6D Merge

R. B. Palmer (BNL)
Friday 4/18/12

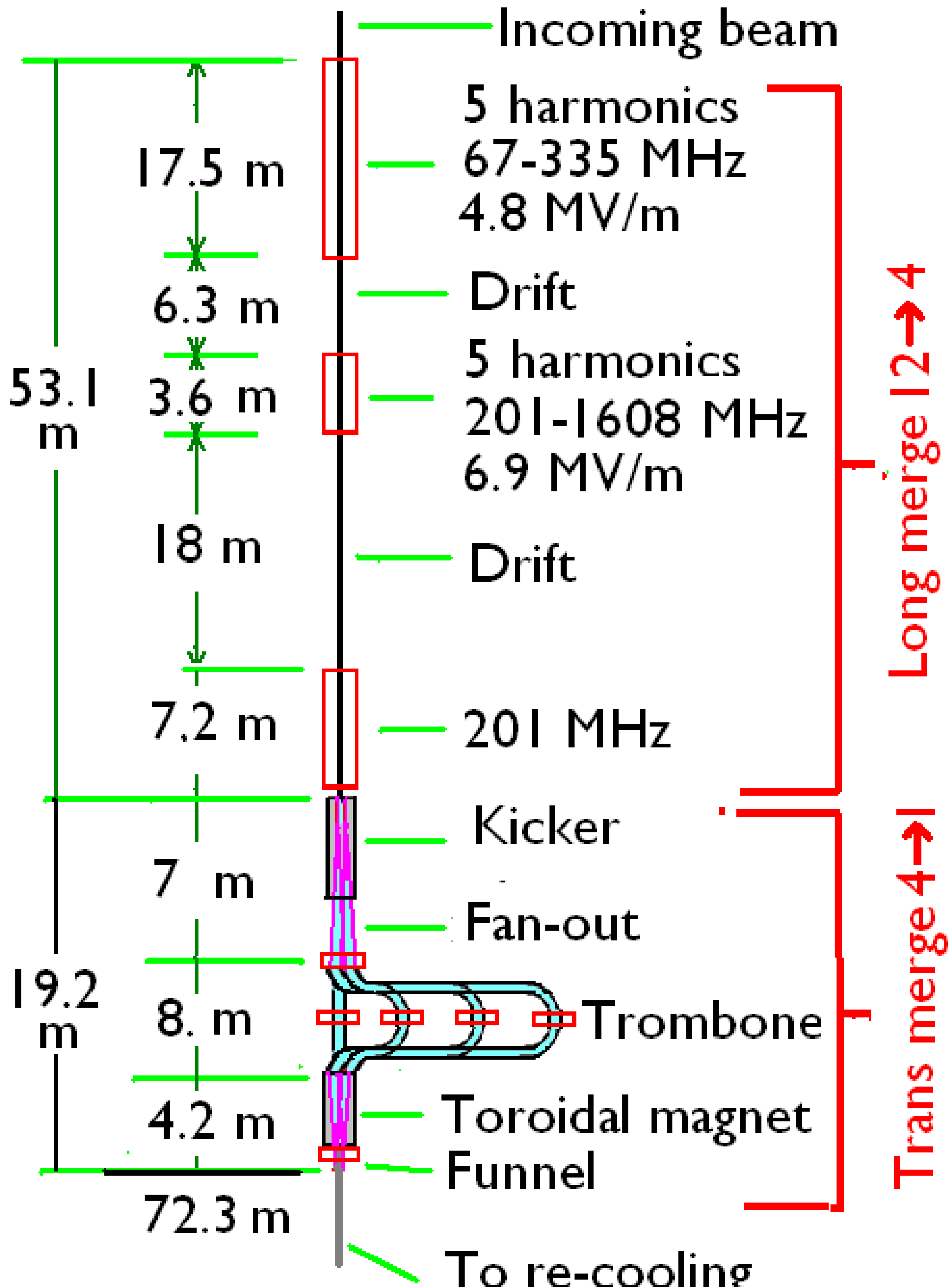
Earlier

- Neuffer et al[3] has presented a longitudinal merge of 12 bunches using a helical channel with a linear relation between energy and longitudinal velocity.
- We had achieved a 6 dimensional merge of 12 bunches using the same helical channel.
- But this required rf with 4 harmonics down to 135 MHz that would be very hard to locate inside such a channel

Here we present a system

- Using a simple linear transport with its non-linear relation between energy and longitudinal motion, requiring non-linear and asymmetrical energy modulation, but achievable with 5 harmonics down to 67 MHz.

Schematic



Incoming beam
17.5 m
5 harmonics
67-335 MHz
4.8 MV/m
6.3 m
Drift
53.1 m
3.6 m
5 harmonics
201-1608 MHz
6.9 MV/m
18 m
Drift
7.2 m
201 MHz
Long merge 12→4
Kicker
7 m
Fan-out
19.2 m
8. m
Trombone
4.2 m
Toroidal magnet
Funnel
72.3 m
To re-cooling
Trans merge 4→1

Longitudinal merging: 12 $\rightarrow$ 4 bunches

- Use an inverse of Neuffer's phase rotation[1]:
- Keeping bunches contained by rf, with phase shifts to give appropriate bunches acceleration or deceleration.

- In phase rotation, frequencies must changes with position along the channel, to keep the phases correct as the times of bunches change with their different energies.
- To work for multiple groups of 3 bunches it is more difficult because all the rf must be a harmonic of 201/3=67 MHz
- But harmonics of that frequency can still give the required phases.

- After drifting, sawtooth rf aligns the bunches.
- A final drift then brings the groups of 3 to the same times.

Parameters of Longitudinal merge

Average energy	130	MeV
Average beta in longitudinal merge lattice	1	m
Length of longitudinal lattice	53	m

Maximum gradients of rf at differing frequencies

a) First rf		b) Second rf	
Freq. MHz	Max grad MV/m	Freq. MHz	Max grad MV/m
67	4.3	201	8.4
134	8.7	402	12.8
201	13.0	603	14.2
268	14.0	1005	16.1
335	14.8	1407	17.5

Detailed average gradients and phases follow:

Frequencies and phases

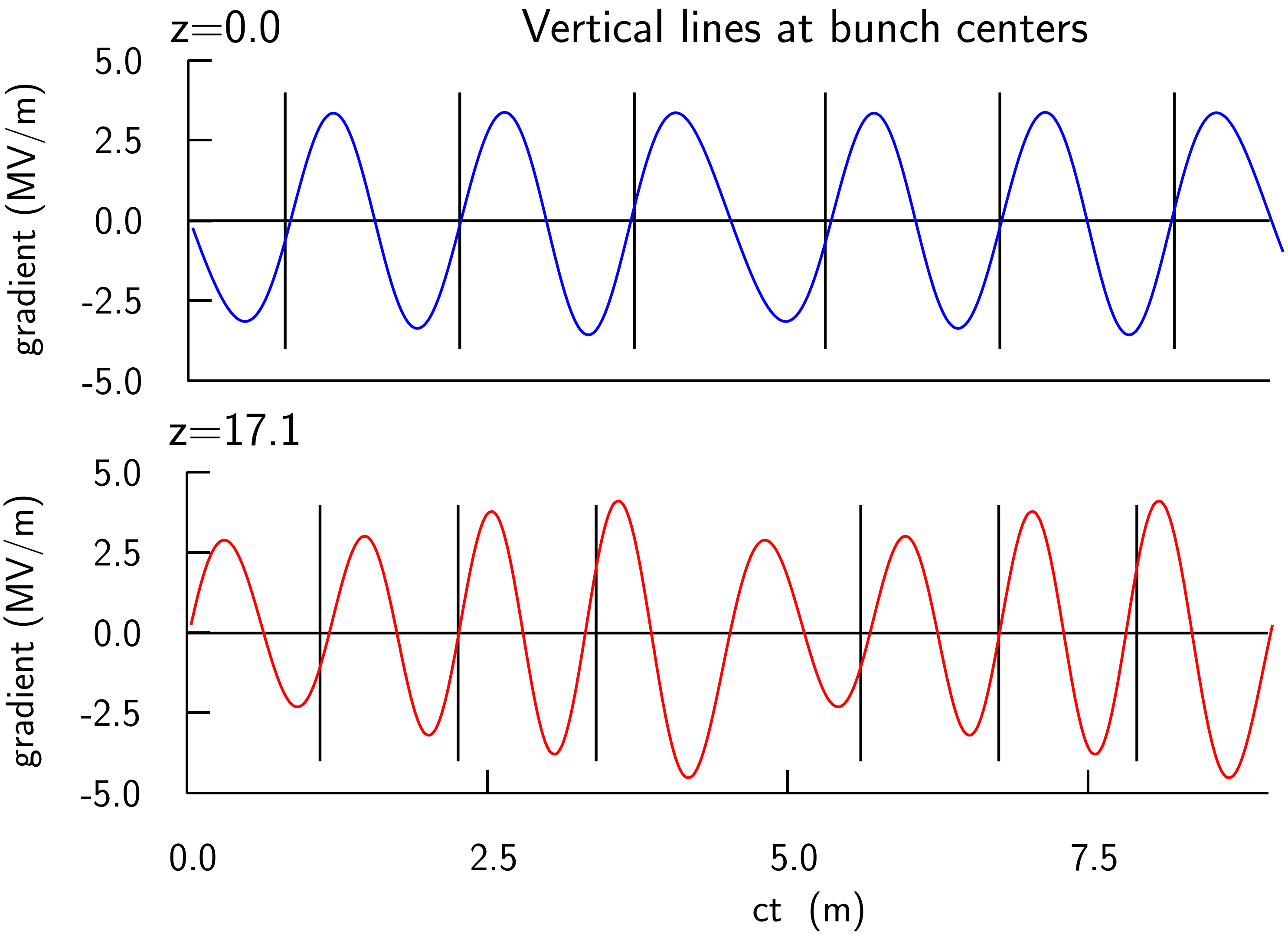
Z m	m	freq MHz	grad MV/m	phase deg
0.9	1	67	0.31	14.7
0.9	2	134	0.85	8.3
0.9	3	201	6.52	4.0
0.9	4	268	1.16	12.0
0.9	5	335	0.41	10.3
1.8	1	67	0.32	14.7
1.8	2	134	0.89	8.2
1.8	3	201	6.50	3.9
1.8	4	268	1.23	12.0
1.8	5	335	0.43	10.1
2.7	1	67	0.33	14.7
2.7	2	134	0.90	8.2
2.7	3	201	6.48	3.9
2.7	4	268	1.25	12.0
2.7	5	335	0.44	10.1
3.6	1	67	0.34	14.8
3.6	2	134	0.94	8.2
3.6	3	201	6.45	3.9
3.6	4	268	1.33	11.9
3.6	5	335	0.46	9.9
4.5	1	67	0.37	14.8
4.5	2	134	1.00	8.1
4.5	3	201	6.39	3.8
4.5	4	268	1.46	11.9
4.5	5	335	0.50	9.5
5.4	1	67	0.40	14.9
5.4	2	134	1.09	7.9
5.4	3	201	6.30	3.6
5.4	4	268	1.64	11.7
5.4	5	335	0.54	9.0
6.3	1	67	0.44	14.9
6.3	2	134	1.18	7.7
6.3	3	201	6.18	3.4
6.3	4	268	1.87	11.6
6.3	5	335	0.60	8.3

Z m	m	freq MHz	grad MV/m	phase deg
7.2	1	67	0.49	14.9
7.2	2	134	1.28	7.5
7.2	3	201	6.00	3.1
7.2	4	268	2.16	11.4
7.2	5	335	0.66	7.4
8.1	1	67	0.53	14.8
8.1	2	134	1.37	7.1
8.1	3	201	5.77	2.7
8.1	4	268	2.51	11.1
8.1	5	335	0.73	6.1
9.0	1	67	0.57	14.5
9.0	2	134	1.45	6.6
9.0	3	201	5.46	2.2
9.0	4	268	2.92	10.8
9.0	5	335	0.79	4.3
9.9	1	67	0.60	13.9
9.9	2	134	1.50	5.8
9.9	3	201	5.07	1.4
9.9	4	268	3.38	10.3
9.9	5	335	0.83	1.9
10.8	1	67	0.60	12.7
10.8	2	134	1.50	4.7
10.8	3	201	4.57	0.4
10.8	4	268	3.90	9.8
10.8	5	335	0.86	178.4
11.7	1	67	0.58	10.7
11.7	2	134	1.43	2.9
11.7	3	201	3.97	178.9
11.7	4	268	4.46	9.1
11.7	5	335	0.85	173.3
12.6	1	67	0.53	6.7
12.6	2	134	1.29	0.2
12.6	3	201	3.25	176.4
12.6	4	268	5.04	8.4
12.6	5	335	0.80	165.1

Z m	m	freq MHz	grad MV/m	phase deg
15.3	1	67	0.27	114.3
15.3	2	134	0.46	133.2
15.3	3	201	0.74	132.2
15.3	4	268	6.49	4.9
15.3	5	335	0.71	88.0
16.2	1	67	0.41	74.6
16.2	2	134	0.50	71.8
16.2	3	201	0.77	52.5
16.2	4	268	6.69	3.2
16.2	5	335	1.07	58.5
17.1	1	67	0.64	58.1
17.1	2	134	0.86	42.7
17.1	3	201	1.47	24.9
17.1	4	268	6.62	1.3
17.1	5	335	1.65	41.1
18.0	1	67	0.86	50.5
18.0	2	134	1.24	31.8
18.0	3	201	2.08	15.6
18.0	4	268	6.23	178.9
18.0	5	335	2.37	30.0
13.5	1	67	0.43	178.6
13.5	2	134	1.06	175.1
13.5	3	201	2.43	172.2
13.5	4	268	5.60	7.4
13.5	5	335	0.71	151.0
14.4	1	67	0.31	159.0
14.4	2	134	0.76	164.2
14.4	3	201	1.55	163.1
14.4	4	268	6.11	6.2
14.4	5	335	0.63	125.2

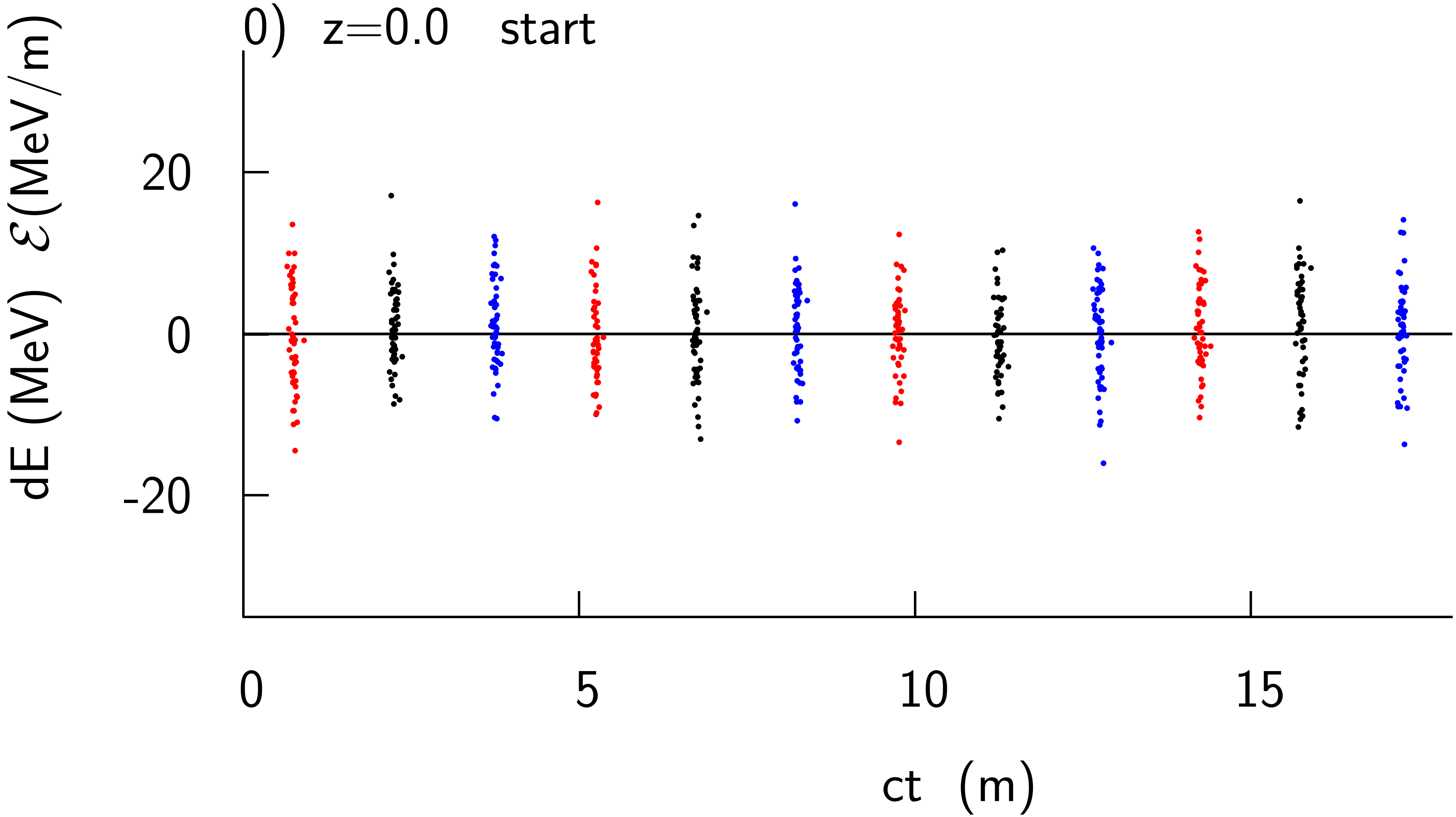
Z m	m	freq MHz	grad MV/m	phase deg
25.2	3	201	0.22	13.1
25.2	6	402	7.65	31.9
25.2	12	804	3.44	63.8
25.2	18	1206	1.78	95.8
25.2	24	1608	0.96	127.7
26.1	3	201	0.22	13.1
26.1	6	402	7.65	31.9
26.1	12	804	3.44	63.8
26.1	18	1206	1.78	95.8
26.1	24	1608	0.96	127.7
27.0	3	201	0.22	13.1
27.0	6	402	7.65	31.9
27.0	12	804	3.44	63.8
27.0	18	1206	1.78	95.8
27.0	24	1608	0.96	127.7
27.9	3	201	0.22	13.1
27.9	6	402	7.65	31.9
27.9	12	804	3.44	63.8
27.9	18	1206	1.78	95.8
27.9	24	1608	0.96	127.7

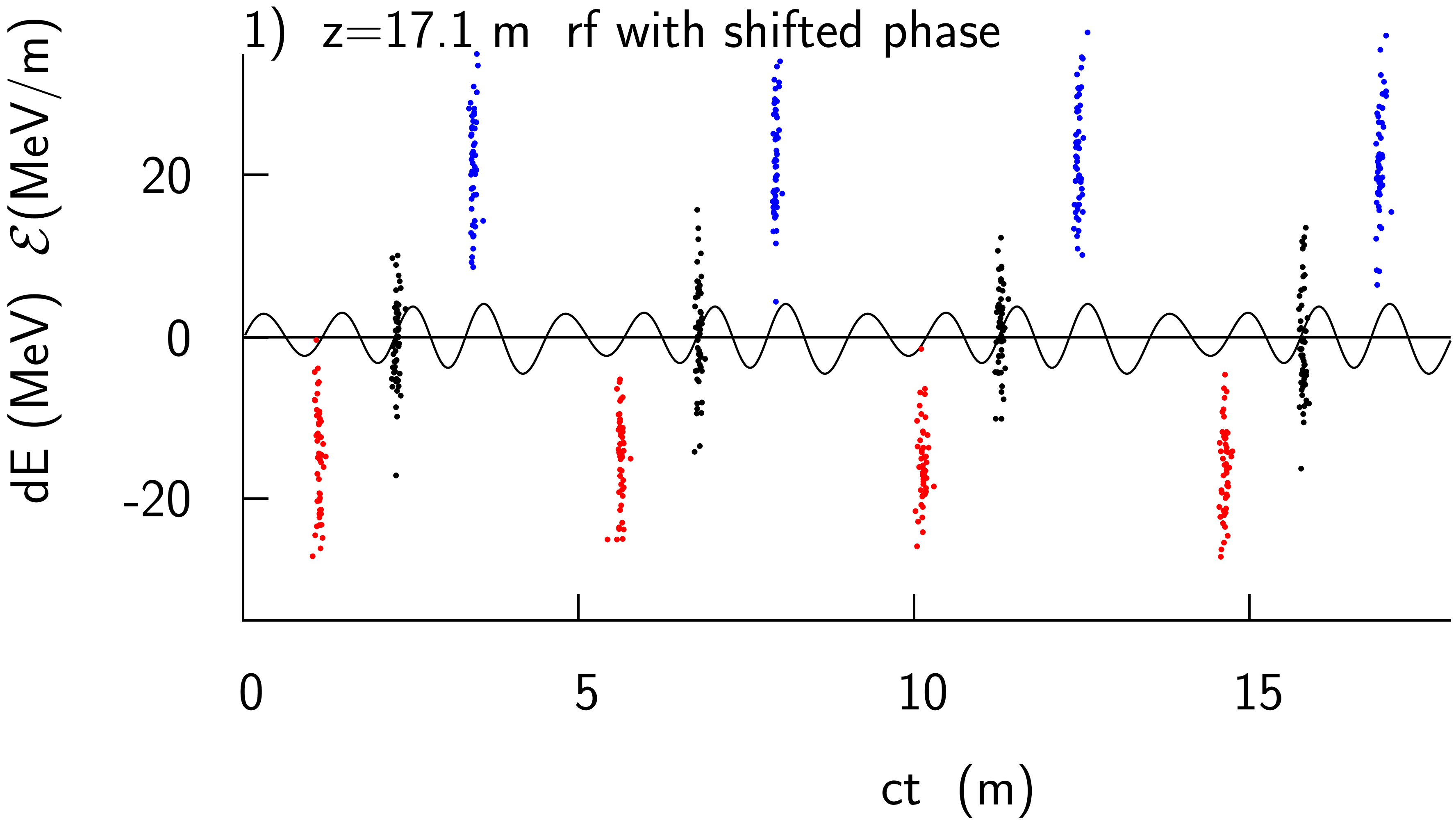
Waveforms from harmonics

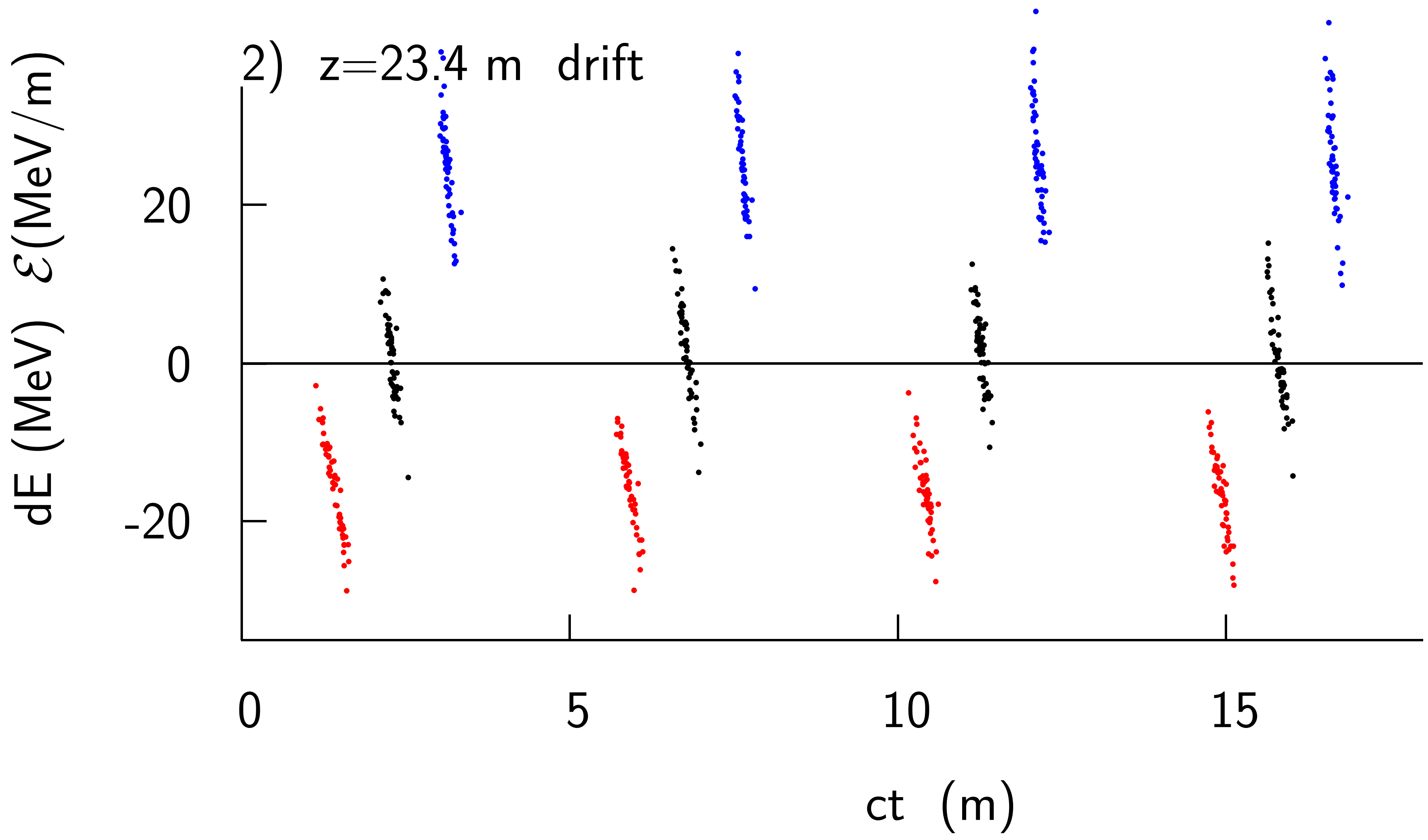


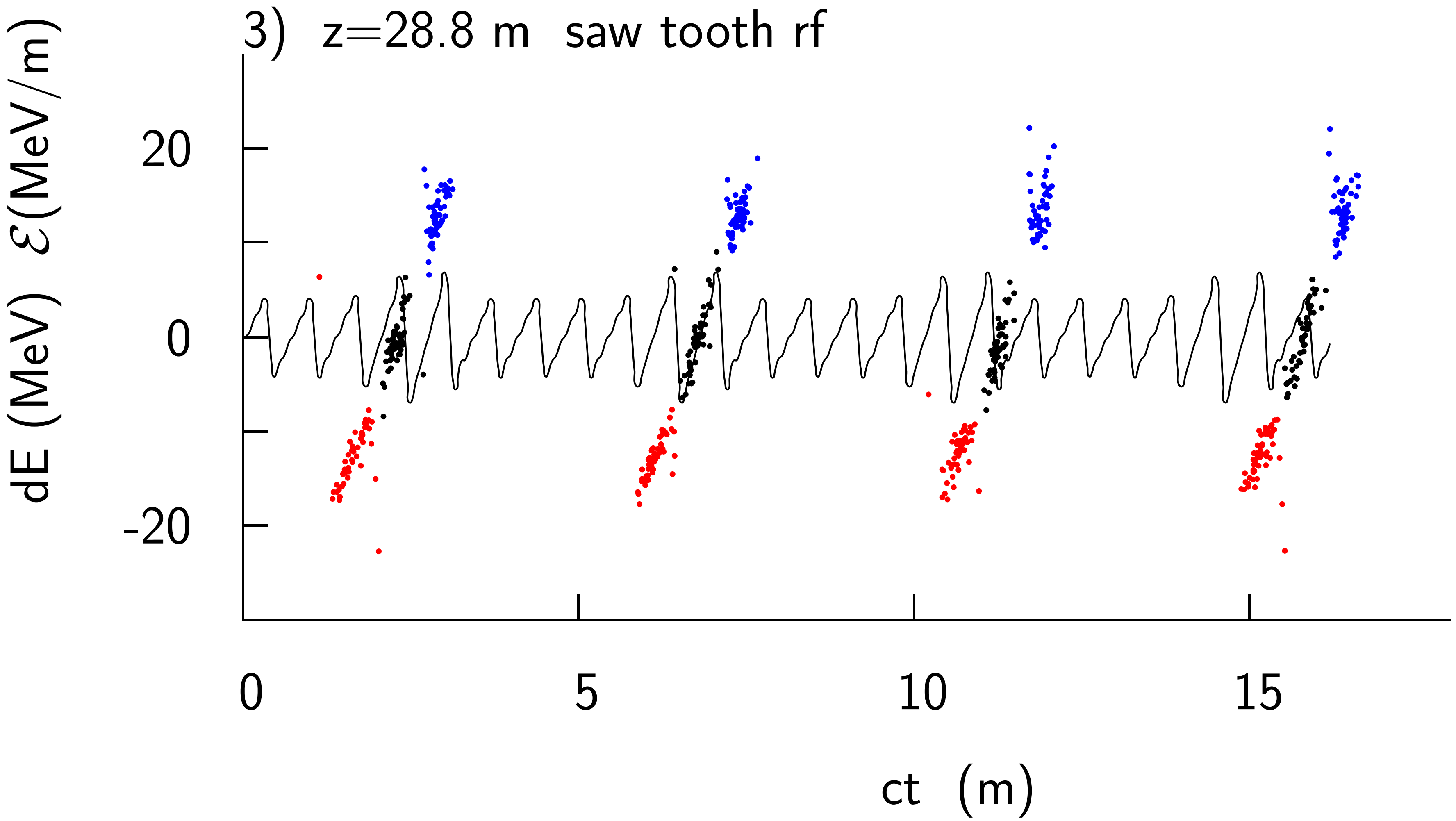
- Note phase shifts to get required pahses
- Note more acceleration than decelleration

Phase Space Plots

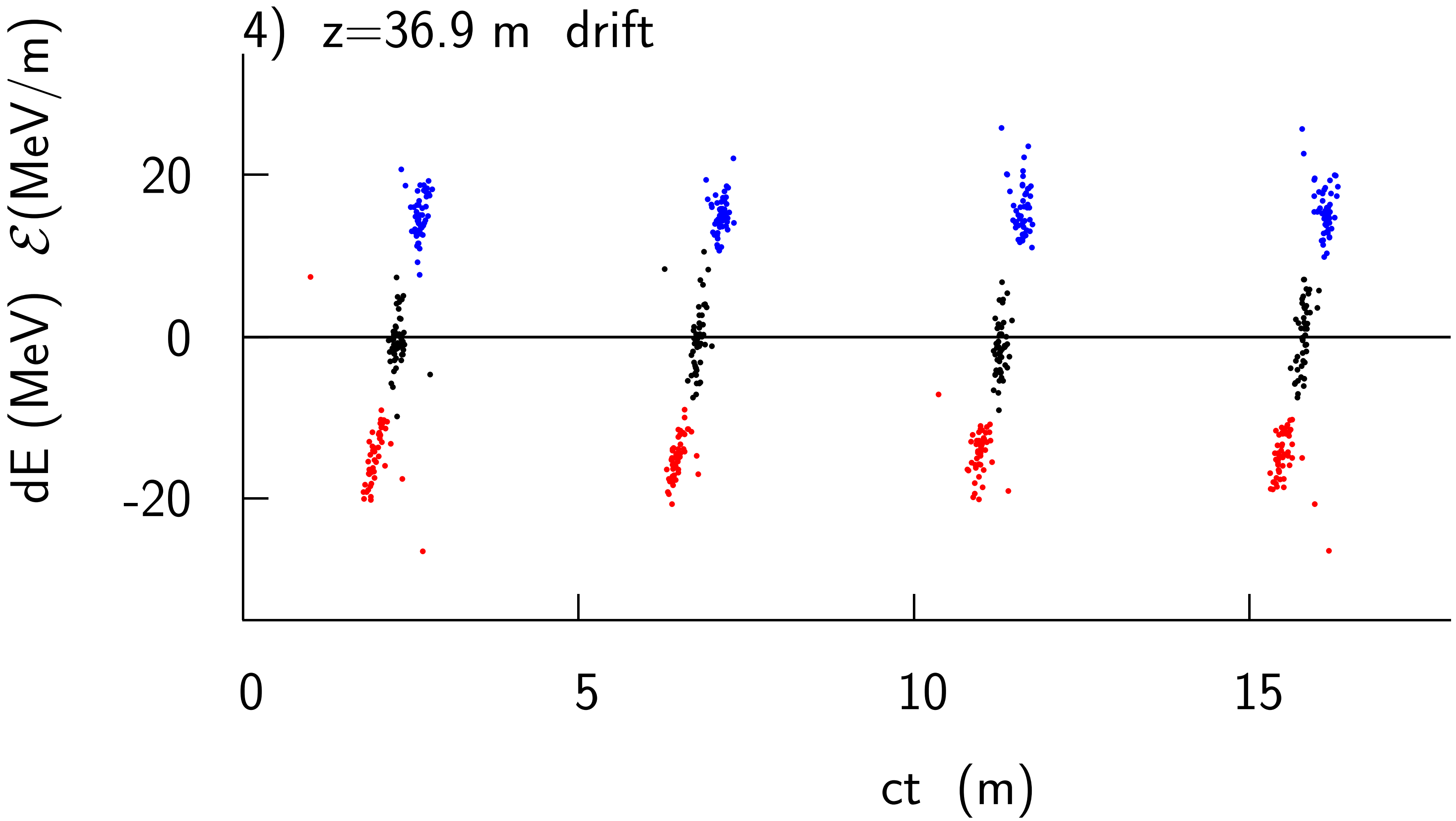


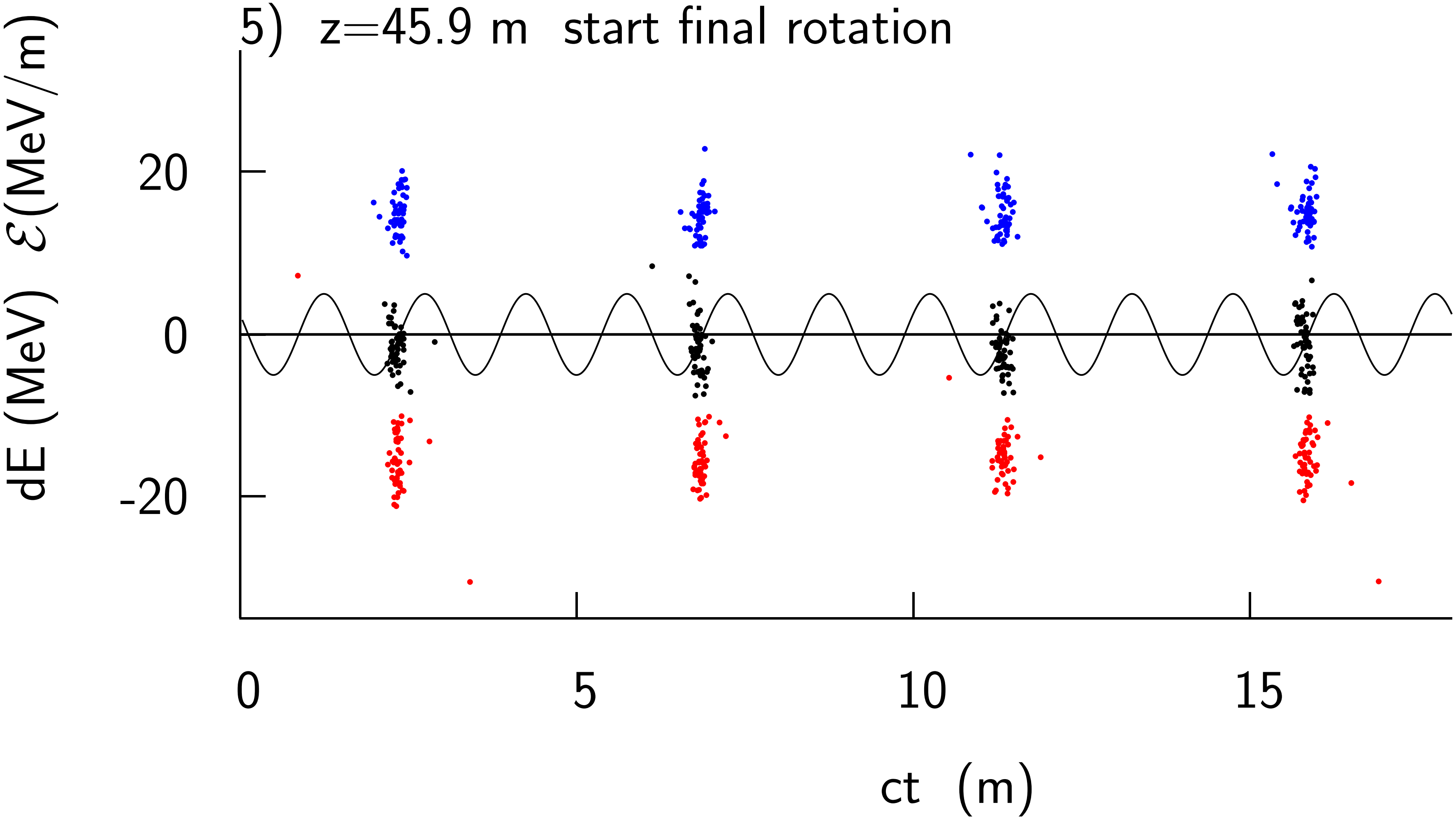

1) z=17.1 m rf with shifted phase
dE (MeV) $\mathcal{E}$(MeV/m)
20
0
-20
0
5
10
15
ct (m)

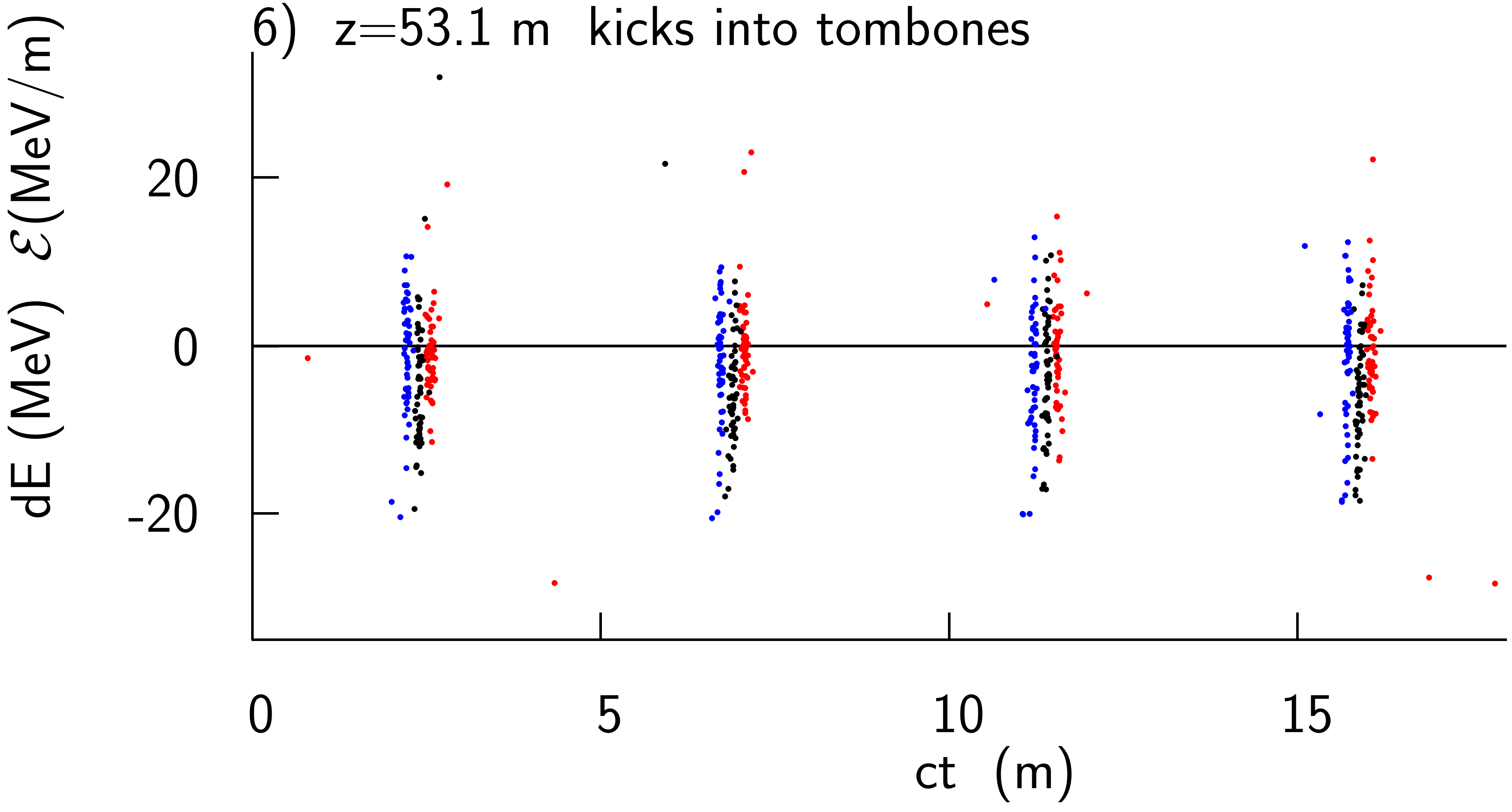

2) z=23.4 m drift
dE (MeV) $\mathcal{E}$(MeV/m)
20
0
-20
0
5
10
15
ct (m)



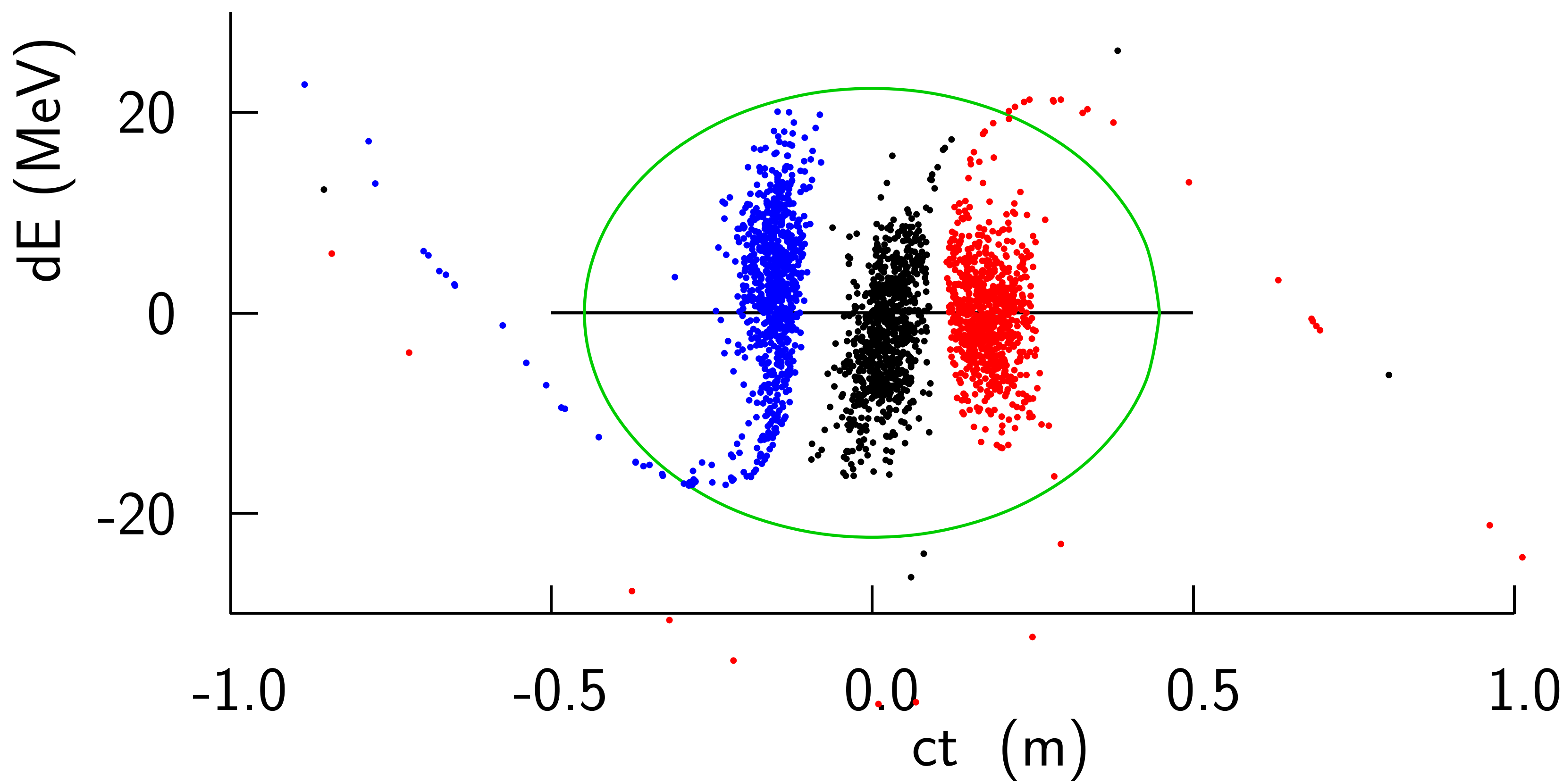
3) z=28.8 m saw tooth rf
dE (MeV) $\mathcal{E}$(MeV/m)
20
0
-20
0
5
10
15
ct (m)


4) z=36.9 m drift
dE (MeV) ℰ(MeV/m)
20
0
-20
0
5
10
15
ct (m)


5) z=45.9 m start final rotation
dE (MeV) $\mathcal{E}$(MeV/m)
20
0
-20
0
5
10
15
ct (m)


6) z=53.1 m kicks into tombones
dE (MeV) $\mathcal{E}$(MeV/m)
20
0
-20
0
5
10
15
ct (m)

Detail after final rotation

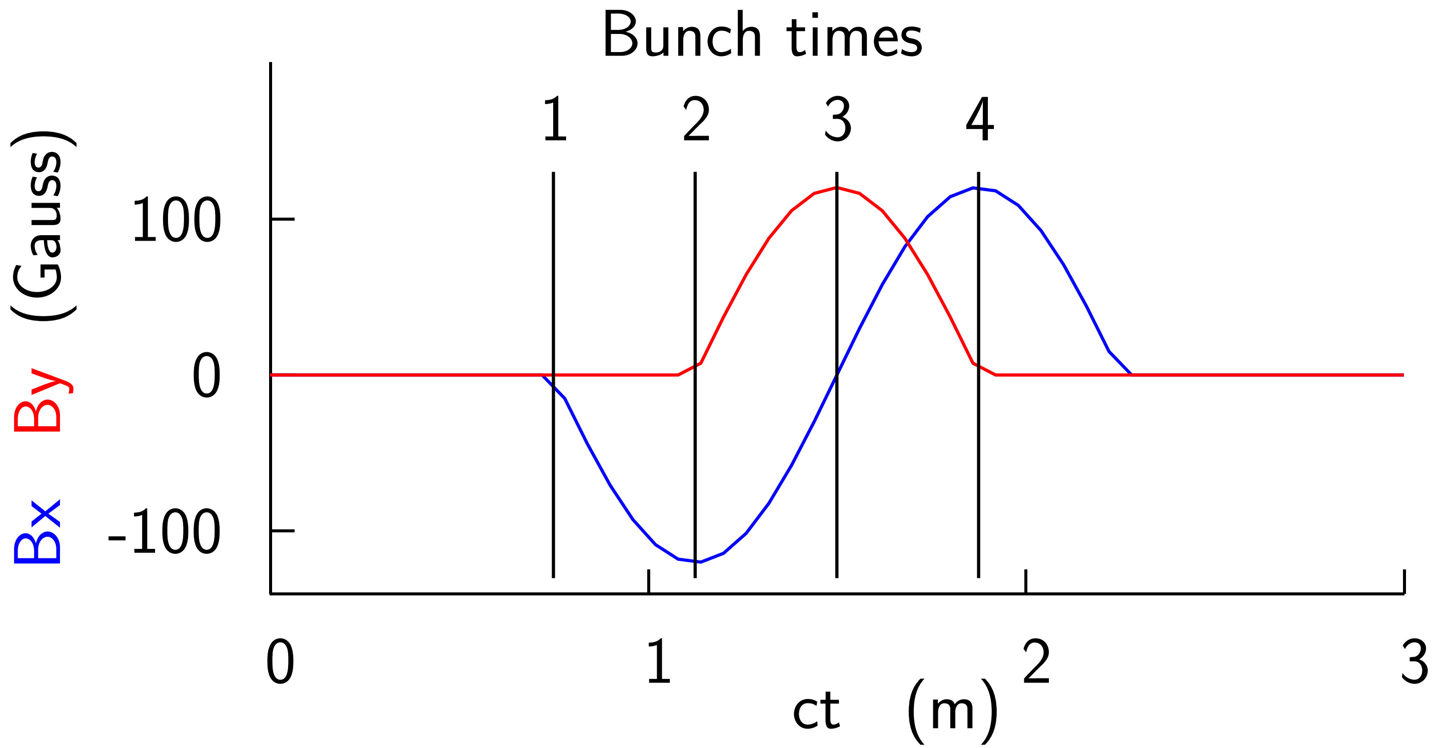


After cut on indicated phase space:

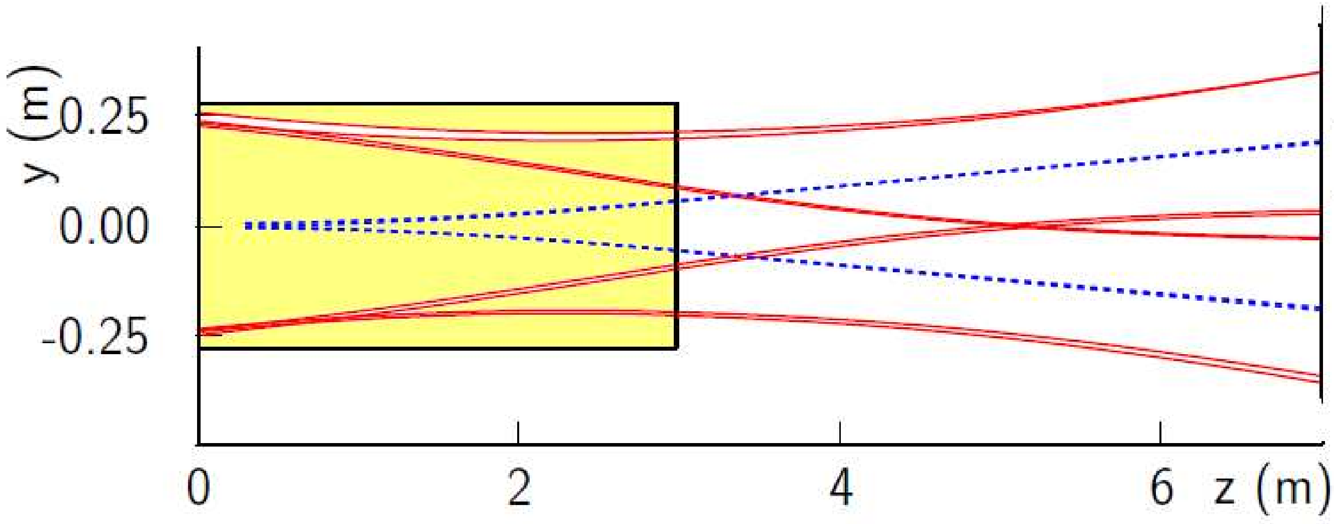
rmsct=0.14 (m) rmsE/E=3.14 % transm=96.4 (%)

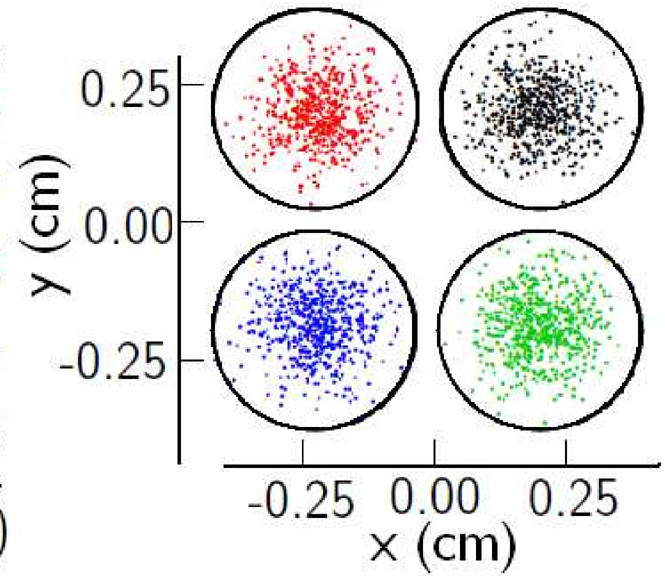
Transverse merging: $4 \rightarrow 1$ bunch

- Use a kicker with both x and y periodic fields
- Kicking the four bunches into four different channels, with differing lengths to bring all four to the same time:
  a Trombone as proposed by Ankenbrandt[2].
- Merge these bunches using a four part toroidal magnet.



Kicker and Fanout





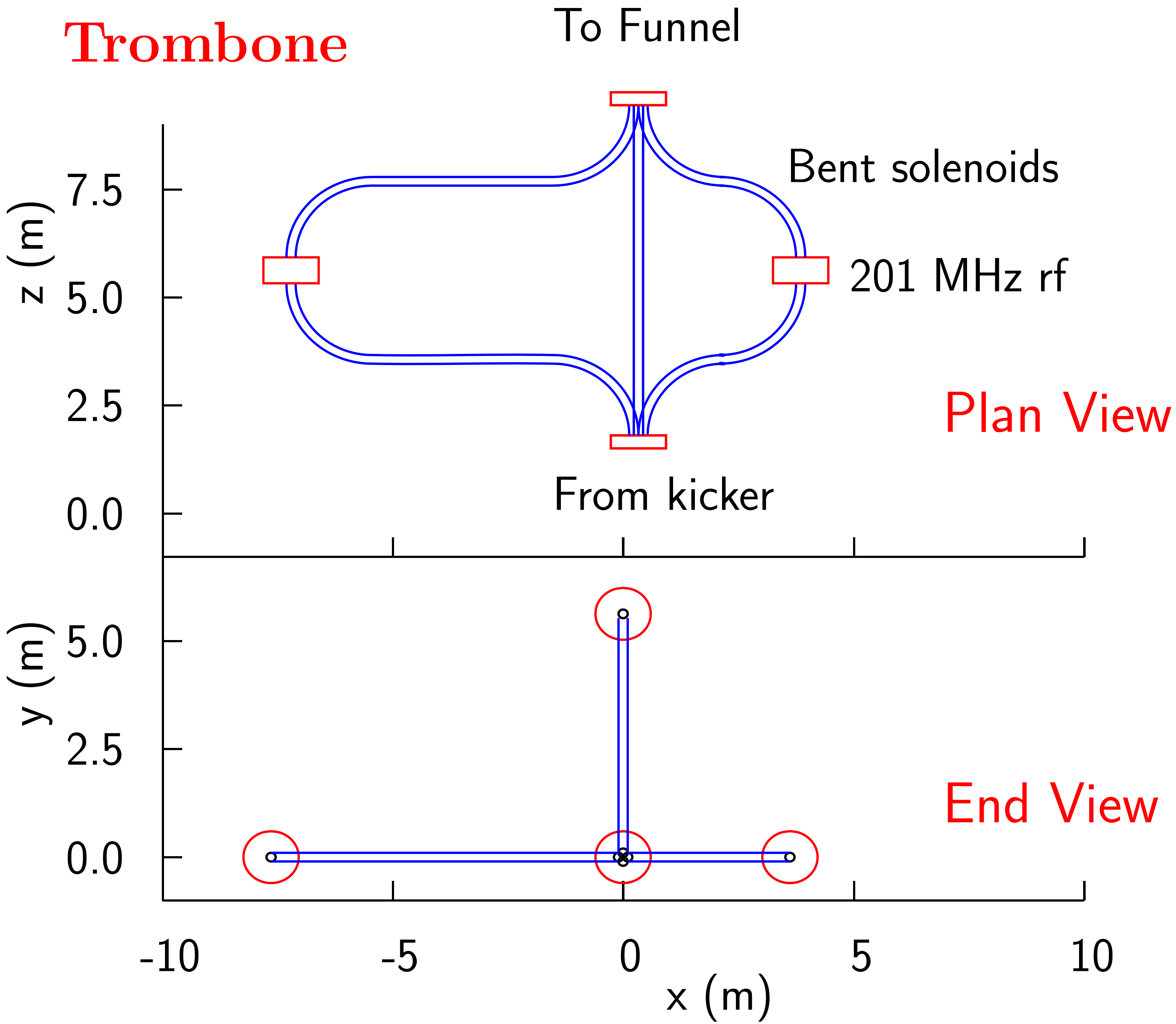
4 sigma beam outlines

xy of muons at end

Kicker field	120	Gauss
Kicker length	3	m
Kicker radius	30	cm
Fanout drift	4	m

After initial 201 MHz rf, 4 beams are matched into 4 different 'trombone[2]' bent solenoid transports with rf at their centers and end.

Trombone



To Funnel
Bent solenoids
201 MHz rf
From kicker
Plan View
End View
z (m)
y (m)
x (m)
7.5
5.0
2.5
0.0
5.0
2.5
0.0
-10
-5
0
5
10

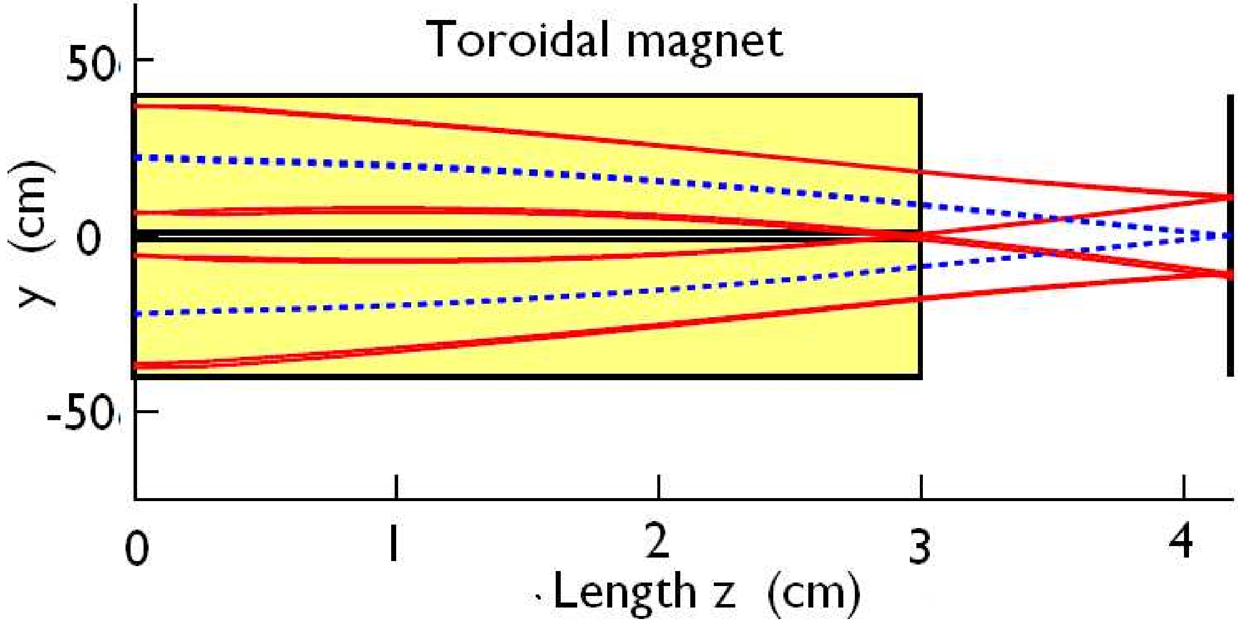
Trombone parameters and performance

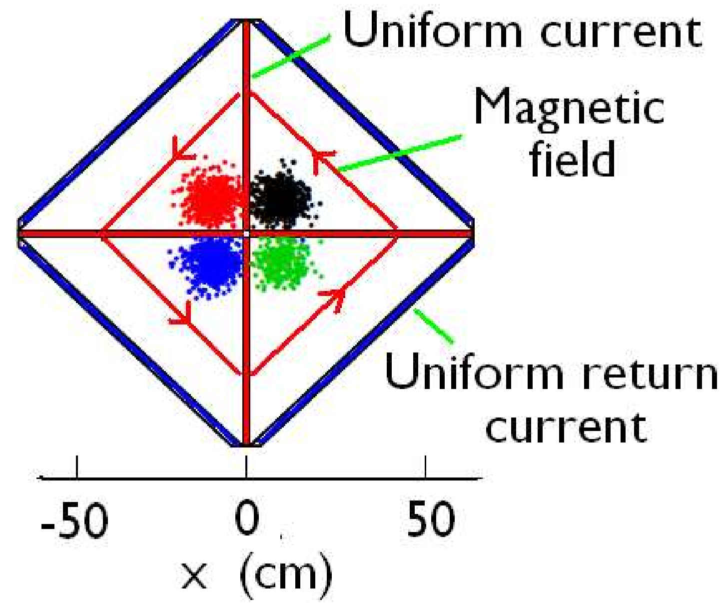
Solenoid fields	1.59	T
Curvatures	0.5678	m^{-1}
Dipole fields	0.4	T
Arc lengths	2.766	m
rf frequencies	201	MHz
Lengths of rf in trombones	0.6	m
Initial & final rf lengths	0.3	m
Initial & final rf gradients	8.6	MV/m

Simulations of trombones done using ICOOL[4]

	Length m	Mid $\mathcal{E}_{\rm rf}$ MV/m	$\epsilon_\perp$ mm	Dif %	$\epsilon_\parallel$ mm	Dif %	Transm %
Initial			1.20		8.92		100
1	8.25	0	1.20	0	8.90	-0.2	100
2	12.27	5.8	1.23	+2.5	8.85	-.7	99
3	16.20	12.2	1.25	+4.2	9.05	+1.4	98
4	20.30	17.5	1.24	+3.3	9.21	+3.3	98
ave.	14.25		1.23	2.5	9.00	0.9	98.75

Funnel merging 4 beams from 4 trombones





4 sigma beam outlines

xy of muons
at end of toroid

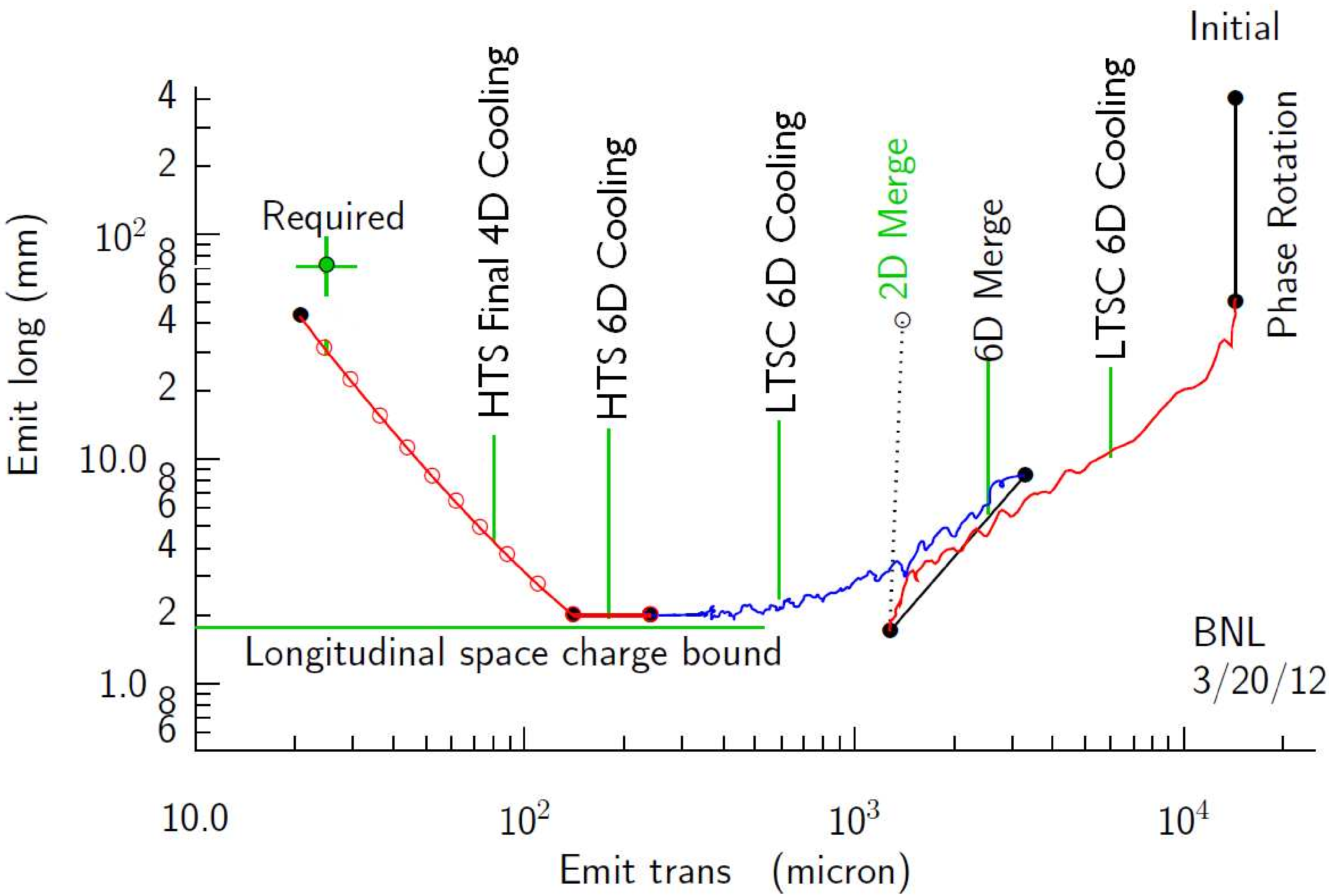
Toroidal field	240	Gauss
Septum thickness	2	cm
Current density	240	Gauss
Radius	75	cm
Length	300	cm

Combined performance

Initial $\epsilon_\perp$	1.3	mm
Initial $\epsilon_\parallel$	1.7	mm
Final $\epsilon_\perp$	3.5	mm
Final $\epsilon_\parallel$	9.0	mm
Long merge transmission	96	%
Kicker and capture	99	%
Trombone	98.75	%
Transverse funnel	98	%
Decay in 53+19=72 m	94.5	%
Overall transmission	87	%

Cooling Sequence with this merge

ICOOL Simulations of 6D cooling are for Guggenheim lattices



Conclusion

- For efficient initial capture we 'phase shift' muons into 12 bunches
- For luminosity we merge these bunches when initial cooling allows
- Merging in only longitudinal space matches poorly back into re-cooling
- Cooling in all 6 dimensions matches well
- We present a way to do this:
  - using harmonic rf in a simple transport, for the longitudinal part;
  - a kicker and trombones for the transverse part.
- The average decay length is 72 m
- The combined transmission of 87%

- Work is needed on design of rf systems, kicker, toroid, and matching
- Full simulation in 3 dimensions is planned

References

References

[1] D. Neuffer, MuCool-Note-269, http://nfmcc-docdb.fnal.gov/

[2] C. Ankenbrandt, http://indico.fnal.gov/getFile.py/access?contribId=65 &sessionId=28&resId=0&materialId=slides &confId=2854

[3] D. Neuffer et al, MuCool-Note-548, http://nfmcc-docdb.fnal.gov/

[4] R. Fernow, Proc. 2005 Part. Acc. Conf., p. 2651.