Magnet Requirements for Cooling

Science & Technology Facilities Council
ISIS Neutron and Muon Source

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Magnets for Capture/Cooling

- Magnets important for cooling section
  - Beam is high emittance
    - Contain to prevent large beam sizes
    - “Simple” things like bends need to be done carefully
  - Cooling requires tight focussing to be effective
- Use solenoids and solenoids + dipoles

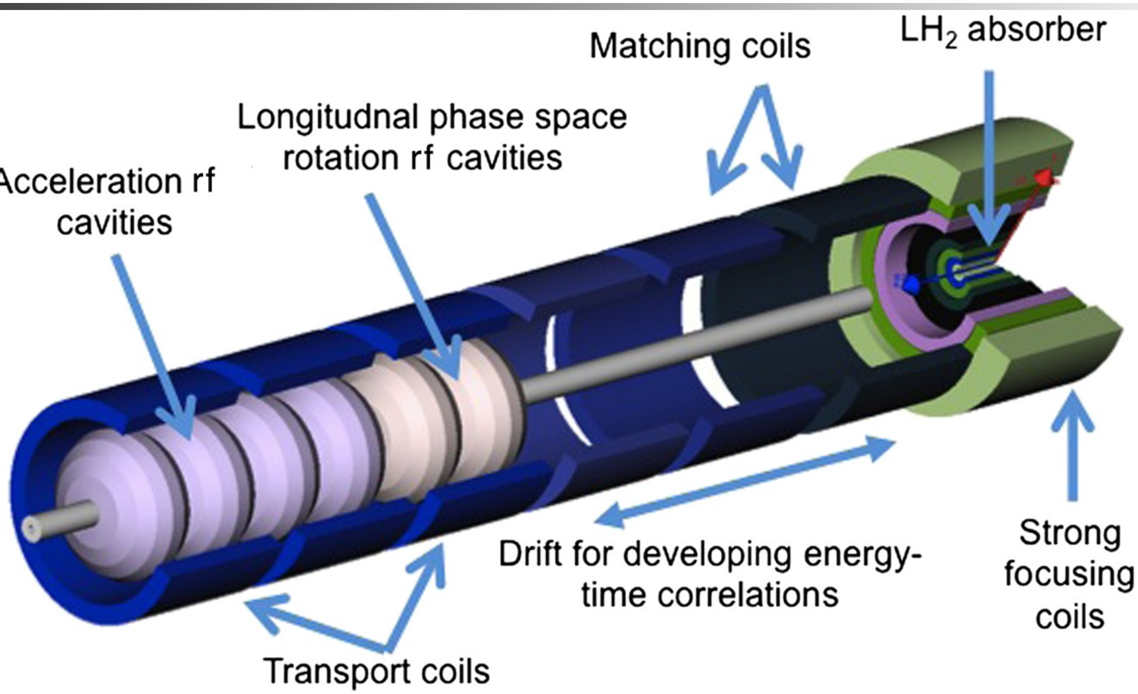
References

Subsection	Contact	Reference	Lattice Files
Capture			
Particle Selection	Scott Berg	Proc. IPAC2014 TUPME022	With Rogers – not run
Buncher	Dave Neuffer?	https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4355	With Rogers – not run
Phase Rotator	Dave Neuffer?	https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4355	With Rogers – not run
Initial Cooling			
HfoFo – gas filled		https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4377	With Rogers – run
HfoFo – vacuum		https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4377	?
Charge Separation			
Charge Separation	Cary Yoshikawa	https://www.osti.gov/biblio/1113648	?
6D Cooling			
Rectilinear	Diktys Stratakis	https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.031003	With Rogers – run
Helical snake	Katsuya Yonehara	https://iopscience.iop.org/article/10.1088/1748-0221/13/09/P09003	With Katsuya
Bunch Merge			
Phase Rotator and trombone	Yu Bao	https://journals.aps.org/prab/abstract/10.1103/PhysRevAccelBeams.19.031001	?
6D Cooling			
Rectilinear	Diktys Stratakis	https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.031003	With Rogers – run
Helical snake	Katsuya Yonehara	https://iopscience.iop.org/article/10.1088/1748-0221/13/09/P09003	With Katsuya
Final Cooling			
Linear Cooling	Hisham Sayed	https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.091001	?
PIC	James Maloney?	https://arxiv.org/pdf/1401.8256.pdf	?
Potato slicer	Don Summers?	https://map-docdb.fnal.gov/cgi-bin/ShowDocument?docid=4403	

Magnets for Capture/Cooling

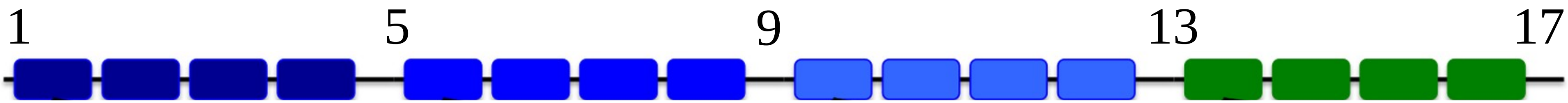
- Baseline:
  - Capture
  - HFoFo
  - Charge separation
  - Rectilinear Cooling
  - Bunch merge
  - Final Cooling
- Alternatives:
  - More rectilinear cooling
  - Helical cooling channel
  - Potato slicer
  - Parametric resonance Ionisation Cooling
- Start with final cooling and go backwards
  - High field, low(er) aperture is probably harder than low field, high aperture

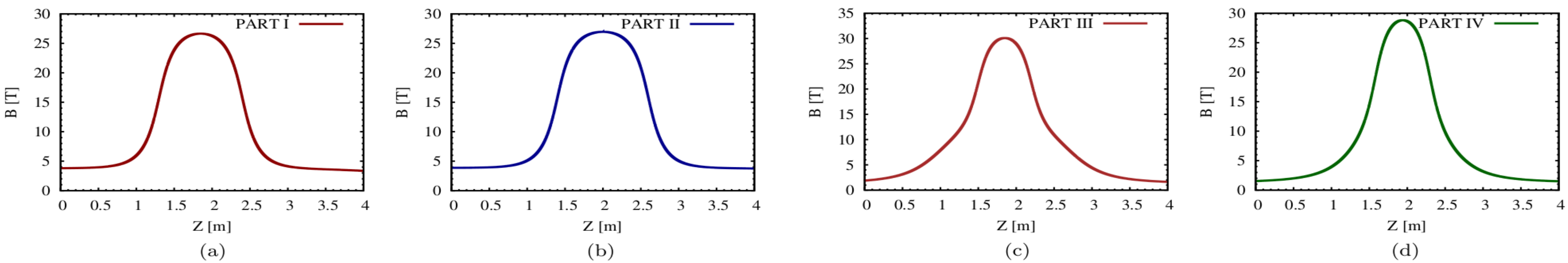
Final cooling



- Challenge is to get very tight focussing
- Go to higher fields and lower momenta
  - Causes longitudinal emittance growth
  - Chromatic aberrations introduce challenges
    - Elaborate phase rotation required to keep energy spread small
    - Move to low RF frequency to manage time spread

Final cooling





Stage	1	5	9	13	17
β [mm]	33	30	26	21	18
ε [mm]	0.3	0.2	0.15	0.11	0.06
p [MeV/c]	135	122	106	88	70
σ(x) [mm]	7.75	5.20	3.89	2.77	1.63
3σ(x) [mm]	23.24	15.59	11.66	8.32	4.89

- Note that constant field regions may require large aperture
  - RF cavities will be large (<100 MHz)

Example magnet design

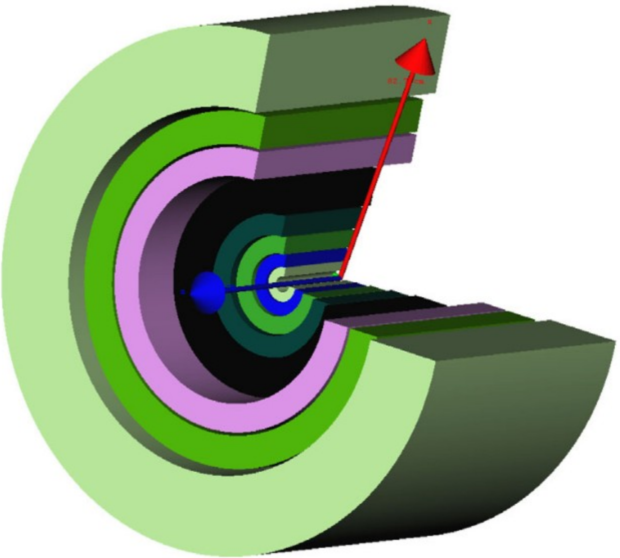
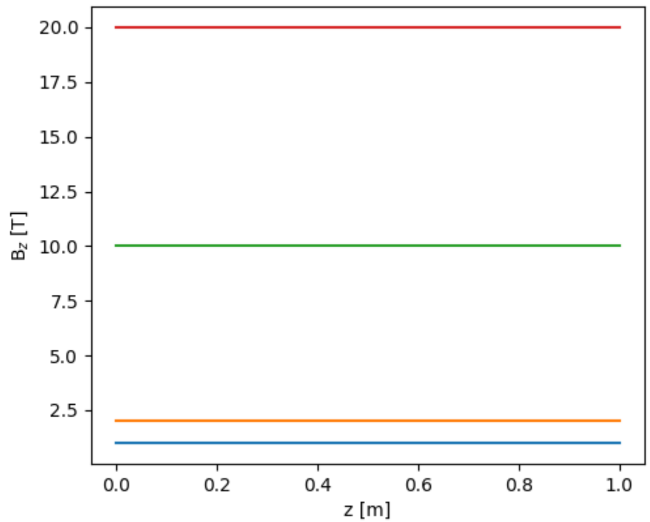
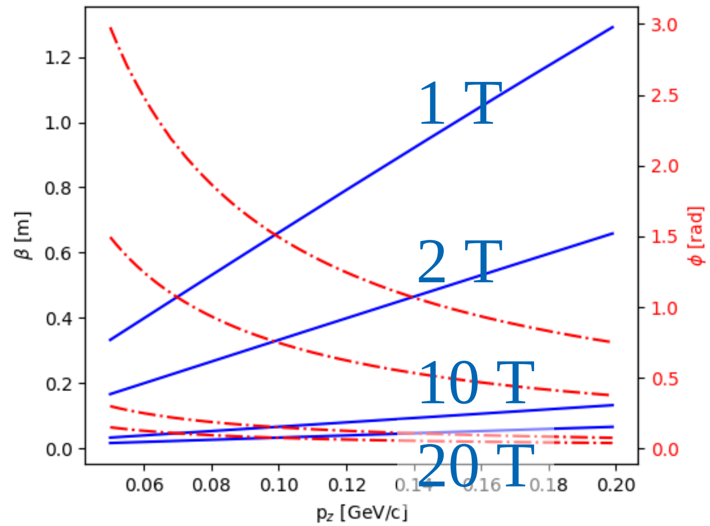


TABLE I. 50 T high-field magnet parameters.

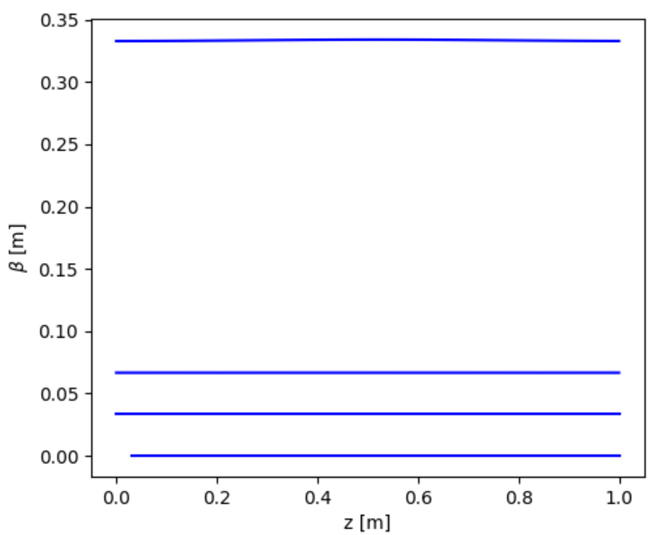
Magnet length [m]	Inner radius [m]	Coil thickness [m]	Current density I/A [A/mm^2]
0.317	0.025	0.029	164.26
0.337	0.055	0.041	142.43
0.375	0.098	0.056	125.88
0.433	0.157	0.067	119.07
0.503	0.228	0.120	85.99
0.869	0.355	0.089	39.60
0.868	0.454	0.104	44.30
0.992	0.575	0.252	38.60

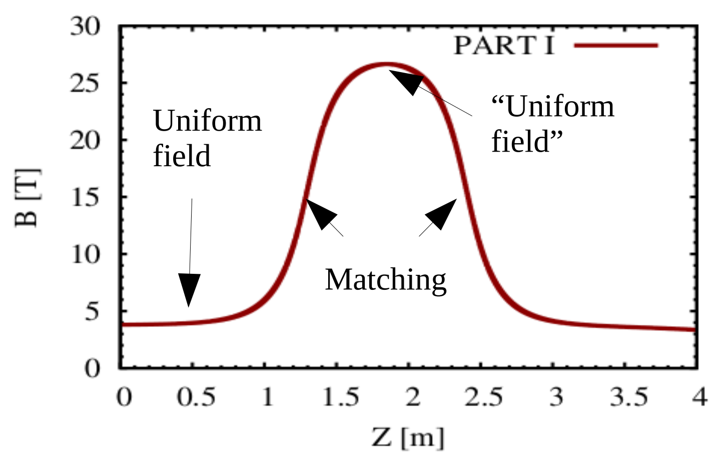
Why the high field?





$$\varepsilon_{min} \sim \beta \sim 1/B_z$$





(a)

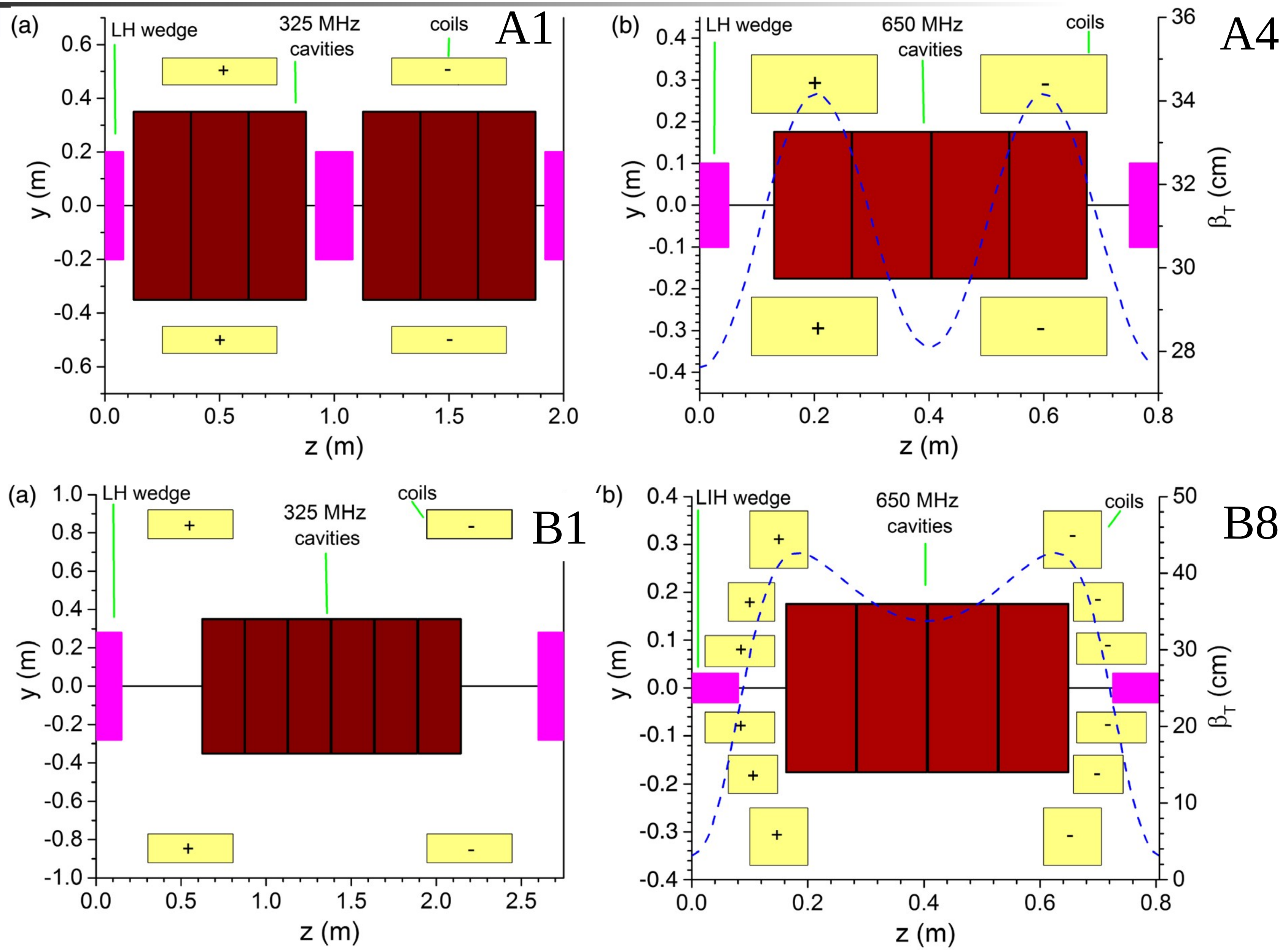
Rectilinear Cooling Channel

- Use strong solenoids to get tight focussing
- Weak dipole fields introduce dispersion for longitudinal cooling
  - Modelled by rotating solenoid perpendicular to field axis
  - Probably in reality want to use a separate dipole coil for tuning
- A1-A4 (before bunch merge) and B1-B4 (after merge)
  - Work in first stability region (phase advance $< \pi$)
- B5-B8 after bunch merge
  - Work in second stability region ($\pi <$ phase advance $< 2\pi$)
  - Fourier harmonics of $B_z(z)$ chosen for momentum acceptance

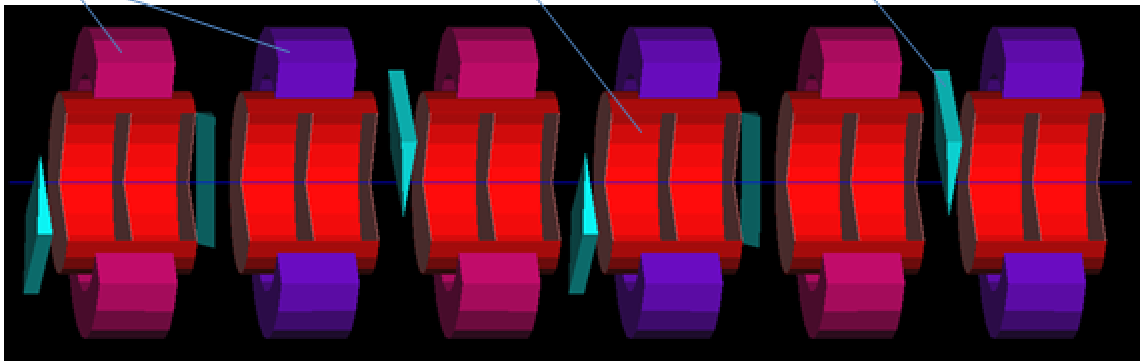
Rectilinear Cooling Channel

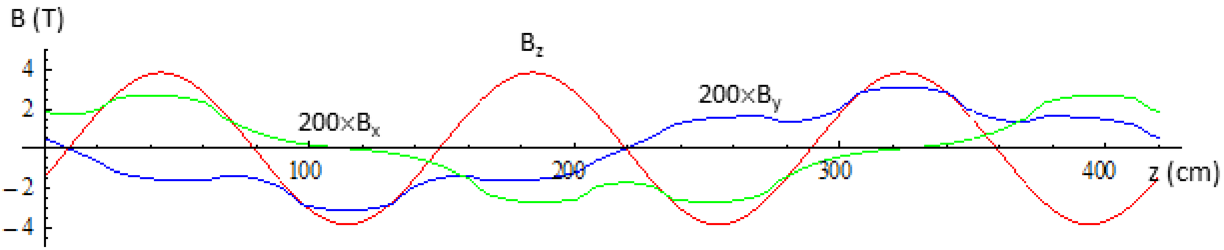
Beam

Beam



HFoFo





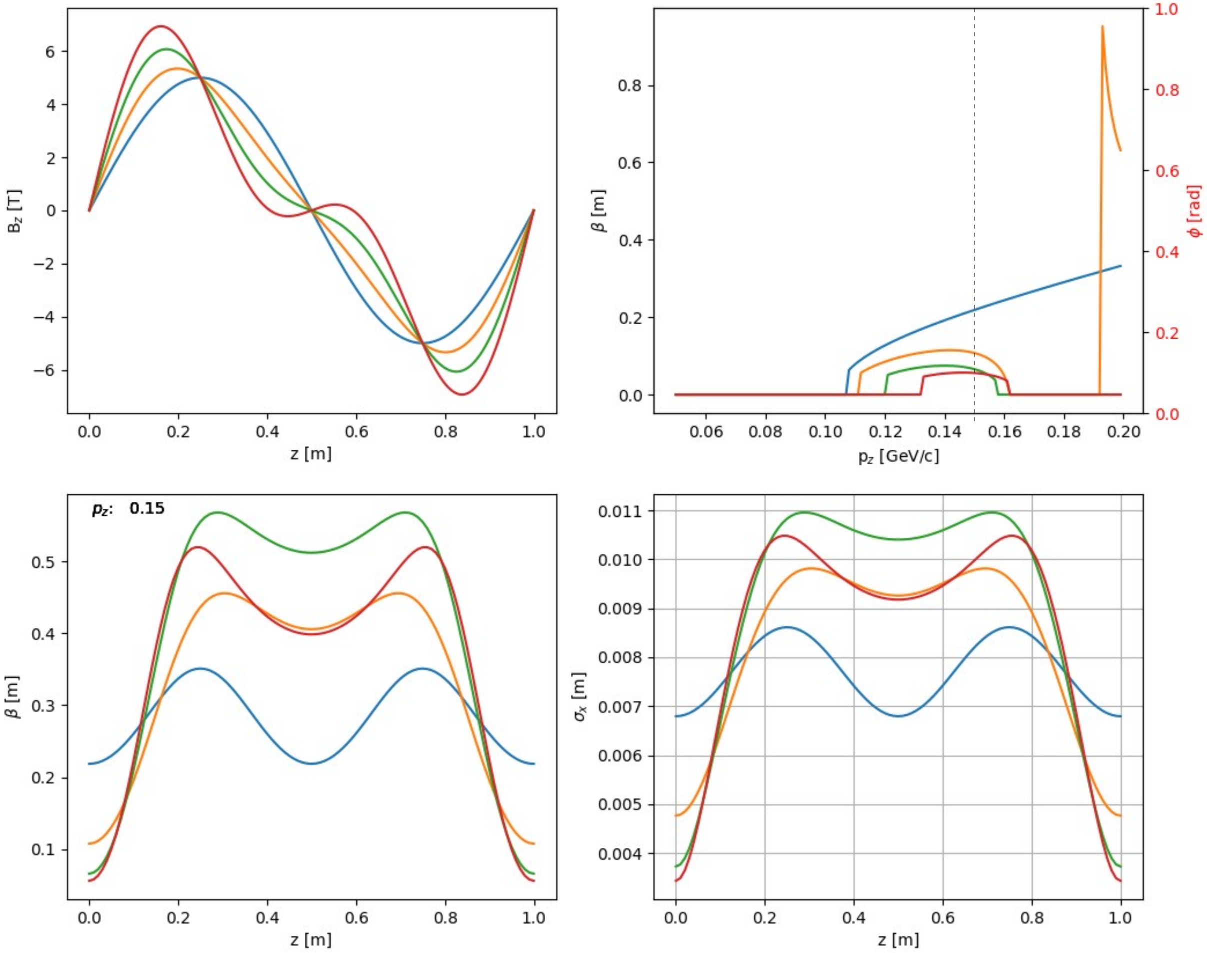
- HFoFo
  - First cooling cell
  - Similar to rectilinear cooling from magnet point of view

Rectilinear Cooling Channel

Stage	Beam pipe radius [mm]	Solenoid peak on-axis field [T]	Tilt angle [deg]	Dipole peak field [T]
HfoFo	400	4	0.22	0.02
A1	300	2.2	3.1	0.12
A2	250	3.4	1.8	0.11
A3	190	4.8	1.6	0.13
A4	132	6	0.7	0.07
B1	280	2.2	0.9	0.03
B2	240	3.4	1.3	0.08
B3	180	4.8	1.1	0.09
B4	140	6	1.1	0.12
B5	90	9.8	0.7	0.12
B6	72	10.5	0.7	0.13
B7	49	12.5	0.8	0.17
B8	45	13.6	0.6	0.14

Effect of harmonics

$$B_z = B_0 \sin(kz) + B_1 \sin(2kz)$$



Mixing different harmonics of B_z

Cooling:

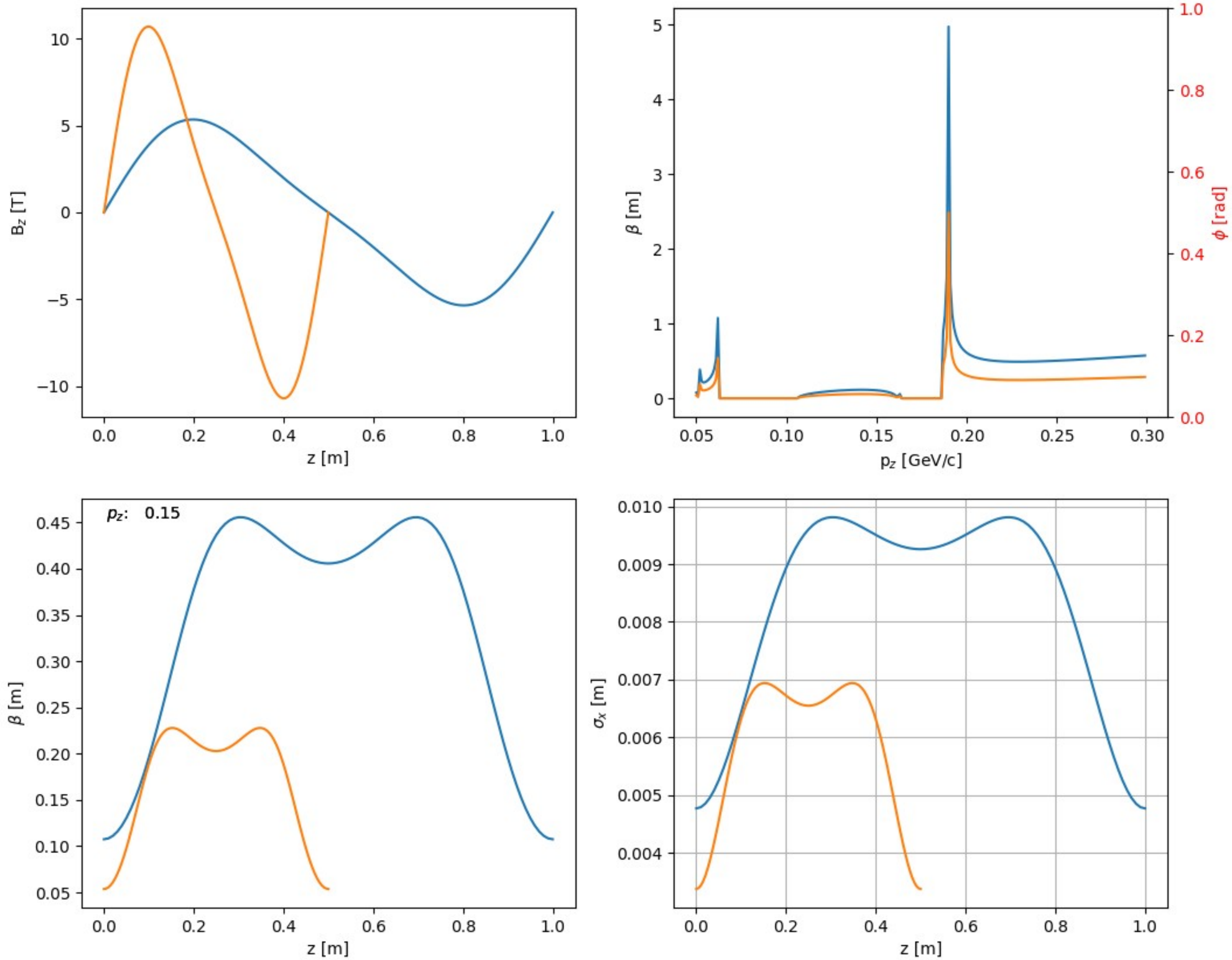
$\varepsilon_{min} \sim \beta_{min}$

Aperture:

$\varepsilon_{max} \sim \beta_{max}$

Scaling

$$B_z = B_0\sin(kz) + B_1\sin(2kz)$$



$B_0 \to 2B0$

$B_1 \to 2B1$

$k \to 2k$

Question: How short can we make the cells? How high field?

Rectilinear B8 magnet design

H. Witte et al, IPAC2014, WEPRI103

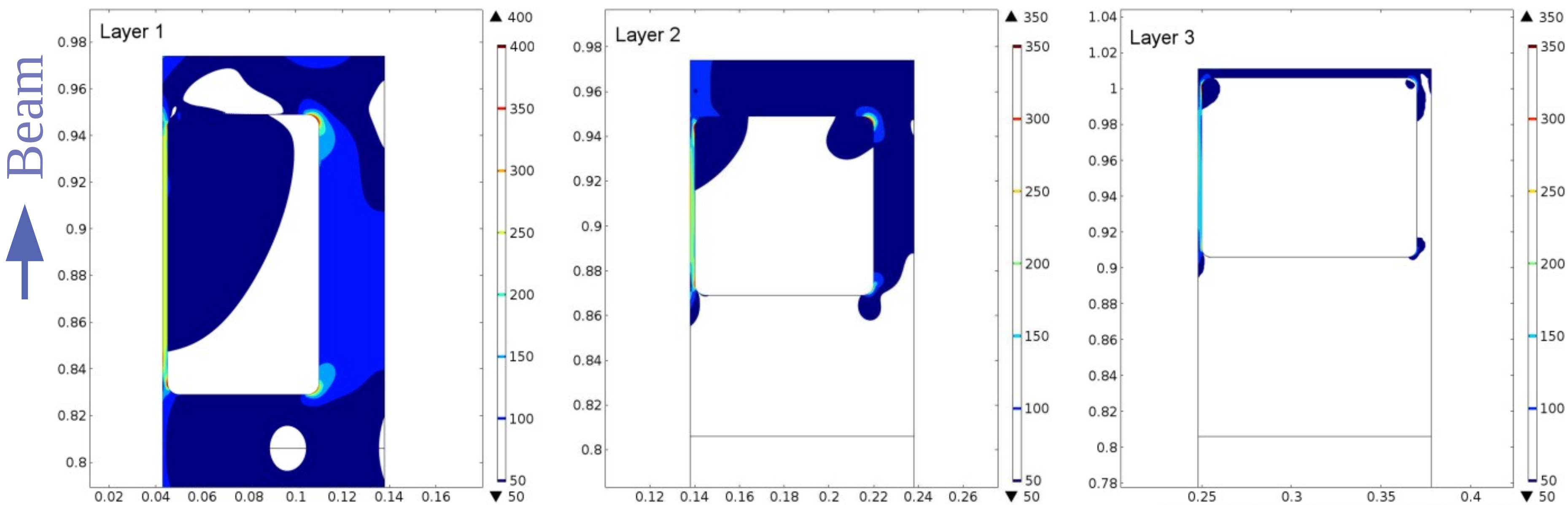
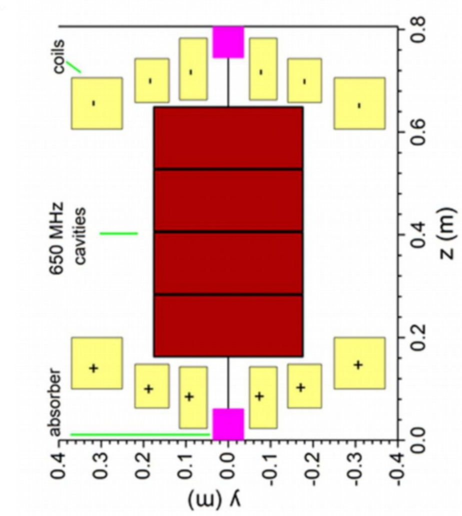


Figure 3: Von-Mises stress (in MPa, for σ > 50MPa

- Studied in COMSOL
- Dipole saddle coil added in magnet bore



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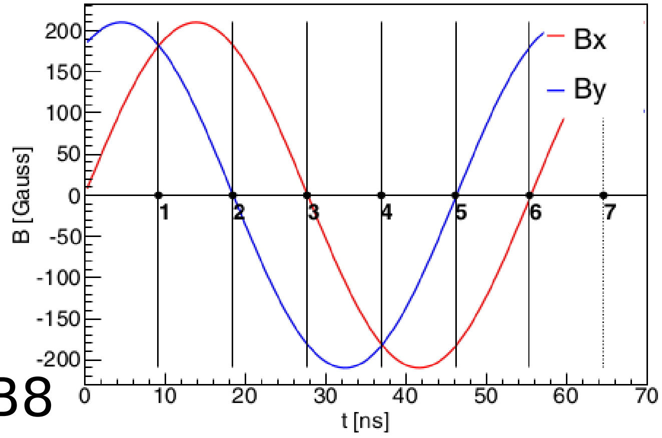
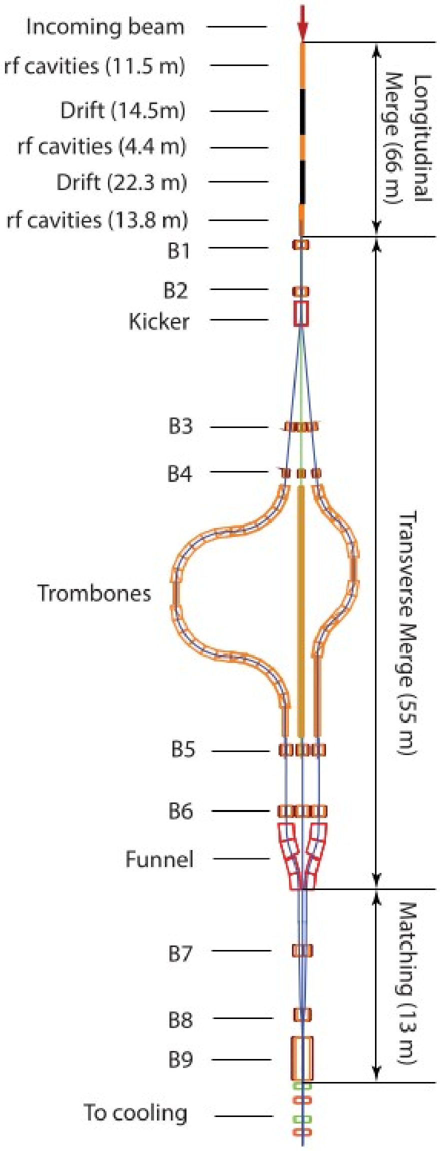
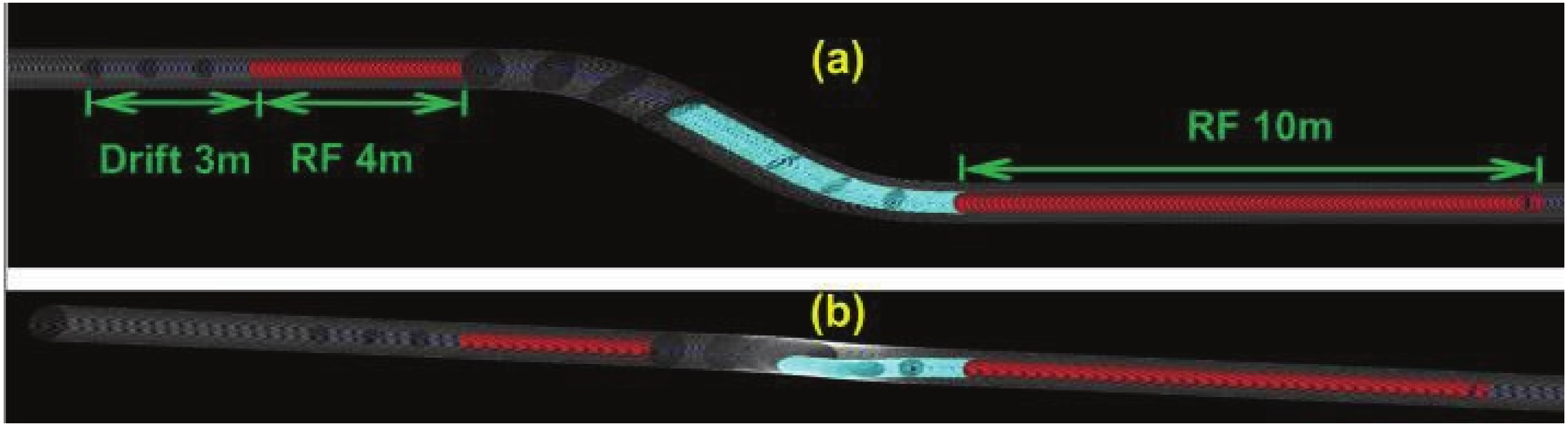
Bunch merge

- "Rotating" Kicker
  - 0.022 T, dual axis
  - 18 MHz frequency
  - 2 m long
  - 1 m diameter
- CW Solenoids B1 – B8
  - 0.4 to 1.2 T
  - 0.6 to 1.4 m diameter
  - 1 m long
- CW Solenoid B9
  - 2.6 T
  - 1.5 m diameter
  - 3.65 m long





Solenoids and Bent Solenoids



- Also solenoids in many places
  - e.g. Front end 2 T, 500 mm radius? TBC
  - Bent solenoids
    - Few degree bend, no dipole just solenoid field
    - Charge separation may require “elliptical” solenoids or large aperture
      - Design is rather immature
    - In capture region bent solenoid experiences ~ 100s kW of beam power

Technology challenge - Solenoids

- **Personal View!**
- High field solenoids
  - State of the art solenoids required in many places
  - Transfer of “laboratory-class” solenoid to “accelerator-class”
- Radiation load
  - Not aware of detailed assessment of effect of muon decays on magnet systems
  - $c\,\tau_{\mu} \sim 660$ m
  - Target and particle selection clearly have issues with secondaries
- Quench protection
  - Extremely compact magnet schemes throughout the muon source
  - Quench in one magnet likely to induce quench in all magnets
    - ~ km line of quenching magnets!
  - Needs care
    - Can this be managed in PSU?
    - Do we need an optics solution (fire break)?

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Discussion

- Few questions raised in the slides
- Priorities:
  - Final cooling – higher fields → more luminosity
  - Rectilinear cooling – can outperform “final cooling” given stronger magnets; is this feasible?
- “Demonstrator”
  - Are there any questions which need beam to resolve?