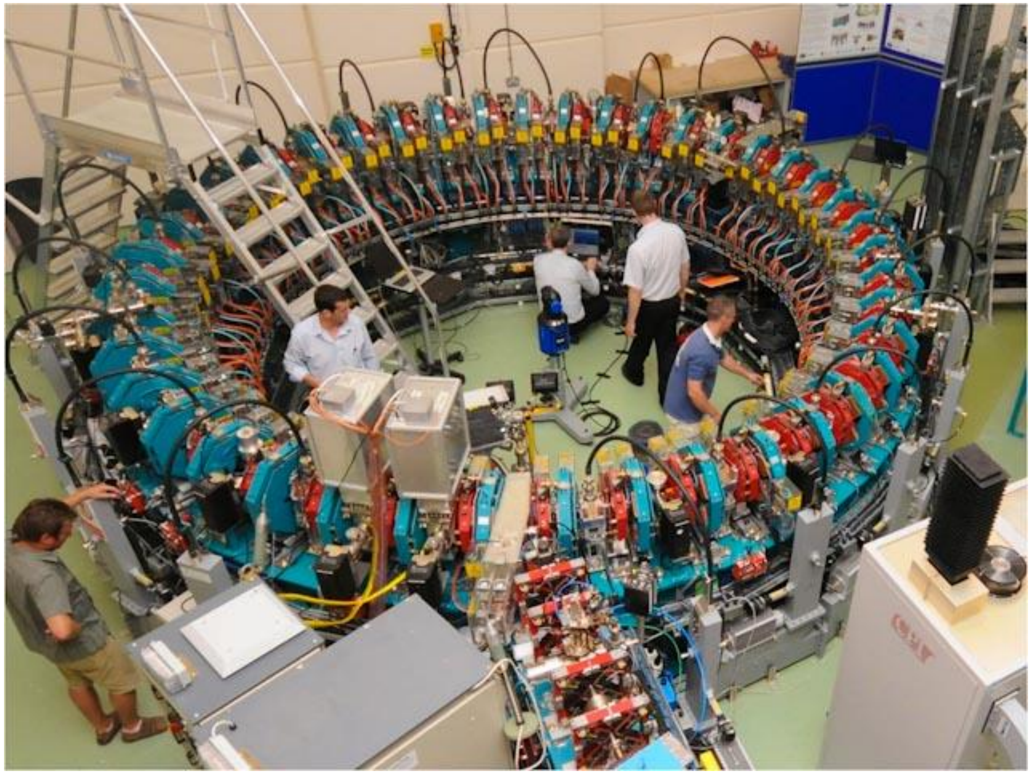
INJECTION AND EXTRACTION FOR THE EMMA NS-FFAG



Bruno Muratori, STFC, ASTeC

Contents

Project Overview

BASROC (The British Accelerator Science and Radiation Oncology Consortium, BASROC)

- CONFORM project (**CO**nstruction of a **N**on-scaling **F**FAG for **O**ncology, **R**esearch, and **M**edicine)
- 4 year project April 2007 – March 2011
- 3 parts to the project
  - EMMA design and construction ~ £6.5m (~$9M)

Electron **M**odel for **M**any **A**pplications (EMMA)

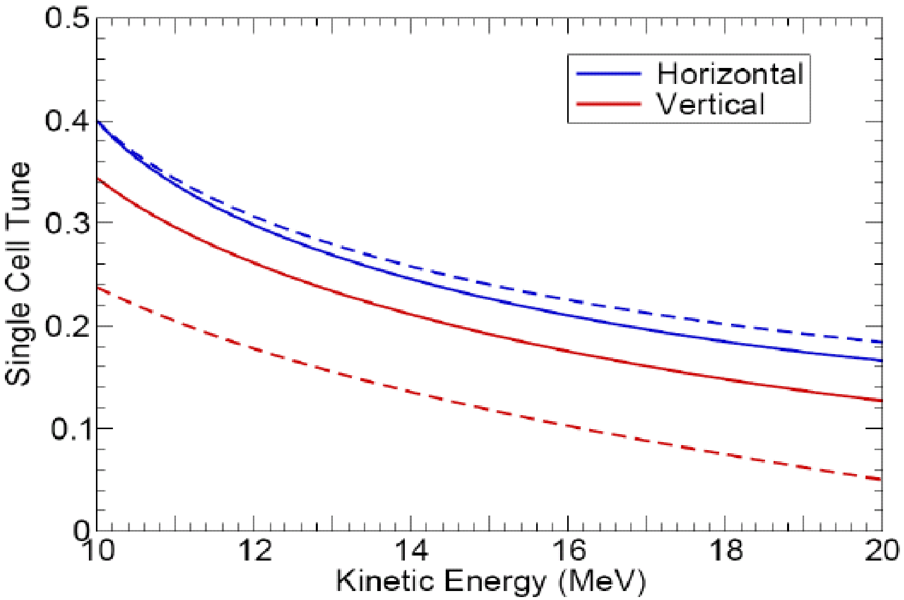
  - PAMELA design study
  - Applications study

EMMA International Collaboration

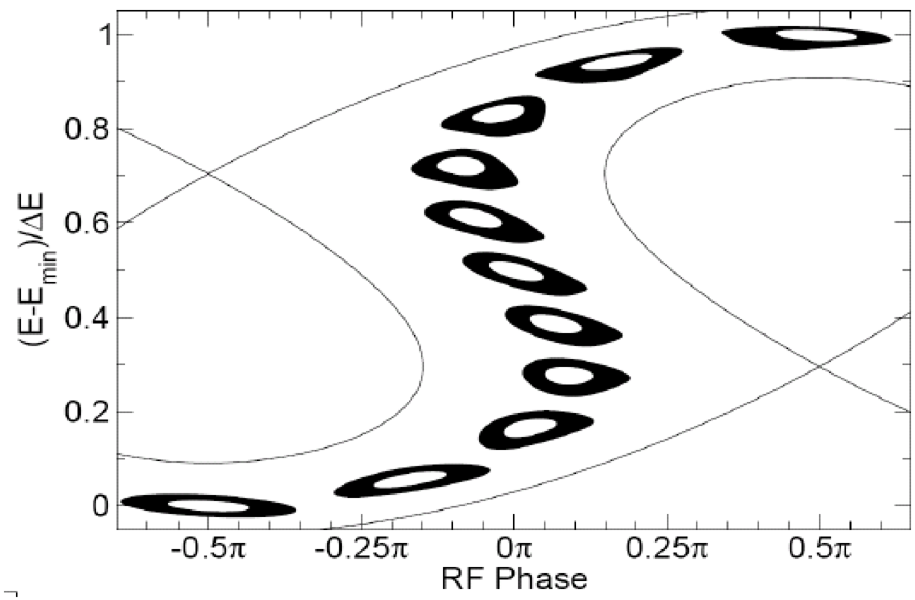
- EMMA design is an international effort and we recognise and appreciate the active collaboration from:
  - Brookhaven National Laboratory
  - Cockcroft Institute UK
  - Fermi National Accelerator Laboratory
  - John Adams Institute UK
  - LPSC, Grenoble
  - Science & Technology Facilities Council UK
  - TRIUMF

EMMA Goals

(1) Rapid acceleration with large tune variation (natural chromaticity)



(2) Serpentine acceleration (results from parabolic ToF)

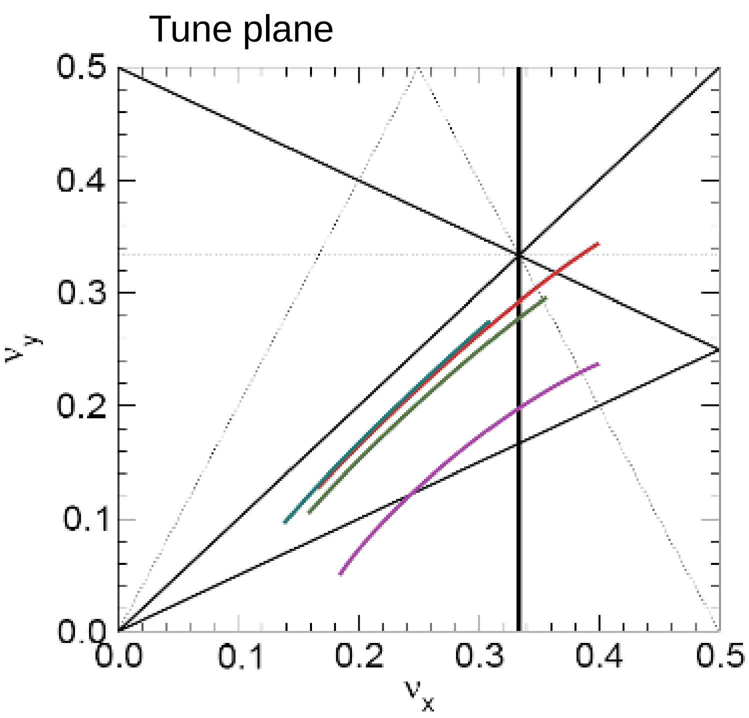


(3) Map the transverse and longitudinal acceptances.

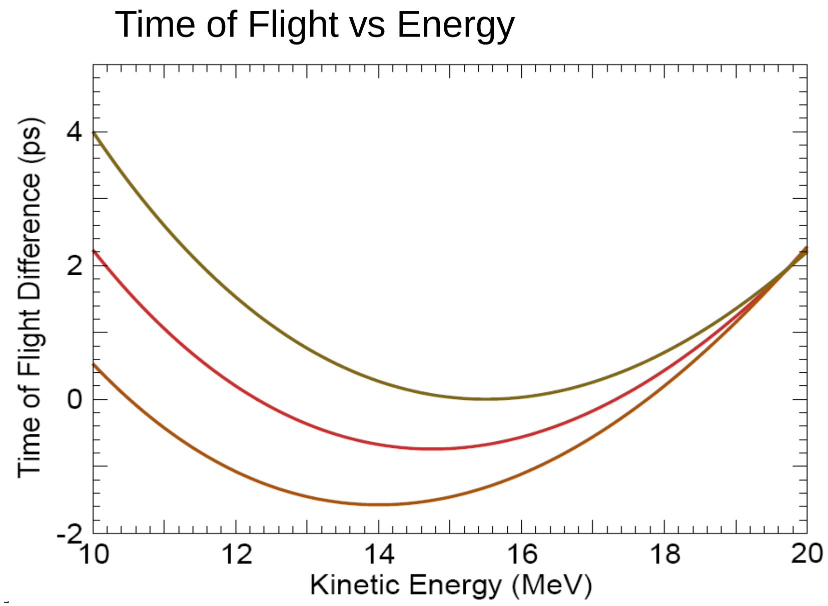
Graphs courtesy of Scott Berg BNL

Lattice Configurations

Understanding the NS-FFAG beam dynamics as function of lattice tuning & RF parameters



- Example: retune lattice to vary resonances crossed during acceleration



- Example: retune lattice to vary longitudinal Time of Flight curve, range and minimum

Graphs courtesy of Scott Berg BNL

Accelerator Requirements

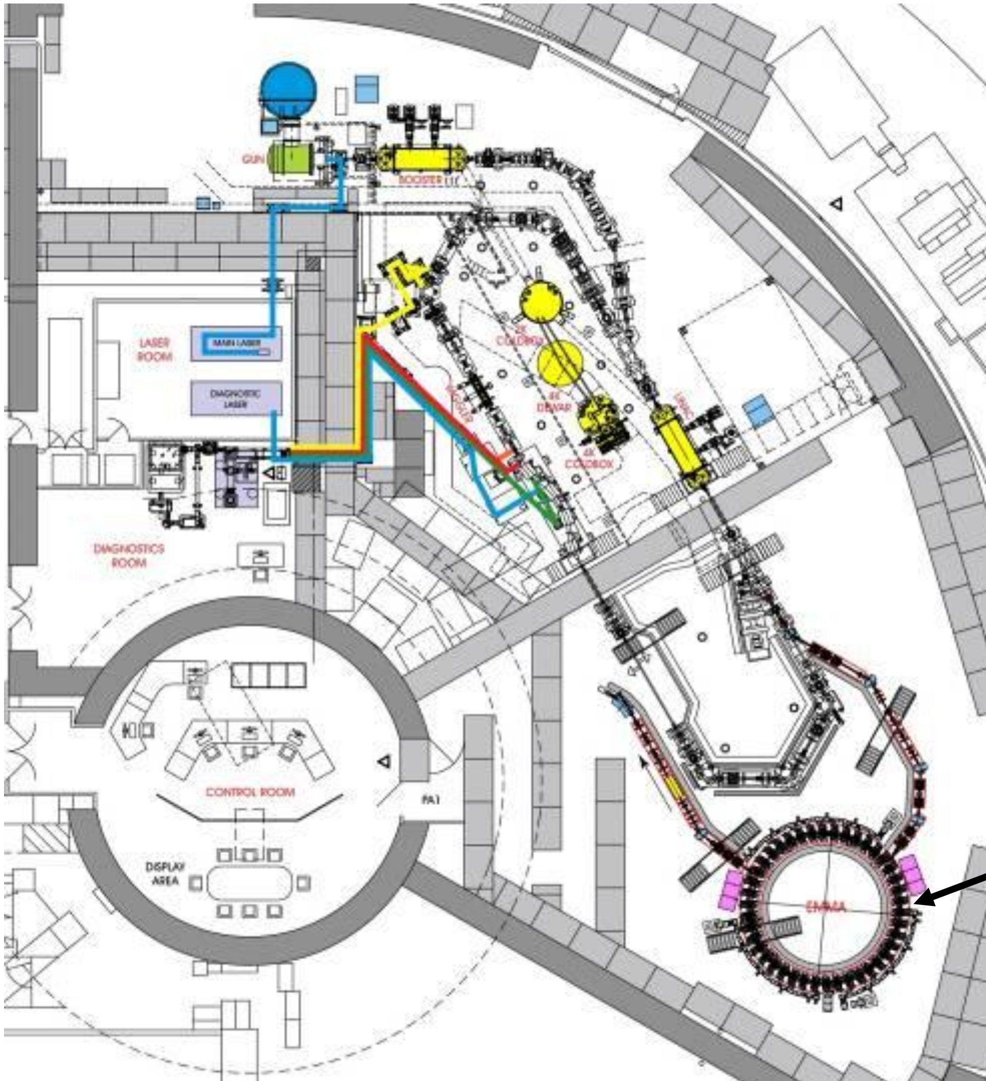
- Injection & extraction at all energies, 10 - 20 MeV
- Fixed energy operation to map closed orbits and tunes vs momentum
- Many lattice configurations
  - Vary ratio of dipole to quadrupole fields
  - Vary frequency, amplitude and phase of RF cavities
- Map longitudinal and transverse acceptances with probe beam

EMMA to be heavily instrumented with beam diagnostics

LAYOUT AND LATTICE

ALICE

Accelerators and **L**asers **I**n **C**ombined **E**xperiments



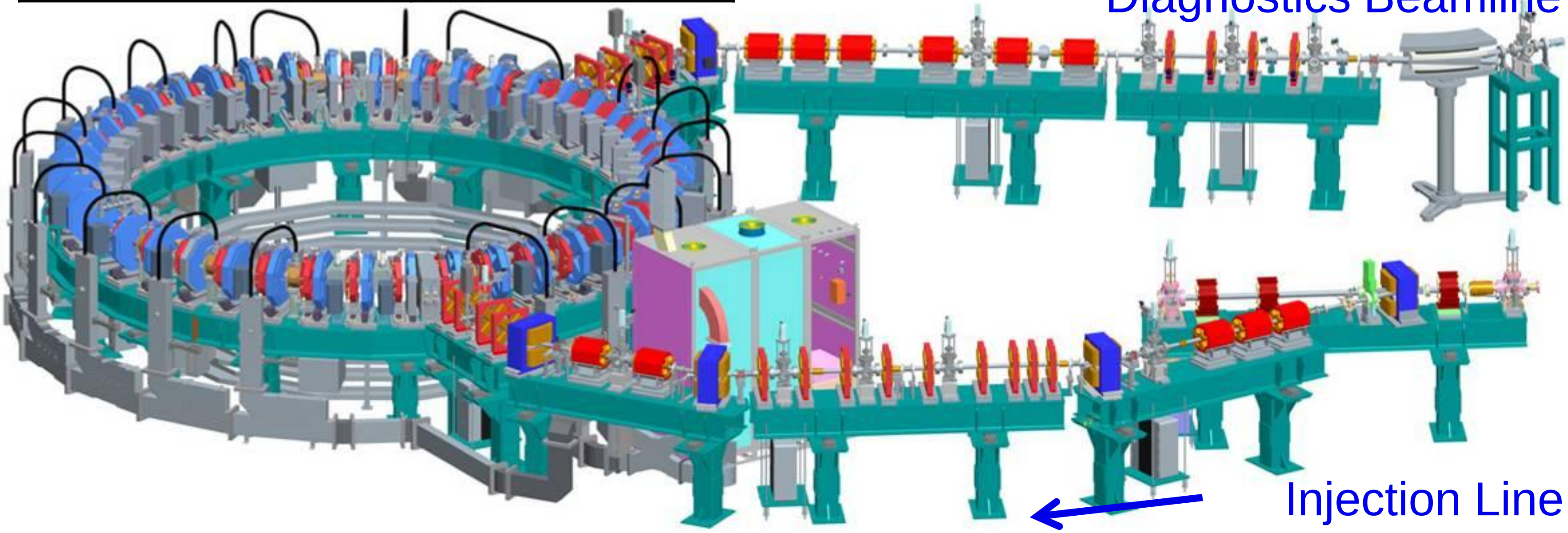
Parameter	Value
Nominal Gun Energy	350 keV
Injector Energy	8.35 MeV
Max. Energy	35 MeV
Linac RF Frequency	1.3 GHz
Max Bunch Charge	80 pC
Emittance	5-15 mm-mrad

EMMA

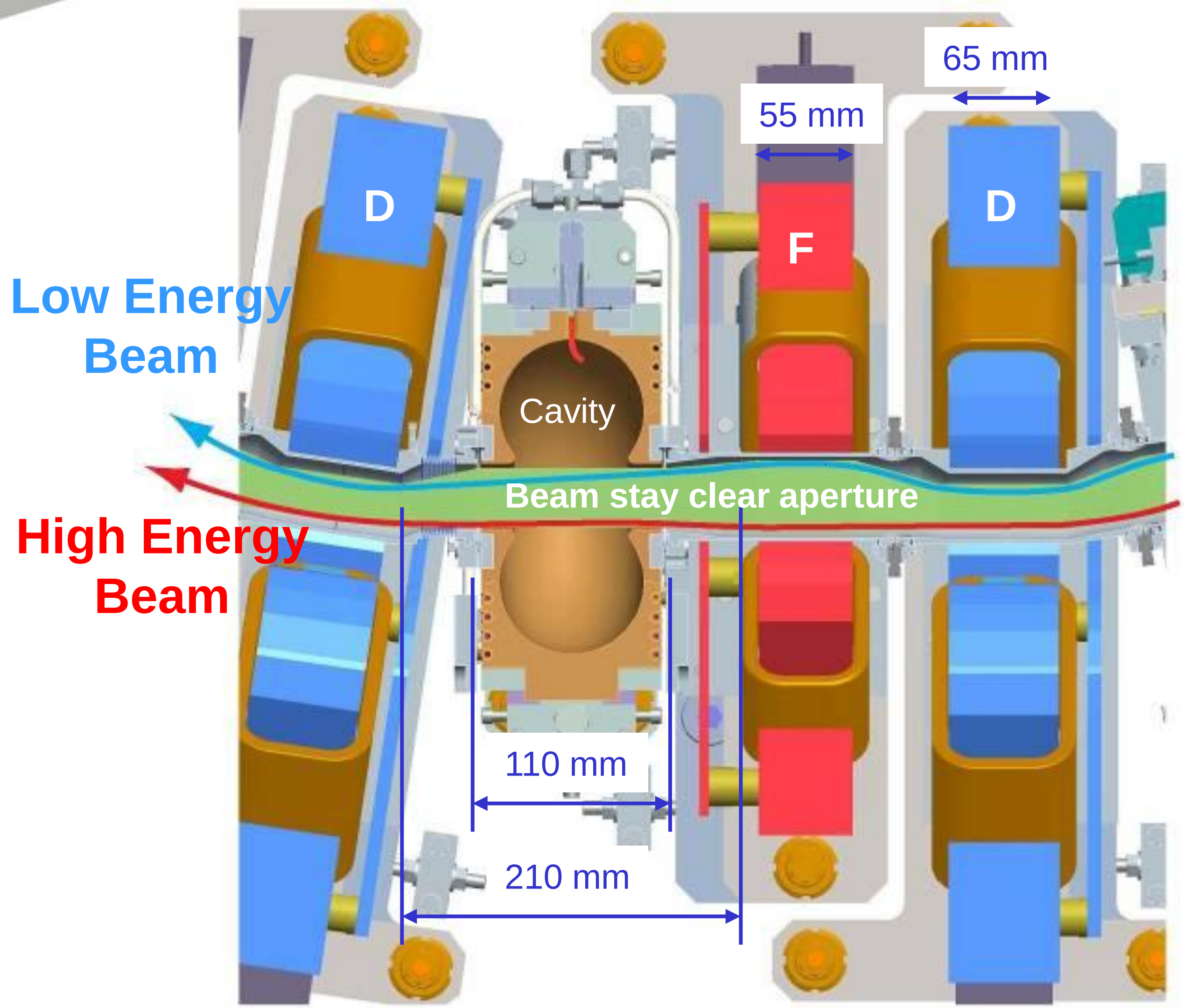
EMMA Parameters & Layout

Energy range	10 – 20 MeV
Lattice	F/D Doublet
Circumference	16.57 m
No of cells	42
Normalised transverse acceptance	3π mm-rad

Frequency (nominal)	1.3 GHz
No of RF cavities	19
Repetition rate	1 - 20 Hz
Bunch charge	16-32 pC single bunch



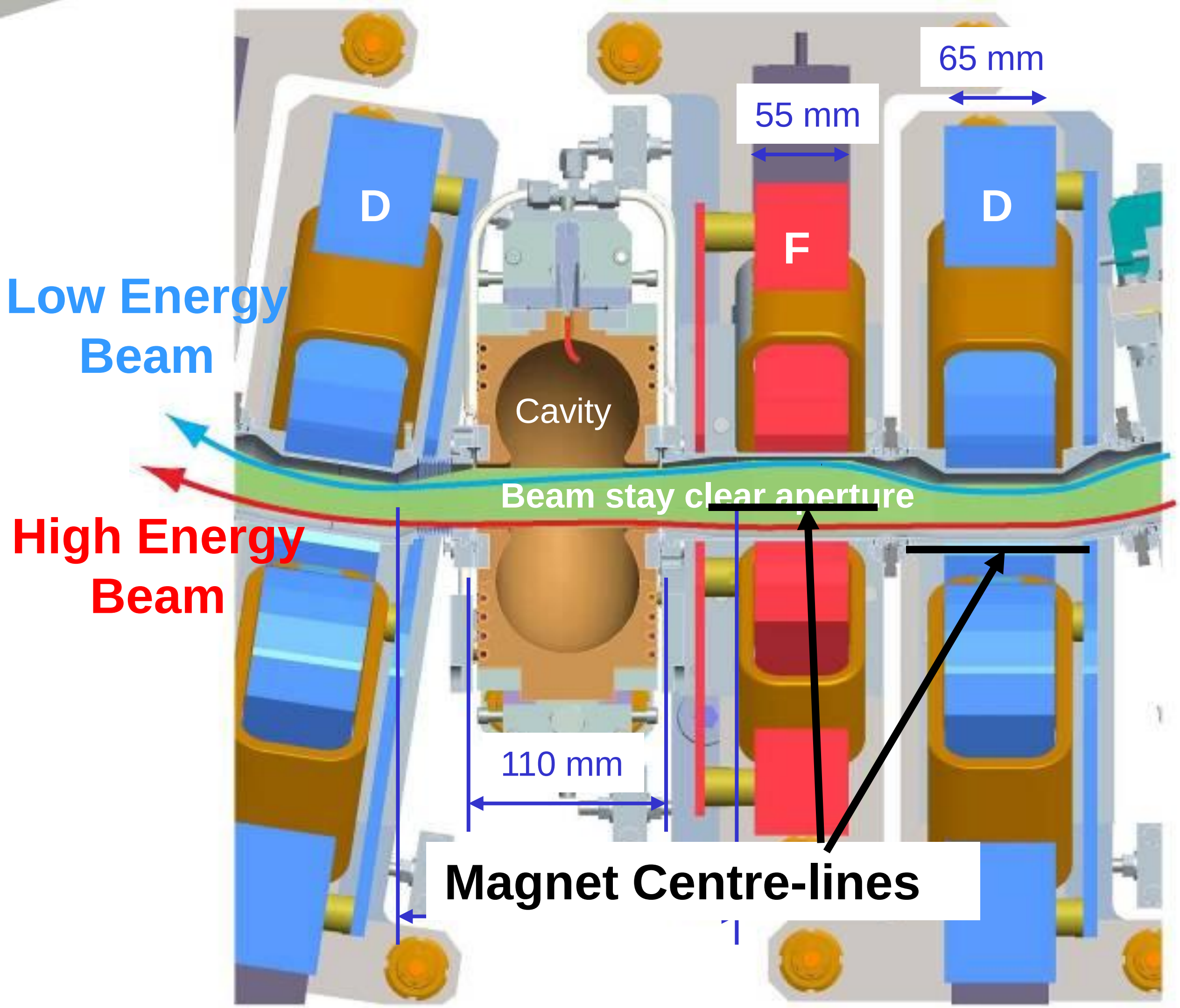
EMMA Ring Cell



Long drift	210 mm
F Quad	58.8 mm
Short drift	50 mm
D Quad	75.7 mm

- 42 identical doublets
- Apart from injection and extraction

EMMA Ring Cell



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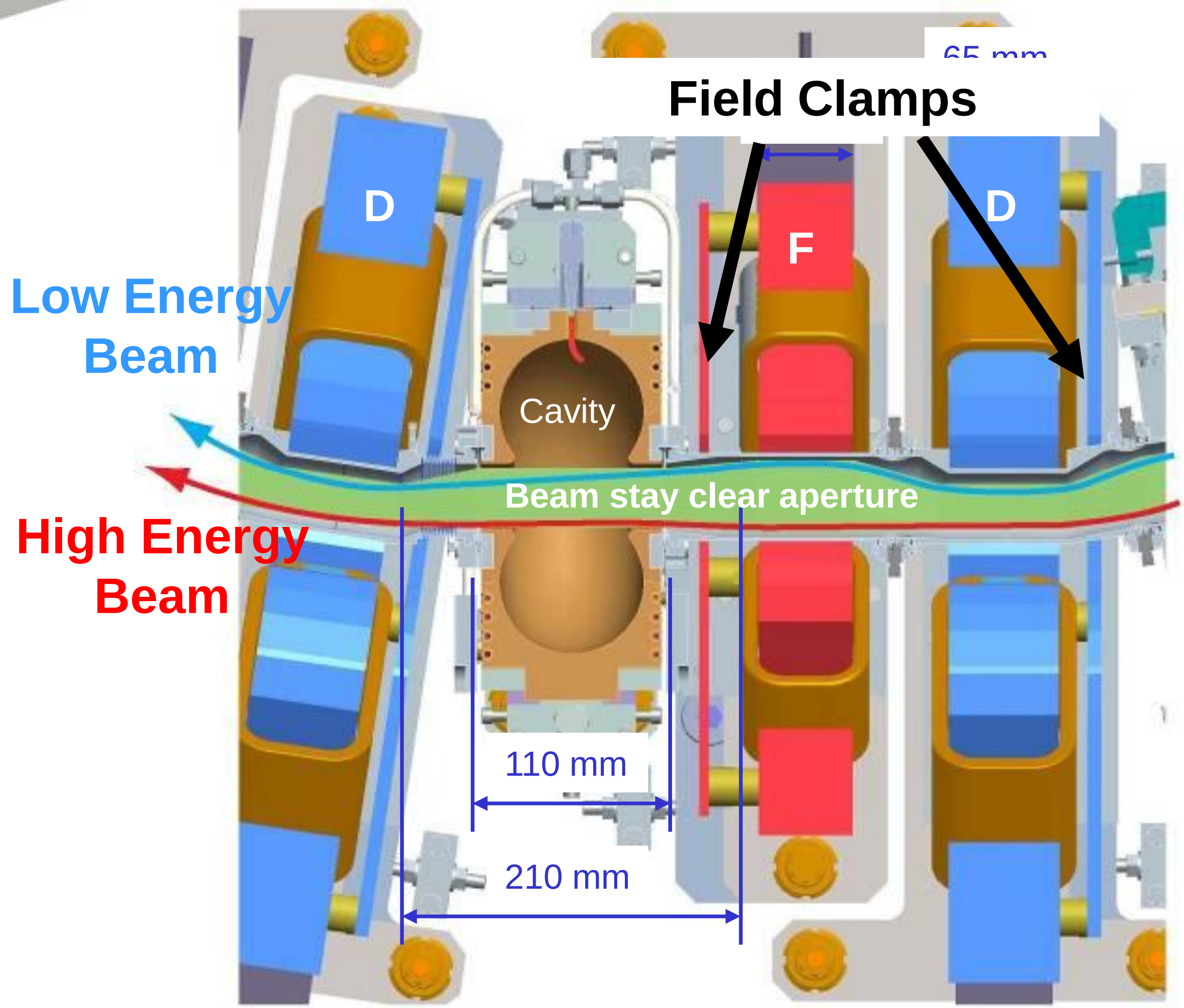

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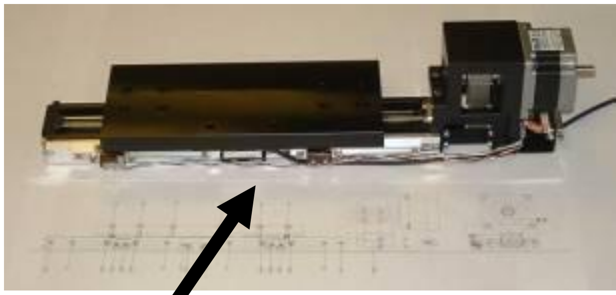

Independent slides

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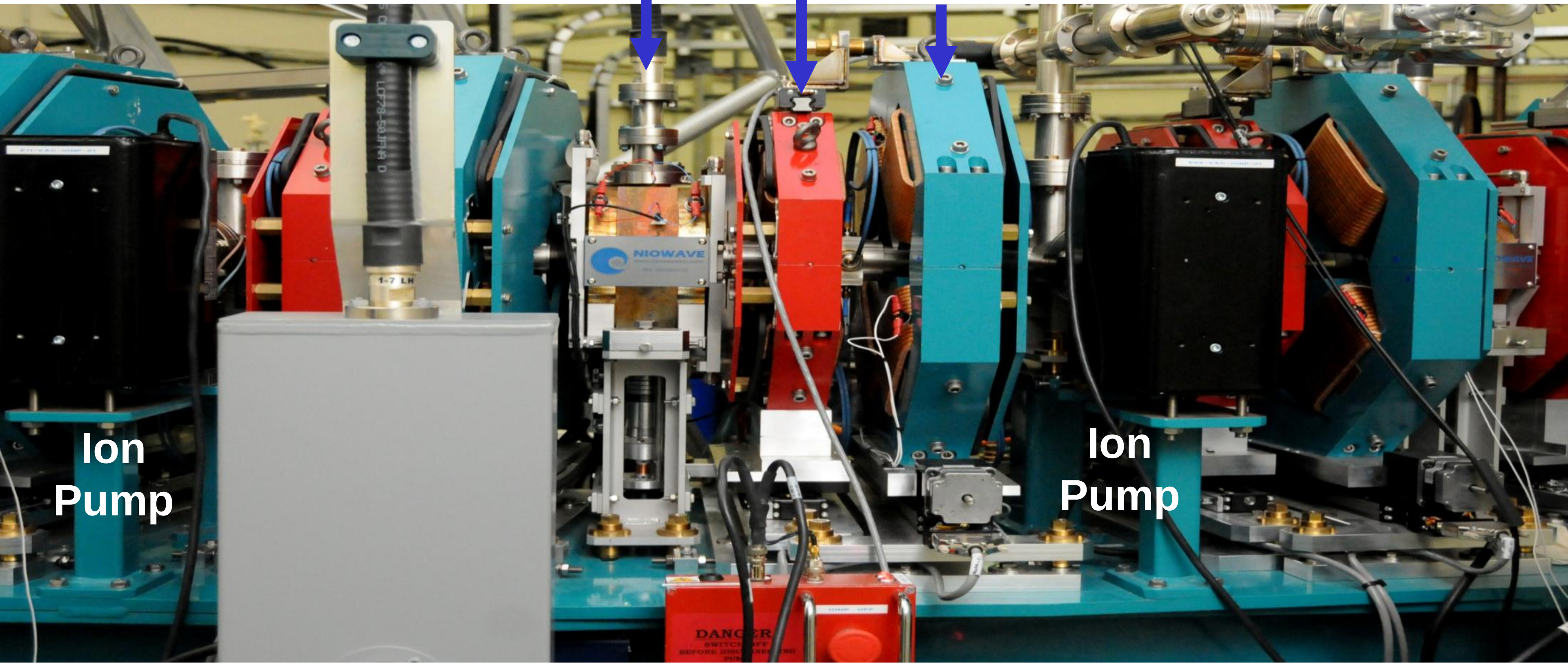
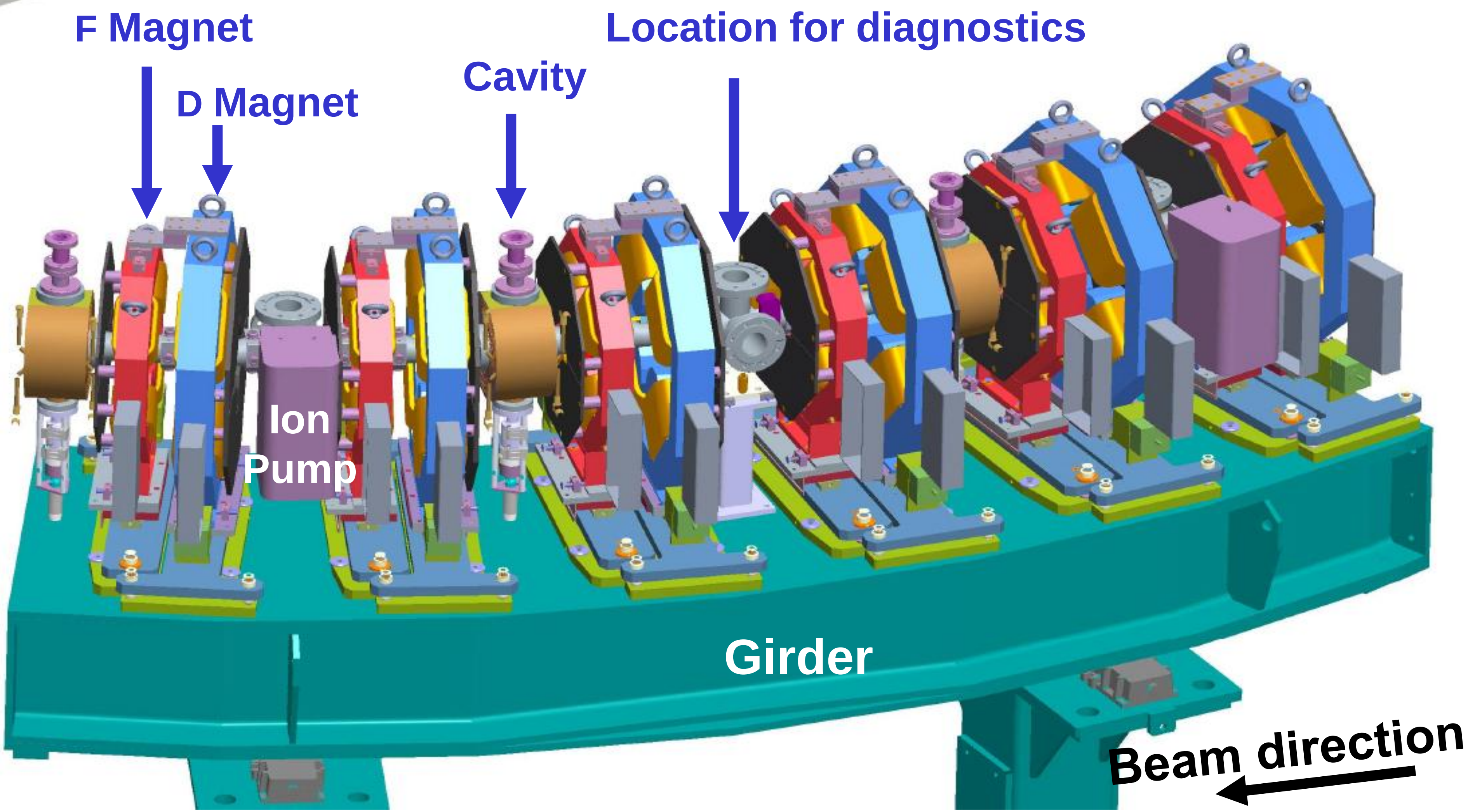
EMMA Cell

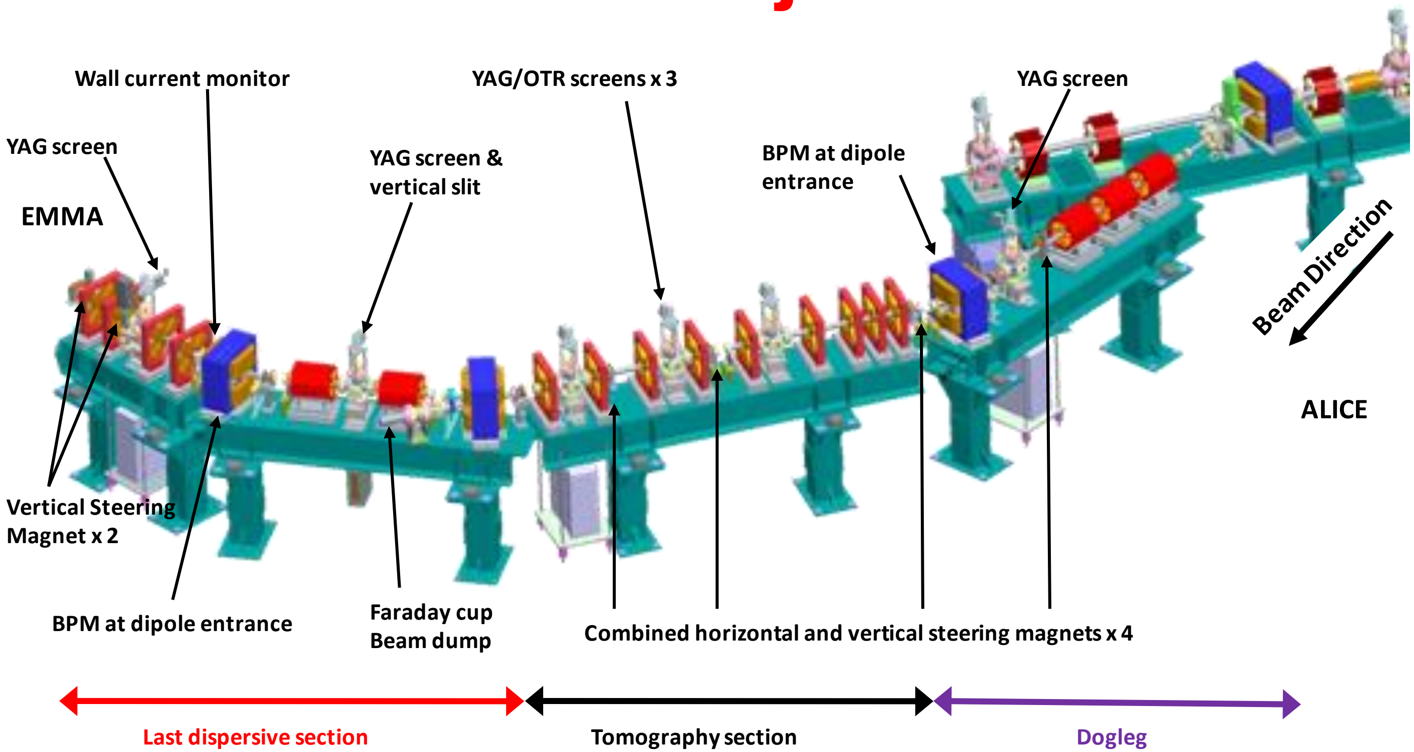


A 6 Cell Girder Assembly



INJECTION & EXTRACTION

Injection line



- Dogleg to extract beam from ALICE
- Tomography (dual purpose)
- Dispersive section to match to EMMA ring with 6 parameters but can be done with 11 variables & maybe more if needed

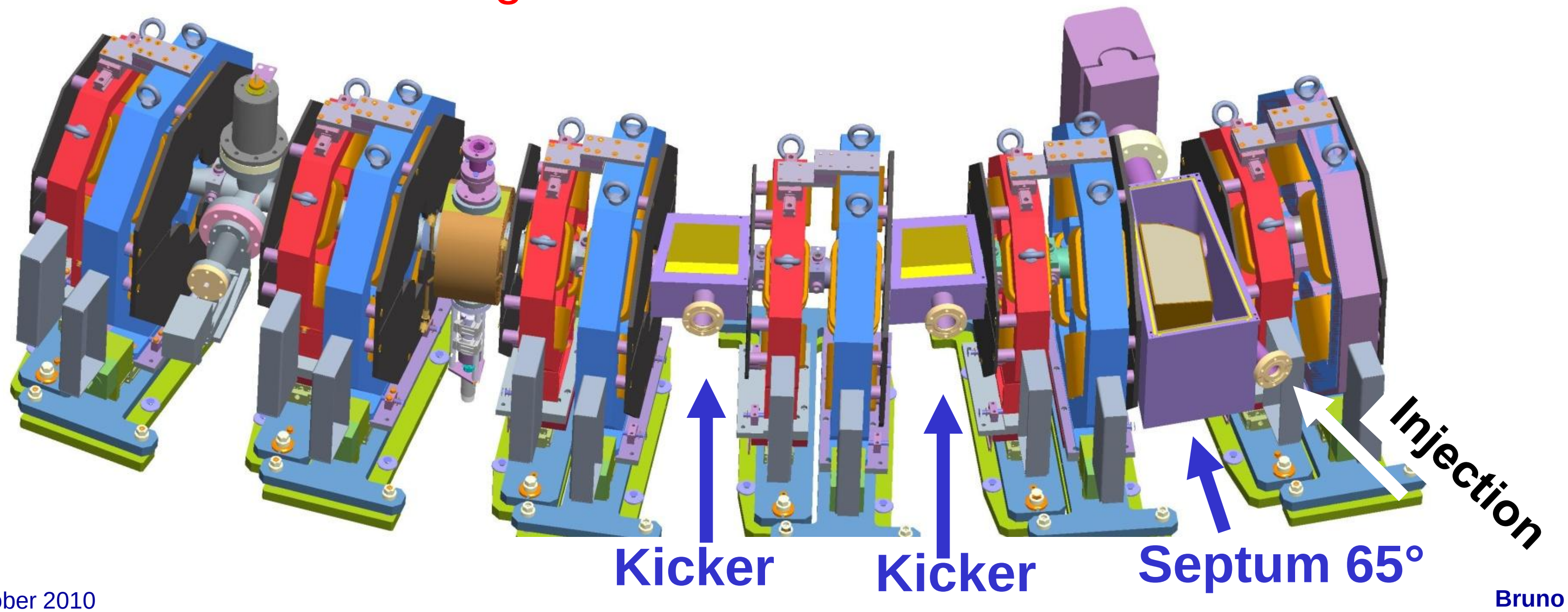
Injection line

- Different energies means different RF focusing & Twiss
- Minimise energy spread (done & < 0.05 % at 15 MeV)
- Done by straightening the bunch with ALICE linac off-crest
  - Yet more difference in RF focusing seen
- Tomography provides **fixed** point (when matched correctly)
  - Need only keep first screen after that & can further vary quadrupoles to match into EMMA ring
  - Tomography can also be used for comparisons in extraction line where an identical straight will be present
- Beam not perfectly centred in injection line but can achieve good injection nonetheless

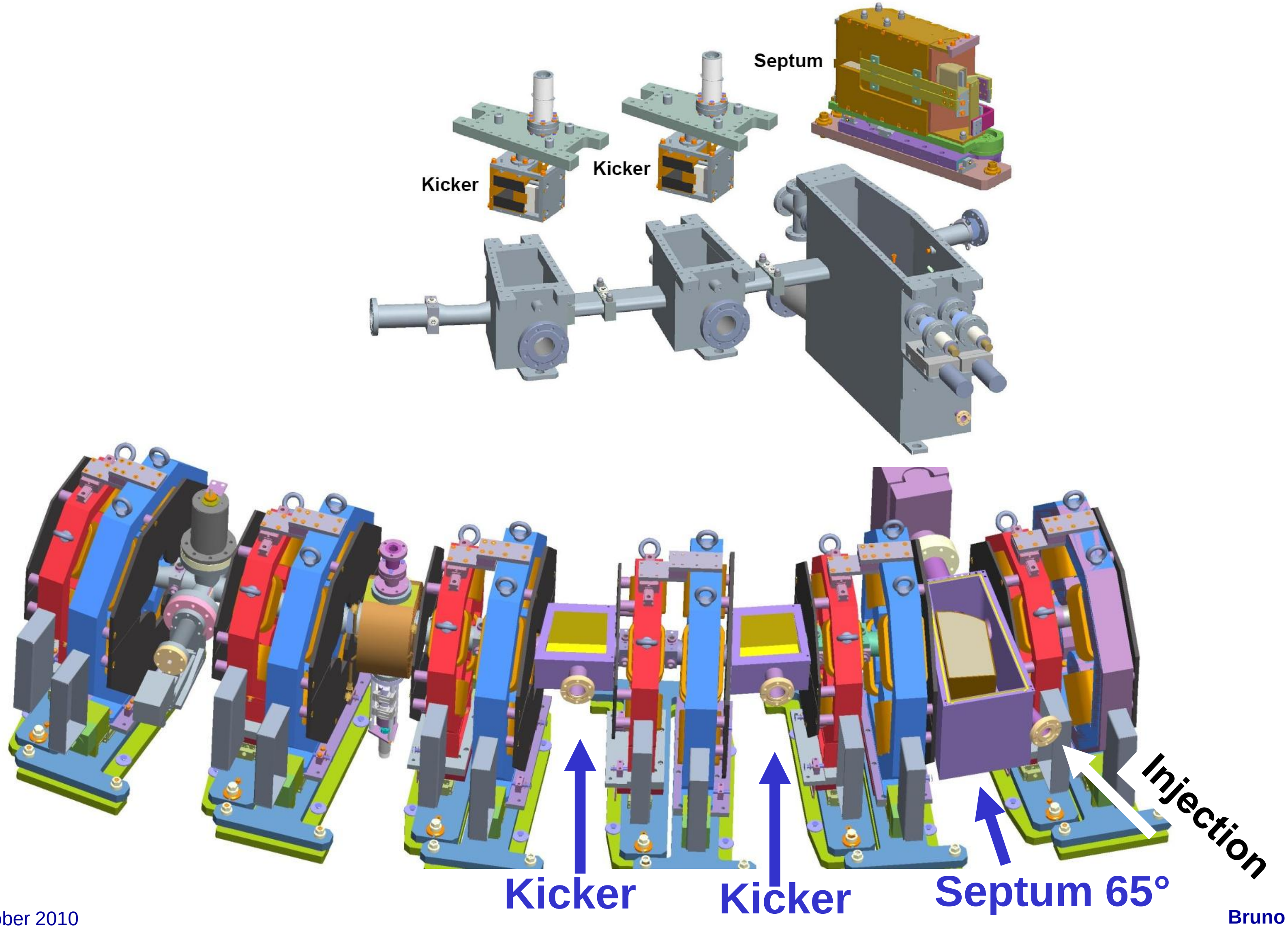
Injection & Extraction

- Large angle for injection (65) and extraction (70) very challenging !!
- Injection/Extraction scheme required for all energies (10 – 20 MeV)
- Many lattices and many configurations of each lattice required
- Very limited space between quadrupole clamp plates for the septum and kickers construction

Extensive 3D magnet modelling conducted to minimise the effect of stray septum fields on circulating beam



Injection Region



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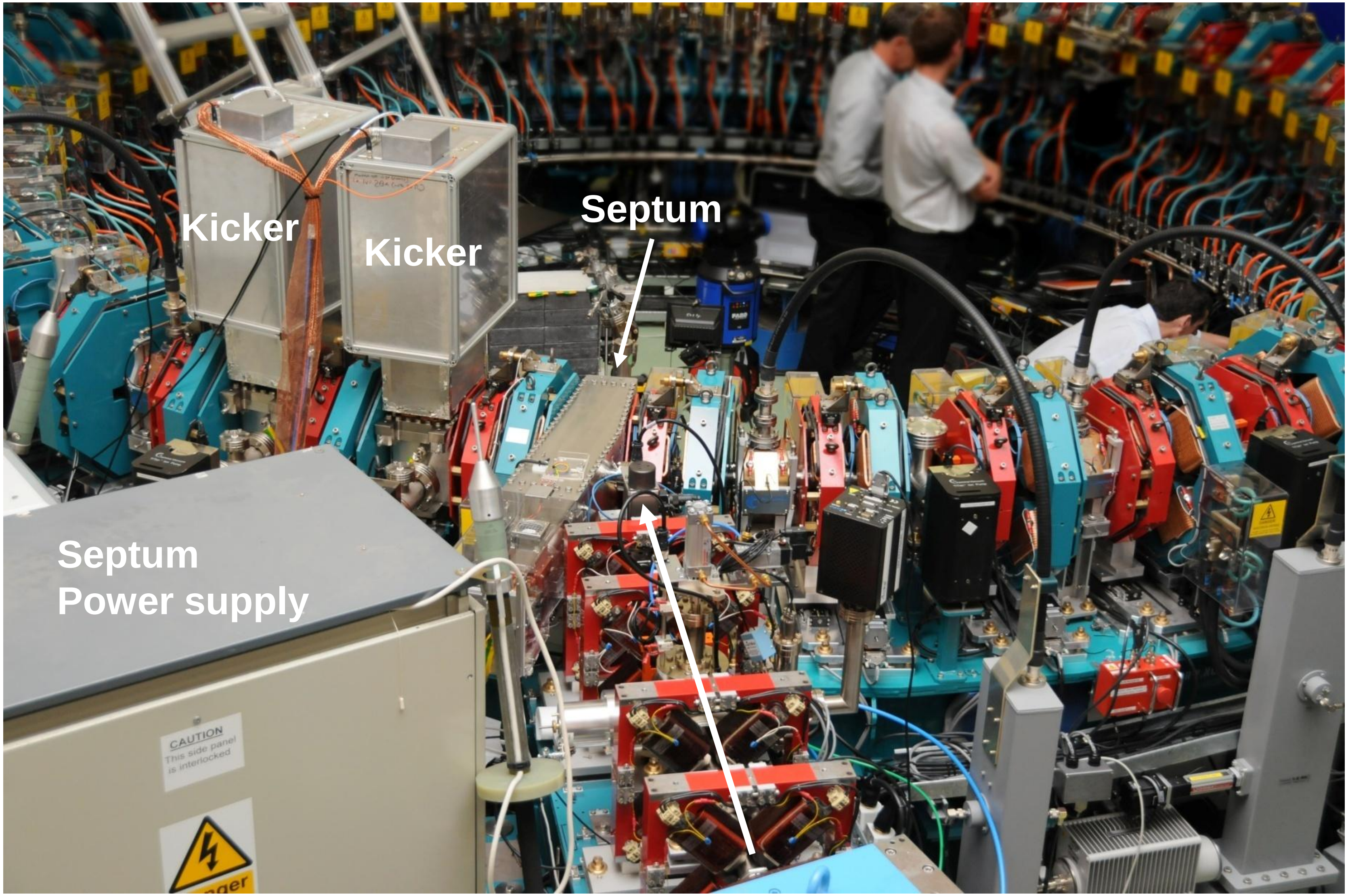
Injection


Kicker
Kicker
Septum
Septum
Power supply
CAUTION
This side panel
is interlocked

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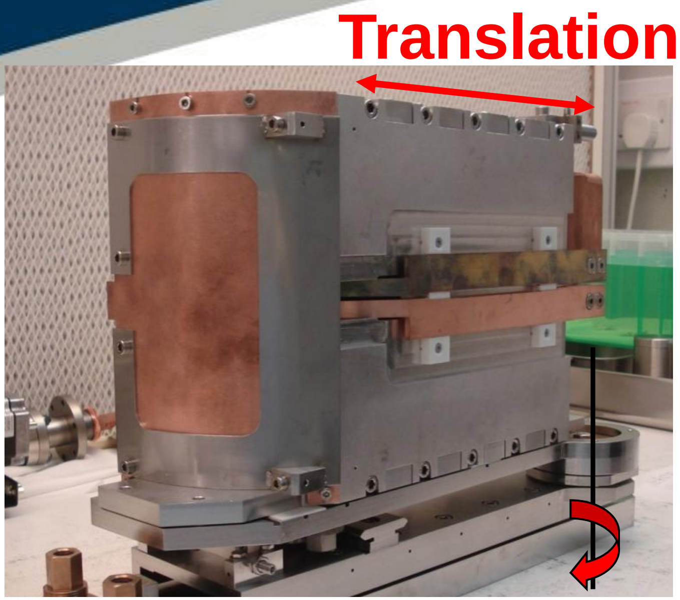
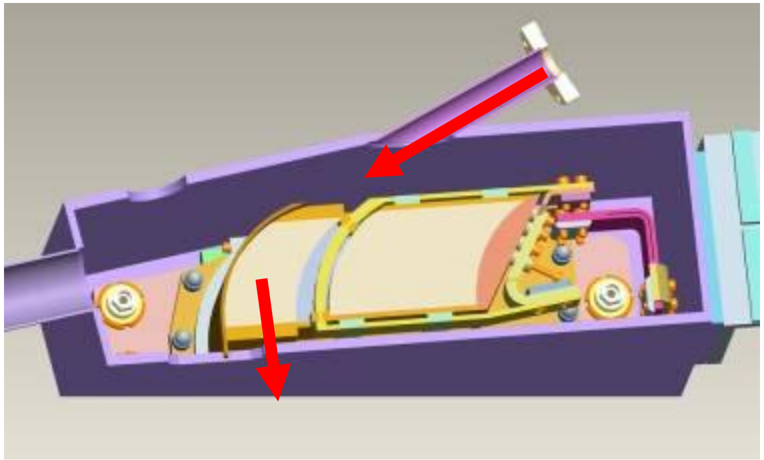
Septum Design



Septum out of vacuum chamber



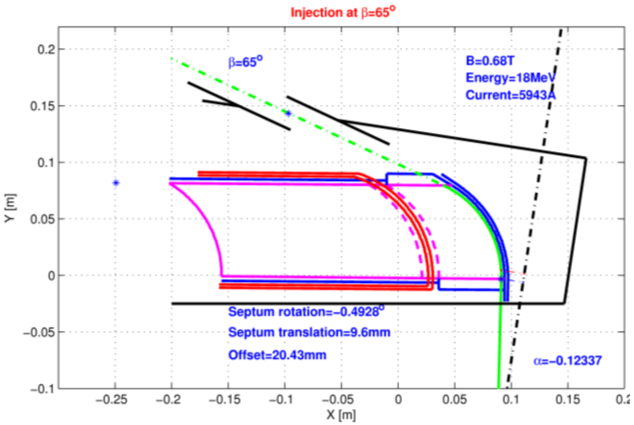
Section view of septum in vacuum chamber

Maximum beam deflection angle	77	degrees
Maximum flux density in gap	0.91	T
C core magnet gap height	22.0	mm
Internal horizontal beam 'stay-clear'	62.5	mm
Turns on excitation coil	2	
Excitation half-sine-wave duration	25	μs
Excitation peak current	9.1	kA
Excitation peak voltage	900	V
Septum magnet repetition rate	20	Hz

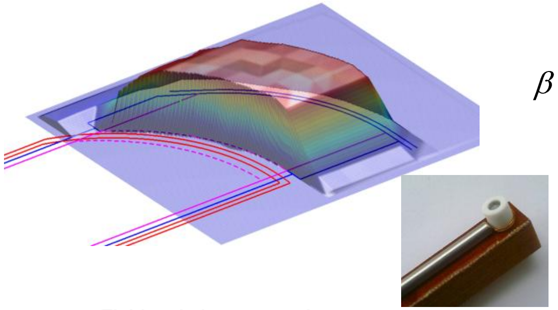
- Septum length ~ 10 cm
- Inject/Extracts from 10-20 Me
- For all lattice configurations
- Translation -3.2 to 11.5 mm
- Rotation – 0.4 to 0.7 degrees

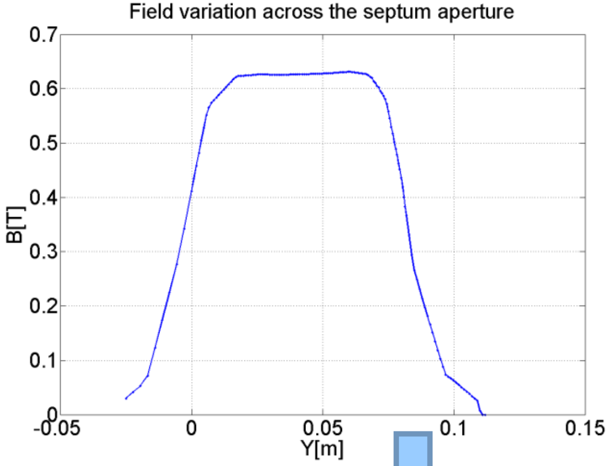
Injection septum

➢Concept



➢3D field map

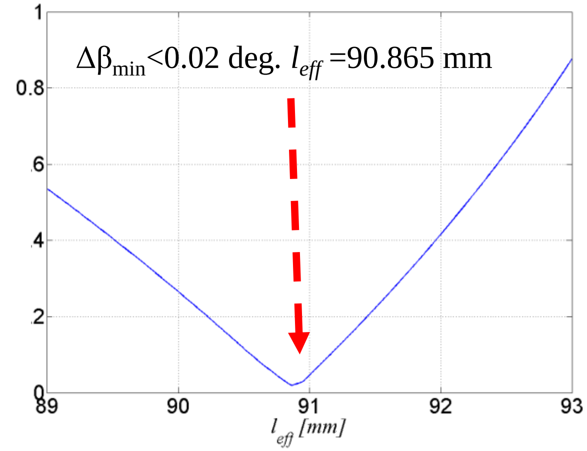




$$l_{eff} = \frac{\int_{-\infty}^{\infty} B(y)\,dy}{B_N} = 91.4\,mm$$

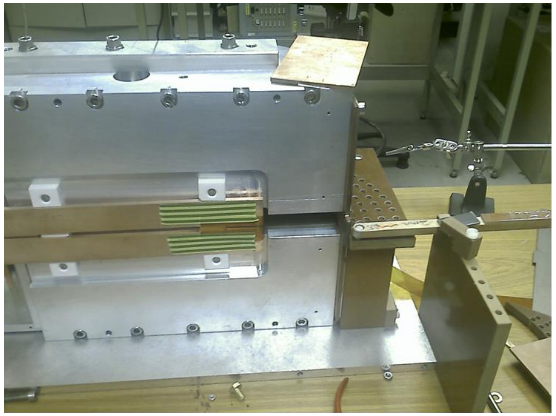
➢BPM data analysis

$$\beta = \sin^{-1}\left[B_N e l_{eff} c \left(E\sqrt{1-\left(\frac{E_0}{E}\right)^2}\right)^{-1} - \sin(\alpha+\varphi)\right] + \varphi$$



$$l_{eff} = 90.865\ \text{mm}$$

➢Magnetic measurements



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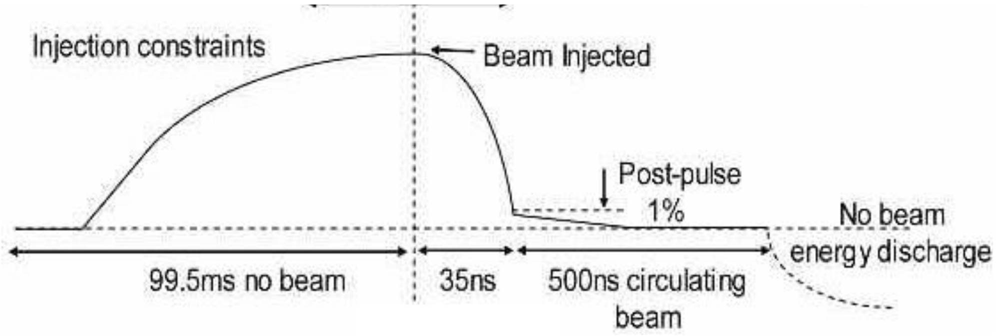
Kicker Magnet, Fast Switching

Magnet length	0.1m
Field at 10MeV (Injection)	0.035T
Field at 20MeV (Extraction)	0.07T
Magnet Inductance	0.25μH
Lead Inductance	0.16μH
Peak Current at 10/20MeV	**1.3kA**
Peak Voltage at Magnet	14kV
Peak Voltage at Power Supply	23kV
Rise / Fall Time	**35nS**
Jitter pulse to pulse	**< 2nS**
Pulse Waveform	½ Sinewave

Kicker Magnet Power Supply parameters With compact design and require:

- **Fast rise / fall times 35 nS**
- **Rapid changes in current 50kA/μS**
- **Constraints on pre and post pulses**



Prototype R&D led to a contract with APP for production units

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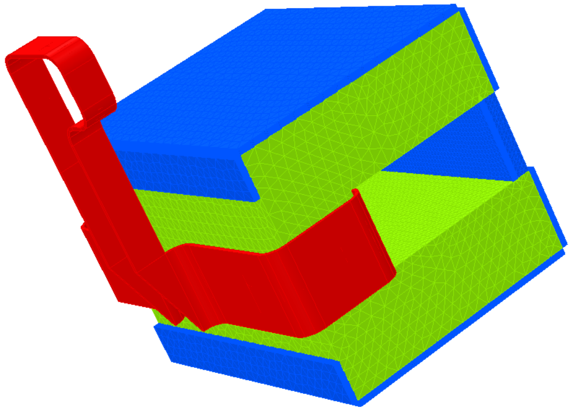
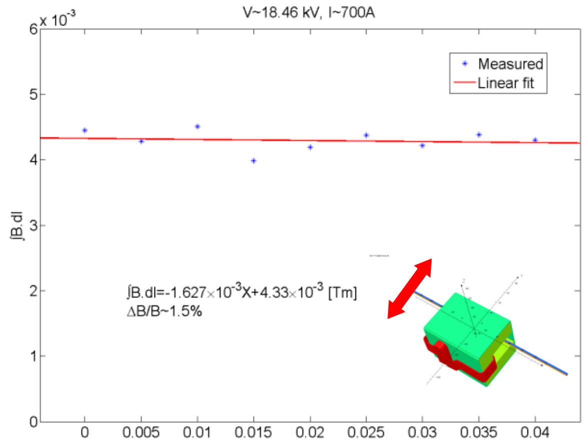
Kickers

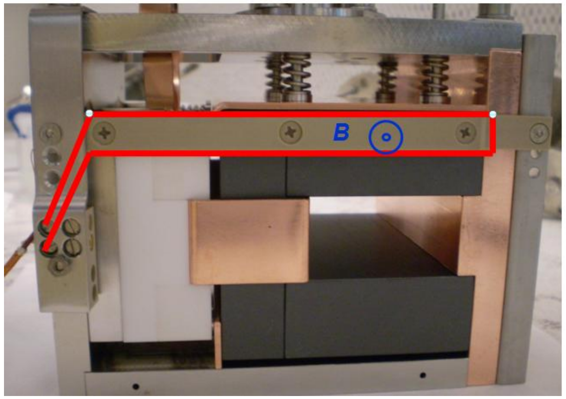
➢Concept



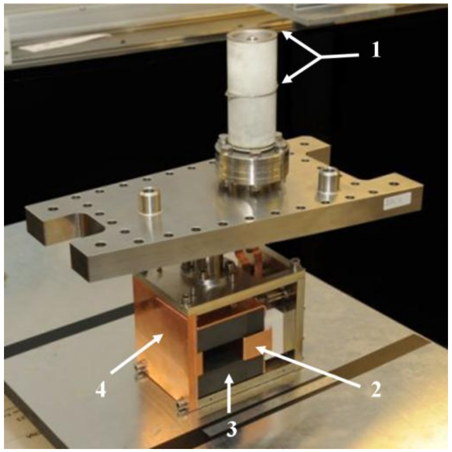
➢Field quality

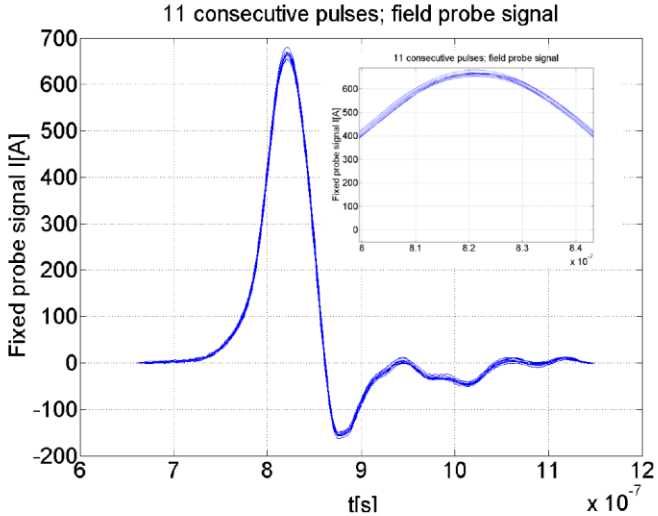


➢In-situ field probe



➢Before installation





Max. strength 0.007 Tm

Effective length 130 mm

Field variation 1.5%

Fall time 58 ns

Timing jitter 1.7 ns

Amplitude stability 4%.

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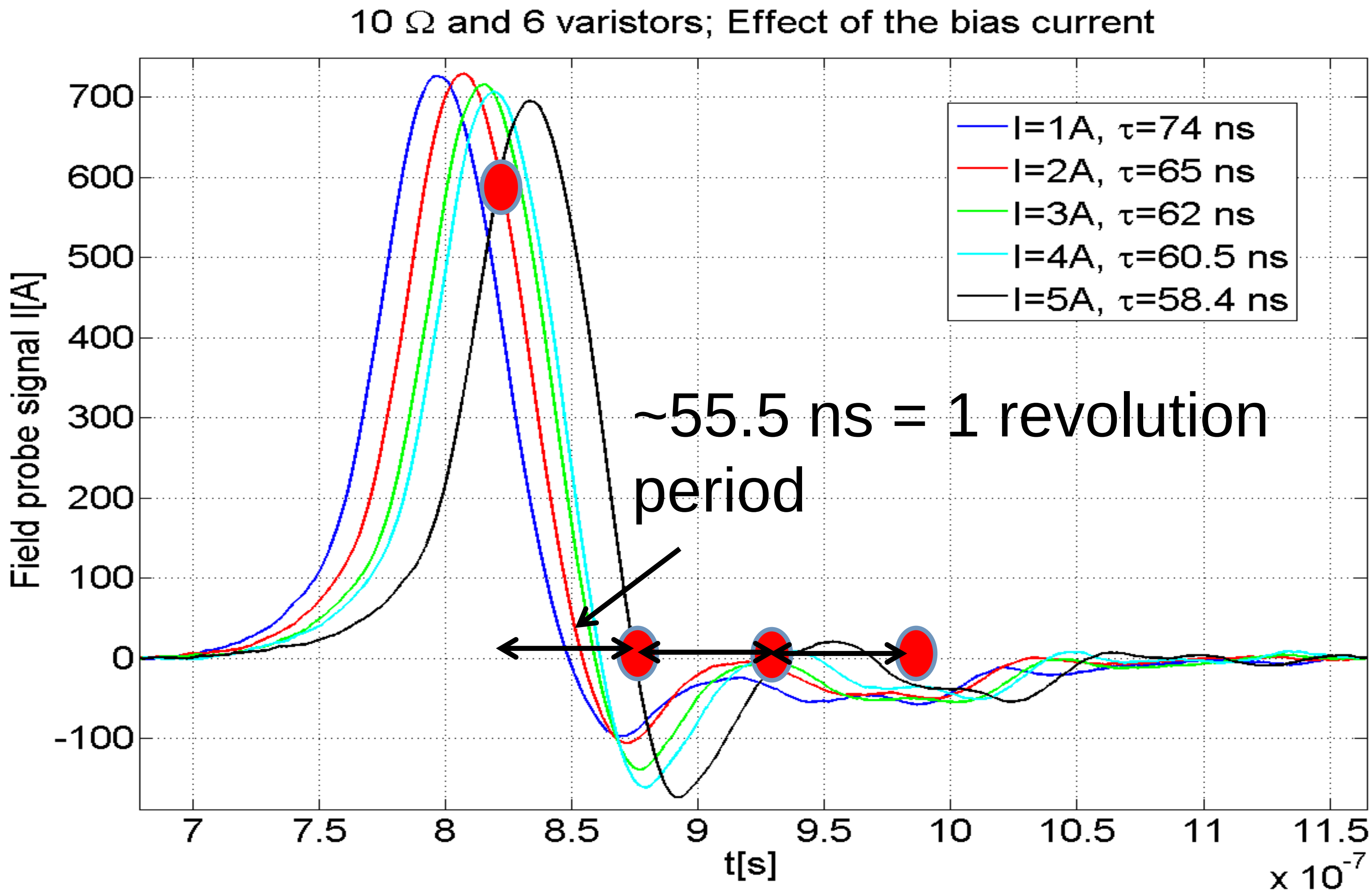
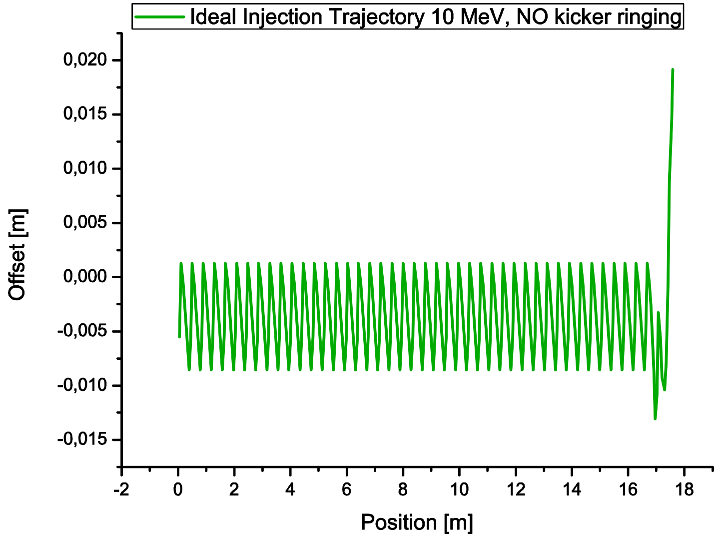
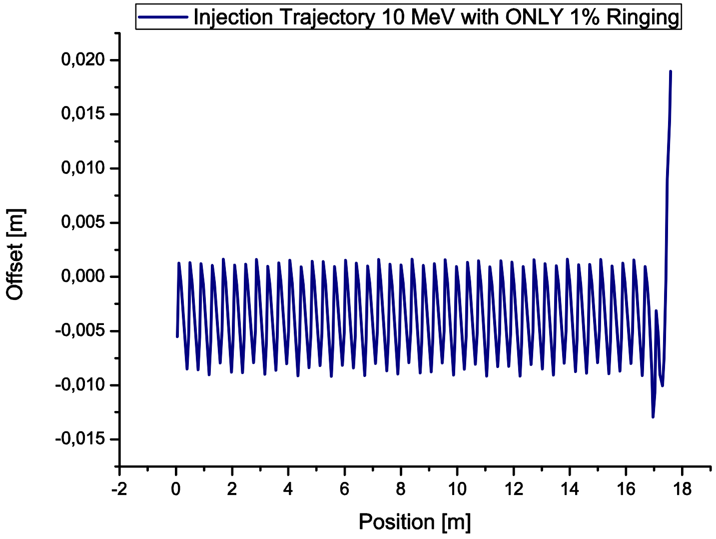
Measured Current Pulses from Kicker Magnet



Kicker ringing

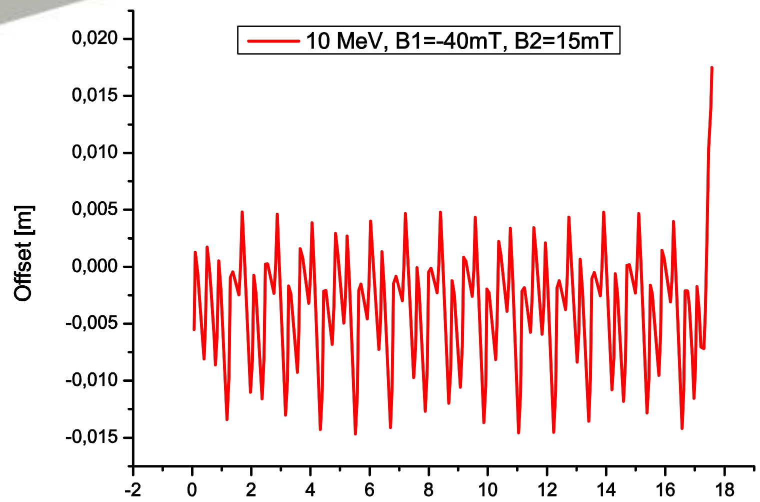


- Ideal case without ringing
- Can have few % ringing
- Cannot have 10 %

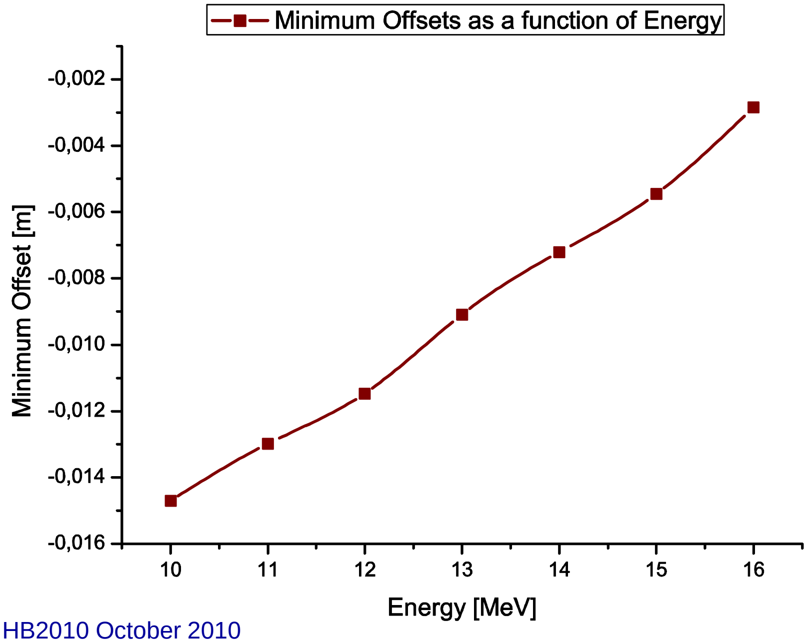


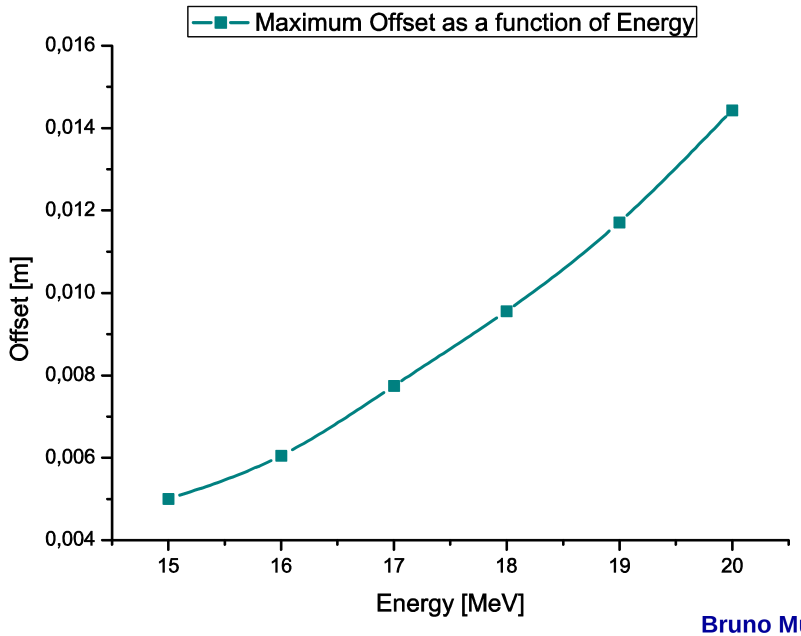
- Only solution is to have multi-turn injection (~ 2)
- Final kicker strength required is ~ the same

Kicker ringing

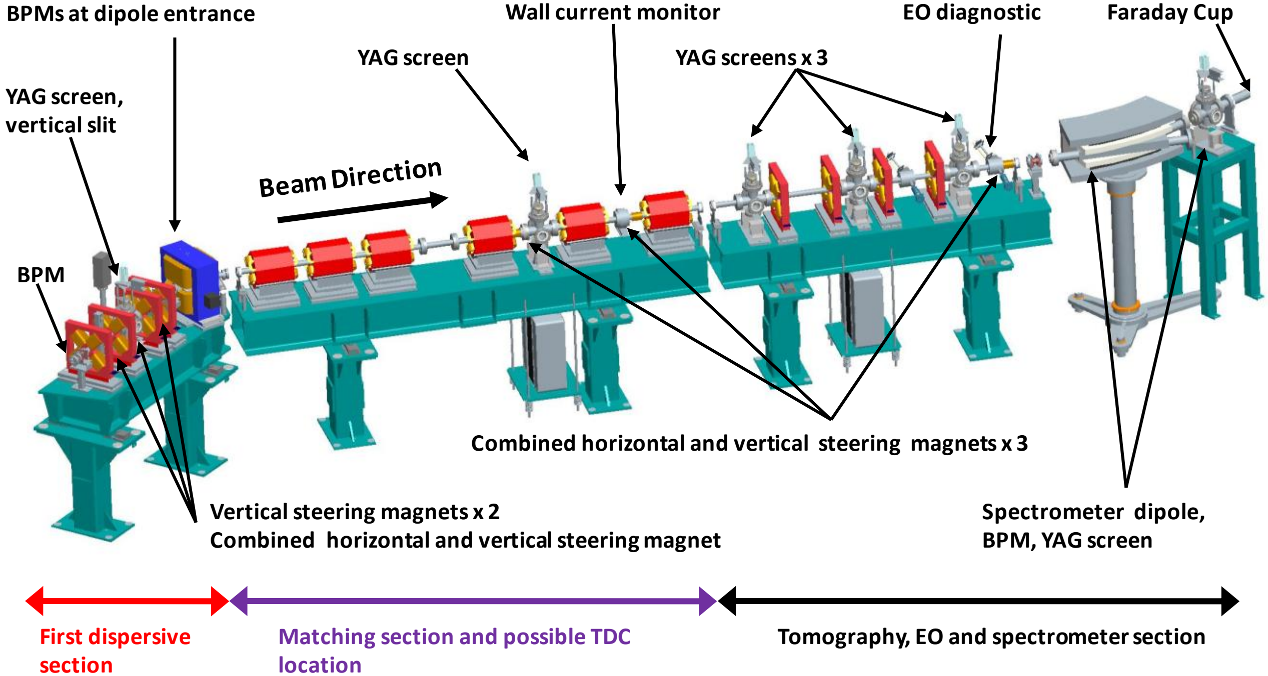


- Minimise orbit excursions essential
- Two turn injection feasible over entire EMMA range of energies
- Ideal beamexcursions: - 8 to 12 mm
- Two-turn exc.: ~ -15 to 15 mm





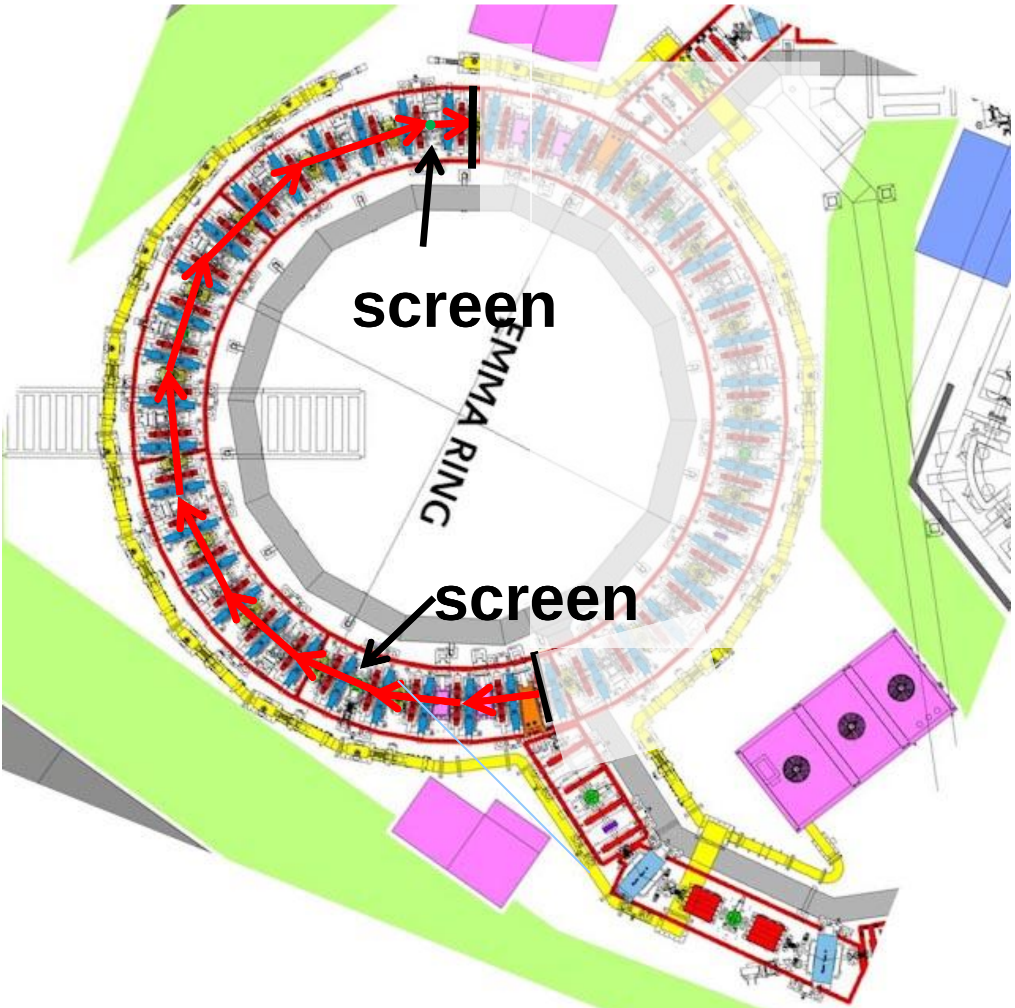
Extraction

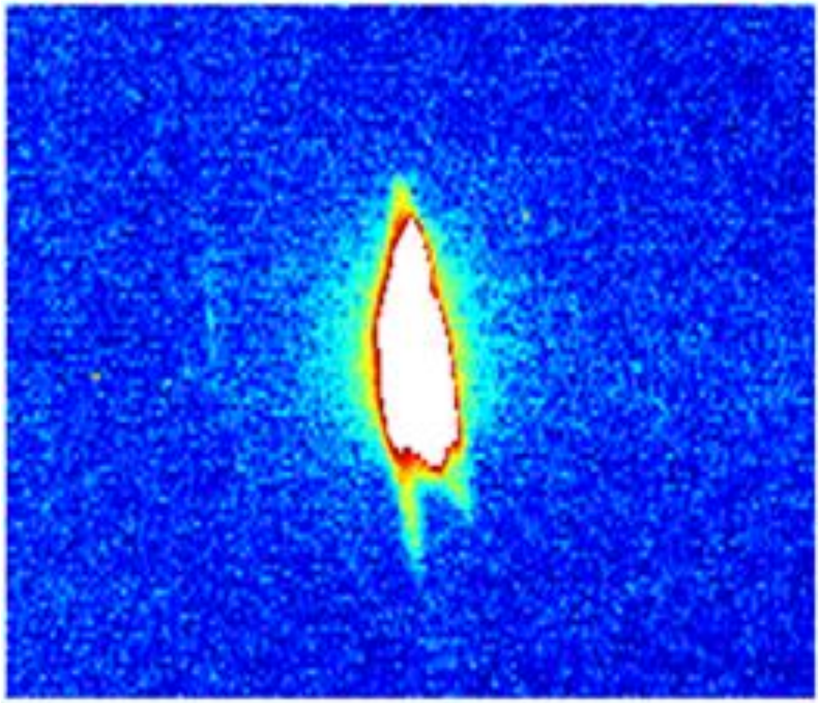


- Do not yet extract the beam (additional level of complexity)
- When we do, there should be plenty of diagnostics for further understanding the beam & what EMMA has done to it
- Projected emittance, slice emittance, bunch length, energy spread, slice energy spread, electro-optic measurements

COMMISSIONING

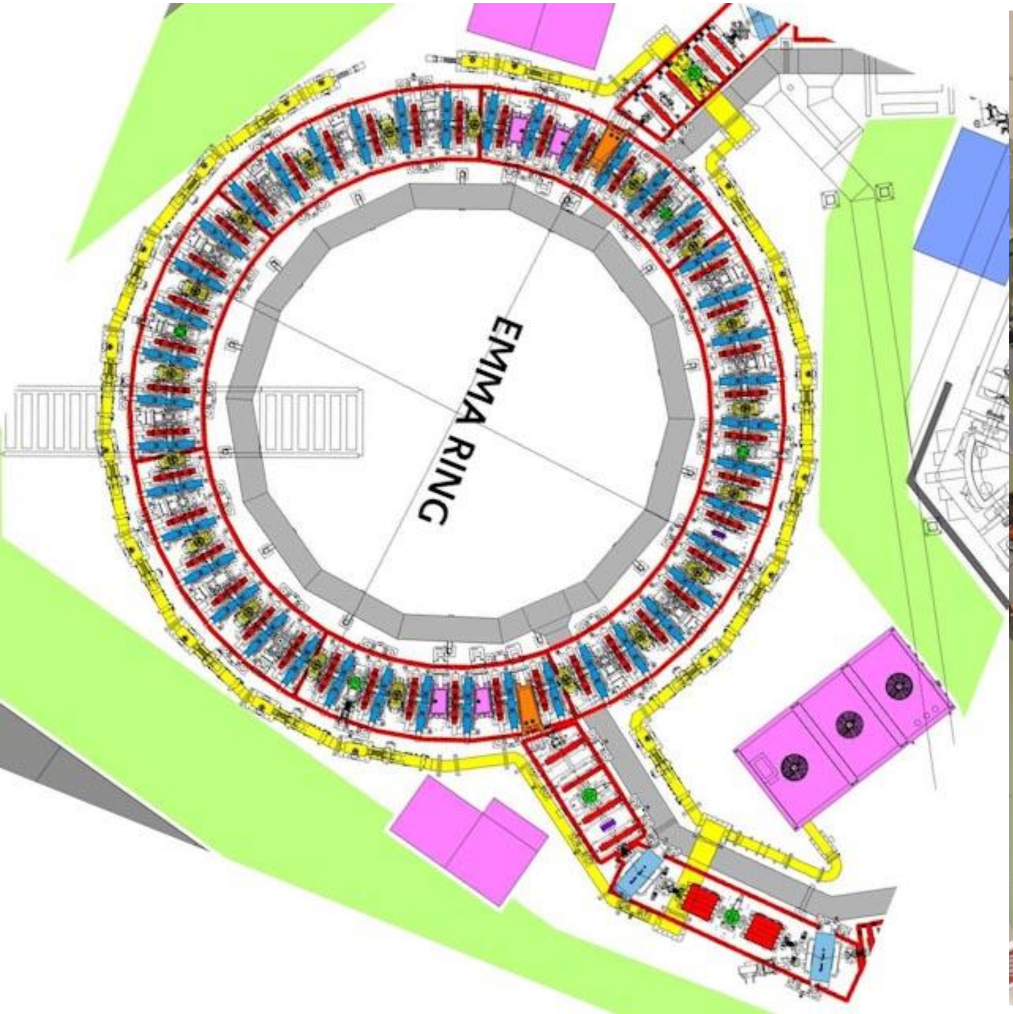
4 Sector Commissioning

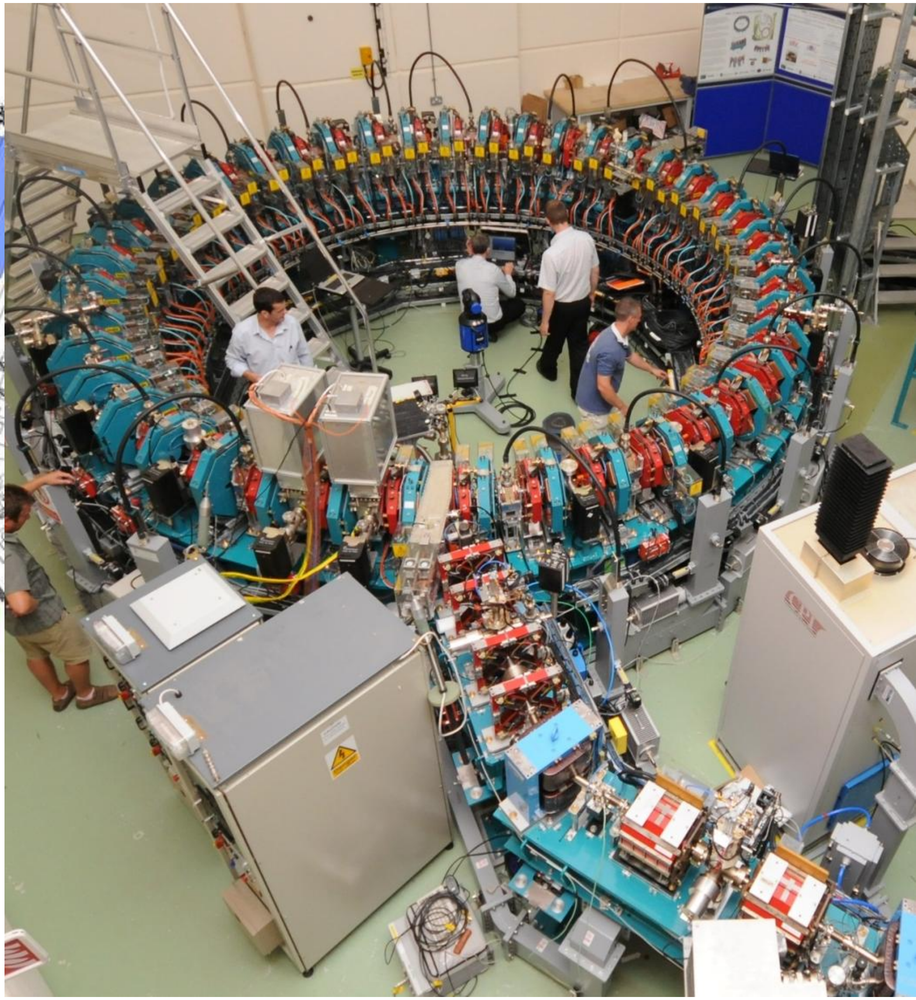




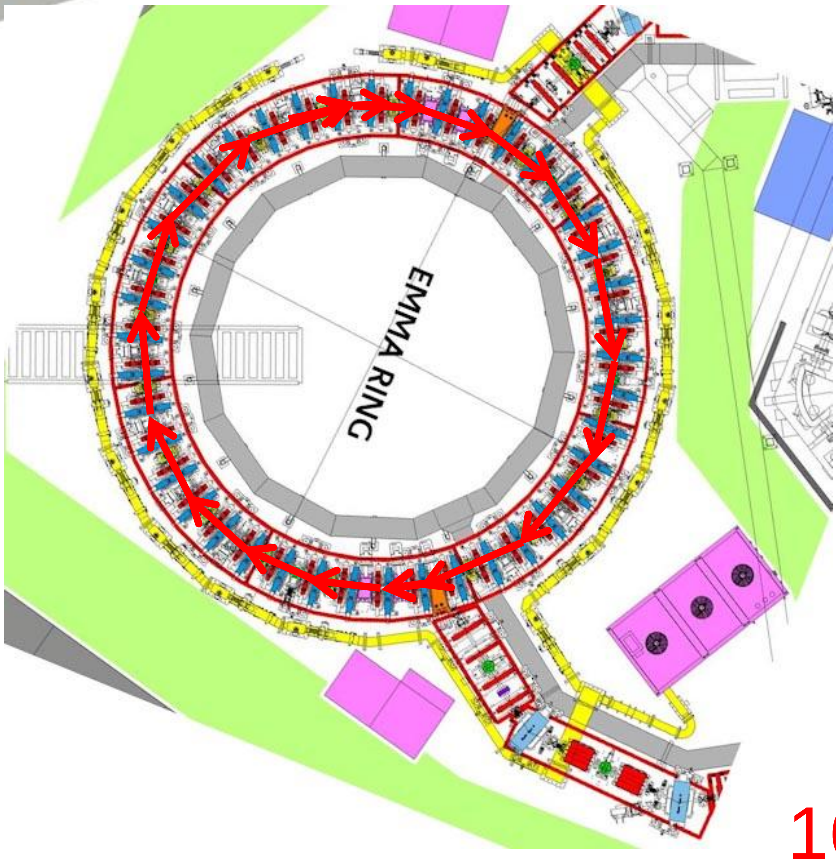
Beam image on screen
At the end of 4 sectors
22 cells
22:37 on 22.6.2010

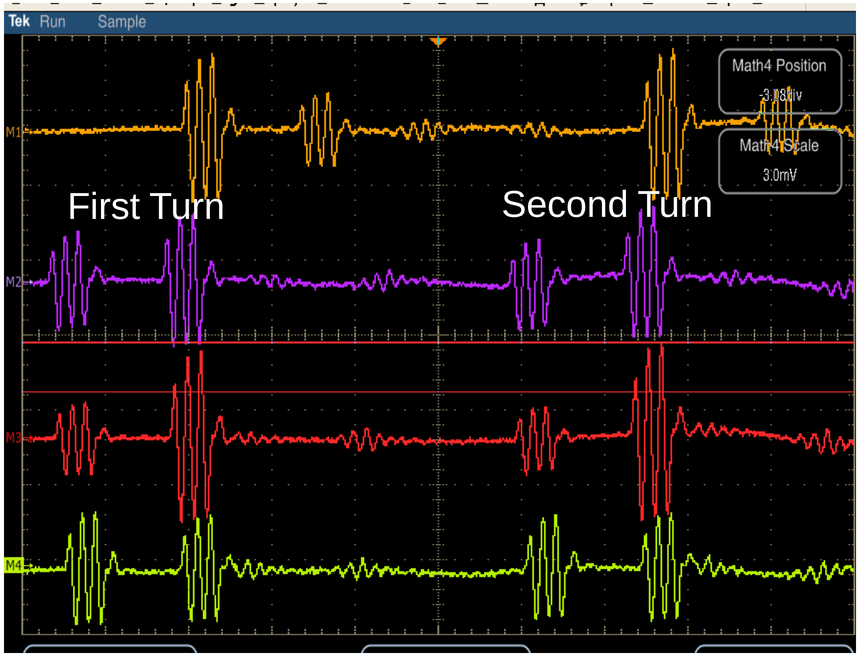
Realisation of EMMA August 2010





Complete Ring

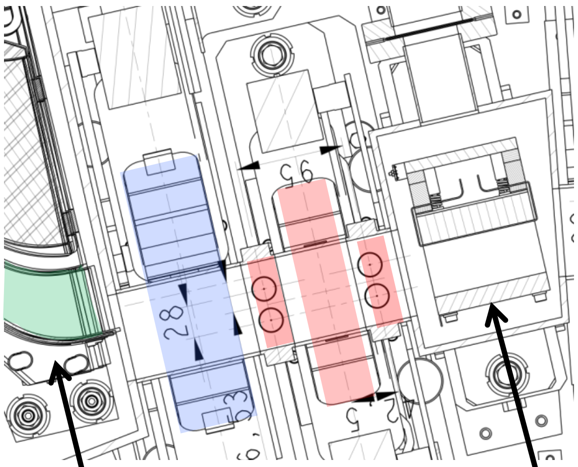




16th Aug 2010

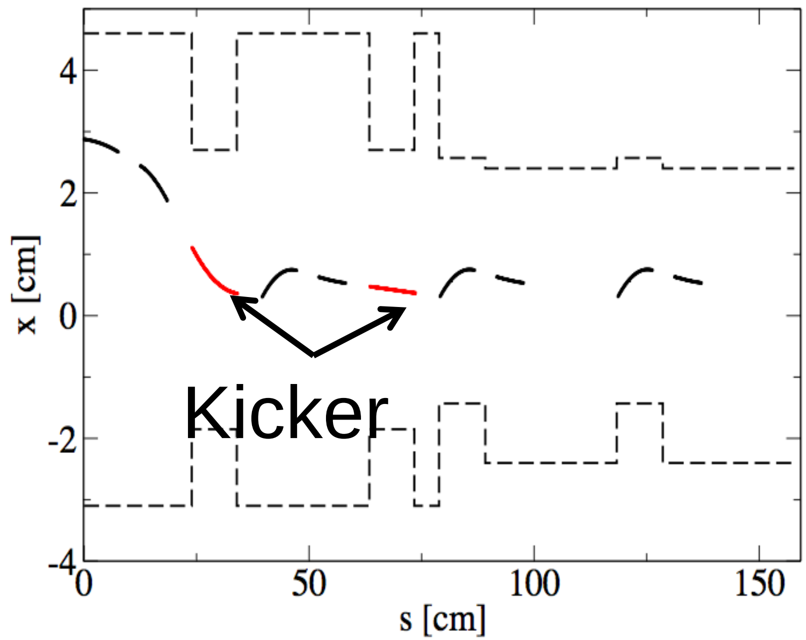
- Still have to look at raw BPM signal & only 12 BPMs are currently available at any one time

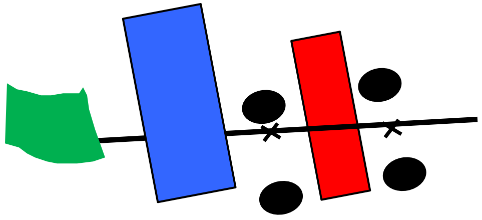
Optimisation of injection



Septum

Kicker

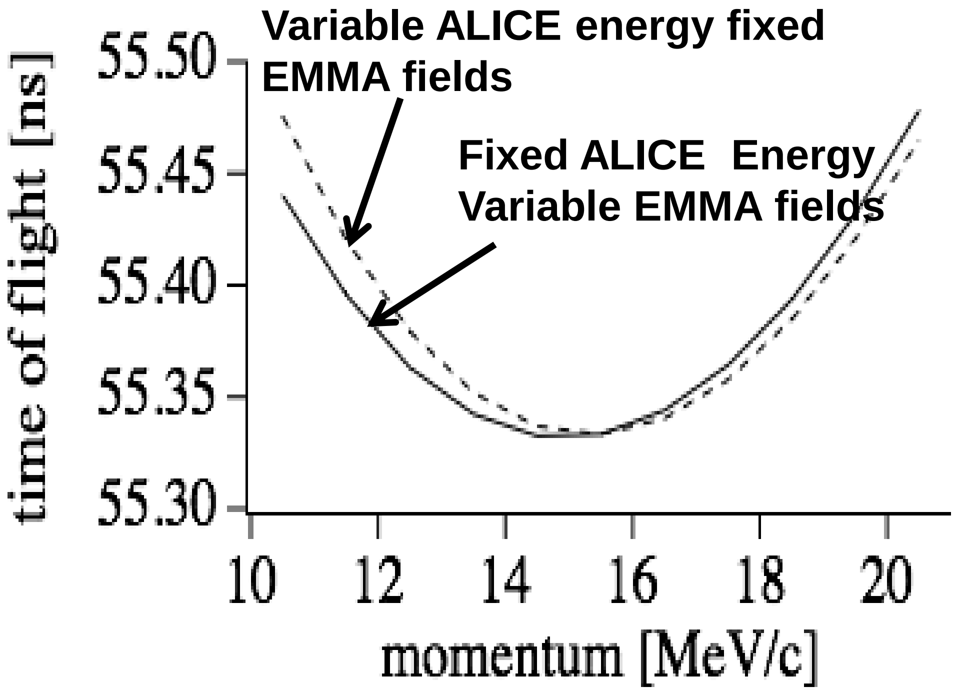


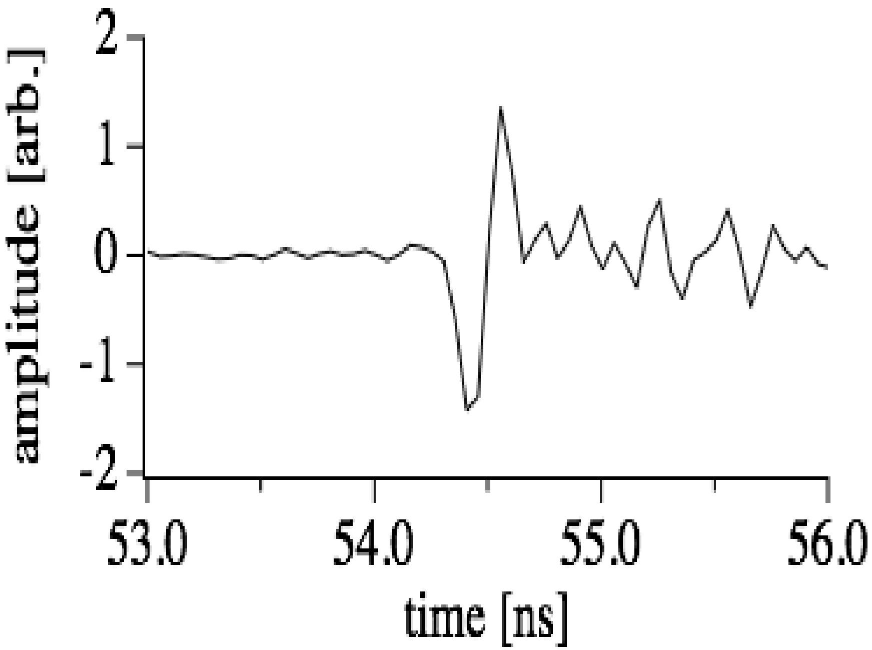


Angle at end of SEPT determined from BPM offsets with quads OFF

- Use code to determine kicker strengths close to pragmatic strengths
- Orbit kinks between cells are due to rotation of coordinate system

Time of Flight



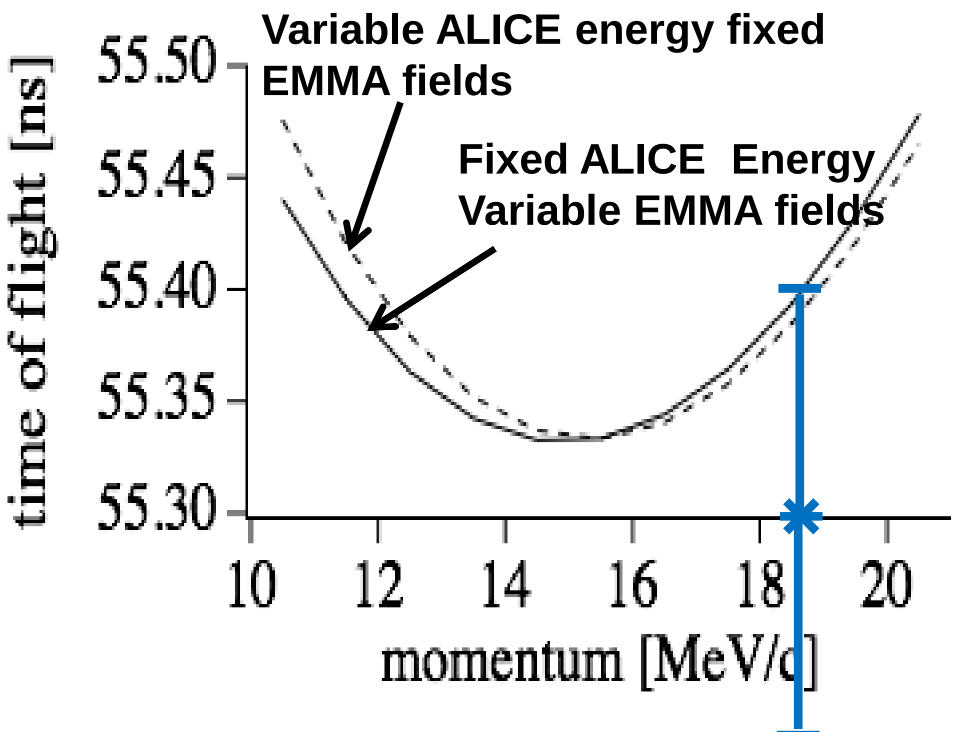


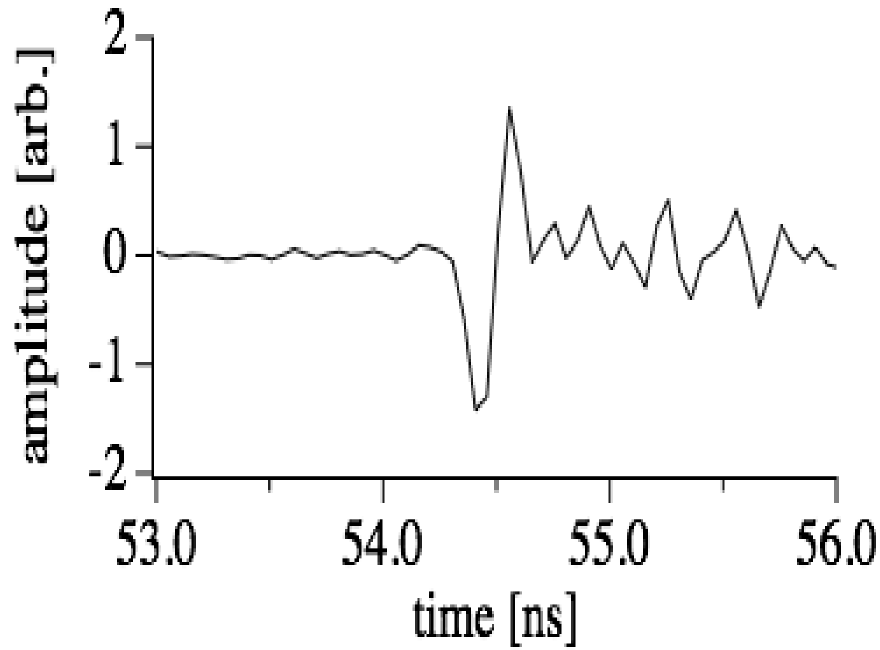
- Time of flight is determined by path length, not by speed
- Use different magnetic strength as easier than retuning ALICE injector

- Raw signal of one BPM electrode for time of flight measurement ALICE injector

Time of Flight

Revolution time @ equiv 18.5 MeV/c, equivalent momentum = 55.3+/-0.1 ns





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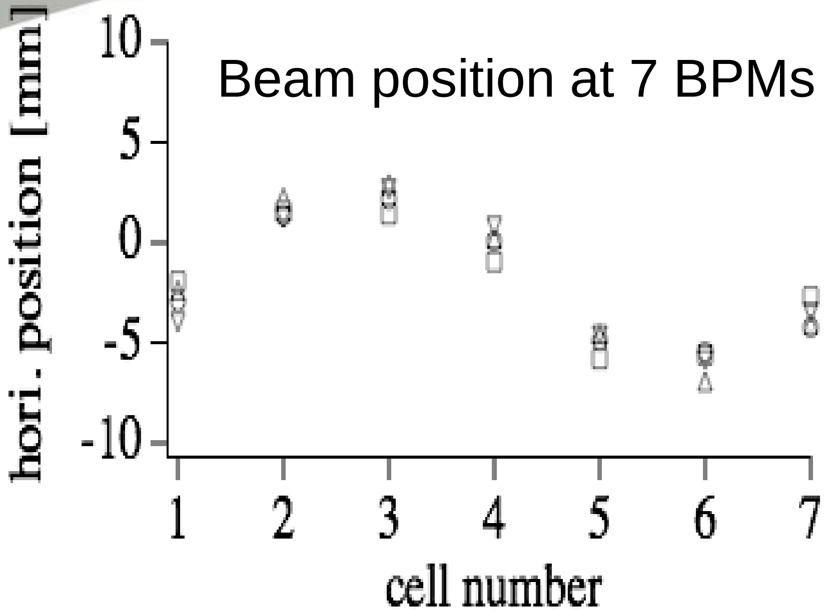
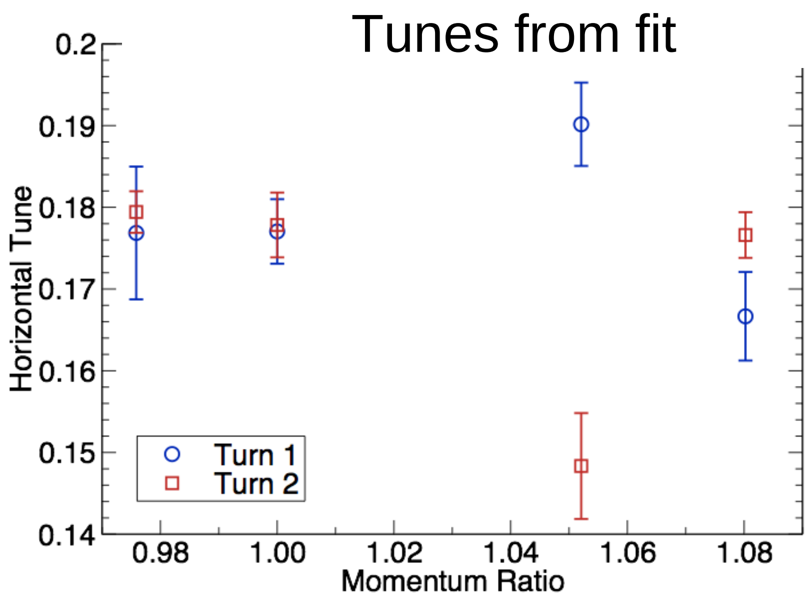
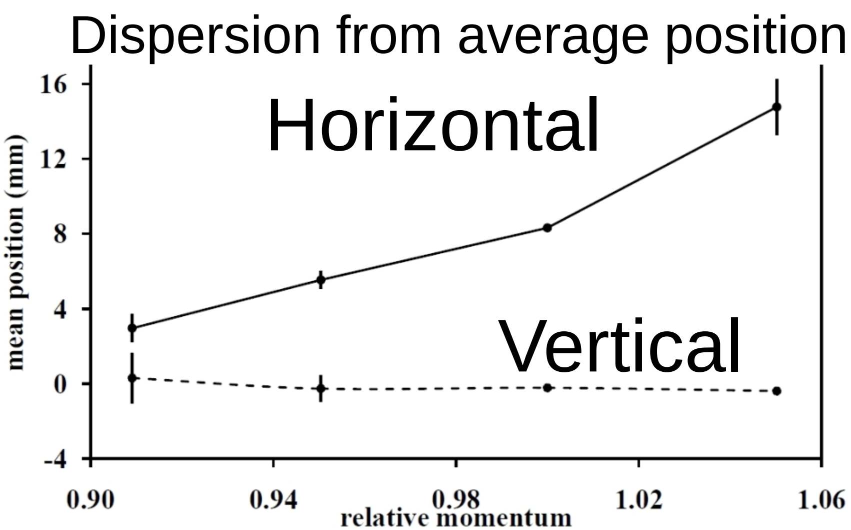
- Raw signal of one BPM electrode for time of flight measurement ALICE injector

Betatron oscillation tunes & dispersion







At 100% effective momentum (15.5 MeV/c)

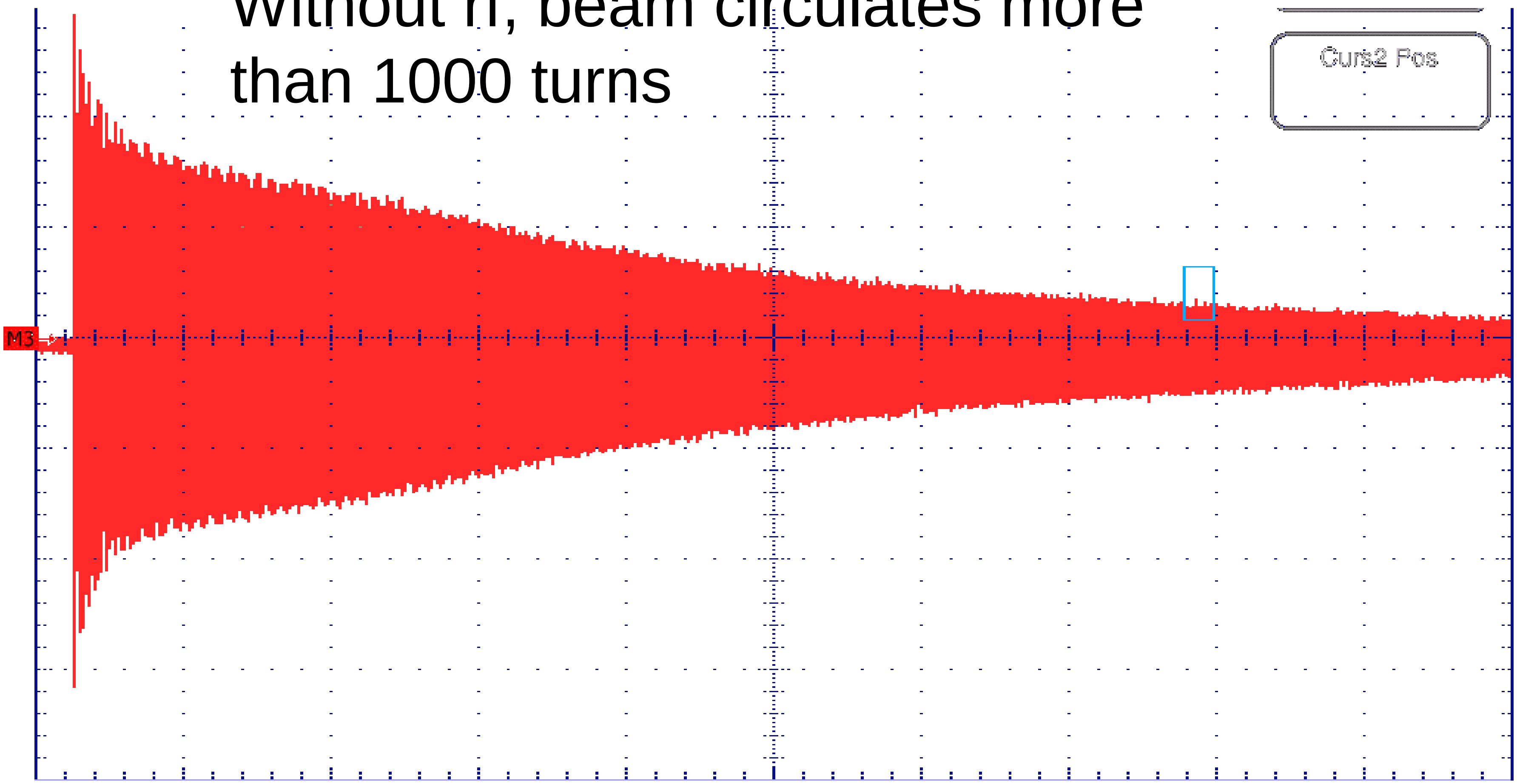
Horz disp =82mm

Vert. disp. = 3mm

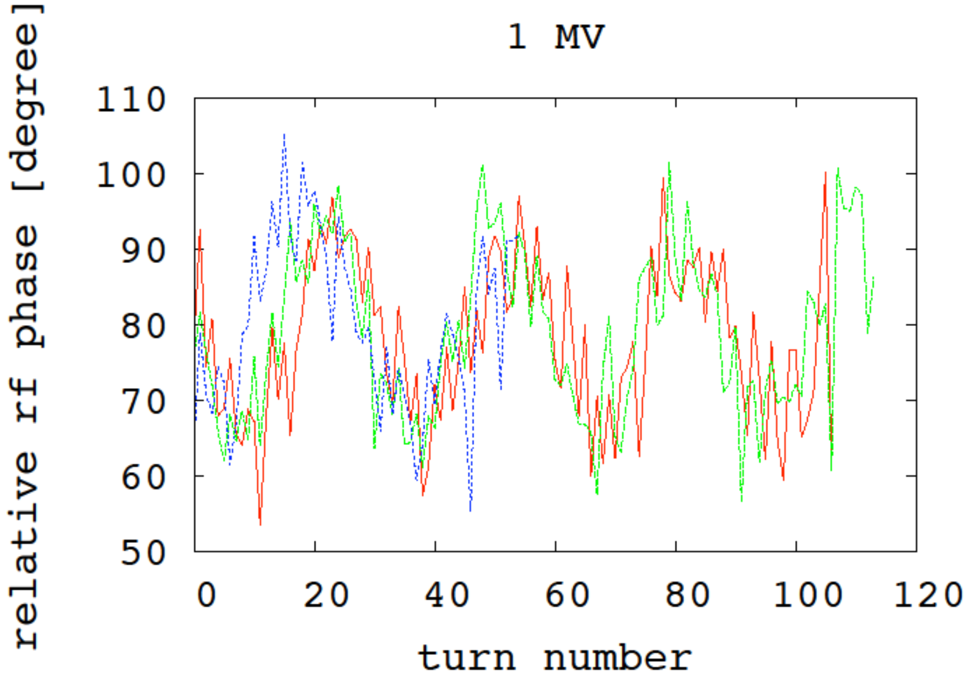
Consistent to predicted values

Coasting beam no RF

Without rf, beam circulates more than 1000 turns



Synchrotron Oscillations



- Still have problem tuning 19 cavity phases
- RF buckets around transition momentum still separated
- Seen RF bucket & synchrotron oscillations inside it
- Going to adjust each cavity phase separately

Next Steps

- Commissioning now
  - LLRF system fully functional and tested at ALICE & off frequency
  - Verification of successful acceleration, inside/outside bucket
- Characterisation
  - Tunes and ToF fn of E ~ 1MeV steps
  - Tune accelerator to match required lattice
- "EMMA Experiment"
  - Acceleration 10 – 20 MeV
  - Resonance crossing

  - Detailed bench marking with codes
  - Scan aperture in phase space (both longitudinally and transversely)
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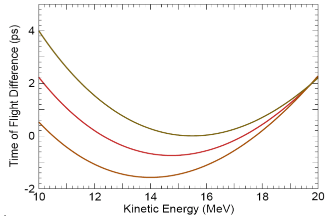

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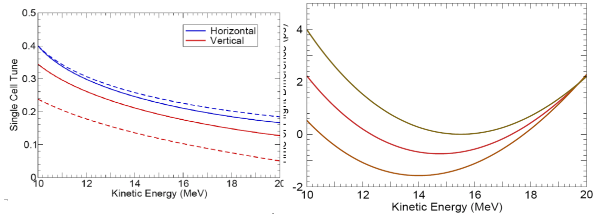

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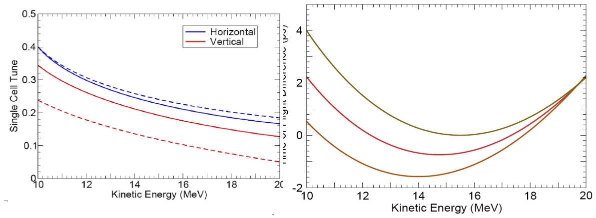

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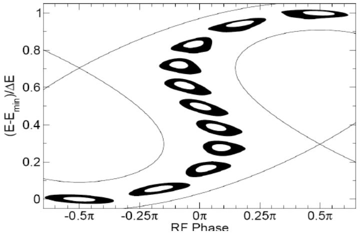

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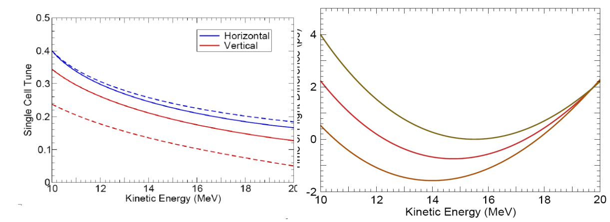

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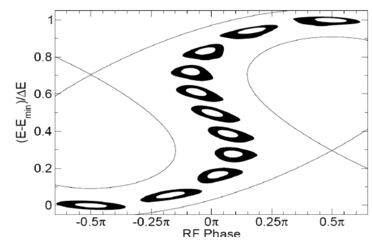

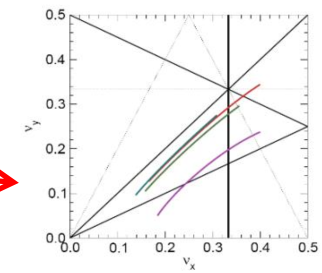

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Summary

- **Design and construction phase of the project is complete**
- **Injection / extraction complicated but workable solution**
- **Commissioning of the full ring is underway:**
  - Many 1000s of turns at fixed energy and for various energies
  - Time of flight measurements have been measured at various quadrupole settings and various equivalent energies
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A key aim is to:-

Verify this new concept works (accelerate !)
Compare results with studies & gain real experience

Bruno Muratori

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Apply lessons learnt to new applications!

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- Commercial Suppliers

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Thank you for your attention !

Please read paper for more details