Study IIa FFAG Injection/Extraction

Scott Berg, Rick Fernow, Bob Palmer

Version 4 for TRIUMF
4/16/2004

- Introduction
- ICOOL Simulations
- Septum and Kicker specifications
- Conclusion

Introduction

Lattice parameters taken from Scott's Friday 27 Feb talk

$E_{\min}$ (GeV)	5		10	
$E_{\max}$ (GeV)	10		20	
$V/\omega\Delta T\Delta E$	1/8		1/12	
$A_{\perp n}$ (mm)	30			
L_0 (m)	2			
L_Q (m)	0.5			
V per cell (MV)	7.5			
Empty cells	8			
ν_x, ν_y at $E_{\min}$	0.35			
n	90		105	
C (m)	606.918		767.953	
V total (MV)	675.0		787.5	
	QD	QF	QD	QF
L (m)	1.612338	1.065600	1.762347	1.275747
ρ (m)	15.2740	-59.6174	18.4002	-70.9958
x_0 (mm)	-1.573	7.667	1.148	8.745
r (cm)	14.0916	15.2628	10.3756	12.6256
B_0 (T)	1.63774	-0.41959	2.71917	-0.70474
B_1 (T/m)	-9.1883	8.1768	-15.4948	12.5874

$$\frac{1}{\zeta} = \frac{V}{\omega\ \Delta t\ \Delta E} = \textbf{8 and 12 for 5-10 and 10-20 respectively}$$

Procedure

- Determine beam maximum size vs. length at injection and final energies
- Place Kicker in 2 m straight
- Place Septum in following 2 m straight
- Use 2 hole magnet after septum
- Maintain same betatron motion in injection channel, but different bending
- Matching to next ring not yet studied
- Inject from
  - Outside the ring (natural but requires greater kick because initial beam is stored on the inside), or
  - Inside the ring (unnatural but uses smaller kick)

Use of ICOOL

1. Find closed orbit and betas

   - Generate a few (10-20) initial particles covering the range of energies, each with a small angular amplitude in x or y, and initial x position corresponding to an assumed quadratic dispersion
   - Track, using a hard edged approximation, these particles through 100 or more cells, outputting their positions at the end of each cell
   - Plot, for each particle, their angles and positions thus forming phase ellipses
   - Obtain beta functions from the shape of the ellipses
   - Use ellipse centers to define the closed orbit position for each momentum
   - Fit closed orbit positions vs. momentum to a quadratic
   - Iterate

2. Find beam envelopes of circulating beams

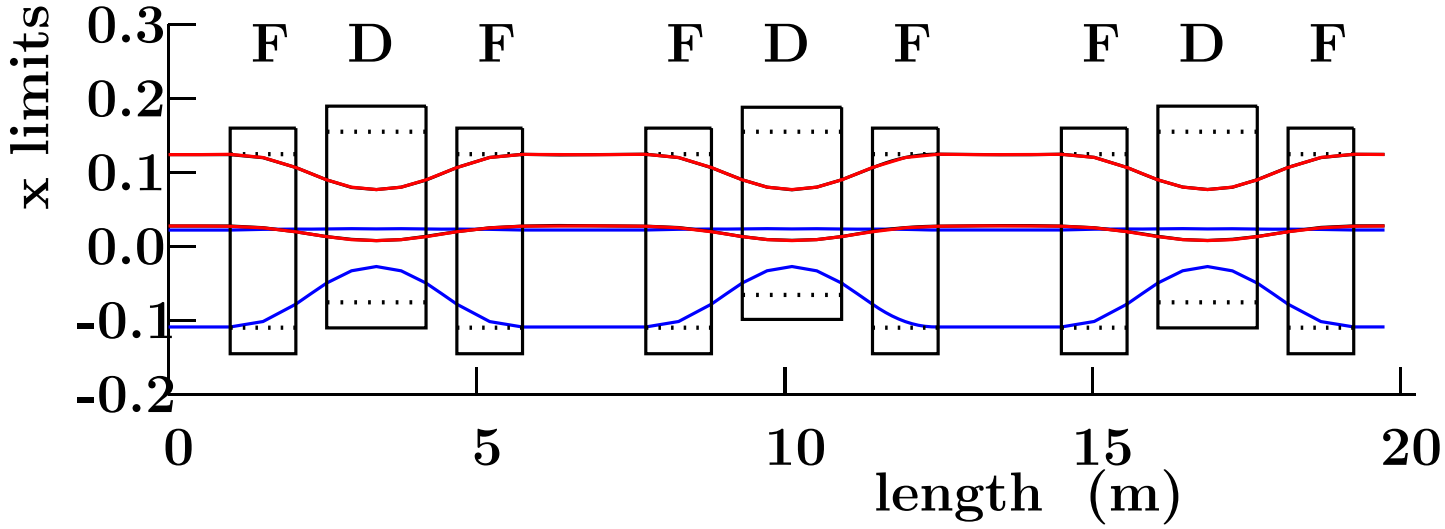
   - Generate, at each initial momentum, tracks (20) distributed uniformly round a phase ellipse in x (or y) with beta and center as determined above, and amplitude corresponding to the acceptance of 30 pi mm
   - Track these particles through a few cells, outputting data every few cm
   - Observe maximum and minimum extents in x (or y)

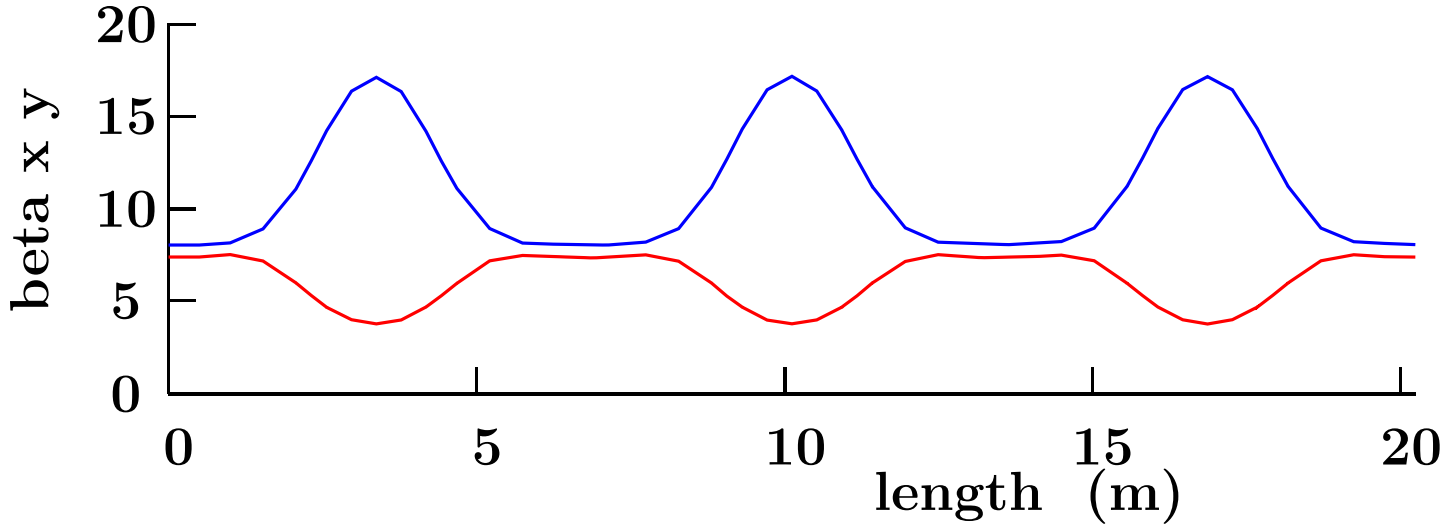
3. Find beam envelopes of injected beam

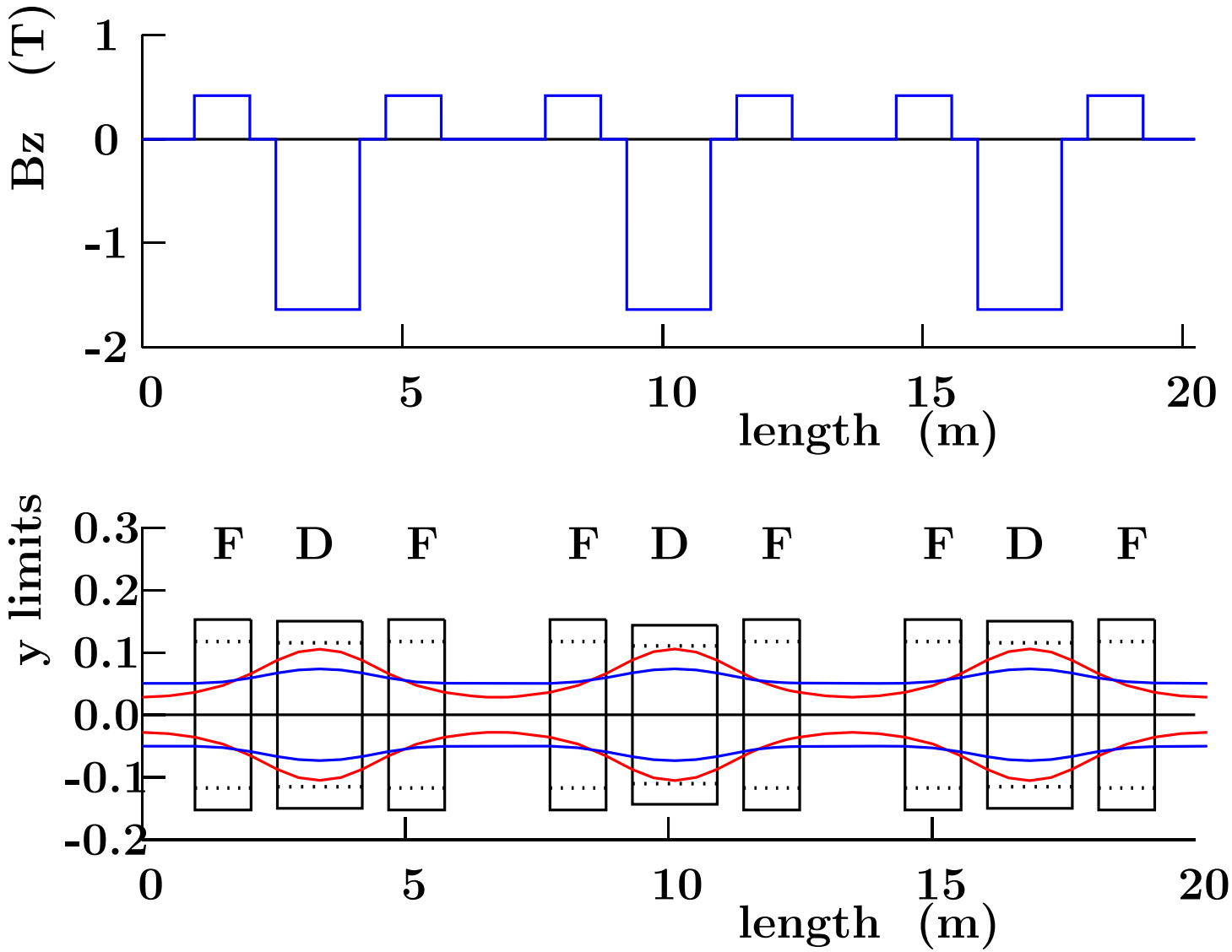
   - Generate, at the injection momentum, tracks (20) distributed uniformly round a phase ellipse in x (or y) with beta and center as determined above, and amplitude corresponding to the acceptance of 30 pi mm
   - Introduce distributed error kicks (RKICK DIP) representing the kicker and septum magnets. By using RKICK, the coordinated remain relative to the circulating beam. If dipole magnets were introduced instead of RKICKs, the coordinates would have been relative to the injected beam.
   - Track these particles through the cells, outputting data every few cm
   - Observe maximum and minimum extents in x, and compare with the circulating beam bounds as obtained above.

Beams in Ring

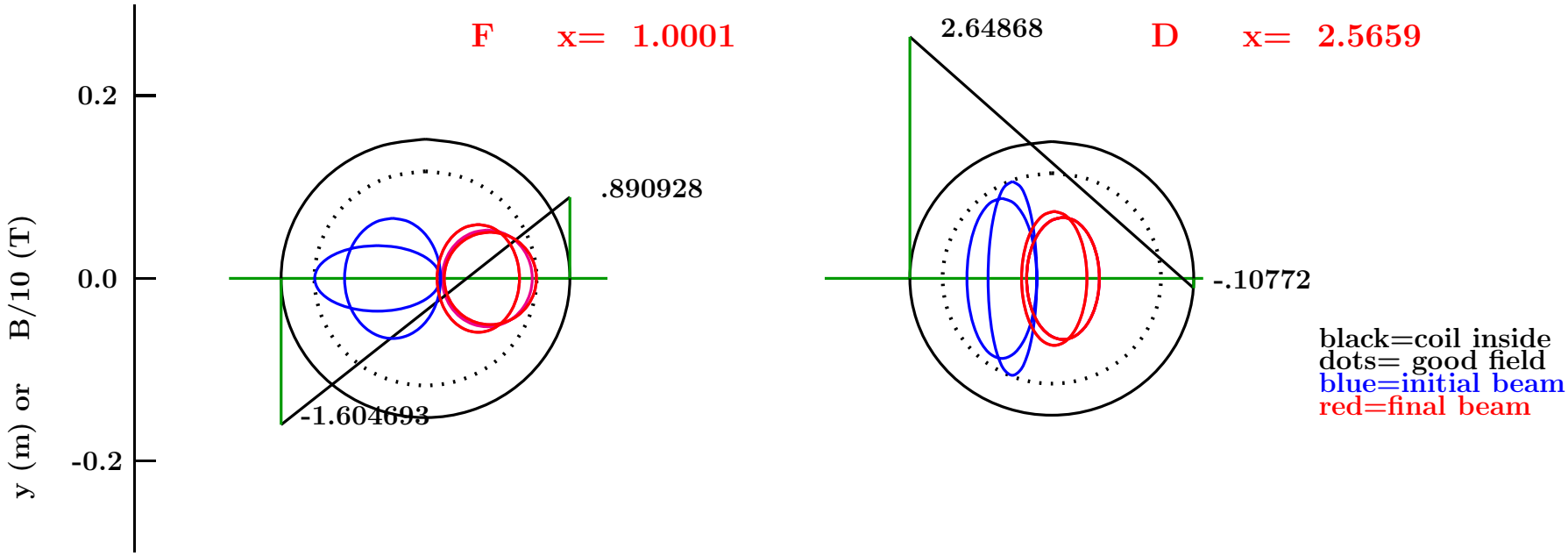
Study IIa 5-10 ffag (s1e0)






Bz (T)
1
0
-1
-2
0
5
10
15
20
length (m)
y limits
0.3
0.2
0.1
0.0
-0.1
-0.2
F D F F D F F D F
0
5
10
15
20
length (m)

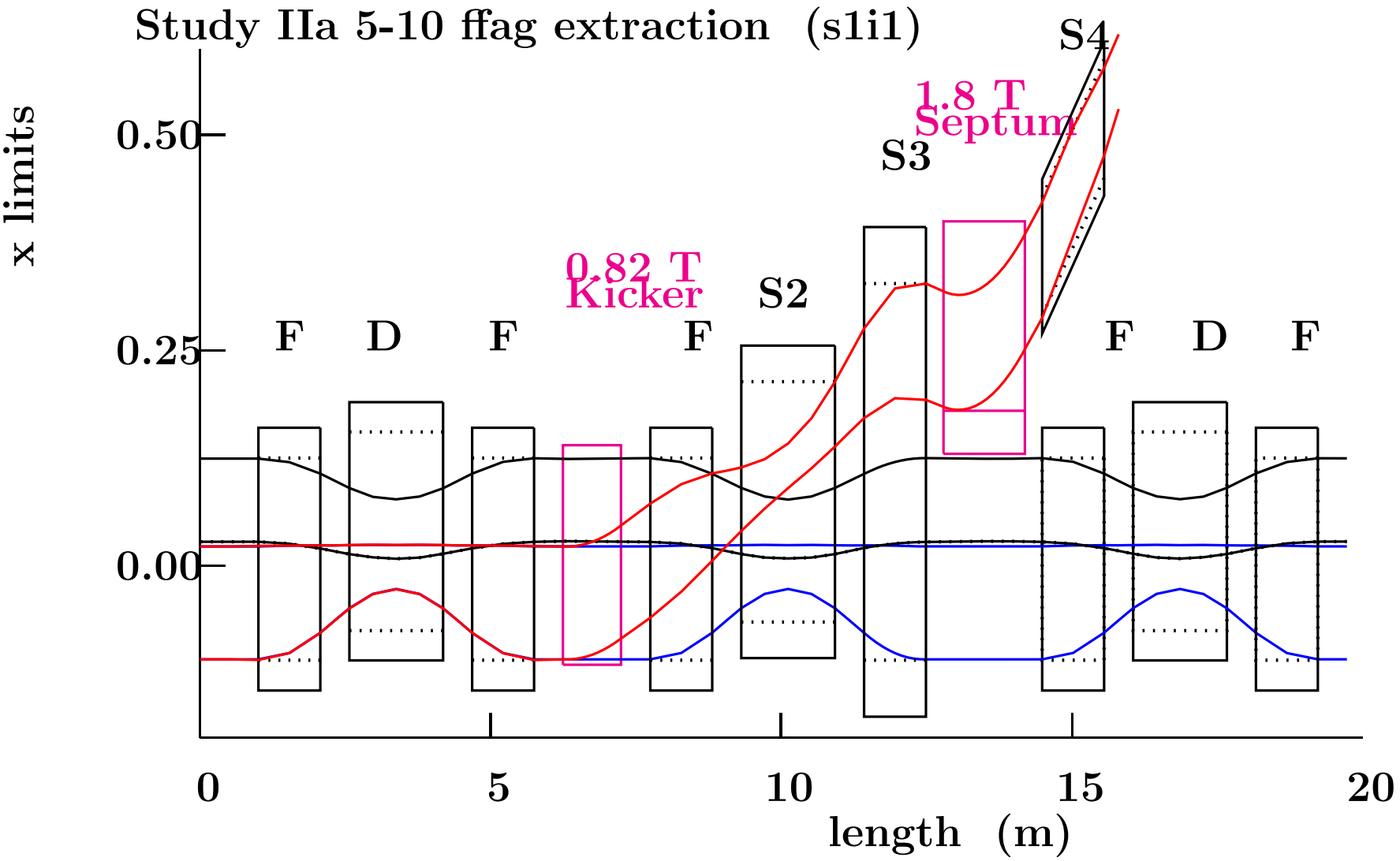
Magnet sections

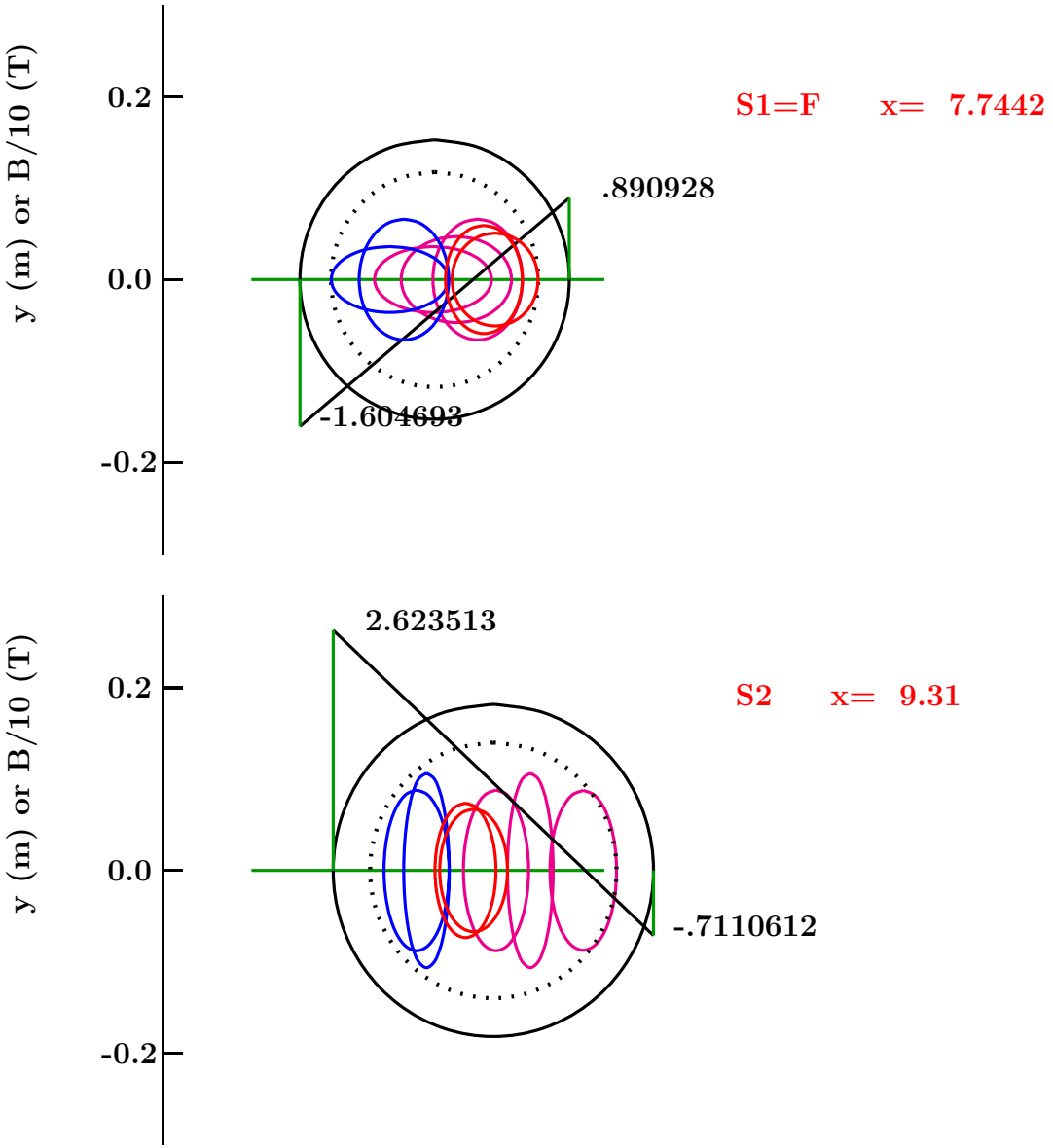


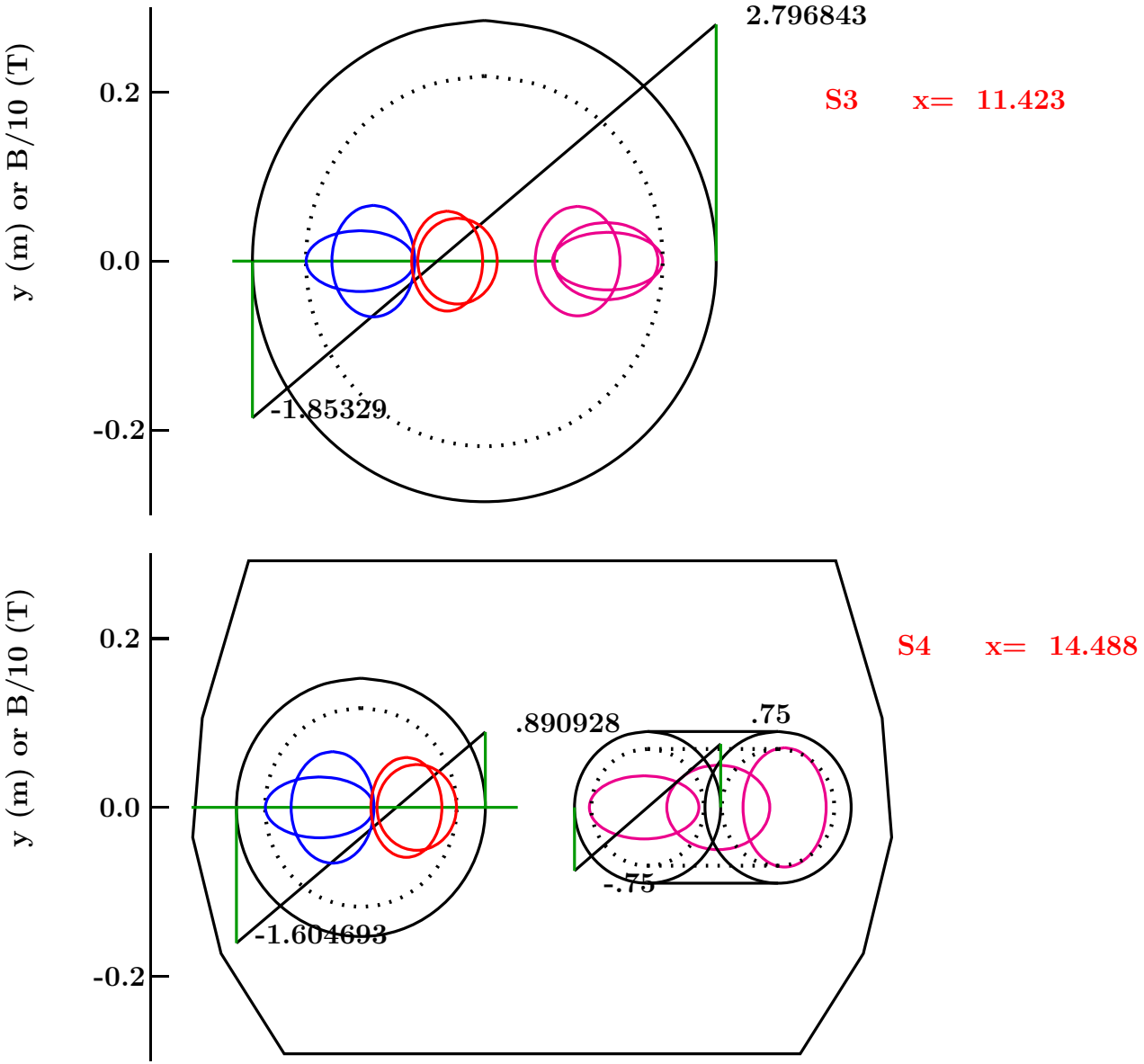
Note: I moved D magnet outward to reduce peak field

magnet	Len m	rad cm	B_{cen} T	Grad T	B1 T	B2 T
F	1.07	15.3	-0.04	8.2	-1.6	0.9
D	1.61	15.0	0.13	-9.2	2.6	-0.1

Injection from Outside

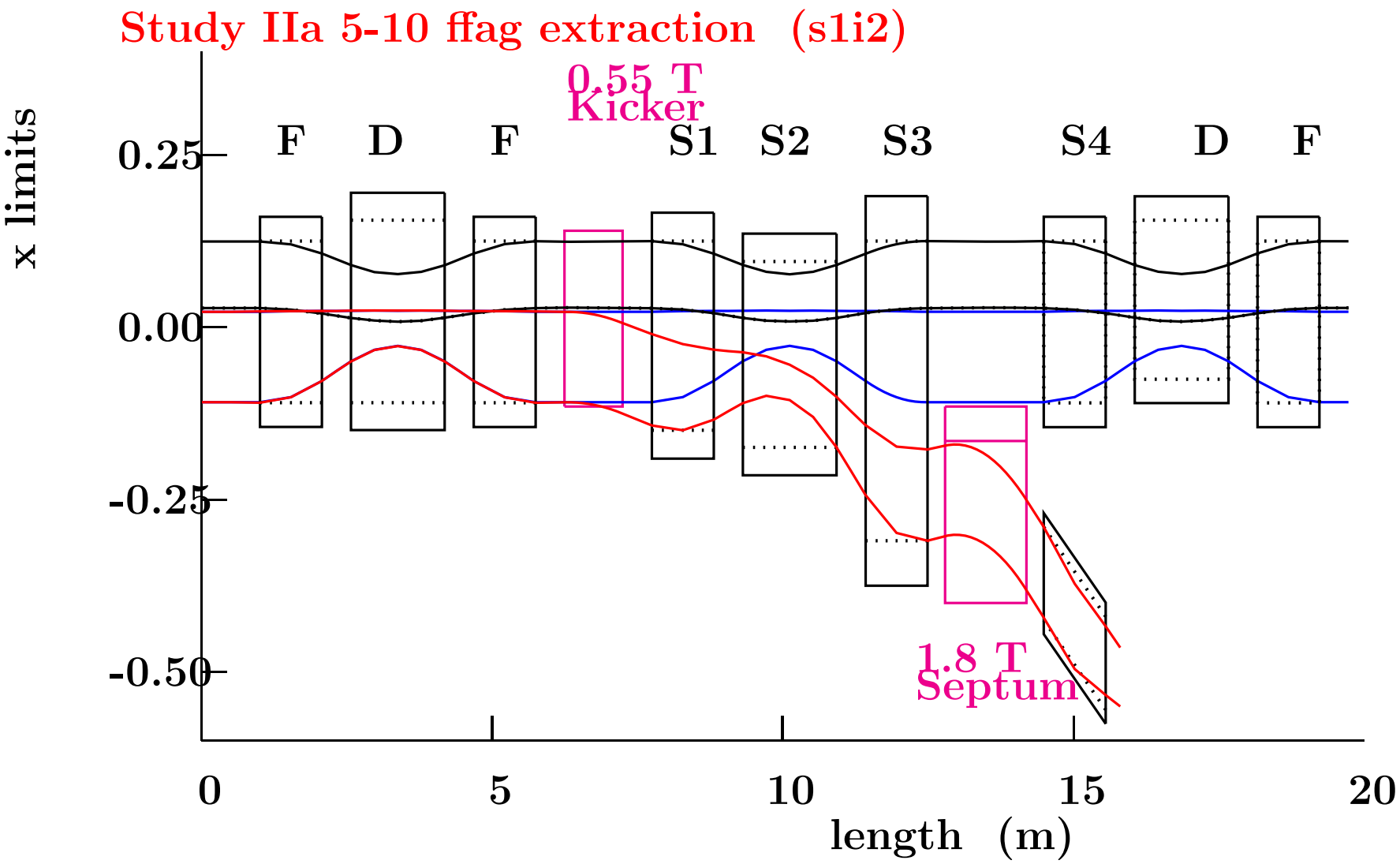


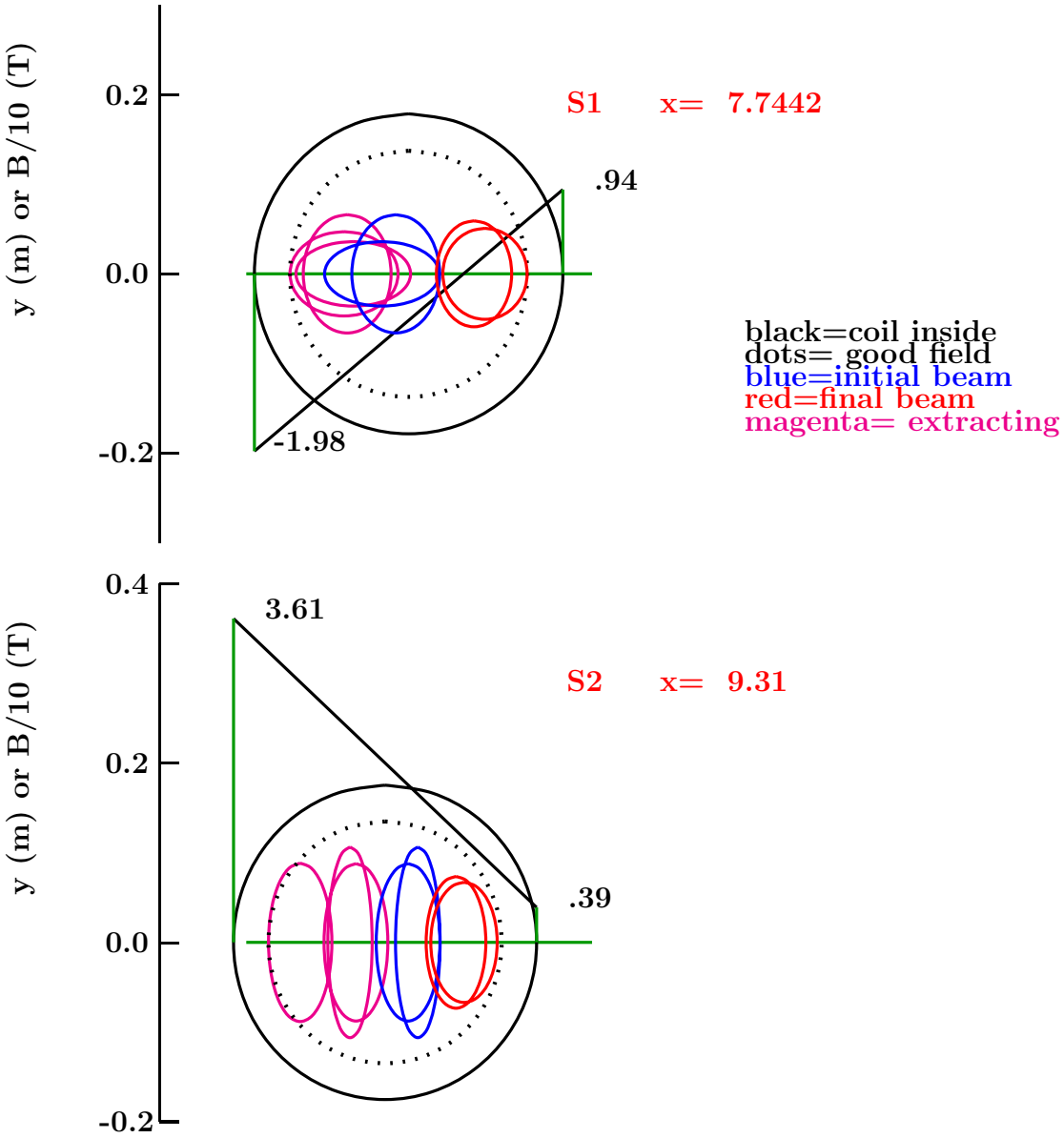

y (m) or B/10 (T)
0.2
0.0
-0.2
S1=F x= 7.7442
.890928
-1.604693
y (m) or B/10 (T)
0.2
0.0
-0.2
2.623513
S2 x= 9.31
-.7110612

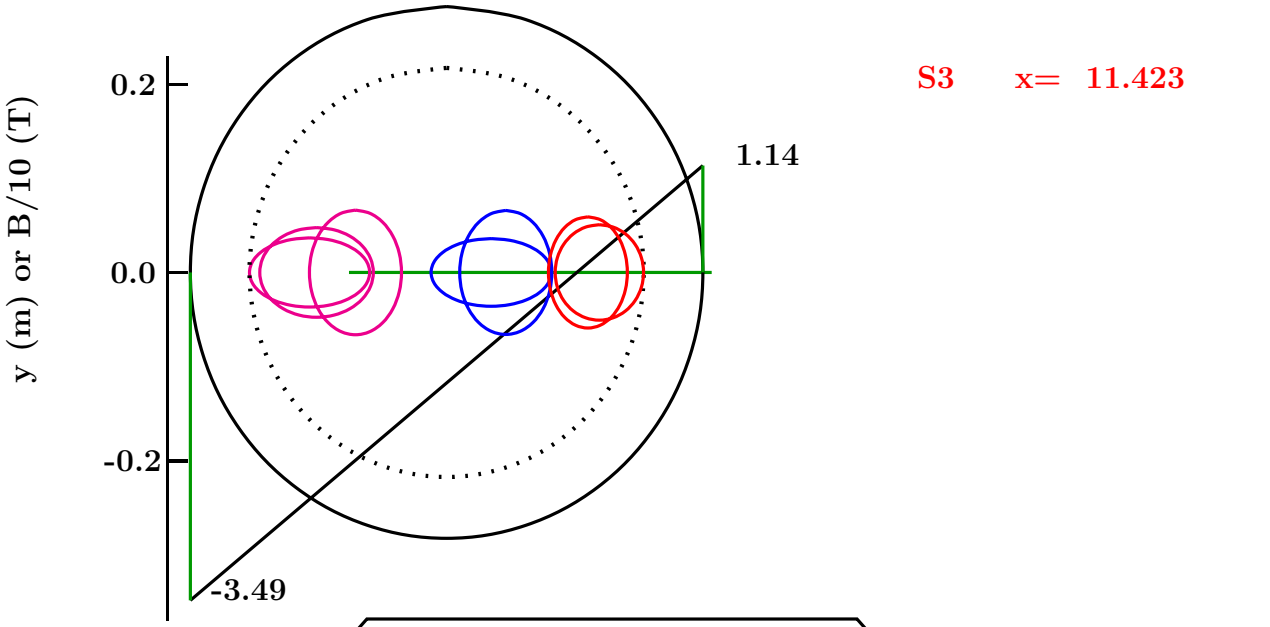

y (m) or B/10 (T)
0.2
0.0
-0.2
2.796843
-1.85329
S3 x= 11.423
y (m) or B/10 (T)
0.2
0.0
-0.2
.890928
.75
-.75
-1.604693
S4 x= 14.488

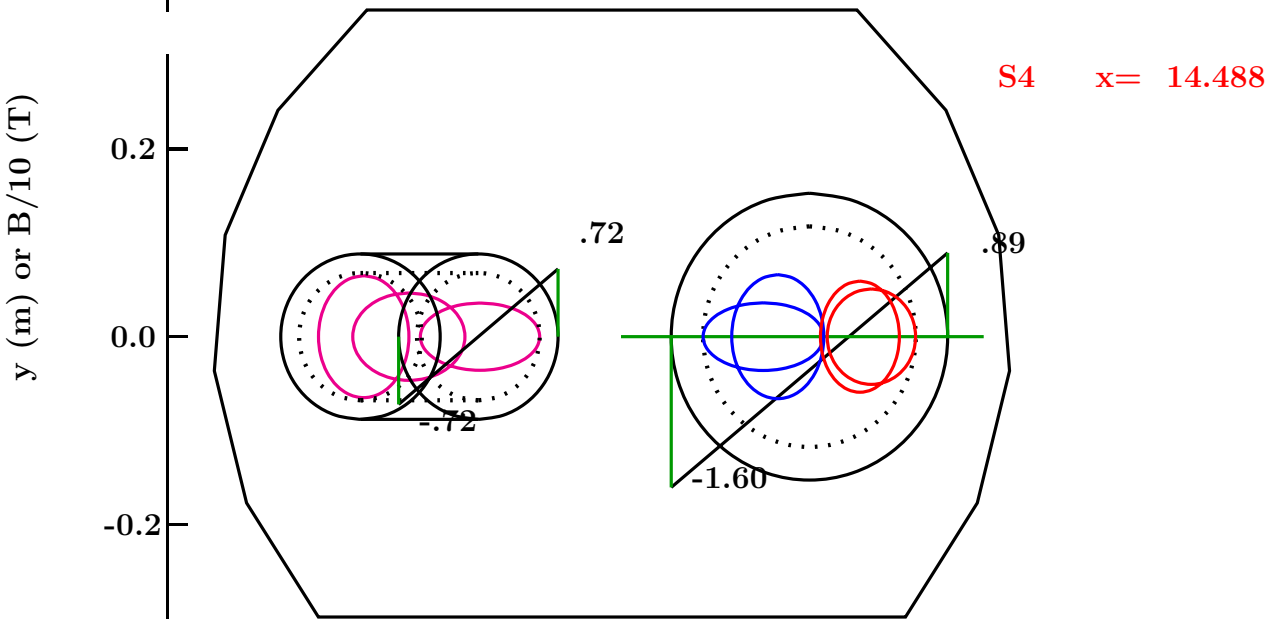
magnet	Len m	rad cm	B_{cen} T	Grad T	B1 T	B2 T
S1	1.07	15.3	-0.04	8.2	-1.6	0.9
S2	1.61	18.1	0.10	-9.2	2.6	-0.7
S3	1.06	28.4	0.05	8.2	-1.9	2.8
S4(1)	1.07	15.3	-0.04	8.2	-1.6	0.9
S4	1.07	9.0	0.25	8.2	-.75	.75

Injection from Inside



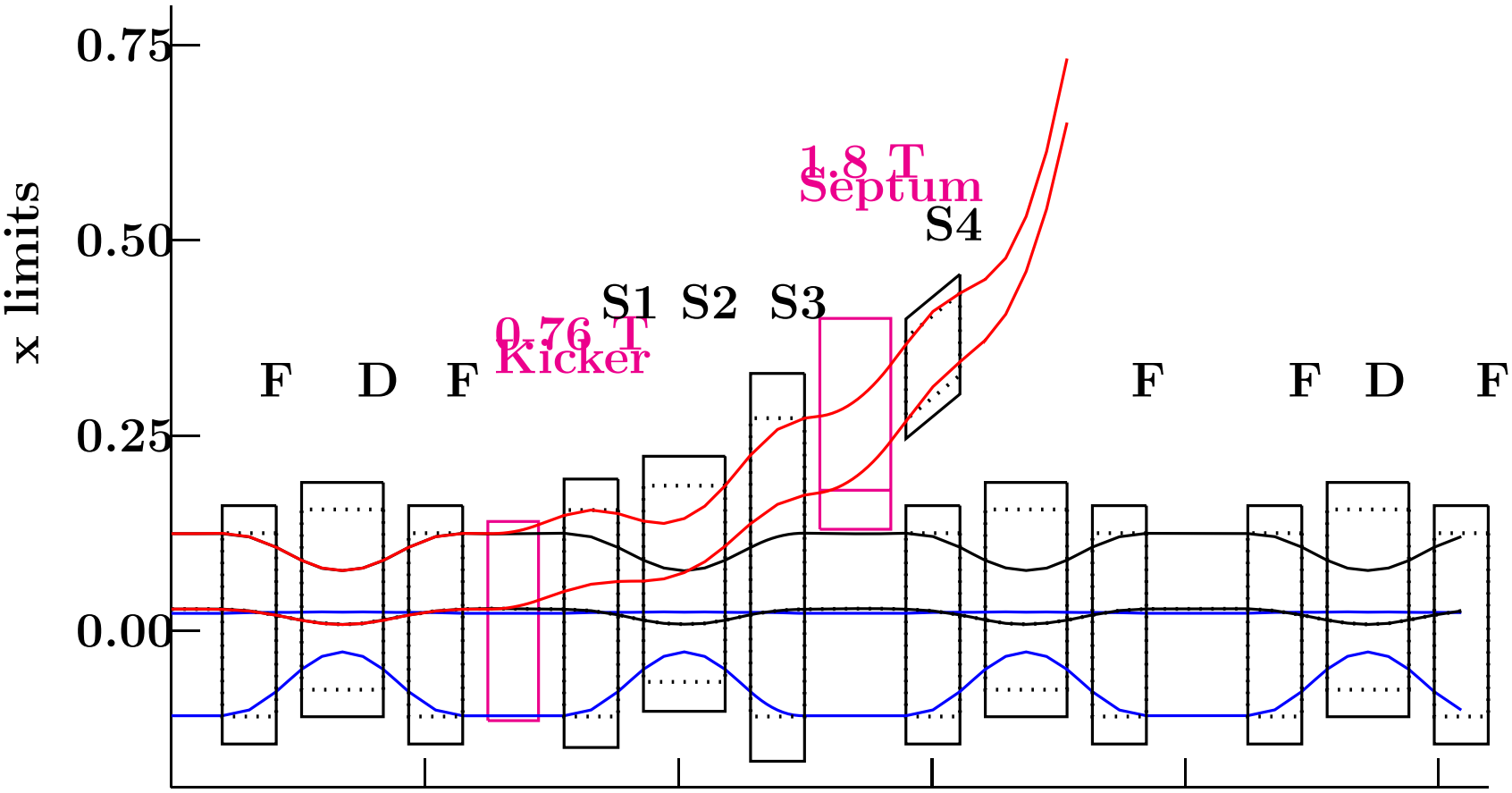

y (m) or B/10 (T)
0.2
0.0
-0.2
S1 x= 7.7442
.94
-1.98
black=coil inside
dots= good field
blue=initial beam
red=final beam
magenta= extracting
y (m) or B/10 (T)
0.4
0.2
0.0
-0.2
3.61
S2 x= 9.31
.39

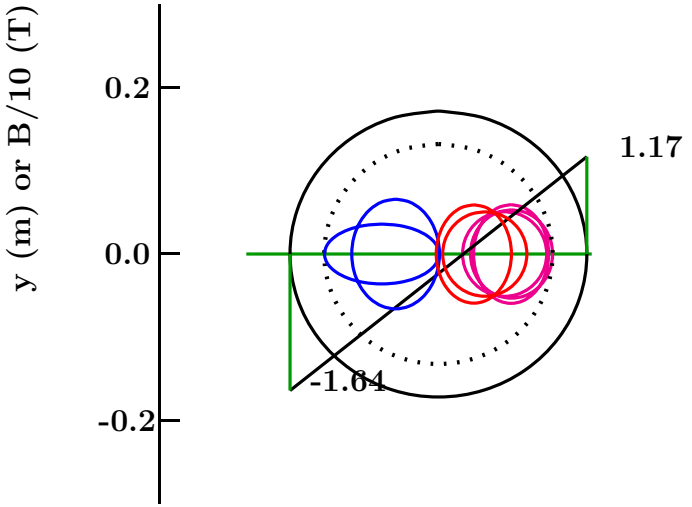

S3 x= 11.423
y (m) or B/10 (T)
0.2
0.0
-0.2
1.14
-3.49


S4 x= 14.488
y (m) or B/10 (T)
0.2
0.0
-0.2
.72
-.72
.89
-1.60

magnet	Len m	rad cm	B_{cen} T	Grad T	B1 T	B2 T
S1	1.07	17.8	-0.05	8.2	-2.0	0.9
S2	1.61	17.5	0.20	-9.2	3.6	0.4
S3	1.06	28.3	-0.12	8.2	-3.5	1.1
S4(1)	1.07	15.3	-0.04	8.2	-1.6	0.9
S4(2)	1.07	8.8	-0.33	8.2	-.75	.75

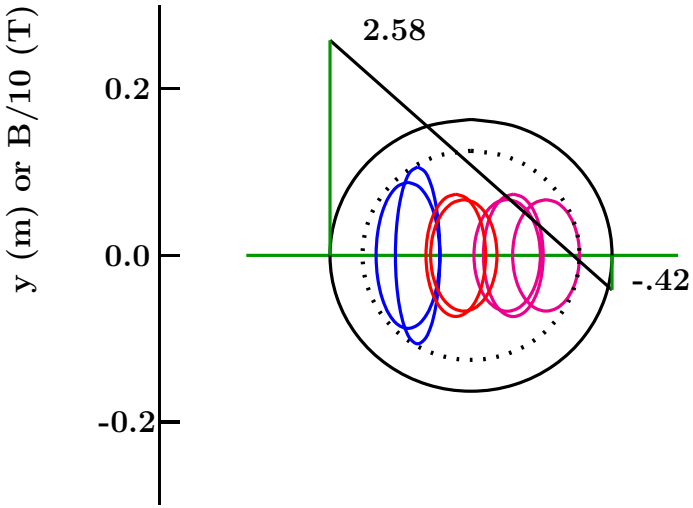
Extraction to Outside





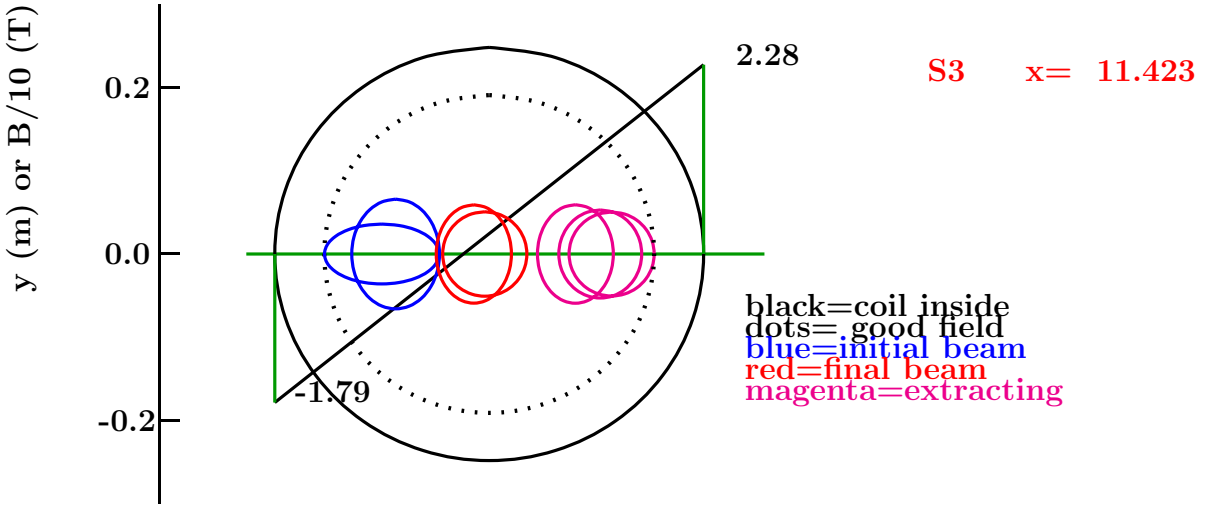
S1 x= 7.7442

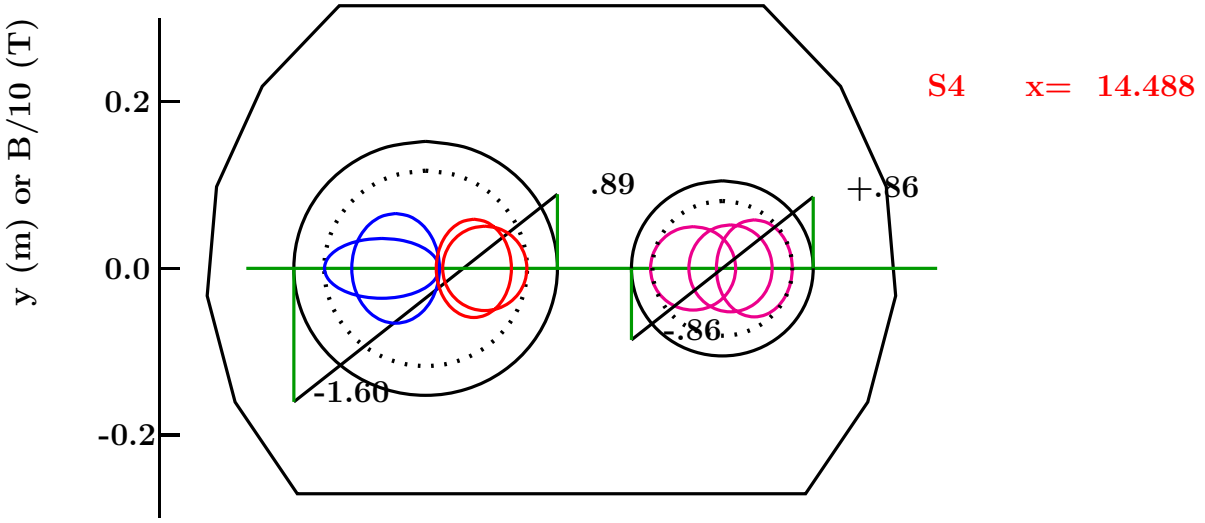
black=coil inside
dots=good field
blue=initial beam
red=final beam
magenta=extracting



S2 x= 9.31

black=coil inside
dots=good field
blue=initial beam
red=final beam
magenta=extracting

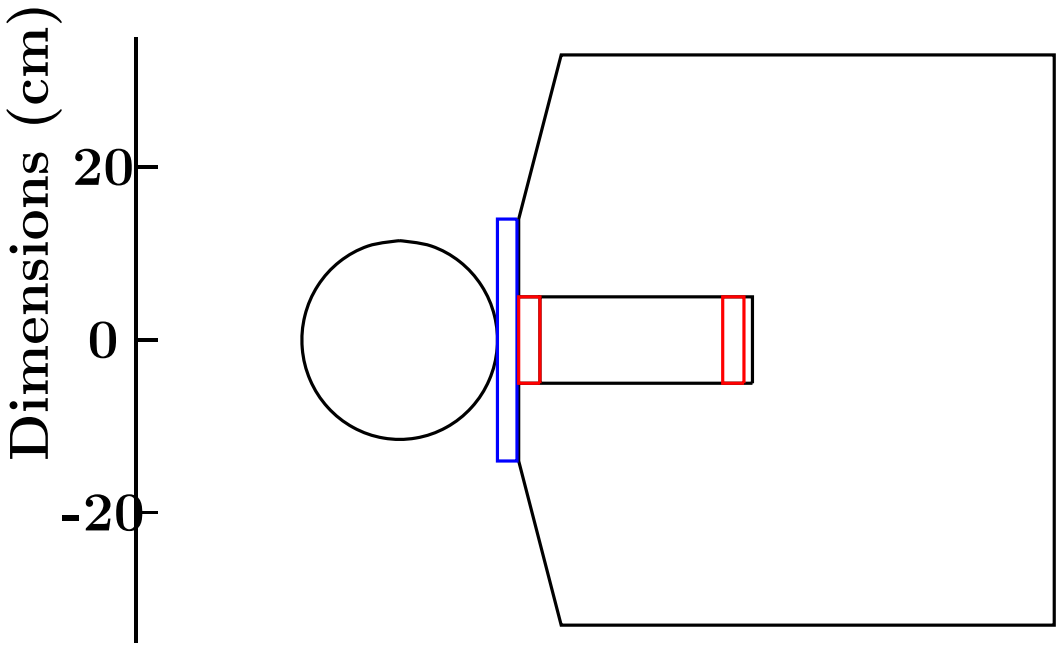

y (m) or B/10 (T)
0.2
0.0
-0.2
2.28
-1.79
S3 x= 11.423
black=coil inside
dots= good field
blue=initial beam
red=final beam
magenta=extracting


y (m) or B/10 (T)
0.2
0.0
-0.2
.89
+.86
-.86
-1.60
S4 x= 14.488

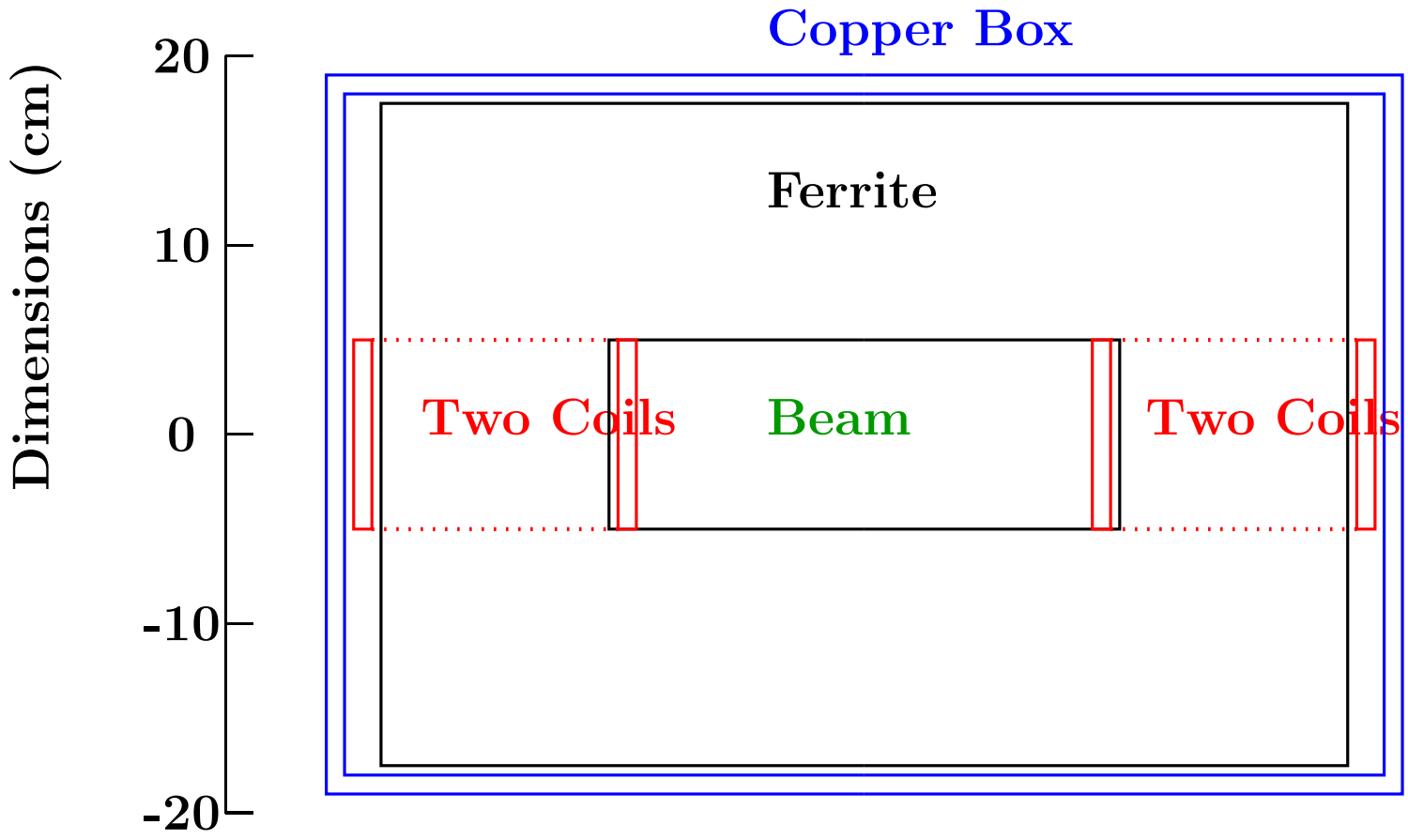
magnet	Len m	rad cm	B_{cen} T	Grad T	B1 T	B2 T
S1	1.07	17.2	-0.02	8.2	-1.6	1.2
S2	1.61	16.3	0.11	-9.2	2.6	-0.4
S3	1.06	24.8	0.02	8.2	-1.8	2.3
S4(1)	1.07	15.3	-0.04	8.2	-1.6	0.9
S4(2)	1.07	9	0.0	8.2	-.75	.75

Injection Septum Parameters

length	m	1.4
Field	T	1.8
Height	cm	10
Width	cm	23
septum	cm	5



Injection Kicker



Formulae

$$I = \frac{B\ X}{\mu_o}$$

$$V = \frac{B\ Y\ L}{t_{\text{rise}}}$$

$$U = \frac{B^2\ L\ X\ Y}{2\ \mu_o}$$

$$\mu_o = 4\ \pi\ 10^{-7}$$

Theoretical minium Stored Energy for given Acceptance:

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

for A=30 pi mm and L=1 m: U (minimum)=702 J
Kicker Energy will be greater than this because

a) kicker spans both beams,
b) must kick past finite septum,
c)phase advance not ideal

Parameters

		Inj out	Inj in	Ext out	10-20Ext	10-20Inj	RFOFO	$\bar{p}$	Ind
Length	m	1.0	1.0	1.0	1.0	1.0	1.0	≈5	1.0
B_o	T	.82	.55	0.76	1.17	.87	.42	≈0.018	0.6
Y	m	.1	.1	.1	.076	.076	.42	.08	
X	m	.235	.25	.25	.195	.195	.63	.25	
I	kA	65	44	60	71	53	105	3.6	
U	J	2660 [1]	1274	2430	3415	1890	8200	≈13	1600
Max pole B	T	2.6	3.6 [1]	2.6	4.2	5.6			
Length [2]	m	1.5	1.5	1.5	1.5	1.5	1.0	≈5	1.0
B $[2]_o$	T	.55	.37	0.51	.78	.58	.42	≈0.018	0.6
U [2]	J	1770	850	1620	2280	1260	8200	≈13	1600

Note [1]Chose Injection from Inside

- Injection from inside has easier kicker
- Only slightly harder special magnets

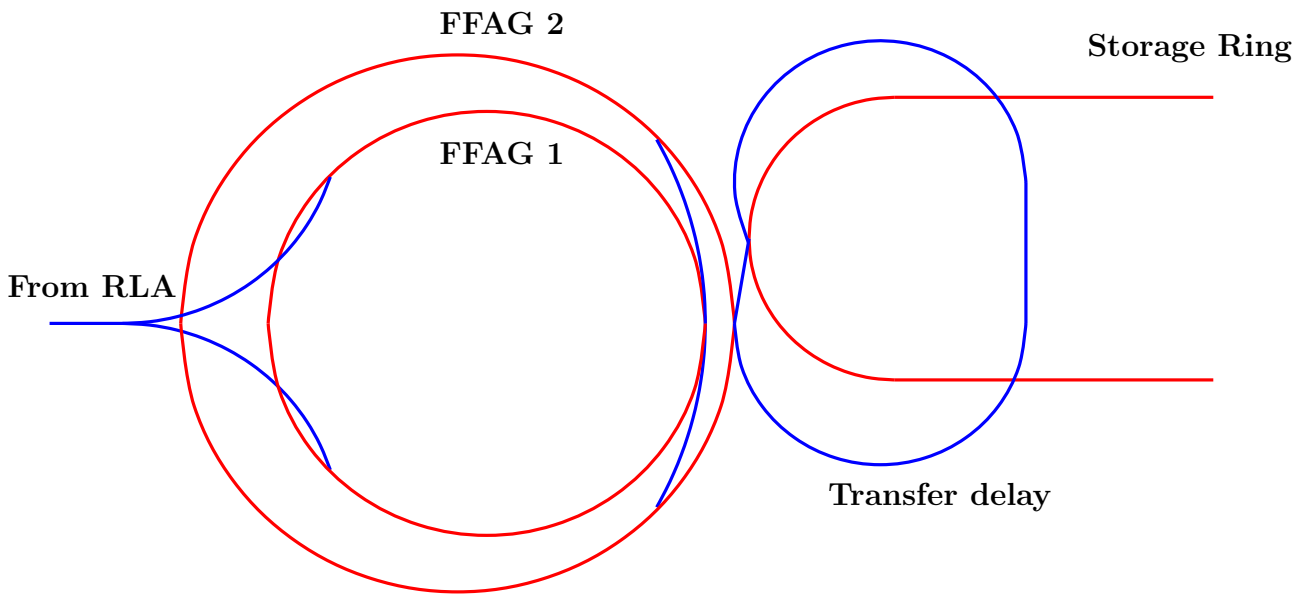
Note [2] Field and Stored Energy can be reduced by

- Special higher field F Quads (B max=3 T vs 1.6 T)
- Now Shorter (e.g. 56 cm vs 106 cm)
- Allows longer kicker (length 1.5 m vs. 1.0 m)
- 2/3 field and stored Energy

Layout

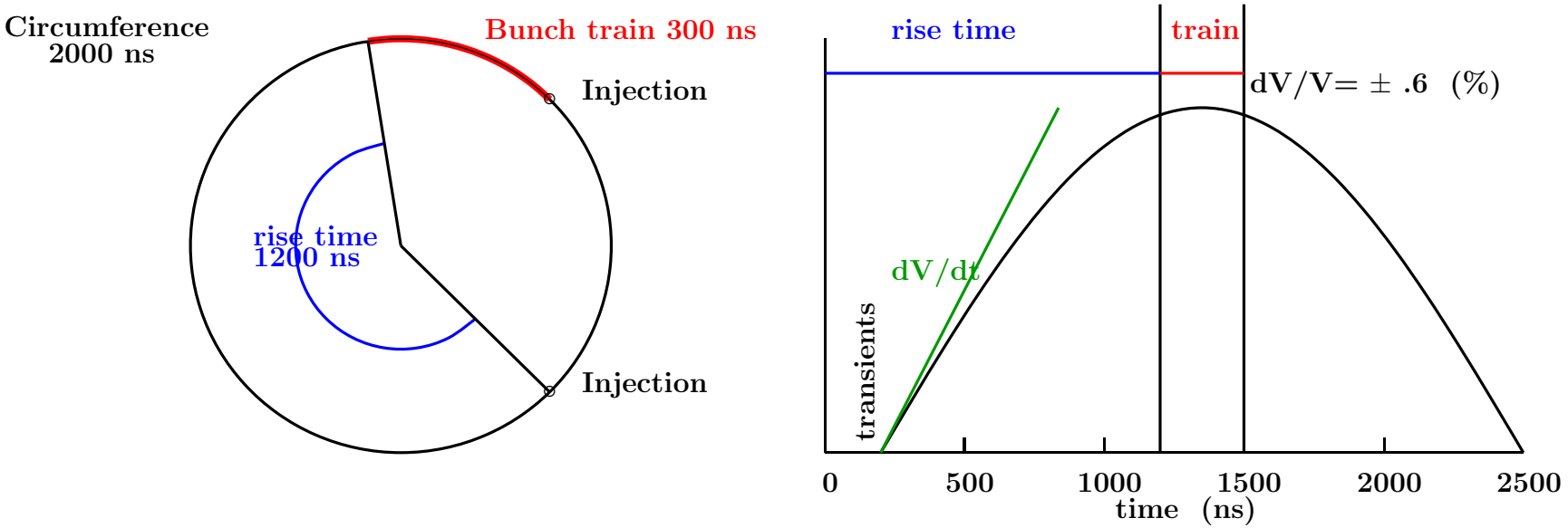
- Inject from Insides because easier kicker
- Share ejection of two signs (since ejection kicker is more difficult)
- But use separate injectors to reduce transfer line lengths
- Uses 2+2+3=7 straight sections in each ring (Scott allowed for 8)

Schematic Layout



Required Rise time

Assume: Injection at +/- 45 degrees, Extraction at 0 degrees
e.g. for injection into 5-10 GeV ring



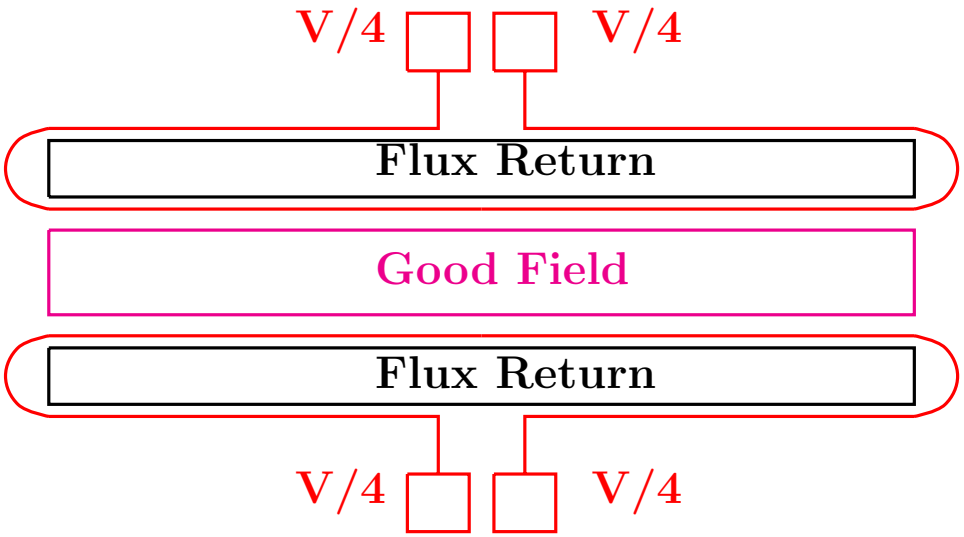
injection 5-10: $\mathrm{dt} = \left(\mathrm{circ} \times \frac{3}{4} - \mathrm{train} - \mathrm{transient}\right) \times \frac{2}{\pi} = 640 \quad \mathrm{ns}$

extraction 5-10: $\mathrm{dt} = \left(\mathrm{circ} \times \frac{4}{4} - \mathrm{train} - \mathrm{transient}\right) \times \frac{2}{\pi} = 950 \quad \mathrm{ns}$

injection 10-20: $\mathrm{dt} = \left(\mathrm{circ} \times \frac{3}{4} - \mathrm{train} - \mathrm{transient}\right) \times \frac{2}{\pi} = 875 \quad \mathrm{ns}$

extraction 10-20: $\mathrm{dt} = \left(\mathrm{circ} \times \frac{4}{4} - \mathrm{train} - \mathrm{transient}\right) \times \frac{2}{\pi} = 1270 \quad \mathrm{ns}$

Circuit to minimize Supply Voltage



Parameters including Voltage

		Inj 5-10 in	Ext 5-10t	inj 10-20	Ext 10-29	RFOFO	$\bar{p}$	Ind
Length	**m**	**1.5**	**1.5**	**1.5**	**1.5**	**1.0**	**≈5**	**1.0**
t_{fall}	**ns**	**640**	**950**	**875**	**1270**	**50**	**90**	**40**
$t_{pulse\ length}$	**ns**	**300**	**300**	**300**	**300**	**100**	**500**	**100**
B_o	**T**	**.37**	**0.51**	**.58**	**.78**	**.42**	**≈0.018**	**0.6**
Y	**m**	**.1**	**.1**	**.076**	**.076**	**.42**	**.08**	
X	**m**	**.25**	**.25**	**.19**	**.19**	**.63**	**.25**	
U [2]	**J**	**850**	**1620**	**1260**	**2280**	**8200**	**≈13**	**1600**
$V_{1\ turn}$	**kV**	**230**	**240**	**208**	**193**	**5,700**	**800**	**1000**
V_{supply}	**kV**	**±58**	**± 60**	±52	**± 48**	**190**	**80**	**190**

- **Stored Energy similar to Induction Linac**
- **Rise time Much slower**
- **Voltage moderate**
- **Similar to Input pulser to Induction Magnetic Amplifier**

Conclusions

- **Injection/extraction needs 2 cells for one sign, 3 cells for both**
- **Septum and beam magnets reasonable**

- **Injection from inside favored for kicker energy ($> 2\times$)**
- **Use of special short beam magnets helps injection, but higher order perturbation needs study**
- **Half sin wave (or full sin wave to restore voltage) gives flat enough top**

- **Stored Energy $\approx 1/4$ of RFOFO cooling ring kicker**
- **But Stored energy still $\approx 100\times$ conventional kicker**
- **Pulse rise time 20 times cooling ring or conventional**
- **Making voltage reasonable**

- **Kicker and Switch needs study**
- **But probably ok**

Conclusions for other lattices:

- Doublet or FODO assymetry is ugly for two signs
- Split tune solution:
  - Good for extraction, advance=.25 (vs. .2) is ideal
  - Hard for injection, advance=.4 (vs..35) too near 0.5
    but doable with more short quads and septum between F and D magnets
- For Lower Energy Rings, if smaller circumference
  - Rise time gets shorter
  - Voltage rises and becomes harder
- For p Rings with long train of bunches
  - B lower, but width still large
  - Stored E less than muon case, but much larger than conventional
  - Rise time short
  - Voltage could be a problem