MUON COLLIDER FINAL COOLING IN 30-50 T SOLENOIDS

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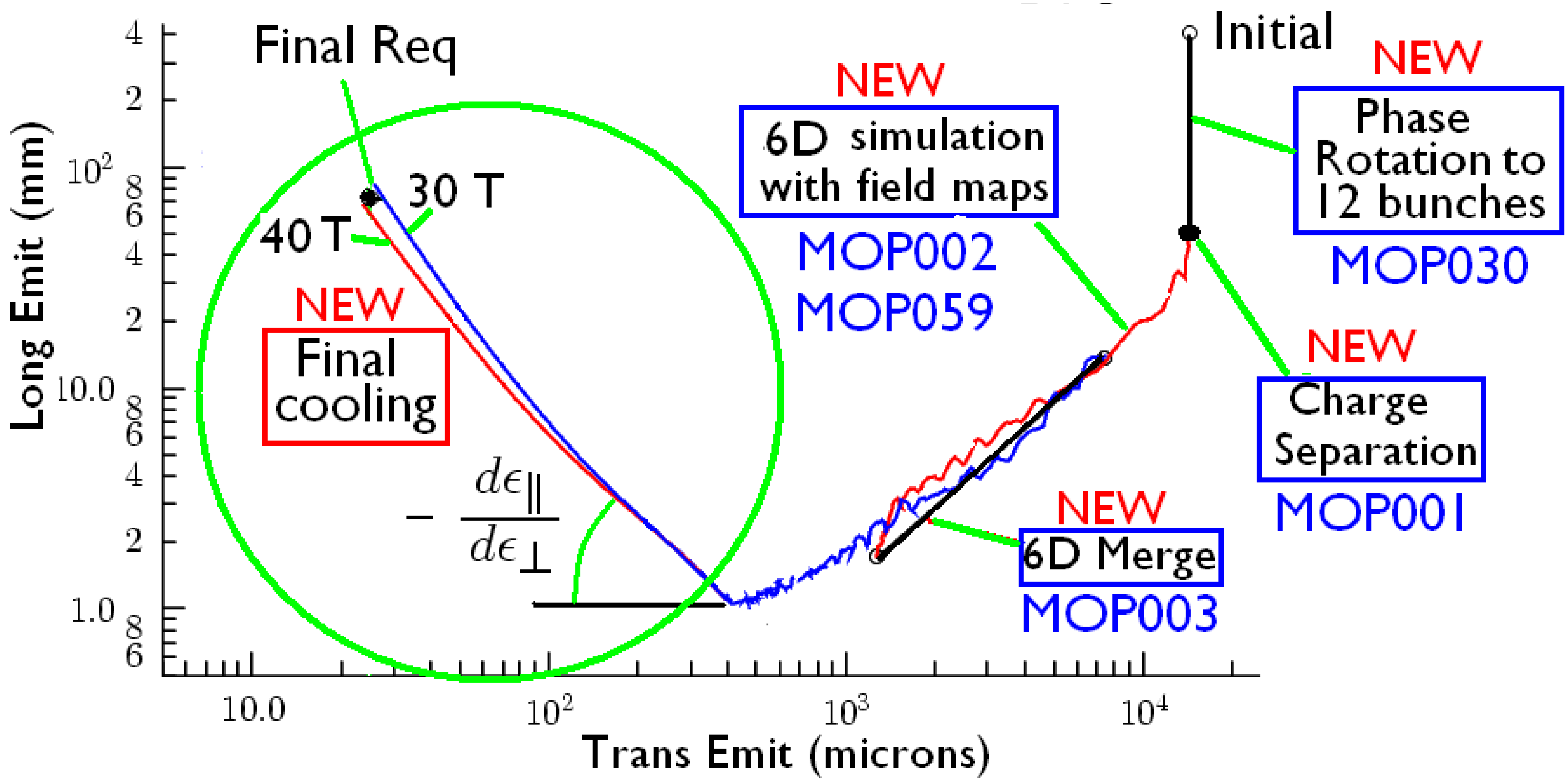


Simulations of ionization cooling scheme for Muon Collider

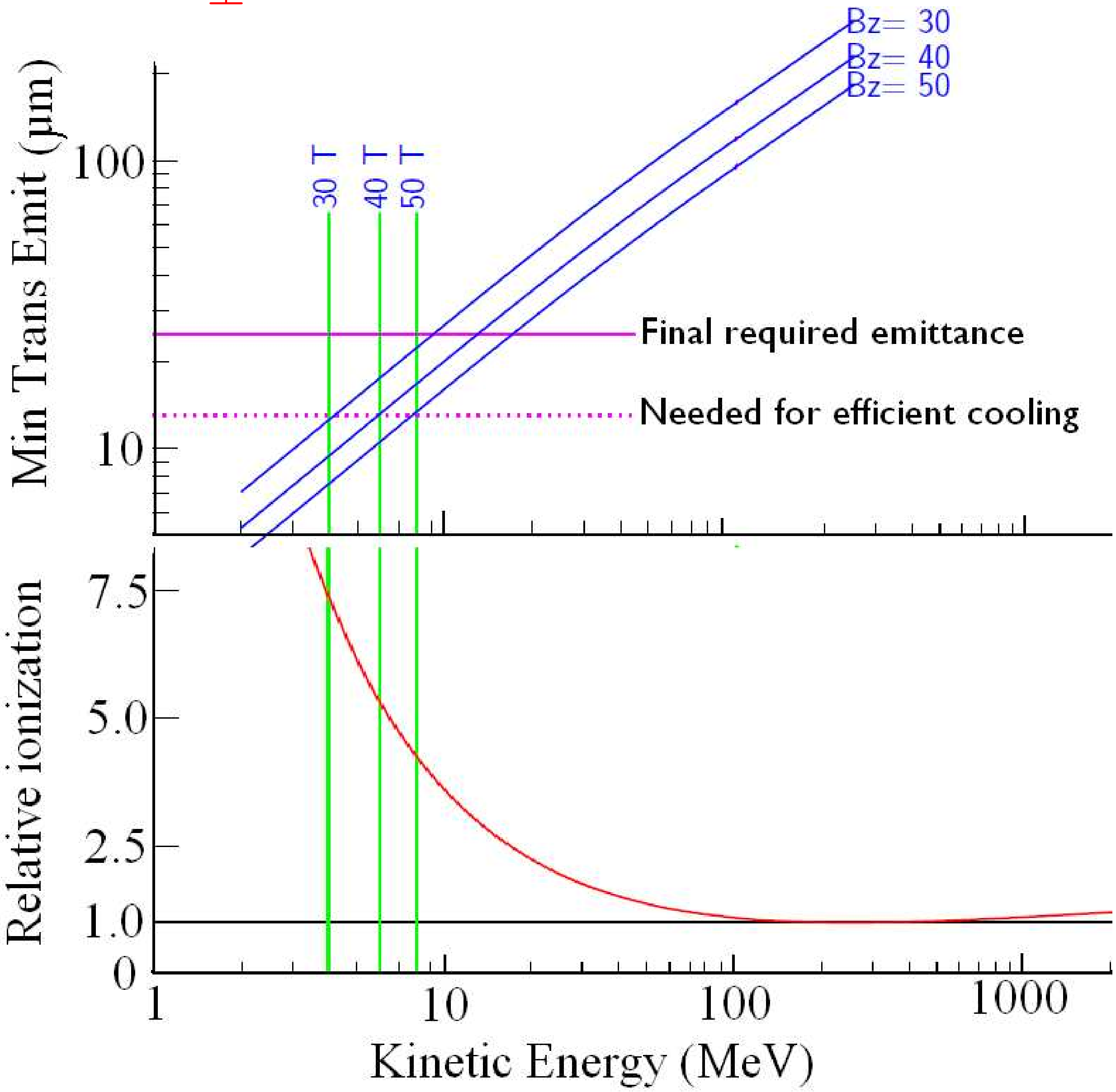
Ionization Cooling to low $\epsilon_\perp$ in Solenoids

$$\epsilon_{x,y}(\min) \;\propto\; \frac{E}{B\; L_R\, dE/dz}$$

- Lower E focuses stronger & increases dE/dz
  $\rightarrow$ lower $\epsilon_{x,y}(\min)$

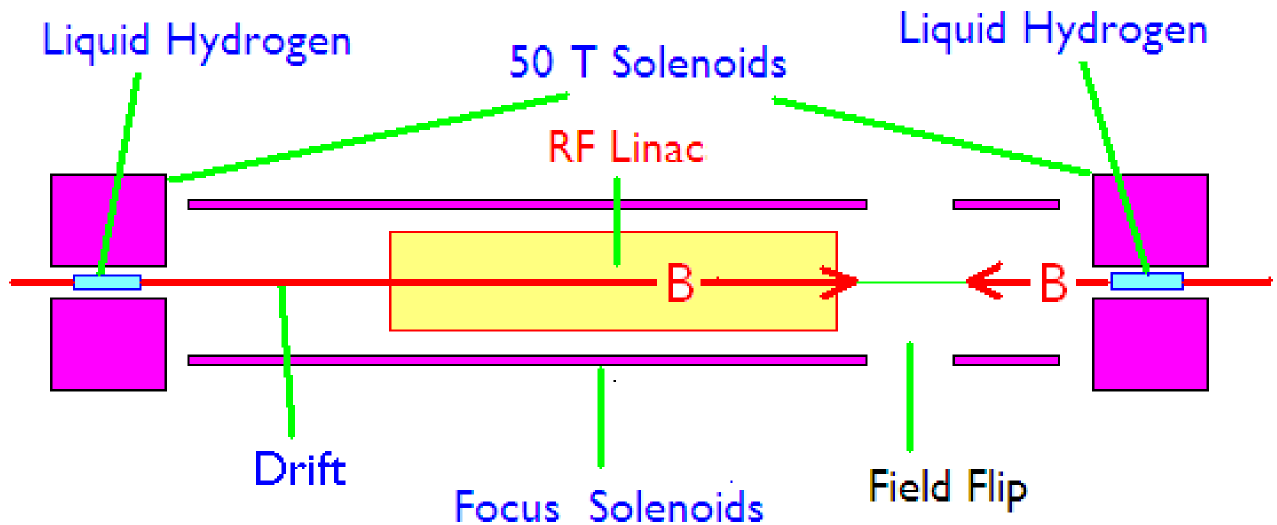
- But it increases dE/E from neg slope
  $\rightarrow$ Increased $\epsilon_{||}$

- This is acceptable

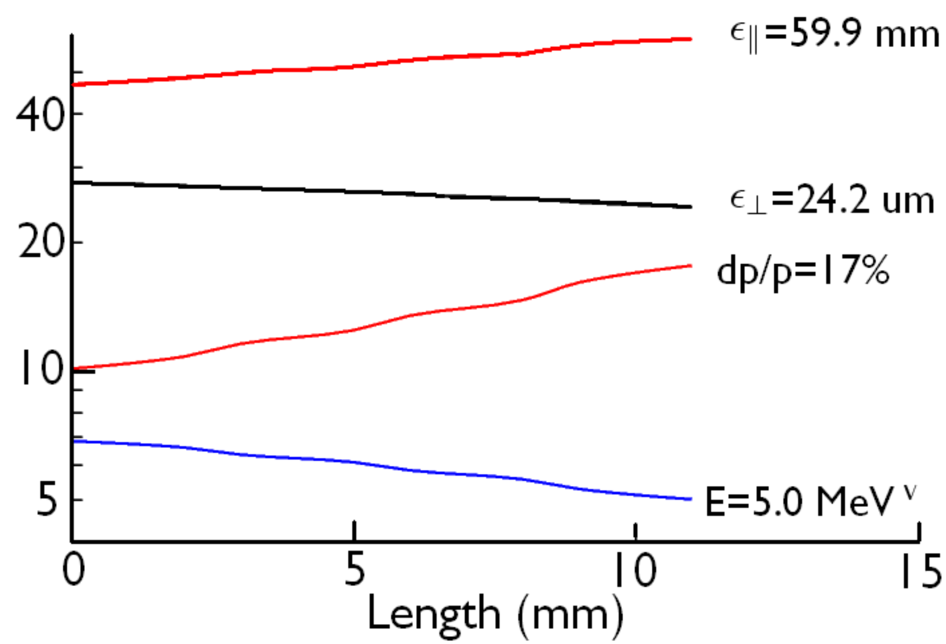


One (of ≈ 14) Stage of Final Cooling

Schematic



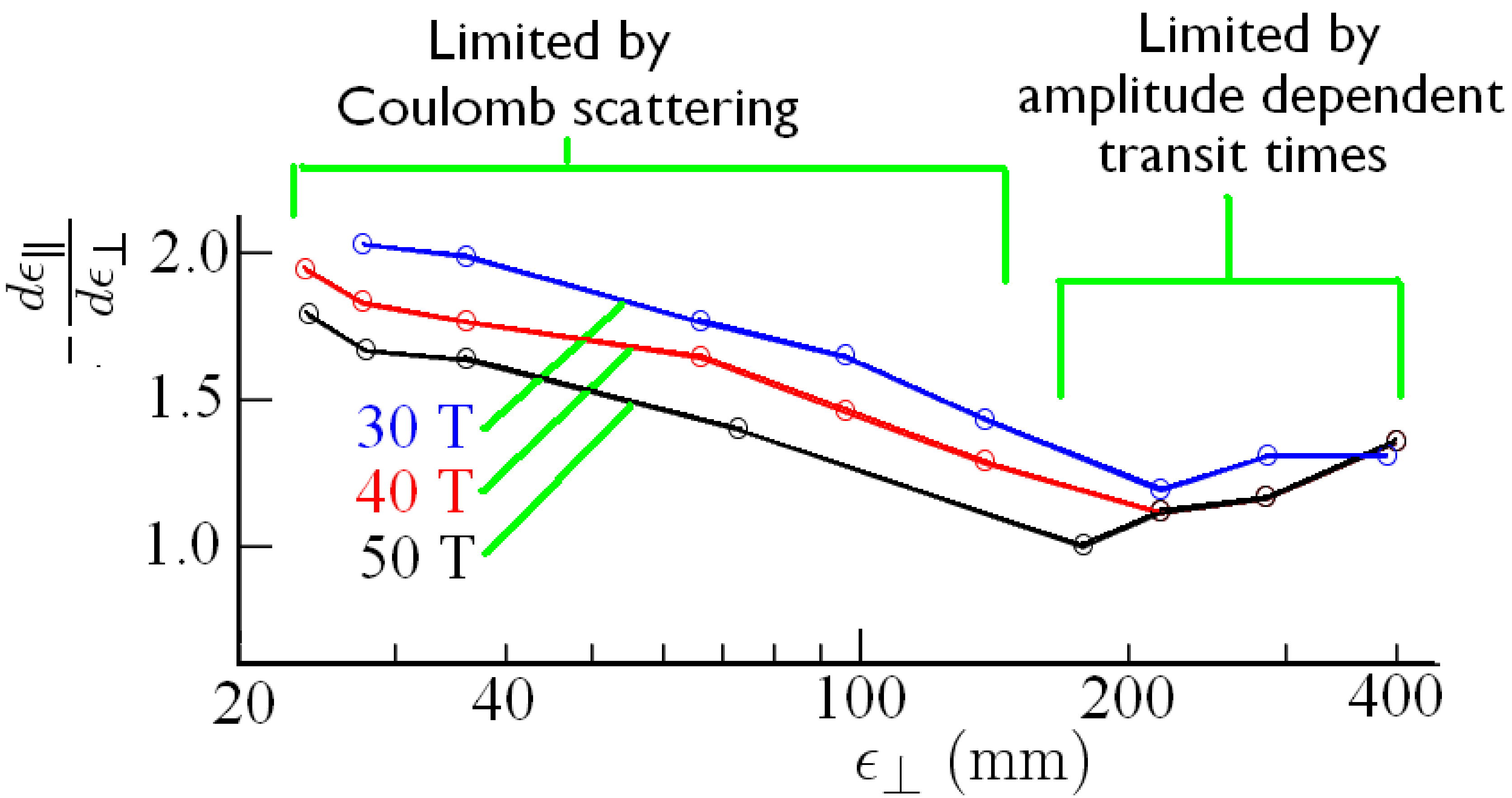
Example parameters vs length from ICOOL simulation of cooling in the hydrogen absorber in 40 T solenoid



Optimization of each stage to minimize slopes $\frac{d\epsilon_\parallel}{d\epsilon_\perp}$

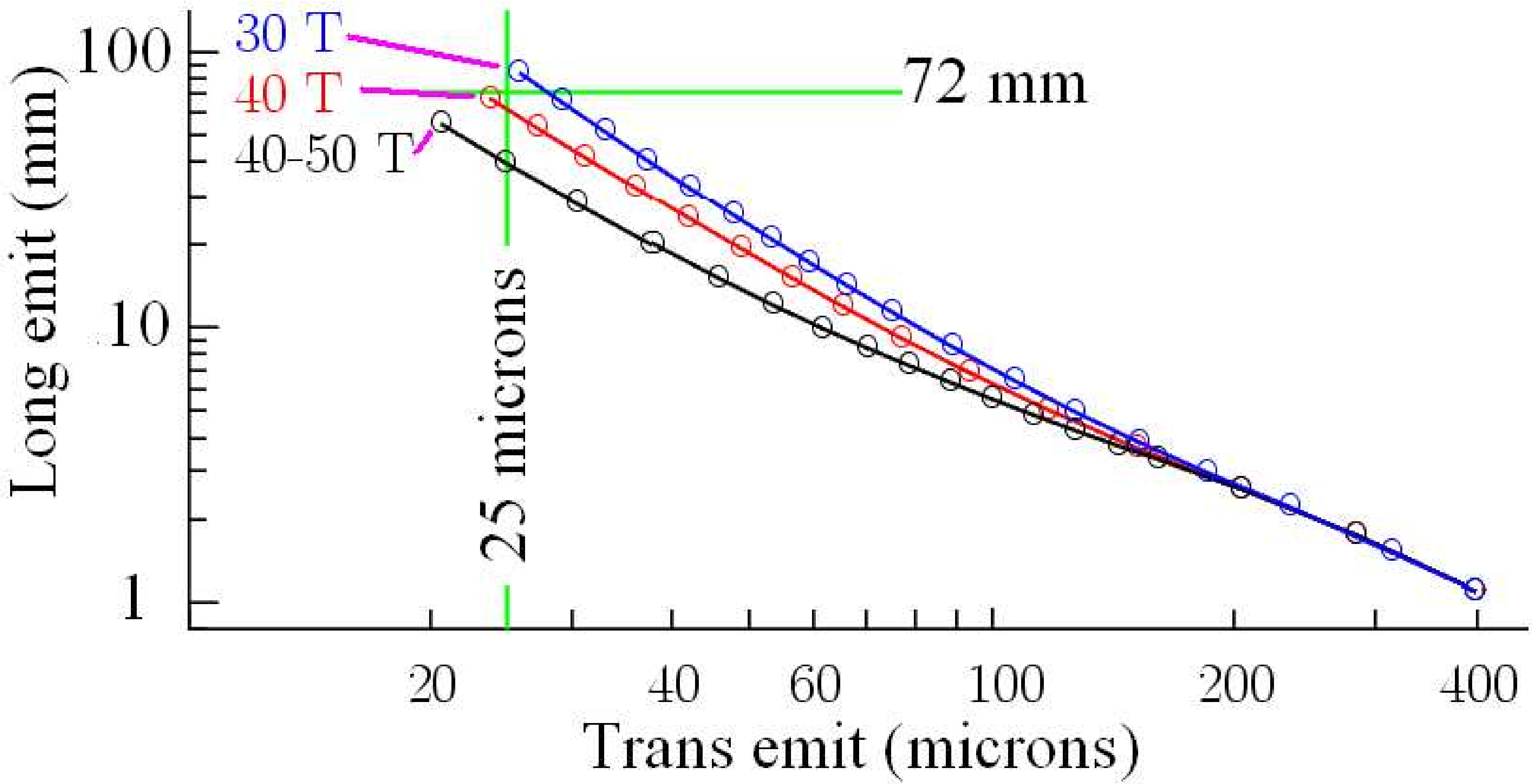
(Slope 2.0 $\equiv$ constant 6D emittance)

- Adjusting initial E, dE/E, and Length, to minimize slopes
- Assuming ideal matching & re-acceleration



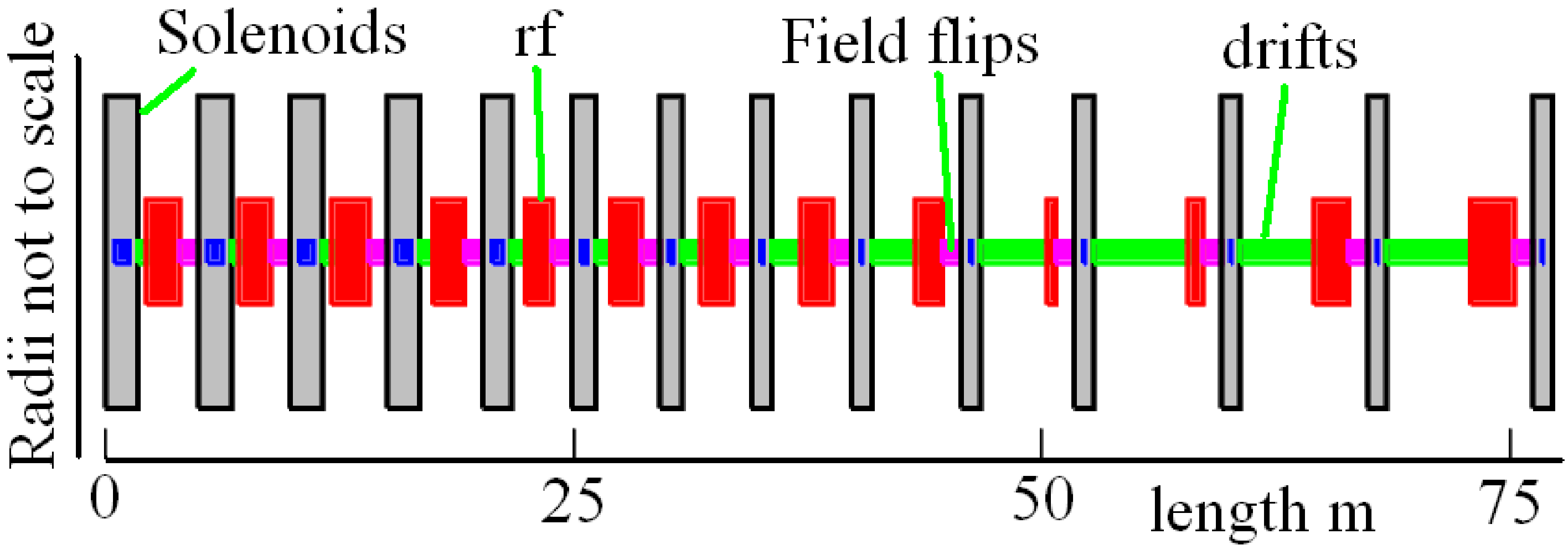
Longitudinal vs. transverse emittances for 3 B_{sol} fields.

- Assuming negligible dilution in match & re-acceleration



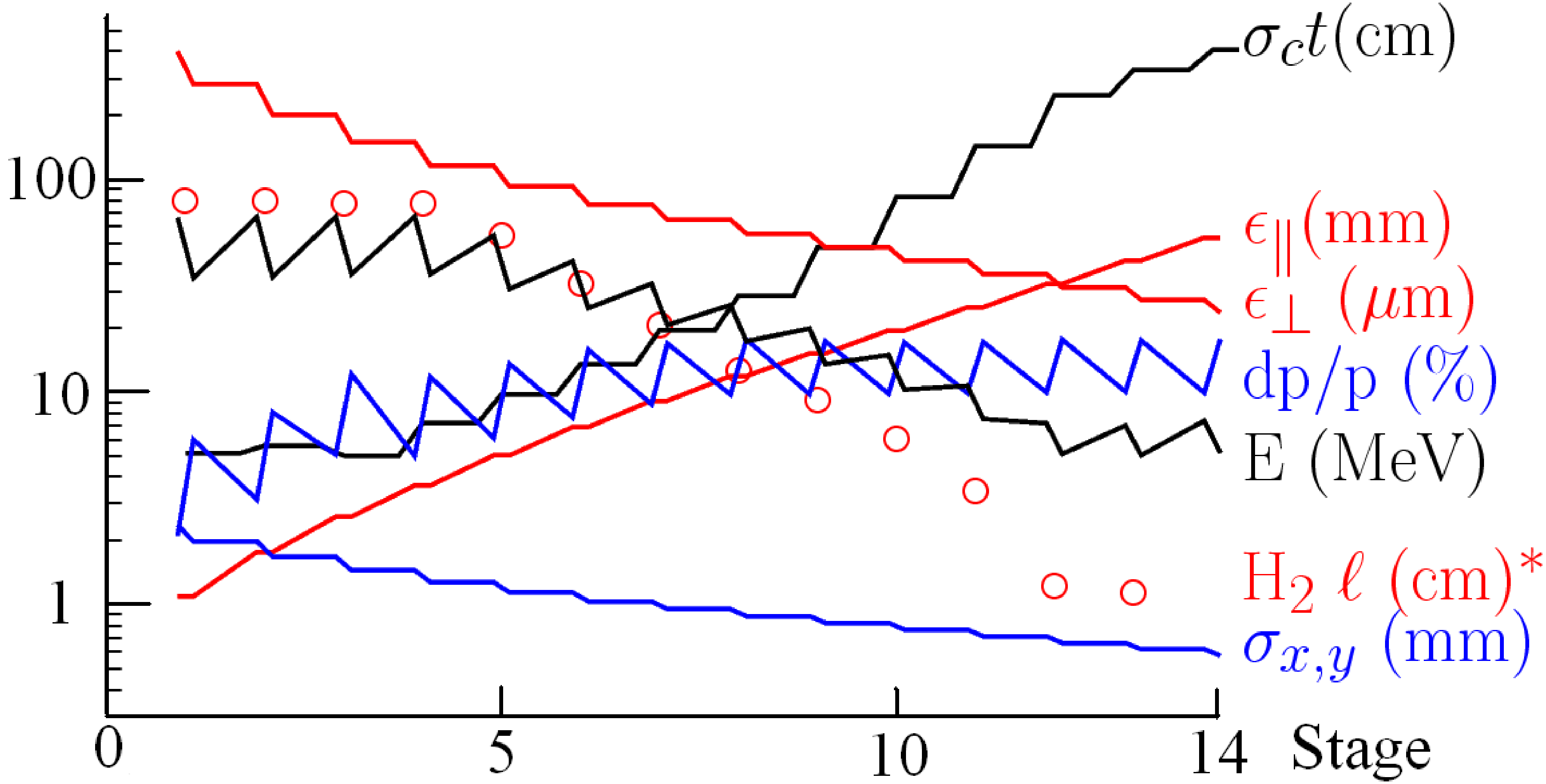
- 40 T meets requirements
- 30 T close enough to be acceptable

Lengths of elements in 40 T sequence



- Drifts for phase rotation to match bunch lengths longer at end from long bunches
- Absorber and magnet lengths longer at start

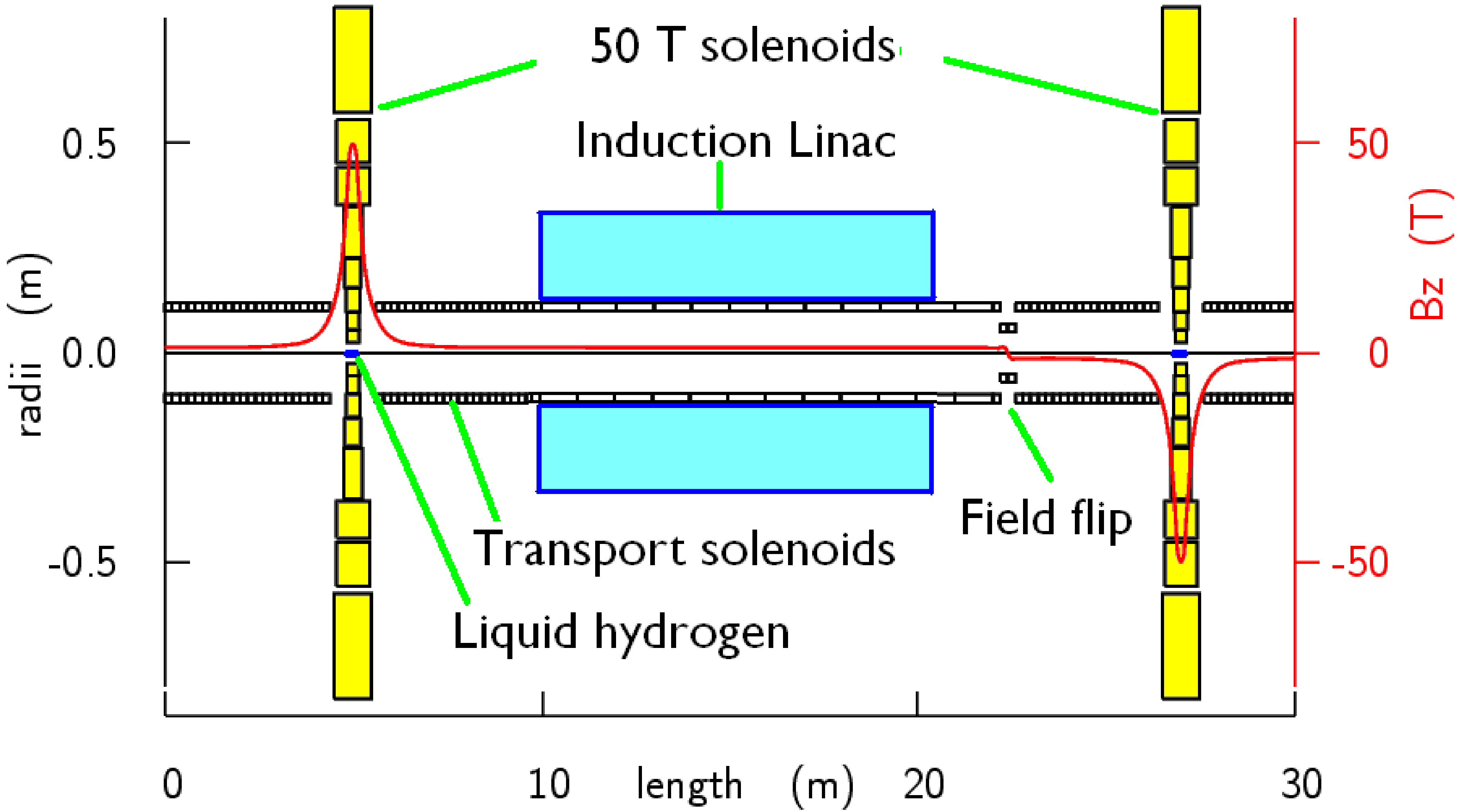
Parameters vs. stage for the 40 T sequence



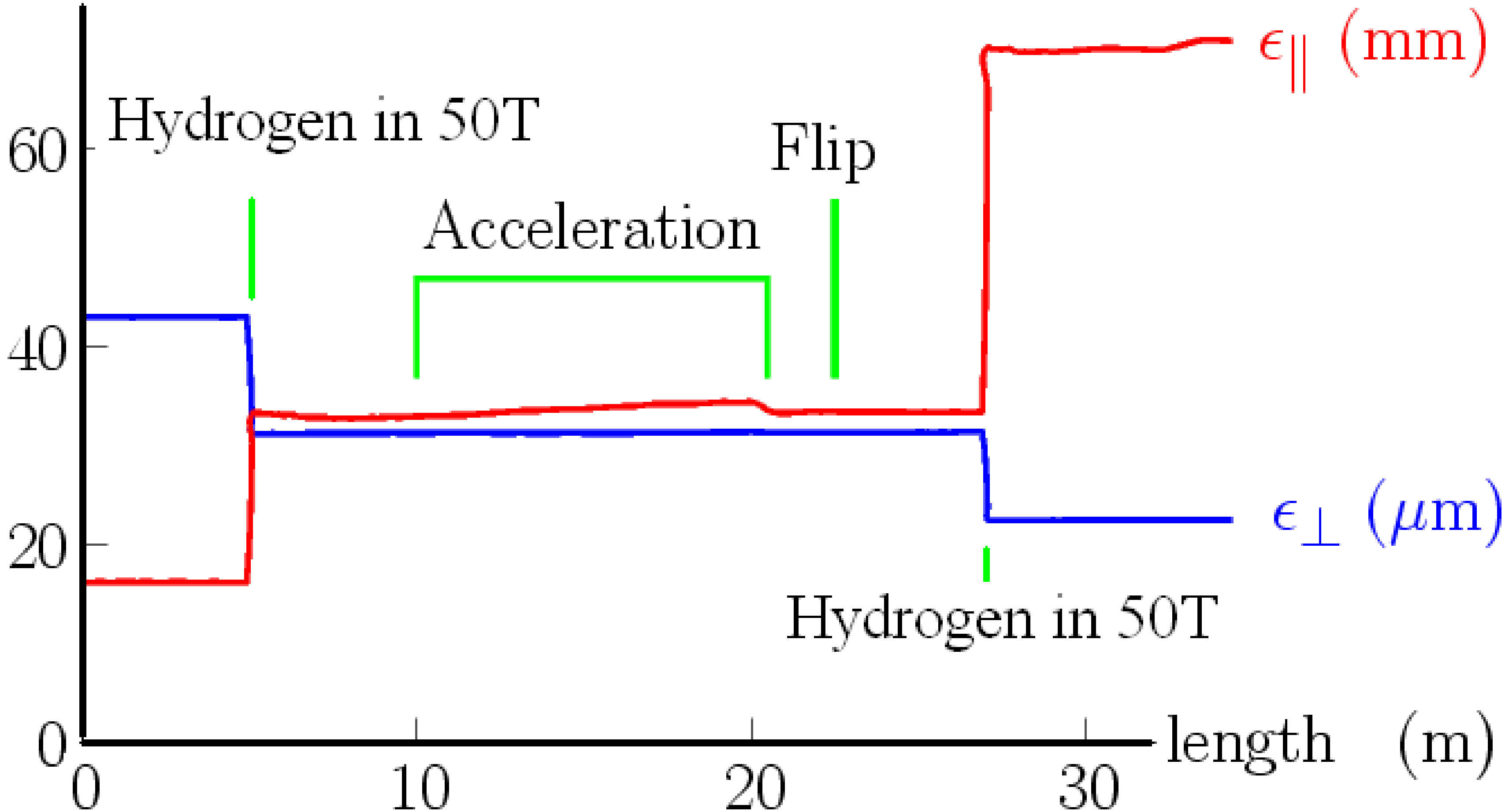
- Bunch lengths 6 cm at start, to 4 m at requiring 200 MHz (15 MV/m) at start to Induction linacs (1 MV/m)
- Beam gets very small σ 0.65 mm
- Hydrogen 75 cm at start, to 1.2 cm, (* $\approx$ 100 x longer if gas)

Matching & acceleration

So far, done only between last 2 stages with 50 T



ICOOL simulation with match & re-acceleration



- Negligible dilution in match and field flip
- Loss less than analytic estimate

Conclusion

- Final Cooling to 25 μm can be achieved in 30-50 T solenoids at sufficiently low energy
- Matching and re-acceleration simulated for one case : last two stages with 50 T which showed negligible dilution
- Assuming negligible dilution for all cases:
  - Sequences meet requirements with 40 & 50 T
  - 30 T probably also acceptable
- Post Script (not in paper)
  - If gas used for stages 12-14, max pressure 2.2 Atm
  - If 15 degree liquid used for 1-11 then pressures $<$ 4 atm.
  - 6.5 mm diam. aluminum windows for 7 atm are 4 μm thick
  - Simulated effect of windows reduces cooling rate by 3%

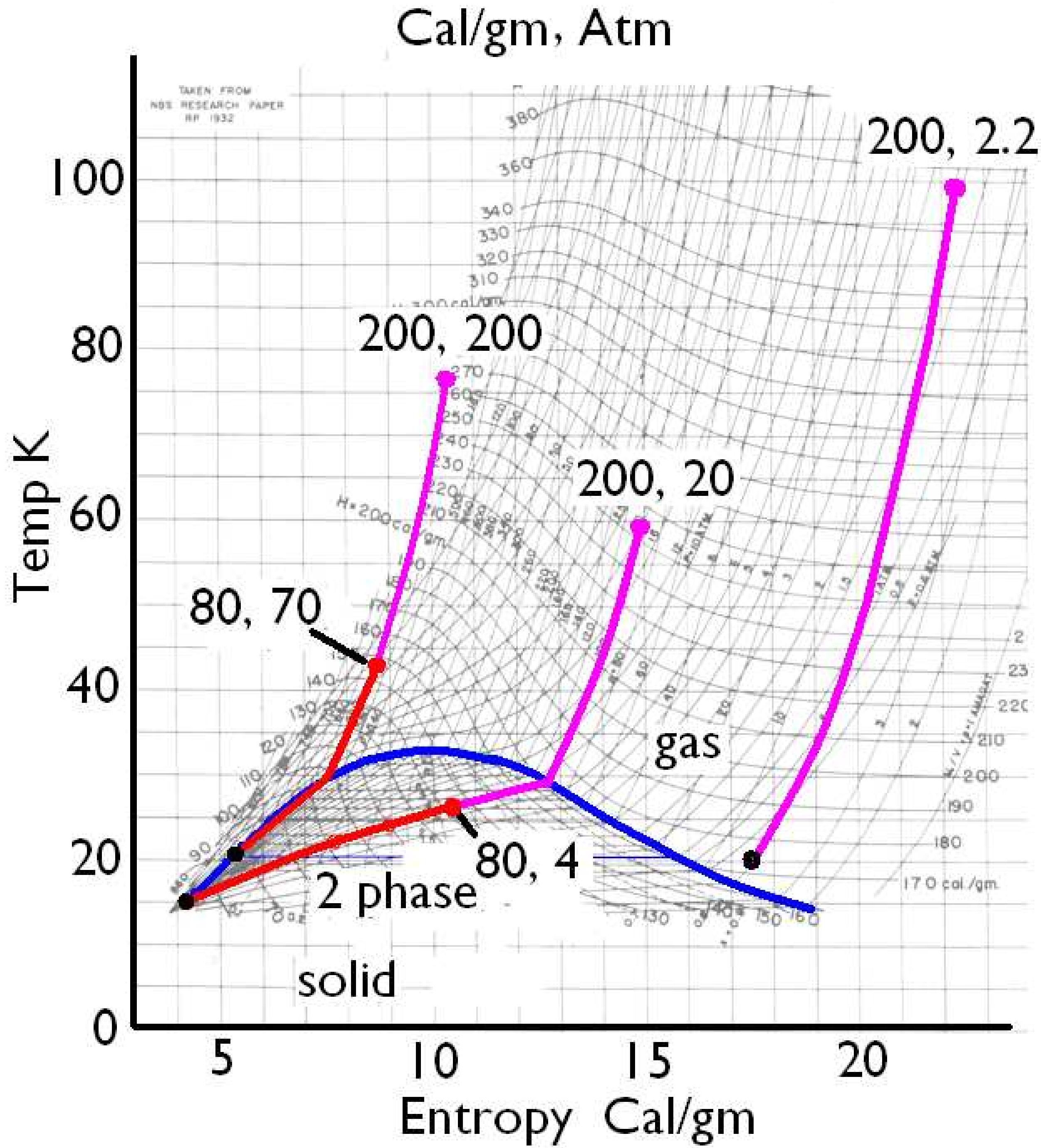
Entropy

- Stages 12-14:
  J/m$\leq$ 200 Cal/gm

  if gas:
  P_{max}=2.2 atm.
  gas leng
  1.2 $\times$ 128=154 cm

- Stages 1-11:
  J/m$\leq$ 80 Cal/gm

  if 15 K:
  $P_{max} \leq 4$ atm.
  Leng $\geq$ 3.5 cm



Hydrogen windows

Assume, for all stages, the window diameters:

$$d_{\rm final} \ = \ 10 \ \sigma_{x,y}$$

For the last stage: $d_{\rm final} \ = \ 10 \ \times \ 0.65 \ = \ 6.5$ mm

Assume thicknesses scaled from MICE:

$$t_{\rm final} \ = \ t_{\rm MICE} \, \frac{d_{\rm final}}{d_{\rm MICE}} \ = \ 180 \, \frac{6.5}{300} \ = \ 3.9 \ \ \mu{\rm m}$$

The MICE windows, and thus these windows, are designed for 6.9 atm. internal pressure and should easily hold 4 atm. over the very limited area of the beam, but we must check fatigue and how to make them. A second 4 μm safety window will also be required.

Effect of windows on cooling

ICOOL simulation of stage 14 of 40 T sequence. 8 micron ($\approx\ 2 \times$ 3.6) aluminum windows at start and end of hydrogen. Three runs with 50,000 tracks

1. Without windows cooling $\epsilon_\perp$ from 27.6 to 24.2 μm
   change in emittance=3.4 μm
2. With two 8 μm windows: $\epsilon_\perp$ from 27.6 to 24.3 μm ($\Delta\epsilon$=0.1)

   Since this is so small, we ran with 10 times the thickness:
3. With two 80 μm windows: $\epsilon_\perp$ from 27.6 to 25.2 μm ($\Delta\epsilon$=1.0)

Scaling from (#3 − #1):

$$\frac{\text{scaled loss of cooling}}{\text{total cooling}} = \frac{1.0/10}{3.4} = 2.9\ \%$$

This is probably acceptable, but should be included in all simulations