Simulations of a proton FFAG with space charge

FFAG'12, Osaka, Japan

Overview

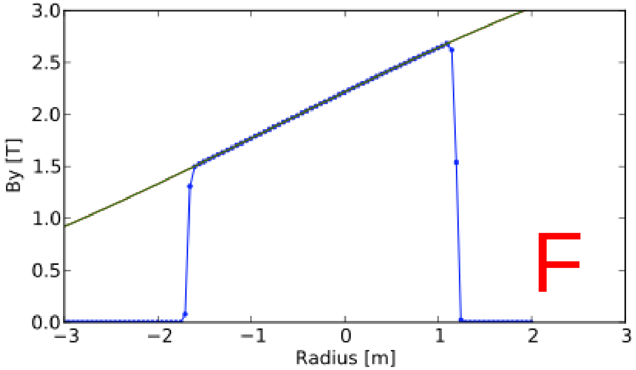
- Motivation
- 4-cell 1GeV FFAG
  - Single energy simulations
  - Serpentine acceleration with SC
- 6-cell 1GeV FFAG simulations
  - Single energy simulations
  - Serpentine acceleration with SC
- Two discussion points:
  - Cost to build an FFAG vs linac
  - Terminology
- Summary

Motivation

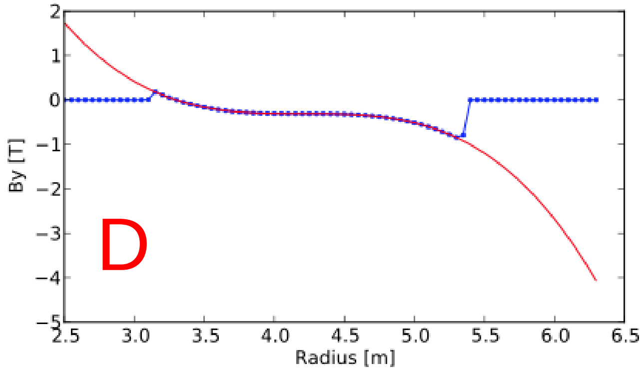
- For ADS & other high power beam applications a CW beam offers many advantages
  - Lower peak current (lower space charge forces)
  - Flexible beam structure depending on injector (can leave ‘gaps’ if you want to)
  - Implies fixed RF & fixed field – less to go wrong?
- Would harness full potential of the FFAG
  - We’ve been promising “improved performance” with FFAGs but have we delivered it?

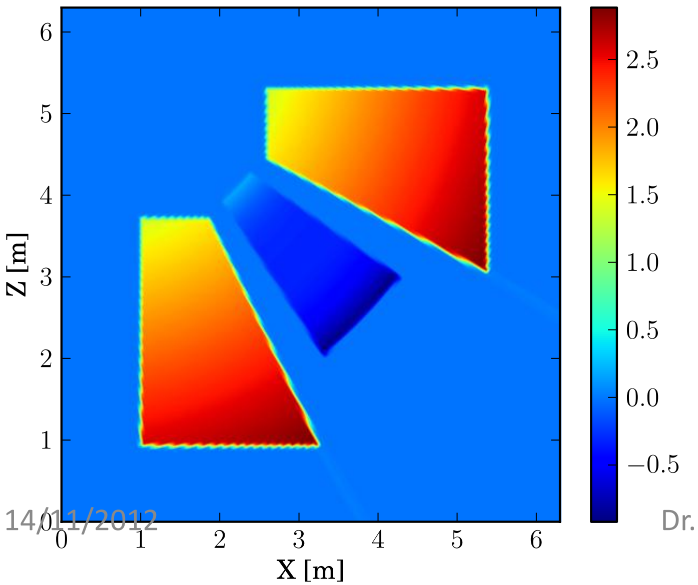
4-cell Lattice design

Parameter	250 MeV	585 MeV	1000 MeV
Avg. Radius [m]	3.419	4.307	5.030
ν_x/ν_y (cell)	0.380/0.237	0.400/0.149	0.383/0.242
Field F/D [T]	1.62/−0.14	2.06/−0.31	2.35/−0.42
Magnet Size F/D [m]	1.17/0.38	1.59/0.79	1.94/1.14



Total tune variation = 0.12 (H) / 0.56 (V)

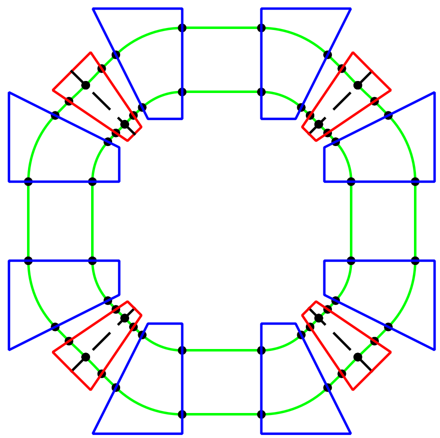


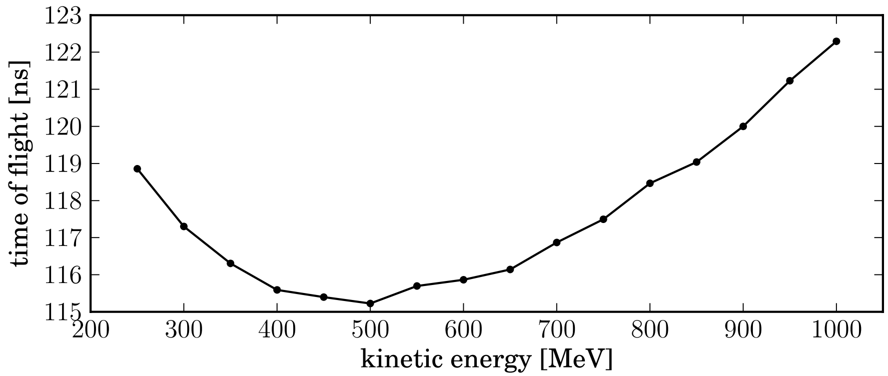


C. Johnstone et al, AIP conference proceedings 1299, 1, 682-687 (2010)

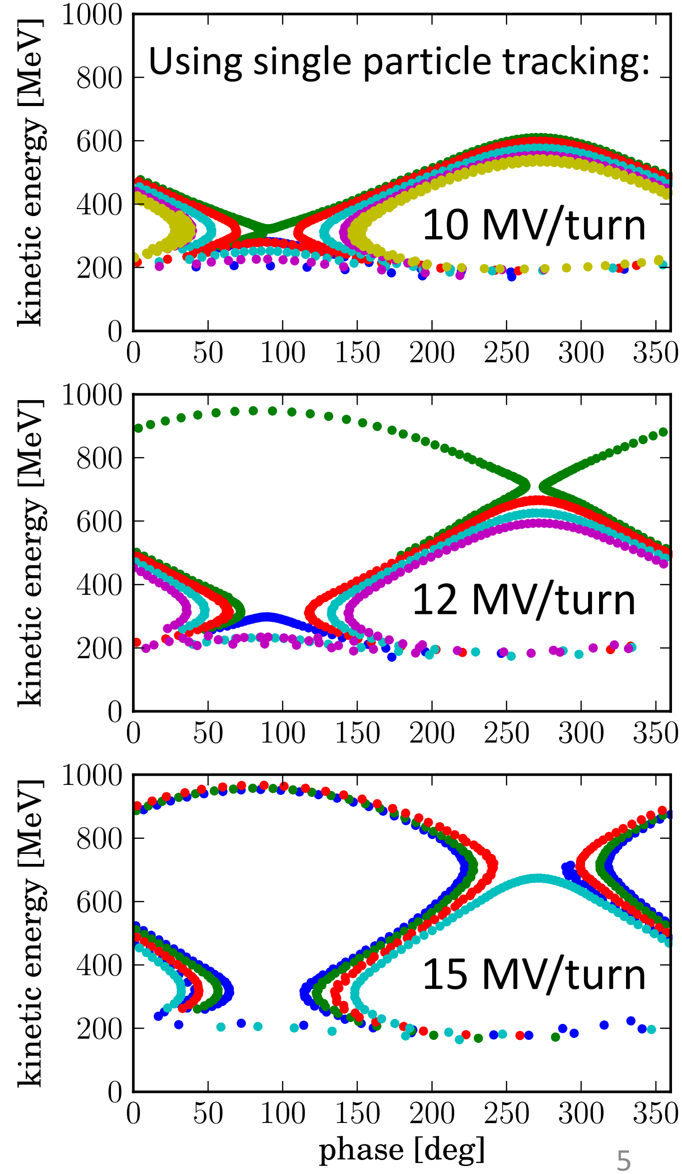
Serpentine channel acceleration

- Using Carol's 4-cell 1 GeV FFAG ring
- 330MeV-1GeV
- Serpentine acceleration is possible due to 3% time of flight variation





From IPAC'11, S. L. Sheehy, WEPS088



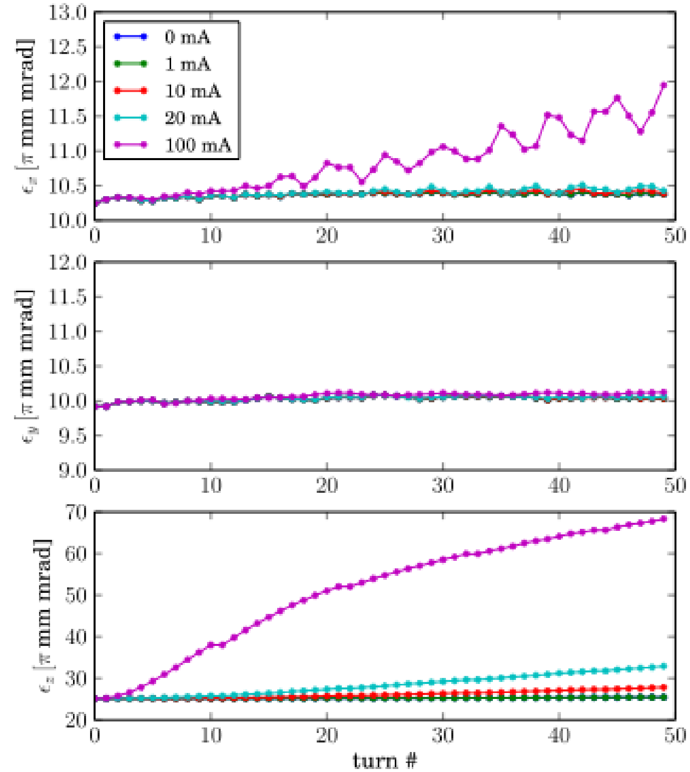
Motivation continued…

- Serpentine channel acceleration was not something I was going to pursue, until…
- Discussions with Mori-san and others at HB2012 in Beijing led me to consider whether 'almost' isochronous is good enough if we have small chromaticity.
  - (Ref. Yamakawa et al. HB2012 paper also suggests using serpentine channel in FFAG.)
- But… I have concerns over achievable RF voltage…
  - (h=1 needs voltage of 20 MV/turn in racetrack ring)
- Mori suggests possibility of superconducting large horizontal aperture cavities?
  - have these ever been designed?
  - (Or should we think about finding someone to design one?)

I concluded that regardless of the issue of large V/turn, it would be interesting to know what happens in the serpentine channel with space charge…

Setting up the simulation in OPAL

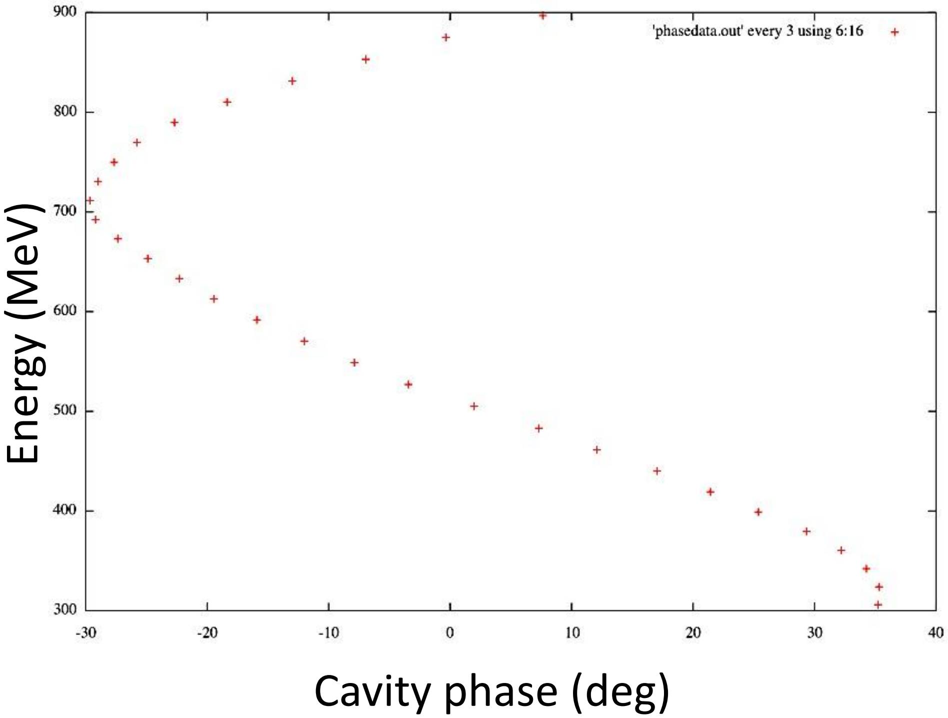
- Beam matching at 300 MeV
- Single energy tracking at realistic intensities shows no emittance growth.
- At very high intensities emittance grows, as expected.
  - (See HB2012 MOP258)



Single bunch
10 π mm mrad in horiz/vertical
Length ~ 4% of ring circumference
50 turns at 300 MeV with no acceleration
Current is average of full turn

Setting up the simulation

- Harmonic number = 1 (for now)
- Space charge 'off' – track bunch of 2000 particles with parabolic profile

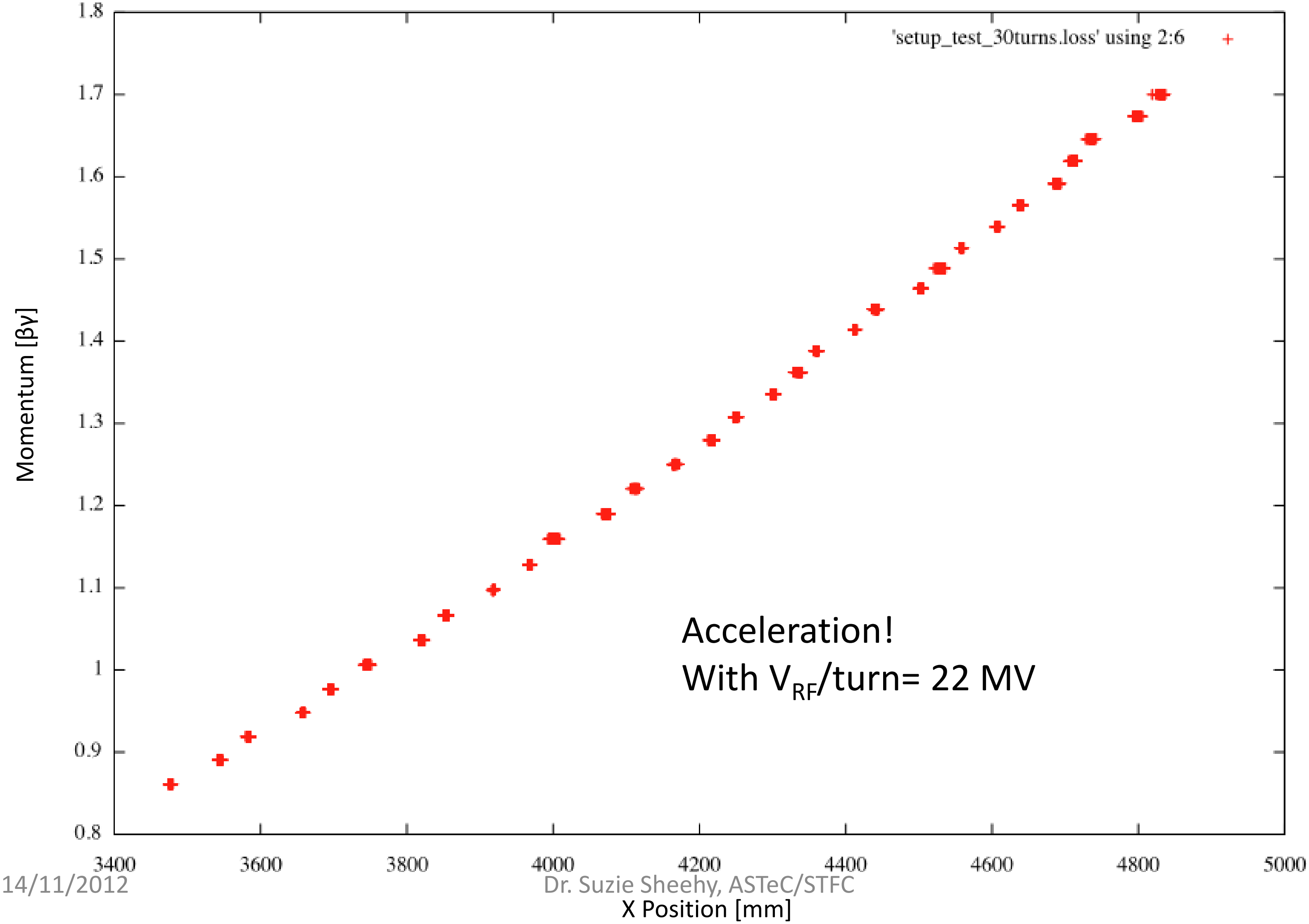


Issue: OPAL outputs after set num of tracking steps NOT azimuthal position ie. not a full 'turn' if not perfectly on phase! In the newer version of OPAL (1.1.9) I can use 'probe' element to get 'screen-like' physical position readout (in process of updating on SCARF).

For now – the following simulations were run overnight on my quad core desktop!

Turn-by-turn orbit with bunch

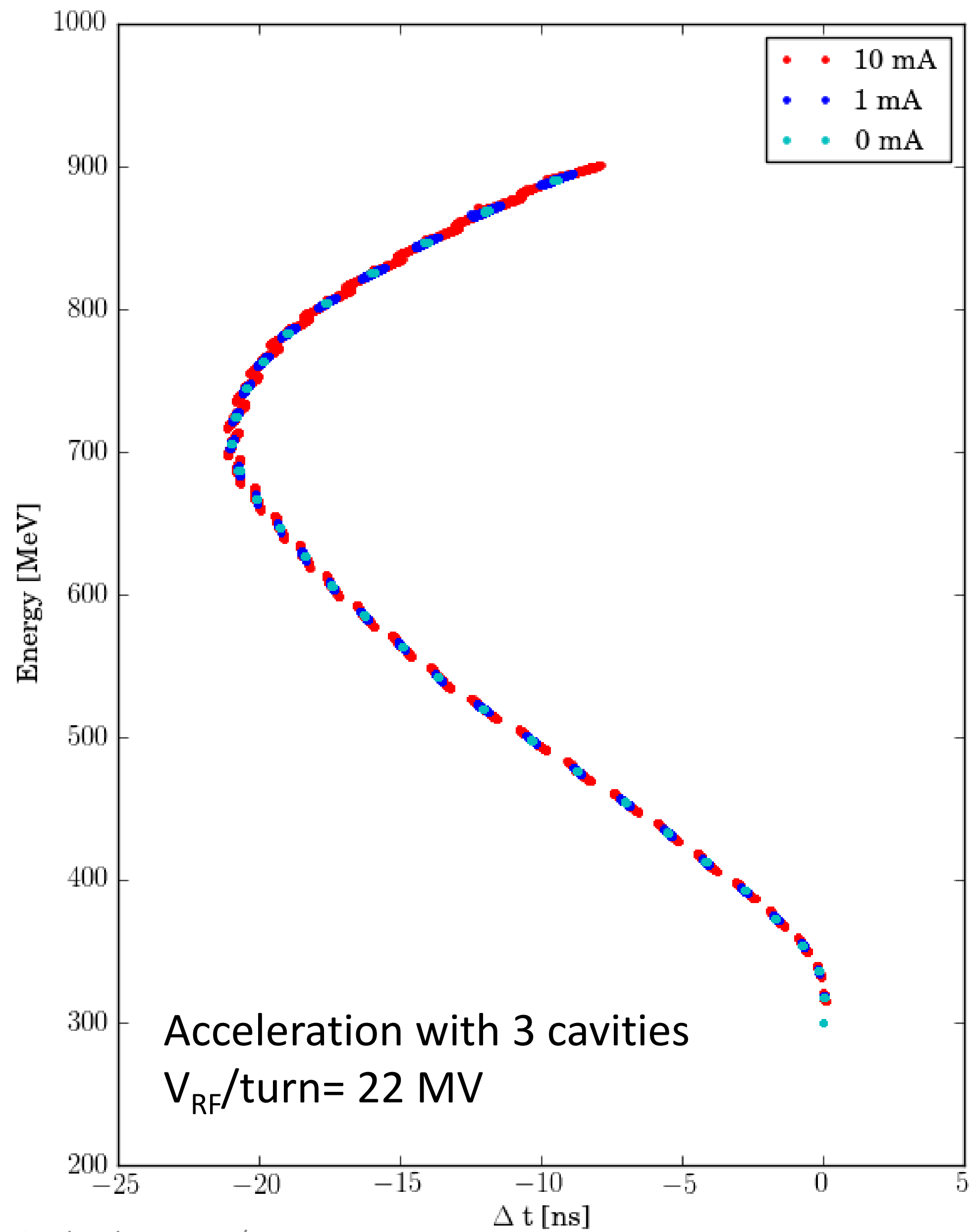
- Try a short & small 1 π mm mrad beam to see what happens
- Using 'probe' element to get turn-by-turn at 0 degree position, 200 particles



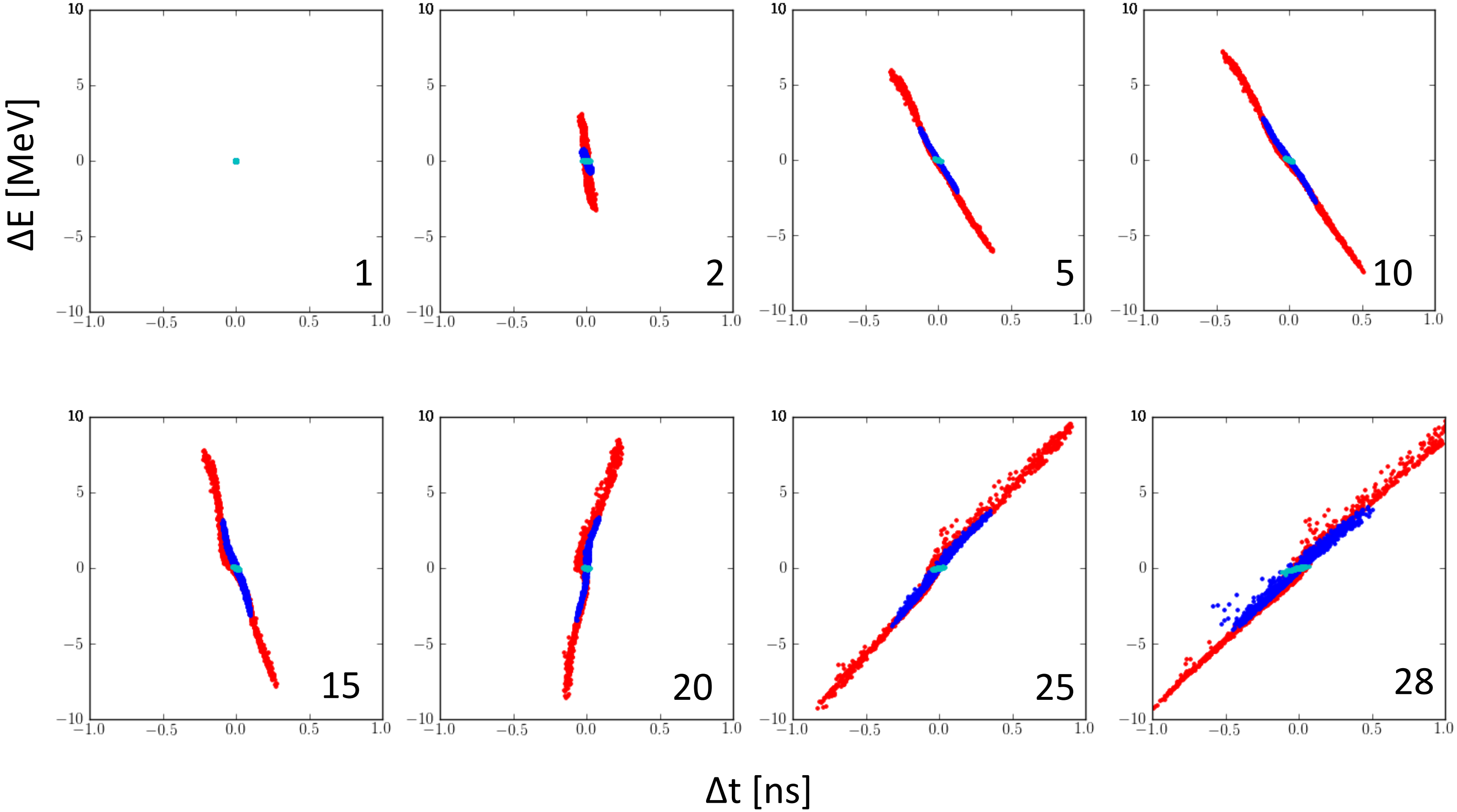
With space charge 'on'

- 1 pi mm mrad bunch
- Tracked for 30 turns in serpentine channel
- Vary (average) beam current up to 10 mA
- 10 MW beam at 1 GeV

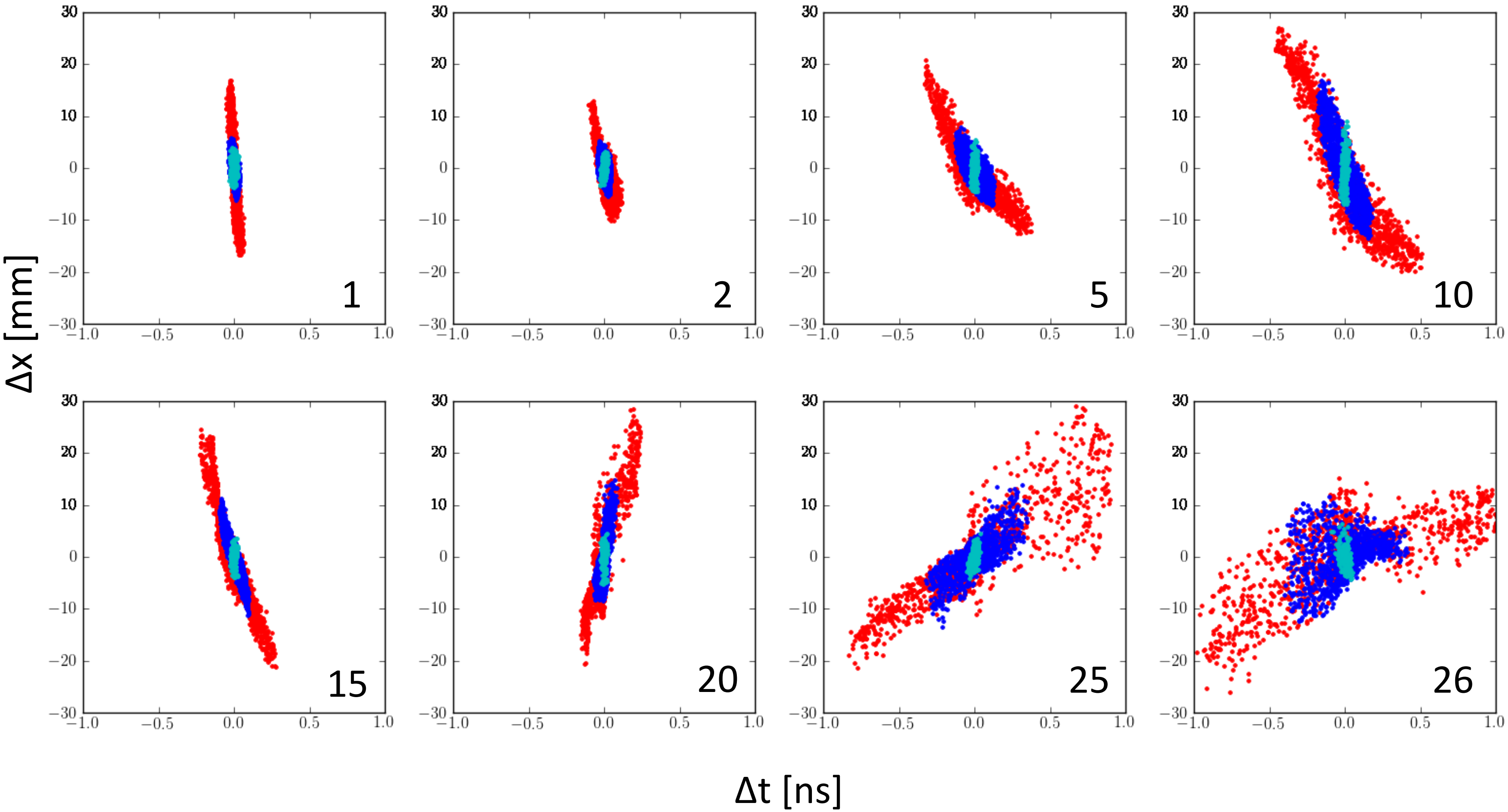
- NOTE: VERY SHORT BEAM!
- Total beam length approx. 1cm so peak current = 22A!
- Lots of space charge!!



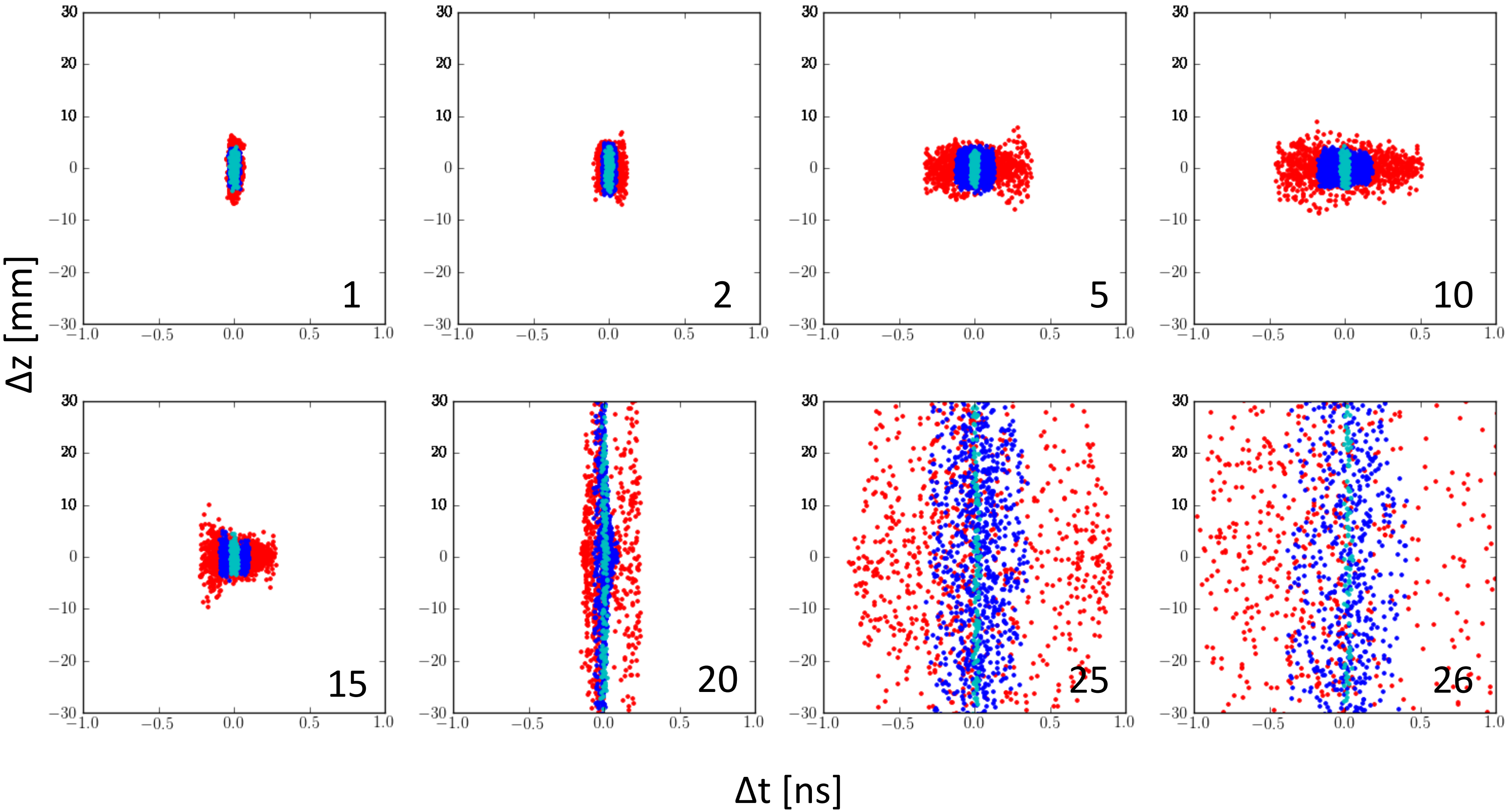
Longitudinal evolution



Horizontal pos vs time



Vertical pos vs time

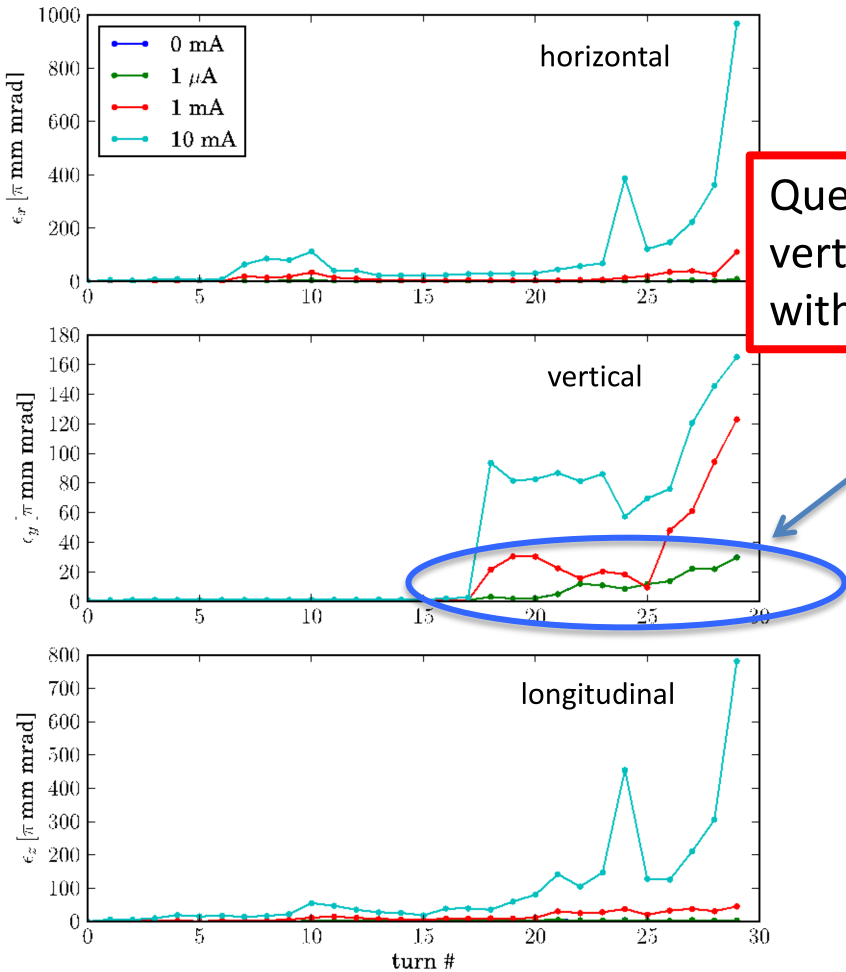


Emittance evolution

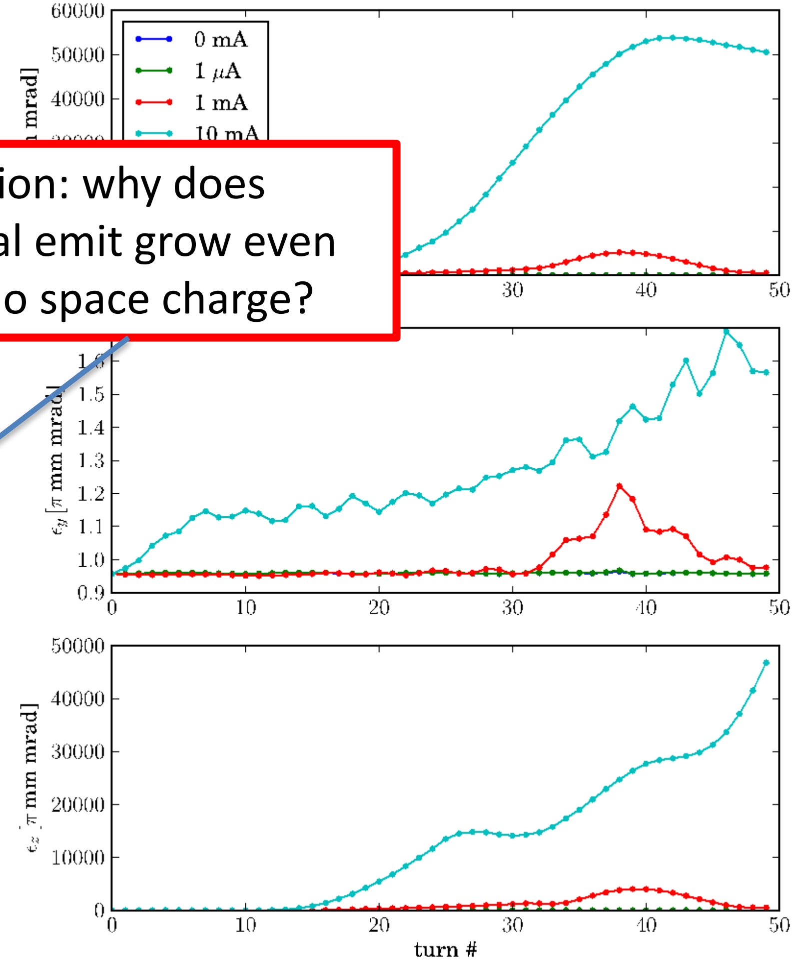
(NB as discussed before these are per 'turn' wrt time so not 'real' turns)

NOTE DIFFERENT SCALES!!

300 MeV – 30 turn serp. Accel.



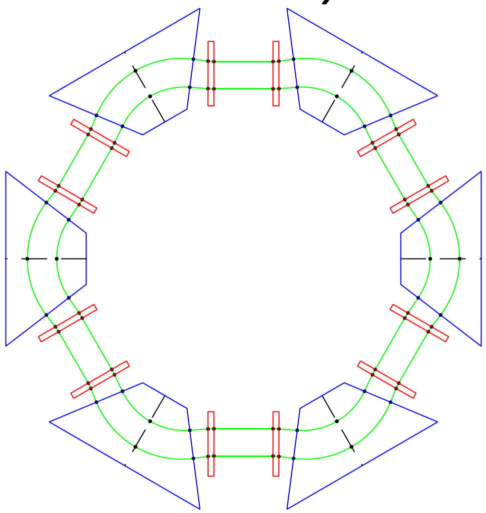
300 MeV – no acceleration



Question: why does vertical emit grow even with no space charge?

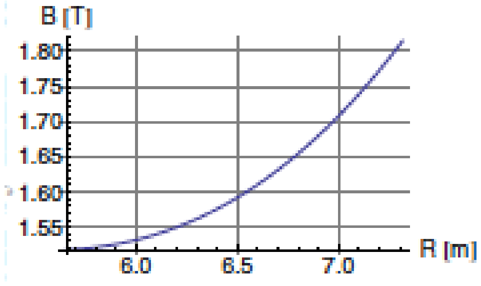
6-cell 1GeV Ring

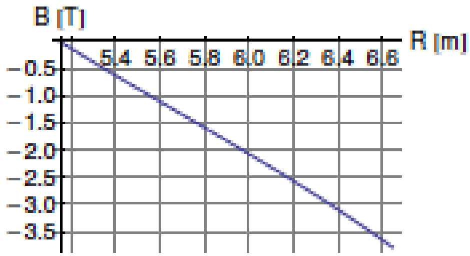
- Initially I had issues modeling this ring as short magnets were not well-reproduced with the interpolation in OPAL
- I now have a much finer field map! (thanks to K. Makino)
- The main driver behind this design was to achieve better *isochronicity* but the vertical tune variation also improved.



Parameter	330 MeV	500 MeV	1000 MeV
Avg. Radius [m]	5.498	6.087	7.086
ν_x/ν_y (cell)	0.297/0.196	0.313/0.206	0.367/0.235
Field F/D [T]	1.7/−0.1	1.8/−1.9	1.9/−3.8
Magnet Size F/D [m]	1.96/0.20	2.79/0.20	4.09/0.20

- Total tune variation = 0.42 (H) / 0.234 (V)
- Lower B field (cf 2.35T in 4-cell design)
- Larger radius

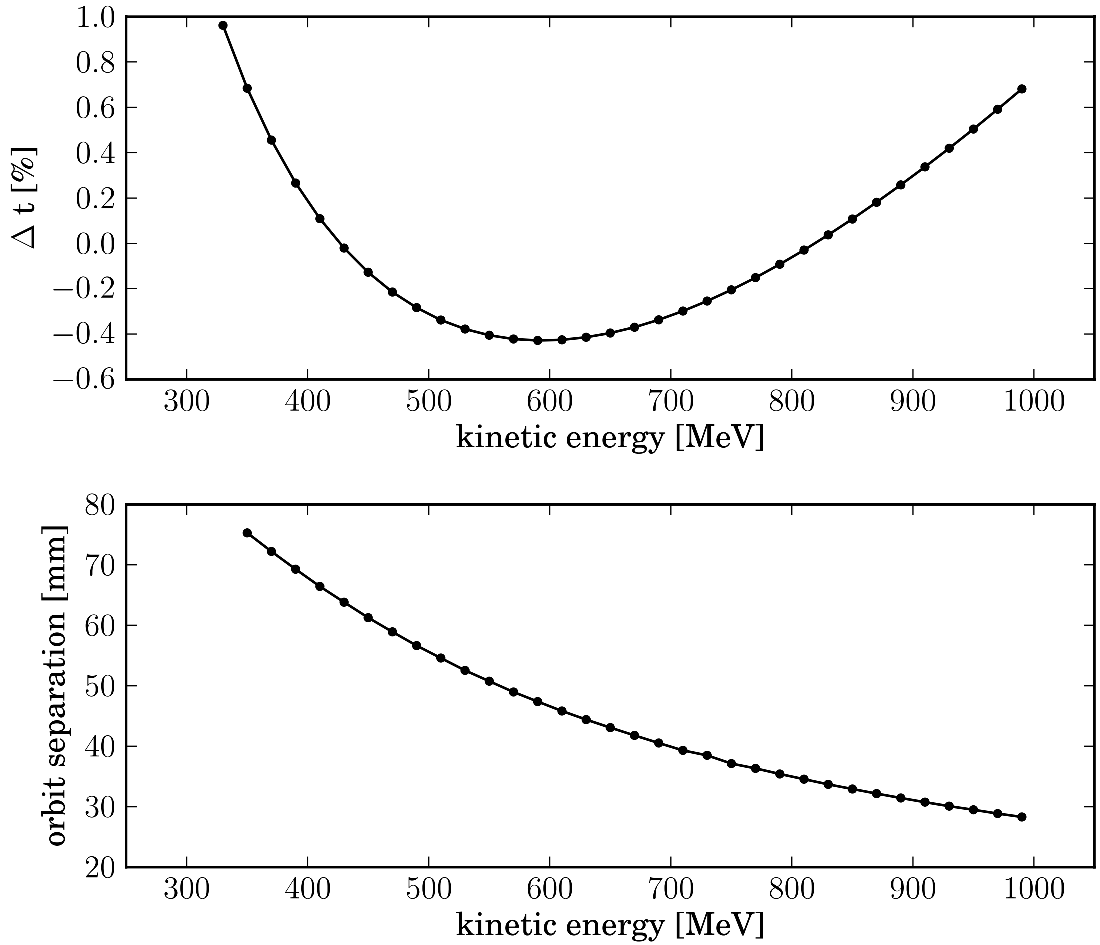




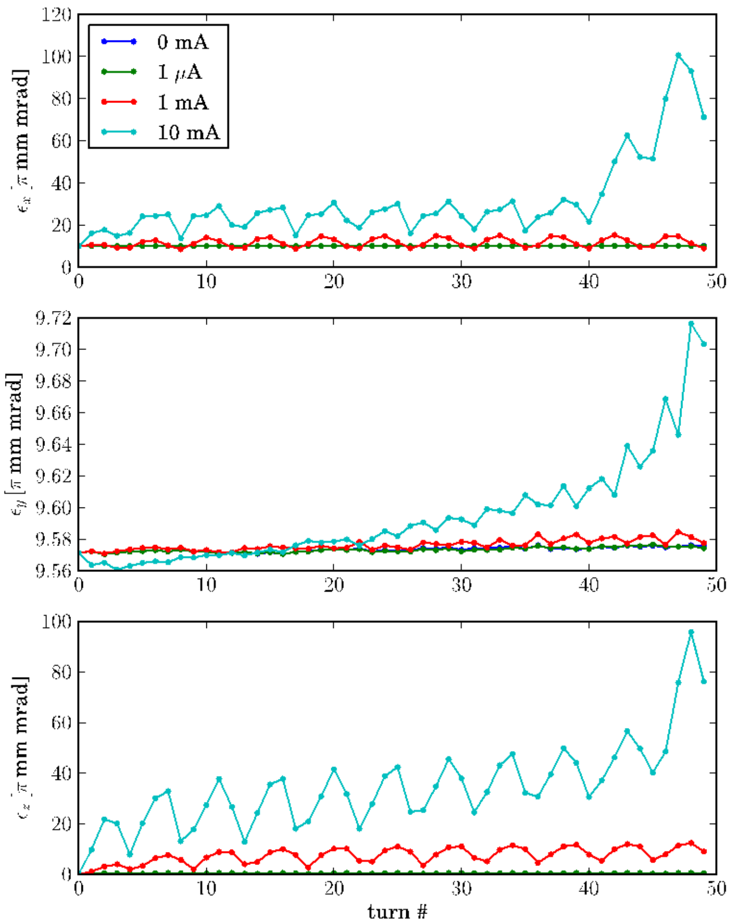
Field profiles from C. Johnstone, IPAC’12, THPPR063

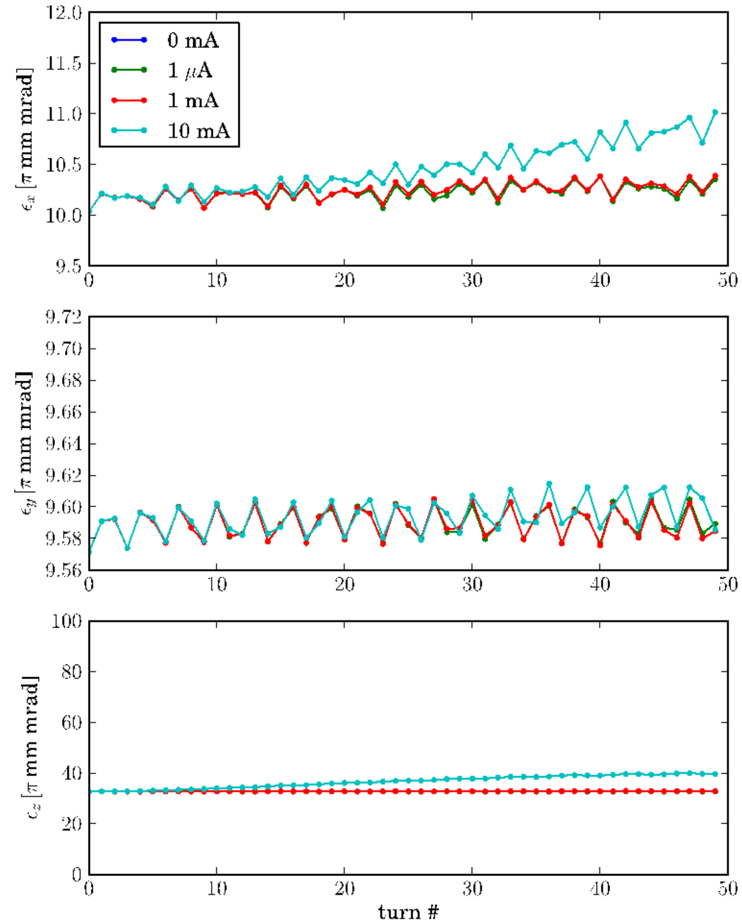
6-cell 1 GeV Ring

Single energy closed orbits separation & TOF in 20 MeV steps



Single energy with space charge





- No acceleration, 10 pi beam
- 50 turns with space charge
- Short beam (0.04% ring)

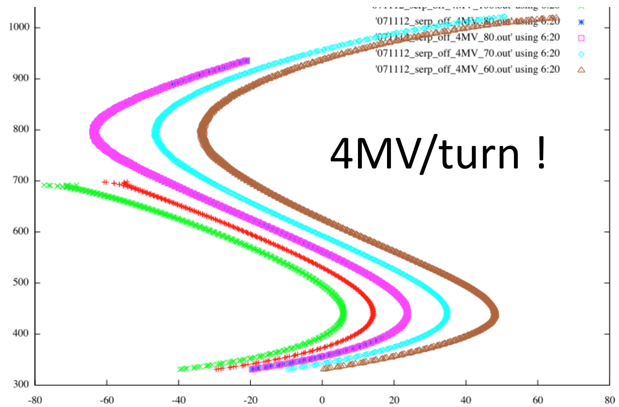
- No acceleration, 10 pi beam
- 50 turns with space charge
- Longer beam (4% ring)

Serpentine channel

- Much smaller TOF variation than 4-cell version
- Required RF frequency & energy gain per turn to open up the serpentine channel (δE) can be estimated by

$$f_{RF} = \frac{1}{T_{min} + \delta T/4}$$

$$\delta E = \frac{\omega\, \delta T\, \Delta E}{16}$$



total energy gain required is ΔE and $\omega = 2\pi F_{RF}$

In this case, we expect **δE ~ 3.7 MV/turn**.

(A few quick simulations confirm this)

If we make it 'isochronous enough', perhaps we can use the serpentine channel without superconducting cavities?

Acceleration & space charge

- Use 'reasonable' 8MV/turn (equiv. 4 PSI-type cavities)
- Beam matched at 330 MeV
- Same emittance & length beam as in 6-cell simulations

Summary so far…

- The two rings are comparable in terms of emittance growth with single energy tracking.
- The 6-cell ring has a serpentine channel at a much lower voltage/turn due to improved isochronicity
- A small emittance/length beam is transmitted fine using the serpentine channel – 4-cell design seemed to grow in vertical, waiting to see for 6-cell design.
- Still need to try a more realistic beam.
- Some interesting beam distribution shaping effects in serpentine channel with space charge.

How much would it cost?

- *Argument for FFAGs has been: 'smaller than a linac, so must be cheaper to build!' but I would like some evidence to support this*...
- Email discussion with S. Holmes & V. Lebedev:

  2-8 GeV RCS total = $150M
  - Technical Components $84M
  - Conventional Construction $67M

  Pulsed Linac total = $210M
  - Technical Components $134M
  - Conventional Construction $76M

Aside… terminology

- I’m going to call this an “FFAG Cyclotron”

We should use terminology familiar to those outside of our sub-field.

- Radial sector cyclotron with reverse bends… ?
- FFAG is a blanket term for a wide range of machines. ‘Scaling’ and ‘non-scaling’, ‘linear’ and ‘non-linear’ tends to confuse others
- Some are more similar to cyclotrons, some to synchrotrons. Yet outside of FFAG workshop, no-one knows the difference.
- They are mostly pitched for applications - no-one will take the risk on a completely new technology, but this *isn’t* completely new!

In Australia we have a tendency to call a spade a spade. In the FFAG field we have the tendency to call a spade a ‘non-linear non-scaling quasi-isochronous earth removal device’. Who wants one of those? No-one. They just want a spade.

References

Lattice design:

- C. Johnstone, P. Snopok, F. Meot, In Proc. IPAC’12, pp. 4118 (THPPR063).
- C. Johnstone et al, AIP conference proceedings 1299, 1, 682-687 (2010)
- C. Johnstone, Proc. Cyclotrons (2010)

Serpentine channel (for practical formulae):

- S. Koscielniak, C. Johnstone, Nucl. Instrum. Meth. Phys. Res. A (523), pp. 25-49, 2004.

Radial sector ‘FFAG cyclotron’:

- M. K. Craddock and Y-N. Rao, ‘FFAGs and cyclotrons with reverse bends’, in PAC (2009) Vancouver.
- M. K. Craddock, talk at FFAG’08, Manchester.