# Final Cooling in 30-50 T Solenoids

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- Simulated performances for 30, 40, and 50 T
- Performance vs. B
- More details of 40 T solution
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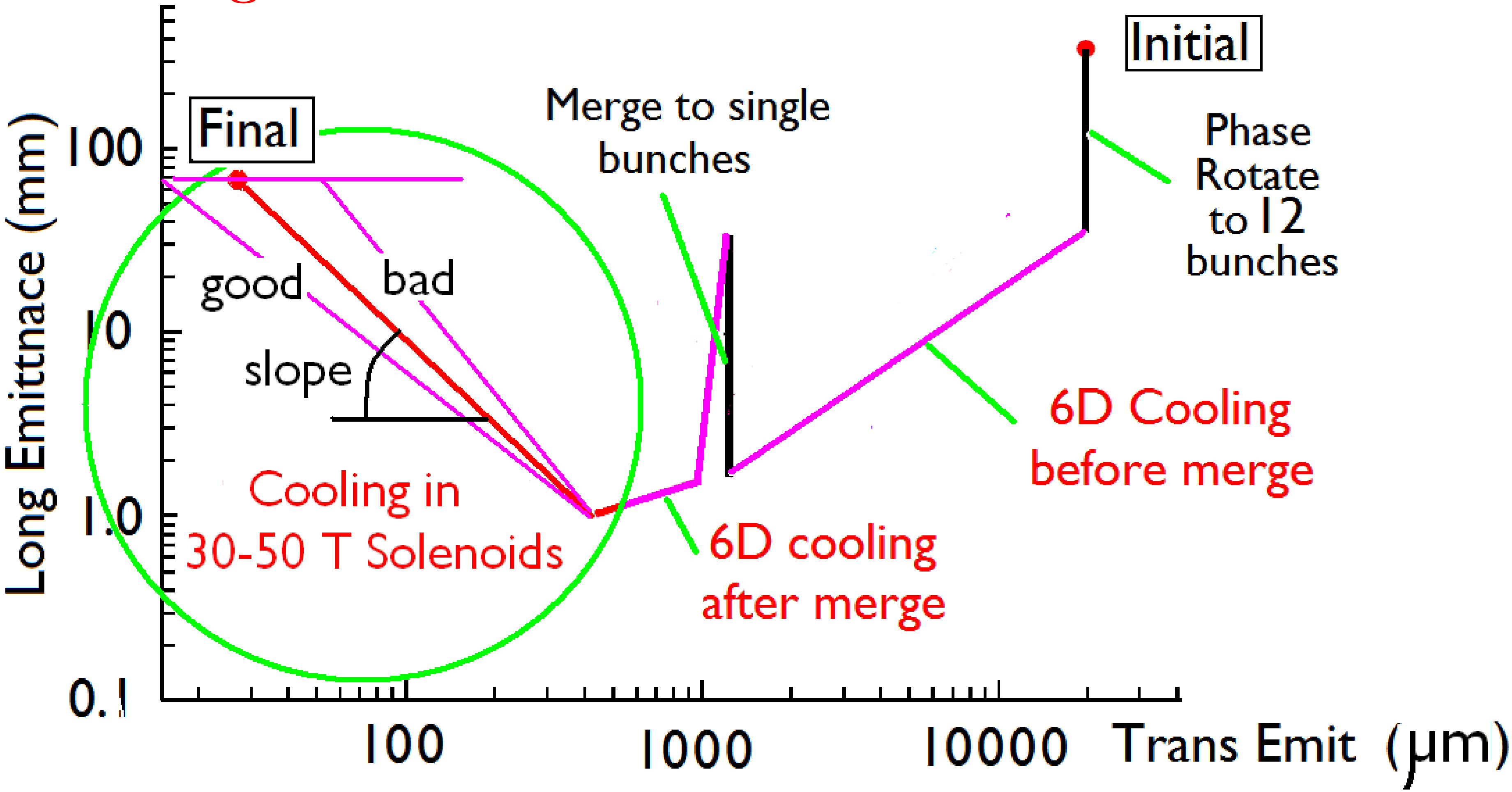
# Cooling Scheme




- IN: $\epsilon_\perp$=400 $\mu$m $\epsilon_\parallel$=1.1 mm Goal: $\epsilon_\perp$=25 $\mu$m $\epsilon_\parallel$=72 mm
- Transmission goal: 70%

# Minimum emittances vs. B and Energy

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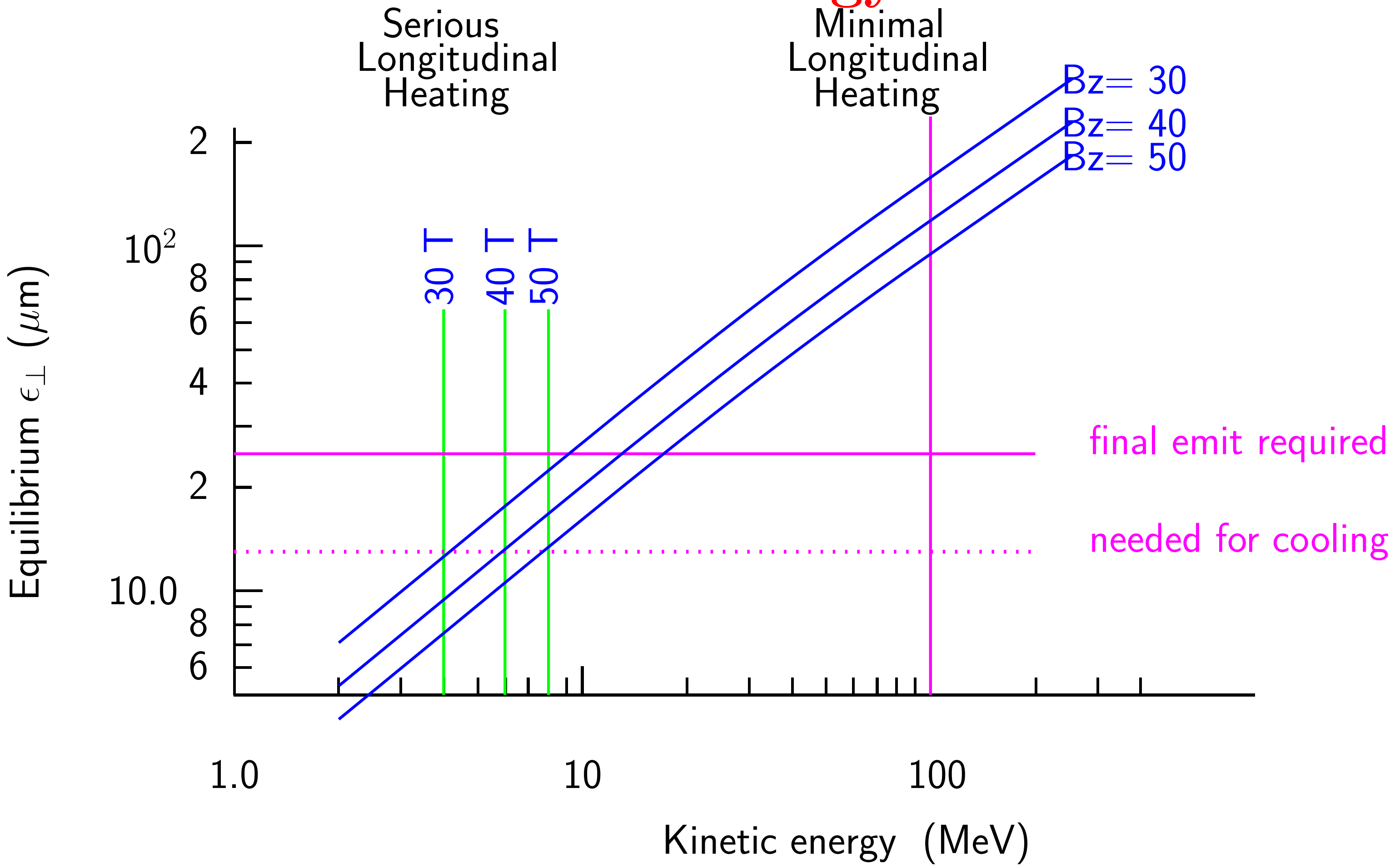
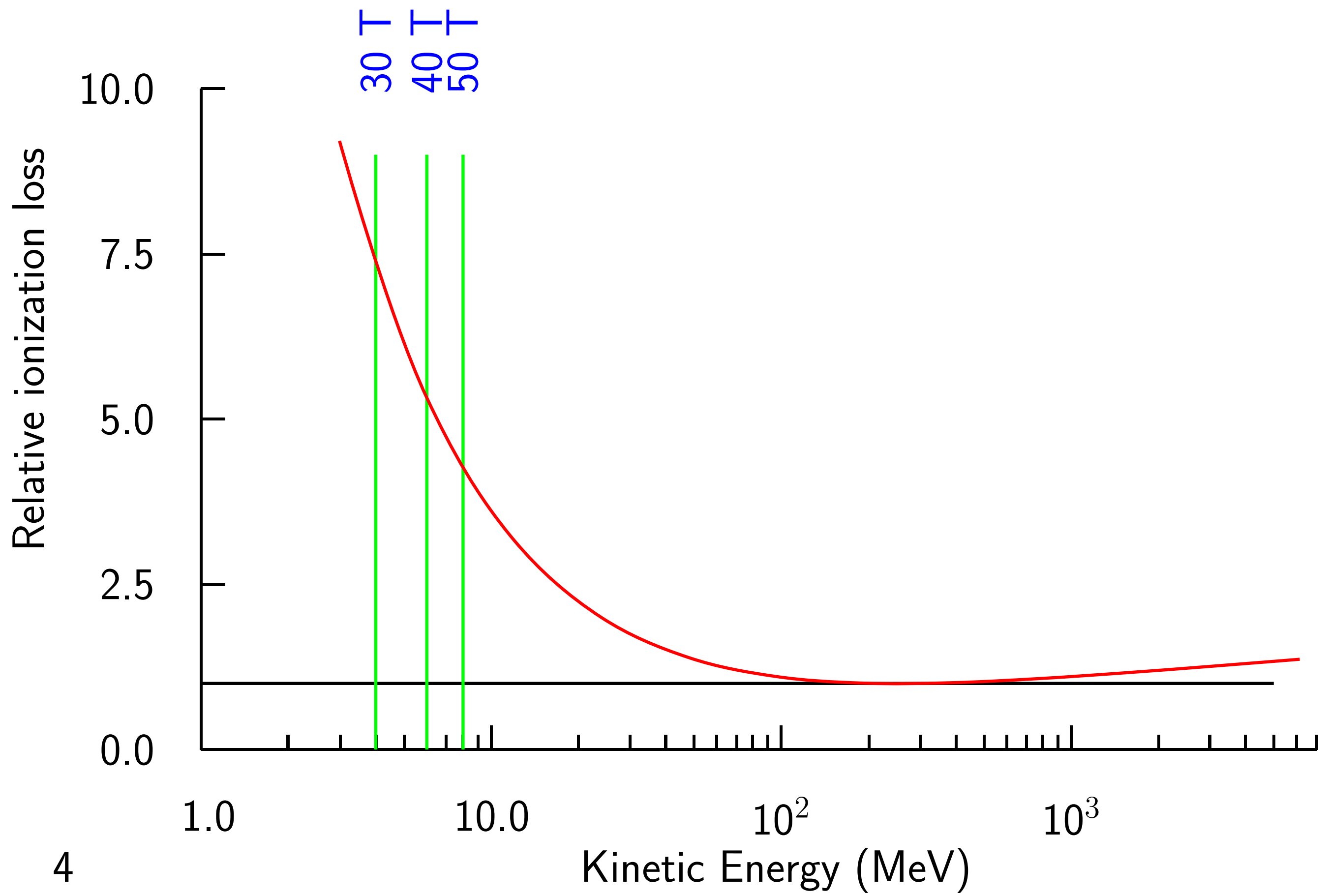



- At lower energies
  - Focusing stronger & Energy loss greater
- Cooling to any emittance, with any B, if energy is low enough!

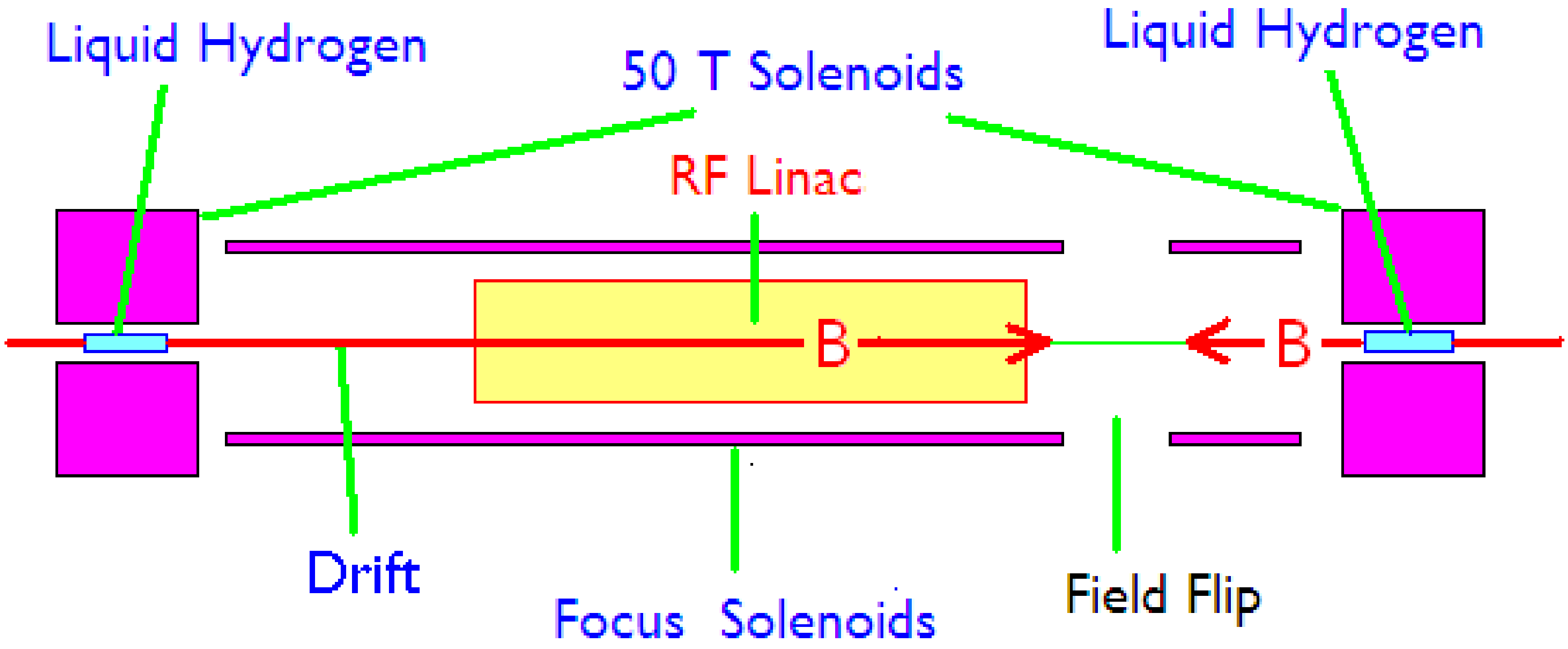
# Energy loss






- But the lower the energy, the steeper the slope of dE/dx vs. energy
- And the faster dE/E rises: giving worse longitudinal heating

# One stage



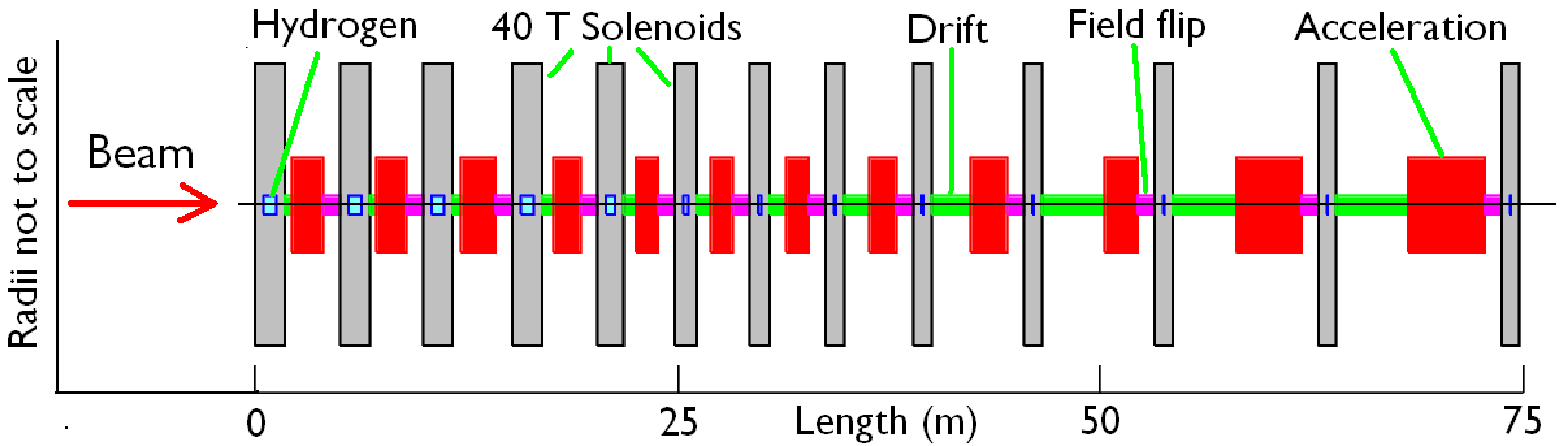

- Cooling limited to $\approx 20\%$ before dE/dx $\longrightarrow$ excessive
- Drift needed to phase rotate to new longer bunch and ok dE/dx
- Field must be reversed to avoid angular momentum build up

# Design & Optimization

- For each stage, with starting emittances from last stage, choose
  - Initial energy
  - Initial energy spread
  - Hydrogen length
- Run ICOOL only for length in hydrogen with fixed field
- Assume no dilution from match & re-acceleration (justified later)
- Calculate decay in length for phase rotation & acceleration
- Optimize for:
  - A minimum slope of $d\epsilon_{\parallel}/d\epsilon_{\perp}$ to achieve or beat goal emittances
  - A reasonable $\Delta\epsilon_{\perp}/\epsilon_{\perp}$ to keep down number of stages
  - Moderate particle loss for given emittance reduction

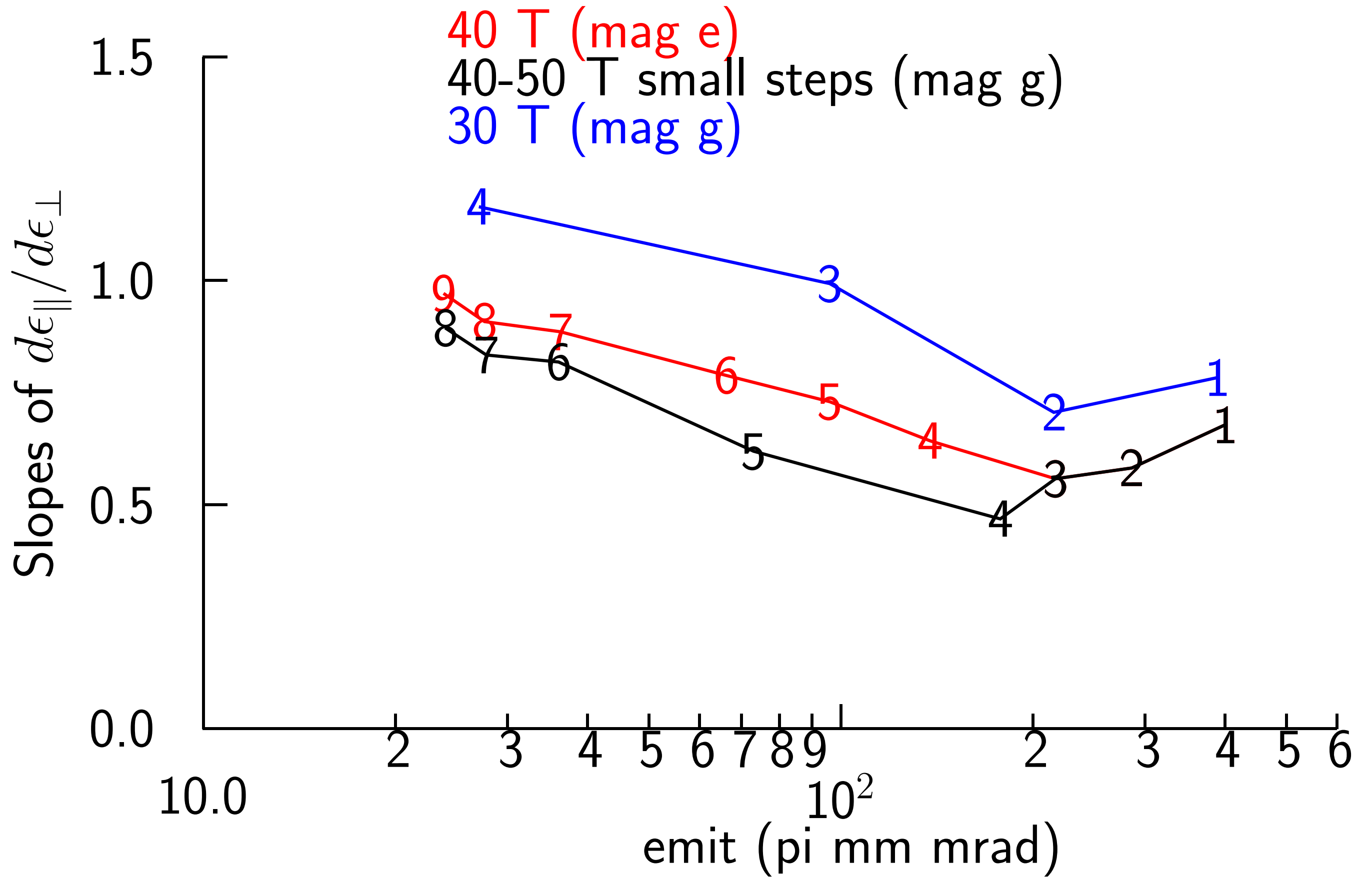
# Example solution

13 stage, all magnets at 40 T




- Each stage cools transverse emittances by ≈ 20%
- Longitudinal emittance increases by a similar amount
- A reasonable dp/p requires growing bunch lengths

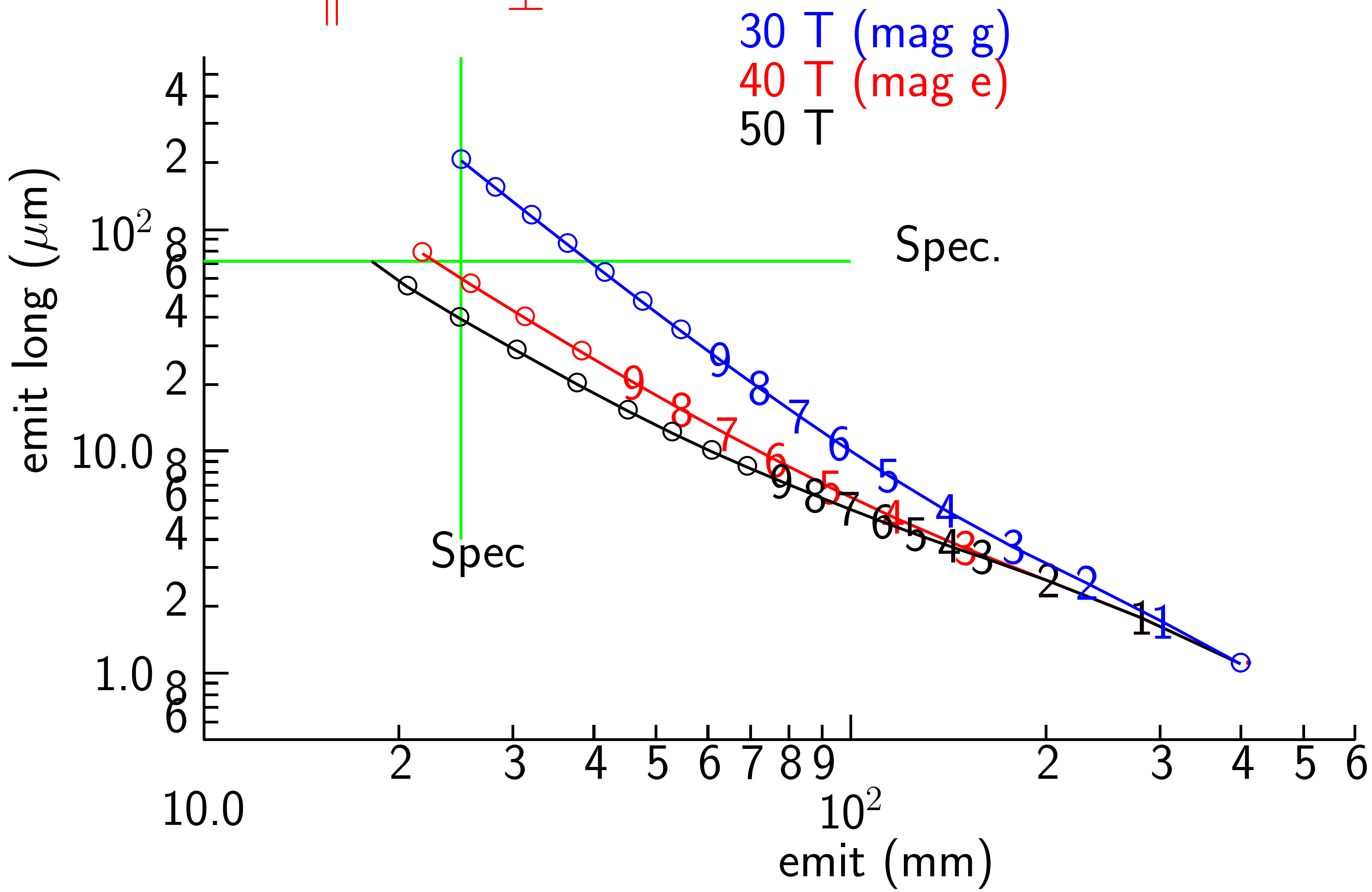
# Simulated performances for 30, 40, & 50 T




- Worse at start from amplitude effect on short bunches
- Worse at end from long emittance growth at low energies

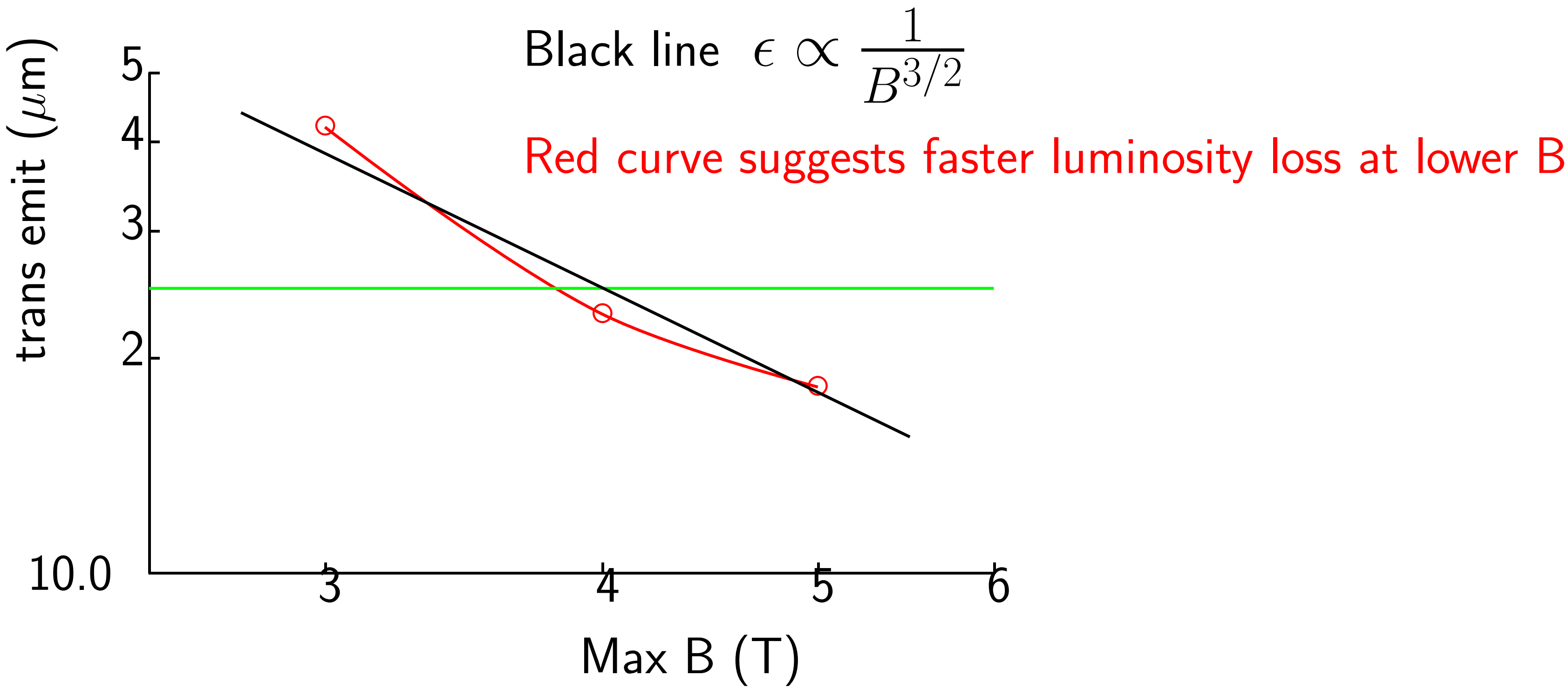
- Note: interpolation between solutions

# Simulated $\epsilon_\parallel$ vs. $\epsilon_\perp$




- 40 T solution meets emittance goals
- 50 T solution provides greater margin and/or improved performance
- 30 T does not meet emittance requirements

# Final $\epsilon_\perp$ at specified $\epsilon_\parallel$ vs. Max B (T)




- Counter-intuitive result
- But situation is complicated
- And optimization not yet automated

# Luminosity Consequences

- For fixed $\beta_\perp$ and $N_\mu$
  - $\mathcal{L} \propto 1/\epsilon_\perp \propto \mathrm{B}^{3/2}$

$$\frac{\mathcal{L}(30)}{\mathcal{L}(40)} = \left(\frac{30}{40}\right)^{3/2} = 0.64$$

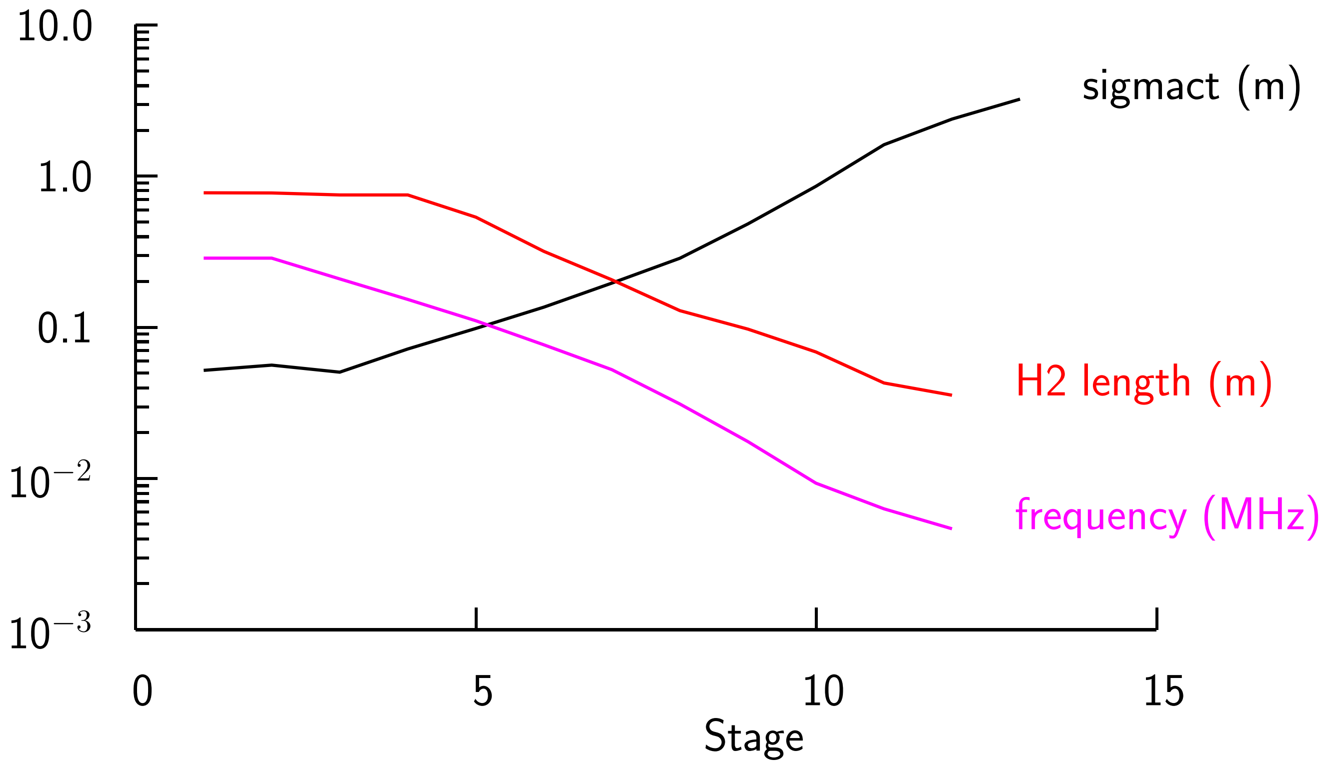
  - But this requires larger gradient IP quads

- For fixed IP quad gradients & locations, and fixed $N_\mu$
  - $\beta_\perp \propto \epsilon_\perp$
  - so $\mathcal{L} \propto 1/\epsilon_\perp^2$
  - $\mathcal{L} \propto \mathrm{B}^3$

$$\frac{\mathcal{L}(30)}{\mathcal{L}(40)} = \left(\frac{30}{40}\right)^{3} = 0.42$$

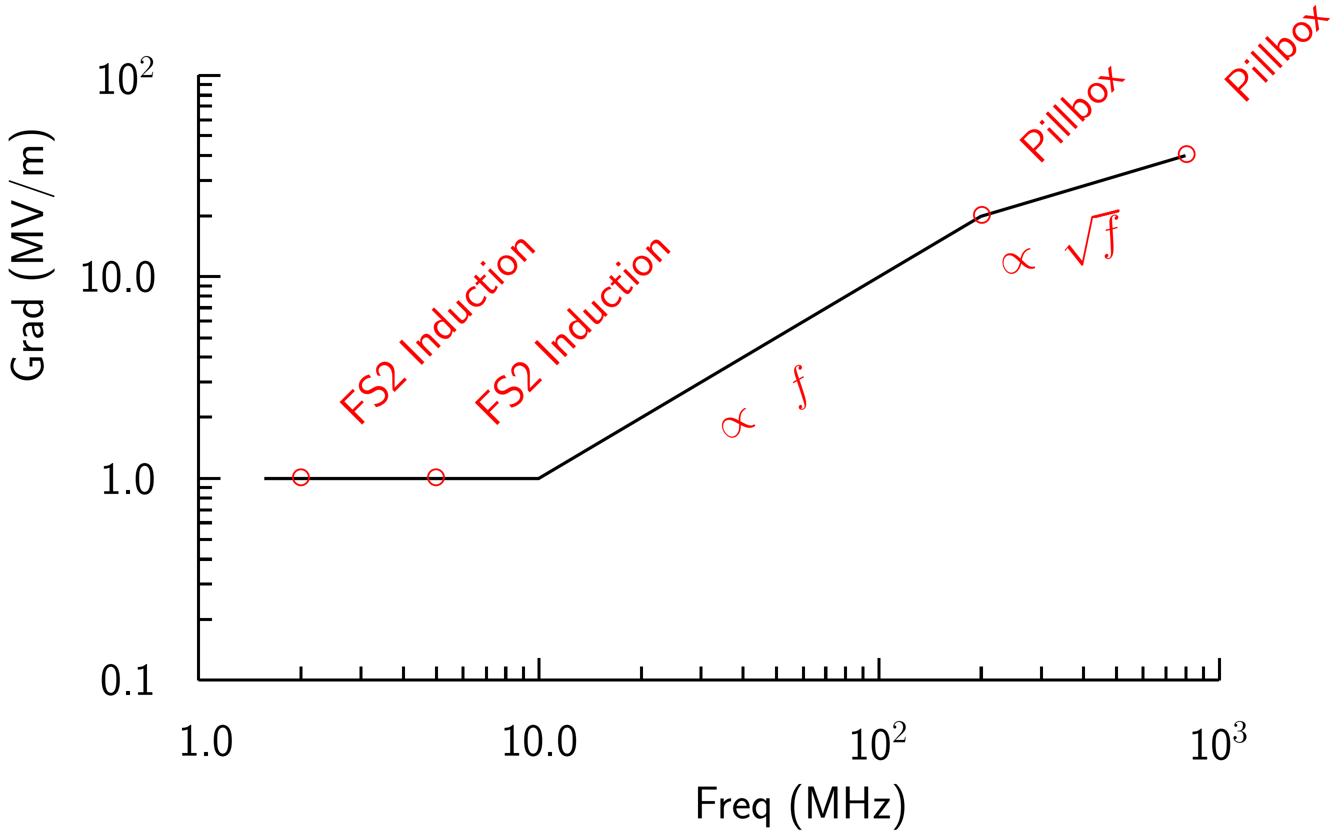
- But these scaling relations are very aapproximate and if $N_\mu$ can be increased, the losses are less

# Some Details of 40 T Solution



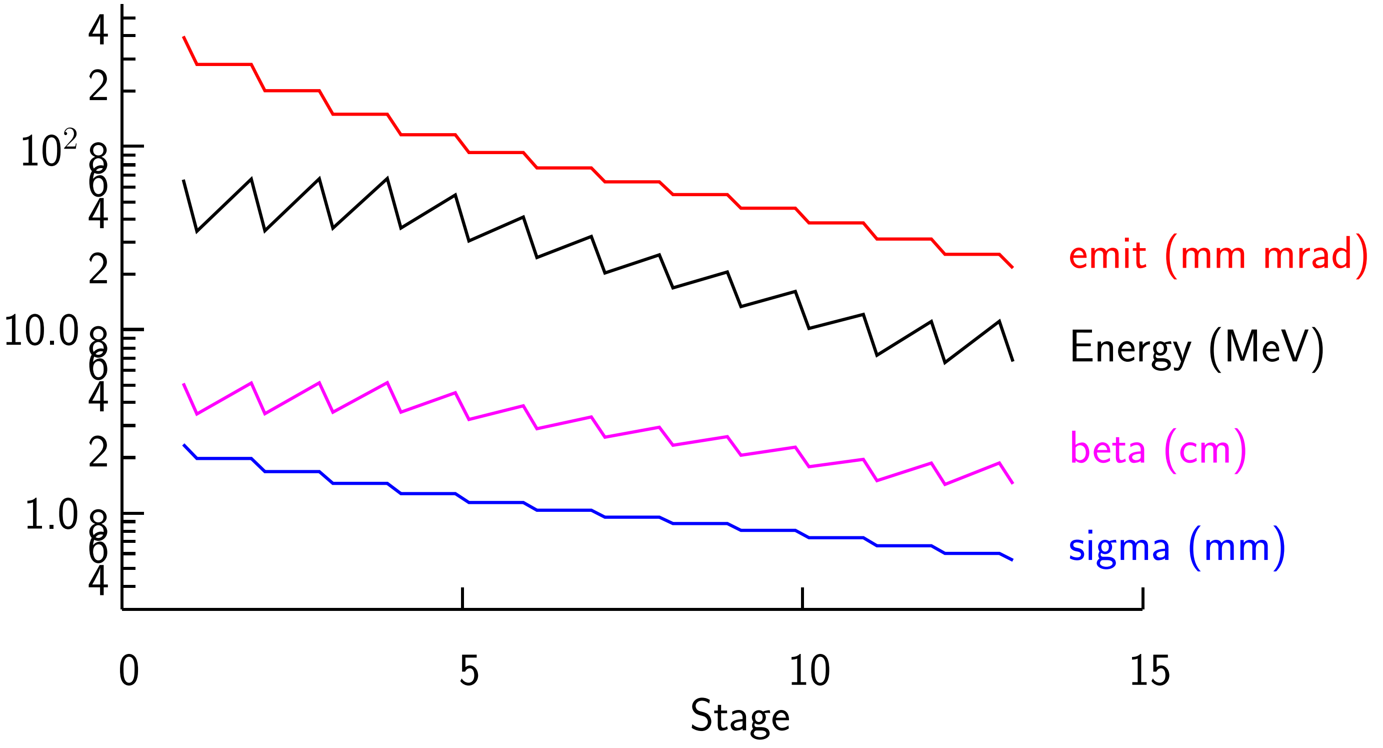

- Hydrogen and magnet lengths fall from 75 cm to $\approx$ 4 cm
- Bunch rms length rises from 5 cm to 300 cm
- RF frequency falls from $\approx$ 300 MHz to $\approx$ 4 MHz

# Assumed gradients




- Only induction linacs give required gradients for long bunches

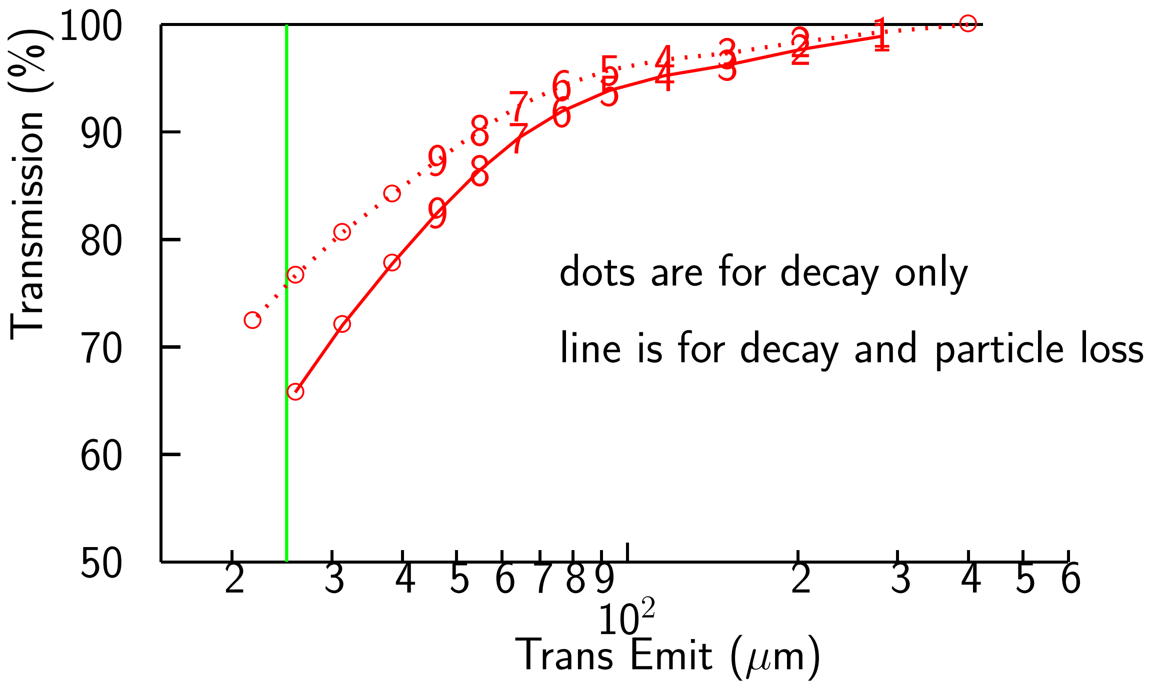
# More Details of 40 T solution




- Beam rms radii fall from 2 cm to ≈ 6 mm
- Beam energy falls from 70 MeV (135 MeV/c) to ≈ 6 MeV

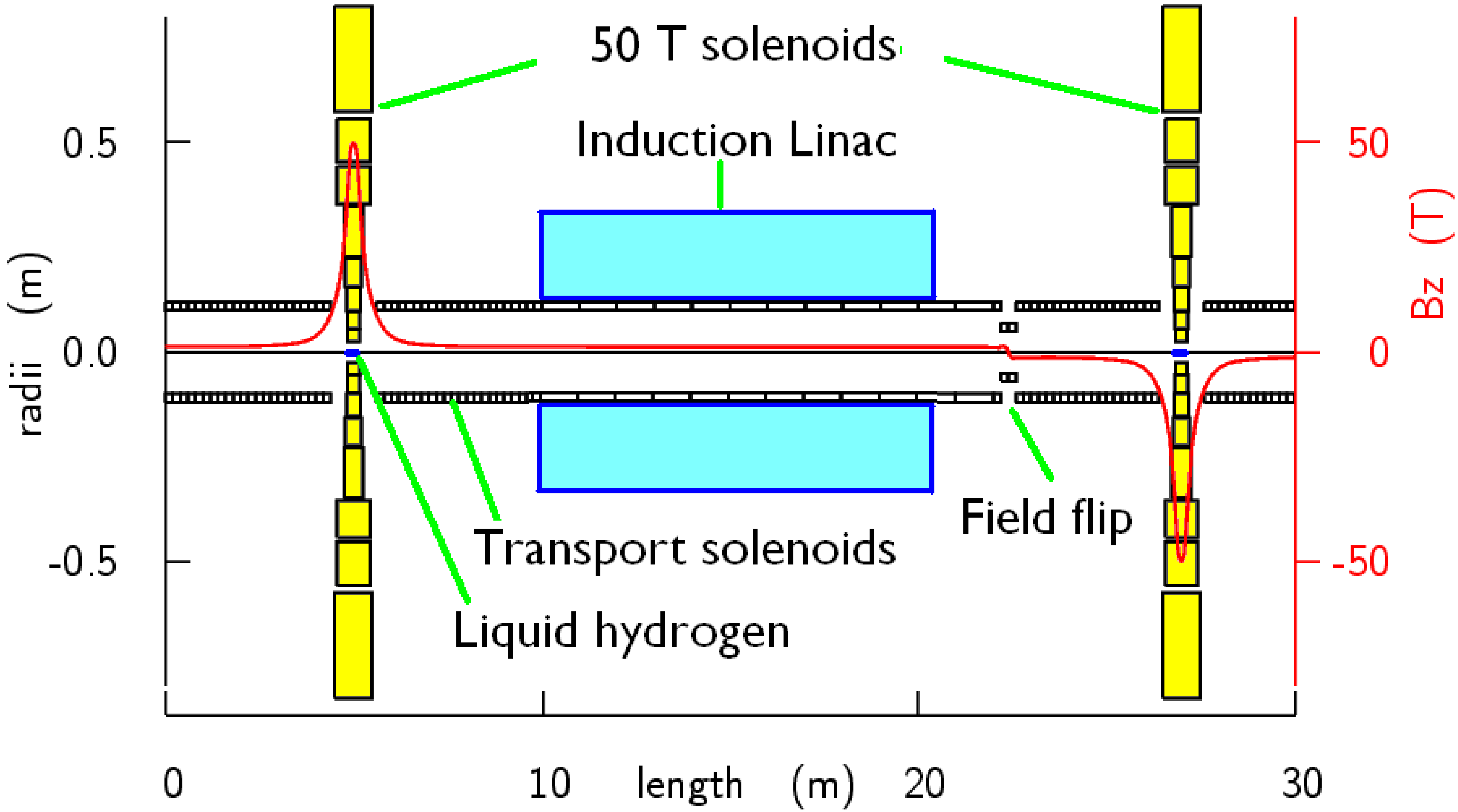
# Simulated transmission

- Muon losses from simulation
- Decay calculated from required drift and acceleration



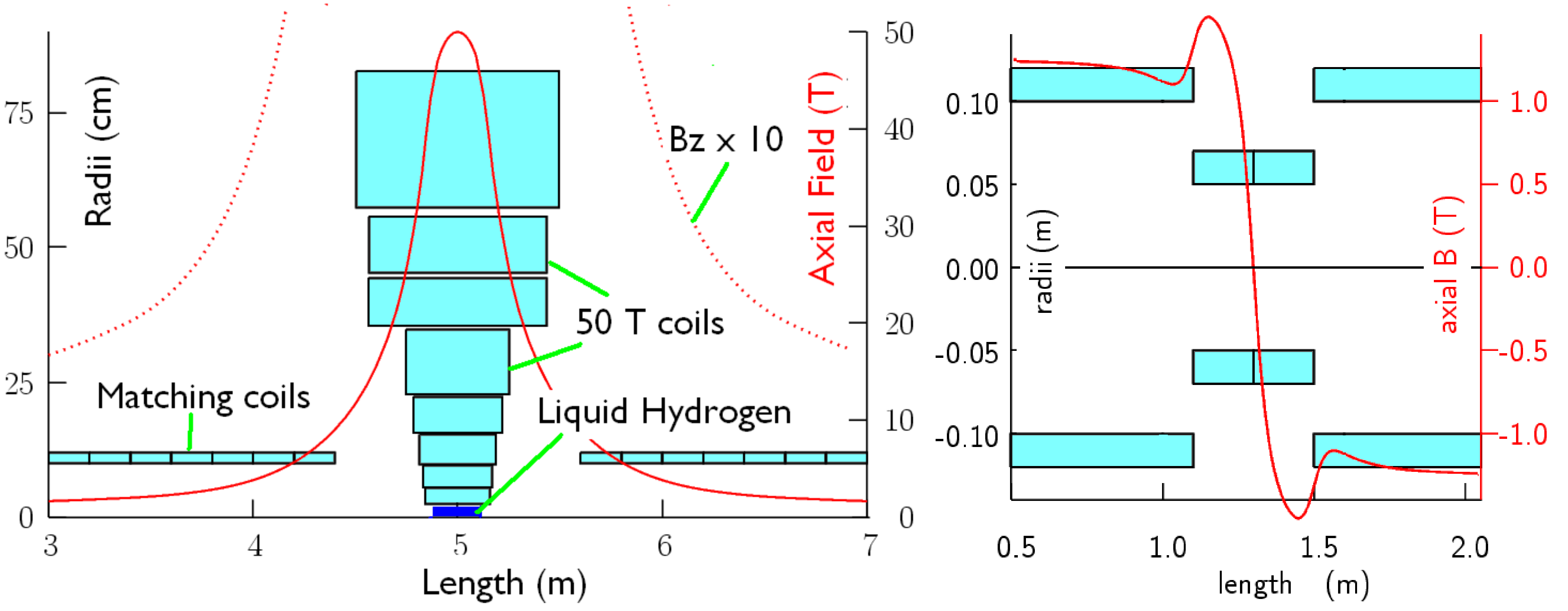

- Losses dominated by decay in phase rotation and acceleration
- Losses a little above goal: 65% vs. goal of 70%
- More than made up by other systems (discussed later)

# Example of matching & re-acceleration




- This example is from the 50 T sequence
- It includes the final and penultimate stages

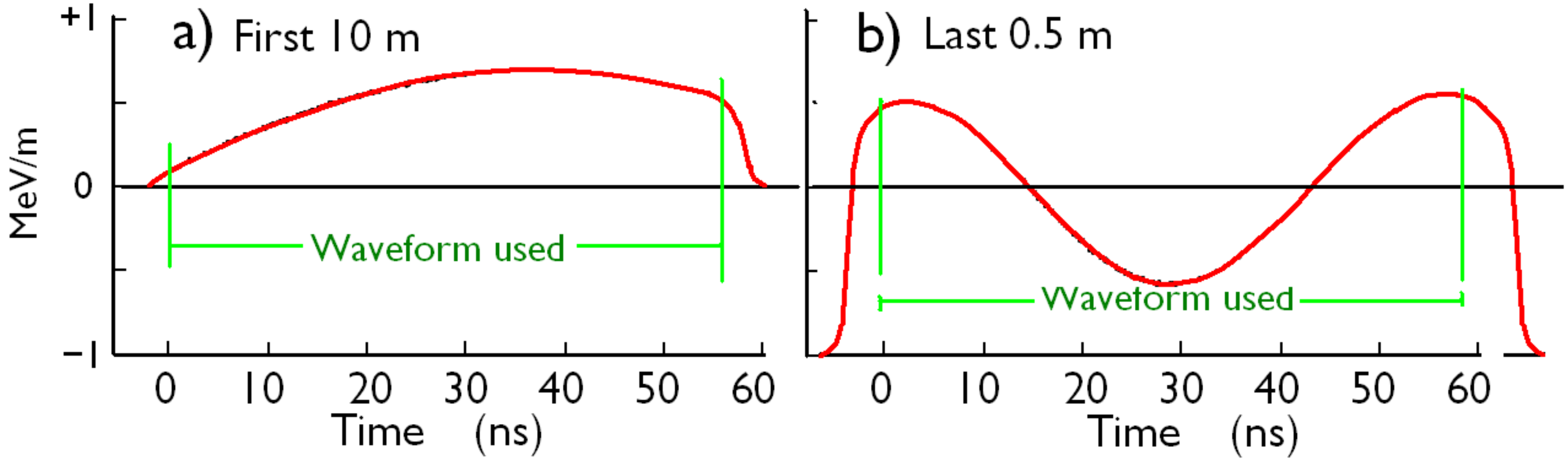
# Detail of 50 T matching & field flip




- Adiabatic match from 50 T → 1.25 T
- Rapid field flip with beta matching

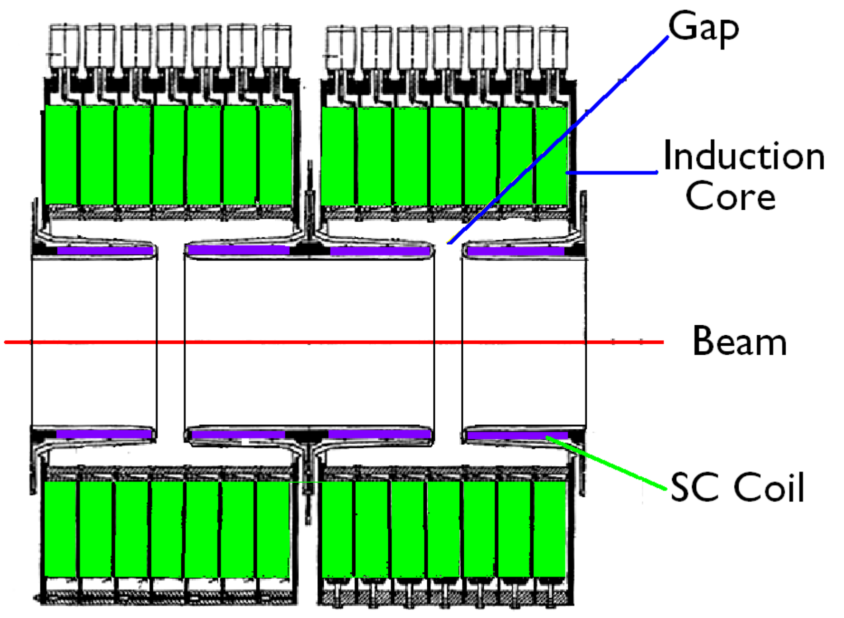
# Induction Linac

Induction Linac
Waveforms

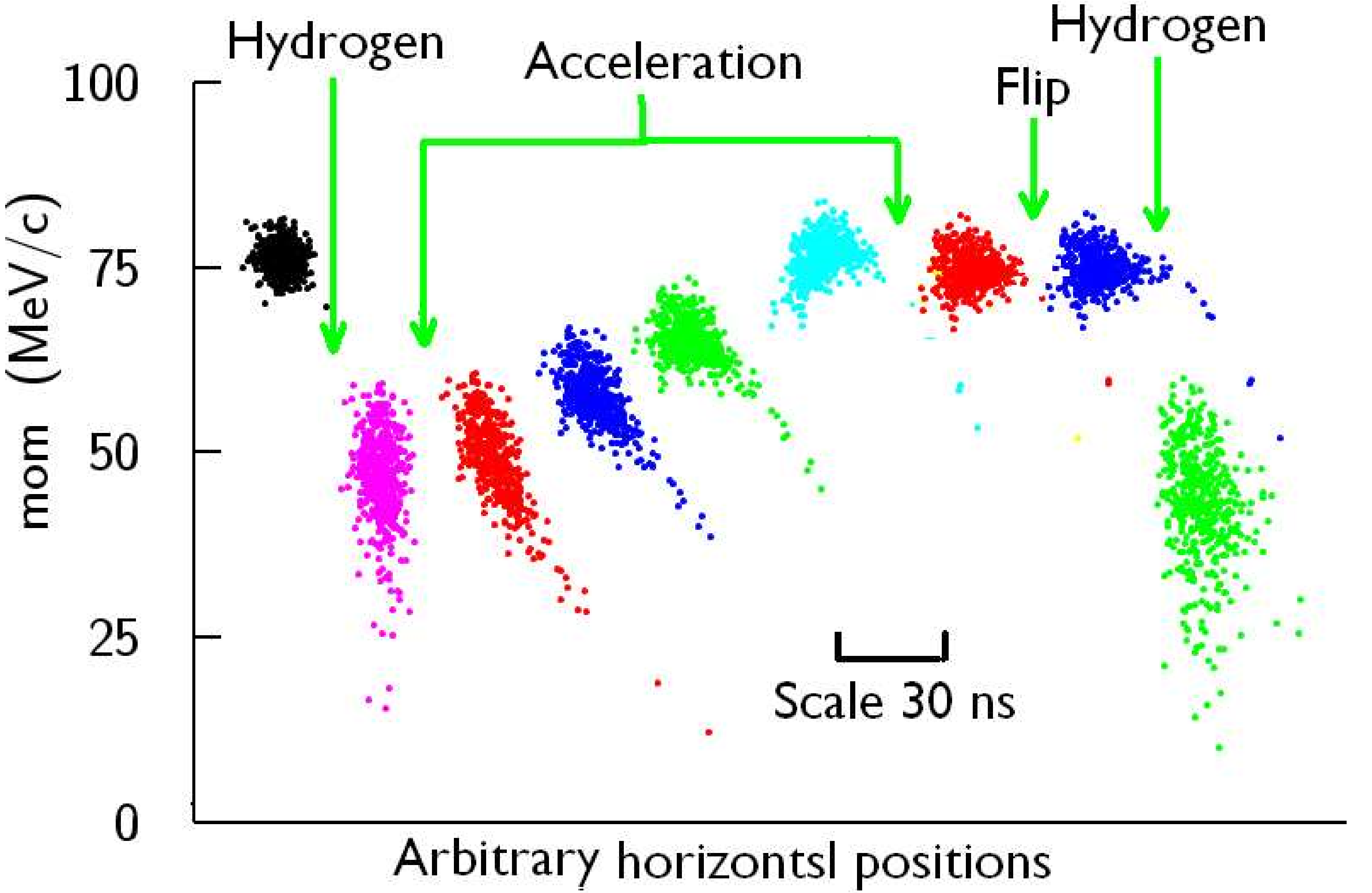



- Real solution would use single modified pulse shape

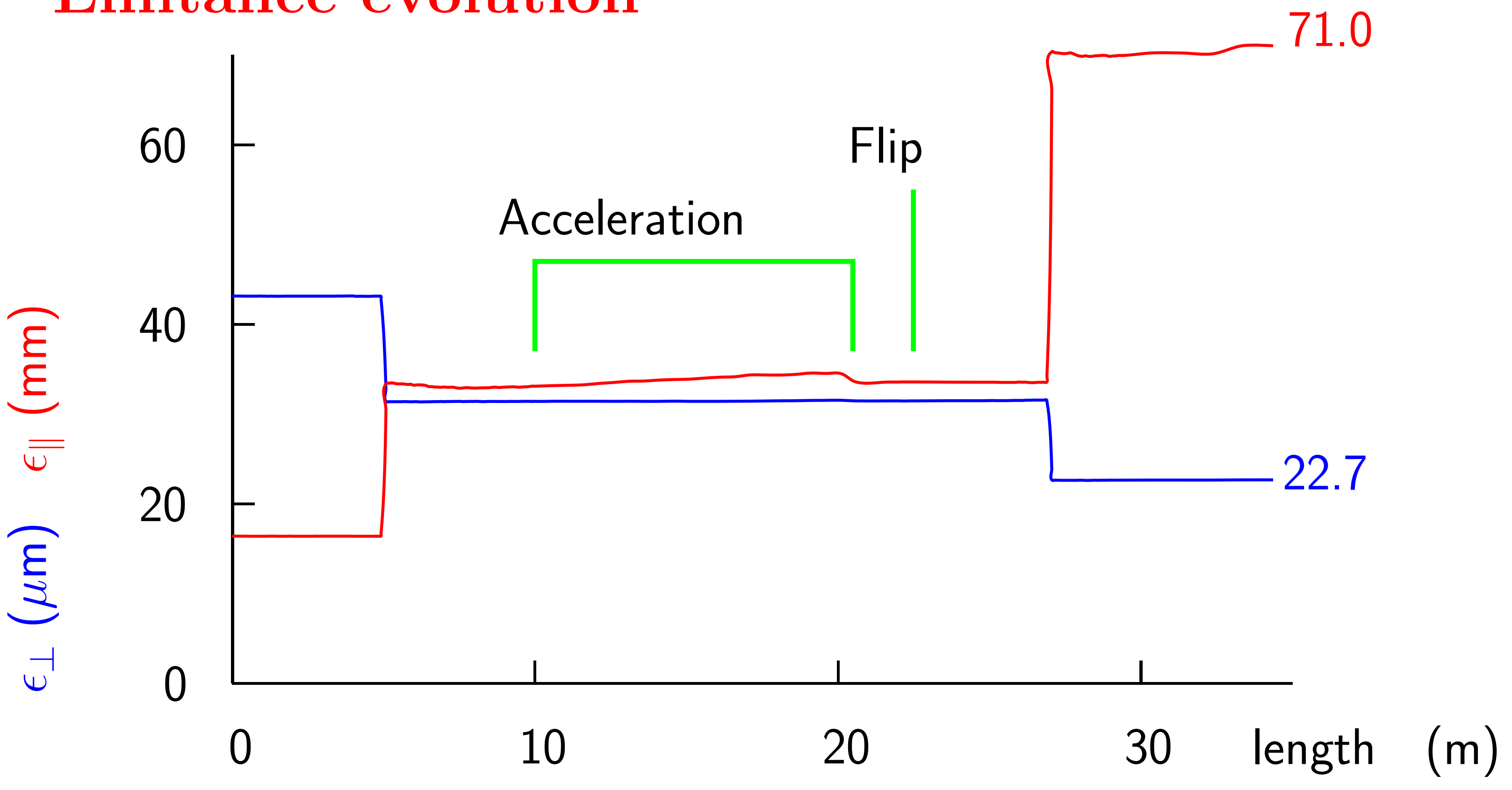
Study II
Induction design



# Phase space evolution



# Emitance evolution




- In match and re-acceleration:

  0.01% $\epsilon_\perp$ dilution    0.5% $\epsilon_\parallel$ dilution    7.3% loss

- Negligible dilutions justify design assumption above

# System Transmission

Example from recent compilation with 8 GeV protons and MARS 15:

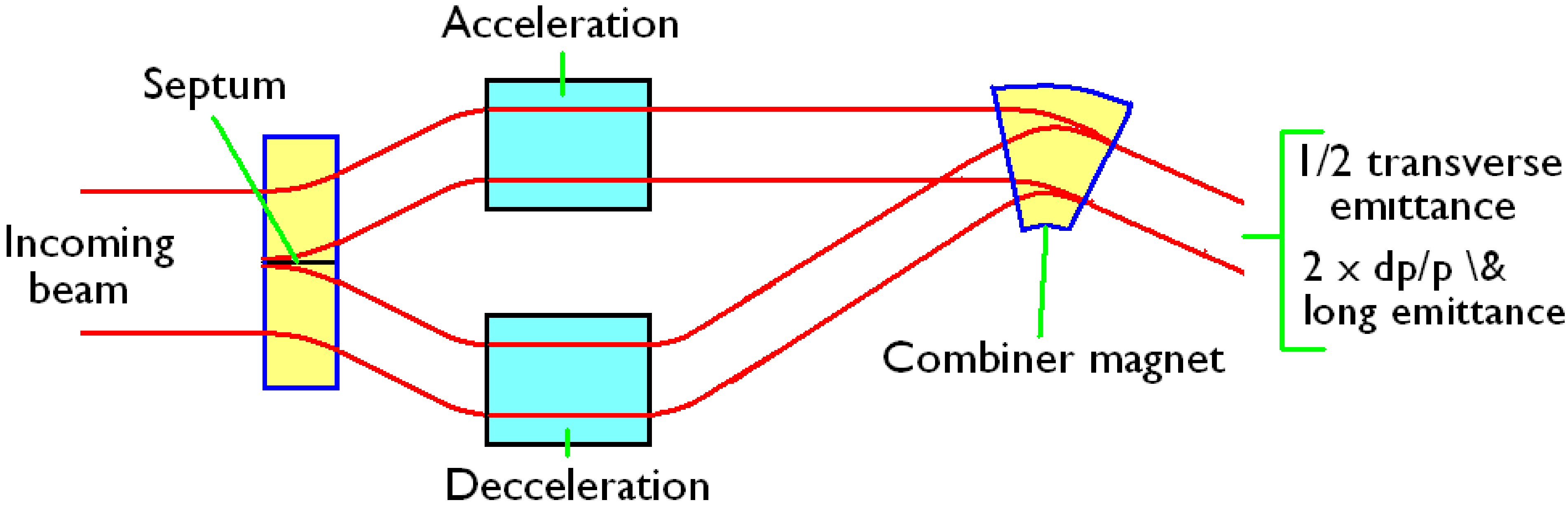
| | transmission | cumulative | mu/p |
|---|---|---|---|
| After rotation | | 1.0 | 0.219 |
| Best 21 bunches | 0.7 | 0.7 | 0.153 |
| Charge separation | 0.9 | 0.63 | 0.138 |
| 6D Cooling before merge | 0.47 | 0.30 | 0.065 |
| Merge | 0.88 | 0.26 | 0.057 |
| 6D Cooling after merge | 0.48 | 0.12 | 0.027 |
| 40 T Cooling | 0.65 | 0.08 | 0.018 |
| Acceleration | 0.7 | 0.057 | 0.0125 |

- 40 T cooling has higher losses than goal
- But made up by improved production at 8 GeV
- For 2 $10^{12}$ muons requires 1.6 $10^{14}$ 8 GeV protons/bunch
- Power at 15 Hz: 3.1 MW (cf 4 MW baseline)
- We still have a margin

# Other Final Cooling schemes to study

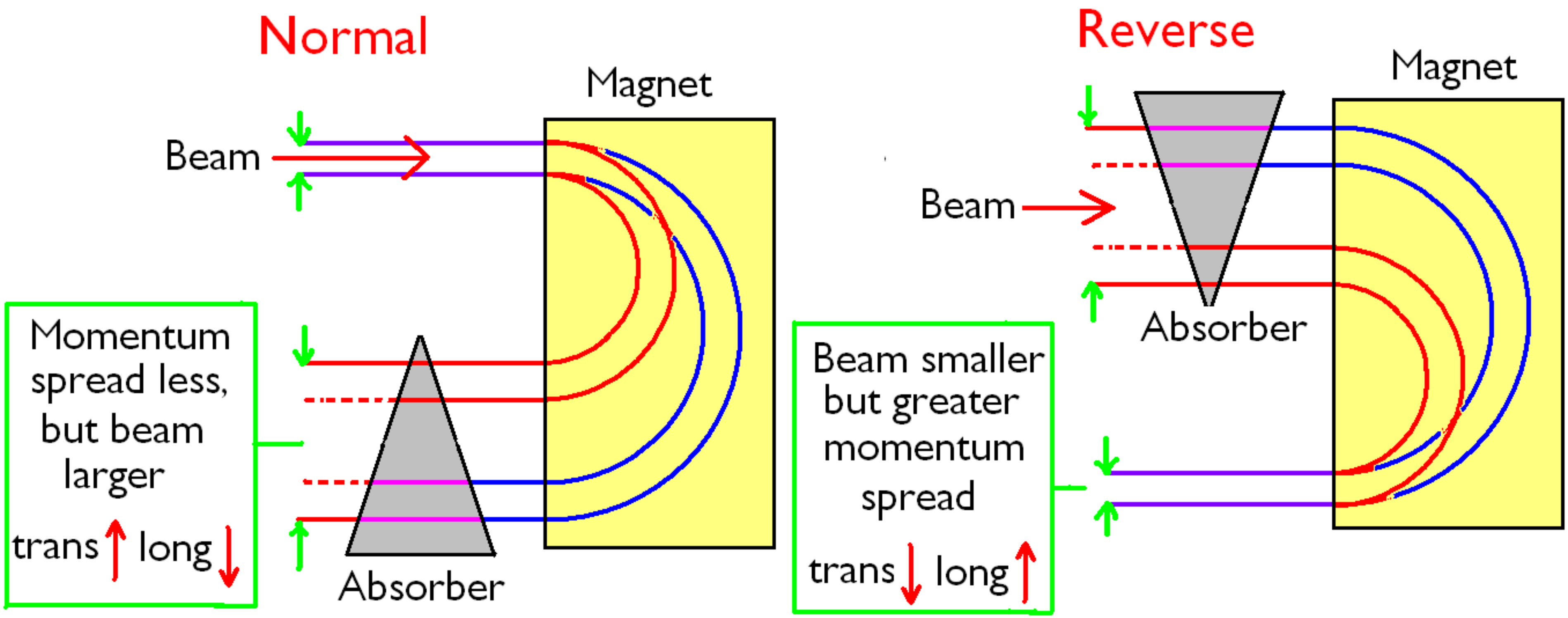
- The object is to achieve lower transverse emittances
  - to allow lower muons/bunch at higher rep. rate
  - easier p driver, less collective effects,
  - less detector background
- Reverse emittance exchange in wedges
  Could be done inside 40 T solenoids
  Not yet simulated
- Emittance exchange at higher energy using septa
  Not yet simulated
- Use of either requires more efficient earlier cooling

# Septum emittance exchange




- Should be done also in orthogonal direction
  or use septa in x and y followed by 4 channels
- Can be done at any energy
- Will be less efficient than 40-50 T cooling for $\epsilon_\perp > 25 \ \mu$m
  but, in principle, will work for any emittance

# Reverse emittance exchange in wedges




- Still requires low beta from strong solenoid
- But lowers emittance faster, is less affected by scattering
- Can exchange to lower emittances

# TASKS

- Include hydrogen windows
- Automate optimization of multi-stage systems
  to reduce possible systematic errors

- Simulate full sequence of stages at chosen field
- Study space charge and loading
- Confirm simulations using G4-beamline

- Integrate into full capture-cool-acceleration scheme
  - Design late 6D cooling to match required 135 MeV/c mom.
  - Design initial acceleration of 6 MeV, very long, output bunches
- Demonstrate 40 T solenoid (discussed in later talks)
- Study schemes for lower emittances

# Conclusion

- Sequence of 40 T cooling stages appears to meet emittance goals
  - Sequence of 50 T solenoids would give more margin, lower emittance and somewhat improved luminosity
  - 30 T solution would cause significant performance loss (factor 0.4 - 0.6)
- Lower transmission (65% vs. 70%) of 40T solution appears more than compensated by gains elsewhere
- Simulation of matching and re-acceleration between last stages showed negligible dilution and acceptable transmission
- Two methods that might get to lower transverse emittances need study
  But they probably require improvements in 6D cooling
- There is much work still to be done