An Induction Kicker for Muon Cooling Rings

and other Applications Needing Very Large Apertures

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Study 2 cooling is 100 m
If Ring is to be cheaper:
Circ $\ll$ 100 m

say 30 m

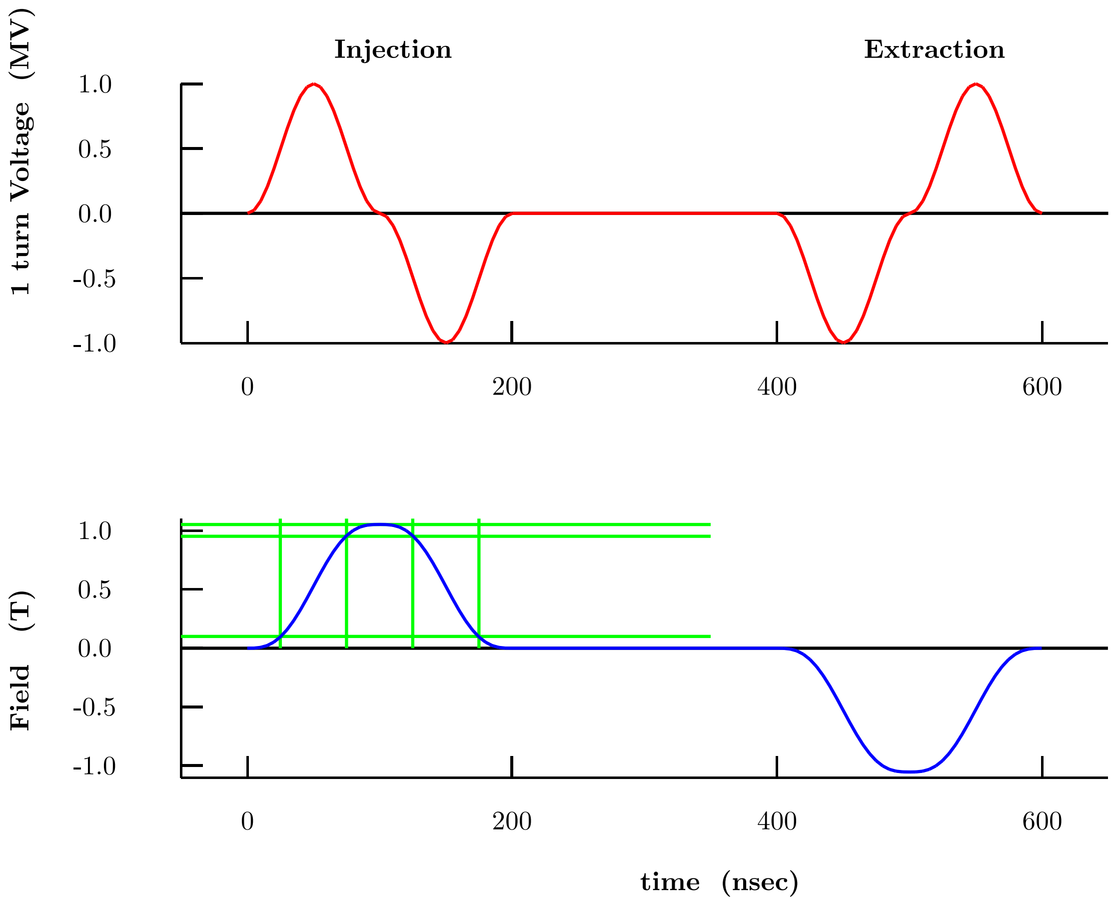
e.g. Balbakov 4 sided ring,
Palmer 11 cell ring

Balbakov 8 cell (60m) more expensive
Palmer 5 cell (16 m circ) req faster kicker
30m is Compromise

Time = 100 nsec

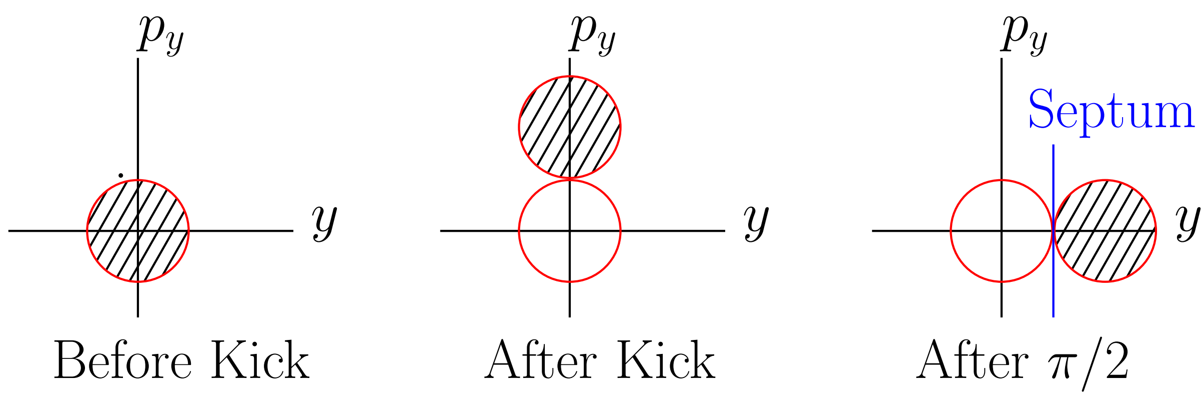
50 nsec for train
50 nsec for kicker rise

Required Volts and Current



- If req. δB $\leq$ +/- 5 %
- circ/2 = rise 10% to 90% = 50 nsec

Minimum Required kick



Defining

For Aperture:

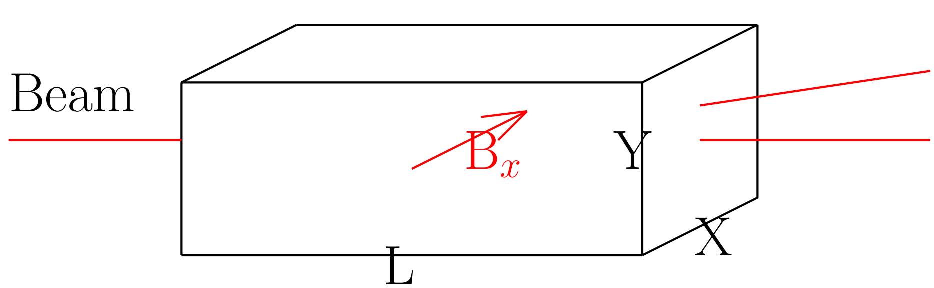
$$f_\sigma = \frac{\text{Ap}}{\sigma}$$

For leakage flux:

$$\Phi \;=\; f_\Phi \; B_x \; L \; Y$$

For finite μ's:

$$\int B dl/\mu \;=\; f_\mu \; B \; X$$



Formulae

$$\Delta p_y \;=\; B_x\; L\; c \;=\; m_\mu\; 2\; f_\sigma\; \sqrt{\frac{\epsilon_n\; \beta\gamma}{\beta_y}}$$

$$X \;=\; 2\; f_\sigma\; \sqrt{\frac{\epsilon_n\; \beta_x}{\beta\gamma}}$$

$$R \;=\; \frac{Y}{X} \;\approx\; \left(1 \;+\; \frac{L}{2\; \beta_y}\right)$$

$$I \;=\; \frac{f_\mu\; B\; X}{\mu_o} \;=\; \frac{f_\mu\; 4\; f_\sigma^2\; m_\mu}{\mu_o\; c}\quad \frac{\epsilon_n}{L}$$

$$V \;=\; \frac{f_\Phi\; B\; Y\; L}{t_{\rm rise}} \;=\; \frac{f_\Phi\; 4\; f_\sigma^2\; m_\mu\; R}{c}\quad \frac{\epsilon_n}{\tau}$$

$$J \;=\; f_\mu\, f_\Phi\; \frac{B^2\; L\; X\; Y}{2\; \mu_o} \;=\; f_\mu\, f_\Phi\; \frac{m_\mu^2\; 8\; f_\sigma^4\; R}{\mu_o\; c^2}\quad \frac{\epsilon_n^2}{L}$$

Note

- V independent of E, $\beta_\perp$
- V & I $\propto \epsilon_n$
- J $\propto \epsilon_n^2$

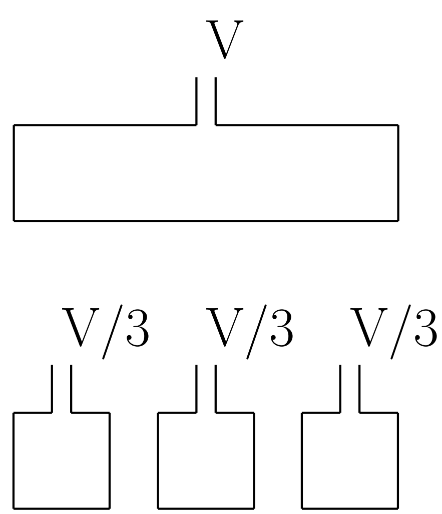
- muon $\epsilon_n \gg$ other ϵ_n's
- So muon kicker Joules $\gg$ other kickers
- Nearest are $\bar{p}$ kickers

		μ Cooling	CERN $\bar{p}$	Ind Linac
f_Φ		1.05		
f_μ .		1.05		
f_σ		3		
m_μ	V	1.05 10^8		
c	m/s	3 10^8		
ϵ_n	π mm	10		
β_x	m	1.0		
$\int Bd\ell$	Tm	.30	.088	
L	m	1.0	$\approx$5	5.0
t_{rise}	ns	**50**	**90**	**40**
t_{pulse}	ns	**100**	**500**	**100**
$\beta\gamma$		2		
B	T	**.30**	**$\approx$0.018**	**0.6**
X	m	.42	.08	
Y	m	.63	.25	
I	kA	105		
V_{1turn}	kV	**3,970**	**800**	**5,000**
U_{magnetic}	J	**10,450**	**$\approx$13**	**8000**
n_{parallel}		20	10	32
n_{units}		12	10	10
$I_{\mathrm{p.s.}}$	kA	192		73
$V_{\mathrm{p.s.}}$	kV	182	80	190
$U_{\mathrm{p.s.}}$	kJ	870		800

Note

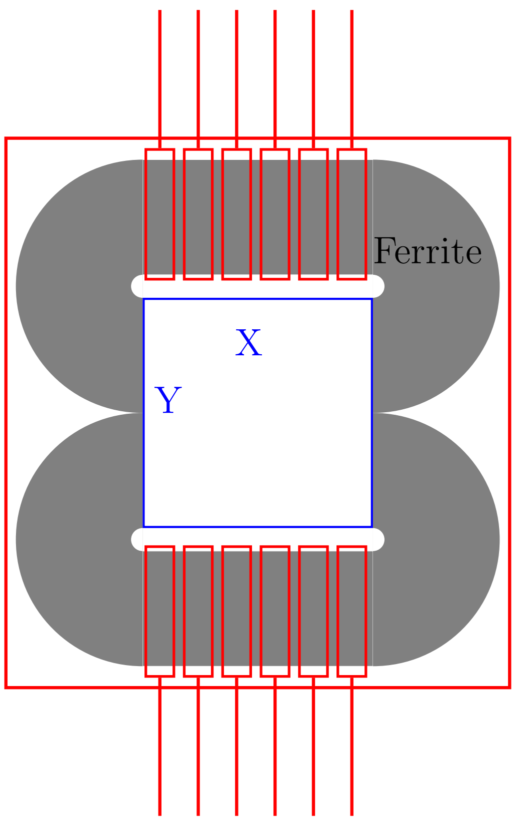
- J is 3 orders above $\bar{p}$
- But same order as 5 m Induction
- And t same order as Induction
- But V is too High

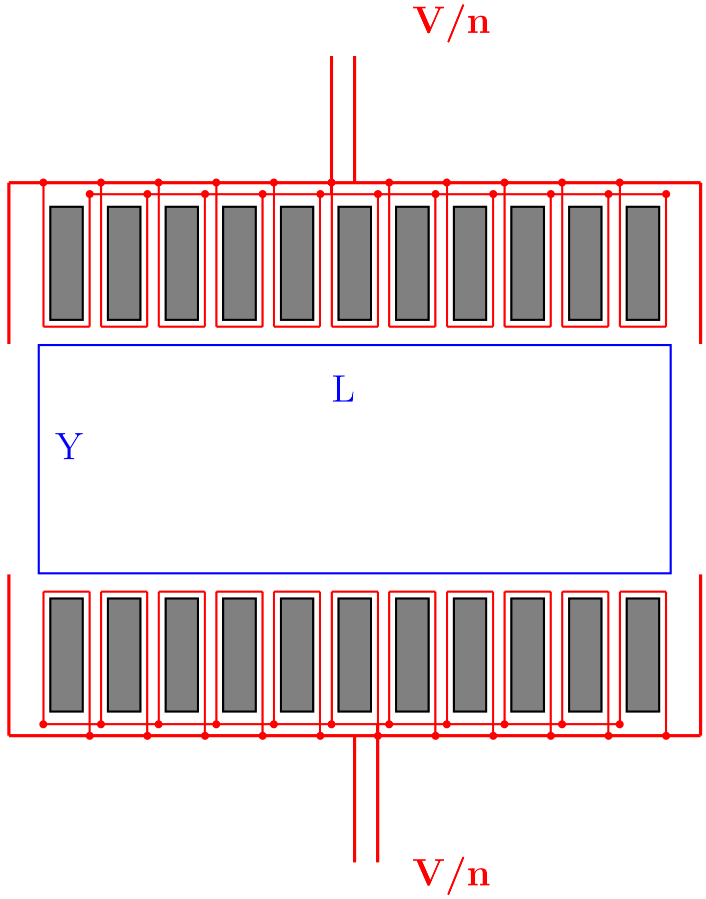
- Because L/X only ≈ 3
  Conventional subdivision only /3



New Idea

- Drive Flux Return
- Subdivide Flux Return
- Conducting Box Removes Stray Field Return





End View

Side View

- Divide yoke by (2 × 11)
- connect 11 loops in parallel
- V / loop = 3970/22 = **182 kV**
- I / side = 105 × 11 =**1155 kA**

- 6 Drivers per yoke, then:

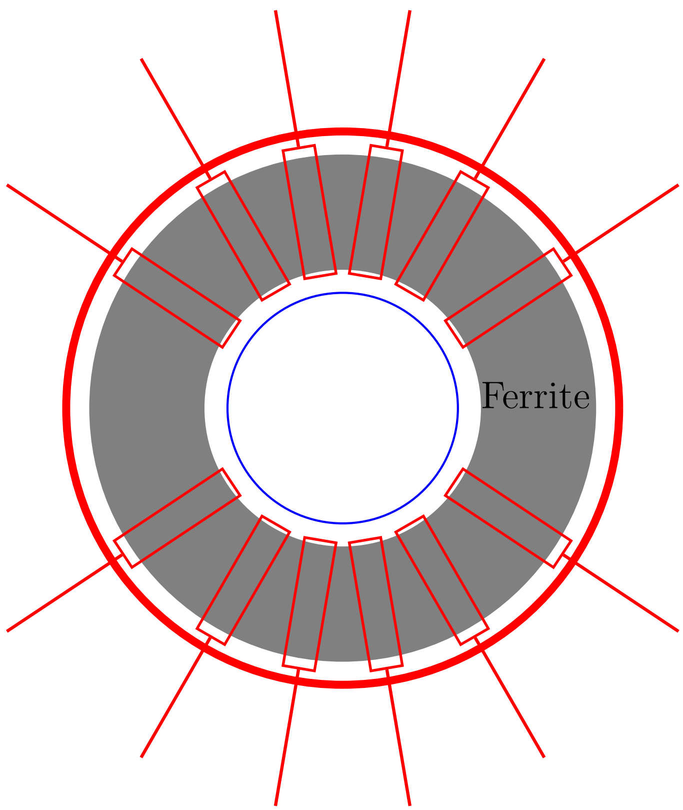
- number of drivers = 2 × 6 =**12**
- I / driver = 1155/6 = **192 kA**
- U / driver = 1045/12 = **870 J**

- U / driver ≈ U / Induction driver
- V / driver ≈ V / Induction driver
- I is higher from inductive load

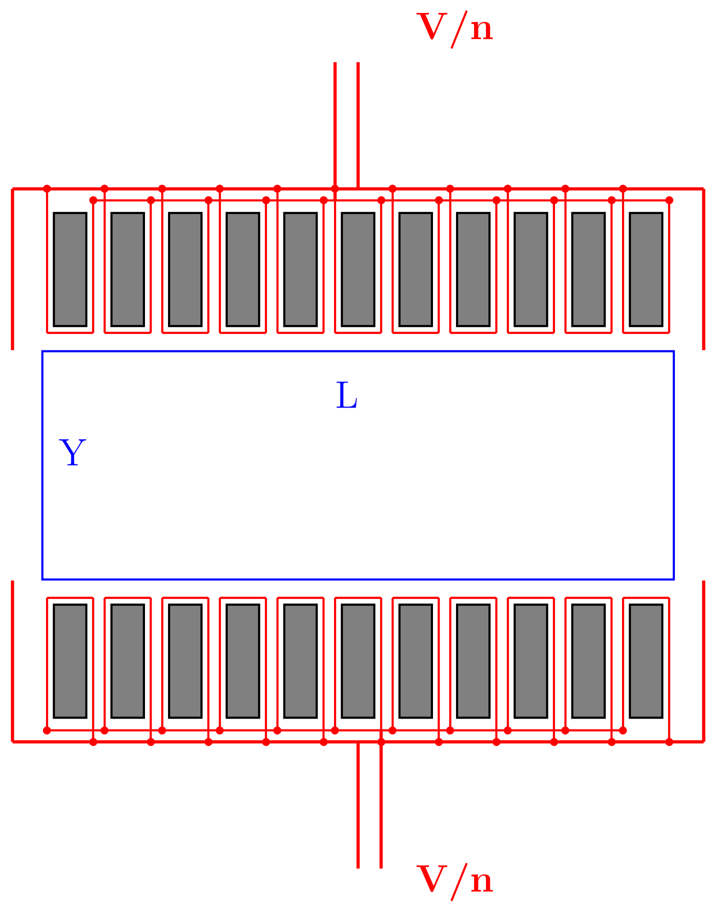
If the load must be made resitive, then the total energy would be 4 times higher (V × I × t_{pulse} vs. V × I × t_{rise} /2).

Cos Theta Version

- J≈ × $\pi/4$
- V's not the same for different phi's



End View



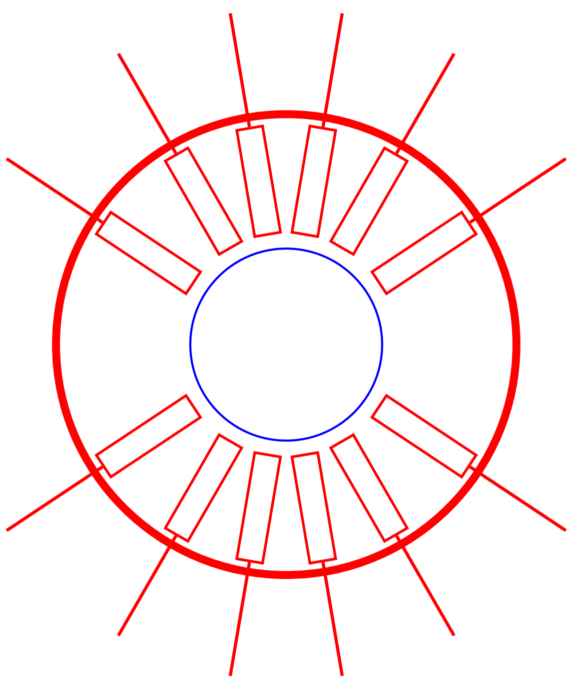
Side View

Works with no Ferrite

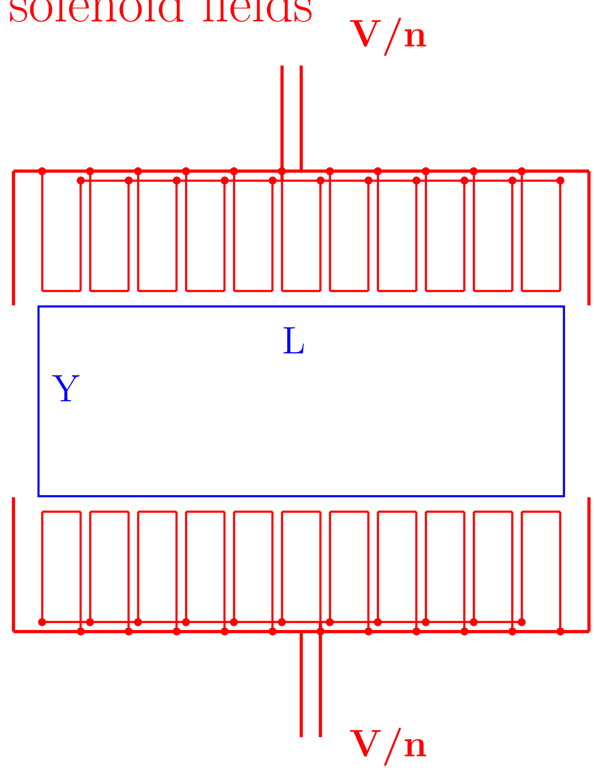
- V = the same
- J≈ 2×
- I≈ 2×

But

- No rise time limit
- Not effected by solenoid fields

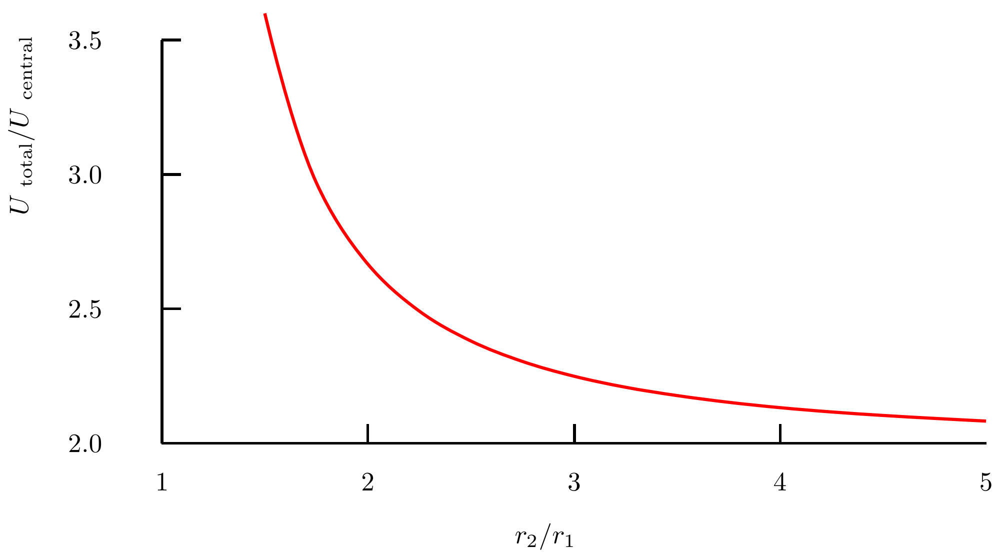


End View



Side View

Stored Energy vs. rad 2



e.g.

$r_2/r_1 = 3$:

U(no Fe) = 2.25 × U(Fe)

”Resonant” Mag Amp Driver

Assume:

- A single compression stage;
- Negligible cable distance from driver to kicker;
- A sudden saturation at I_s from an initial large inductance L_1 to a small inductance L_2;
- A purely inductive kicker magnet with inductance L;
- Start the clock at t=0 with the drive capacitor C charged to V_o and no current flowing.

Initially: long time constant τ_L

$$\tau_L = \sqrt{(L + L_1)C}$$

$$V_{\text{Capacitor}} = V_o \cos\left(\frac{t}{\tau_L}\right)$$

$$V_{\text{Kicker}} = V_1 \left(\frac{L}{L + L_1}\right)$$

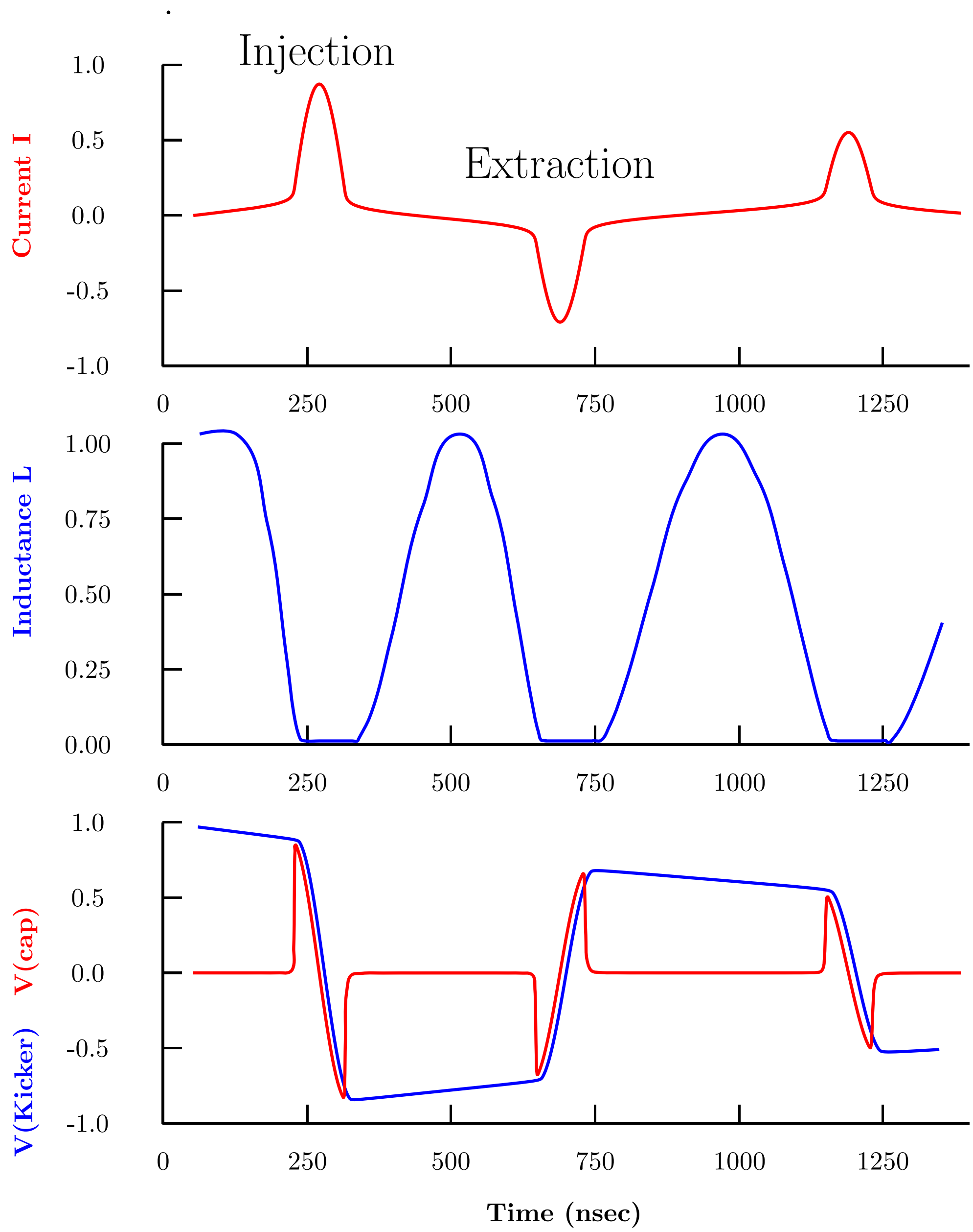
$$I = I_o \sin\left(\frac{t}{\tau_L}\right)$$

When current = saturation current: Short time constant

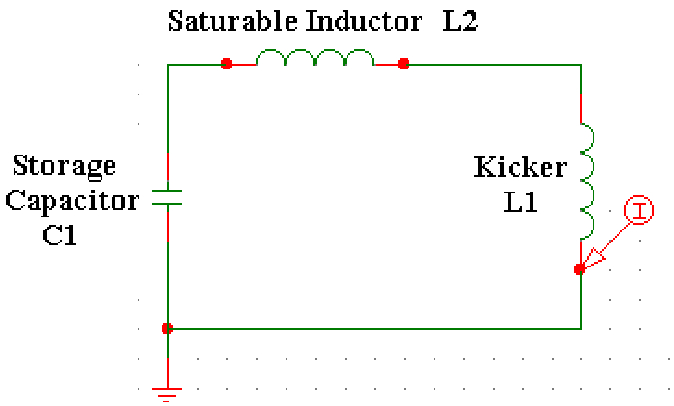
$$\tau_S = \sqrt{(L + L_2)C}$$

If $\tau_L \approx 100 \times \tau_S$,

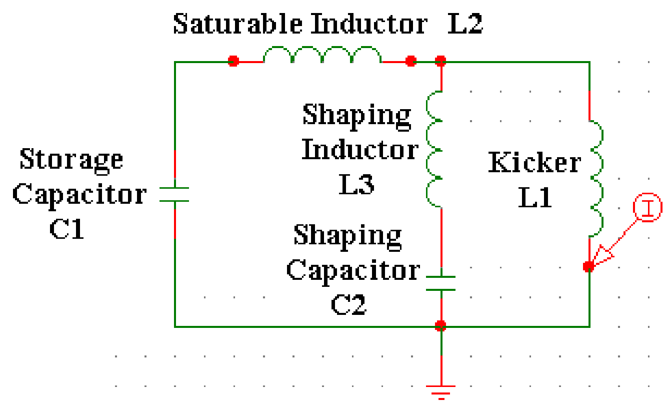
Optimistic ?



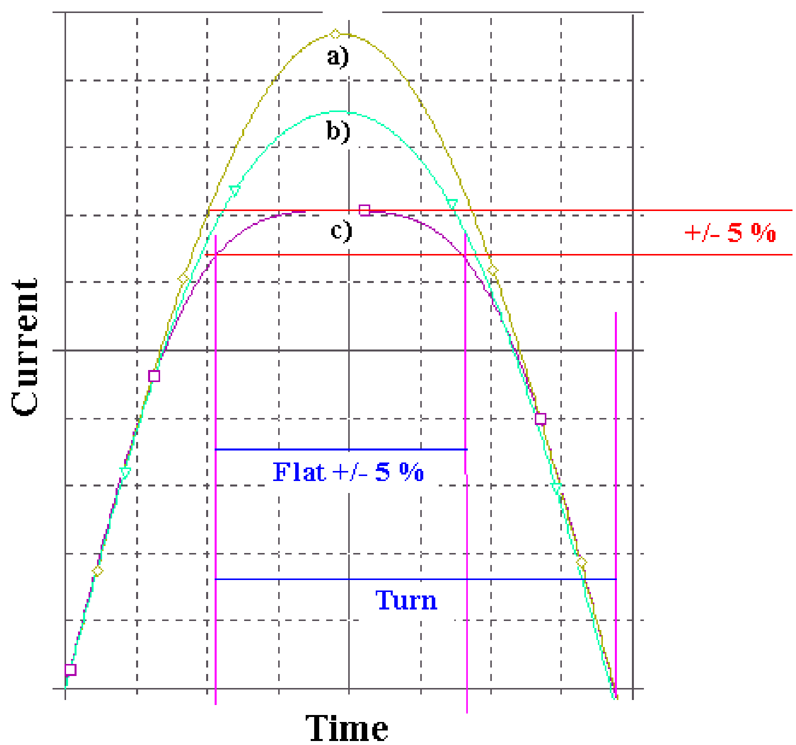
Increased Flat Top



Circuit a)



Circuits b) and c)



case	C1	L1	L2	C2	L3	V/Va	U/Ua	flat/turn
a)	142	100	7			1.0	1.0	0.46
b)	120	100	7	20	90	0.88	1.29	0.52
c)	100	100	7	40	53	0.73	1.89	0.57

Circuit Model

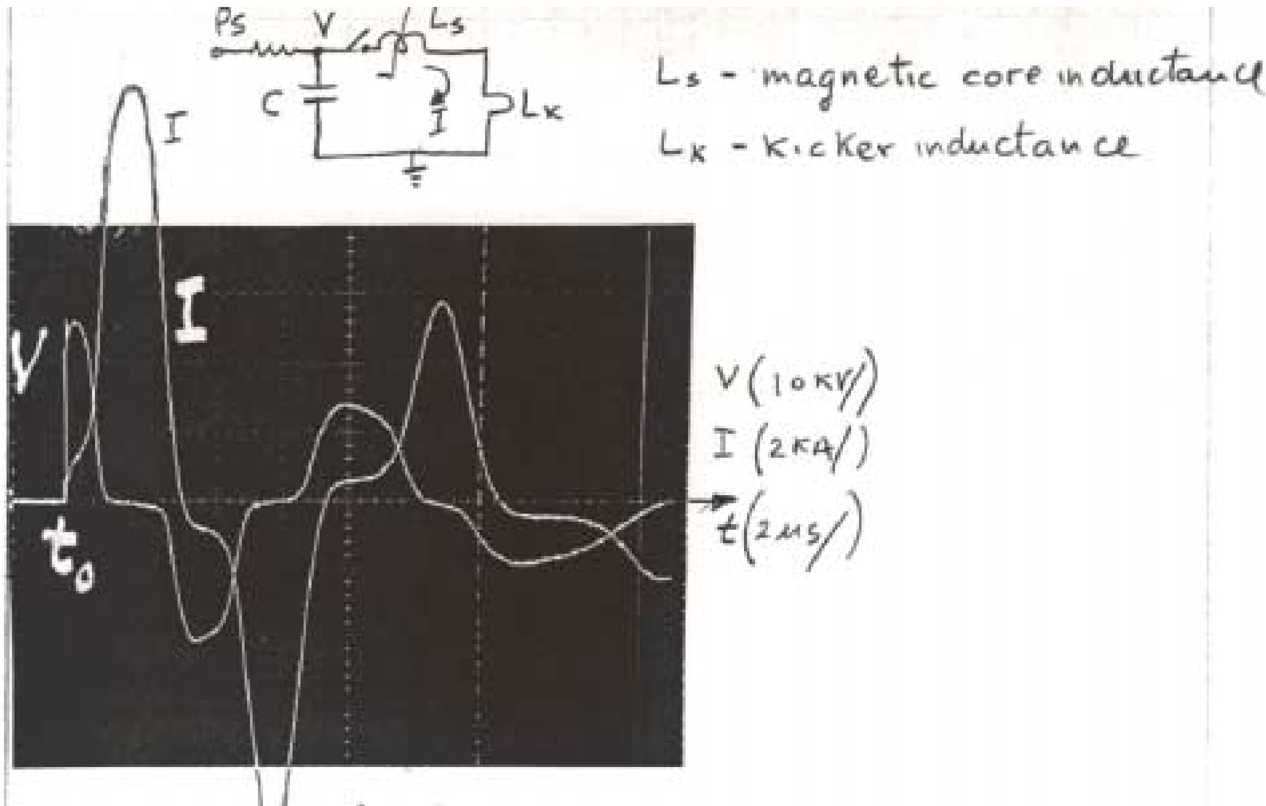


fig. 1

- May be hard for many turns
- Not simulated with initial stages

Conclusion

This study suggests that even the first cooling ring injection and extraction problems may be soluble.

But much work remains.

The proposed kicker could also have application in FFAG acceleration of large emittance beams for neutrino factories.