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What we learned from EMMA

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ASTeC/STFC Rutherford Appleton Laboratory
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Cyclotron 2013, Vancouver

Content

- Introduction of non-scaling FFAGs
- Highlights for the last few years
- What we learned from EMMA

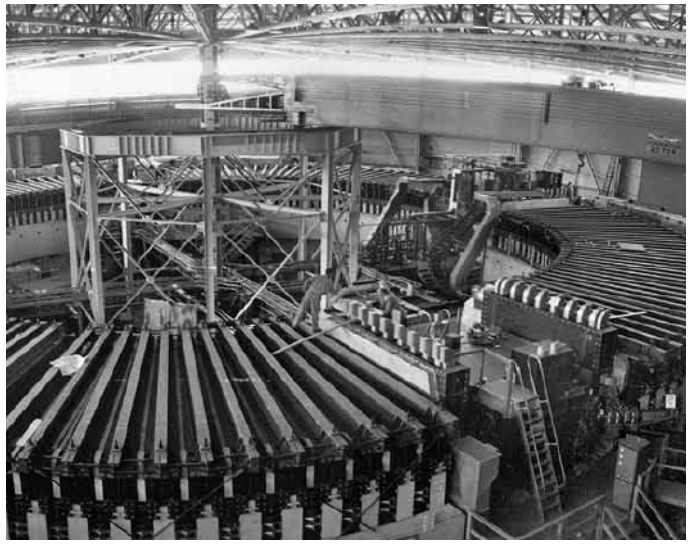
Introduction

From weak to strong focusing

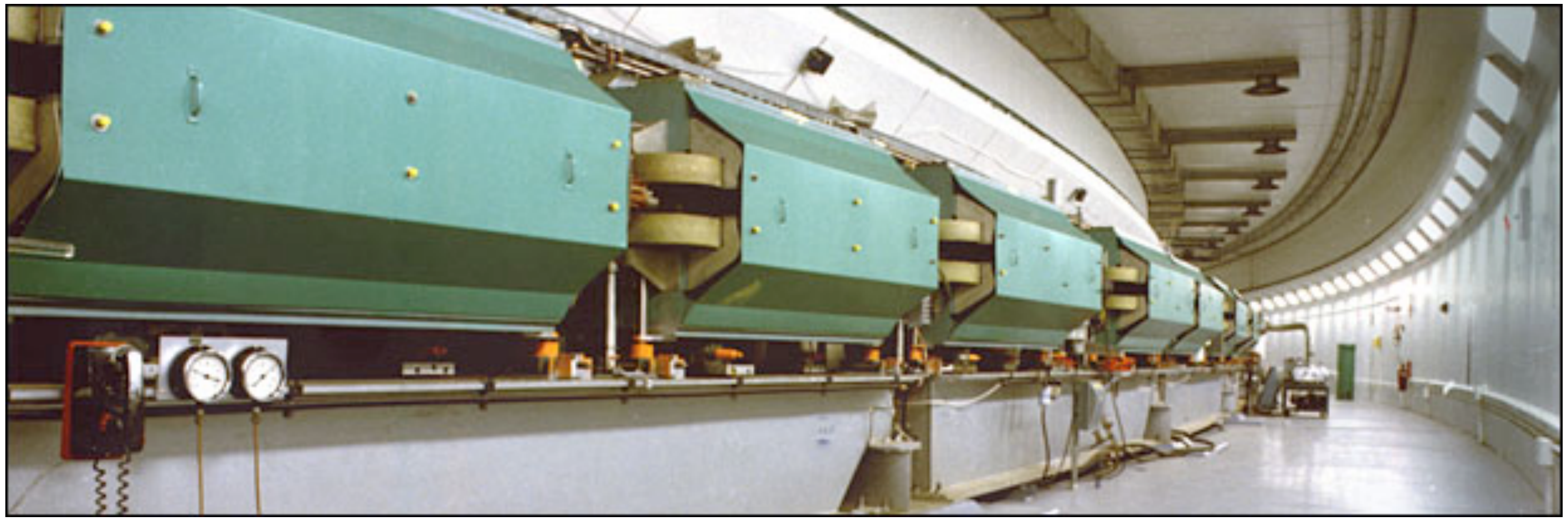
Weak focusing synchrotron

Strong (or Alternating Gradient) focusing

Bevatron



Brookhaven AGS



Small beta function

Beam size becomes small for the same emittance

Small dispersion function

Orbit shift due to momentum spread becomes small

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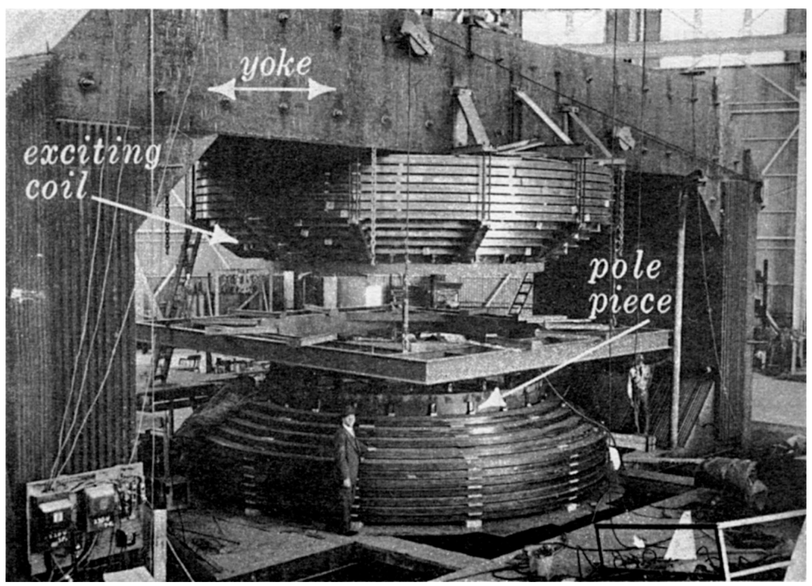
From cyclotron to FFAG

Cyclotron

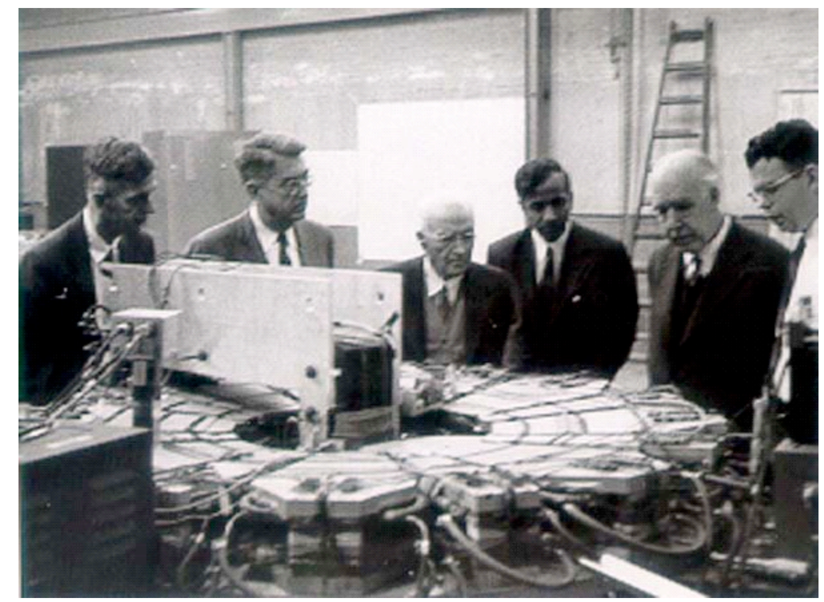
Synchro-cyclotron

Fixed Field Alternating Gradient (FFAG)



184 inch Berkley synchrocyclotron

MURA electron FFAG



Strong focusing

Beam size is small

Orbit excursion is small

→ Small chamber
Small magnets
Higher energy

(in addition) **Constant tune**

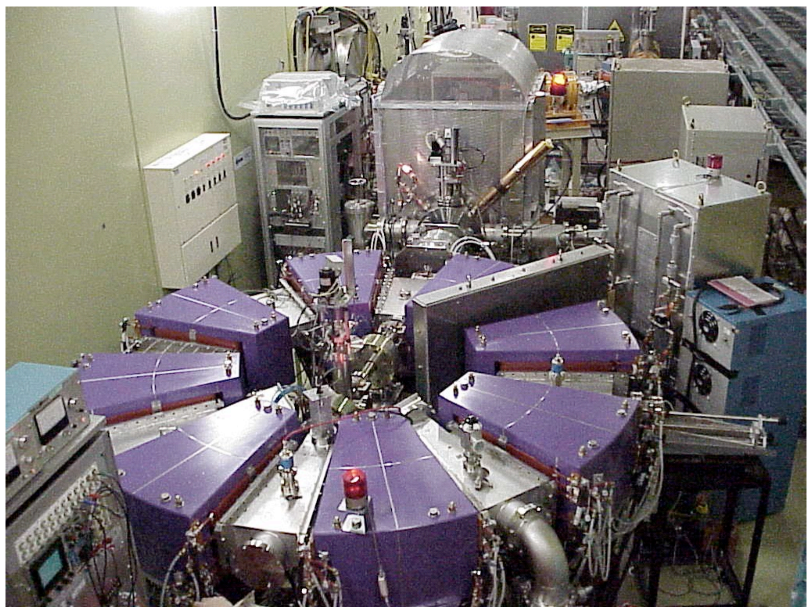
Avoid resonance crossing

Pulsed operation

Low average current

From scaling to non-scaling FFAG

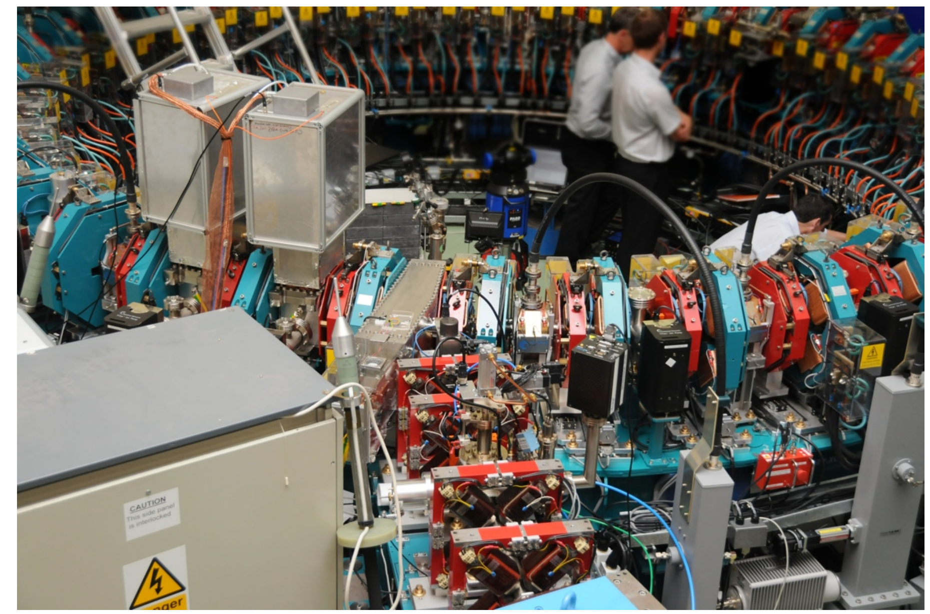
Scaling FFAG



KEK PoP FFAG

Non-scaling FFAG

EMMA



Stronger focusing

Beam size is small
Orbit excursion is small

→ Small chamber
Small magnets
Higher energy

~~Constant tune~~

Cannot avoid resonance crossing

Pulsed operation

Low average current

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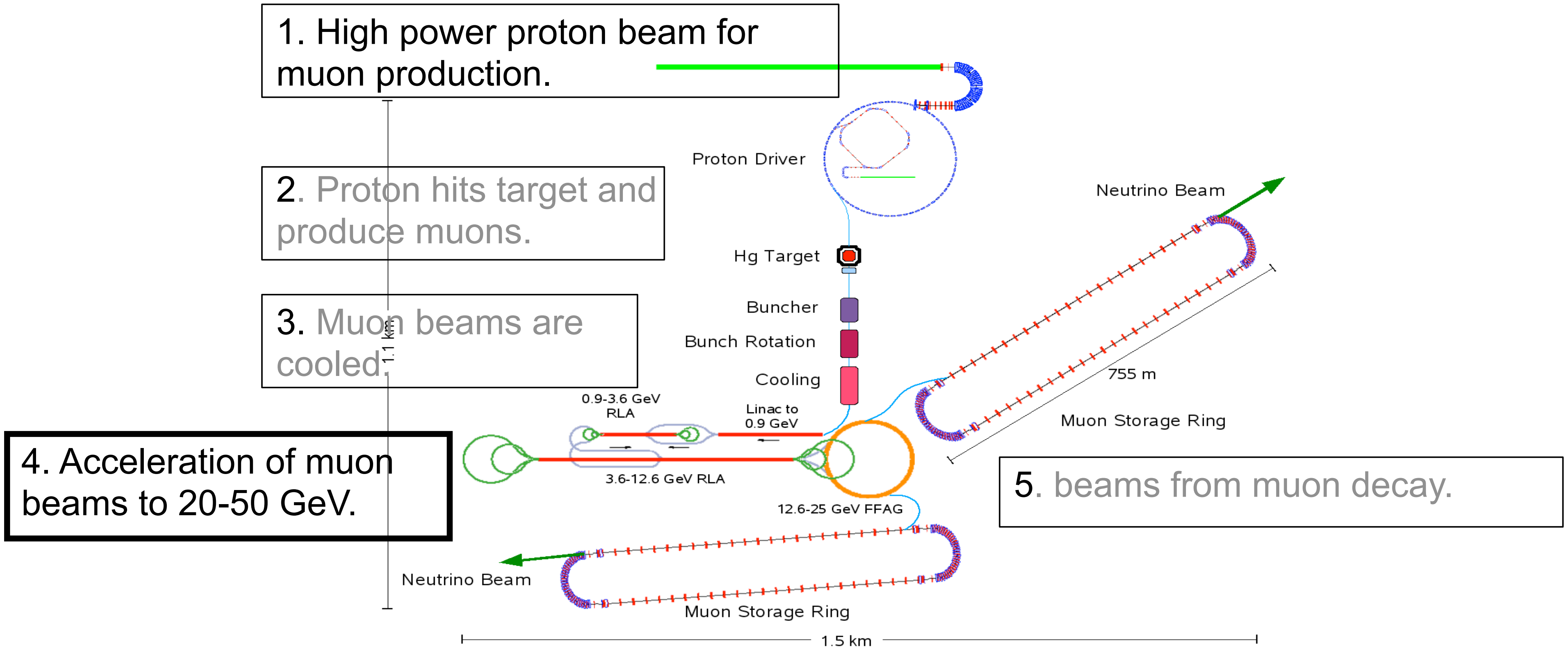
Motivation behind Accelerator for muons



Muon beams does not stay in FFAG for long

Resonance may be harmless

Emittance of muon beams is huge

Large machine acceptance is required

High momentum gain is preferable

Orbit excursion should be as small as possible

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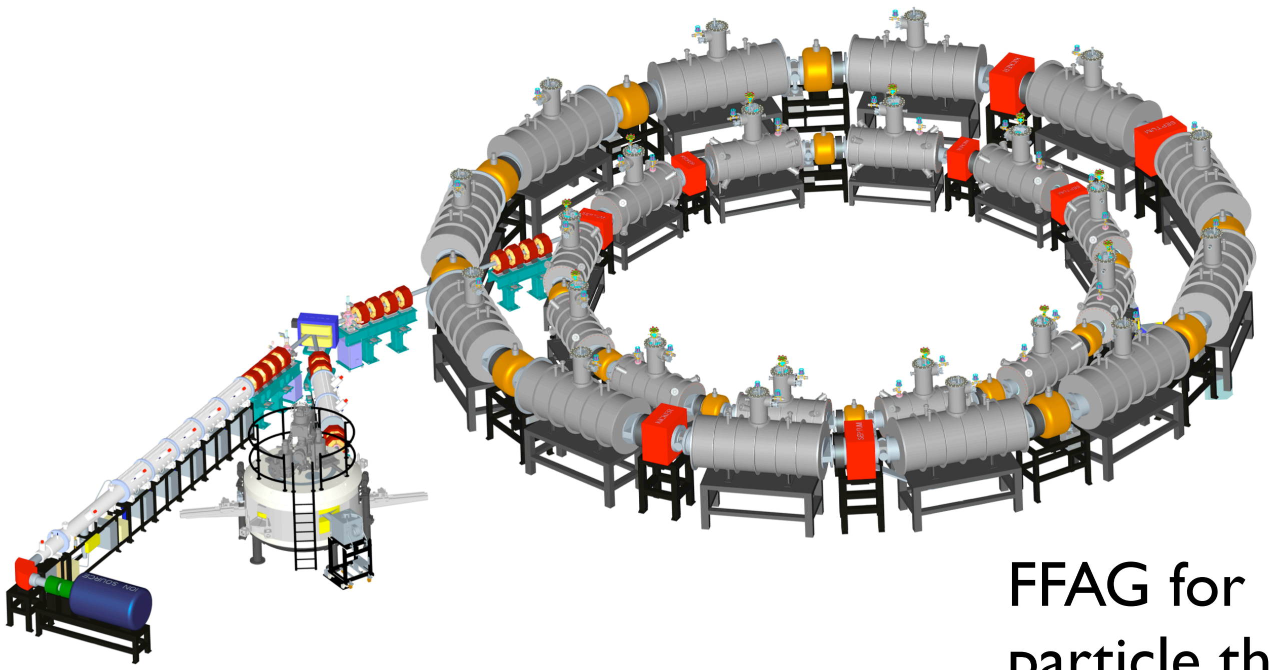
From concept to demonstration

What a nice idea!   (by Johnstone and Mills)

Fixed field accelerator (like cyclotron) with the size of synchrotron magnets.

Idea was initially proposed as a muon accelerator for a neutrino factory.

Applications of the same concept were further considered.



FFAG for particle therapy

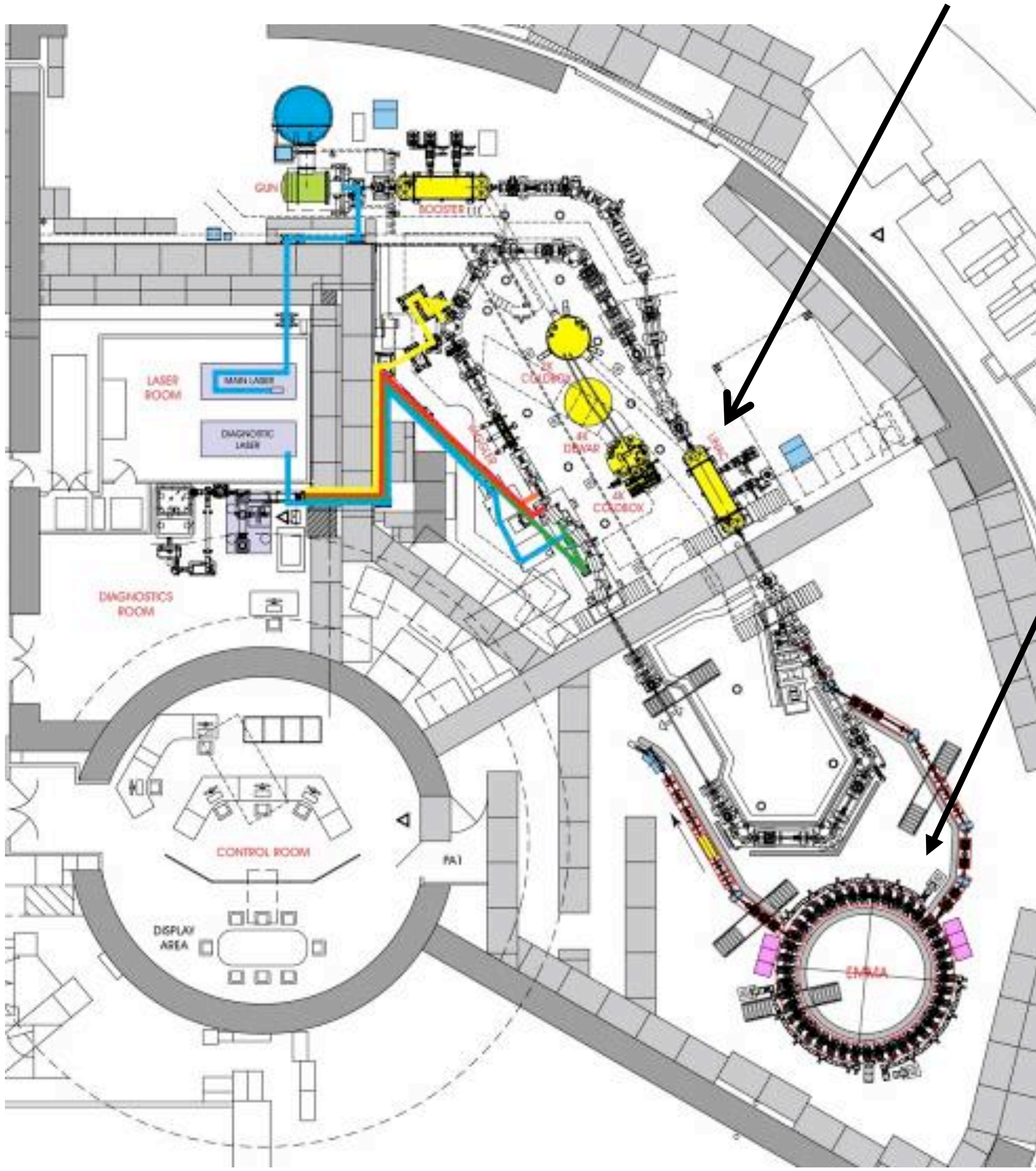
EMMA (Electron Model for Many Applications).

Highlights for the last few years

Home of EMMA

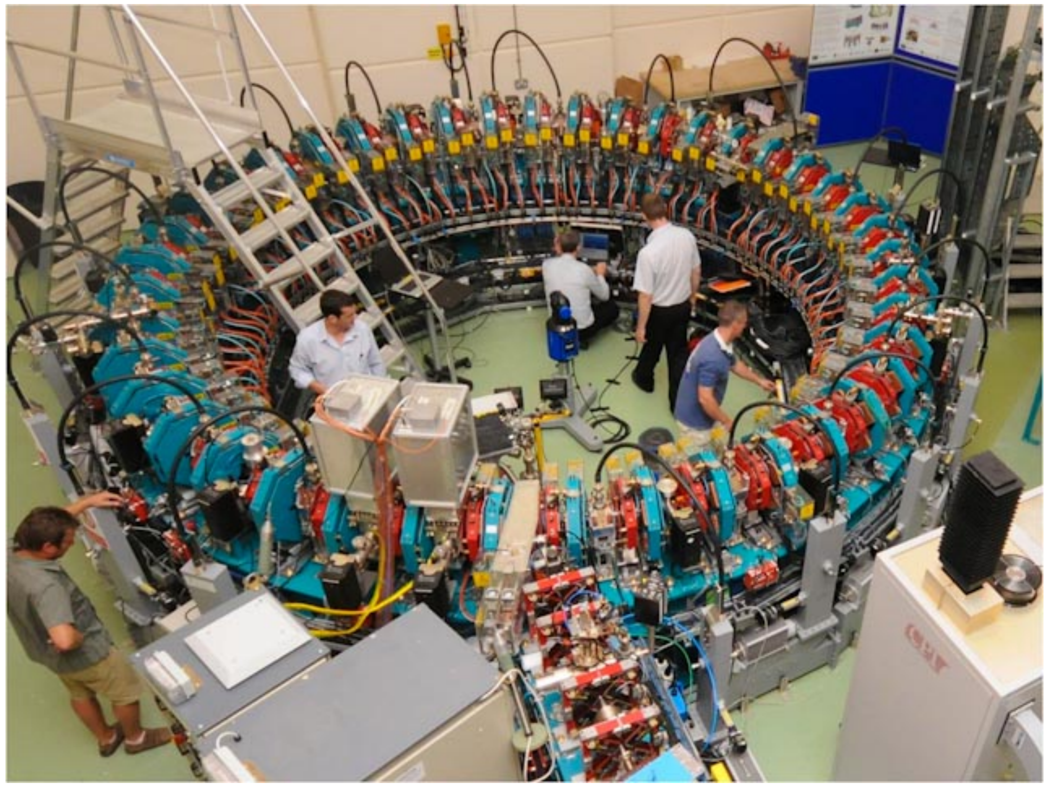
Built at Daresbury Laboratory in the UK

ALICE (Accelerators and Lasers in Combined Experiments)



EMMA

Parameter	Value
Particle	electrons
Momentum	10.5 to 20.5 MeV/c
Cell	42 doublet
Circumference	16.57 m
RF Frequency	1.301 GHz
RF voltage	2 MV with 19 cavities

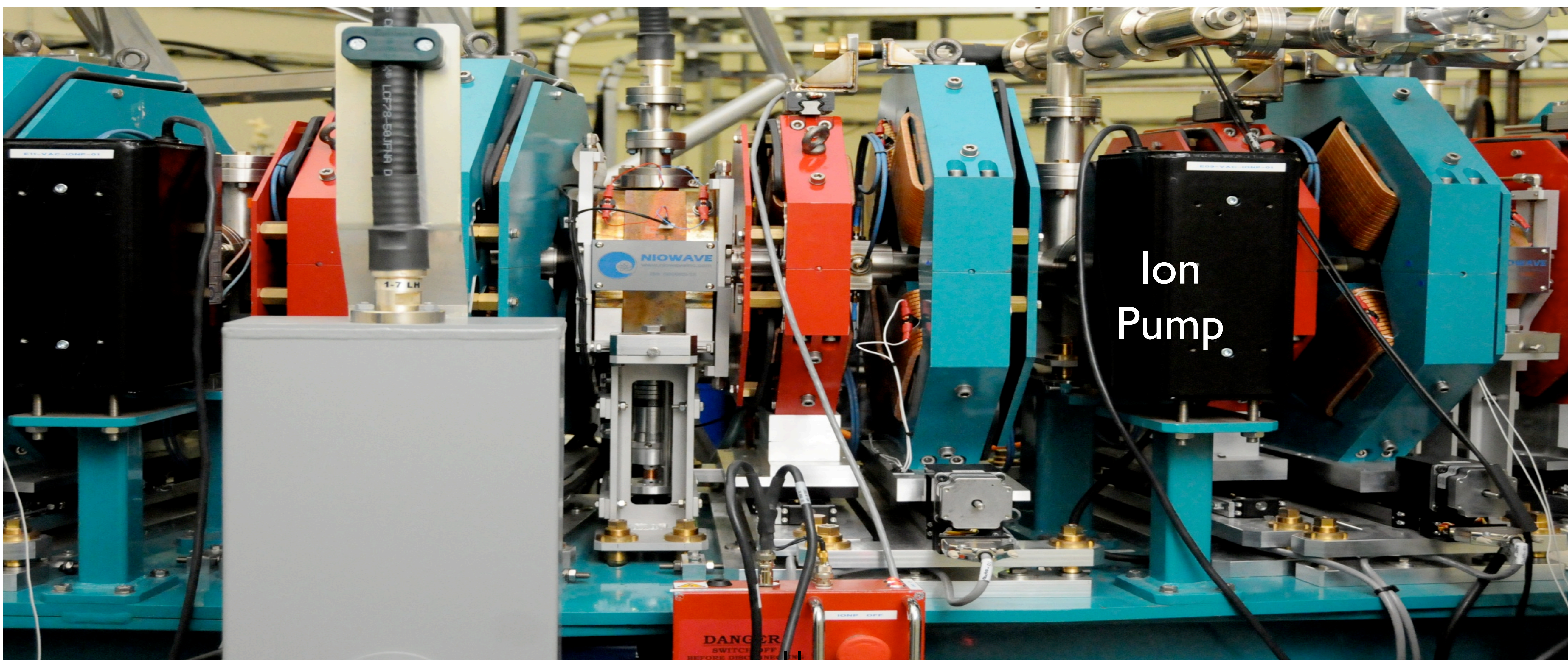


EMMA in pictures

F-QUAD

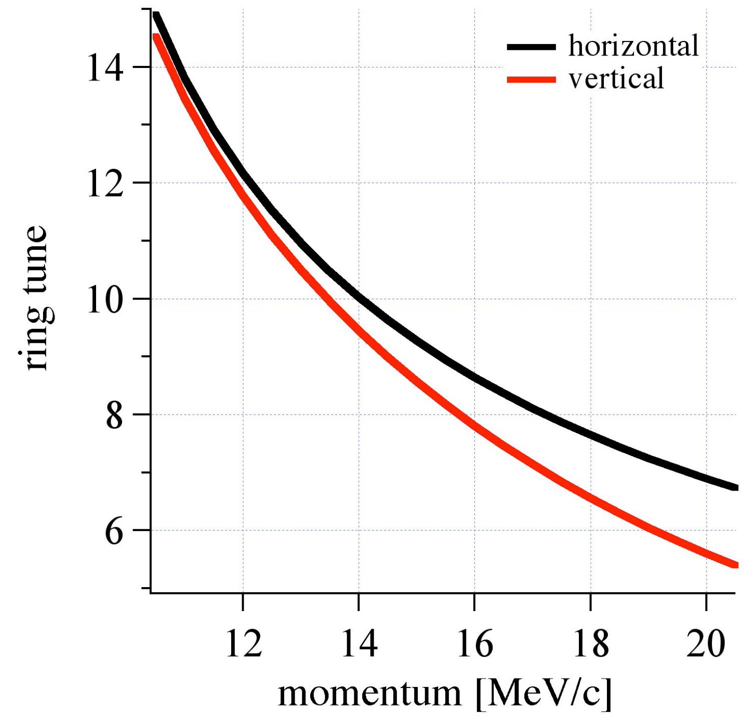
rf cavity

D-QUAD

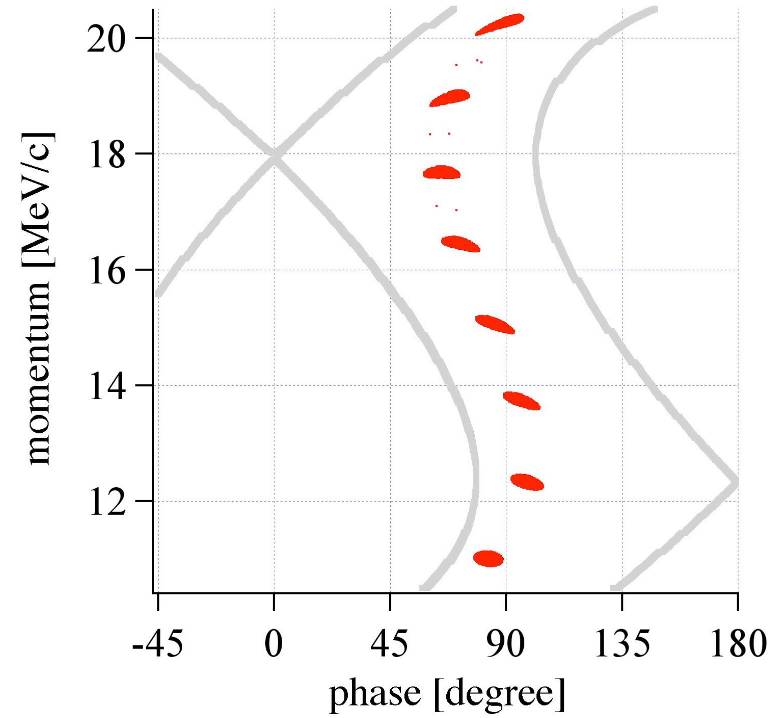


Three main goals

(1) Fast acceleration with resonance crossing.



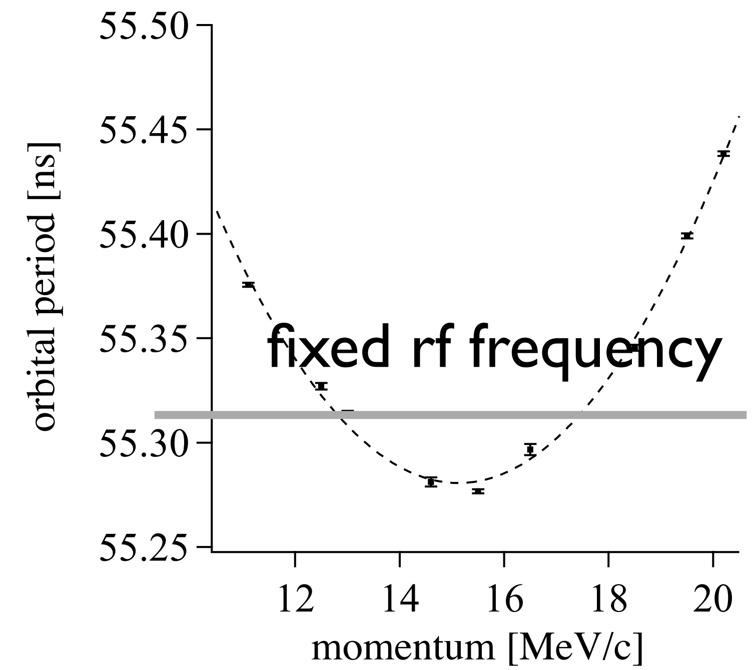
(2) Serpentine channel acceleration.

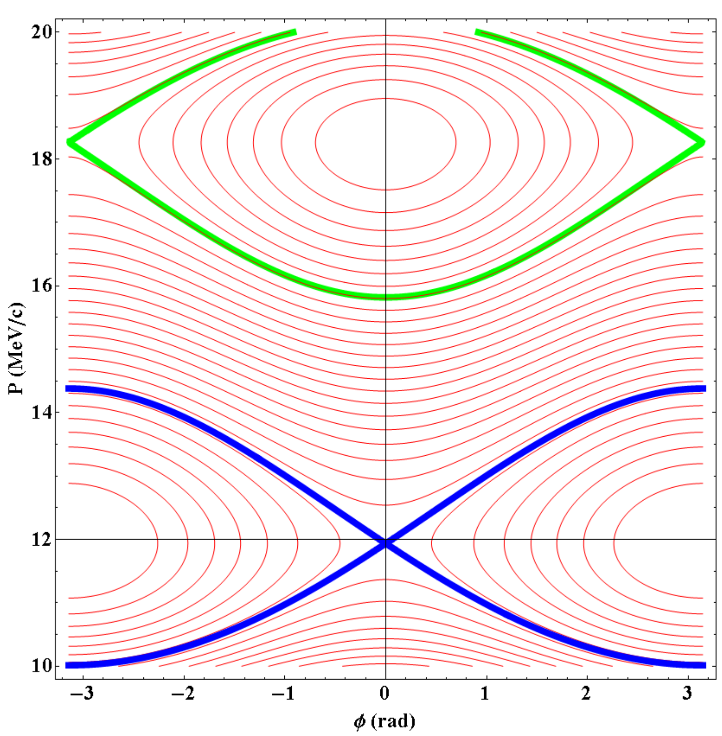


(3) Large acceptance (strong focus.)

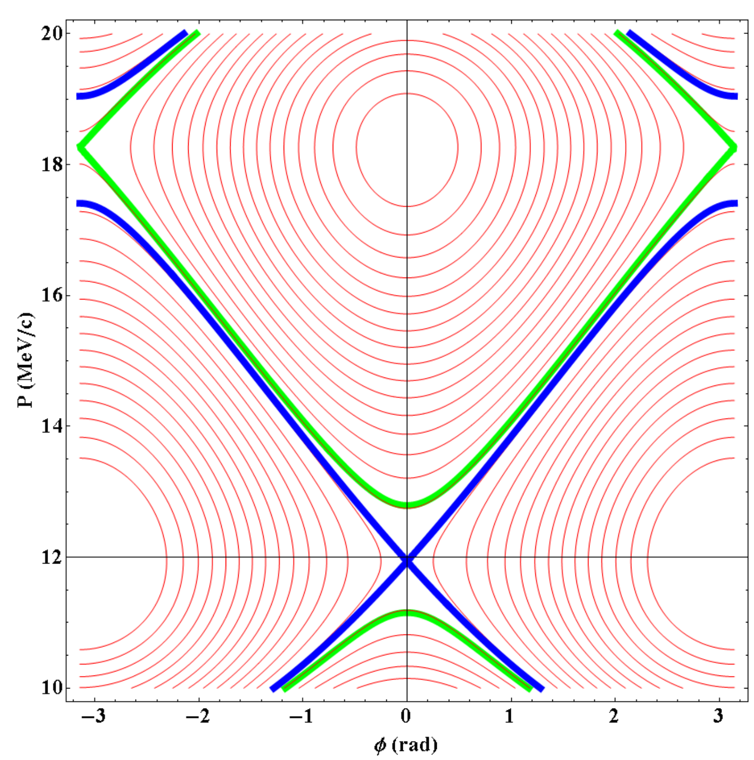
Serpentine channel

When orbital period is almost constant and has parabolic dependence on momentum, path outside rf buckets emerges in longitudinal phase space.

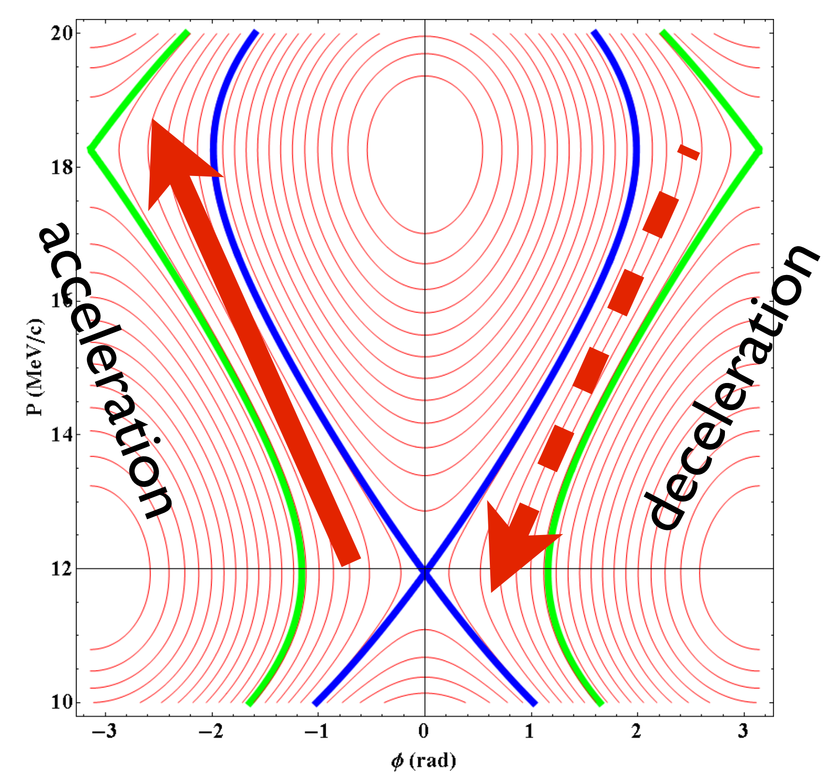




rf voltage is not enough



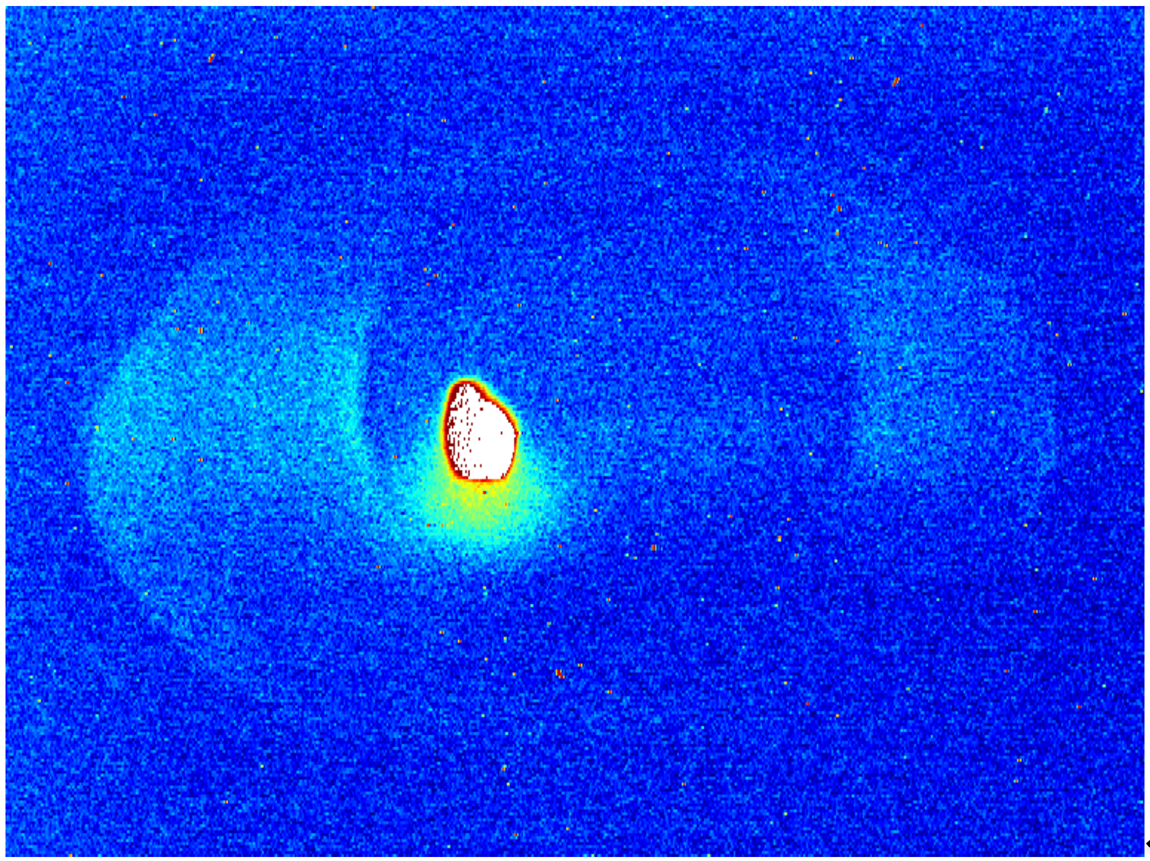
at critical rf voltage

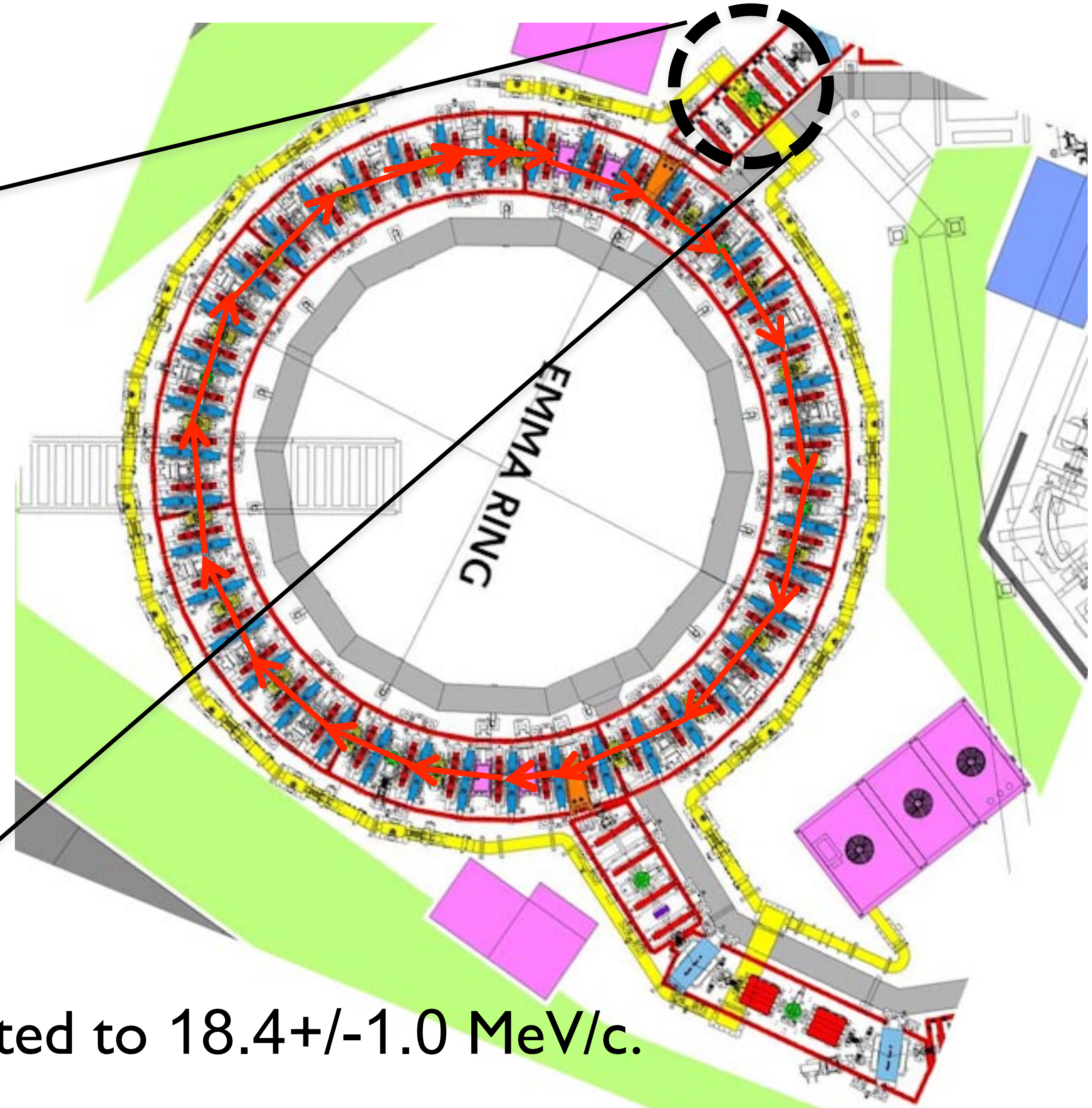


rf voltage is enough to open channel

Momentum measurement at extraction

Beam image after extraction on 18 April 2011



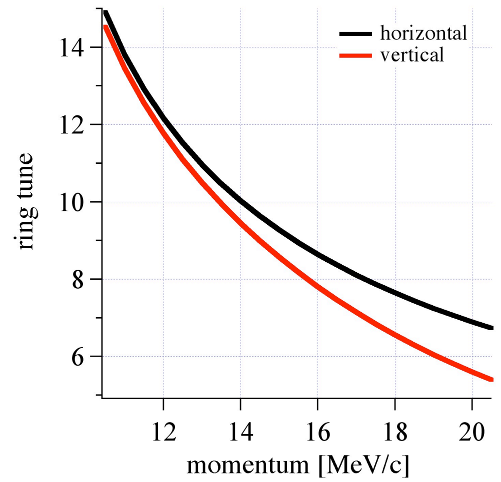


12.0+/-0.1 MeV/c beam is accelerated to 18.4+/-1.0 MeV/c.

With rf voltage of 1.9 MV

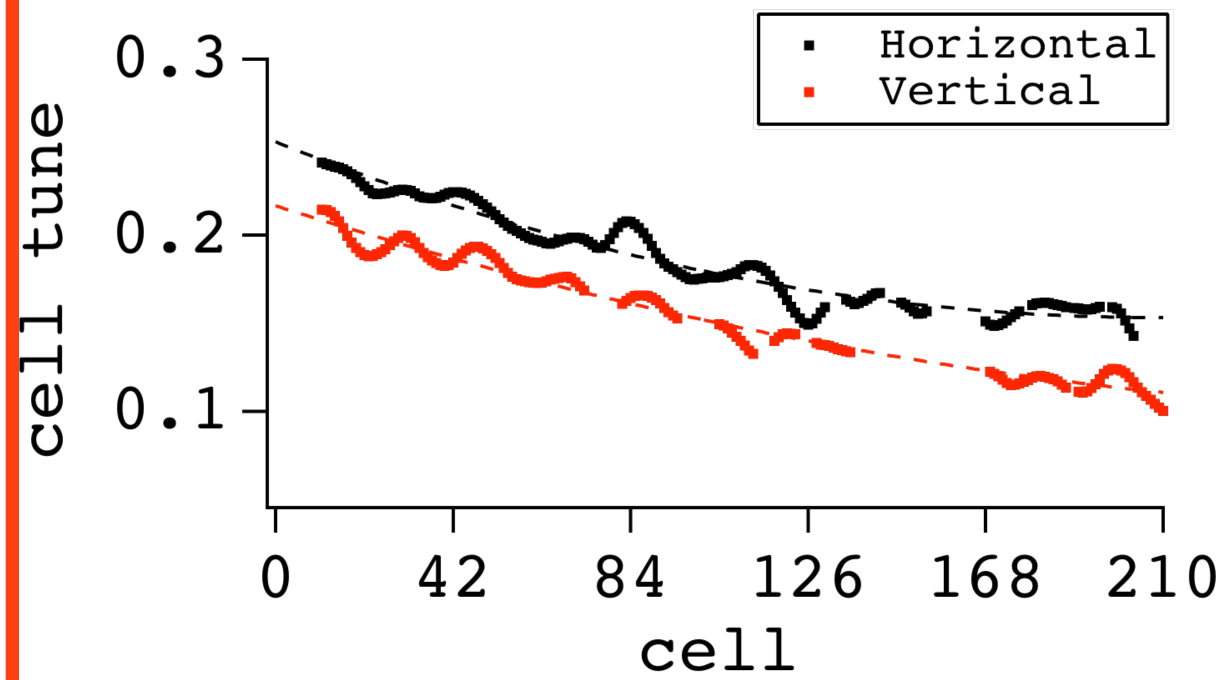
Acceleration with resonance crossing

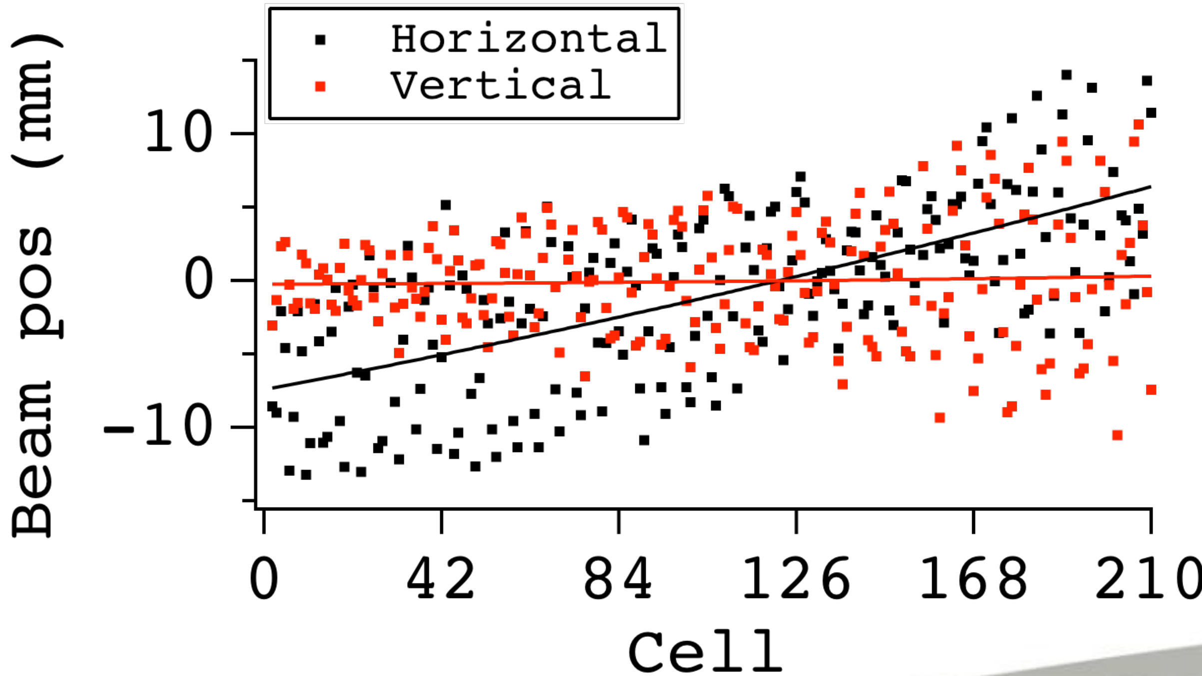
Rapid acceleration with large tune variation



Highlight 1

Tune decreases and hor. orbit increases monotonically in measurement.





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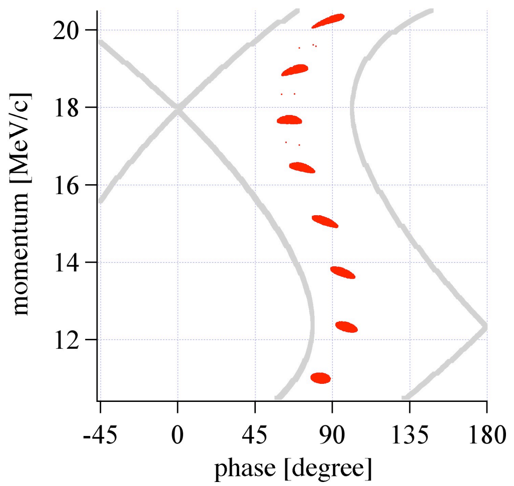
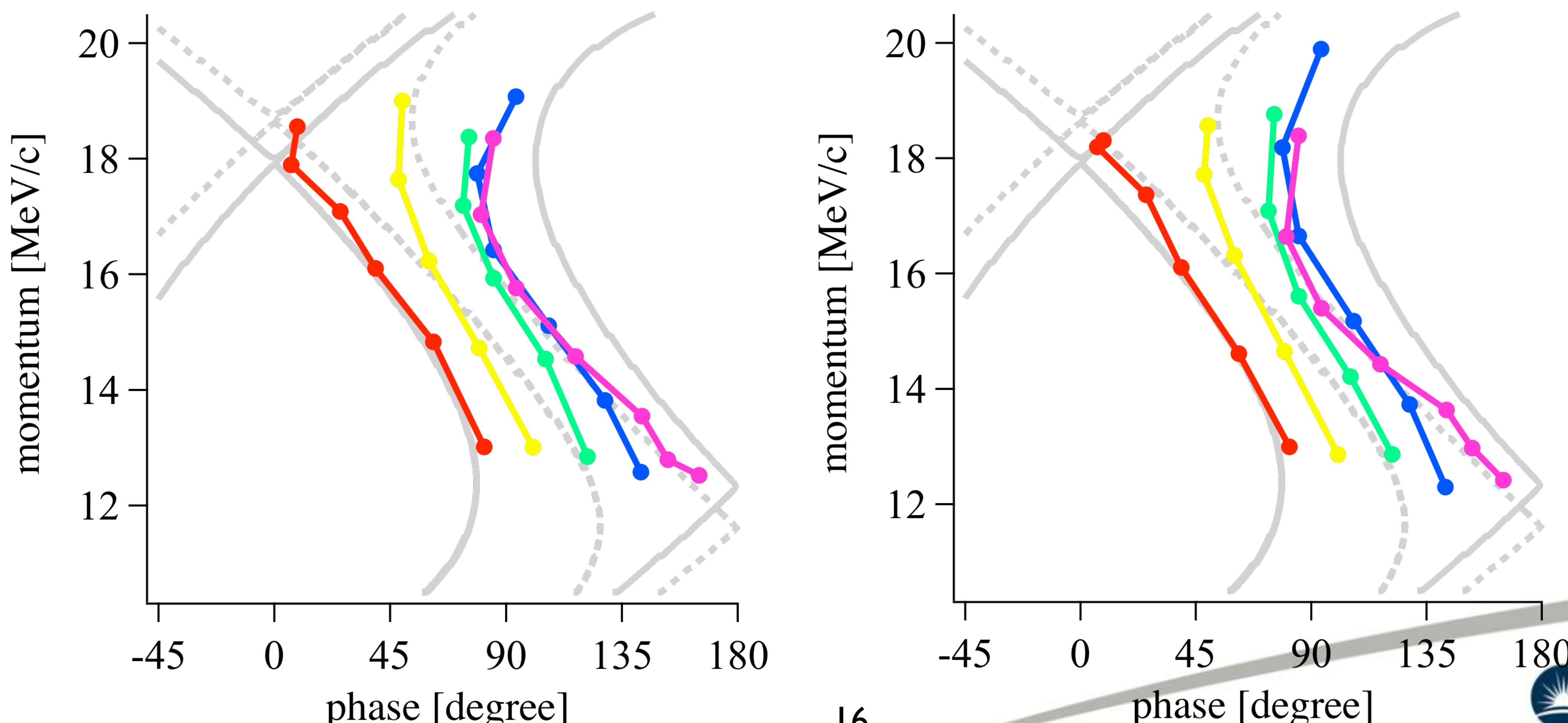
Serpentine channel acceleration

Serpentine channel acceleration outside rf bucket



Highlight 2

Longitudinal trajectory measured experimentally.

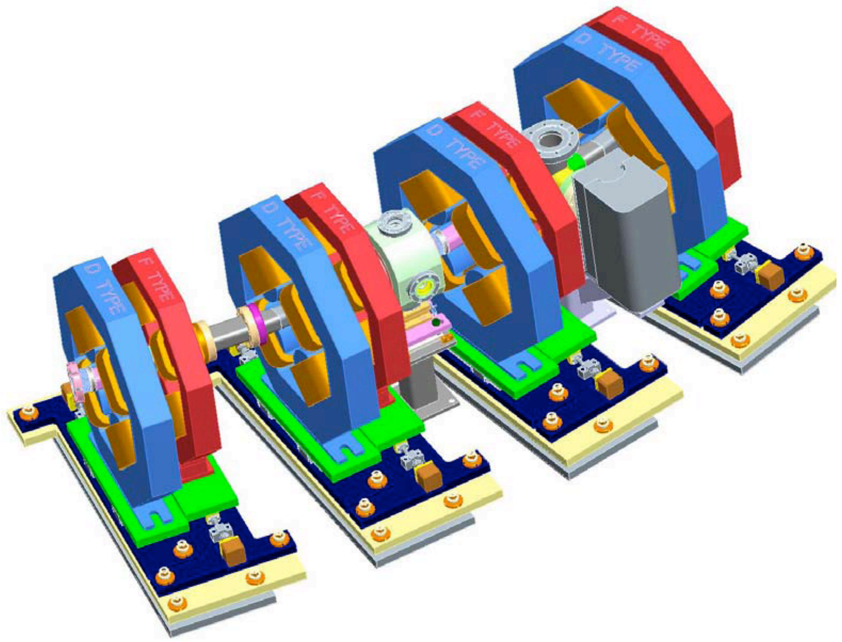


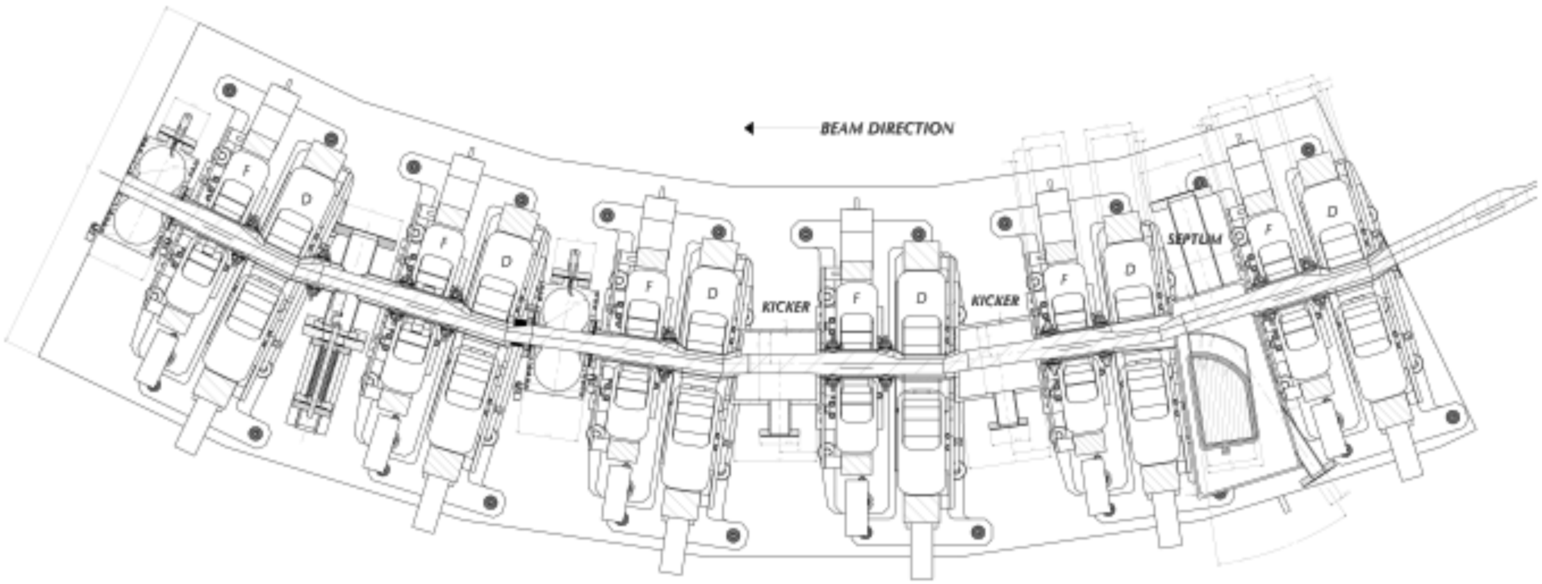
What we learned

What we learned (1)

very small dispersion lattice

"Cyclotron" with synchrotron size magnets.





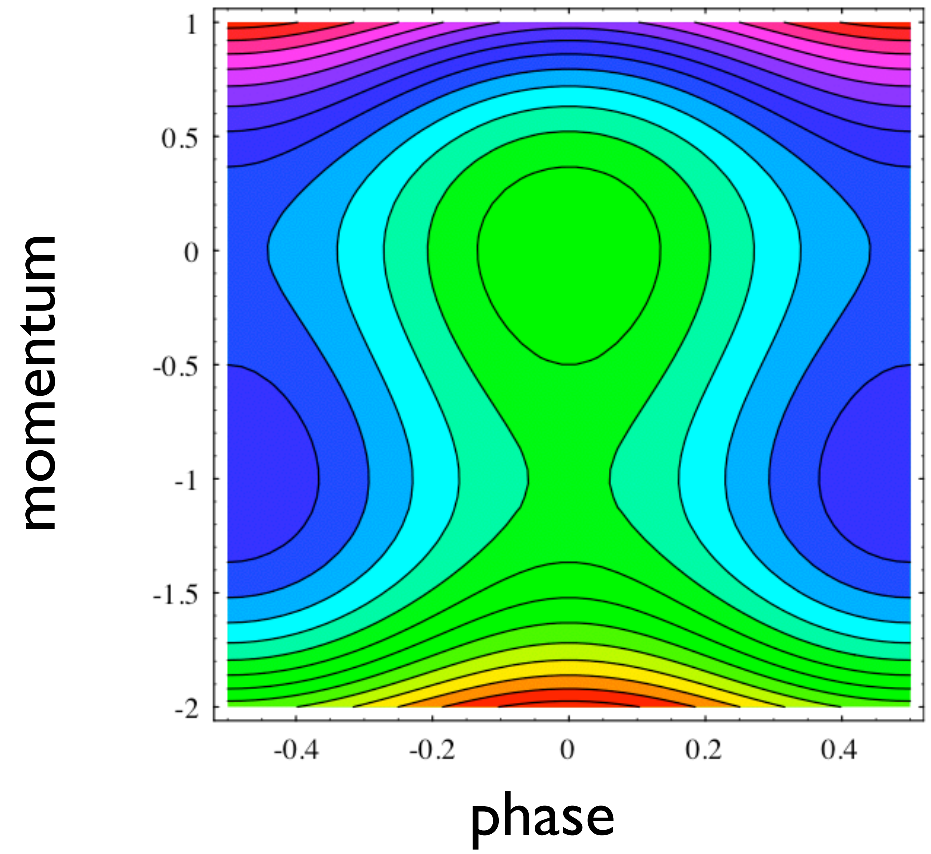
Very small orbit excursion can be realised by very small dispersion function lattice.

Optics is stable.

What we learned (2)

almost isochronous lattice

For ultra-relativistic particles, small orbit excursion makes the lattice almost isochronous.



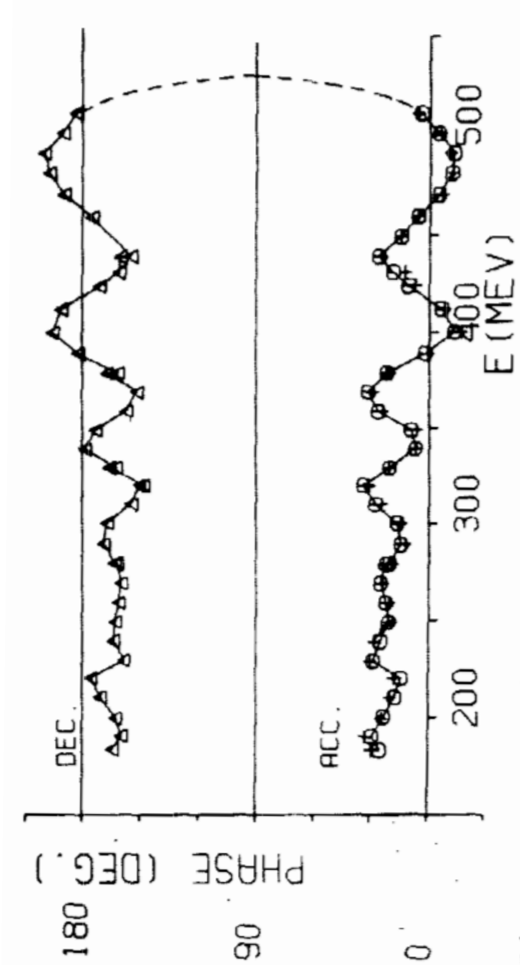


Fig. 2. Phase histories of accelerating and decelerating beams, obtained by timing an external beam.

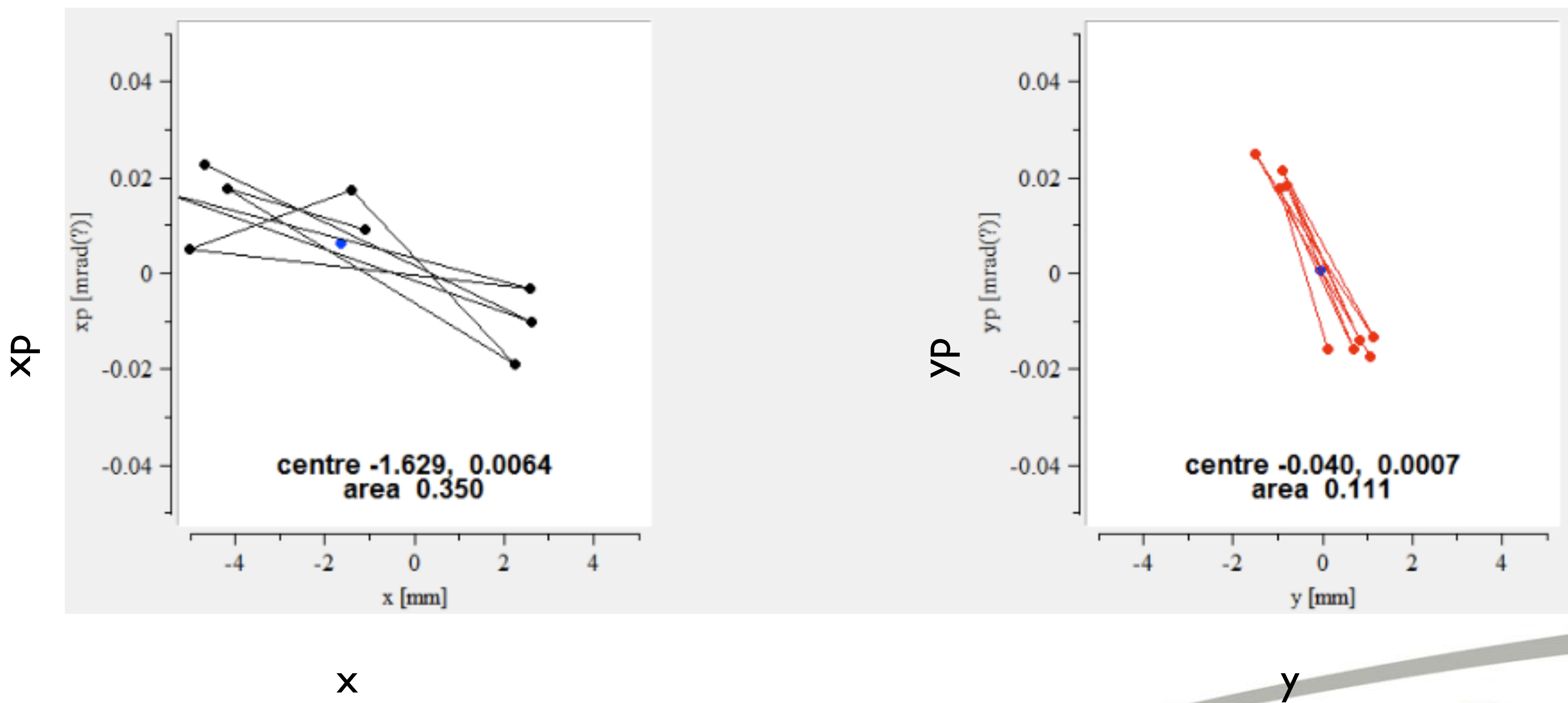
Fixed frequency rf can be used for acceleration within a short time period.

Dynamics is very similar to longitudinal motion in a nearly isochronous cyclotron. (by Craddock)

What we learned (3a)

large acceptance

Very strong focusing lattice gives huge physical acceptance, more than 1000 pi mm mrad (normalized).



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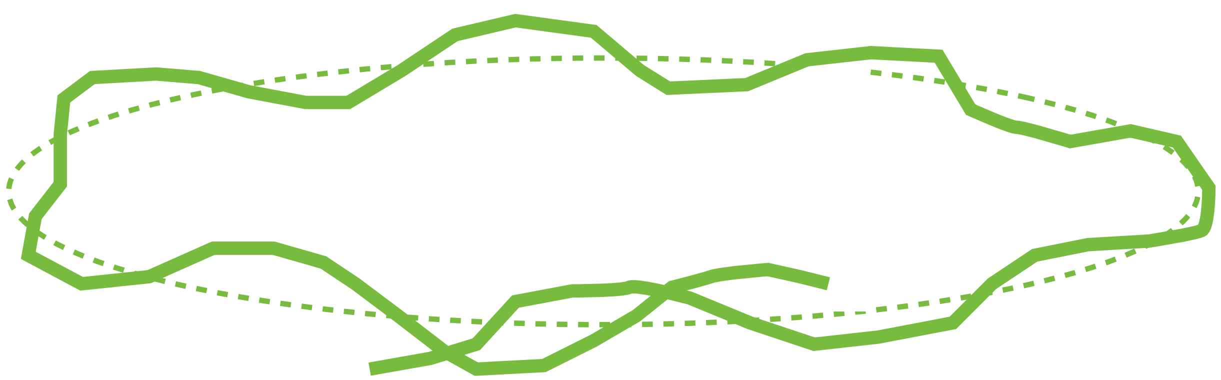
What we learned (3b)

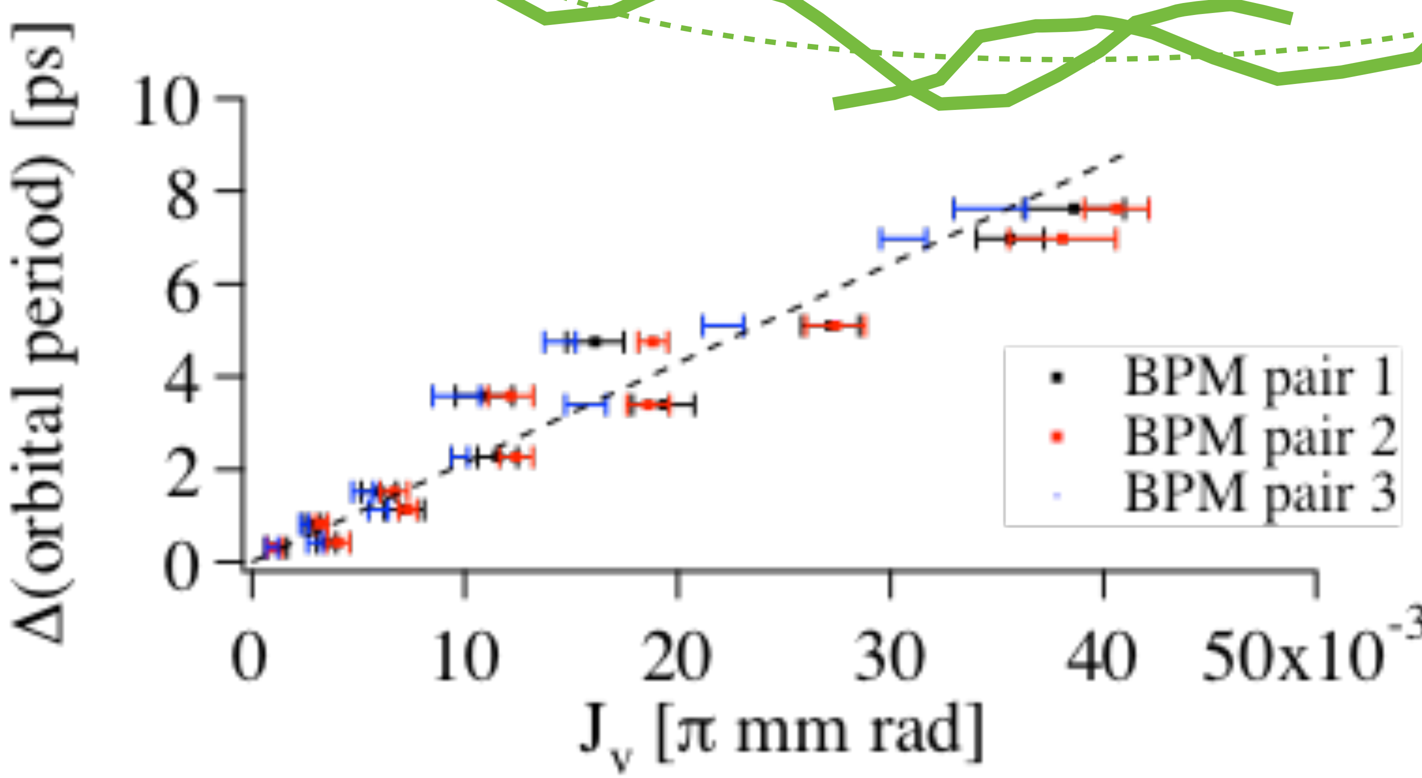
amplitude dependent orbital period

Large transverse amplitude particles circulate slower without chromaticity correction.

betatron oscillation around a ring



Large amplitude particle follow the longer path.



Shift of orbital period linearly depends on action (single particle emittance).

What we learned (4)

orbit correction

Orbit correction algorithm similar to that of synchrotron could be applied and reduced COD indeed.

Synchotron

$n_m \times n_c \quad n_c \times 1 \quad n_m \times 1$

$$[A]\,[c] = -\,[m]$$

LNS FFAG

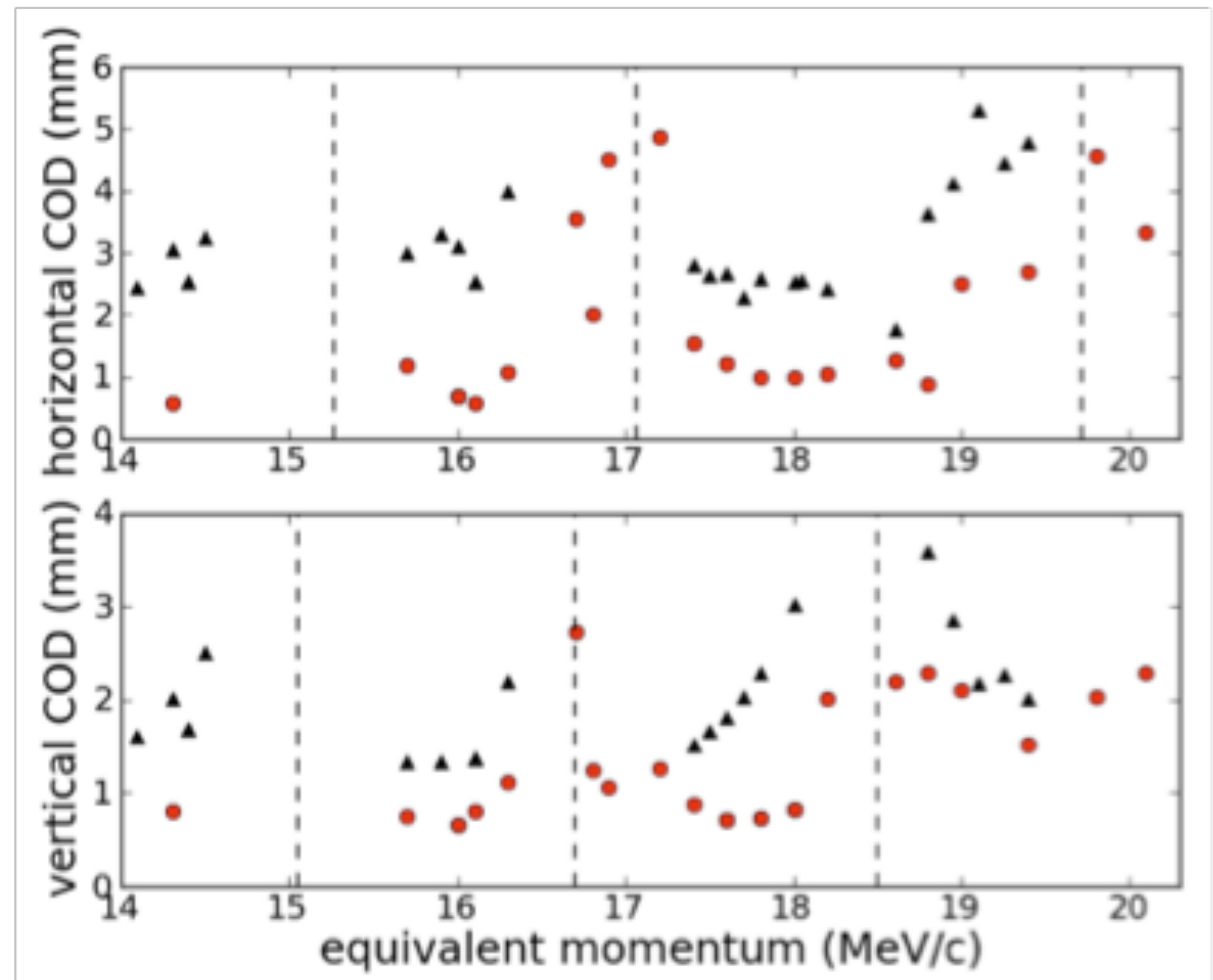
$p \times n_m \times n_c \quad n_c \times 1 \quad p \times n_m \times 1$

$$\begin{bmatrix} A_{p1} \\ A_{p2} \\ \dots \\ A_{pf} \end{bmatrix} [c] = - \begin{bmatrix} m_{p1} \\ m_{p2} \\ \dots \\ m_{pf} \end{bmatrix}$$

A : response matrix

c : corrector srength

m: COD measurement

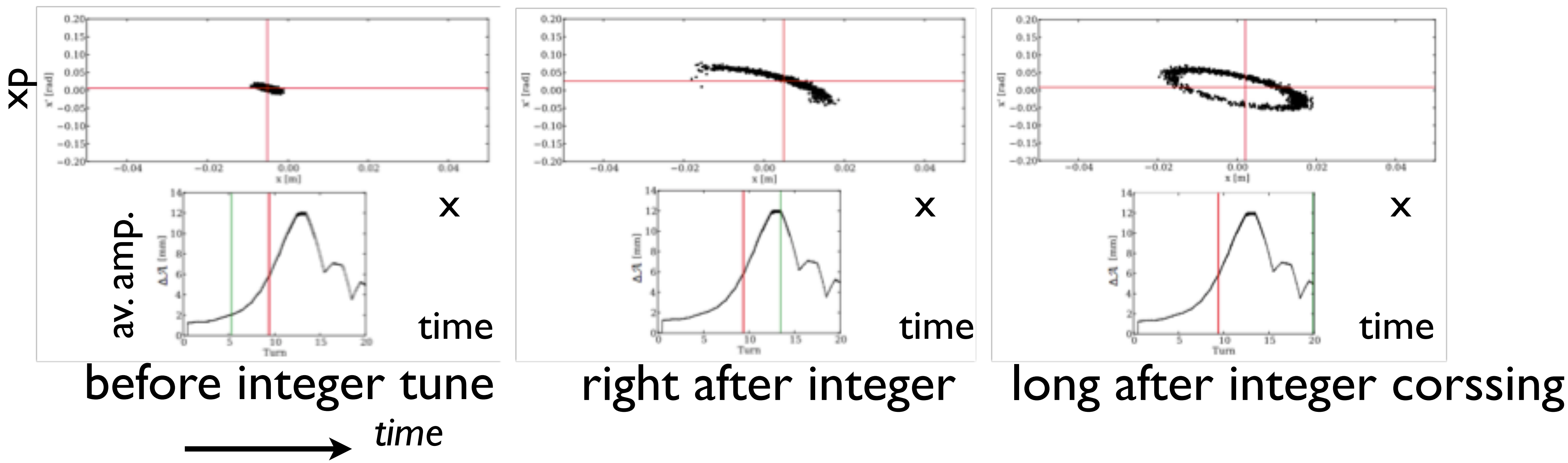


COD before (black) and after (red) correction based on response matrix measured at 14.3, 16.1 and 18.0 MeV/c and solve c by SVD.

What we learned (5)

integer tune crossing

Integer tune crossing itself is not harmful. It only excites coherent motion, not emittance growth.



Natural chromaticity with finite momentum spread causes decoherence and emittance growth.

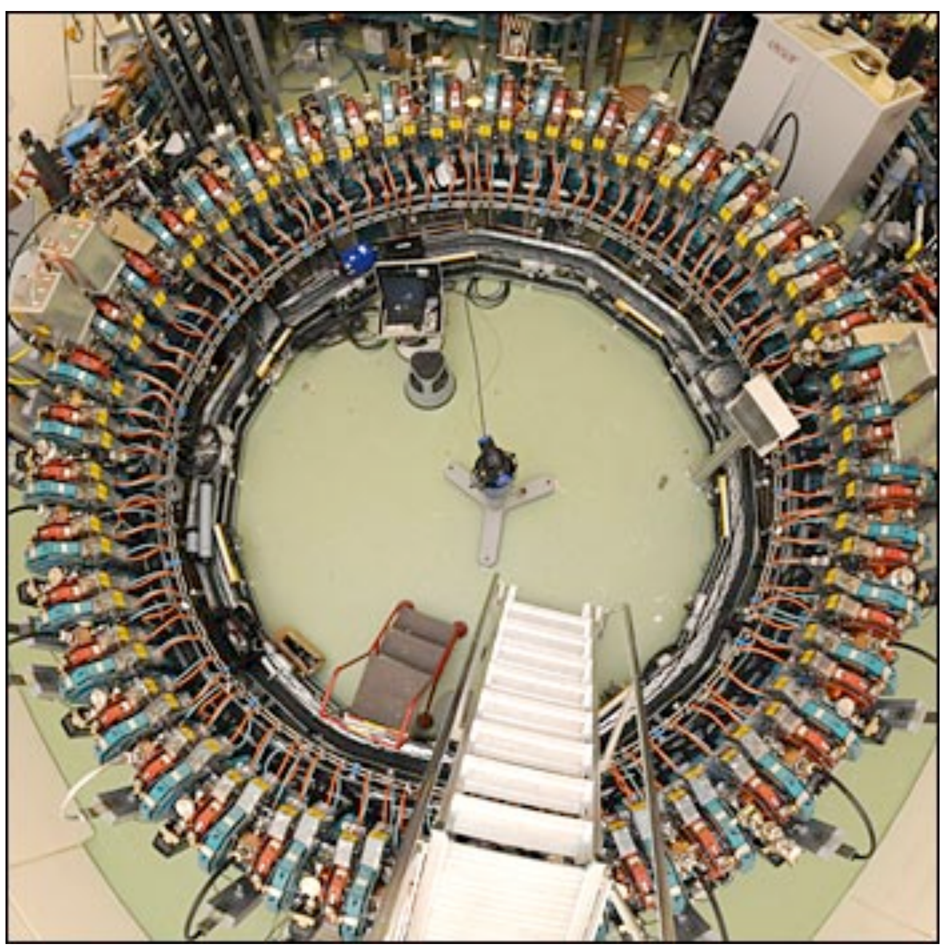
This is not the case in cyclotrons.

What we learned (6)

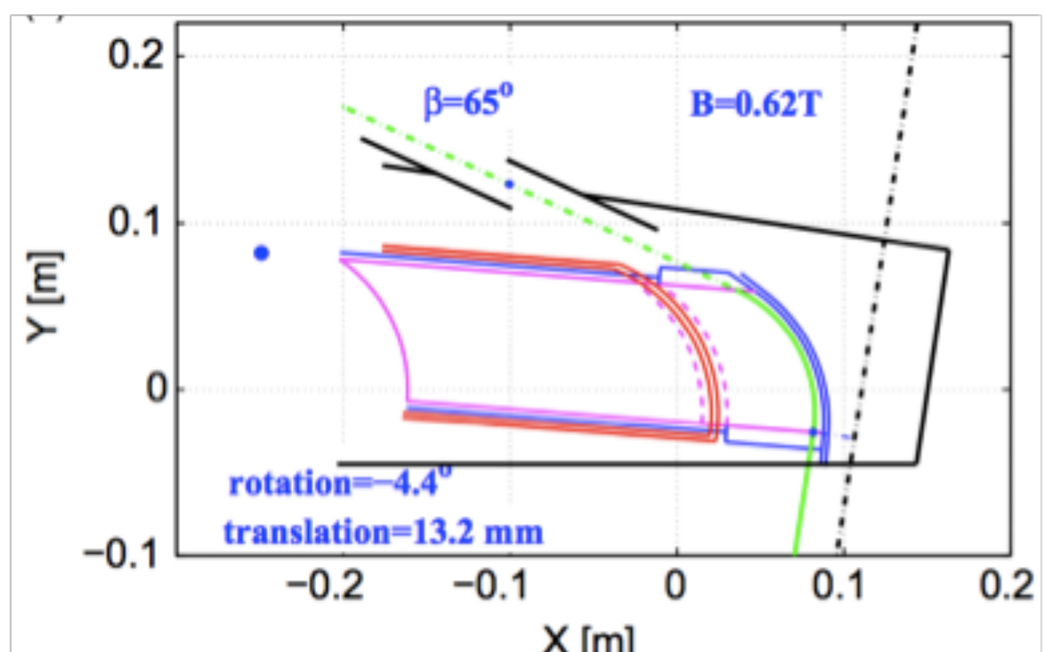
injection and extraction

Need compromise between small orbit excursion and long enough straight for injection and extraction.

EMMA may stress too much on small dispersion.



- Designs facilitating inj/ext have been found.
- Large angle septum



65 degree septum

- Insertion or superperiod

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What we learned (7)

other minor things

- Adjusting rf phase of 19 cavities is relatively harder because of high rf frequency of 1.3 GHz compared with more conventional frequency for cyclotron like a few 10 MHz.
- The size of beam chamber is about the same as that of synchrotrons and the same type of Beam Position Monitor could be used. However, beam orbit is far off-centre by design. Accuracy and sensitivity in the entire area need to be assured.

You could say EMMA (a linear non-scaling FFAG) is one kind of cyclotron, but ...

Summary

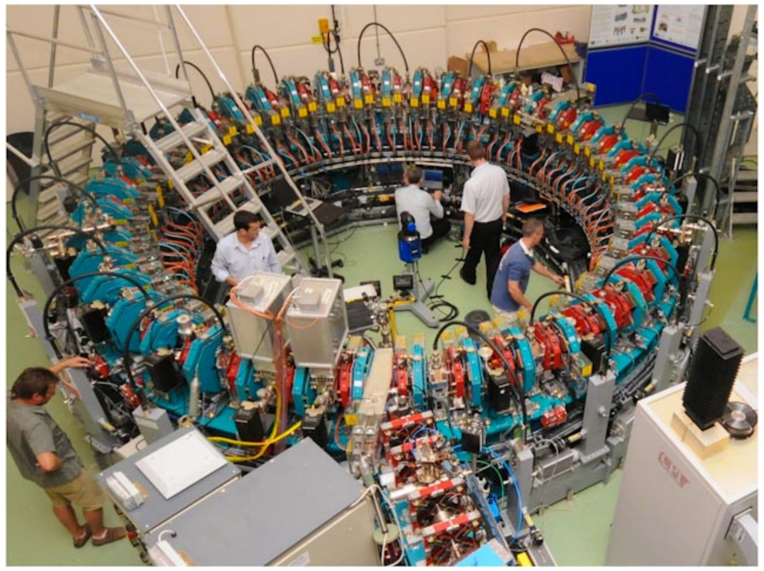
Good compromise between small dispersion and long straight

Much smaller magnets. "Cyclotron with synchrotron size magnets."

Almost isochronous so that fixed frequency rf system.

Resonance can be crossed during acceleration.

Much faster decoherence due to large chromaticity and more momentum spread.



Huge acceptance.

Orbital period depends on transverse amplitude.

Same technique to restore ideal orbit as synchrotrons.