Neutrino Factory Studies

R B Palmer
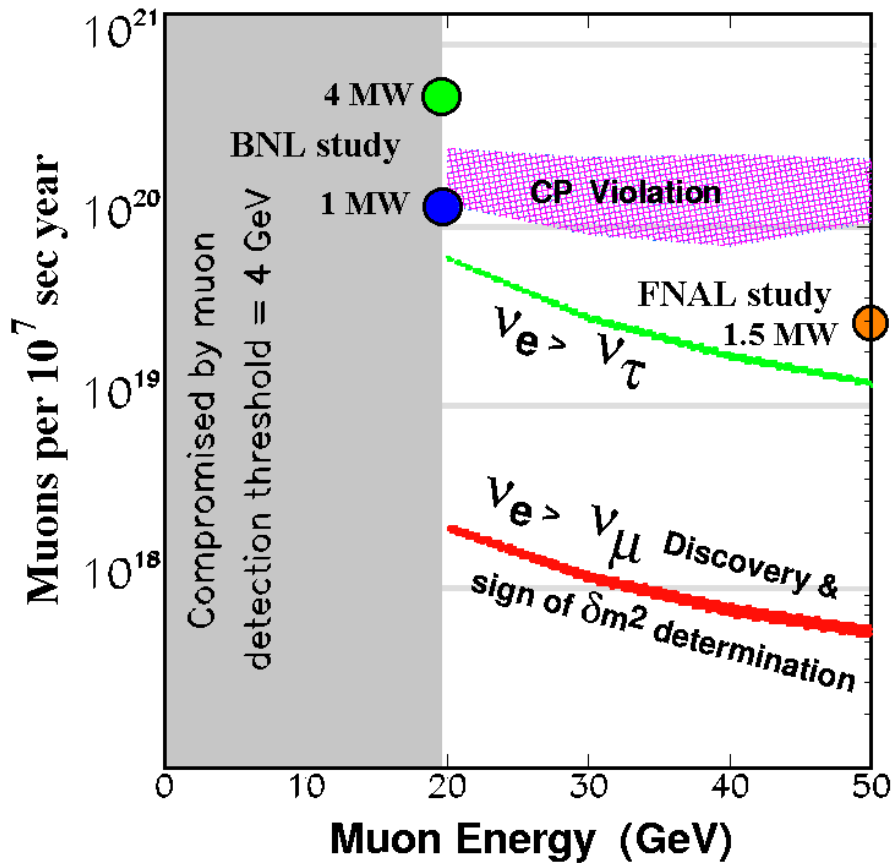
LBNL   3/15/03

Some of Andy's Roles

- **Being Old**
  but I am gaining on him

- **Being right**
  or at least agreeing with me

- **Being anti-windsurfing**
  I will come to this

- **Saving the Collaboration from war**
  Muon (Neutrino Factory) Collaboration Spokesperson 99-02

- **Being wrong, I hope**
  "you can't half the cost"   **(NUFAC02, London)**

- **Working to prove himself so**
  FFAG's to the rescue
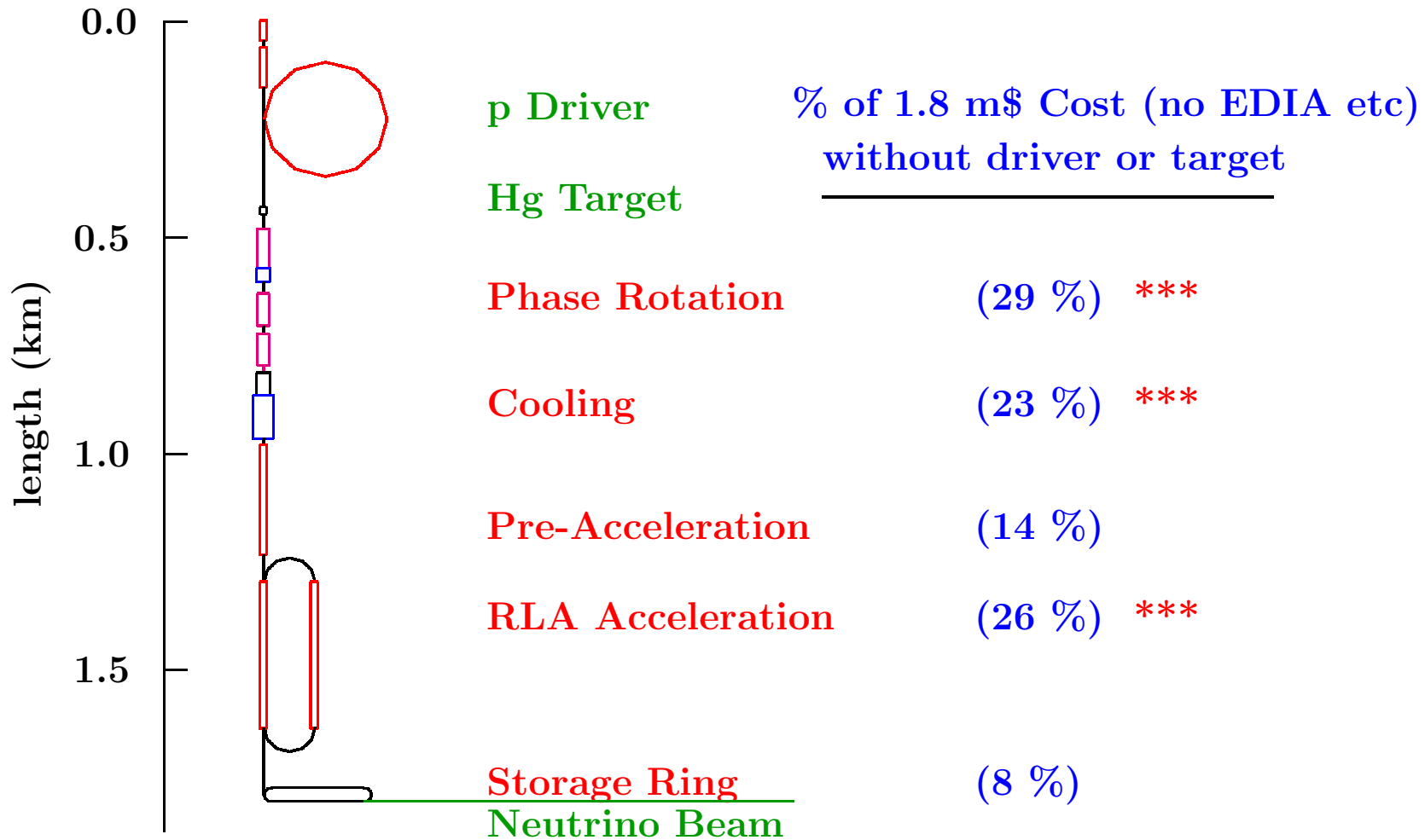
Muon Ring Neutrino Factory

L = 2800 km, $\sin^2 2\theta_{13} = 0.04$

Muons per 10^7 sec year

4 MW
BNL study
1 MW
CP Violation
Compromised by muon detection threshold = 4 GeV
$\nu_e > \nu_\tau$
FNAL study
1.5 MW
$\nu_e > \nu_\mu$ Discovery &
sign of $\delta m2$ determination

Muon Energy (GeV)

- Study 1 Performance too low
- Study 2 with 2 MW OK

- muon decays in straight section / $1\ 10^7$ sec
- For Detector mass 50 kT
- Best distance: 2000 - 3000 km

Study 2 Neutrino Factory

length (km)

0.0

0.5

1.0

1.5

p Driver

Hg Target

% of 1.8 m$ Cost (no EDIA etc)
without driver or target

Phase Rotation   (29 %)   ***

Cooling   (23 %)   ***

Pre-Acceleration   (14 %)

RLA Acceleration   (26 %)   ***

Storage Ring   (8 %)
Neutrino Beam

***   78 % of cost   will discuss these

1) PHASE ROTATION

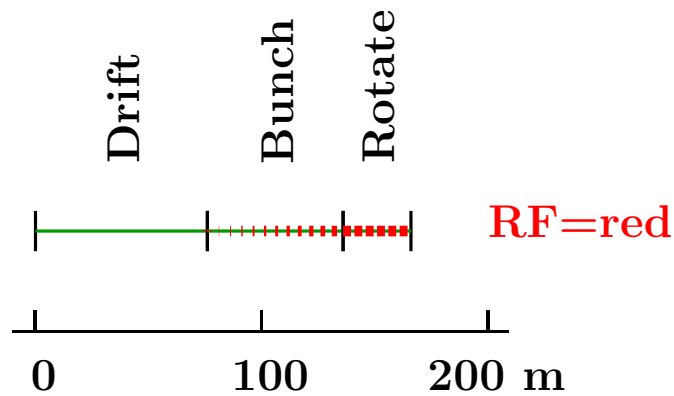(Used to reduce dp/p prior to Cooling)

Study 2 with Induction Linacs

dE

Drift   Ind. Linac   Buncher

dt
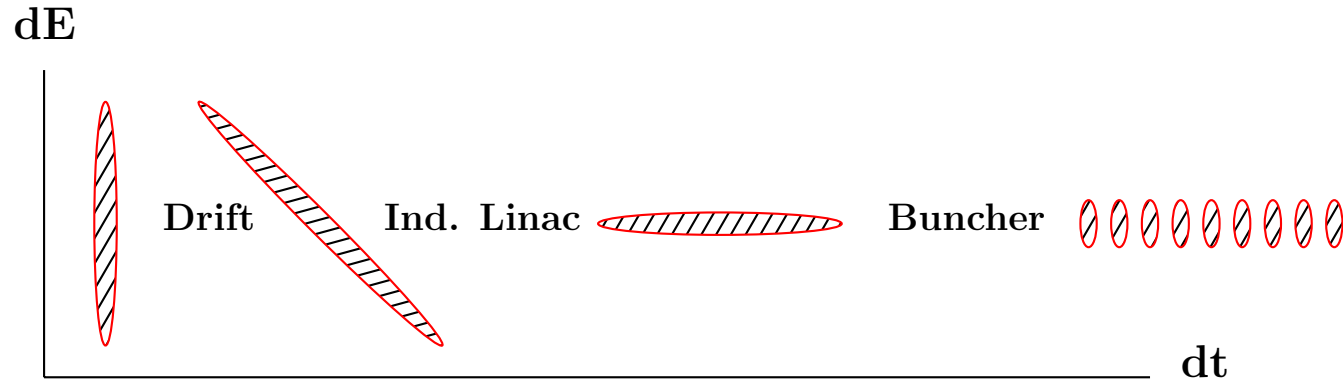
Bunched Beam Rotation with 200 MHz RF   (Neuffer)

dE

RF Buncher
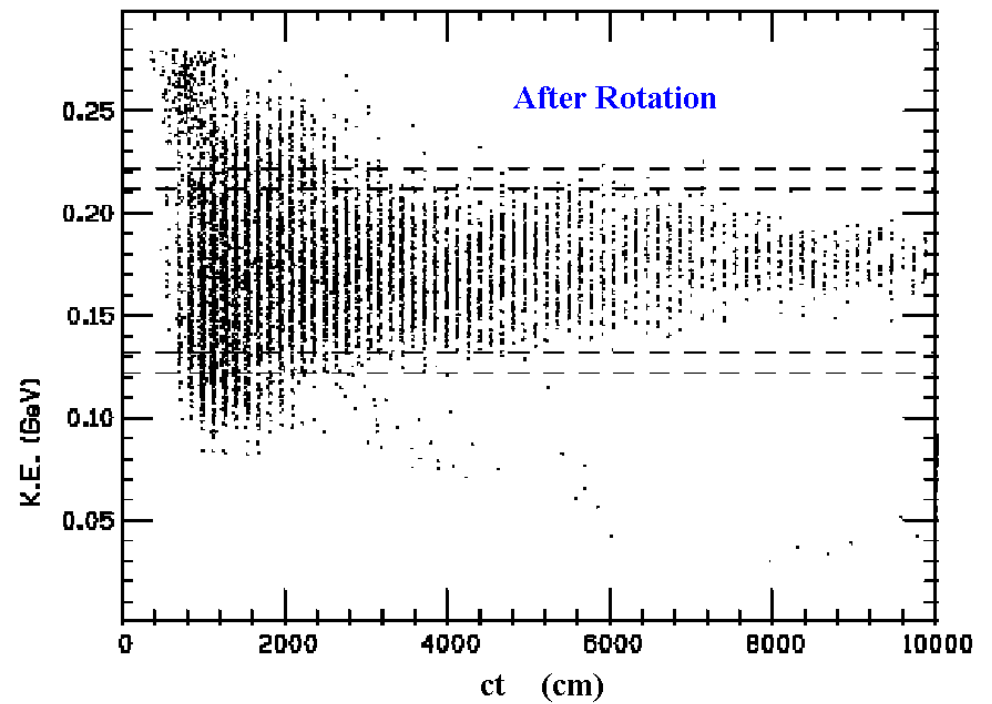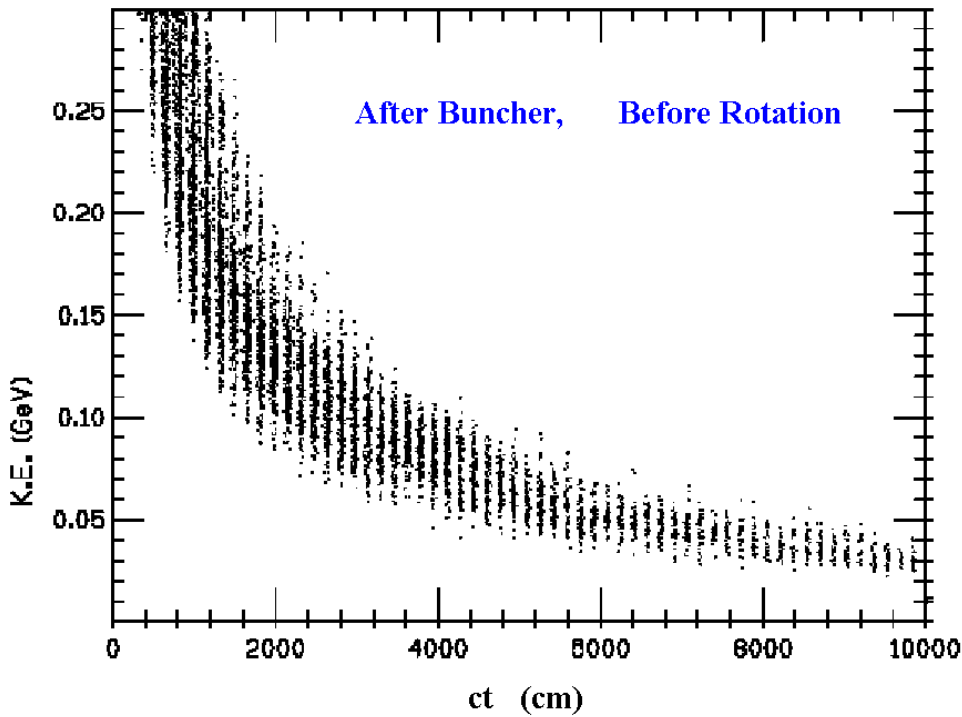
Drift   RF Rotate

dt
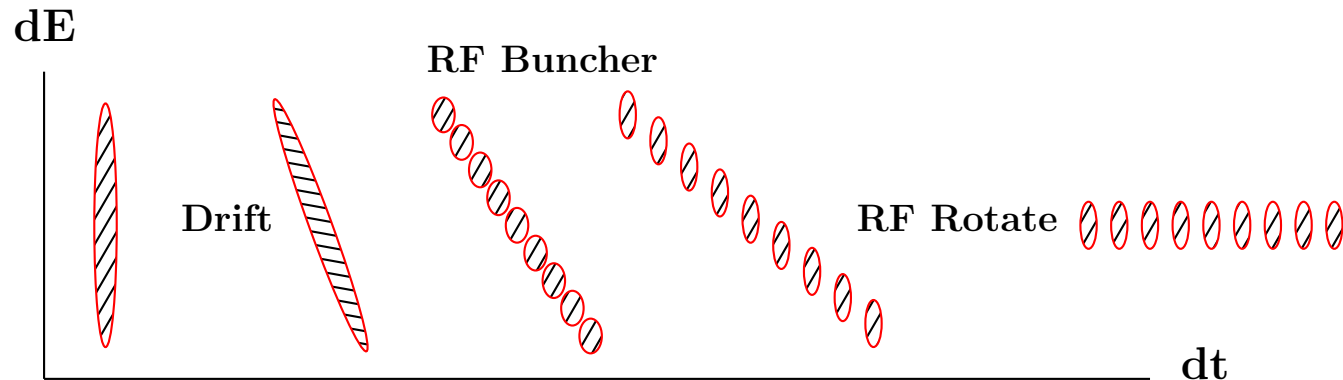
- 200 MHz RF is cheaper than Induction Linacs

- But RF frequency must vary along bunching channel
  (high mom. bunches move faster than low)
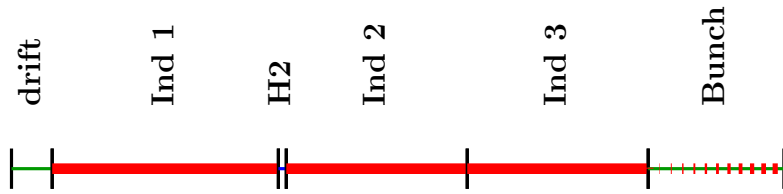
Simulation   (Several Programs, Inc. ICOOL)

Drift   Bunch   Rotate

RF=red

- About as efficient as Study 2
- But captures both charges

After Buncher,   Before Rotation

K.E. (GeV)

ct   (cm)

After Rotation

K.E. (GeV)

ct   (cm)

Compare with Study 2

- **Study 2**

- **e.g. Bunch Beam Rotation**
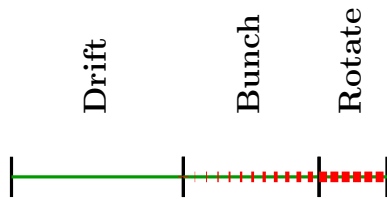
	Study 2	Now	Factor
Tot Length (m)	328^1	166	51 %
Acc Length (m)	269^2	35	13 %
Acc Type	Induction^3	Warm RF	

- **Approx 2 times performance**

- **Expect Substantial Savings**

- **Neuffer claims approx 1/4**
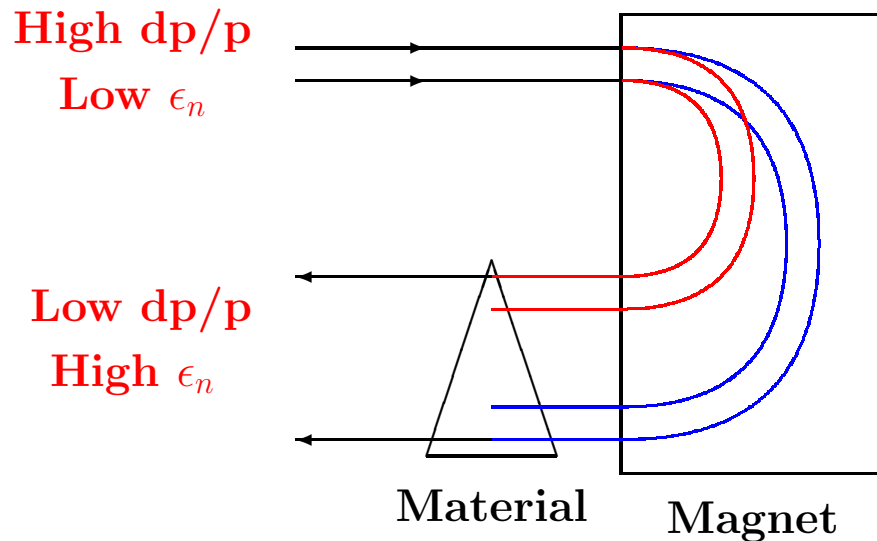
  BUT

- **Not yet matched into cooling ***

2) COOLING

Cooling Concepts

• **TRANSVERSE**

$p_\parallel$ less
$p_\perp$ less

$p_\parallel$ restored
$p_\perp$ still less

Material   Acceleration

• **LONGITUDINAL EMIT EXCH**

High dp/p
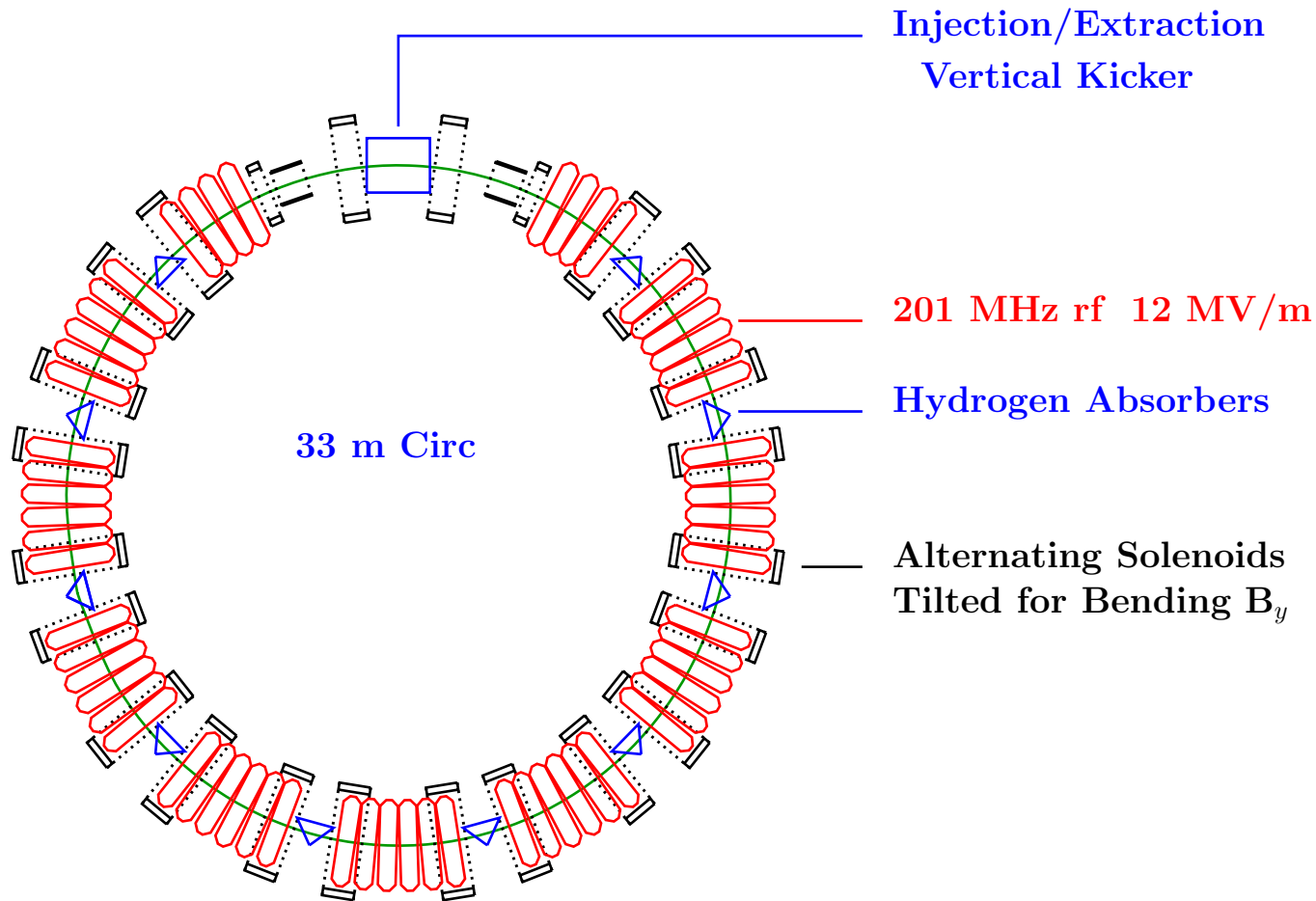Low ϵ_n

Low dp/p
High ϵ_n

Material   Magnet
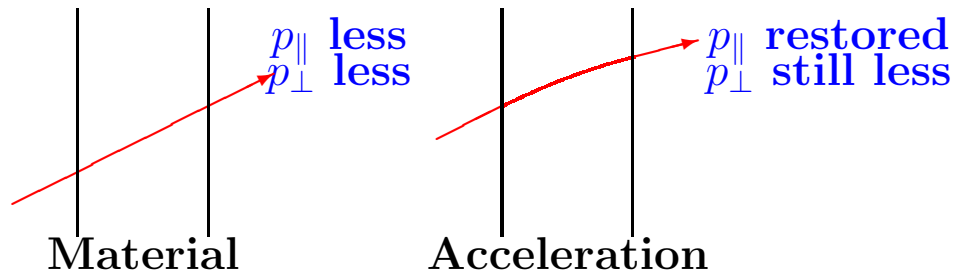
• Needs Low density Material
  to reduce scattering
  Liquid Hydrogen

• Strong Focusing
  Solenoids

• Dispersion
  e.g. In a Ring

"RFOFO" Cooling Ring

V. Balbekov, J.S. Berg, R. Fernow, J. Gallardo, W. Lau, R.B. Palmer, L. Reginato, D. Summers Y. Zhao

Injection/Extraction
Vertical Kicker

201 MHz rf 12 MV/m

Hydrogen Absorbers

Alternating Solenoids
Tilted for Bending B_y

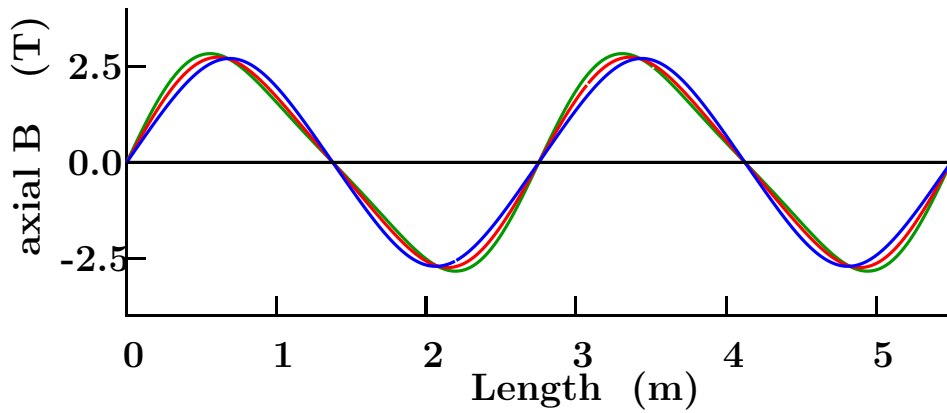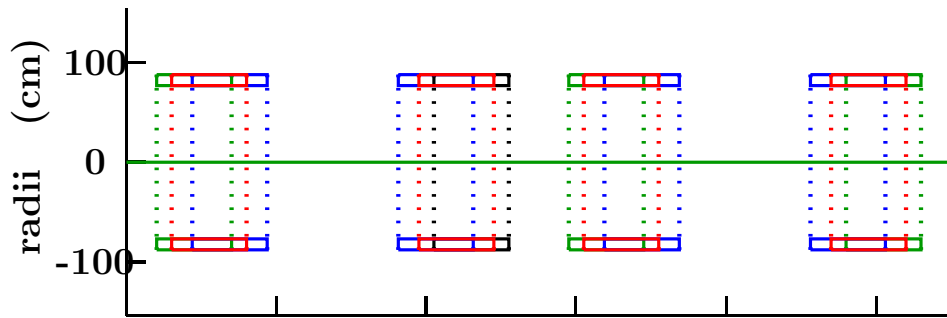33 m Circ

"RFOFO" (The St Croix Windsurfing Story)

Alternating Solenoid Focus

- Greater aperture and stonger focus than Quads

- Average Bs=0 (needed for angular momentum)

- But Momentum Dependence of Beta
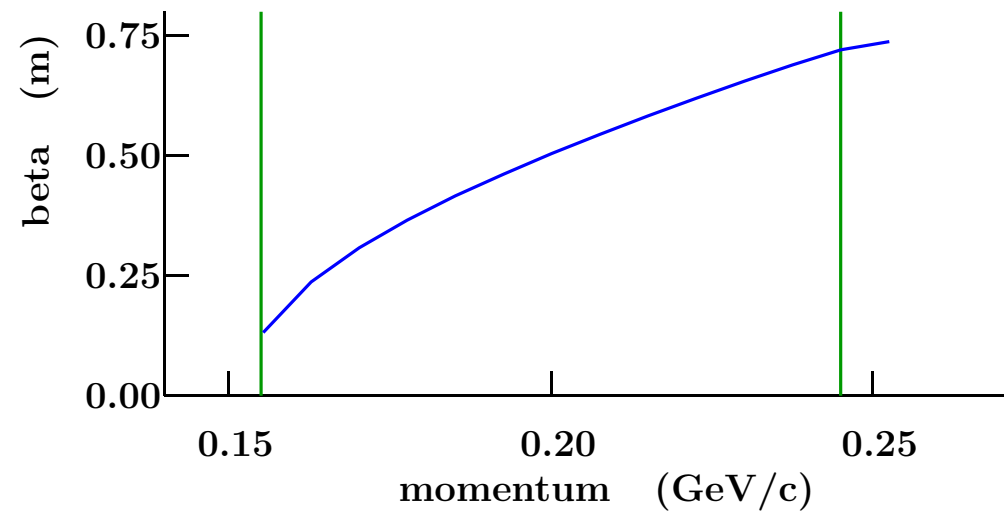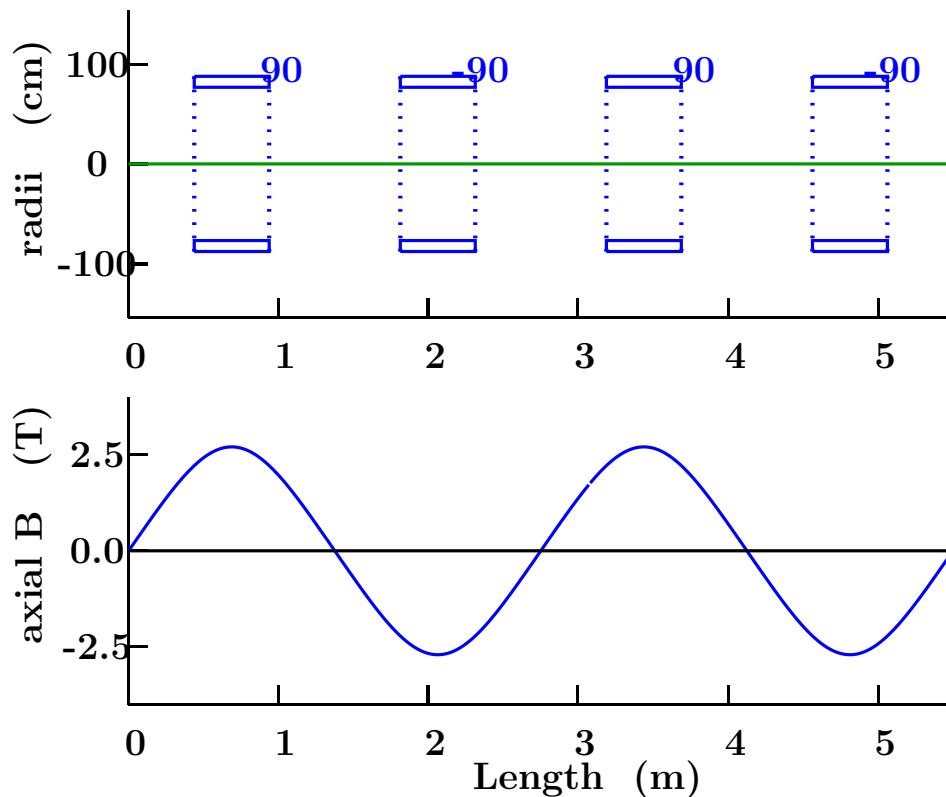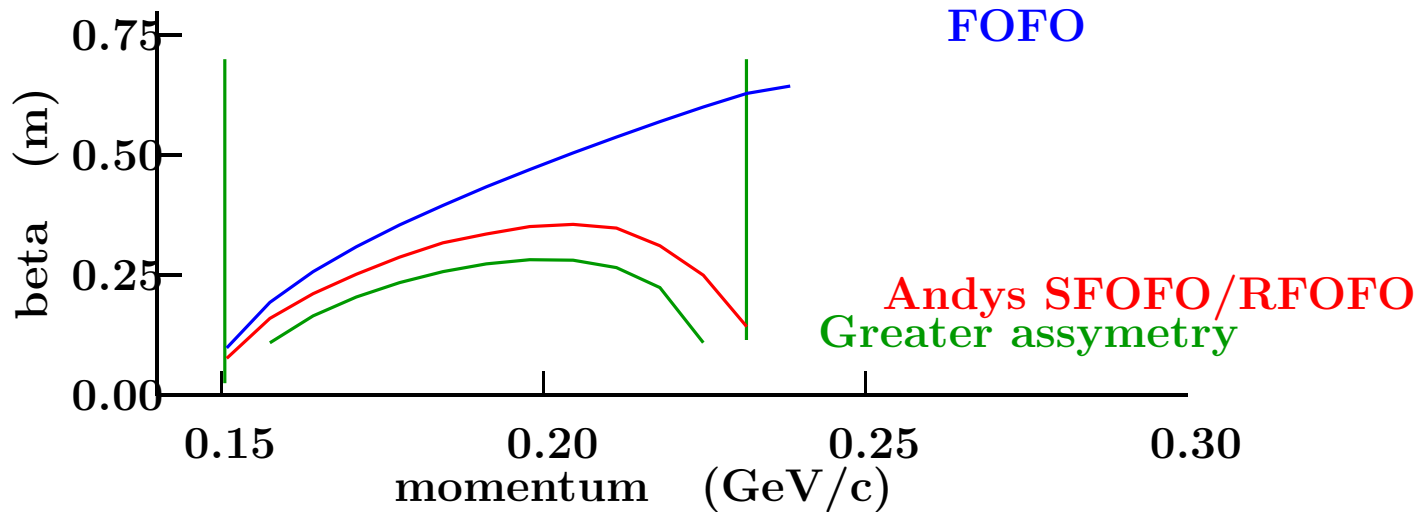

- Andy Suggests Breaking the symmetry

- I give up my windsurfing and try it

Andy's Super FOFO

• Break the symmetry

• Introduce a second Resonance

• Lowers and flattens beta's

FOFO

Andys SFOFO/RFOFO

Greater assymetry

Performance

- **ICOOL Simulation**

- **No Windows**

- **No Injection/Extraction Gap**
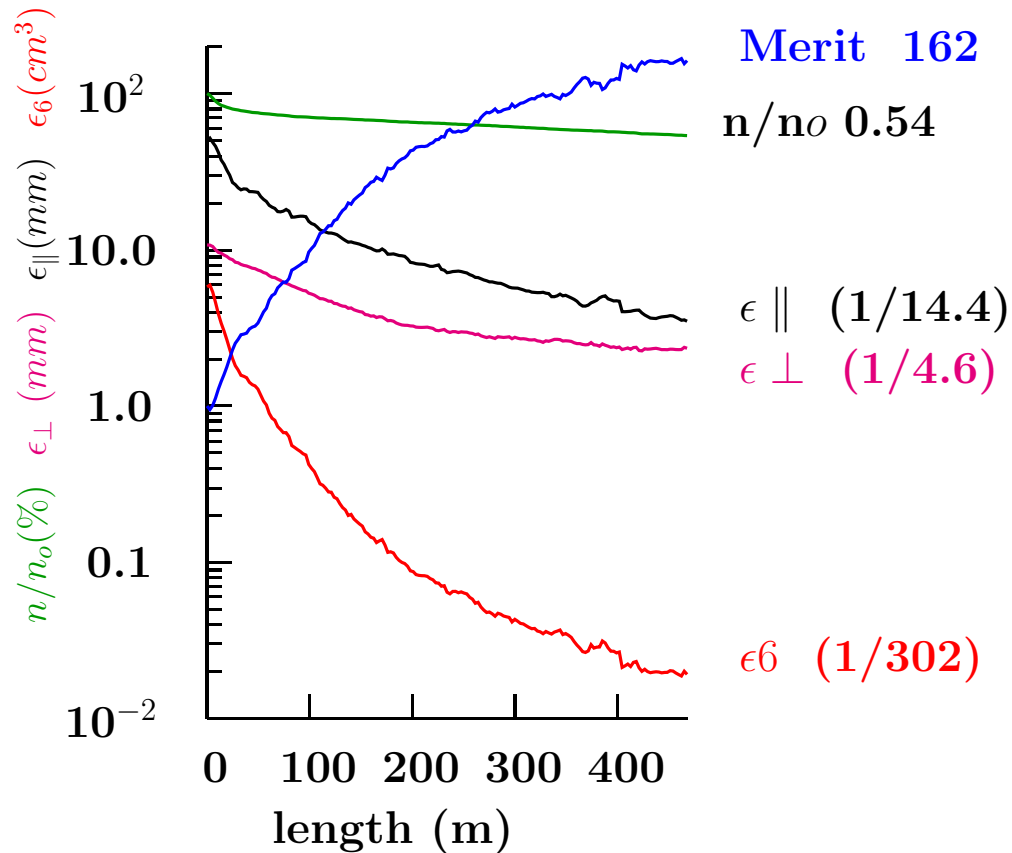
- **Very Good cooling (Merit up to 160)**
  (without windows or injection/extraction)

- **Real fields from real coils (Balbekov)**

- **Injection/Extraction seems OK**

Merit 162

n/no 0.54

$\epsilon \parallel$ (1/14.4)

$\epsilon \perp$ (1/4.6)

$\epsilon 6$ (1/302)

length (m)

Compare with Study 2

- Study 2 Cooling

2.75 m Cells   1.65 m Cells

- e.g. RFOFO Cooling Ring

|	Study 2	Now	Factor
Tot Length (m)	108	33	30 %
Acc Length (m)	54	16	30 %
Acc Grad	16 MV/m	12 MV/m	66 %

1. Without windows or injection/extraction

- Expect Substantial Savings

- Unofficially: Approx 1/3

BUT

- Absorber heating needs study

- Very thin windows required

- Phase Rotation needs modification ***

- Super-kicker needs development ***
  1000 times pbar kickers

3) ACCELERATION

1. Recirculating Linear Accelerator as in Study 2
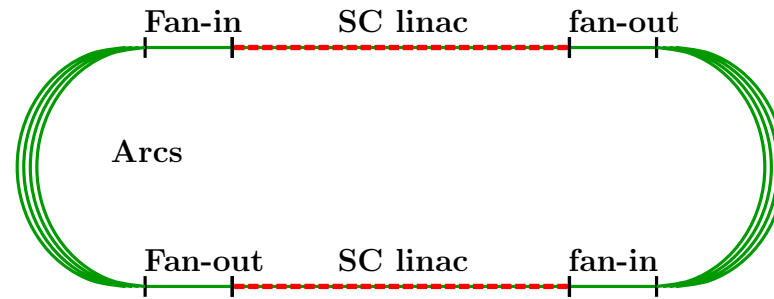
- only 4 turns: much SC Acceleration needed
- Many arcs: 4 km of beam-line

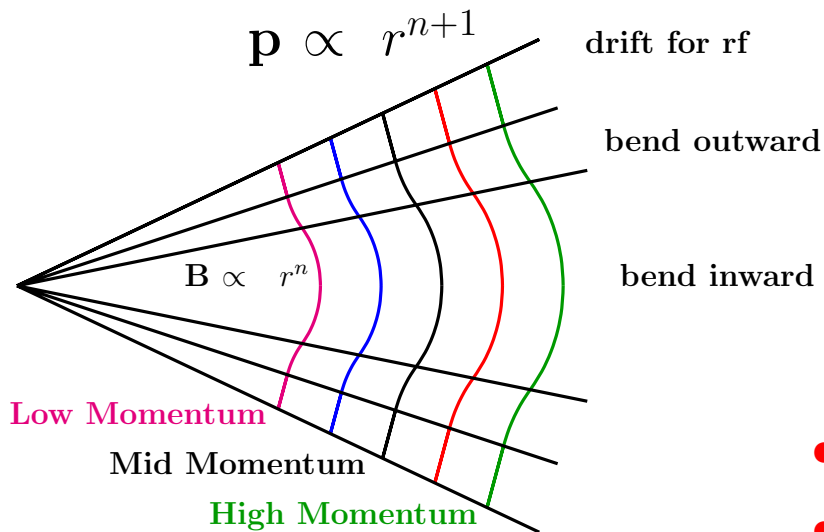FFAGs: "Fixed Field Alternating Gradient" Acceleration:
More turns   Less RF

2. Scaling FFAG   (Japanese Effort)
Non-Isochronous: Requires Frequency Modulation or Very Low Frequency

3. Non-Scaling FFAG   (Carol Johnstone et al)
Isochronous and More compact than Scaling
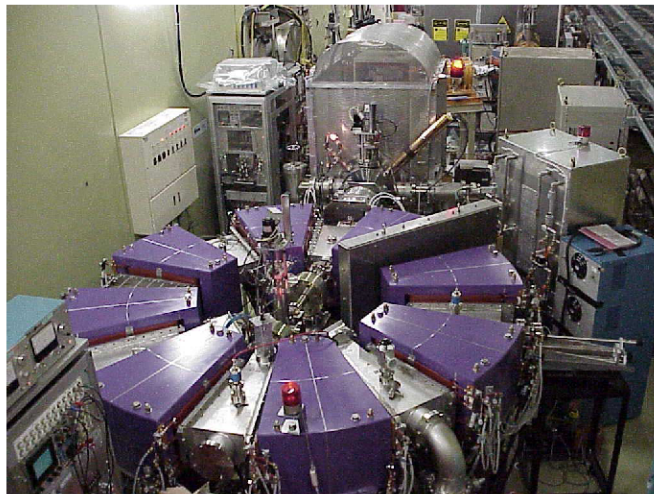
Scaling FFAG (proposed by Japan)

$$\mathbf{p} \propto r^{n+1}$$

drift for rf

bend outward

$$\mathbf{B} \propto r^n$$

bend inward

Low Momentum

Mid Momentum

High Momentum

- Invented at MURA in 60's
- eg spiral Ridge Cyclotron

POP FFAG at KEK

- Δp limited only by aperture
  but only 1:2 for Japan 20 GeV
- Non-isochronous
  Low Frequency RF (25 MHz)
- Short gaps
  Non-superconducting RF
- Large magnet apertures
  Expensive

Figure C.2: Top-view of the POP FFAG

Non-scaling FODO FFAG   (Proposed by Carol Johnstone)

Combined function strongly focusing FODO (without sextupoles)

High Energy

Low Energy

F

RF   RF

D   D

Path length vs momentum:

dct/turn (m)

1.25

1.00

0.75

0.50

0.25

0.00

scaling (10-20)

Carol (10-20)
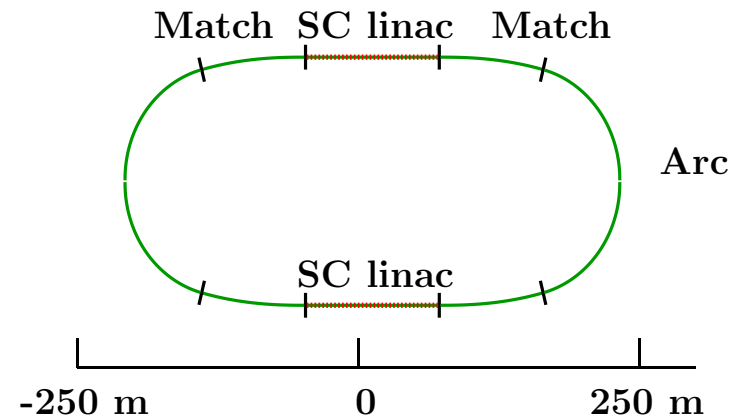
10.0   12.5   15.0   17.5   20.0
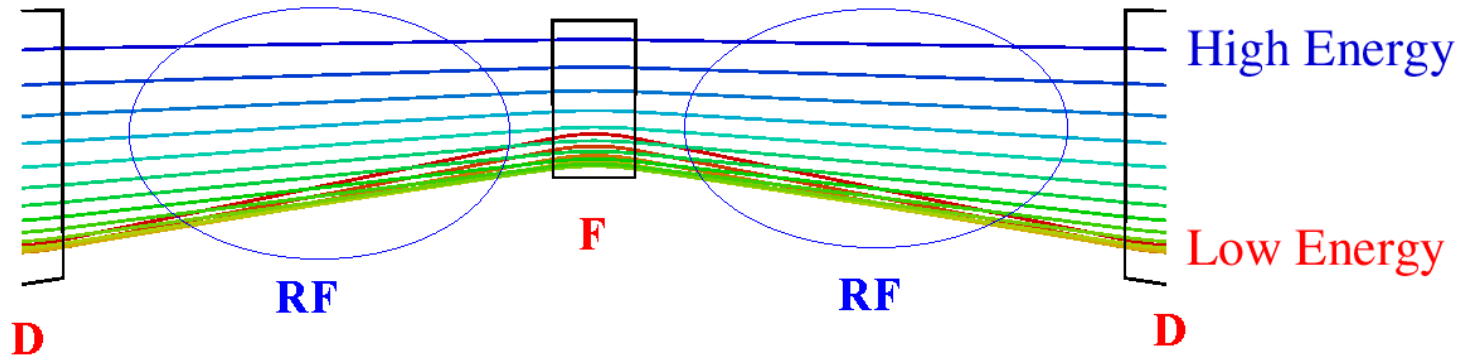
Momentum (GeV)
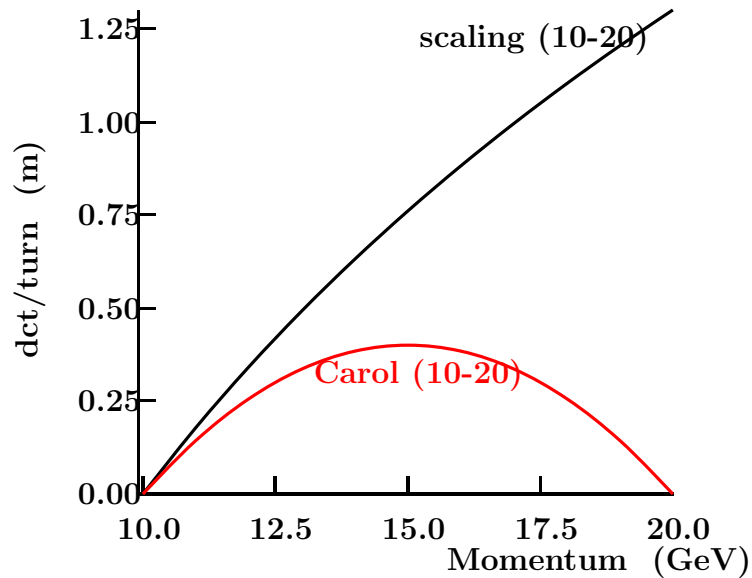
- Less path length difference for same energy range
- Non-monotonic
- Allows 200 MHz (vs. 25 MHz for scaling)
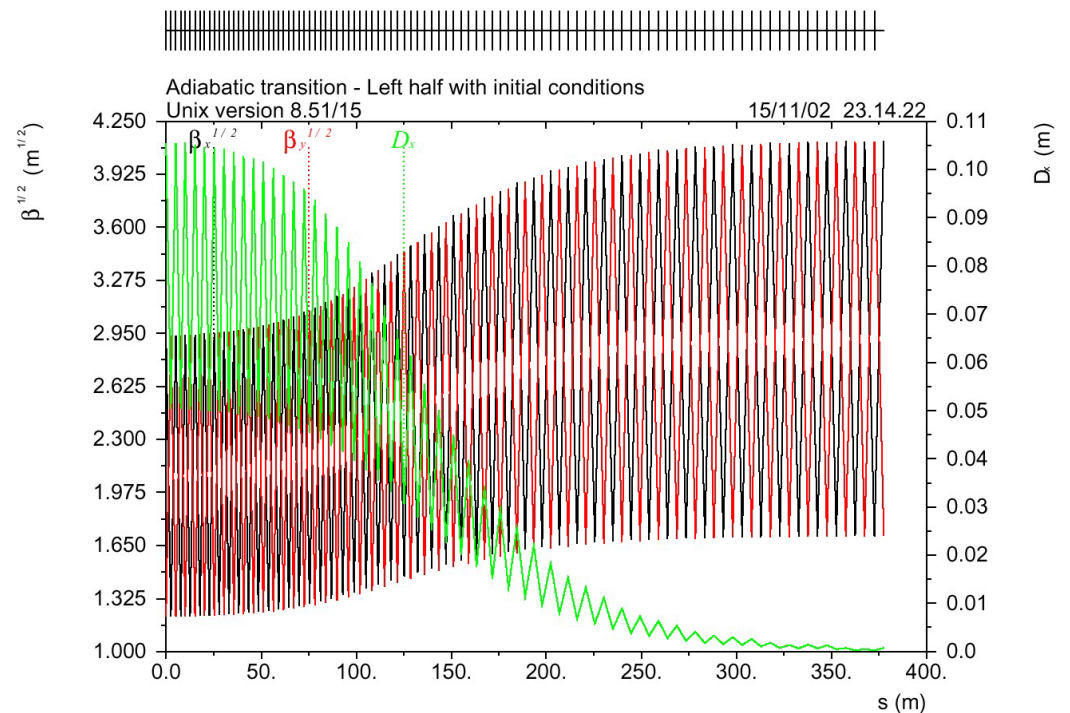- but gaps still short:
- non-superconducting RF

New Idea from LBNL Workshop:
(Berg, Johnstone, Keil, Palmer, Sessler)

- Using Carol's lattice
- Put RF in straight sections
- Make tight arc
- Adiabatically match between them

- Large acceptance
- 3 m gaps OK for SC RF
- Smaller circumference
- Smaller aperture magnets

Match SC linac Match

Arc

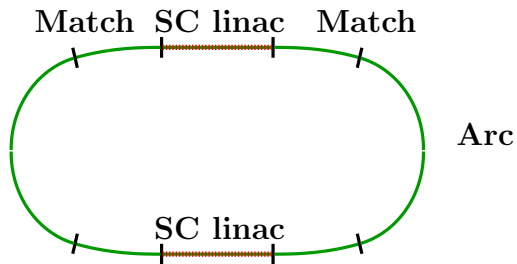SC linac

-250 m   0   250 m

Adiabatic transition - Left half with initial conditions
Unix version 8.51/15   15/11/02 23.14.22

$\beta_x^{1/2}$ $\beta_y^{1/2}$ D_x

$\beta^{1/2}$ (m$^{1/2}$)

D_x (m)

s (m)

Compare with Study 2

- Study 2 RLA
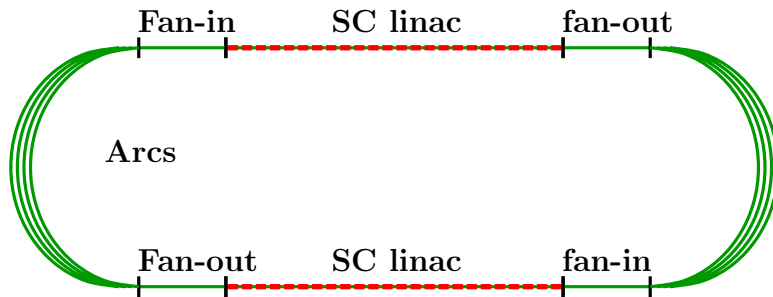
- e.g. Racetrack FFAG

- Acceptance 2 times Study-2

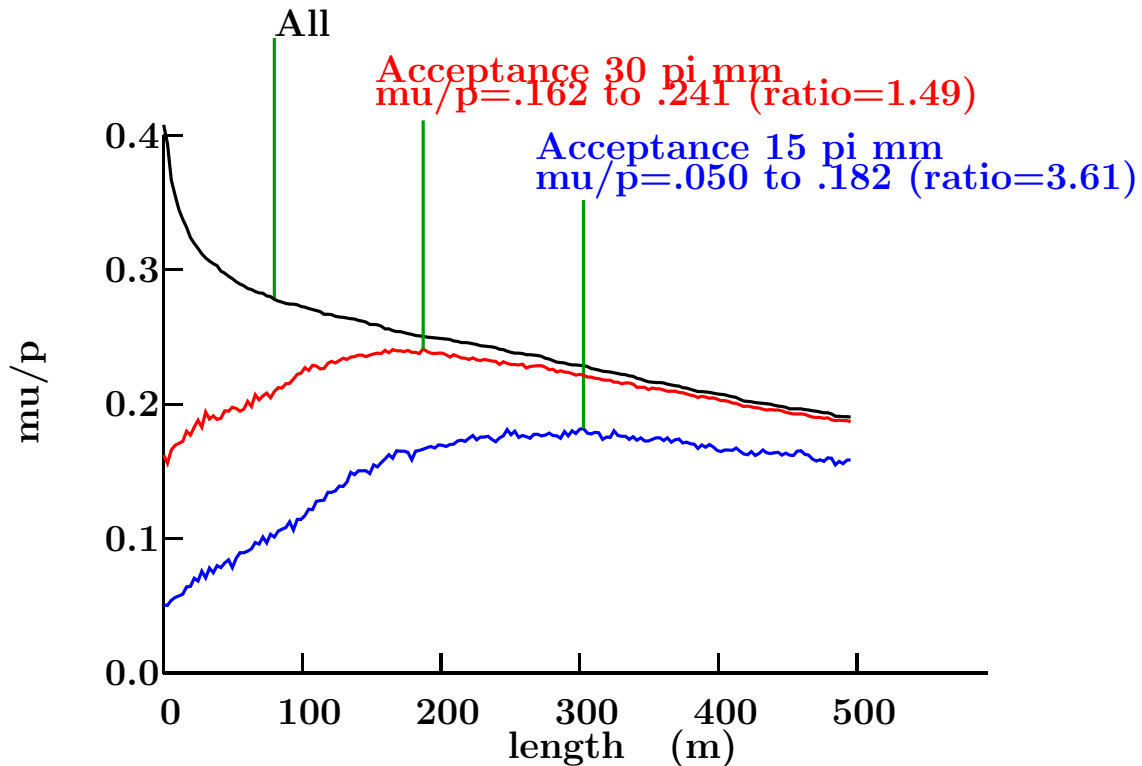|	Study 2	Now	Factor
Acceleration	2.5-20	6-20	80 %
Vac Length[1]	3261	730	22 %
Tun Length[2]	1494	730	49 %
Acc Length[3]	288	102	35 %
Acc Grad.	16	8	50 %

- Substantial Savings
  Unofficially: Approx 1/2

  BUT

- Match not yet Designed

- More Pre-acceleration required

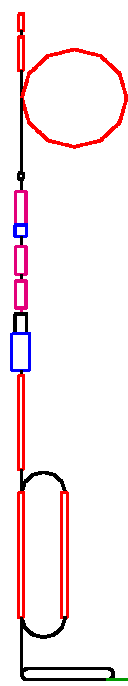- Inject/extract not designed

- Other Options

Performance vs Acceptance and Cooling

- **Performance at 30 pi mm without cooling**
  approx equal to Performance at 15 pi mm with cooling

- **Not a new idea: Mori at KEK has proposed no cooling for a lomg time**

- **Note: We still need (approx 3) cooling rings for a Muon Collider**

- **If both signs, Performance**
  approx equal to 2 times

Cost Reduced Neutrino Factory

Warning: The following is not official

Mike Zisman should not be listening   this is for Andy

	% of 1.8 m$ Cost (no EDIA etc) without driver or target		
	Study-2	**New**	**No cooling**
p Driver			
Hg Target			
Phase Rotation	(29 %)	(8 %)	(8 %)
Cooling	(23 %)	(8 %)	(0 %)
Pre-Acceleration	(14 %)	(14 %)	(14 %)
RLA Acceleration	(26 %)	(13 %)	(13 %)
Storage Ring	(8 %)	(8 %)	(8 %)
Neutrino Beam			
	100%	**51%**	**43%**

Conclusions

- **If 30 pi mm acceptance and both signs:**
- **Above Study-2 Performance without cooling, at below 1/2 cost**
- **If no cooling: little R&D Needed**
  - Phase rotation as now designed
  - No Hydrogen Absorbers etc
  - No Super Kicker required
- **Cooling can be Phase 2**

- **Andy may be wrong**
- **Thanks to Andy**

  BUT

- **Much more work needed**
- **But it is fun**
- **You see why Andy works on this though nobody pays him**