Science & Technology Facilities Council

BASROC CONFORM

TECHNICAL DESCRIPTION AND STATUS OF THE EMMA NON-SCALING FFAG

Neil Bliss **3rd October 2007**

CYCLOTRONS

18th International Conference on Cyclotrons and their Applications 2007

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- EMMA Aims & Objectives
- ERLP injector
- EMMA Technology decisions & status
- Project Specification, Cost and Timescales
- Conclusions and next steps

BASROC

- British Accelerator Science and Radiation Oncology Consortium
- BASROC is an umbrella group of academic, medical and industry specialists in accelerator and medical technology with the aim of promoting the use of accelerators in science, industry and medicine. More detail at www.basroc.org.uk/
- BASROC will sponsor and provide oversight to projects, such as the CONFORM Project

CONFORM

- BASROC has been successful in being awarded its first grant from RCUK BASIC TECHNOLOGY RESEARCH PROGRAMME
- Project Name is CONFORM (COnstruction of a Nonscaling FFag for Oncology, Research, and Medicine) www.conform.ac.uk/
- Total funds £6.9m over 3.5 year project lifecycle
- Project start date was 1st April 2007
- Project leader is Professor Roger Barlow, University of Manchester and The Cockcroft Institute
- 3 parts to the project are funded
  - EMMA design and construction
  - PAMELA design study
  - Applications study

CONFORM

- EMMA: The Electron Model for Many Applications. It is a design and construction project for a 10-20 MeV electron accelerator. It will be an entirely experimental machine used to learn how to design ns-FFAGs for a variety of applications. It will be built at Daresbury Laboratory using the Energy Recovery Linac Prototype (ERLP) as the electron injector
- PAMELA: The Particle Accelerator for MEdicaL Applications. It is a design study for a proton ns-FFAG that we can submitted to a funding agency. "Energy/No. of rings under discussion". It will be a prototype(s) to demonstrate biological experiments leading to a medical ns-FFAG to be realised in practice for hadron therapy. With the intention to build a complete facility for the treatment of patients using hadron beams. It is planned to construct PAMELA it in a new building on the Churchill Hospital site in Oxford for the Department of Radiation Oncology and Biology and strengthen the case for hadron therapy in UK
- Applications: Work package to focus on exploitation of FFAG technology in a wider context than just medical applications

Project Management

- CONFORM Project leader and Principle Investigator is Professor Roger Barlow, University of Manchester and The Cockcroft Institute
- Chair of Project Board and Project Sponsor is Professor Mike Poole, STFC, Director of ASTeC and The Cockcroft Institute
- EMMA - Project leader: Dr Rob Edgecock, STFC RAL, funding - £5.6m
- PAMELA - Project leader: Professor Ken Peach John Adams Institute for Accelerator Science, University of Oxford *and* Royal Holloway, University of London funding - £865k
- Applications - Project leader: Dr Karen Kirkby, University of Surrey funding - £273k

EMMA Collaboration

- We are holding regular phone meeting (every 2 or 3 weeks)
- Project Reviews held at Daresbury
  - Hardware review on 1 July 06
  - Design Reviews on 4 Jan 07 and 26 Feb 07
- Active participation:
  - Brookhaven National Laboratory
  - CERN
  - Fermi National Accelerator Laboratory
  - Laboratoire de Physique Subatomique et de Cosmologie
  - Science & Technology Facilities Council UK
  - John Adams Institute UK
  - The Cockcroft Institute UK
  - TRIUMF
  - ………..
- Presentations stored on the CONFORM web page at https://www.conform.ac.uk/documents/emma/ec%20-%20emma%20collaboration%20meetings/

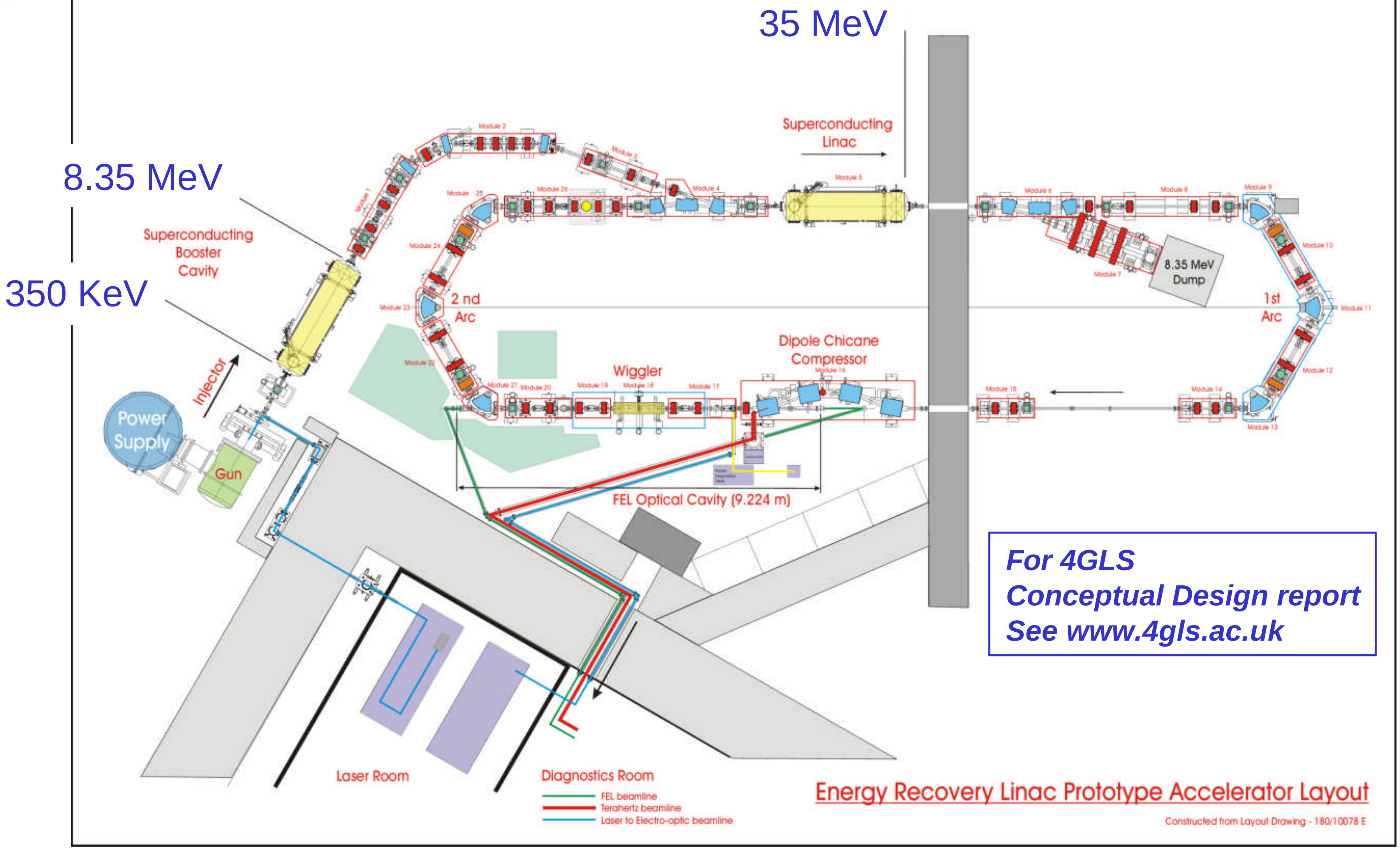
Aims & Objectives of EMMA Project

- Prove that a NS-FFAG can successfully accelerate particles
- Study linear non-scaling FFAGs under particular circumstances
  - Rapid acceleration
  - Relativistic energies
  - Main application currently: muon acceleration
- Two important characteristics of non-scaling FFAG lattices
  - Rapid acceleration through many resonances
  - Unique longitudinal dynamics

Aims & Objectives of EMMA Project cont.

- To test our understanding of the underlying dynamics
  - How does emittance growth depend on which resonances we cross?
  - How does longitudinal behaviour change with machine parameters
    - RF frequency
    - Energy where machine is isochronous
  - Coupling of transverse and longitudinal motion
  - What effect do errors have on performance
    - Magnet position
    - Field strength
    - RF phase errors
- Use the information gained to inform the design of PAMELA and Applications sub projects

ERLP

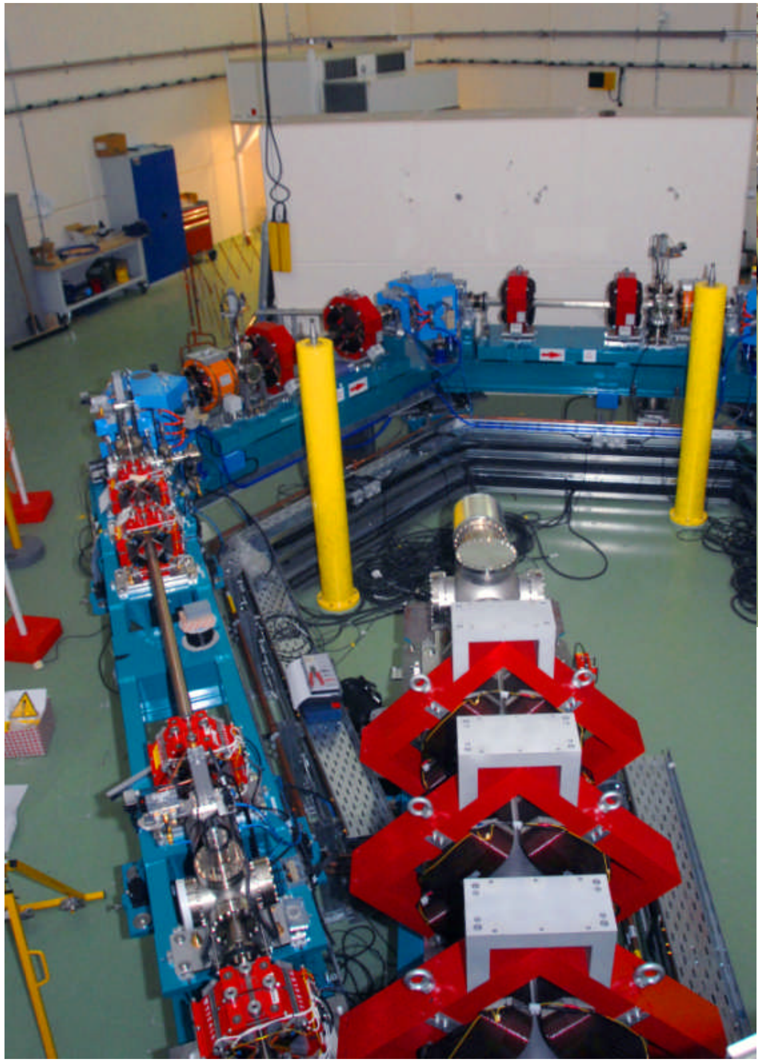


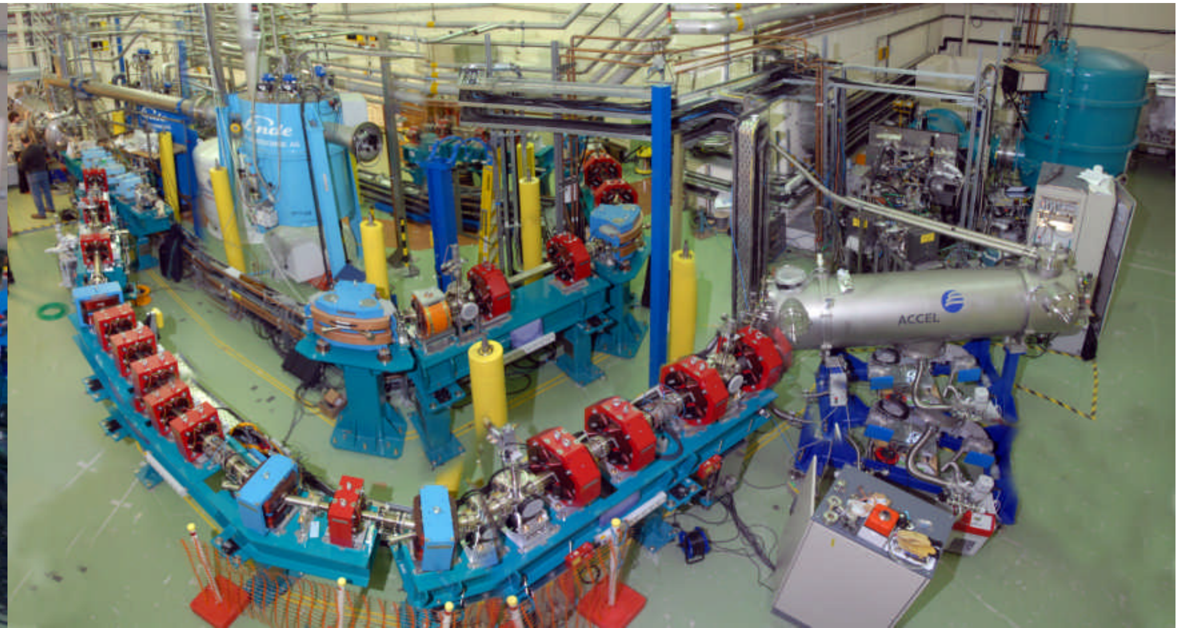
For 4GLS
Conceptual Design report
See www.4gls.ac.uk

ERLP Parameters

Parameter	Value
Nominal Gun Energy	350 keV
Max. Booster Volts	8 MV
TL 2 Energy	8.33 MeV
Max. Linac Volts	26.67 MV
Max. Energy	35 MeV
Linac RF Frequency	1.300 GHz (+/- 1 MHz)
Bunch Repetition Rate	81.25 MHz
Bunch Spacing	12.3 ns
Max Bunch Charge	80 pC
Particles per Bunch	5×10^8

ERLP Injector

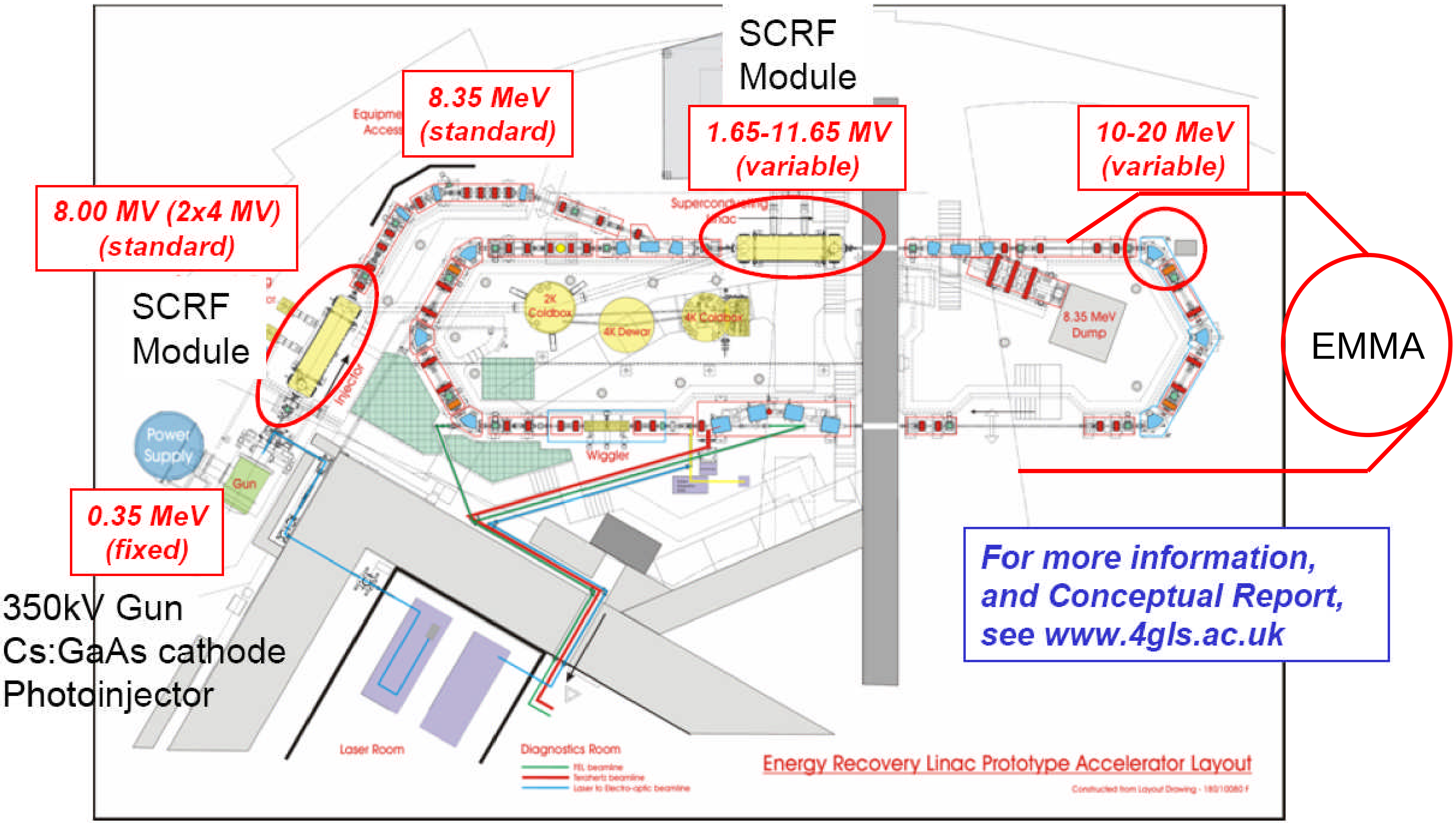




Currently commissioning

- All modules are now installed and under vacuum
- Currently commissioning
- Stable cryogenic systems at 2K (1.8K)
- SCRF Modules are currently being commissioned with RF
- Photoinjector commissioned 22 Nov 07
- Beam through Module 1 (8.35 MeV) 14 Jan 08
- Beam through Module 2 (35 MeV) 14 Feb 08
- **Energy recovery demonstrated** 20 Mar 08

ERLP Injector



For more information, and Conceptual Report, see www.4gls.ac.uk

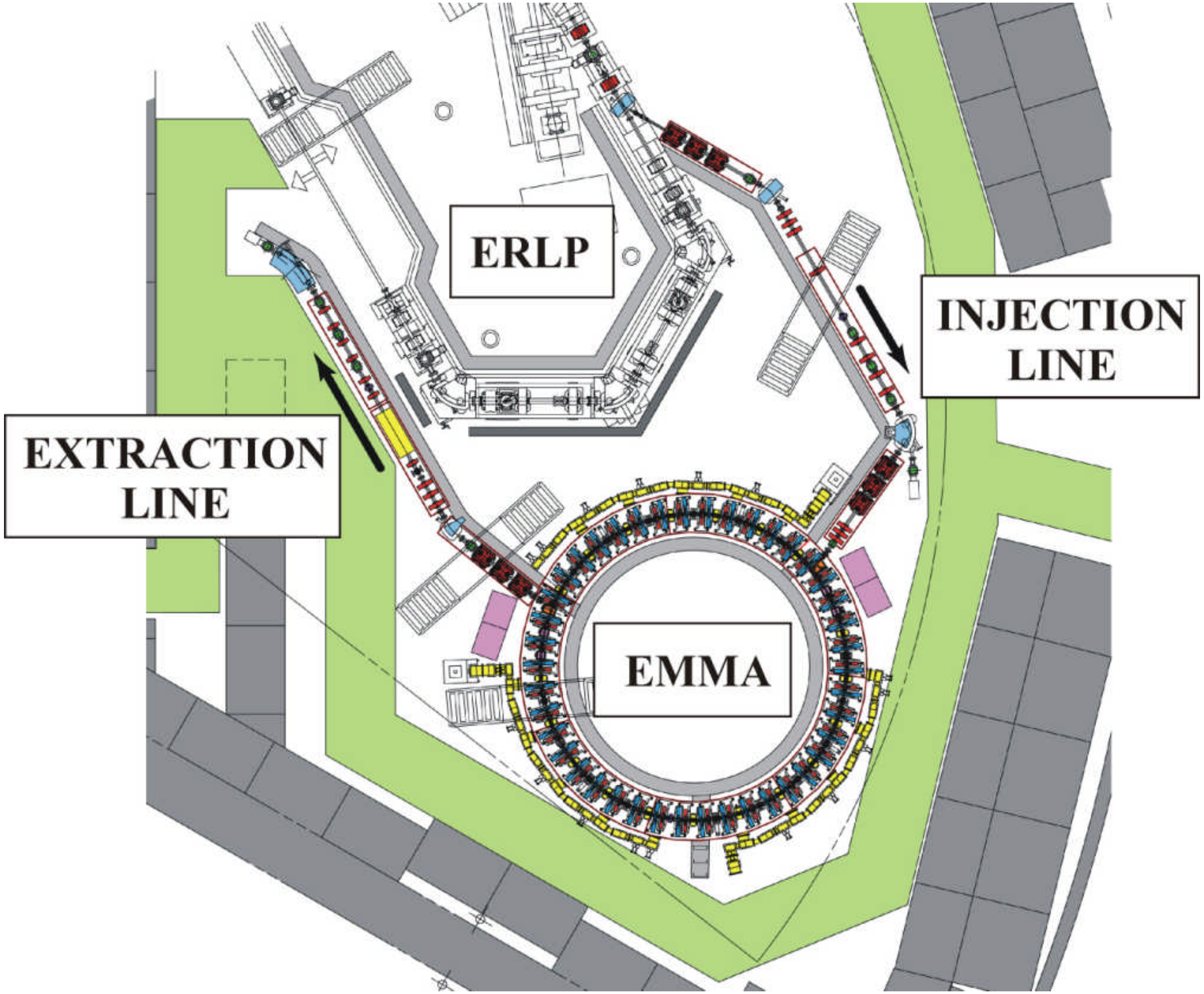
EMMA Basic Parameters

Energy range	10 – 20 MeV
Lattice	F/D Doublet
Circumference	16568.202 mm
No of cells	42
Normalised transverse acceptance	3 mm
Frequency (nominal)	1.3 GHz
No of RF cavities	19
Average beam current	13 • A
Repetition rate	1, 5, 20 Hz
Bunch charge	16-32 pC single bunch

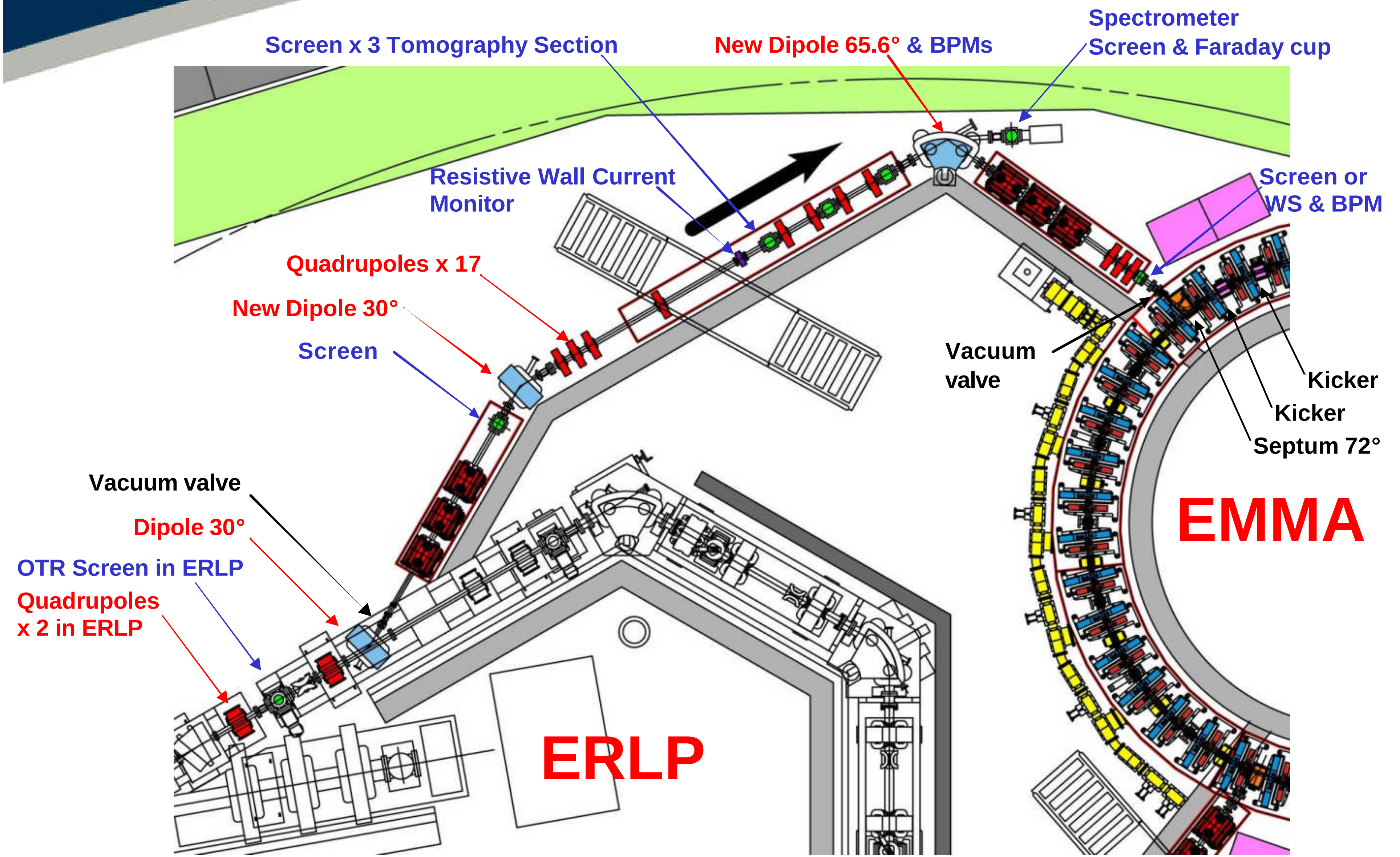
EMMA LAYOUT

Building constraints:

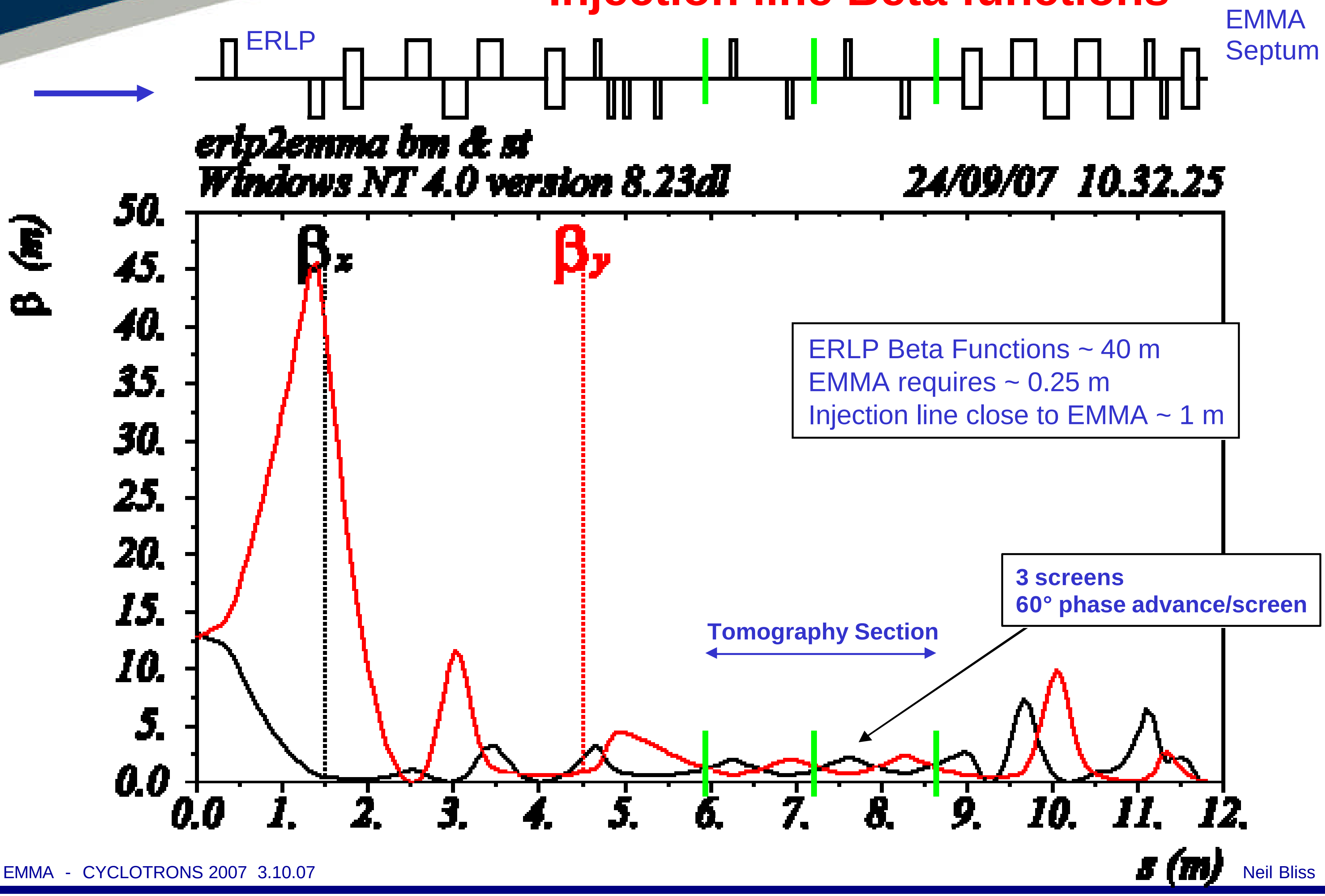
- Injection line
- Diagnostic beamline
- Position of ring



INJECTION LINE



Injection line Beta functions



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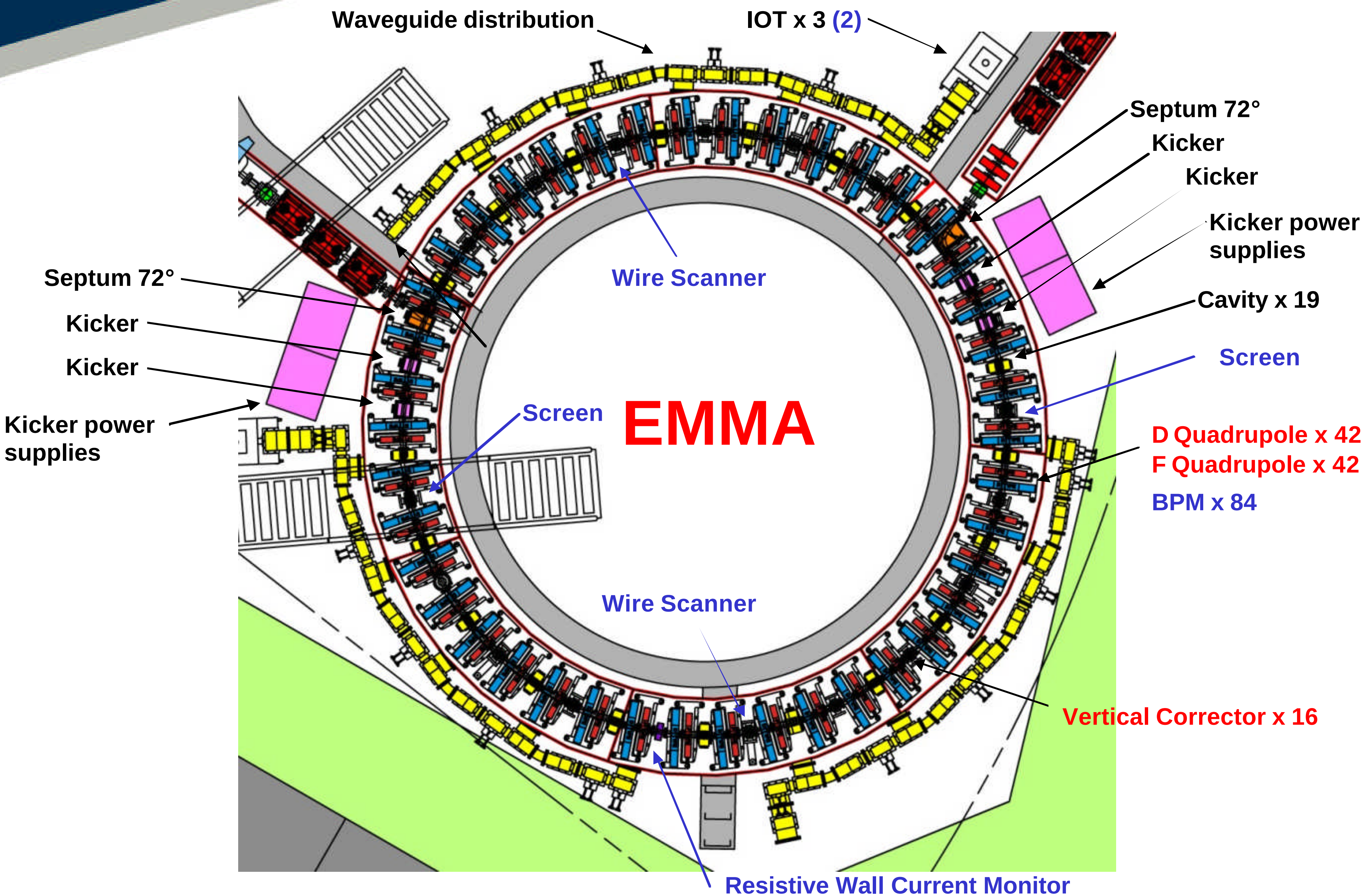
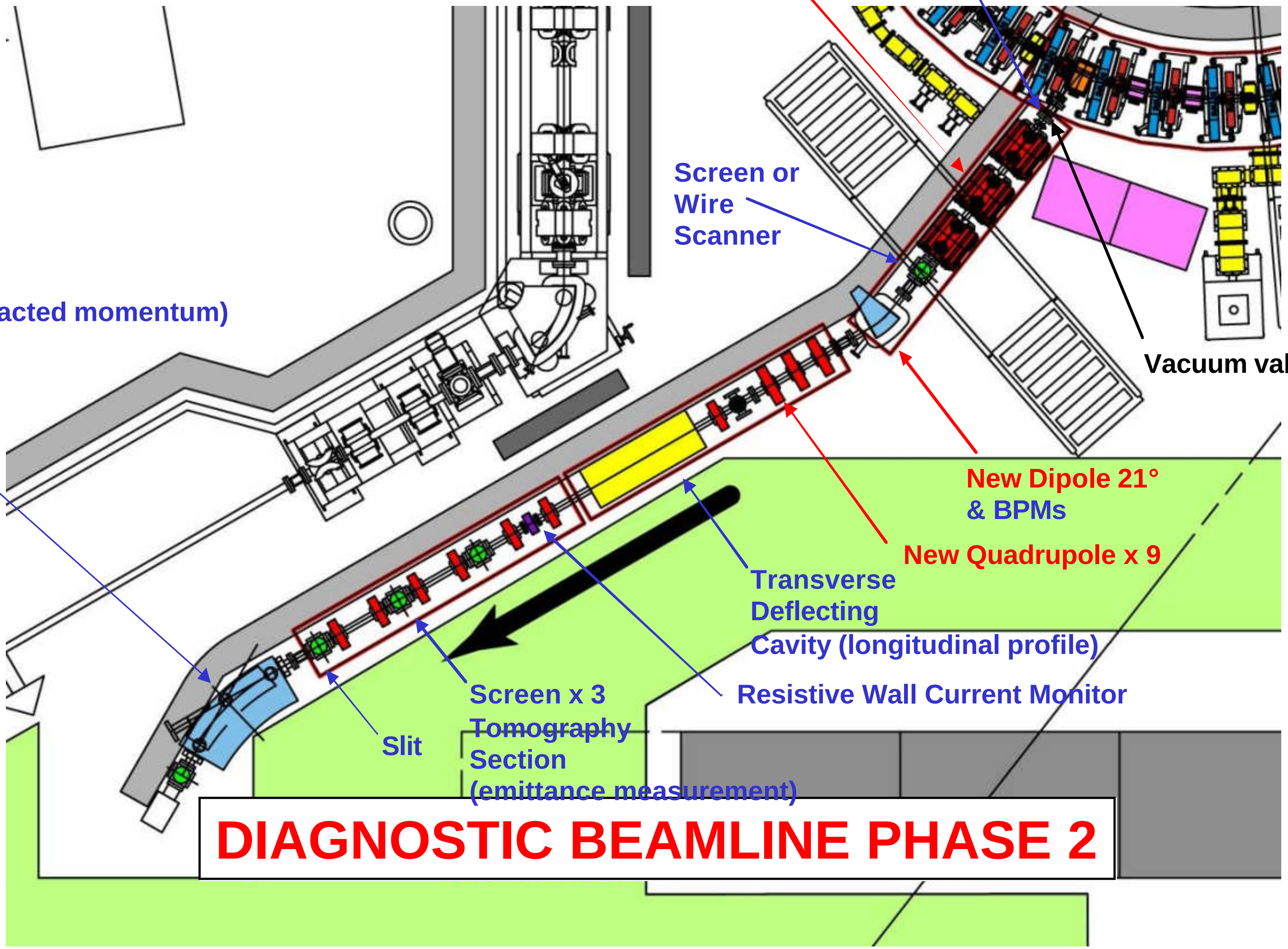
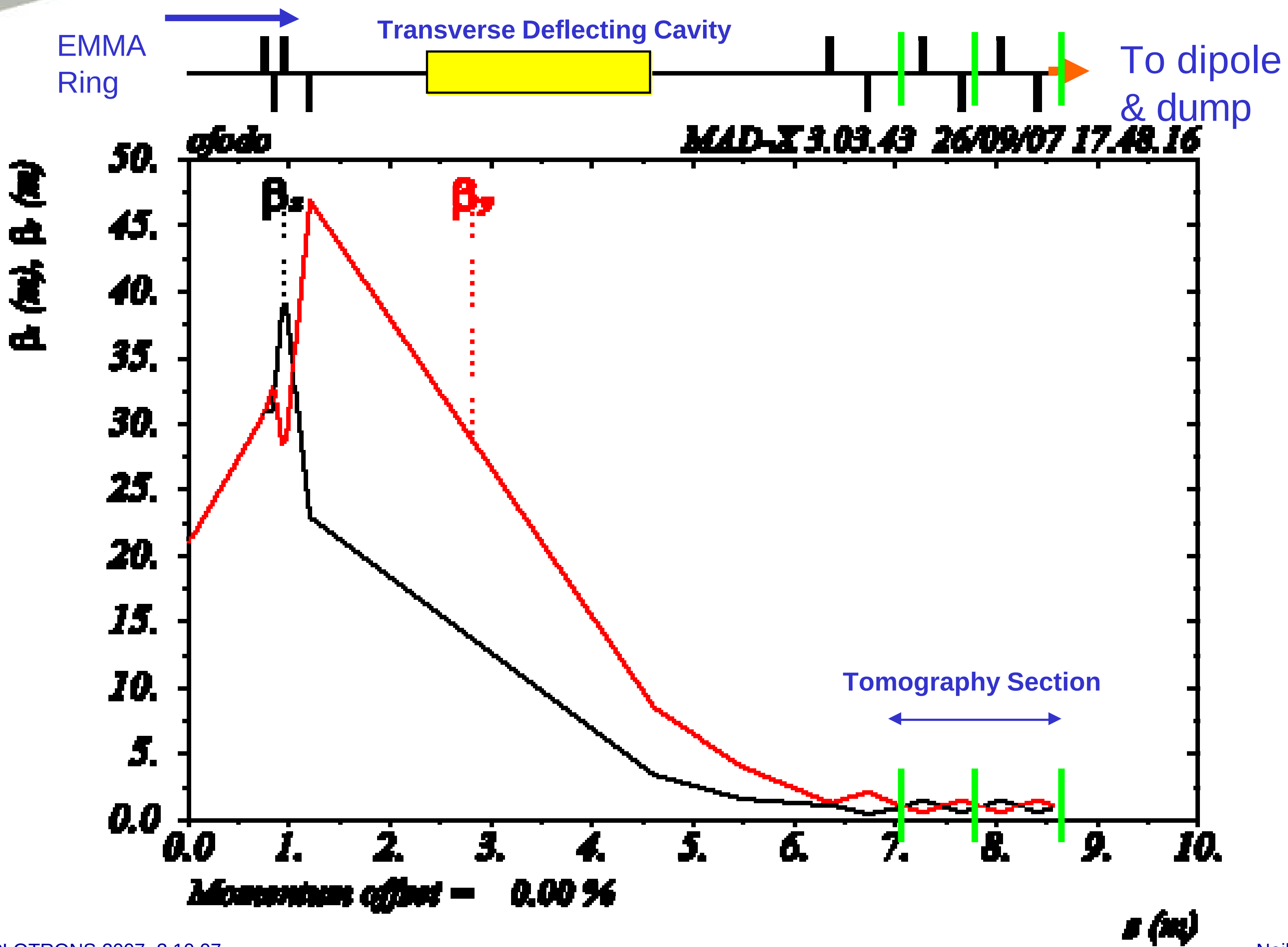




DIAGNOSTIC BEAMLINE PHASE 2

Diagnostics Beamline Beta functions



The FFEMMAG Computer Code

Stephan Tzenov

- The FFEMMAG Code, which is under development at DL is a computer programme to simulate the reference orbit, the accelerated orbit, dispersion and lattice functions of EMMA. It:

1) Calculates the accelerator modes of the reference orbit map;
2) Solves the equations for the accelerated orbit and determines the median plane beam footprint;
3) Calculates the dispersion function;
4) Calculates the generalized Twiss parameters, as well as the betatron tunes.
5) Future plans to extend the code include simulations of the dynamic aperture and resonance crossings.

Cell Drawing

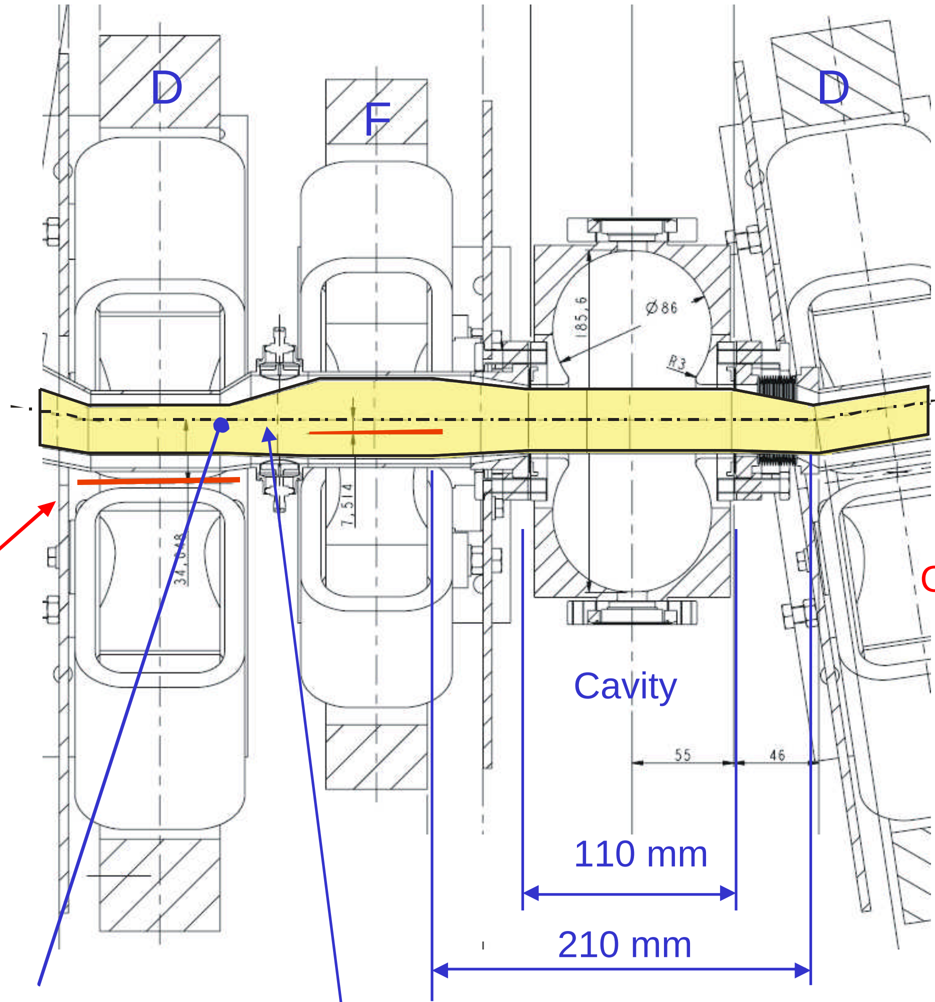
- 42 identical cells
- Cell length 394.481 mm

- D, F magnet and Cavity all parallel

Long drift	210.000 mm
F Quad	58.782 mm
Short drift	50.000 mm
D Quad	75.699 mm

Magnet Reference Offsets
D = 34.048 mm
F = 7.514 mm

Magnet Yoke Lengths
D = 65 mm
F = 55 mm



Beam Aperture Requirements

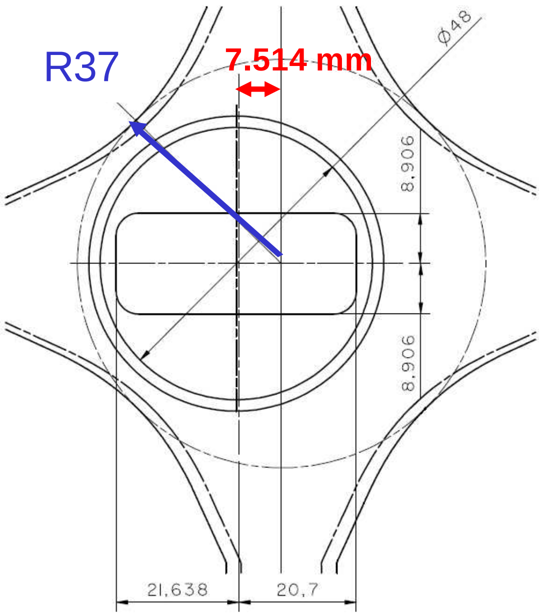
	D	F	Cavity
Min. hor. chamber	-7.416 mm	-21.638 mm	-16.936 mm
Max hor. chamber	+18.789 mm	+20.700 mm	+17.814 mm
Half height	± 11.676 mm	± 8.906 mm	± 10.571 mm

+ ve towards outside of ring
- ve towards inside of ring

Vacuum Chamber Apertures

Magnet translation

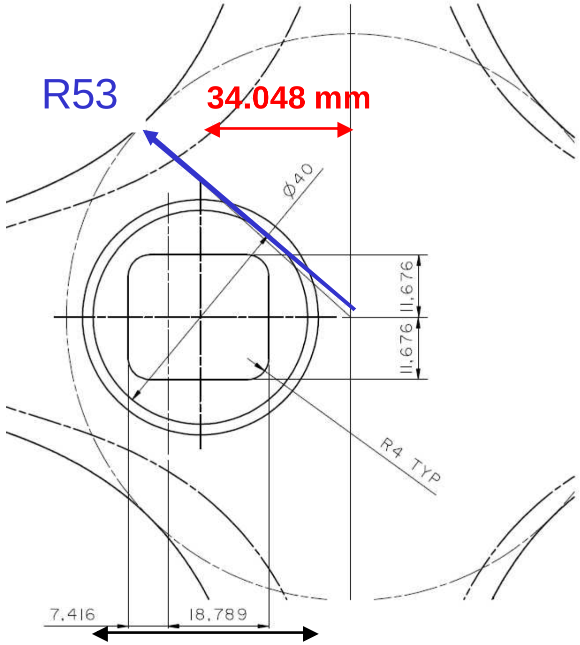
- 2.611 mm +2.698 mm



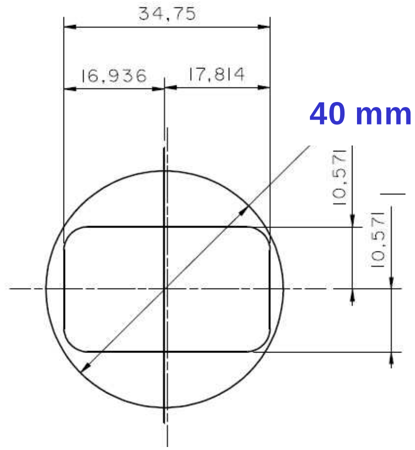
F Magnet Section
Tube OD 52 mm, ID 48 mm
Seamless tube St. St. 316L

Magnet translation

- 5.297mm +14.511mm



D Magnet Section
Tube OD 44 mm, ID 40 mm
Seamless tube St. St. 316L



Section thro. Cavity
ID 40 mm

4 CELLS

Without field clamp plates shown

Pop in Diagnostics
Screens 2 per ring
Wire scanners 2 per ring

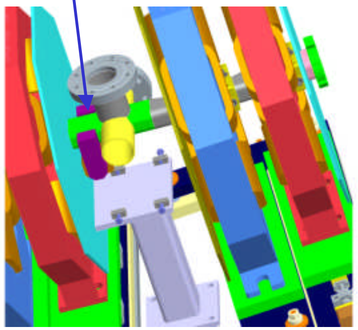
D Magnet
42 per ring

F Magnet
42 per ring

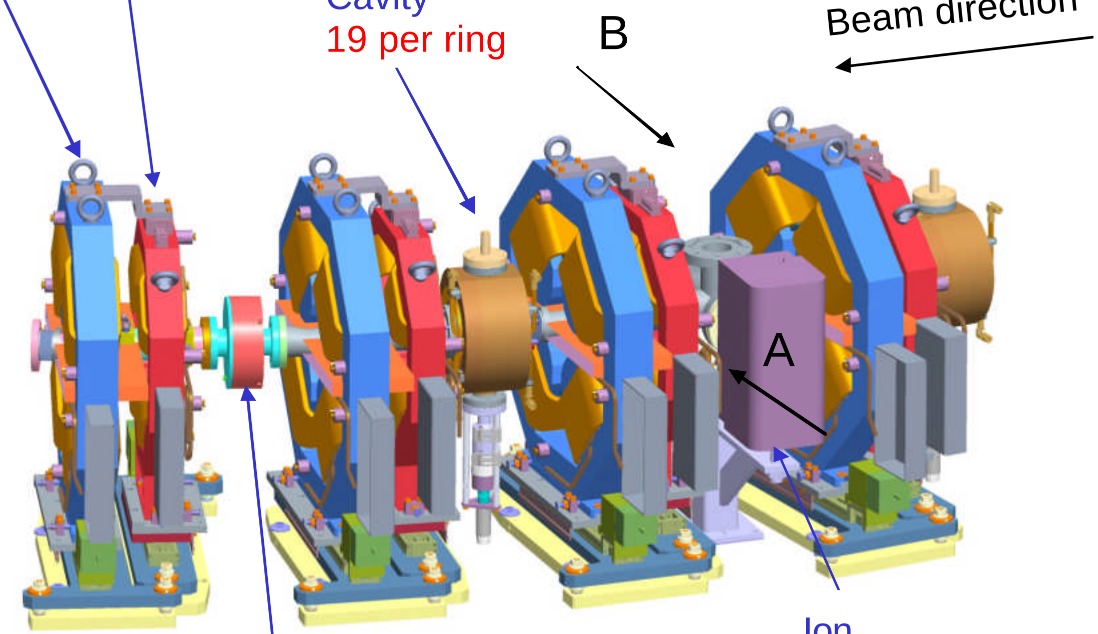
Vertical corrector
16 per ring

Cavity
19 per ring

Beam direction



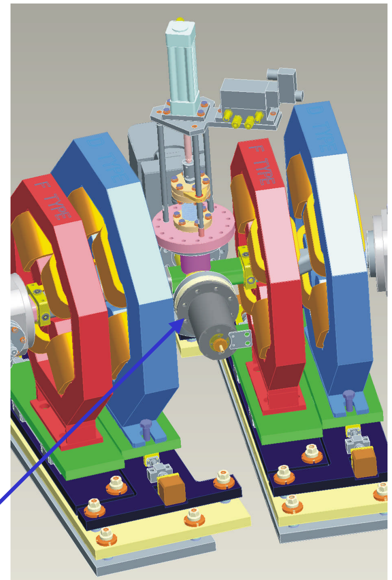
View on A
with Ion Pump removed
Field clamp plates shown



Resistive wall monitor
1 per ring

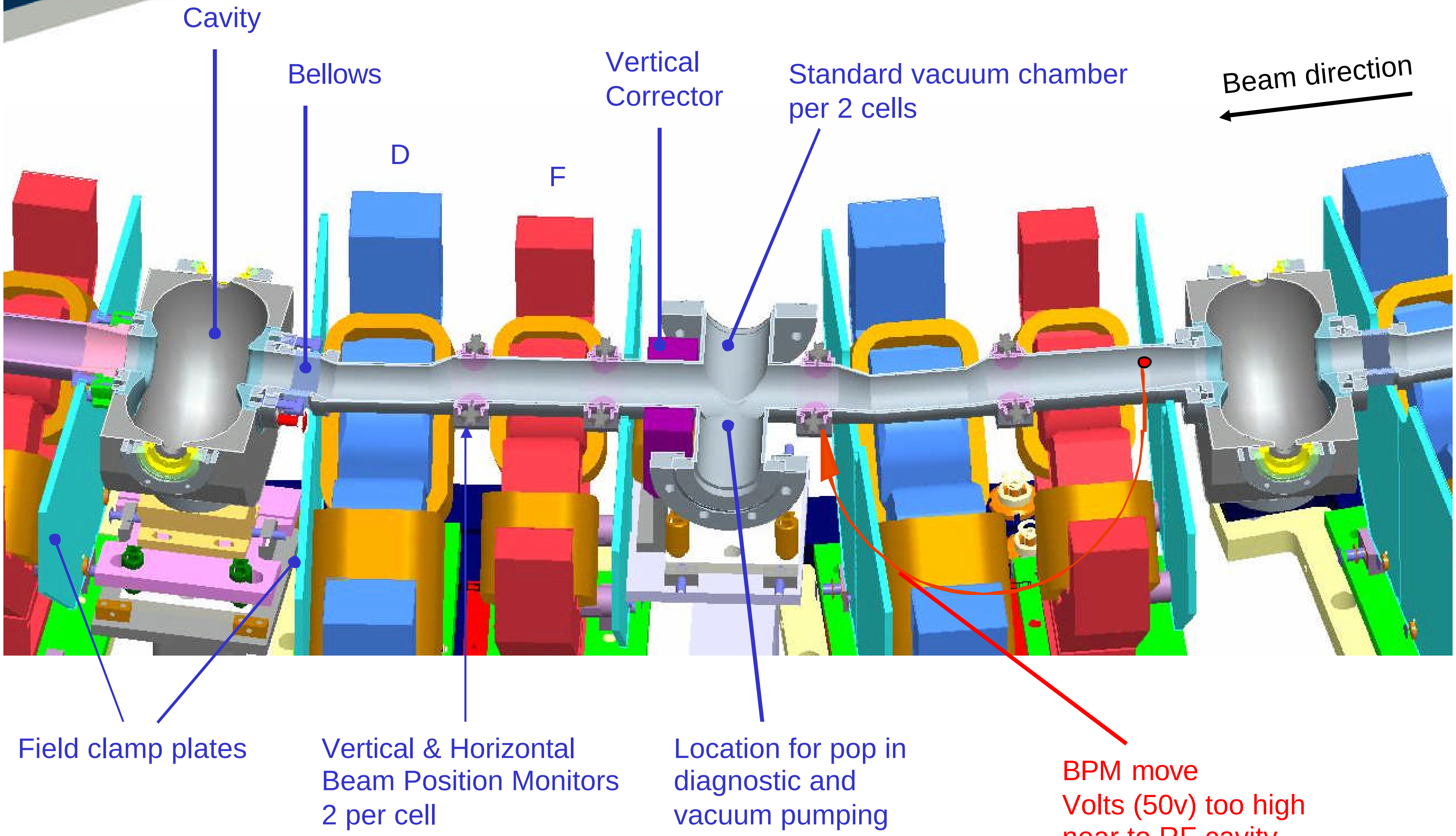
Ion
Pump
location

Screen Camera



View on B
with screen shown

2 Cell Section

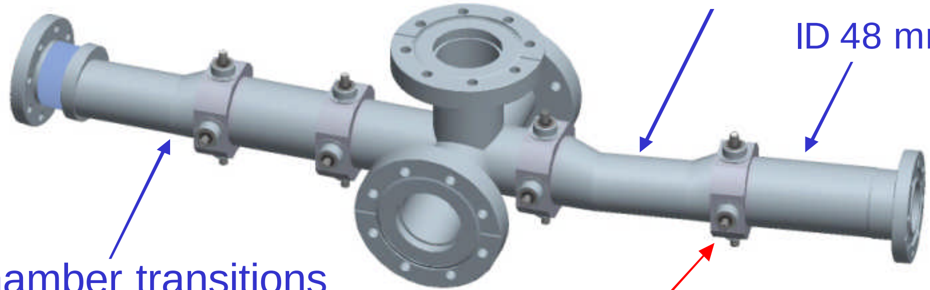


BPM Detail

Standard vacuum chamber
for 2 cells. Circular cross-section
Material - stainless steel

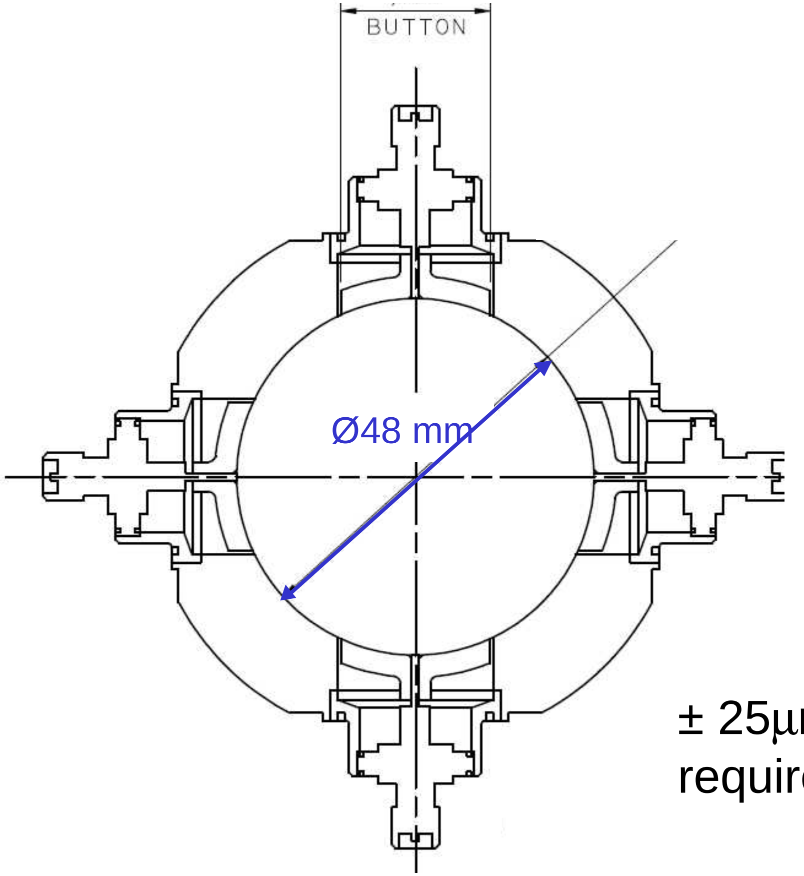
ID 40 mm

ID 48 mm



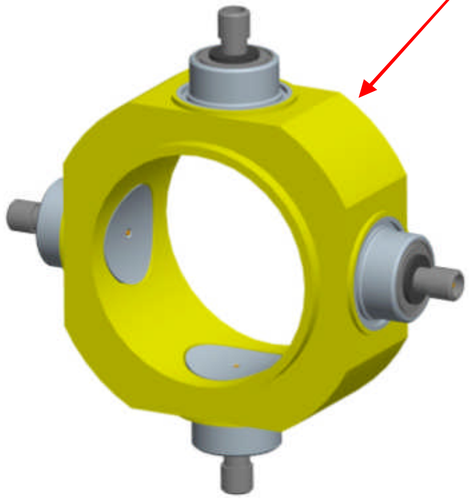
Chamber transitions

20 mm (~• d/8)



Cross-section

± 25µm r.m.s.
required resolution



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

Ring Magnet Design

Magnet Type	Units	QD	QF
Quantity		42	42
Inscribed radii	mm	53.0	37.0
Good gradient region	mm	-56.0, -9.9 (±32) 3D modelling results	+15.8, -32.0 (±22.9)
Good gradient quality	%	± 0.1	± 0.1
Gradient strength (standard)	T	0.367	-0.403
Gradient strength (max)	T	0.440	0.483
Translation	mm	+14.5 -5.3	+2.7 -2.6

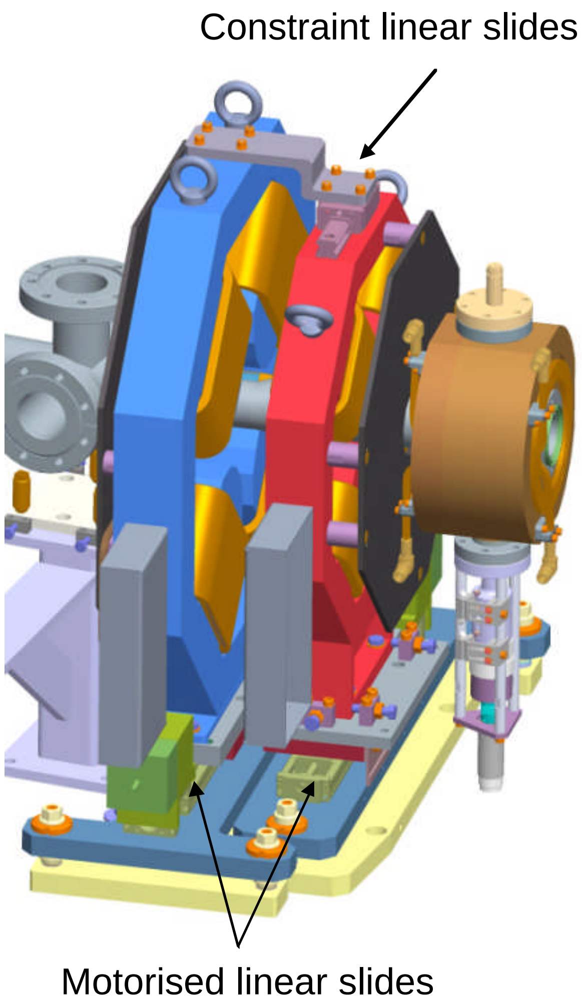
- Yoke thickness is the same order as the inscribed radii, end effects dominate
- Interaction between the 2 magnets being taken into consideration
- Full 3D modelling in CST EM Studio and results cross-checked with OPERA-3D
- Straight line pole face adopted to improve good field region. Only ±14 mm for F with conventional hyperbolic pole face

Five pole face facet design for both F & D

Ring Magnet Design Cont.

- Decision made that field clamp plates are required
- Adding field clamp plates reduce the field in BF by 11% and BD by 18%
- Field clamp plates are attached to and move with the magnets
- Hole in field clamp plate is the same as the pole shape
- Additional constraint linear slide at the top of the magnets implemented to maintain alignment tolerances

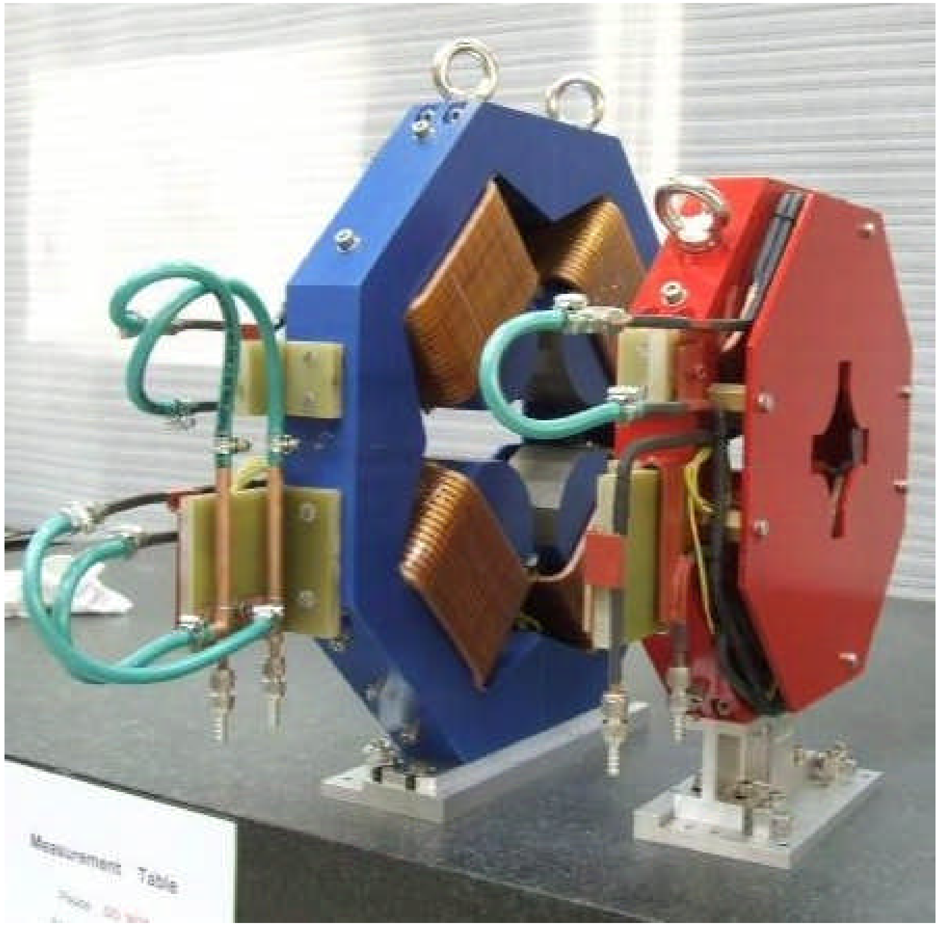
Parameter	**F magnet**	**D magnet**	**Units**
Current	213.4	263.5	A
Turns in coil	11	11	
Yoke thickness	55	65	mm
Pole width	73	100	mm



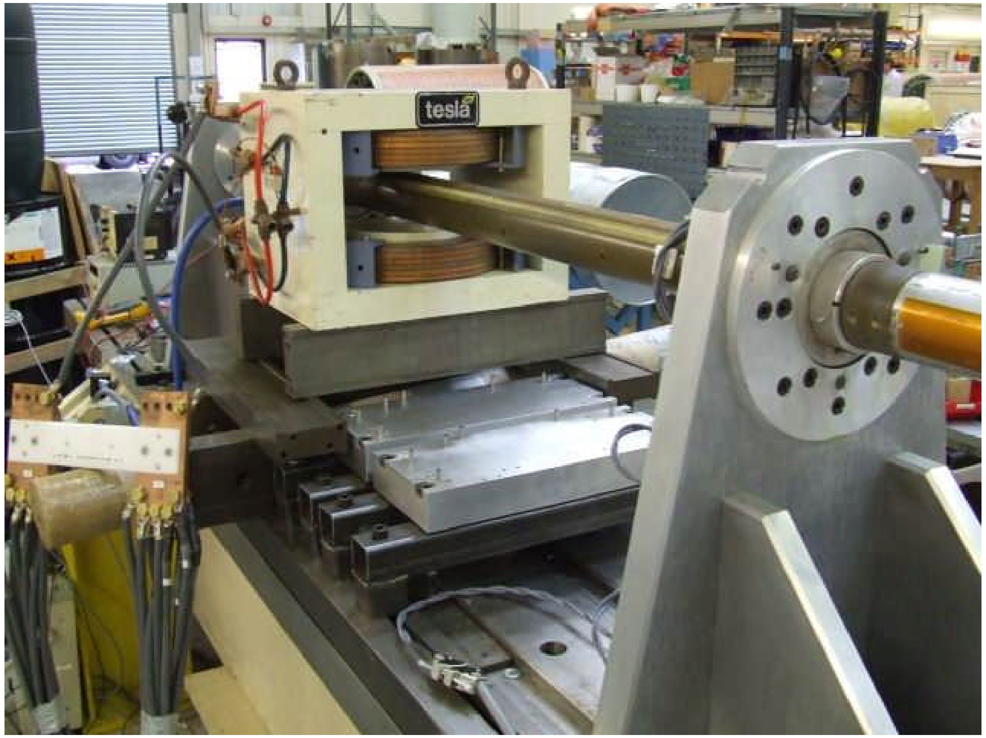
Ring Magnet Timescales

- Prototype magnets are constructed and magnet measurements at supplier has started
- OJEC tender exercise for production magnets is due to start this month (October 2007)
- Delivery of production magnets required 16 Jun - 1 Aug 2008

Ring Magnet Prototypes



D & F Prototype magnets

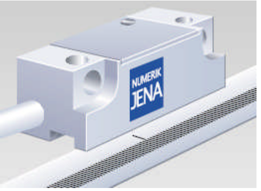


Rotating Coil Bench

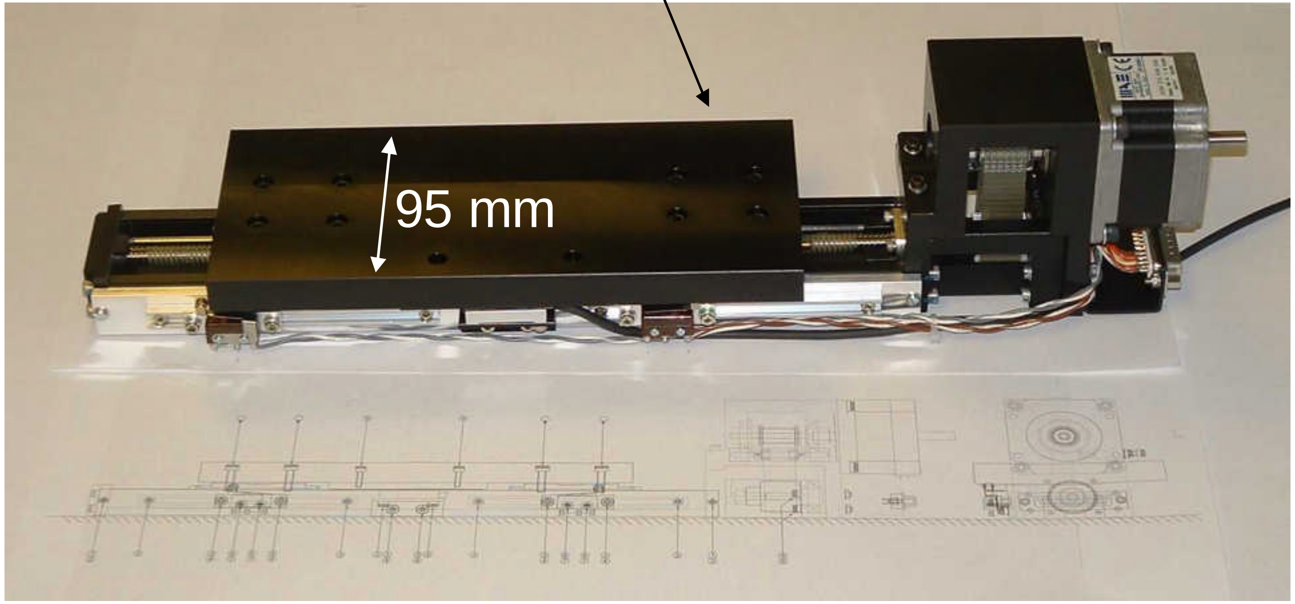
Magnet Linear Slide

Model Type	Rail Length (mm)	Positioning Accuracy reproducibility over 300mm (mm)	Running Parallelism over 300mm (mm)
THK KR26	300	±0.003	0.01

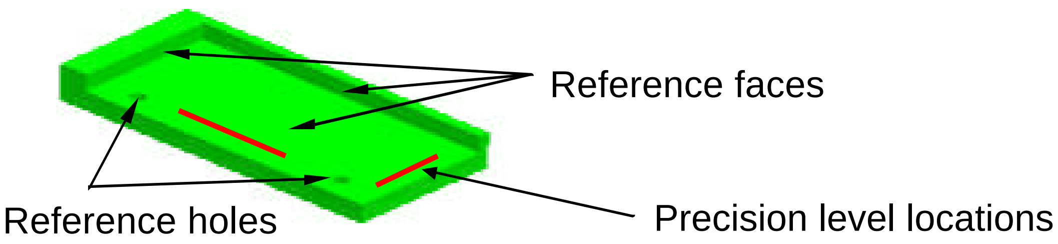
THK slide with motor, limit switches and NUMERIK JENA linear encoder 1 micron repeatability



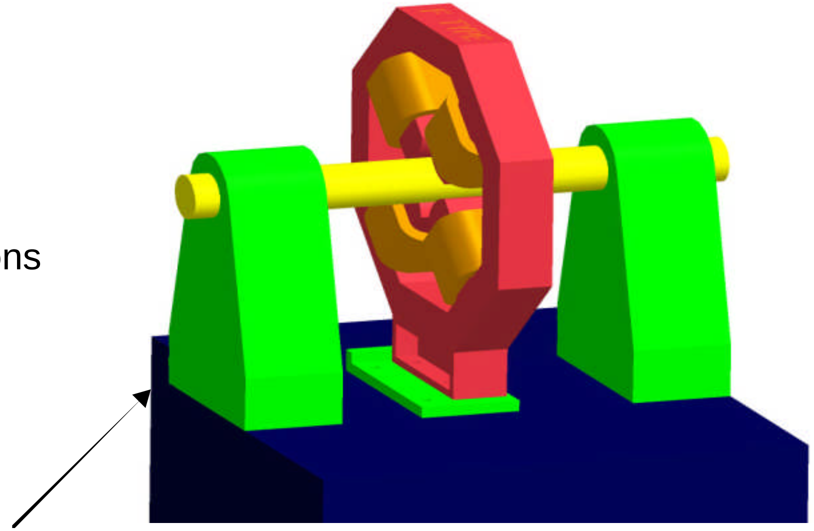
• Closed loop drive
• Planning to measure the accuracy of these slides over the magnet movement range DQuad = 20 mm, FQuad = 6 mm
• Budget for assembly – slide, motor, limit switches, belt drive, encoder and motion controller only £1.84k



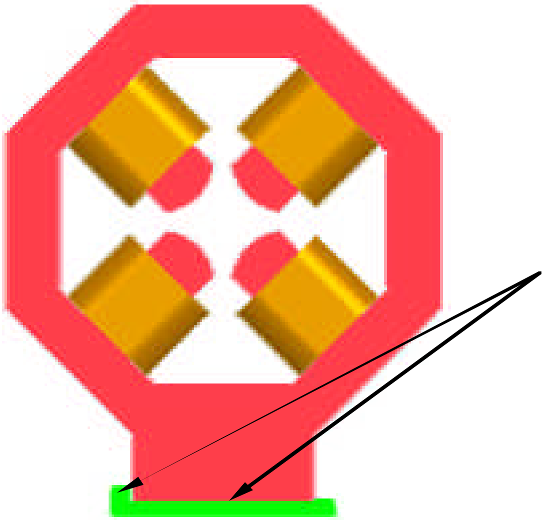
Magnetic centre fiducialisation



Survey plates under magnets with holes
that take the laser tracker reflector spheres



- Alignment edges on rotating coil bench
- Survey plates aligned to rotating coil centre with shims

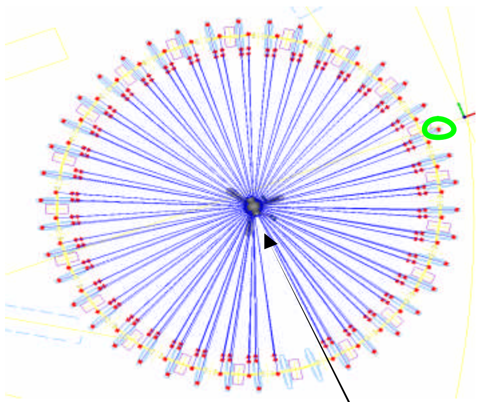


Relative
adjustment

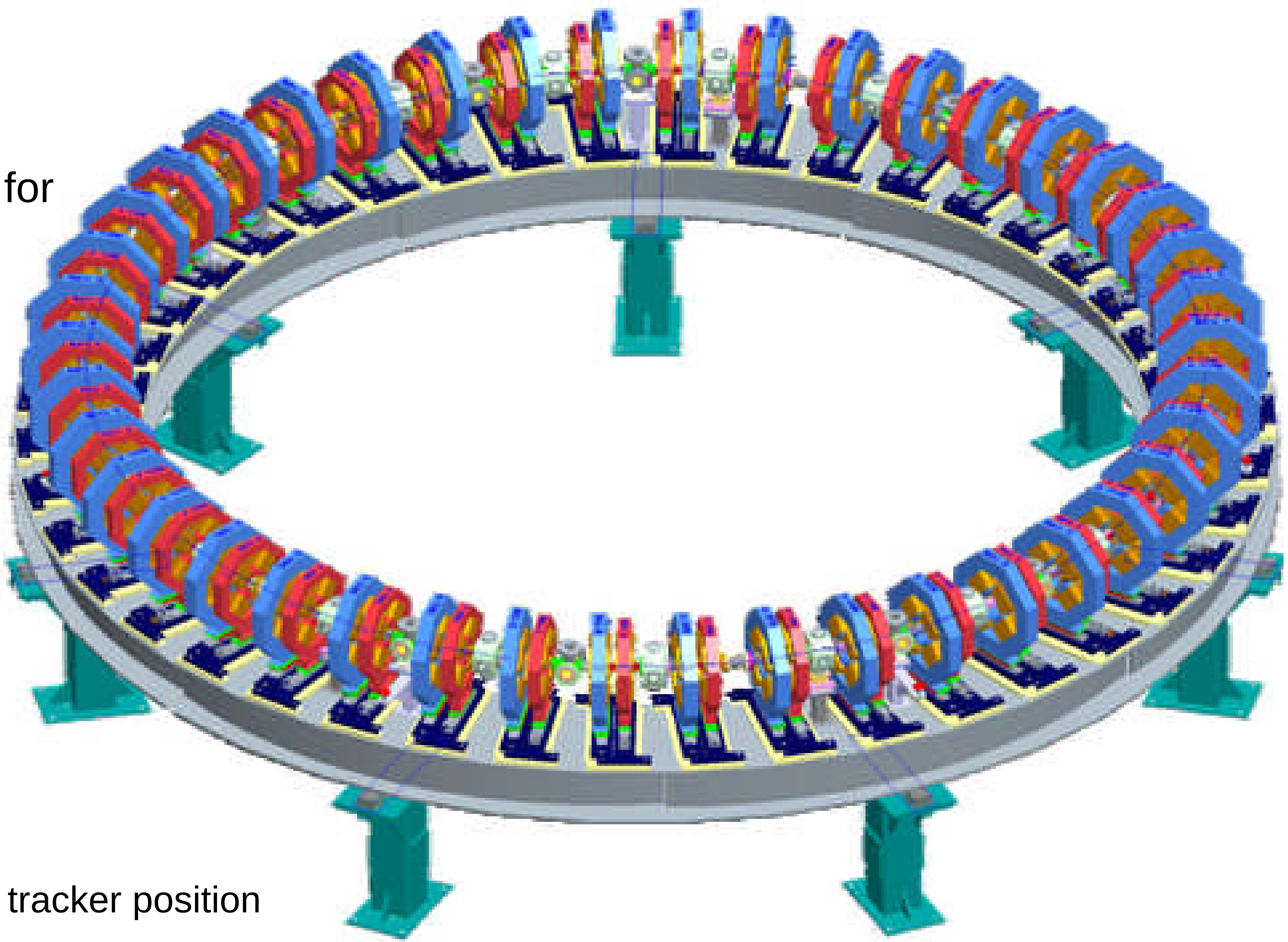
+/- 25• m (1•)

EMMA Ring

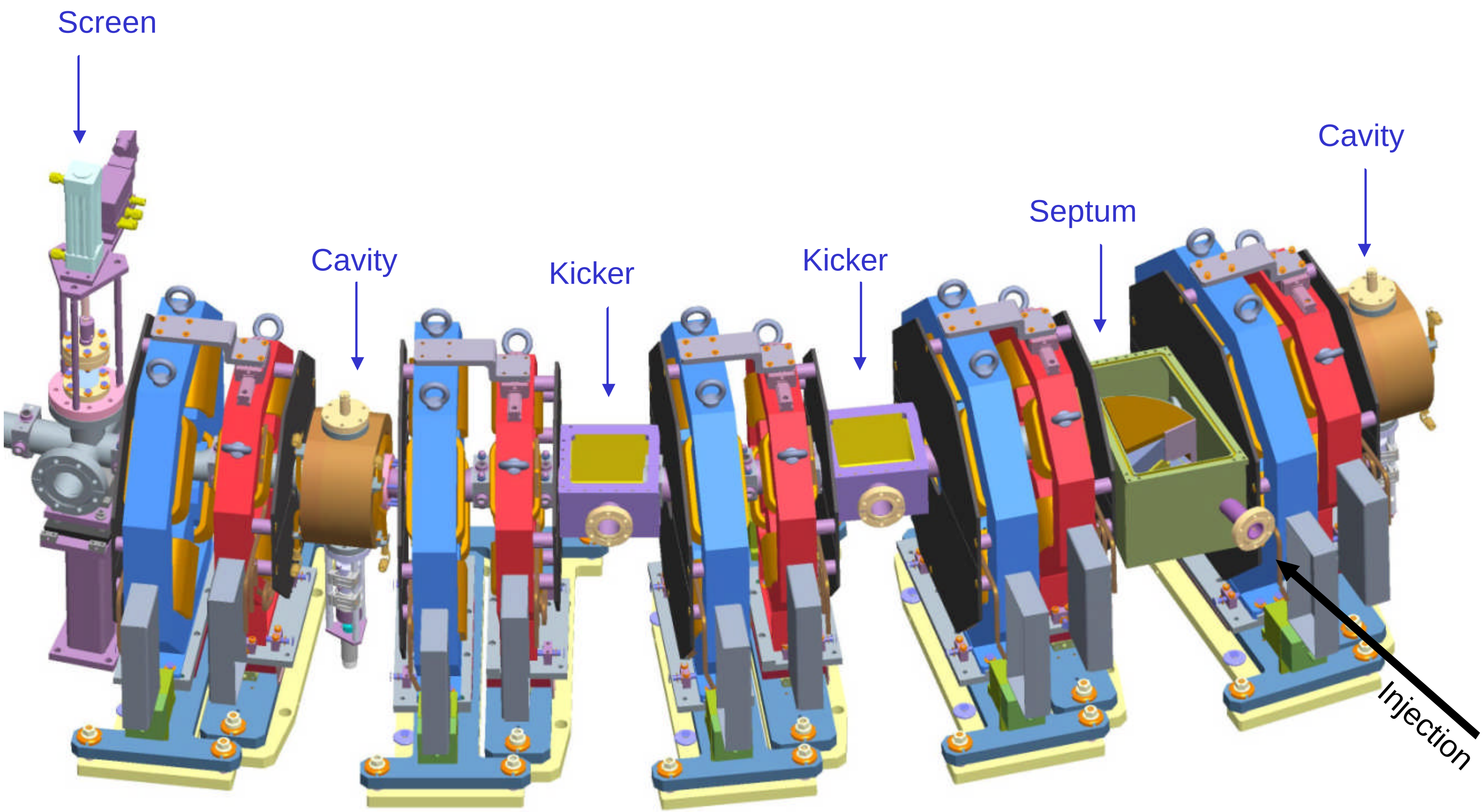
- Magnetic centre fiducialisation **+/- 25• m (1•)**
- Individual Magnet alignment
- **+/- 25• m (1•)**
- Keep centre of the ring clear for laser tracker lines of site
- Single girder concept constructed from 7 sectors



Single laser tracker position

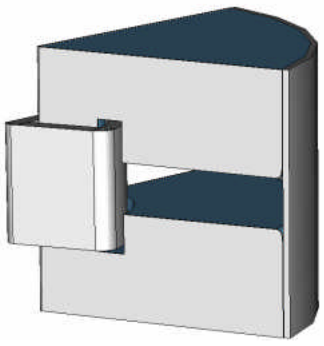


Injection Region



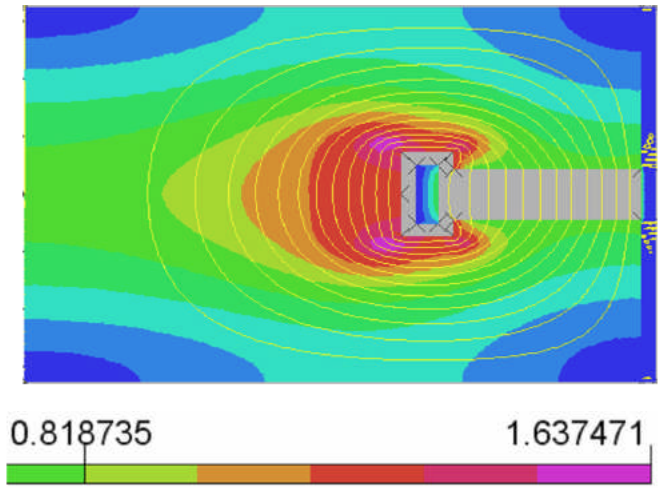
Septum Magnet design

- 2D work complete
- Particular attention has been paid to avoiding the possible saturation of the core material since the latter would limit the field strengths in the magnet gap and prevent high-energy operation
- Max. flux density in the magnet core is of the order of 1.6 T at 20 MeV
- 3D work in progress to ensure that stay fields do not affect the circulating beam



Design concept

Bending angle	72^{o}
Driving current amplitude 10 – 20MeV	4.9 – 9.8 kA
Outer radius	• 115 mm
Inner radius	• 80 mm
Pole gap	18 mm
Inductance	• 0.32 • H
Averaged eddy current heating (20 MeV, 10 Hz)	• 2.5 W



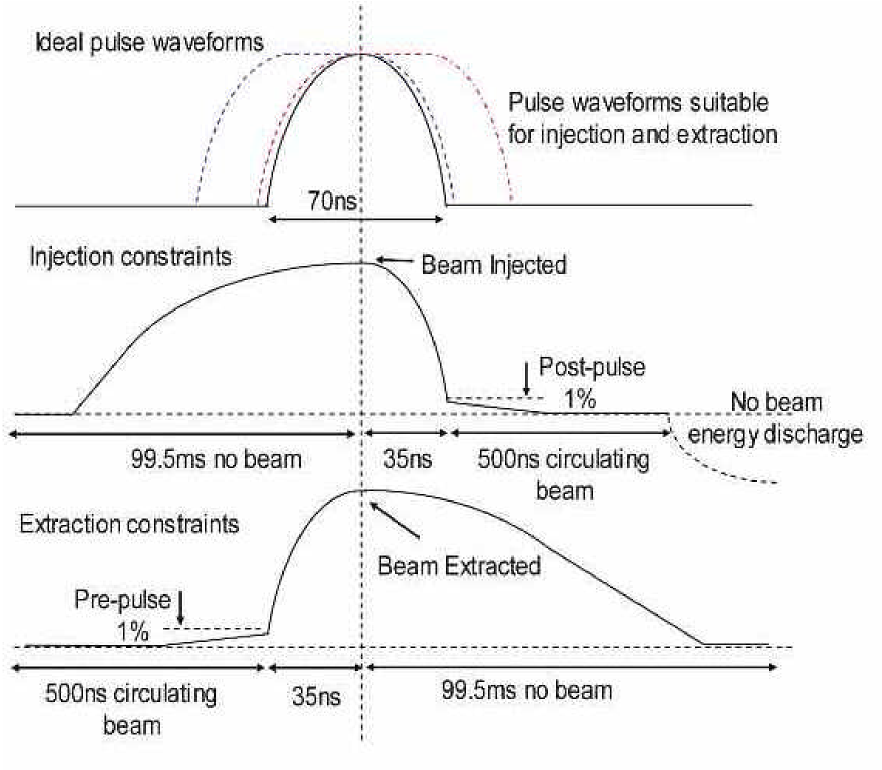
2D flux-density distribution

EMMA 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	Half Sinewave

Kicker Magnet Power Supply parameters are directly affected by the compact design and require:

- Fast rise / fall times 35 nS
- Rapid changes in current 50kA/µS
- Constraints on Pre and Post Pulses 2nS



Applied Pulse Power Collaboration

Design and construction of thyristor prototype units using magnetic switching and Pulse Forming Network techniques

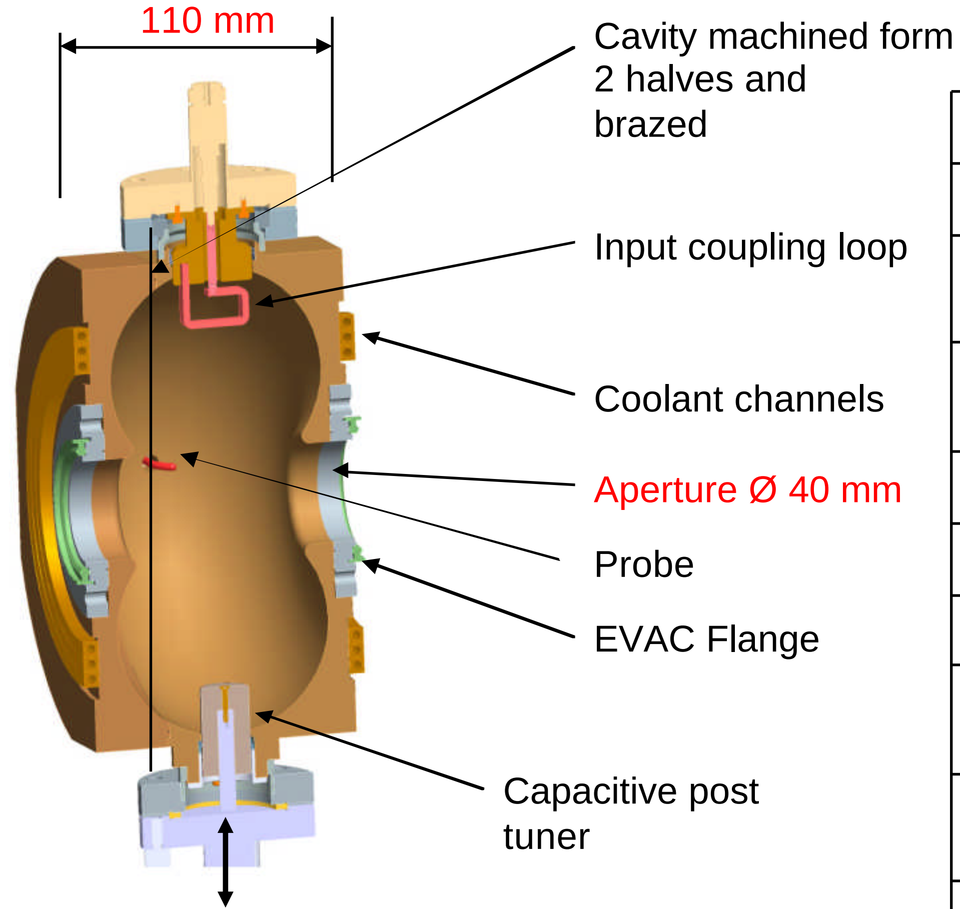
Daresbury Laboratory Feasibility Study

Design and construction of thyratron prototype unit assisted by E2V

RF Requirements

- Voltage:
  - Voltage required 20 - 120 kV/cavity, based on 19 cavities (parameter a=1/6)
  - Up to 180kV/cavity is desirable but not essential (parameter a=1/4)
  - 360 kV un-necessary (parameter a=1/2)
- Frequency:
  - Chosen frequency for the RF system is 1.3GHz, to both match the ERLP RF systems and also allow for the use of developed and mature LLRF systems at this frequency
  - Range requirement 5.6 MHz (1.295981 to 1.301554 GHz)
- Cavity phase:
  - Remote and individual control of the cavity phases is essential
- Cavity design constraints: Available length: 110 mm flange to flange. Aperture diameter 34.7 mm min. We have chosen diameter 40 mm to simplify vacuum chamber by removing offsets + some clearance

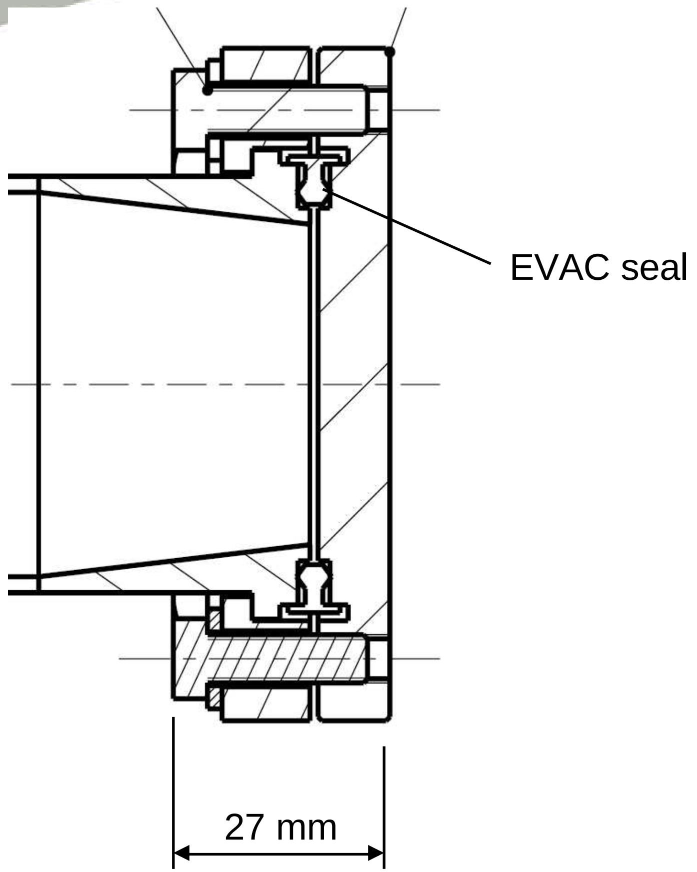
Cavity Design

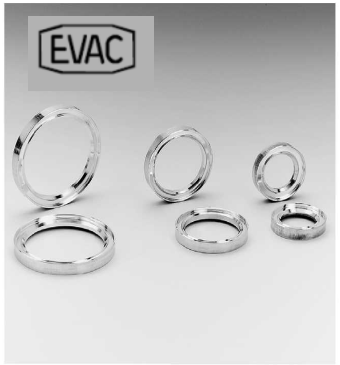


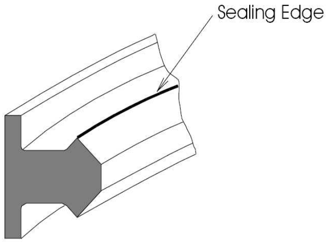
Normal conducting single cell re-entrant cavity design

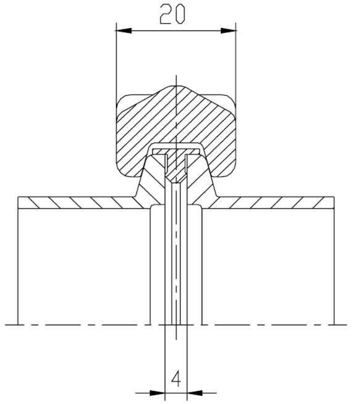
Parameter	Value	
Frequency	1.3 GHz	
Theoretical Shunt Impedance	4.3 MΩ	
Realistic Shunt Impedance (80%)	3.44 MΩ	
Qo	23,000	
R/Q	120 •	
Tuning Range	+1.5 to -4 MHz	
Accelerating Voltage	120 kV	180 kV
Power (kW)	2.1 kW	4.7 kW
P_{total} including 30% overhead	2.7 kW	6.1 kW

Cavity Flange Design









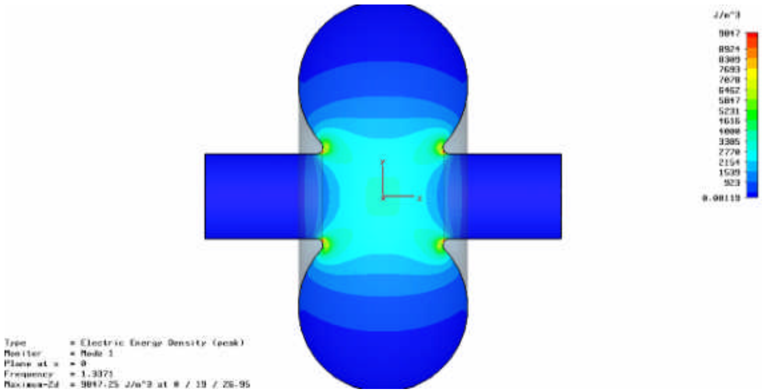
Normal KF flange arrangement with chain clamping ring

37 mm for equivalent CF flange
10 mm saving per cell
required to fit in field clamp plate, larger BPM and increased internal size of RF cavity

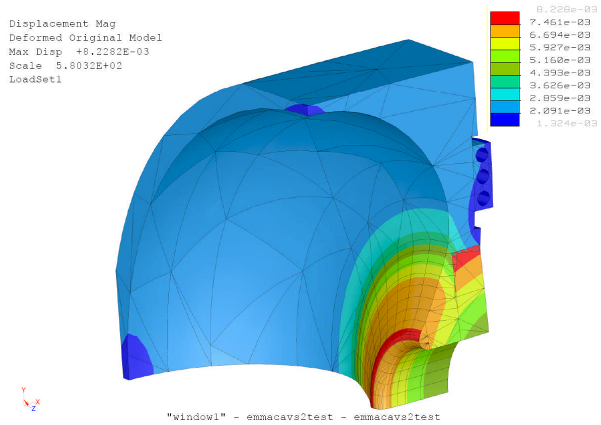
EVAC gasket Pt No: 34.142.140-az
Seal material soft aluminium
Seal has an outer aligning ring
Leak rate = <1x 10 $^{-11}$ mbar litre s-1
Temperature range = -271°C to 150°C
Flange material stainless steel 316L

FEA Results

- Peak power 6.1 kW
- Averaged power load over the whole cavity surface is 200 W
- Max. temperature rise = 9°C
- Max. Stress = 27 N/mm2
- Deflection of nose cone = 8.2µm



Electric Volumetric Energy Density (J/m3)
As output from CST Microwave Studio Model



Mechanical Case (b) Thermal Deformation + Vacuum Pressure Load :
The maximum absolute deflection (red) is 8.22E-3mm or **8.2**m**m**

Prototype Cavity Procurement Status

• RF design	complete
• Structural and Thermal FEA	complete
• Engineering drawings and manufacturing specification	complete
• Tender return against 7 companies by	5 Oct 2007
• Place contract by	12 Oct 2007
• Delivery by (estimated at 12 -16 weeks)	31 Jan 2008
• Test at DL by	14 Feb 2008

Production Cavities

• Place OJEC advert for production cavities by	Dec 14
• Place contract for production cavities by	3 Mar 2008
• Stage delivery of cavities in batches of 3	16 Jun - 1 Aug 2008

RF Power Sources

Thales IOT

20 kW (CW)

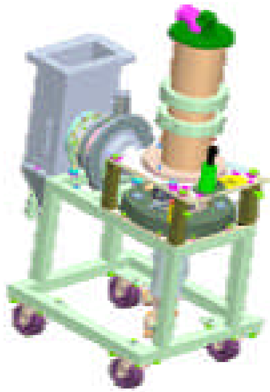
30 kW (Pulsed)

No PSU

e2v Amplifier

16 kW (CW)

20 kW (Pulsed)

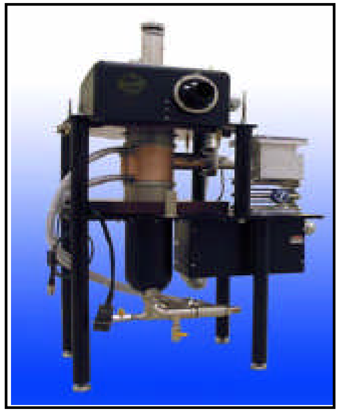


CPI IOT

30 kW (CW)

80 kW (pulsed)

No PSU etc



e2v Klystron

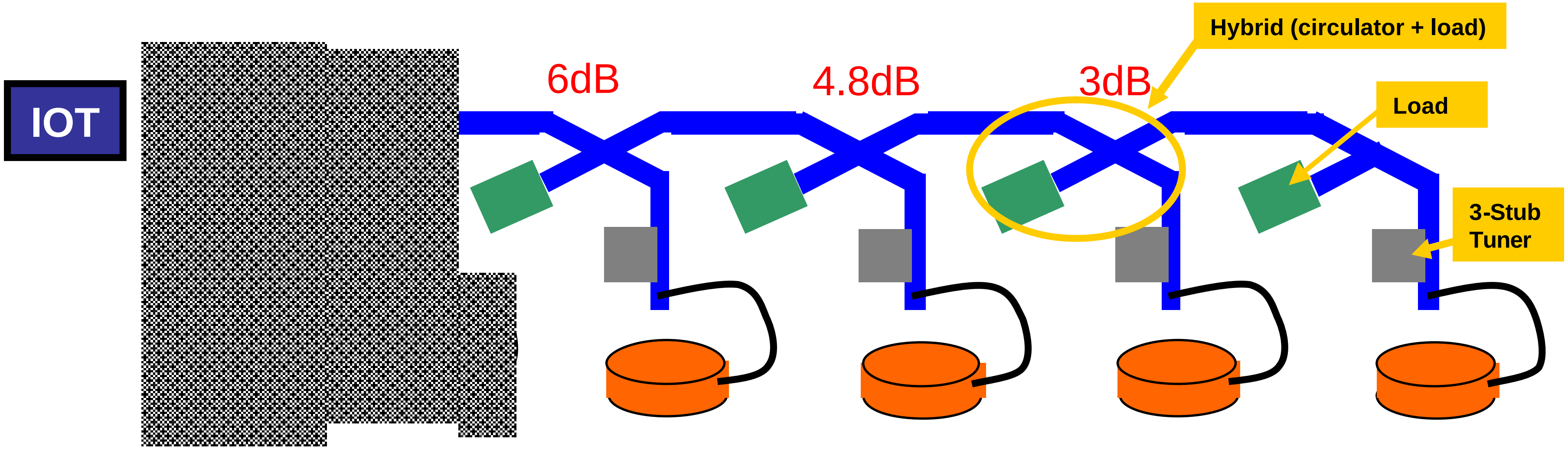
160 kW (CW)

>170 kW (Pulsed)

Power Delivery

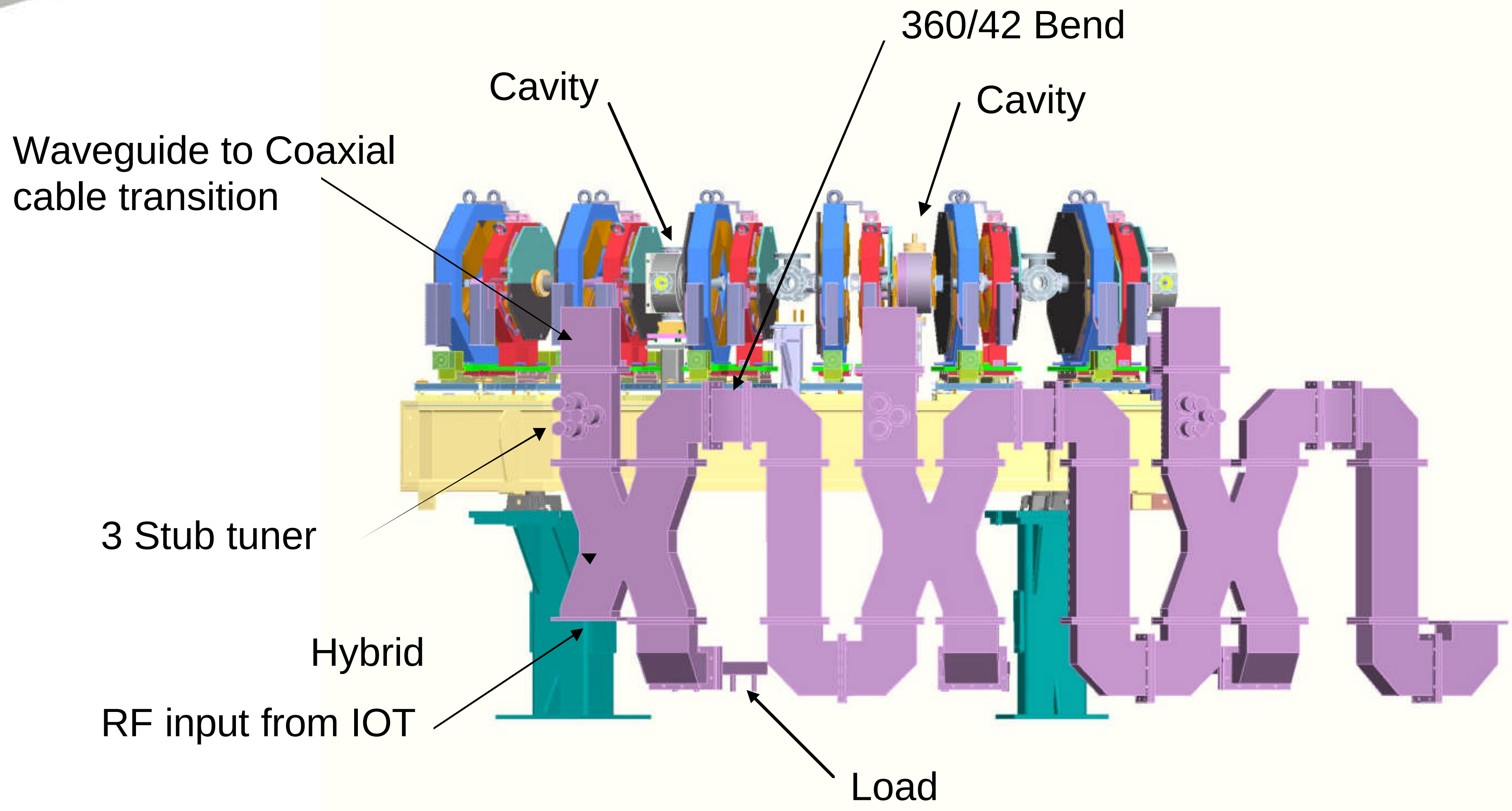
	160 kW Klystron	80 kW IOT	Units
No. of Cavities	19	19	
No. of Power Sources	1	2	
R_{sh}	3.4	3.4	MW
V_{acc}/Cavity	120 (180)	120 (180)	kV
Cavities/source	19	1x9/1x10	
RF Power/Cavity (including overhead)	2.73 (6.1)	2.73 (6.1)	kW
Distribution and Control Overhead	40	40	%
Total Ring RF Power	51.3 (115.9)	51.3 (115.9)	kW
Max Ring Power Available	160	160	kW
RF Power Overhead	108.7 (44.1)	108.7 (44.1)	kW

RF Waveguide Cascade Distribution Schematic
(5 cavity split example)



Splits	6	5	4	3	2
% power split	16.6%	20%	25%	33%	50%
Hybrid dB	7.8 dB	7 dB	6 dB	4.8 dB	3 dB

RF Waveguide Distribution CAD Model



Science & Technology Facilities Council

BASROC CONFORM

Timescales

ID		Task Name	Duration	Start	Finish
1		**Funding available**	**0 days**	**Mon 02/04/07**	**Mon 02/04/07**
23		**EMMA Project Plan**	**1363 days**	**Fri 01/04/05**	**Fri 09/07/10**
24		Conception	9.8 mons	Fri 01/04/05	Fri 30/12/05
25		Feasibility Phase	16.25 mons	Mon 02/01/06	Fri 30/03/07
26		**Project approval notified**	**0 days**	**Fri 01/12/06**	**Fri 01/12/06**
27		Design	12 mons	Mon 02/04/07	Mon 10/03/08
28		Design review 1	1 day	Mon 12/11/07	Mon 12/11/07
29		Design review 2	1 day	Tue 29/01/08	Tue 29/01/08
30		Procurement	16.2 mons	Mon 30/04/07	Fri 01/08/08
31		**All major components on site**	**0 days**	**Fri 01/08/08**	**Fri 01/08/08**
32		Infrastructure upgrade	10 mons	Tue 01/04/08	Wed 14/01/09
33		Off line assembly and test sub systems	8.2 mons	Mon 09/06/08	Mon 02/02/09
34		Installation in Accelerator Hall	4.1 mons	Tue 03/02/09	Wed 27/05/09
35		Test systems in Accelerator Hall	2 mons	Thu 28/05/09	Wed 22/07/09
36		Construction project close out review	1 day	Thu 23/07/09	Thu 23/07/09
37		**EMMA construction complete**	**0 days**	**Thu 23/07/09**	**Thu 23/07/09**
38		Commission with electrons	2 mons	Fri 24/07/09	Thu 17/09/09
39		Construction project post implementation review	1 day	Fri 18/09/09	Fri 18/09/09
40		Detailed experimental programme	0 days	Fri 18/09/09	Fri 18/09/09
41		Full ring studies	6 mons	Mon 21/09/09	Fri 05/03/10
42		Advanced ring studies	4.5 mons	Mon 08/03/10	Fri 09/07/10
43		**EMMA phase 1 beam studies complete**	**0 days**	**Fri 09/07/10**	**Fri 09/07/10**

Cost Breakdown

	Item	Cost (Incl. VAT)
	EMMA	
1	RF CAVITY SYSTEM	£ 1,641,500
2	DIAGNOSTICS	£ 492,400
3	MAGNETS	£ 502,430
4	MECHANICAL & VACUUM CHAMBERS	£ 391,250
5	VACUUM EQUIPMENT	£ 134,300
6	CONTROLS	£ 121,662
7	ELECTRICAL	£ 442,450
8	COOLING & SERVICES	£ 70,000
9	CIVIL	£ 34,000
10	**sub total**	**£ 3,829,992**
11	EMMA Staff	**£ 1,808,000**

£ 5,637,992

Conclusions Next Steps

- Funding in place
- Definition phase is now well advanced
- A lot of work to do:
  - Make decision of RF power source
  - Provide solution for the low level RF system
  - Test prototypes – Magnets, cavity ………
  - Firm up on injection and extraction scheme trajectories
  - Engineering of injection and extraction devices
  - Matching ERLP operation for EMMA
  - Finalise design of transfer line from ERLP to EMMA and diagnostics beamline
- We aim to have an operating NS-FFAG at DL in September 2009

Acknowledgements

- All the team
  - Internal staff
  - All the collaborators