Cooling for 3 TeV Collider

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Take parameters from 1998 Snowmass Study

E_μ	$\mathcal{L}$	<B>	N_μ	$f_{\rm bunches}$	P_μ	$\beta_\perp = \sigma_z$	dp/p	emit$_\parallel$	emit$_\perp$	$\Delta\nu$
TeV	10^{33} cm^{-2} s^{-1}	T	10^{12}	Hz	MW	mm	%	mm	mm	
3	70	5.3	2	30	28	3	0.16	.05	72	.044

N_μ/N_p = 0.17 (current front end) $\times$ 1/5 (allowance for decay losses)

For 24 GeV protons: N_p/bunch=$3\ 10^{13}$
For 12 GeV protons: N_p/bunch=$6\ 10^{13}$

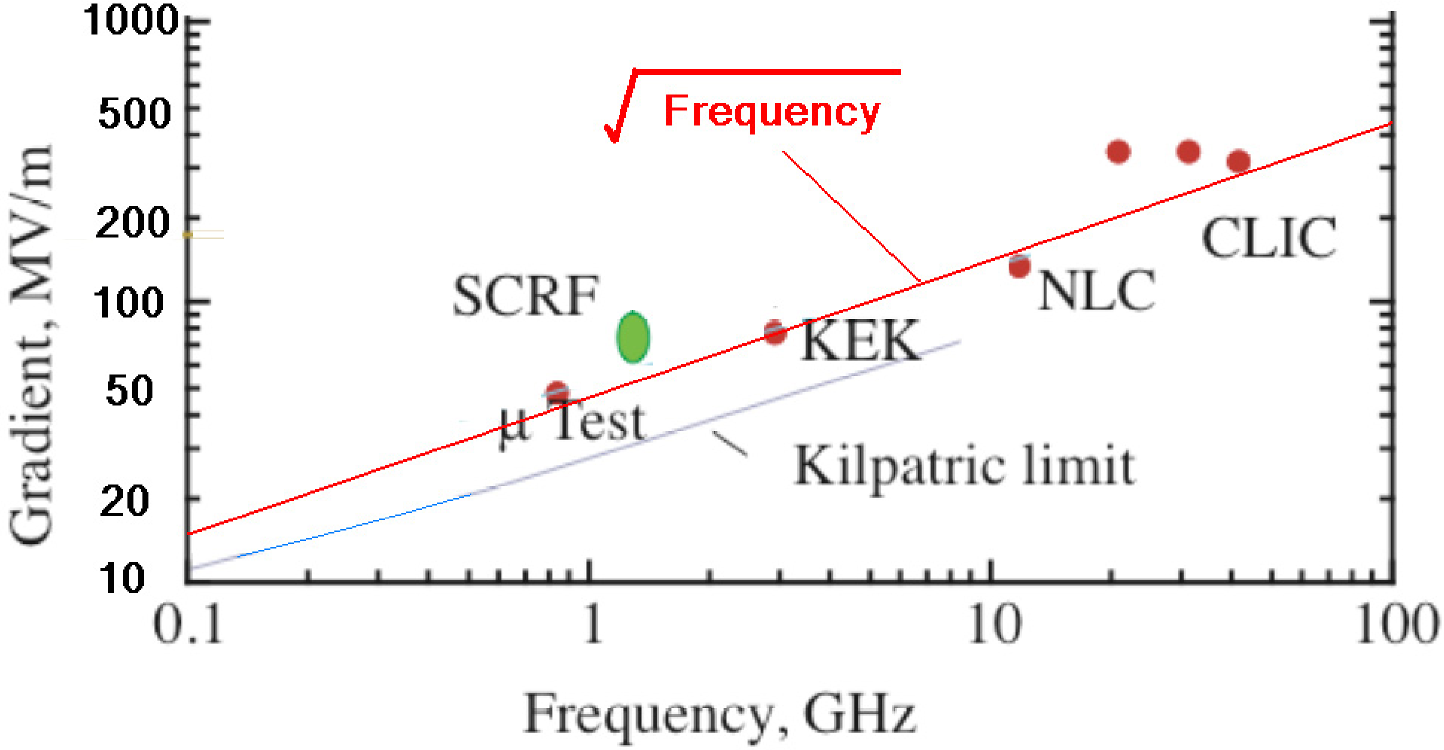
Note: $\frac{\text{Luminosity}}{\text{Beam power}} \propto$ Tune Shift Independent of emittances

But lower emittances reduce required muons per bunch

What is best RF frequency

• Maximum Accelerating Gradients

from Norem



assume:

Frequency	MHz	800	200	88	5
Gradient	MV/m	32	16	5 *	1.25 *

* When f = 88 MHz gradient $\approx 1/2$ the root law, from higher $\mathcal{E}_{\rm s}/\mathcal{E}_{\rm acc}$

• Cooling "Efficiency" vs. Decay

Amount of cooling per relative decay loss:

$$\eta \;=\; \frac{d\epsilon/\epsilon}{dn/n} \;=\; (c\tau/m_\mu)\;\frac{<\mathcal{E}>}{\beta_{\rm v}}$$

Favors highest frequency

• To minimize wall power consumption

Stored RF energy per beam energy change

$$\frac{dU}{dE} \;\propto\; \mathcal{E}\;\lambda^2 \;\propto\; \frac{1}{f^{3/2}} \qquad \text{for root dependence}$$

Stored energy is lost each pulse, so Wall power W

$$<W> \;\;\propto \frac{1}{f^{3/2}}$$

Favors highest frequency

(Peak Power $\propto\;\; <W>/\tau_{\rm fill}\;\propto\; f^{3/2}/f^{3/2} \;=\; \text{constant}$)

• Frequency limit from iris aperture

Acceptance at target from 20 T Solenoid and R=8 cm:

$$A = \frac{R^2\ c\ B}{2\ m_\mu} = \frac{0.08^2\ 0.3\ 20}{2\ 20} \approx 0.18 \quad (\pi\ \mathrm{m})$$

If at RF: $\beta_\perp \approx 1m$ and $p \approx 200$ MeV/c, then the req. iris radius R_{iris}

$$R_{\mathrm{iris}} = \sqrt{\frac{A\ \beta_\perp}{\beta_v \gamma}} = \sqrt{\frac{0.18}{2}} \approx 0.3 \quad (\mathrm{m})$$

The minimum wavelength for this aperture

$$\lambda \geq \frac{R_{\mathrm{iris}}}{0.2} = 1.5\ \ (\mathrm{m})$$

which corresponds to $\boxed{\mathrm{f} \leq\ 200\ \mathrm{MHz}}$

After finite longitudinal cooling, higher frequencies will be allowed

• Longitudinal Acceptance at Capture

Longitudinal Emittance from target:

$$\epsilon_{\parallel} \;=\; \beta\gamma c \, \frac{\sigma_E}{E} \, \sigma_t$$

σ_t from decay $\approx$ 3 nsec. For dE/E=80% and $\beta\gamma = 2$:

$$\boxed{\epsilon_{\parallel} \;\approx\; 0.5 \quad (\mathrm{m})}$$

Maximum emittance in RF Bucket

$$\epsilon_{\mathrm{bucket}} \;\propto\; \beta^3 \sqrt{\gamma}\, \delta^2 \sqrt{\frac{1}{f \;\mathcal{E} \;\cos\phi}} \;\propto\; \frac{1}{f^{3/4}}$$

- For 200 MHz, p=200 MeV/c and δ=10%: $\boxed{\epsilon_{\mathrm{bucket}} \approx 0.03 \quad (\mathrm{m})}$
  but with 40 bunches $\boxed{\epsilon_{\mathrm{buckets}} \approx 30 \times 0.03 \;=\; 1.0 \quad (\mathrm{m})}$

- For 5 MHz (2.5 MV/m) without re-bunching $\boxed{\epsilon_{\mathrm{bucket}} \approx 0.48 \quad (\mathrm{m})}$
  One bunch sufficient

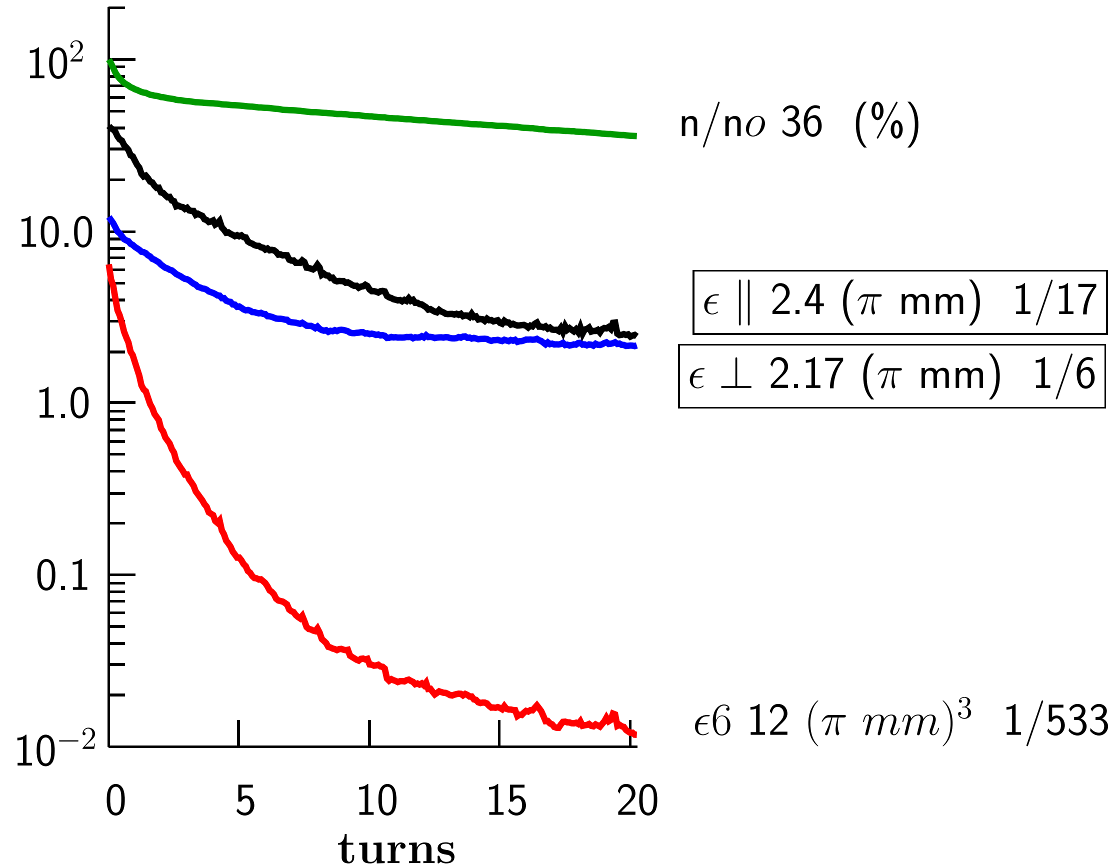
- But 88 MHz (5 MV/m) without re-bunching $\boxed{\epsilon_{\mathrm{bucket}} \approx 0.04^* \quad (\mathrm{m})}$

Philosophy

- Use 200 MHz to minimize decay loss
- Use Neuffer phase rotation to match pion production
- Use Guggenheim ring for inital cooling
- Re-combine bunches in linear channel (Reverse Phase Rotation)
- Later cooling now in a ring
- Final cooling in sequence of Li Lenses
- Acceleration & Collider Ring

• Initial Cooling in Guggenheim ring (or Helix)

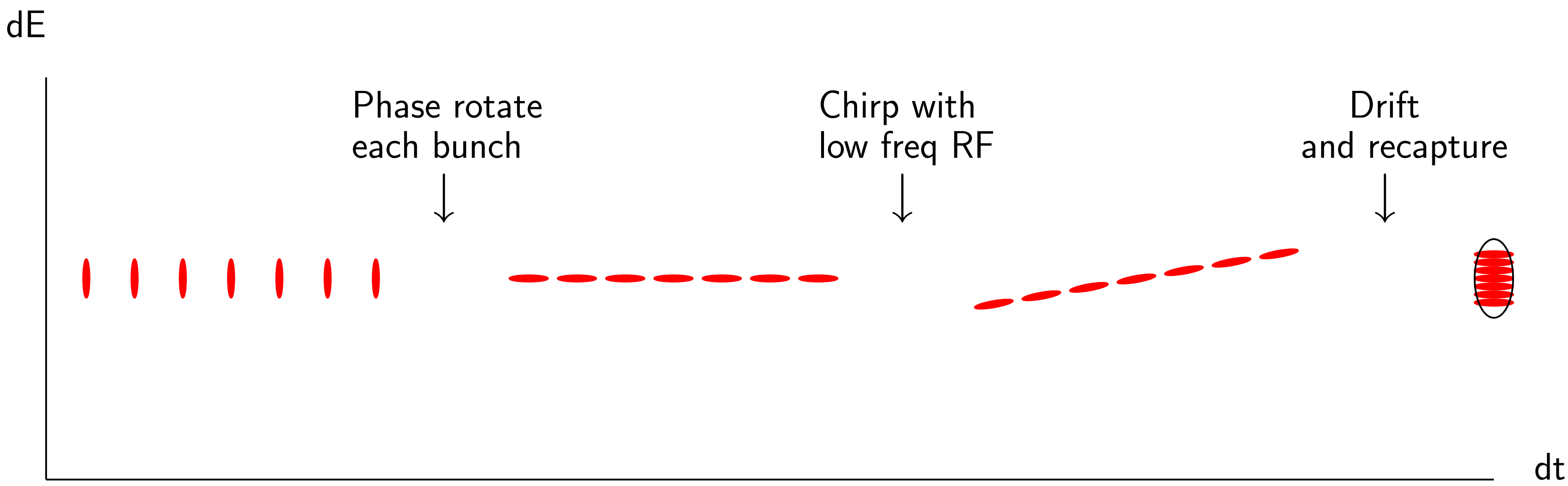
- Use RFOFO Ring Design but in Helix version that will
  - Avoid difficult Injection/Extraction problem
  - Avoid Absorber heating Problem
  - Allow "tapering" to reduce losses



- Assume same final $\epsilon_\perp = 2.2$ (pi mm)
- Step frequency 200 to 800 MHz
  $\epsilon_\parallel$ $2.4 \rightarrow 1.2$ (pi mm)

• Bunch re-combination

- Bunches now have small longitudinal phase space and can be combined
- Can be done in linear channel
- Reverse of conventional phase rotation
- Separate channels needed for two signs



Cooling ring after bunch re-combination

- Injection extraction now ok
- Plausible beta of 8 cm gives $\epsilon_\perp = 400$ (pi mm mrad)
- Assume same final longitudinal emittance $\epsilon_\parallel = 1.2$ (pi mm)

• Compare emittances with Requirements

	Required	Achievable	Achievable/Req
Transverse	$50\ 10^{-6}$	$400\ 10^{-6}$	8.0
Longitudinal	$70\ 10^{-3}$	$1.2\ 10^{-3}$	1/60
6 D	$180\ 10^{-12}$	$190\ 10^{-12}$	≈ 1

Suggests Final Reverse emittance Exchange

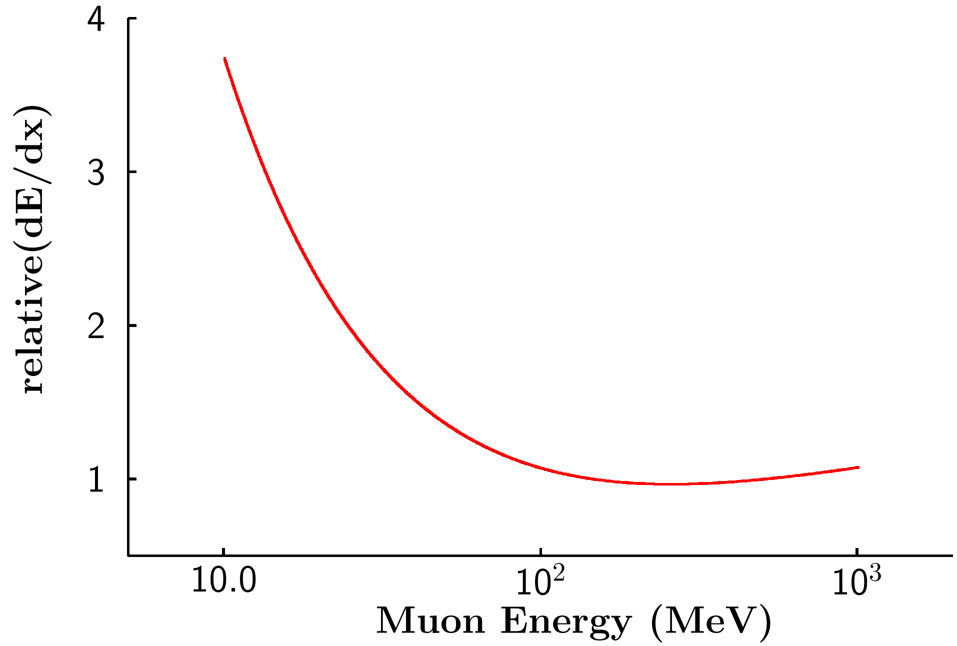
1. Wedges with wrong Dispersion
   appears hard to get low beta and high dispersion
2. By use of septa (potato slicer)
   probably inefficient
3. Very Low energy in Li Lens

Li Lens at very low Energy

Remember:

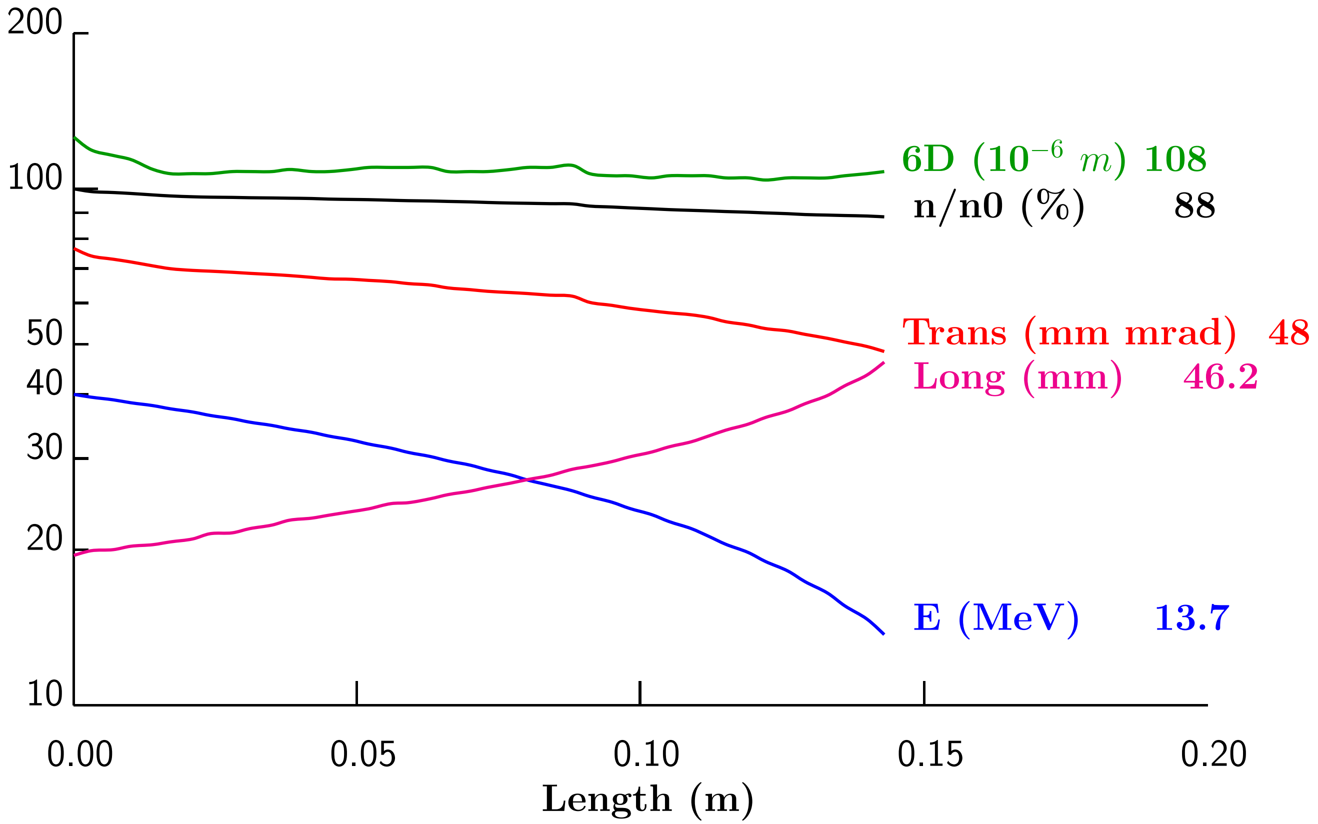
$$\epsilon_{x,y}(min) = \frac{\beta_\perp}{\beta_v \; J_{x,y}} \; C(mat, E)$$

$$J_{x,y} = 1 \qquad\qquad C(mat, E) \propto \frac{1}{L_R \; d\gamma/ds}$$



- dE/dx $\times$ 4 at 10 MeV
- C(mat,E) = 1/4 10 MeV
- Equilib. emittance $\times$ 1/4
  = 50 (pi mm mrad)
- Now meets trans. requirement

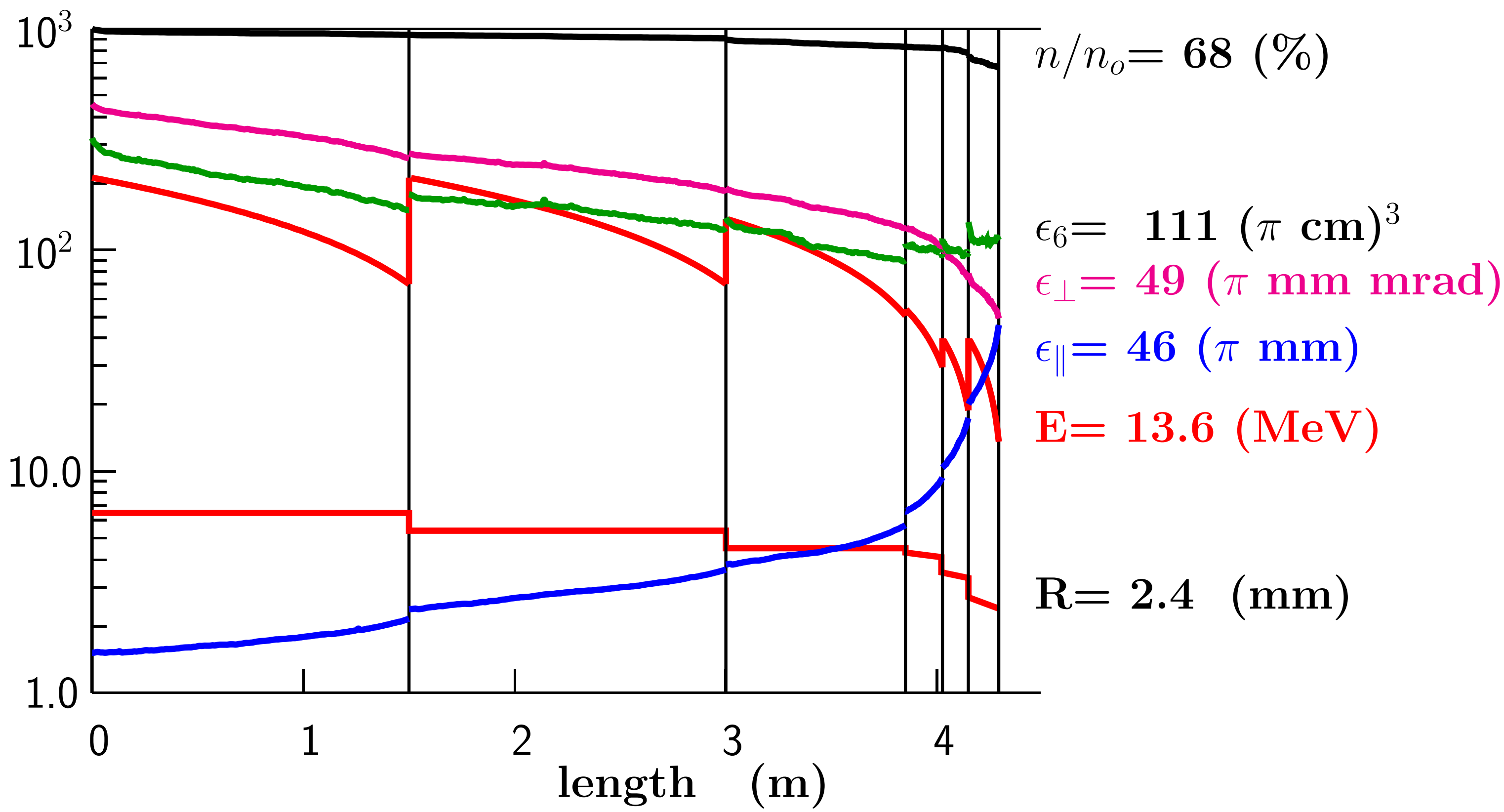
ICOOL simulations of a Low Energy Li Lens



- Required transverse emittance achieved
- Longitudinal emittance rises
- But 6D emittance conserved
- Effective emittance exchange

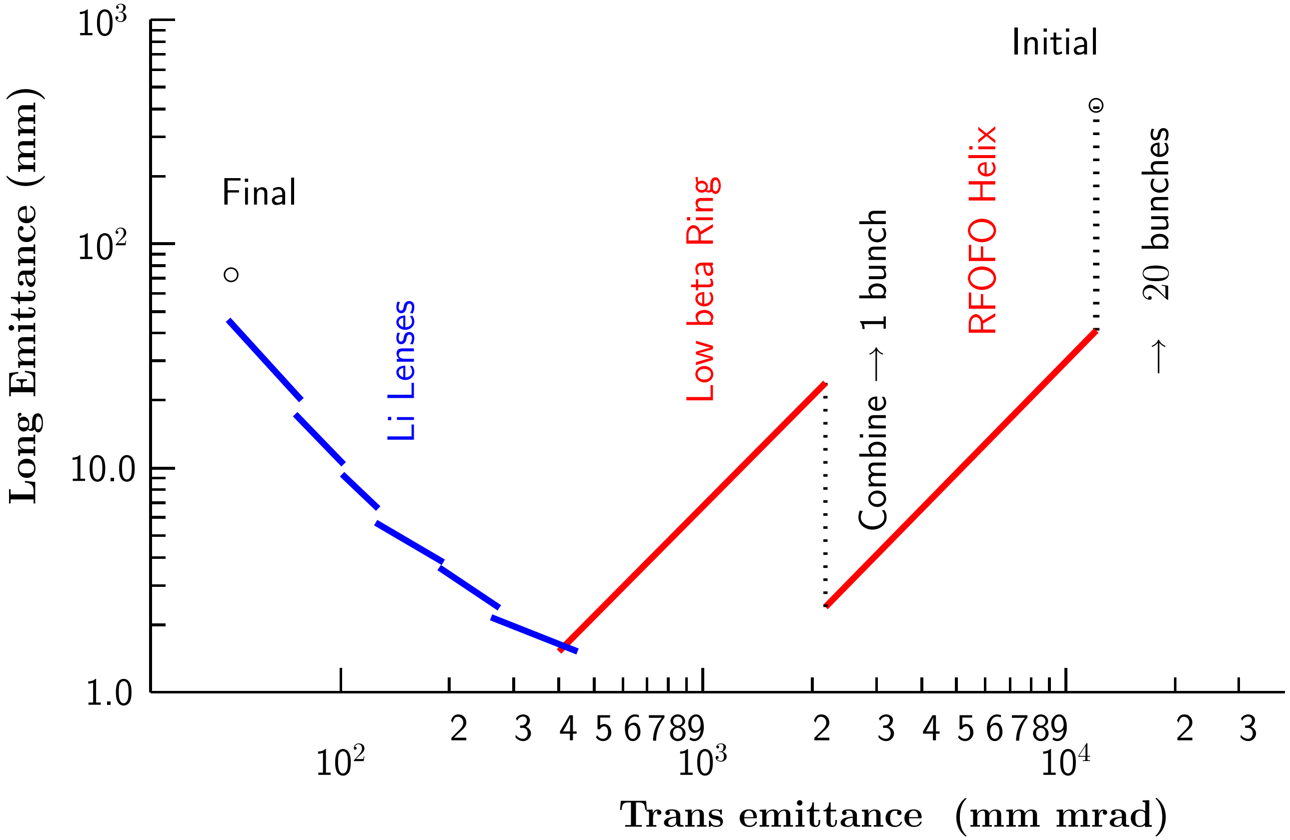
• ICOOL simulations of a Sequence of Li Lenses

- Limit surface fields to 10 T radii at 3 sigma
- Linacs between lenses inserted as almost ideal elements



- Li Lenses cool transverse and heat longitudinal
- Early lenses cool 6D
- Final lens just conserves 6D It does reverse emittance exchange

• Long vs transverse emittance plot



Work needed on

- Bunch combiner
- Low beta cooling ring
- Matching in and out of Li Lenses

Conclusion

- 200 MHz prefered to avoid decay losses
- Multi-bunching required to capture long phase space
- Initial cooling must be in Guggenheim ring or helix
- Re-bunching appears practical
- A cooling ring can now be used
  but hard to get to required emittance
- Lithium Lenses at falling energies achieve required emittances

- To be done next
  1. Match into and out of Li Lenses
  2. Design Lower emittance cooling ring
  3. Design Bunch combiner

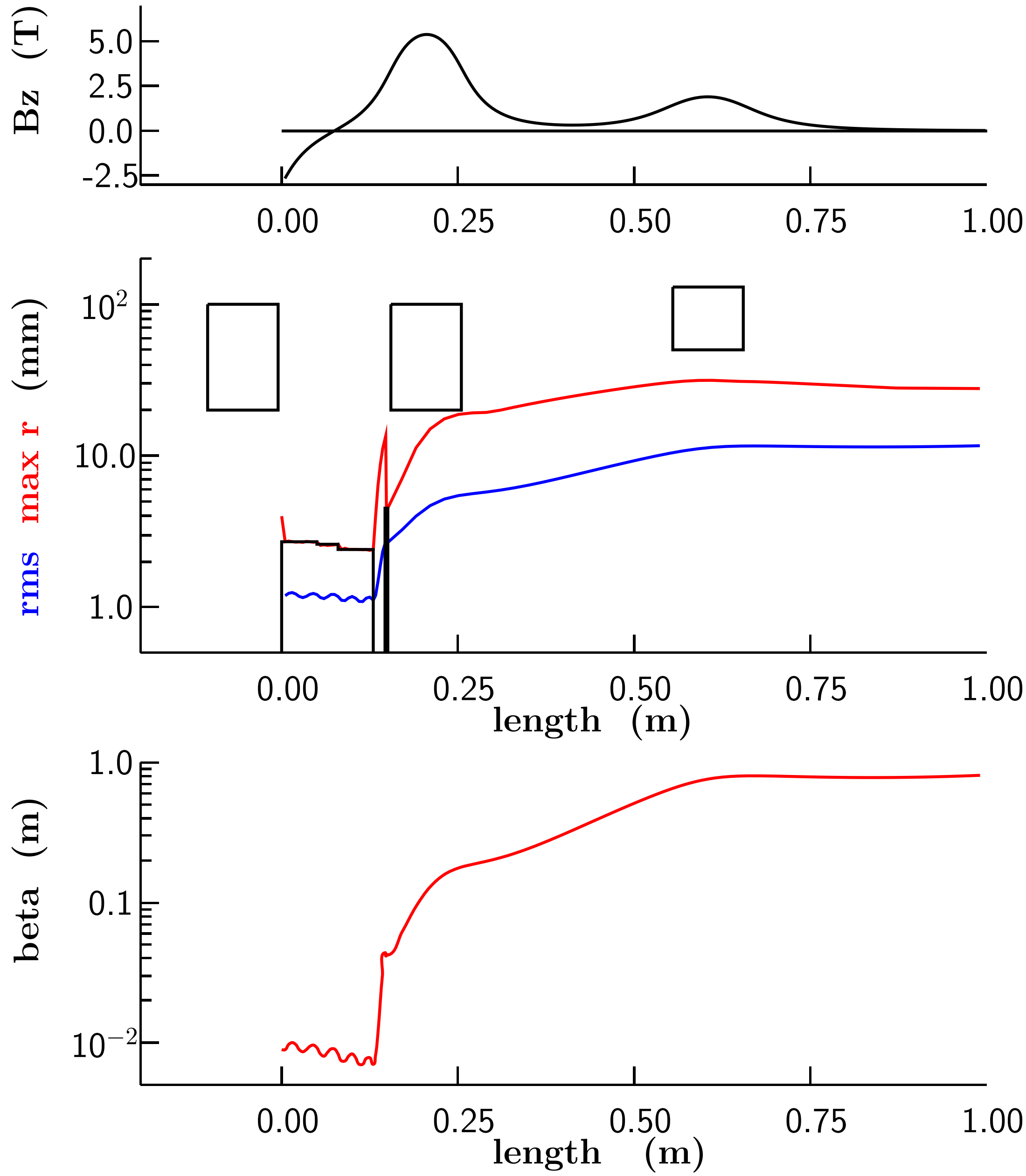
1) Start work on matching in and out of Li Lenses

- **Start with hardest: out of final lens**
- For large dp/p acceptance 15% rms
- Large beta missmatch 1 cm to 1 m

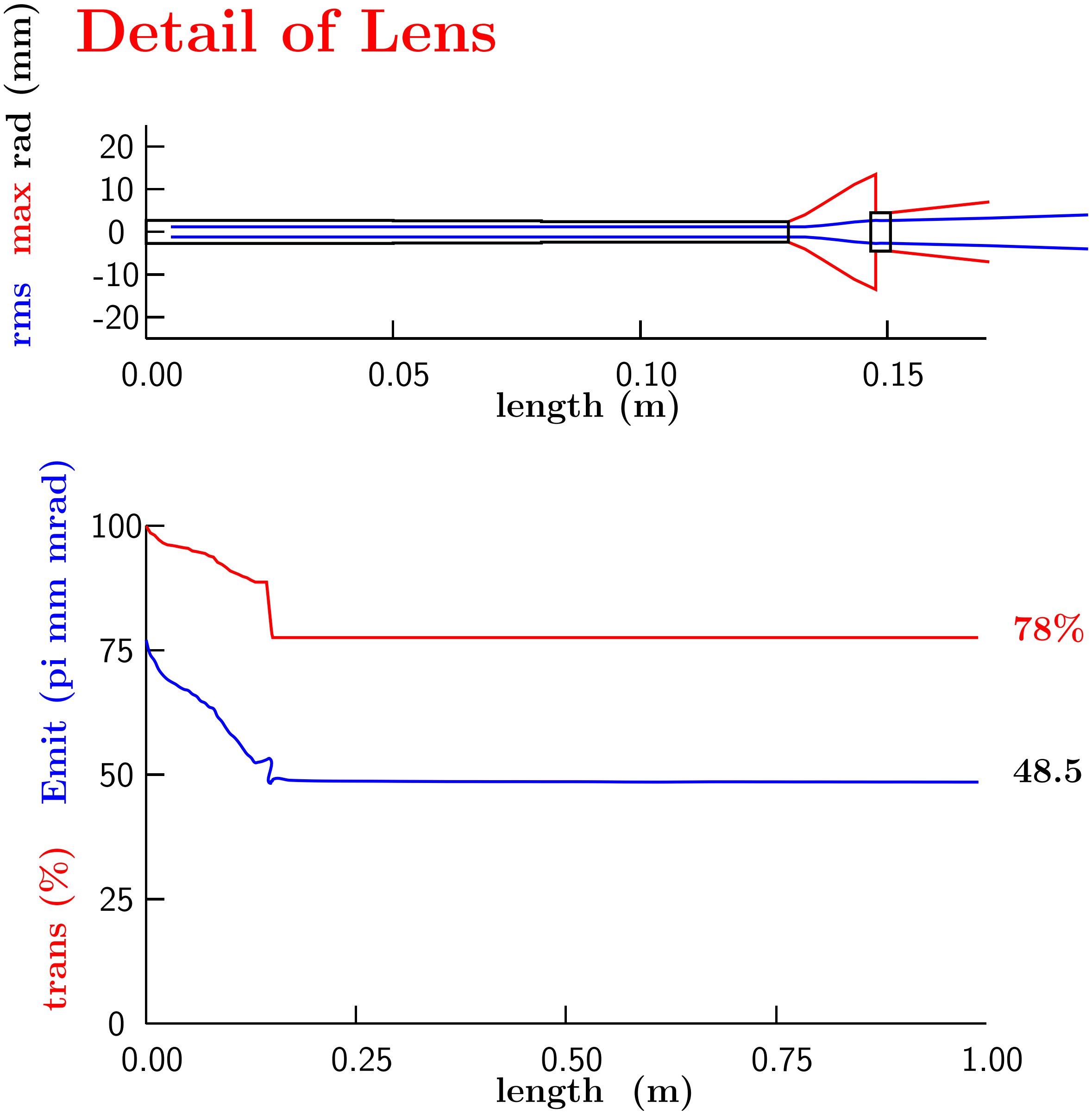
- Increase beta in 3 stages

1. Small Li Lens
2. 6 T solenoid
3. 2 T solenoid

ICOOL Simulation



Detail of Lens



Match achieved, but extra 10% loss