Cooling with Magnetic Insulation

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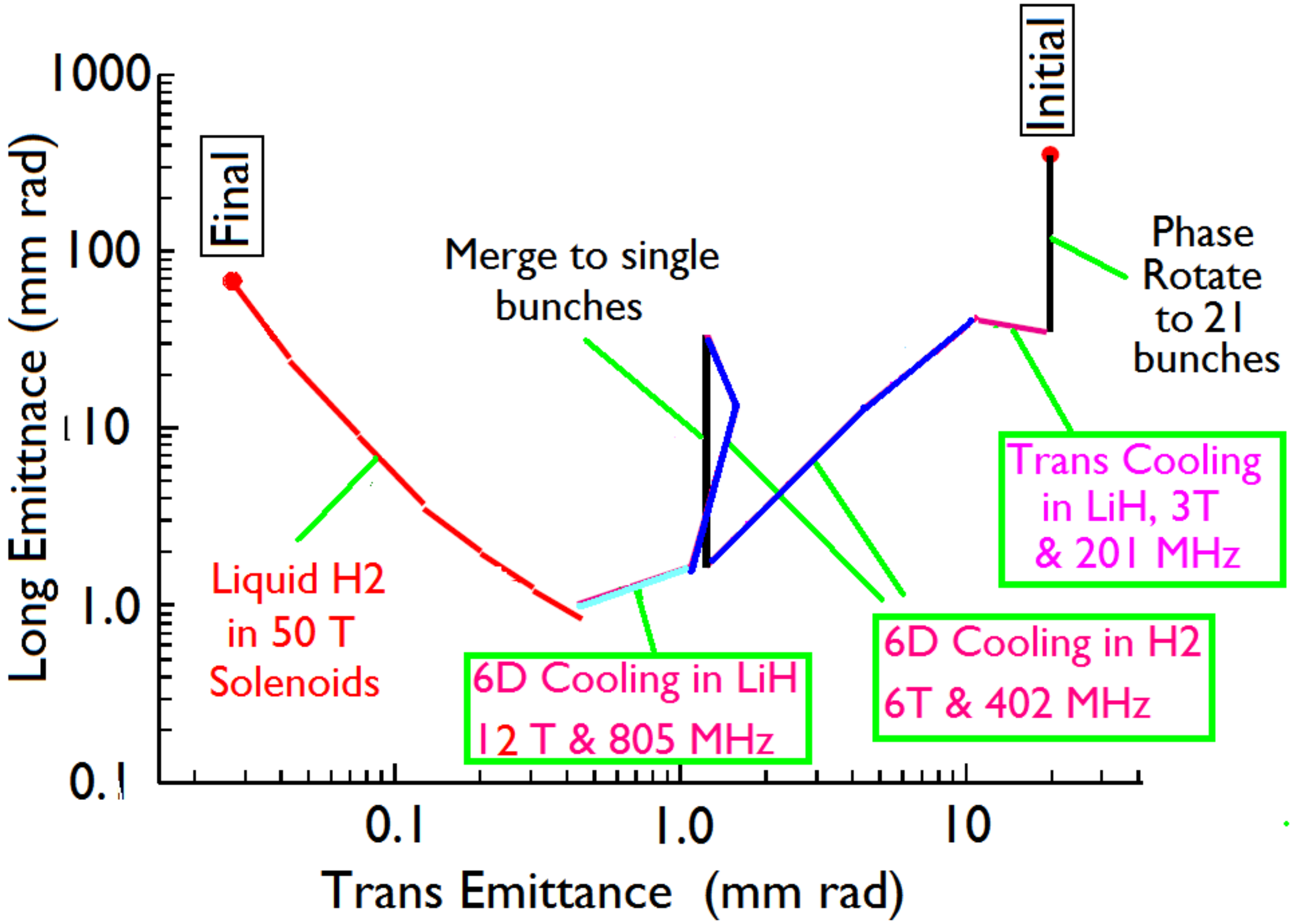
- Introduction to complete cooling system
- Defining 'Efficiency' Q
- Estimated transmissions, using Q, for old lattices

- Breakdown problem in fields
- Solutions by Systems
  - Pre-cooling
  - 201-402 MHz RFOFO
  - 201-402 MHz HCC
  - Final 805 MHz 6D
- Conclusion



Most Serious Questions

1. Breakdown in Cooling rf and effect on #1 Discussed here
2. Transmission
3. (Early 50 T cooling)

Transmission and definition of 'Efficiency' Q

If one multiplies the transmissions of all simulations, the result is around 1% and quite unacceptable. But much of the losses come from poor initial matching and lack of tapering. To estimate transmission with good matching and tapering we define a cooling efficiency Q

$$Q_6(z) = \frac{d\epsilon_6/\epsilon_6}{dN/N} \tag{1}$$

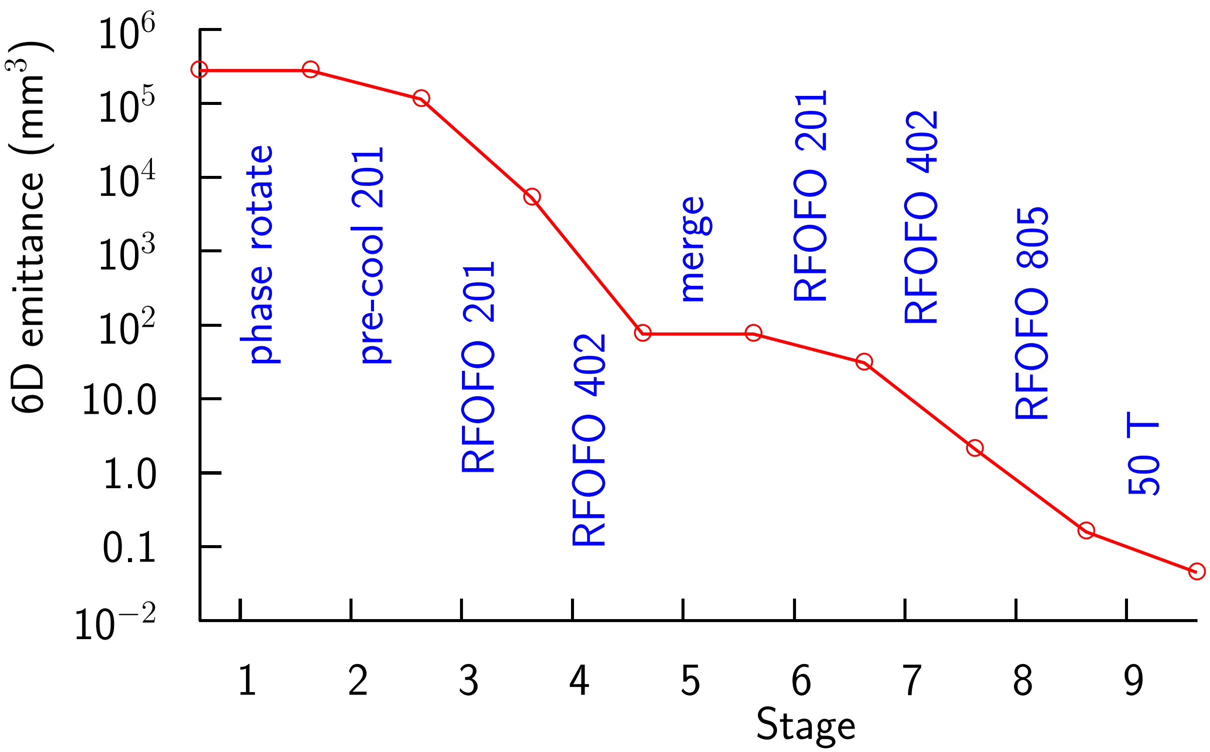
Note, if $Q_6(z)$=constant, then

$$\int_o^n \frac{d\epsilon_6}{\epsilon_6} = Q_6 \int_o^n \frac{dN}{N}$$

$$\mathrm{Ln}\left(\frac{\epsilon_6(n)}{\epsilon_6(o)}\right) = Q_6 \ \mathrm{Ln}\left(\frac{N(n)}{N(o)}\right)$$

$$\frac{N(n)}{N(o)} = \left(\frac{\epsilon_6(n)}{\epsilon_6(o)}\right)^{1/Q_6} \tag{2}$$

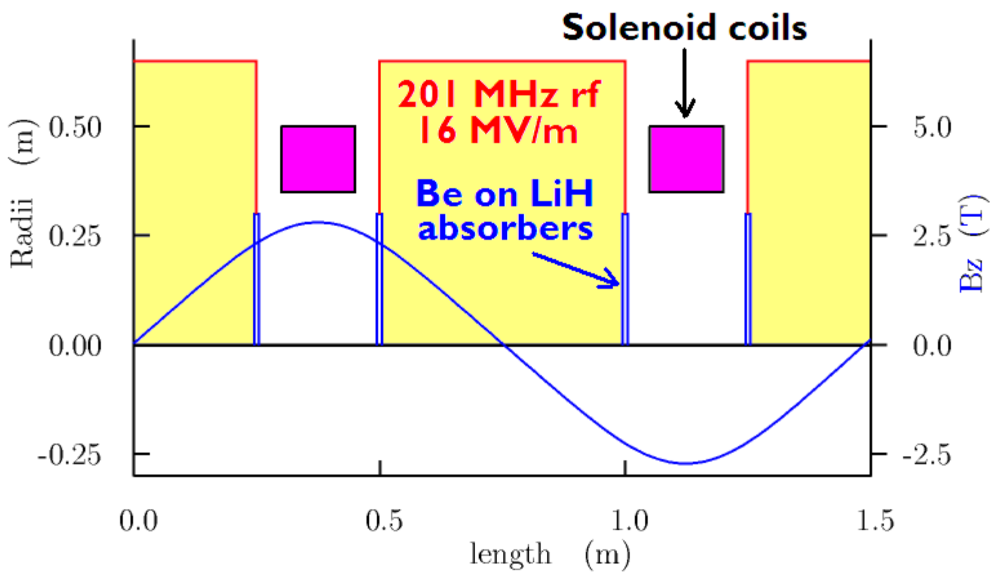
6D emittances vs. stage

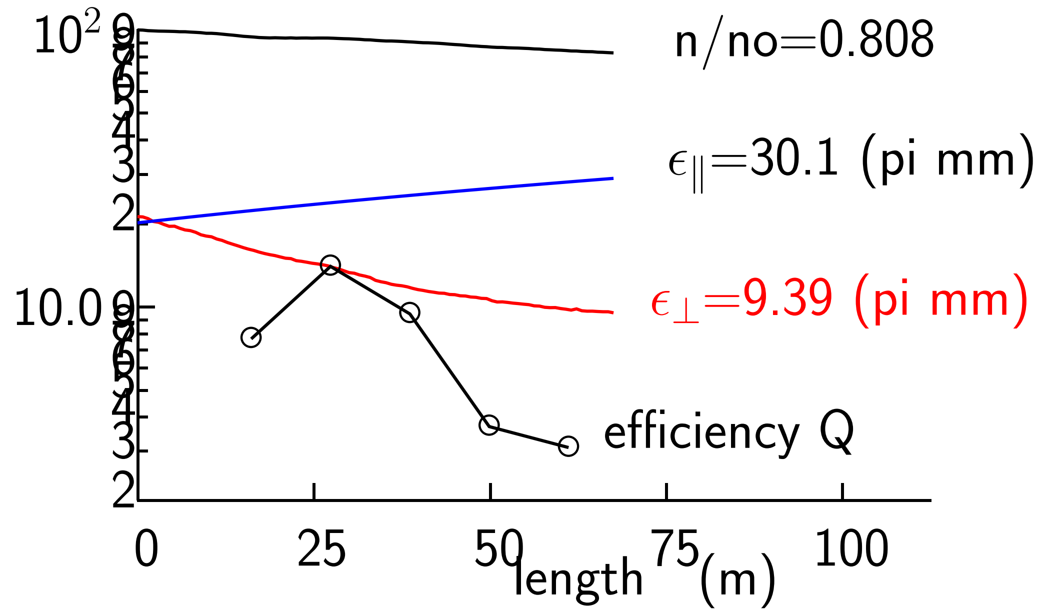


Stages	$\epsilon_6(1)$	$\epsilon_6(2)$	Ratio
Pre-Cool	280,000	115,000	2.4
201 &402 MHz RFOFOs	115,000	2.1	55,000
805 MHz RFOFO	2.1	0.15	13
50 T	0.15	0.045	3.6
All	280,000	0.045	6 10^6

We now need the Q's for each system to get predicted losses

Efficiency vs. length for Pre-cooling



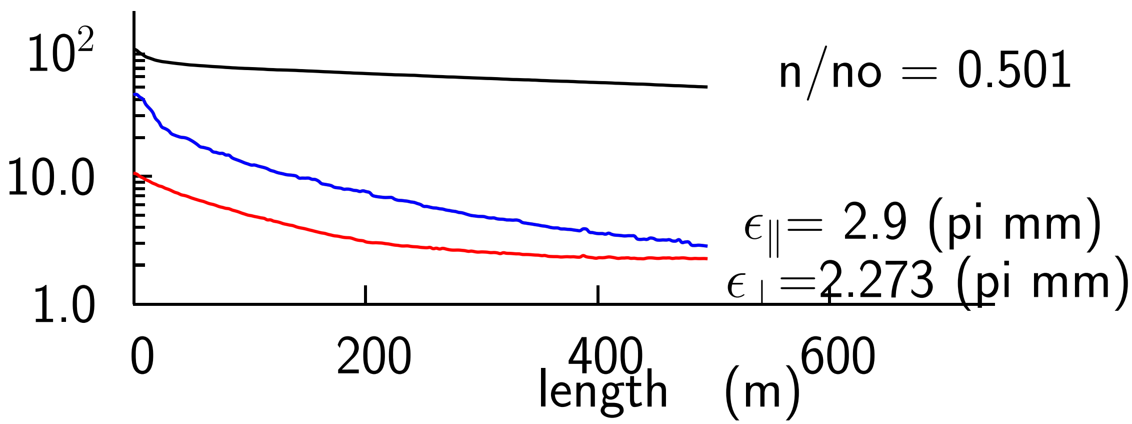


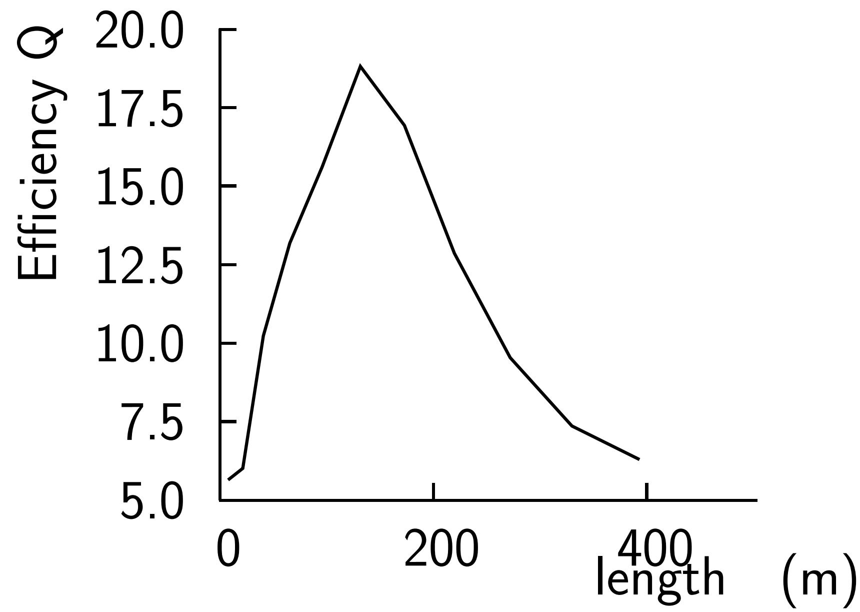
- Mismatch and Scraping losses at start
- Decay losses as emittances approach equilibrium at end
- Sweet region in between $\boxed{Q \approx 10}$
- If tapered then the entire channel is operated in the sweet region
- 4D cooling in RFOFO lattices from 280,000 to 115,000 (mm^3) So expected

$$\frac{n_{final}}{n_{initial}} = \left(\frac{115,000}{280,000}\right)^{1/10} = 0.91$$

Efficiency vs. length for old RFOFO

- Mismatch and Scraping losses at start
- Decay losses as emittances approach eqilibrium at end
- Sweet region in between Q≈ 15
- If tapered then the entire channel is operated in the sweet region

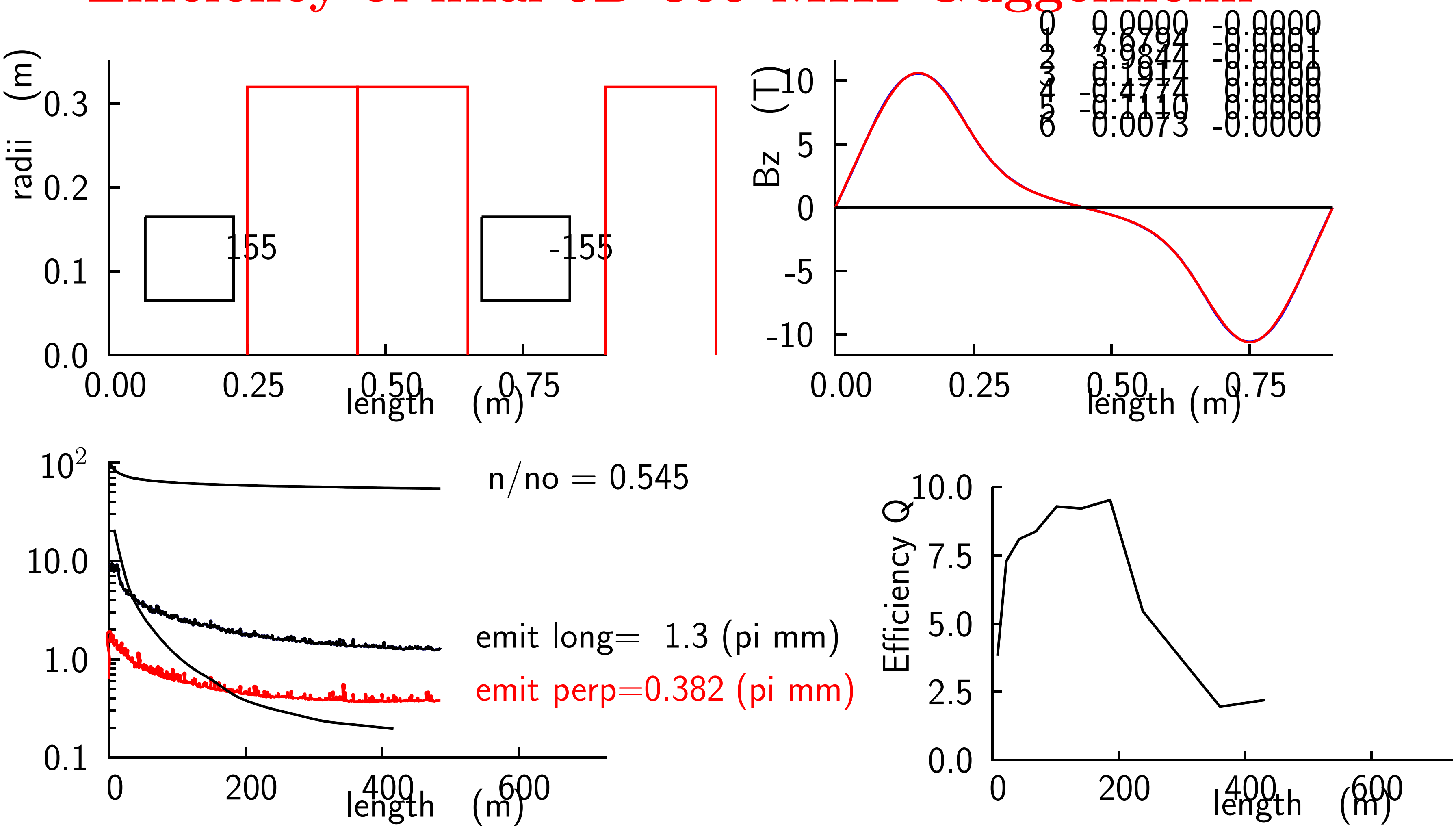




Required 6D cooling in RFOFO lattices from 280,000 to 2.1 (mm^3) So expected

$$\frac{n_{final}}{n_{initial}} = \left(\frac{2.1}{115,000}\right)^{1/15} = 0.48$$

Efficiency of final 6D 805 MHz Guggenheim



- Sweet region in between Q≈ 8
- Required 6D cooling from 2.1 to 0.16 (mm^3) So expected

$$n_{\frac{final}{n_{initial}}} = \left(\frac{0.16}{2.1}\right)^{1/8} = 0.72$$

Transmission for whole scheme

Stage	ϵ_1/ϵ_2	Q	trans
For use of only 15 bunches	-	-	0.7
Charge separation	-	-	0.9
Losses in 4D Pre-cooling at 201 MHz	2.4	10	0.9
Losses in 6D Guggenheims at 201 & 402 MHz	55,000	15	0.48
Losses in merging	-	-	0.7
Losses in 805 MHz 6D	13	8	0.72
Losses in 50 T cooling	3.6	-	0.7
Losses in Acceleration			0.7

$$Trans \;=\; (0.7\times\; 0.9\times 0.9\times 0.48\times\; 0.7\times 0.72\times 0.7\times 0.7\times) \;=\; 0.075$$

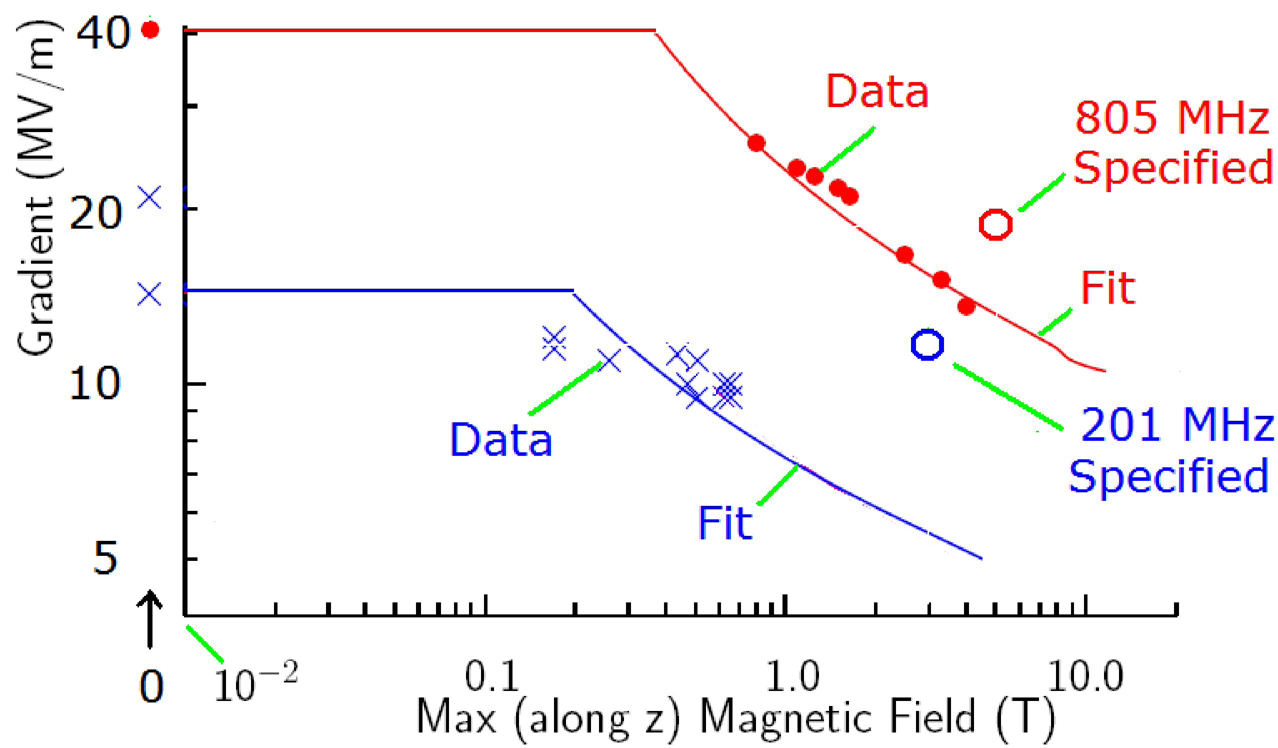
which what we have been estimating before

rf Breakdown problem

- Current design, and cavity construction, will not work

High Pressure Gas

- HCC (Muons Inc)
- Gas in early RFOFO lattices
  - Effect of beam unknown
  - Integration of rf still a problem (see below)

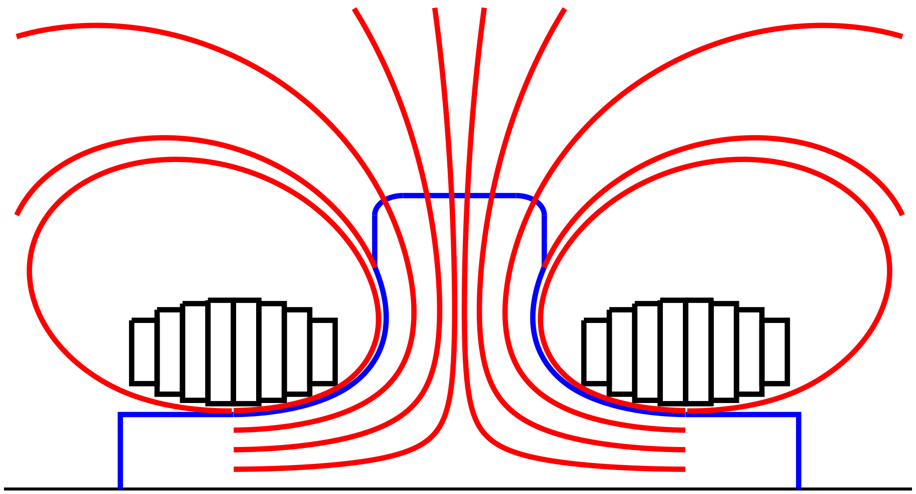


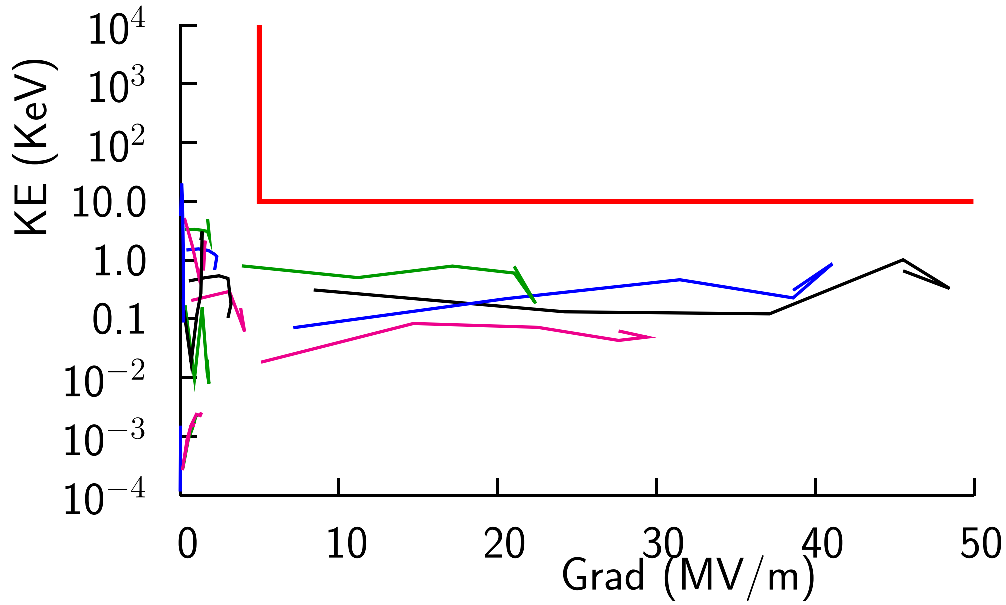
Vacuum rf

- Bucking the field at rf should work
  - Are losses a problem ? see below
- Magnetic insulation should work
  - Are losses a problem ? see below
- Treatment of cavity surfaces (eg ALD)
  - Will not a single defect cause a spark that damages the surface

Magnetic Insulation

Form cavity surface to follow magnetic field lines

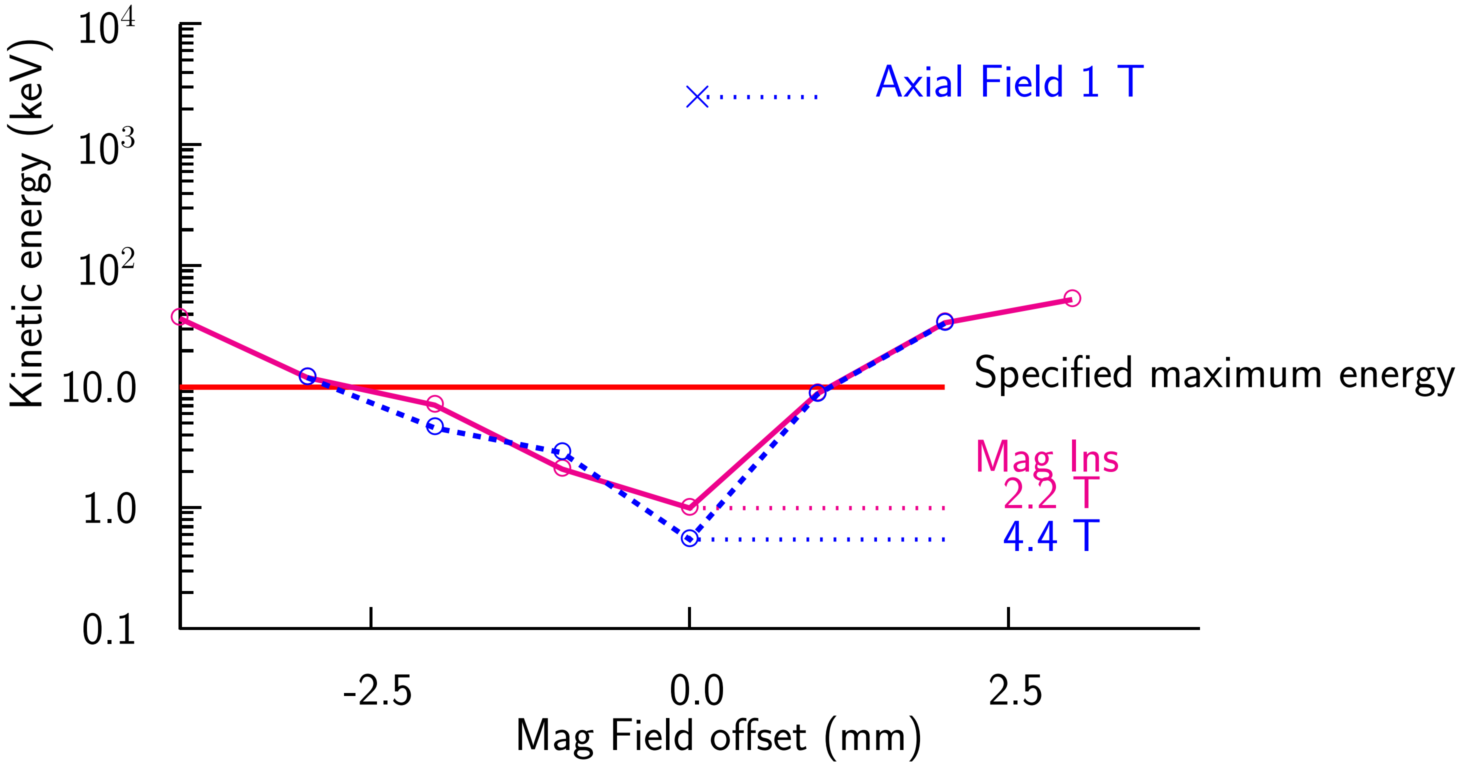




- All tracks return to the surface
- Energies are very low
- No dark current, No X-Rays, no damage
- Multipacter ?   Grateful to SLAC for help

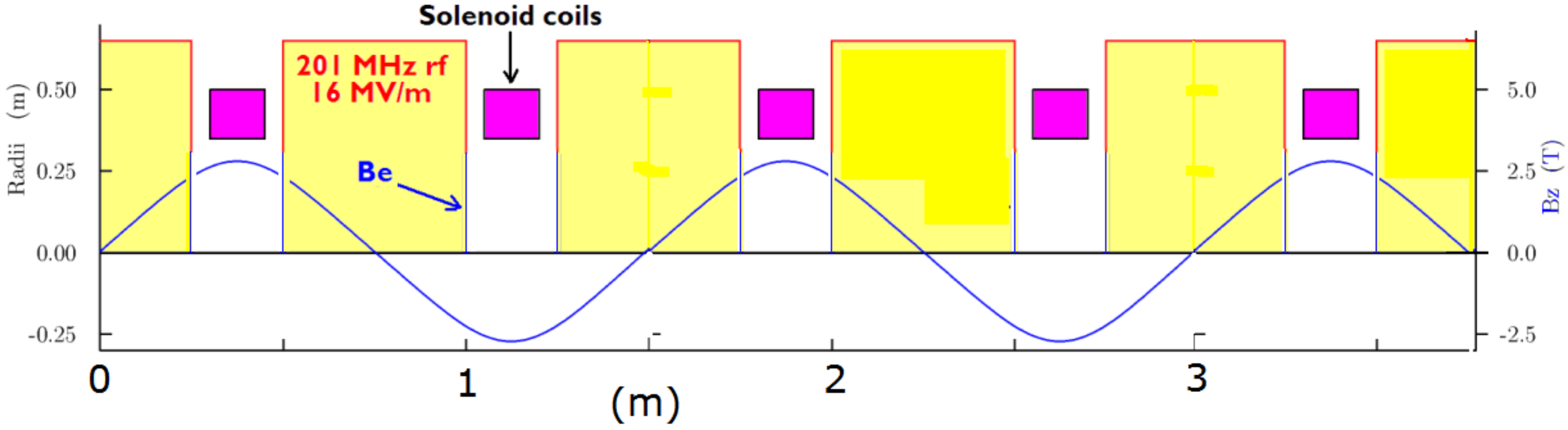
Sensitivity to errors

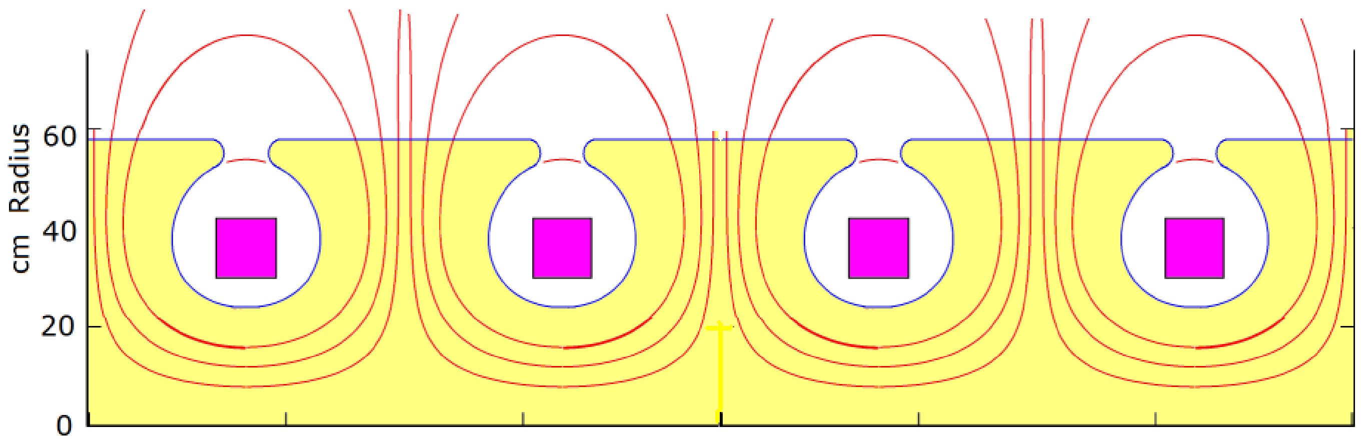
For tracks starting with $\mathcal{E} > 5$ MV/m :
plot maximum final energies vs. z displacement of magnetic fields



- Meets requirements for axial displacements up to $\pm$ 1 mm for 805 (4 mm for 201 MHz)
- Little effect of doubling the strength of the magnetic fields
- Energies down by $>$ 2 orders of magnitude from axial field case

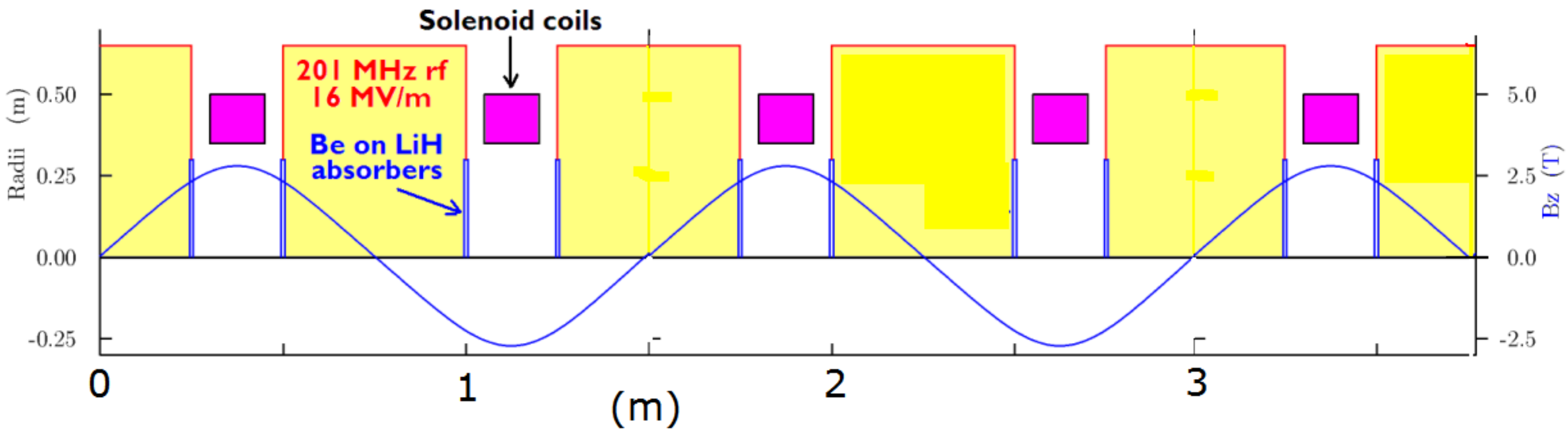
Mag insulated Phase Rotation Lattice

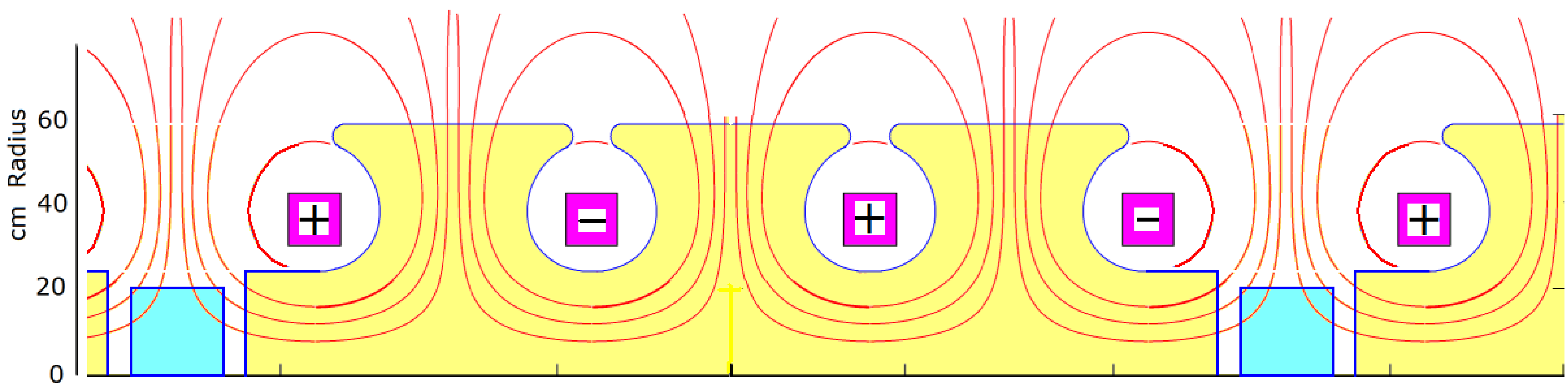




- Fields on axis are identical
- So losses expected to be the same

Mag insulated Pre-cooling Lattice





- Fields on axis are identical
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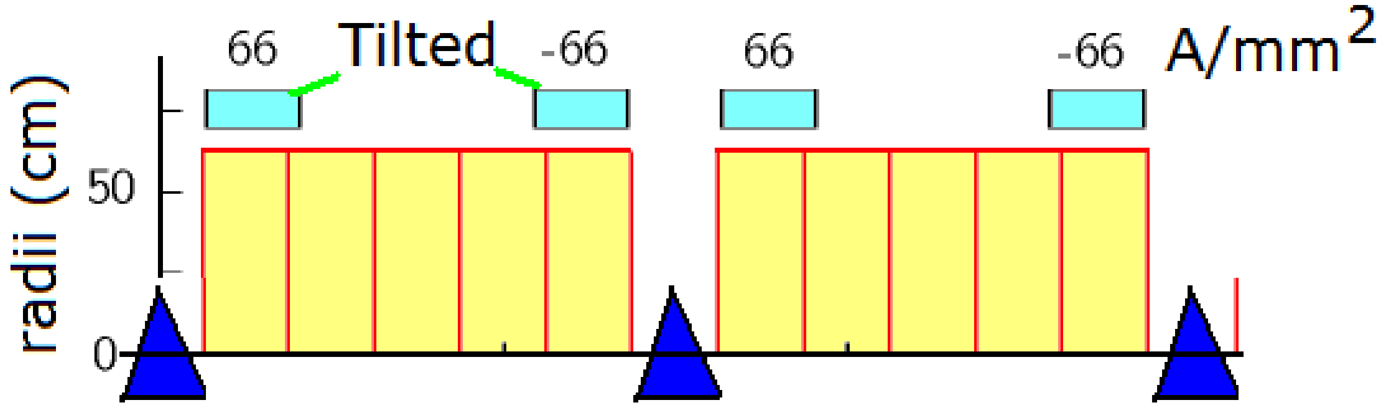
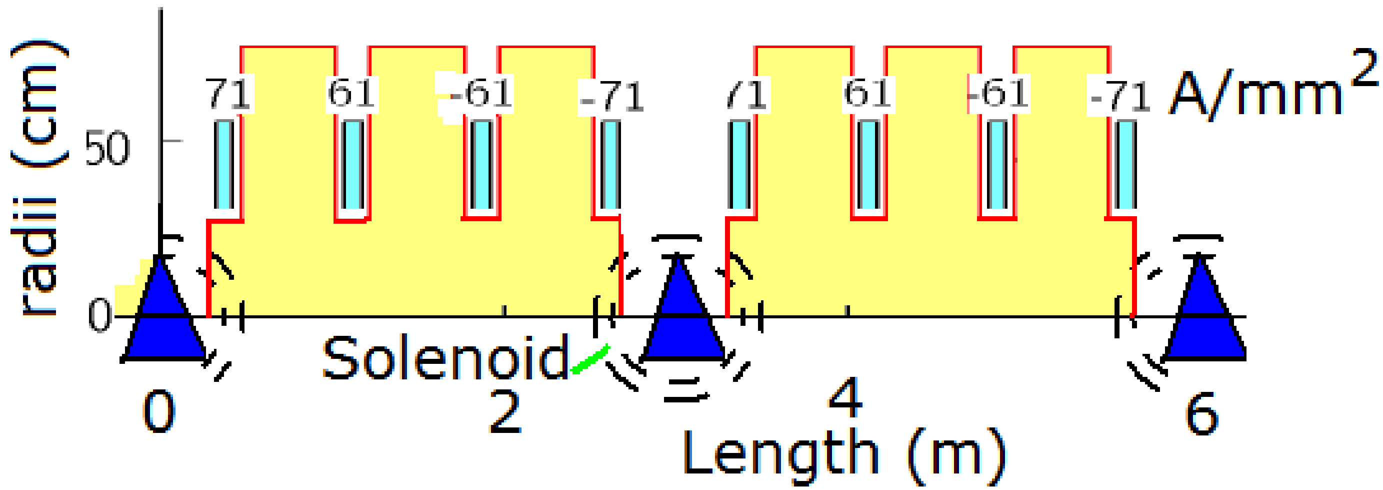
Mag insulated 201 & 402 MHz RFOFO lattices

Old RFOFO
with coils outside



Approximated
lattice using
coils in open irises

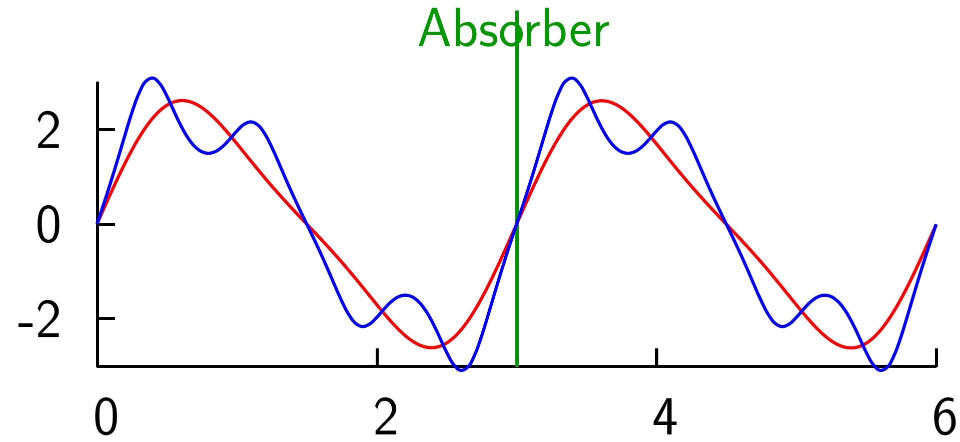


This is not quite the magnetically insulated lattice, since it does not have the outer reverse coils, but the fields on axis will be very similar

Tilting the coils in the mag ins case may also be possible. This would probably be prefered

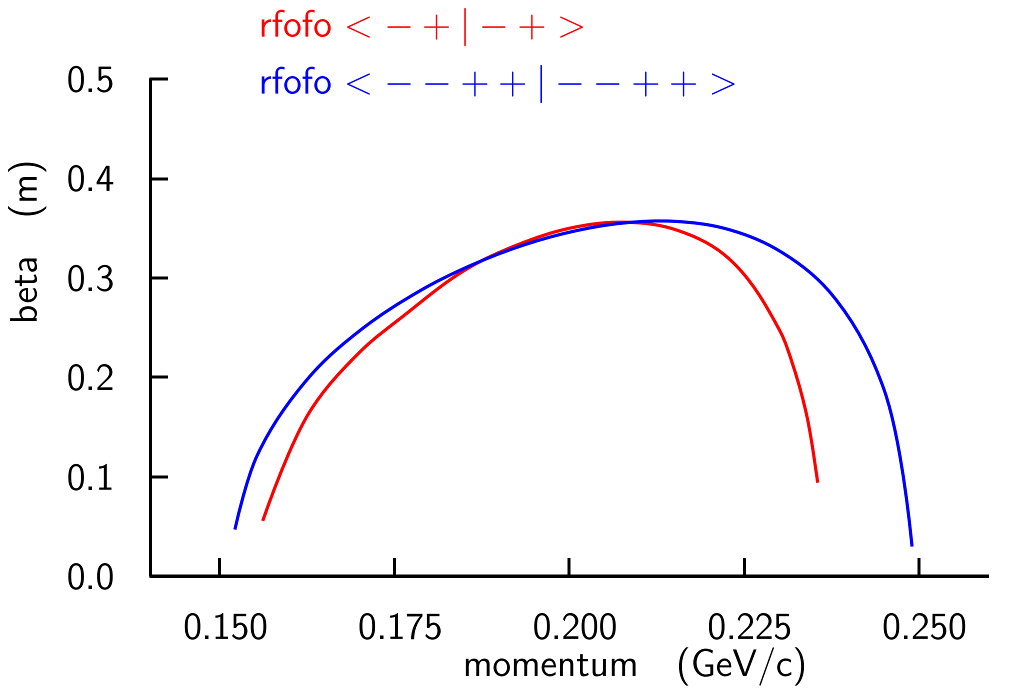
Fields vs. z

Red is for coils outside
Blue is for coils in irises



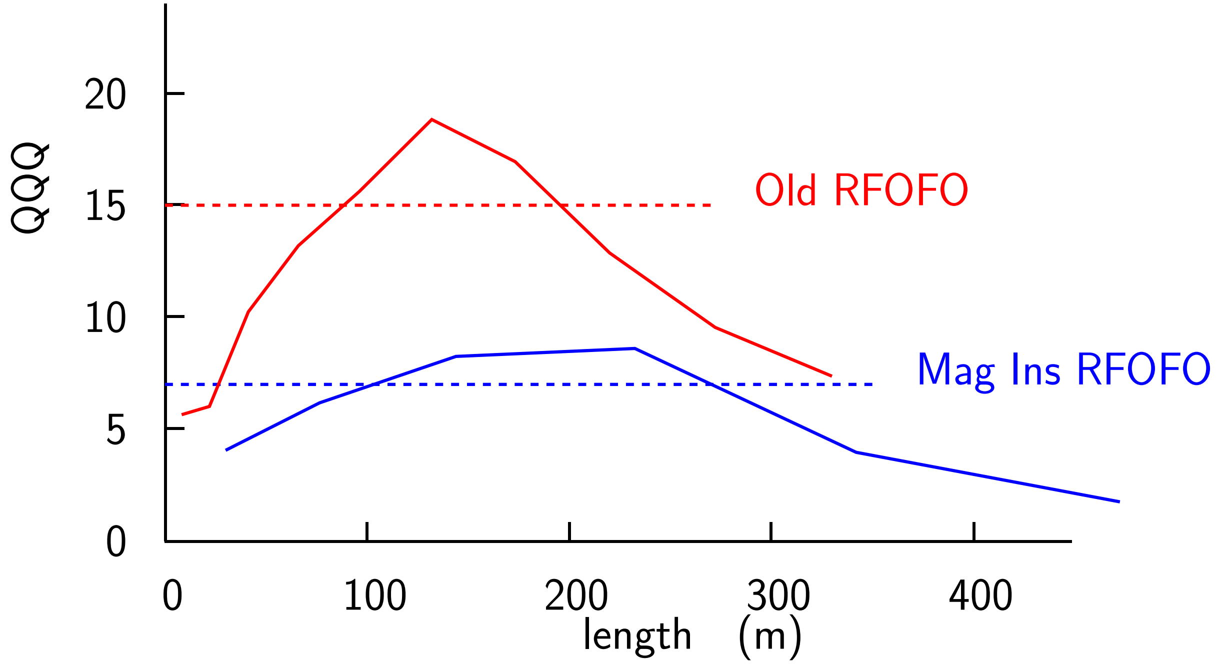
Betas vs. Momentum

Red is for coils outside
Blue is for coils in irises



- Open cell RFOFO has significantly more momentum acceptance than old version
- But richer harmonic content that could lead to losses

Compare Lattices for 201 & 402 MHz 6D cooling



	freq MHz	Cell m	Bz_{max} T	B_{coil} T	$< \mathcal{E} >$ MV/m	ϵ_{min} π mm rad	Q_{max}	$Q_{assumed}$	Trans %
Old RFOFO	201	2.75	3	5	8.6	2.2	18.5	15	7.5
Mag Ins RFOFO	201	3.0	3.2	6	7.9	3.7	8.6	7	3.3

- Poor performance of Mag-Ins could be an ICOOL artifact
- But if real, makes Mag-Ins unsuitable for early 6D Cooling
- Final cooling is another matter

Consider options with High pressure gas

- Adding gas to RFOFO rings
  - Allows use of coils outside rf
  - Use minimum pressure to stop breakdown (15 atm at 70 deg)
  - Use LiH for emittance exchange
  - Some study by Gallardo
  - Needs more work

- Helical Cooling Channel (HCC)
  - Need solutions to integrate rf
  - Cavity with noses (Balbekov) (Consider this)
  - Ceramic loading (Popovic)

HCC eg 201 MHz case

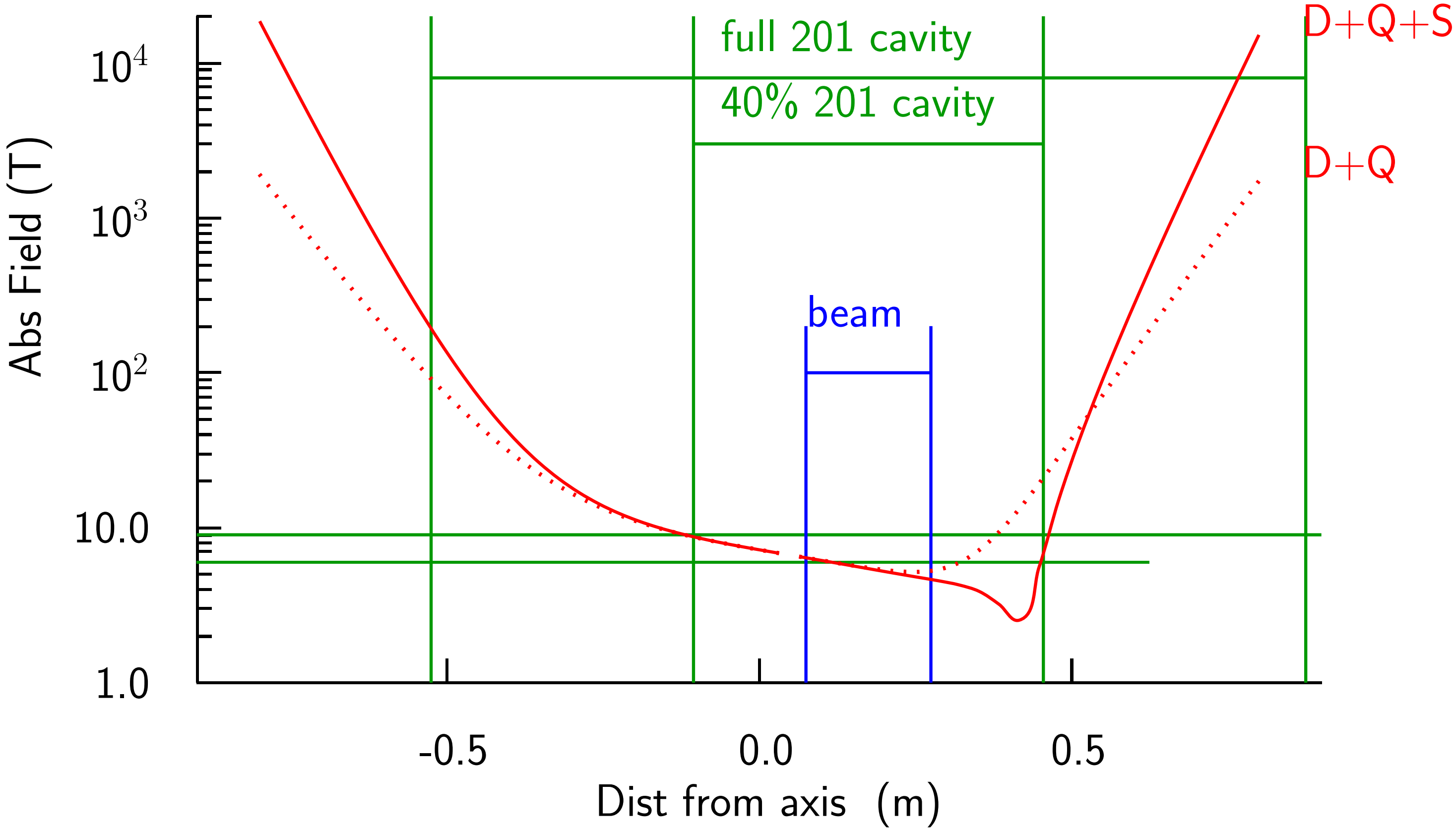
(Muons Inc)

Use Balbekov specication $\lambda = 1.5 \times \Lambda$

Use Yonehara: sol + helix(dipole + grad + sextupoles)

$\Lambda = 1\ m \qquad \lambda = 1.5\ m \qquad f = 201 MHz$

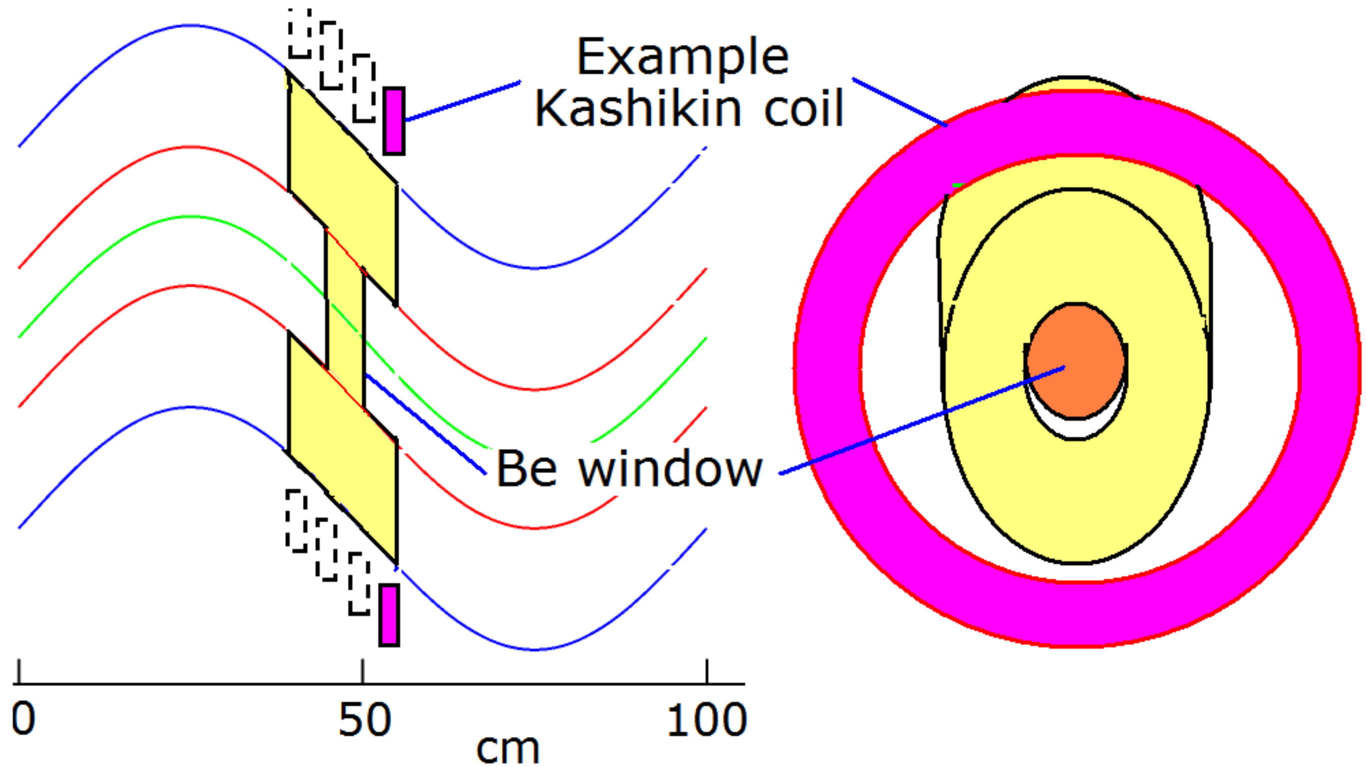
Set cavity outside radius to keep Bmax $\leq$ 9 T (cf B(pipe)= 6 T



Maximum fields are true independent of how you generate them

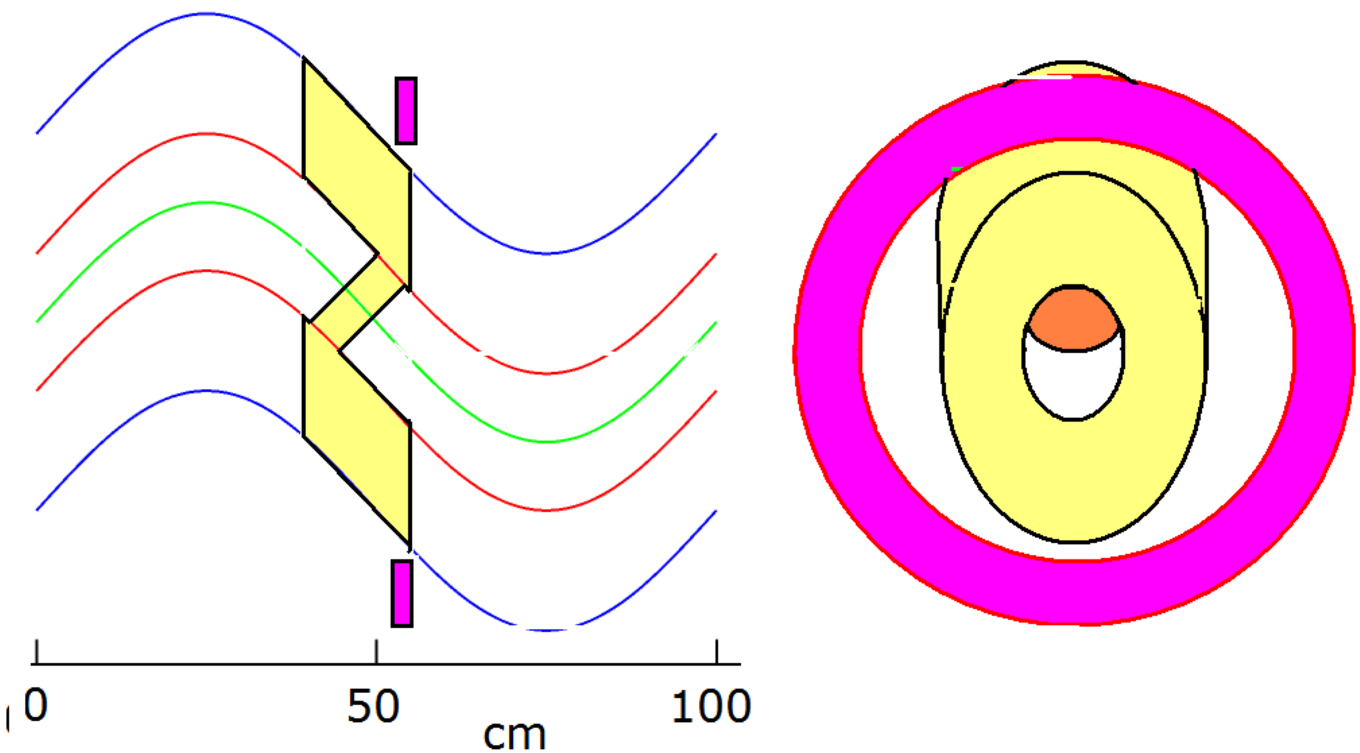
Cavity Design 1

- Adjust length of gap/len to get cavity inside 40% full cavity
- $\approx$ 50 MV/m at 805 MHz $\qquad\qquad$ $\approx$ 25 MV/m at 201 MHz
- gap/length $\approx$ 2.7



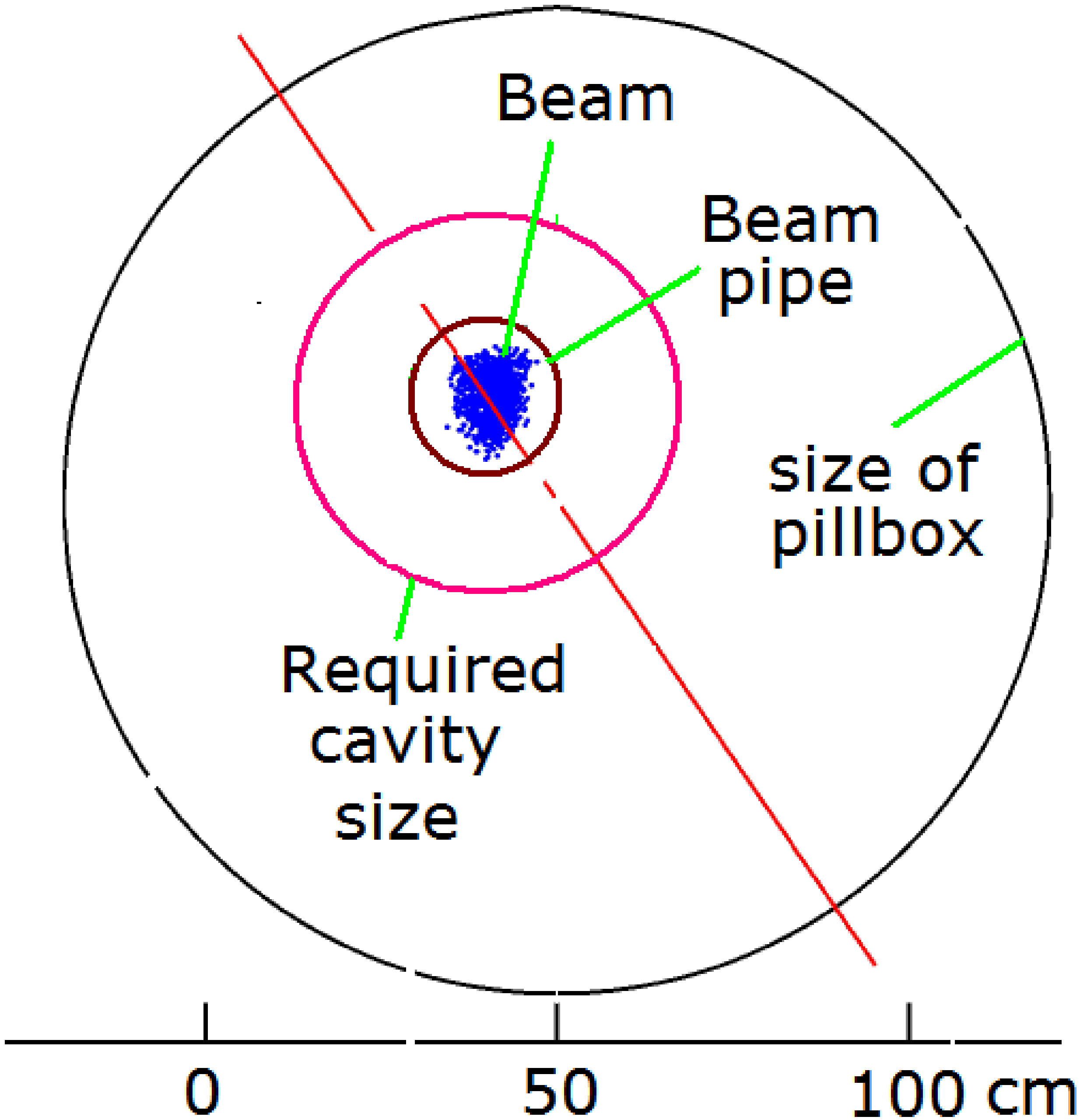
$$< \mathcal{E} > = \frac{25}{2.7\ \sqrt{2}} \times \mathcal{E}_s \ = \ 5.9$$

Design 2

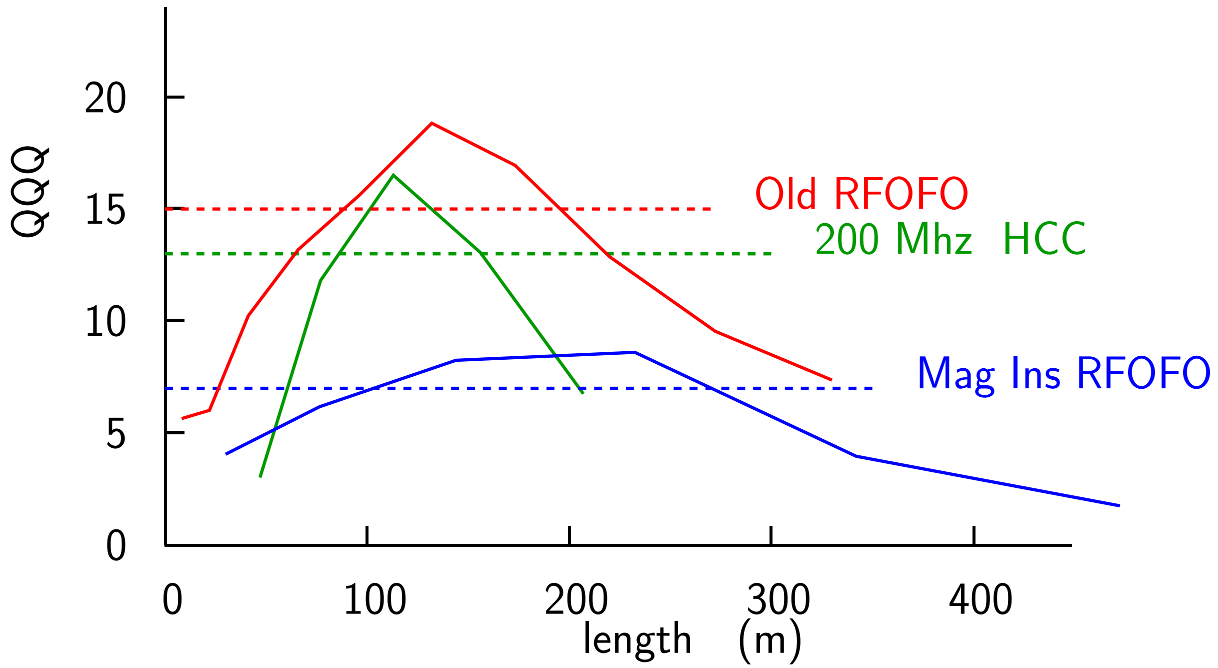


$$< \mathcal{E} > = \frac{25}{2.7} \times \mathcal{E}_{\rm s} \; = \; 8.6 \qquad \mathrm{MV/m}$$

ICOOL Simulation



Compare Lattices for 201 & 402 MHz 6D cooling



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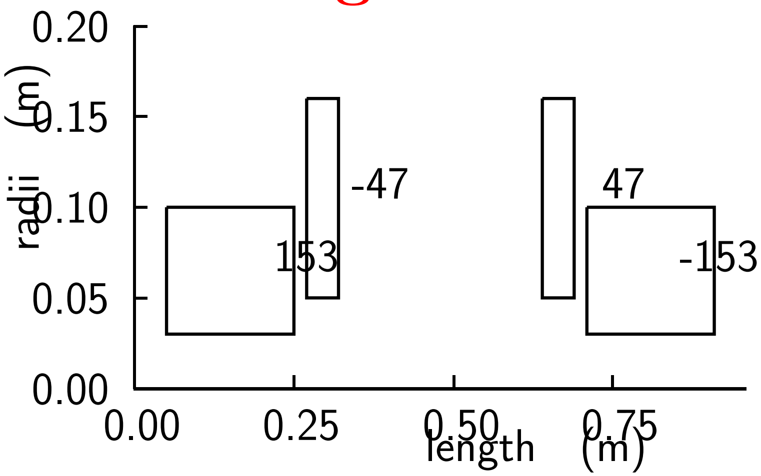
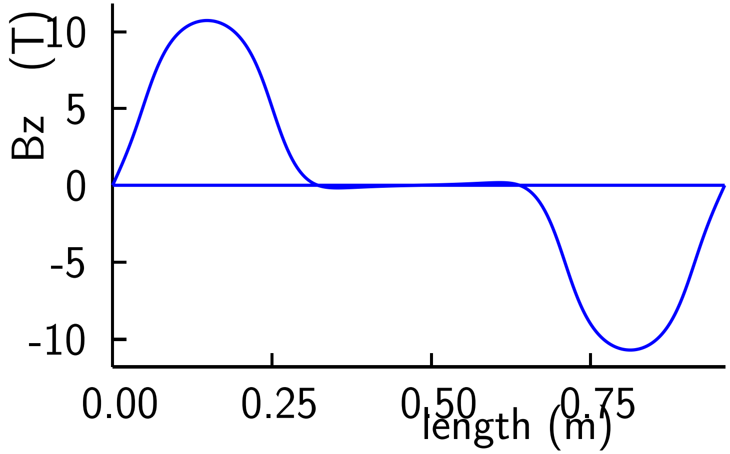
Mag Ins RFOFO	201	3.0	3.2	6	7.9	3.7	8.6	7	3.3
HCC	201	1.0	6	$\geq$9	8.6	1.8	16.5	13	6.8

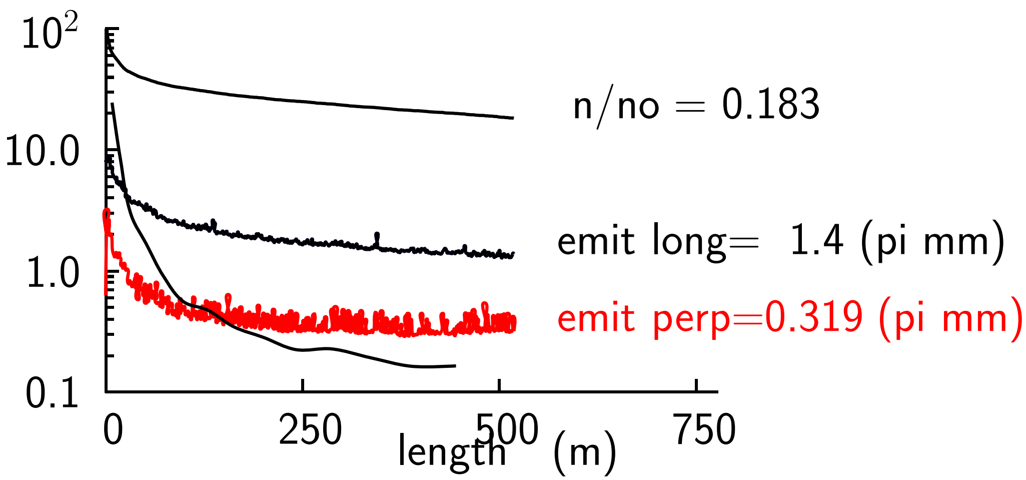
Last stage of 6 D cooling

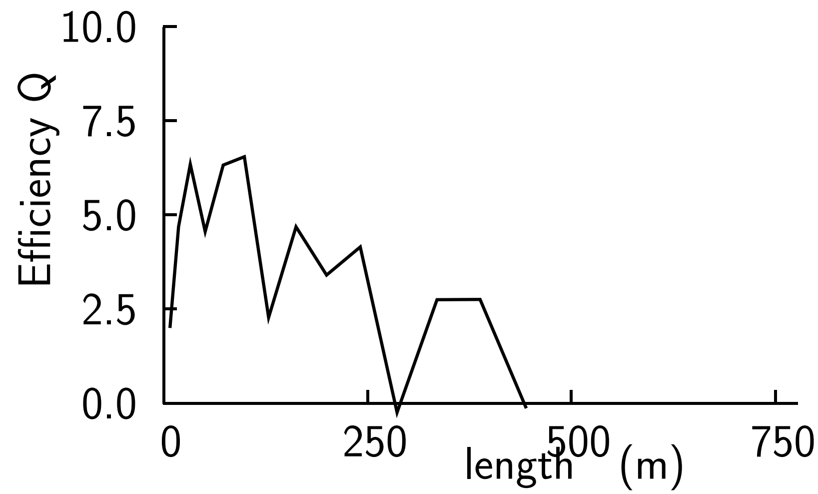
- Old RFOFO
  - Does not work
- Bucked field RFOFO
  - Does not work well (see below)
- Mag Ins
  - Probably acceptable
- HCC
  - B(coil) = 30 T
  - Λ=20 cm
  - Very short compact magnets
  - eg 8 2.5 cm 30 T solenoids
  - Not realistic

Bucking the fields at the rf   e.g. 805 MHz lattice









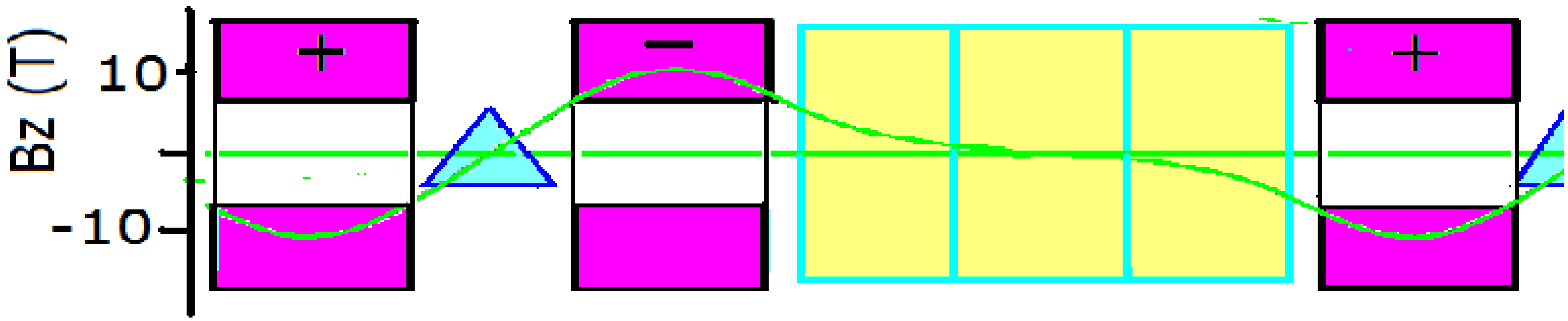
Sweet region in between only $\boxed{Q\approx 4}$ (c.f. 9) and:

$$\frac{n_{final}}{n_{initial}} = \left(\frac{0.16}{2.1}\right)^{1/4} = 0.52$$

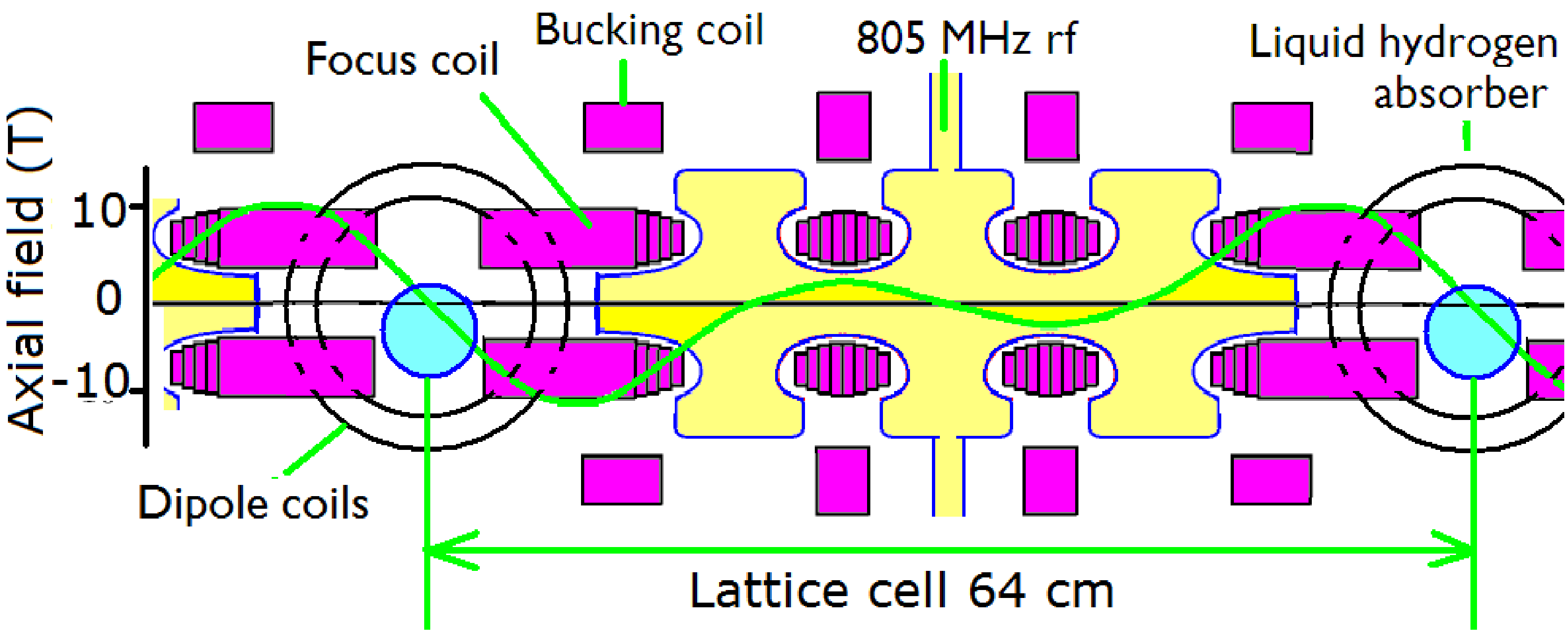
52% c.f.72% Which is not so good

Mag-Insulated version of 805 MHz lattice

Old simulated lattice



Mag Ins version
Not yet simulated



- Fields in mag-ins case are very close to original
- Q's will also be close, and for the short section it is not very sensetive to Q

Conclusion

- Overall transmission is a critical question
- Without tapering, and with imperfect matching, losses in ICOOL simulations are unacceptable
- It is useful to determine efficiencies (Q) vs z in cooling simulations
- Good matching and tapering should maintain the efficiencies at their 'sweet' values
- With this assumption, transmission is around 7% as assumed in HEMC parameters

- Breakdown appears a problem for all stages
  - Magnetic insulation ok for pre-cooling
  - High pressure gas in Guggenheims needs study
  - HCC may be best for early 6D
  - Magnetic insulation probably ok for final 6D