NuFact15

Final Cooling Concepts in the Muon Accelerator Program

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Muon Accelerator Program

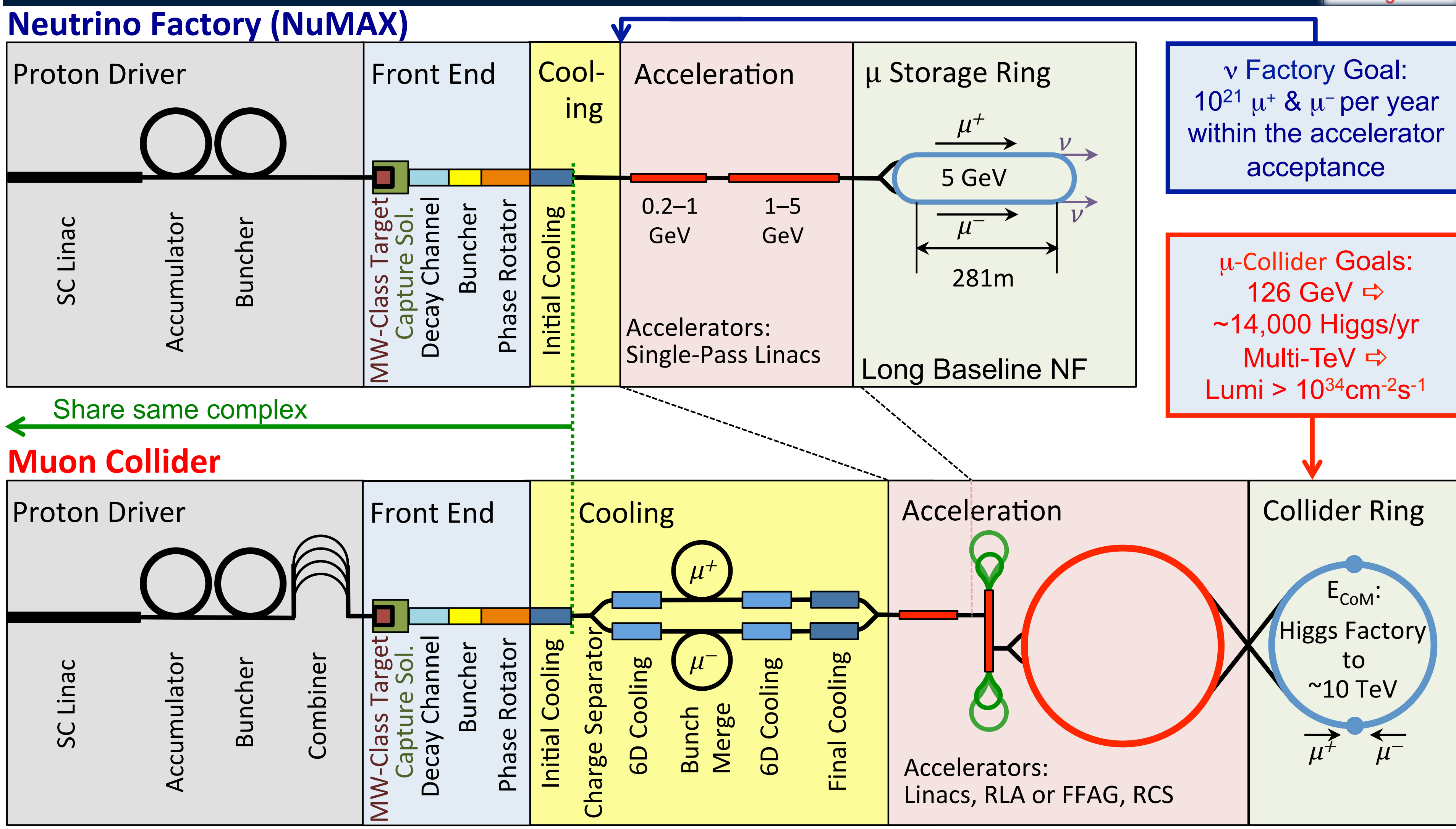
Fermilab

Outline

- Introduction
  - MAP Initial Baseline Selection Process
  - MAP Cooling Overview
- Final Cooling Concepts
  - Baseline
  - Alternates
- Conclusion

INTRODUCTION

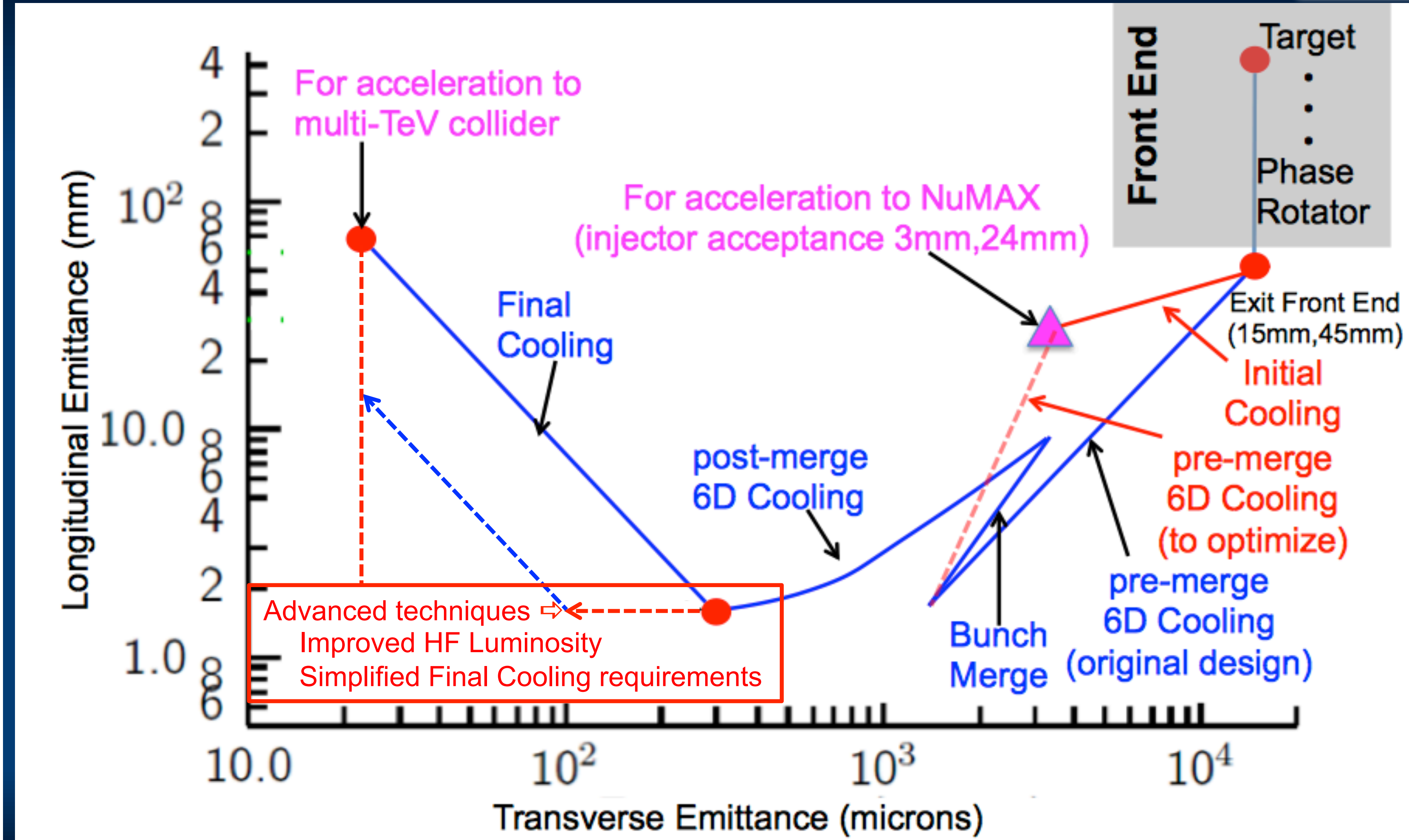
Muon Accelerator Systems



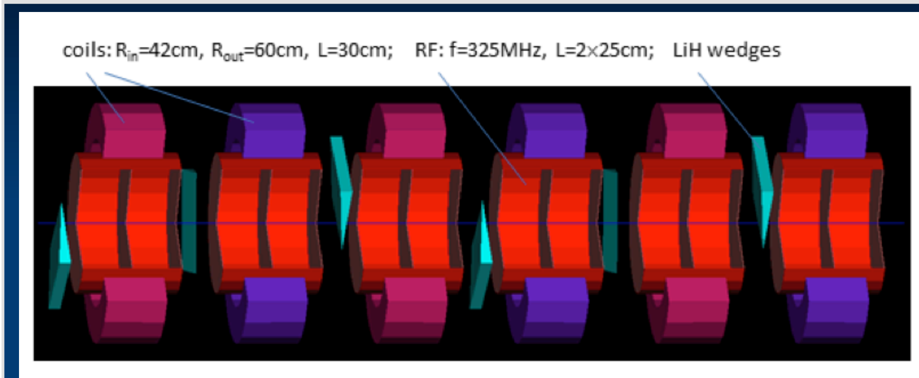
Initial Baseline Selection Process

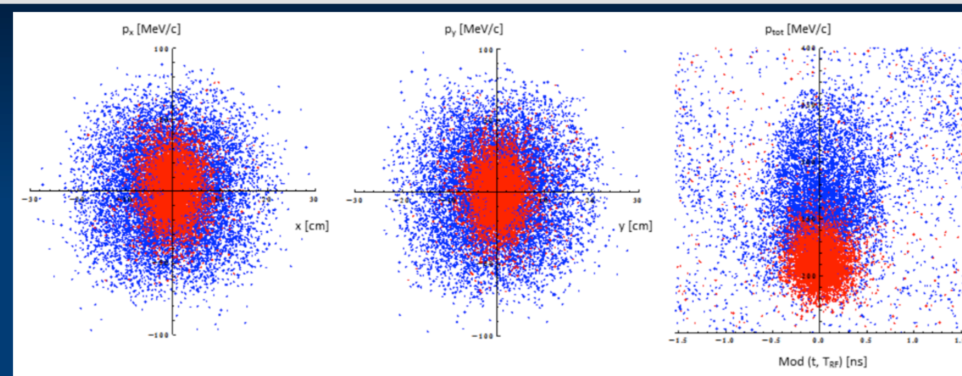
- MAP was created as a Feasibility Study for Muon Accelerator Design and Technology
- Initial Baseline Selection Process
  - Develop sub-system designs with:
    - Realistic technology performance limits (continuously updated based on the MAP technology R&D program)
    - Implementing engineering constraints in lattice design
    - Full end-to-end simulations including all known beam physics
  - Evaluate candidates, identify any potential showstoppers, and identify the most readily buildable design
  - Integrate all sub-system designs
    - Evaluate cross-system impacts
    - Iterate sub-system designs as necessary
  - Complete a full end-to-end facility performance evaluation
- Same process can apply within individual sub-systems (e.g. across different sections of the cooling system)

Muon Ionization Cooling (MASS)

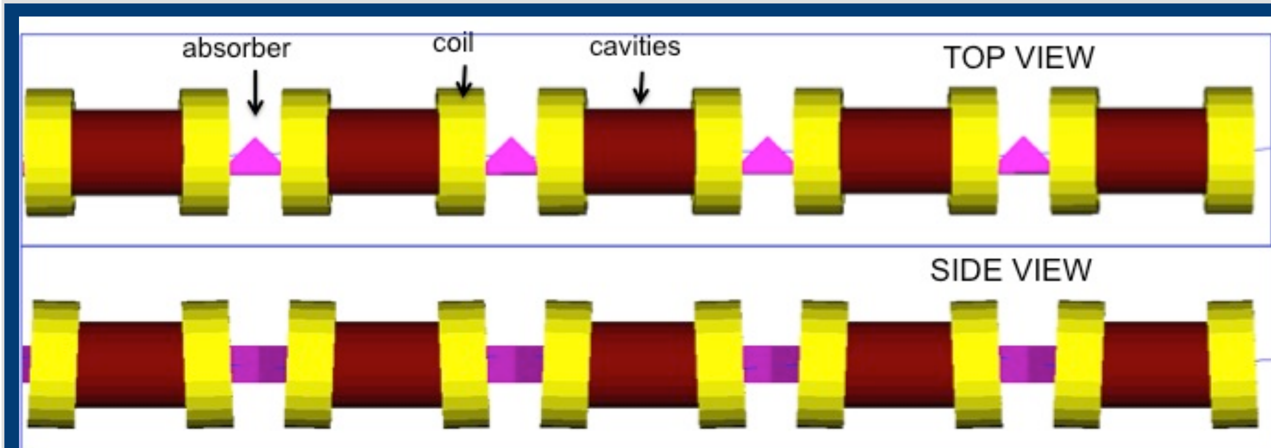


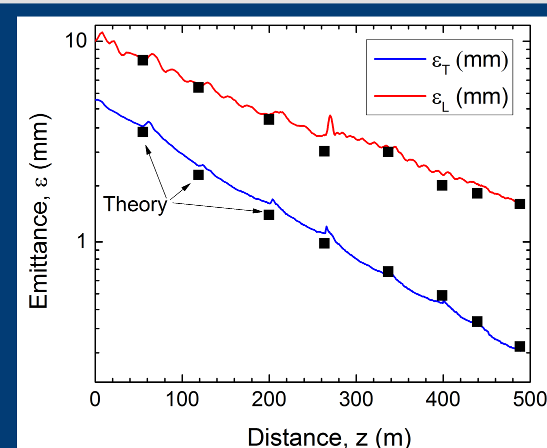
Muon Ionization Cooling (Design)





Initial 6D Cooling: ε_{6D} 60 cm^3 ⇨ ~50 mm^3; Trans = 67%



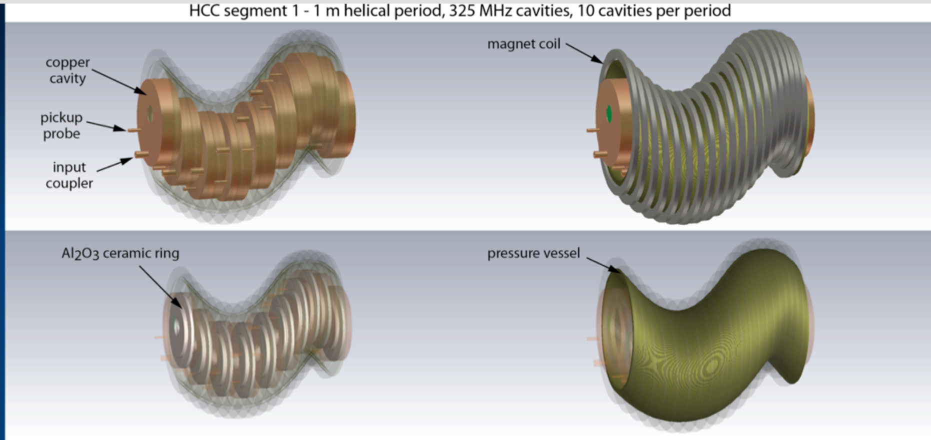


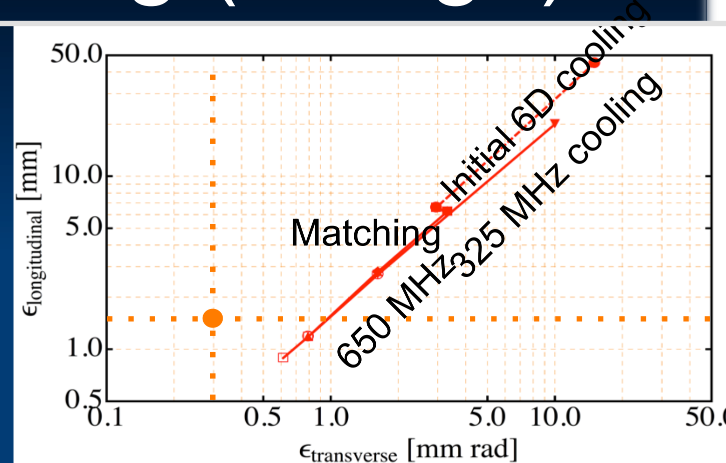
6D Rectilinear Vacuum Cooling Channel (replaces Guggenheim concept):

ε_T = 0.28mm, ε_L = 1.57mm @488m

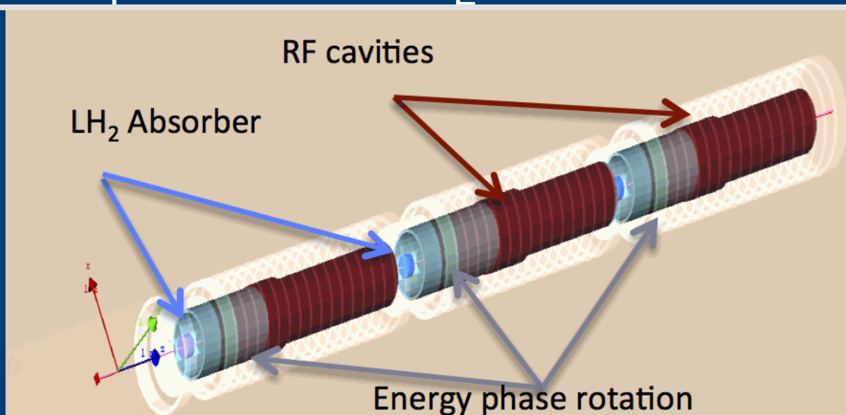
Transmission = 55%(40%) without(with) bunch recombination

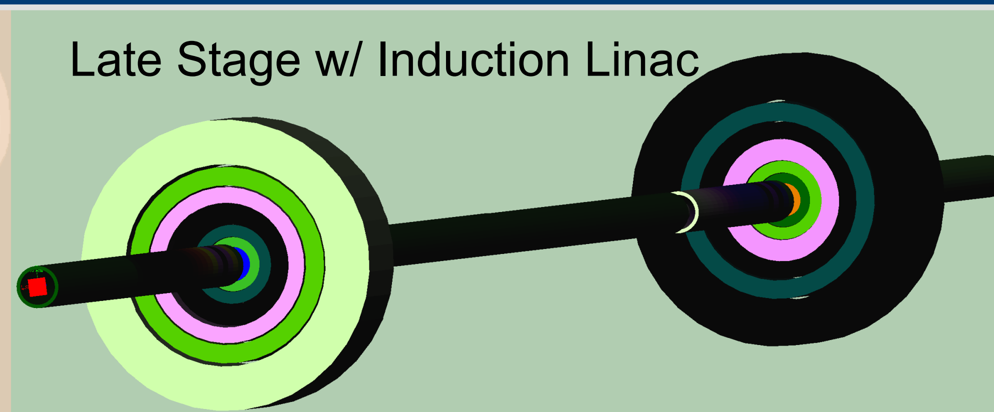
Muon Ionization Cooling (Design)





- Helical Cooling Channel (Gas-filled RF Cavities):
  ε_T = 0.6mm, ε_L = 0.3mm





- Final Cooling with 25-30T solenoids (emittance exchange):
  ε_T = 55μm, ε_L = 75mm

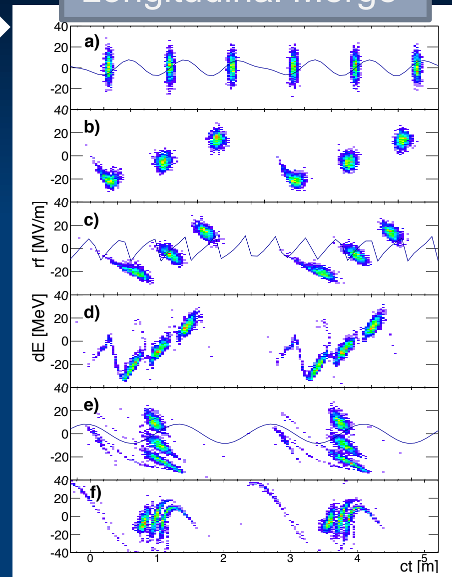
Muon Ionization Cooling (Design)

Bunch Merge

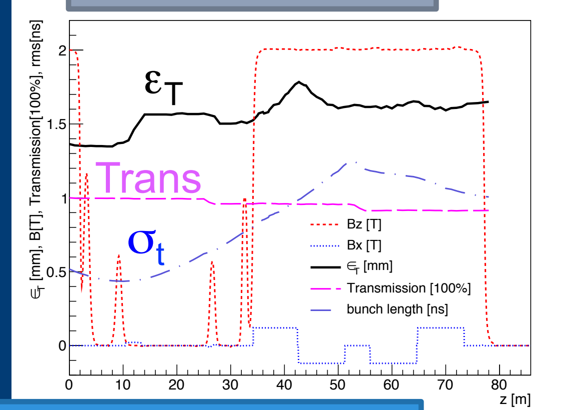
- MAP Baseline Designs offer
  - Factor >10^5 in emittance reduction
- Alternative and Advanced Concepts
  - Hybrid Rectilinear Channel (gas-filled structures)
  - Parametric Ionization Cooling
  - Alternative Final Cooling
    - ⇨ Early stages of existing scheme
    - ⇨ Round-to-flat Beam Transform
    - ⇨ Transverse Bunch Slicing
    - ⇨ Longitudinal Coalescing (at ~10s of GeV)

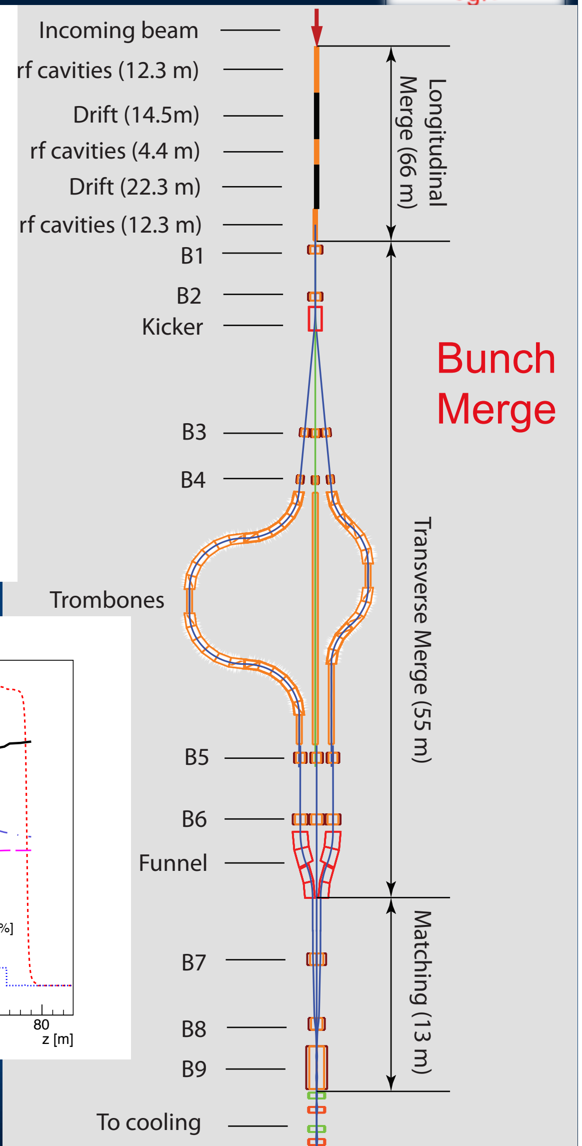
⇨ *Considerable promise to exceed our original target parameters*

Longitudinal Merge



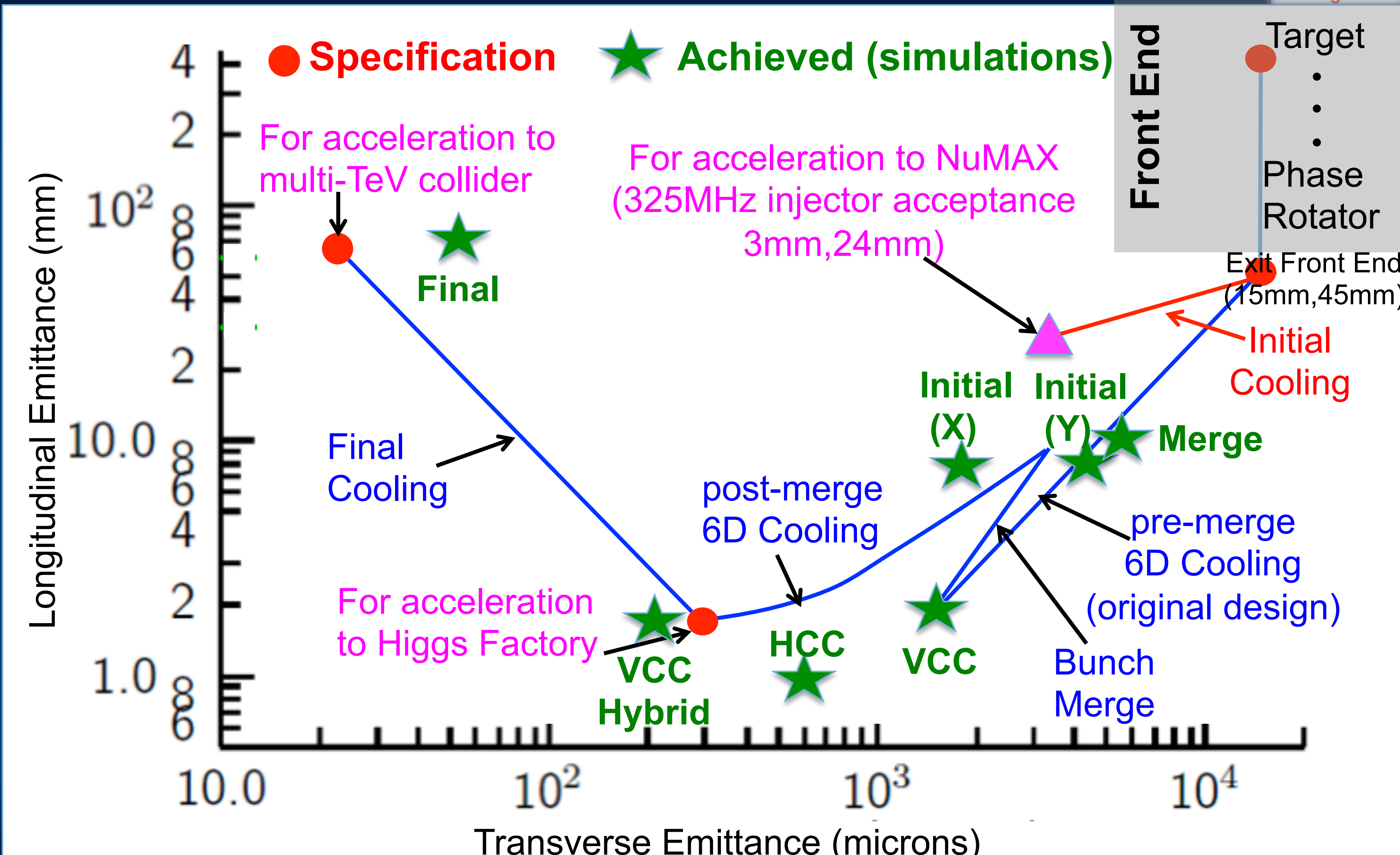
Transverse Merge





MASS identified extension of the 6D cooling concepts and modification of Final Cooling scheme to be one of most likely areas of performance improvement

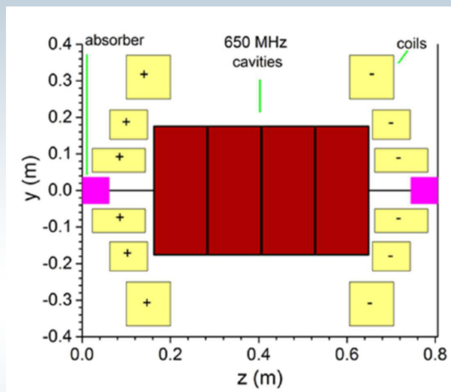
Cooling: The Emittance Path

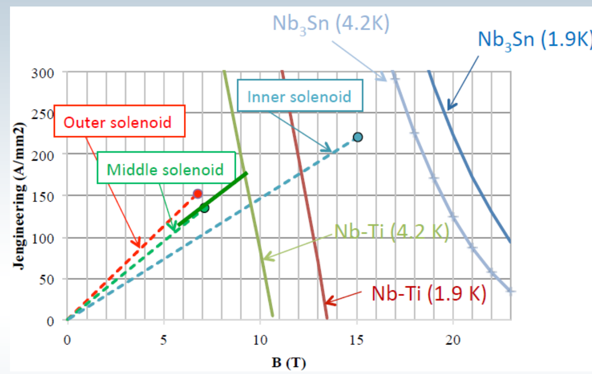


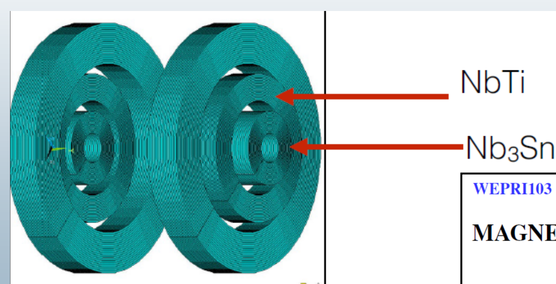
Cooling Technology Status I

- Magnets
  - MAP Initial Baseline Selection (IBS) process
    ⇨ 6D cooling baselines that do ***not*** require HTS magnets
  - HTS Solenoids could be part of a higher performance 6D Cooling Channel and for parts of the Final Cooling Channel

Magnet feasibility studies (last stage)







	% of the load line at operational current		
	Inner solenoid	Middle solenoid	Outer solenoid
Nb-Ti @ 4.2 K	-	76%	74%
Nb-Ti @ 1.9 K	-	59%	58%
Nb3Sn @ 4.2 K	88%	-	-
Nb3Sn @ 1.9 K	81%	-	-

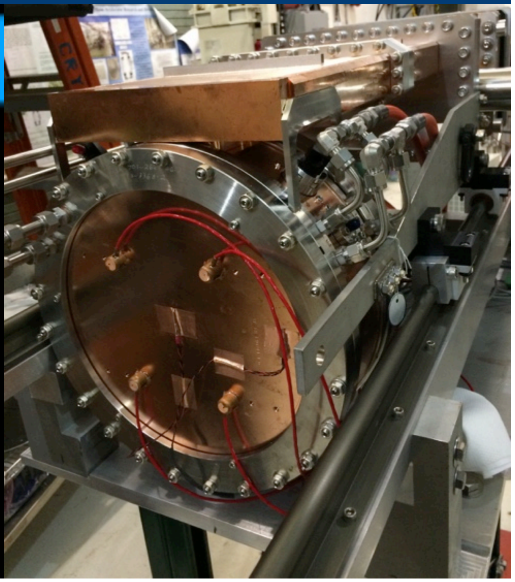
WEPRI103 Proceedings of IPAC2014, Dresden, Germany

MAGNET DESIGN FOR A SIX-DIMENSIONAL RECTILINEAR COOLING CHANNEL - FEASIBILITY STUDY*

H. Witte†, D. Stratakis, J. S. Berg, R. B. Palmer, Brookhaven National Laboratory, Upton, NY, USA
F. Borgnolutti, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Cooling Technology Status II

- RF Cavities
  - *Successful test in magnetic field* of the MICE RF Module shows
    - The importance of cavity surface preparation
    - The importance of designs incorporating detailed magnetic simulation
  - High Pressure Gas-Filled RF Cavities provide a *demonstrated route to the required gradients with high intensity beams*
  - Vacuum RF: recent B-field tests consistent with our physical models
    - **805 MHz "Modular" Cavity:** *A test vehicle to characterize breakdown effects in vacuum cavities*



FINAL COOLING CONCEPTS

Acknowledgments in Advance

- Following work carried out primarily by:
  - Baseline concept (high field/low energy channel):
    - H. Sayed, R. Palmer, S. Berg, D. Neuffer
  - Alternative concepts
    - D. Neuffer, D. Summers, T. Hart, J.G. Acosta
  - Through the years, many other MAP members have weighed in on the final cooling issue. Sorry that I can't name them all…
- Special thanks to H. Sayed, D. Neuffer and D. Summers who provided materials for this talk
- Any mistakes in the following slides rest with me

Final Cooling Emittance Targets

- For initial design studies, start with
  6D Cooling Target:

  $\varepsilon_T = 300\ \mu m$
  $\varepsilon_L = 1.5\ mm$

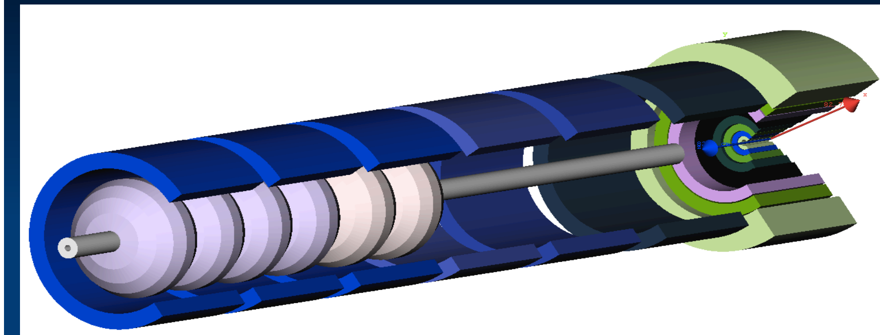
- *IBS effort would have followed with actual 6D system outputs for end-to-end simulation of performance*

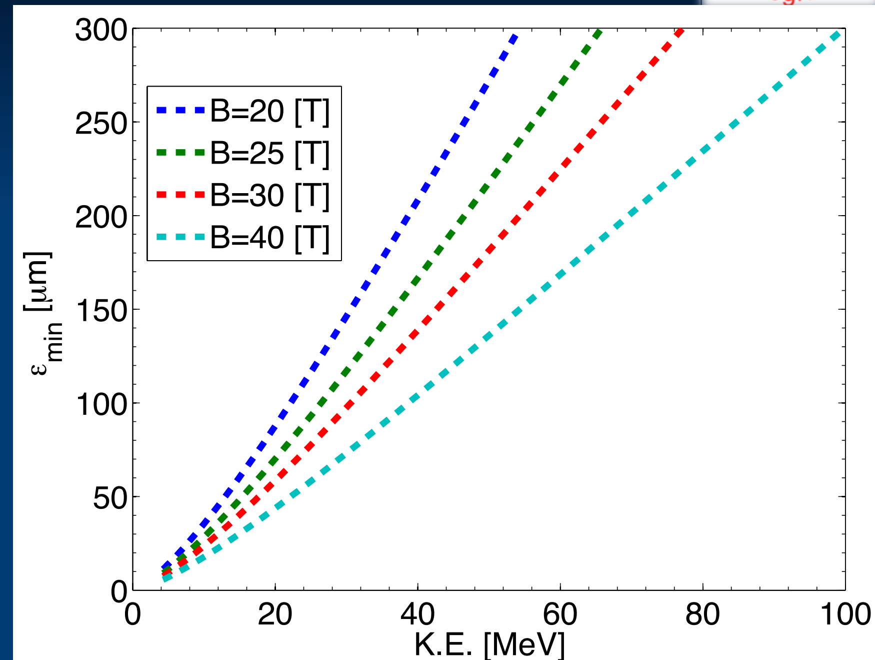
- Target values for Final Cooling based on required transverse emittances to provide lumi ~$10^{34}\ cm^{-2}s^{-1}$ at
  1 TeV:

  $\varepsilon_T = 25\ \mu m$
  $\varepsilon_L = 72\ mm$

- MAP Preliminary Baseline Concept is emittance exchange in a high field/ low energy channel

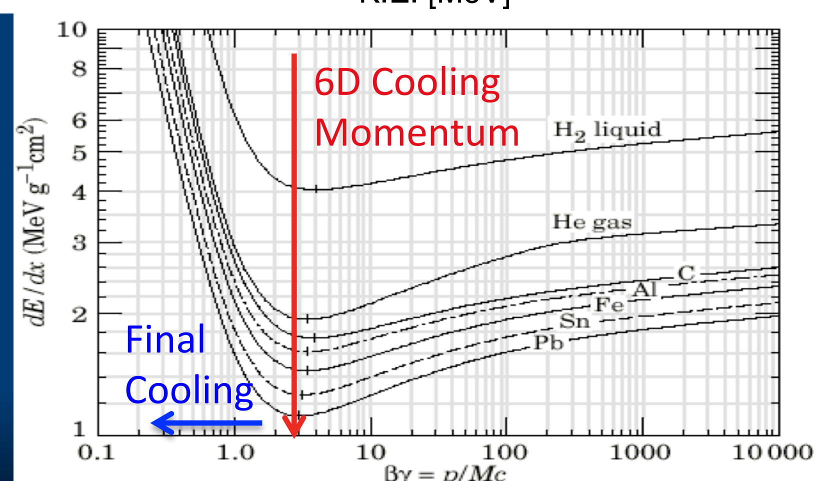
High Field/Low Energy Cooling





- Minimum emittance achievable in a long solenoid field cooling channel

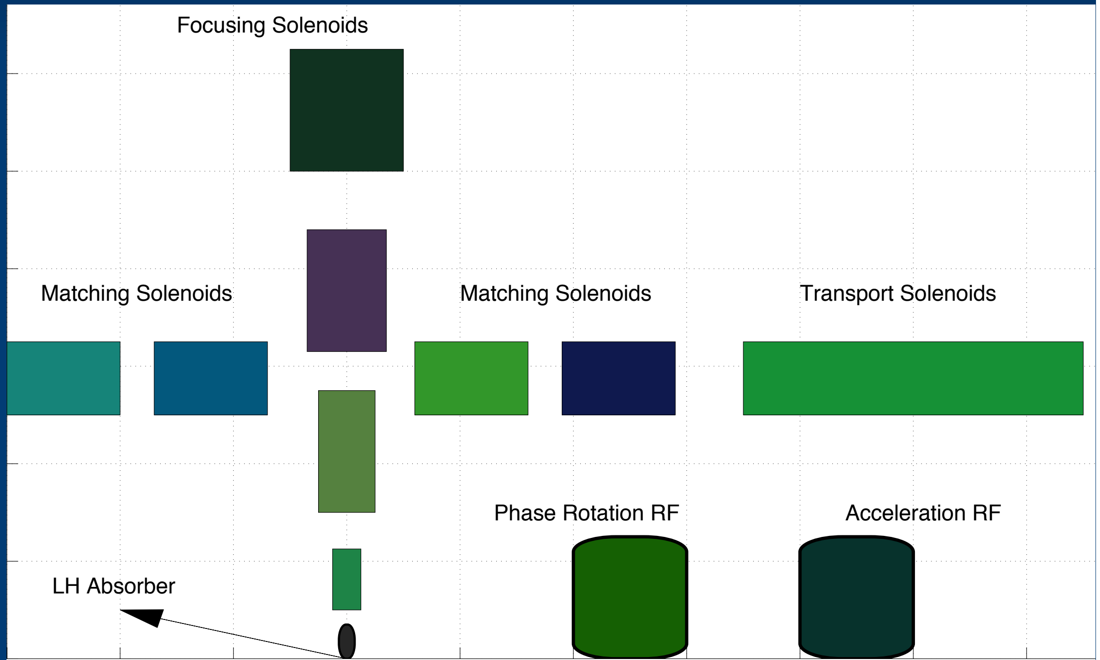
$$\epsilon_{\perp}(min) \propto \frac{E}{BL_R(dE/ds)}$$



- High Field – Low Energy Cooling Channel Challenges
  – Requires long absorbers (to reduce cost)
  – Large energy spread from long absorbers and running on the negative slope of dE/ds curve
    - Longitudinal and transverse matching
    - Losses due to low energy tail

High Field Cooling Channel Design

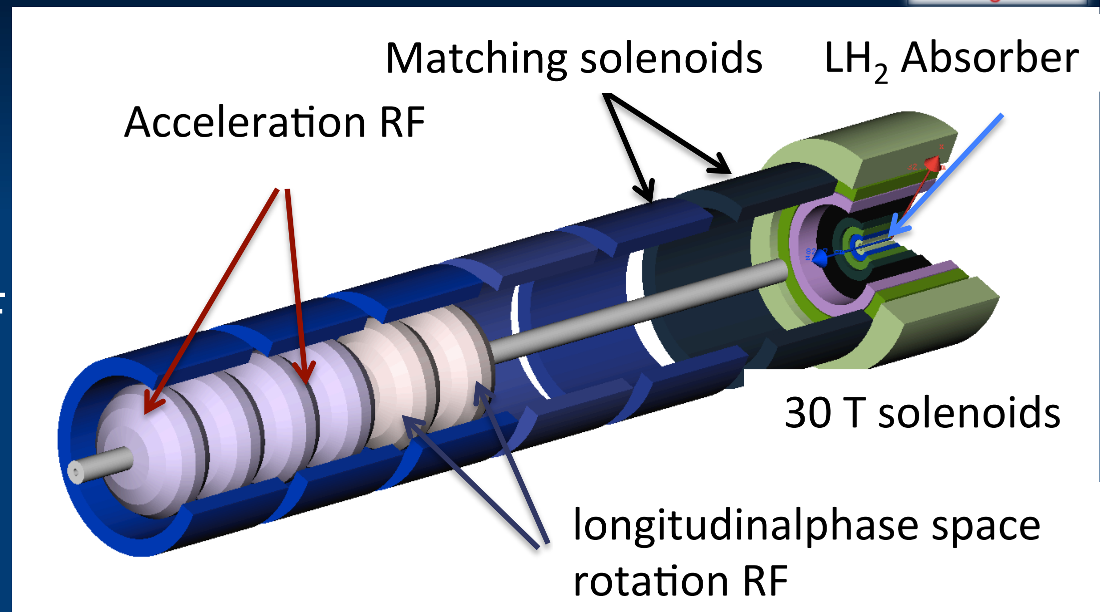
- MAP IBS baseline candidate
- Lattice
  - 16 Stages with:
    - High field solenoid magnet (25-30 T)
    - 3.5 T transport solenoid field through the channel
    - Asymmetric transverse match into and out of the high field solenoids
    - Energy phase rotation to maintain low energy spread
      - Increases bunch length
      - Reduce the RF frequencies gradually
    - Accelerating RF cavities



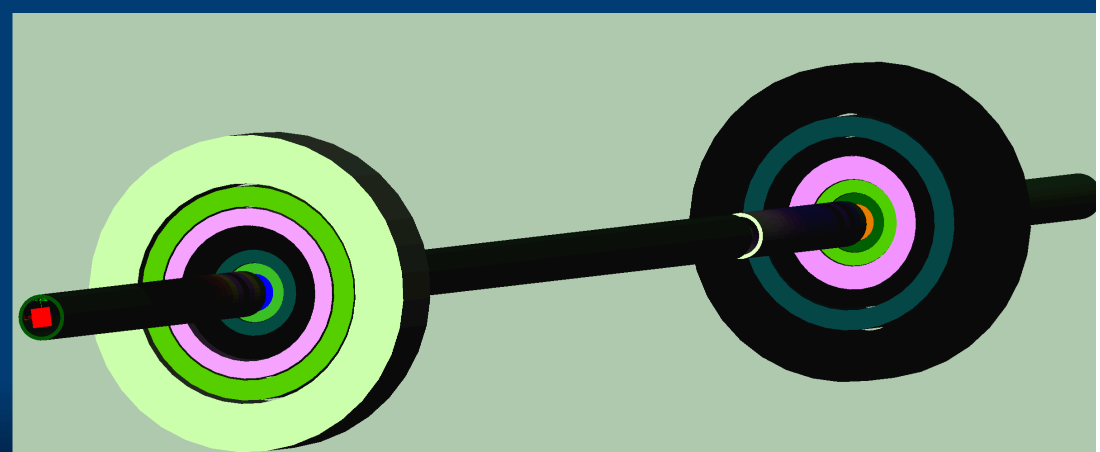
Asymmetric transverse match especially in early stages with long absorbers

High Field Cooling Channel Design

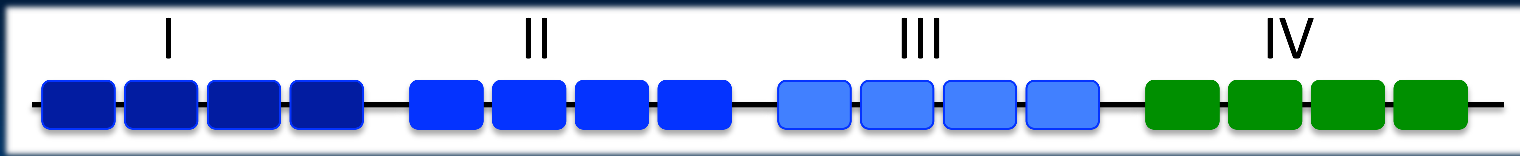
- Lattice Features
  - Early Stages
    - Short bunches ⇔ Relatively high frequency 325 MHz RF
    - RF located inside transport solenoids



  - Late Stages
    - Long bunches ⇔ Relatively high frequency 20 MHz RF
    - Transport solenoid inside of induction linac

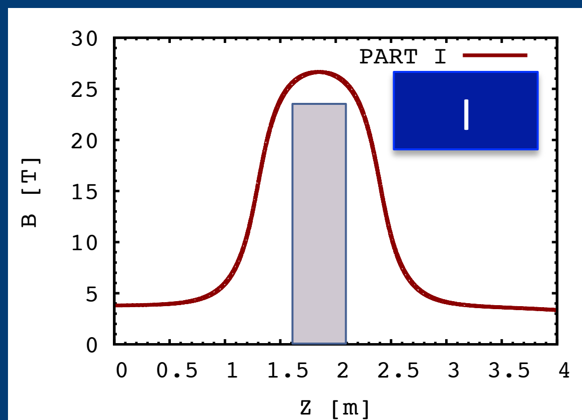


High Field Cooling

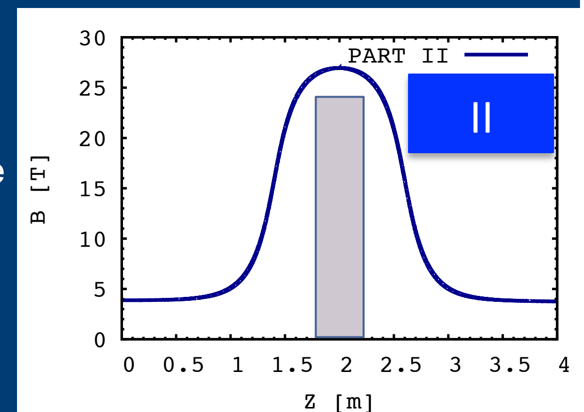


- Long absorbers: 65 ⇨ 59 cm
- Limit field integral to limit transverse-longitudinal coupling

⇨ Increase in σ_t

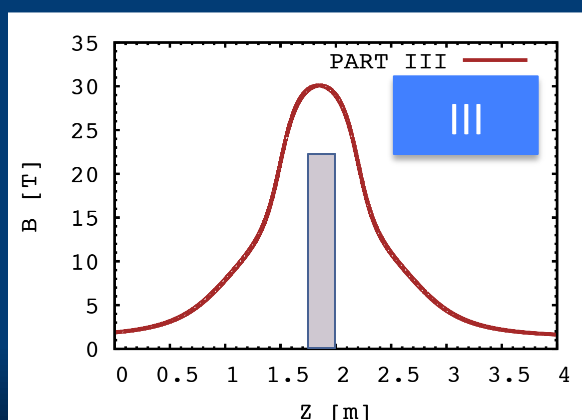


- Long absorbers: 57 ⇨ 40 cm
- Lower transverse amplitudes
- Lengthened bunch

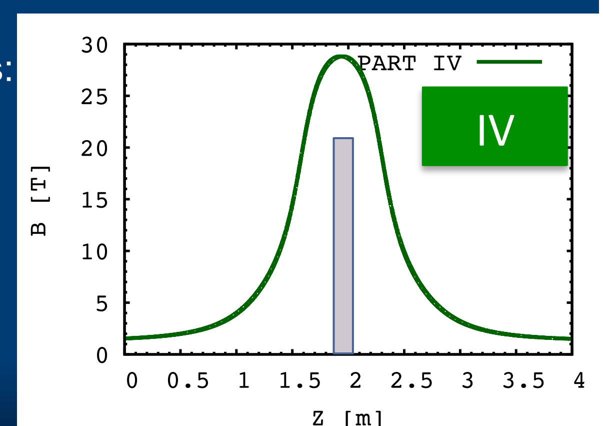


- Medium absorbers: 35 ⇨ 20 cm
- Increased energy spread

  ⇨ unwanted chromatic effects

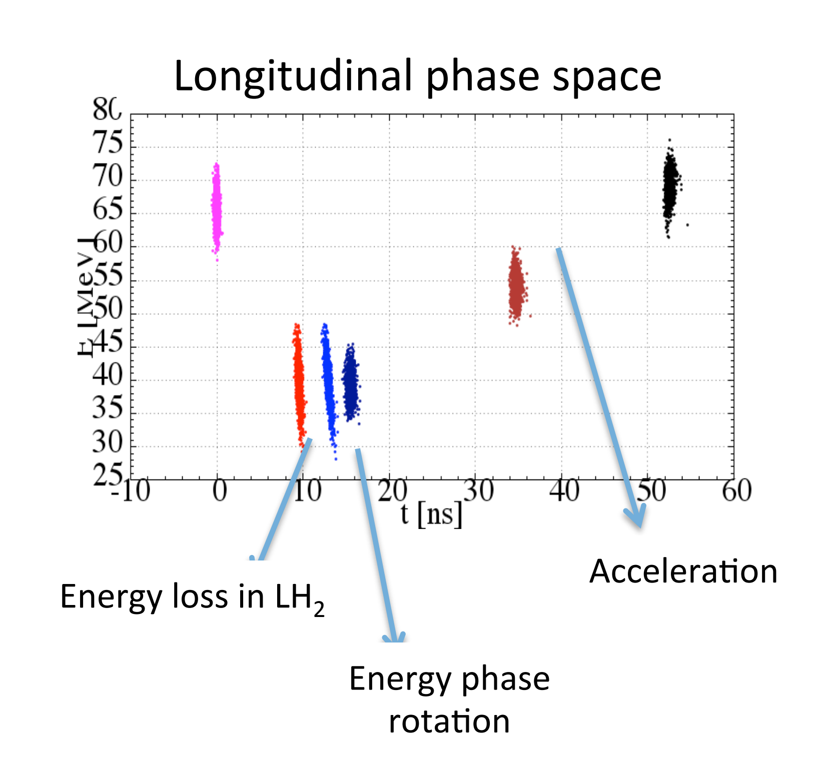


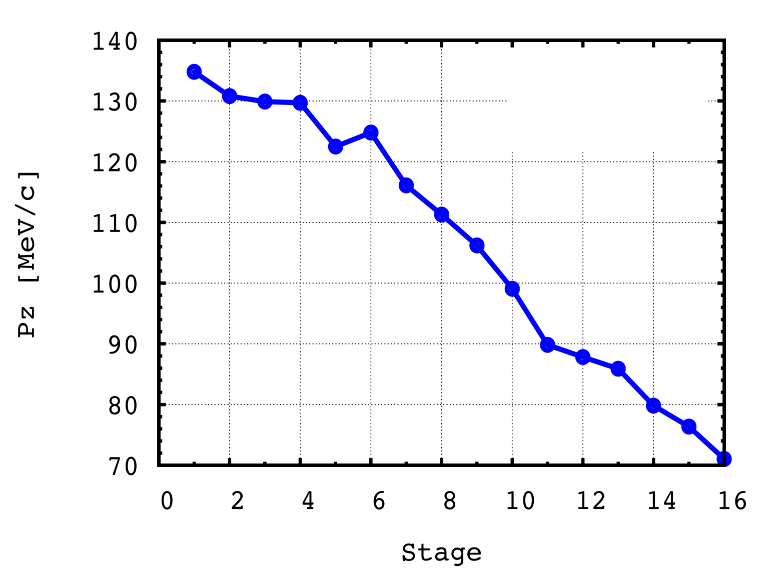
- Short absorbers: 20 ⇨ 10 cm
- Very small transverse amplitudes

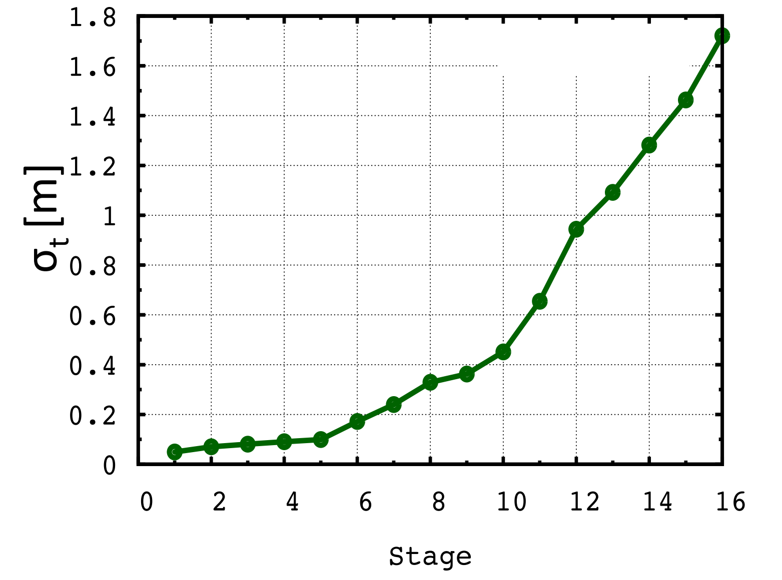


Beam Energy, Bunch Length & Longitudinal Phase Space

- Control of energy spread & bunch length
  - Energy spread increases inside LH2 absorbers
  - Energy phase rotation to decrease energy spread on the expense of the bunch length
  - Optimization of drift length for time-energy correlations which gives the required energy spread for the following stage



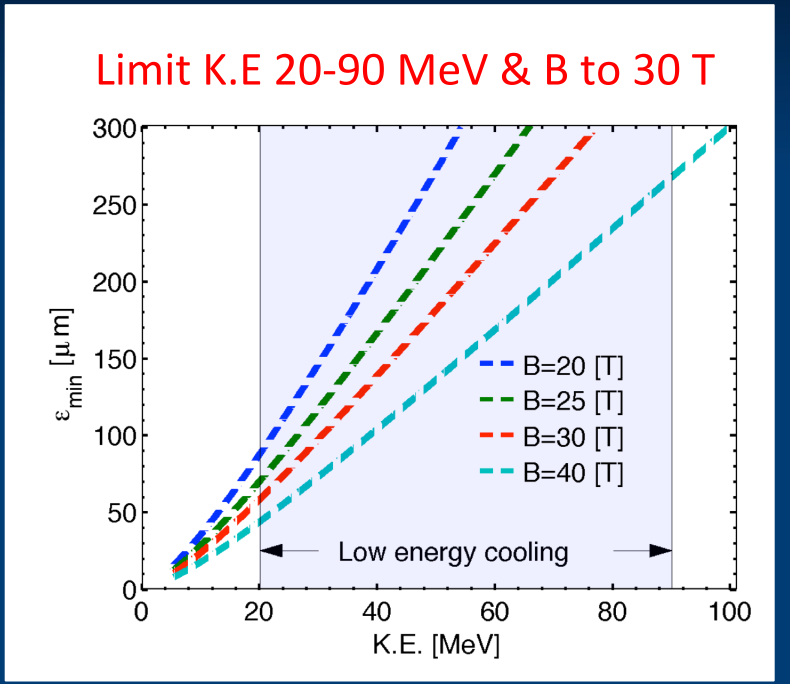


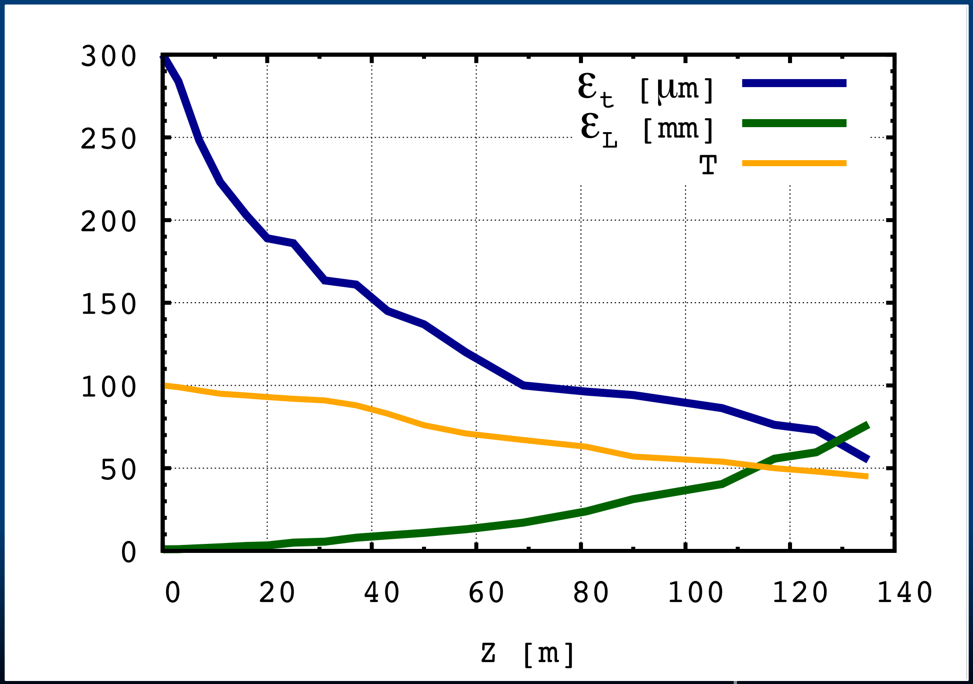


End-to-End Simulation of 25-30 T Channel

- G4BEAMLINE simulation:
  - Magnetic fields computed in G4BEAMLINE with realistic coil configuration and current settings
  - RF cavities modeled as cylindrical pillboxes
  - Initial Gaussian beam with:

    ε_T = 300 μm-rad, ε_L = 1.5 mm,
    P = 135.0 MeV/c





First end-to-end study of high field - low energy cooling concept with realistic (engineering) design constraints

Achieves 55 μm transverse emittance 2.2x larger than target, but system can be engineered

Comments

- The preceding represents a realizable design
  - Essentially at the half-way point in the IBS process
  - However, have not yet achieved the desired performance for a high energy collider (by factor of 2.2)
    - Could be accomplished by using higher field magnets in design (a technology risk running counter to the MAP Feasibility Assessment guidelines)
- However, a set of alternative/hybrid options under consideration as well
  - Have significant potential to meet or exceed the collider requirements
  - Estimate ~1 man-year of effort required to carry out initial evaluations and design work
  - Not (yet) well-investigated due to premature termination of MAP Feasibility Study

Alternate (including Hybrid) Options

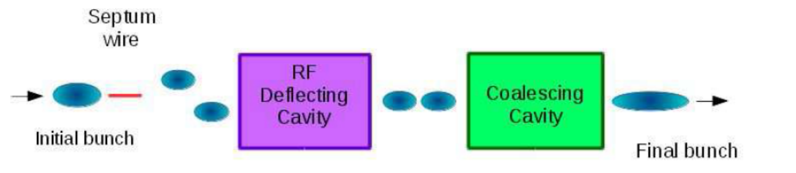
- Key issue:
  - The dominant effect in the final cooling channel is simple emittance exchange
- What other ways are there to provide that?
  - Transverse slicing of bunches with longitudinal recombination
    - Possibly utilizing a round-to-flat beam transform
  - Thick wedge absorbers
- Design choices may feed back into how the 6D cooling chain is structured

Alternate Approach I

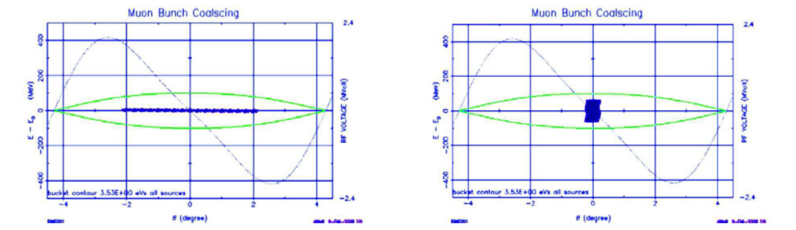
- Summers/Hart
  1. 6D Cooling without spin flips (to increase beam angular momentum)
     - $\varepsilon_{x,y}$ (ε_t) → ~10^{-4} m, ε_L → ~0.004 m
  2. Round to flat beam transformation (demonstrated for e- sources)
     - ε_t → ε_x =0.0004; ε_y =0.000025m
  3. Transverse bunch slicing (in x as shown) with extraction septum
     - ε_x =0.000025; ε_y =0.000025
  4. High energy bunch recombination (snap coalescence based on FNAL pbar coalescence scheme)
     - ε_x =0.000025; ε_y =0.000025, ε_L=0.07m

Final Transverse to Longitudinal Emittance Exchange

- ϵ_{xyz}(0.0714, 0.141, 2.418) → (0.025, 0.025, 70) mm-rad



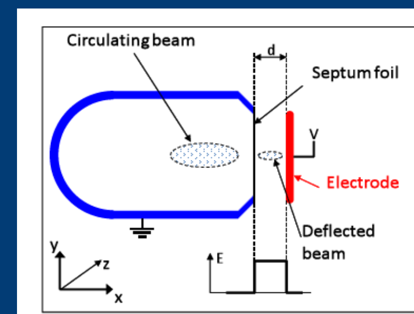
- Slice the bunch into 17 parts with septa (2 parts in cartoon).
- Form 3.7 m long bunch train with CLIC RF deflector cavities.
- Snap bunch coalesce muons into 1 bunch with RF in a ring. Packing fraction approaches 87%. See arXiv:1505.01832



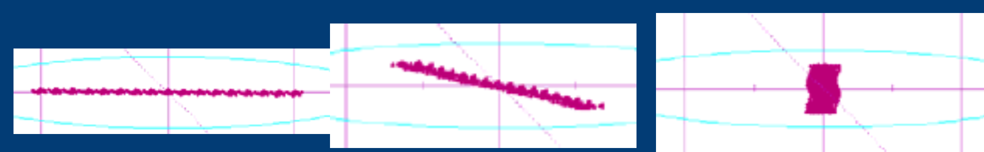
Alternate Approach II

- Neuffer – “Skip the round to flat transform…”

1. Cool bunch to $\varepsilon_T \sim 10^{-4}$ m (solenoid or quads or Li lens) with $\varepsilon_L \sim 3\times10^{-3}$ m



2. Transverse slice to 10 bunches:
   - 10^{-4} m (ε_x) × 10^{-5} m (ε_y)
   - Separated longitudinally
3. Accelerate as bunch train; recombine longitudinally
   - 10^{-4} m (ε_x) × 10^{-5} m (ε_y)
   - $\varepsilon_L \sim 3\times10^{-2}$ m

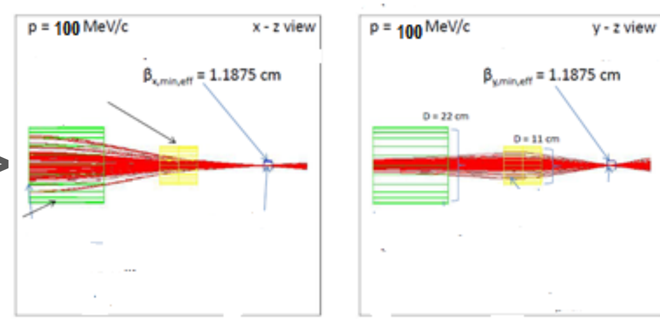


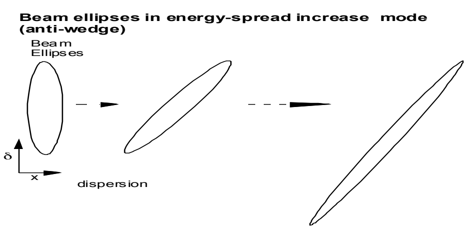
- Collide as flat beams;
  - luminosity ~ same as ε_t= ~3×10^{-5} m

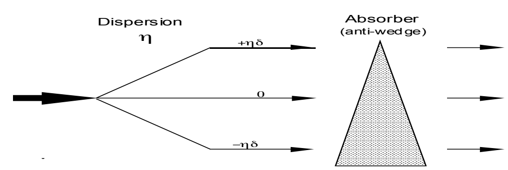
Alternate Approach III

Variant: "thick" wedge transform

- **Use wedge to increase δp/p**
  - increase ε_L, **decrease ε_x**
- **If δp/p introduced by wedge >> δp/p_{beam};**
  - **can get large emittance exchange**
    - exchanges x with δp (Mucool 003)
      - also in CERN 99-13, p.30
- **Example:**
  - 100 MeV/c; δp=0.5MeV/c
    - $\varepsilon_\perp = 10^{-4}$m, β_0=1.2cm
    - Be wedge 0.6cm, 140° wedge
  - **obtain factor of ~5 exchange**
  - **$\varepsilon_x \rightarrow 0.2 \times 10^{-4}$m; δp=2.5 MeV/c**
- **Much simpler than equivalent final cooling section**



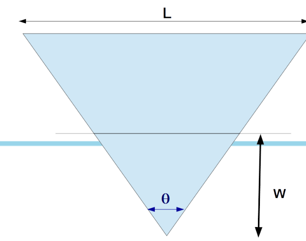




$$\varepsilon_1 = \varepsilon_0 \left[(1-\eta_0\delta')^2 + \frac{\delta'^2\sigma^2}{\delta_0^{\,2}} \right]^{-1/2}$$

Example Wedge Parameters

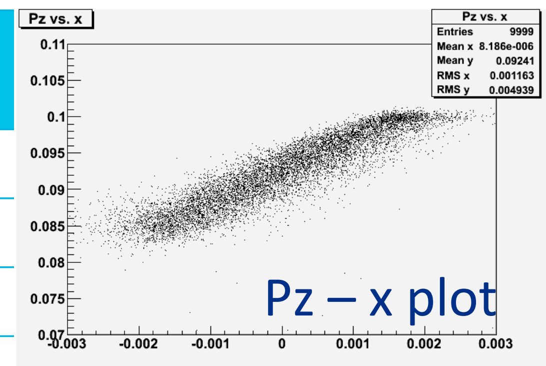
Numerical examples



Dave Neuffer

- **Wedge parameters**
  - **Diamond, w=1.75mm, θ = 100°(4.17mm thick at center)**

z(cm)	P_z	ε_x(μ)	ε_y	ε_L(mm	σ_E MeV	6-D ε increase
0	100	97	95.5	1.27	0.46	1.0
0.4	96.4	33.4	96.3	4.55	1.64	1.24
0.8	92.4	**22.7**	96.5	8.94	3.22	1.65



  - **reduces ε_x by factor of 4.3, ε_L increases by factor of 7.0**
    - **first half of wedge more efficient than second half …**
- **Second wedge ?**
  - **if matched to same optics (P_z → 100 MeV/c, σ_E→0.46 MeV)**
    - ε_x : 23 →27μ; ε_y :97 → 23 μ

Example Hybrid Scenario

1. Employ first ~5-6 segments of baseline final cooling system
   - ε_x = 0.13 mm ε_y = 0.13 mm ε_L =3 mm
   - stretch beam to $\sigma_{ct} \rightarrow$ 0.6m, δE=0.5MeV
2. Wedge Exchange 1
   - $\varepsilon_x \rightarrow$ 0.03 mm ε_y = 0.13 mm ε_L =15 mm
   - stretch beam to $\sigma_{ct} \rightarrow$ 3m, δE=0.5MeV
3. Wedge Exchange 2
   - $\varepsilon_x \rightarrow$ 0.03 mm $\varepsilon_y \rightarrow$ 0.03 mm ε_L =75 mm
4. Reaccelerate and combine bunches at high energy (~10 GeV)

Alternates Summary

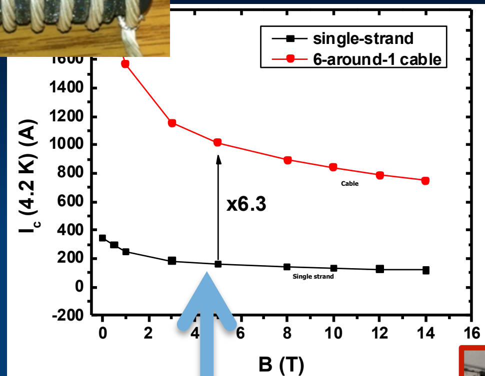
- All of the alternative options need detailed design and simulation
  - Validate parameters
  - Ensure designs can meet basic engineering parameter to be realizable
- Significant potential exists to meet (or exceed) target cooling parameters required for a high energy collider

Conclusion

- First detailed study of the Final Cooling Channel satisfying the MAP IBS specifications now complete
  - Even with the inclusion of technology constraints (feasibility assessment criteria), the baseline is within a factor of 2.2. of the target parameters
- Other options exist, which would have been targeted for full exploration as part of the MAP IBS process
  - MAP funding ramp-down may slow progress on these concepts, but the basic issues are defined so that work can be continued when funding is available
- Overall, the probability that a final design is able to reach the target cooling parameters appears very high

BACKUP SLIDES

Cooling Technology R&D

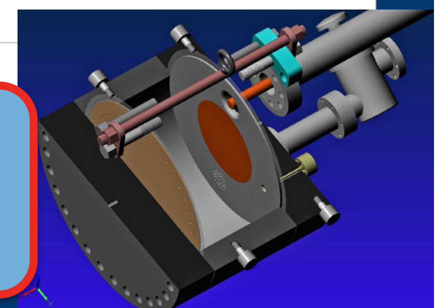


Breakthrough in HTS Cable Performance with Cables Matching Strand Performance

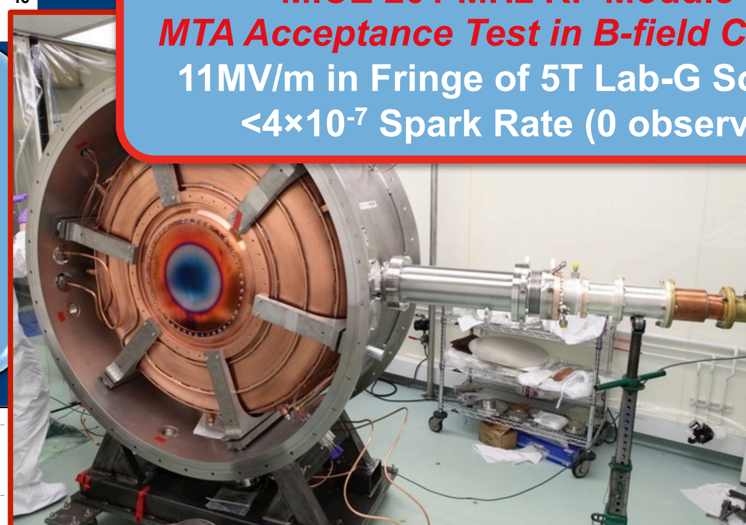
FNAL-Tech Div
T. Shen-Early Career Award

Successful Operation of 805 MHz "All Seasons" Cavity in 5T Magnetic Field under Vacuum

MuCool Test Area/Muons Inc

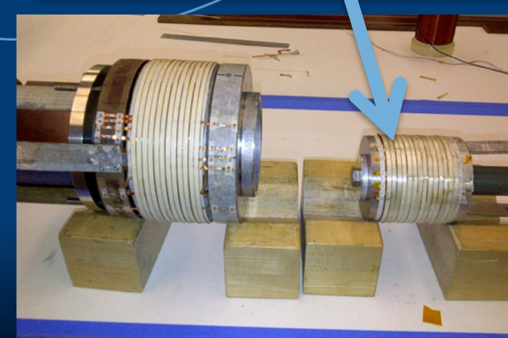


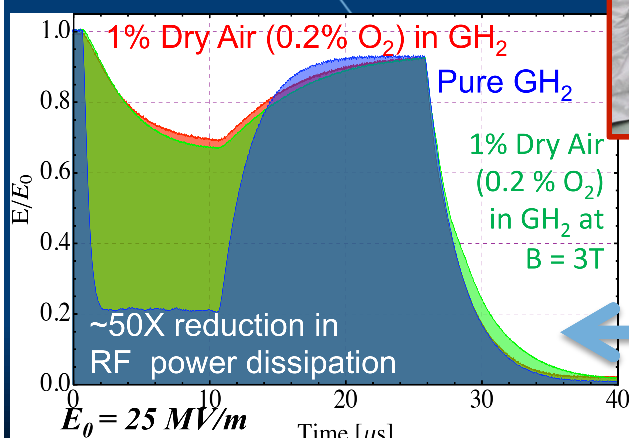
MICE 201 MHz RF Module –
MTA Acceptance Test in B-field Complete
11MV/m in Fringe of 5T Lab-G Solenoid
$<4\times10^{-7}$ Spark Rate (0 observed)



World Record HTS-only Coil
15T on-axis field (16T on coil)

R. Gupta
PBL/BNL





Demonstration of High Pressure RF Cavity <u>in 3T Magnetic Field with Beam</u>

Extrapolates to required
μ-Collider Parameters

MuCool Test Area