.

Acceleration Costs

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With acknowlegements to Carol Johnstone and Mori San

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- Introduction on Desirable Acceptances
- Costing Assumptions
- Loading and Longitudinal Dynamics
- Comparison of Lattices
- Conclusion

Acceptances

	Trans Acc π mm	Trans Emit π mm	Long Acc π mm	Long Emit π mm
After Target	182[1]	20	∞	2000[2]
At end of Study-2 Phase Rotation	100	12	200×60[3]=12,000	40×60[3]=2400
At end of Study 2 Cooling	15	2.5	150×60[3]=12,000	30×60[3]=1800[4]
Of Study-2 Acceleration	15		150×60[3]=12,000	30×60[3]=1800
Of Large acceptance Acceleration[2]	30		150×60[3]=12,000[5] or ≈4000[6]	

1. For 20 T, r = 8 cm : 240/105*0.08*1000=183
2. Including decay straggling: $\beta\gamma$=2 × 3 ns × c × 100%
3. Approx number of Study-2 bunches = 60
4. Reduced by scraping from start of study-2 cooling
5. If 200 MHz and study-2 number of bunches
6. If 25 MHz and single bunch

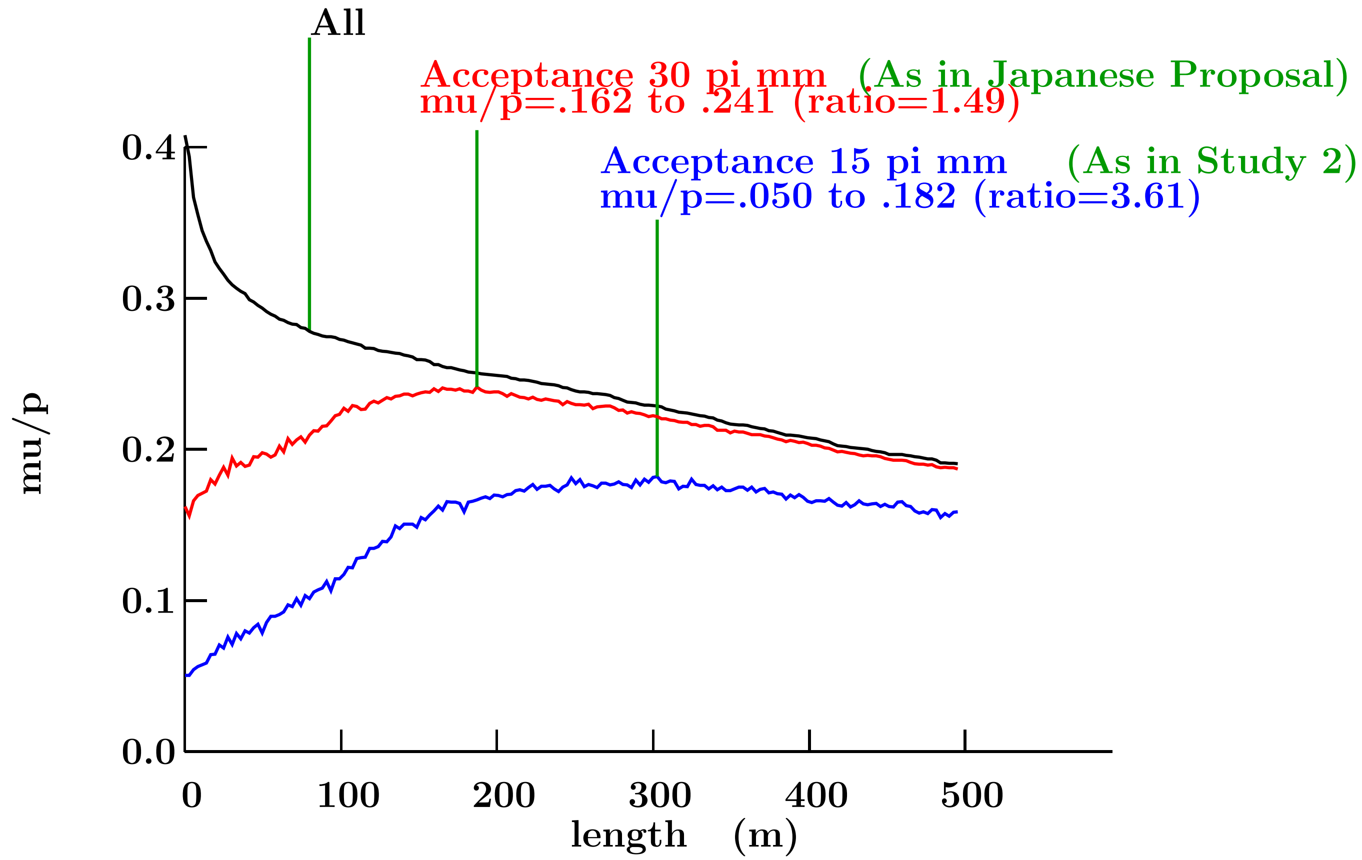
for transverse:

- at 2.5 sigma in x and y we need acceptance approx 6 times emittance
- Study 2 phase rotation acceptance not sufficient for initial emittance
- Acceptance of 15 pi mm matches Study-2 cooled emittance
- But Mori San has long said that cooling may not be needed if the acceptance is 30 pi mm

for longitudinal

- re bunching at 200 MHz (compared with straight 25 MHz) appears to increase acceptance by 3 times, but there is significant dilution during bunching, so the gain may not be real.

Performance vs Accelerator Acceptance



- Mori San is right
- 30 pi mm and no cooling $\approx$ 15 pi mm and study-2 (or RFOFO Ring) cooling
- Question: Which is cheaper ?
- Performance with 30 pi mm and pre-cooling could give even better performance but should use a system with greater acceptance than Study-2 or RFOFO Ring: Note sharp inital drop in transmission.

COSTS

SC Cavities

SC	cost M$/GeV
Cavities	$30 \times 16/G$
Power	$89.16/4.375 = 20.4 \times g/16$
Cryo	$28/4.375 = 6.4 \times g/16$
Total at 16 GV/m	56.8

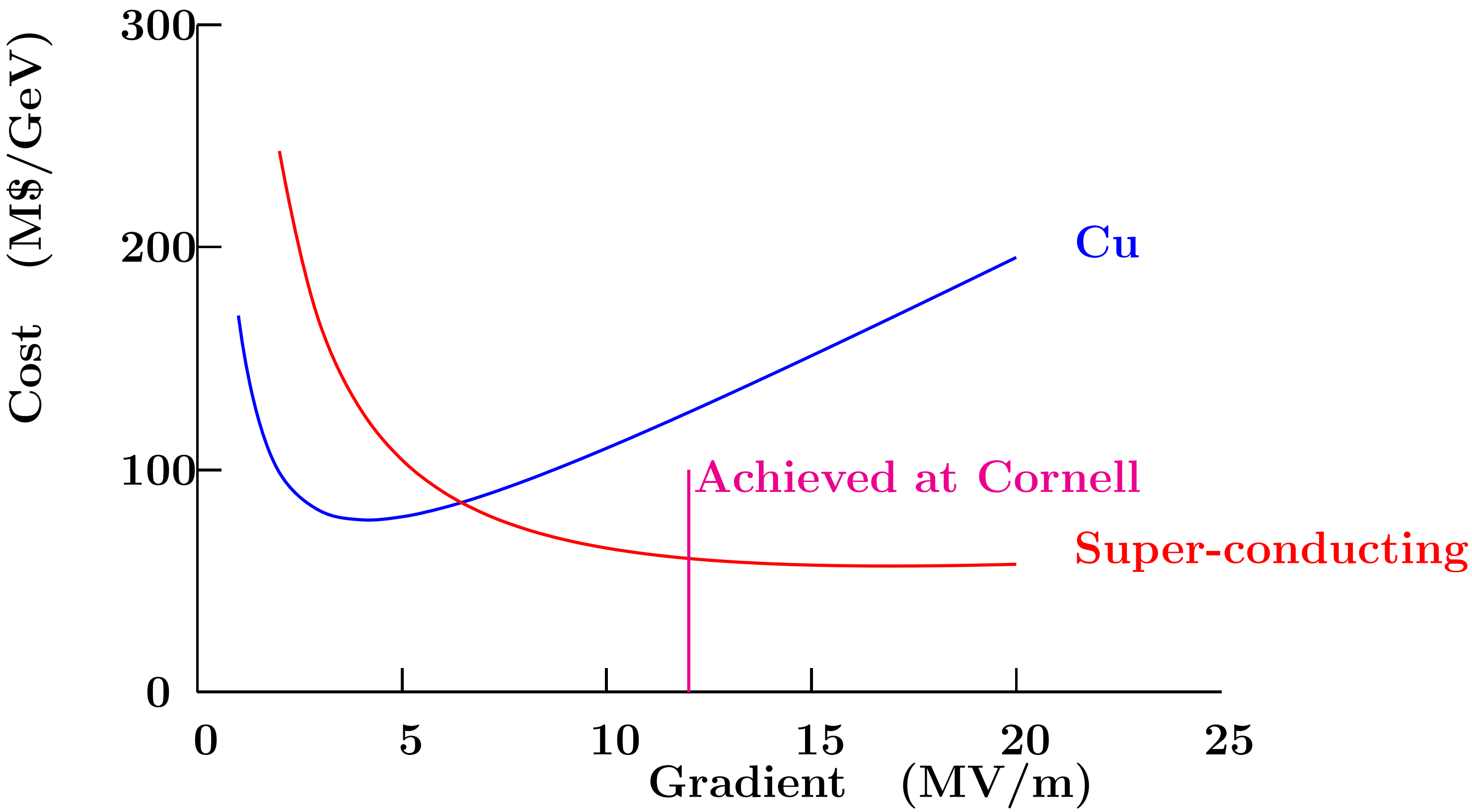
- RF power and cryogenics same as Study-2
- SC cavities 2 $\times$ Study-2 after discussion with Padamsee

Cu Cavities

Cu	cost M$/GeV
Cavities	$\approx\ 10 \times 16/G$
Power	$\approx\ 150 \times G/16$
Total at 16 MV/m	160
Total at 3 MV/m	81

- assuming 125 k$/ 75 cm cavity for open cavity, about half of study-2 with foils
- RF 25% more than study-2 allowing for less Shunt Impedance than foil cavities

RF cost vs Gradient



- SC cost min at 17 MV/m $\approx$ 55 M$/GeV
- Cu Cost min at 4 MV/m $\approx$ 75 M$/GeV (1.4 $\times$ SC)

But Loading will require gradients $\geq$ 12 MV/m, where

- Cu is 130 M$/m (2.4 $\times$ SC)
- But, to keep B low, SC requires an approximately 2 m straight for a single 75 cm cavity and even this requires that the magnets be off when the SC cavity is cooled

SC Magnet Costs

Green[1], including factor of 1.34 for 12 years inflation at 2.5%

$$\text{Green Est (M\$)} \quad = \quad 1.34 \times 0.77 \; (\text{B } \pi \text{R}^2 \text{ L})^{.631}$$

cost rising as $B^{.63}$ not true for long accelerator dipoles. Estimate ok at high B (LHC), too high for low B (RHIC).

$$\text{Palmer Est (M\$)} \quad = \quad 22.5 \;\; \text{B}^{1.5} \; \text{R}' \; (\text{L} \; + \; 20 \; \text{R}')$$

$$\times 1.5 \text{ (if quad)}, \qquad \times \left(\frac{\text{n}}{\text{m}}\right)^{-1/3} \text{ (quantity)}, \qquad \text{R}' \; = \; \text{R} + 0.003 \text{ B}, \qquad \text{B in T, R\&L in m}$$

	n	L m	R m	B T	cost k$	Green k$	G/real	Palmer k$	P/real
RHIC Q	**300**	**1.10**	**0.040**	**4.30**	**29.0**	**98.8**	**3.41**	**27.8**	**0.96**
LHC	**300**	**30.00**	**0.028**	**8.30**	**708.0**	**765.2**	**1.08**	**733.3**	**1.04**
RHIC	**300**	**10.00**	**0.040**	**5.30**	**149.0**	**452.5**	**3.04**	**150.0**	**1.01**

* **Costs corrected for inflation of 2.5% for 11 years = 1.31**

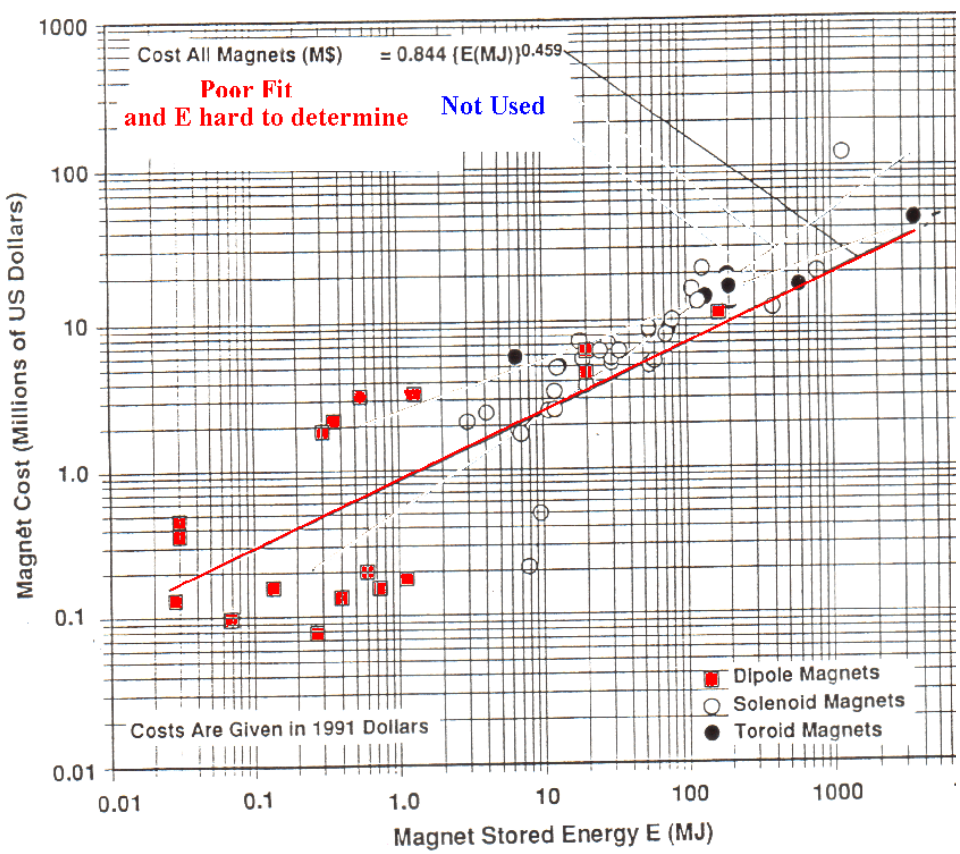
- **For Field Quality:** $\text{R} \; = \; \frac{\text{(Max beam width)}}{2} \; \times \; 1.3$
- **Costs are less than Study-2 RLA**

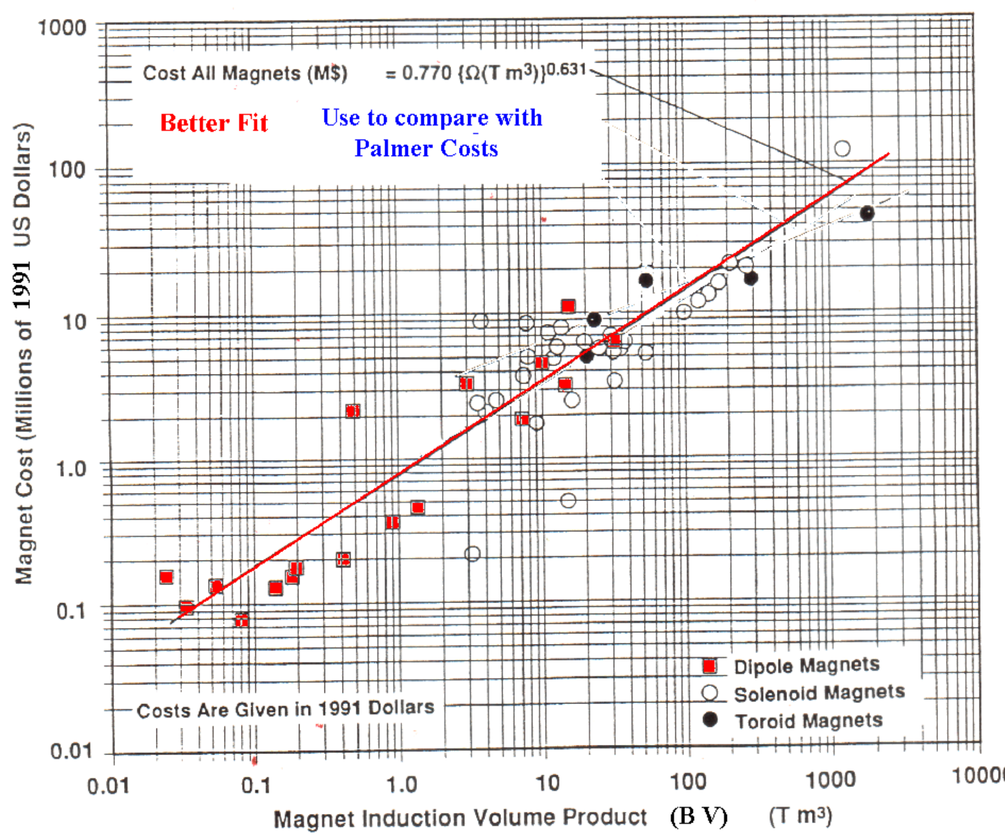
[1] Avd. in Cryo Eng. 37, Feb 1992

Mike Green Data and fits

Mostly of single magnets, and thus higher than RHIC or LHC Production, as observed

Fits are for all magnets, but looks reasonable for Dipoles only





Linear Costs

	source	Cost/length K$/m
Vacuum $\propto$ beam pipe	Use	4.6
Diagnostics $\propto$ beam pipe	”	1.2
Other $\propto$ beam pipe	”	4.2
Civil $\propto$ tunnel	”	15
Total		25

- Vacuum and diagnostics taken from Study-2
- ”Other” taken from Loew’s study of SLAC
  includes survey stands cable trays moving equipment etc
- Civil costs also increased by about 20% from Study-2 to equal Loew’s number

Loading

Sets a lower limit on accelerating gradients, or on maximum number of turns

The R/Q of a cavity is dependent only on its geometry, and relates the stored energy U to the acceleration Voltage V:

$$(R/Q) \ = \ \frac{V^2}{2 \ \omega \ U}$$

For a pillbox cavity with L=$\lambda/2$: R/Q = 121 Ω.
For SC cavities it is lower (R/Q $\approx$ 50 Ω).

$$\frac{\Delta V}{V} \ = \ \frac{\Delta U}{2 \ U} \ = \ \frac{N_\mu \ e \ V \ \ n}{V^2/\omega(R/Q)} \ = \ \frac{N_\mu \ e \ \omega \ (R/Q)}{g\mathcal{E}} \ n$$

where the gap $g = 0.75$ m, , $\omega = 2\pi \ 200$ MHz, $\mathcal{E}$ is the accelerating gradient, and n is the number of turns.
For mu/p = 2 $\times$ Study-2 (both signs), and P = 1 MW at 15 Hz:

$$N_\mu = N_p \ \times \ \mu/p \ = \ 1.7 \ 10^{13} \times 0.23 \times 2 \ = \ 8 \ 10^{12}$$

If we accept a maximum voltage drop of 10% (or 20% for 2 and 4 MW examples), then

for $\mathcal{E}$=12 MV/m, $\frac{\Delta V}{V} \approx$ 0.9 % per turn, allowing approximately 11 turns
for $\mathcal{E}$=6 MV/m, $\frac{\Delta V}{V} \approx$ 1.8 % per turn, allowing only 6 turns

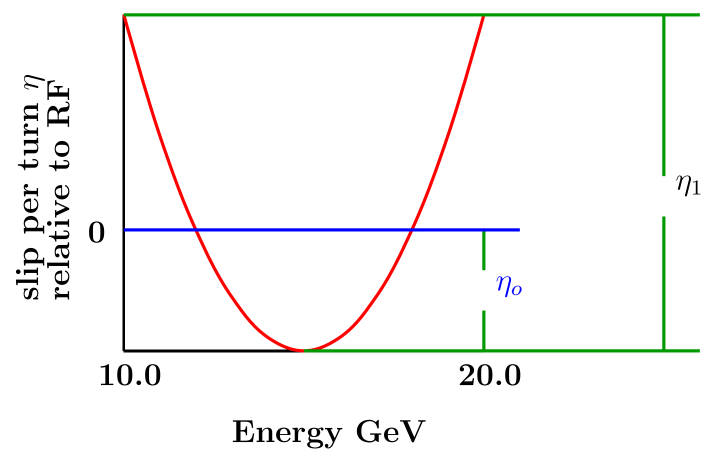
Phase Slip

Scaling FFAG is in no way isochronous and requires low frequency (25 MHz). Non-Scaling FFAG's are isochronous at mid-energy but eta rises approximately parabolically at lower and higher energies:

Let δ be the fraction of the total acceleration after n turns, η the difference of path length per turn, η_1 the maximum such path difference (assumed the same at intimal and final energies), and η_o the value of η at the mid-energy, then:

$$\delta = \frac{E - E1}{E2 - E1}$$

$$\eta(\delta) \;=\; \eta_1 \left((2\delta - 1)^2 \;-\; \frac{\eta_o}{\eta_1} \right)$$



Defining
$$\zeta \;=\; \frac{2\pi\eta_1\ (E_2 - E_1)}{\lambda\ V}$$

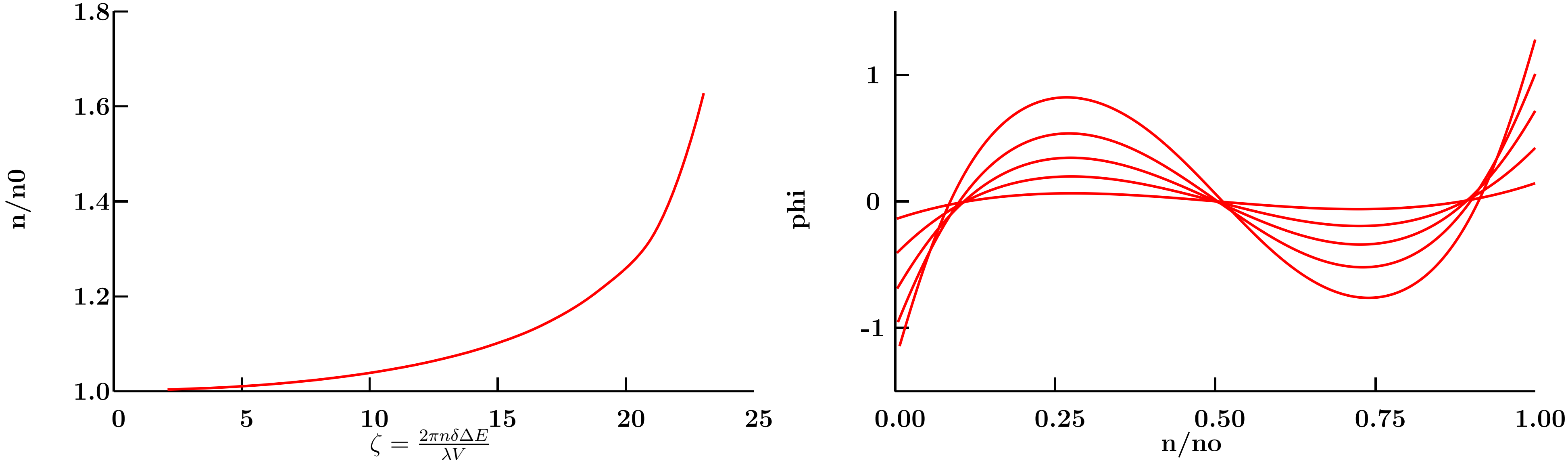
then
$$\phi(\delta) \;=\; \phi_o \;+\; \int_o^1 \zeta\ \left((2\delta - 1)^2 \;-\; \frac{\eta_o}{\eta_1} \right)\ d\delta$$

and
$$\frac{n}{n_o} \;=\; \int \frac{dn}{n_o} \;=\; \int \frac{1}{\cos(\phi(\delta))}\ d\delta$$

where
$$n_o \;=\; \frac{E_2 - E_1}{V}$$

n/n_o is a measure of how many extra turns are needed because of the phase slip, and it depends on ζ, the initial phase ϕ_o and the offset η_o

We can then search for values of η_o, and ϕ_o to obtain minimum n/n_o's as a function of ζ and η_1:

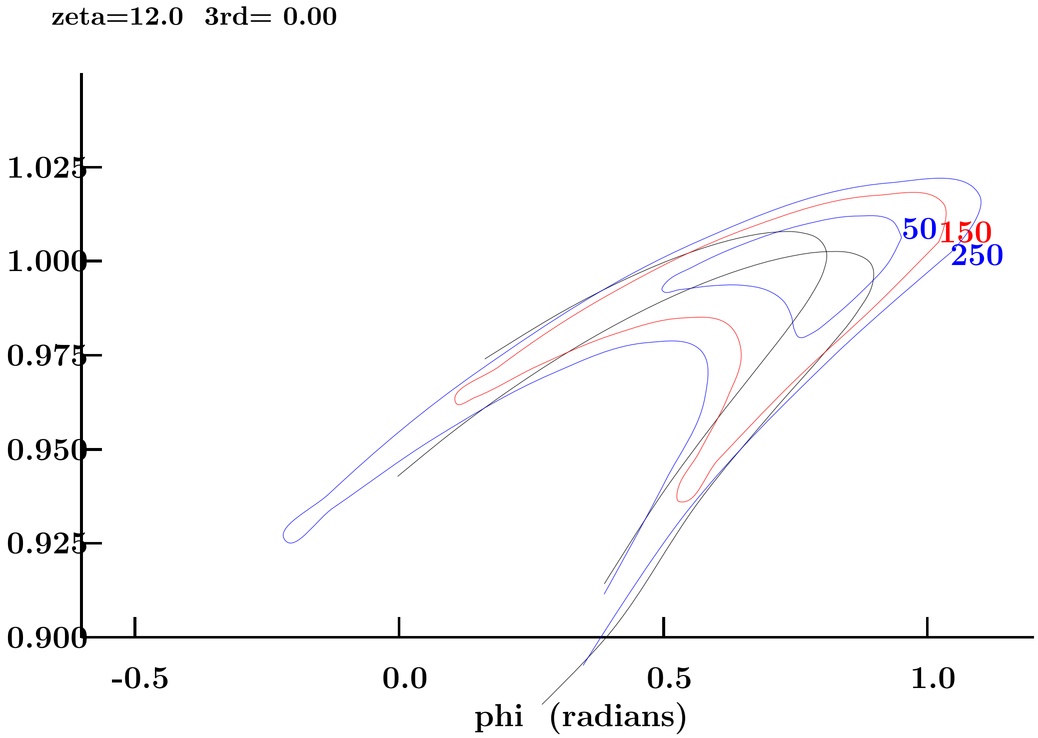


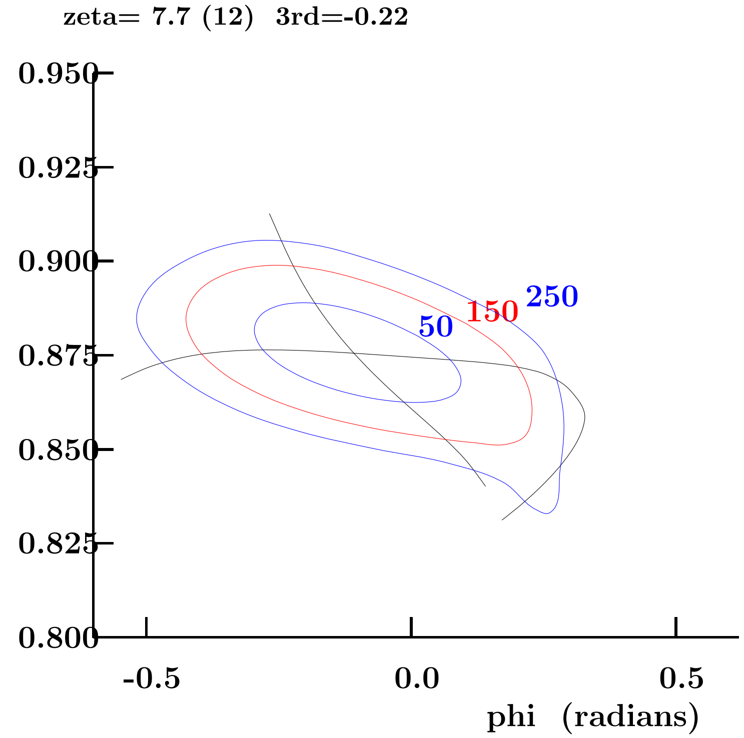
The n/n_o plot would suggest that ζ could be up to about 16 (for 20% more turns and thus 20% more decay loss)

But for acceptance it has to be even lower

Longitudinal Acceptance

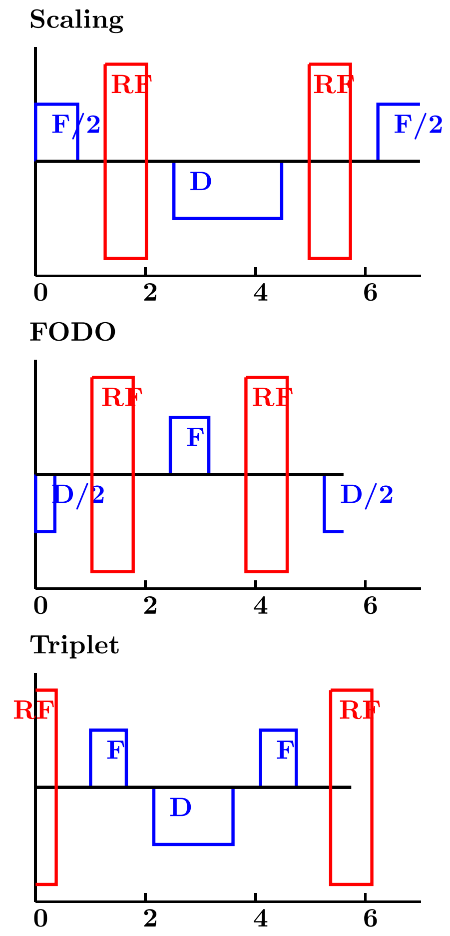
Without attention, there is severe distortion of longitudinal phase space. Adding third harmonic cavities helps, allowing a maxumum ζ of about 8, for 150 pi mm acceptance.





Lattices Compared

- Note: all lattices considered have 30 pi mm longitudinal acceptance ($2 \times$ Study-2 assumption)
- Coil Inside radius at 1.3 times required aperture this assumption needs study

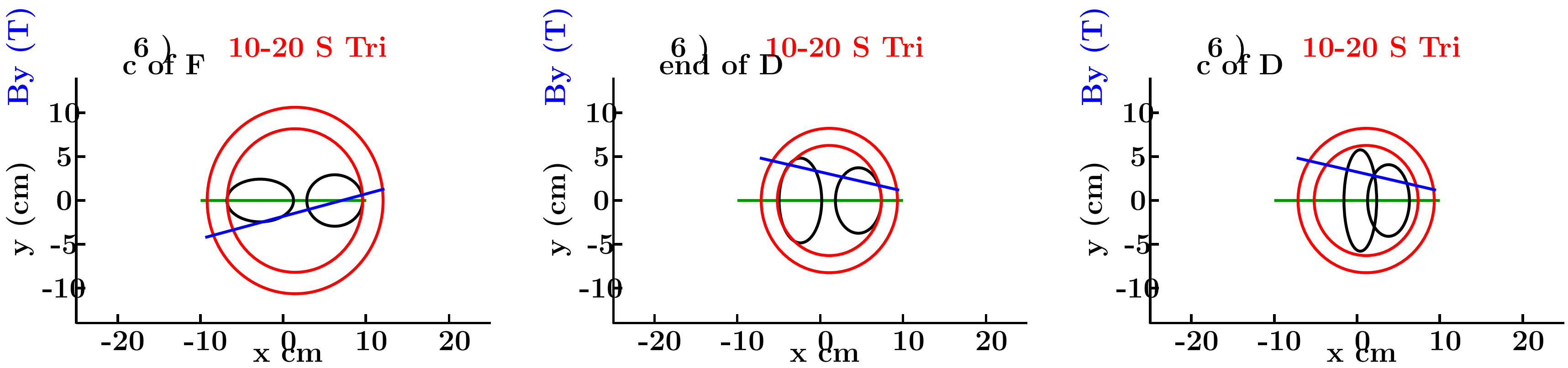


1. Study-2 RLA 2.5 to 20 GeV in 4 passes
2. Scaling FFAG for 10-20 GeV from Japan as of September 2002
3. Non-scaling FODO FFAG for 10-20 Gev (My scaled version of Scott's version of Carol's Lattice)
4. Non-scaling Triplet FFAG for 10-20 GeV (My scaled version of Scott's version of Dejan's Lattice)

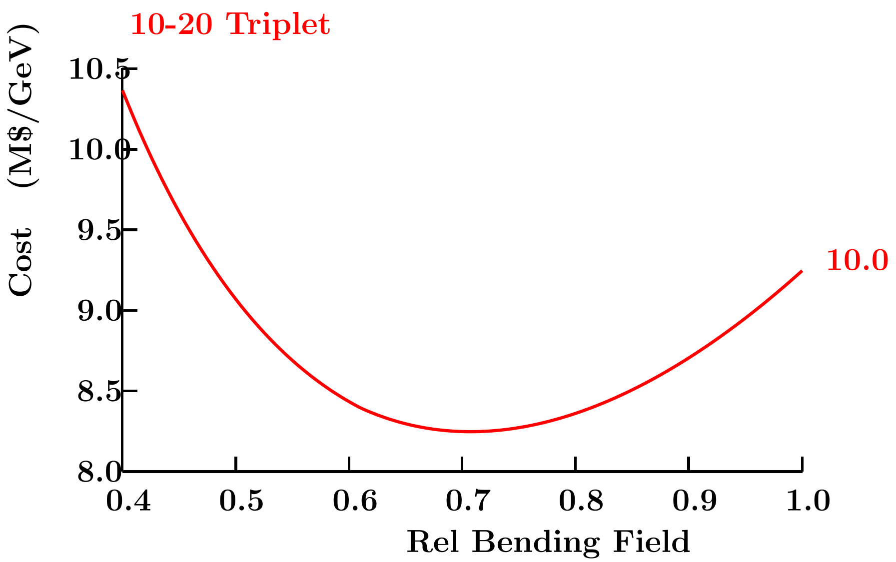
For last two cases:

- Beam offsets, gradients and betas calulated by Scott
- Beam sizes at initial and final energies determined
- Bending fields and resulting offsets scaled by factor
- Aperture, peak fields and cost calculated
- Minimum cost case taken

e.g. Triplet



Note: fields are always lower on the outside (positive x) of the ring. suggesting that C magnets can be designed for injection extraction without disturbing the lattice.



Magnet Costs

	n	cell	L	R	Bmin	Bmax	G	/mag	circ	Tot	Tot/GeV
		m	m	m	T	T	T/m	k$	km	M$	M$/GeV
RLA 2.5-20	100	0.00	0.69	0.123	-0.9	0.9	7.3	53.1			
linacs	50	0.00	1.22	0.123	-0.9	0.9	7.3	78.2			
	36	0.00	0.69	0.160	-0.6	0.6	3.4	118.0			
	18	0.00	1.22	0.160	-0.6	0.6	3.4	169.0			
chicane	40	0.00	2.52	0.178	0.3	0.3	0.0	131.8			
	36	0.00	0.69	0.123	-0.9	0.9	7.3	74.7			
	18	0.00	1.22	0.123	-0.9	0.9	7.3	109.9			
arc 1	40	0.00	2.52	0.135	0.5	0.5	0.0	86.3			
	42	0.00	0.69	0.079	-1.9	1.9	23.0	48.4			
	21	0.00	1.22	0.079	-1.9	1.9	23.0	75.2			
arc 7 2.5 20	46	0.00	2.52	0.082	1.7	1.7	0.0	51.2	1446	64.7	3.7
Scale 10-20	180	6.99	1.53	0.203	-2.5	-6.4	-9.4	485.7			
10.0 20	180	6.99	1.96	0.203	2.5	6.4	9.4	523.1	1257	181.6	18.2
FODO 10-20	108	5.60	0.70	0.143	-3.1	6.4	31.2	423.2			
10.0 20	108	5.60	0.70	0.059	3.8	7.6	30.6	92.4	605	55.7	5.6
Triplet 10-20	185	5.24	0.65	0.106	1.4	-4.3	25.6	101.5			
10.0 20	92	5.24	1.44	0.084	1.2	5.0	-21.8	92.5	484	27.3	2.7

- RLA has greater circumference (1.45 km) and more magnets (808) than any other, but the apertures and fields are lower, giver a modest magnet cost
- Scaling FFAG has larger apertures (41 cm) and greater circumference (1.2 km) than either non-scaling design
- The Triplet, though with more magnets than the FODO (277 vs 216), has lower fields (5 vs 7.6 T) and smaller apertures (21 cm vs 29 cm), and thus lower magnet cost (27 vs 56 M$)

RF and Total Costs

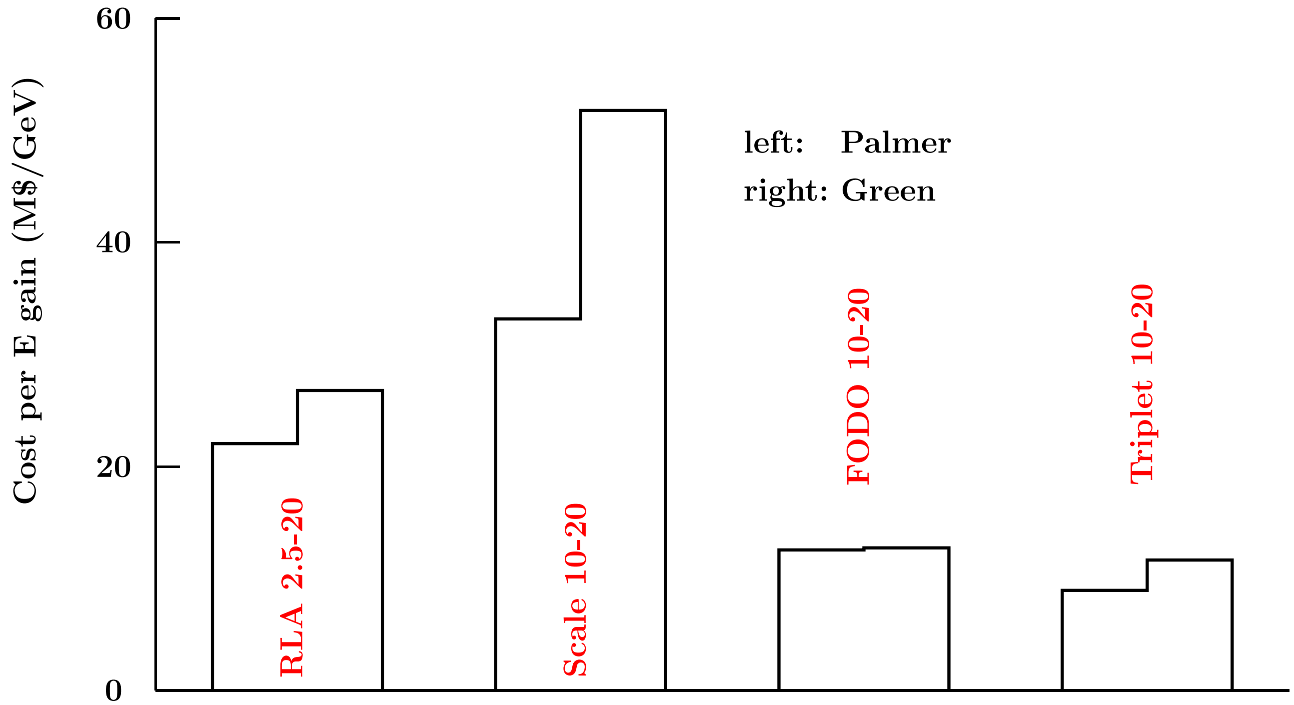
	n	ζ	n/n0	ave $\mathcal{E}$ MV/m	slip m	V GV	ng	gap m	grad MV/m	fill	rf	dV %	RF M$	mag M$	Lin M$	Tot M$	cost/dE M$/GV
RLA 2.5-20	4		1.00	3.0	0.00	4.38	48	11.0	12.0	.78	SC	3	263	65	58	386	22.0
Scale 10-20	14		1.27	0.8	1.29	0.94	360	1.75	12.0	.12	Cu	1	(119)	182	32	(332)	(33.2)
FODO 10-20	(12)	18	1.2	1.5	0.39	0.91	108	2.10	12.0	.82	SC	9	55	56	15	125	12.5
Trip 10-20	16(13)	7.1	1.08	1.2(1.7)	0.14	.6(.83)	92	2.00	12.0	1.0	SC	10	50	27	12	89	8.9

- RF cost for Scaling example is for 200 MHz (not 25 MHz) but should be of same order
- Decay loss is least for the RLA (ave grad 3 MV/m), greatest for the scaling (0.75 MV/m), and intermediate for the non-scaling designs(15 & 1.7 MV/m)
- Loading with 25 MHz RF is not a problem because of stored Energy $\propto \lambda^2$
- For the FODO the value of ζ gives an acceptable n/no (1.2), but is too large to allow a longitudinal acceptance of 150 pi mm. ζ can be reduced by further lowering the bending fields, but the cost gets higher. ζ can also be lowered by decreasing the space for RF and using Cu, instead of SC, cavities. But the cost is higher.
- The $\zeta = 7$ for the triplet lattice is ok for 150 pi mm longitudinal acceptance.

- The Triplet non-scaling FFAG is superior and less expensive than the FODO.
- The Scaling FFAG appears to be more expensive the non-scaling designs.
- The non-scaling triplet FFAG appears to be less than half the cost of the RLA, but lower energy FFAG's yet to be designed and costed.

Warning: Such cost scaling is not always reliable and engineering studies will be needed to confirm these conclusions.

Comparison with Green Cost Formula



- The Conclusions appear insensitive to the cost method

Conclusion

- **Study-2 RLA now has 30 pi mm acceptance (Bogacz)**
- **Scaling FFAG's have 30 pi mm acceptances (Mori)**

- **Non-Scaling Triplet 10-20 GeV FFAG has 30 pi mm acceptance and is cheaper per GeV than RLA or Scaling FFAG**
- **Work started on lower Energy non-scaling FFAG's, but not finished.**
- **So conclusion for full energy range (0.2 to 20 GeV) not certain yet, but**

- **But cost differential between 15 and 30 pi mm is probably less than cost of cooling and would give the same (Study-2) performance**
- **Adding pre-cooling would give performance $\approx 2 \times$ study-2[2], and could be in a later phase**
- **Using both signs doubles performance of either phase:**
  - **2 signs, no cooling, $\approx 2 \times$ study-2**
  - **2 signs, with pre-cooling, $\approx 4 \times$ study-2**
- **Pre-cooling probably not in a ring, because the kicker problem 10,000 times conventional**

[2] 1.2 10^{20} mu decays in one straight/10^7 sec at 1 MW