High Current Proton FFAGs for ADSRs

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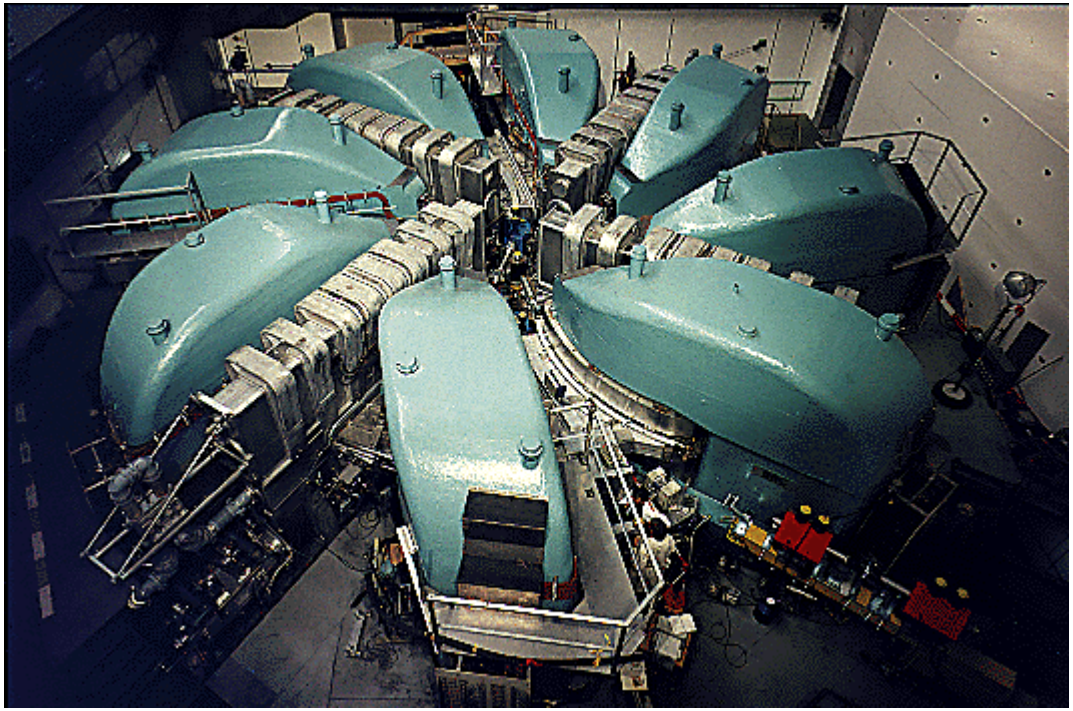
Beam Requirements

- Beam Requirements
  - For 600 MW power station
  - 40% thermal-to-electric efficiency
  - Need 1.5 GW thermal
  - Spallation optimal around 1GeV
  - For 150× gain (depends on neutron yield, core k)
  - Need 10 MW beam

Beam Requirements

- 10 MW needs a high current
- Current 20mA @ 500MeV or 10mA @ 1GeV
  - PSI main Cyclotron 590 MeV x 2 mA
  - 15 m diameter



Beam Requirements

- 10mA @ 1GeV
  - = 6.2 x 10^{16} Protons per second
  - With 1kHz acceleration cycle
  - = 6.2 x 10^{13} Protons per cycle
- These are high bunch charges, so space charge may be an issue

Space charge

- Each proton in the bunch feels a repulsive force from the other protons
- This increases with charge density
- The effect is suppressed at high energy
- The first effect is transverse defocusing which can be expressed as a tune shift

Space charge

- Approximate tune shift for synchrotron:

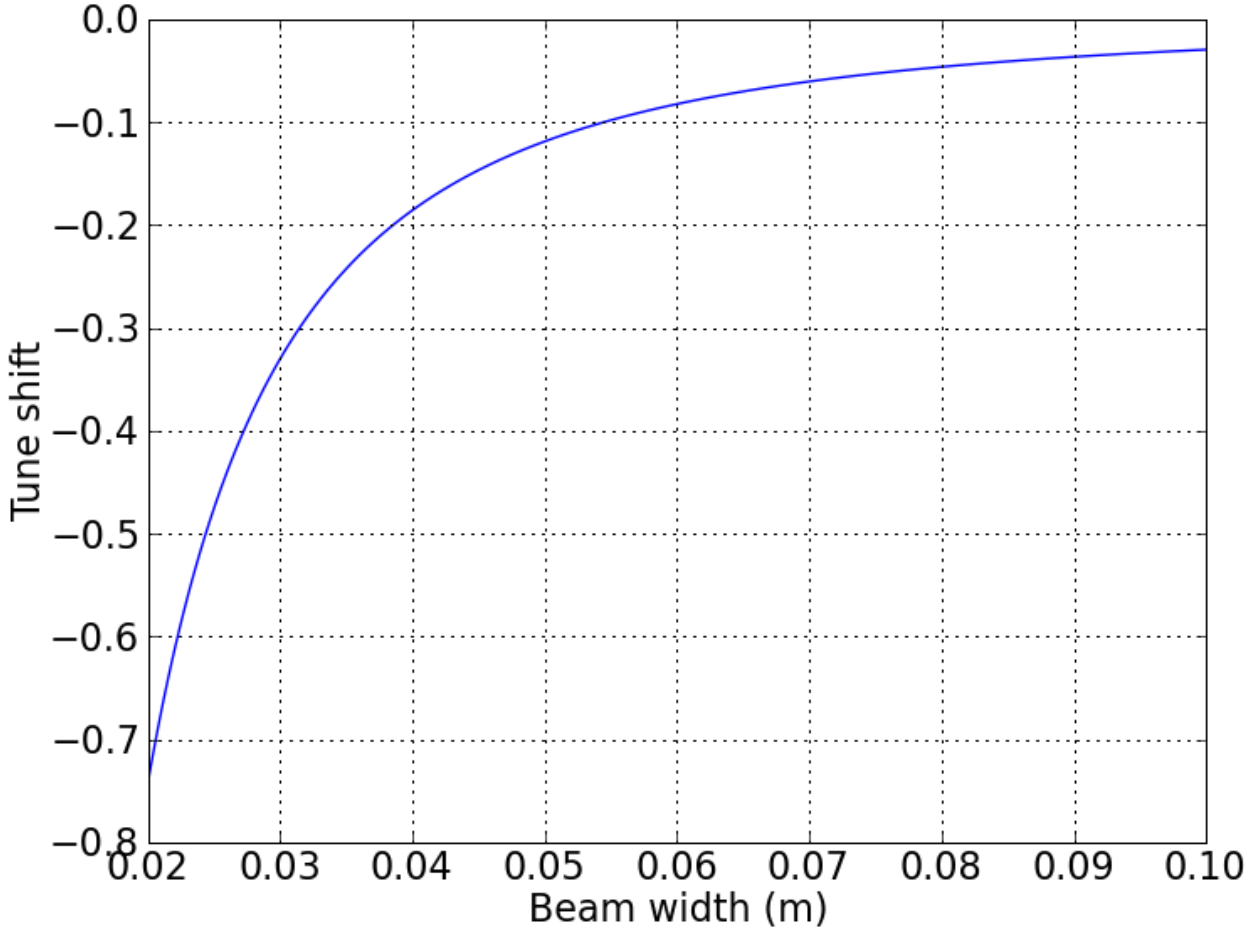
$$\delta Q \approx \frac{-r_0 R N}{2 Q \beta^2 \gamma^2 S}$$

r_0 : classical proton radius
R : machine radius
N : number of protons
Q : tune
β,γ : relativistic factors
S : beam cross section

- Worst effect when energy is low
- Rule of thumb is to keep below 0.25
  - In synchrotrons this is to avoid resonances, the limit may be different for an FFAG

Space charge

- For my 30 m circumference ring, injecting at 70MeV with 6.2×10^{13} protons

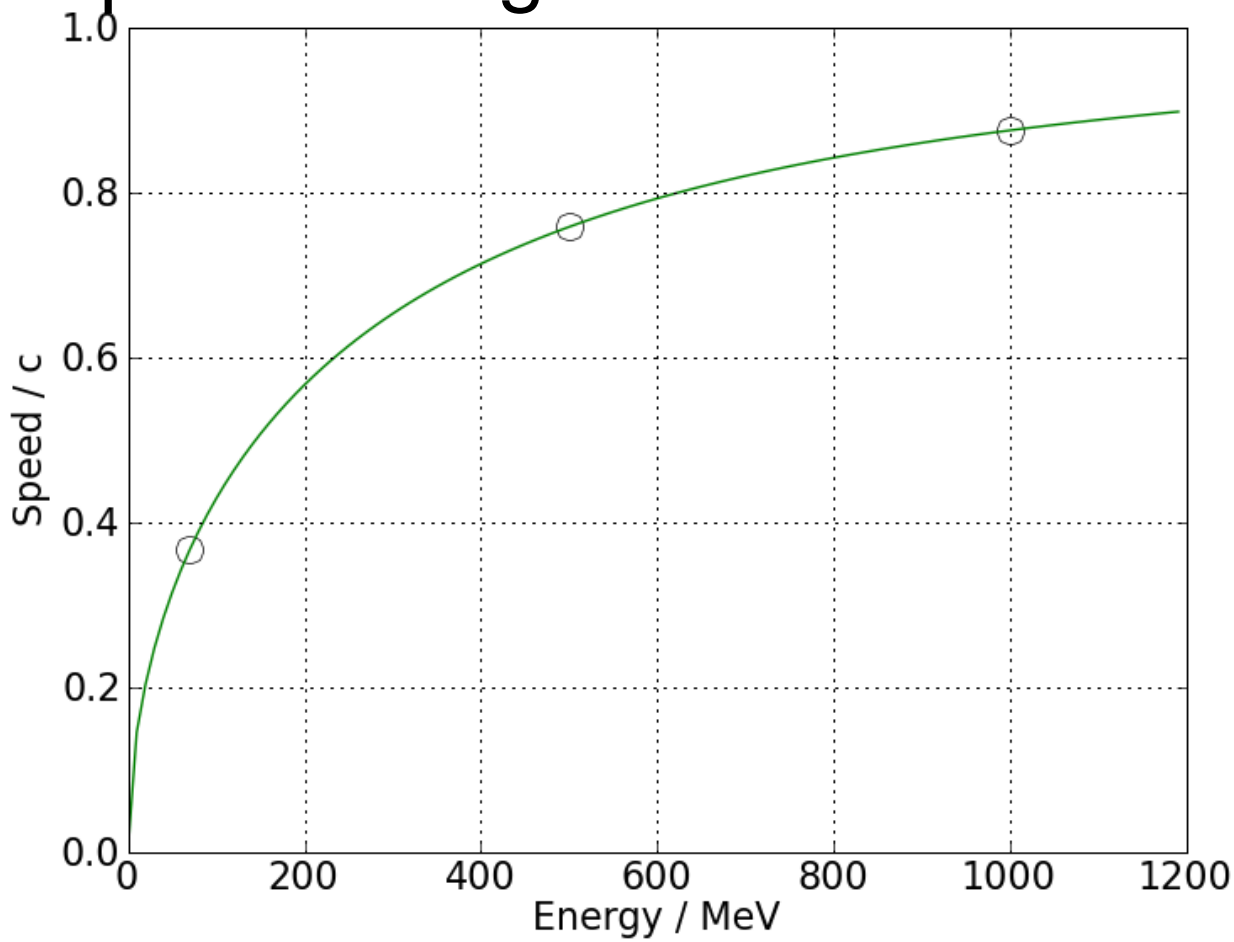


Space charge

- If the bunch charge could be reduced then we can use smaller beams
- If we can accelerate several bunches per cycle then less charge per bunch
- Formula is only approximate
- Need to run simulations in a space charge aware code

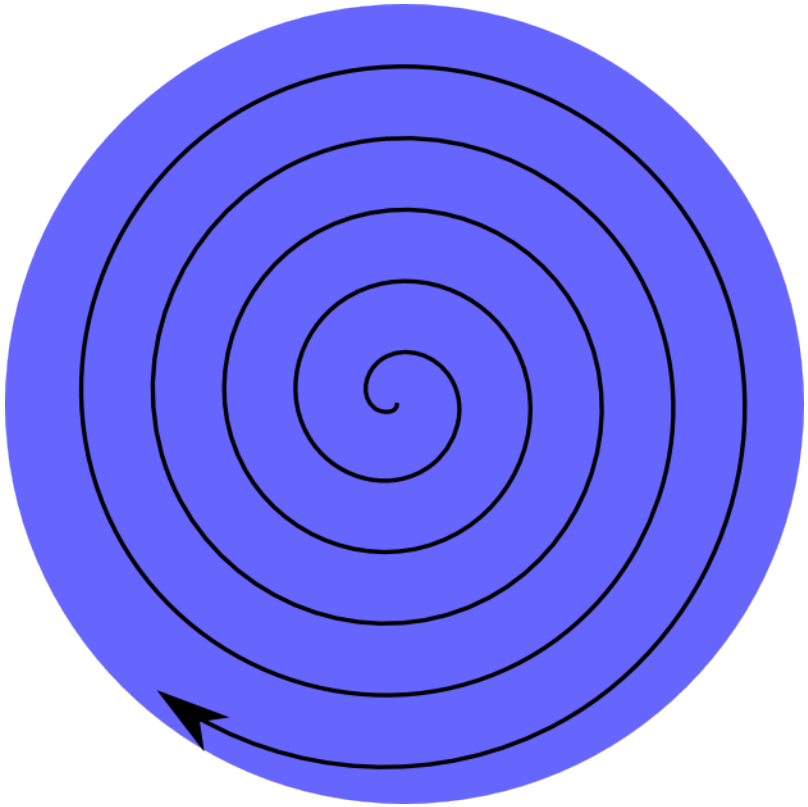
Beam Requirements

- Accelerate to 500 – 1000 MeV
- Large speed change



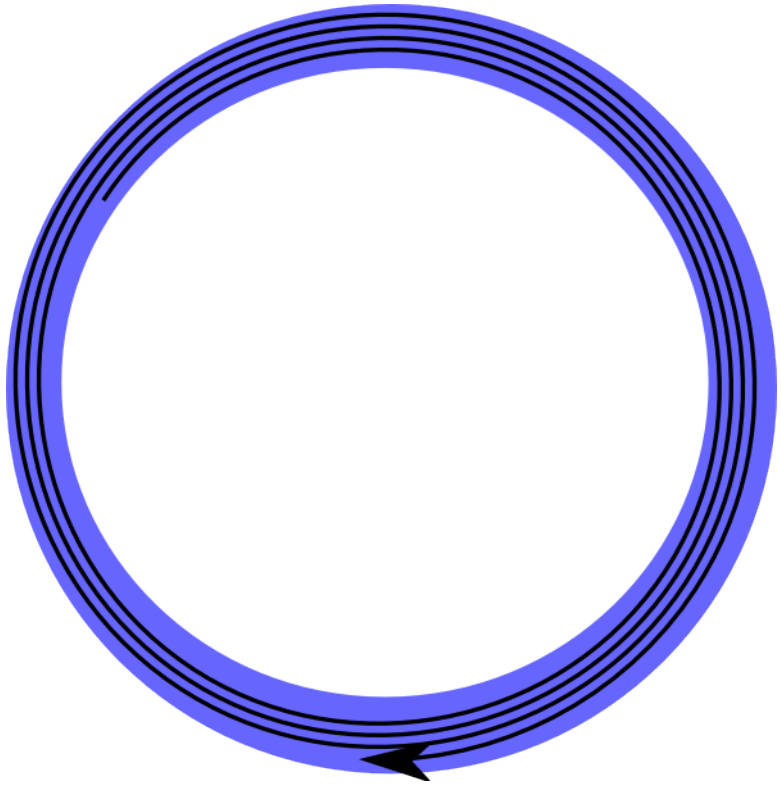
Cyclotron

- Path length and speed increase proportionally
- Orbit time constant



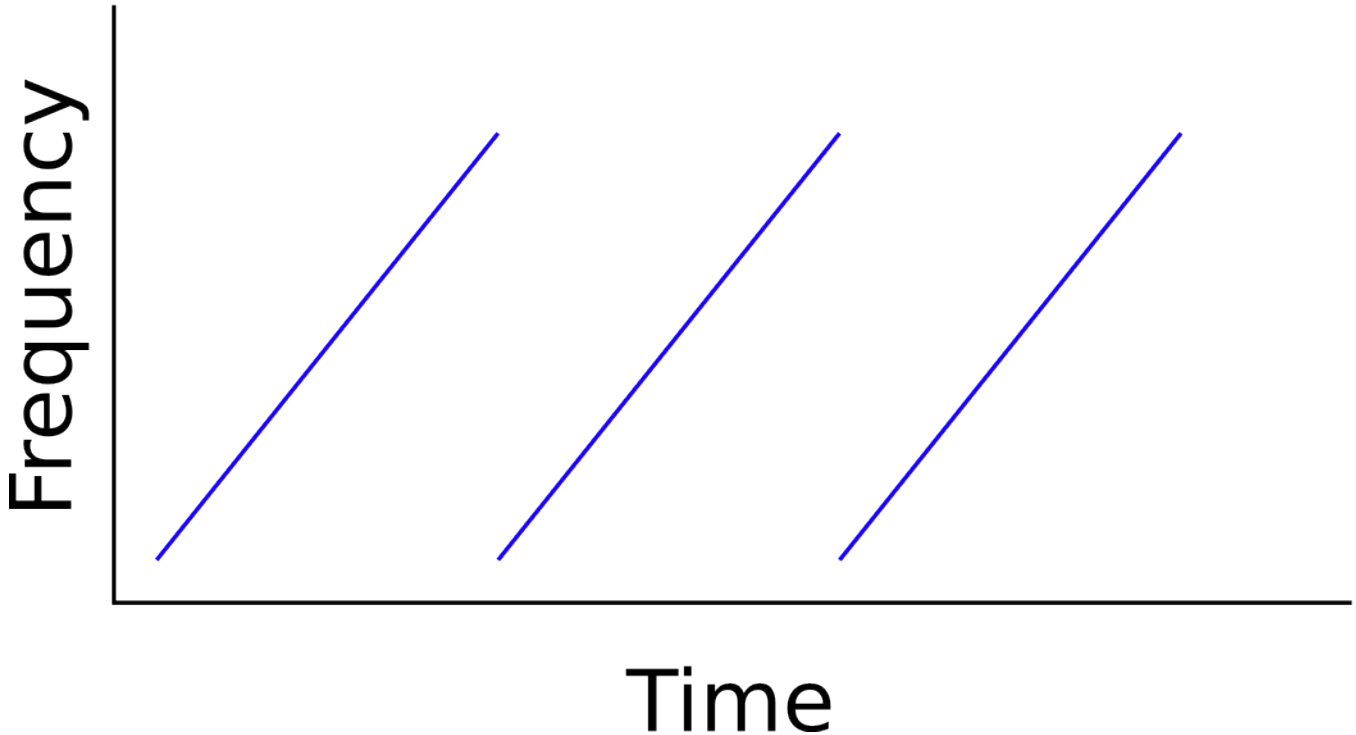
FFAG

- Radius change is small, but speed still changes
- Orbit time decreases



- So revolution frequency must change

Must sweep RF frequency



Duty Factor

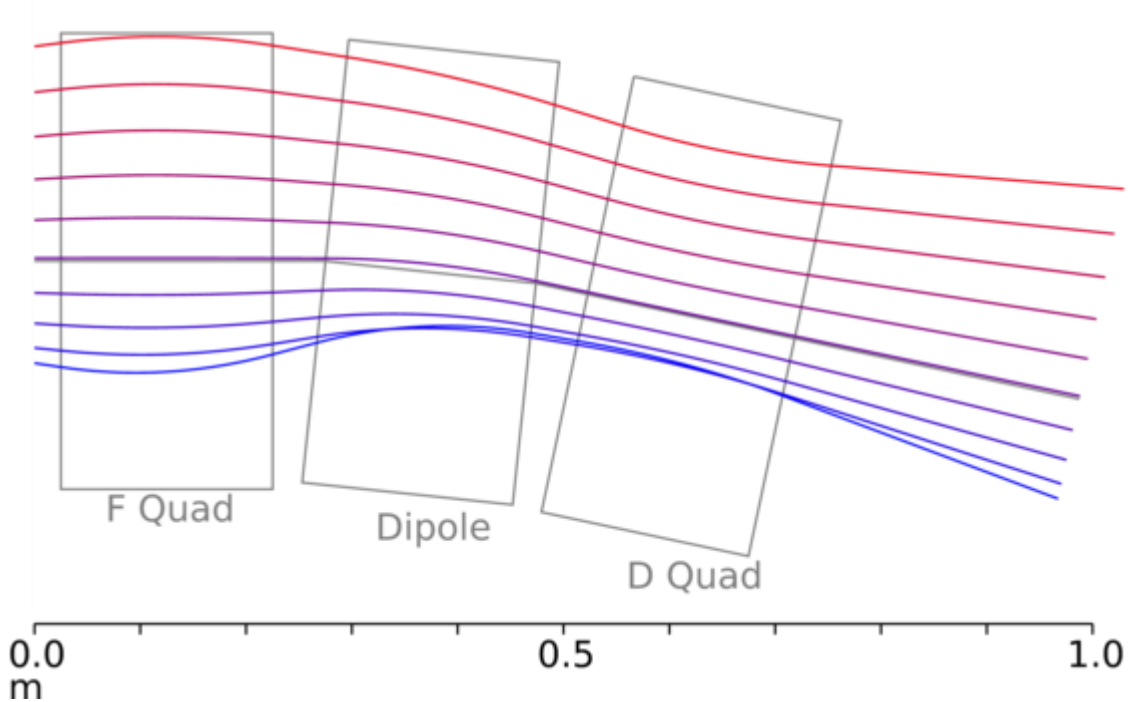
- Can only inject when RF is matched to injection energy
- Inject on turn 1, wait for N turns, extract
- Duty cycle is 1/N

Inject on turn 1 and 2

- On turn 2, the frequency has only shifted a small amount
- If we inject again then it may be close enough
- Now duty cycle is 2/N

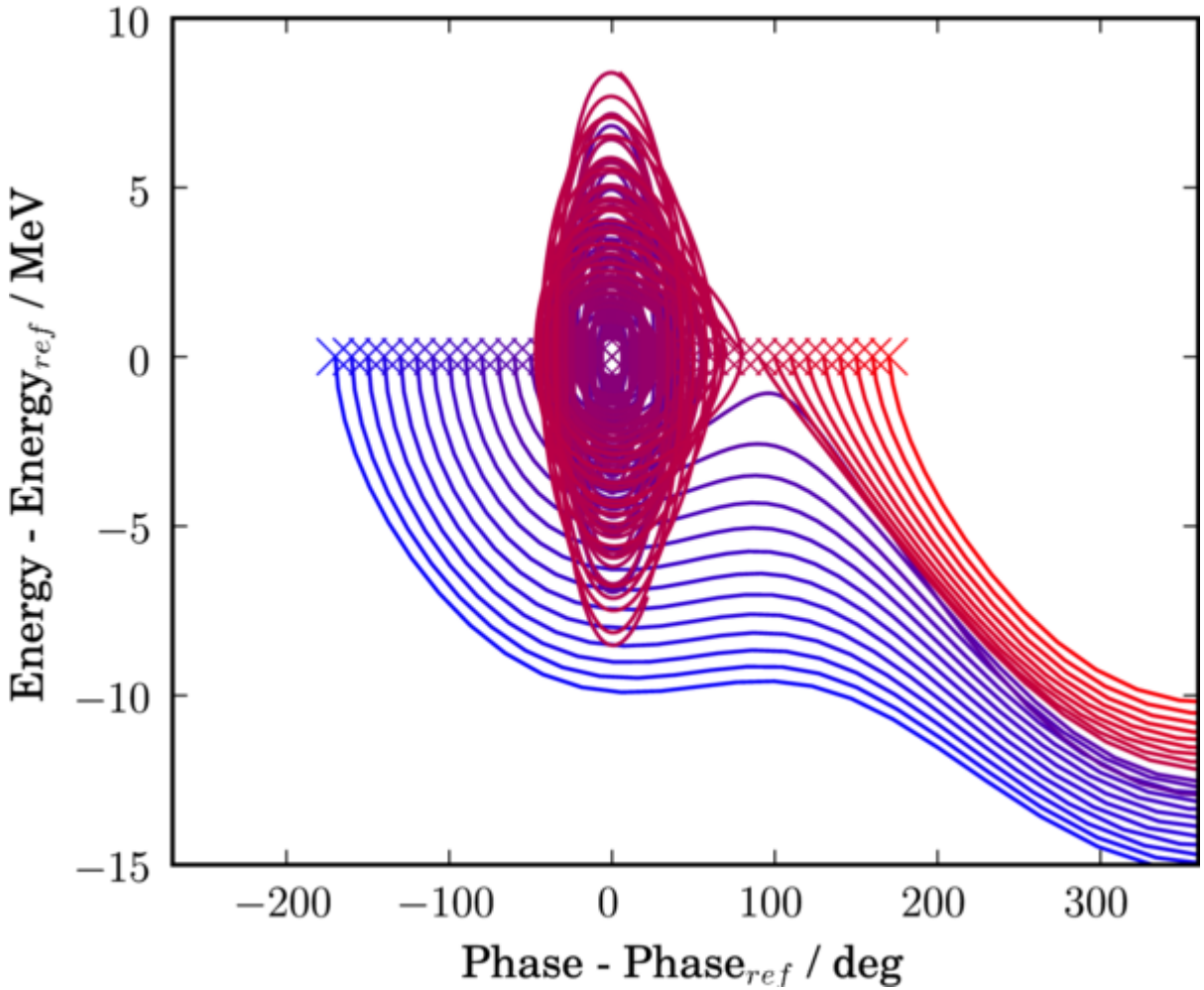
Simulation

- Simple Foc-Dipole-Defoc-Drift lattice
- 30 x 1 m cells
- 1 cavity
- 70 → 500 MeV
- 1000 turns
- Harmonic 1
- Zgoubi



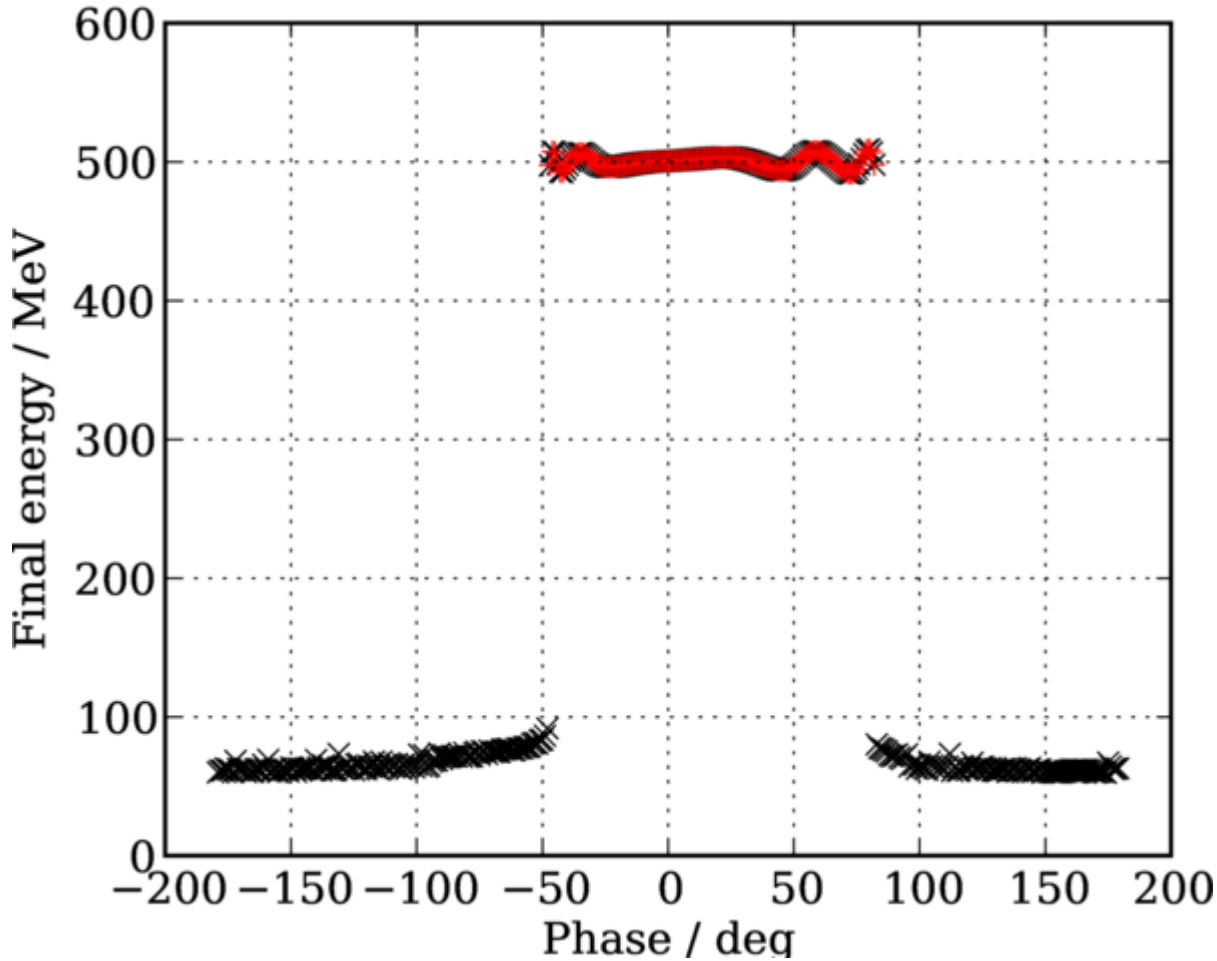
First lap injection

- Energy phase space, particles injected over 360º



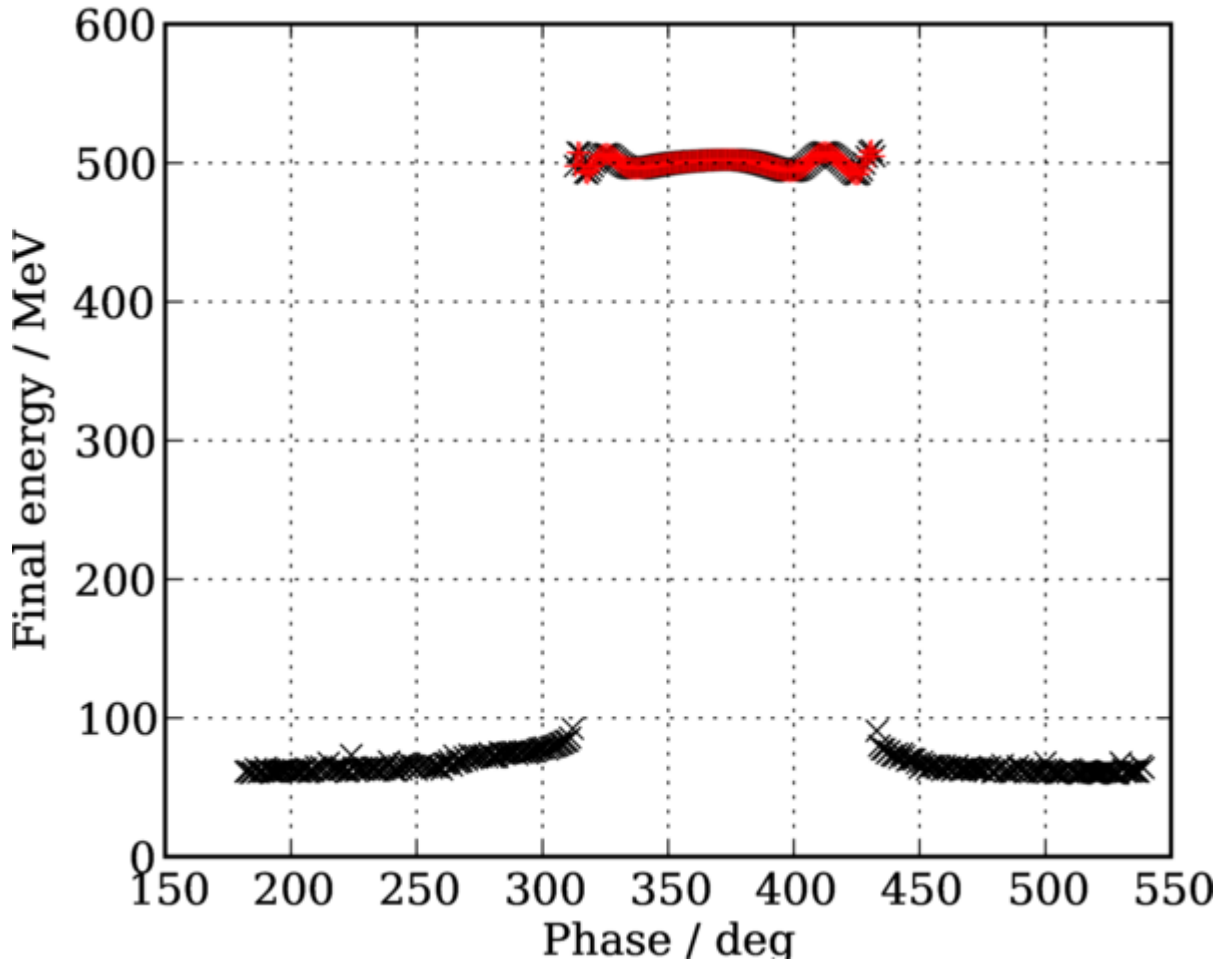
Final Energy

- Energy after 1000 turns



130º acceptance

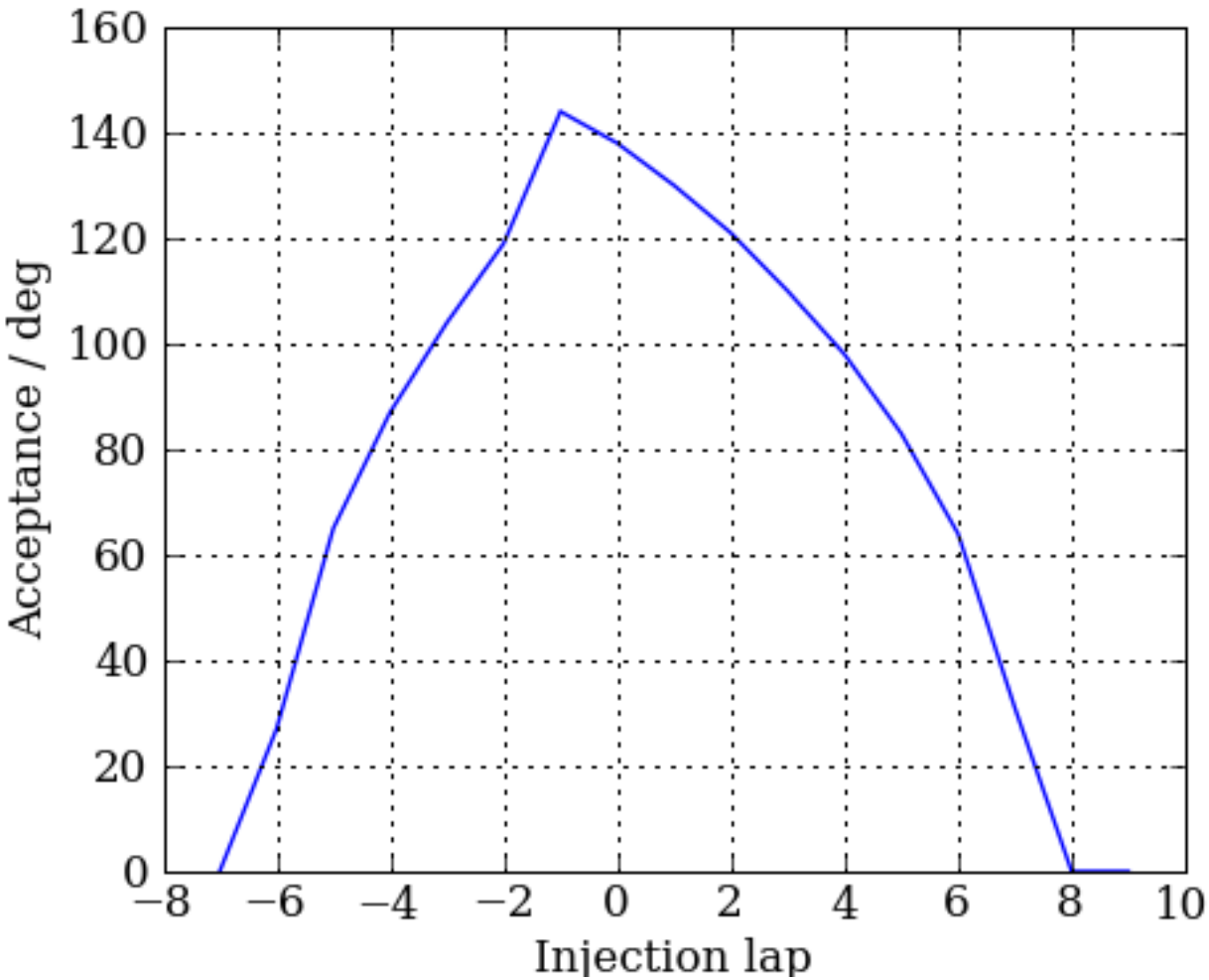
Second lap injection



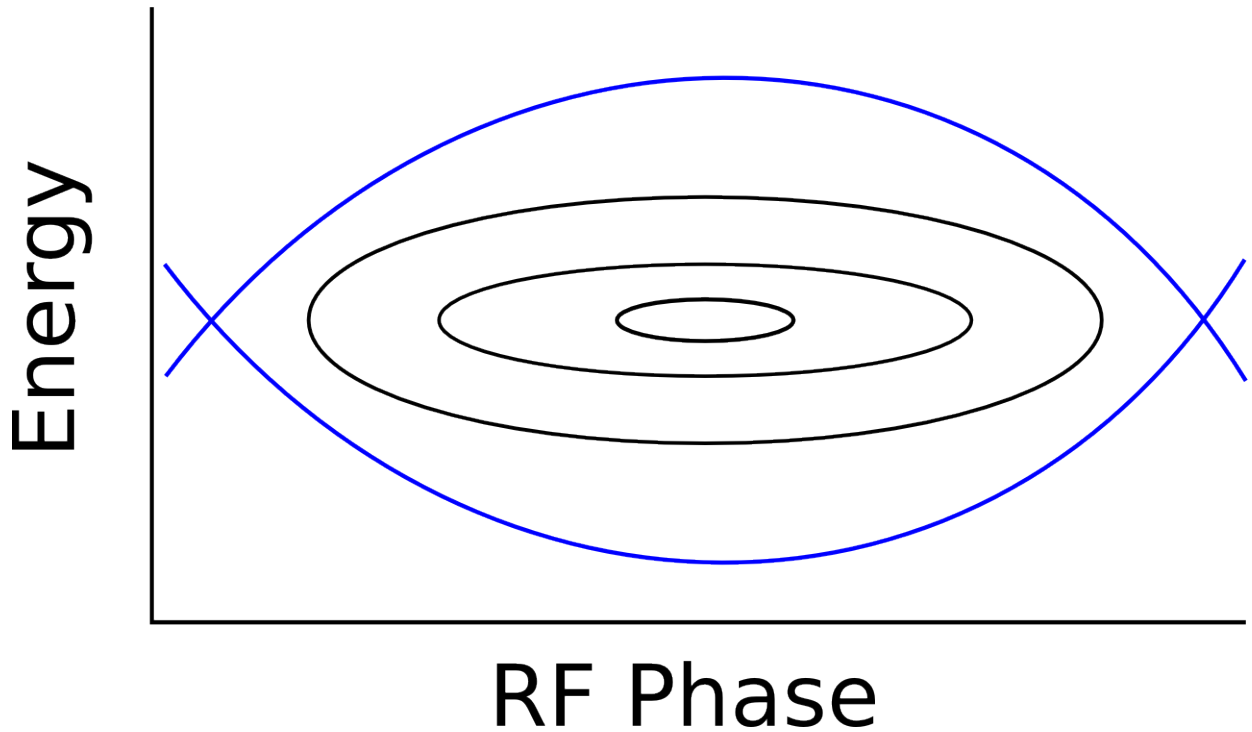
120º acceptance

Multi turn injection

- Inject before and after RF frequency matches



What are we seeing



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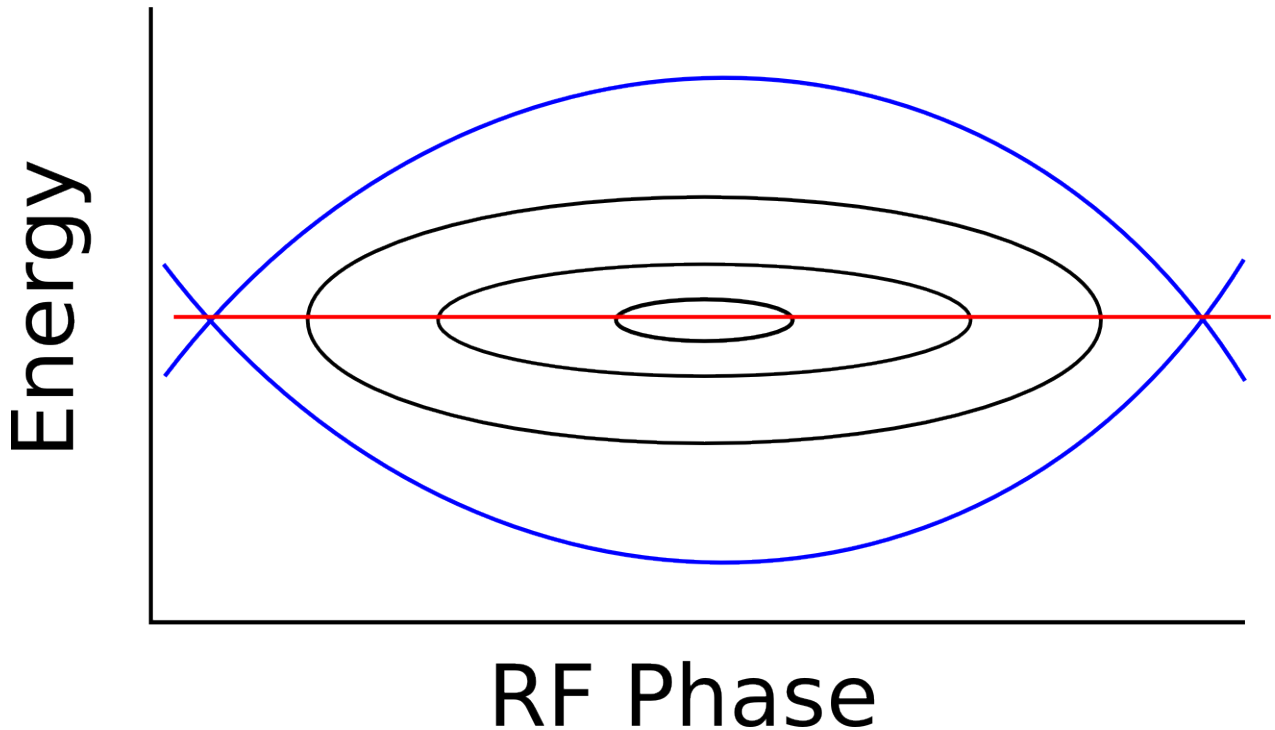

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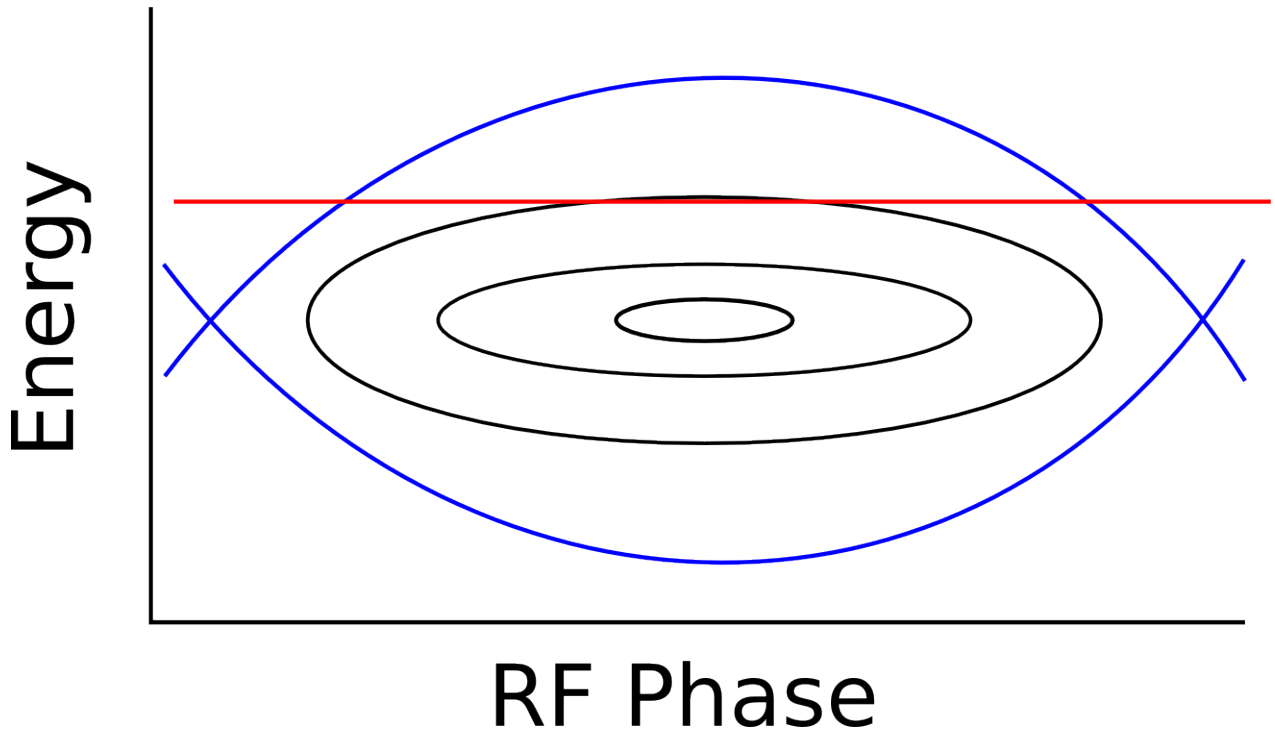

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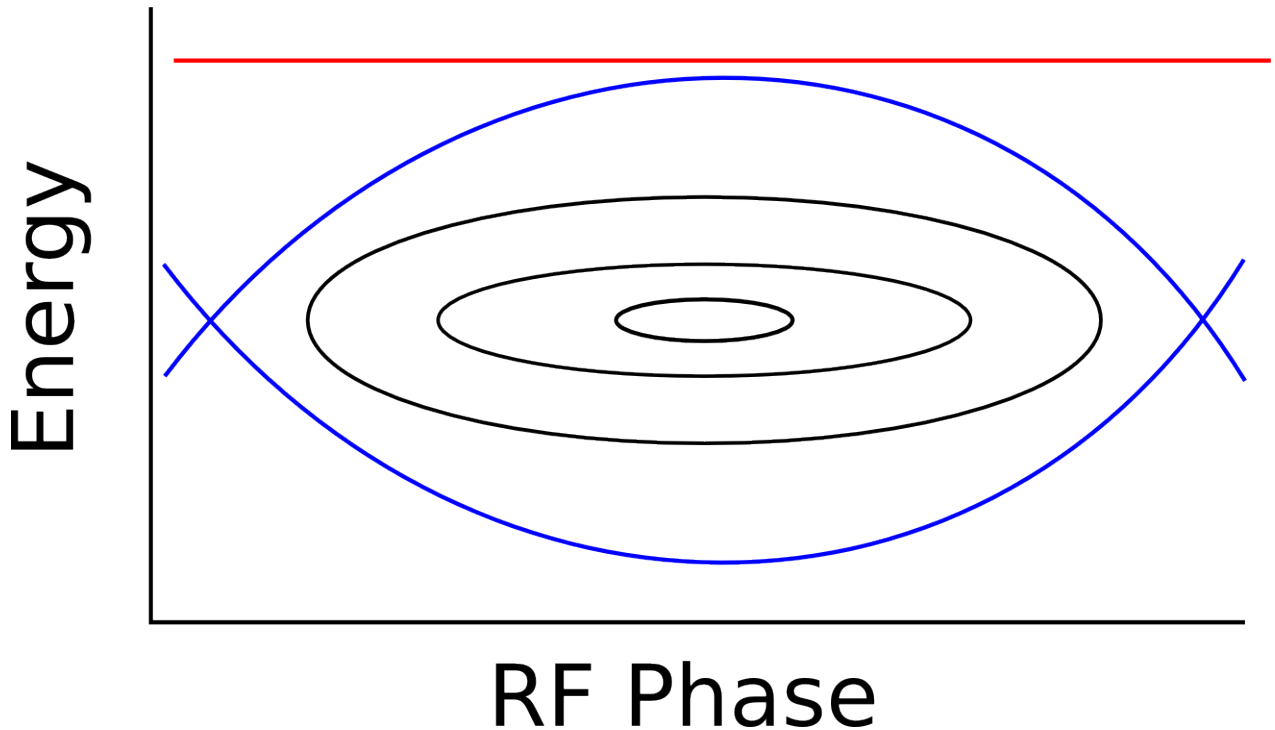
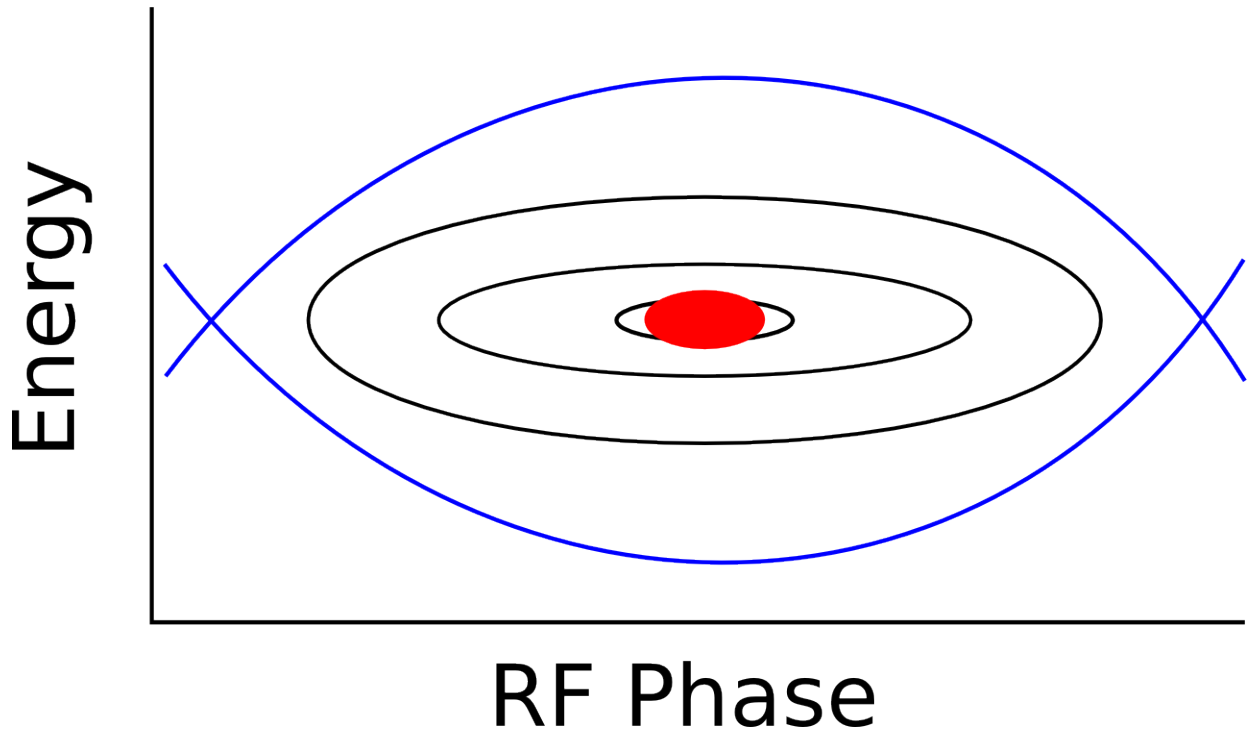
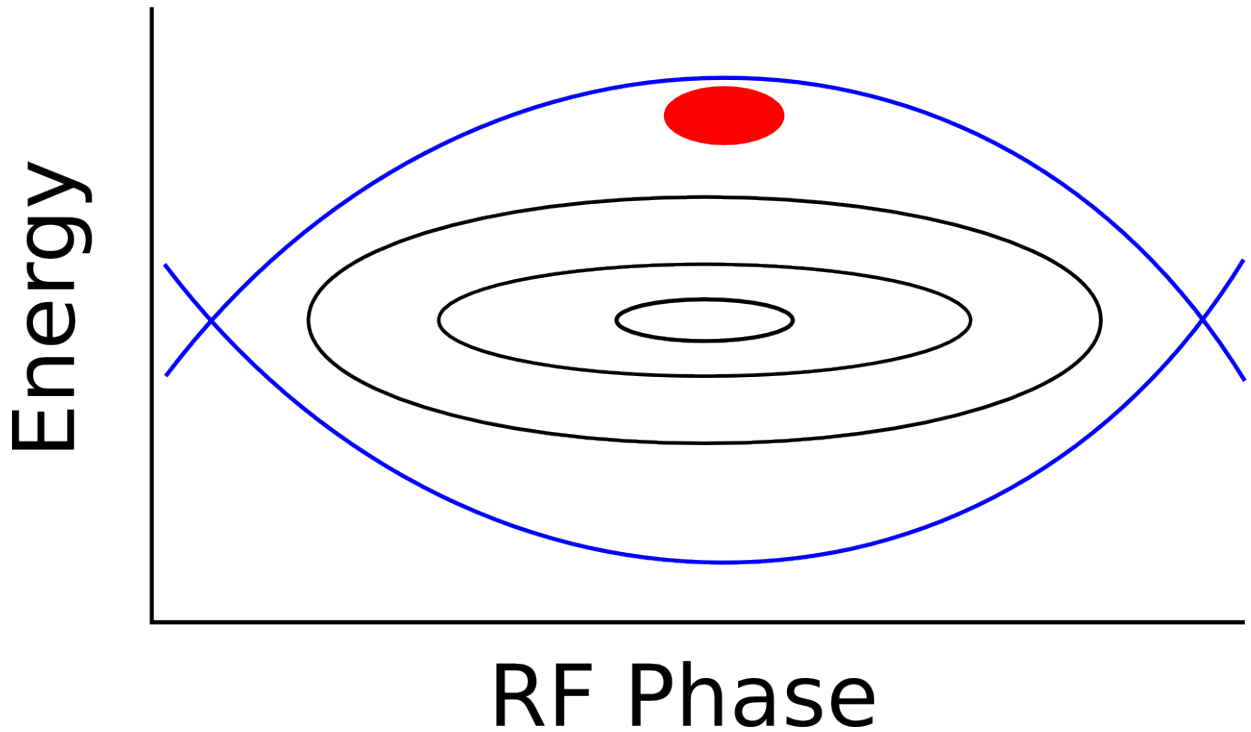


With a realistic beam

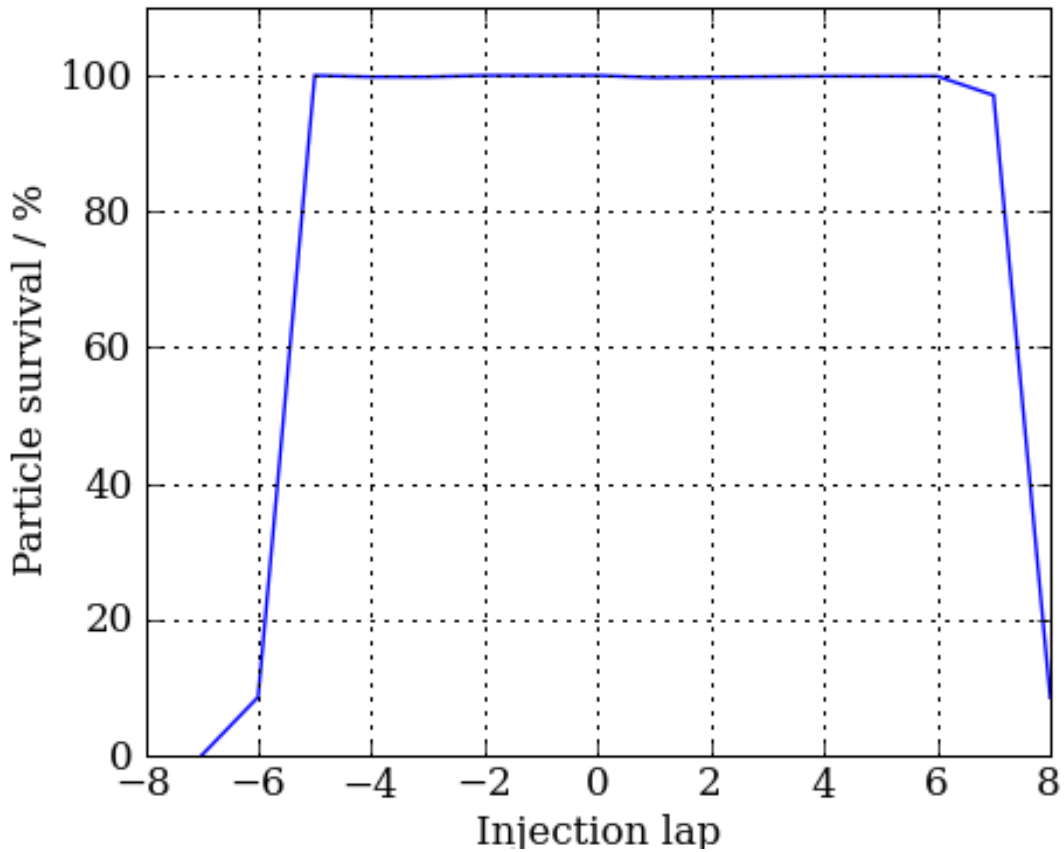


With a realistic beam



With a realistic beam

- Survival for particles in a bunch
- Parameters based on PSI injector output



Other tricks

- FFAGs have a lot of freedom for RF programs.
  - Could have a fill period, with a constant frequency, then once full sweep the RF
  - But if rep rate is limited by RF sweep rate, then this is a trade off
  - May be fill and extract simultaneously (careful choice of harmonics)
- Multiple accelerating frequencies
  - Can't keep many beams harmonic, without huge harmonic numbers
  - If some beams aren't harmonic then they get negative kicks

Multiple bunch + space charge

- If there are multiple bunches on top of each other is it any different from 1 large bunch.
- Or is an offset in longitudinal phase space enough to stop them interacting
- Need simulations

Conclusion

- ADSR needs a very high beam current
- This is around traditional space charge limits
- For proton FFAGs around 1 GeV it is necessary to sweep the RF frequency
- This limits the time when you can inject, reducing the duty cycle
- Some of this loss can be recovered, by injecting on laps surrounding the matched one

Pyzgoubi

- Zgoubi is a very capable tracking code maintained by François Méot and Scott Berg
- Widely used for FFAG simulation
- But tricky to make input files by hand
- Pyzgoubi is a python interface that uses more readable input files

Zgoubi input sample

```
'MULTIPOL'  QF
2
6 2.208947037893755 -5.072134730870179e-01 1.6409348483 0 0
0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0
0.1
1 0 0 0
```

Zgoubi input sample

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```
'MULTIPOL'  QF
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6 2.208947037893755 -5.072134730870179e-01 1.6409348483 0 0
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0 0 0 0 0 0 0 0 0 0 0
0 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0
0 1 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0
0.1
1 0 0 0
```

Output track

Bore size

Length

Equivalent in pyzgoubi

```
MULTIPOL('QF', IL=2, XL=6, R_0=2.208947037893755,
         B_1=-5.072134730870179e-01, B_2=1.6409348483,
         C_0=1, CS_0=1, XPAS=0.1, KPOS=1)
```

Pyzgoubi

- Input is a python source code
  - Can do in-line maths
  - Can do loops, branches, use commandline args
- Can read in plt, fai files, analyses with numpy/scipy, plot with matplotlib
- Has functions for finding closed orbits, twiss parameters.

Pyzgoubi

- Just release a new version (0.3)
- http://www.hep.man.ac.uk/u/sam/pyzgoubi/
- https://sourceforge.net/projects/pyzgoubi/
- (or search for pyzgoubi)
- Thanks to David Kelliher + Scott Berg

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Thanks