A Pulsed Muon Synchrotron
& comarrison with RLA's

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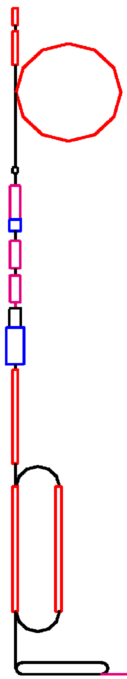
1) INTRODUCTION to NEUTRINO FACTORIES

US Study-2: Good Performance
But Cost 1.74 B$ (inc. 10% 'other', European Accounting)

Need to reduce to 1/2



(p Driver)	% of Cost	
Hg Target	(6 %)	
Phase Rotation	(27 %)	Neuffer Scheme cost ≈ 1/3 ??
Cooling	(22 %)	Cooling Ring cost≈ 1/3 ??
Acceleration	(37 %)	????
Storage Ring	(7 %)	????

Compare RFOFO with Study 2

- Similar components
- 33m vs. 108 m (study 2) (Cost $\approx 317 \times 33/108 \approx 100$ M$)
- Same Transverse cooling
- 1/14 Long emittance vs. none
- 2nd ring could reduce Trans another 1/5

Lower emittances → Lower Acc Costs ?

Possible Acceptances of Accelerator

	Study-2	1 ring	2 rings
Trans Acceptance	15	15	4
Long Acceptance	150	35	35

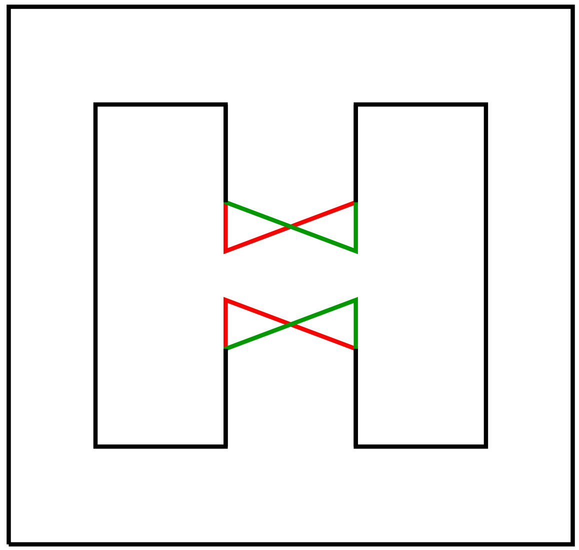
Possible New Acceleration Scheme

1. Linac: .2 to 1 GeV/c
2. RLA: 1 to 4 GeV/c
3. Pulsed Synchrotron: 4 to 20 GeV/c discuss this

Don Summers' Proposed Arc Lattice

- Magnet Ends Cost $'s
- Magnet Ends have Eddy Current Losses

- Use Combined Function
- Continuous magnet
- Alternating Gradients



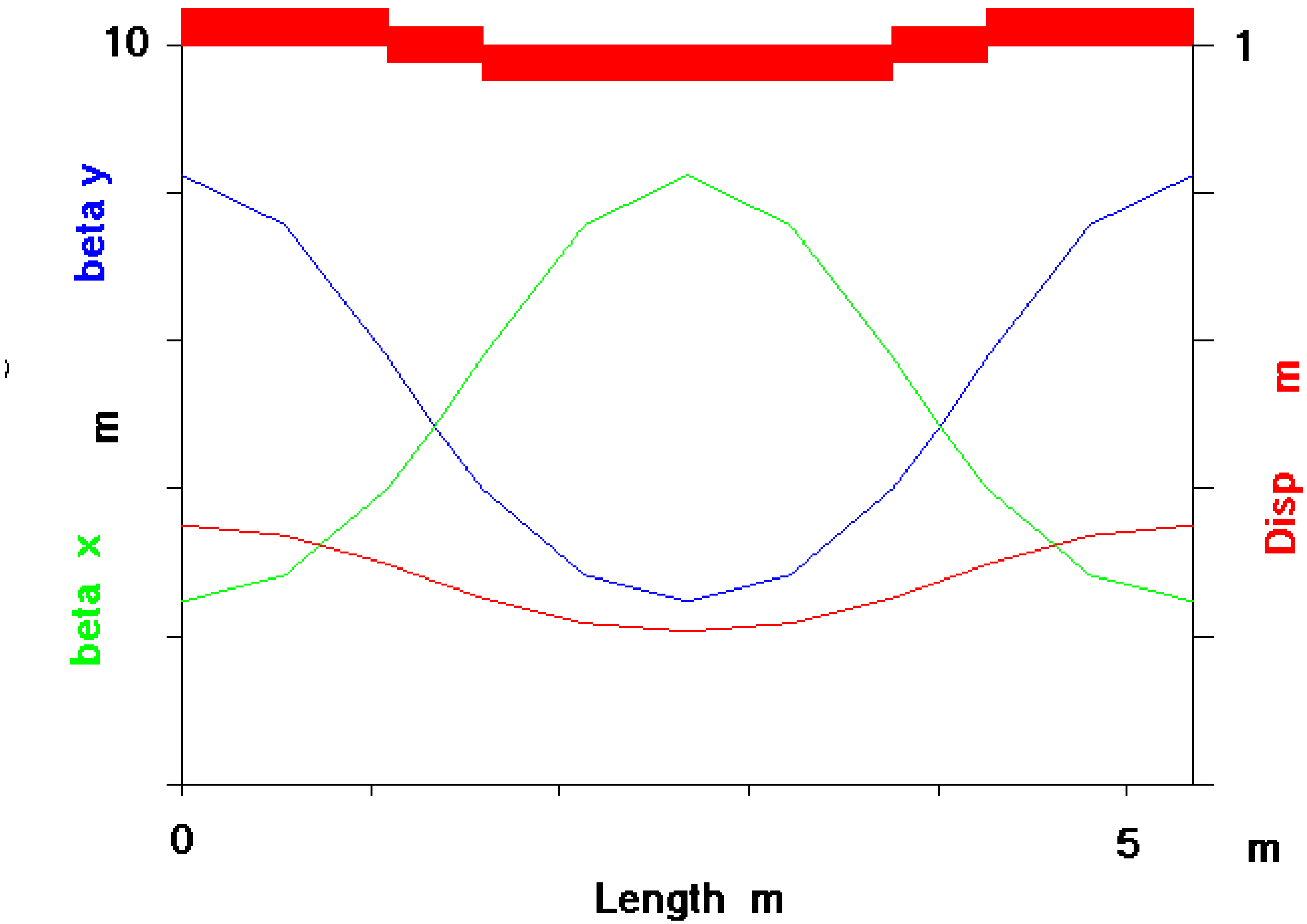
II A SPECIFIC PULSED ACCELERATOR DESIGN

Requirements for Pulsed Synchrotron

Initial Energy	$\mathbf{E}_{\rm in}$	**(GeV)**	**4.0**
Final Energy	$\mathbf{E}_{\rm out}$	**(GeV)**	**20.0**
Assumed Proton Power	P_p	**MW**	**4**
Muons/proton	$N_{\mu/p}$		**0.15**
Muons/bunch train	$\mathbf{N}_\mu$		**5 10^{12}**
Bunch and RF Frequency	f_{RF}	**(MHz)**	**201**
Bunches/train	$\mathbf{n}_{\rm bunches}$		**10**
Length of train	$\ell_{\rm train}$	**(m)**	**15**
Effective Repetition Rate	$f_{\rm rep}$	**(Hz)**	**30**
Acceptable decay loss	ξ	**(%)**	**15-25**
Normalized Trans. Acceptance	$A_\perp$	**(π mm radians)**	**4**
Normalized Longitudinal Acceptance	$A_\parallel$	**(π mm radians)**	**35**

Arc Lattice

20 T/m gradient
Bending field of 0.9 T

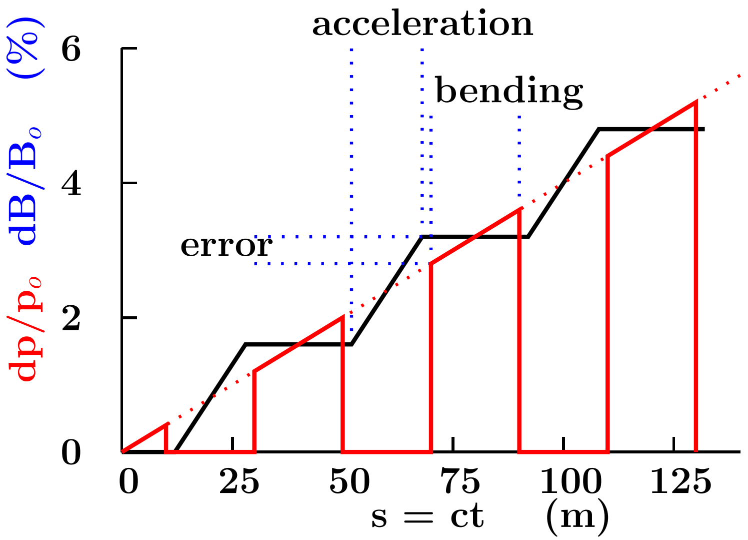


Parameters of a Single Arc Cell

Cell length	m	5.28
Combined Dipole length	m	2.24
Combined Dipole $B_{central}$	T	0.9
Combined Dipole Gradient	T/m	20.2
Pure Dipole Length	m	0.4
Pure Dipole B	T	1.8
Momentum	GeV/c	20
Phase advance/cell	deg	72
beta max	m	8.1
Dispersion max	m	0.392
Bend/cell	rad	0.0785*

Errors from Momentum vs. Bend Field tracking

RF must be distributed around the ring to avoid large errors



$$\mathrm{Max}\Delta p \;=\; \frac{1}{2\; n_{\mathrm{turns}}\; m_{\mathrm{RF\;\;Stations}}}(p_2 - p_1) \;=\; \frac{1}{2\;\,12\;\,18}16$$

$$=\; .037 GeV/c$$

- **At injection: 0.92 % (but beam fills pipe: Bad)**
- **at extraction: 0.12 %**

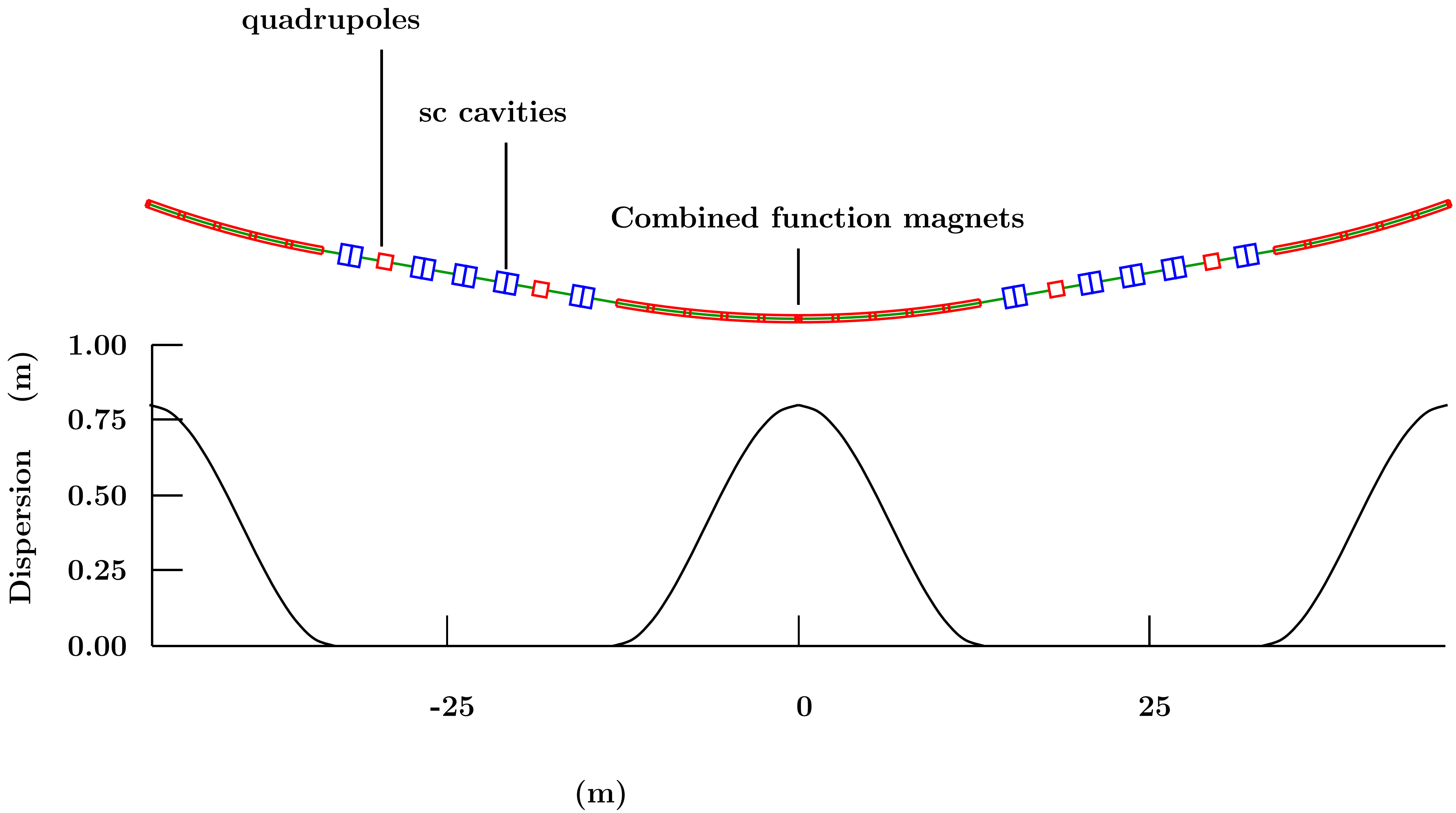
So: Correct B vs. s for injection:

$$\frac{dT}{ds}\; I_i \;=\; -\frac{1}{c}\;\frac{dB}{dt}$$

- **Error at injection: 0%**
- **at extraction: 0.83 % (but beam $\ll$ pipe: OK)**

5 cell arc segments made as single magnet

Phase Advance: 5 x 72 = 360 deg.



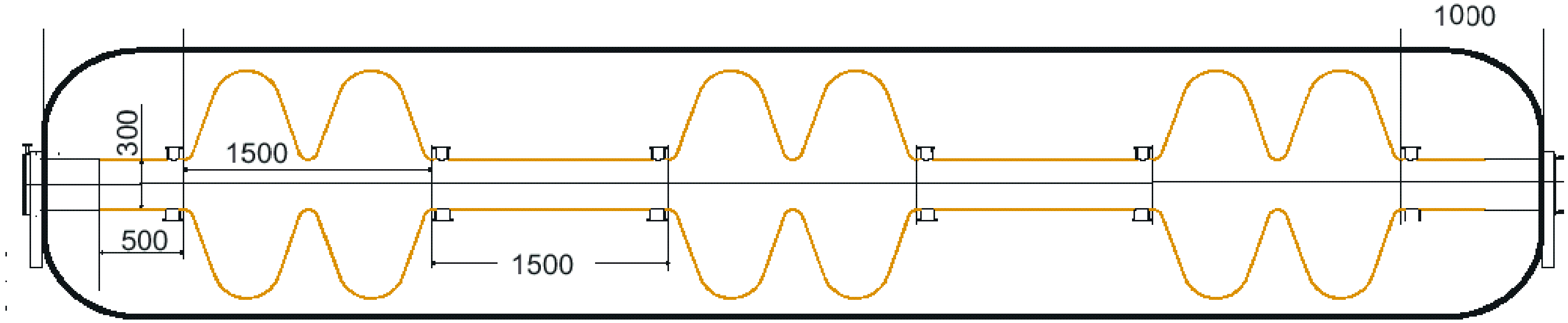
Straight Sections

Need long gaps for SC Cavities:

ϕ	deg	77
$L_{cell}/2$	m	11
L_{quad}	m	1
dB/dx	T/m	7.54
a	cm	5.8
β_{max}	m	36.6
σ_{max}	m	.0195
B_{pole}	T	0.44
U_{mag}/quad	J	$\approx$ 3000

The number of quadrupoles is 16 x 2 + 2 x 4 = 40
Stored energy of 117 kJ ($\approx$ 7 %)
Full circumference is now 18*26.5 + 16*22 + 2*44 = 917 m

Super Conducting RF Similar to Study-2



Frequency	**MHz**	**201**
Gap	**cm**	**75**
Grad	**MV/m**	**15**
Stored Energy	**kJ**	**1.1**
Muons per train		$\mathbf{5\ 10^{12}}$
Passes		**12**

Energy to Beam:

$$12 \quad 5\ 10^{12}\ 1.6\ 10^{-19}\ 17\ 10^{6}\ 0.75 \quad = \mathbf{120} \quad \mathbf{J}$$

$$= \mathbf{8.2\ \%}$$

Voltage Drop: $\frac{\Delta\mathcal{E}}{\mathcal{E}} = \mathbf{4.1\ \%}$

Injection/Extraction

Minimum Kicker Parameters

$$B_x = \frac{\Delta p_y}{L\ c} = \frac{m_\mu\ 2}{L\ c} \sqrt{\frac{A_n\ \beta\gamma}{\beta_y}}$$

$$V = \frac{B_x\ Y\ L}{t_{\rm rise}} = \frac{4\ m_\mu}{c} \quad \frac{A_n}{t_{\rm rise}}$$

$$U = \frac{B_x^2\ L\ X\ Y}{2\ \mu_o} = \frac{m_\mu^2\ 8}{\mu_o\ c^2} \quad \frac{A_n^2}{L} \propto A_n^2$$

- **For t=500 nsec $A_\perp$=4 π mm L=2 m**
- **V = 2 $\times$ 9 = 18 kV ($\approx$ $\bar{\rm p}$ kickers)**
- **U = 2 $\times$ 9.5 = 19 J ($\approx$ $\bar{\rm p}$ kickers)**

MACHINE DESIGN
Ave. Acceleration Gradient vs. Decay

For Decay Loss: $\xi = 0.15$

$$\mathcal{E}_{\mathrm{ring}} = \frac{\mathrm{m}_\mu}{\tau} \frac{\ln\left(\frac{\mathrm{E2}}{\mathrm{E1}}\right)}{\ln(1 - \xi)} = 1.58 \quad \mathrm{MV/m}$$

RF=17 MV/m, loading=5%, RF packing =22%, phase=20 deg

$$\mathcal{E}_{\mathrm{staights}} = 17 \quad 0.95 \quad 0.22 \quad \cos(20) = 3.3\mathrm{MV/m}$$

$$\frac{\mathrm{Straight}}{\mathrm{Arc}} = \frac{1}{\left(\frac{\mathcal{E}_{\mathrm{straight}}}{\mathcal{E}_{\mathrm{ring}}} - 1\right)} \approx 0.9$$

If 25% decay loss: Straight/ Arc $\approx$ 0.4: a significant saving!

Required Momentum Acceptance

$$\text{Momentum acceptance} \qquad \Delta_p \;=\; \sqrt{\frac{A_\parallel}{\beta_\parallel\ (\beta_v \gamma)}}$$

where

$$\beta_\parallel \;=\; \frac{1}{2\pi}\sqrt{\frac{\gamma\ \lambda_{RF}\ m_\mu\ \eta}{\mathcal{E}_{\rm Ring}\ \sin(\phi)}}$$

and

$$\eta \;\approx\; \frac{D_{\rm ave}}{R}$$

For our ring $\Delta p\ \approx$ 1 %

Magnet Cross Sections vs. Field Gradient

Scaling from Synch lattice:

$$\beta_\perp(\mathrm{max}) \quad = \quad 8\ (\mathrm{m})\ \frac{20(\mathrm{T/m})}{G_B}$$

$$\mathrm{Dispersion(max)} \quad = \quad 2\ \times\ 0.4\ (\mathrm{m})\ \frac{\beta_\perp(\mathrm{max})}{8\ (\mathrm{m})}$$

factor of 2 to allow for uncorrected Dispersion swings

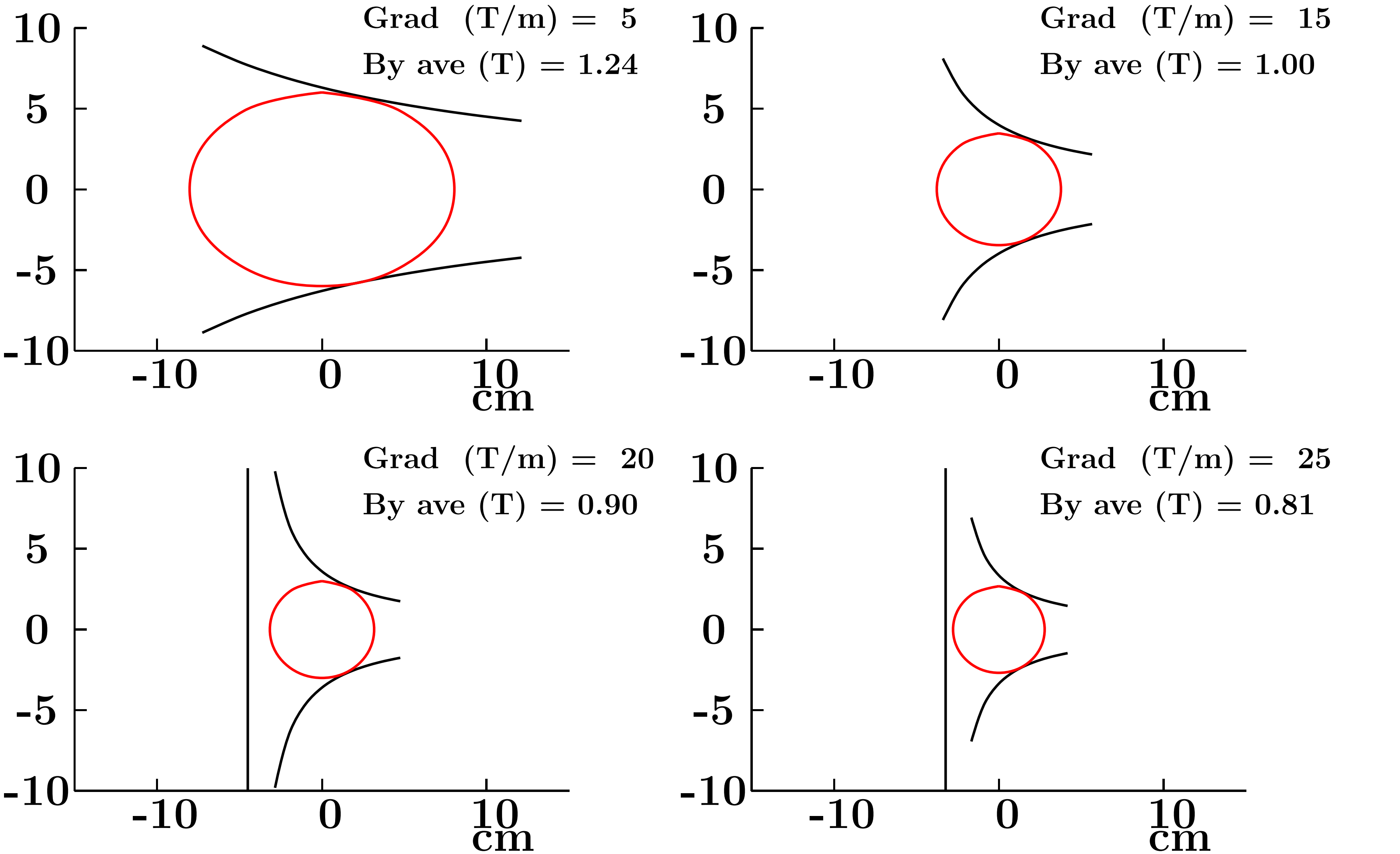
$$\text{Vert half aperture} \qquad a_y \ = \ \sqrt{\frac{\beta_\perp\ A_n}{\beta\gamma}}$$

$$\text{Horiz half aperture} \qquad a_x \ = \ \sqrt{a_y^2\ +\ (D\ \Delta_p)^2}$$

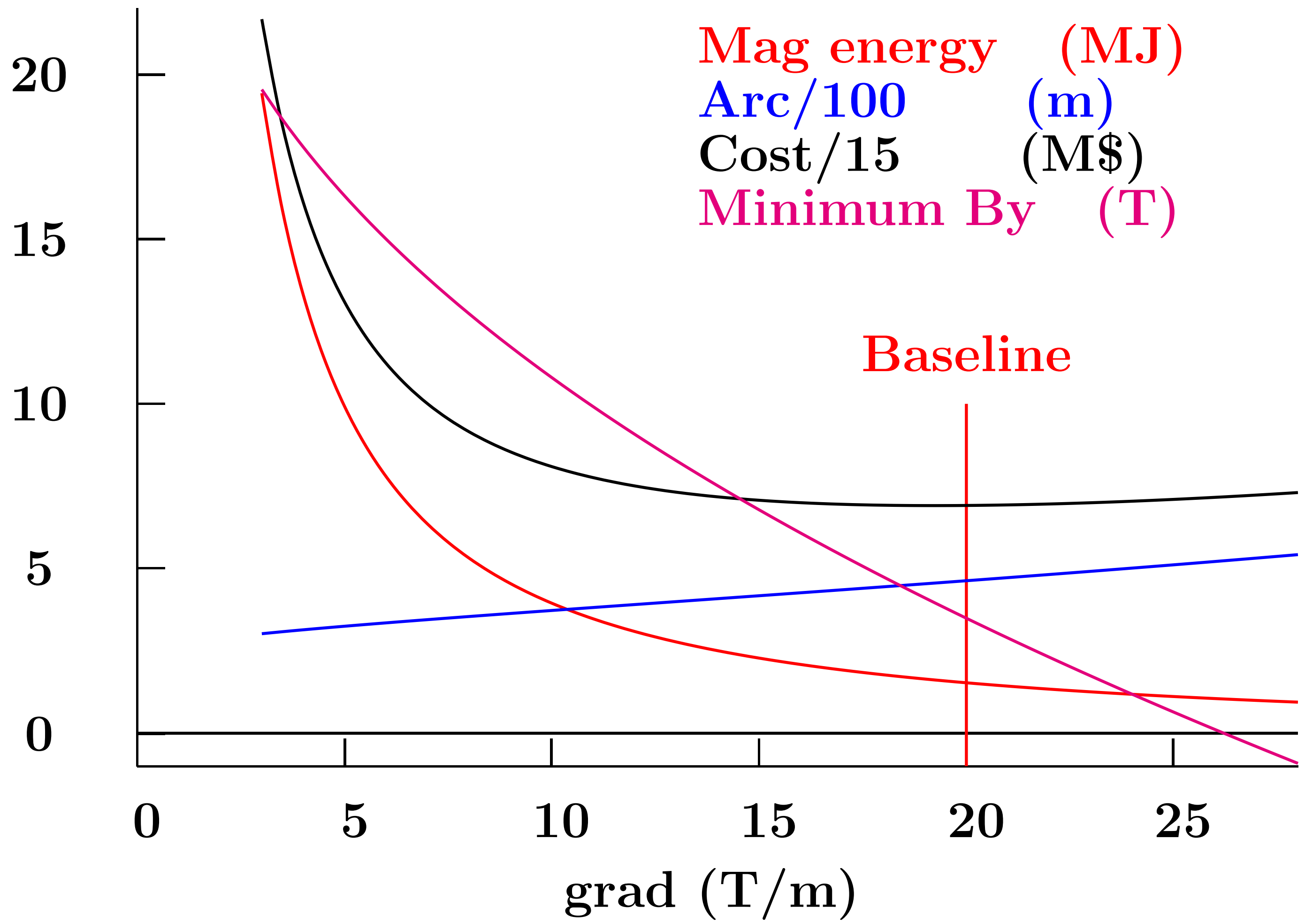
For field Gradient G_B:

$$\text{Bending B} \ = \ B_{\mathrm{max}} \ - \ 1.5\ a_y\ G_B$$

Magnet Sections vs. G_B



Including Costing from Part III

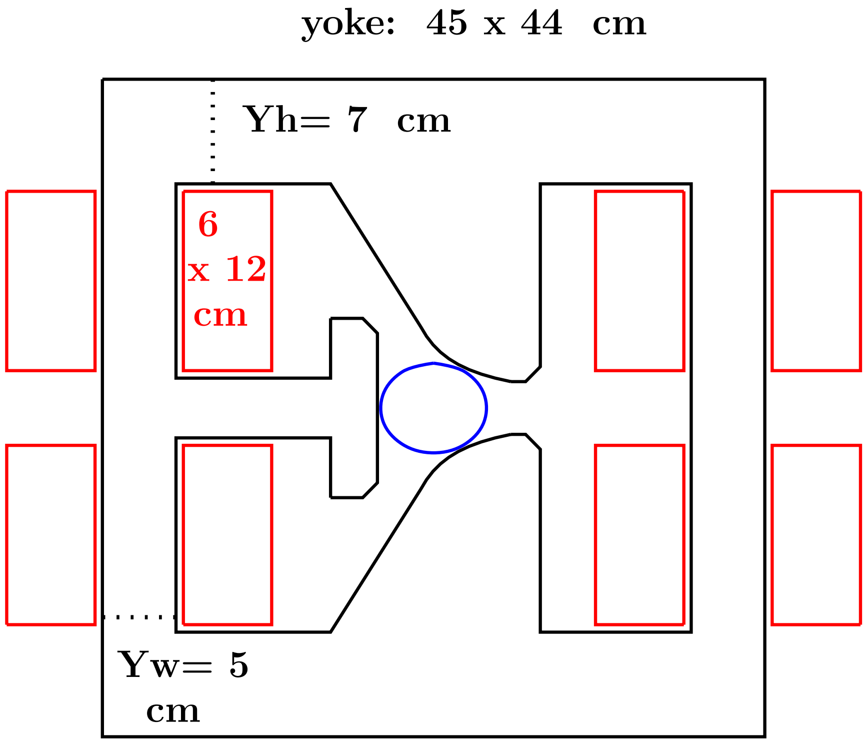


Parameters vs. Field Gradient

G T/m	Ax cm	Ay cm	B T	B1 T	B2 T	n	U MJ	V MV/m	arc m	str m	circ M$	$mag M$	$RF M$	$tot
5.0	11.59	18.95	1.29	0.82	1.76	17	9.91	0.96	325	285	610	145	52	196
9.0	8.64	12.56	1.15	0.59	1.72	15	4.54	1.08	364	319	682	70	58	128
13.0	7.19	9.76	1.05	0.41	1.68	14	2.77	1.19	400	350	750	46	64	110
17.0	6.29	8.14	0.96	0.27	1.65	12	1.92	1.29	435	382	817	35	69	104
21.0	5.66	7.07	0.89	0.14	1.63	11	1.43	1.40	472	414	886	29	75	104
25.0	5.18	6.30	0.82	0.03	1.61	11	1.11	1.52	511	448	960	25	81	106

Select Gradient for Minimum Cost

Circumference is greater, but Magnet is Small



Why are other rings not so optimized?

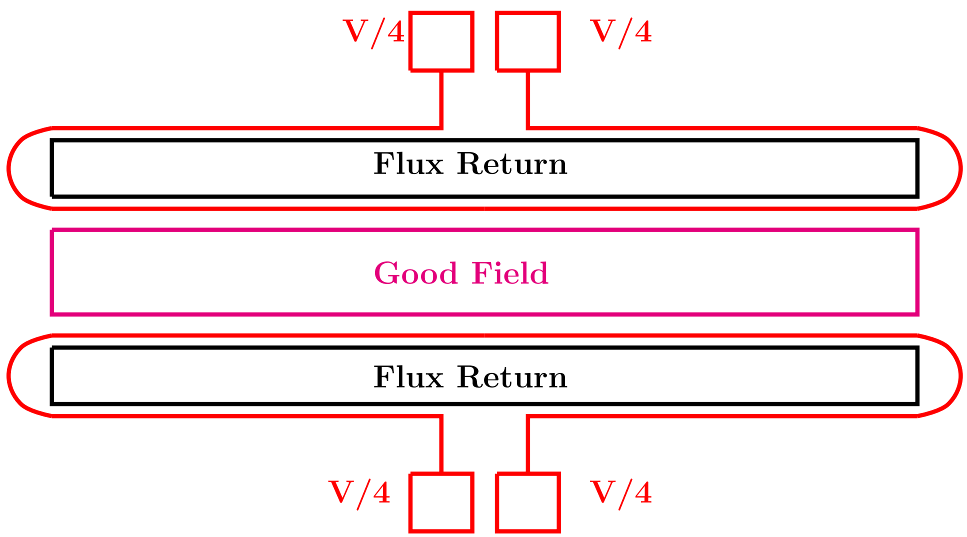
Magnet Power Supply Parameters

$$\text{Ramp Time} \qquad t = \frac{\Delta E\ \tau_\mu}{m_\mu} \frac{ln(0.85)}{ln(20/4)} = 35\ \mu\text{sec}$$

$$\text{Current} \qquad I \approx \frac{B_o\ 2\ A_y}{\mu_o} \left(\frac{1\ +\ \text{Grad(T/m)}}{100} \right) = 51.6 \quad \text{kA}$$

$$\text{Voltage for one 25m magnet} \quad V_{\text{tot}} \approx \frac{d\Phi}{dt} = 2\ \frac{2\ A_x\ L\ B_o}{t} = 99\ \text{kV}$$

V can be reduced to 25 kV if:



Pulsing Circuit

- dc current component
- harmonic (the fourth)

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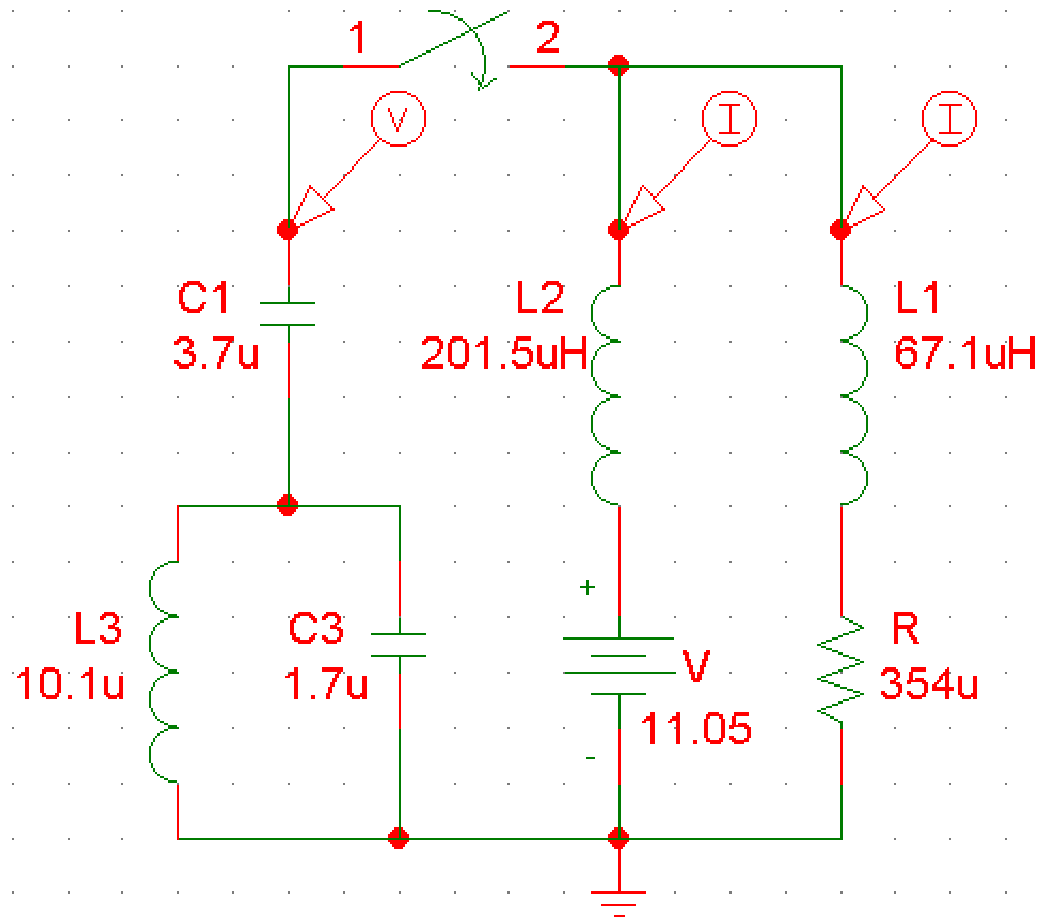

Pulse Waveforms

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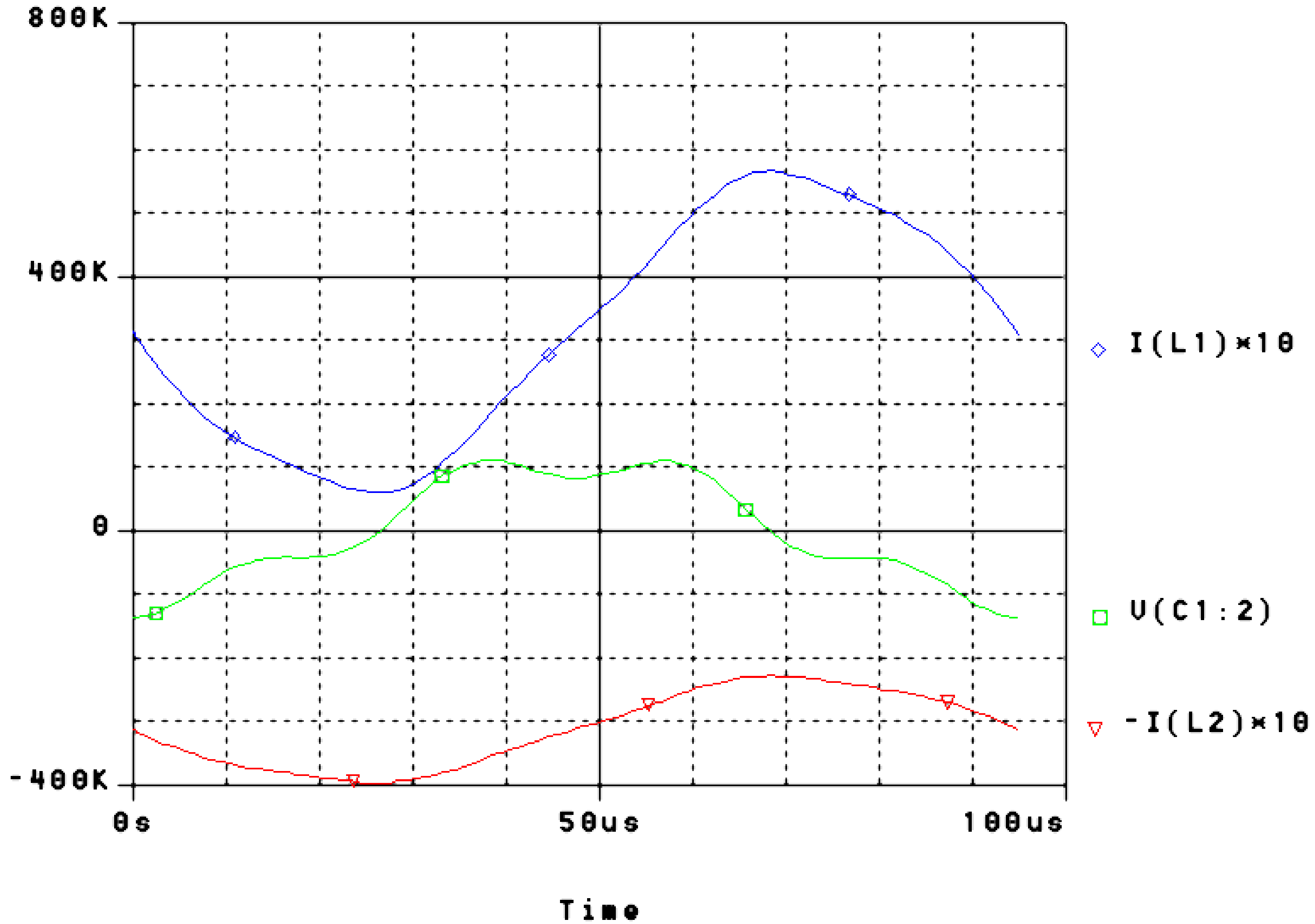


Power Supply Performance

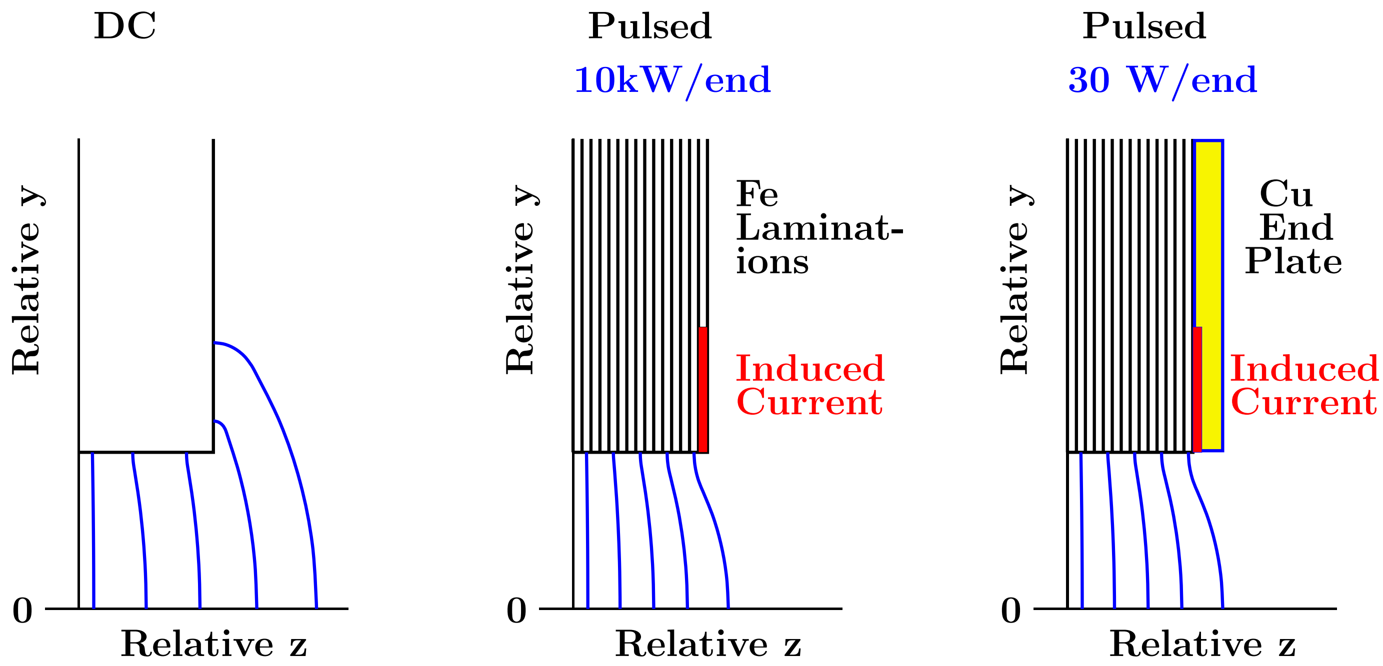
Δ(dB/dt)	+/− 10 %†
B_{DC}	0.6 × $B_{20\ GeV}$
B_{max}	1.05 × $B_{20\ GeV}$
$B_{switched}$	0.45 × $B_{20\ GeV}$
f (kHz)	10.25
$U_{\rm switched}/U_{\rm total}$	1.05 × 0.45 = 27 %

† A further harmonic will reduce this

**** Can be Reduced by Slow Pulsing the 'DC'**

Magnet Losses

At Ends



Perhaps Magnets can be Shorter

Loss Summary

DC Ohmic (with 'pulsed' DC)	**4.8 MW (1.6 MW)†**
Eddy Current in .5 mm (1 mm) wires	**300 kW (1.2 MW)†**
Eddy Current in 100 μm (200 μm) laminations	**180 kW (0.72 MW)†**
Magnet ends with (without) Cu plates	**≈3 kW (≈360 kW)**
Hysteresis Loss	**small**

†Further reduction by 1/2 if not wound on flux returns

More reason to make magnets shorter

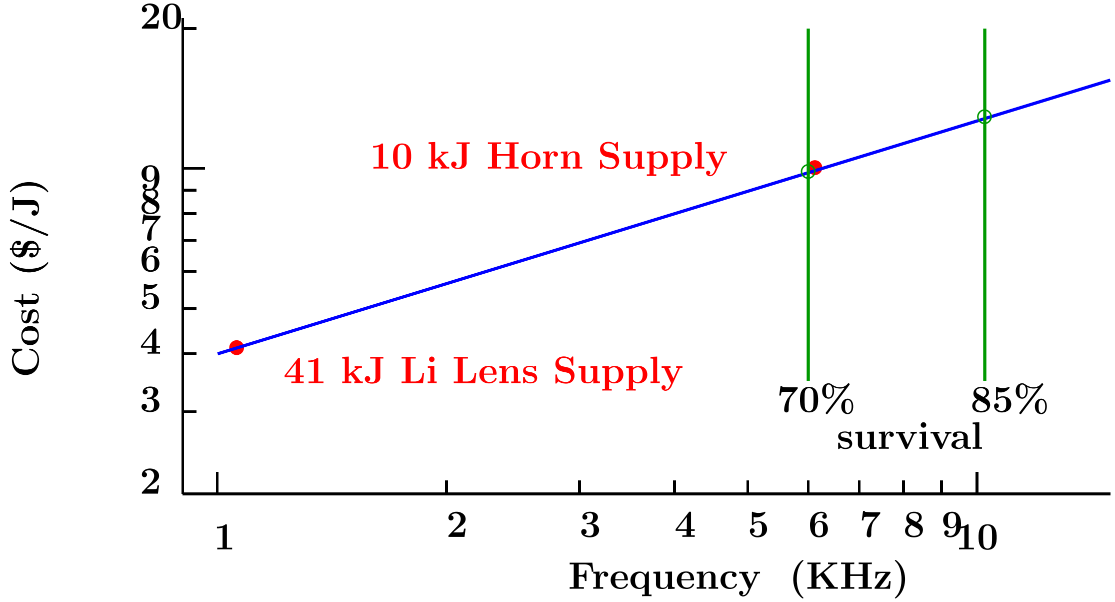
Costs

- SC Linac (from Study 2)
  48 M$/GV of acceleration

- pulsed Magnets from Fermi Booster
  1.93 $/J (for dipoles) 5.45 $/J (for Quads)

- Vac, Diagnostics, Civil (from Study 2)
  18.9 k$/m

- Pulsed Supplies



Cost Summary

Item	Scaling	Fudge	Cost M$
SC Cavities RF Power SC Cryostats	ΔE=1.39 GV ΔE=1.39 GV ΔE=1.39 GV	1.05[1] 1.05[1] 1.05[1] x 1.5[2]	21 29.4 14.2
RF			65
Pulsed Combined Function Quadrupoles	Stored Energy=1.59 MJ Stored Energy=0.12 MJ	2[3] 2[3]	11.8 1.3
Magnets			14.1
Pulsed Supplies Chokes	Switched Energy=0.45 MJ at 10 kHz Stored Energy=1.8 MJ	1 1	6 3
Pulse Curcuit			6.9
Vaccum and Diagnostics Civil	Length of Beam pipe=917 m Length of Tunnel=917 m	1 1	5.3 12
Linear			17.3
Kickers etc			?
Total Study-2			105.3 385

1. Correction for beam loading
2. Correction for more shorter cryostats
3. Correction for higher frequency

4. Correction for higher repetition rate

27% Cost, but Acceptance: Study-2 RLA $\gg$ This Synchrotron

III COST SCALING TO STUDY DEPENDENCIES

For Pulsed Synchrotron

$$\mathrm{Cost(M\$)} \;=\; 48\ \mathrm{V(MV)} \;+\; 9.8\ \mathrm{U(MJ)} \;+\; 4.2\ \mathrm{U(MJ)}\ \sqrt{\frac{\mathrm{f}}{5.1\ \mathrm{kHz}}} \;+\; 18.9\ L(km)$$

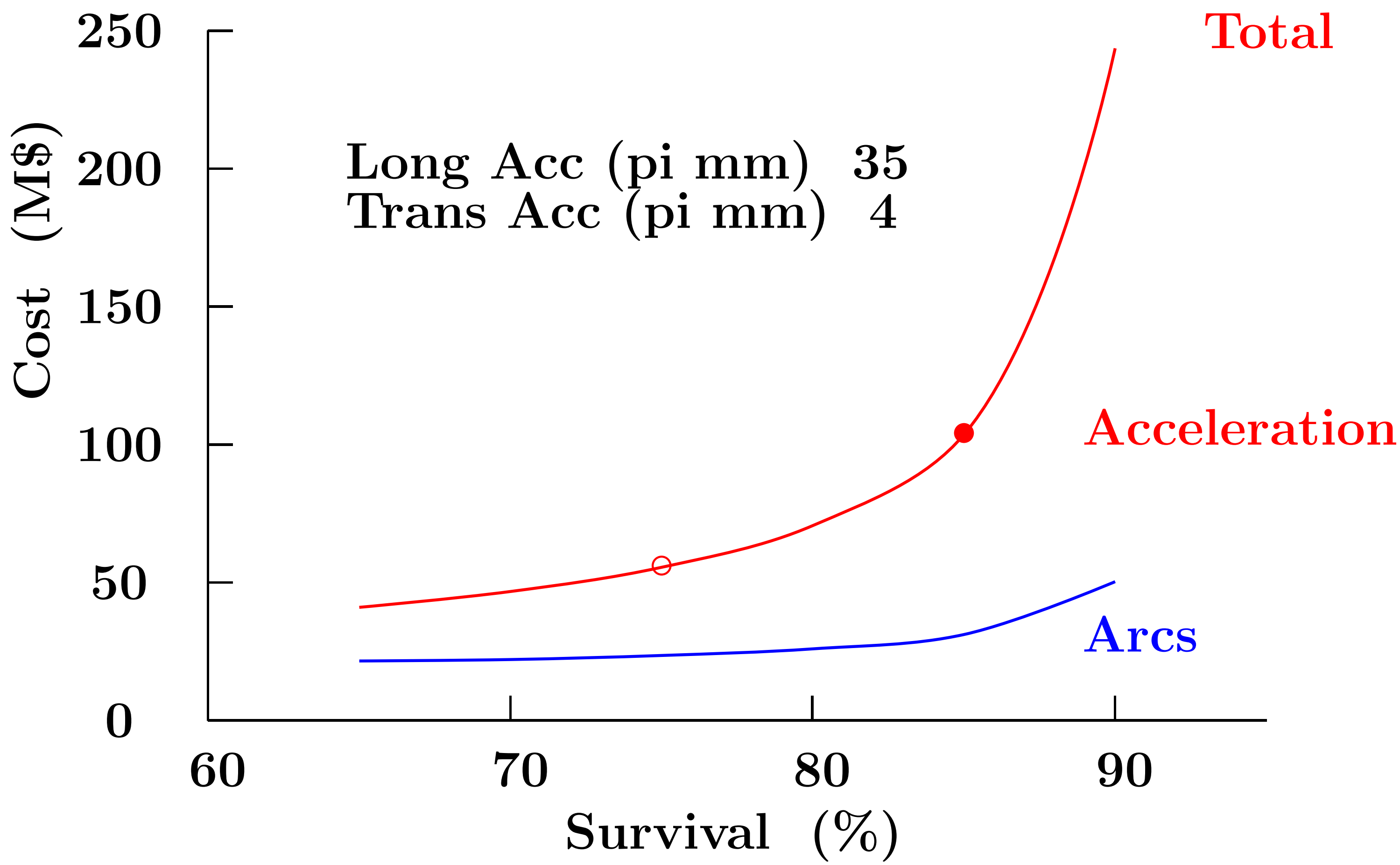
For RLA

$$\mathrm{Cost(M\$)} \;=\; 48\ \mathrm{V(MV)} \;+\; 2.4\ \mathrm{U(MJ)}\ \mathrm{n_{turns}} \;+\; 13\ (L_{\mathrm{straight}} \;+\; L_{\mathrm{arc}})(km) \;+\; 5.8\ (L_{\mathrm{straight}}(km) \;+\; L_{\mathrm{arc}}(km)\ n_{\mathrm{turns}})$$

Warning: scaling the designs may not be realistic but we will do it anyway

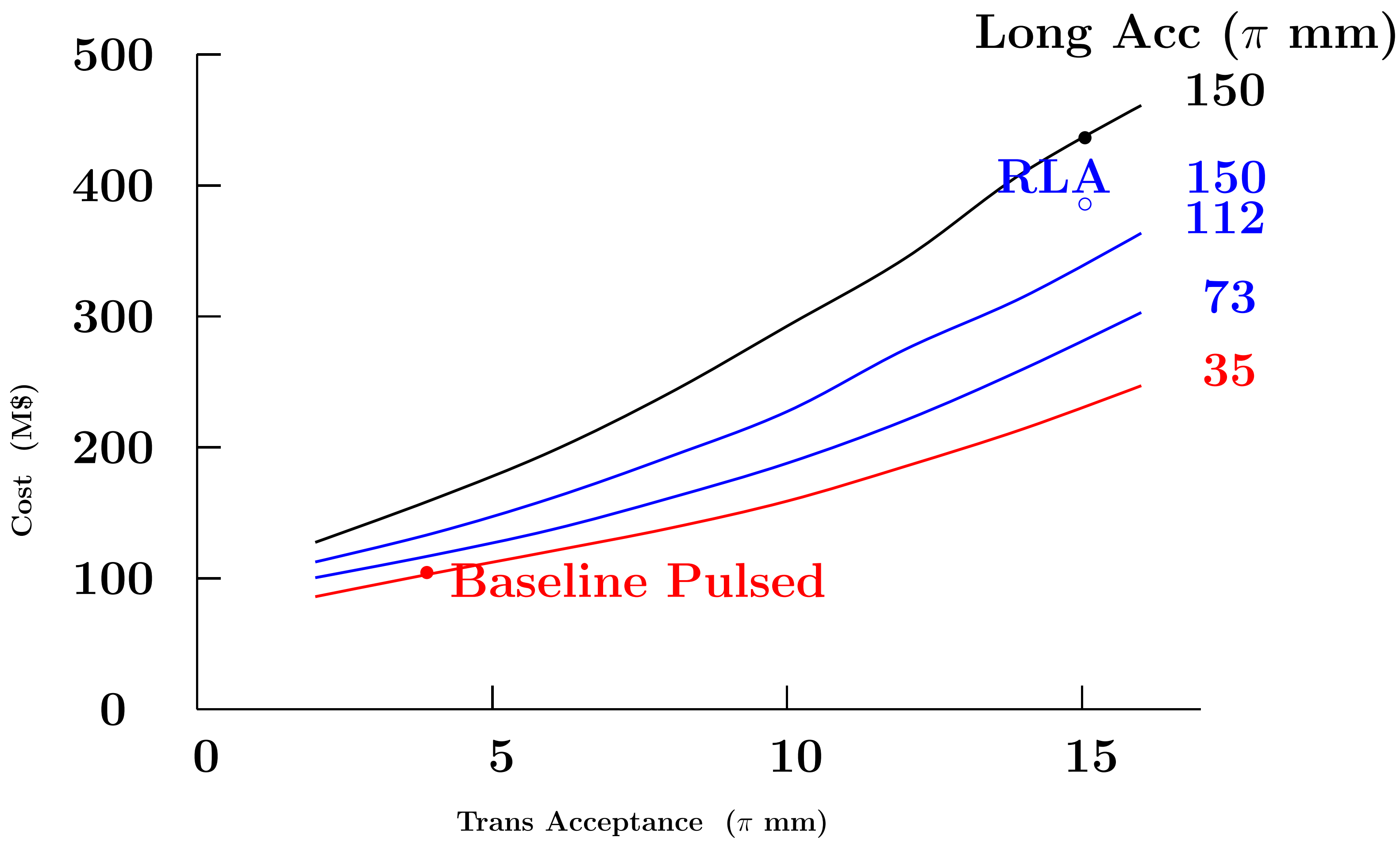
For each case: Vary Field Gradient & Minimize Cost

vs. Allowed Decay Loss



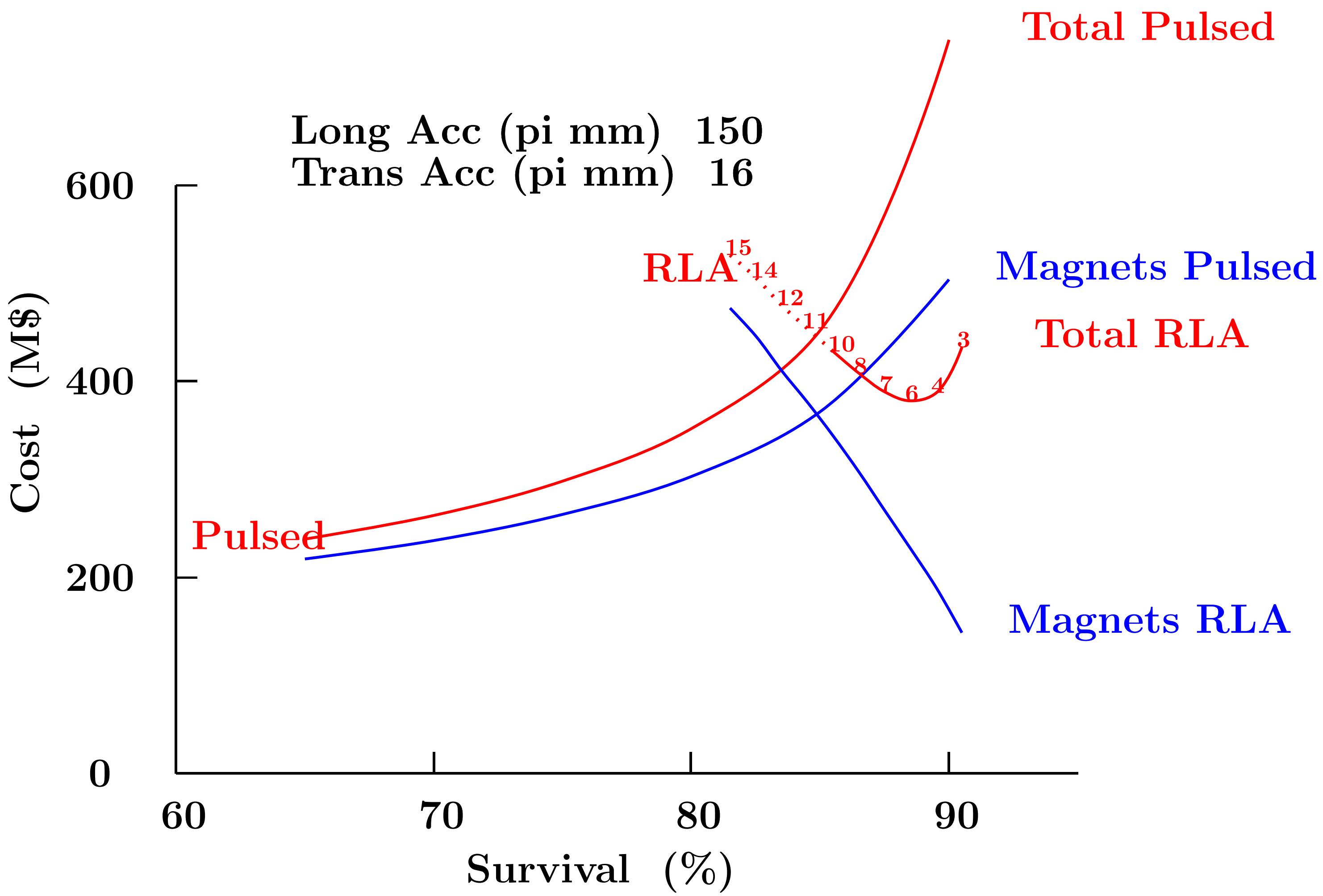
Factor 2 saving if 75% vs 85%

Cost vs. Acceptance



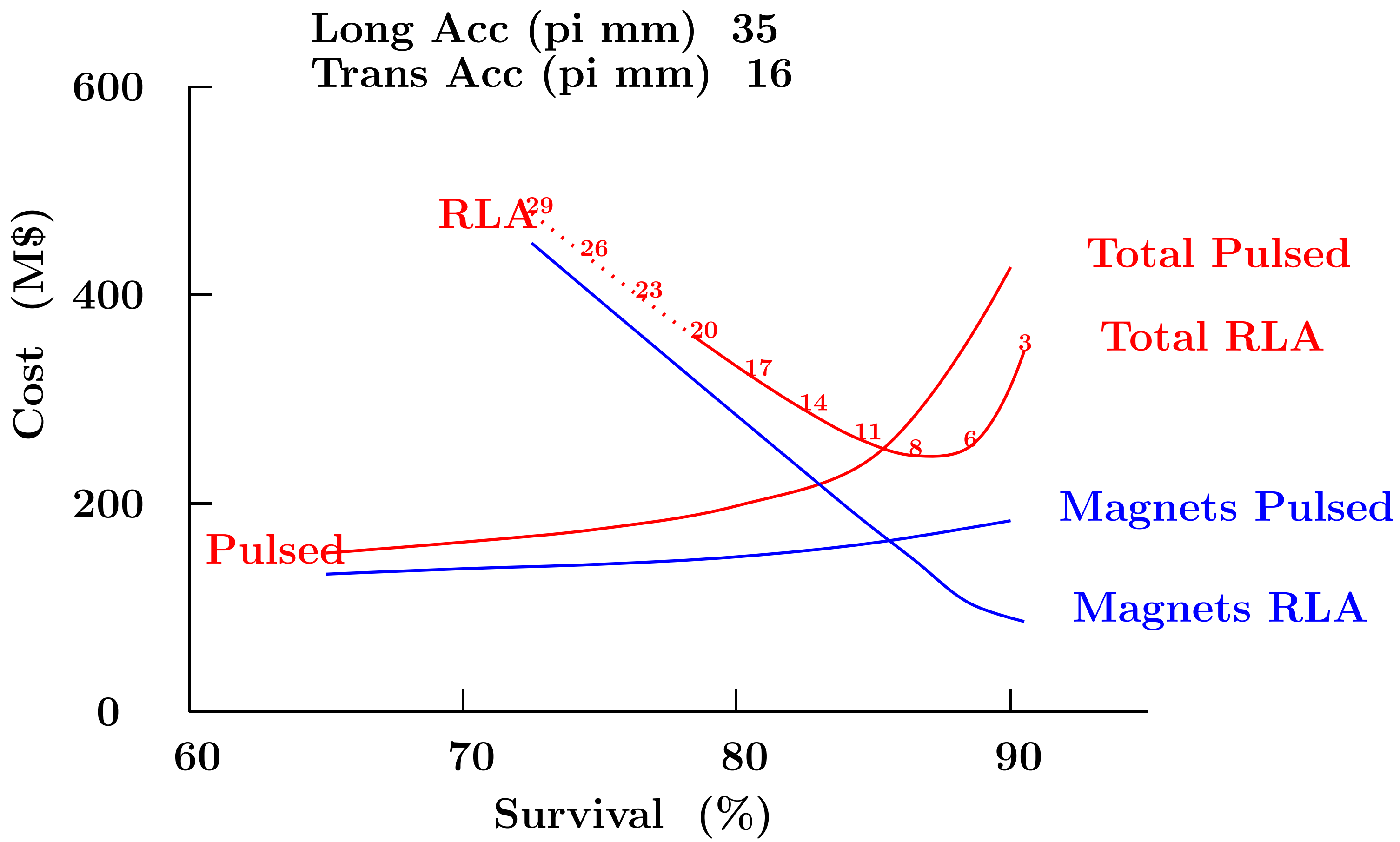
- **For Study-2 acceptance: Pulsed $\approx$ RLA !**

With Study-2 Acceptances



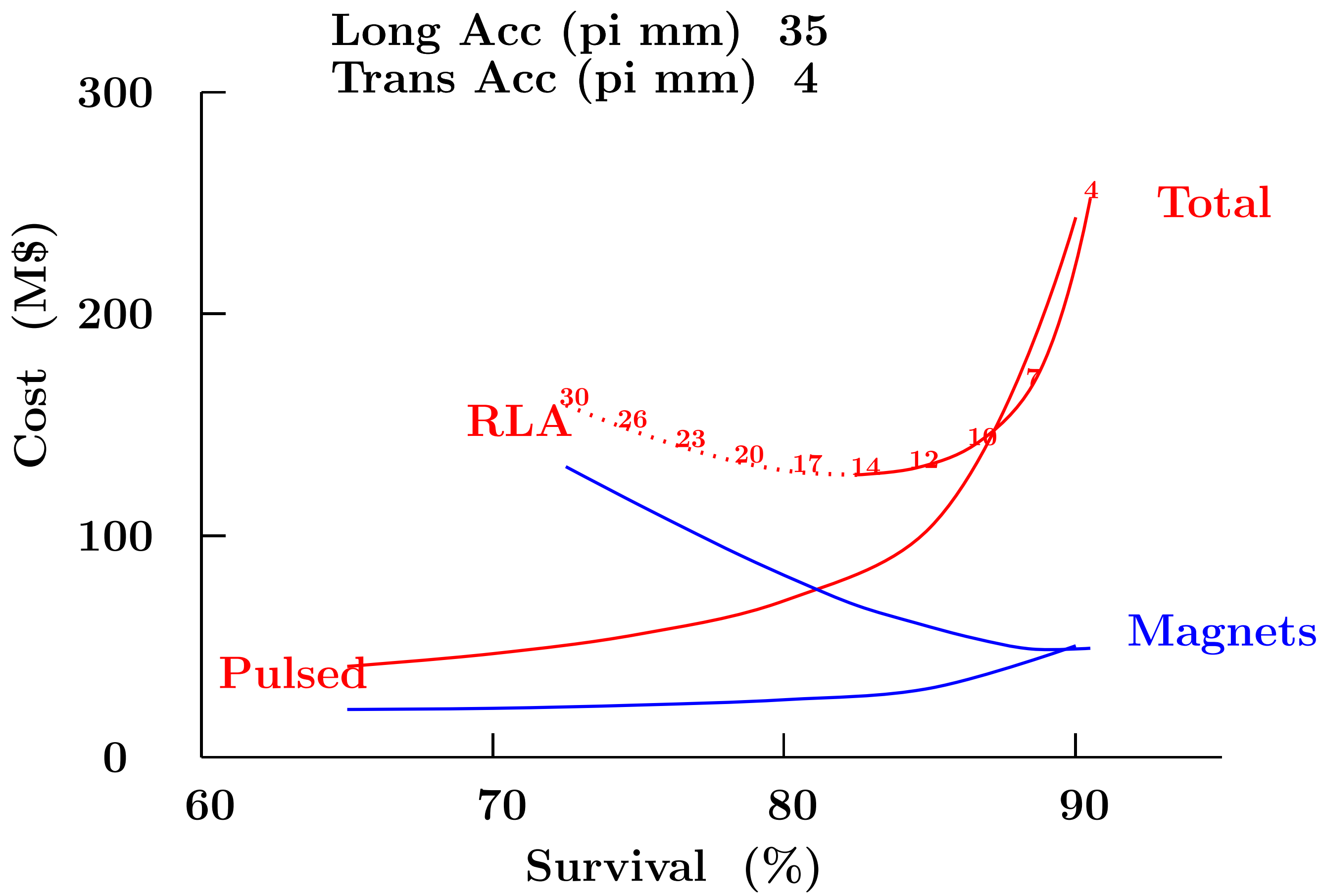
- Pulsed cheaper if Loss <82%
- Cost=80% of RLA for Loss=75%

With Lower Long Acc: (1 Cooling Ring)



- Pulsed Cheaper for Loss <85%
- Cost=71% of RLA for Loss=75%

With Lower Long. & Trans Acc: (2 Cooling Rings)



- Pulsed Cheaper for Loss <87%
- Cost=43% of RLA for Loss=75%

Cost Scaling Summary

	Study-2 Linear Cooling	1 Ring Cooling	2 Ring Cooling
Trans. Acceptance	15	15	4
Long. Acceptance	150	35	35
	π mm	π mm	π mm
		Costs	
	M$	M$	M$
RLA	380	246	129 (229)†
Pulsed: 85 % Survival	450	245	104 (204)†
Pulsed: 75 % Survival	300	176	56 (156)†

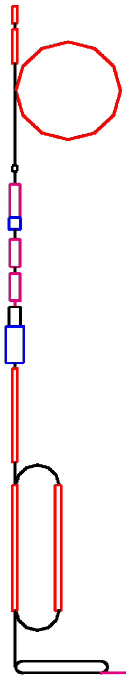
† With 100 M$ added for the Second Cooling Ring

- No correction for Savings in the Storage Ring with low Acceptances, which could be of order 50 M$ (out of 107 M$)

Conclusion

- **The cost of a combined function lattice, for a given acceptance, is minimized by the strongest possible field gradients, despite less bending & larger circumference.**
- **A DC, plus a bipolar pulsed current, appears significantly cheaper than a simple mono-polar magnet pulse.**
- **A preliminary cost estimate suggests that a low acceptance pulsed synchrotron might cost 27% of the Study 2 RLA, (but the acceptances are not the same)**
- **Scaling suggests:**
  - **For the same Study-2 acceptances and decay loss, the RLA and Pulsed costs are comparable.**
  - **With acceptances from one Cooling Ring, and 25% decay: Pulsed cost is 71% of an RLA with the same acceptance, and 46% the study-2 RLA**
  - **With acceptances after 2 Cooling Rings, costs are further reduced, but with the second ring included, total costs appear similar to those with one Ring.**

Conclusion Continued



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Hg Target	(6 %)	
Phase Rotation	(27 %)	Neuffer Scheme cost $\approx 1/3$??
Cooling	(22 %)	Cooling Ring cost$\approx 1/3$??
Pre Acceleration	(12 %)	????
RLA	(23 %)	Pulsed Synchrotron cost$\approx 1/2$??
Storage Ring	(7 %)	????

- Factor of 2 total cost reduction may be attainable,
- But will Savings Survive Engineering ?
- And will Performance be Acceptable ?
- Much work remains