NUFAC 05 Cooling Discussion

Frascati June 23 2005

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Subjects I will discuss

1. Absorber Material ?
2. What is the best Energy ?
3. What is the best RF Frequency ?
4. A Serious Assumption
5. Optimized Cooling for Factory
6. Cooling for a 3 TeV Collider

Subjects #1 - #5 are some of those that will be addressed in the Scoping Study for the World design Study (WDS). Although the conclusions may change, the arguments are worth reviewing.

Absorber Material

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

At ionization minimum ($E \;\approx\; 100$ MeV)

material	T ^{o}K	density kg/m^3	dE/dx MeV/m	L_R m	C_o 10^{-4}
Liquid H_2	20	71	28.7	8.65	38
Liquid He	4	125	24.2	7.55	51
LiH	300	820	159	0.971	61
Li	300	530	87.5	1.55	69
Be	300	1850	295	0.353	89
Al	300	2700	436	0.089	248

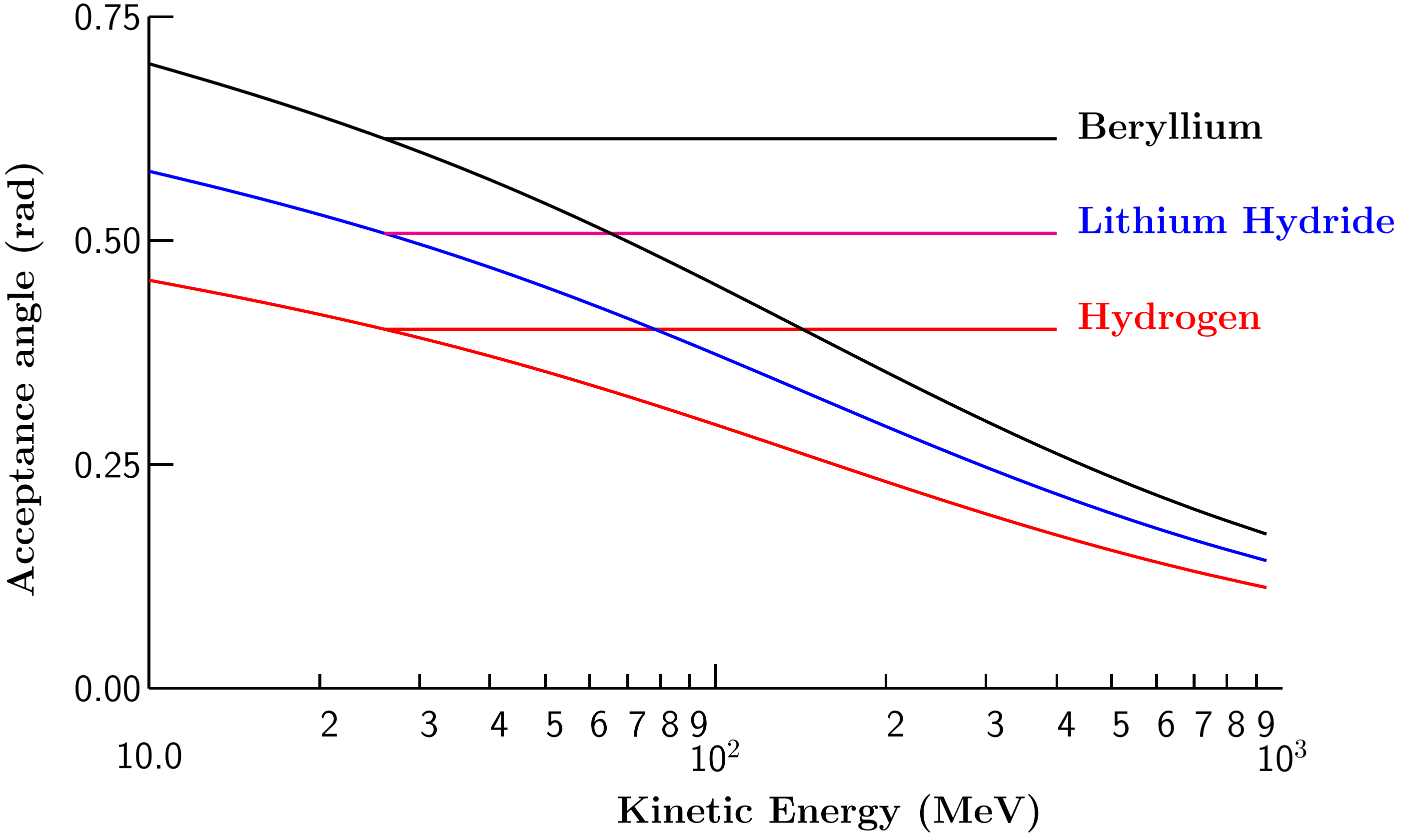
- Liquid Hydrogen is best, but has cryogenic and safety complications, and requires windows.
- Hydrogen gas equally good but requires high pressures and thick windows
- LiH is solid, but requires lower beta for same minimum emittance

• Beam Divergence Angles

Even if beta could be made arbitrarily small

$$\sigma_\theta = \sqrt{\frac{\epsilon_\perp}{\beta_\perp \, \beta_v \gamma}} = \sqrt{\frac{C(mat, E)}{\beta_v^2 \gamma}}$$

For 50 % of maximum cooling rate, an aperture at 3 σ

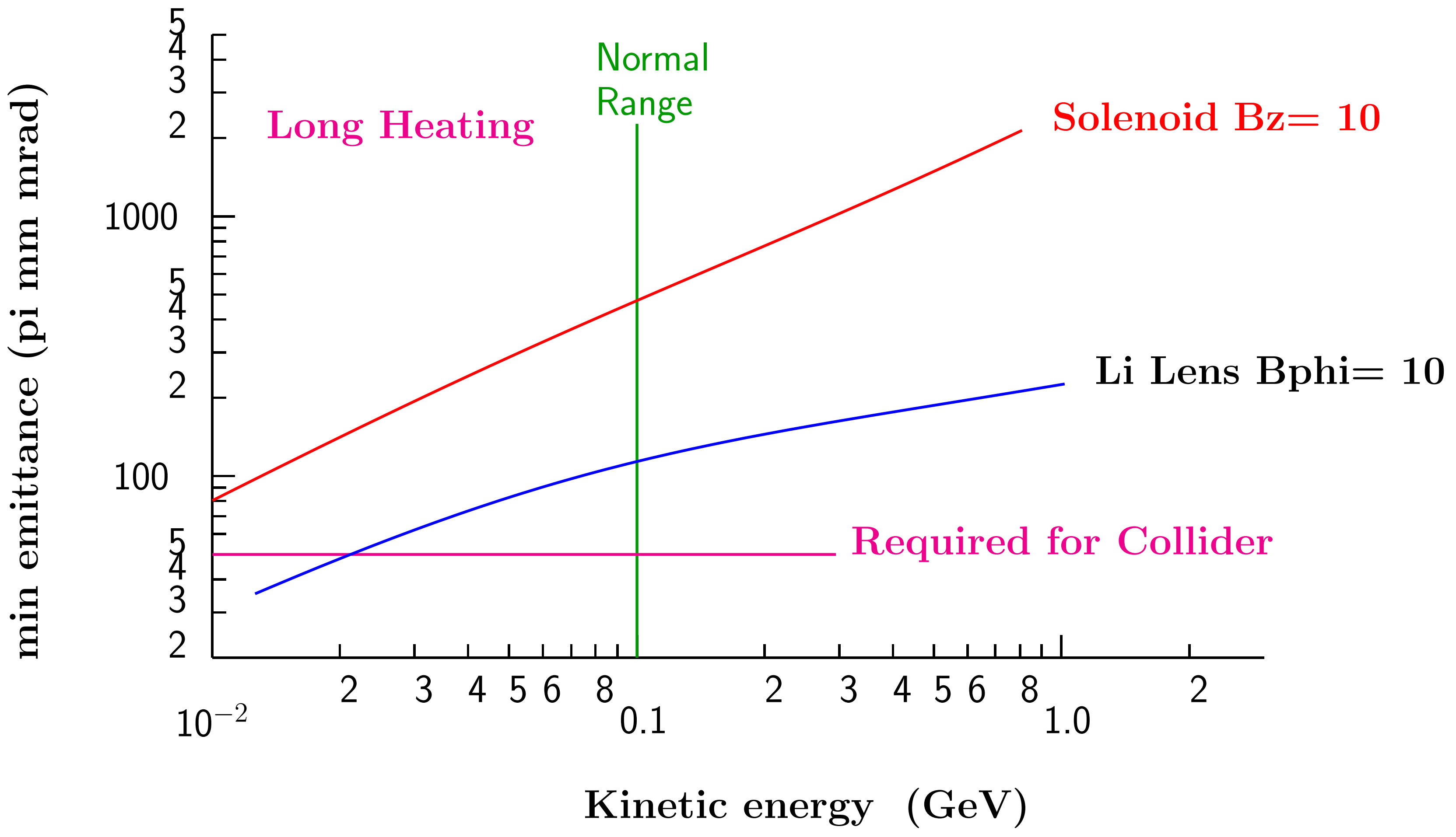


What is Best Energy

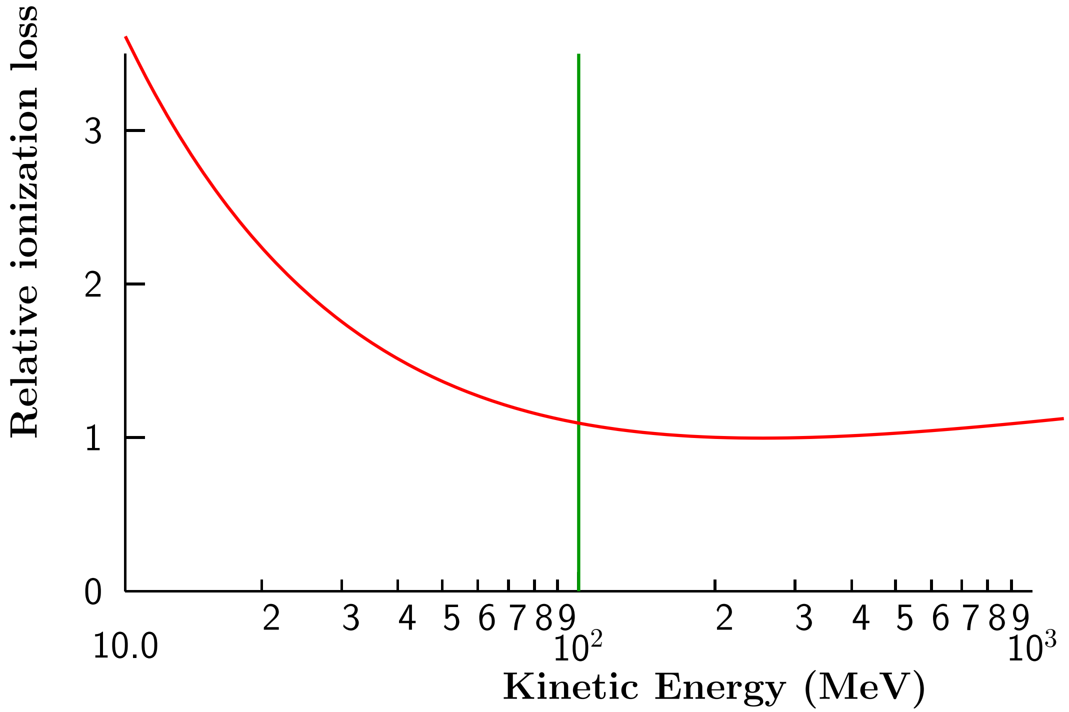
- **Min Transverse emittance lower at low energies**

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

C(mat,E) lower $\quad \beta_\perp$ lower



- **But to avoid longitudinal blow-up**

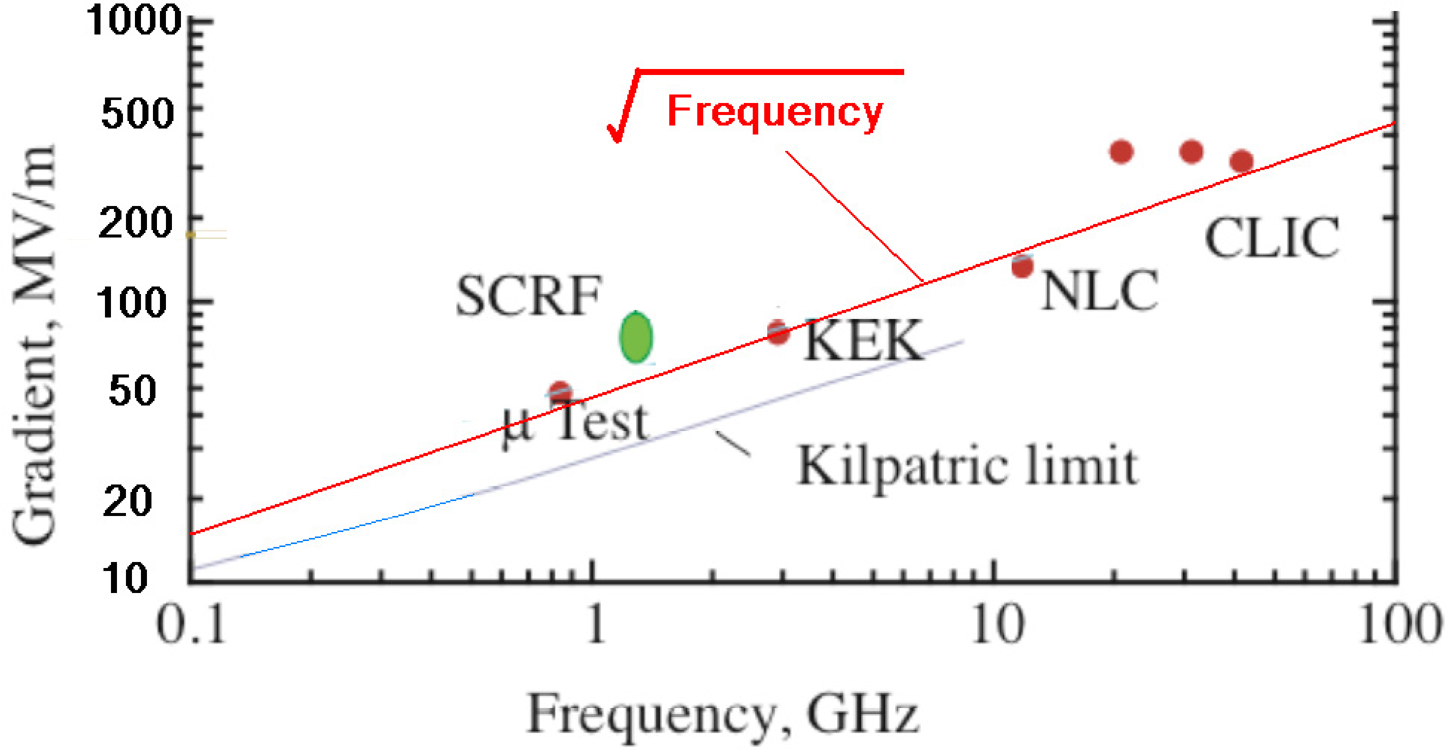


$$\boxed{E \geq 100 \quad \text{MeV}}$$

What is best RF frequency

- **Maximum Accelerating Gradients**

from Norem



assume:

Frequency	MHz	800	200	88	5
Gradient	MV/m	32	16	5 *	2.5

* 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:

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

- **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

$$<W>\;\propto\frac{1}{f^{3/2}}\qquad \boxed{\text{Favors highest frequency}}$$

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

- **Cost per GeV of acceleratio**

This needs to be determined in Scoping Study

$\boxed{\text{Will probably favor higher frequencies}}$

• 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 $\boxed{\text{f} \leq\ 200\ \text{MHz}}$

After finite longitudinal cooling, higher frequencies will be allowed

• Why use lower frequency ? e.g. Japan 5 MHz

Longitudinal Emittance from target:

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

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

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

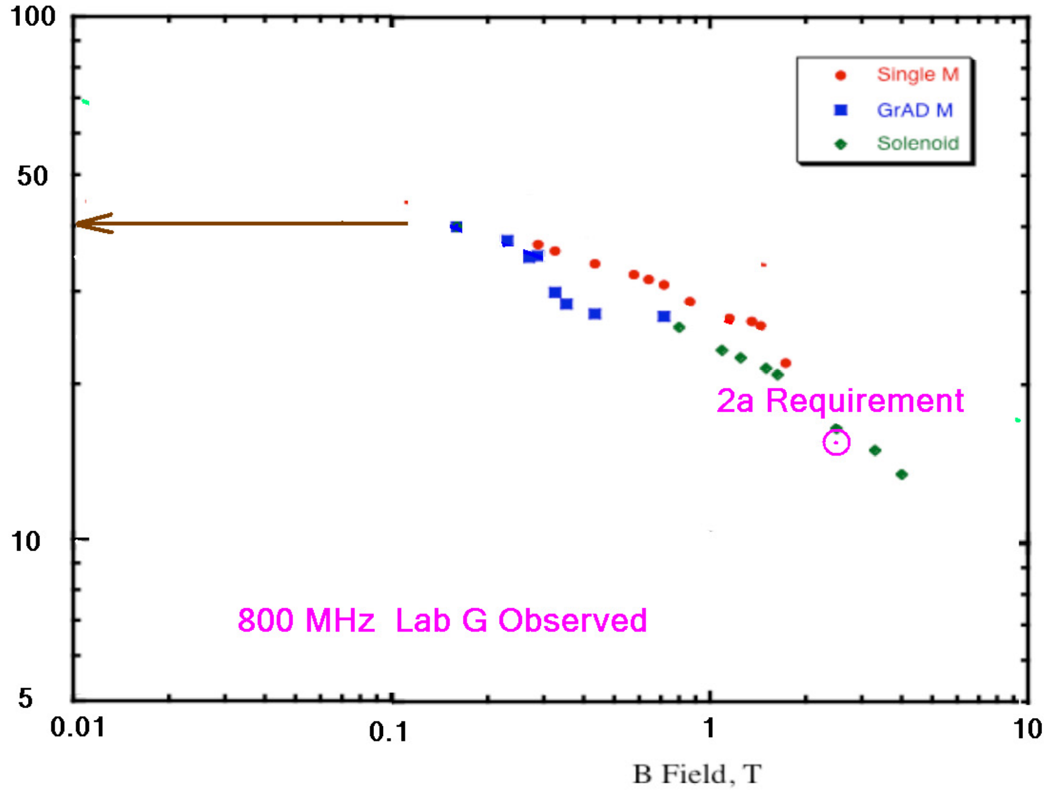
Maximum emittance in RF Bucket

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

- For 200 MHz, p=200 MeV/c and δ=10%: $\boxed{\epsilon_{\mathrm{bucket}} \approx 0.03 \quad (\mathrm{m})}$
  Has less acceptance
  Requires comparison simulations with standard initial production
- 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 $\boxed{\epsilon_{\mathrm{bucket}} \approx 0.04^* \quad (\mathrm{m})}$
  Should phase rotate and rebunch into $\geq$ 13 bunches ($\geq$ 150 nsec)

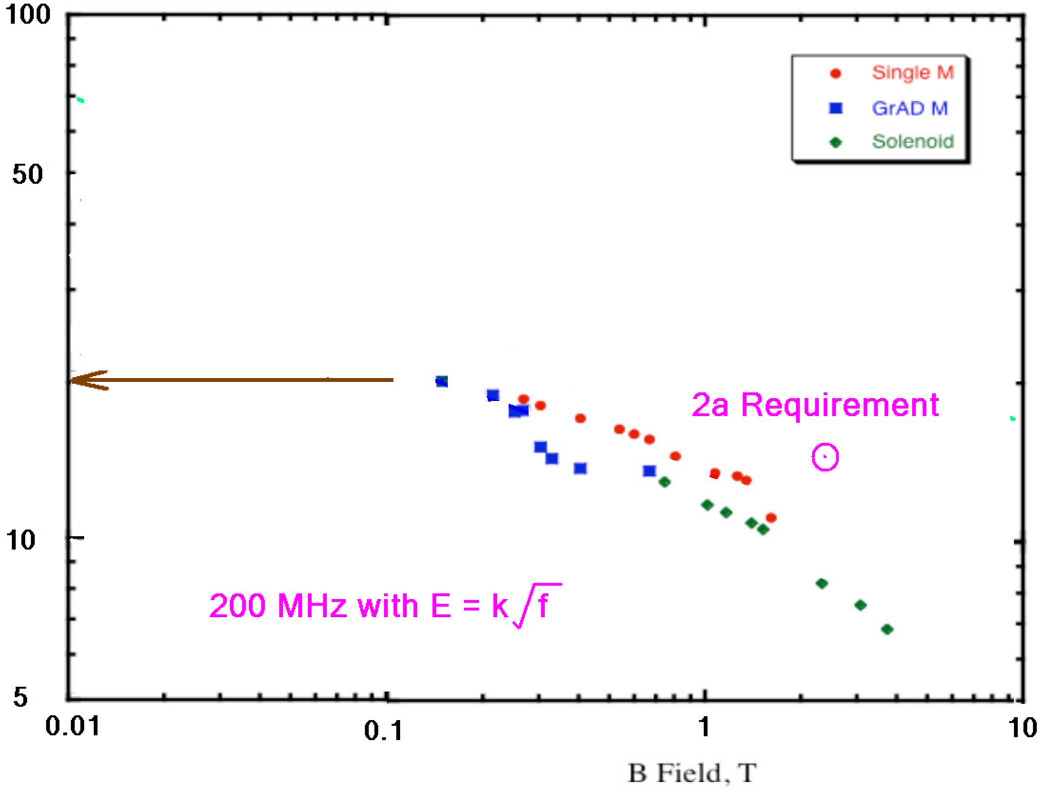
A serious assumption in our Studies

- **Maximum Gradient vs, Local Fields at 800 MHz**



- At zero B: $\mathcal{E} \propto \sqrt{\mathrm{f}}$ but we do not gave a good theory for this
- We certainly do not know scaling for finite B
- Assume they scale the same

• Max Grad vs Local Fields scaled by $\sqrt{f}$ to 200 MHz



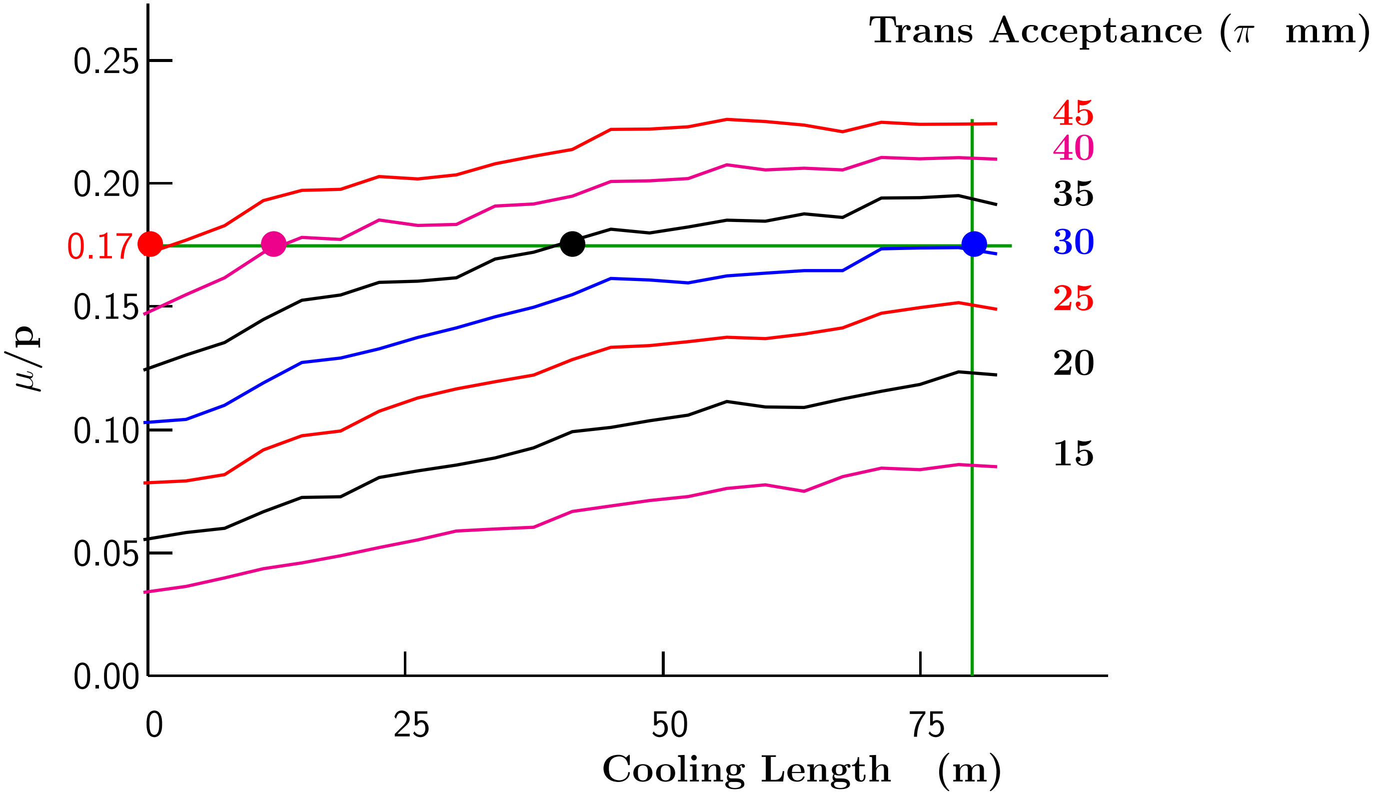
- Independent of field gradient !
- Specified Fields may not be attainable
- May be improved by coatings/material
- But may require redesign of lattices
- Is 88 MHz geometry better ?
- Importance of Tests at Fermi MTA

Optimized Cooling

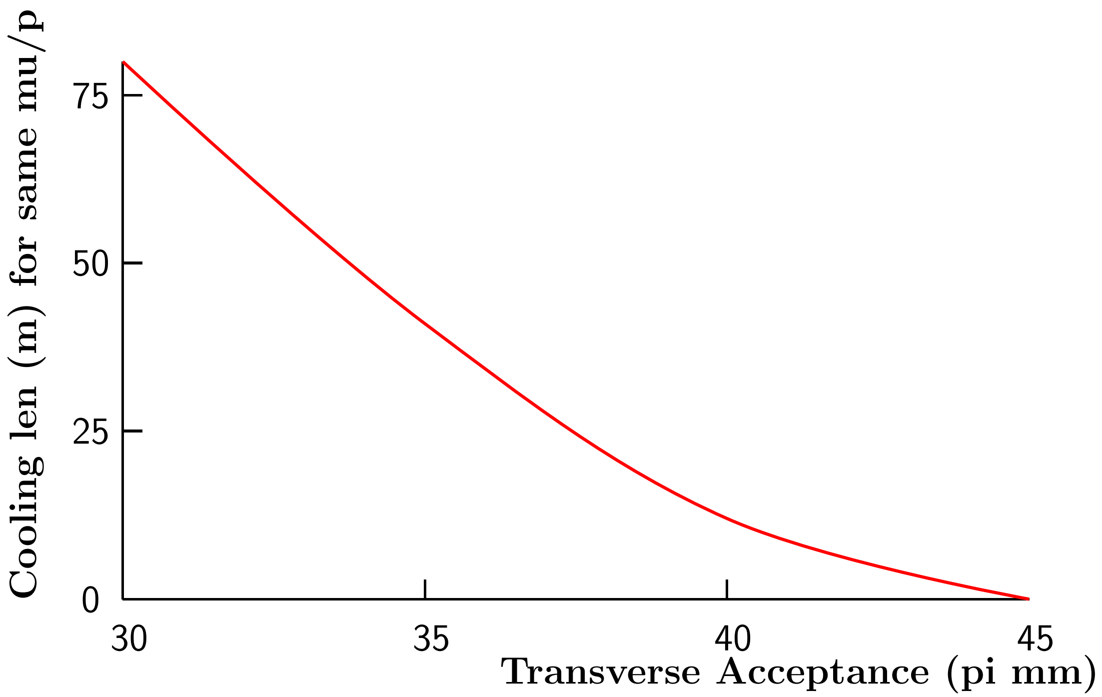
• Cooling vs Accelerator Acceptance

- Using US Study 2a (APS Neutrino Matrix) as example
- Use ICOOL for performance simulation

Muons per proton for different Cooling length and acceleration apertures



• Cooling needed for same 0.17 Muons per proton vs Acceleration aperture

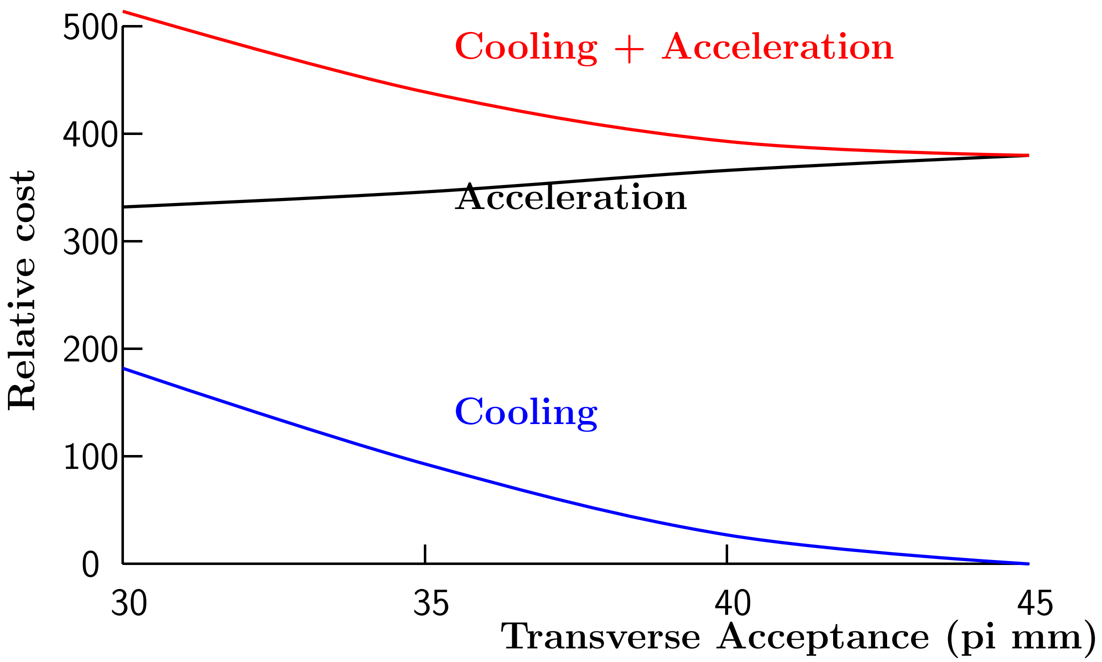


• Estimating Costs

- Hard
- Mostly scale from study 2
- Needs much more work

• (Acc + Cooling) Costs for same μ/p vs. acceptances

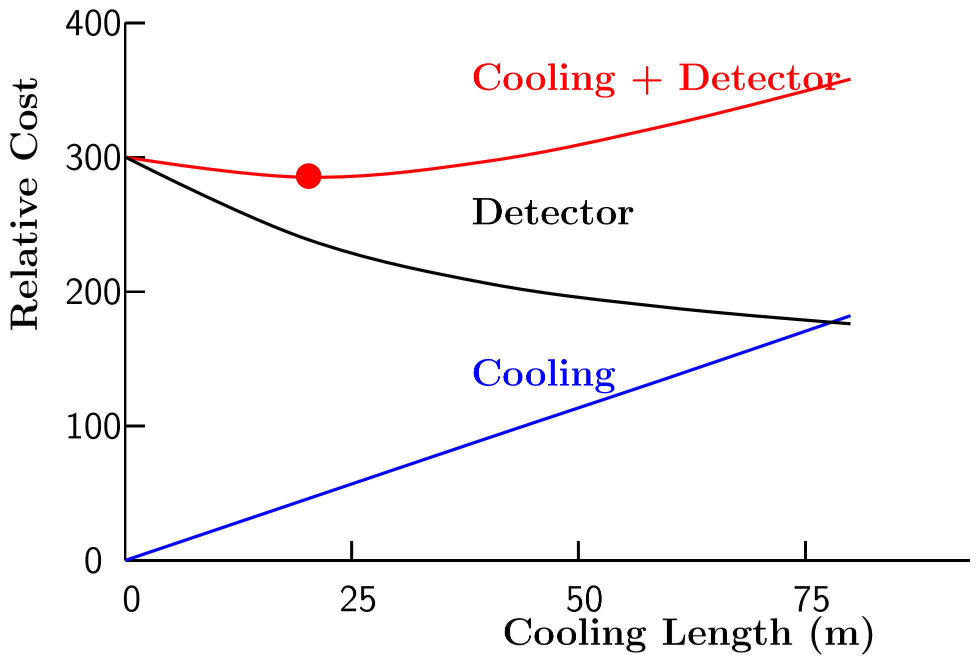
- Accelerator costs for two FFAG's from Berg
- Linac and RLA costs scaled from relative FFAG costs



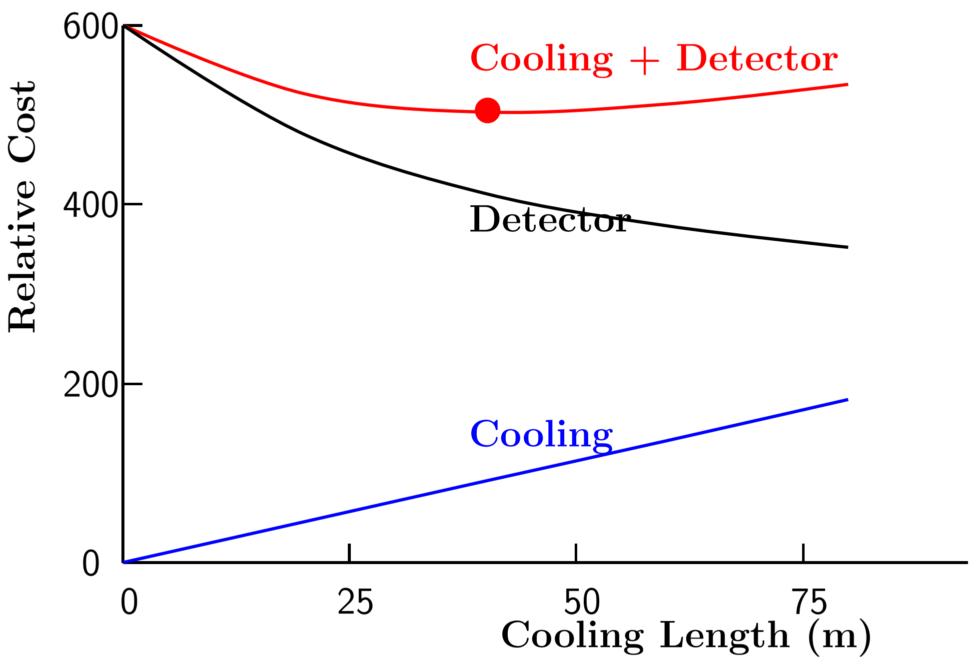
- Minimum cost appears to be with NO cooling
- Not known if lower energy $>$ 30 pi mm accelerations are practical
- Certainly their costs are not really known
- But the case for cooling is not obvious

• Cooling vs Detector Size

- Pick base detector cost in very approximate unloaded M$
- Scale detector size (and cost) to achieve same number of events with different cooling lengths



≈ 300 M$ Detector (Blondel)



≈ 500 M$ Detector (Berg)

- Resulting minimum depends on chosen detector cost
- But minima are with relatively little cooling

• Other advantages of minimal Cooling

- Even if some cooling is included, its success is not essential
- Factory CDR can be produced before MICE completed

• Advantages of using no cooling

- Less R&D Required we have little time before Alain's "window"
- No field "flips"
- Reduced Requirement on capture acceptance
  - Smaller aperture phase rotation RF
  - Smaller or lower field focusing in drift
  - Lower Capture Field
- Less dependence on use of RF in magnetic fields
- MICE still important for Muon Collider (Next)

"Template" of Cooling for a 3 TeV Collider (cf Cline talk)

Take parameters from 1998 Snowmass Study

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

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

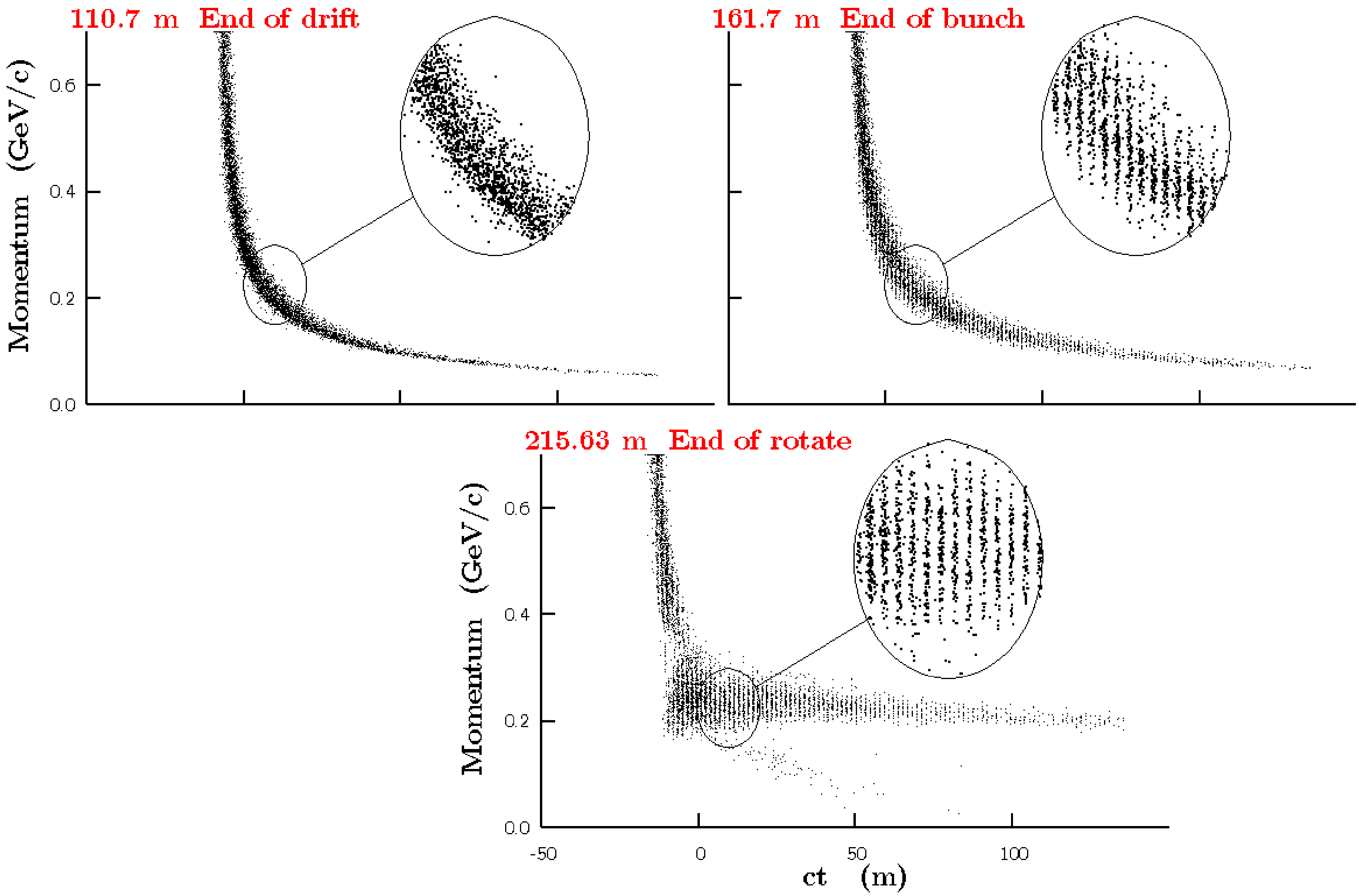
For 24 GeV protons: N_p/bunch=3 10^{13}
For 12 GeV protons: N_p/bunch=6 10^{13}

Sequence:

- Mercury Target and 20 T capture (as in Study 2)
- Bunched Beam Phase Rotation into 40 bunches of each sign (as in Study 2a)
- Initial Cooling in a helix version of RFOFO Ring (Guggenheim)
- Bunch re-combination (Reverse Phase Rotation)
- Cooling in Ring
- Sequence of Li Lenses

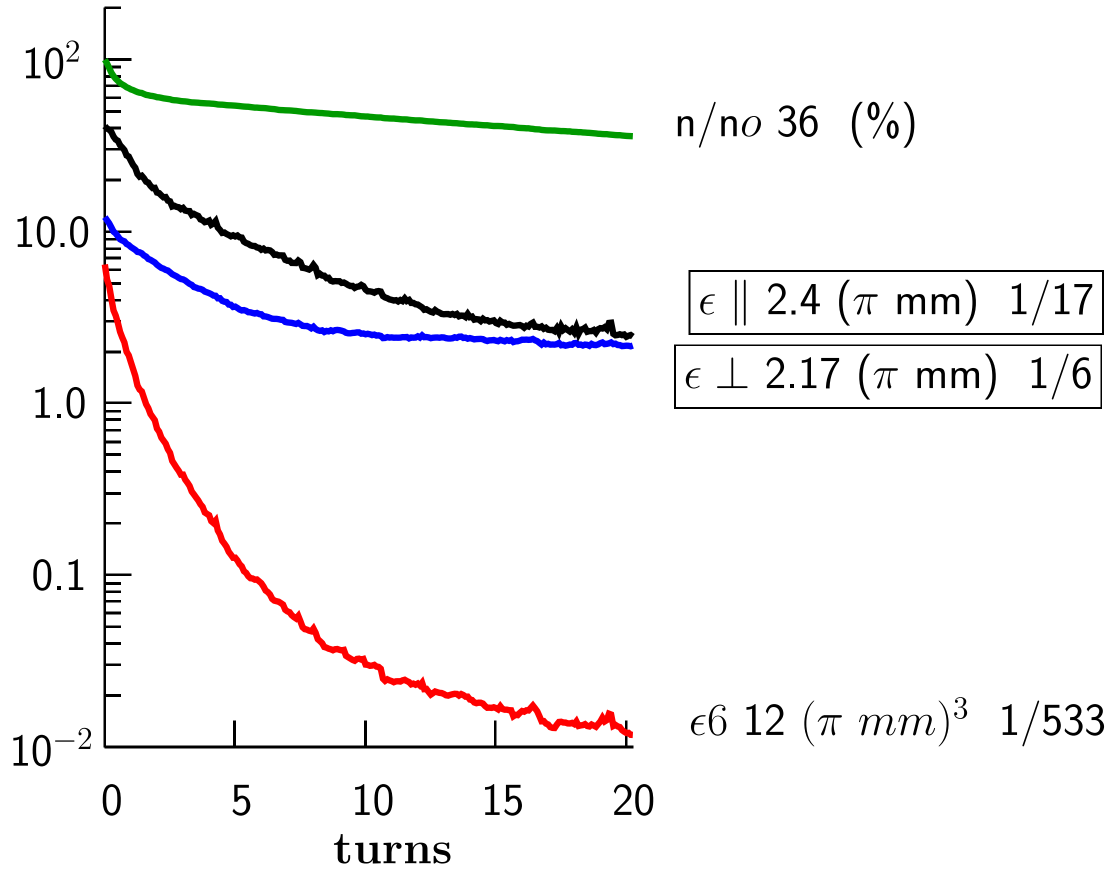
- Acceleration & Collider Ring

- **Bunched Beam Phase Rotation (Neuffer)**
- Variable frequency RF (300 → 200 MHz) bunches
- Shift in frequency then rotates



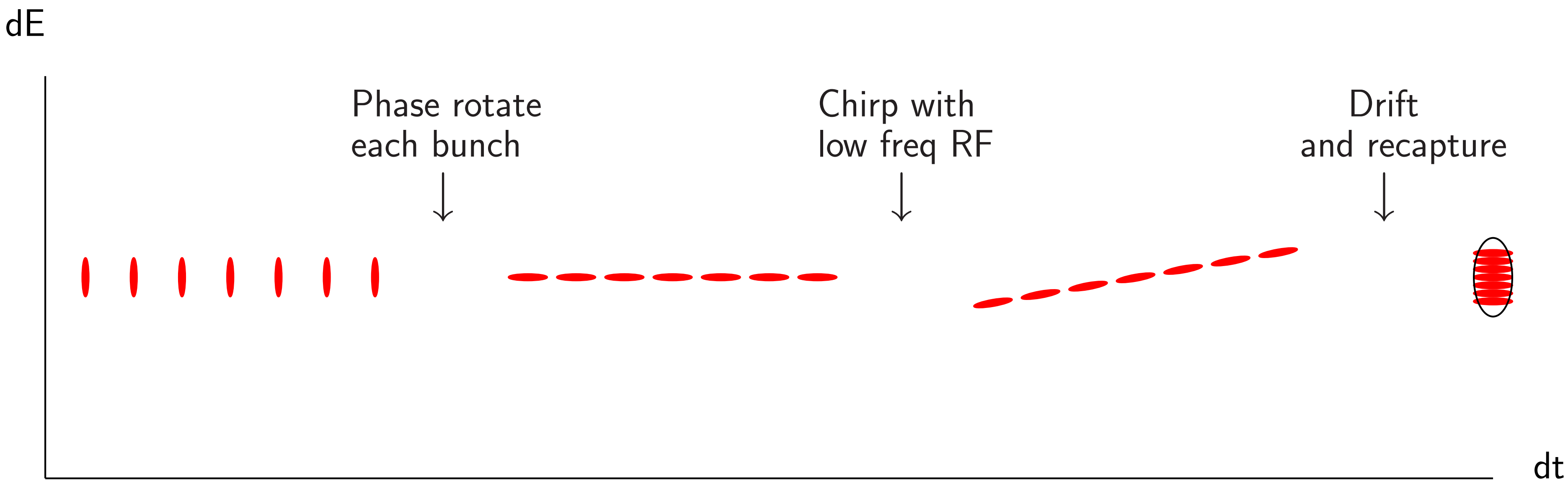
• Initial Cooling Helix

- 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 bunched
- Reverse of conventional phase rotation

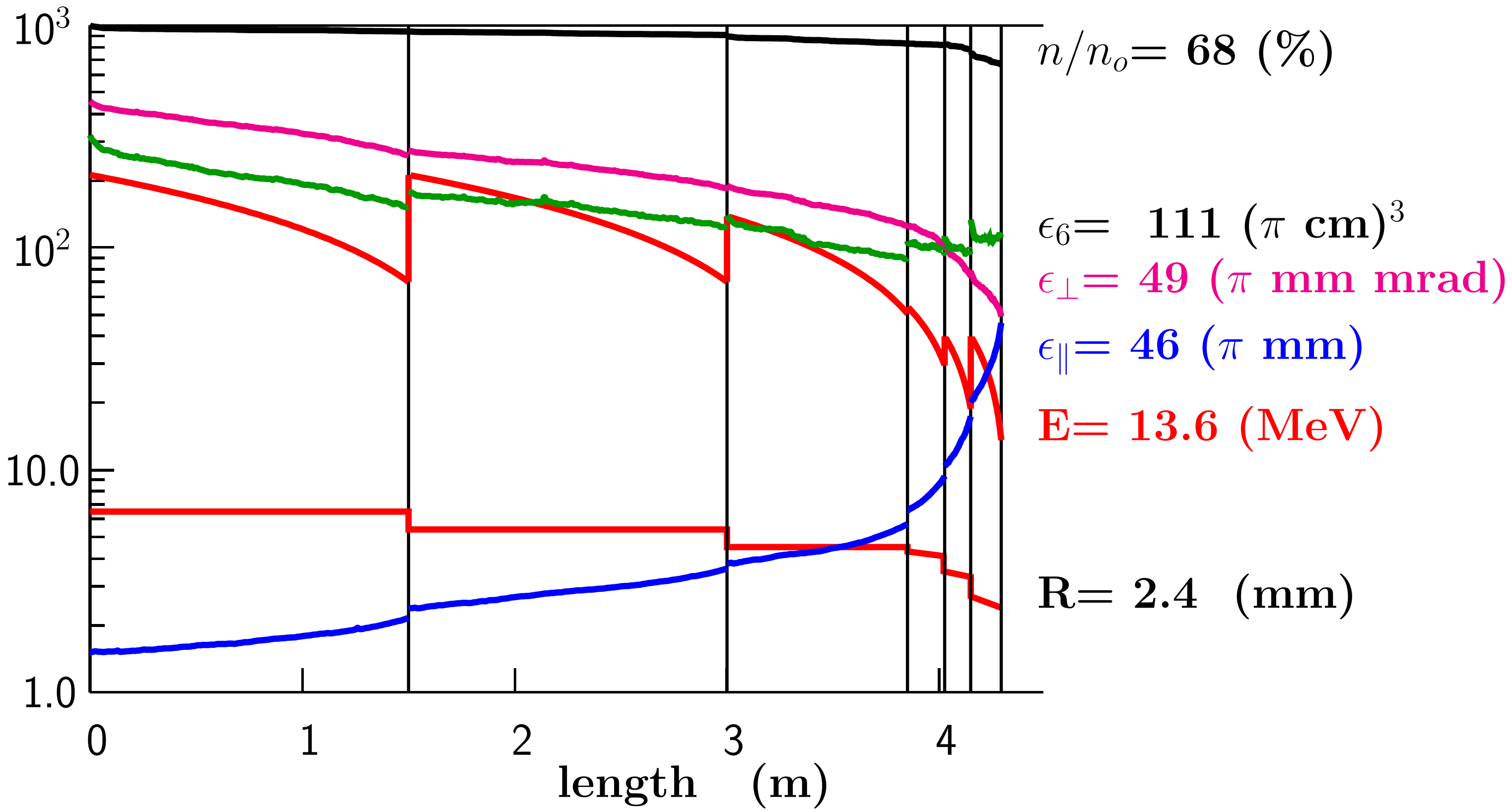


• Cooling ring

- Plausible $\epsilon_\perp = 450$ (pi mm mrad)
- Same $\epsilon_\parallel = 1.2$ (pi mm)
- Single bunch and low emittance, so ring OK

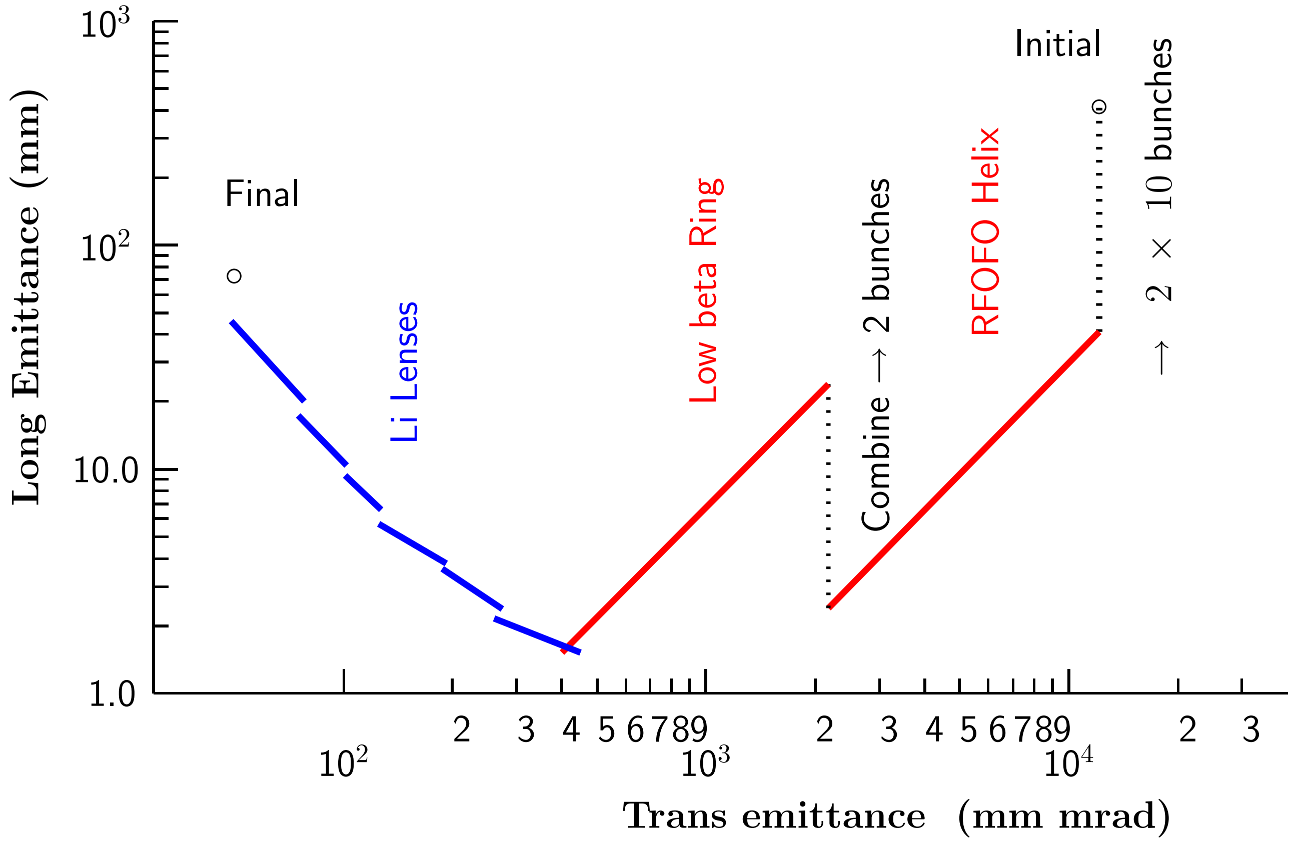
• ICOOL simulations of a Sequence of Li Lenses

- 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

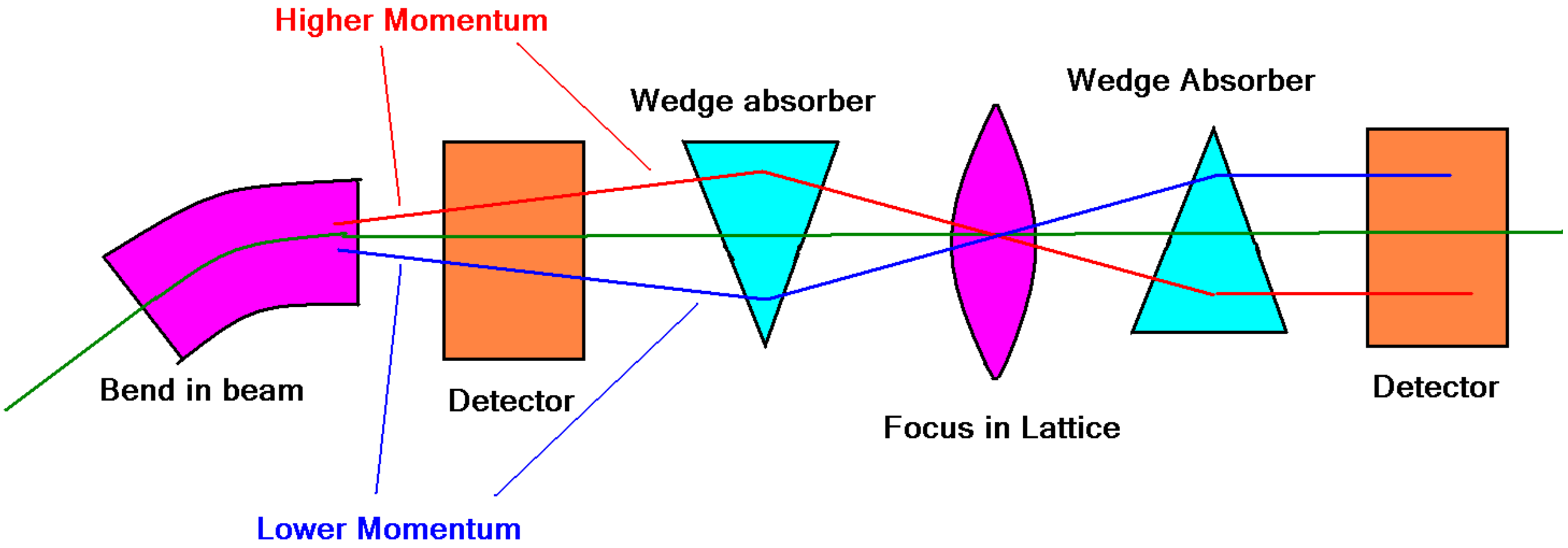
Discusion

- Use of materials other than Hydrogen
- Frequency other than 200 MHz
- Expectation of field effect on breakdown
- Cooling vs. no cooling
- Collider parameters

- Emittance Exchange in MICE
- PIC vs. Super FOFO
- Gas filled Helix

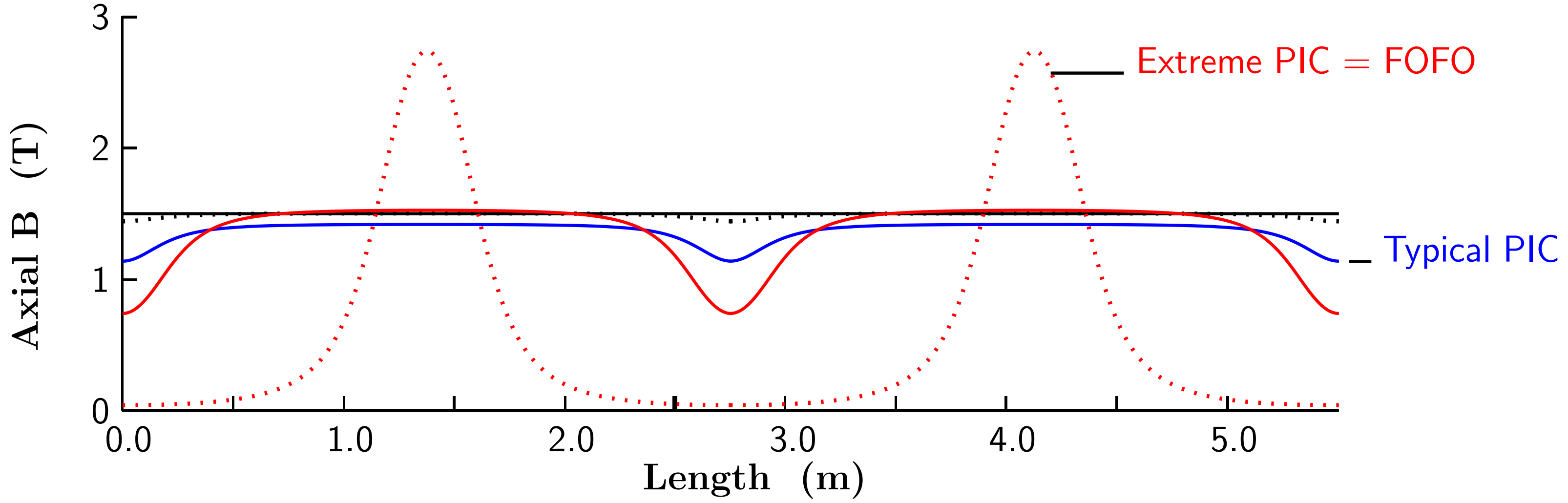
- Exchange before phase rotation (Helix or bent solenoid)
- Friction cooling and Inverse Cyclotron
- Other ?

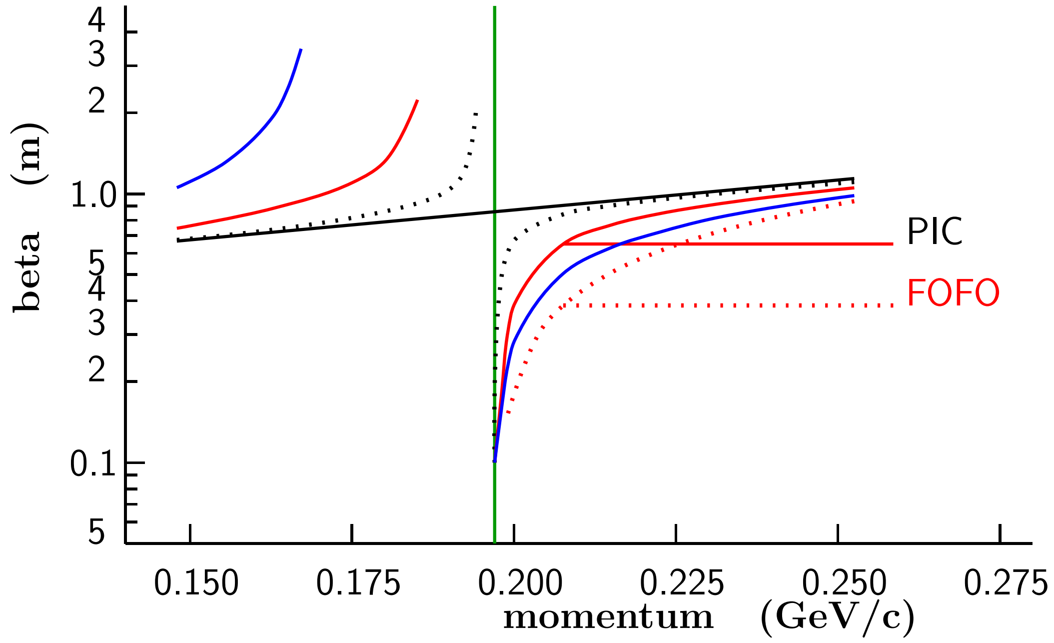
Emitance Exchange in MICE



- Probably no need of dipole for Stage 5
- ? in Stage 6

Decreasing beta in Solenoids by adding periodicity Parametric-Resonance Ionization Cooling (PIC) (Derbenev) / FOFO (Palmer)

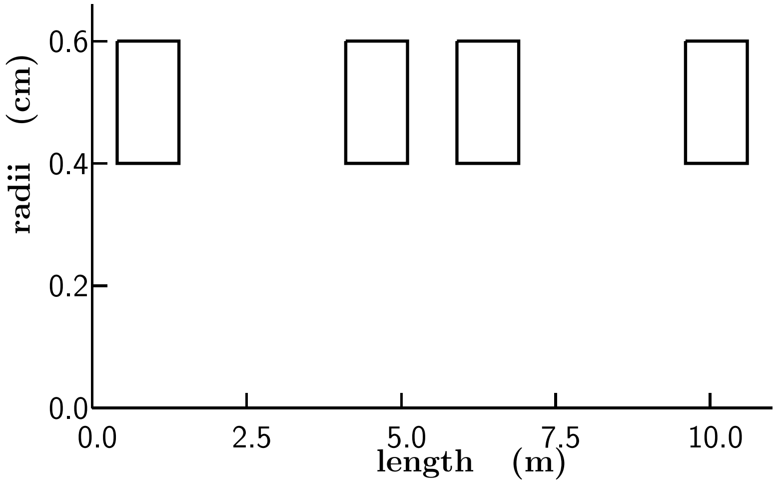


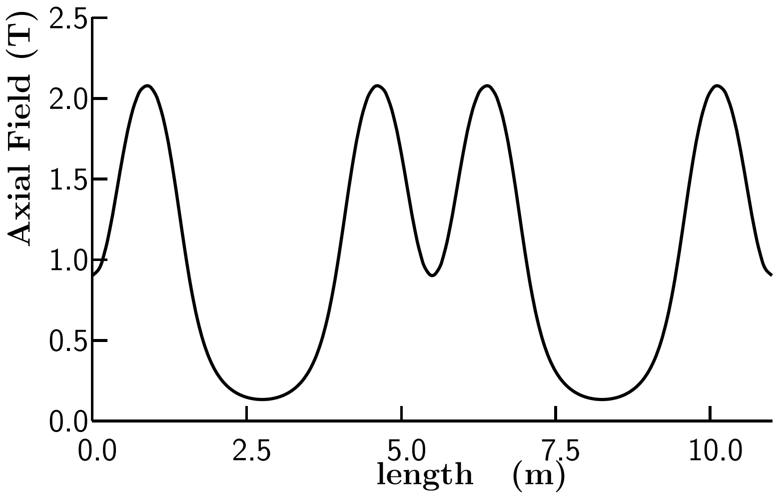


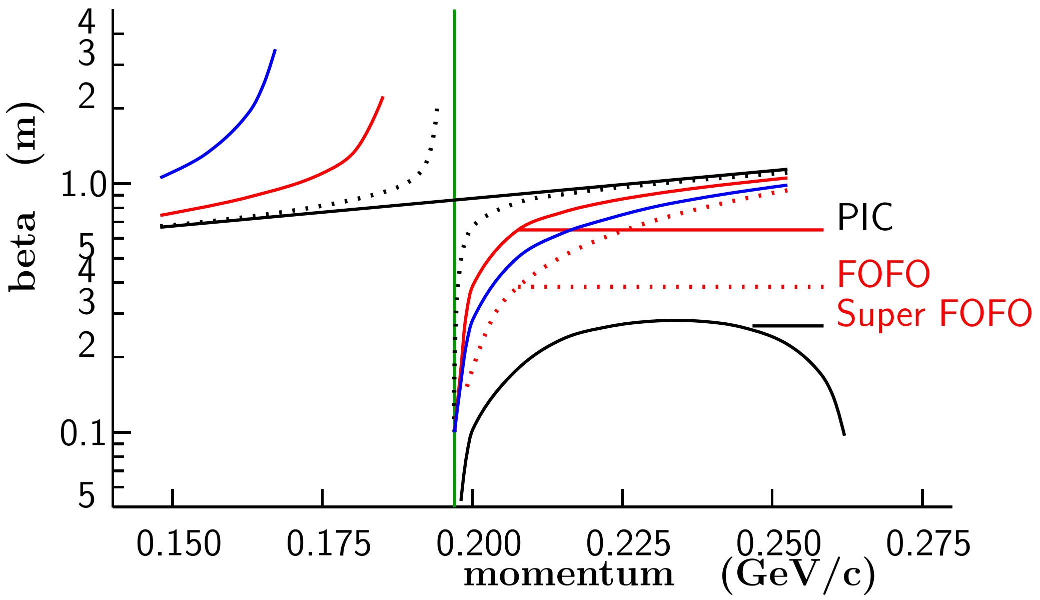
- Resonances introduced
- Betas reduced locally
- Momentum acceptance small

Super FOFO

Double periodicity

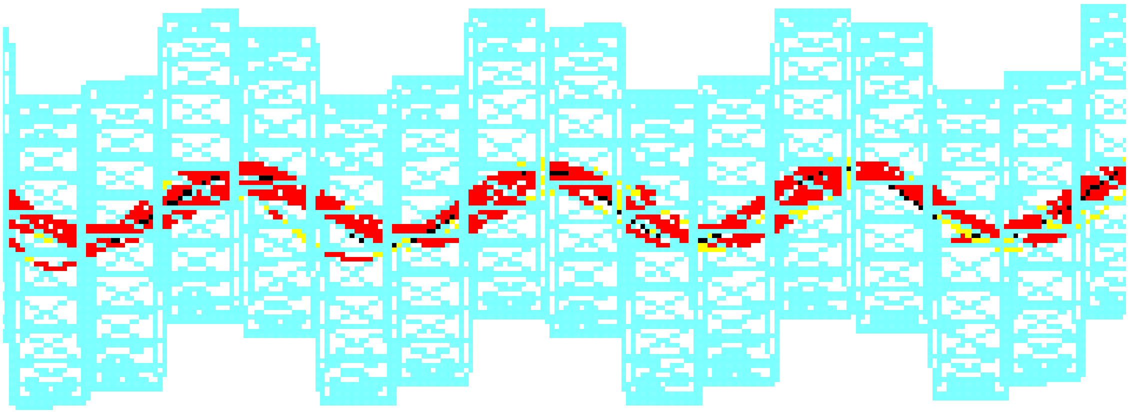


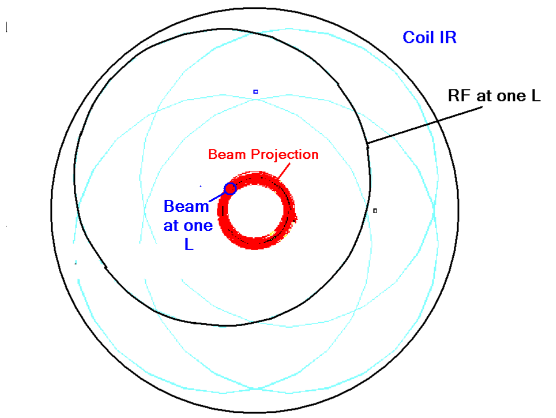




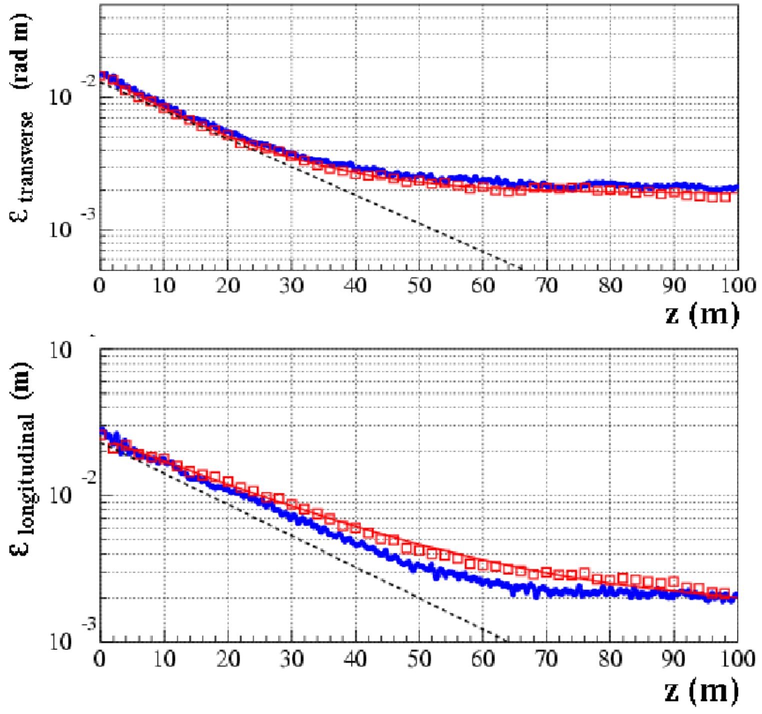
- Beta lower over finite momentum range
- Beta lower by about 1/2 solenoid

Cooling in gas with helical field (Derbenev, Rol Johnson, Muons Inc.)



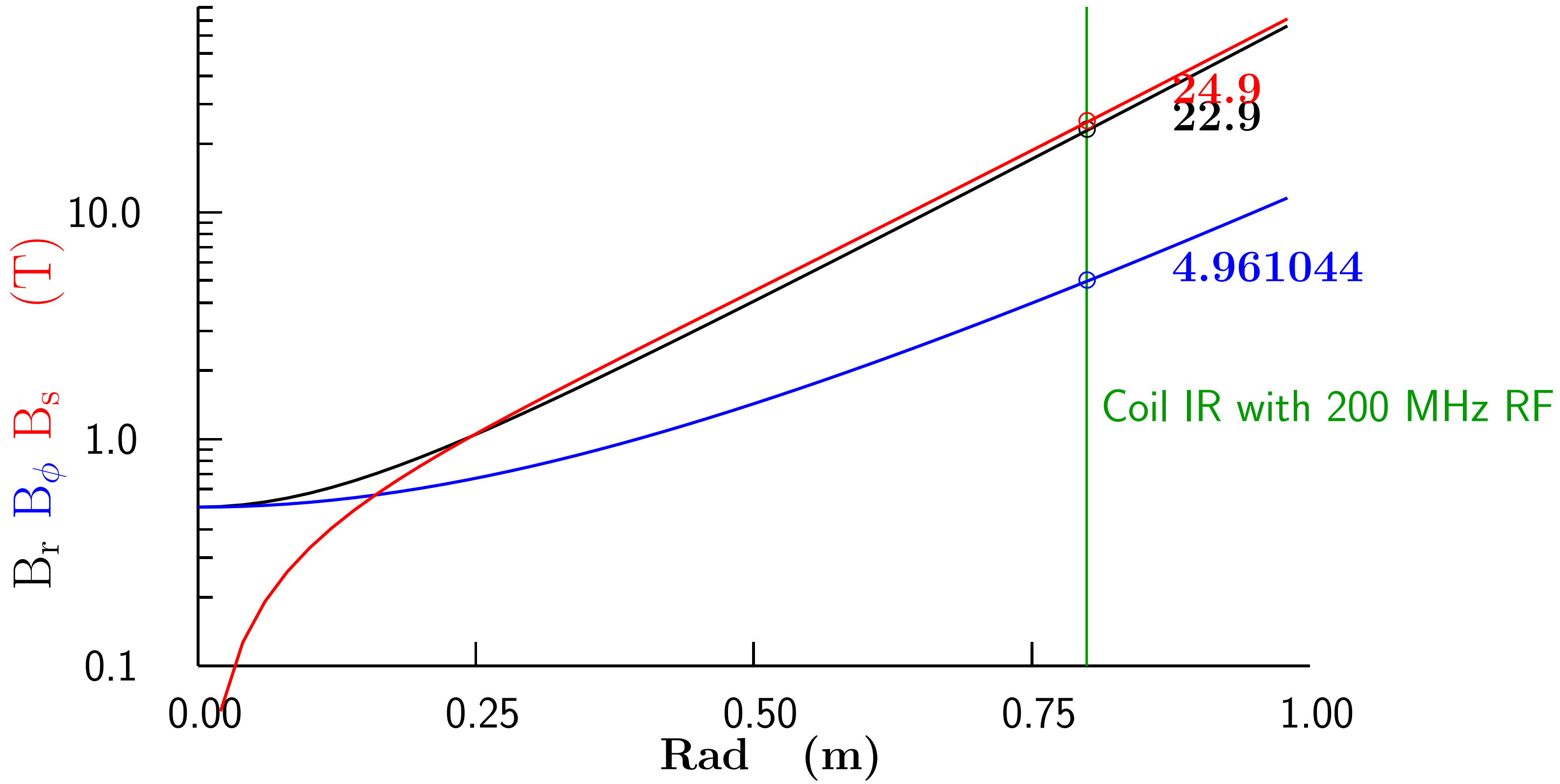


- Gas used partly for higher gradients
  Not yet demonstrated
- $J_z < 1$ can be set to 2/3
- Cooling in 6 dimensions
  of order 1000
- Moderate fields at beam
  Bz=3.5 T. Br=.5 T
- Better Performance than
  RFOFO Ring

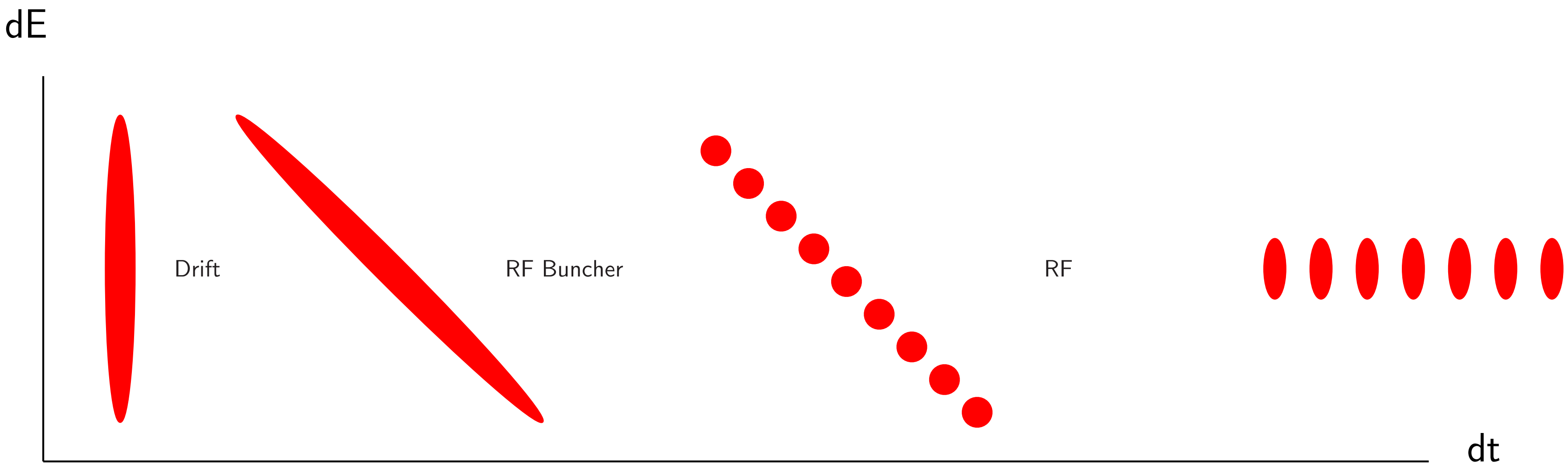


But Helix Fields at Coils > 24 T

For: $\lambda = 1$ m
$B_\perp = 0.5$ T



- Increasing pitch: hurts ds/dp
- Decreasing helix B: hurts ds/dp
- Lowering RF $\lambda \rightarrow$ lower emit + higher B's
- Exploring emittance exchange before bunching and RF


dE
Drift
RF Buncher
RF
dt