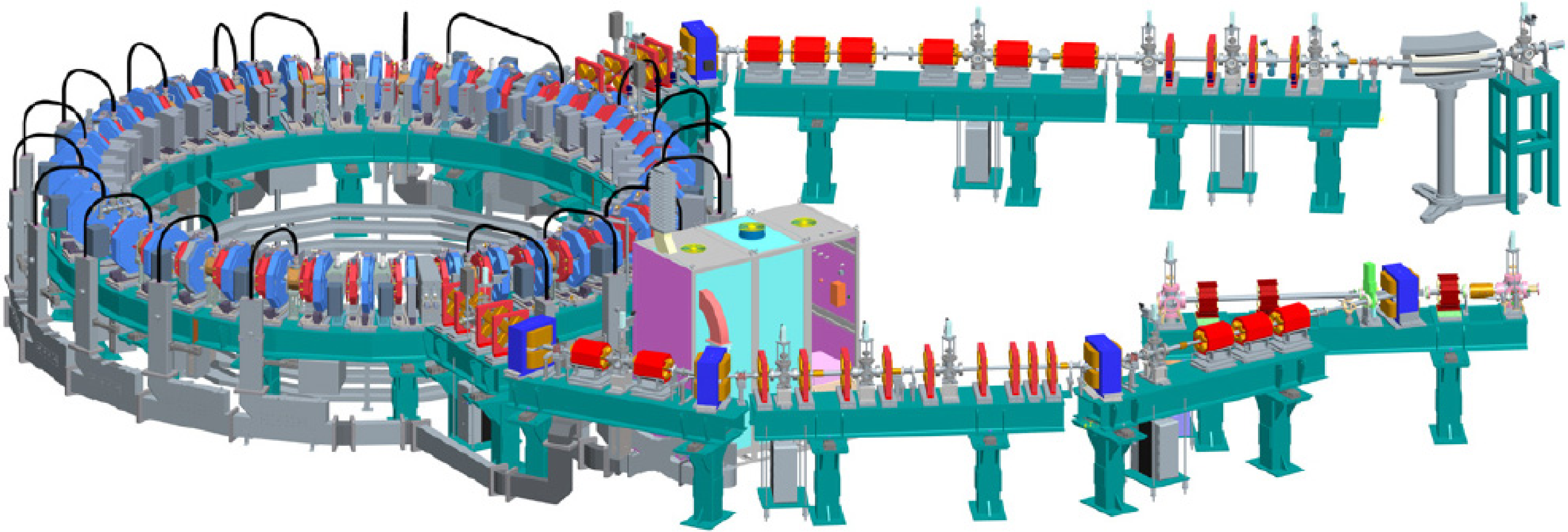
EMMA

the World's First Non-Scaling FFAG Accelerator



Susan Smith STFC Daresbury Laboratory

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Science & Technology Facilities Council

BASROC CONFORM

Contents

INTRODUCTION

Project Overview

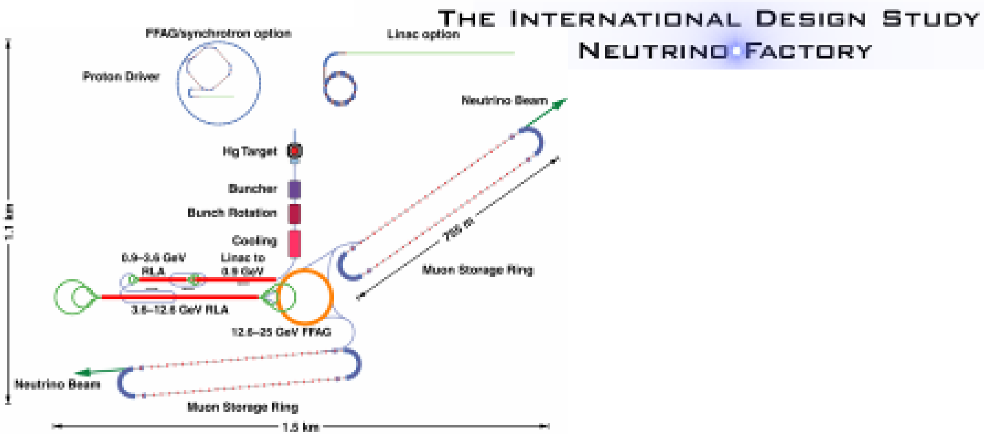
BASROC (The British Accelerator Science and Radiation Oncology Consortium, BASROC)

- 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 **TH4GAC03, "Pamela Overview", Ken Peach Thursday PM**
  - Applications study

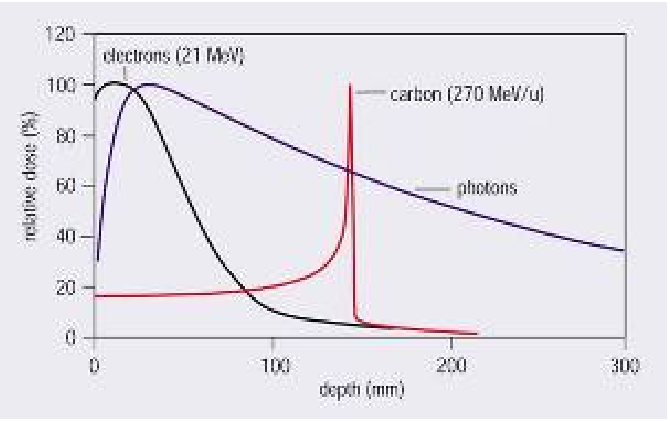
Applications of ns-FFAGs

Neutrino Factory



TU1GRC04 "FFAG Designs for the IDS…", Scott Berg

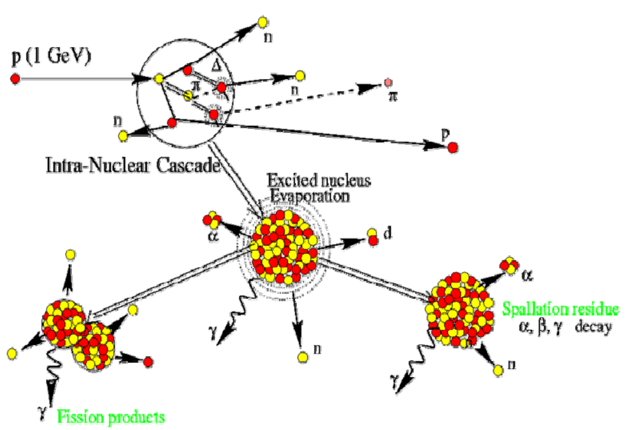
Proton & Carbon Therapy



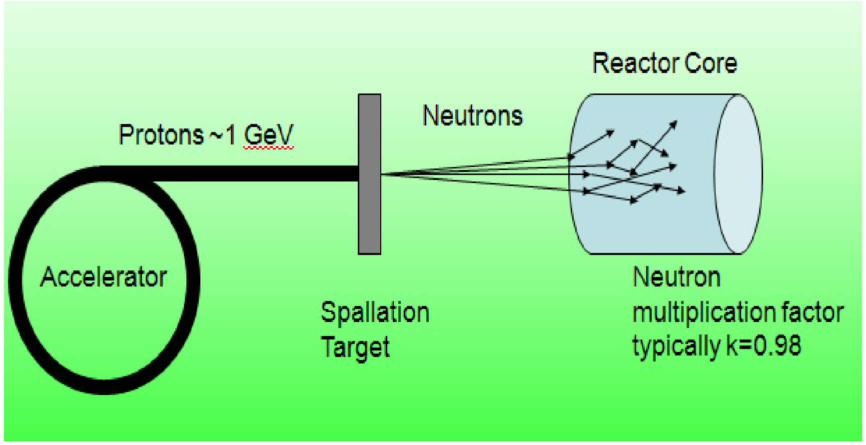
TH4GAC03 "Pamela Overview", Ken Peach

High power proton driver

Dedicated Muon Source



Sub-critical Thorium Reactor



TU6PFP029 C. Bungau et al

WHAT ARE NON-SCALING FFAGS? WHY EMMA?

Scaling FFAGs

- **F**ixed **F**ields => Rapid acceleration
- **A**lternating **G**radient =>Reduced magnet apertures compared to cyclotron
- Large 6D acceptance
  - High average and peak beam currents
- Beam can be extracted at a number of energies
- Fixed tunes
- Fixed orbit shape (largely increases with radius)
- Variable time of flight

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 $dG/G < 2 \times 10^{-4}$

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

THE INTERNATIONAL COLLABORATION

Science & Technology Facilities Council

BASROC CONFORM

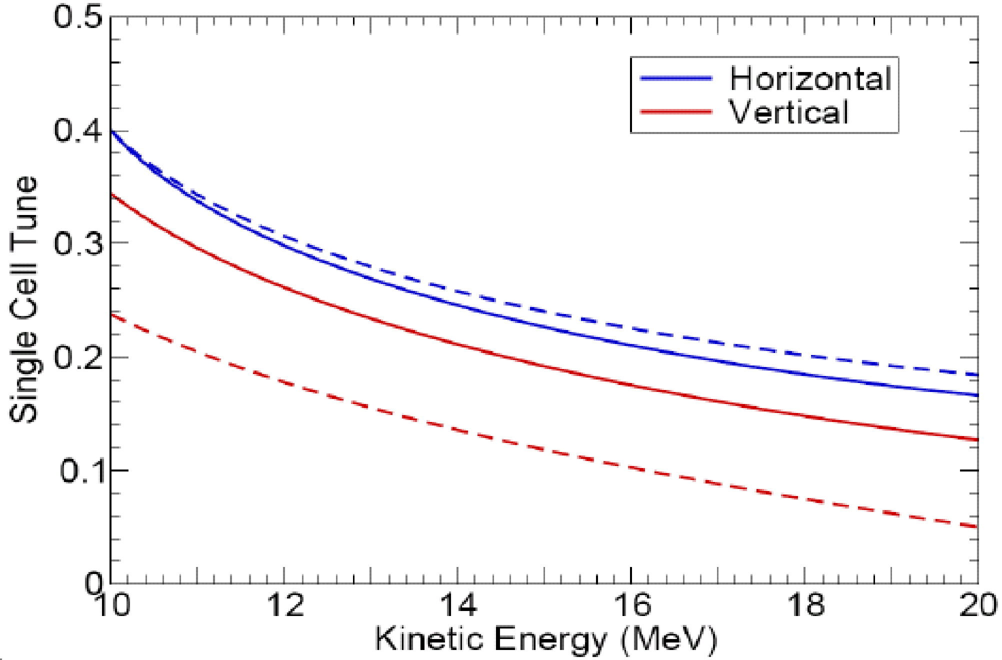
EMMA International Collaboration

- 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

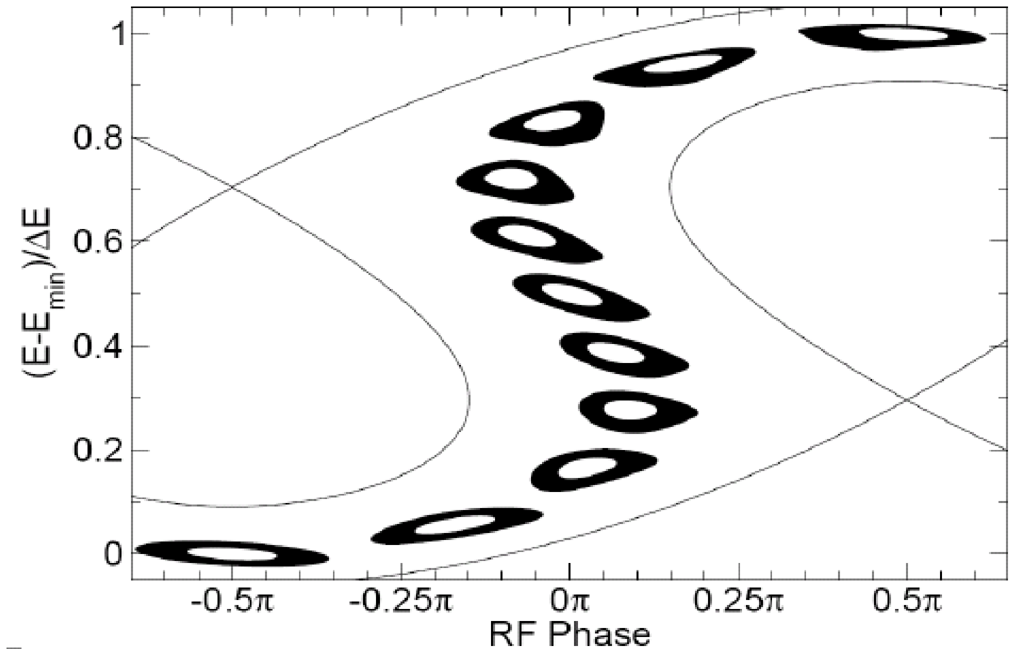
EMMA GOALS AND REQUIREMENTS

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.

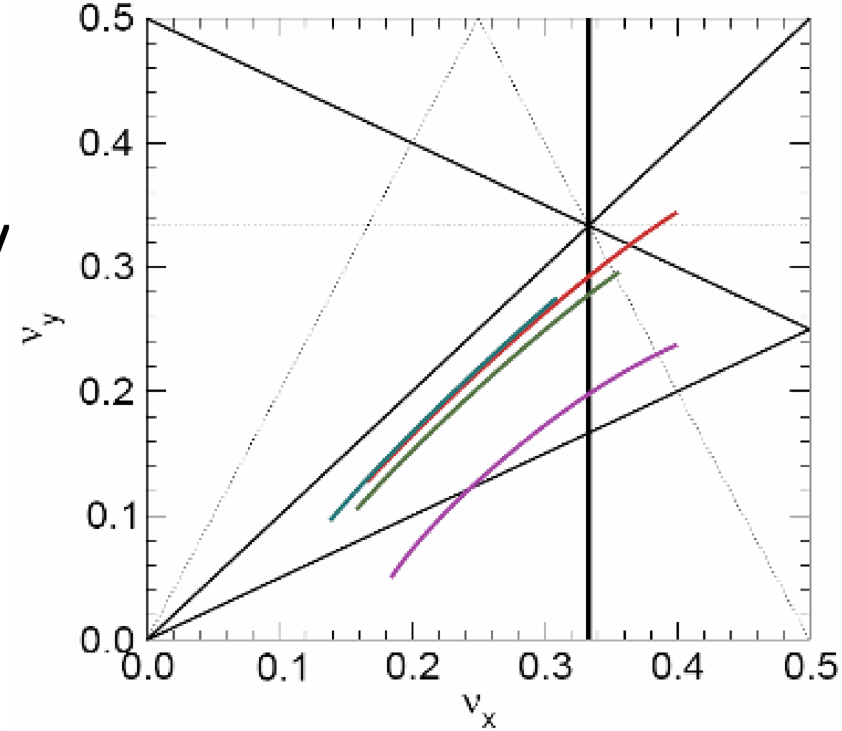
Graphs courtesy of Scott Berg BNL

Lattice Configurations

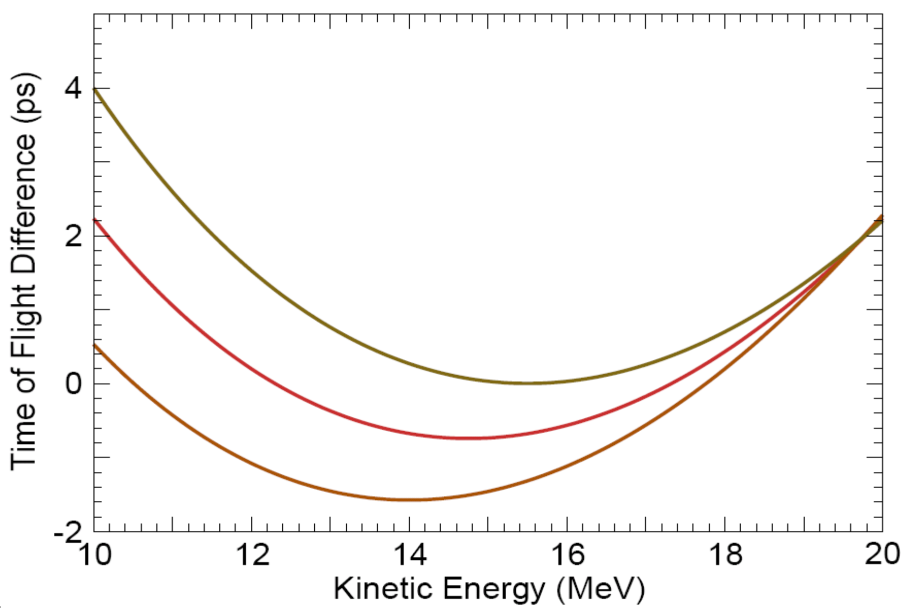
Understanding the NS-FFAG beam dynamics as function of lattice tuning & RF parameters

- Example: retune lattice to vary resonances crossed during acceleration

Tune plane



Time of Flight vs Energy



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

Graphs courtesy of Scott Berg BNL

BROOKHAVEN NATIONAL LABORATORY

Accelerator Requirements

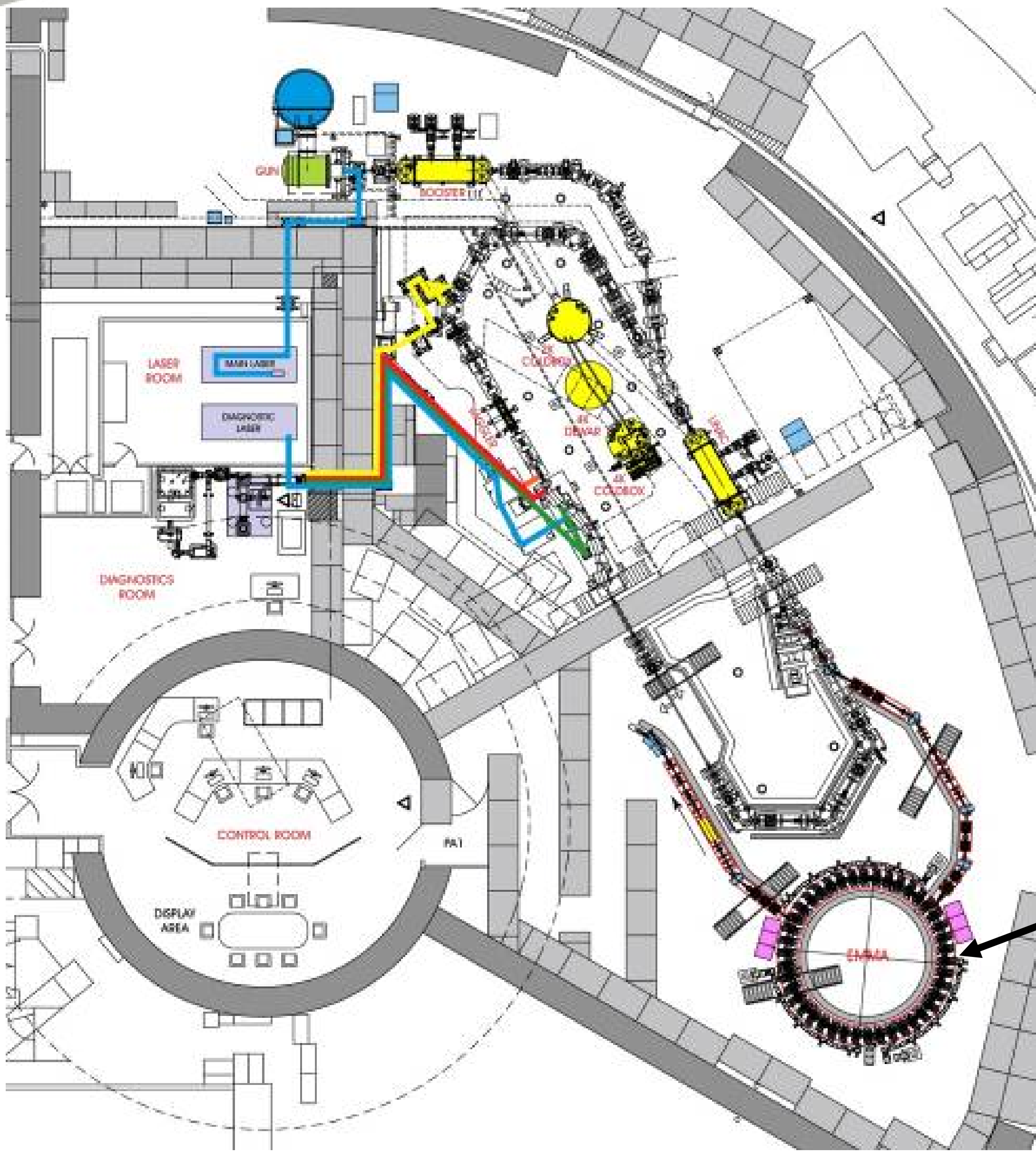
- Injection & extraction at all energies ,10 - 20 MeV
- Fixed energy operation to map closed orbits and tunes vs momentum
- Many lattice configurations
  - Vary ratio of dipole to quadrupole fields
  - Vary frequency, amplitude and phase of RF cavities
- Map longitudinal and transverse acceptances with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

EMMA to be heavily instrumented with beam diagnostics

LAYOUT AND LATTICE

ALICE

Accelerators and Lasers In Combined Experiments



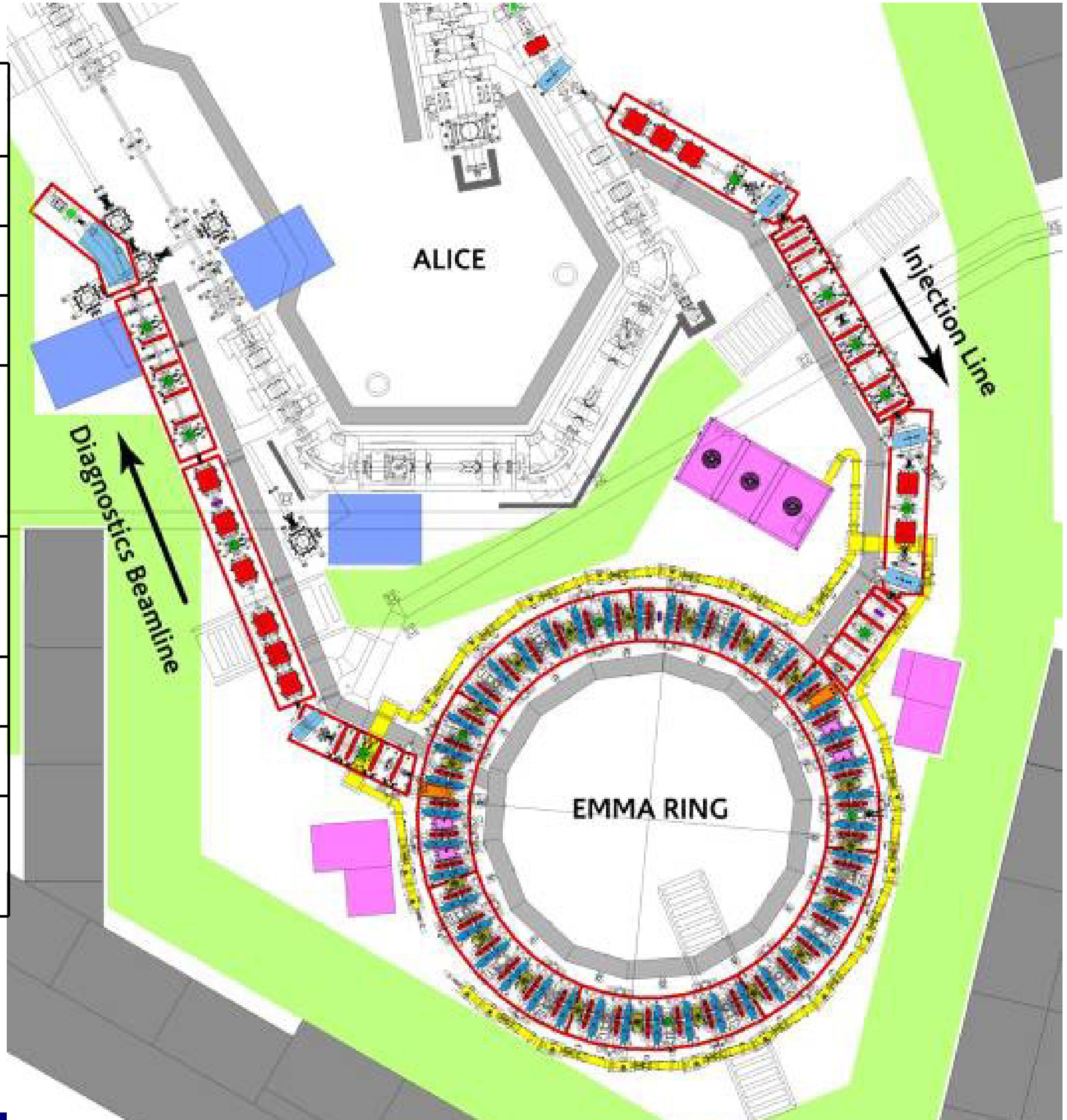
Parameter	Value
Nominal Gun Energy	350 keV
Injector Energy	8.35 MeV
Max. Energy	35 MeV
Linac RF Frequency	1.3 GHz
Max Bunch Charge	80 pC
Emittance	5-15 mm-mrad

EMMA

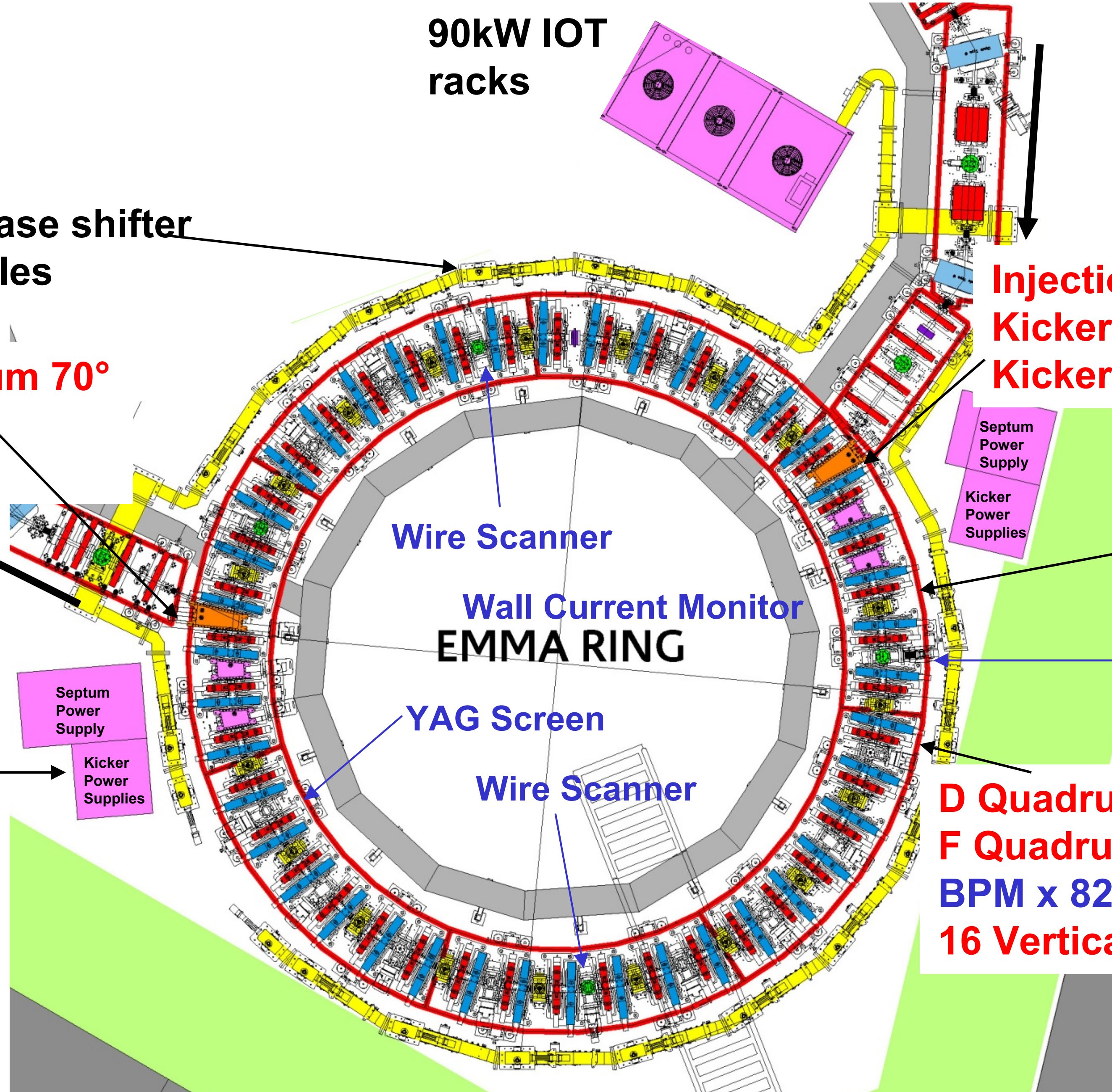
TU5RFP083 " Progress on ALICE Commissioning… ",Yuri Saveliev

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



90kW IOT racks
RF distribution
17 hybrid and phase shifter waveguide modules
Injection Septum 65°
Kicker
Kicker
Extraction Septum 70°
Kicker
Kicker
Septum Power Supply
Kicker Power Supplies
Wire Scanner
Wall Current Monitor
EMMA RING
RF Cavities x 19
YAG Screen
YAG Screen
Septum Power Supply
Kicker Power Supplies
Septum & kicker power supplies
Wire Scanner
D Quadrupole x 42
F Quadrupole x 42
BPM x 82
16 Vertical correctors

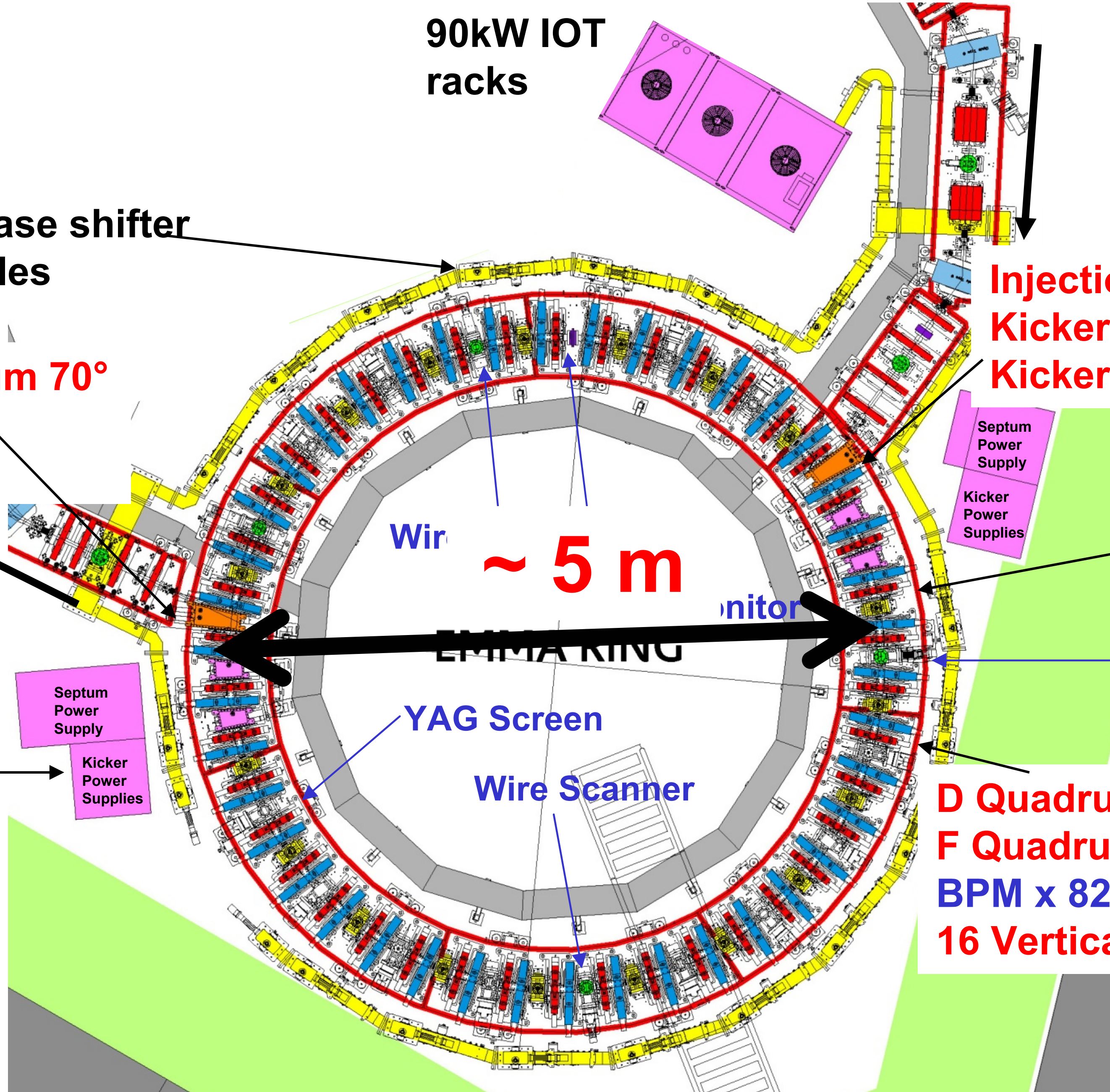
EMMA Ring

90kW IOT racks

RF distribution
17 hybrid and phase shifter waveguide modules

Extraction Septum 70°
Kicker
Kicker

Injection Septum 65°
Kicker
Kicker



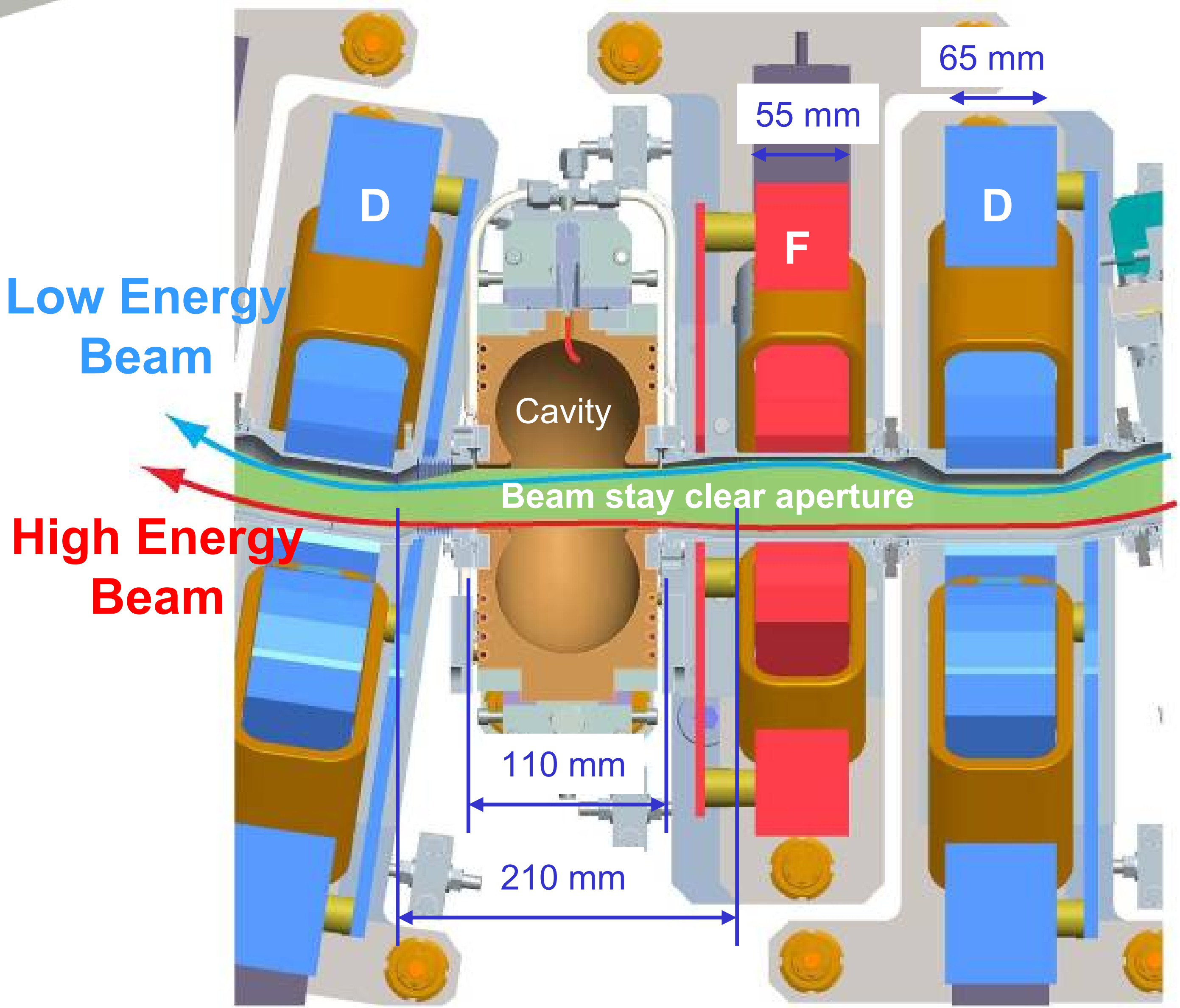
RF Cavities x 19

YAG Screen

Septum & kicker power supplies

D Quadrupole x 42
F Quadrupole x 42
BPM x 82
16 Vertical correctors

EMMA Ring Cell



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

42 identical cells
Cell length 395 mm

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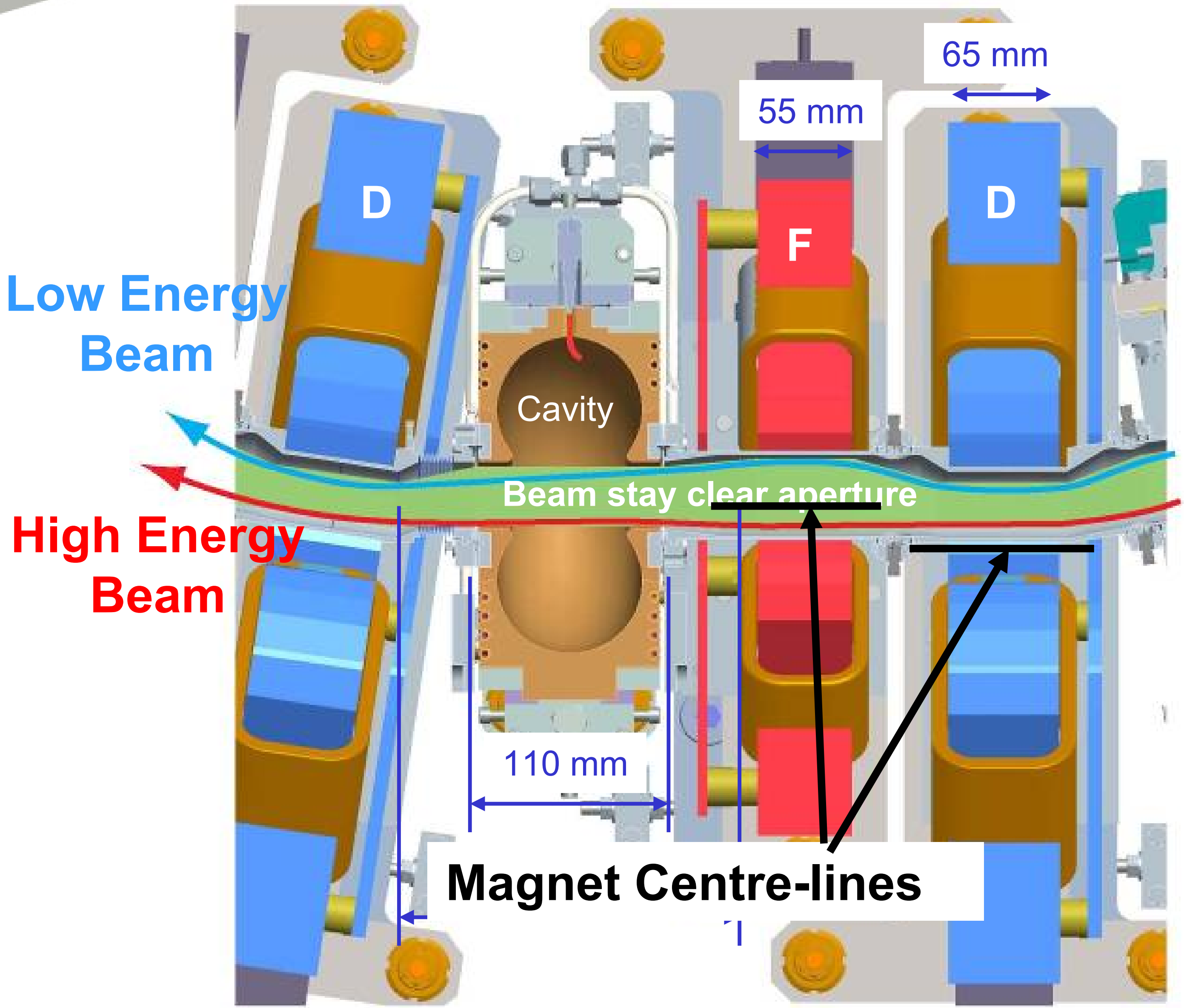
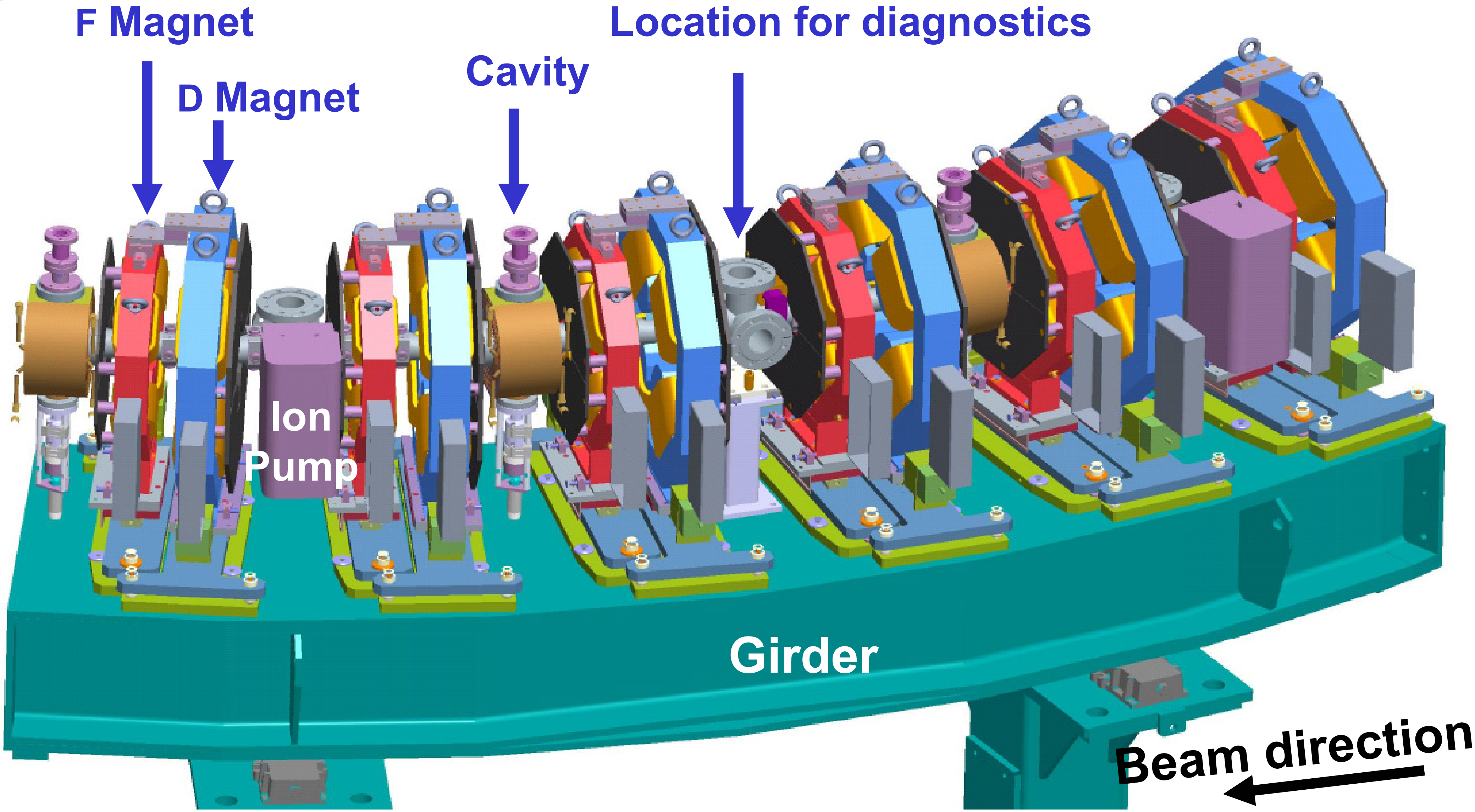
EMMA Ring Cell



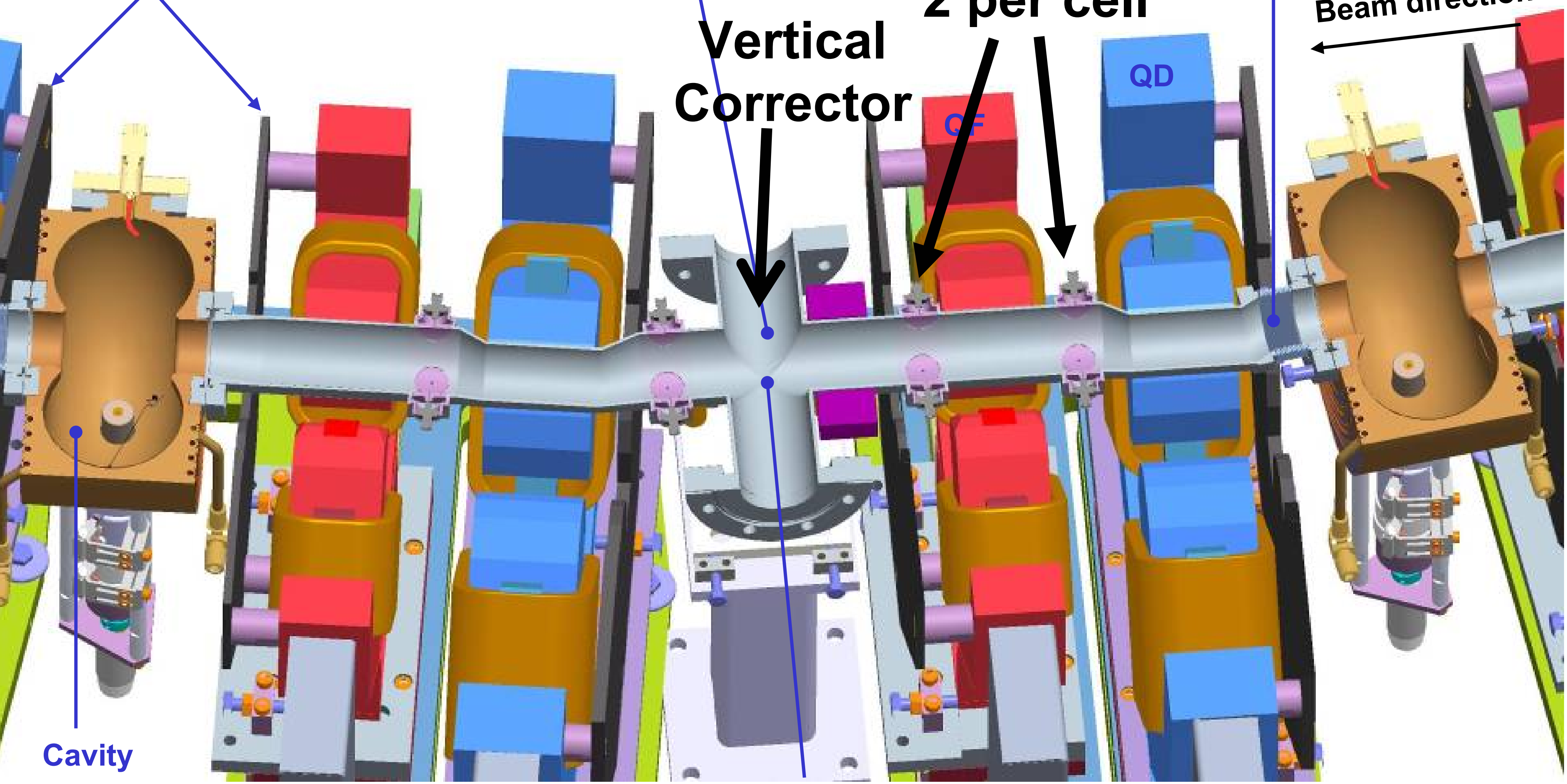
Long drift	210 mm
F Quad	58.8 mm
Short drift	50 mm
D Quad	75.7 mm

42 identical cells
Cell length 395 mm

A 6 Cell Girder Assembly



EMMA Ring Section



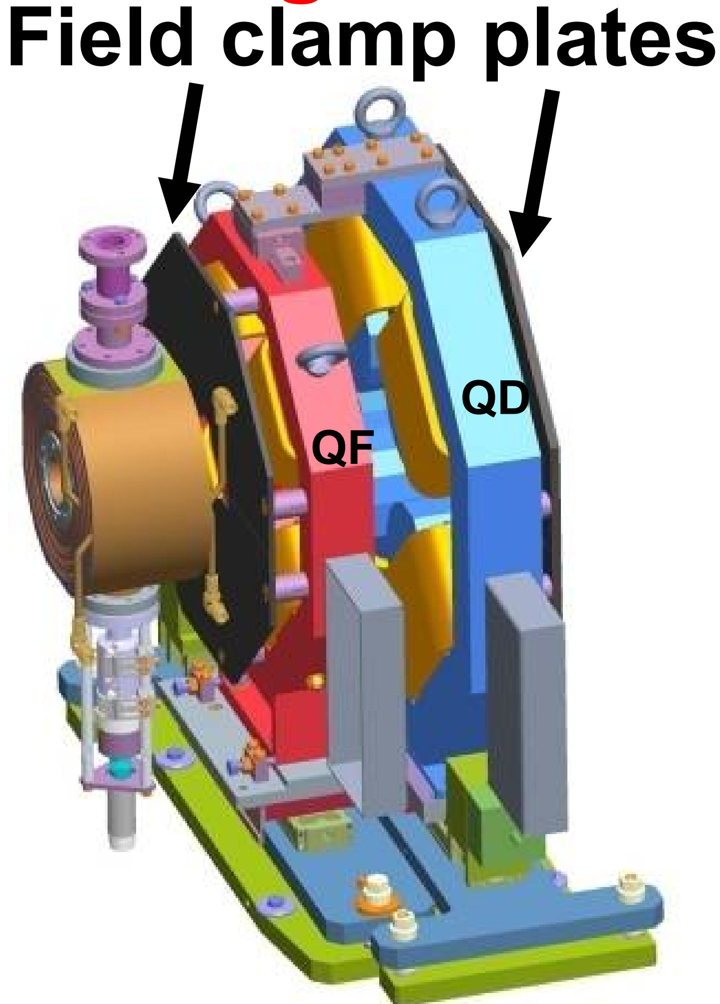
MAGNETS & MAGNET CHALLENGES

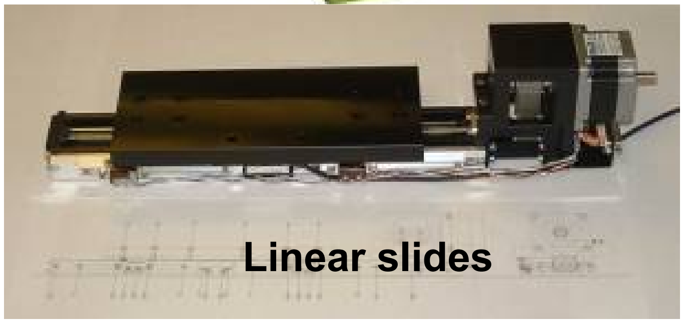
Talk TU1RAI02 Neil Marks, "Non-Scaling FFAG Magnet Design Challenges"

Ring Quadrupole Magnets

Requirements / Design

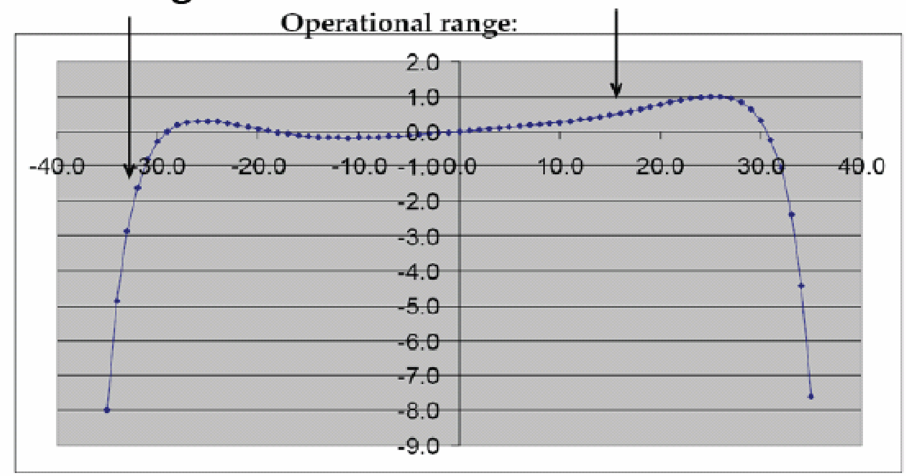
- Adjust dipole & quadrupole components independently
  - Mount magnets on independent radial linear slides
- Fields identical in every cell despite kickers and septum
  - Field clamps at cell entrance face of QD & exit face of QF
- Very large good field region for range of orbits
  - Optimised pole profile



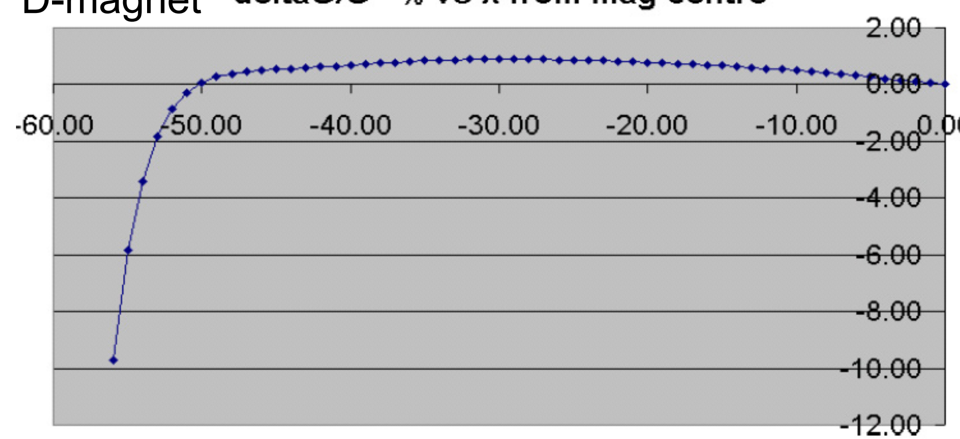


Prototype Ring Magnets

F-magnet field error ×10³



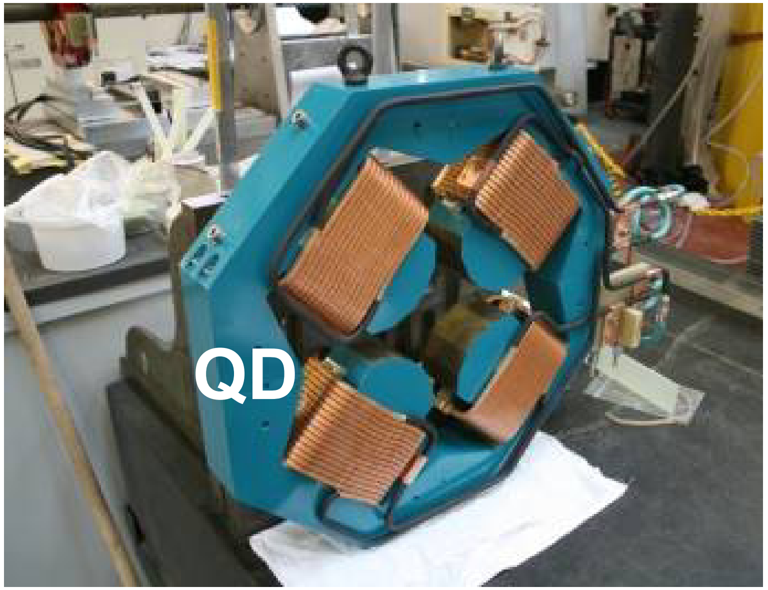
D-magnet

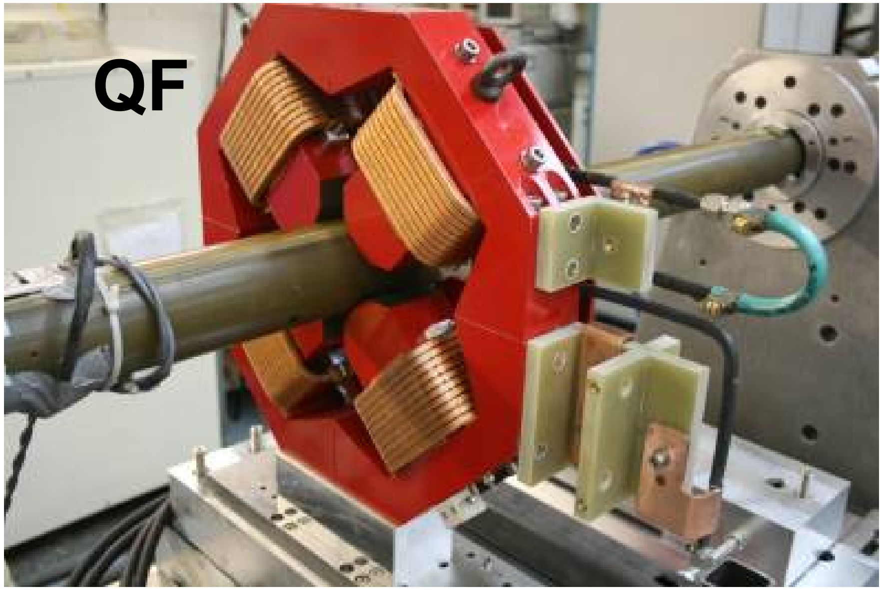


- Good field gradient quality requirement is ± 1.0% over a good gradient region of
  - QF +15.8, -32.0 mm
  - QD - 56.0 , -9.9 mm

Production Quadrupole Status

- Magnet construction is complete
- QF x 34 delivered
- QD x 34 delivered
- Field measurements are in progress on the remaining 16 magnets
- Complete delivery scheduled for the end of May

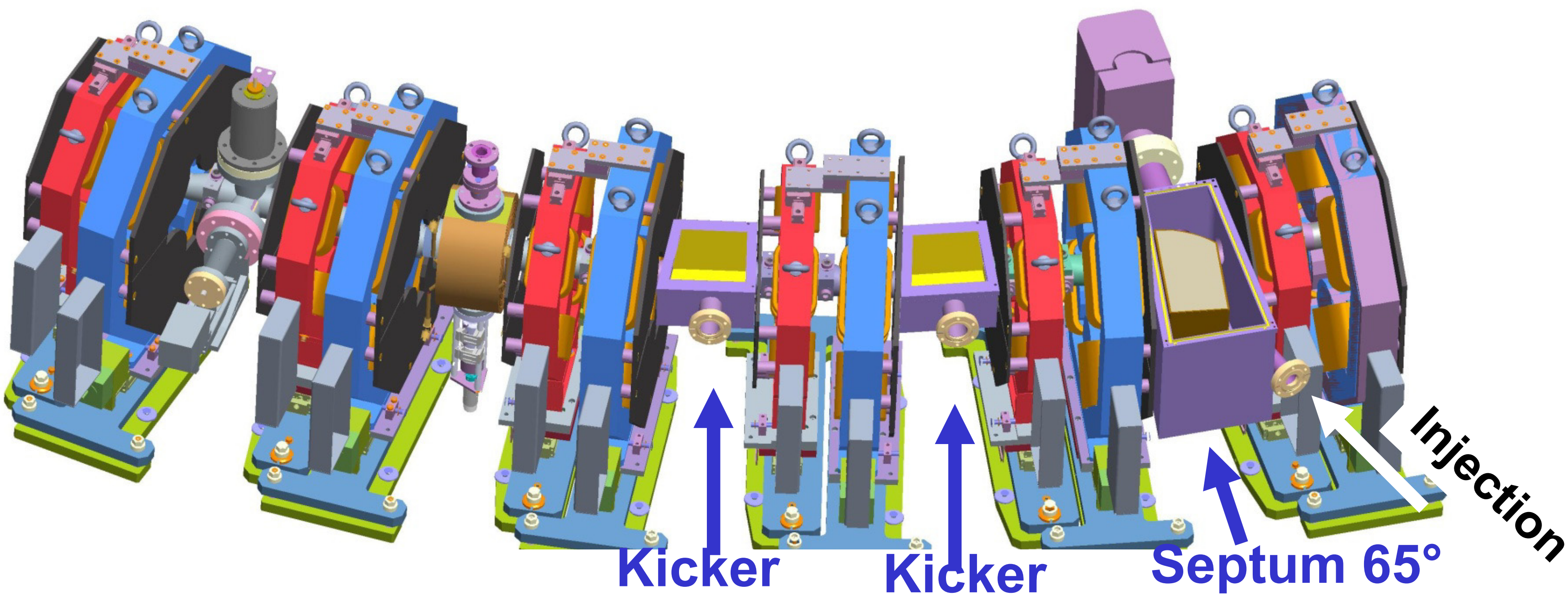




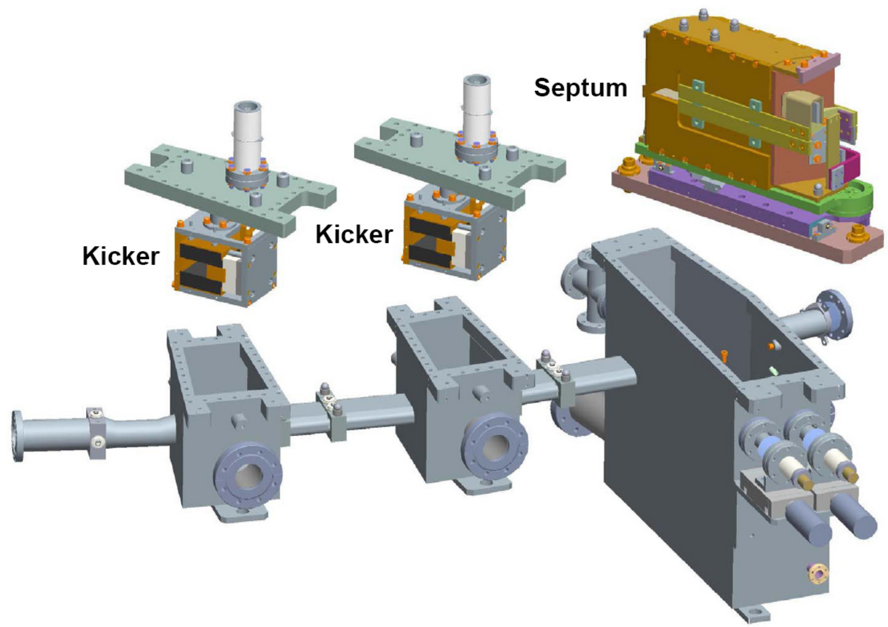
Injection & Extraction

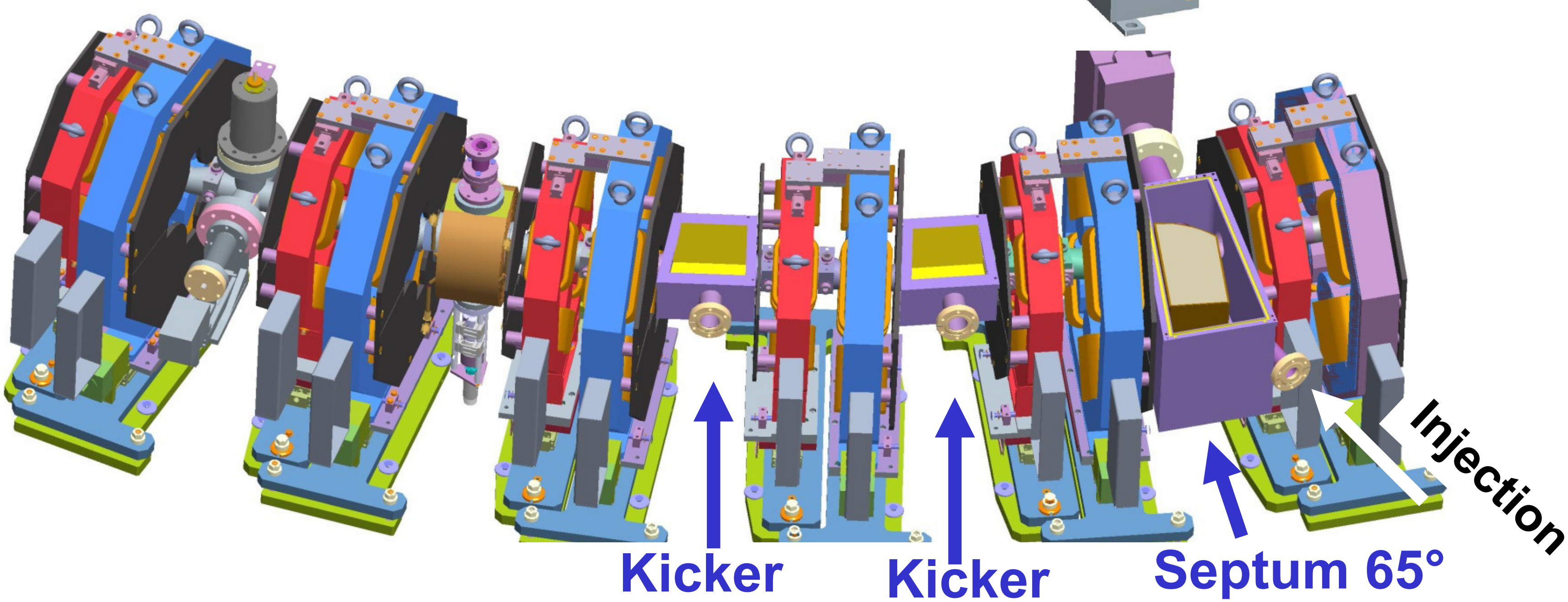
- Large angle for injection (65°) and extraction (70°) very challenging !!
- Injection/Extraction scheme required for all energies (10 – 20 MeV)
- Many lattices and many configurations of each lattice required
- Very limited space between quadrupole clamp plates for the septum and kickers construction

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

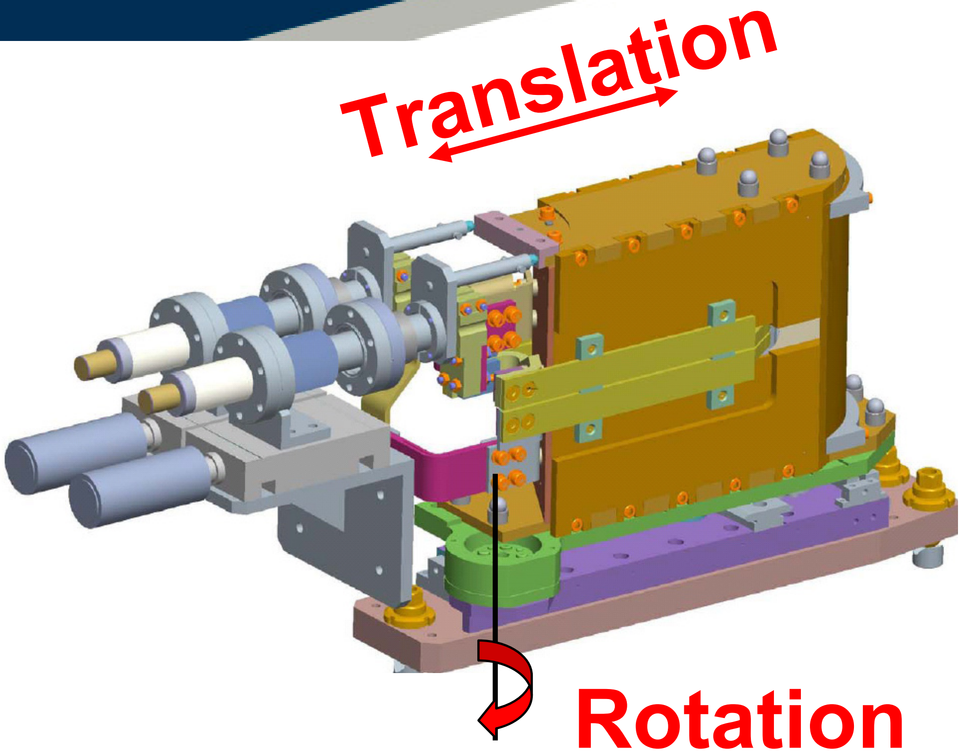


Injection Region

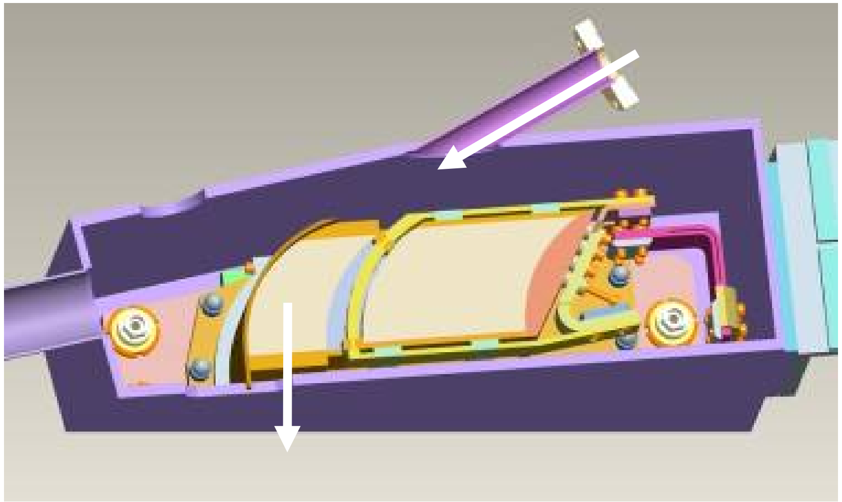




Septum Design



Septum with vacuum chamber removed

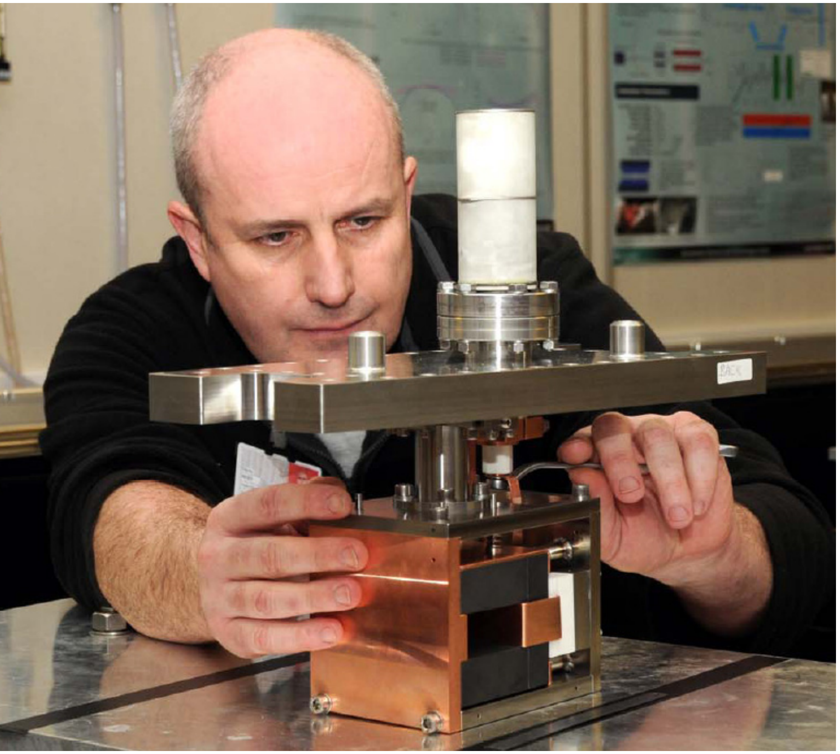


Section view of septum in vacuum chamber

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

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

Kicker



Maximum beam deflection	105	mR
Horizontal good field region	± 23	mm
Minimum vertical gap at the beam	25	mm
Horizontal deflection quality	± 1	%
Minimum flat-top (+0, -1%)	≥5	ns
Field rise/fall time (100% to 1%)	**< 50**	**ns**
Kicker magnet repetition rate	20	Hz

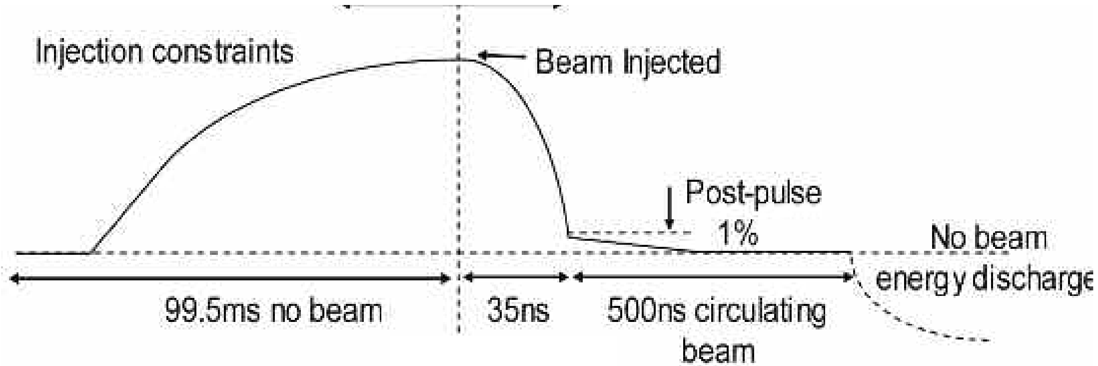
- Inject/Extracts from 10-20 MeV
- For all lattice configurations (Amplitude range including polarity changes)
- Explore the large EMMA horizontal acceptance
- Correction initial horizontal trajectory during acceleration

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 which are due for deliver end of June

DIAGNOSTICS

Diagnostics (1)

FR5REP109 Bruno Muratori

Measurement	Device	Number	Required resolution
Beam position	4 button BPM	2/plane/cell in ring 4 in injection 3 in extraction	50 μm
Beam profile	OTR / YAG screens	2 in ring, 6 in injection & extraction line	20-30 μm pixel size
Beam profile	Wire scanners	2 in ring	10 μm
Beam current	Wall current monitor	1 WCM 1 scope	2%
Phase	WCM	As above	10°
Transmission	WCM	As above	2%

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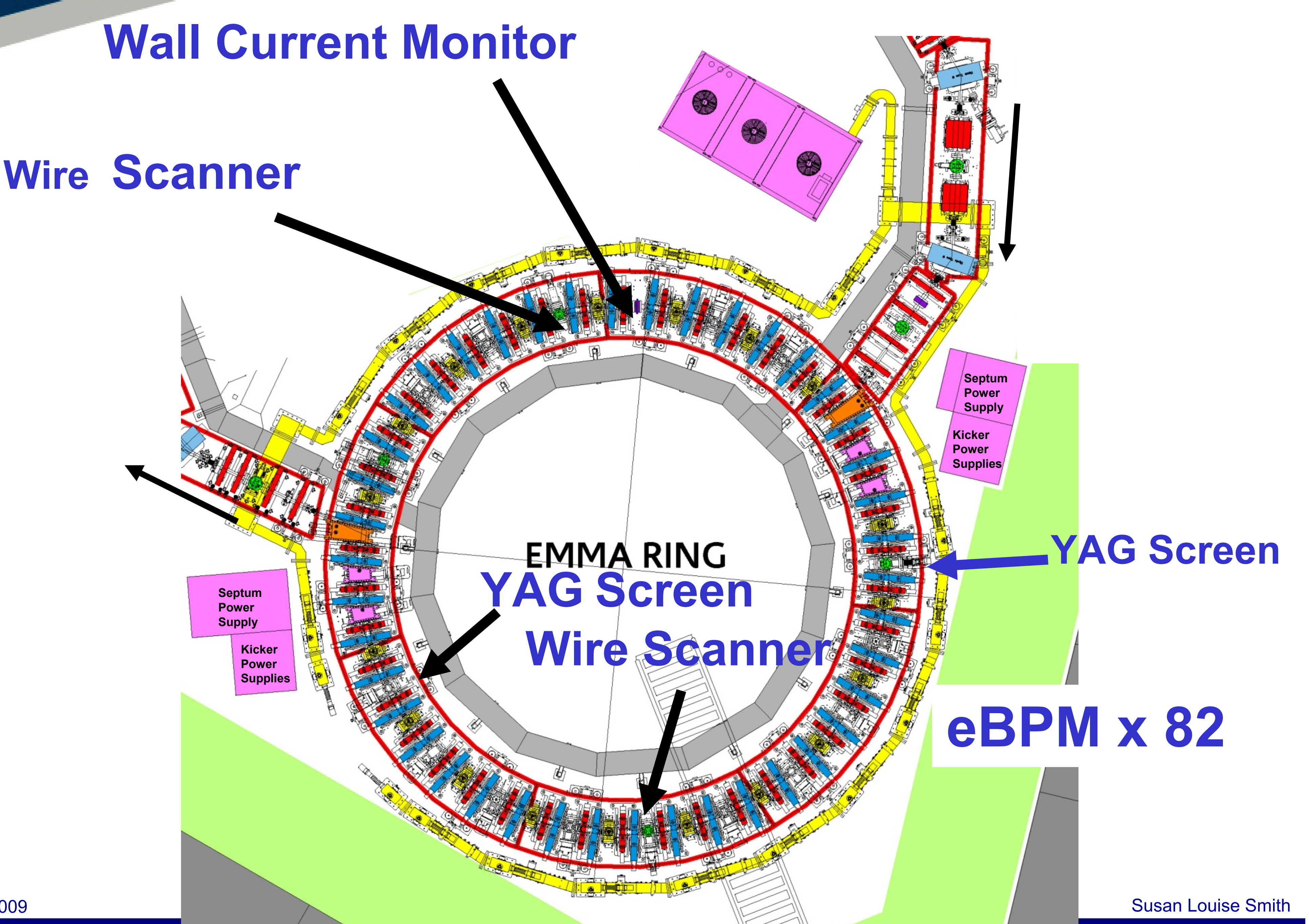
Diagnostics (2)

FR5REP109 Bruno Muratori

Measurement	Device	Number	Required resolution
Bunch charge	Faraday cup	1 at injection, 1 at extraction	2%
Beam loss	Beam loss monitor	4 in ring	2%
Momentum	BPMs and TOF from WCMs	Already included elsewhere	100 keV
Emittance	Tomography diagnostic	Injection & extraction lines	10%
Extracted momentum	Spectrometer	1 (diagnostics line)	1%
Longitudinal profile	Electro-Optic system	1 (diagnostics line)	<1 ps

EMMA Ring



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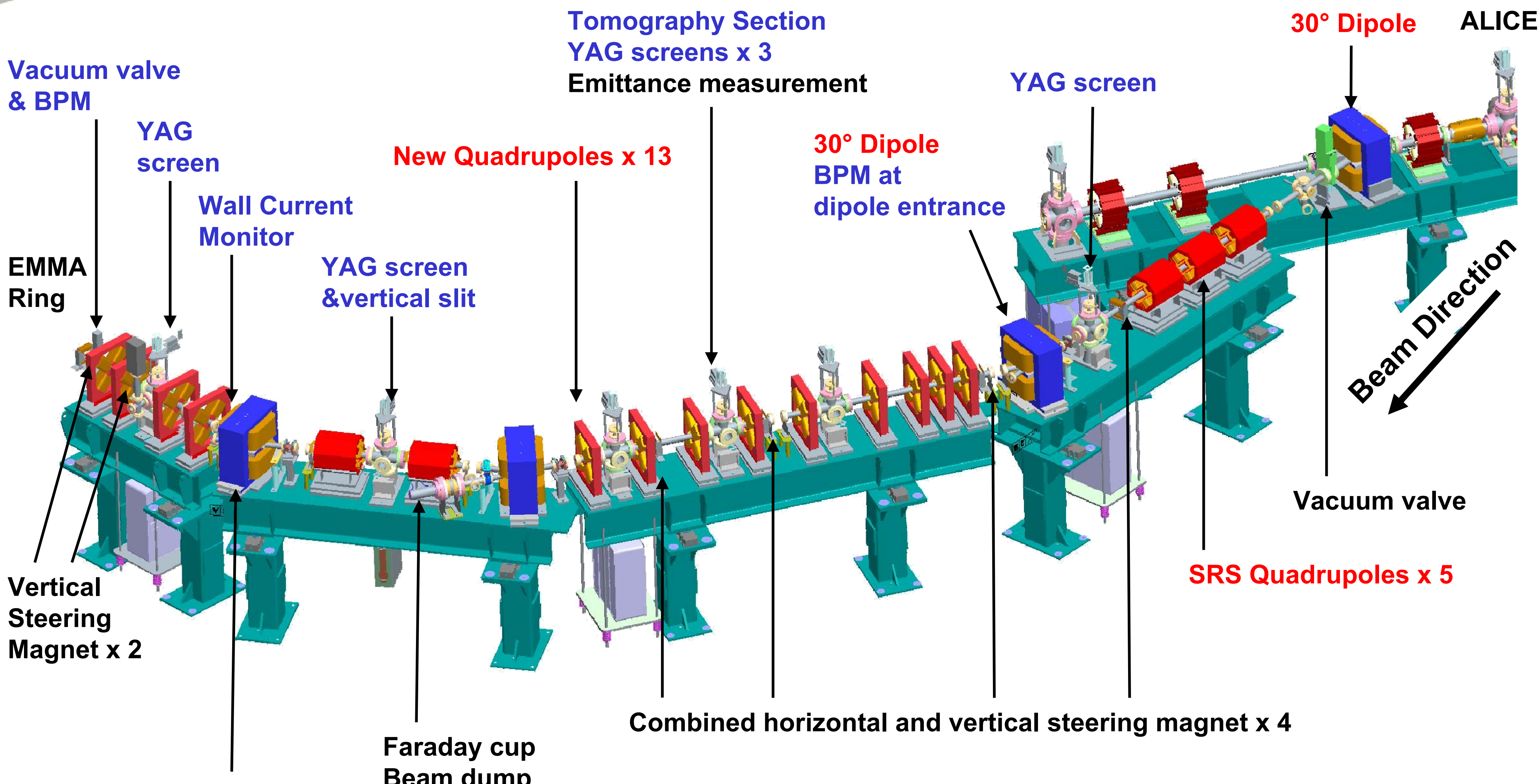
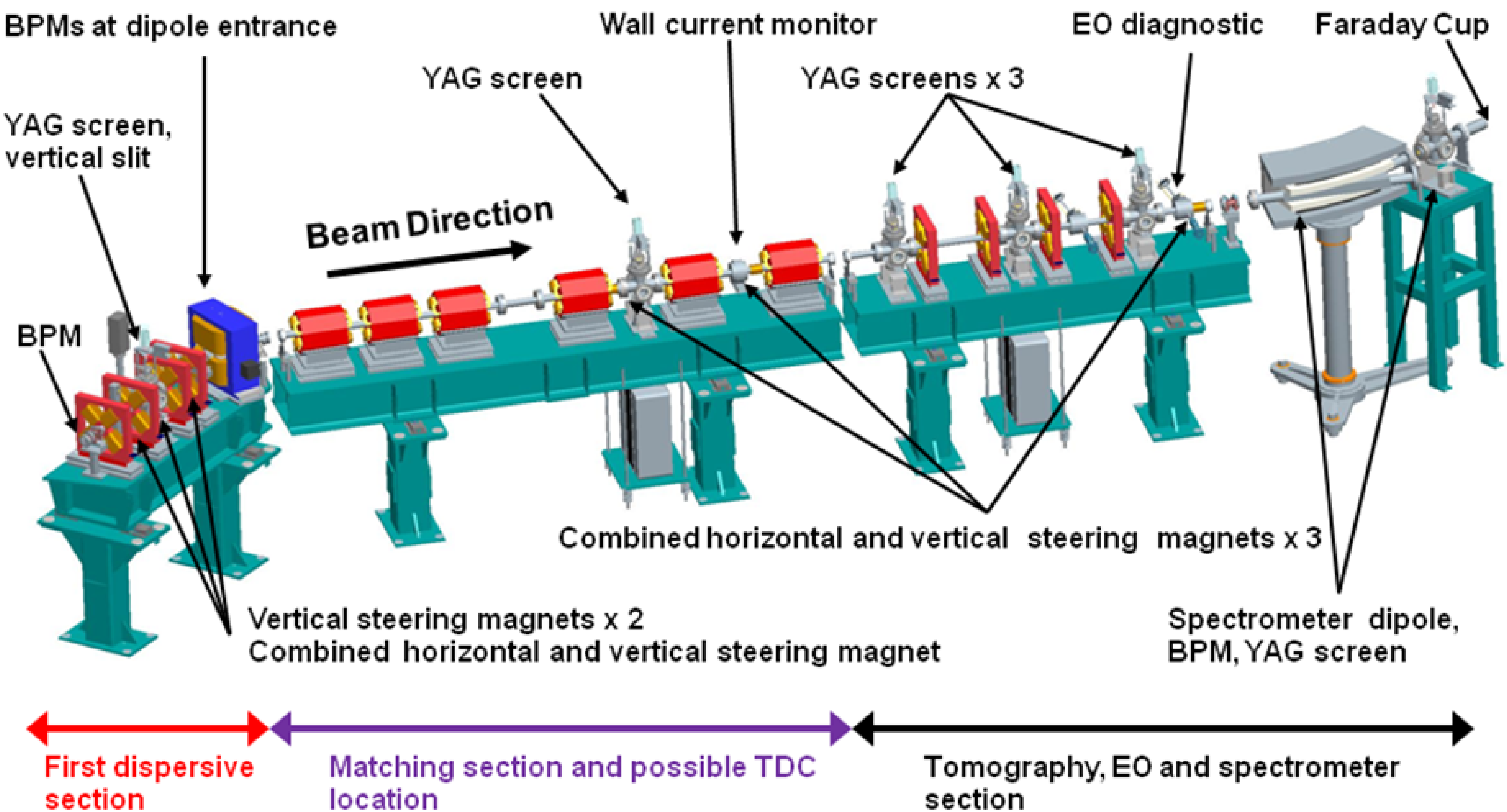
EMMA INJECTION LINE



FR5REP107 David Holder

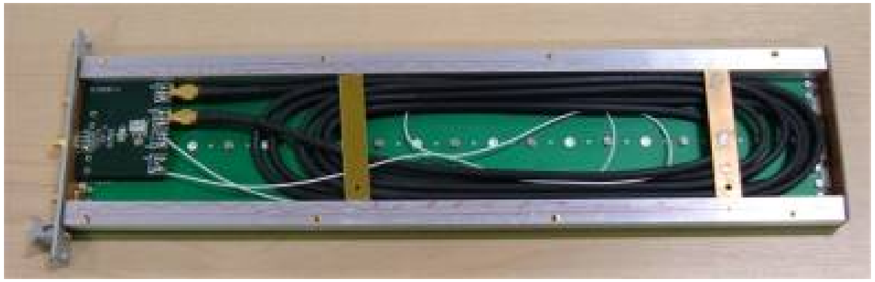
DIAGNOSTICS BEAMLINE LAYOUT

FR5REP109 Bruno Muratori

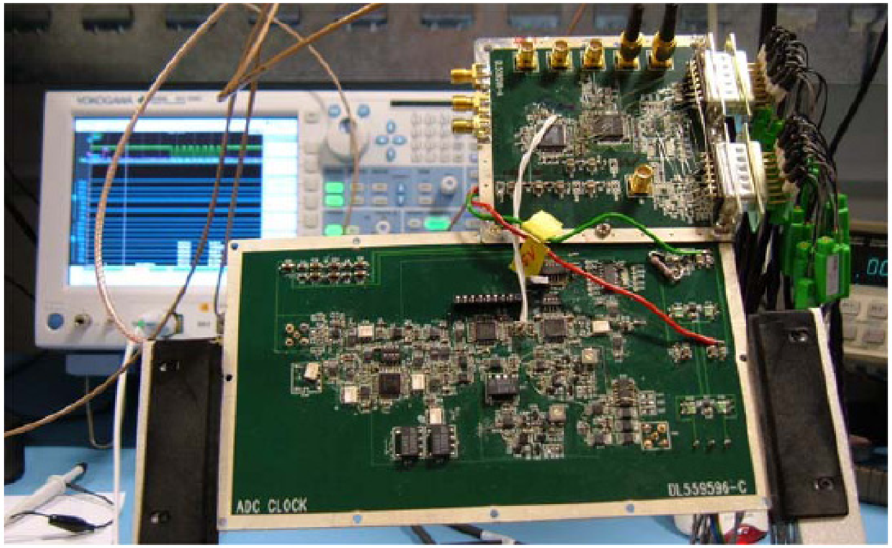


Electron Beam Position Monitors

- The BPM electronics system has to deliver 50 μm resolution over a large aperture
- Locally mounted coupler cards
  - Amplifies signals from opposite buttons, coupler and strip line delay cables give a 12 ns delay, signals combined in single high quality coax
- Detector card in rack room outside of shielded area
  - Prototype tested and moving to a VME style card design



Prototype Coupler



RF Detector, Clock Control and ADC

Vacuum chamber & BPM

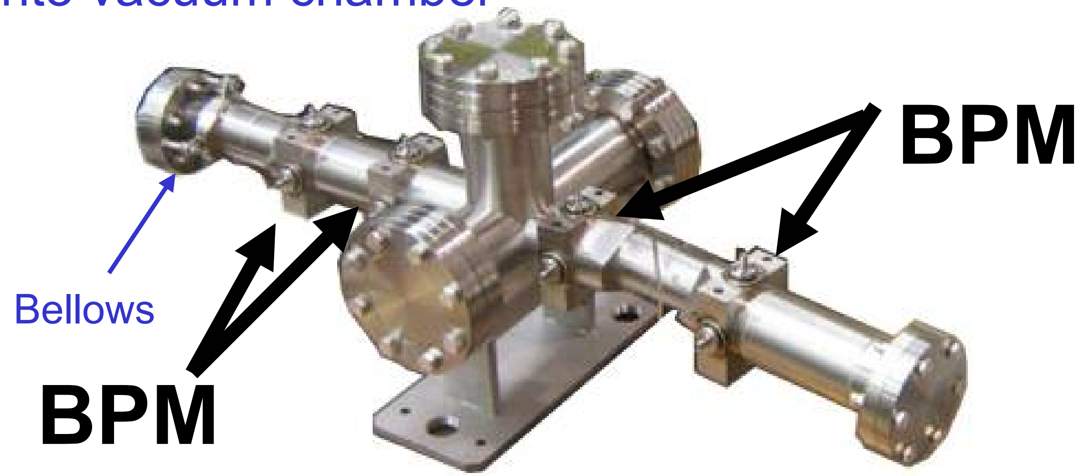
- Standard vacuum chambers each covering 2 cells are being constructed at

VG Scienta

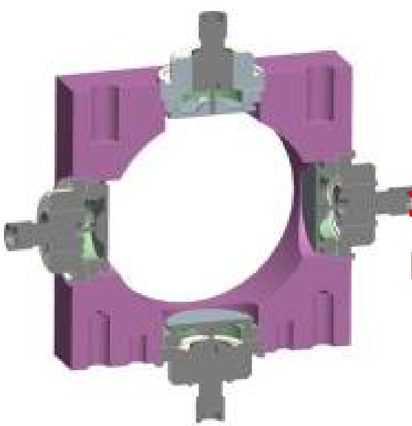
- 12 chambers are delivered

- Remaining chamber are scheduled to be delivered in May

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



Standard vacuum chamber. Material stainless steel



± 25μm r.m.s. resolution required

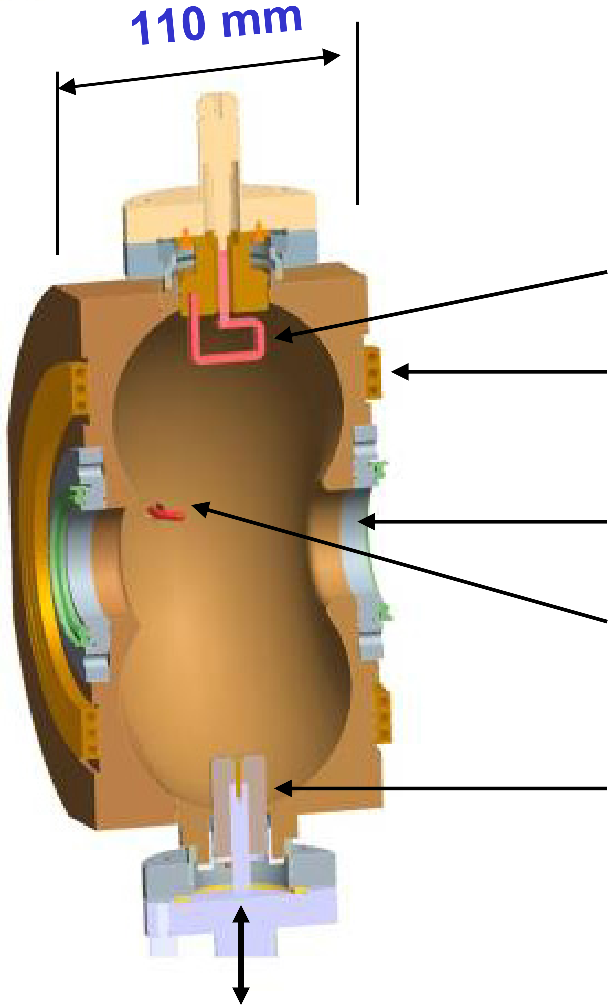
BPM block cross-section showing pickups

RADIO FREQUENCY

RF Requirements

- Voltage:
  - 20 - 120 kV/cavity essential, based on 19 cavities
  - Up to 180 kV/cavity desirable (future upgrade)
- Frequency:
  - 1.3 GHz, compact and matches the ALICE RF system
  - Range requirement 5.6 MHz
- Cavity phase:
  - Remote and individual control of the cavity phases is essential

Cavity Design



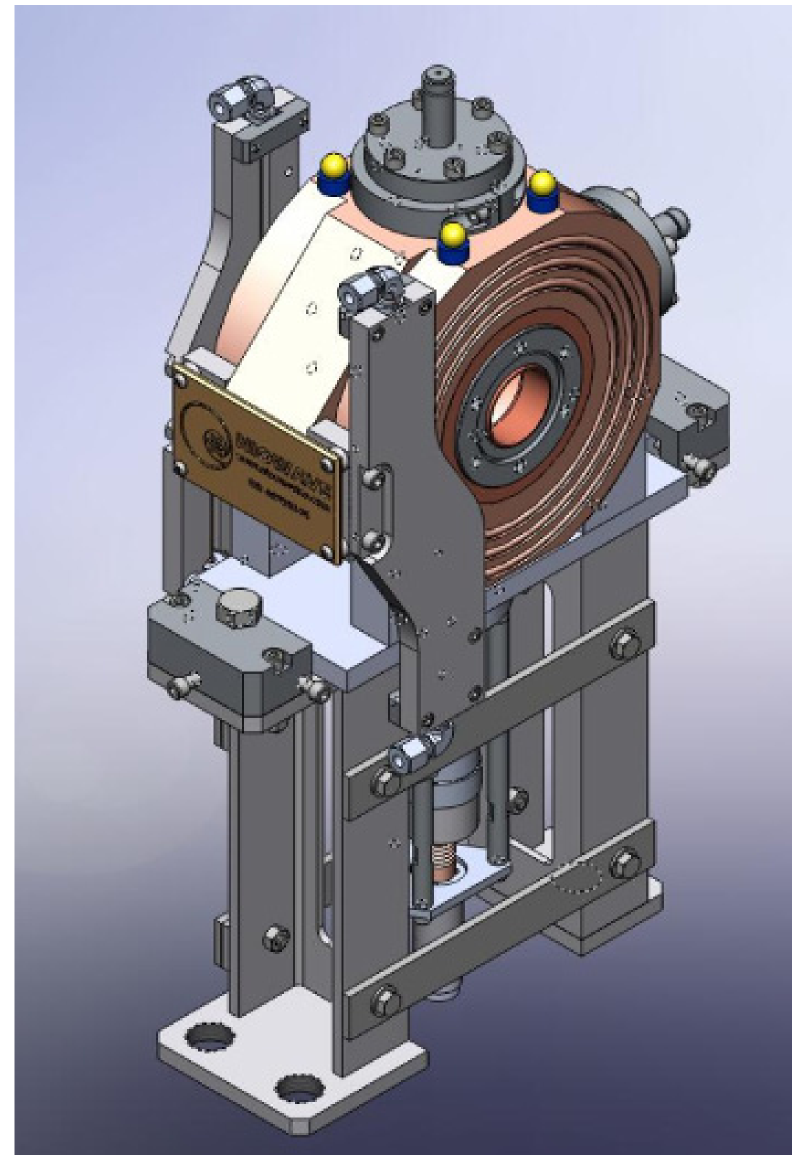
Normal conducting single cell re-entrant cavity design optimised for high shunt impedance

Parameter	Value
Frequency	1.3 GHz
Theoretical Shunt Impedance	2.3 MΩ
Realistic Shunt Impedance (80%)	**2 MΩ**
Qo (Theoretical)	23,000
R/Q	100 Ω
Tuning Range	-4 to +1.6 MHz
Accelerating Voltage	120 kV
Total Power Required (Assuming 30% losses in distribution	**90 kW**
Power required per cavity	3.6 kW

Cavity Construction

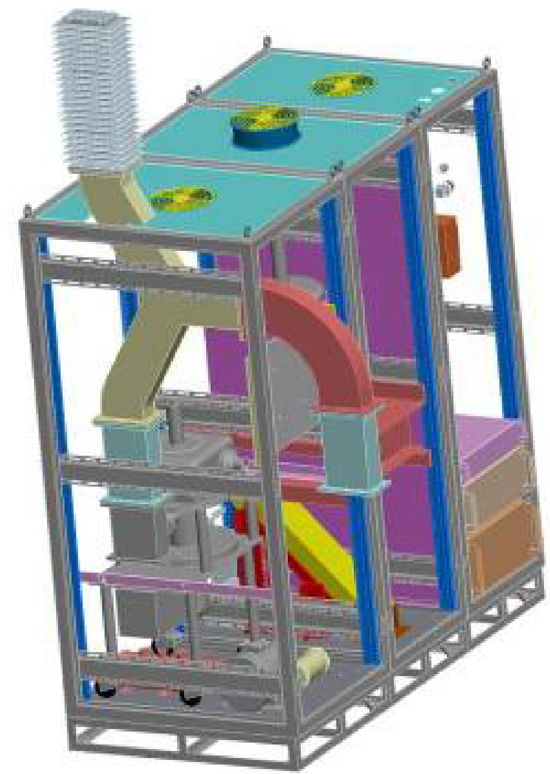
- Manufacture of prototype cavities and 19 production cavities completed by **Niowave**
- High quality manufacture including electron beam welding of body to reduce distortion
- Chemical etching adopted to improve Q (Qo 18,500 to 20,400)

Exceeds EMMA specification



RF Source

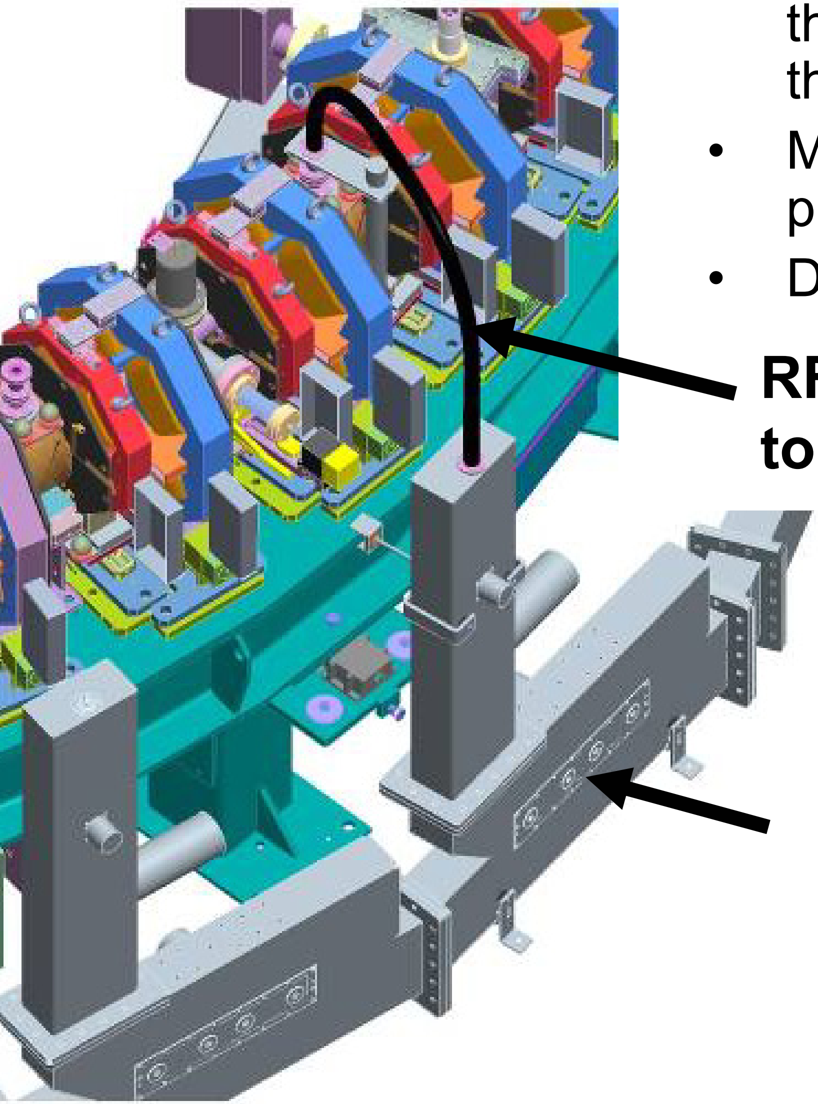
- A single 100kW (pulsed) IOT supplying the 19 RF cavities distributed around EMMA
- VIL409 high power RF amplifier system in 3 racks
- Tested to ensure required bandwidth
- Software and system tests are in progress
- Delivery scheduled for July 2009



CPI 100 kW (pulsed) IOT

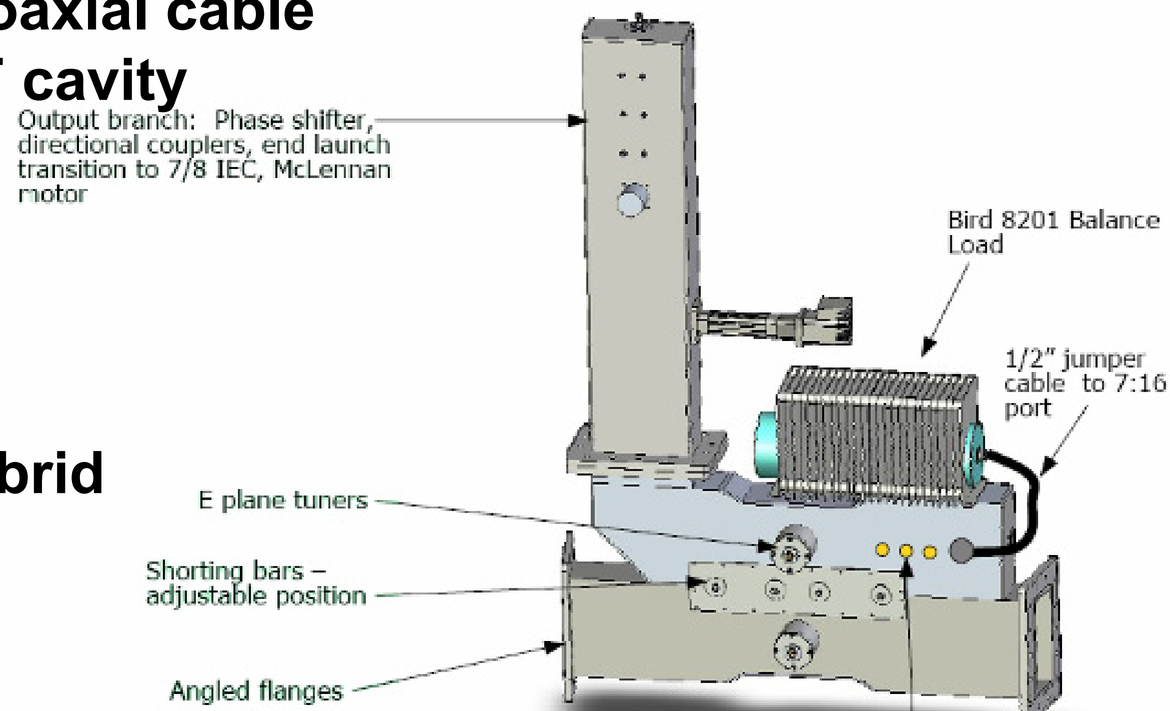
Cascade RF Distribution

- 17 hybrid and phase shifter modules located around the EMMA ring in a cascade configuration splitting the RF power equally to 19 cavities
- Manufacture by Q-Par Angus is complete, tests in progress
- Delivery scheduled for June 2009



RF coaxial cable to RF cavity

Hybrid



Hybrid

Low Level RF

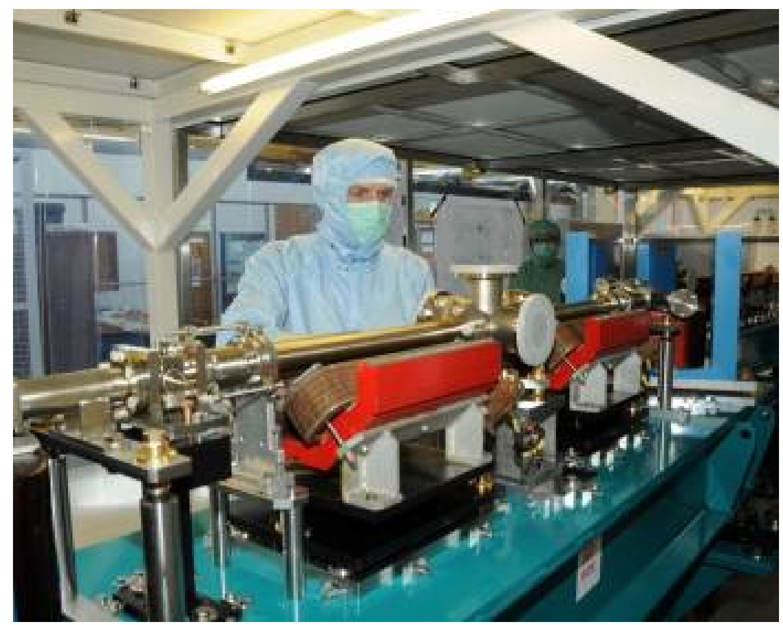
- Stability of the accelerating field is provided by the LLRF
- Includes hardware and software to optimise the **amplitude** and **phase** during operation and for the **frequency** of operation to be set
- LLRF tests have been completed using:
  - CPI IOT at power level 5 kW
  - 2 EMMA cavities
  - Power split equally using a 3 dB hybrid and phase shifter waveguide module
  - Amplitude stability 0.006% (spec. 0.3%)
  - Phase stability 0.009^{o} (spec. 0.3^{o})

System required by September for full tests in October 2009

ASSEMBLY STATUS

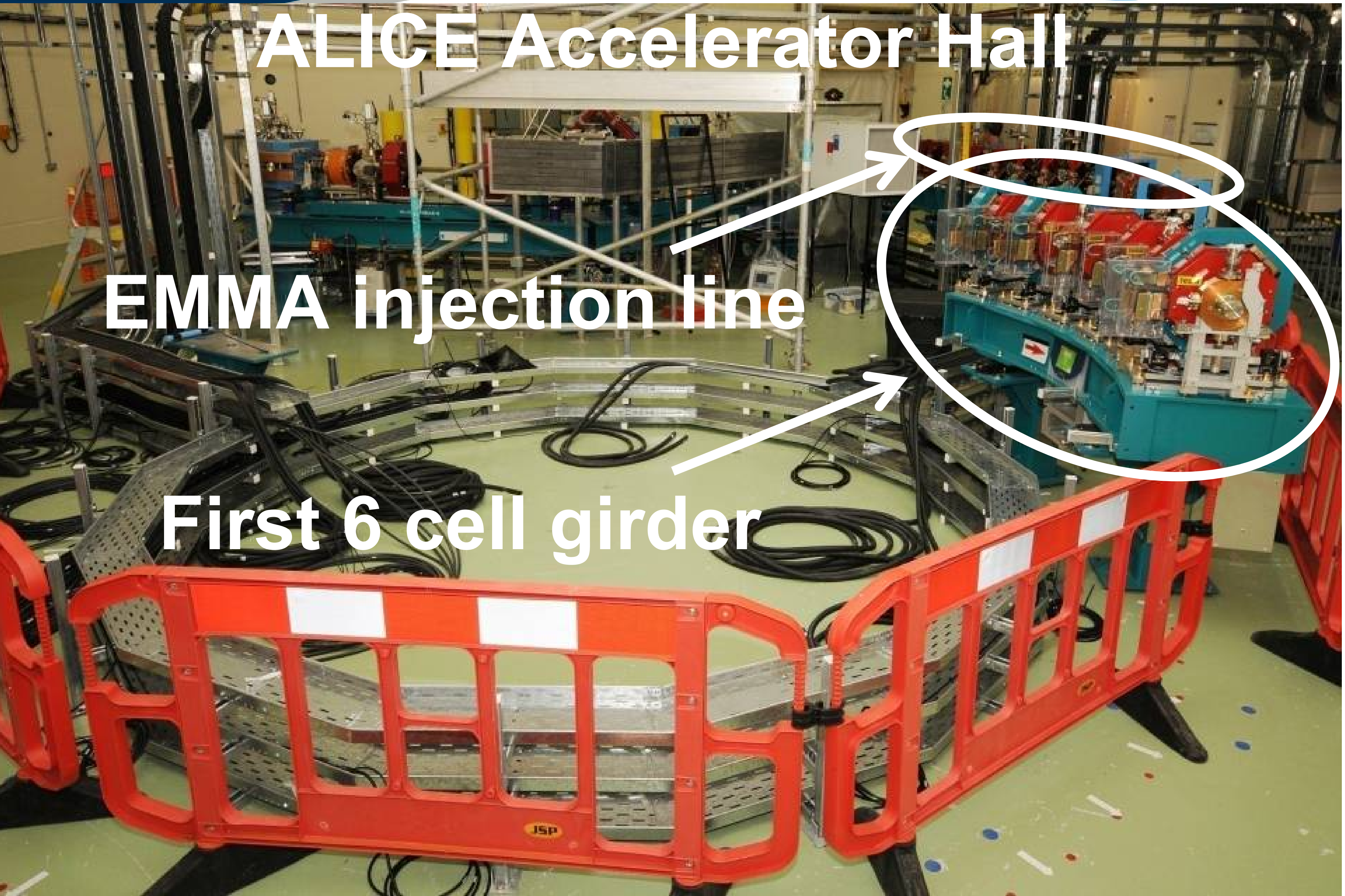
Off Line Assembly

Injection Line Modules



6 Cell Ring Module
1/7th of Circumference

ALICE Accelerator Hall



EXPERIMENTS

Experiments

- Examine effects of **resonance crossing** and the importance of which resonance is crossed;
- **Measurement of TOF**, and minimum of TOF by changing the frequency until no synchrotron oscillations are seen and calculating the TOF from the frequency;
- Look at relationship of TOF to lattice parameters and tune and tune versus energy using BPM readings;
- **Map longitudinal & transverse phase**;
- **Benchmark lattice properties** achieved to the simulations;
- Study the variation of “all parameters” to lattice properties;
- Interpretation of BPM readings;
- Examine phase space at injection by changing septum and kicker settings to validate models;
- Scan aperture in phase space with a pencil beam to paint the full acceptance of the EMMA ring (both longitudinally and transversely);
- Explore acceptance with and without acceleration;
- Benchmark measured dynamic aperture with and without acceleration against the simulations

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SCHEDULE

Schedule

Off line build of modules	Oct 2008 - Aug 2009
Installation in ALICE Accelerator Hall	Mar - Sep 2009
Test systems in Accelerator Hall	Jul - Oct 2009
Injection line ready for beam	Aug 2009
EMMA ring ready for beam	31st Oct 2009
1st beams in to EMMA	Nov 2009

SUMMARY

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Summary

- Design phase of the project is complete
- Procurement is underway with major contracts placed
- Major components started to arrive in October 2008,
- Off-line build is in progress at Daresbury and installation of the ALICE to EMMA injection line is underway
- Will commission the injection line in late August
- Plan to deliver 1st electrons into the ring in November

A key aim is to:-

Show non scaling FFAG acceleration works, compare results with the theoretical studies and gain real experience of operating such accelerators

The next step will be to apply the lessons learnt to new applications!

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