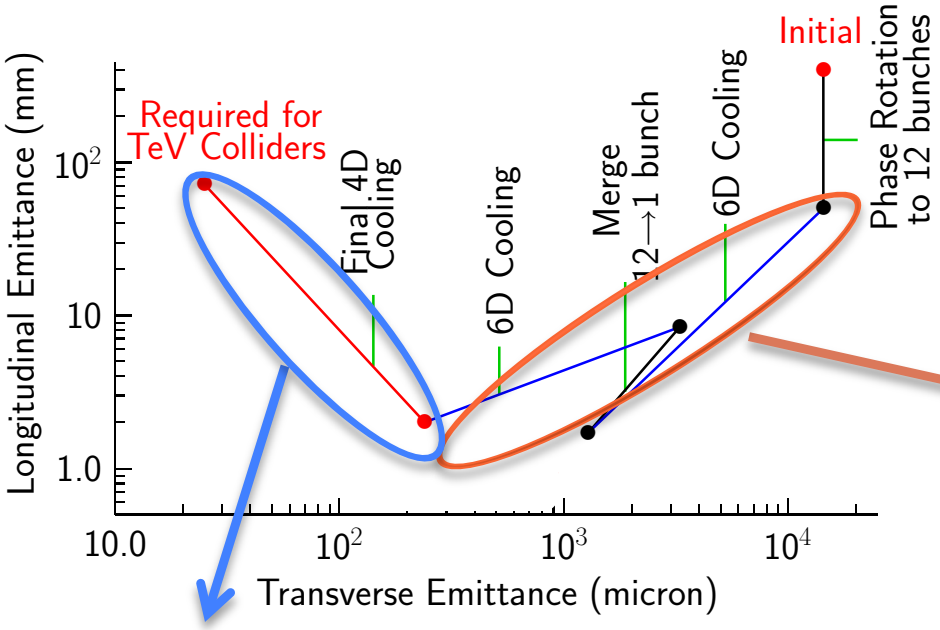
- Tapered Rectiliniar VCC channel
- Helical Cooling Channel HCC



- **High field cooling Channel**
- **Target :ε_T= 25 μm ε_L= 72 mm**



MUON COLLIDER COOLING CONCEPT

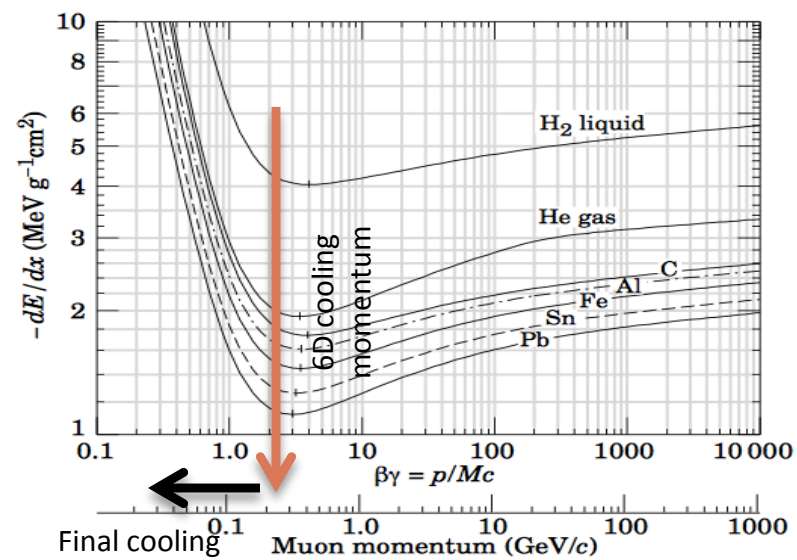


- Muon production
- Muon Capture
- Bunching into 12 microbunches
- Energy phase rotation of microbunches to a common central energy

6D cooling Channels:
Target :ε_T= 300 μm ε_L= 1.5 mm

- **High field cooling Channel**
- **Target :ε_T= 25 μm ε_L= 72 mm**

Energy loss in low z material



Reduction of **ε_T < 300 μm**
→ P < 135 MeV/c + strong focusing 25-40 T
P < 135 MeV/c
→ Positive slope of dE/dx
→ requires small initial ε_L
while limiting the expansion of σ_E

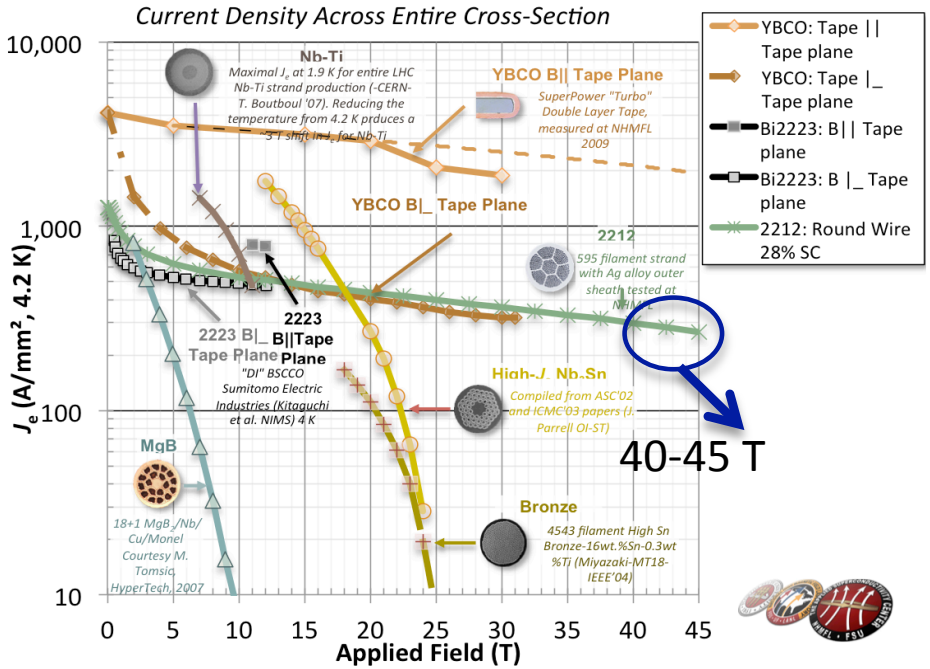
$$\epsilon_{equ,N} = \frac{\beta_\perp E_s^2}{2\beta mc^2 L_R (dE/ds)}$$

HIGH FIELD IONIZATION COOLING CONCEPT

Minimum emittance achievable in a long solenoid field

$$\epsilon_{\perp}(min) \propto \frac{E}{BL_R(dE/ds)}$$

B magnetic field at absorber location
L_R Material radiation length
dE/ds Energy loss in material

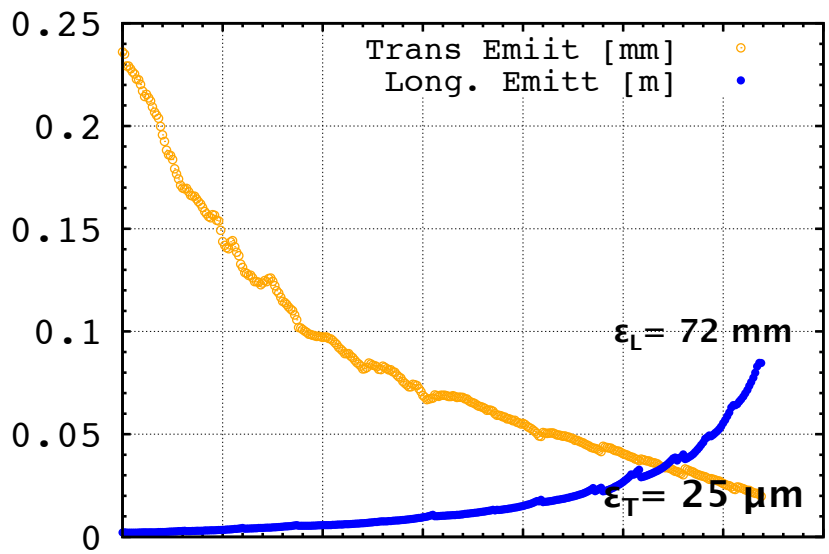


Experimental data from High Magnetic Field Laboratory show the possibility of 40 T fields.

HIGH FIELD IONIZATION COOLING CHANNEL

Conceptual simulation in constant field with no matching - no RF

- Cool in the transverse dimensions while the longitudinal emittance grows
- Reduce energy gradually as we progress in the stages
- Reduce absorber length gradually
- Maintain energy spread within acceptable limits



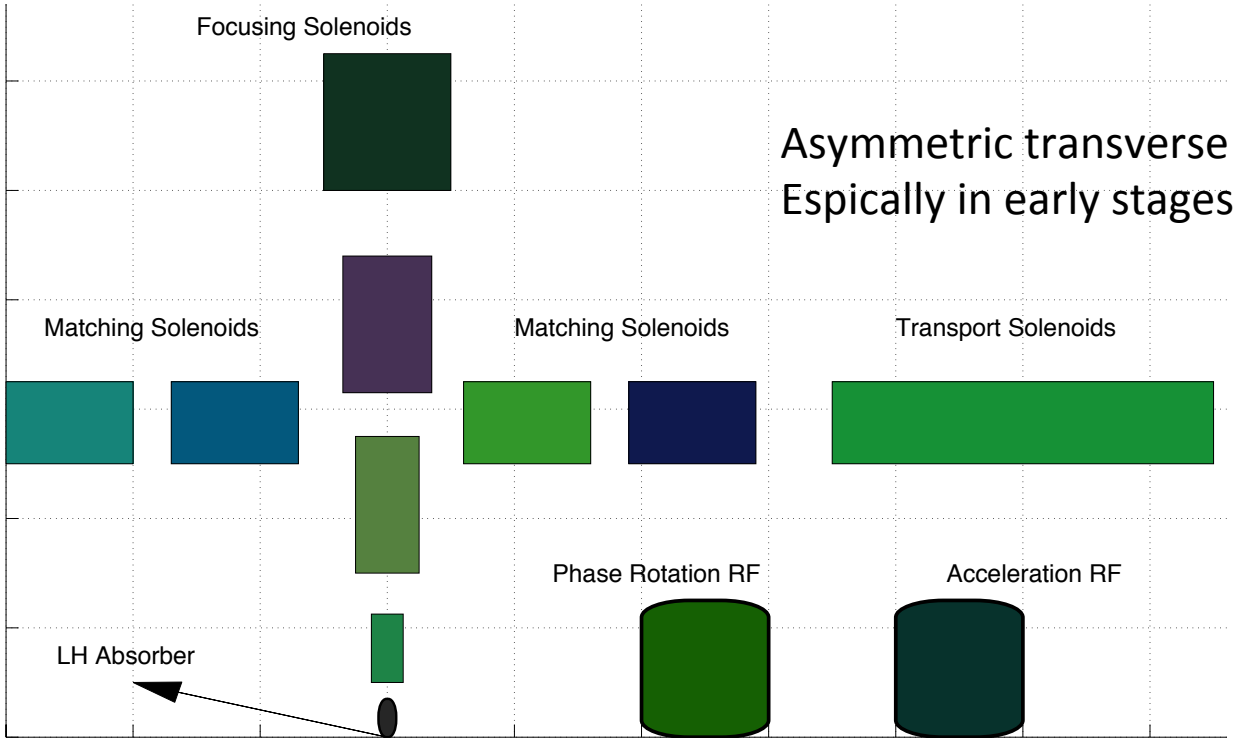
Stages

Emittance reduction in absorbers within constant 40 T - excluding matching and acceleration

HIGH FIELD IONIZATION COOLING CHANNEL DESIGN

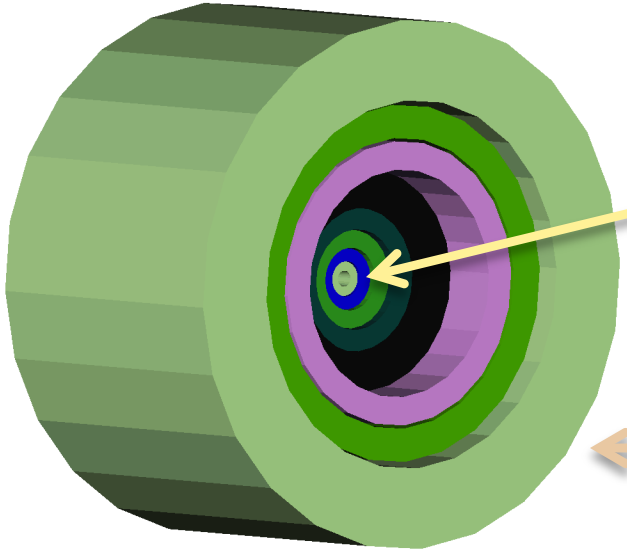
Lattice Design & Structure:

- High field solenoid magnet 25-40 T
- 3.5 T transport field throught the channel
- Asymmetric transverse match to and out of the high field solenoids
- Energy phase rotation to maintain low energy spread
  - → Increases bunch length
  - → Reduce the RF frequencies gradually



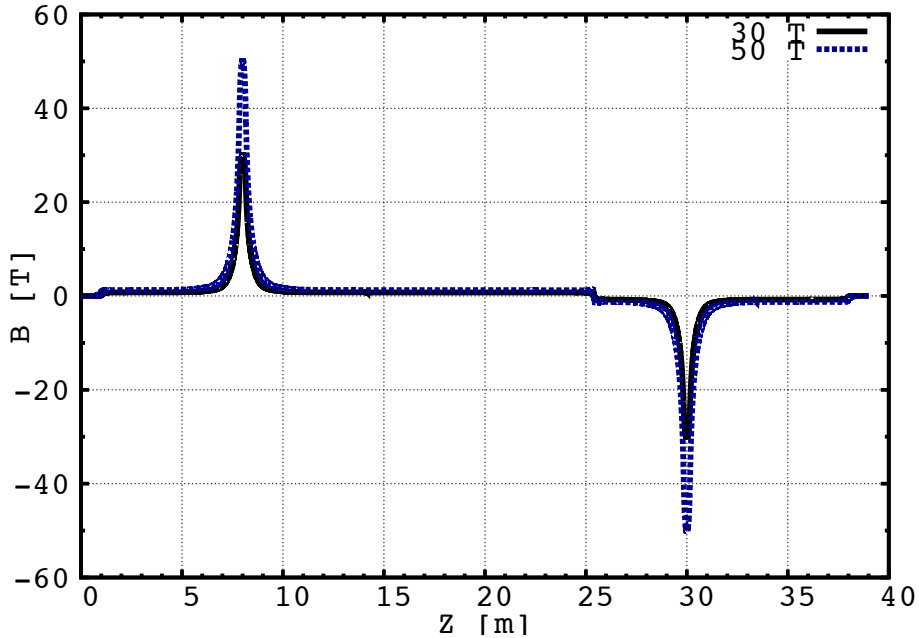
Asymmetric transverse match
Espically in early stages with long absorbers

HIGH FILED 50-30 T MAGNET



Length [m]	Inner radius [m]	Thickness [m]	I/A [A/mm^2]
0.317	0.025	0.029	164.26
0.337	0.055	0.041	142.43
0.375	0.098	0.056	125.88
0.433	0.157	0.067	119.07
0.503	0.228	0.120	85.99
0.869	0.355	0.089	39.60
0.868	0.454	0.104	44.30
0.992	0.575	0.252	38.60

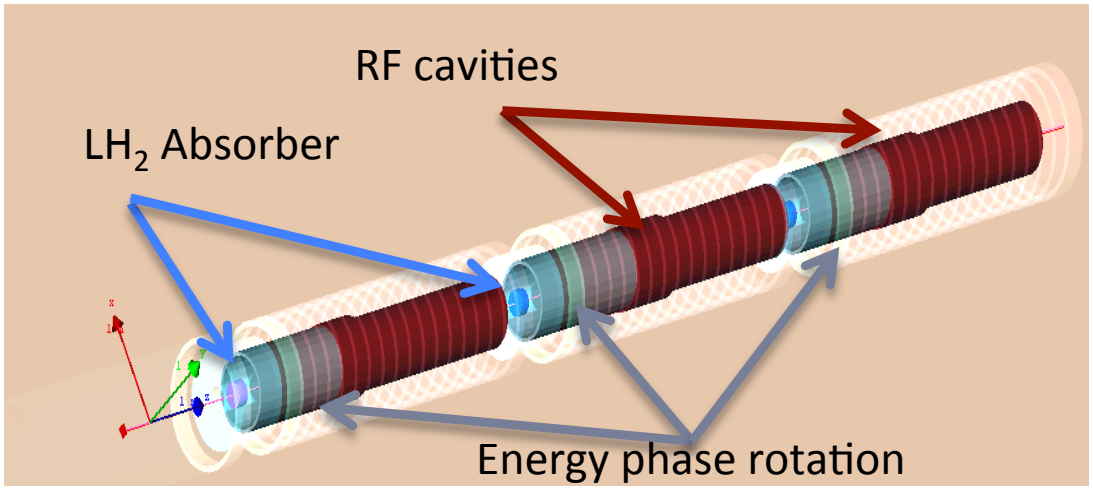
R. Palmer – B. Weggel



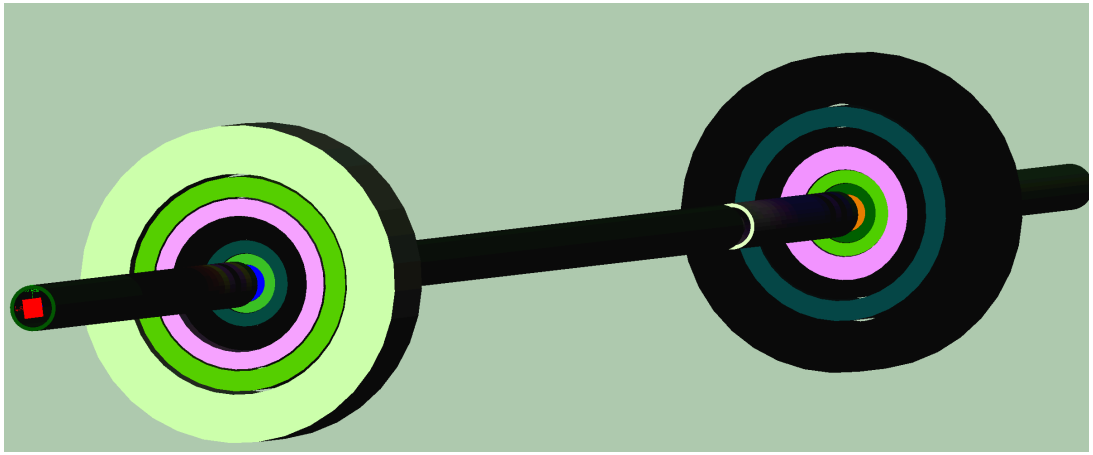
HIGH FIELD IONIZATION COOLING CHANNEL DESIGN

Lattice Design & Structure:

Early Stages: RF inside transport solenoid coils



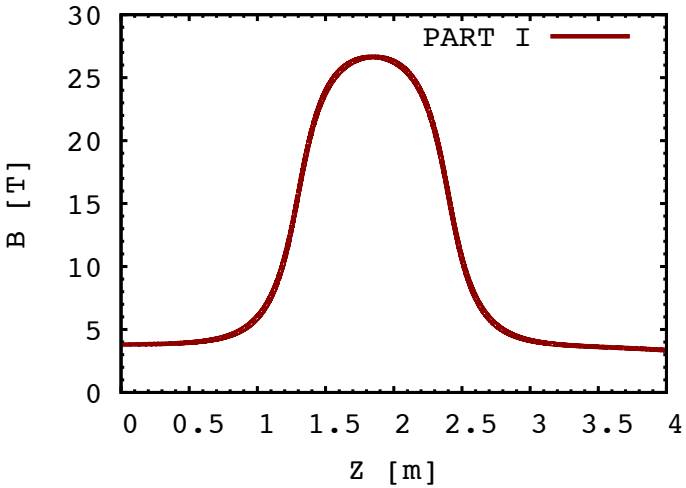
Late Stages: transport solenoid coils inside induction linac



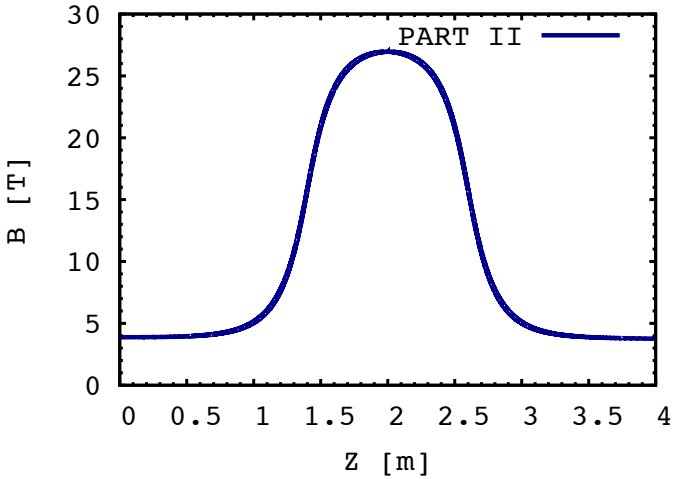
COOLING SOLENOIDS

- Limit field integral to limit the transverse –longitudnal coupling
  - → Limit unnessesary increase in σ_t
- Long absorbers

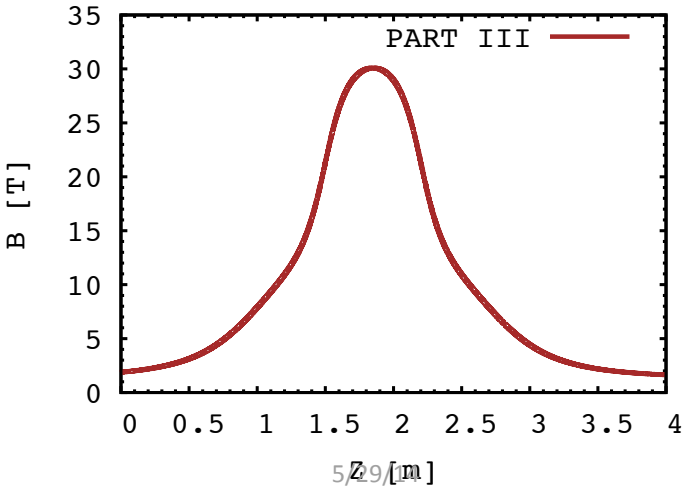
$$\Delta t \approx \frac{p_\perp^2 E}{2c^2 p^3} \int_0^z \frac{B_z(z')}{B_z(0)} dz'$$



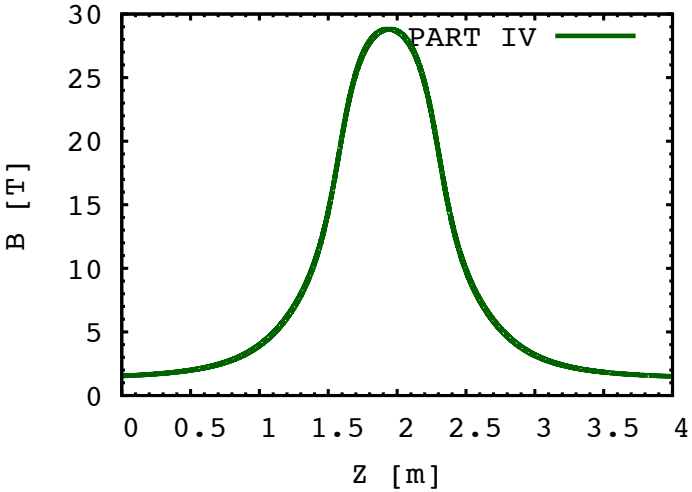
- Long absorbers
- Relativley smaller transverse amplitudes
  + already longer bunch length



- Medium absorber thickness
- Larger energy spread will lead to unwanted chromatic effects

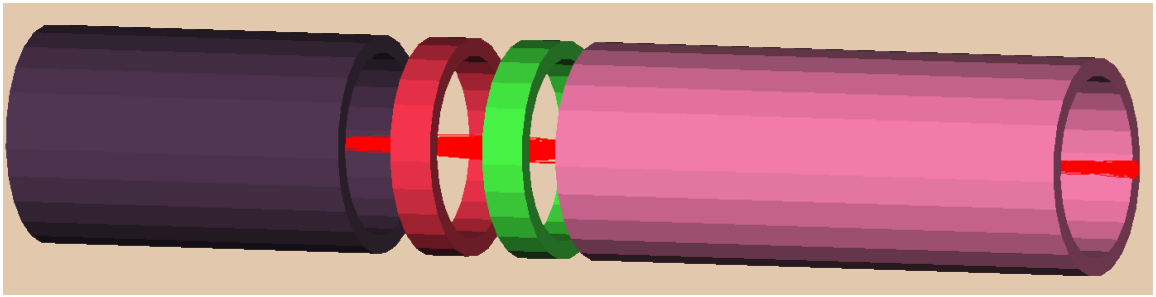


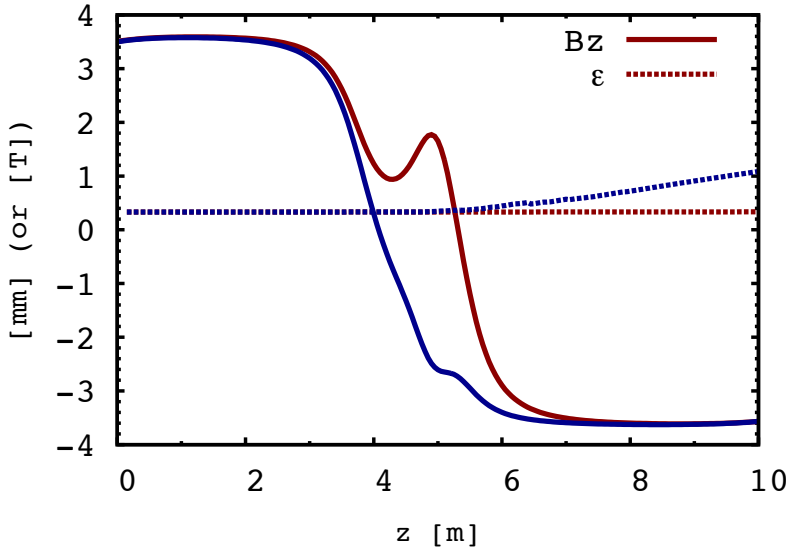
- Small absorber thickness
- Very small transverse amplitudes



Field Flip Match

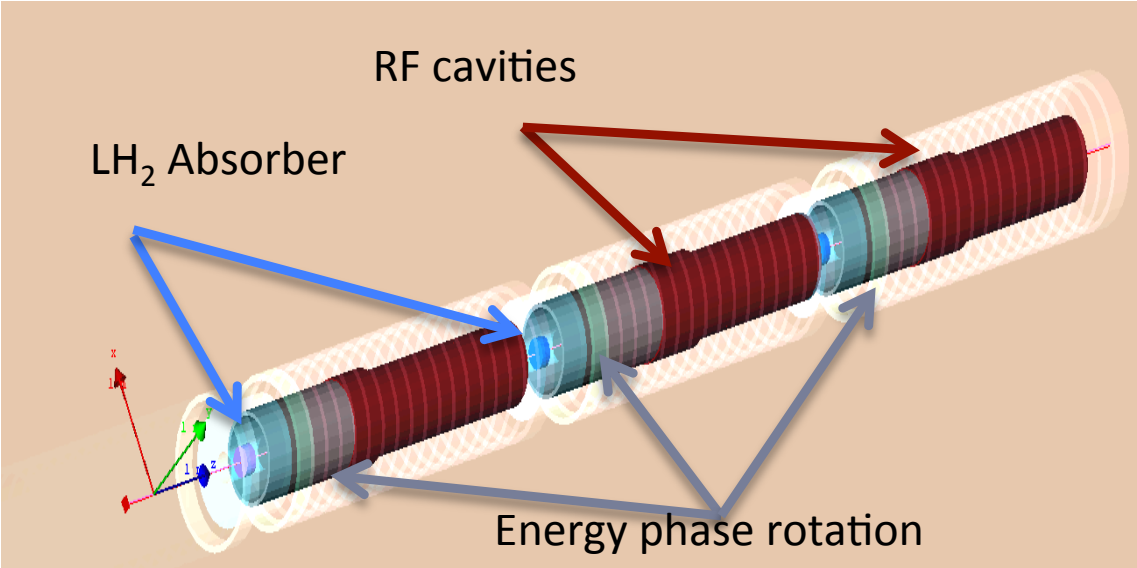
- Field flip required to limit the angular momentum build up
- Field flip may lead to emittance dilution
- Solution: → limited number of field flips
  → Proper optmization for each field flip independently





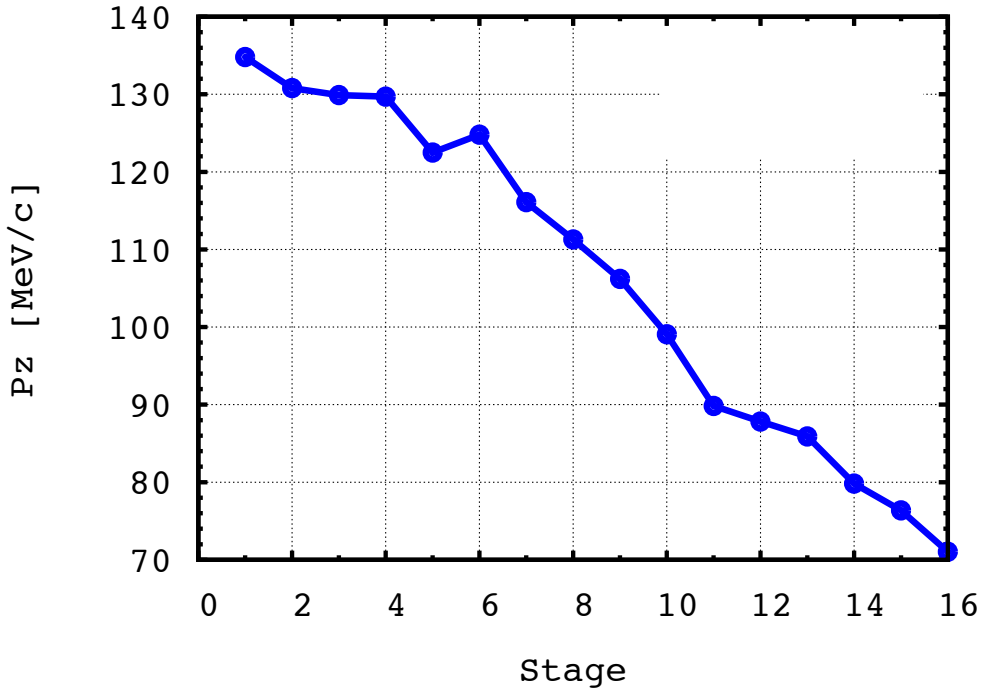
HIGH FIELD COOLING CHANNEL SIMULATIONS

- Muon beam energy falls gradually Pz = 135 → 70 MeV/c
- LH_2 absorber length falls from 65 cm to 13 cm
- Energy phase rotation to maintain the energy spread of the beam after each stage
- Bunch length rises from 5 cm to 180 cm
- RF cavities frequencies fall from 325 MHz to 10 MHz



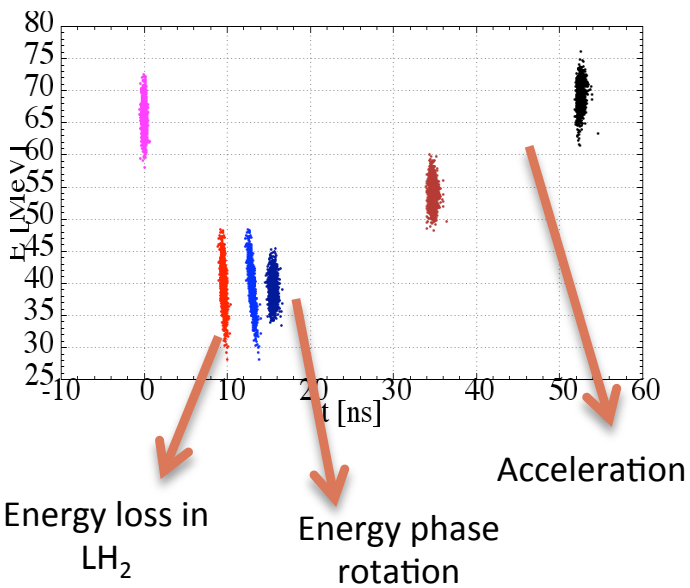
HIGH FIELD COOLING CONCEPT

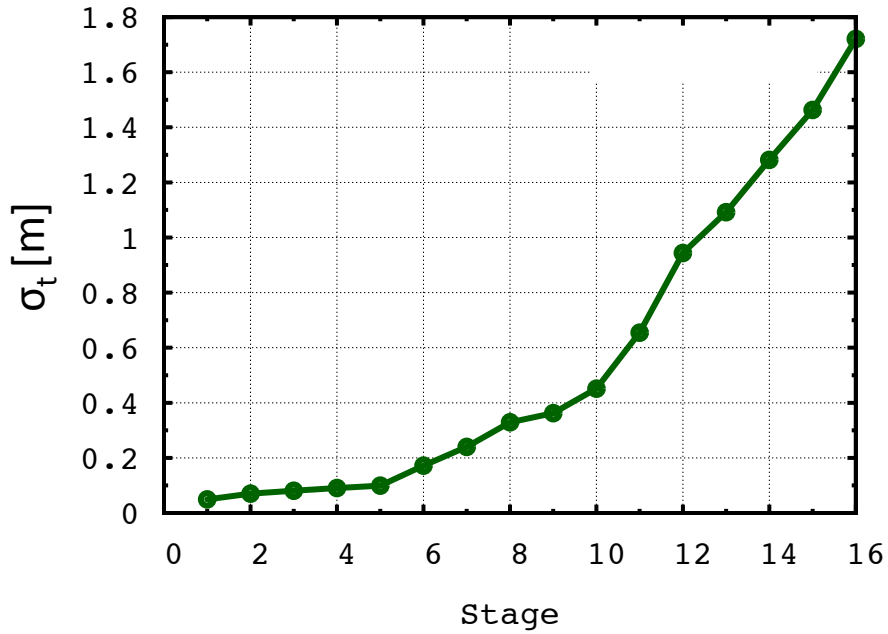
- Drop momentum of the muon beam gradually
- Acceleration gradient requirements falls as well
- LH_2 Absorbers thickness reuced gradually



HIGH FIELD COOLING CONCEPT

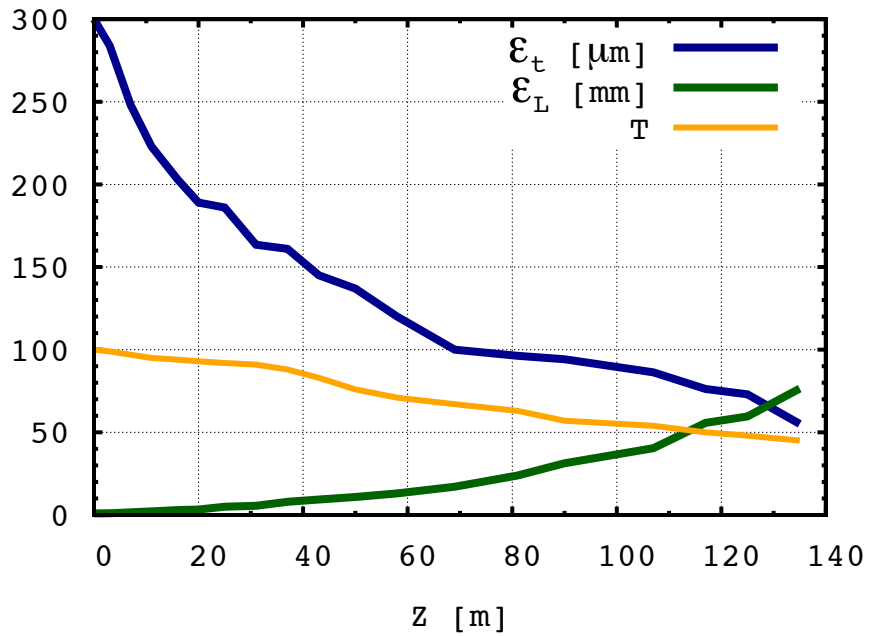
- Control of energy spread & bunch length
  - Energy spread increasea inside LH_2 absorbers
  - Energy phase rotation to decrease energy spread on the expnese of the bunch length
  - Optmization of drift length for time-energy correlations which gives the required energy spread for the following stage





SIMULATION OF 25 – 30 T CHANNEL

Two field flips in stage 5 and stage 10
B = 25-30 T can achieve 55 µm



Conclusion & Summary

- Explored the concept of high field - low energy cooling channel with transverse and longitudnal matching
- Channel design with 30-25 T focusing field presented
- A first pass of a complete design and simulation of a high field cooling channel

→ ε_T = 55 µm ε_L ~> 75 mm

- Field flip frequency is under study

  - Current challenges + working points
- Optmize the 30-25 T channels – find the lowest achievable emittance ?!
- Optmize the 40 T to achive the required 25 µm
- Improve transmission
- Induction linacs –> cost + low acceleration gradient