Progress on Muon Neutrino Factories

with emphasis on BNL contributions

R B Palmer

BNL DOE Revue   4/22/03

Work Of Muon Collaboration (124 members, 33 Institutions)

S. Geer, R Palmer (spokespersons), M. Zisman (Project Manager

1. **Physics Motivation**
2. **Design Studies**
3. **Experimental Programs**
4. **Conclusion**

Physics Motivation

To Study Neutrino Oscillations Beyond a Super-Beam

In particular, the study of CP Violation

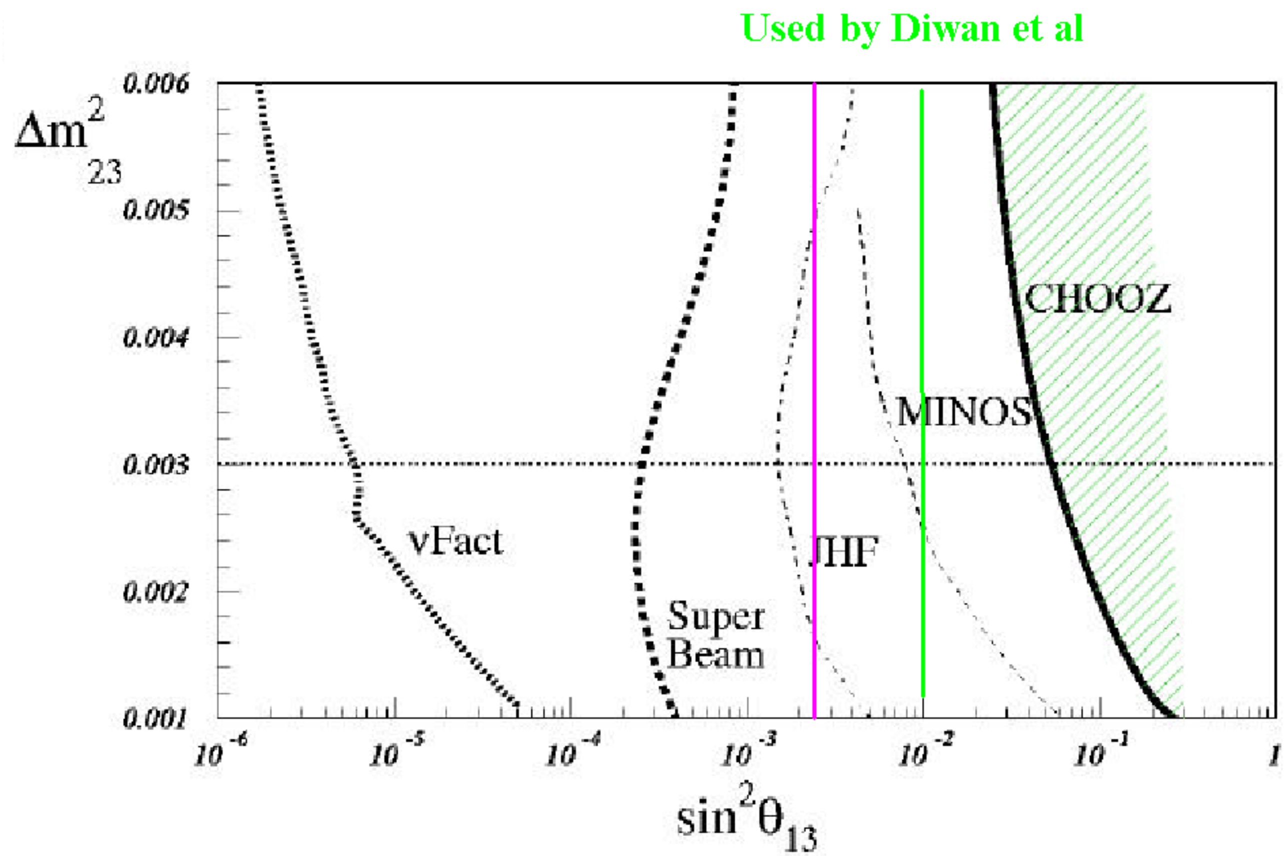
$$\text{In a Ring :} \qquad \mu \rightarrow \nu_\mu + e + \bar{\nu}_e \quad + \text{nothing else}$$

- **Higher Fluxes**
- **Both e and μ neutrinos**
- **Better knowledge of, and purer, beam**
- **Less background**

- **Studies $\nu_e \rightarrow \nu_\mu$ vs. $\nu_\mu \rightarrow \nu_e$ for Super-Beam**
- **Identification by wrong sign μ vs. e identification in Super-Beam**
- **Background $< 10^{-4}$ vs. $\approx 0.7\%$ for Super-Beam**
- **More intense: Requires smaller Detector Mass (50kT vs. 500 kT)**
- **But Detector needs Charge Identification**
  - **Iron Plate Calorimeter**
  - **Water Cerenkov + External Toroid Muon Spectrometer**
  - **Liquid Argon TPC with Magnetic Field**

Critical Question: What is θ_{13}

Limit on Theta(13) vs. Mass Difference

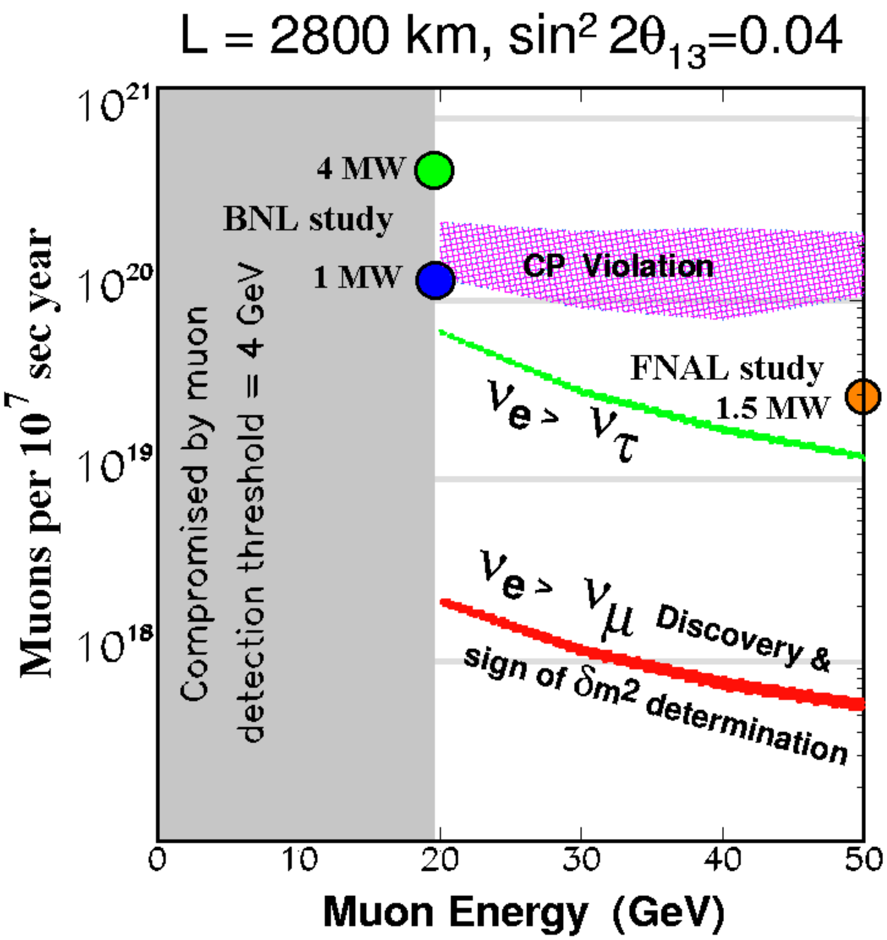


- If $\sin^2\ 2\theta_{13}\ >\ 0.01$ **Super-Beam might see CP**
- If $\sin^2\ 2\theta_{13}\ <\ 0.01$ **Certainly need Factory to see CP**
- **In either case: Factory would increase accuracy**

US Neutrino Factory Feasibility Studies

- **Study I**
  - **Emphasized Feasibility**
  - **Sponsored by Fermi (finished March 00)**
  - **"Entry Level" (≈ 0.2 10^{20} $\mu/10^7$sec at 1 MW)**
- **Study II**
  - **Emphasized Performance with Feasibility**
  - **Sponsored by BNL (finished April 01)**
  - **6 x Higher Flux (≈ 1.2 10^{20} $\mu/10^7$sec at 1 MW)**
- **Current Work**
  - **Emphasize Lower Cost**
  - **Maintain or improve Performance**
  - **Maintain or improve Feasibility**
  - **Study 3 (In about 2 Years)**
- **Collider Study (later)**

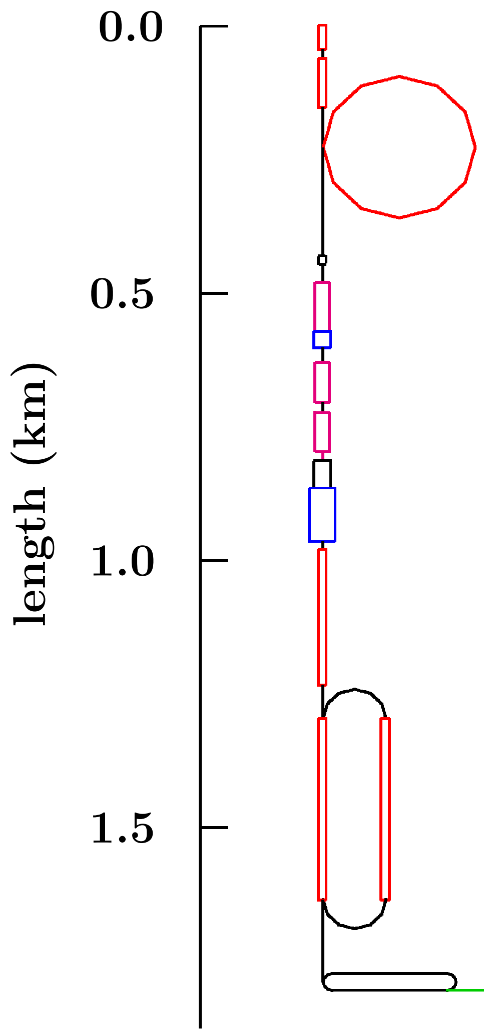
Physics Reach of Studies



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

WIPP=2900 km
Homestake=2500 km

Study-2 Schematic



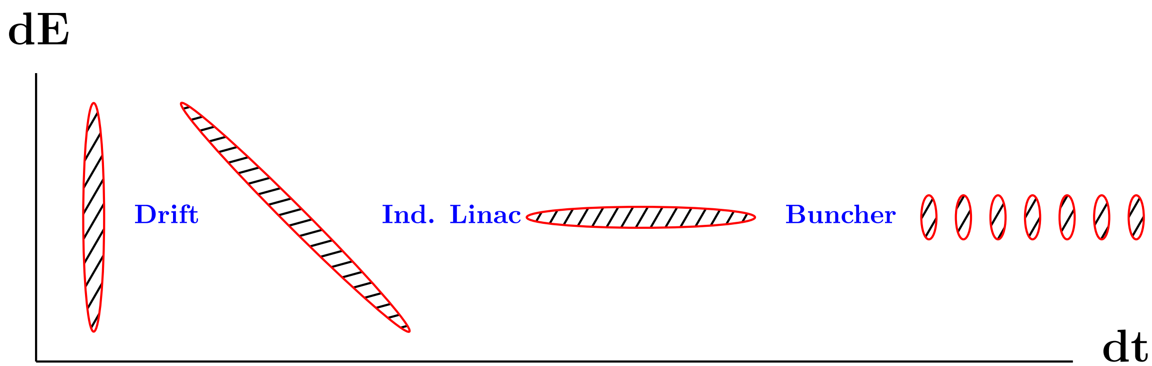
	% of 1.8 m$ Cost (no EDIA etc) without driver or target	
p Driver		
Hg Target		
Phase Rotation	(29 %)	***
Cooling	(23 %)	***
Pre-Acceleration	(14 %)	
RLA Acceleration	(26 %)	***
Storage Ring	(8 %)	
Neutrino Beam		

*** Will discuss savings on these items

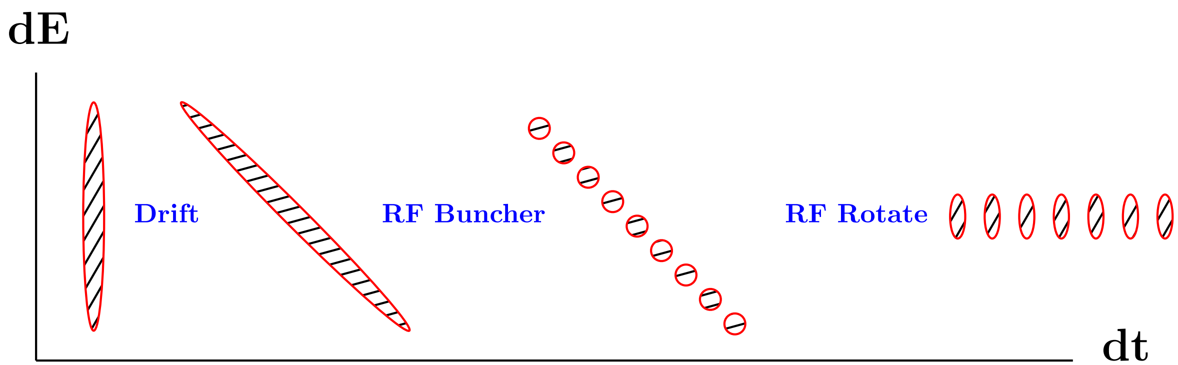
1) PHASE ROTATION (FNAL)

(Reduce dp/p prior to Cooling)

Study 2 with Induction Linacs



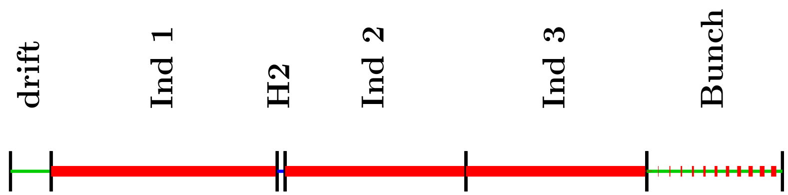
Neuffer's Bunched Beam Rotation with 200 MHz RF



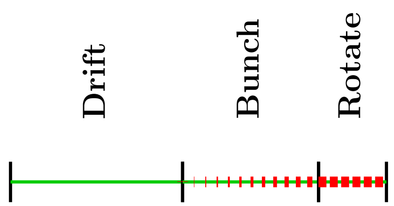
- 200 MHz RF is cheaper than Induction Linacs

Compare with Study 2

- Study 2



- e.g. Bunch Beam Rotation



	Study 2	Now	Factor
Beam Line (m)	328[1]	166	51 %
Acceleration (m)	269[2]	35	13 %
Acc Type	Induction[3]	Warm RF	

1. 18+100+3.5+80+80+47=328
2. 100+80+80+9=269
3. 260 m induction + 9 m RF

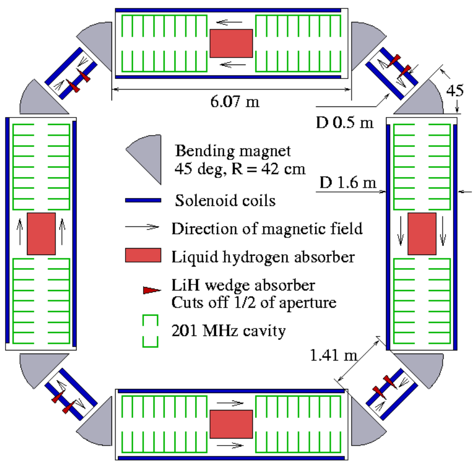
- EXPECT MAJOR SAVINGS $\approx 1/4$

  BUT

- Not yet matched into cooling
  Possible simple solution

2) COOLING RINGS (Three Main Efforts)

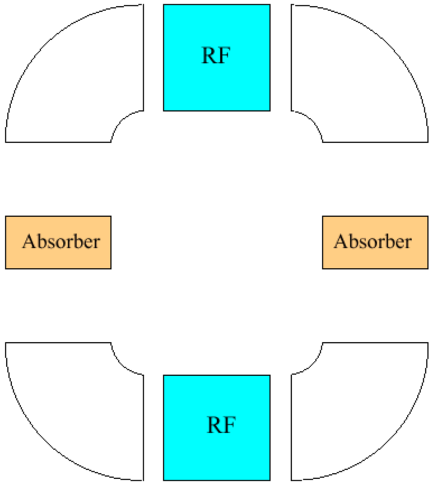
1) TETRA Ring (FNAL) (Balbekov et al)



- Good cooling in all dimensions
- FIRST
  BUT
- Calculated with hard edged unrealistic fields
- Design with real fields proving hard

2) Quad & Bend-only Rings (BNL & LBNL)

(Garren, Kirk, Fukui et al)

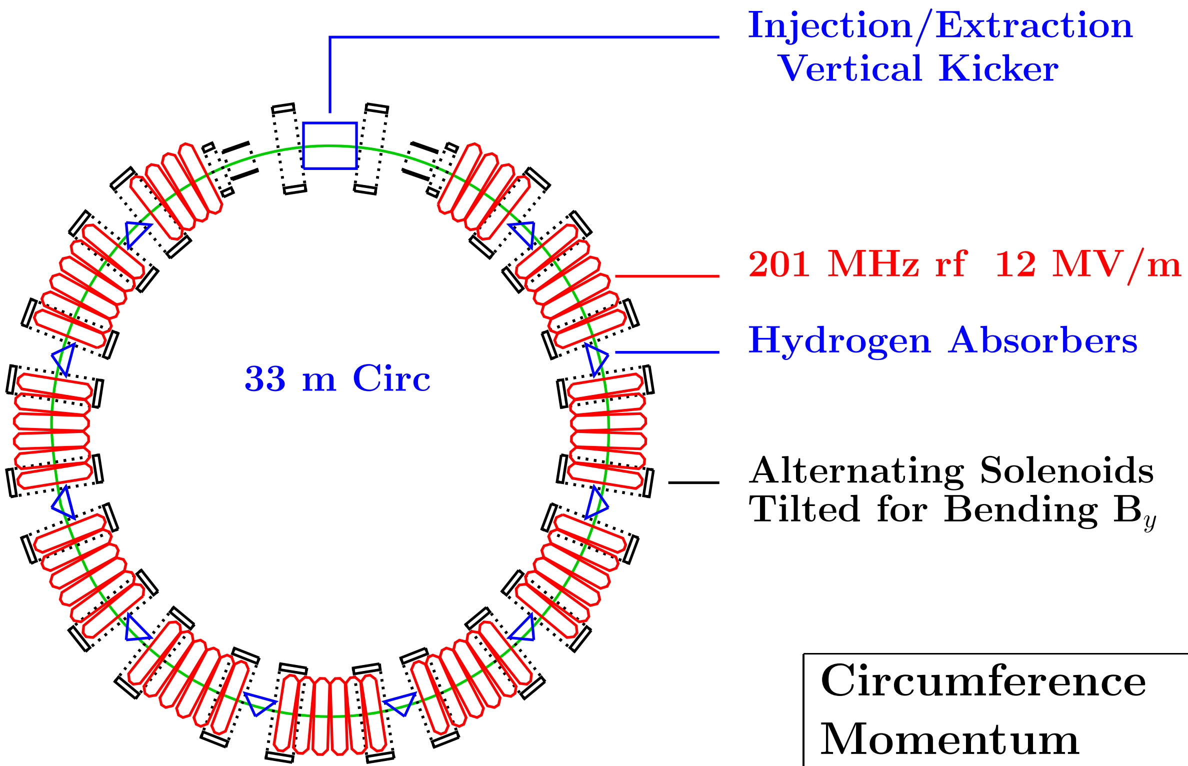


- Very small Rings (circ=3.4 m)
- Good Acceptance with Ideal Fields
- Problems with Real Fields
- Now working on Quad ring with Li Lens cooling for Final Collider Cooling Ring

3)RFOFO Ring Cooler (BNL leading)

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

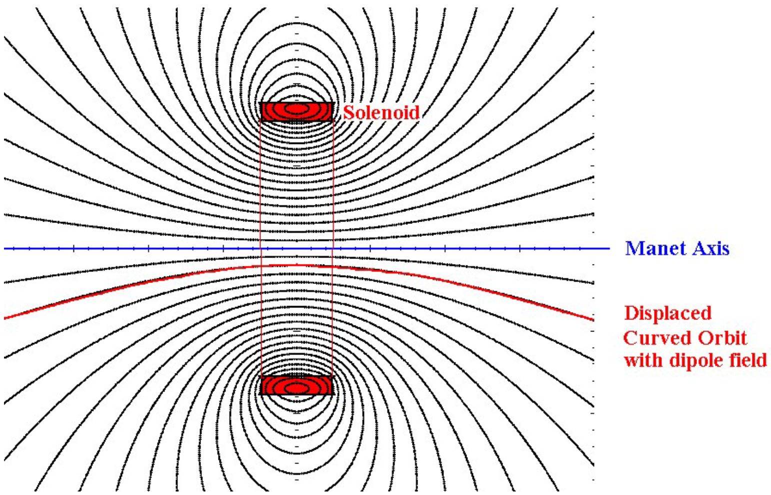
Simple solenoid lattice, RF in dispersion, steep wedge angles

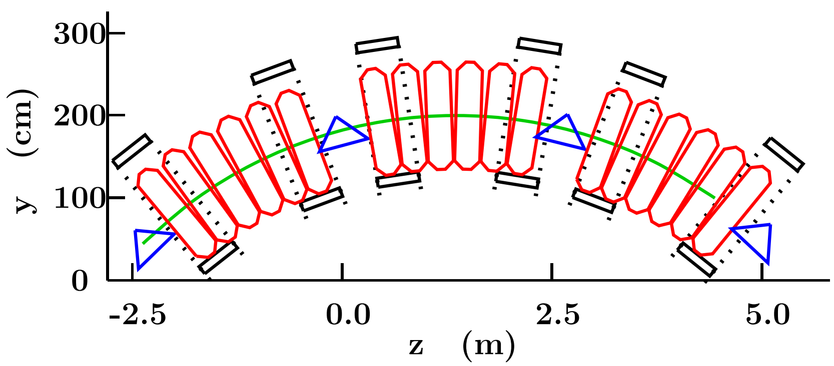


Circumference	m	33
Momentum	MeV/c	200
Maximum axial field	T	3
Ave. bending field	T	0.125
Hydrogen wedge thickness	cm	30
Wedge Angle	deg	100
RF Grad.	MV/m	12

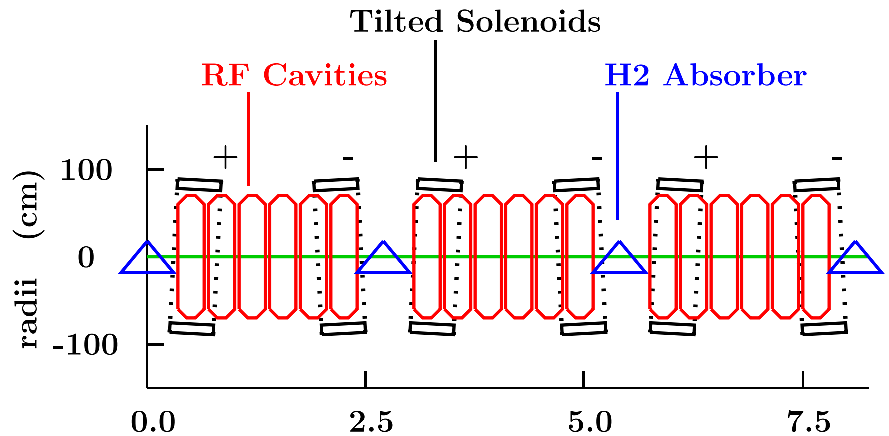
Realistic Coils   Balbekov (FNAL) + Fernow (BNL)

Shifted Coils so beam follows field lines



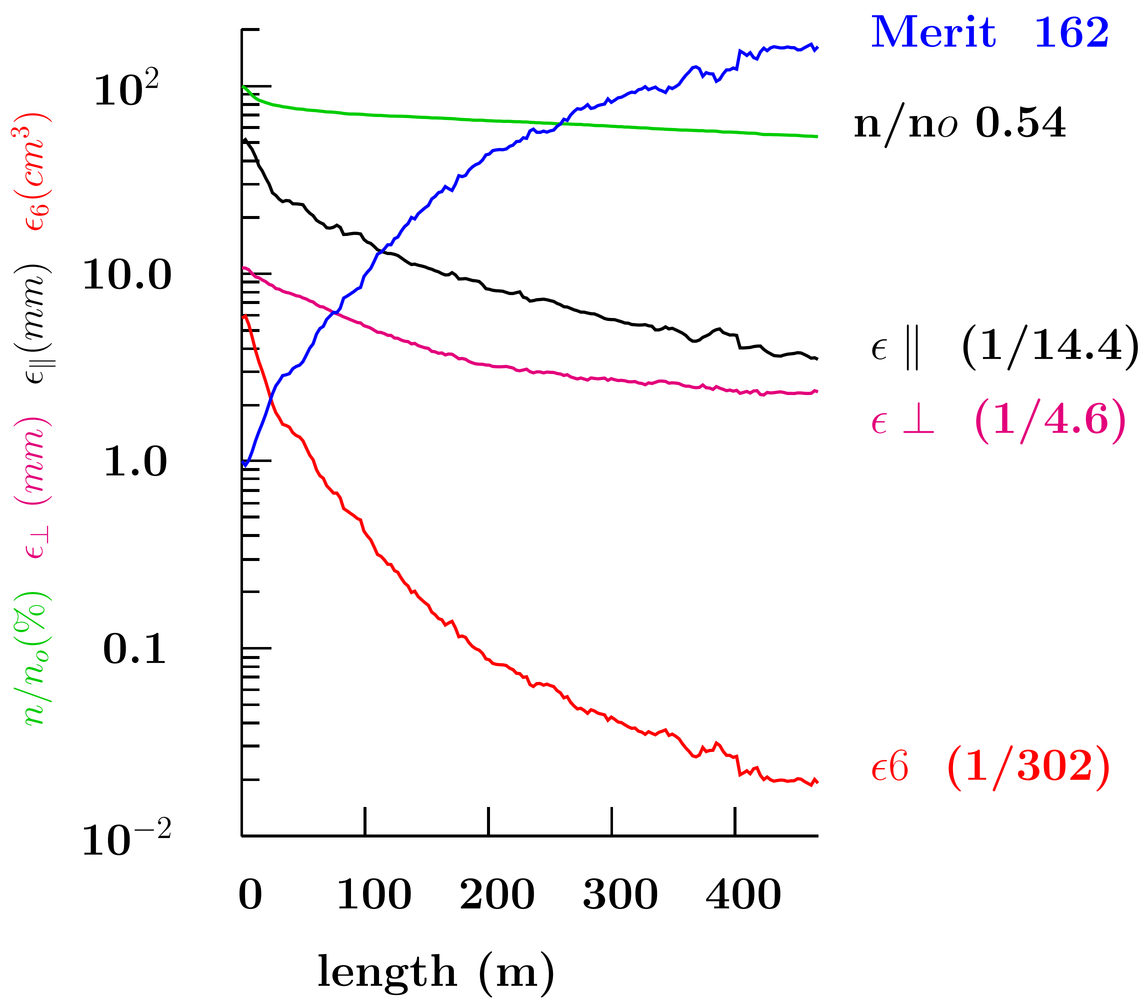


Tilt coils to generate vertical bending field



ICOOL Simulation (Palmer, Fernow (BNL)

Similar results from Balbekov at FNAL



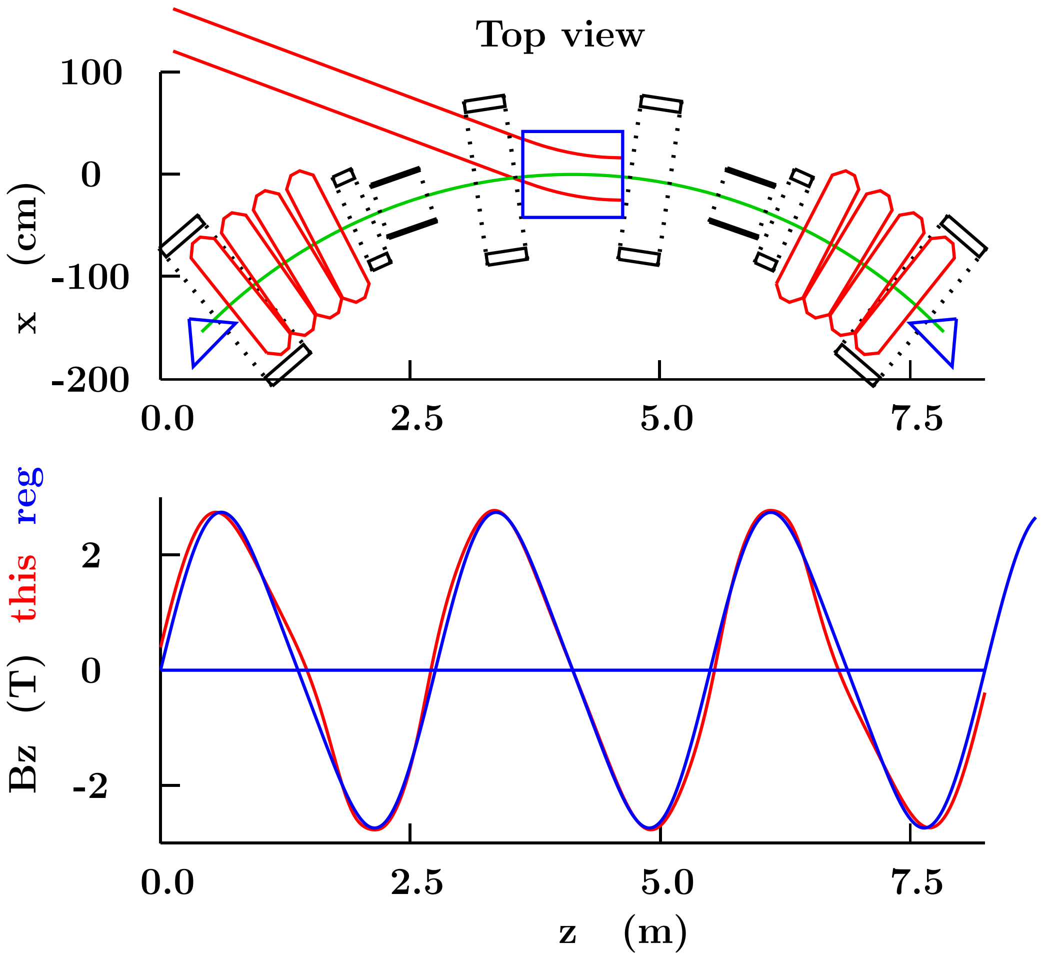
- Study-2 buncher output
- Realistic Maxwellian Fields
- Good cooling

BUT in this simulation:

- No windows (studied)
- No Injection/Extraction
  see following

Injection/Extraction

Transverse matching



Longitudinal matching

- Merit = 55 (cf 126)
- Improvements probable by matching

Kicker

Minimum Required kick $$U \propto \frac{\epsilon_n^2}{L}$$

- muon ϵ_n $\gg$ other ϵ_n's
- So muon kicker Joules $\gg$ other kickers
- Nearest are $\bar{p}$ kickers

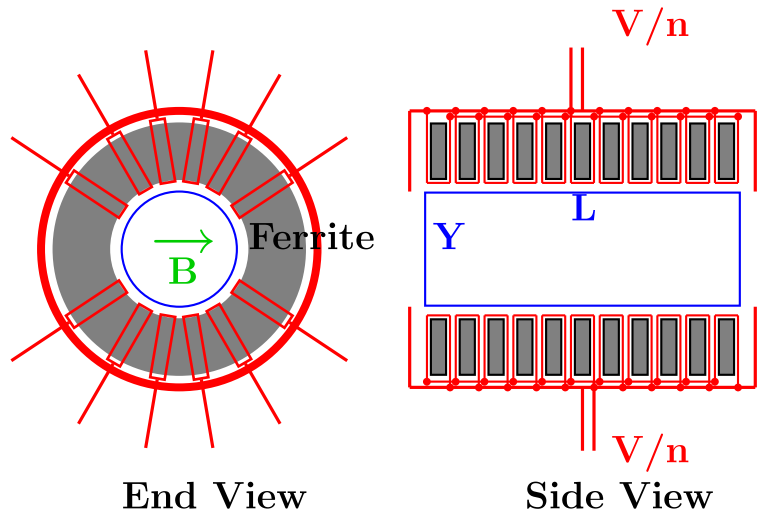
		μ Cooling Ring	CERN $\bar{p}$	5 m of Ind Linac
$\int B d\ell$	Tm	.30	.088	
t_{rise}	ns	50	90	40
$V_{1\text{turn}}$	kV	3,970	800	5,000
U_{magnetic}	J	10,450	≈13	8000

- J is 3 orders above $\bar{p}$
- Same order as 5 m of Induction Linac
- And t same order as Induction Linac

Induction Kicker

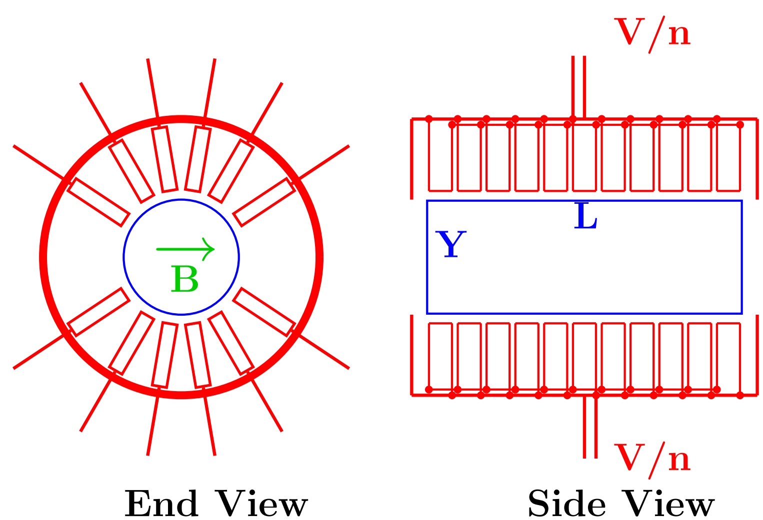
How to use Induction Technology for a Kicker

- Use Magnetic Amplifier PS
- Drive Flux Return
- Subdivide Flux Return



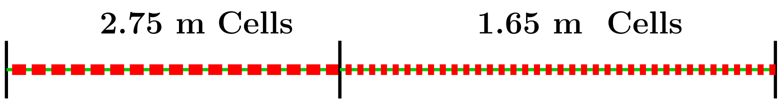
Works with no Ferrite

- V = the same
- U 2.25×
- I 2.25×
- No rise time limit
- Not effected by solenoid fields

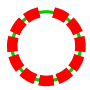


Compare with Study 2

- Study 2 Cooling



- 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 %

- Similar transmission
- Similar Trans emittance
- Less Long Emittance

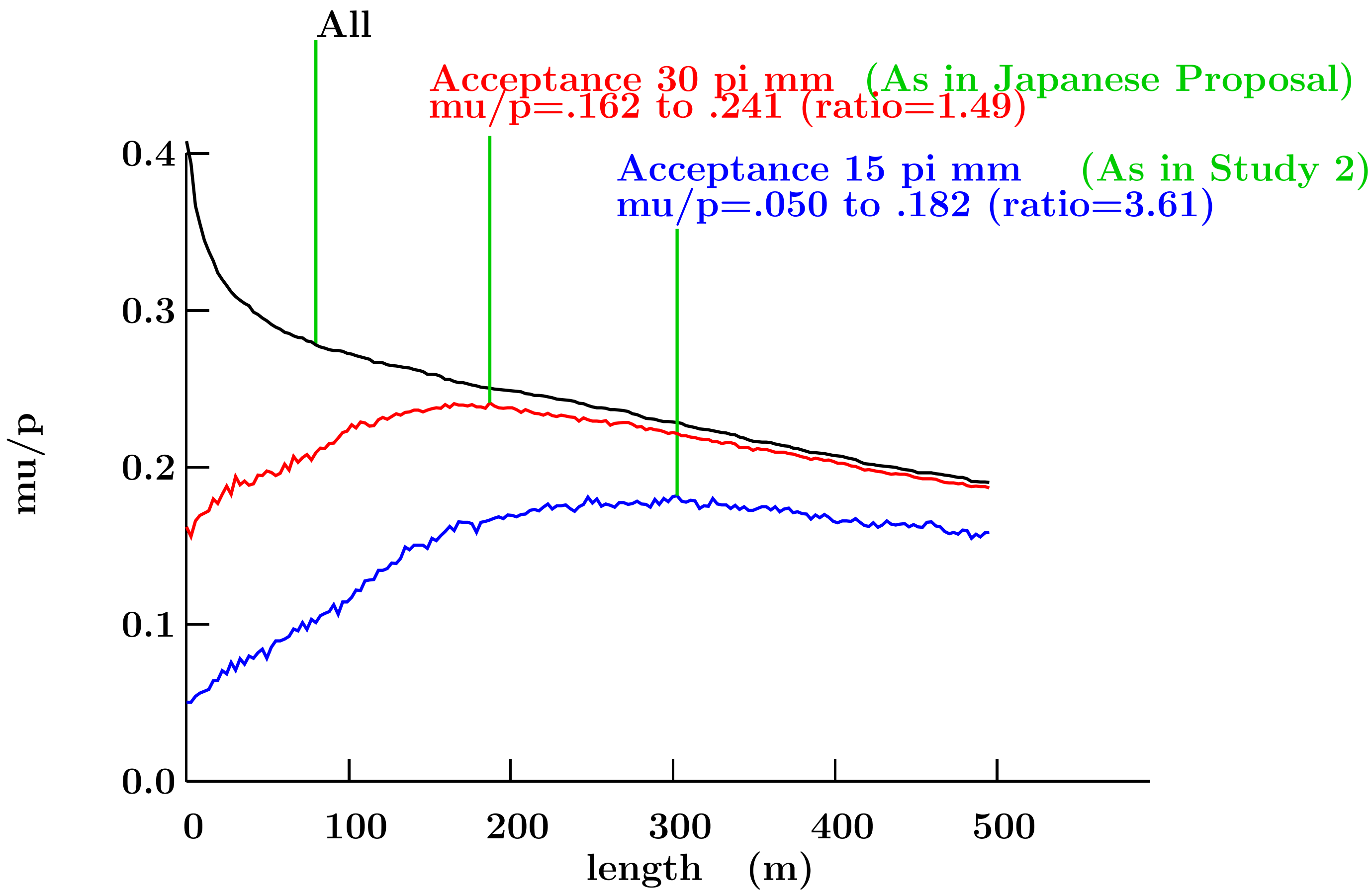
- EXPECT SUBSTANTIAL SAVINGS

BUT

- Need R&D on absorber heating
- Need R&D on thin windows
- Need R&D on kicker

Mu/p with Cooling vs Accelerator Trans Acceptance

Using input from Study-2 Front-End (includes some mini-cooling)



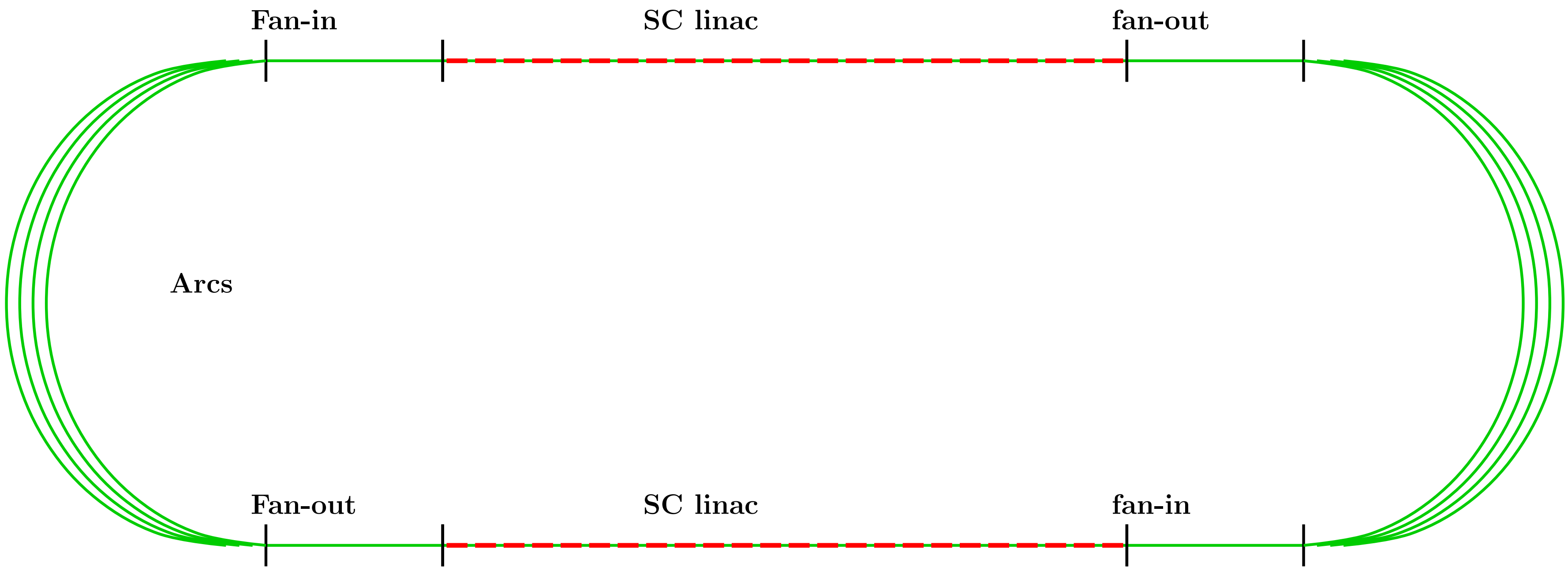
- Performance at 30 pi mm without cooling
  ≈ Performance at 15 pi mm with cooling
- Not a new idea: Mori at KEK has proposed no cooling for a long time
- Note: We still need (approx 3) cooling rings for a Muon Collider
- What does it Cost to increase Acceptance to 30 pi mm ?

ACCELERATION

Aim for 30 π mm Acceptance in all designs

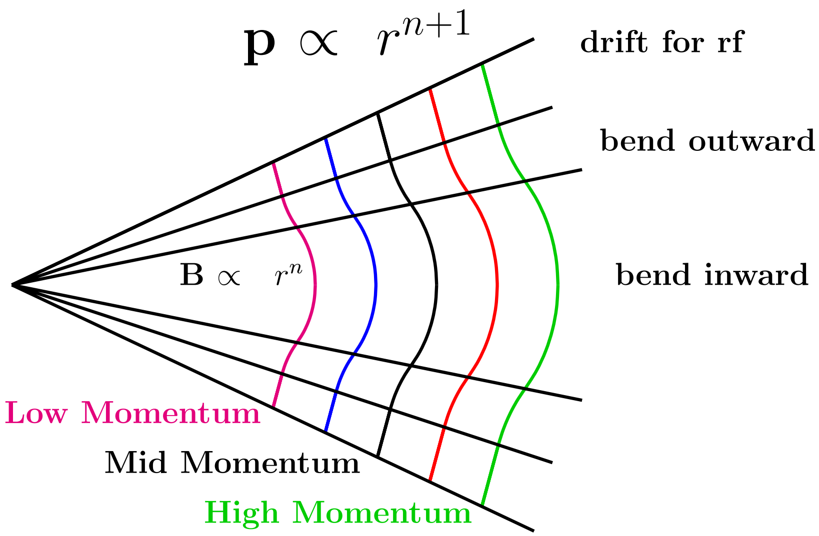
1. **RLA**
   e.g. Study 2 Design
2. **Scaling FFAG (Japanese Effort)**
   Non-Isochronous: Requires Frequency Modulation or Very Low Frequency
3. **Non-Scaling FODO FFAG (Carol Johnstone et al)**
   Isochronous and More compact than Scaling
4. **Non-Scaling Triplet FFAG (Dejan Trbojevic)**
   Even more isochronous and even more compact

1) Recirculating Linac Accelerator (RLA)



- Study 2 design had emittance growth in acceleration **15 → 30 pi mm**
- Recent Study (Bogacz JLAB) Adding Sextupoles: **Growth = few %**
- Study 2 RLA has 30 pi mm acceptance without significant cost increase !
- Pre-Acceleration needs redesign for 30 pi mm

2) Scaling FFAG (proposed by Japan)



POP FFAG at KEK

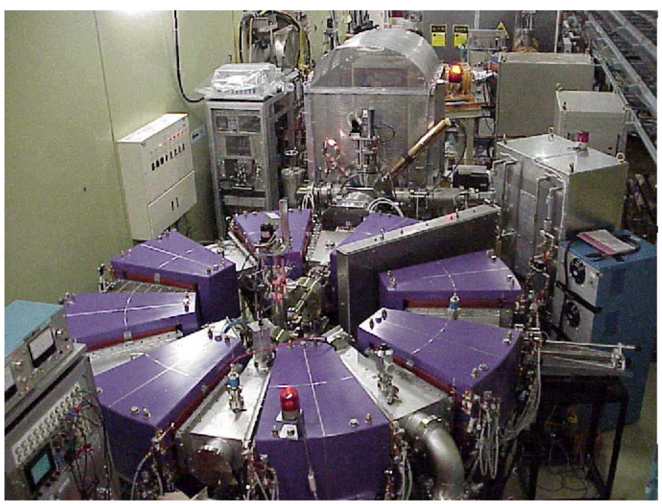


Figure C.2: Top-view of the POP FFAG

- Eliminates multiple arcs
- Allows more turns
- Reduces needed RF Volts
- 30 pi mm Acceptance Simulated
- But Non-isochronous

e.g.

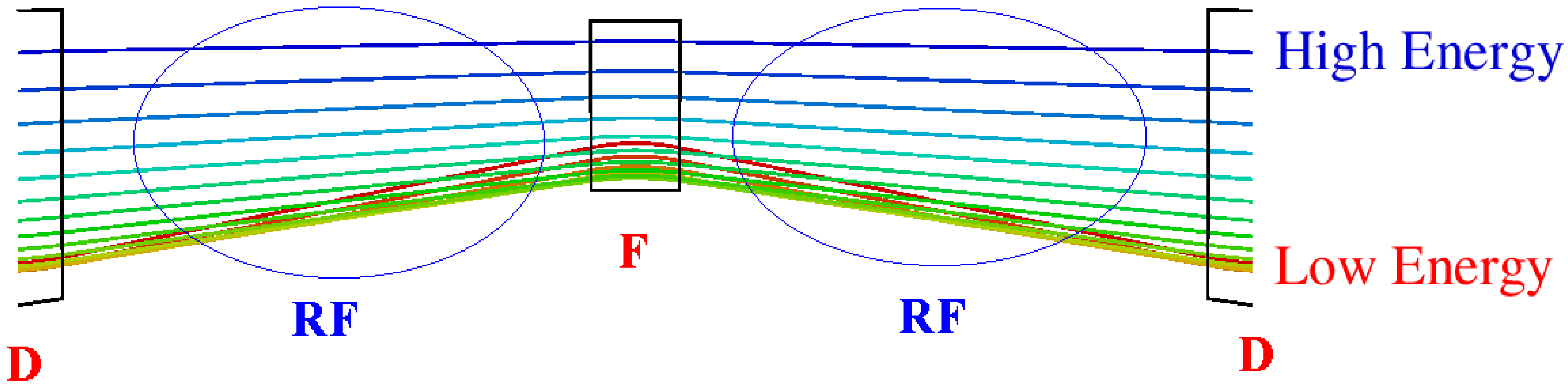
Energy	GeV	10-20
Circumference	m	1257
Max aperture	cm	40
Max Field	T	6.4
Max[1] RF freq.	MHz	25

1) From non-isochronicity (unless freq. is modulated)

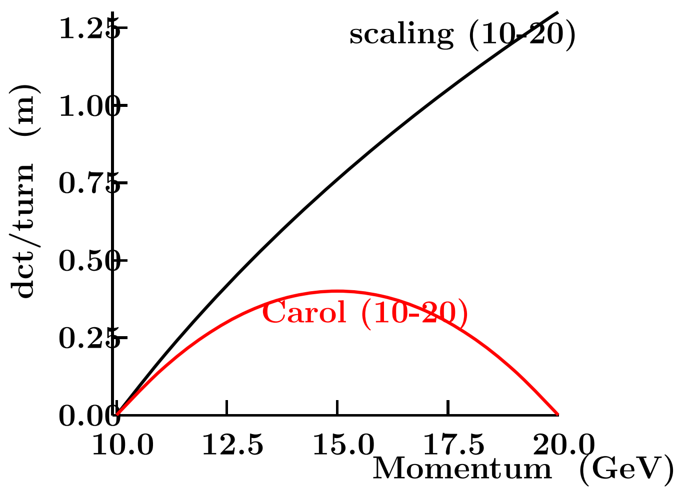
- Large magnet apertures
- Low Frequency, Low Grad, RF
  → More decay Loss
- Does not match RF Phase Rotation

3) FODO FFAG (Carol Johnstone (FNAL))

Combined function strongly focusing FODO

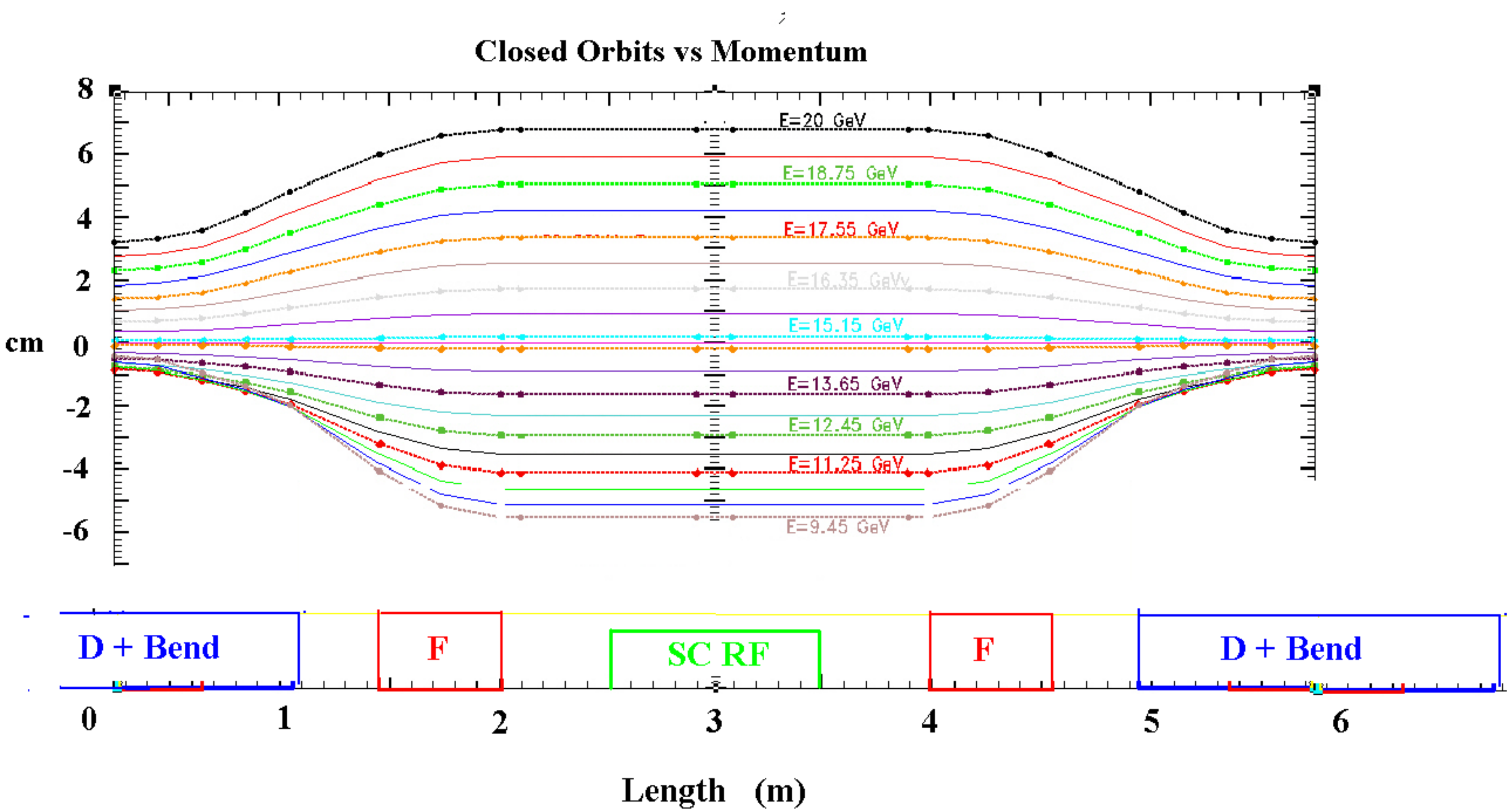


Path length vs momentum:



- Less path length difference for same energy range
- Isochronous at mid-momentum
- Allows 200 MHz (vs. 25 MHz for scaling)
- Smaller Magnets
- Longer (2 m) Gaps allow SC Acc.
- Smaller circumference (600 vs 1250 m)
- 30 pi mm without end fields work in progress

4) Triplet FFAG
(Dejan Trbojevic)



- more isochronous
- allows smaller circumference: 330 m cf scaling 1250 m, FODO 600 m
- Should also have 30 pi mm acceptance needs more work

Compare

		RLA	Scaling	FODO	Triplet
Energy	GeV	2.5-20	10-20	10-20	10-20
Gaps in straights	m	10(SC)	1.7(Cu)	2(SC)	2(SC)
Max aperture	cm		40	24	20
Circumference	m	1494	1257	600	330
Turns		4	14	16	21
Mag cost[1]	M$	63	178	54	55
RF cost[2]	M$	263(SC)	114(Cu)	55(SC)	27(SC)
Other cost[3]	M$	58	32	15	8
Tot cost	M$	384	323	124	90
Cost/GeV	M$	21.9	32.3	12.4	9.0

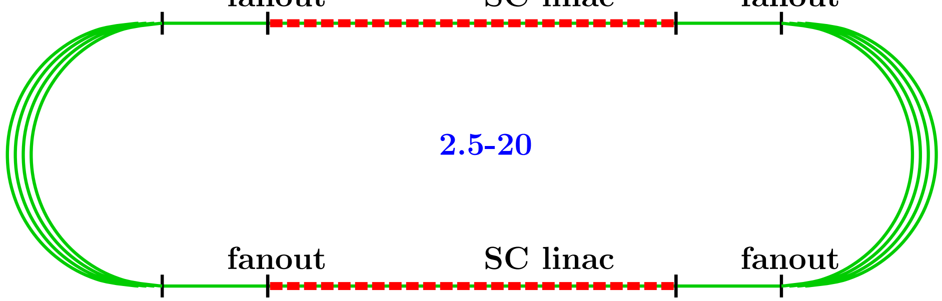
Costs are for comparisons   Not Real Costs

RF Costs here are for 200 MHz, for comparison only

- Real Progress in Cost reduction
- All with 30 pi mm acceptance

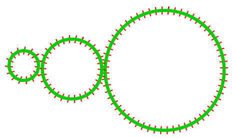
Compare with Study-2

Study 2 RLA



Best FFAG Candidate

2.5-5 + 5-10 + 10-20



	Study 2	Now	Factor
Vac Length	3261[1]	700	21 %
Tun Length	1494[2]	700	47 %
Acc Length	288[3]	100	35 %
Acc Grad.	16	12	66 %

1. 2 linacs + 4 switch-yards + 7 arcs
2. 2 linacs + 4 switch-yards + 2 arcs
3. 2 $\times$ 24 $\times$ 4 $\times$1.5 m

- EXPECT MAJOR SAVINGS $\approx 1/2$

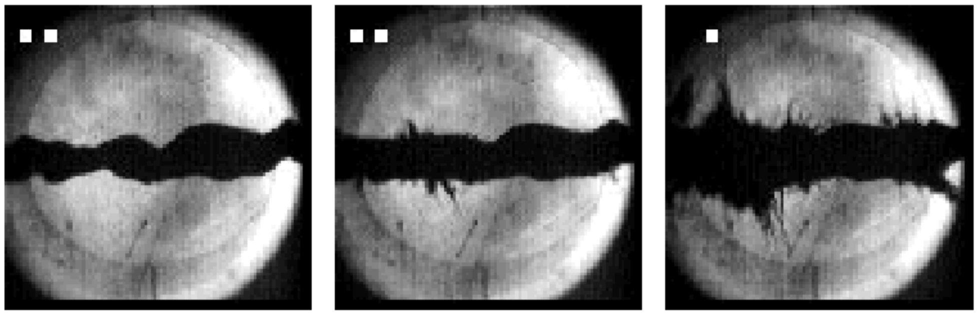
  BUT
- Needs more work
- More Pre-acceleration required
- Inject/extract not designed
- Other Options

EXPERIMENTAL PROGRAM

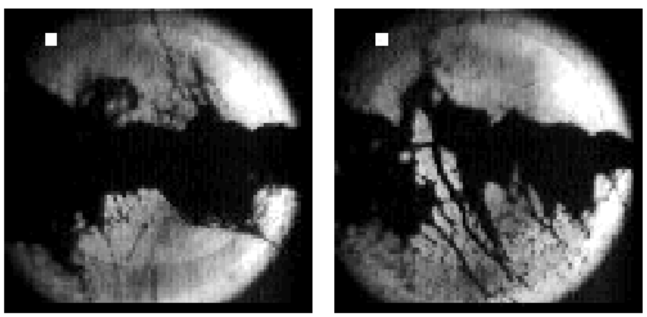
- **Targetry (BNL, Princeton)**
  - **Hg Jet in Beam**
  - **Hg Jet in magnetic Field**
- **SC Cavity work (Cornell)**
- **MUCOOL Collaboration (lead by Fermilab)**
  - **Hydrogen Absorbers**
  - **RF**
- **Cooling Demonstration MICE (Rutherford, FNAL, Geneva, Japan .... inc BNL**

Targetry program BNL, Princeton

AGS Experiment E951 Kirk MacDonald



0 ms 0.75 ms 2 ms



7 ms 18 ms

- **4 Tp/bunch** $(4\ 10^{12})$
- **Non-Explosive Dispersion**
- **Good Result**

But 1 MW Nu-Factory requires:
16 Tp/bunch $(1.6\ 10^{13})$

SO

- **Need further Experiment**

Target Simulation

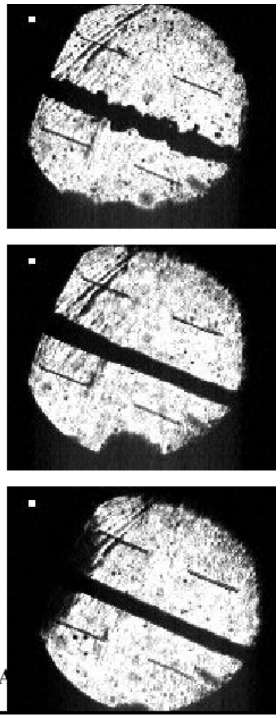
Stabilization From Magnetic Field

Cern Observation without beam

0 Tesla

10Tesla

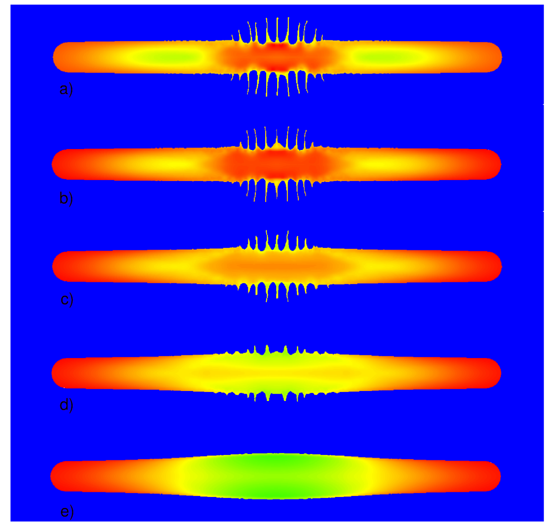
20Tesla



Simulation with beam BNL

R. Samulyak

Stabilizing of the mercury jet by the longitudinal magnetic field



a) B = 0 ; b) B = 2T

c) B = 4T ; d) B = 6T ; e) B = 10T

Magnet changes dynamics: suppresses breakup, increases T

- Need experiment with magnet

SC Cavity work at Cornell Hartill, Padamsee

- SC Progress
  - Build new test pit
  - Design, build, and test 201 MHz SC cavities
    12 MV/m achieved limited by drop in Q
    FS2 16 MV/m, Ring & Acc 12 MV/m

MUCOOL Collaboration (FNAL + LBNL + ...)

Develop Components for Cooling Systems

- Design and Prototype hydrogen absorbers
- Design, build, and test absorber windows
- Construction, and safety testing, of absorber windows

- High power testing of 805 MHz cavities
- High power testing in a magnetic field
- Measurement of X-rays and dark currents

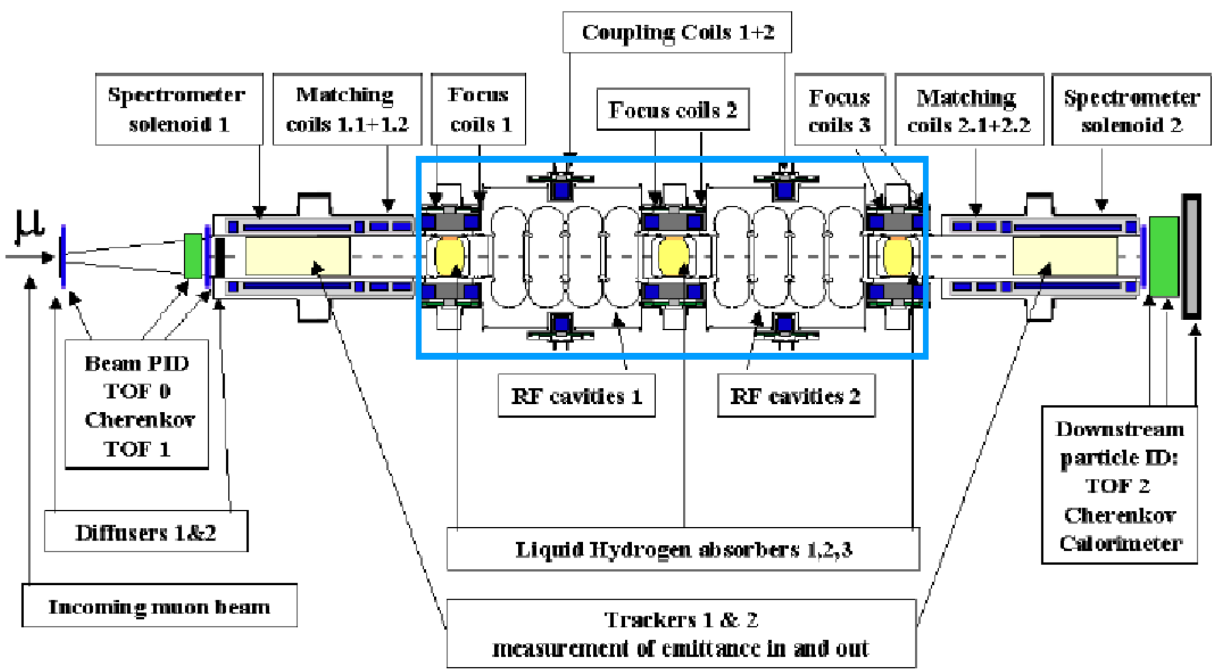
- Design and start Test Area

Needed also for Rotation and Acceleration

- **Construction and radiant heat testing of Be windows for RF**
- **Design of 201 MHz cavities**

Muon Ionization Cooling Experiment (MICE)

- Solid Design based on Study-2 channel
  (very similar components to RFOFO cooling ring)
- International Collaboration:
  (US, Europe, Japan)
- An enthusiastic host lab:
  RAL (UK)
- Funding proposal sent to NSF,
  (and similar requests in Europe)
- Proposal Submitted to RAL



Summary (BNL ***)

- Simulation Progress on Reducing Cost
  - Phase Rotations without Induction Linacs
  - Compact Cooling Rings with 6D cooling ***
  - Compact FFAG Acceleration ***

- Target R&D going well ***,
  but needs magnet & Intensity
- MUCOOL components going well,
  but 200 MHz only just started
- MICE going well ***,
  but will take till 2007 at earliest

- Neutrino Factory without cooling interesting
  - Performance $\geq$ Study 2
  - Substantially Lower Cost
  - No need of Cooling Demonstration
  - Kicker problem removed

Funding

- **BNL Group has reduced staff by 2.5 FTE over last 2 years ($9 \rightarrow 6.5$)**
- **No further reduction expected in Group for FY04**

- **But Collaboration Funds were cut 1/2 from 02 to 03 (3 M$ $\rightarrow$ 1.4 M$)**
- **Had expected restoration in 04**
- **Current Presidential Budget flat in 04**
- **Some Experimental Program will be cut (200 MHz RF, Absorber testing, Target ?)**
- **BNL Target Program is at risk (exploration of Lead battery vs Power Supply)**