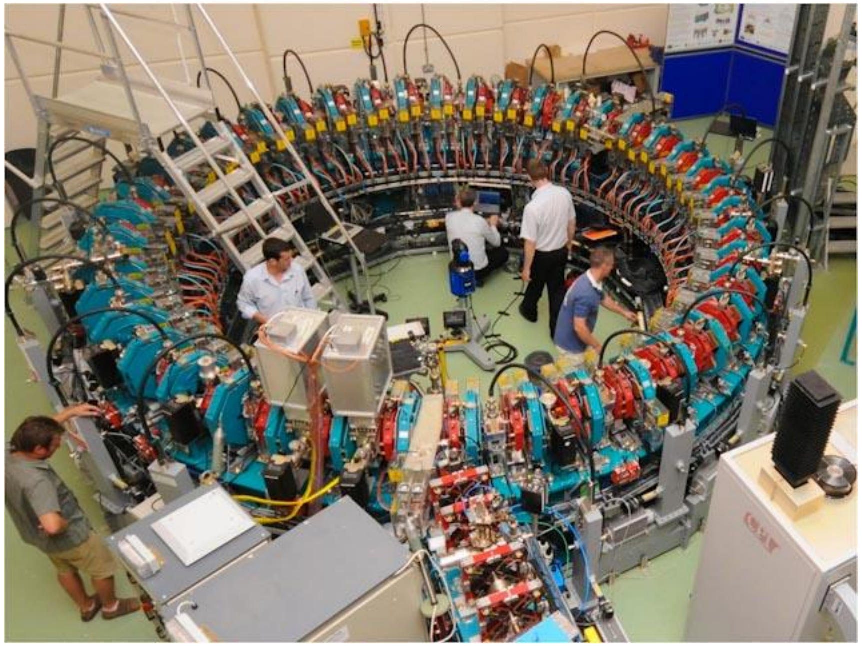
Science & Technology Facilities Council

BASROC CONFORM

EMMA: Design & Commissioning



Bruno Muratori on behalf of the EMMA team,
STFC, ASTeC, Daresbury Laboratory
& Cockcroft Institute

Contents

- Introduction
- The international collaboration
- Applications
- EMMA goals and requirements
- Layout and Lattice
- Injection & Extraction
- Diagnostics
- Radio Frequency
- Beam Commissioning
- Next Steps
- Summary

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)

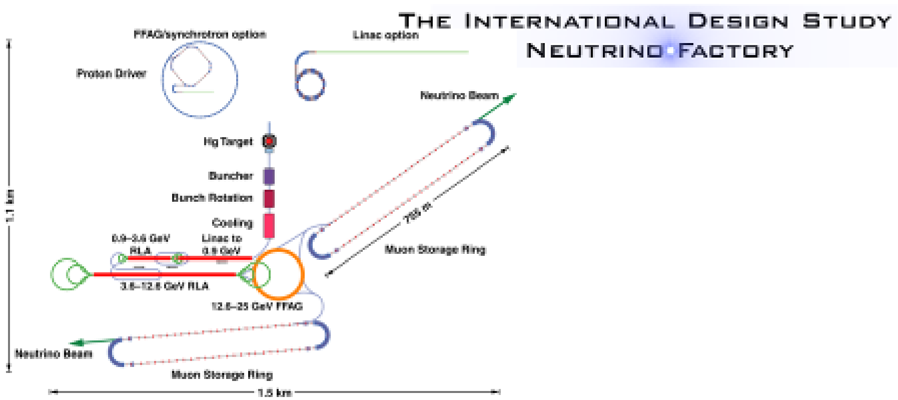
  - PAMELA design study
  - Applications study

EMMA International Collaboration

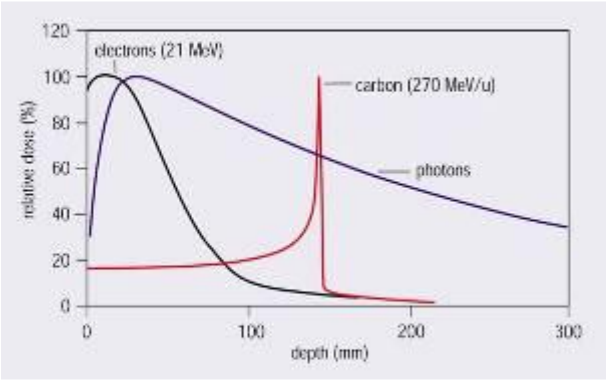
- EMMA design is an international effort and we recognise and appreciate the active collaboration from:
  - Brookhaven National Laboratory US
  - Cockcroft Institute UK
  - Fermi National Accelerator Laboratory US
  - John Adams Institute UK
  - LPSC, Grenoble France
  - Science & Technology Facilities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

Applications of ns-FFAGs

Neutrino Factory

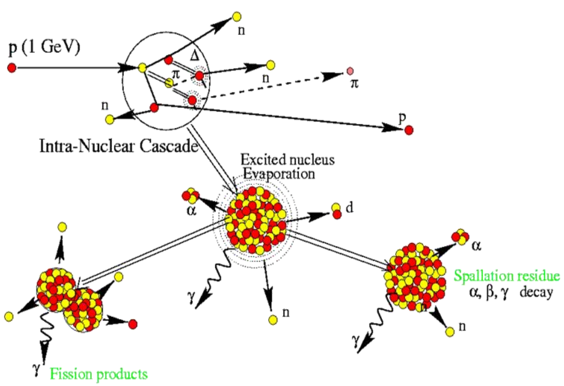


Proton & Carbon Therapy

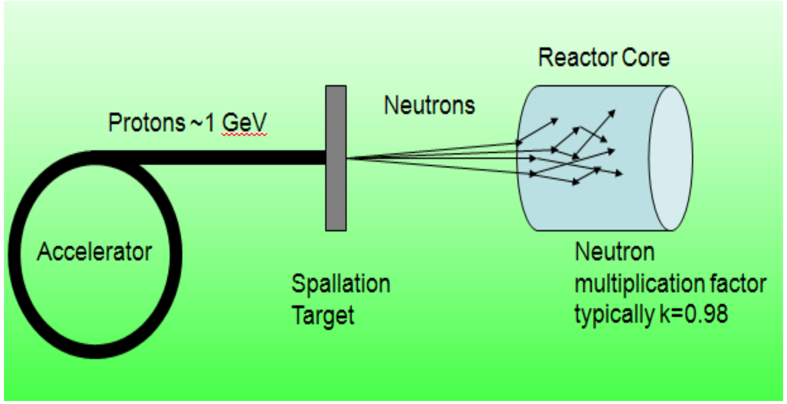


High power proton driver

Dedicated Muon Source

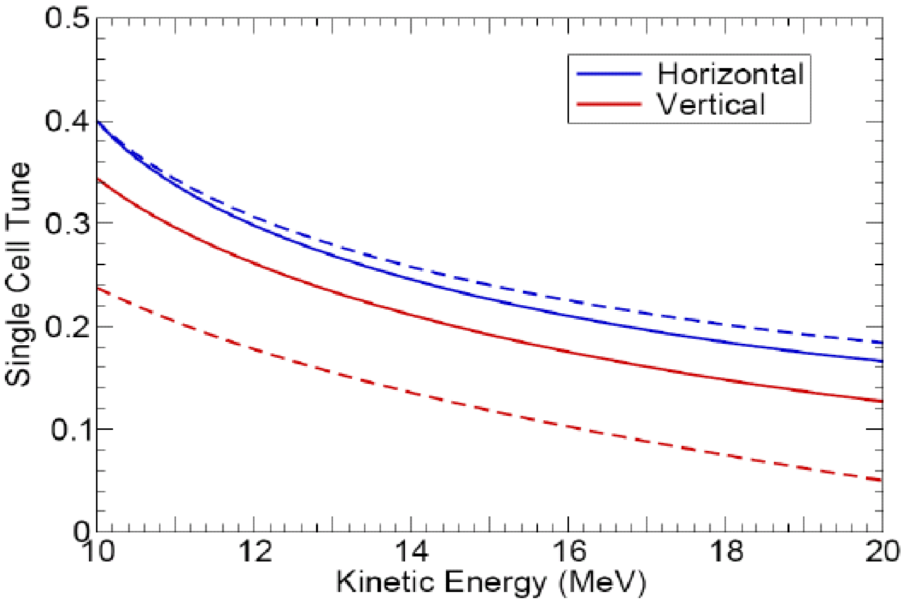


Sub-critical Thorium Reactor

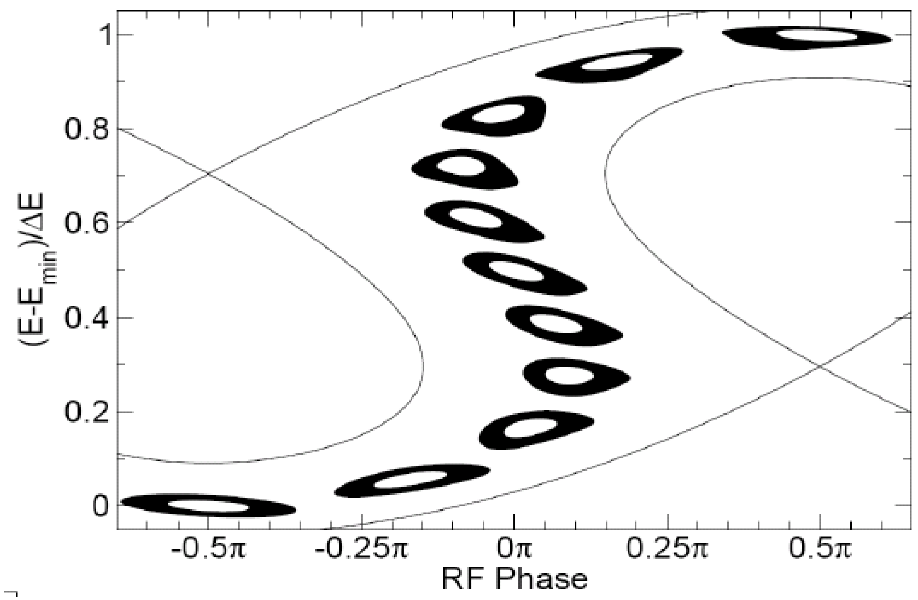


EMMA Goals

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



(2) Serpentine acceleration (results from parabolic ToF)



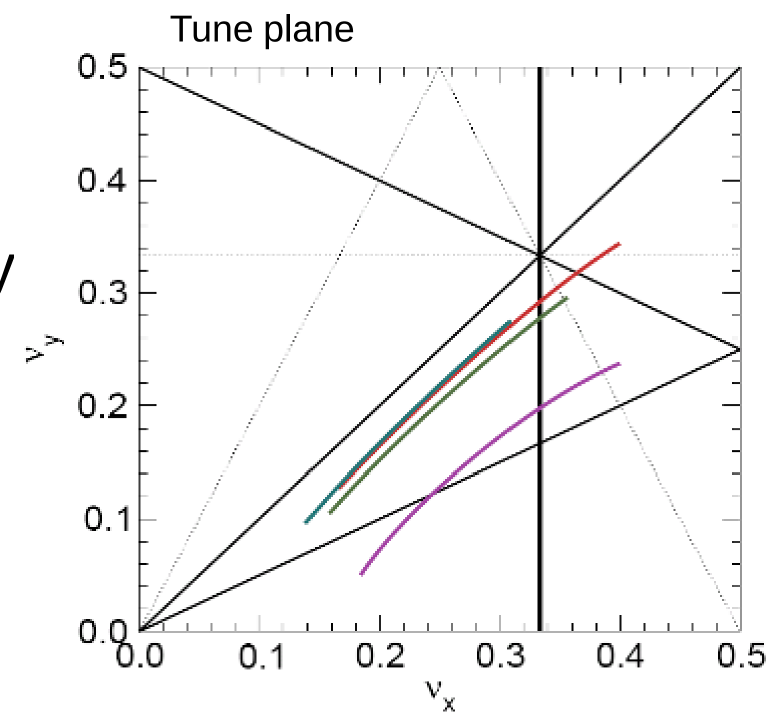
(3) Map the transverse and longitudinal acceptances.

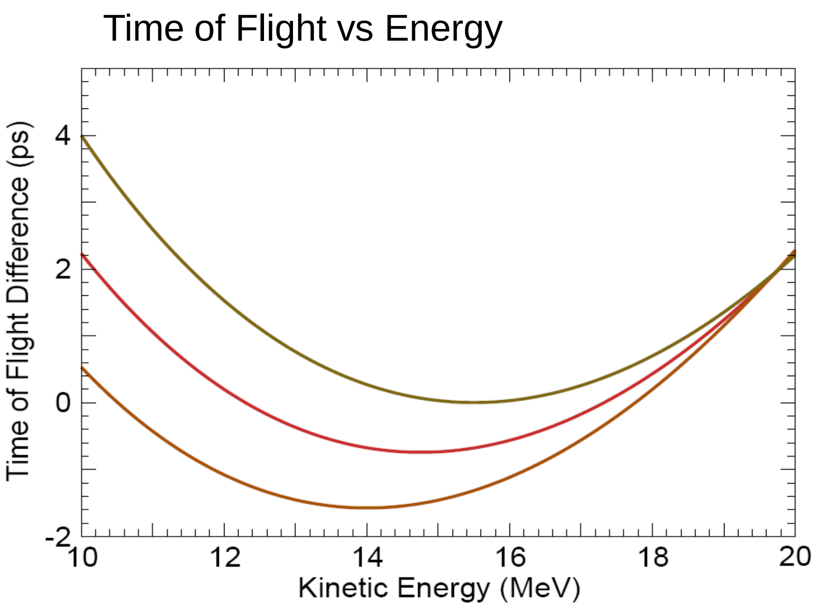
Graphs courtesy of Scott Berg BNL

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

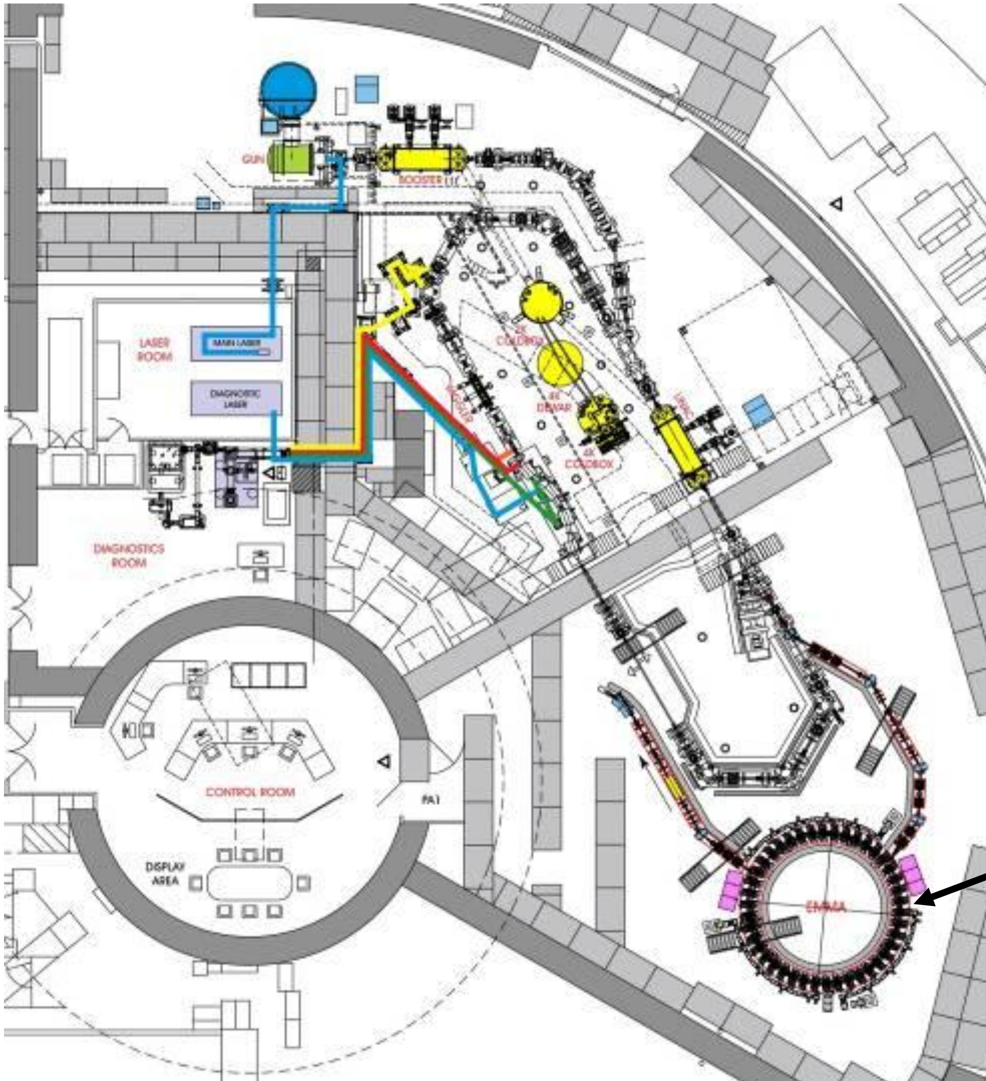
- Injection & extraction at all energies, 10 - 20 MeV
- Fixed energy operation to map closed orbits and tunes vs momentum
- Many lattice configurations
  - Vary ratio of dipole to quadrupole fields
  - Vary frequency, amplitude and phase of RF cavities
- Map longitudinal and transverse acceptances with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

EMMA to be heavily instrumented with beam diagnostics

LAYOUT AND LATTICE

ALICE

Accelerators and Lasers In Combined Experiments



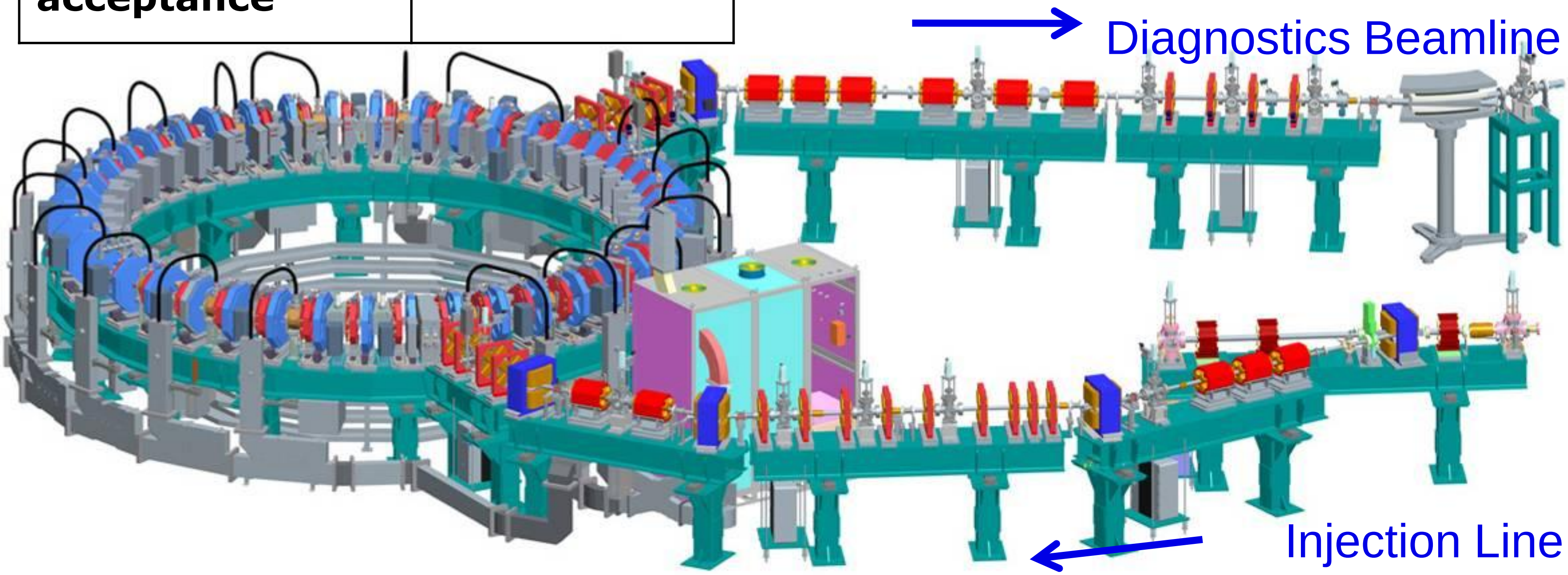
Parameter	Value
Nominal Gun Energy	350 keV
Injector Energy	8.35 MeV
Max. Energy	35 MeV
Linac RF Frequency	1.3 GHz
Max Bunch Charge	80 pC
Emittance	5-15 mm-mrad

EMMA

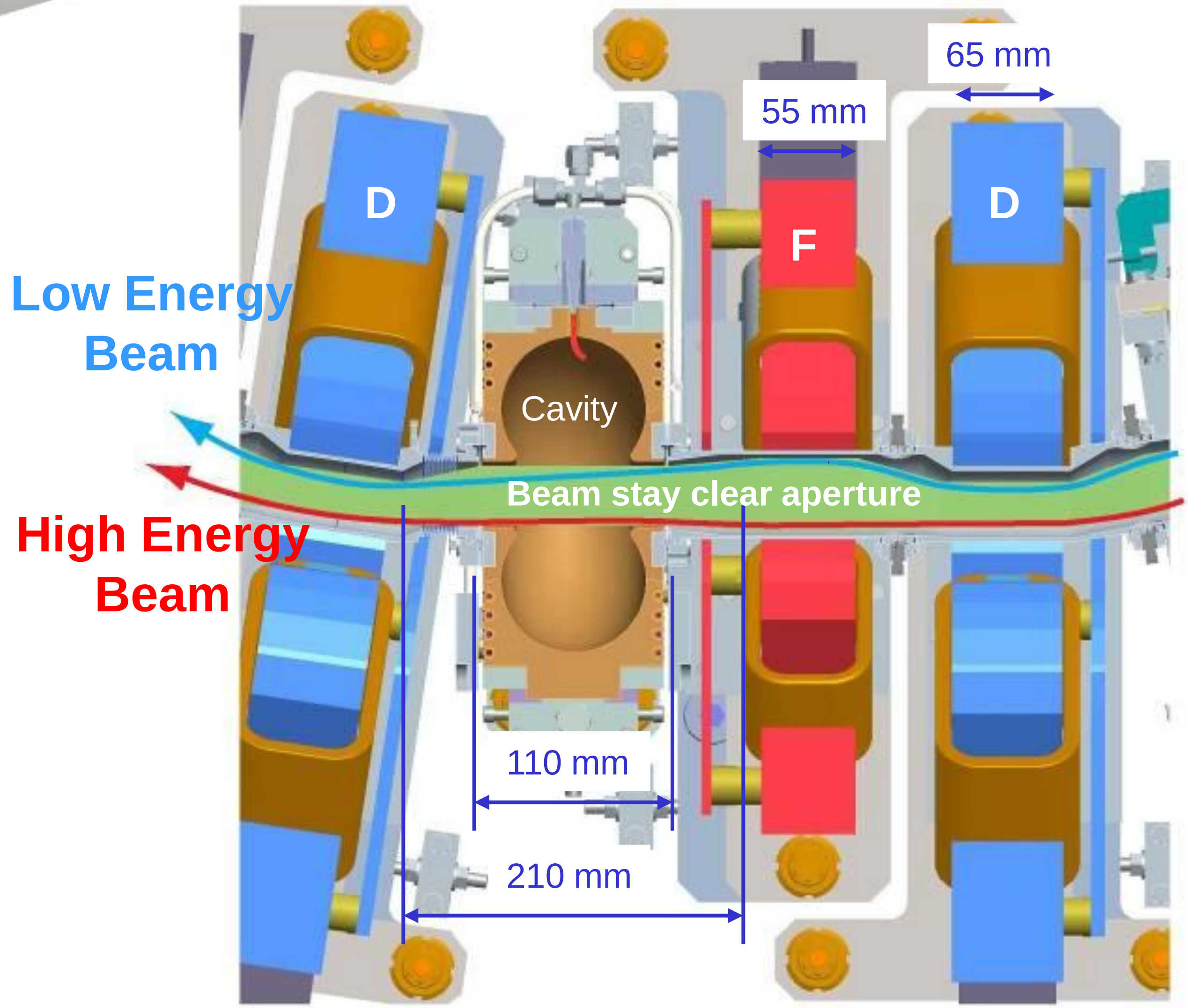
EMMA Parameters & Layout

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

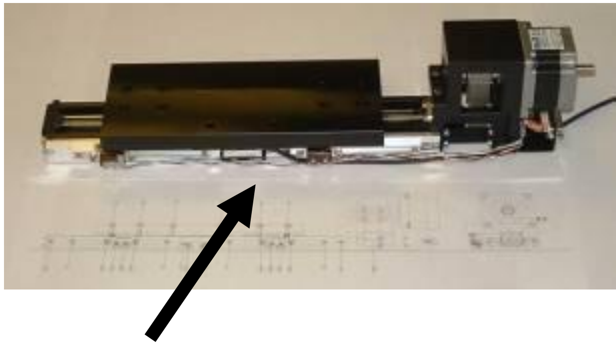


EMMA Ring Cell



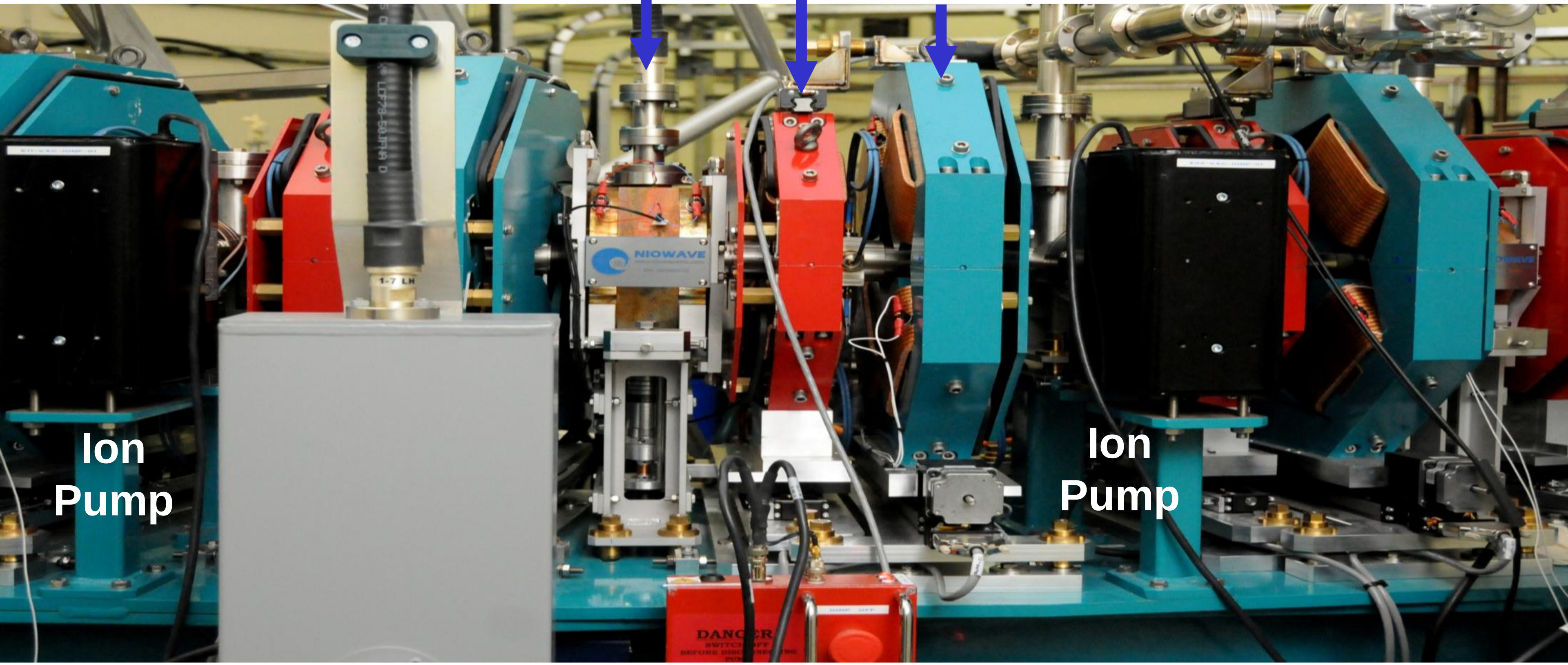
Long drift	210 mm
F Quad	58.8 mm
Short drift	50 mm
D Quad	75.7 mm

- 42 identical doublets
- Apart from injection and extraction

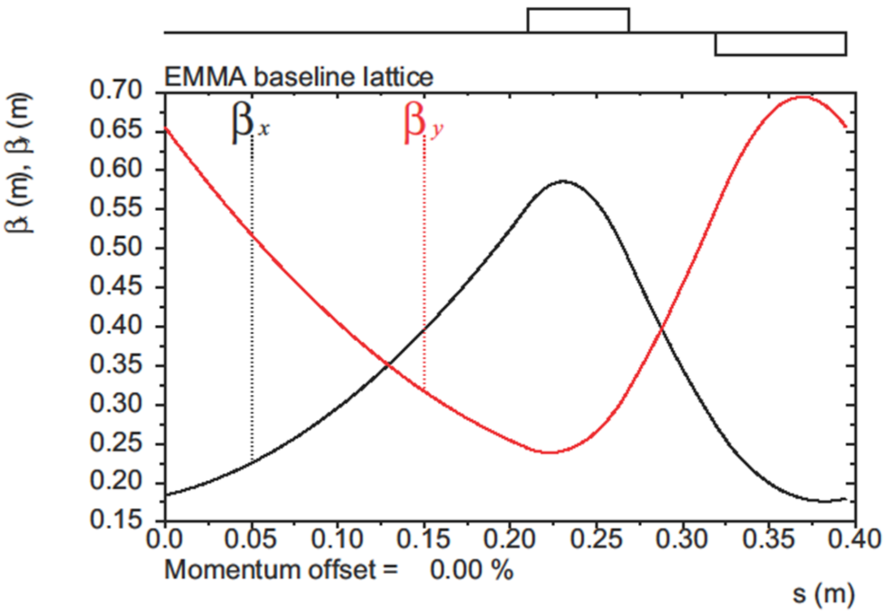


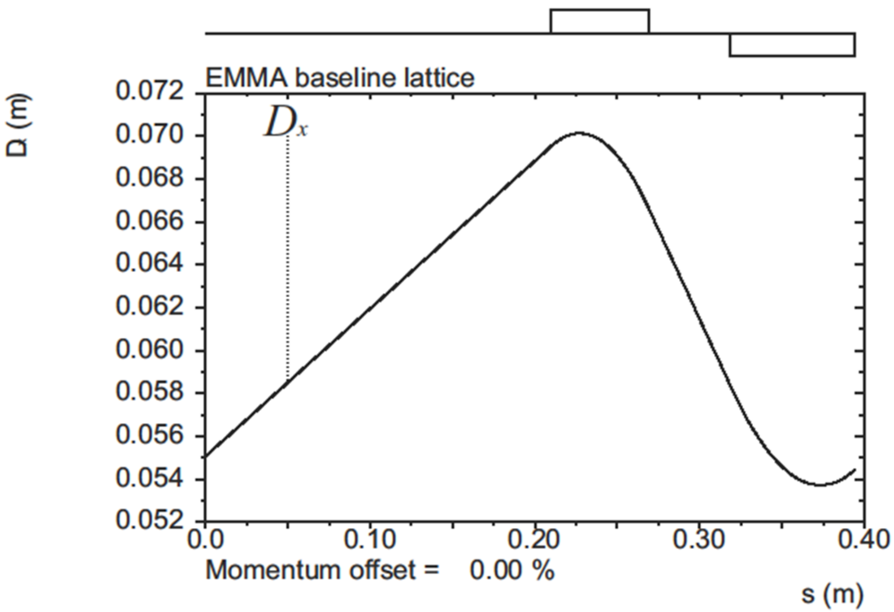
Independent slides

EMMA Cell



EMMA Cell (MAD-X)





- Several programs can be used to match EMMA: MAD-X, PTC, Berg code, Shinji's -code, Zgoubi, FFEMMAG, GPT, ...

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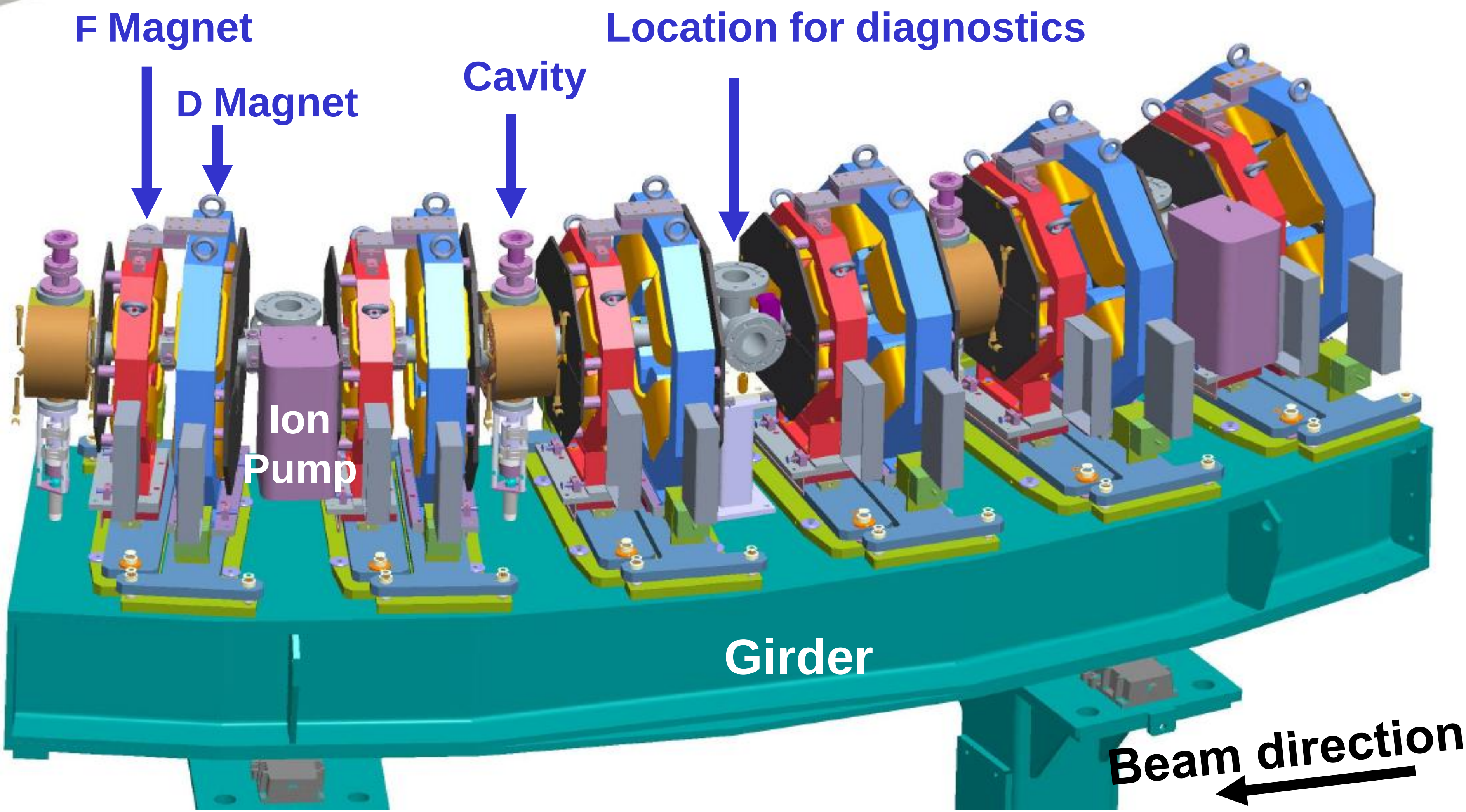
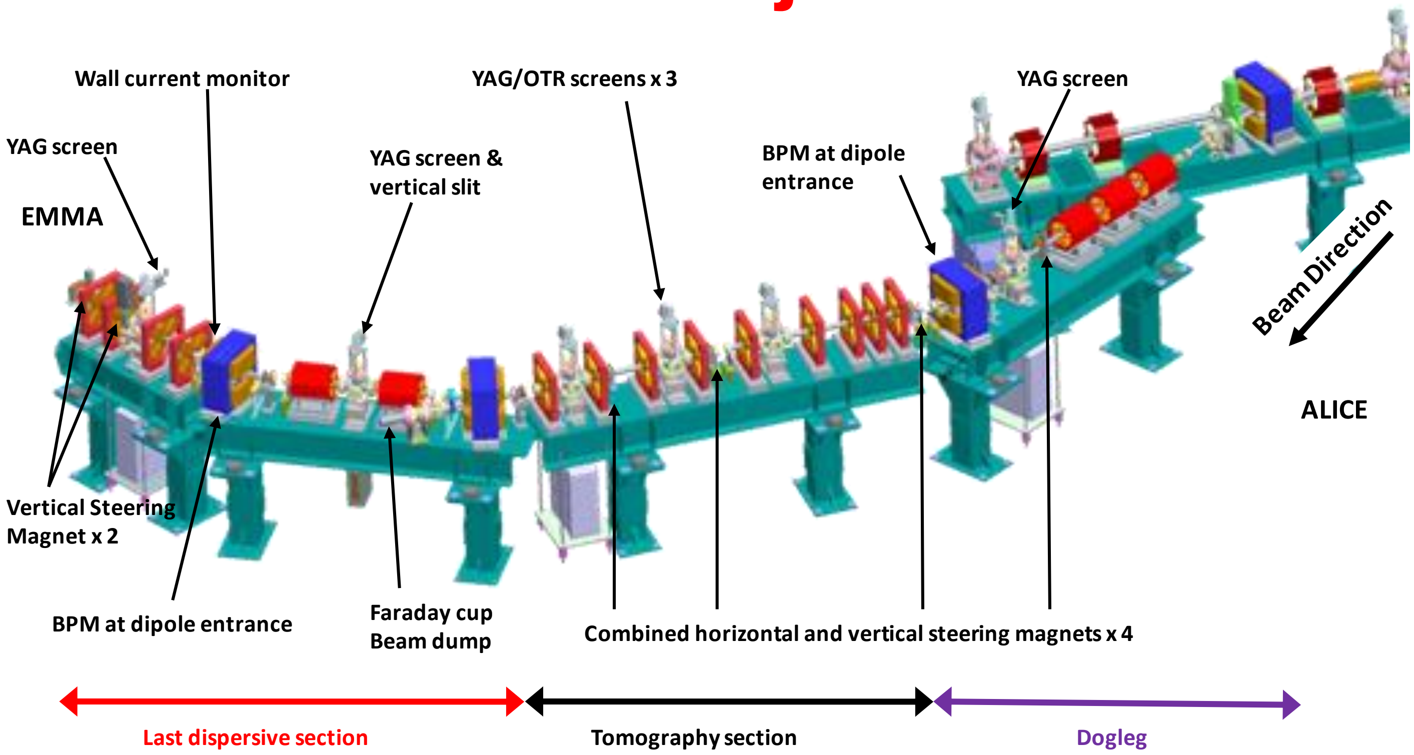
A 6 Cell Girder Assembly



INJECTION & EXTRACTION

Injection line



- Dogleg to extract beam from ALICE
- Tomography (dual purpose)
- Dispersive section to match to EMMA ring with 7 parameters but can be done with 11 variables & maybe more if needed

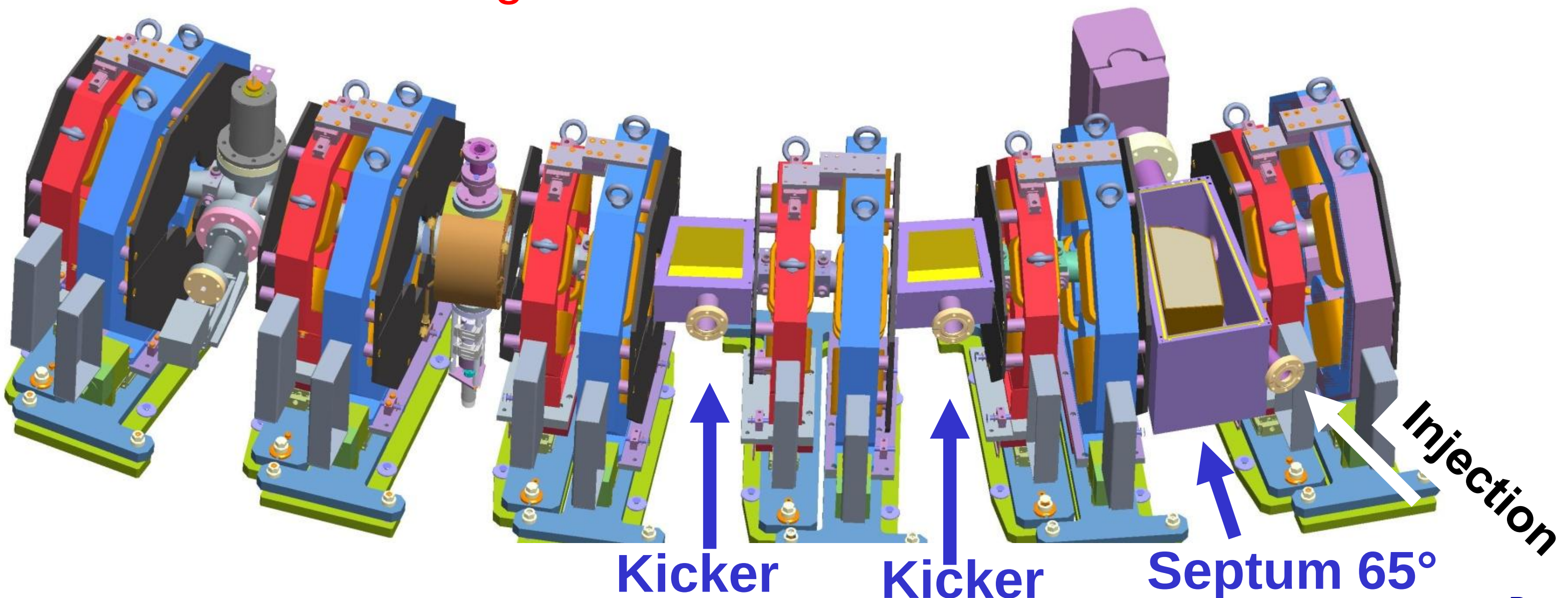
Injection line

- 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

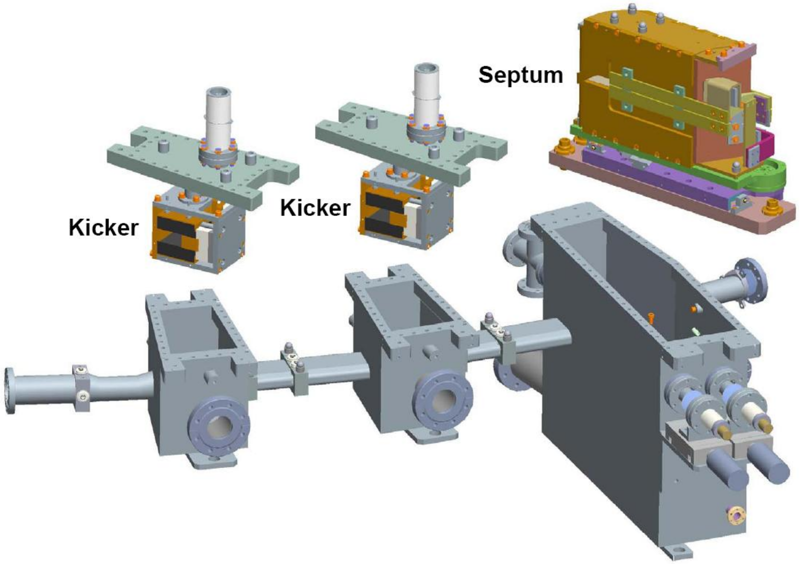
Injection & Extraction

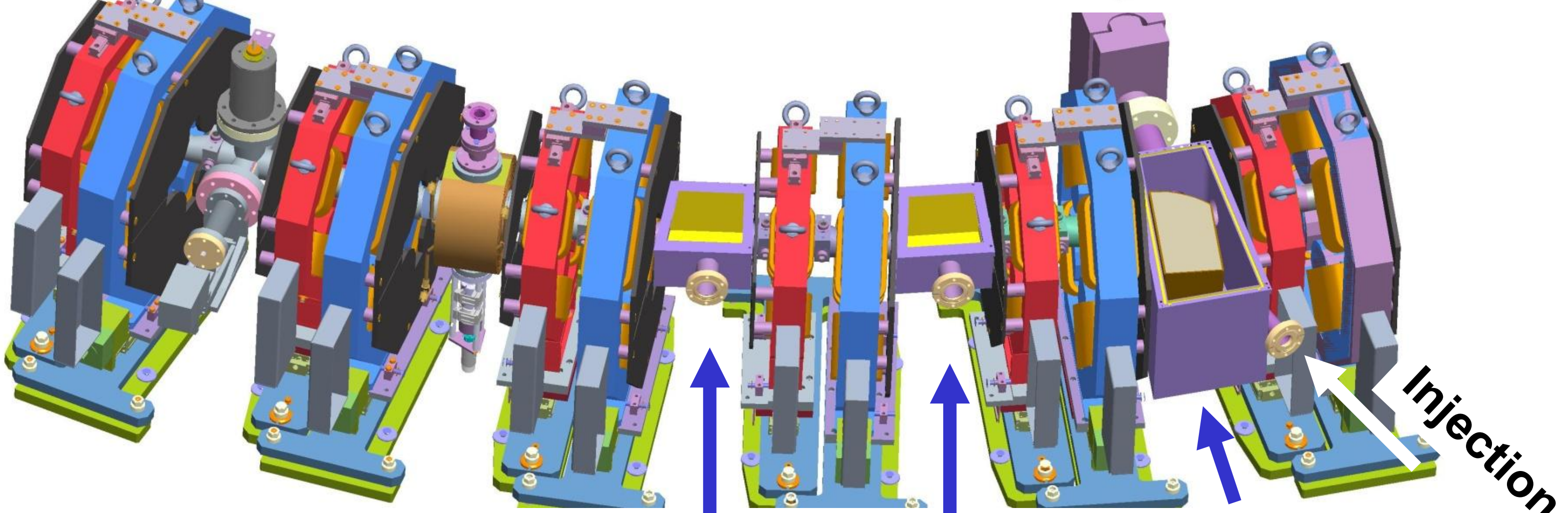
- Large angle for injection (65) and extraction (70) very challenging !!
- Injection/Extraction scheme required for all energies (10 – 20 MeV)
- Many lattices and many configurations of each lattice required
- Very limited space between quadrupole clamp plates for the septum and kickers construction

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



Injection Region





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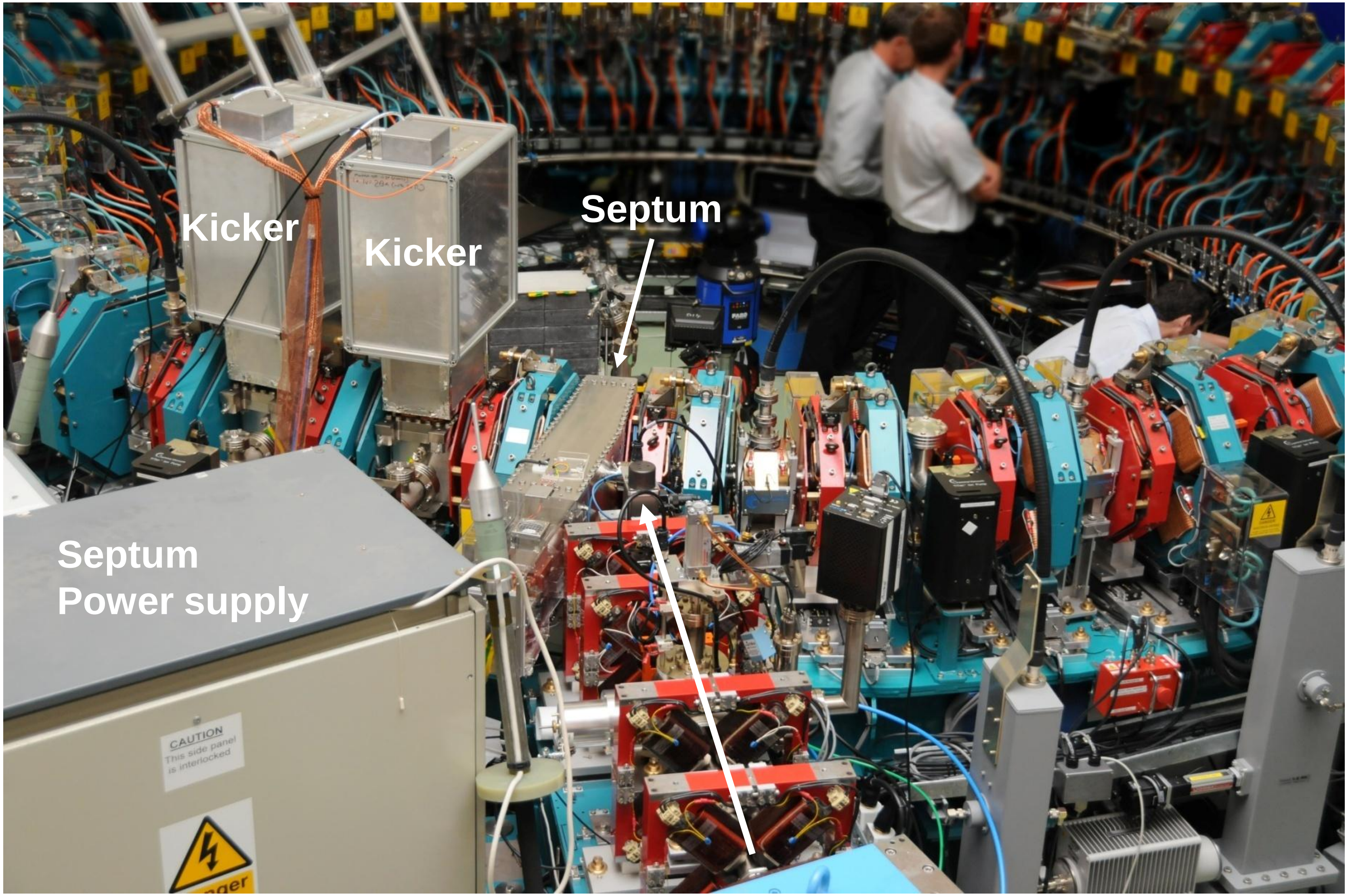
Injection


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

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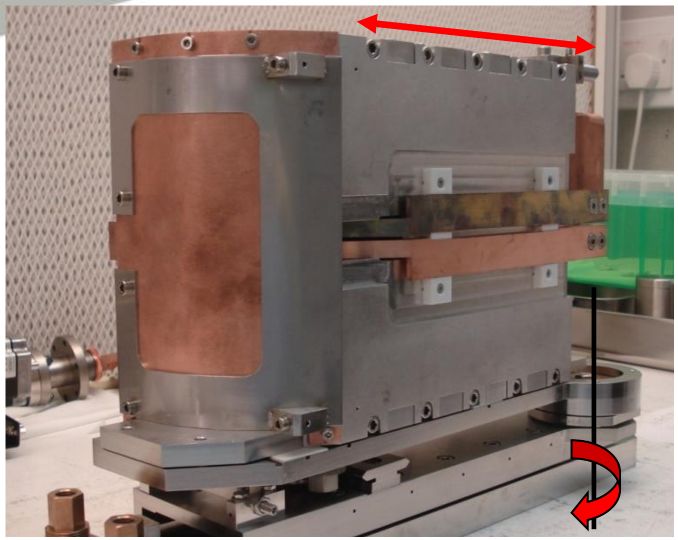
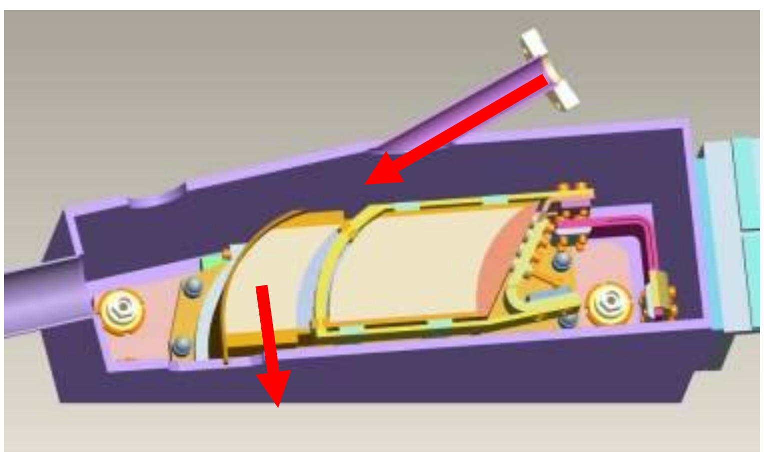
Translation



Rotation

Septum out of vacuum chamber



Section view of septum in vacuum chamber

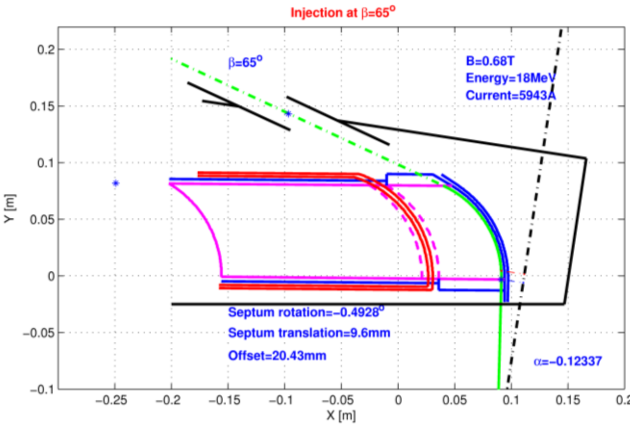
Septum Design

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

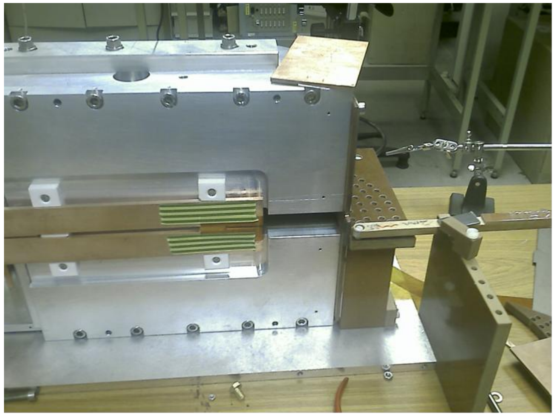
- Septum length ~ 10 cm
- Inject/Extracts from 10-20 MeV
- For all lattice configurations
- Translation -3.2 to 11.5 mm
- Rotation – 0.4 to 0.7 degrees

Injection septum

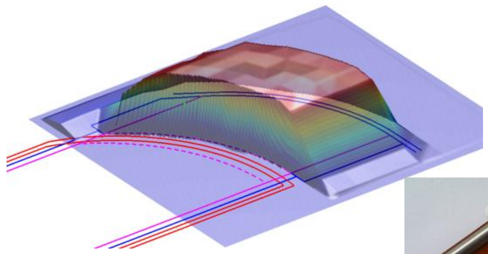
➢Concept

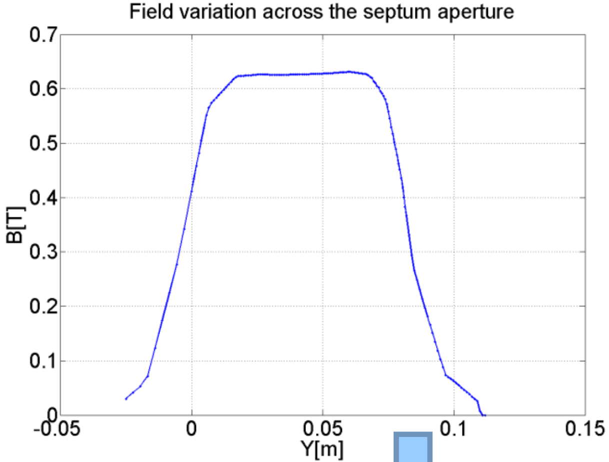


➢Magnetic measurements



➢3D field map

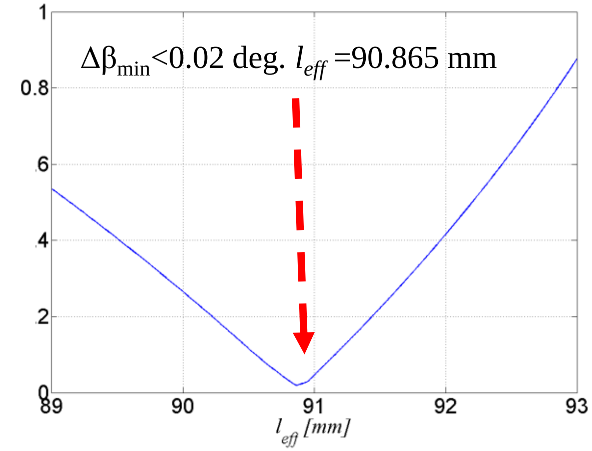




$$l_{eff} = \frac{\int_{-\infty}^{\infty} B(y)\,dy}{B_N} = 91.4\,mm$$

➢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 mm

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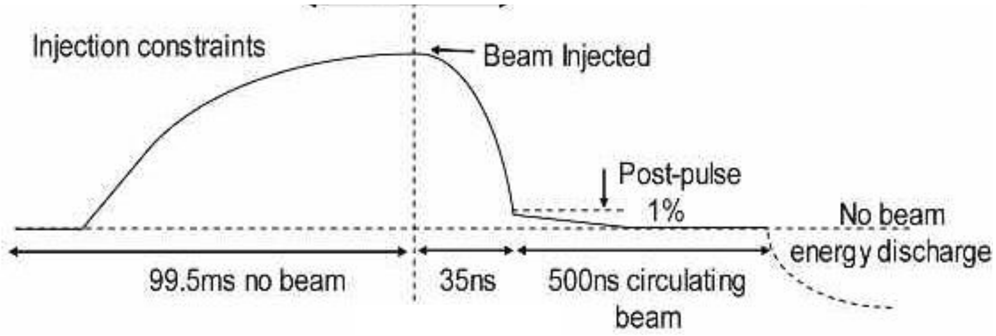
Kicker Magnet, Fast Switching

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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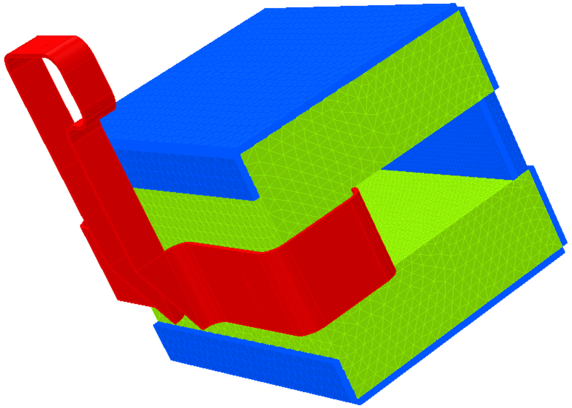
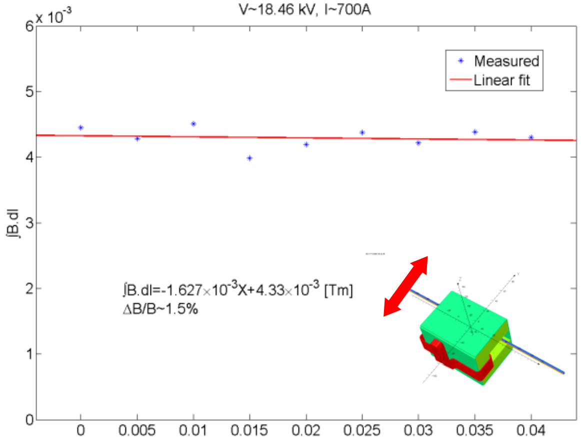
Kickers

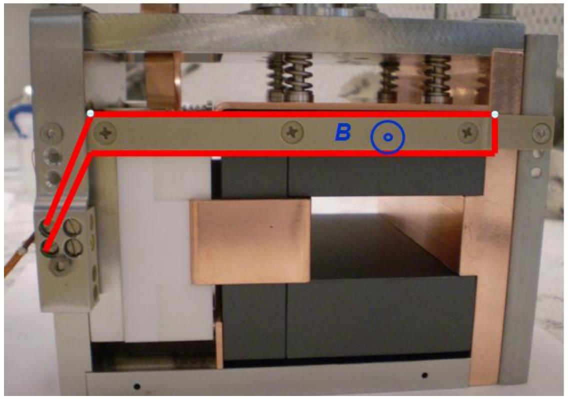
➢Concept



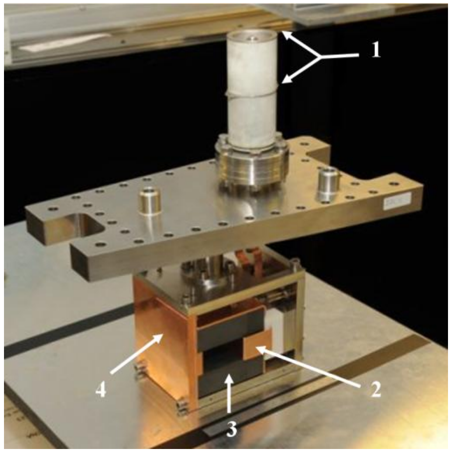
➢Field quality

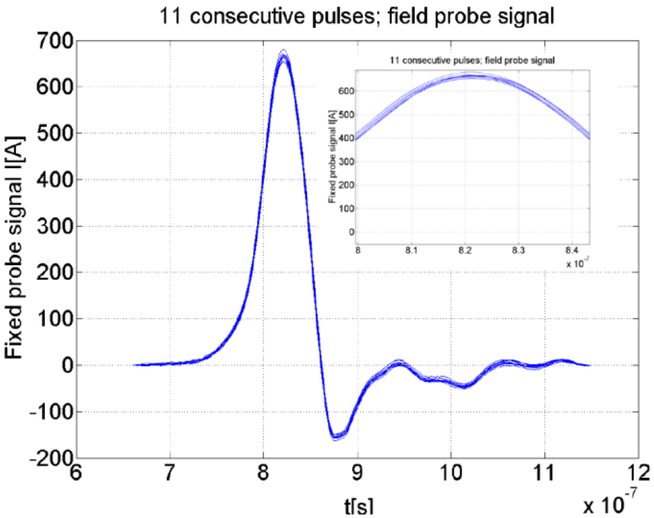


➢In-situ field probe



➢Before installation





Max. strength 0.007 Tm

Effective length 130 mm

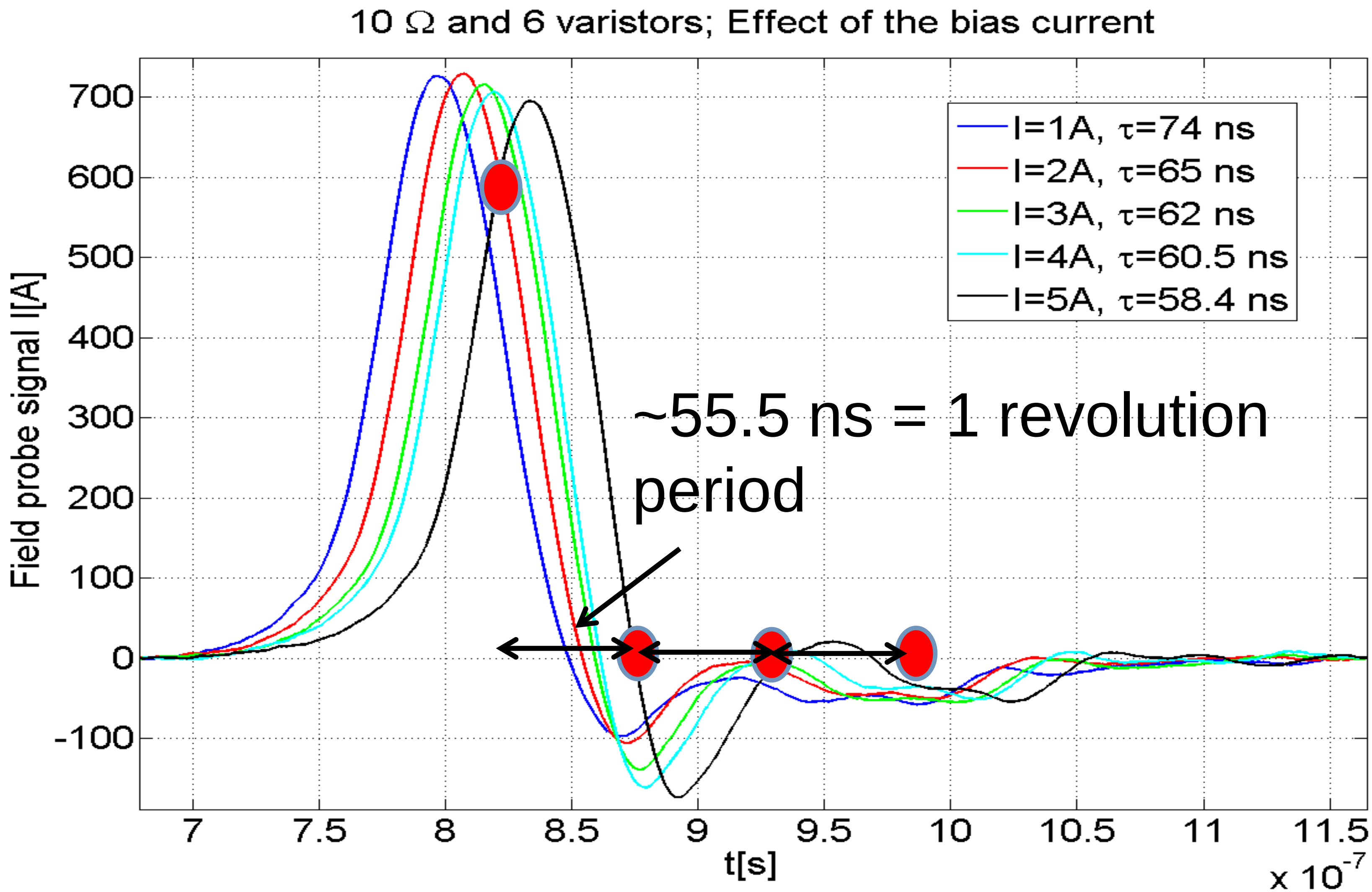
Field variation 1.5%

Fall time 58 ns

Timing jitter 1.7 ns

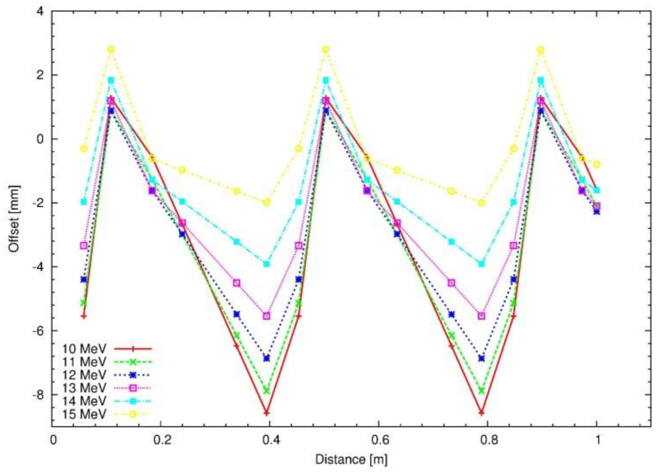
Amplitude stability 4%.

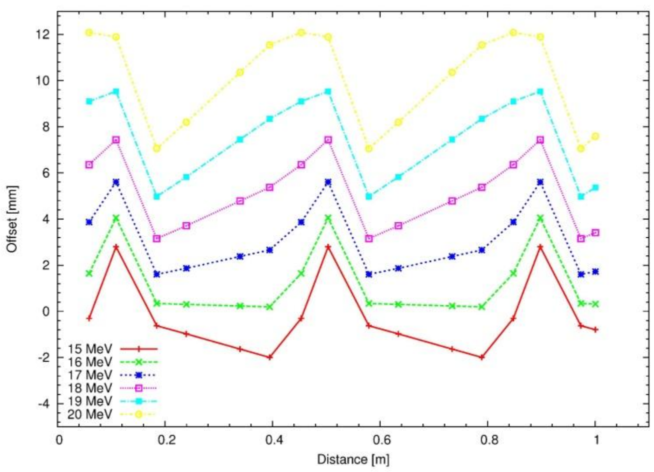
Measured Current Pulses from Kicker Magnet



Trajectory models in EMMA

- Local code FFEMMAG due to S. Tzenov
  - Dedicated only to EMMA modelling (so far)
  - Calculates orbits by back tracking and then tracking through the septum (→ septum designer: Kiril Marinov)
  - Gives required kicker strength
  - Used to accommodate septum stray fields & kicker ringing





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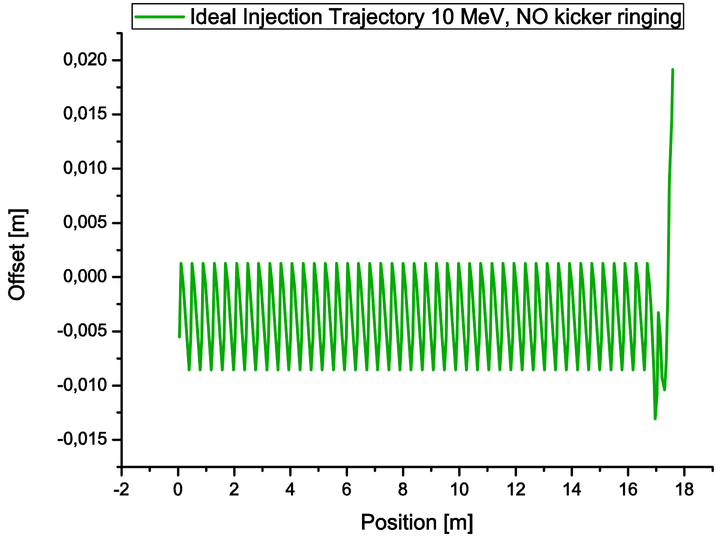
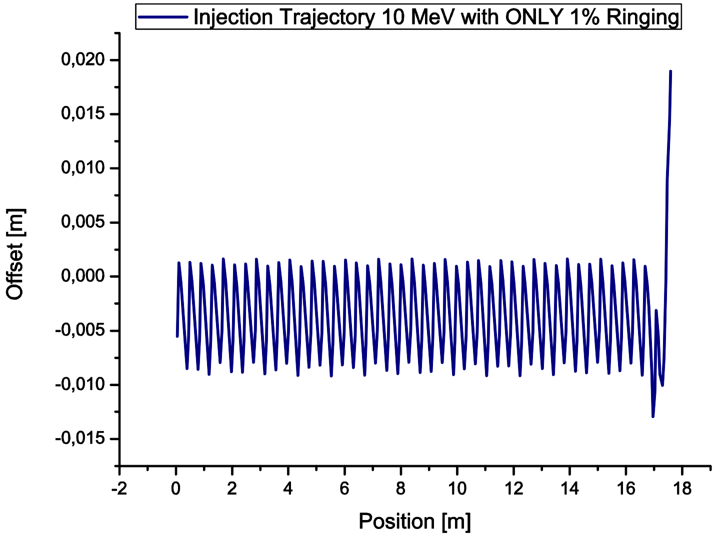
Kicker ringing

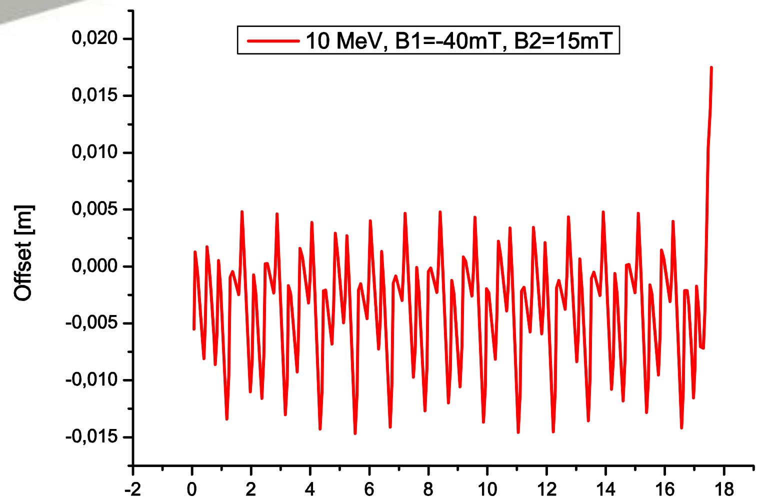


- Ideal case without ringing
- Can have few % ringing
- Cannot have 10 %

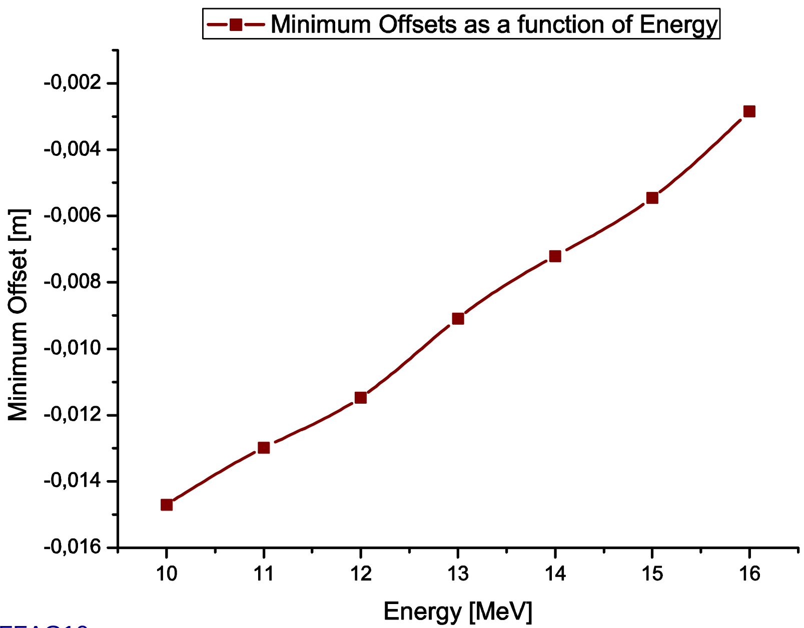


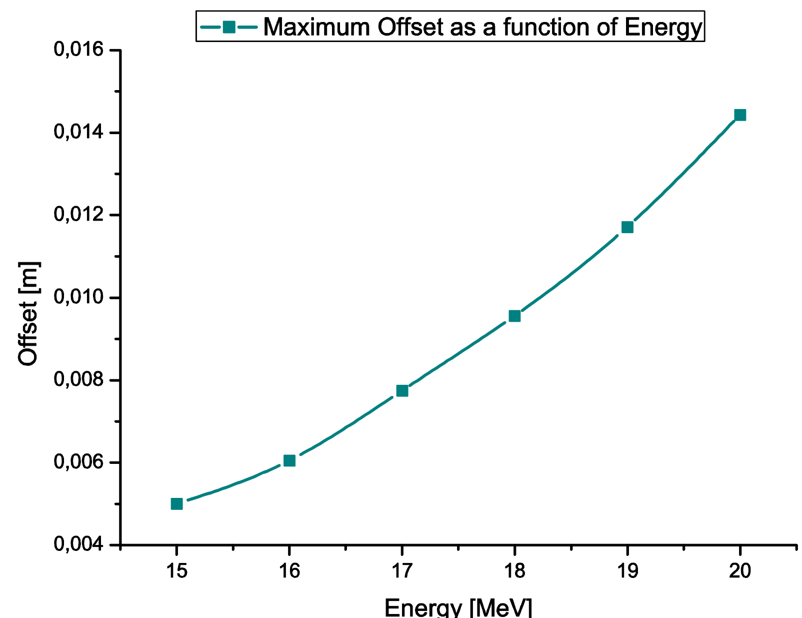
- Only solution is to have multi-turn injection (~ 2)
- Final kicker strength required is ~ the same

Kicker ringing



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





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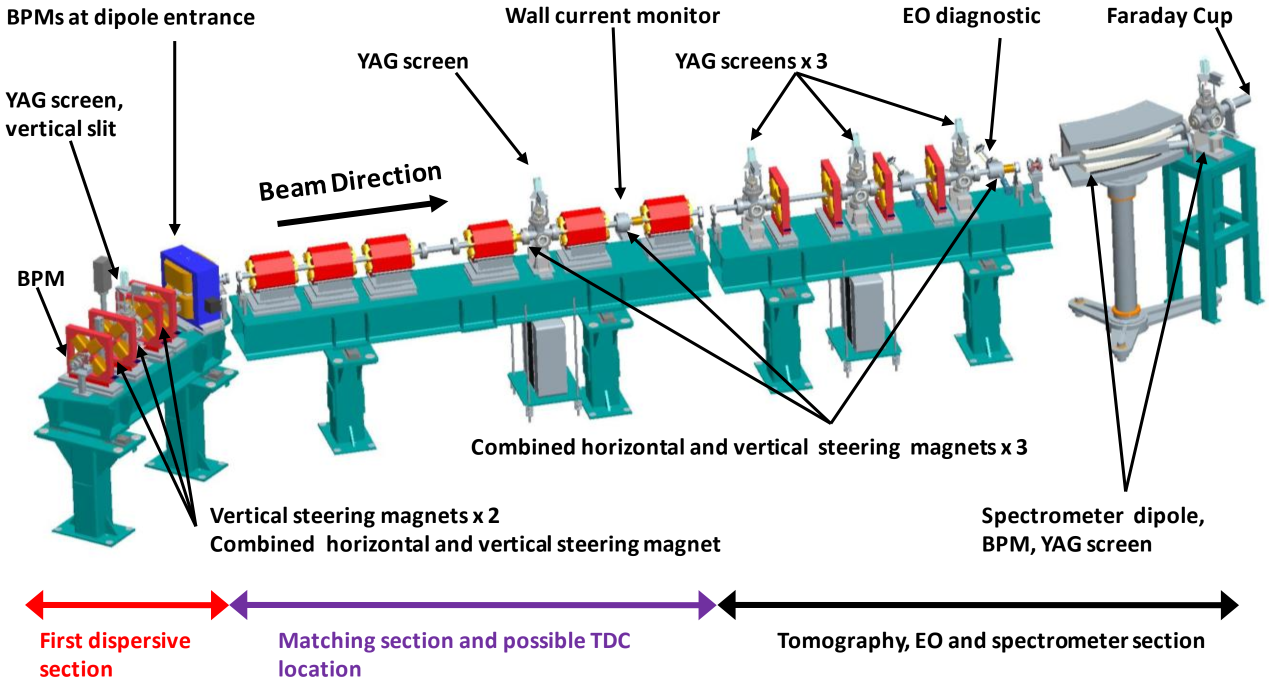
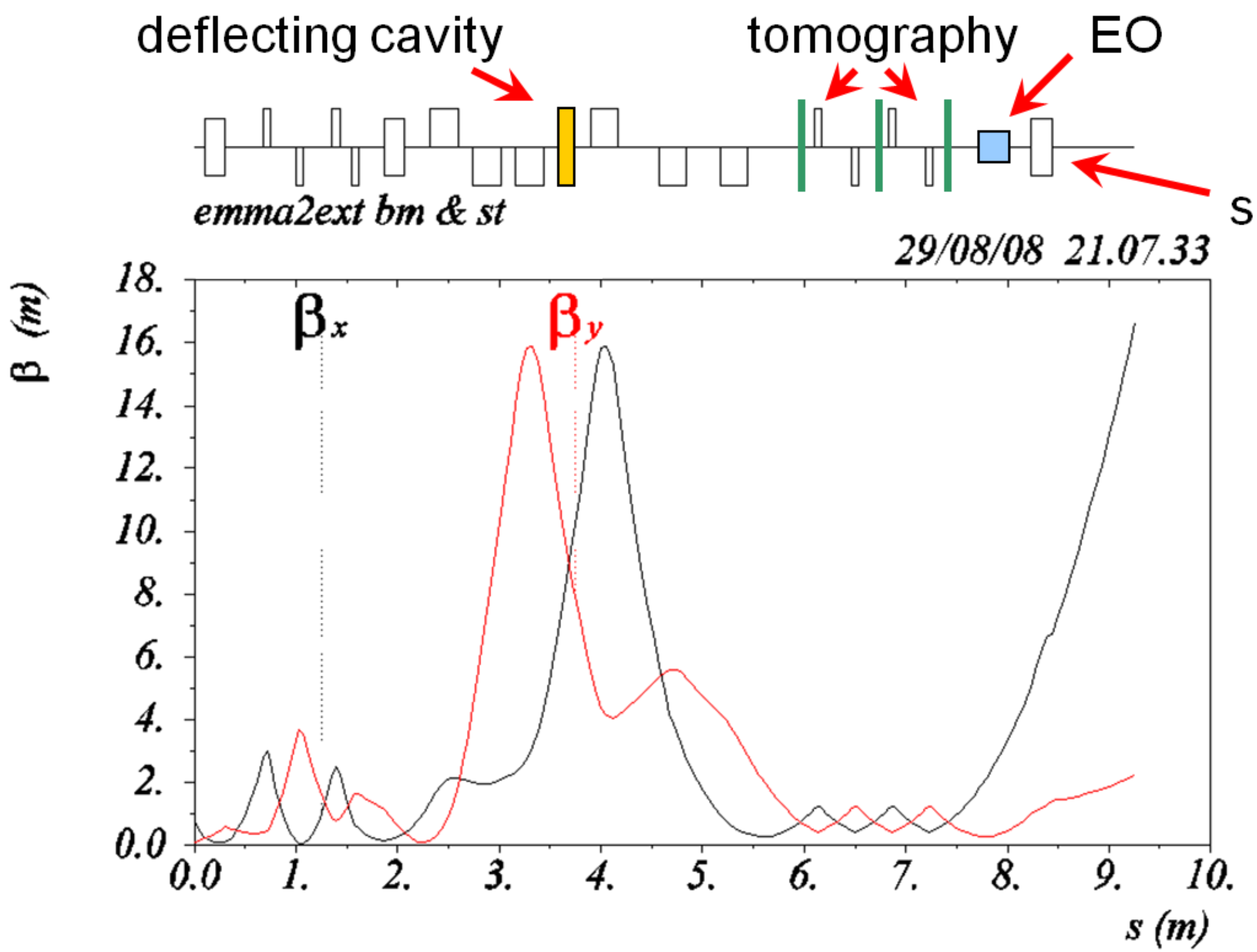
Extraction



- 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, charge, bunch length, energy, energy spread, slice energy spread, electro-optic measurements

Diagnostic line



- 'Dogleg' to close dispersion
- TDC
- Tomography
- EO
- Spectrometer

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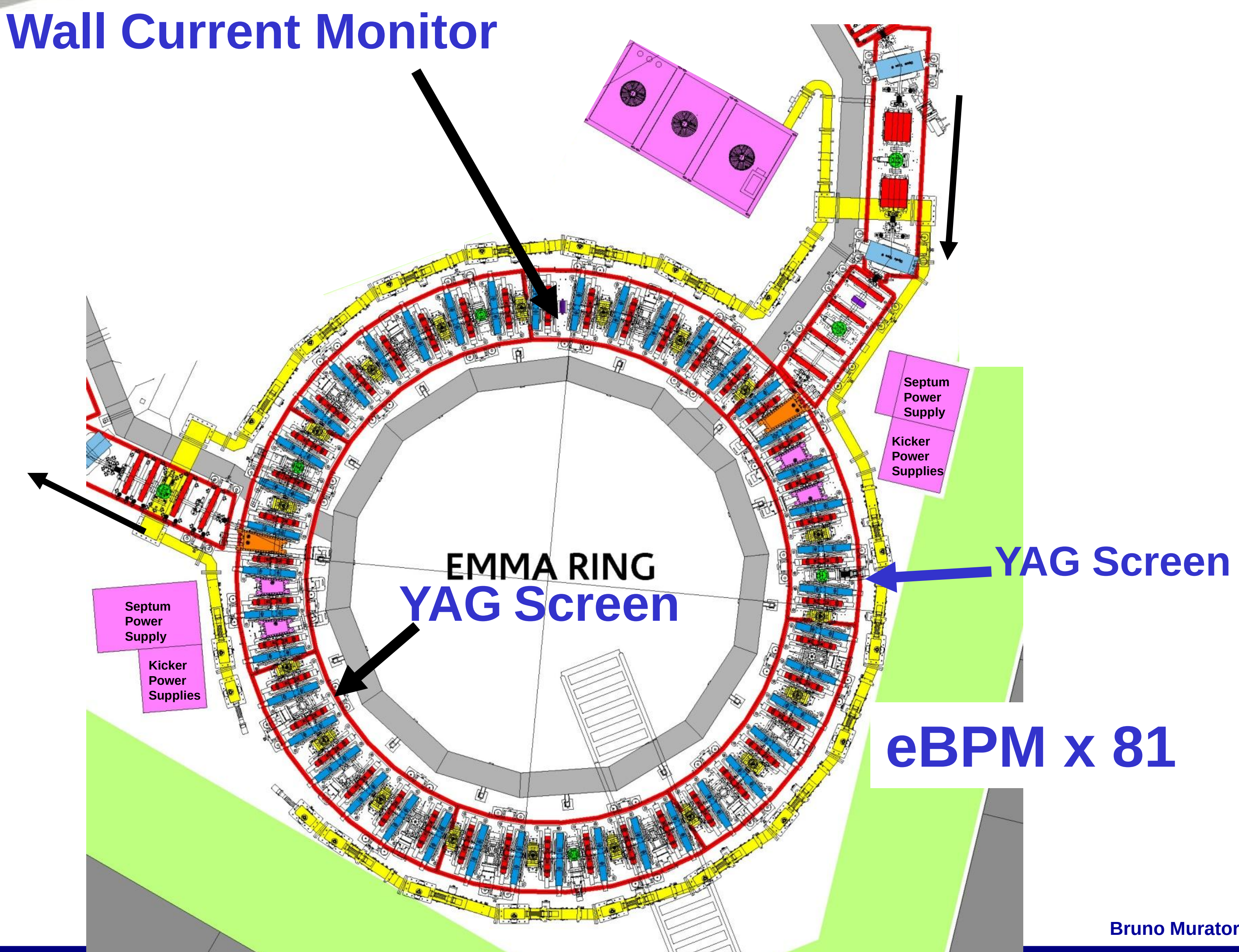
DIAGNOSTICS

EMMA Ring

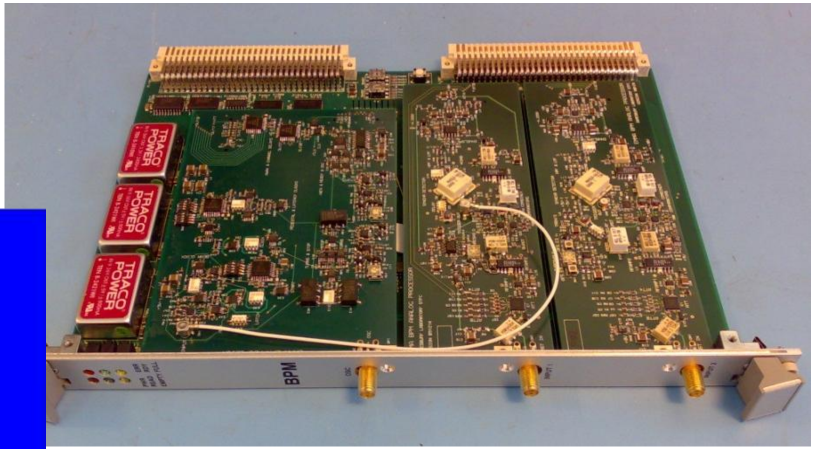


Wall Current Monitor
EMMA RING
YAG Screen
YAG Screen
Septum Power Supply
Kicker Power Supplies
Septum Power Supply
Kicker Power Supplies
eBPM x 81

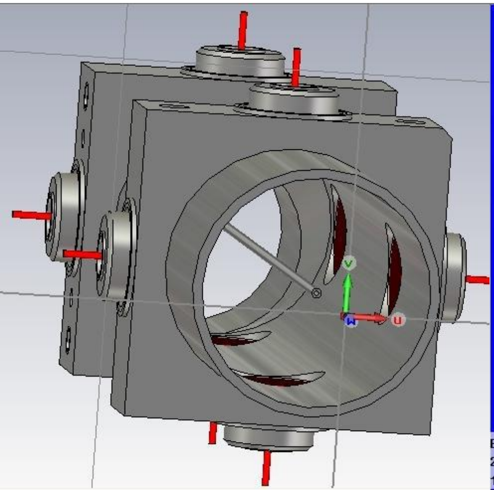
Electron Beam Position Monitors

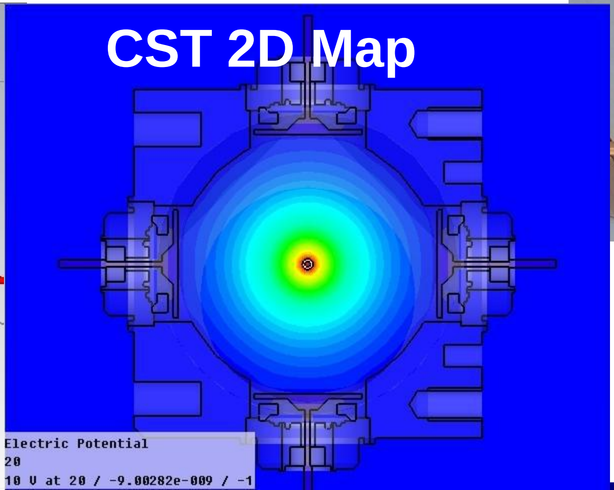
- 50 μm resolution over a large aperture
- Locally mounted coupler cards
  - Amplifies signals from opposite buttons, coupler and strip line delay cables provides two pulses with ¼ rev. period delay on same cable
- VME Detector card in rack room outside of shielded area digitised

Coupler



Detector card



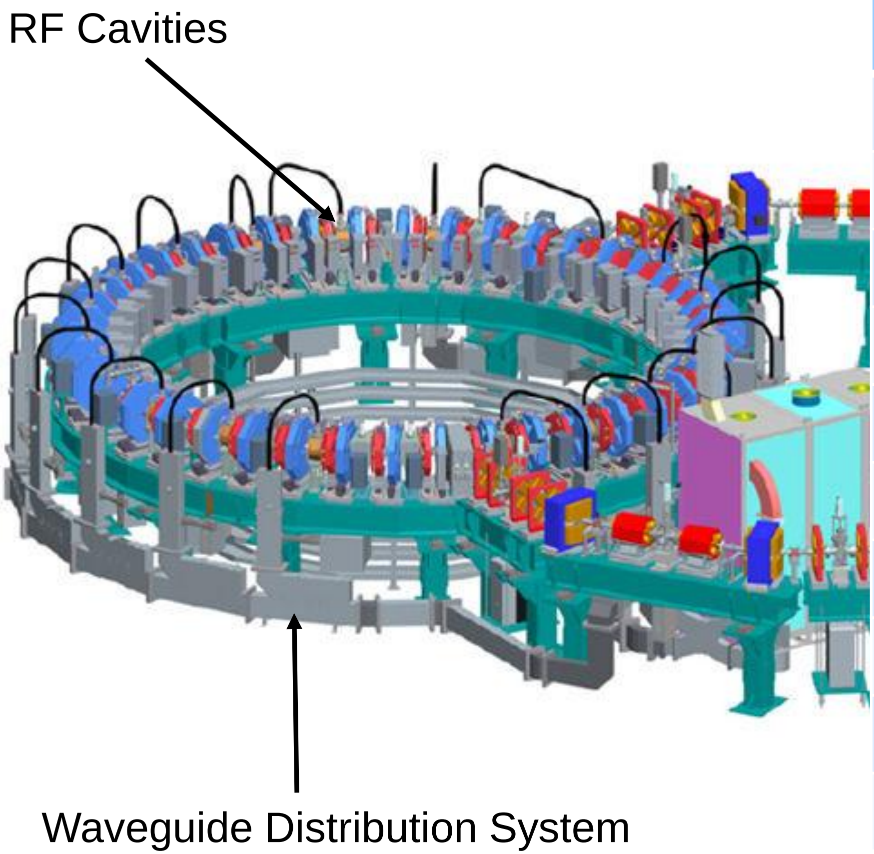


RADIO FREQUENCY

RF Requirements

- Voltage:
  - 20 - 120 kV/cavity essential, based on 19 cavities
- Frequency:
  - 1.3 GHz, compact and matches the ALICE RF system
  - Range requirement 5.6 MHz (-4.0 MHz – 1.6 MHz)
- Cavity phase:
  - Remote and individual control of the cavity phases is essential

RF System Overview



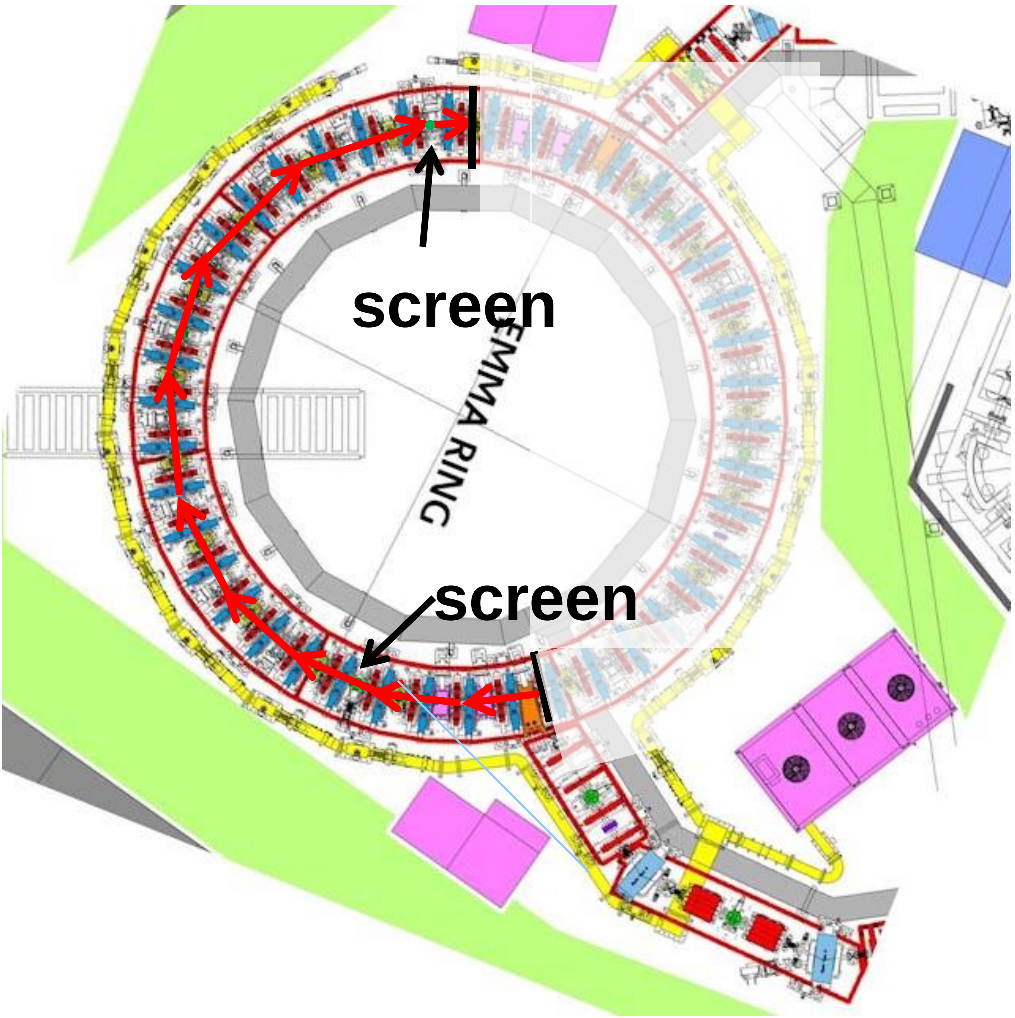
Machine Parameters	Value	Units
Frequency	1.3	GHz
Number of Straights	21	
Number of Cavities	19	
Total Acc per Turn	2.3	MV
Upgrade Acc per Turn	3.4	MV
Beam Aperture	40	mm
Beam Length	1.6	mS
RF Repetition Rate	5-20	Hz
Phase Control	0.3	°
Amplitude Control	0.3	%

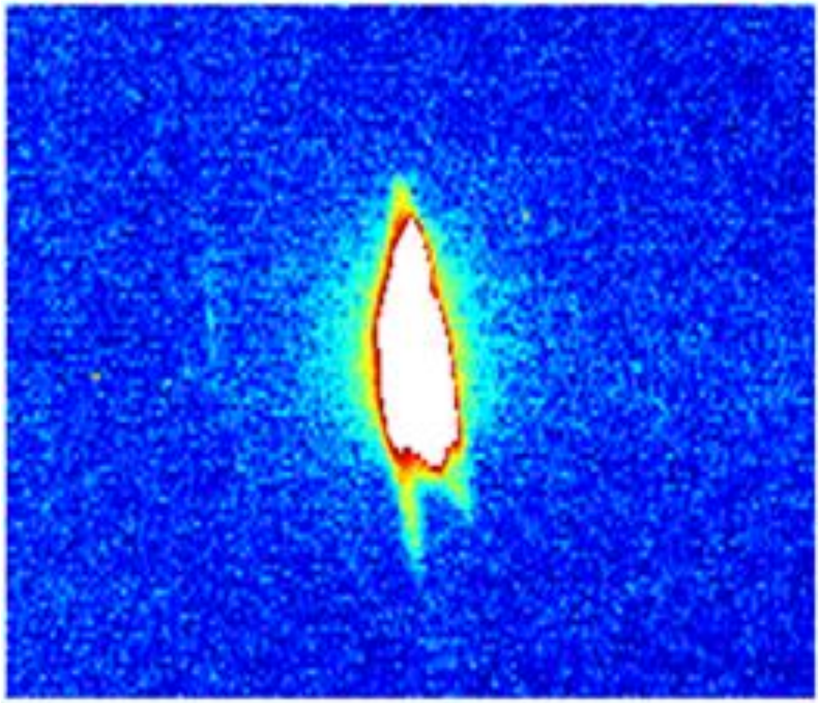
EMMA LLRF

- **Instrumentation Technologies Libera LLRF system provides**
  - Initial cavity setting conditions
  - Control of the cavity amplitude and phase to ensure stable controls the acceleration
- **Diagnostic monitoring**
  - Cavity pick-up loops
  - Forward and reverse power monitoring to each cavity
  - IOT power levels before and after the circulator
- **Novel synchronisation of the accelerators**
  - A 200μs beam pre-trigger used to reset LLRF phase accumulators every beam pulse:
  - The LLRF synchronises itself on every trigger pulse, preserve the relationship between ALICE 1.3 GHz and EMMA offset freq.

COMMISSIONING

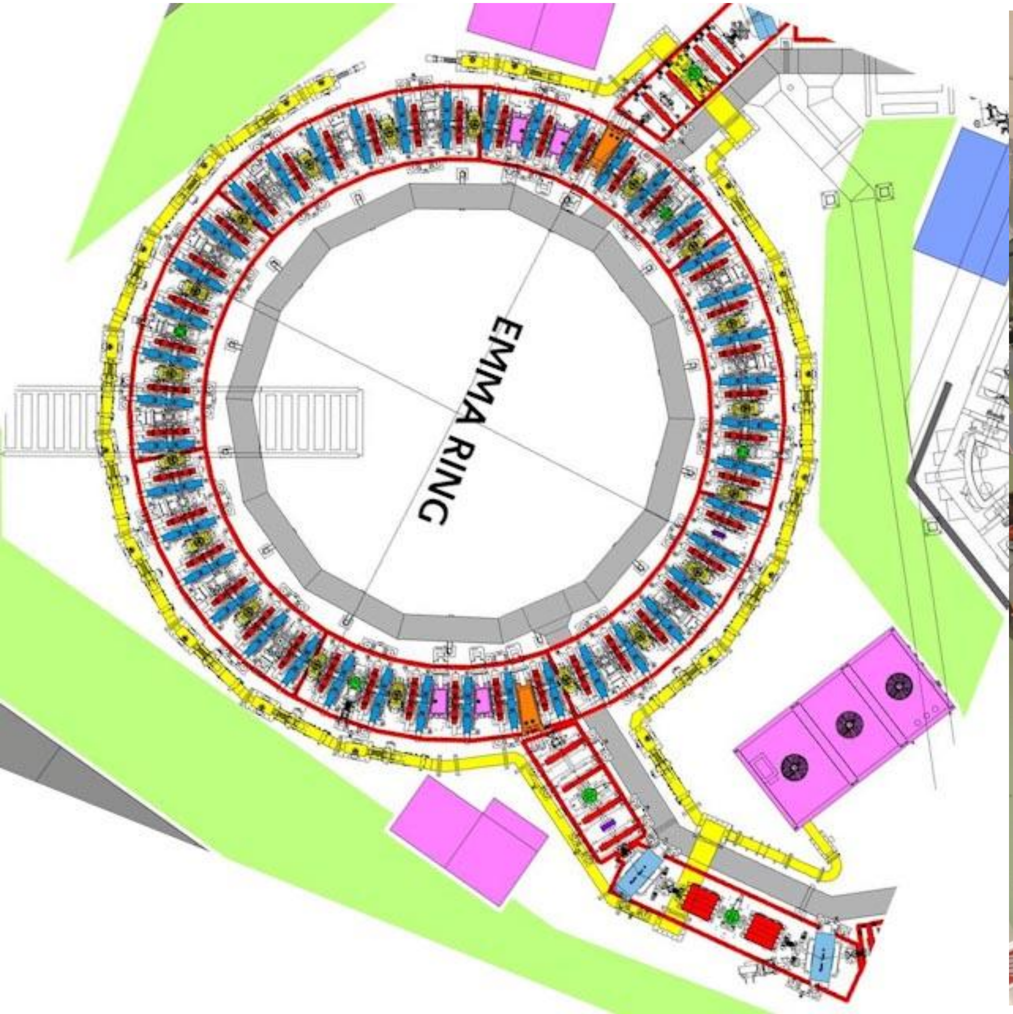
4 Sector Commissioning

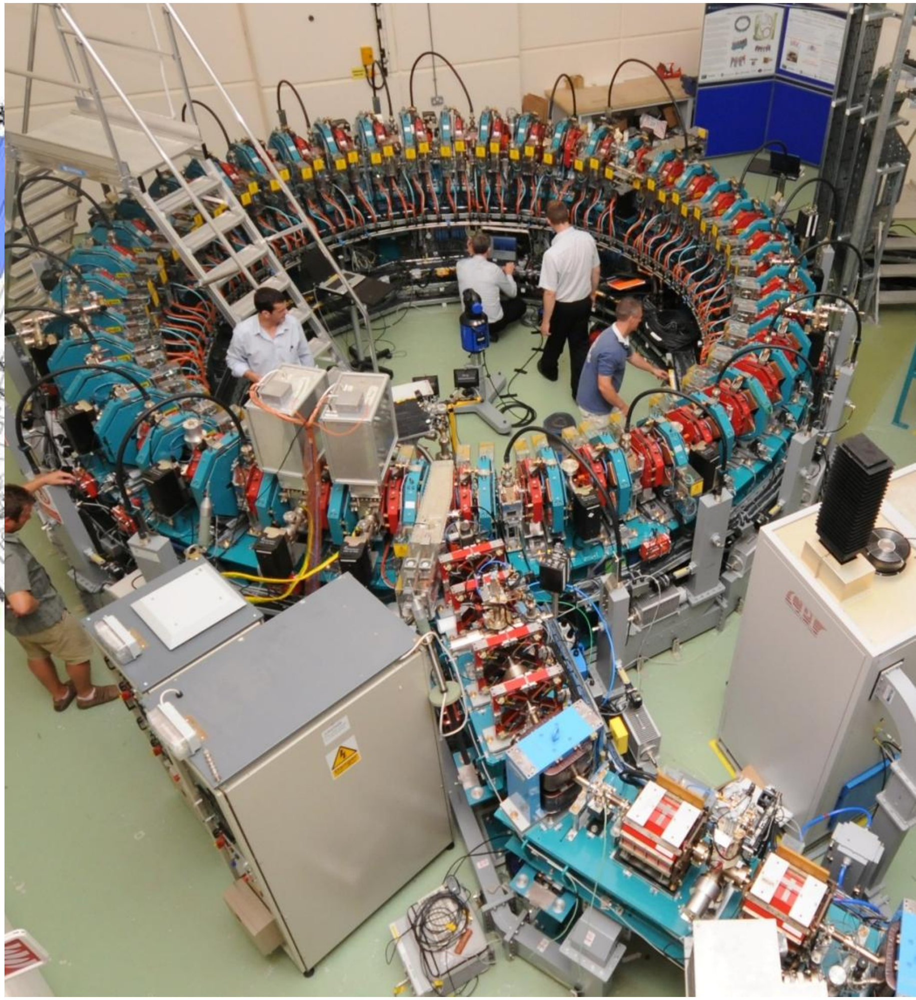




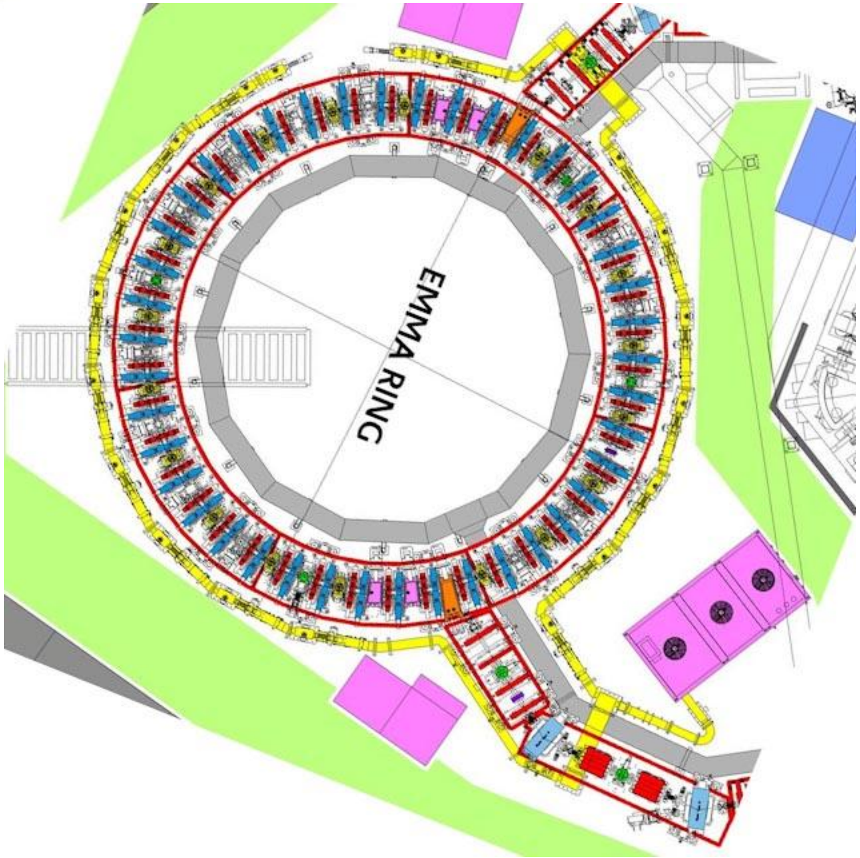
Beam image on screen
At the end of 4 sectors
22 cells
22:37 on 22.6.2010

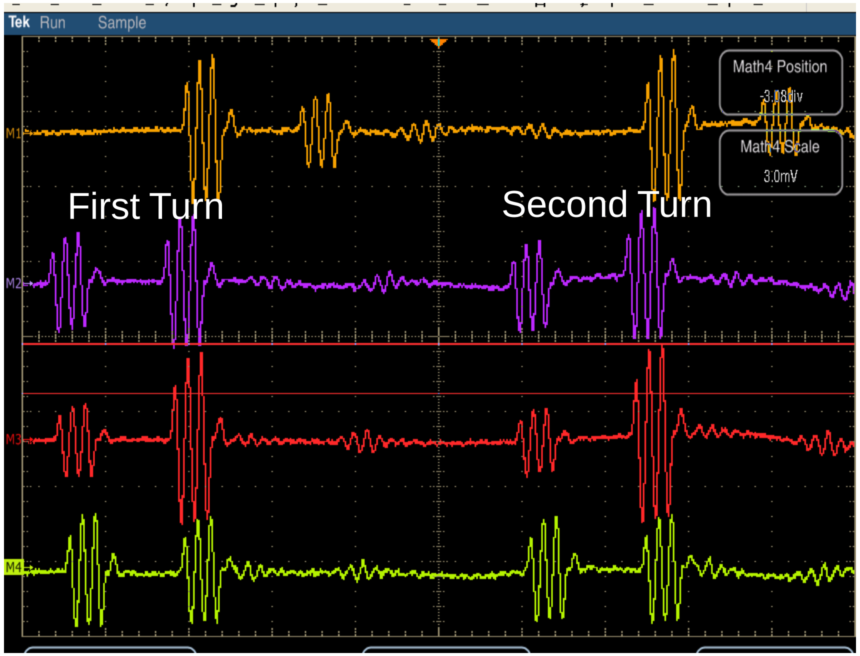
Realisation of EMMA August 2010





Complete Ring

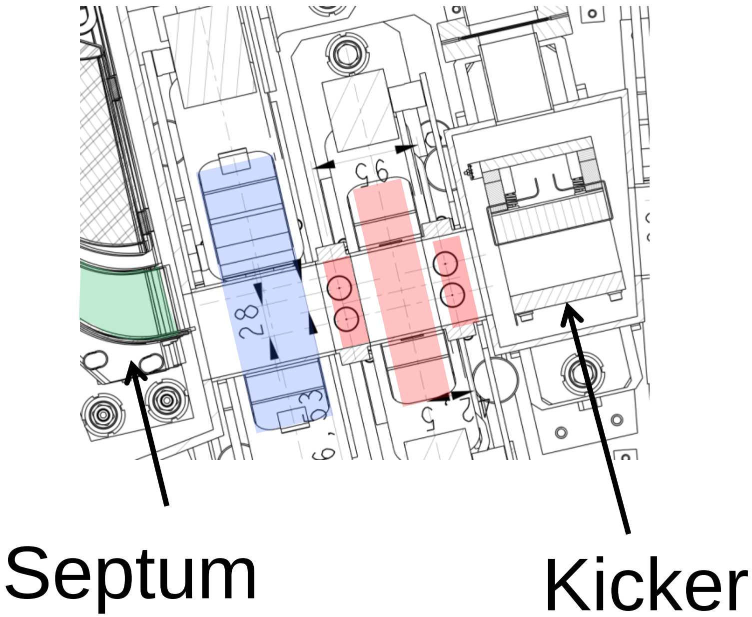


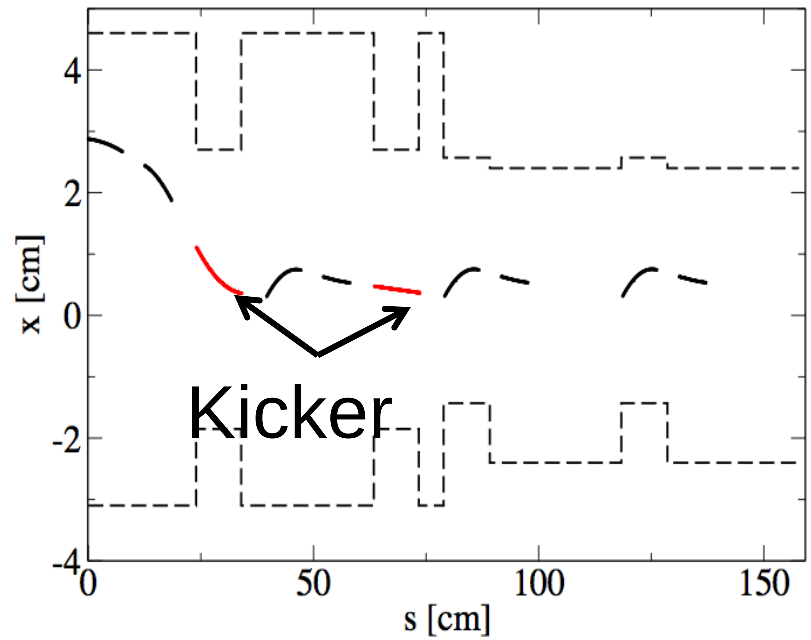


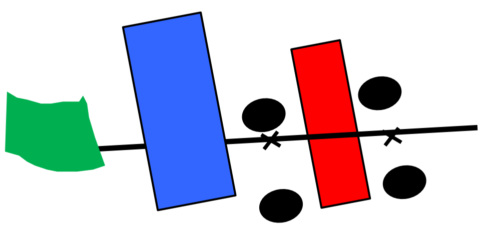
16th Aug 2010

- Still have to look at raw BPM signal & only 12 BPMs are currently available at any one time
- Now routinely achieve 1000+ turns (without RF)

Optimisation of injection





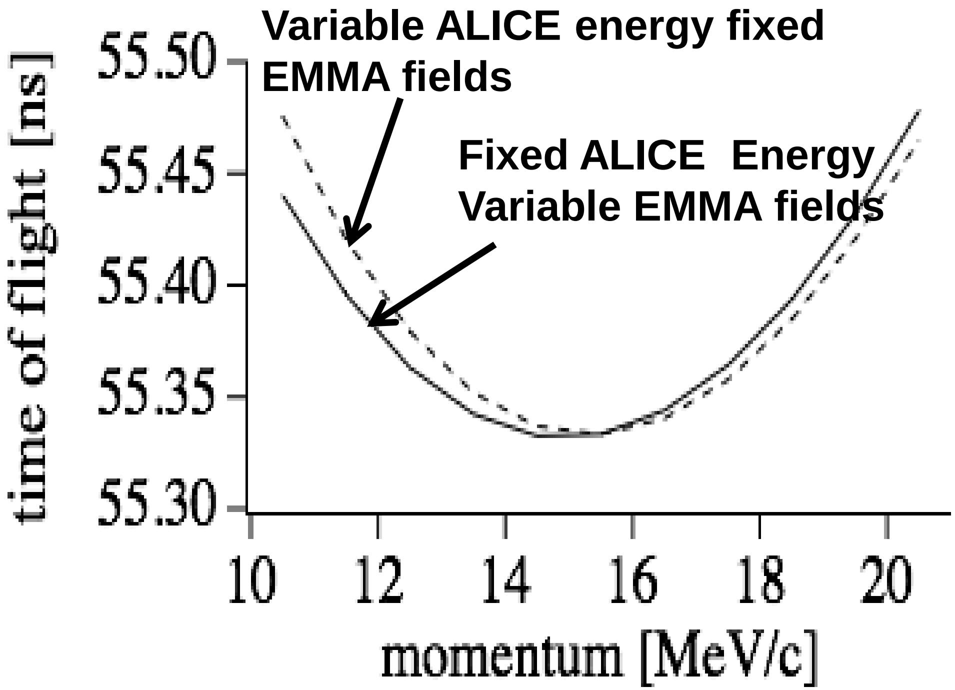


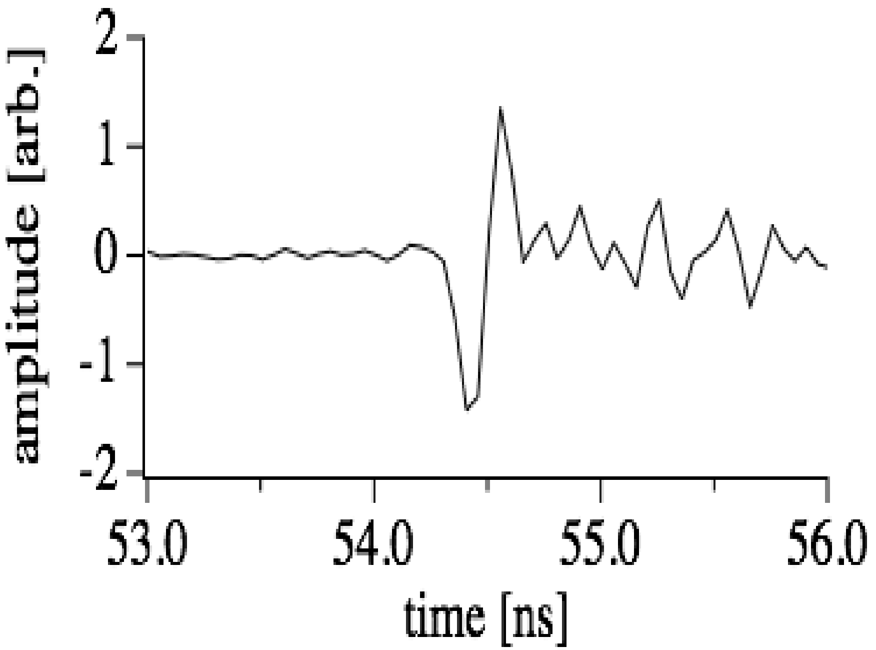
Angle at end of SEPT determined from BPM offsets with quads OFF

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

Time of Flight

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

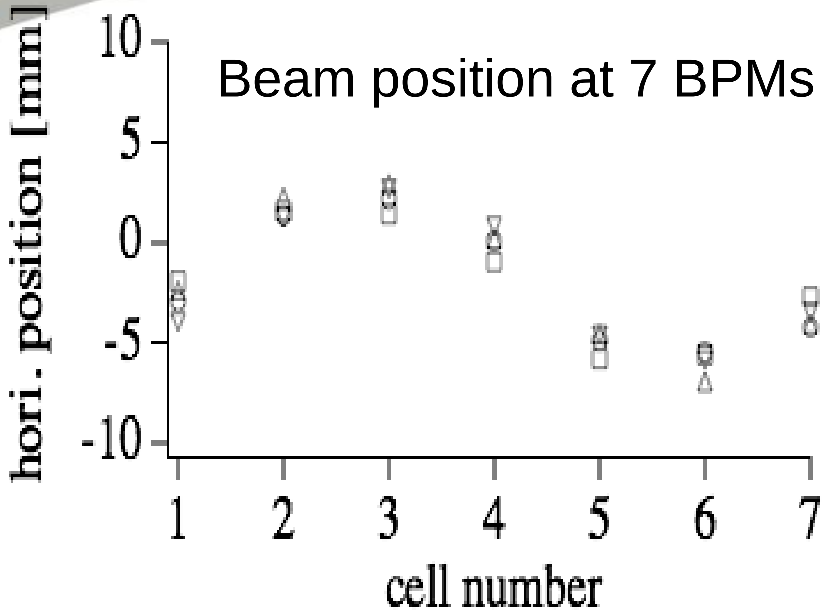


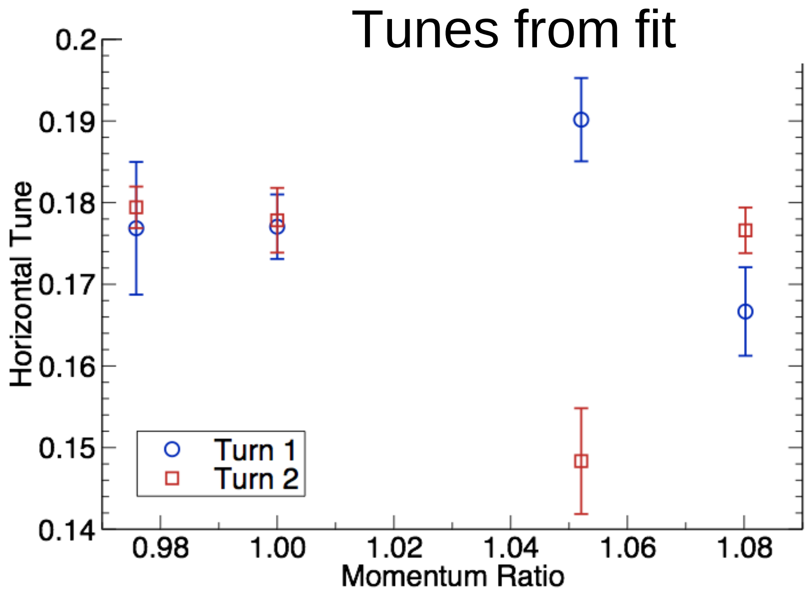


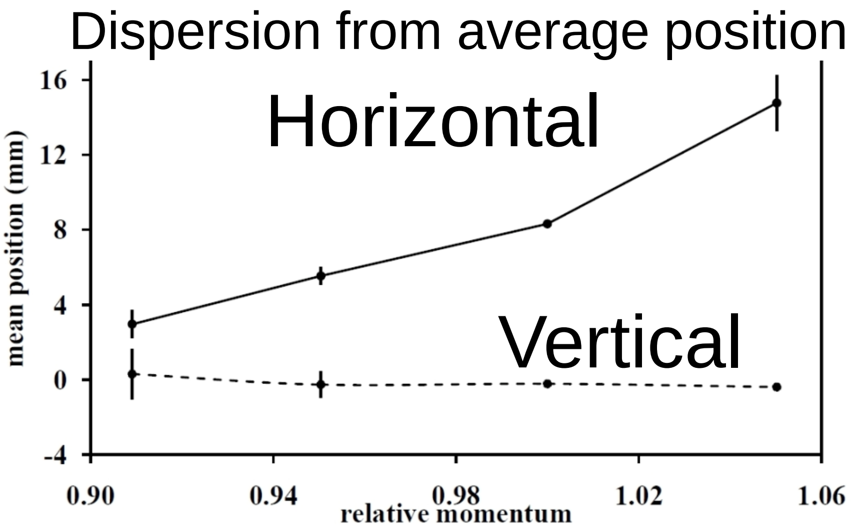
- Time of flight is determined by path length, not by speed
- Use different magnetic strength as easier than retuning ALICE injector

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

Betatron oscillation tunes & dispersion







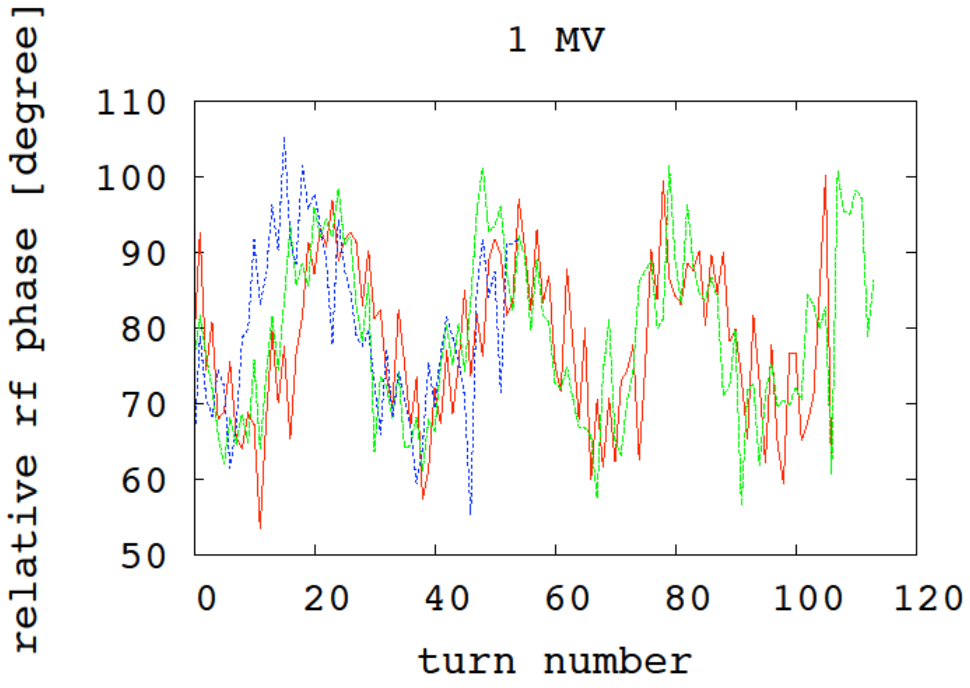
At 100% effective momentum (15.5 MeV/c)

Horz disp =82mm

Vert. disp. = 3mm

Consistent to predicted values

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

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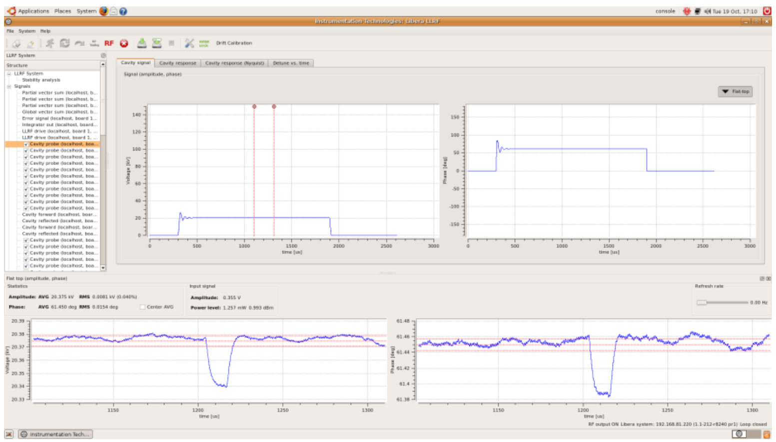
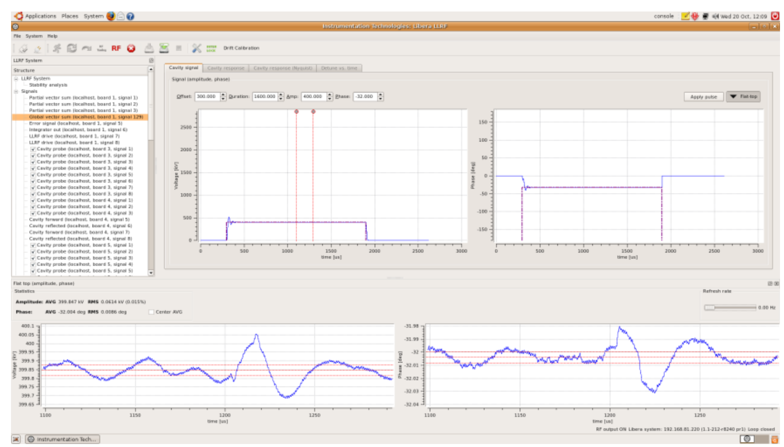
Setting Phases

- To set the phases in the cavities we look at
  - Beam loading & power demand
  - Zero crest (both)
- Can be done for individual cavities and overall





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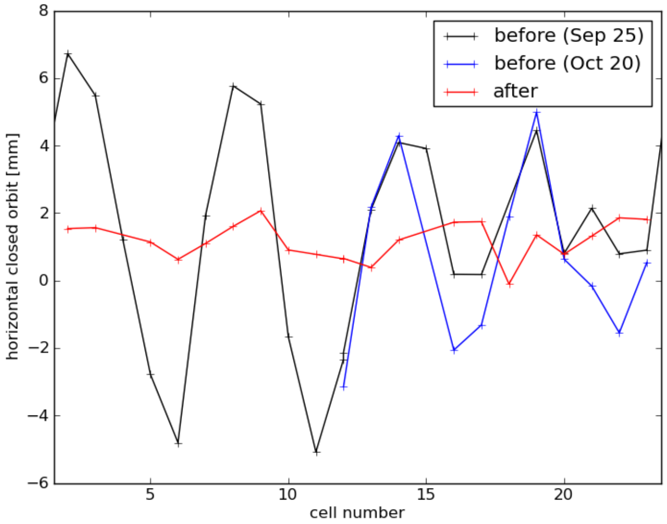
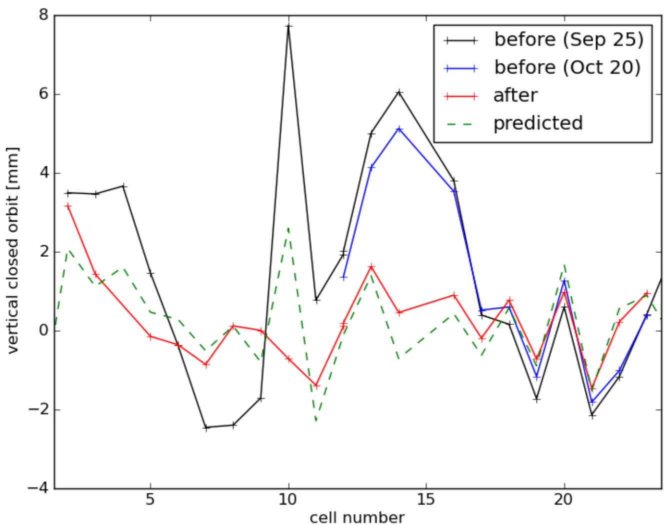
BASROC CONFORM

Orbit Correction





- Can do orbit correction
  - Can be done throughout the ring
  - Both vertically & horizontally
  - Usually done in first quadrant only
- This is almost always the same ...
- Have some misalignments in the ring
- Suspect some vertical correctors

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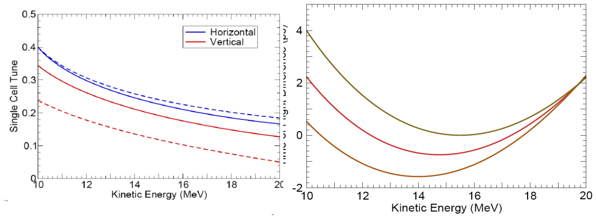
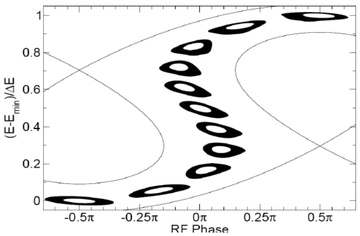
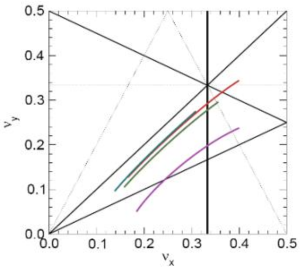
Next Steps

- 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)
  - Benchmark measured dynamic aperture with and without acceleration against the simulations

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
  - The LLRF system commissioning is at an advanced stage and ready for operating to show evidence of acceleration
  - Orbit corrected (both vertically & horizontally)

A key aim is to:-

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

Apply lessons learnt to new applications!

Acknowledgements

All the team

- STFC Daresbury & Rutherford Appleton Labs , Cockcroft Institute, John Adams Institute, Imperial College staff
- International Collaborators
- Commercial Suppliers

Funding from UK Basic Technology Programme

Thank you for your attention !