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BASROC CONFORM

Commissioning EMMA

the World's First Non-Scaling FFAG Accelerator

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STFC, ASTeC, UK

Contents

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INTRODUCTION

Project Overview

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

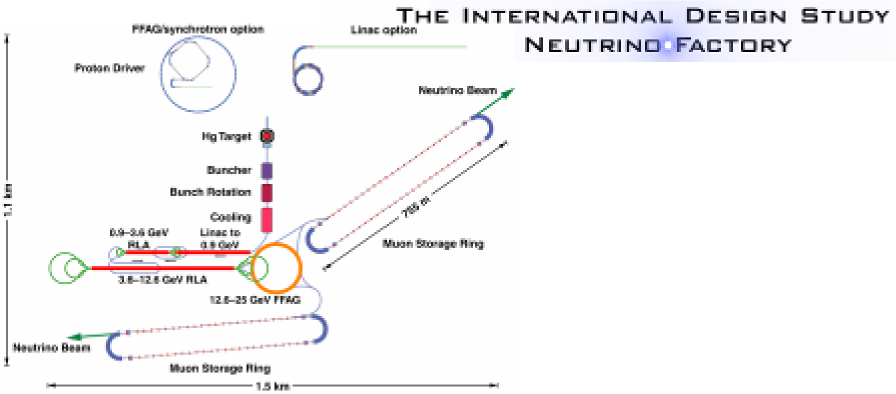
- CONFORM project (**CO**nstruction of a **N**on-scaling **F**FAG for **O**ncology, **R**esearch, and **M**edicine)
- 4 year project April 2007 – March 2011
- 3 parts to the project
  - EMMA design and construction ~ £6.5m (~$9M)

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

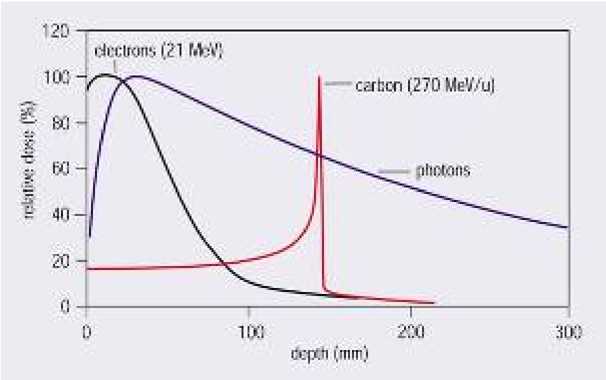
  - PAMELA design study
  - Applications study

Applications of ns-FFAGs

Neutrino Factory

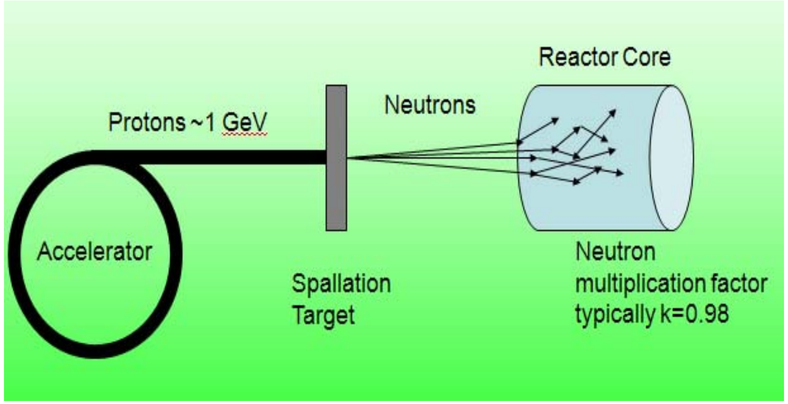


Proton & Carbon Therapy



High power proton driver

Sub-critical Thorium Reactor



Non-scaling FFAG

- Born from considerations of very fast muon acceleration
  - Breaks the scaling requirement
  - More compact orbits ~ X 10 reduction in magnet aperture
  - Betatron tunes vary with acceleration (resonance crossing)
  - Parabolic variation of time of flight with energy
    - Factor of 2 acceleration with constant RF frequency
    - Serpentine acceleration
- Can mitigate the effects of resonance crossing by:-
  - Fast Acceleration ~15 turns
  - Linear magnets (avoids driving strong high order resonances)
    - Or nonlinear magnets (avoids crossing resonances)
  - Highly periodic, symmetrical machine (many identical cells)
    - Tight tolerances on magnet errors dG/G <2x10^{-4}

Novel, unproven concepts which need testing

Electron Model => EMMA!

Muon Acceleration Model

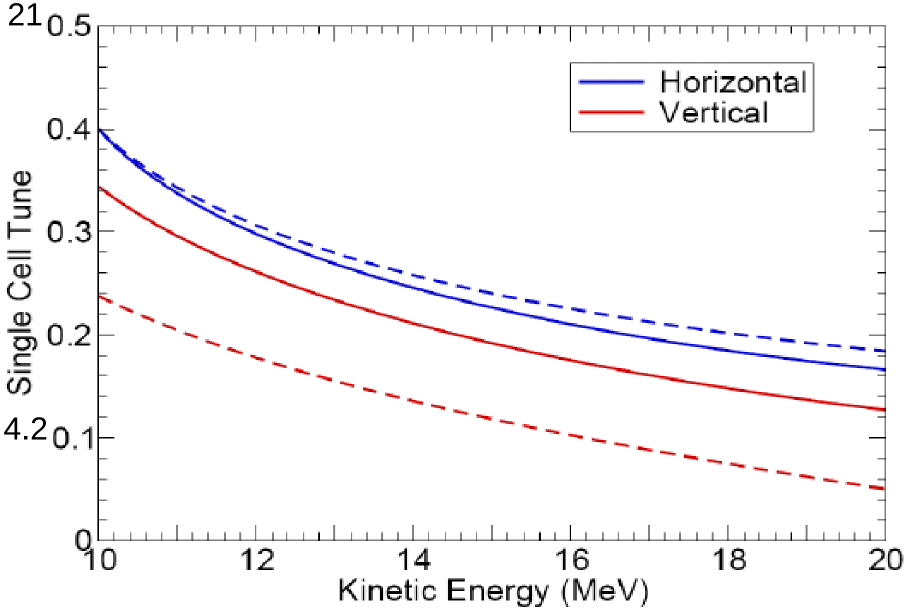
- EMMA was originally conceived as a model of a 10-20 GeV muon accelerator
- Designed to demonstrate that linear non-scaling optics work and to make a detailed study of the novel features of this type of machine
  - Variable tunes with acceleration
  - Parabolic variation of time of flight with energy
    - Serpentine acceleration

EMMA International Collaboration

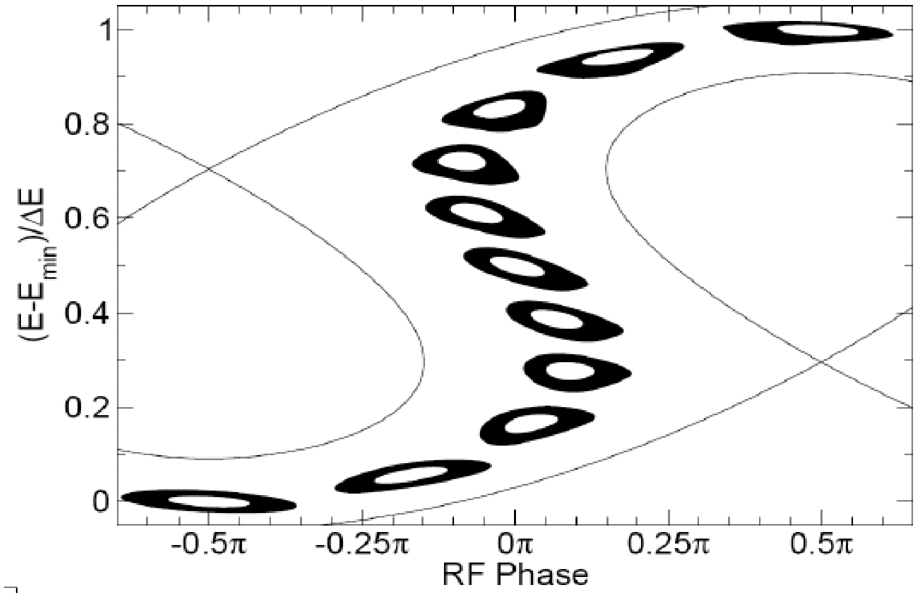
- EMMA design is an international effort and we recognise and appreciate the active collaboration from:
  - Brookhaven National Laboratory
  - Cockcroft Institute UK
  - Fermi National Accelerator Laboratory
  - John Adams Institute UK
  - LPSC, Grenoble
  - Science & Technology Facilities Council UK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

EMMA Goals

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



(2) Serpentine acceleration (results from parabolic ToF)

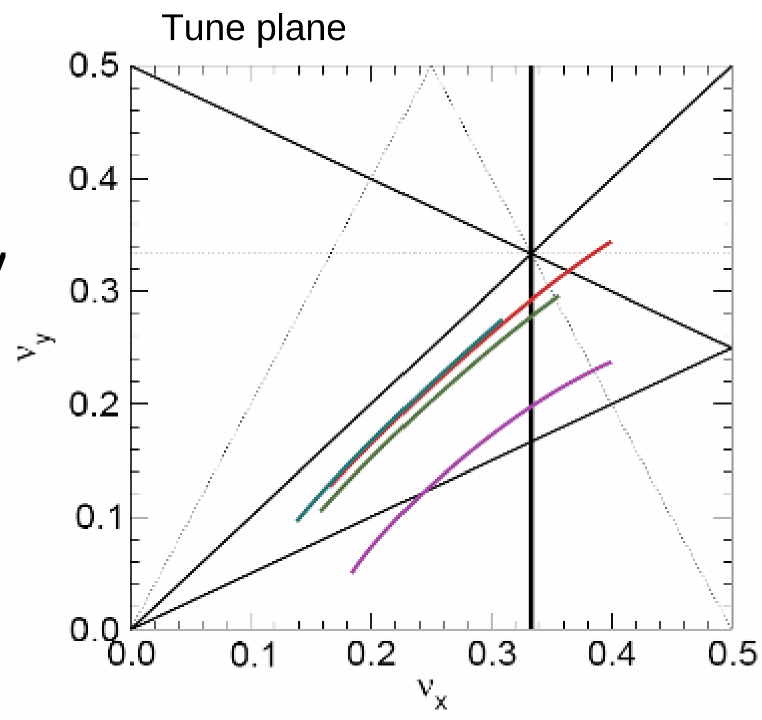


(3) Map the transverse and longitudinal acceptances.

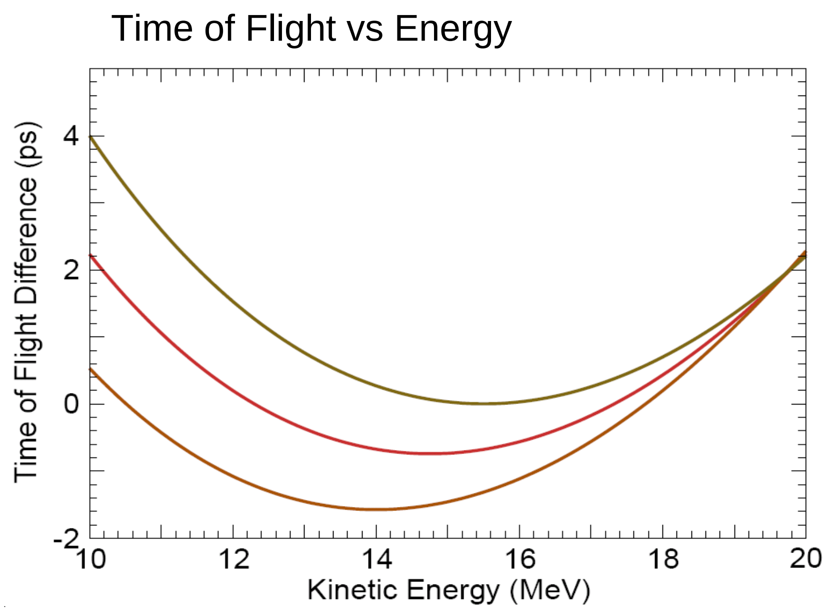
Graphs courtesy of Scott Berg BNL

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

BROOKHAVEN NATIONAL LABORATORY

Accelerator Requirements

- Injection & extraction at all energies, 10 - 20 MeV
- Fixed energy operation 10-20 MeV 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

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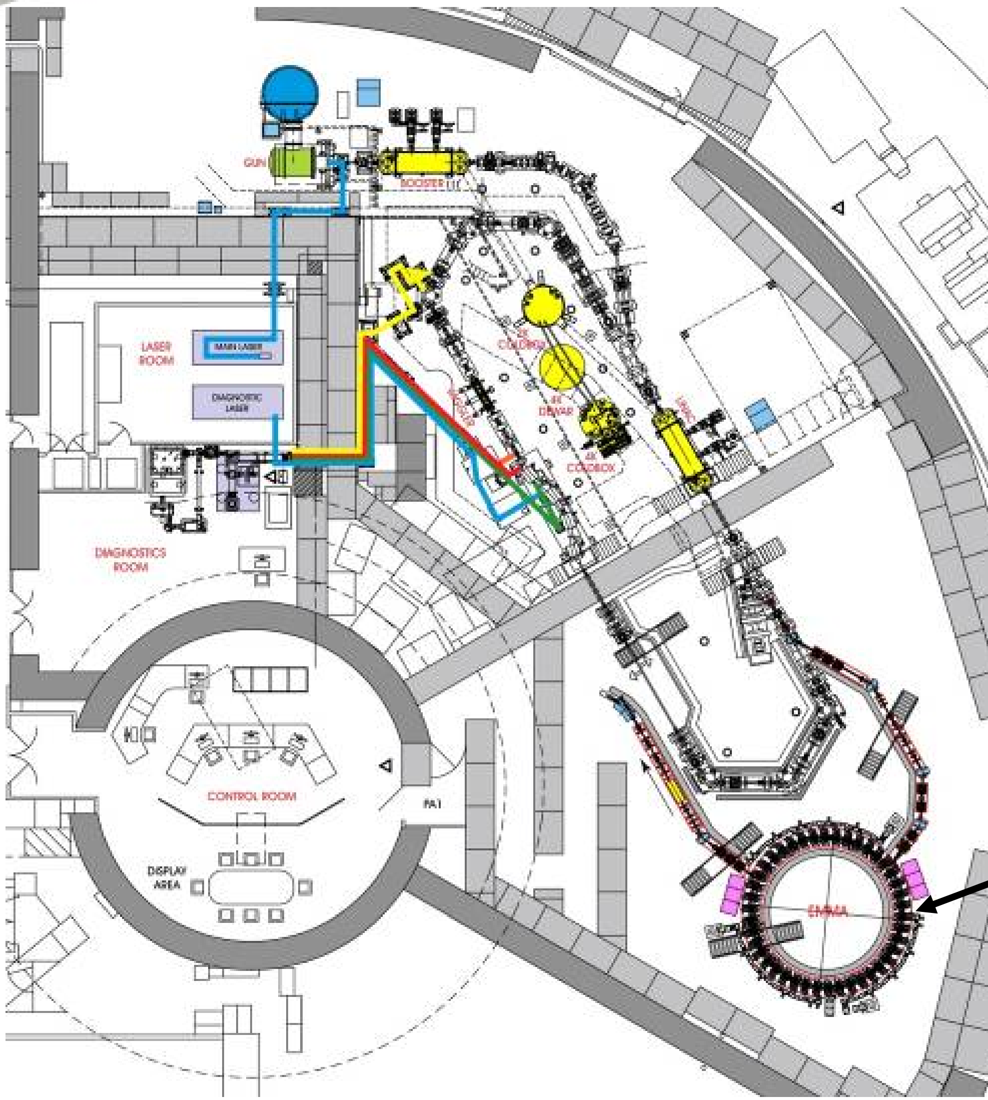
LAYOUT AND LATTICE

ALICE

Accelerators and Lasers In Combined Experiments



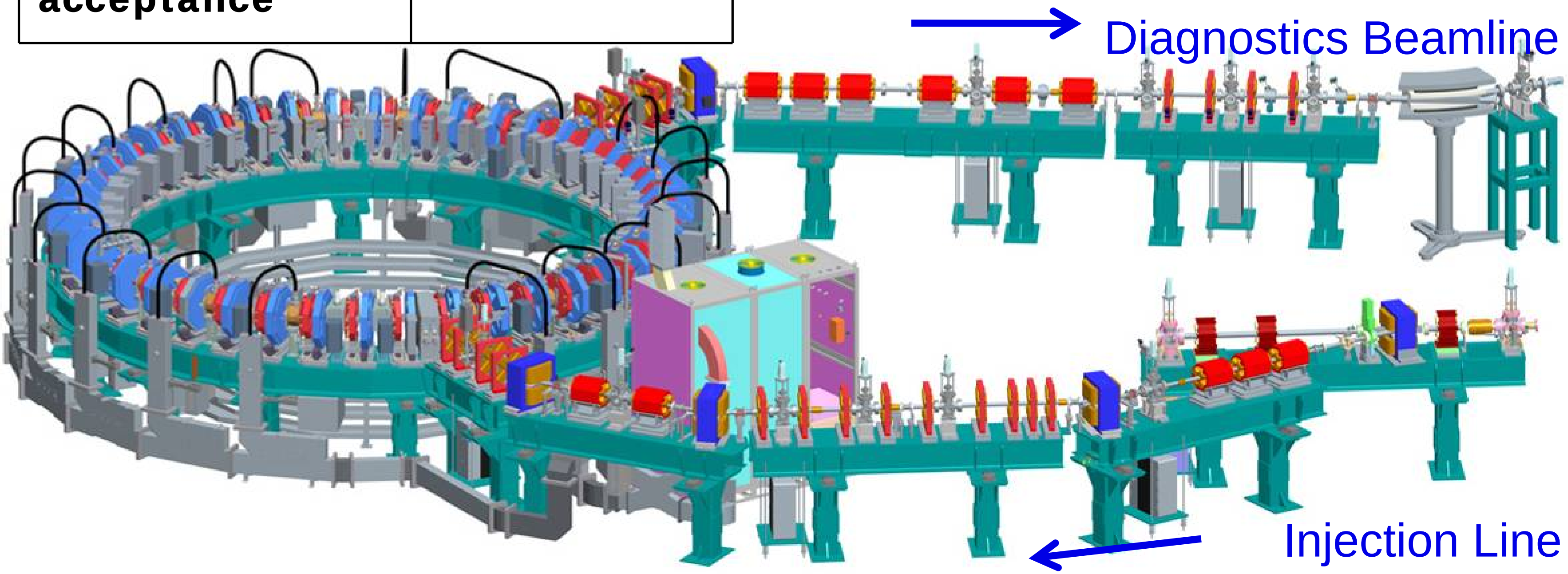
Parameter	Value
Nominal Gun Energy	350 keV
Injector Energy	8.35 MeV
Max. Energy	35 MeV
Linac RF Frequency	1.3 GHz
Max Bunch Charge	80 pC
Emittance	5-15 mm-mrad

EMMA

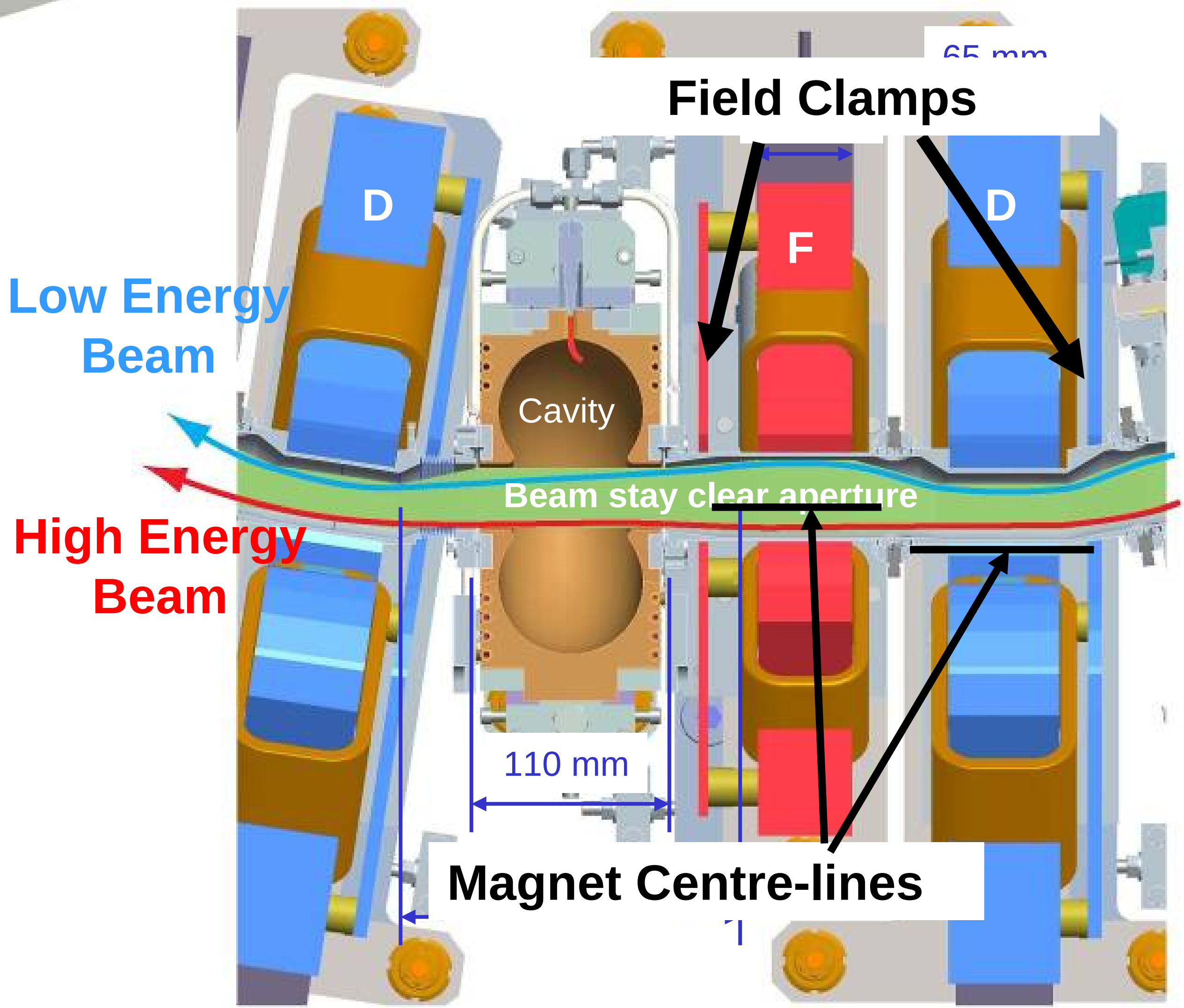
EMMA Parameters & Layout

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

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

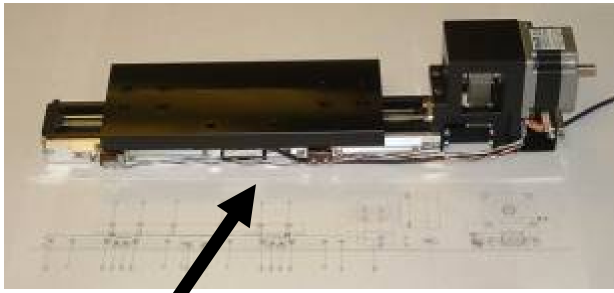


EMMA Ring Cell



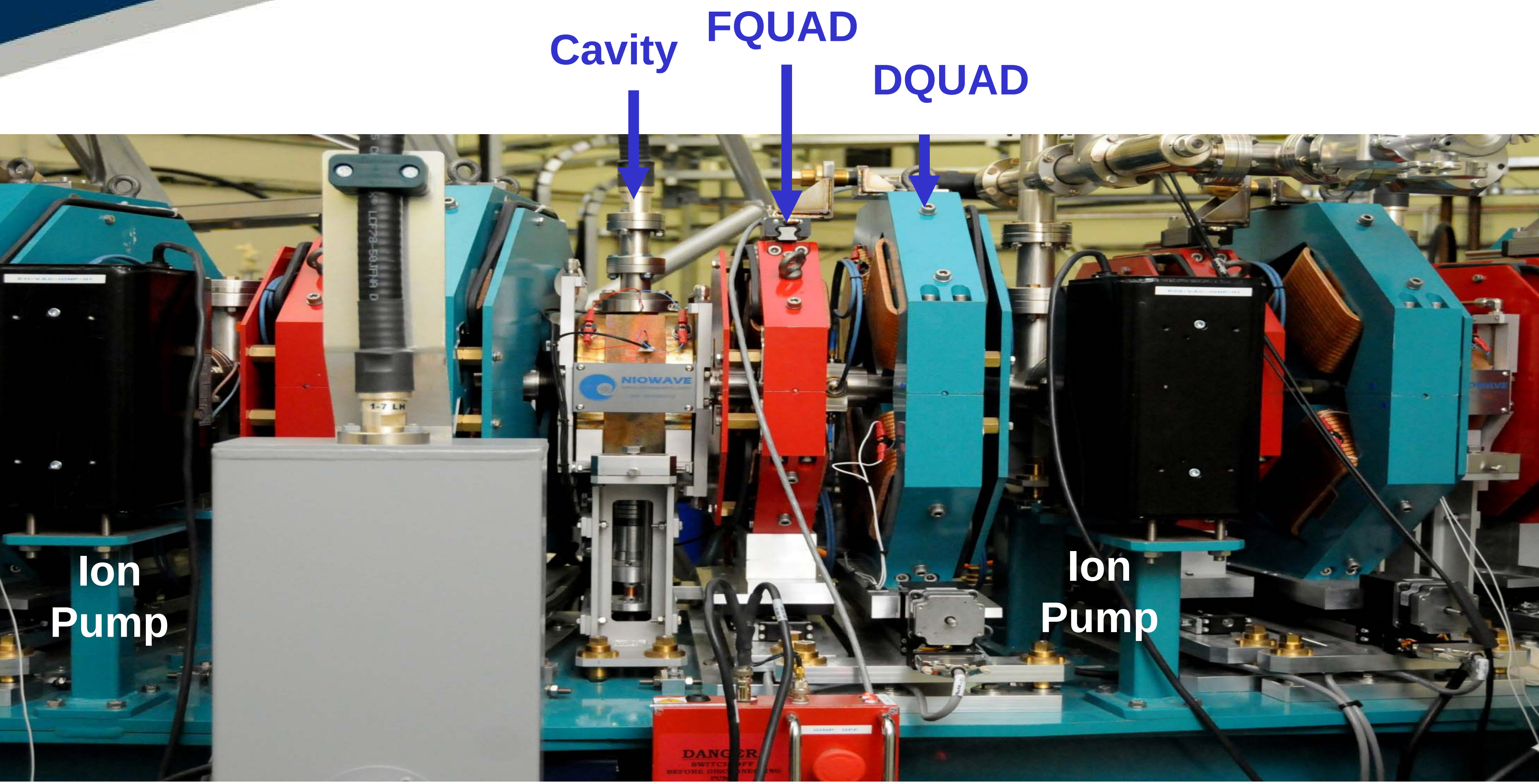
Long drift	210 mm
F Quad	58.8 mm
Short drift	50 mm
D Quad	75.7 mm

42 identical doublets



Independent slides

EMMA Cell



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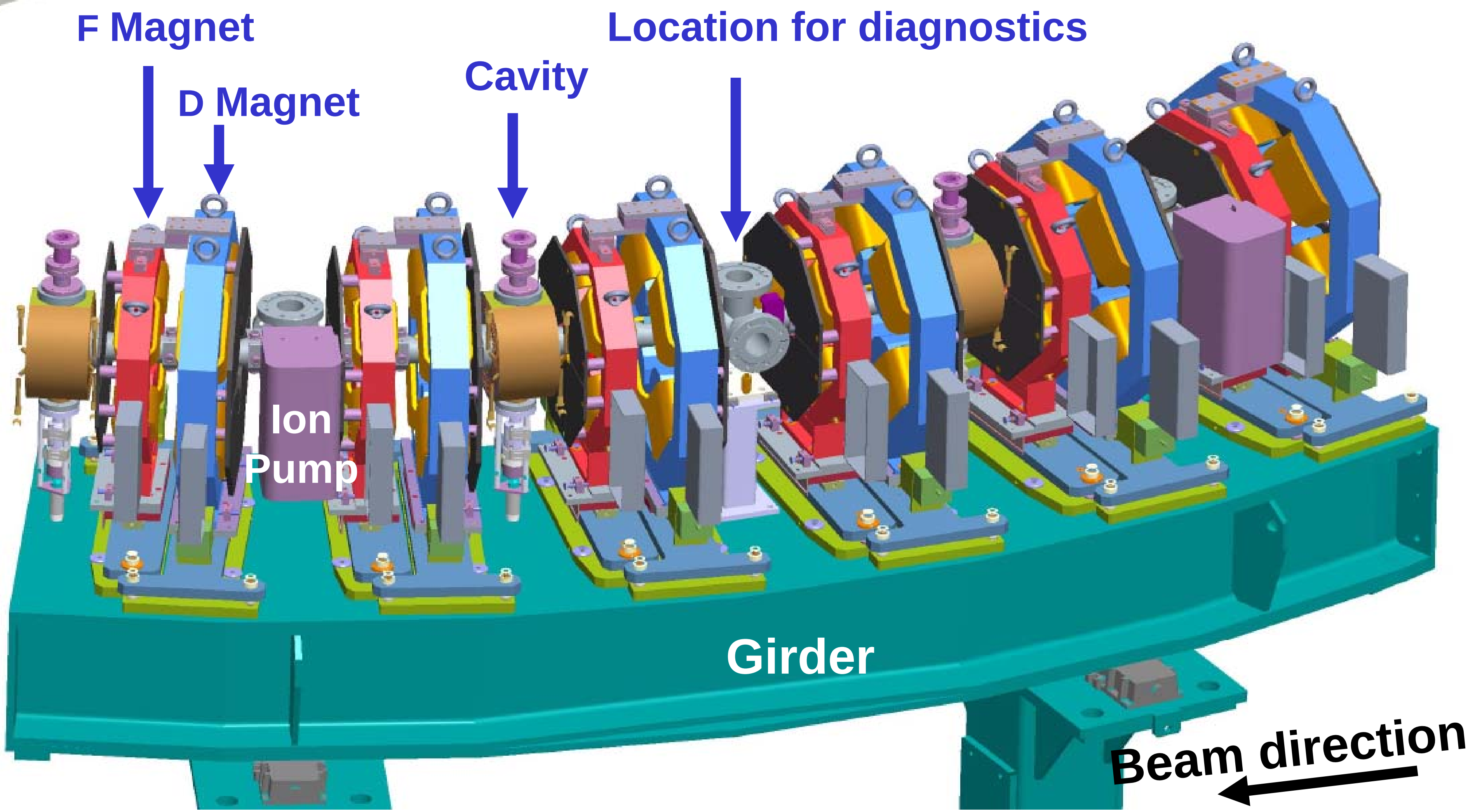
A 6 Cell Girder Assembly

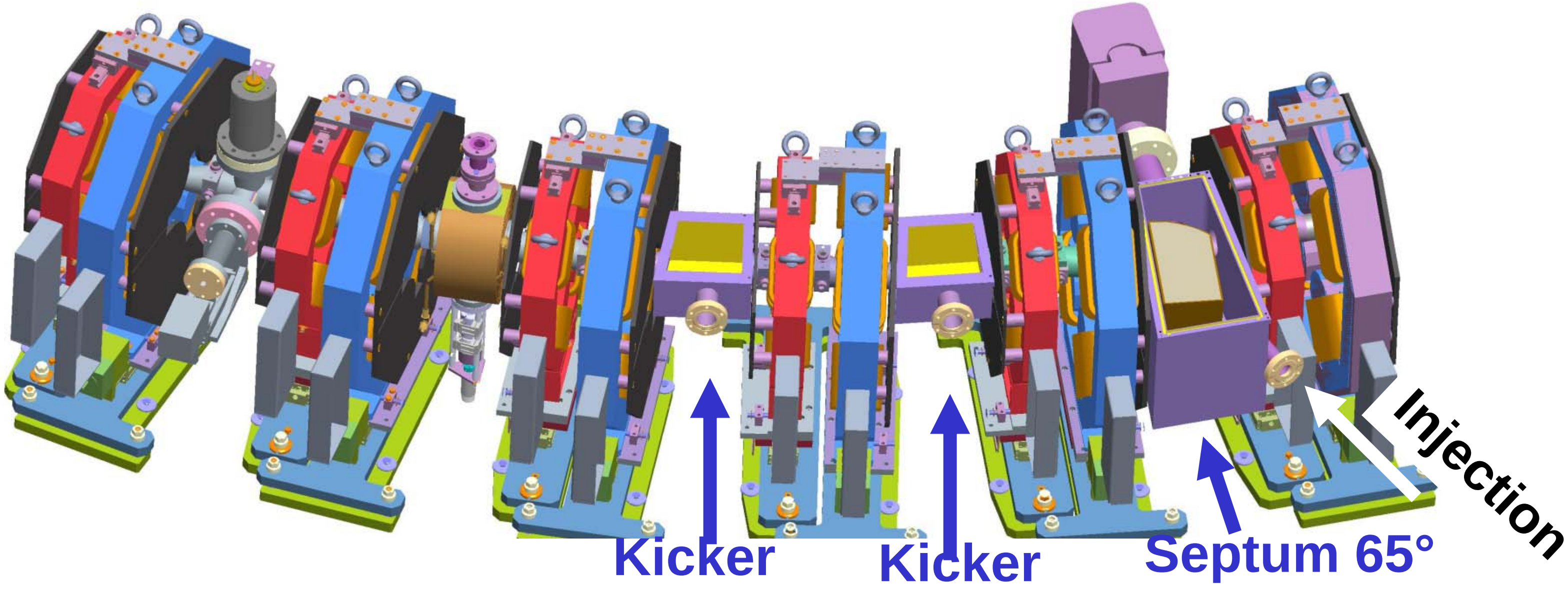


INJECTION

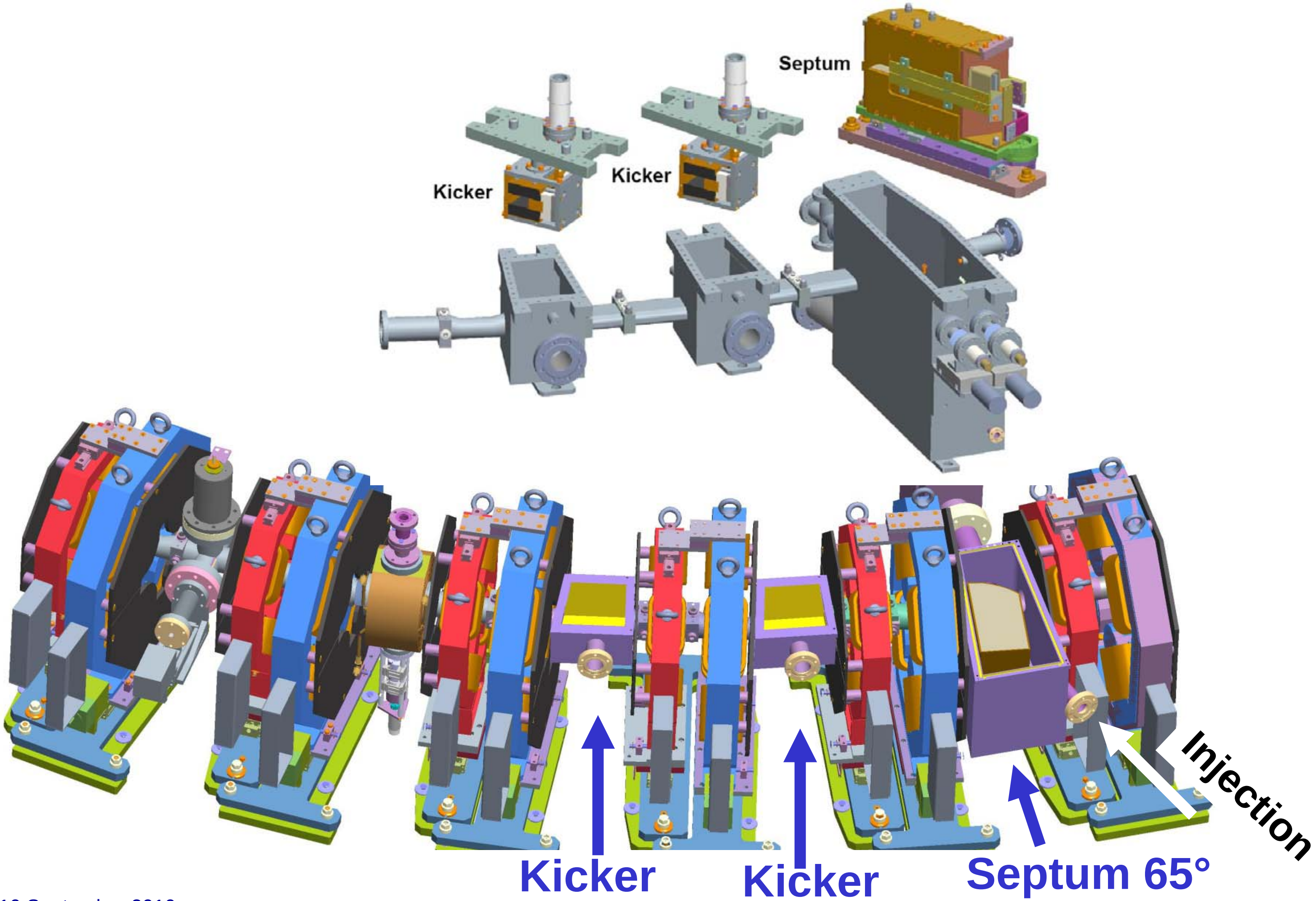
Injection & Extraction

- 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

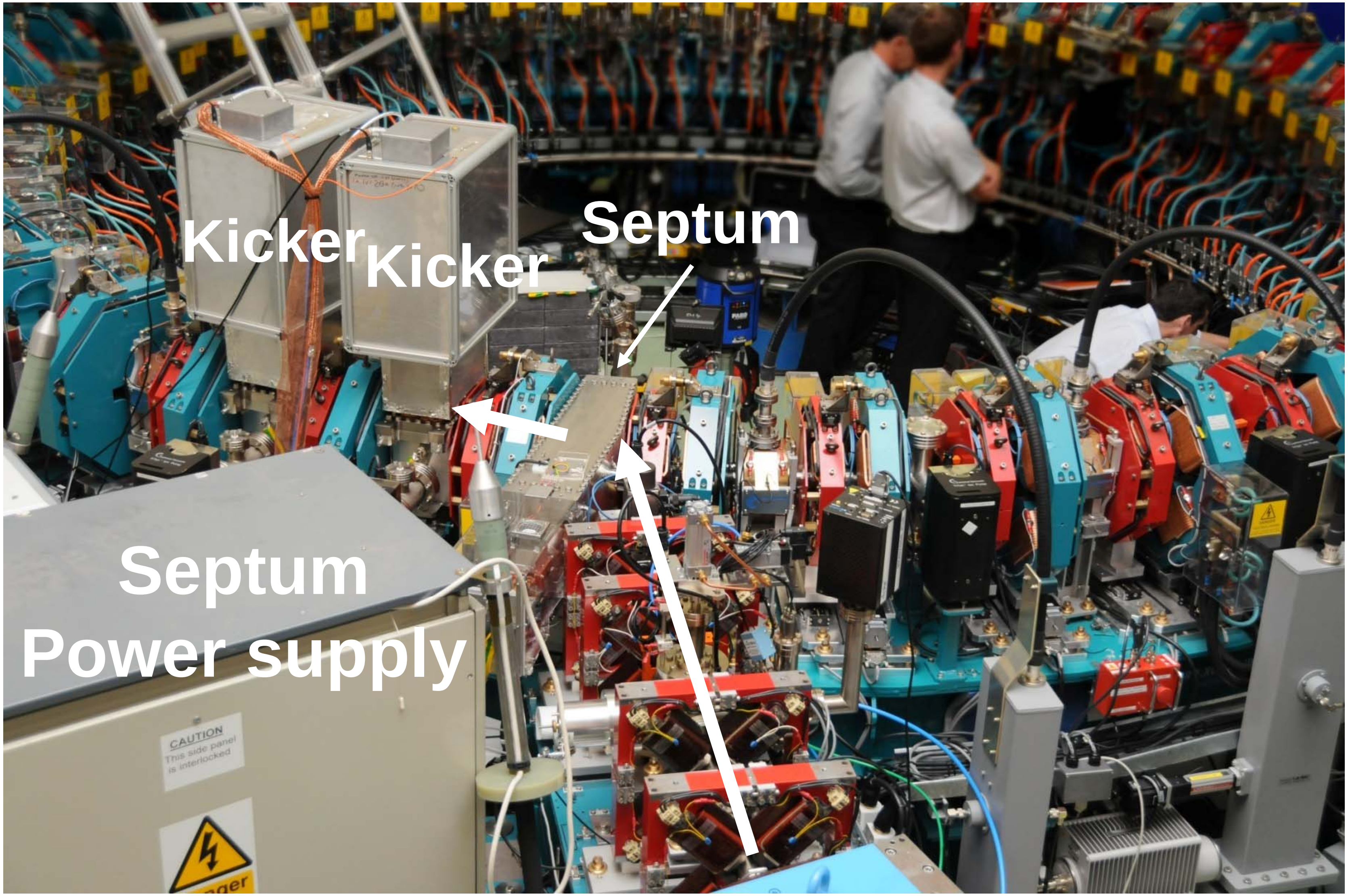
Extensive 3D magnet modelling conducted to minimise the effect of stray septum fields on circulating beam



Injection Region



Injection


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

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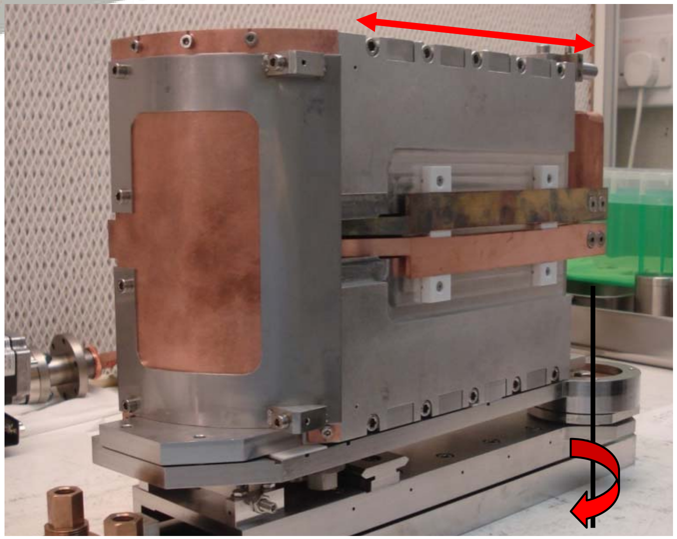
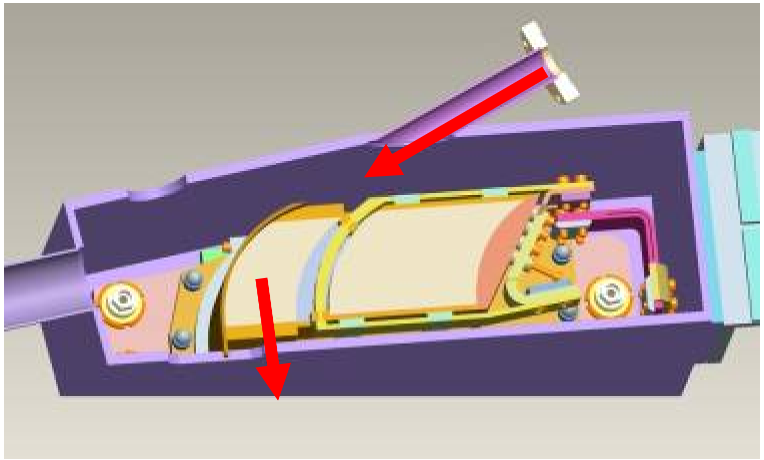
Translation



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**

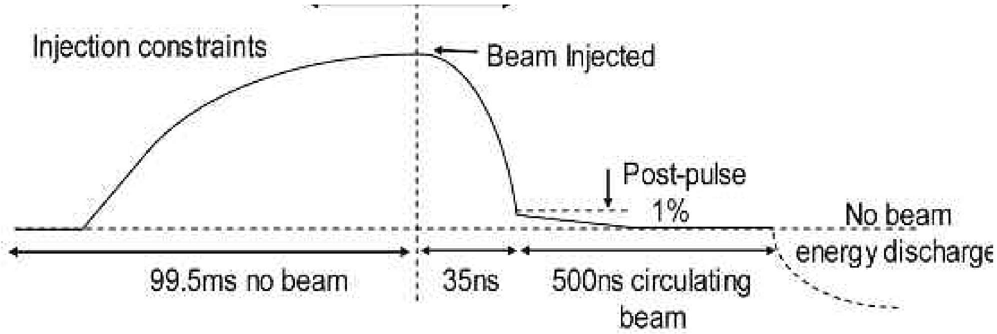
- Inject/Extracts from 10-20 MeV
  For all lattice configurations

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**



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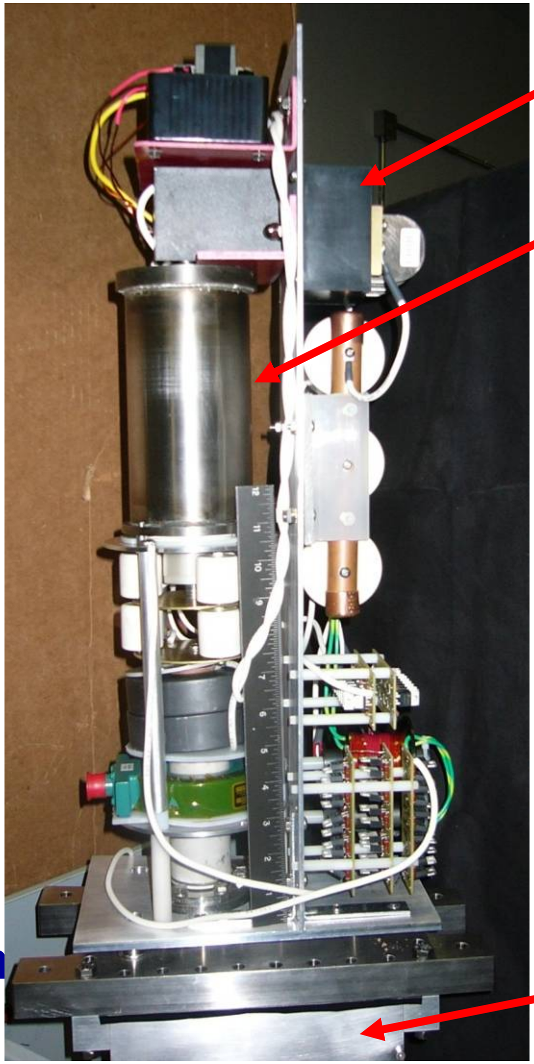


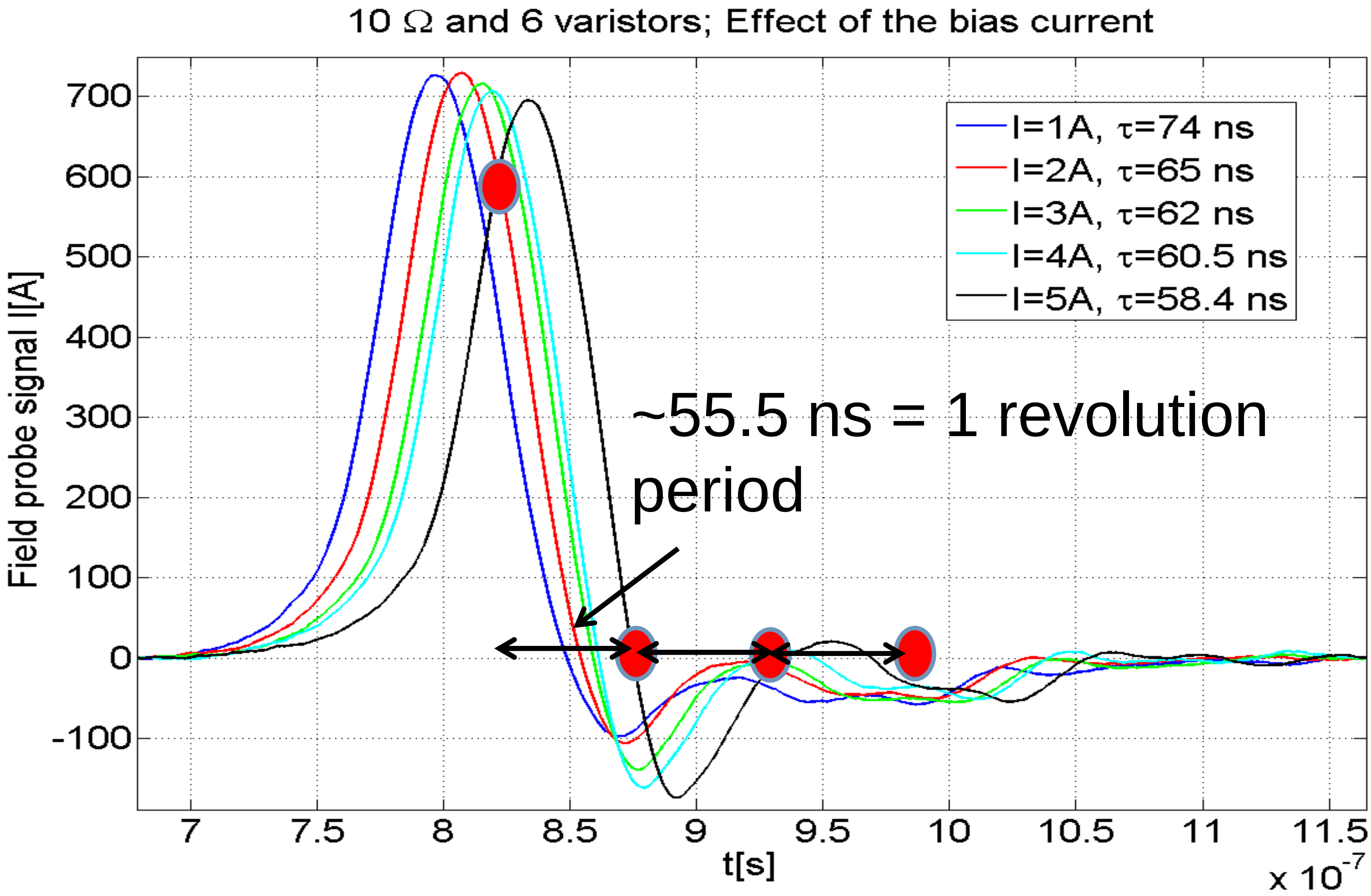
Semiconductor Switch

Magnetic Switch

Magnet

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

Measured Current Pulses from Kicker Magnet

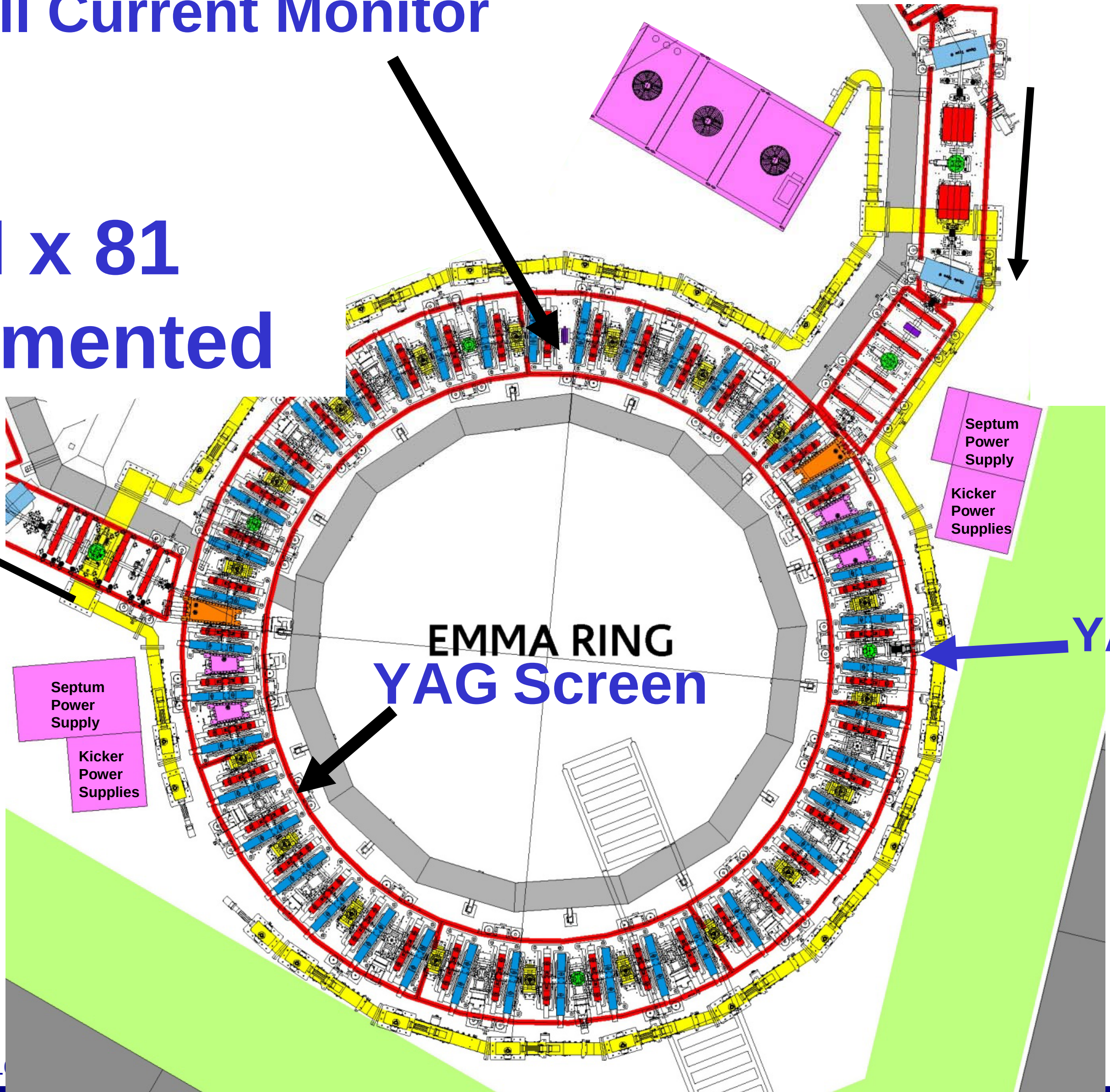


DIAGNOSTICS

EMMA Ring

Wall Current Monitor

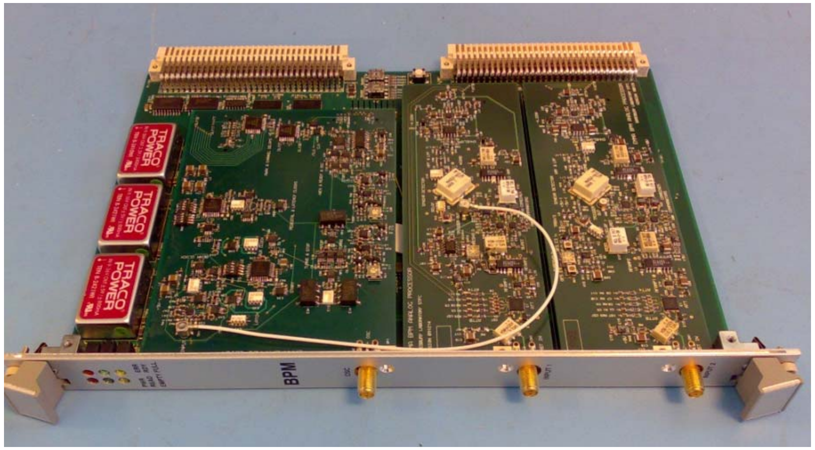
eBPM x 81
½ Instrumented



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

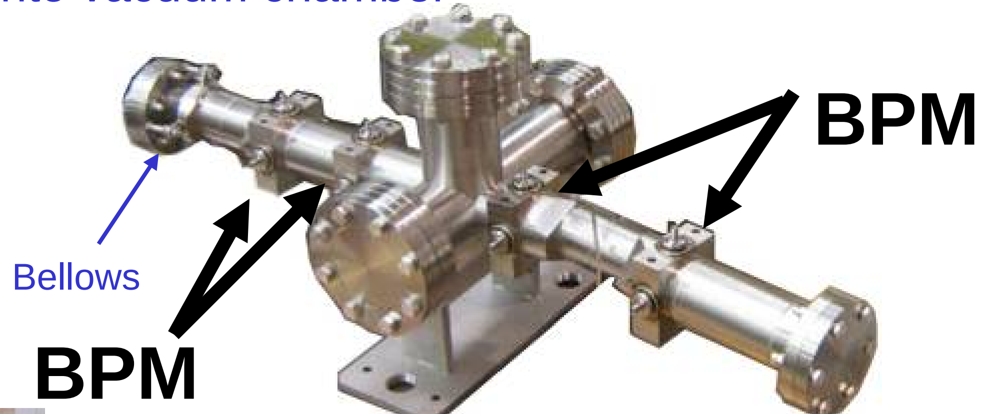


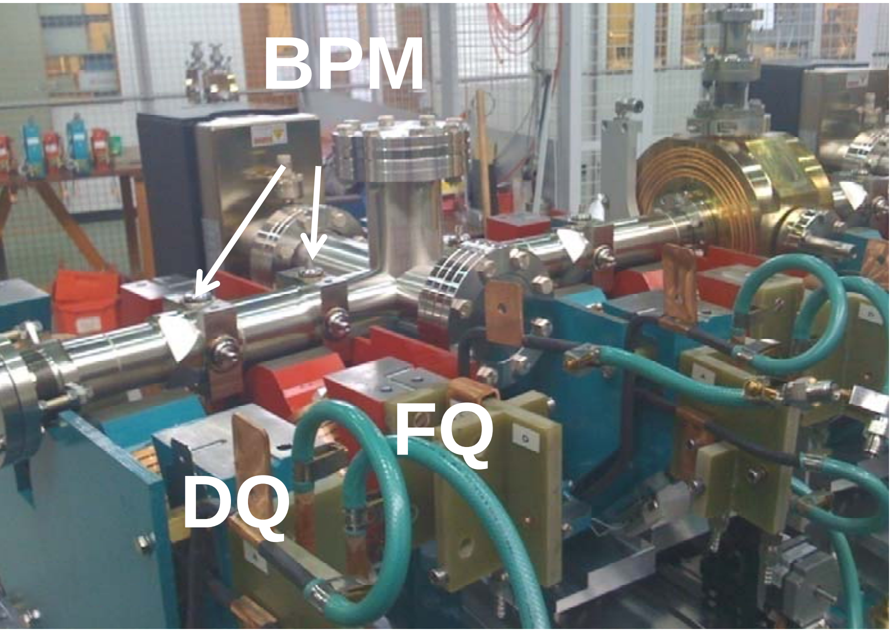
Detector card

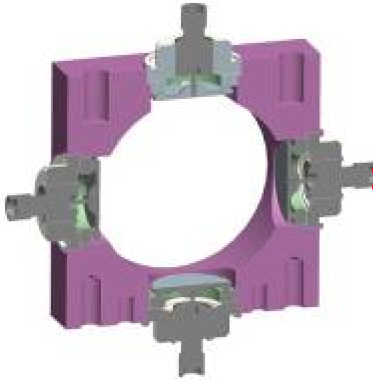
Vacuum chamber & BPM

- Standard vacuum chambers each covering 2 cells

4 x BPM bodies, accurately machined and welded into vacuum chamber





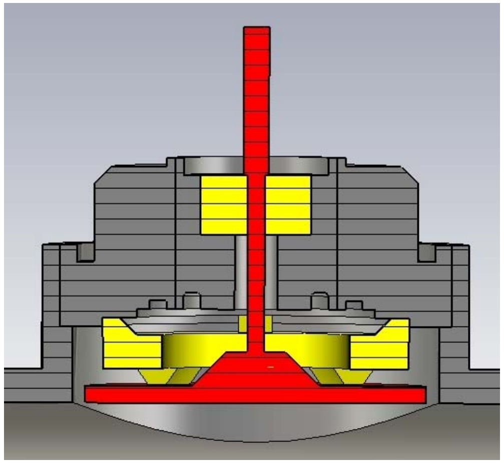


± 25μm r.m.s. resolution required

BPM block cross-section showing pickups

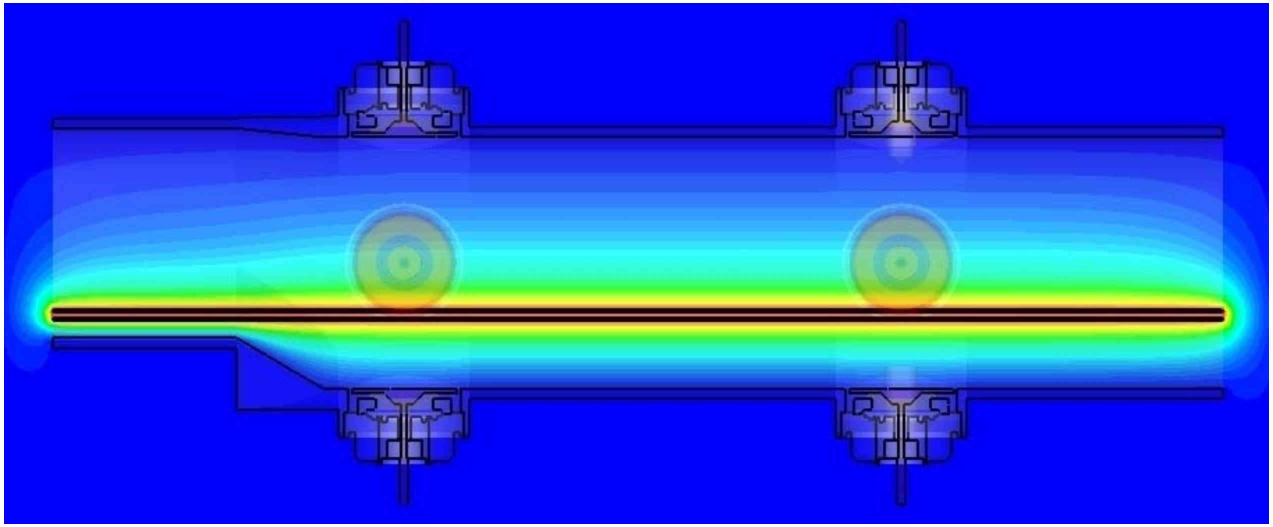
Electrostatic potentials with offset wire

Transverse cross section at BPM plane



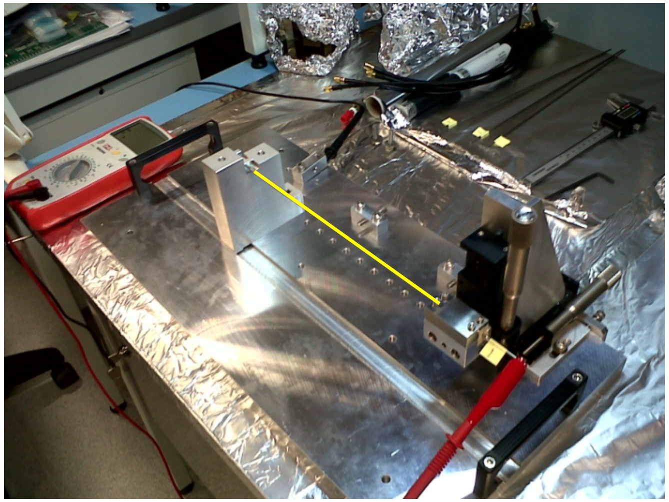
BPM cross section:
Housing: SS-304
Buttons: Inconel-X750
Spacers: Cordierite-447

longitudinal cross section (top view)

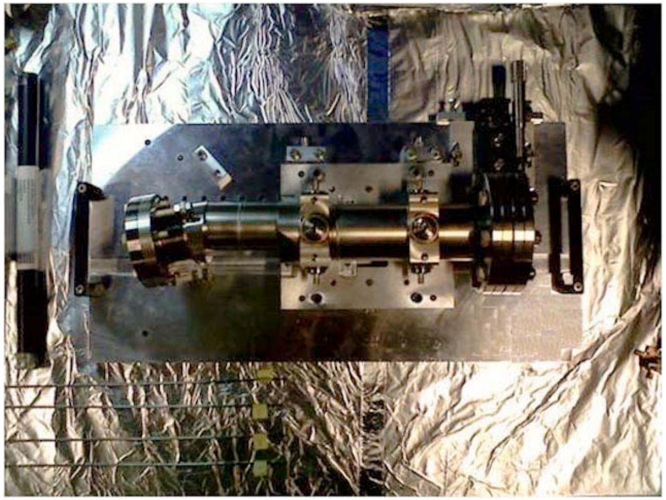


Bench testing: “stretched wire”

Cylindrical wire



Double BPM Vessel



Measurement set-up

Precision test bed
Micrometer driven
BPM vessels can be added without disturbing “wire”

RADIO FREQUENCY

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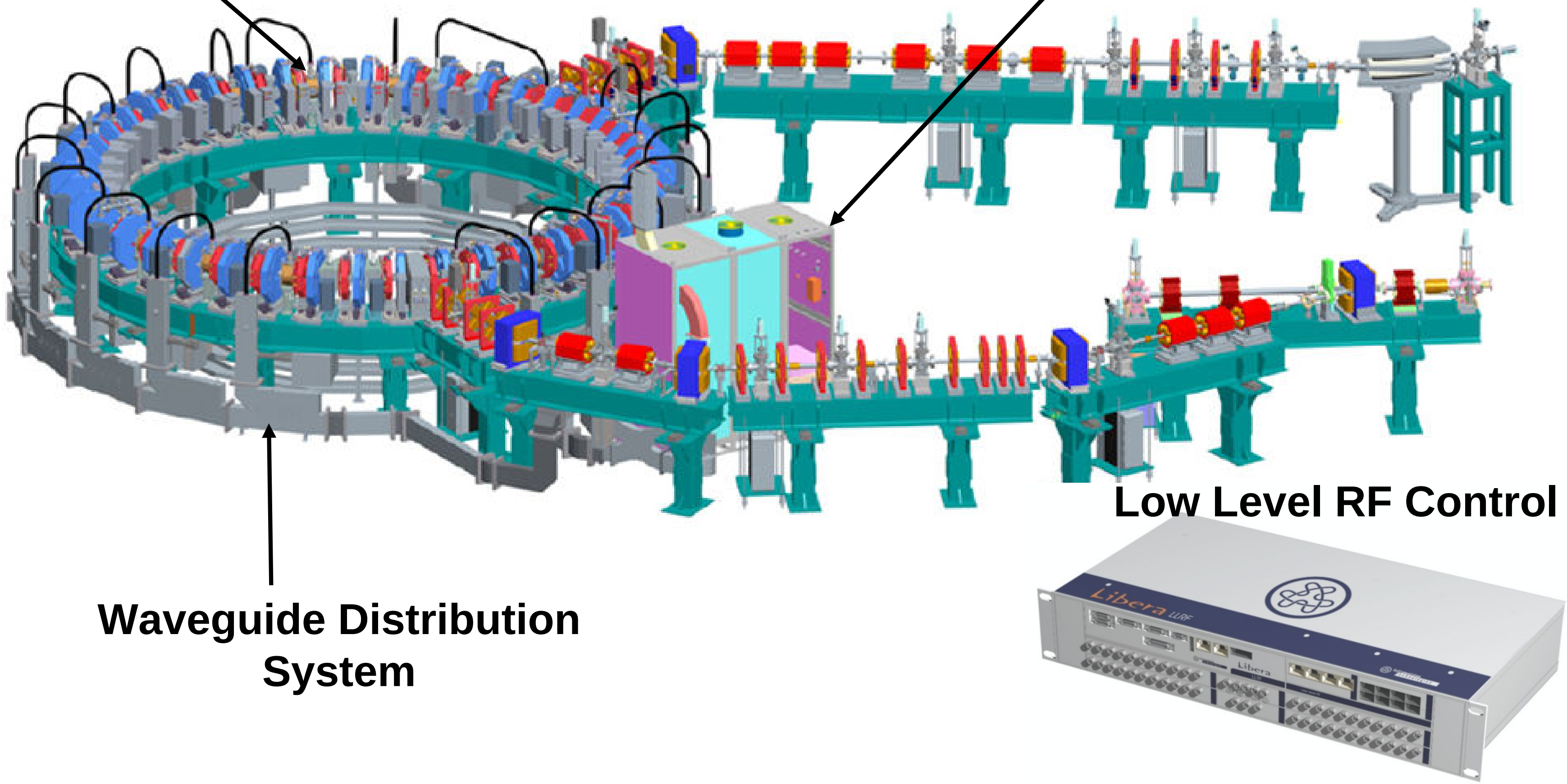
RF Requirements

- Voltage:
  - 20 - 120 kV/cavity essential, based on 19 cavities
- Frequency:
  - 1.3 GHz, compact and matches the ALICE RF system
  - Range requirement 5.5 MHz
- Cavity phase:
  - Remote and individual control of the cavity phases is essential

RF System Overview



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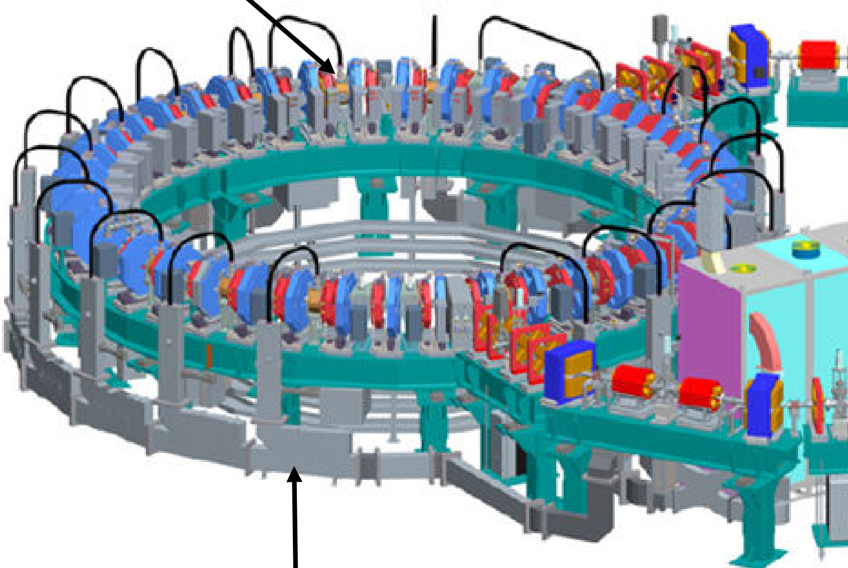
RF System Overview

RF Cavities

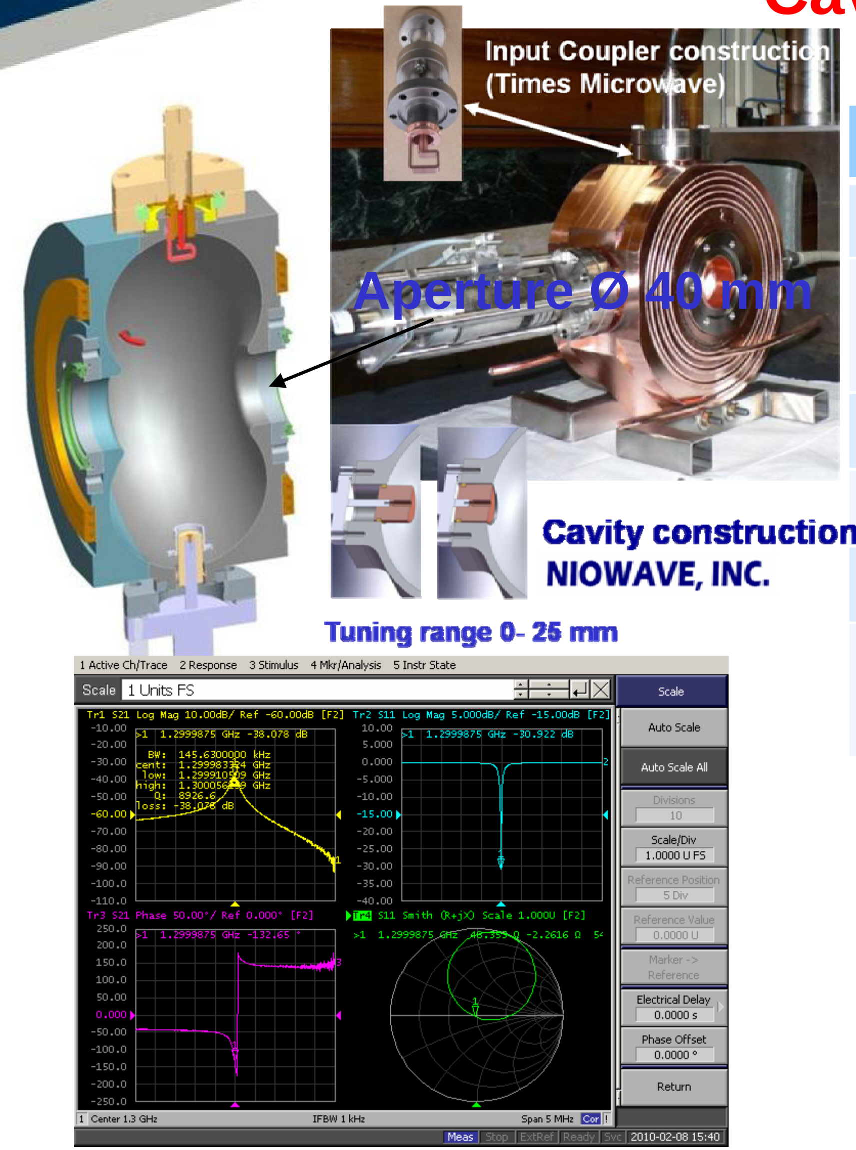


Waveguide Distribution System

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

Low Level RF Control

Cavity Design & Specification

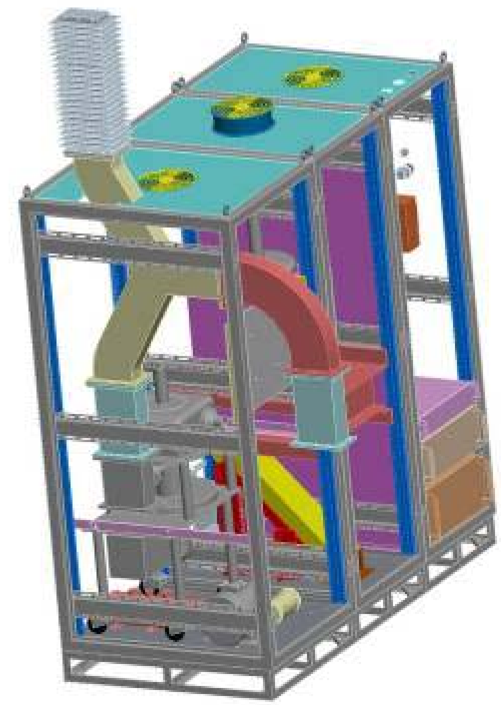


Parameter	Value
Frequency (GHz)	1.3
Shunt Impedance (MΩ) Realistic (80%)	2.0
Qo	20,000
R/Q (Ω)	100
Tuning Range (MHz)	-4.0MHz to +1.5MHz
Ptot incl 30% Overhead (kW)	90

- 20 cavities delivered by Niowave
- Q_0 typically > 19000

RF Source

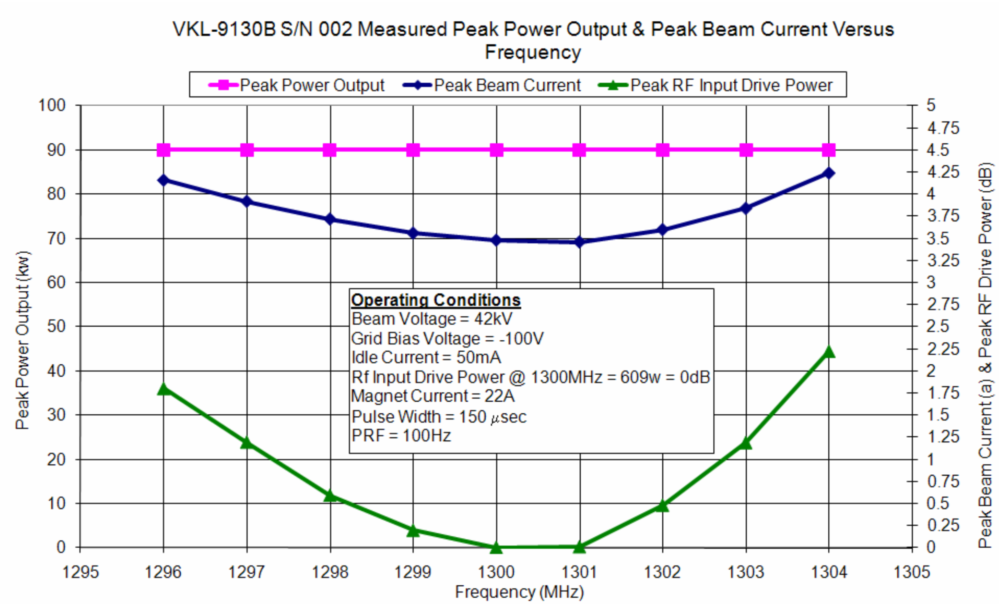
- A single 100kW (pulsed) IOT supplying the 19 RF cavities distributed around EMMA
- VIL409 high power RF amplifier system in 3 racks



CPI 100 kW (pulsed) IOT

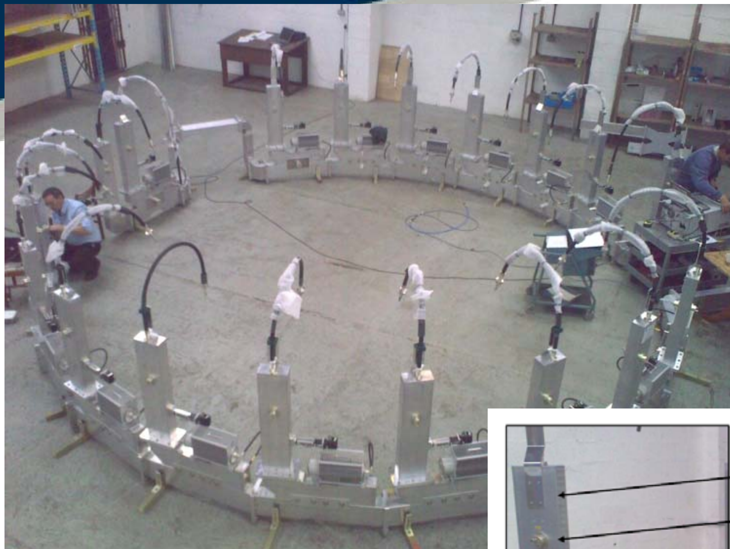
RF Source

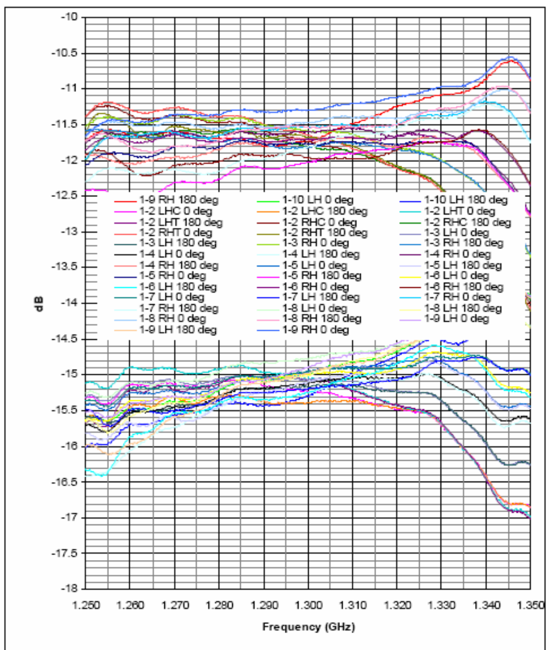
- A single 100kW (pulsed) IOT supplying the 19 RF cavities distributed around EMMA
- VIL409 high power RF amplifier system in 3 racks
- Tested to ensure required bandwidth
- Delivery was completed in July 2009
- Thorough software and system tests completed at Daresbury in September 2009

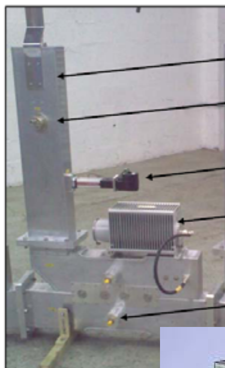


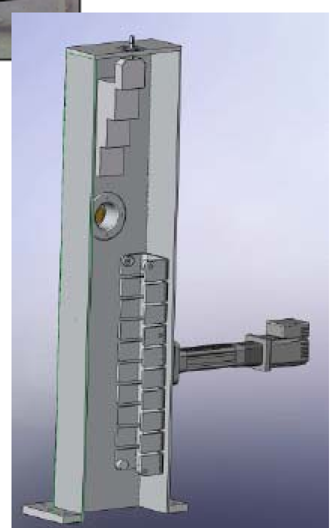
CPI 100 kW (pulsed) IOT

RF Distribution









Distribution system developed by Q-Par Angus (UK).

- Acceptance tests demonstrated:
  - 196 ° of phase shift achievable for each RF distribution, with a resolution of 0.1°
  - <0.2 dB variation measured over operating frequency
  - Isolation tests between ports showed better than 42 dB (typically 50 dB)
  - measurements of the forward and reverse directional couplers showed a coupler directivity of greater than 41 dB (specification >40 dB).

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

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- **Instrumentation Technologies Libera LLRF system provides**
  - Initial cavity setting conditions
  - Control of the cavity amplitude and phase to ensure stable contro… the acceleration
- **Diagnostic monitoring**
  - Cavity pick-up loops
  - Forward and reverse power monitoring to each cavity
  - IOT power levels before and 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 frequ.

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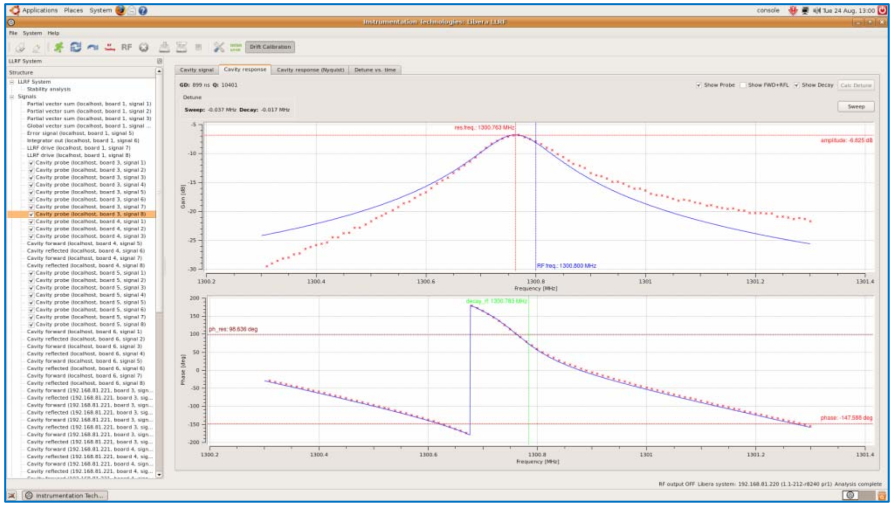
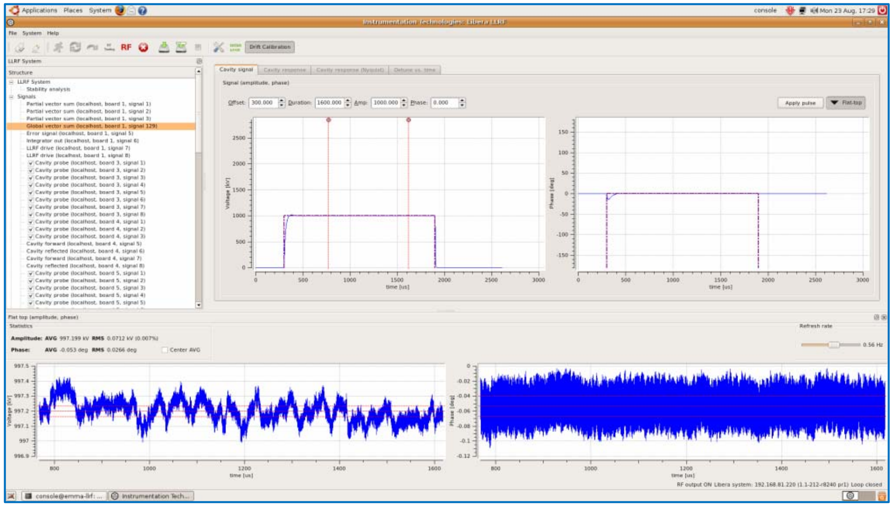
First high power commissioning

Started17/8/10

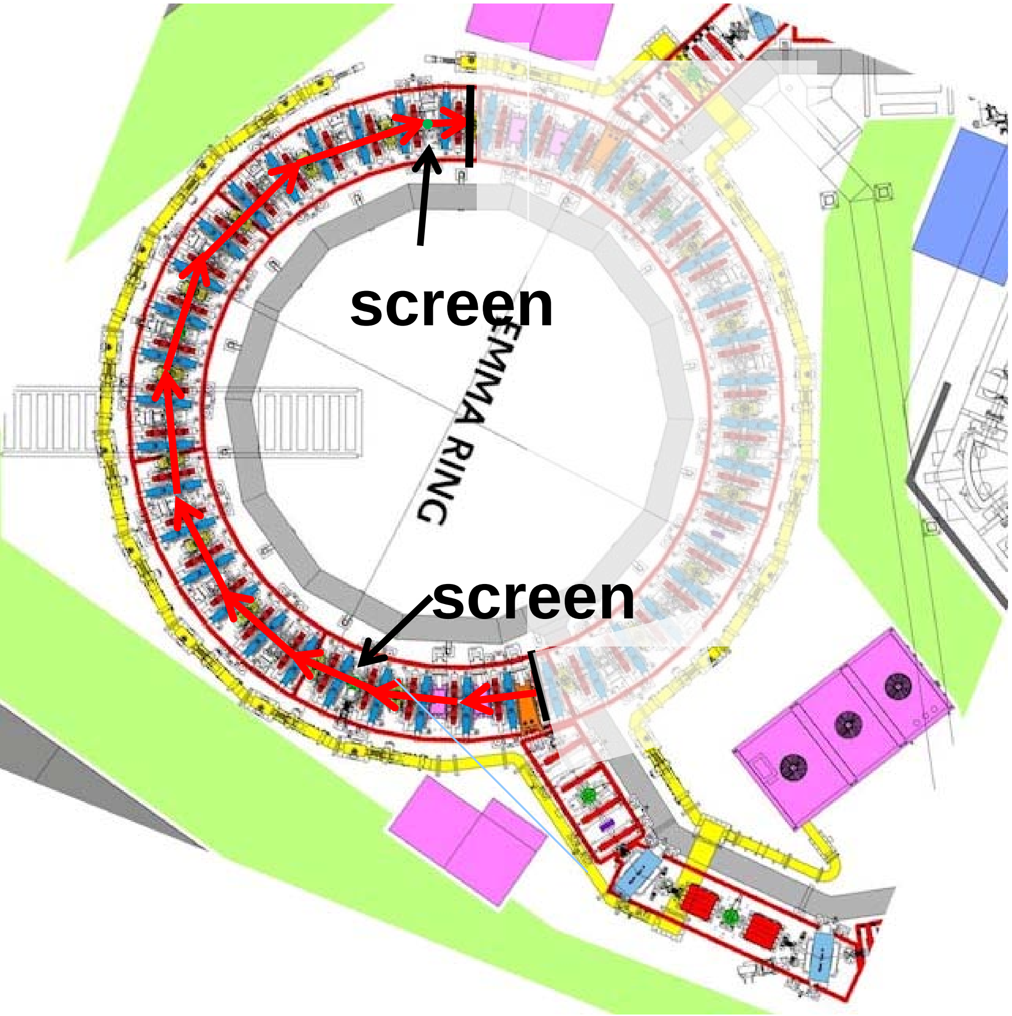


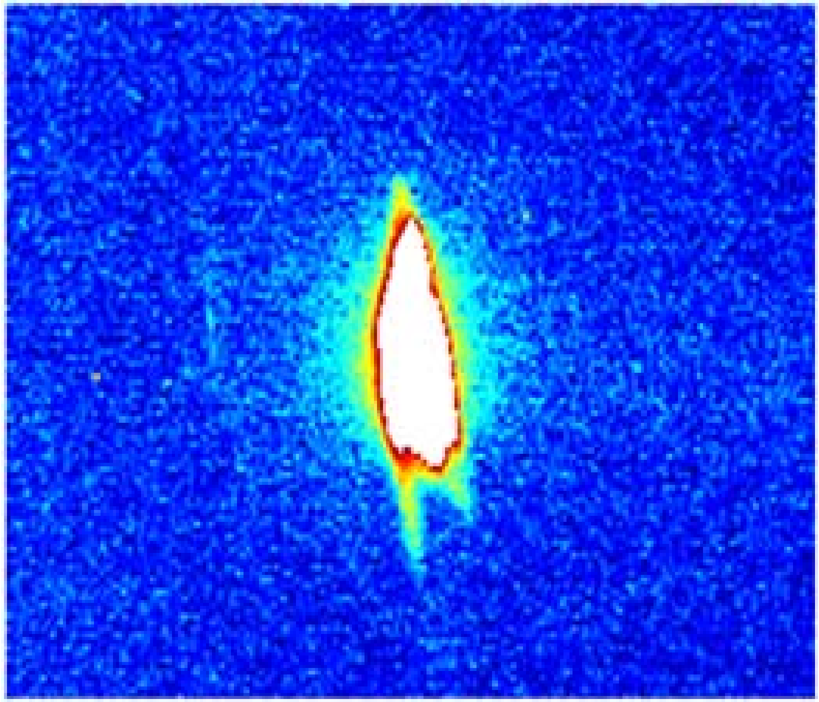


- Excellent cavity control stability (up to 40 kW)
  - – 0.007% rms voltage
  - – 0.027º phase
- Phase synchronisation with ALICE has not yet been demonstrated

BEAM COMMISSIONING

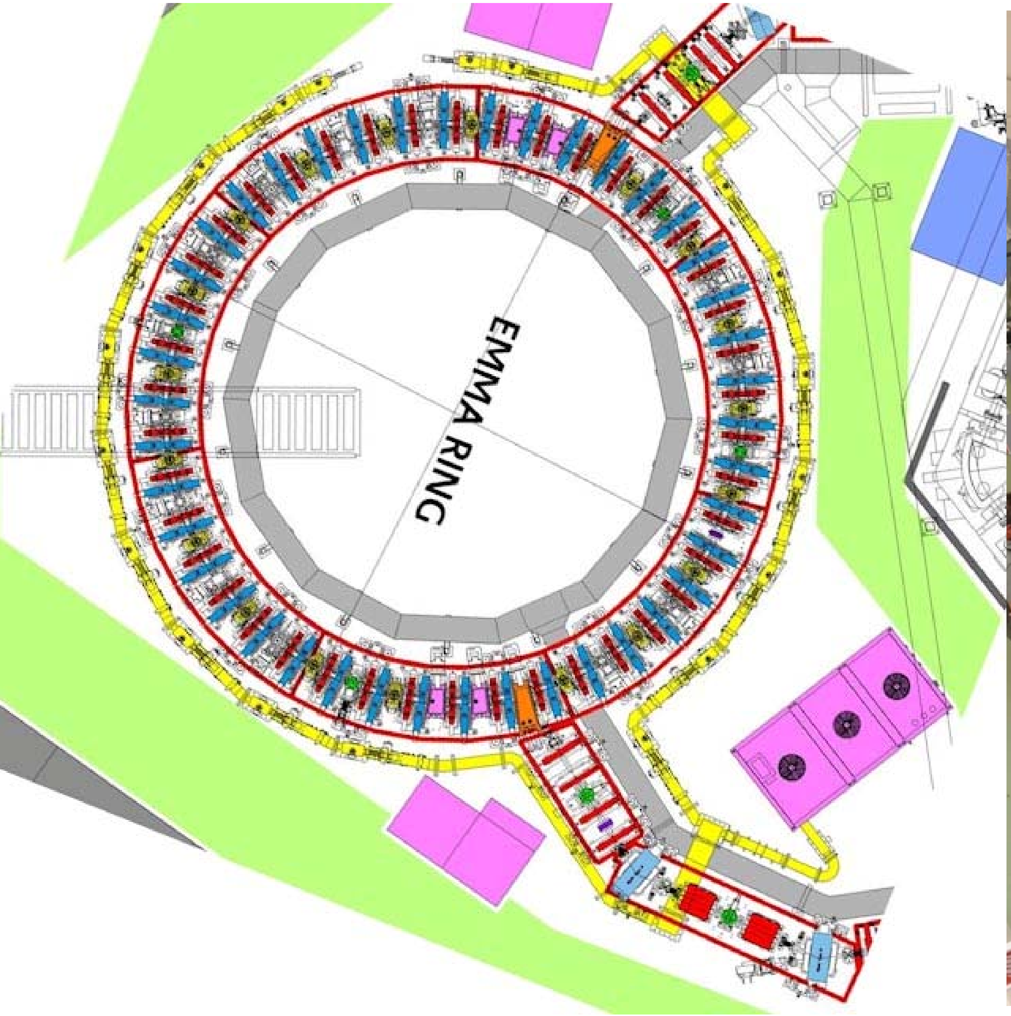
4 Sector Commissioning

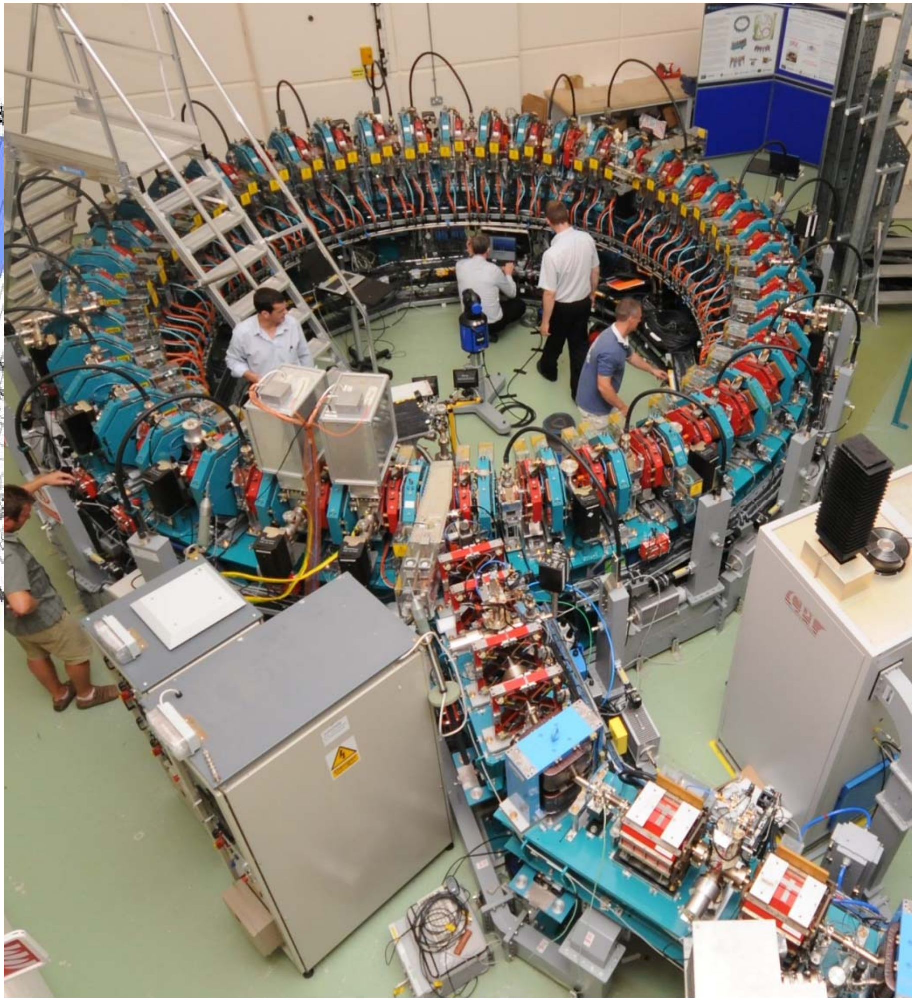




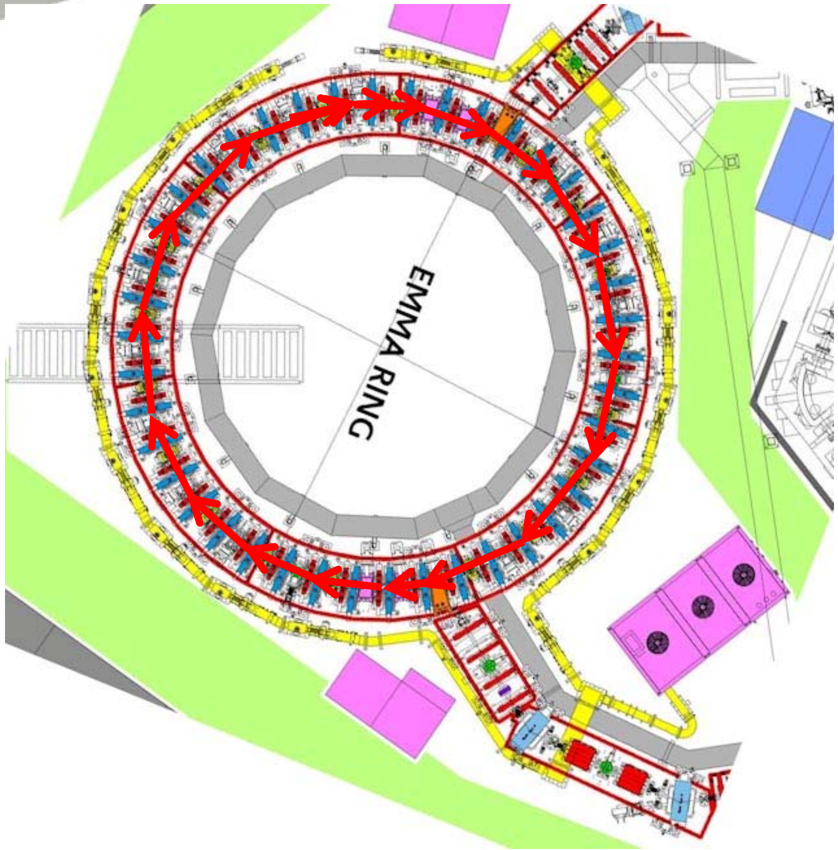
Beam image on screen
At the end of 4 sectors
22 cells
22:37 on 22.6.2010

Realisation of EMMA August 2010

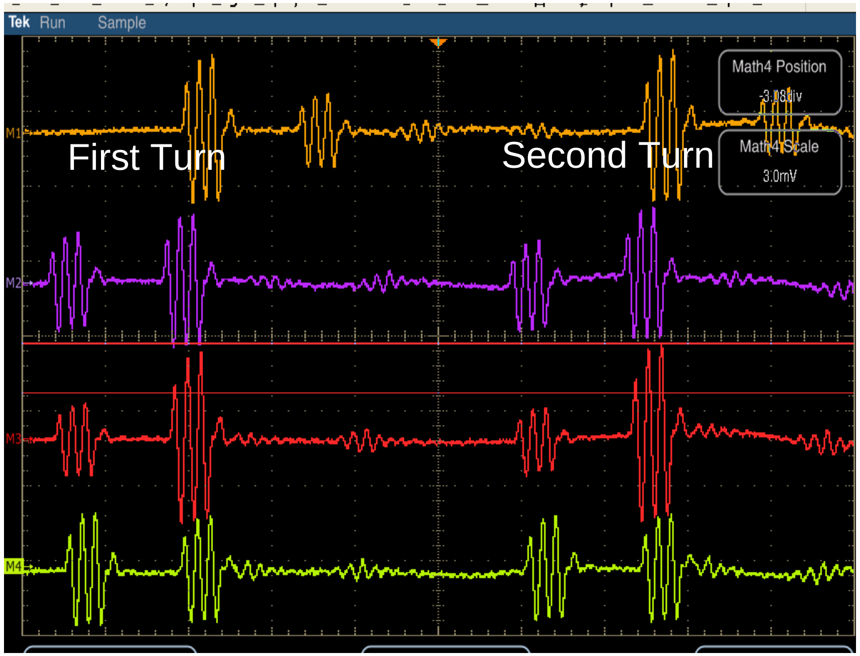




Complete Ring

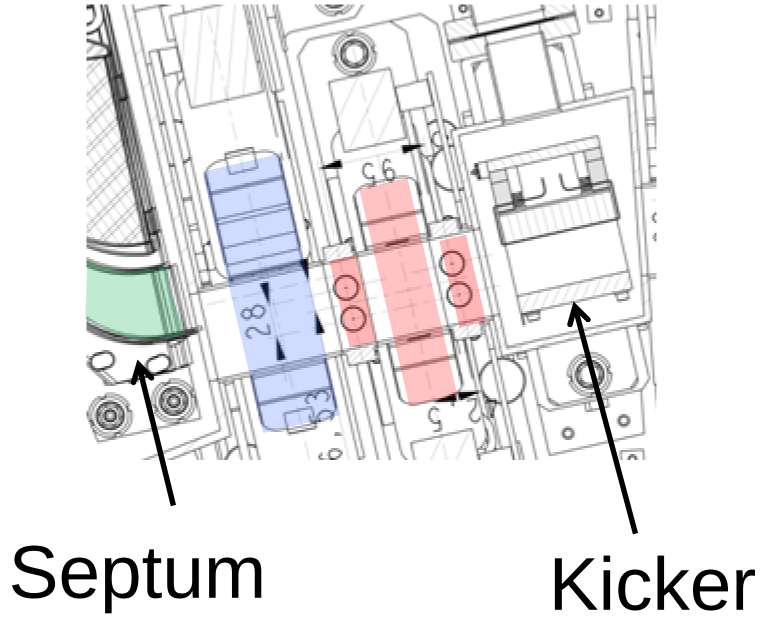


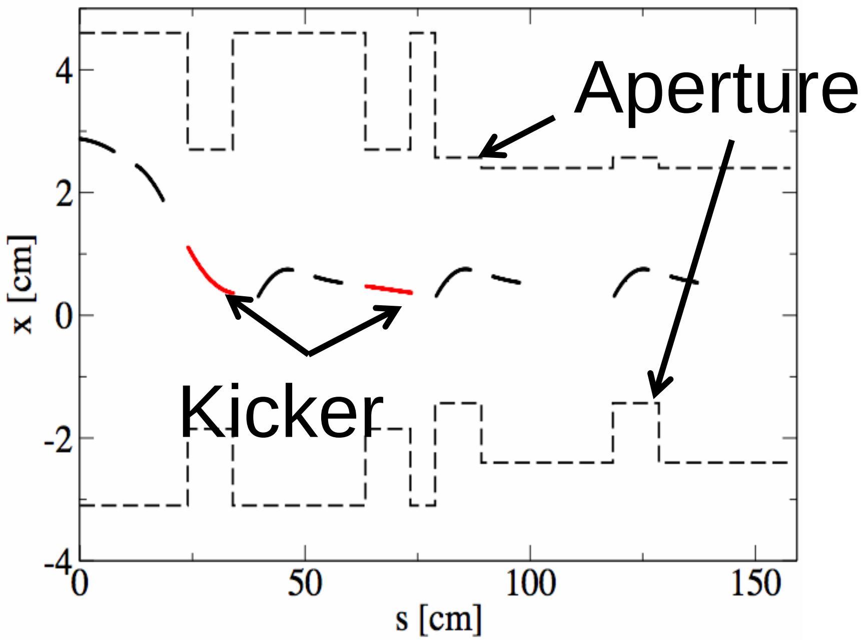
4 BPMs on scope

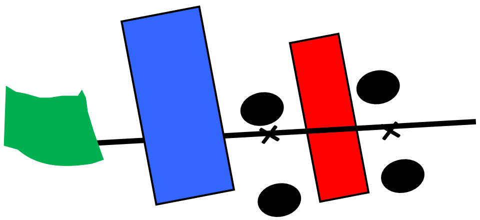


First circulated beam 16th Aug 2010

Optimisation of injection





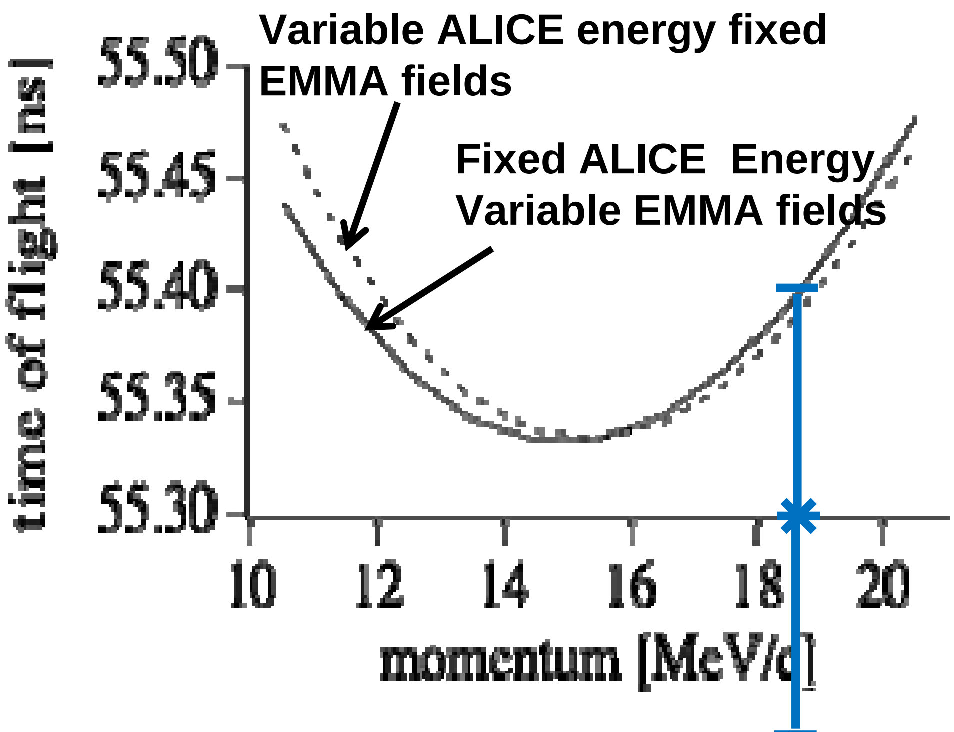


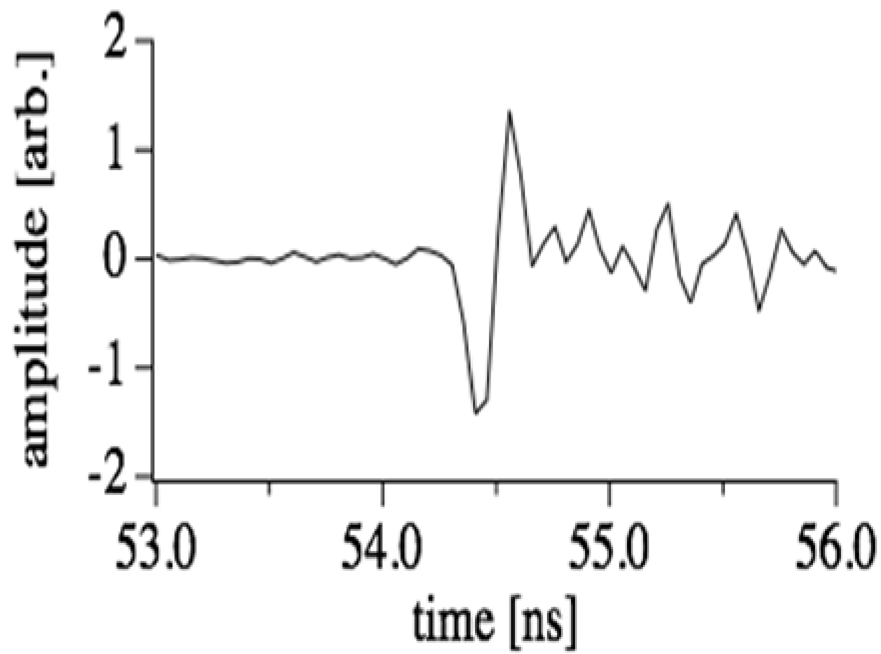
Angle at end of SEPT determined from BPM offsets with quads OFF

- Use code to determine kicker strengths found 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, = 55.3+/-0.1 ns

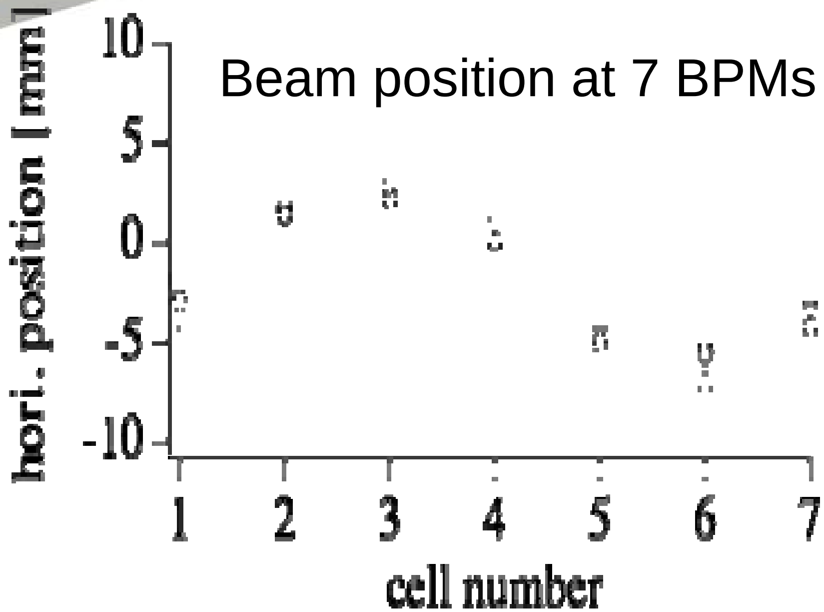


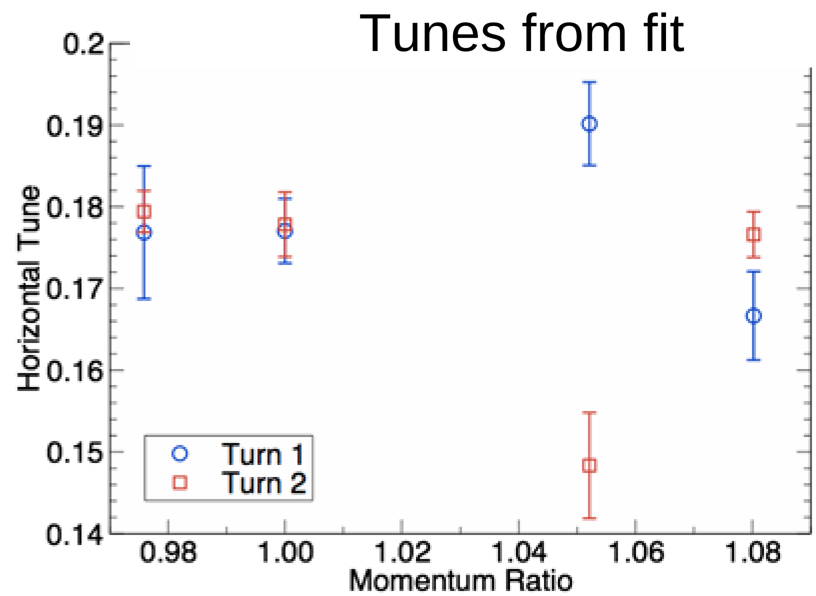


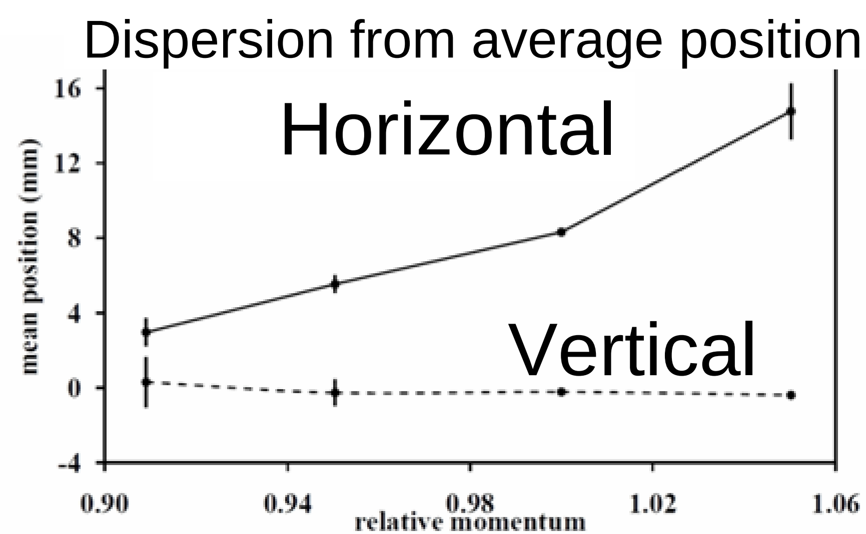
- Time of flight is determined by path length, not by speed
- Use different magnetic strength as easier than retuning ALICE injector

- 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)

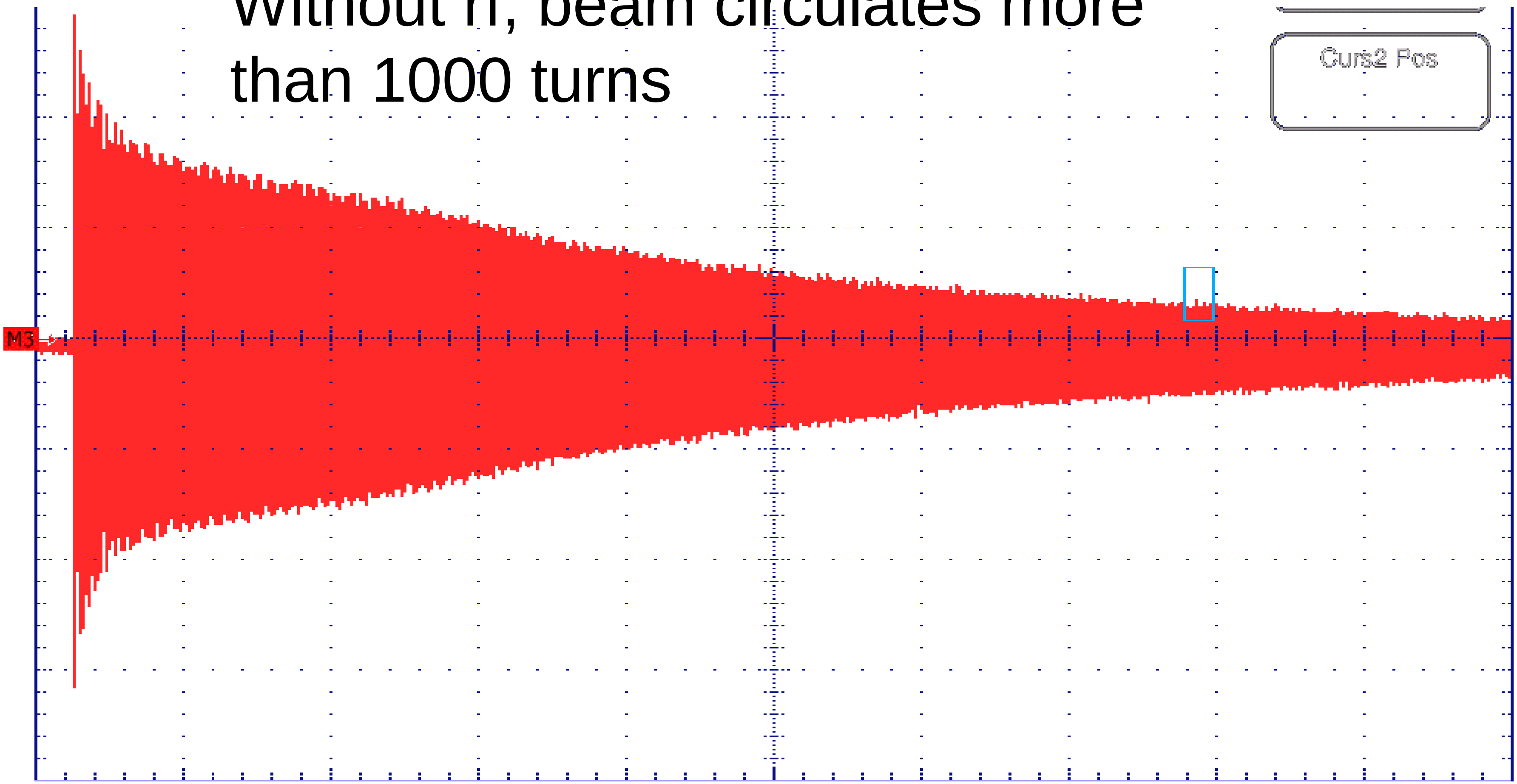
Horz disp =82mm

Vert. disp. = 3mm

Consistent with predicted values

Coasting beam no RF

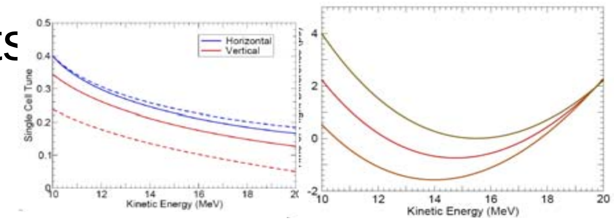
Without rf, beam circulates more than 1000 turns



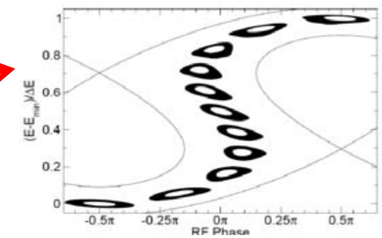
NEXT STEPS

Next Steps

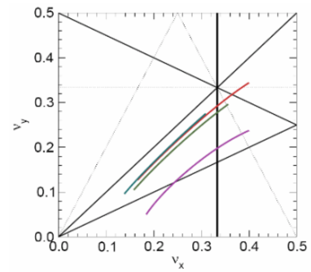
- Commissioning now
  - LLRF system fully functional and tested at ALICE & off frequency
  - Verification of successful accelerator, inside/outs



- 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 ....

MILESTONES

Science & Technology Facilities Council

BASROC CONFORM

Milestones

Project start	Apr 2007
Design phase	Apr 2007 – Oct 2008
Major procurement contracts	May 2007 – Aug 2009
Off line build of modules	Oct 2008 – 15th Jun 2010
Installation in Accelerator Hall	Mar 2009 - Sep 2009
Test systems in Accelerator Hall	Jul - Oct 2009
1st Beam down the Injection line	26th Mar 2010
1st Beam through 4 sectors	22nd Jun 2010
1st Circulating beam in EMMA	16th Aug 2010
1st Accelerated beam in EMMA	**Sep 2010 *********
ALICE & EMMA shutdown	Oct 2010
EMMA Experiments	Jan 2010 – Mar 2011
UK Basic Technology Grant completion	Mar 2011

SUMMARY

Summary

- **Design and construction phase of the project is complete**
- **Commissioning of the full ring is underway:**
  - Many 1000s of turns at fixed energy
  - Time of flight measurements have been measured at various quadrupole settings
  - The LLRF system is commissioning is at an advanced stage and ready for operating to show evidence of acceleration
  - Next start detailed characterisation of the accelerator

key aim is to:-

Verify this new concept works. 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