Progress in Ring Cooler Design

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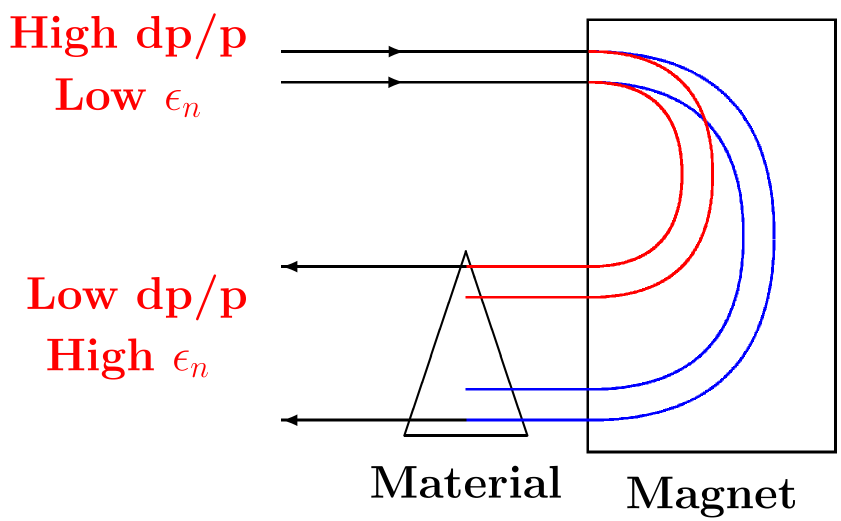
MUTAC at FERMI 1/14/03

1. Introduction
2. Quadrupole Focused
3. Bend (weak) Focused
4. TETRA: Solenoid Focused
5. RFOFO: Alternating Solenoid Focused
6. Conclusion

Introduction to Longitudinal Cooling



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- dp/p reduced
- But σ_y increased
- Long Emittance reduced
- Trans Emittance Increased
- "Emittance Exchange"

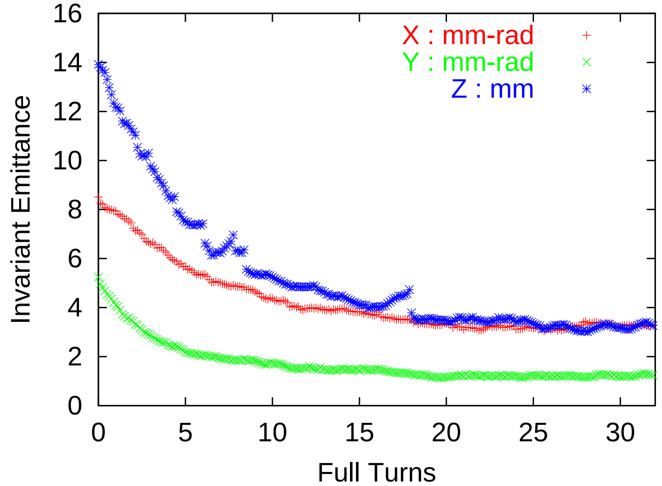
- Needs Bending for Dispersion
- Suggests a Ring

1) Quadrupole Focused Rings

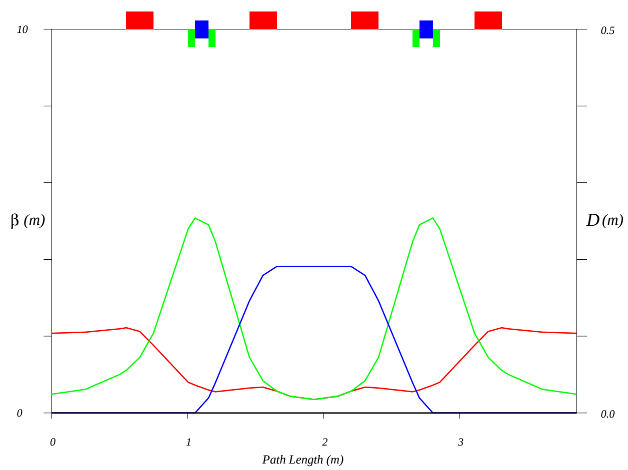
Fukui, Garren, Kirk et al

Easier to design because of greater experience

Circumference	31 m
Momentum	250 MeV/c
Quad pole field	2 T
RF frequency	201 MHz
RF Gradient	16 MV/m



One of 8 Cells



Transmission = 41%

$$\text{Merit} = \frac{\text{Initial 6D emittance}}{\text{Final 6D emittance}} \times \text{Transmission}$$

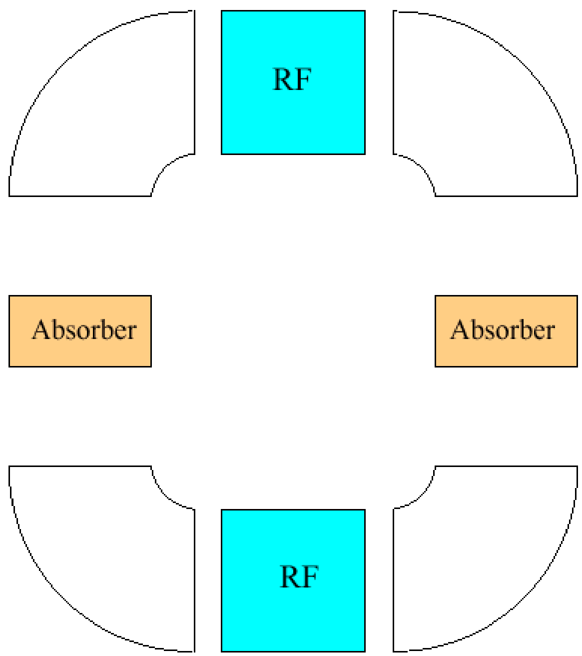
- **Limited acceptance from quad focusing**
  Merit Factor = 16 (FS2 was 15)

2) Bend-only (weak) Focused Rings

Fukui, Garren, Kirk et al

- Gradient, or edge focussed, bend magnets focus in x and y
- Strong bends needed for strong focus

e.g.



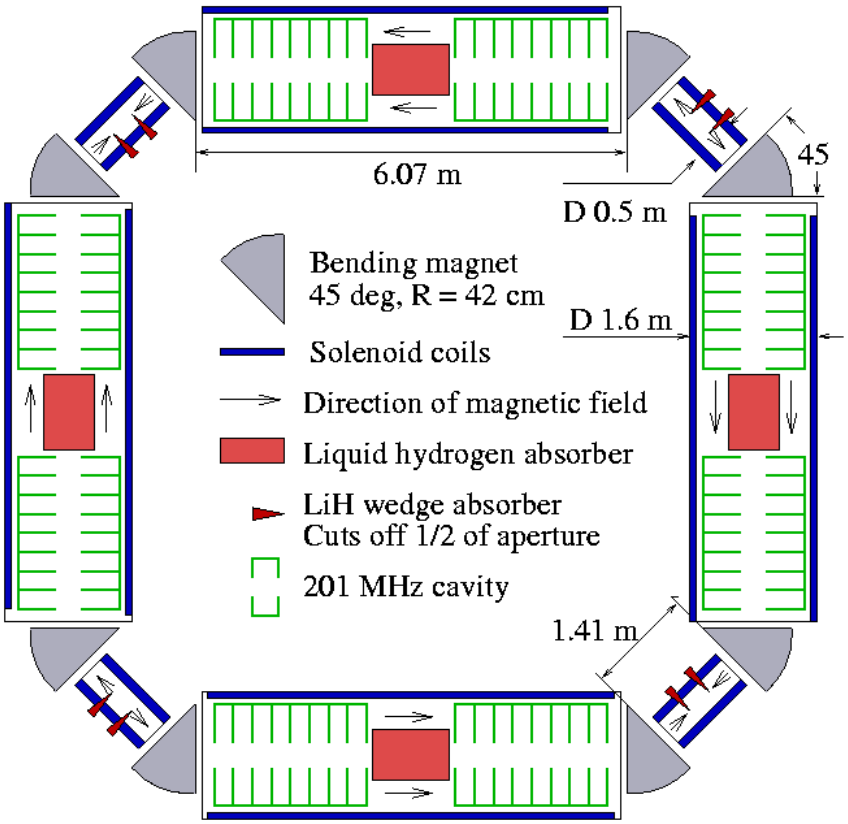
Circumference	m	3.4
Momentum	MeV/c	250
Bend Field	T	3
RF frequency	MHz	201
RF Grad.	MV/m	16
Merit		99

- Very small rings
- Good acceptance with ideal fields
- Questionable acceptance with real fields
- Hard to inject/extract

3) TETRA Solenoid Focused Ring

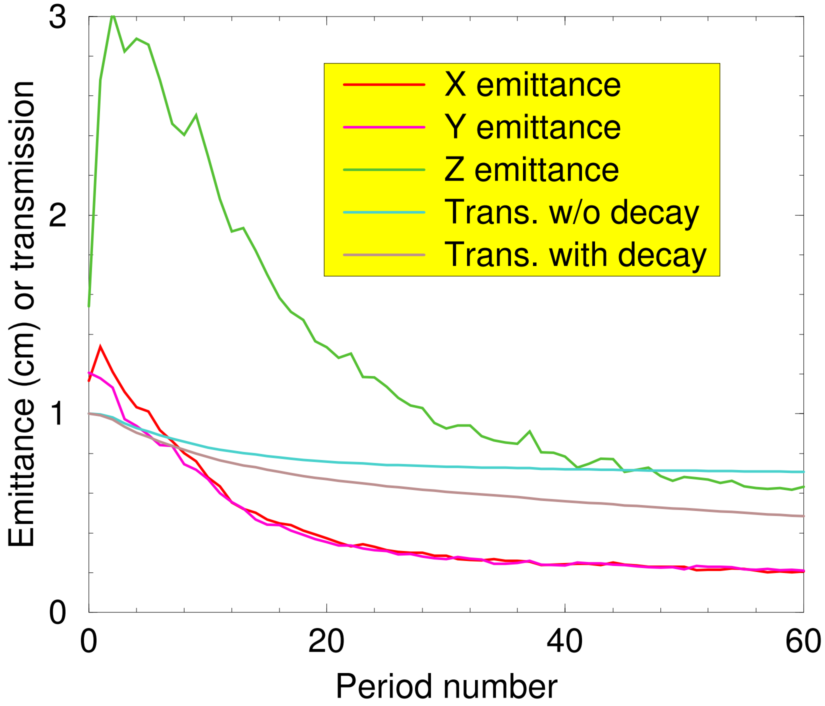
Balbekov et al

Alternate transverse cooling with H2, and emittance exchange in Li wedge



Circumference	36.963 m
Energy	250 MeV
Max B_z	5.155 T
RF frequency	201 MHz
Gradient	15 MV/m

Performance



- **Good cooling in all dimensions**
- **this was the FIRST**
- **Merit Factor 38-94 c.f. Study-2: 15**

BUT

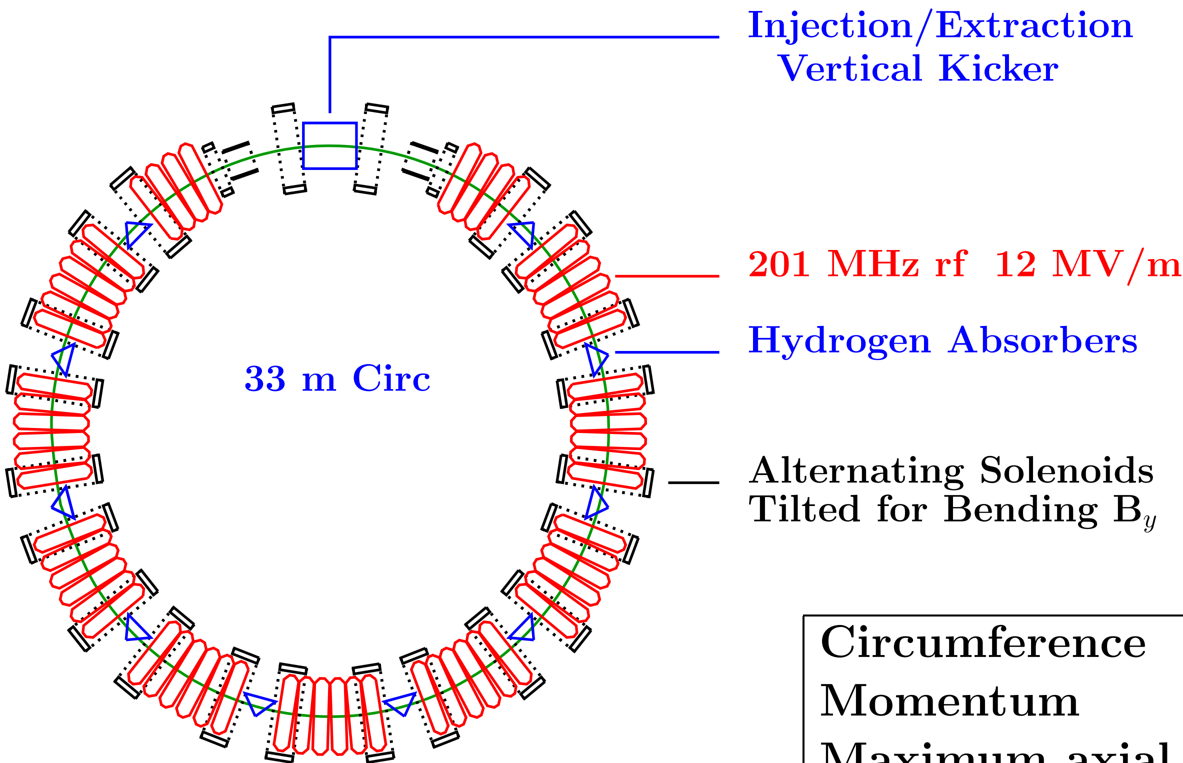
- **Hard edged, non-Maxwellian fields**
- **Design of bend magnets hard**
- **Injection and extraction very hard**
  Merit=3.9 with RF gap

	Before	After	Ratio
$\epsilon_\perp$ (cm)	1.2	0.21	5.7
$\epsilon_\parallel$ (cm)	1.5 (3)	0.63	2.4 (4.8)
ϵ_6 (cm^3)	2.2	0.028	79 (158)
N/N_0, inc. decay	1	0.48	0.48
Merit			38 (76)

4) RFOFO: Alternating Solenoid Focused Rings

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

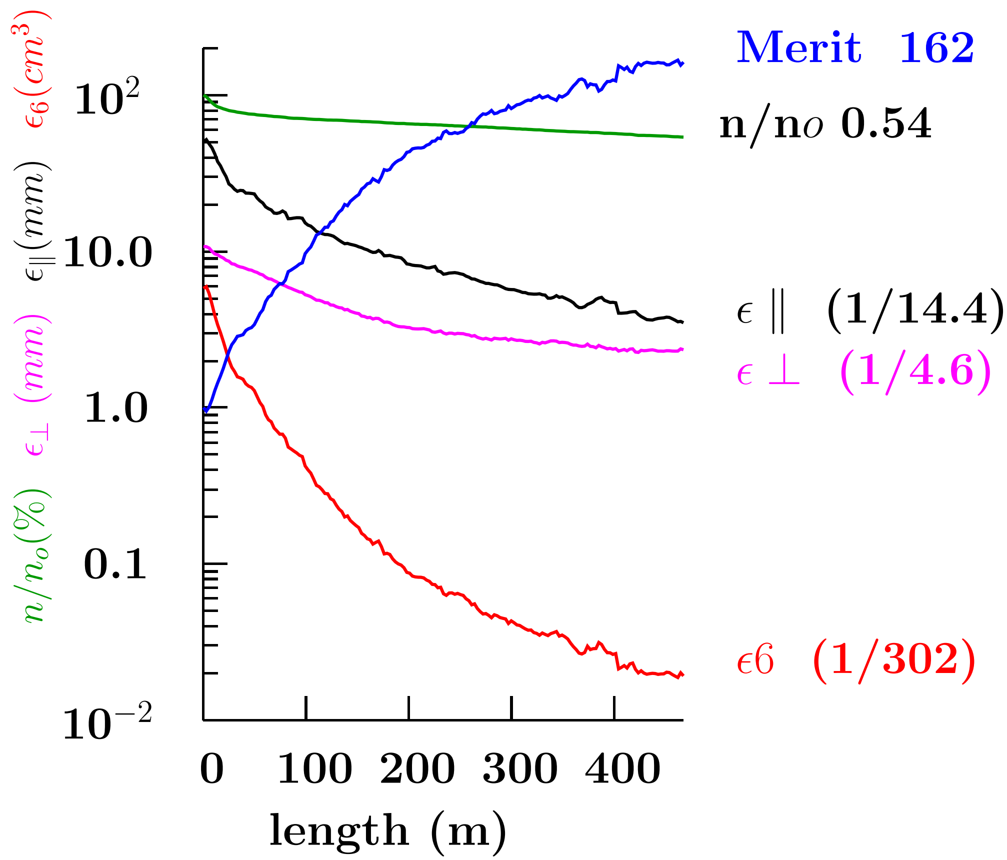


Circumference	m	33
Momentum	MeV/c	200
Maximum axial field	T	3
Ave. bending field	T	0.125
Hydrogen wedge thickness	cm	30
Wedge Angle	deg	100
RF frequency	MHz	201
RF Grad.	MV/m	12

ICOOL Simulation with Maxwellian, almost real, fields

- **Fields on axis from straight lattice applied to the curved reference orbit**
- **Fields off axis from Maxwell**
- **No Windows**
- **No Injection/Extraction Gap**
- **100 deg wedge absorber**

	initial	final	ratio
Trans + decay	1	.54	54 %
$\epsilon_\perp$ (π mm)	10.7	2.3	1/4.6
$\epsilon_\parallel$ (π mm)	50.1	3.5	1/14.1
ϵ_6 (π cm)^3	5.8	0.019	1/302
Merit			162

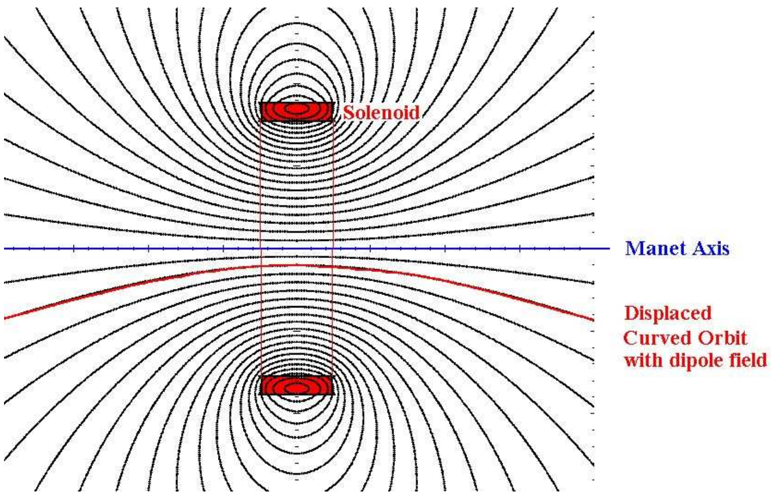


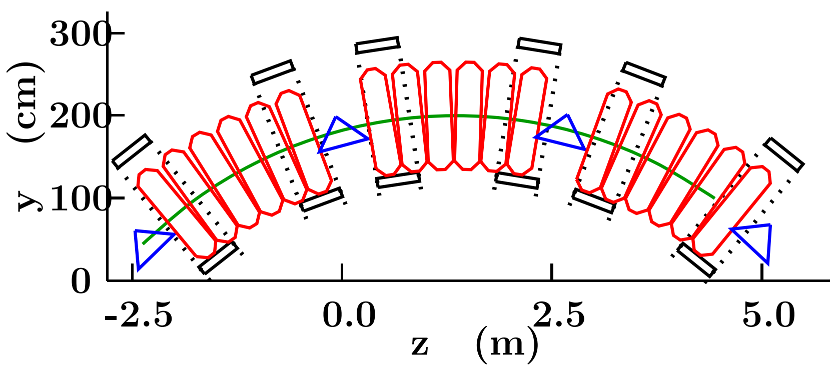
Details Studied:

1. Realistic Fields
2. Effects of windows
3. Required longitudinal acceptance
4. Realistic Absorber Shape
5. Absorber heating
6. Injection/Extraction
7. Induction Kicker

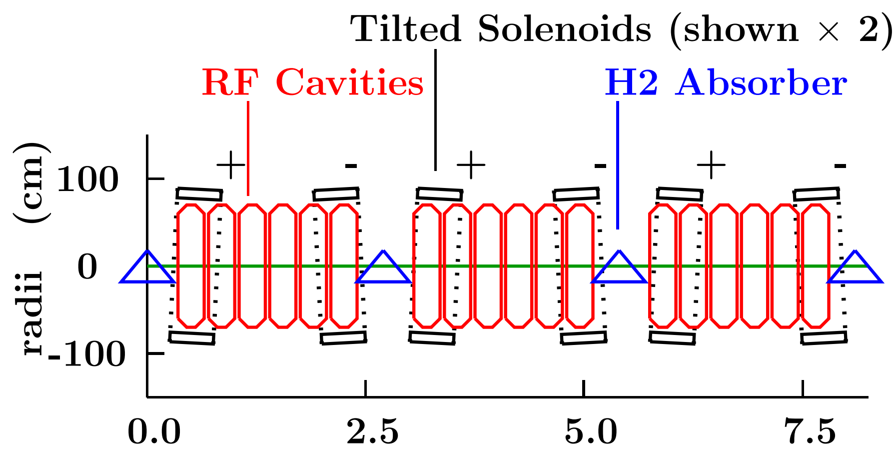
1) Realistic Magnetic Fields (Balbekov)

Shifted Coils so
beam follows field lines

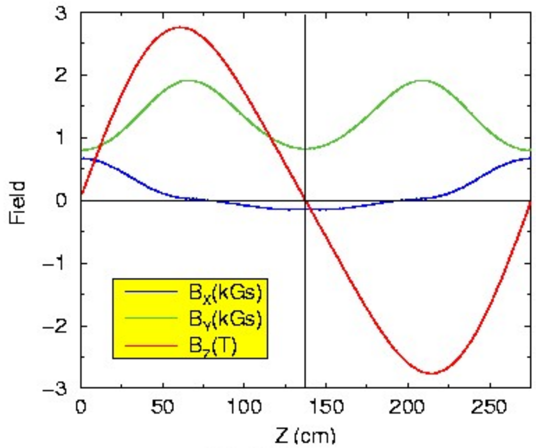




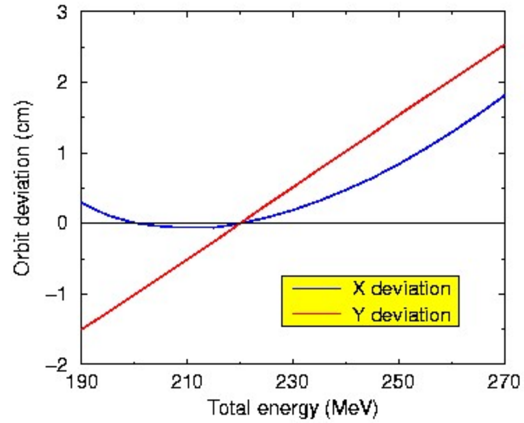
Tilt coils to generate
vertical bending field



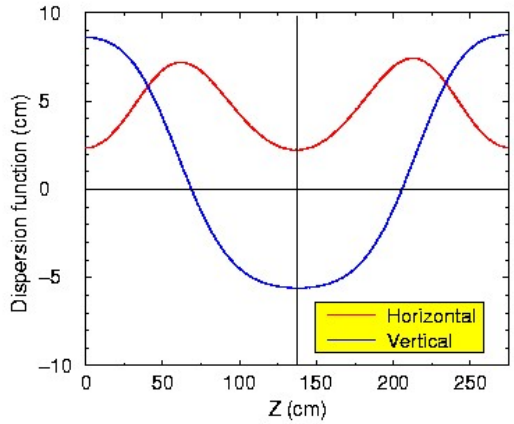
Plots (similar to those in ICOOL approximation)



Fields vs. z



Dispersion vs. Momentum



Dispersion vs. z

Compare Balbekov Simulation with ICOOL approximation

Both with wedge angle=76 degrees (c.f. 100 deg.), and Gaussian inputs

		Balbekov	ICOOL
Transmission (inc.decay)	%	55	59
Initial Trans Emittance	(mm)	12	13.9
Final Trans Emittance	(mm)	2.2	2.0
Initial Long Emittance	(mm)	15.8	15
Final Long Emittance	(mm)	4.8	7.4
Merit Factor		55	50

- More long cooling (more dispersion)
- Less Trans cooling (same reason)
- Slightly better performance

2) Windows for absorber and RF

- ICOOL with Maxwellian but quasi-realistic fields
- Input: as in Study 2, but compressed in time to fit ring
- RF
  - With windows: 6×33 cm cells at 12 MV/m
    (c.f. Study-2: 4×33 cm cells at 16 MV/m)
  - With open cavities: 3×66 cm cells at 10 MV/m

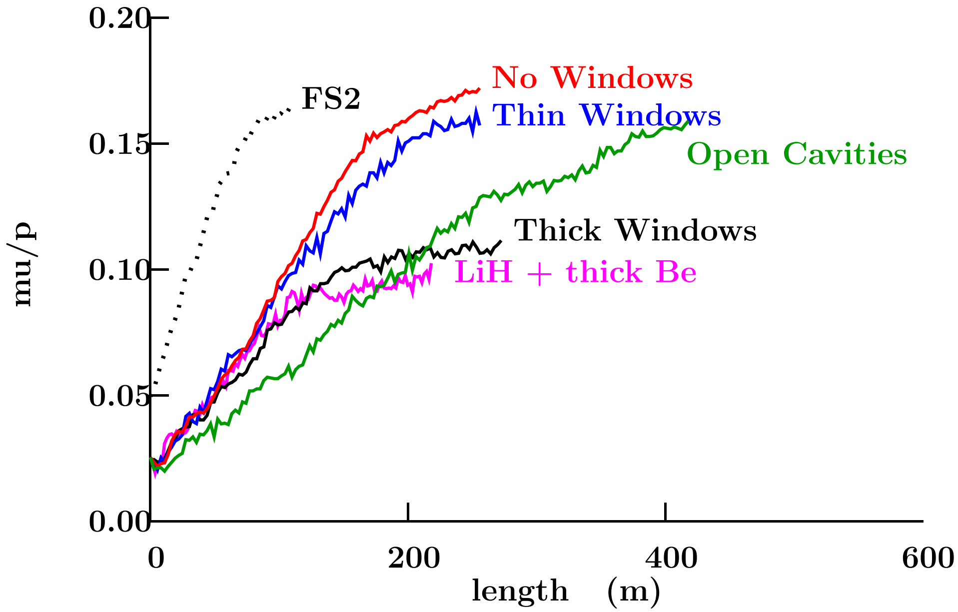
Window Cases tried:

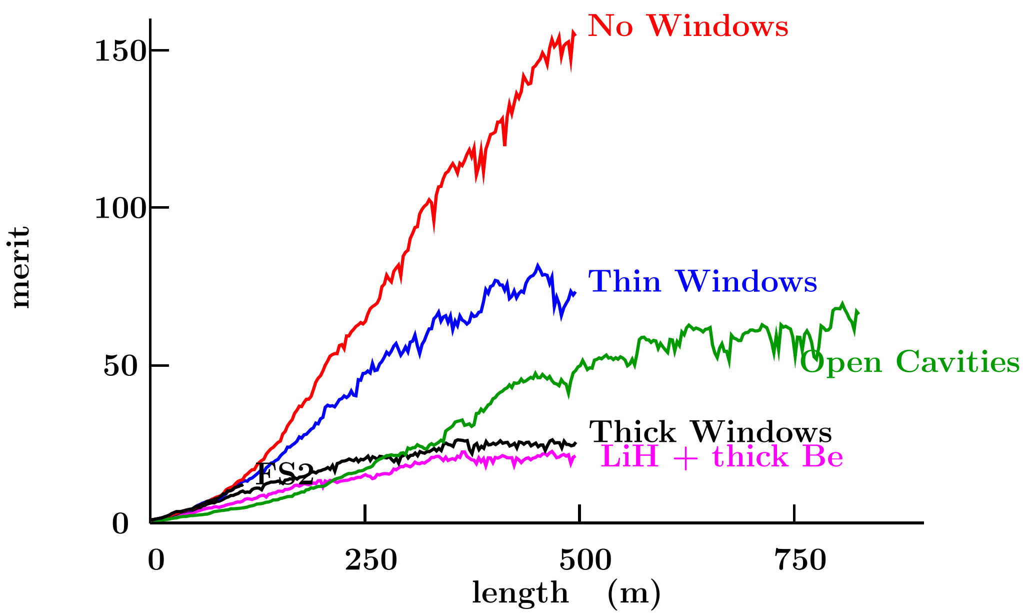
	Absorber μm	RF μm	RF temp deg
c.f. Study-2	360 Al	$3\times700 + 2\times100$ Be	warm
None			-
Thick	360 Al	$5\times350^1 + 2\times50^1$ Be	warm
Thin	125 AlBemet	$5\times50^2 + 2\times25^2$ Be	nitrogen
Open	125 AlBemet	-	warm
LiH		$3\times350 + 2\times50$ Be	warm

1. Half thickness of FS2 because heating $\propto$ (grad)^2

2. $\leq 1/10$ at nitrogen temp because expansion coeff $\approx 1/10$

ICOOL simulations





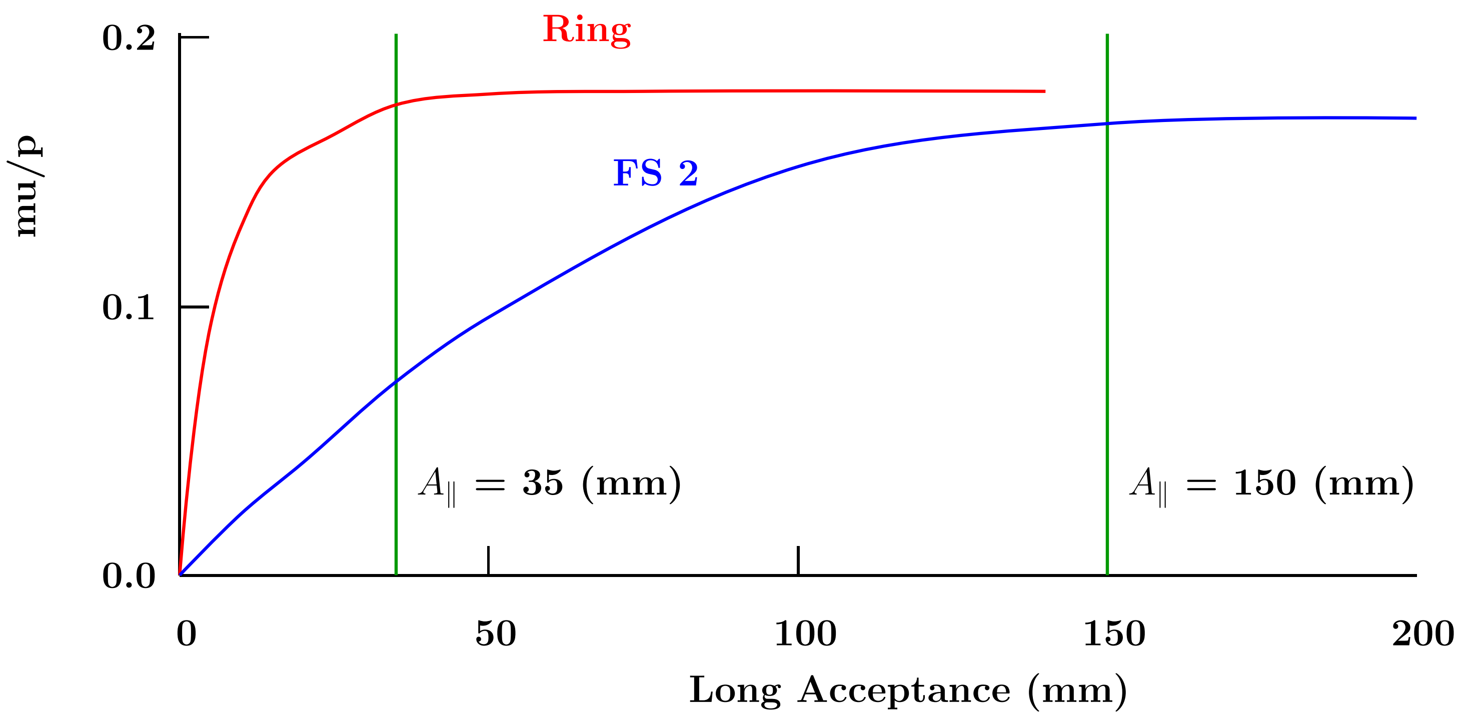
Dots: Study-2 (FS2)
(into 150 mm Long Acceptance)
Lines: Ring
(into 35 mm Long Acceptance)

- **Merit very sensitive to windows**
- **mu/p less sensitive to windows**

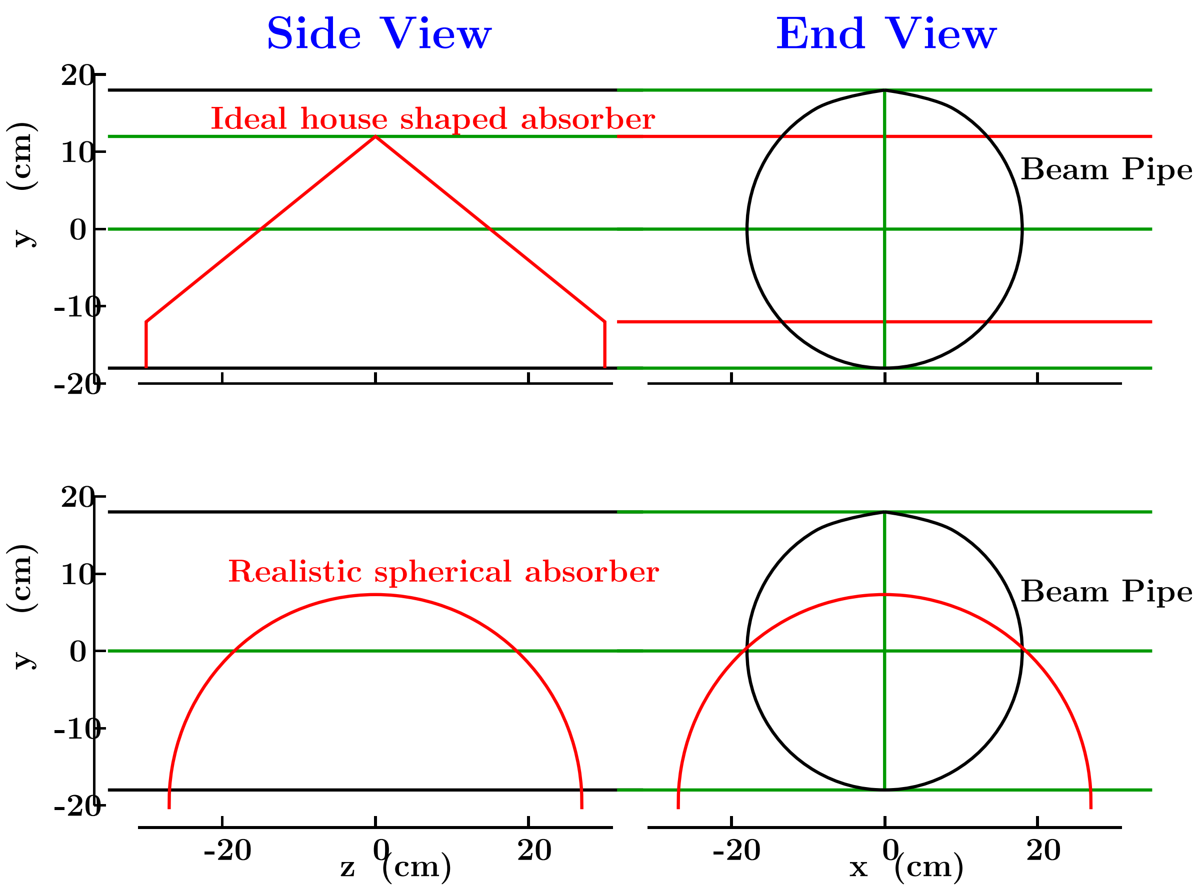
- **Thick windows $<$ FS2**
- **Thin windows $\approx$ FS2**
- **Open cavity $\approx$ Thin**

3) Required Accelerator Longitudinal Acceptance

- **Ring's Long Emittance << FS2**
- **So Long Acceptance can be reduced: 150 $\rightarrow$ 35 mm**



4) More realistic absorber shape



- ICOOL on quasi-realistic fields
- Using stepped cylindrical approximation of shape
- Merit reduced from 150 to 110
- Mu/p reduced by $\approx 5\%$

5) Absorber Heating Calculations

- **Max merit requires 20 turns**
- **But max mu/p reached after 8 turns**

- **Use FS2 bunch parameters**
  - **6 bunches with 20 ms separation at 2.5 Hz for 1 MW**
  - **Continuous bunches with 33 ms separation for 4 MW**

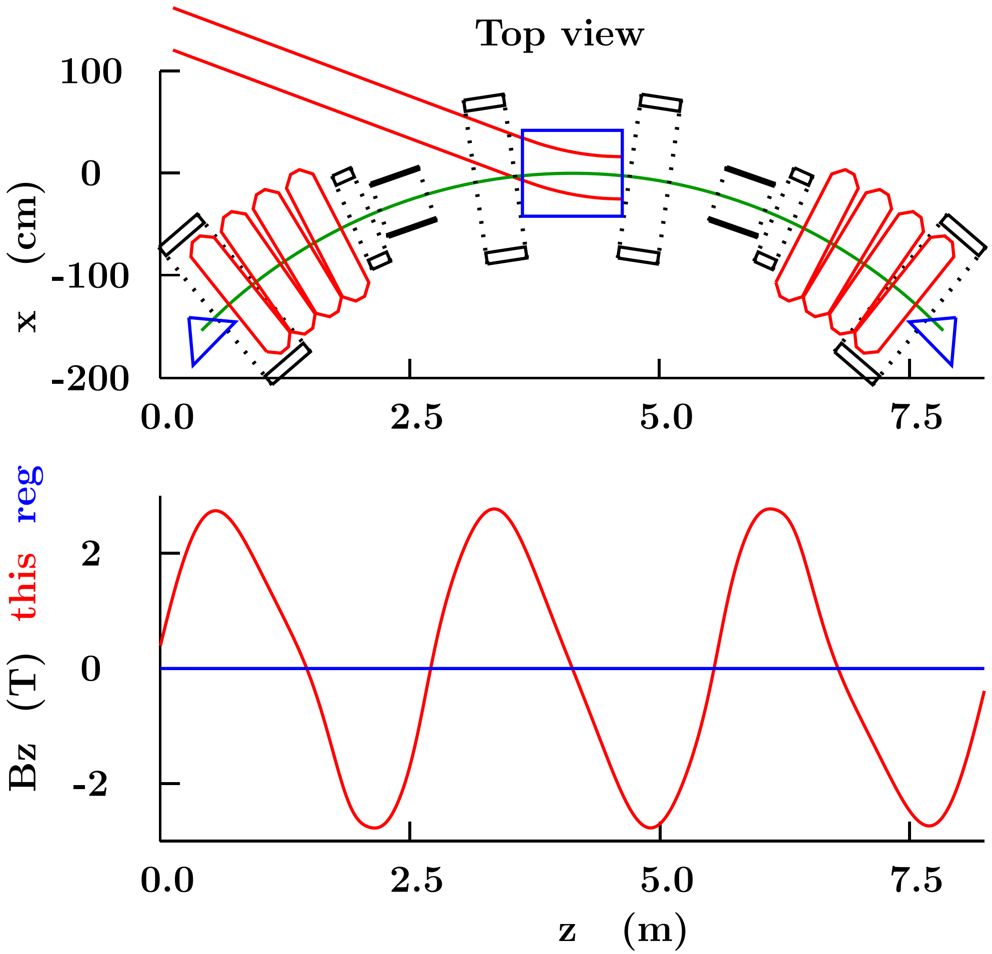
P_p	Driver power	MW	1	4
N_p	Protons/bunch	10^{13}	1.7	3.4
$f_{\rm bunch}$	Bunches/sec	s^{-1}	6×2.5	30
Mu/p	"Ave" muons/proton		0.261	0.27
n	Turns in ring		8	8
J	Energy deposited/bunch	J	91	182
σ_r	"Ave" beam radius	cm	3.11	3.11
ΔT	Temp rise/bunch	Deg	0.33	0.67
P	Ave power dissipated/absorber	kW	1.37	5.48
F	Flow for Δt=2 deg	liters/sec	1.45	5.8
v	Vel in 5 cm pipe	m/s	0.74	2.95

These are all reasonable values

6) Injection/Extraction

Transverse matching

Design coils to duplicate normal cell fields



Longitudinal matching

Gap in RF introduces losses

- Simulated Merit 150 → 90
- Mu/p reduced by 15 %
- Improvements probable by
  - matching
  - raising energy
  - reducing gap in rf

7) Kicker

Minimum Required Kicker Energy:

$$U \leq \left(\frac{a}{\sigma_r}\right)^4 \left(\frac{a_y}{a_x}\right) \left(\frac{m_\mu^2\ 8}{\mu_o\ c^2}\right) \frac{\epsilon_n^2}{L}$$

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

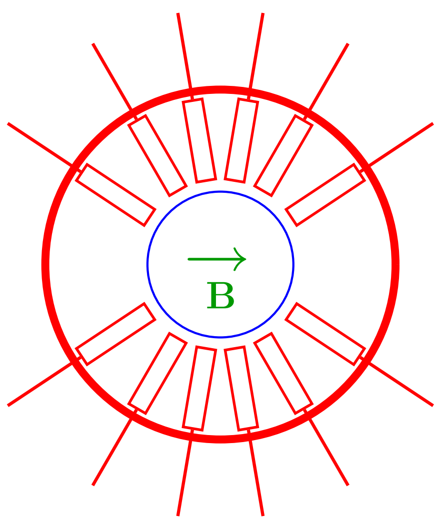
		μ Cooling	CERN $\bar{p}$	Ind Linac
$\int Bd\ell$	Tm	.30	.088	
L	m	1.0	≈5	6.0
B	T	.30	≈0.018	0.6
X	m	.42	.08	
Y	m	.63	.25	
t_{rise}	ns	50	90	40
V_{1turn}	kV	3,970	800	$\times$ 190
U_{magnetic}	J	10,450	≈13	10,000

- J is 3 orders above $\bar{p}$
- Same order as induction
- And t same order
- But V is too high

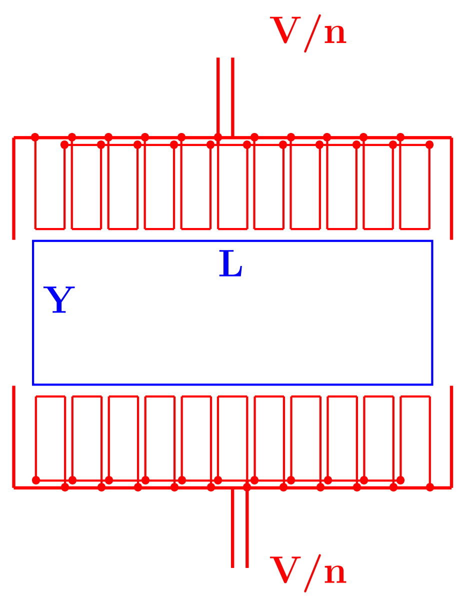
Induction Kicker solves Voltage problem

- Drive flux return
- Subdivide loops and drive in parallel
- Use cos(theta) distribution gives uniform field
- Conducting box removes stray field return

- No rise time limit
- Not effected by solenoid fields



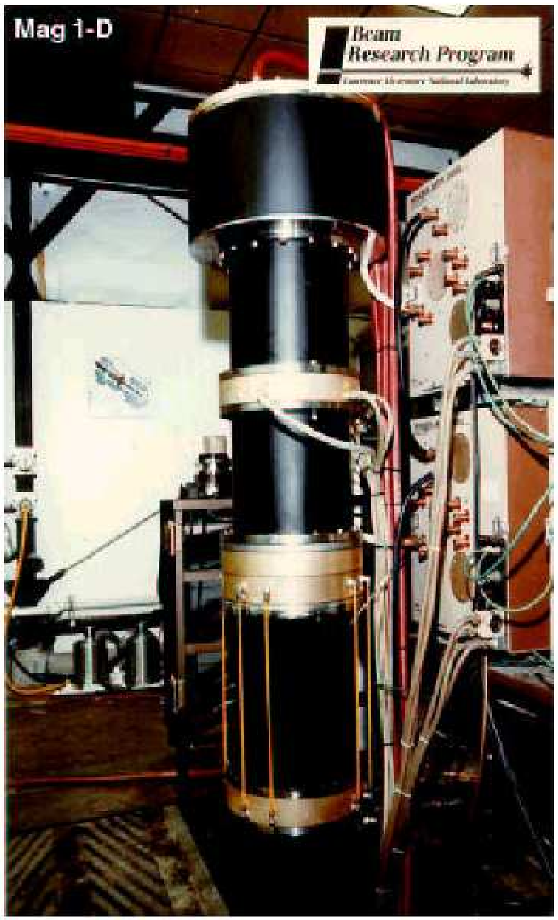
End View

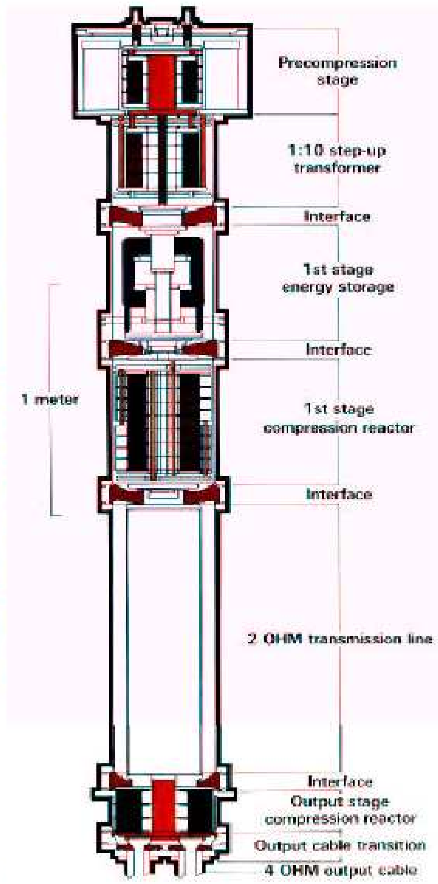


Side View

Mag Amp Driver

- Used to drive Induction Linacs (e.g. ATA or DARHT)
- Switch low current long pulse
- Mag-Amp compresses pulse to high current short pulse



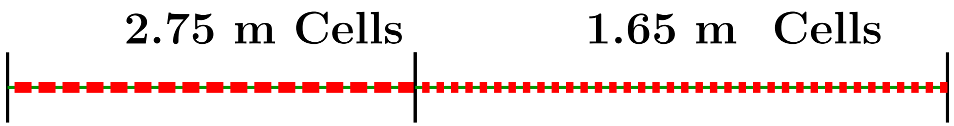


- **Non-resonant:**
  2 Drivers for inj. & extract.
  24 $\times$2 Magamps ($\approx$ 20 M\$)

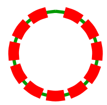
- **Resonant:**
  1 Driver, and 2$\times$efficient
  12 Magamps ($\approx$ 5 M\$)

Cost Reduction? e.g. RFOFO vs. Study 2

- **Study 2 Cooling**



- **RFOFO Cooling Ring**



	Study 2	Now	Factor
Tot length (m)	108	33	30 %
Acc length (m)	54	37	21 %
Acc grad	16 MV/m	12 MV/m	66 %

EXPECT SUBSTANTIAL SAVINGS

Conclusion

- Four approaches studied
- With differing approximations, all give 6D cooling
- RFOFO design simulated, though not all together, with
  - Maxwellian fields from real coils
  - Realistic absorber
  - Absorber and RF windows
  - Gap in lattice for injection

BUT

- Absorber heating needs R&D
- Thin windows desirable needs development
- Injection lattice not designed
- Injection kicker requires R&D

Much progress but still much work