Status and plans for EMMA linear-field non-scaling (NS) FFAG

Presentation by Shane Koscielniak, TRIUMF, at MUTAC, 9th April 2008

EMMA: Electron Model with Many Applications

EMMA: managed, designed and constructed by BASROC at Daresbury Laboratory near Manchester U.K. – with collaborators from N. America & Europe.

BASROC = British Accelerator Science and Radiation Oncology Consortium

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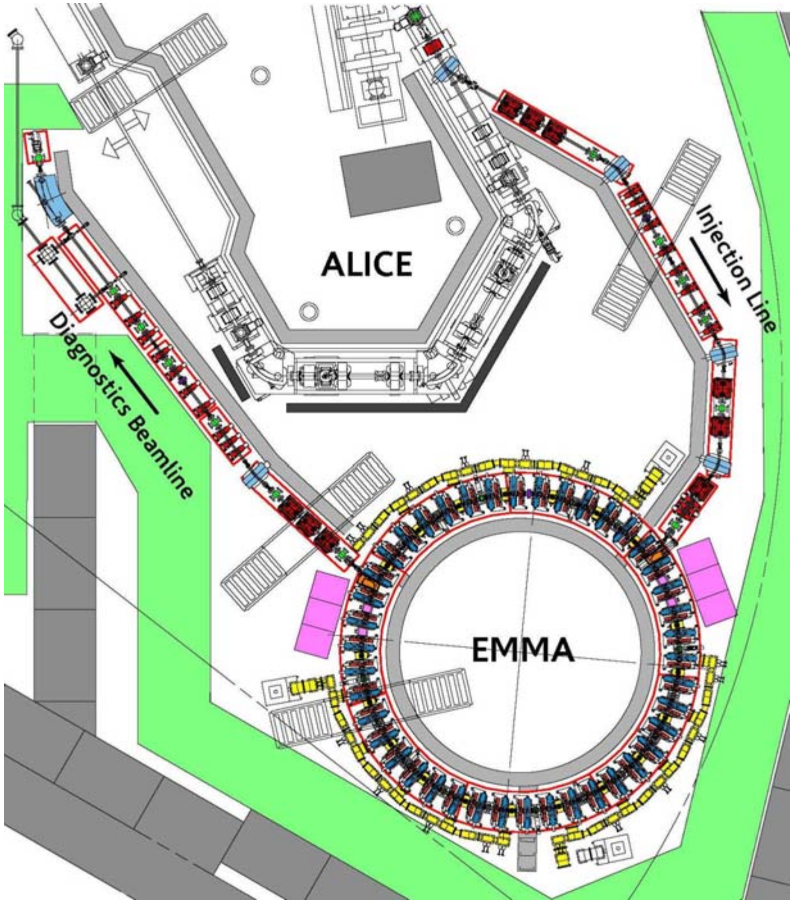


Introduction: FFAGs are circular, strong-focusing accelerators

- d.c.-powered magnets, and are suited to rapid acceleration
- some reverse bending (radial-sector type)
- closed orbits whose average radii (mostly) increase with beam momentum
- large 6D acceptance.

FFAG type	Fixed βtron tunes	Compaction (Δp/p)/(ΔR/R)
Classical, scaling	Yes	Normal
1st Gen linear-field NS	No	Very large

- NS-FFAG properties: resonance crossing, small apertures, parabolic ToF and serpentine acceleration
- Novel, unproven accelerator physics; hence the demonstration model.

Effect of resonances minimized by:

- Symmetry: all cells identical
- Linear magnets: nonlinear resonances weak
- Accelerate rapidly: fast crossing
- Magnet errors: keep them small, $\delta B/B < 2\times10^{-4}$

EMMA: originally conceived as model of a GeV-scale muon accelerator.

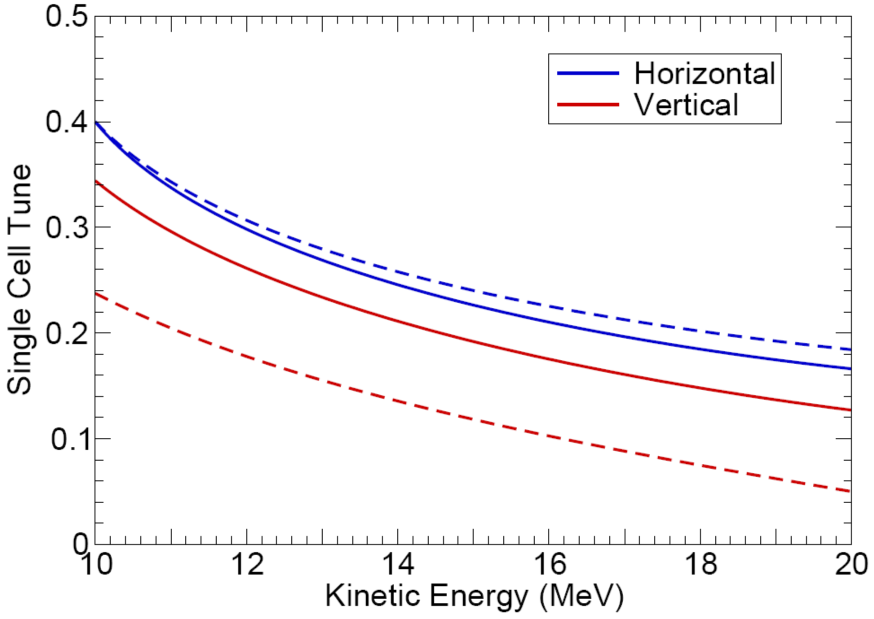
	NFMC	EMMA
Particle type	muon	electron
Energy range	10-20 GeV	10-20 MeV
Circumference	≈ 440 m	16.6 m*
# doublet cells	≈100	42
Cell length	4.4 m	38 cm
Pole-tip field	≈ 2.5 T	≈ 0.25 T
Magnet type	Combined- function	Quadrupoles
RF	200 MHz	1.3 GHz
# acceleration turns	≈ 15	≈ 15
Acceptance (norm.)	≈30 mm	≈3 mm

*Small ring can lead to unexpected problems: very short revolution period, 55 ns, implies short rise & fall times for kicker magnets.

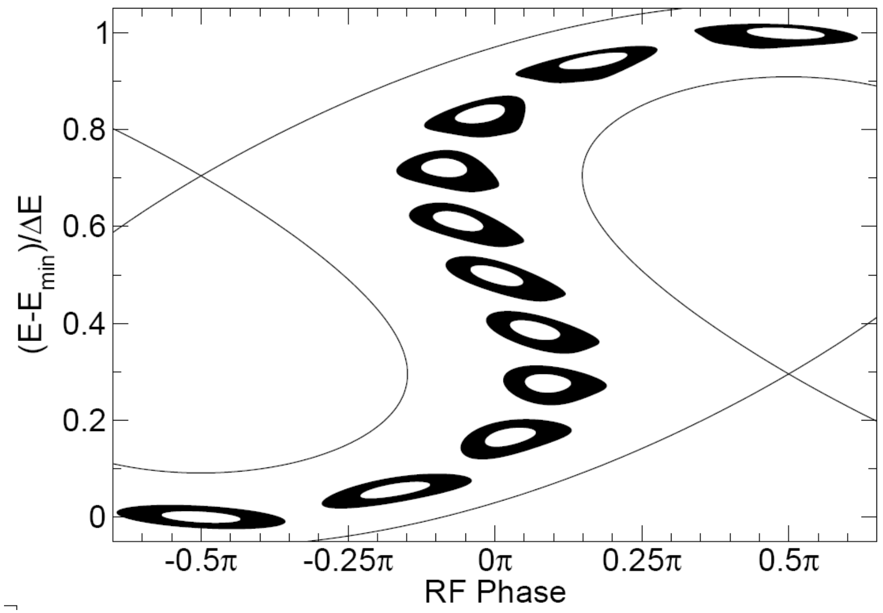
EMMA objectives

EMMA has metamorphosed from a simple “demonstration” objective to a sophisticated instrument for accelerator physics investigation – with operational demands far in excess of the NFMC application. **EMMA will study:**

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



(2) Serpentine acceleration (results from parabolic ToF)

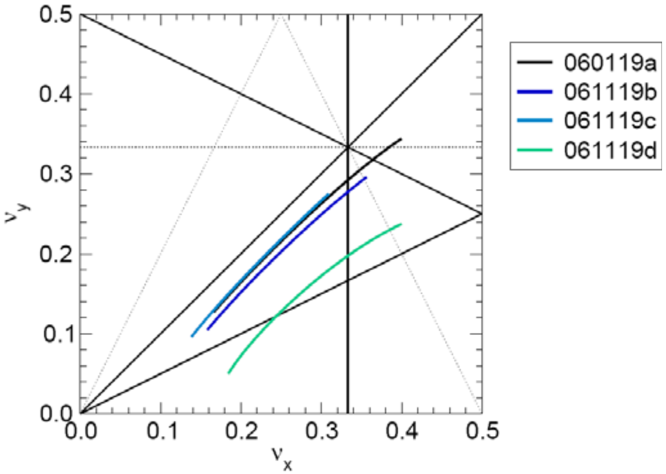


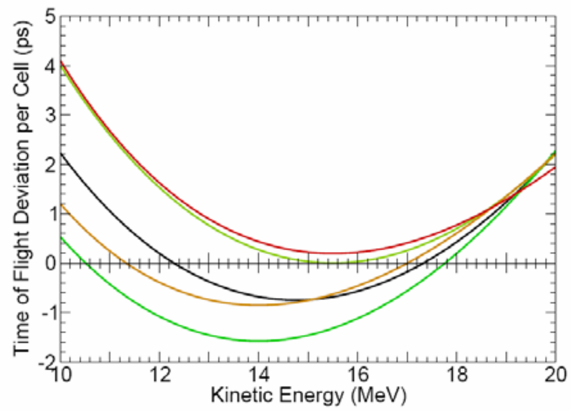
(3) Map the transverse and longitudinal acceptances.

Note, whereas muon beam fills its acceptance, ALICE bunches are high-brilliance small-emittance probes of the EMMA acceptances.

EMMA objectives: to understand the NS-FFAG beam dynamics as function of lattice tuning and RF parameters.

Example: retune lattice to vary resonances crossed during acceleration.



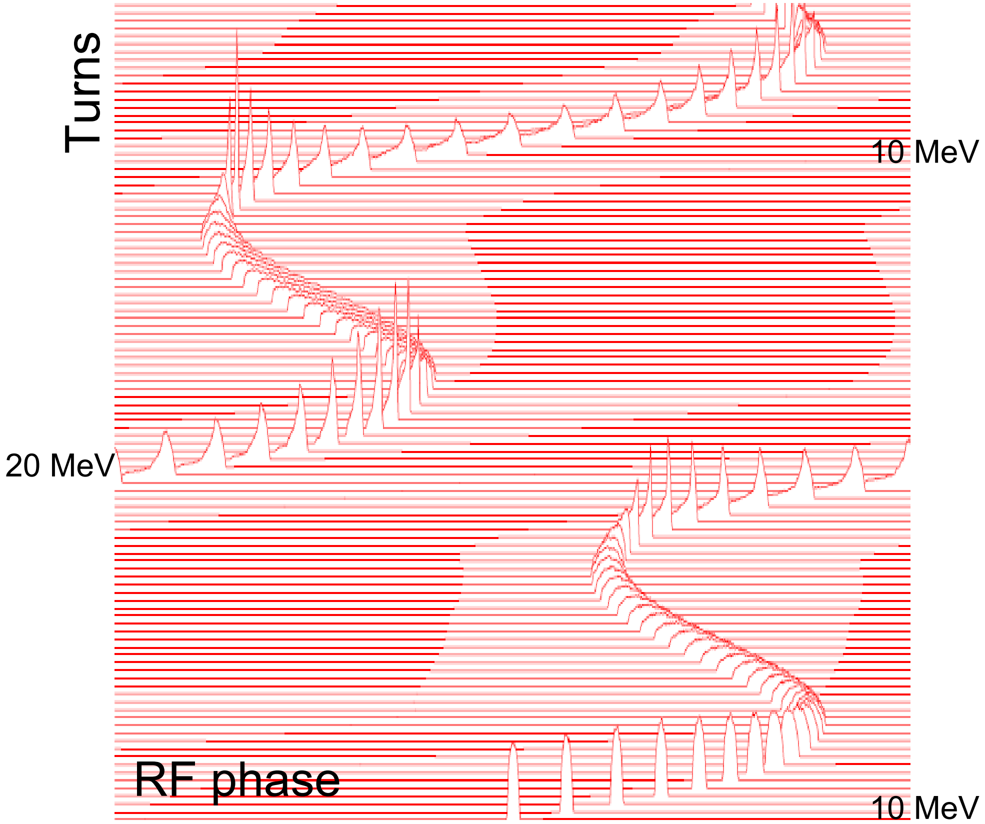


Example: retune lattice to vary longitudinal ToF curve, range and minimum.

EMMA requirements

- Full aperture injection and extraction at any energy (despite changing phase advance between kickers and septum)
- Many lattice retunings (vary ratio of dipole to quadrupole fields)
- Vary frequency, amplitude and phase of RF cavities
- Non-accelerated operation to map closed orbits and tunes vs momentum
- Map longitudinal and transverse acceptances with probe beam
- Heavily instrumented with beam diagnostics, etc.

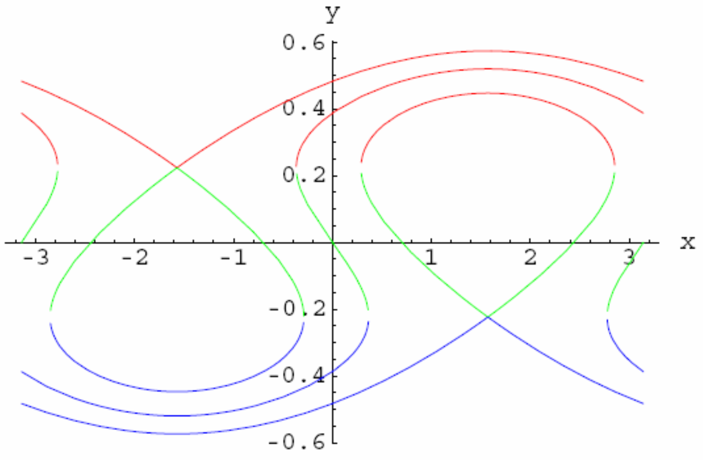
Serpentine Acceleration



Mountain range display of acceleration and deceleration over 10-20 MeV.

turns slightly > ΔE/δE =(energy/voltage)

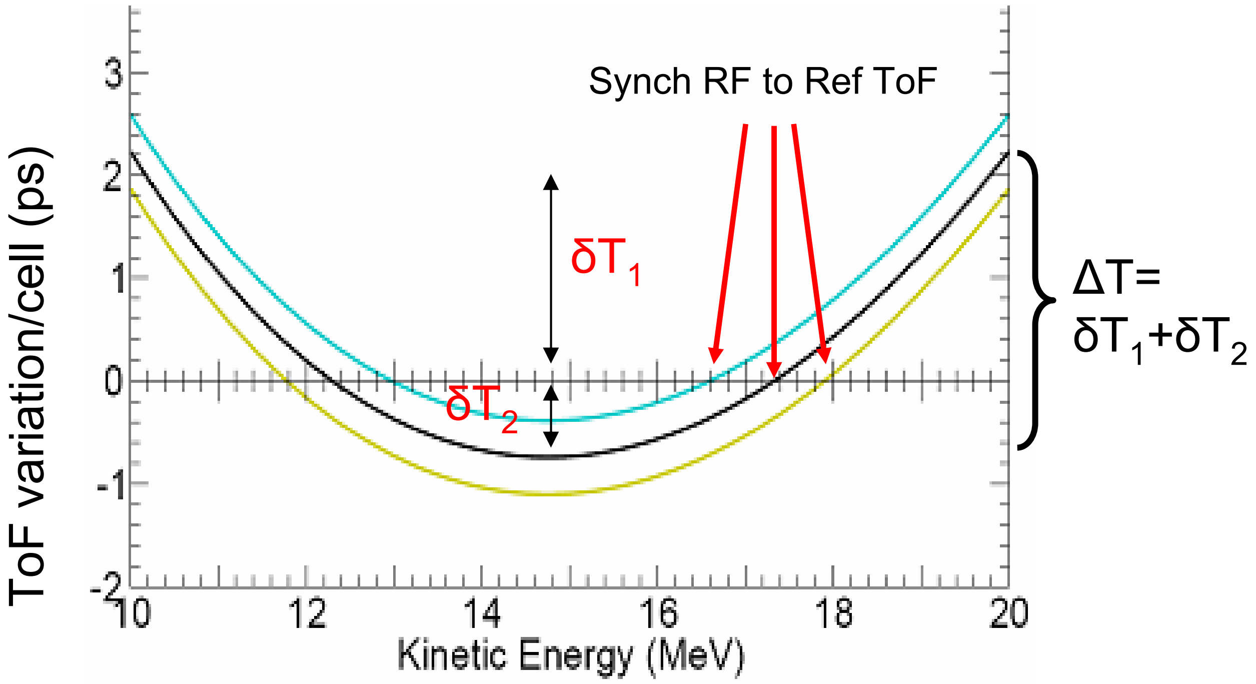
Phase space trajectories



(a,b)=(1/12,1/5)

Consequence of parabolic ToF vs Δp/p and fixed RF

Serpentine Acceleration



δE=energy increment

ΔE=energy range

ΔT=δT1+δT2

ω=2π RF

$a= (\delta E/\Delta E)/(\omega\Delta T)$

$b=\delta T_2/\Delta T$

	a	kV/cavity
opens zero acceptance channel	1/24	30
baseline muon model acceptance	1/12	60
headroom against errors/chromatic	1/6	120
upgrade – larger ToF ΔT	1/4	180

Resonance Crossing (RC)

Try to find its effect on “emittance”. In fact, there are two-types:

- Intrinsic emittance: >3 µm
- Swept-out emittance: < 3 mm

- Originally imagined to explore RC effect by monitoring increase of initially large intrinsic emittance.
- But ALICE injector provides pencil beam which is used to probe RC effect on swept-out emittance.

Swept-out Emittance

Monitor emittance swept out as input centroid is scanned in x,x’ etc
Measurement device: all ring BPMs, and reconstruction from α,β,γ.

Intrinsic Emittance

Verify “probe stays a probe” emittance
Monitoring emittance of the probe (pencil beam).
Measurement device: screens in the injection/extraction lines, and in the ring.
Based on 3 screens and reconstruction of α,β,γ.

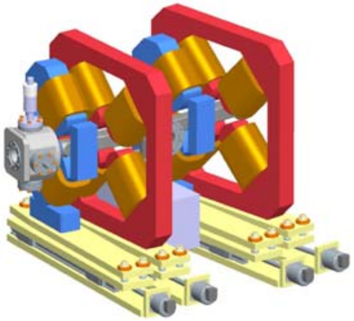
Magnet Design

Requirement	Solution
Adjust dipole & quadrupole components independently	Mount magnets on independent radial sliders –μm precision
Fields identical in every cell – despite kickers and septum	Field clamps at cell exit faces of D & F quads
Very large good field region (GFR) – range of closed orbits	Specialist pole profile – abandon hyperbola & tangent approach
D-clamp field saturation	Clamp thickness increased

Due to extreme compactness of lattice, D & F magnets

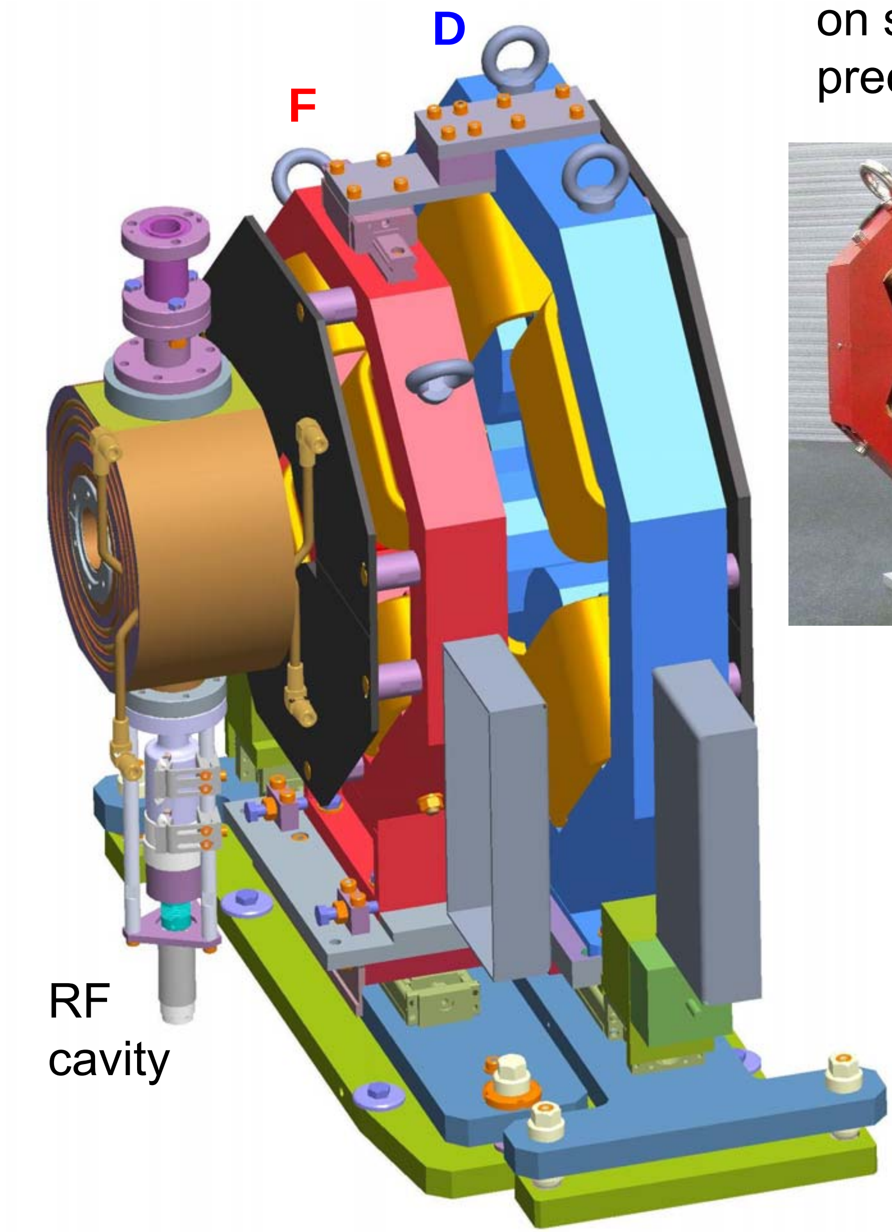
- Are in close proximity. Consequence: field computation and measurement with both magnets in place
- Are short compared with aperture. Consequence: integrated strength is dominated by end-field contributions.

} is essential for exact calculation of COs and tunes.

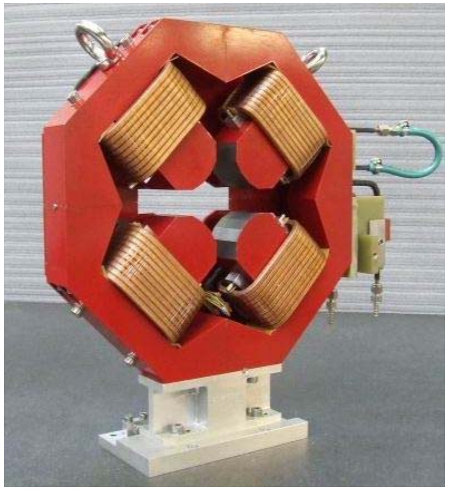


Mirror plate? Range of closed orbits in D-quad is strongly asymmetric about magnet centre. Original plan to use ½-quad with mirror plate; quickly abandoned due to poor field quality. But ½-quad leads to slightly reduced element crowding – benefits injection and extraction. Maybe too hasty a decision?

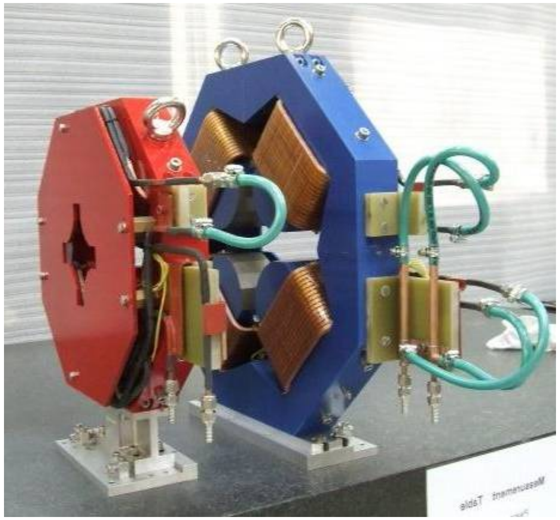
Standard lattice cell, Feb 2008



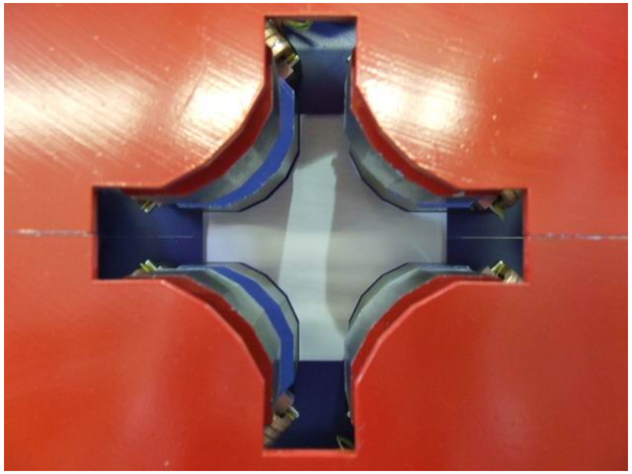
Quads mounted on sliders; μm precision.



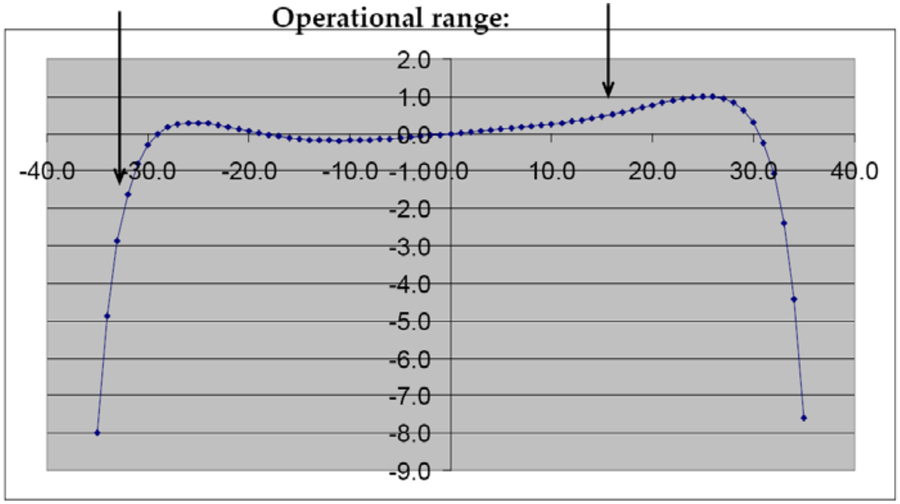
Prototypes from TESLA engineering



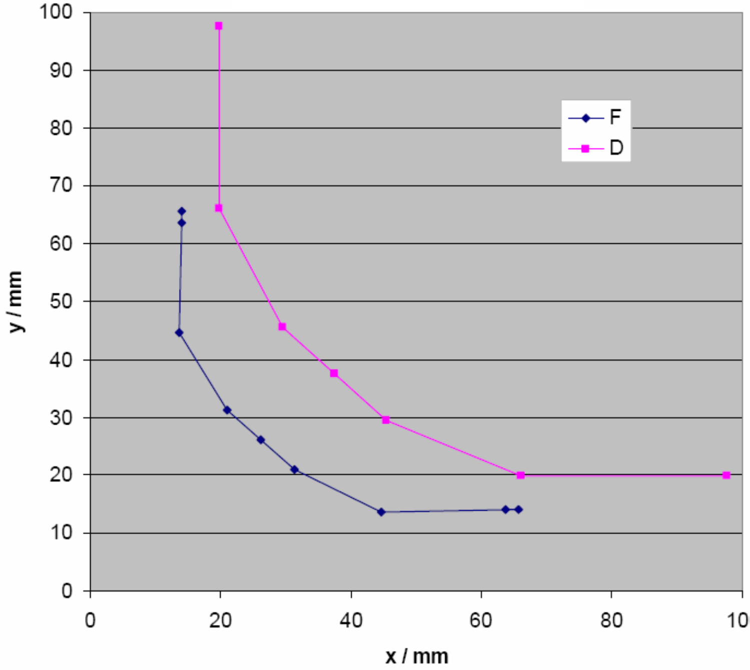
Magnet Design



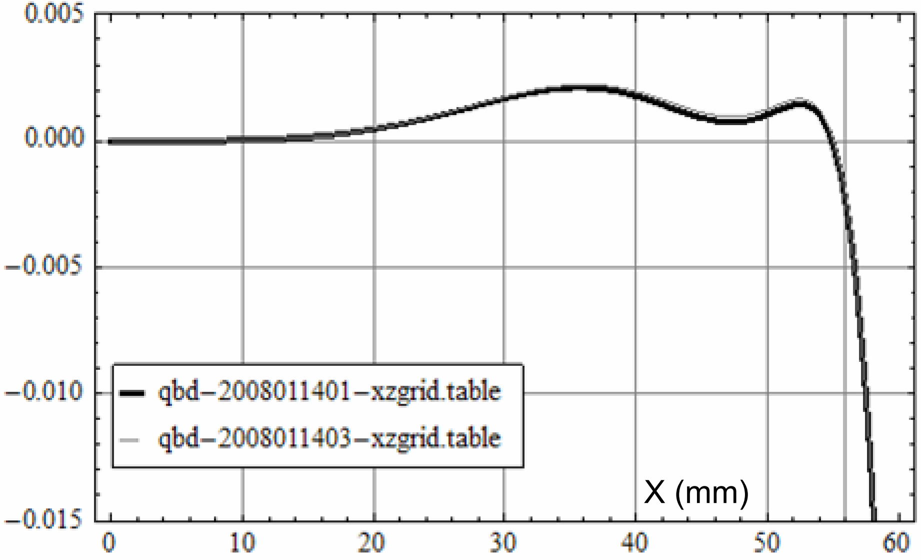
F-magnet field error ×10^3



Pole Profiles



D-magnet field error



Delivery of 84 quads:
16 Jun – 1 Aug 2008

RF System Requirements

- Provide voltage to accelerate (1.2 – 2.4 MV/turn)
- Pass beam for all lattice configurations (40 mm aperture/iris)
- Vary parameters of longitudinal dynamics
- Maintain lattice periodicity (ideal: 1 cell/cavity)
  - Volts/cavity low, reduced cost → 2 cell/cavity → 21 cavity
  - Make space for kickers & septa → break periodicity → 19 cavity
- Provide time and frequency synchronization
  - Reference ToF depends on lattice and “b”
  - Synchronize frequency to reference ToF → 5 MHz tuning range*
  - Adjust phase to insure acceleration → motorised 3-stub phase-tuner

*Both for cavity and RF power source

EMMA RF Specification

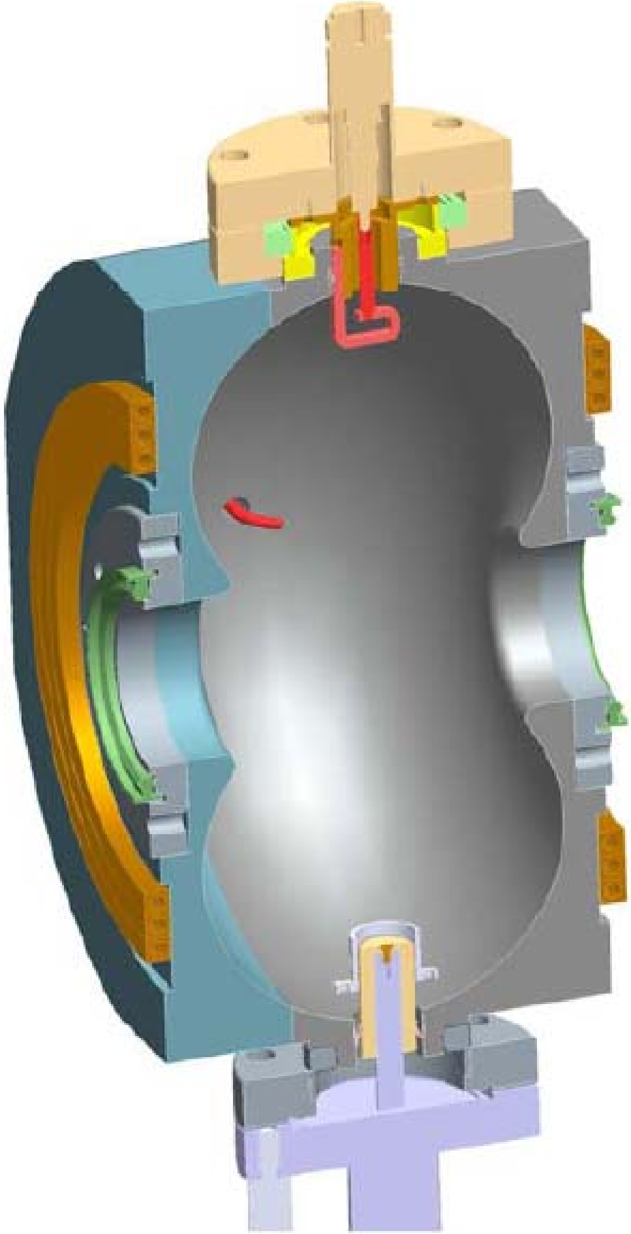
Parameter	value
Revolution frequency	18.06 MHz
Harmonic number	72
Frequency	1.300 GHz
Tuning range	-4 to +1.5MHz
Number of cavities	19
Total Accel/turn	≤2.3 MV
Upgrade Accel/turn	≤3.4 MV
RF repetition rate	10 Hz
RF pulse length	≤50 μs
Aperture/iris	40 mm

Final Cavity Design

Parameter	value	
Frequency	1.3 GHz	
Shunt resistance $R=V^2/(2P)$	4.3 MΩ	
Realistic (80%)	3.44 MΩ	
Q_0 (unloaded)	23000	
R/Q	147	
Vacc (kV)	120	180
Pdiss (kW peak)	2.1	4.7
Ptot* (kW peak)	2.7	6.3

* Losses in RF distribution

HLRF power sources are cost driver → RF cavity design optimized for high shunt resistance. Final design for toroidal cavity inspired by 500 MHz PEP-II design.

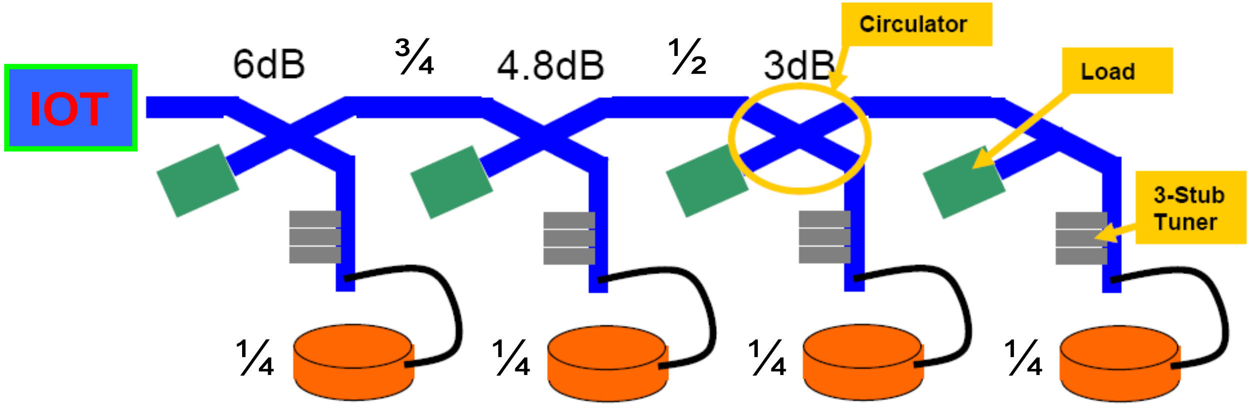


Cavity Status

- Electrical, mechanical and cooling designs completed.
- Al prototype received and tested
- Cu pre-production model ordered.

Aluminium cavity low power tests	Mar 2008
Delivery of Cu cavity	28 Apr 2008
High power tests at DL	May 2008
Placed contract for production cavities	20 Mar 2008
Staged delivery of cavities in 3 batches	14 June -14 Aug 2008

Cascaded HLRF Distribution Scheme

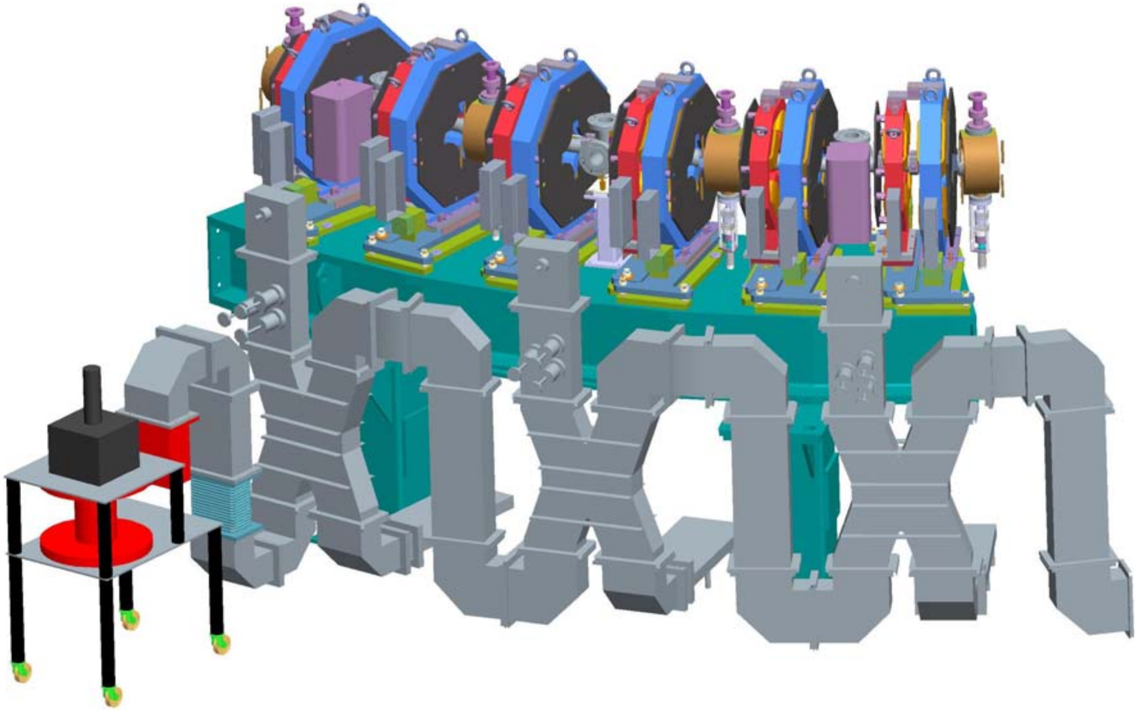


- Same concept regardless of # splits
- Compact System

Example

split	dB
1/4	6
1/3	4.8
1/2	3

Physical Layout



Problem: RF phase advance along beam line differs from that along waveguide, and changes if frequency varies.

Solution: motorized 3-stub tuner & calibration of phase adjustment to systematically change operating frequency.

RF Power Source

A variety of klystron and IOT (Inductive Output Tube) RF power sources were considered before choosing the CPI IOT – tested to 90 kW pulsed, 40 kW c.w. Two CPI/Eimac CHK51320W klystrodes will be purchased.

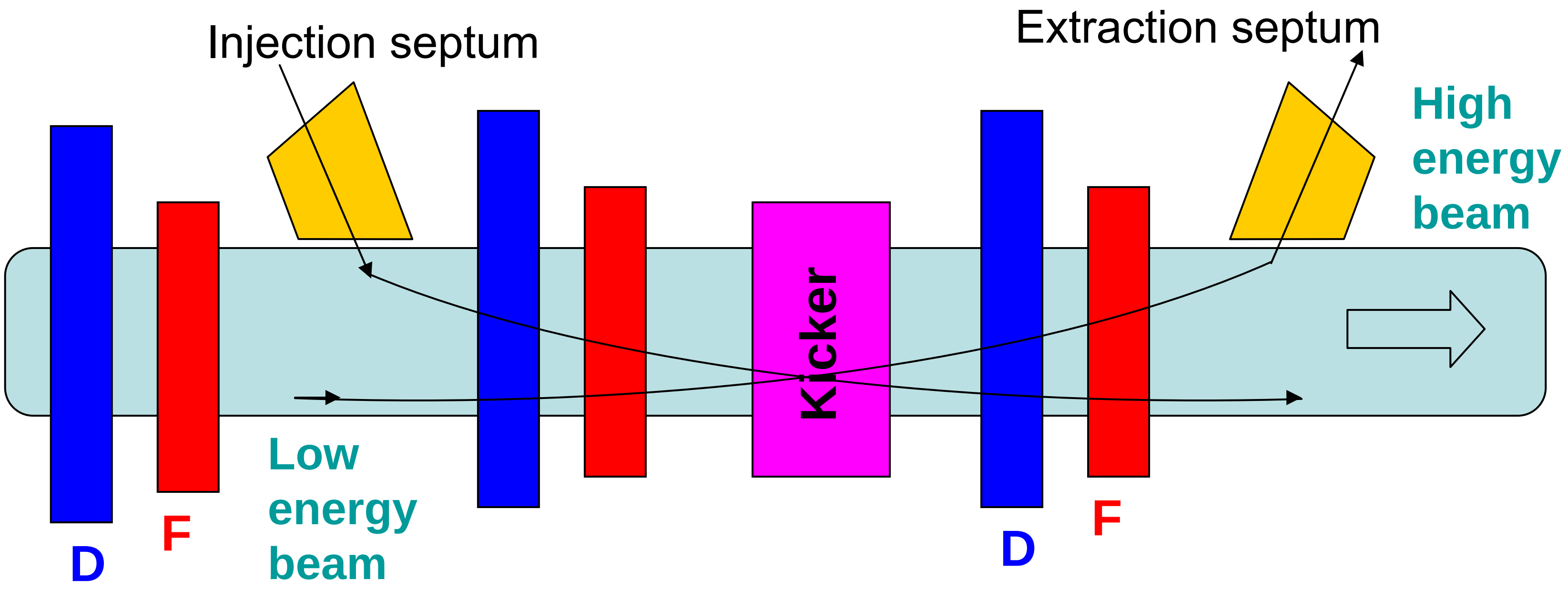
Frequency = 1.3 GHz	base	upgrade
# RF cavities	19	19
# RF power sources	1	2
Vacc/cavity (kV)	120	180
Cavities/source	19	10,9
RF power/cavity* (kW)	2.7	6.3
Distribution & control overhead	30%	30%
Total ring RF power (kW)	51.9	119
Max ring power available	90	180
RF Power overhead (kW)	38	61

EMMA Injection & Extraction requirements

- Inject and extract at any energy 10-20 MeV
- Varying betatron phase advance vs energy
- “Large” radial range of closed orbits – “big” full-aperture kicks
- Inject/extract not just for probe beam centroid, but for full 3 mm (norm) emittance swept out by (x,x’) offset variation
- Inject/extract for a variety of lattice tunings
- Do not use special large-aperture quads – it breaks the ring periodicty!
- Kicker field ≤ 0.6kgauss(bipolar), length ≤ 0.1m.

A tall order!

Injection & Extraction has been a tough nut – but it is cracked!
Hard work by: T. Yokoi, E. Keil, C. Johnstone, S. Berg, etc.



Cartoon of injection onto & extraction from a 10 MeV orbit

Inject/Extract Key points:

- Have to inject onto highest (and lowest) energy orbit
- Have to extract from lowest (and highest) energy orbit
- Not necessarily advantage to inject from inside (low energy orbits) and extract to outside (highest energy orbits).

Inject/Extract Key points:

- Do not inject from inside: element crowding & at edge of good field region
- Hence injection and extraction both on outside of ring

- Injection and extraction are mirror symmetric
- Element order important: different pattern gives different kicks.

First element after injection septum is	Last element before extraction septum is	extraction	injection	injection	extraction
D	F	←SFDKFDS←		easier	harder
F	D	←SDFKDFS←		harder	easier

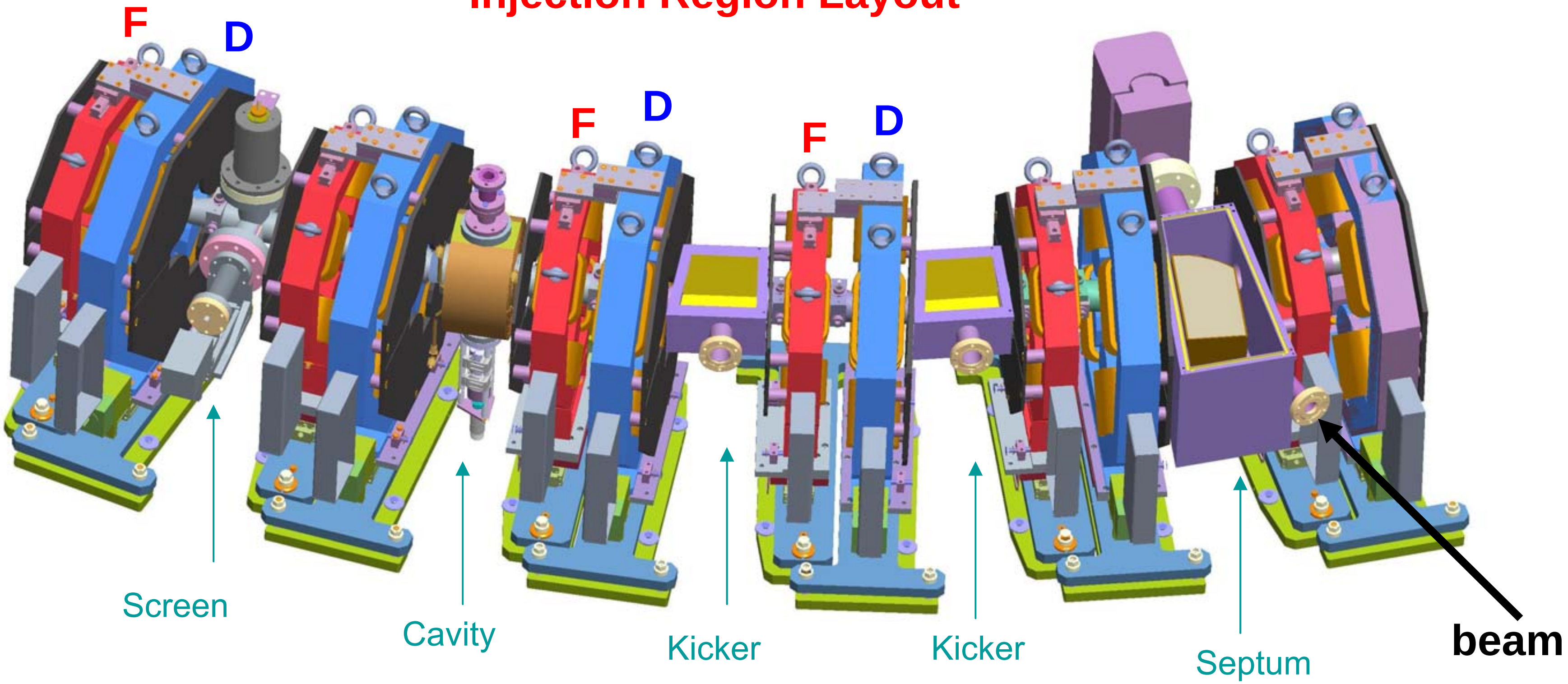
- Easier = all orbits accessible (10-20 MeV)
- Harder = orbits <12 MeV not accesible

Inject/Extract Key points:

Break the stalemate:

- Favour lower energy injection, and higher energy extraction.
- Choose the ←SFDKFDS← sequence

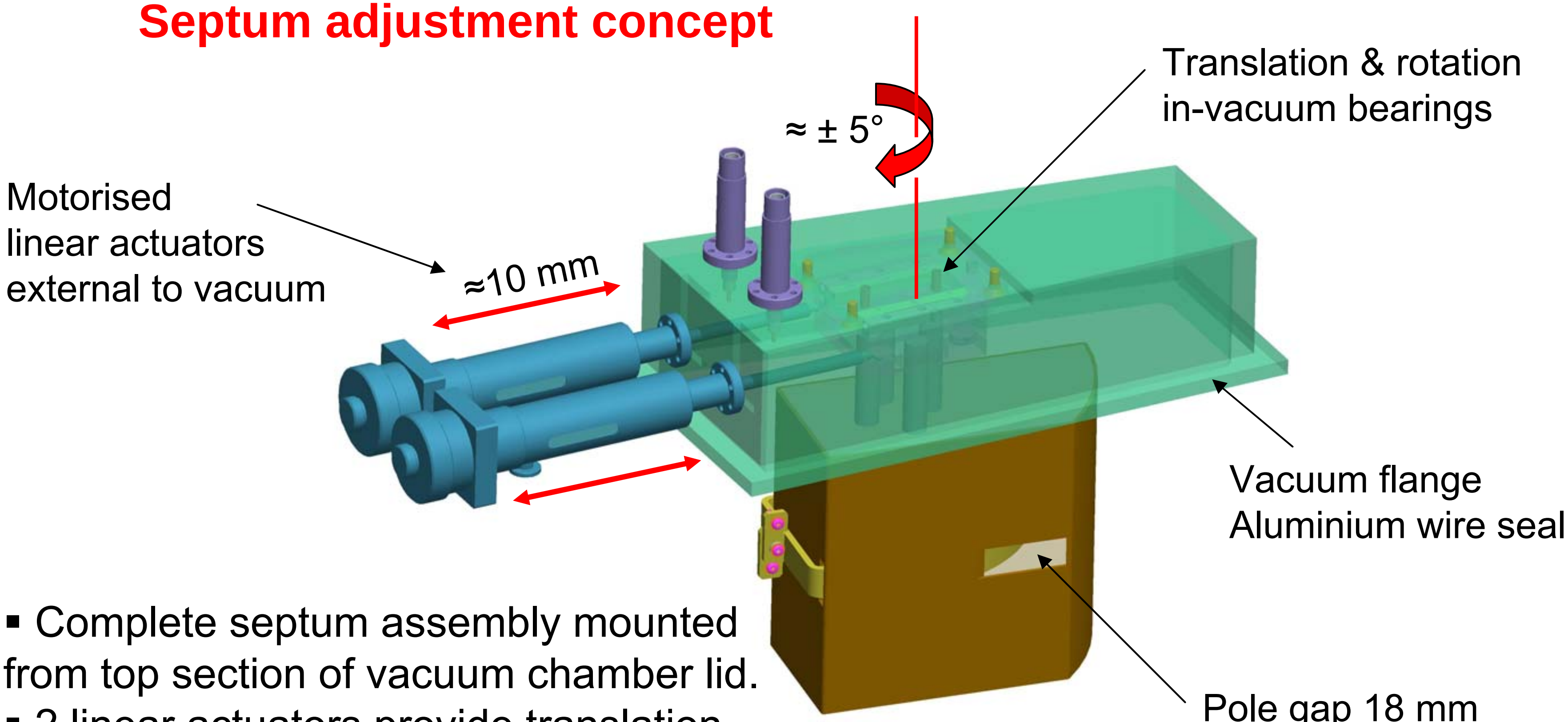
Injection Region Layout



Inject/Extract Key points:

Realize: extraction kicker is free to move inward to access difficult low energy orbits.

Septum adjustment concept



- Complete septum assembly mounted from top section of vacuum chamber lid.
- 2 linear actuators provide translation and rotation of septum.

Diagnostic System Requirements

- Commissioning + injection & extraction
- Lattice optics params as function of momentum
- Transmission
- Serpentine acceleration
- Betatron resonance crossing
- EMMA is heavily instrumented
- Diagnostic instruments to serve both operations and commissioning
- Many devices serve multiple purposes

Parameters relevant to diagnostics

Injected emittance	3-20 μm (norm.)
Model acceptance	3 mm (norm.)
Orbit swing	3 cm
Single bunch	charge 32 pC
Limit trans. space-charge	2 E8 electron
Limit cavity beam-loading	5 E8 electron
Repetition rate	1, 5, 20 Hz

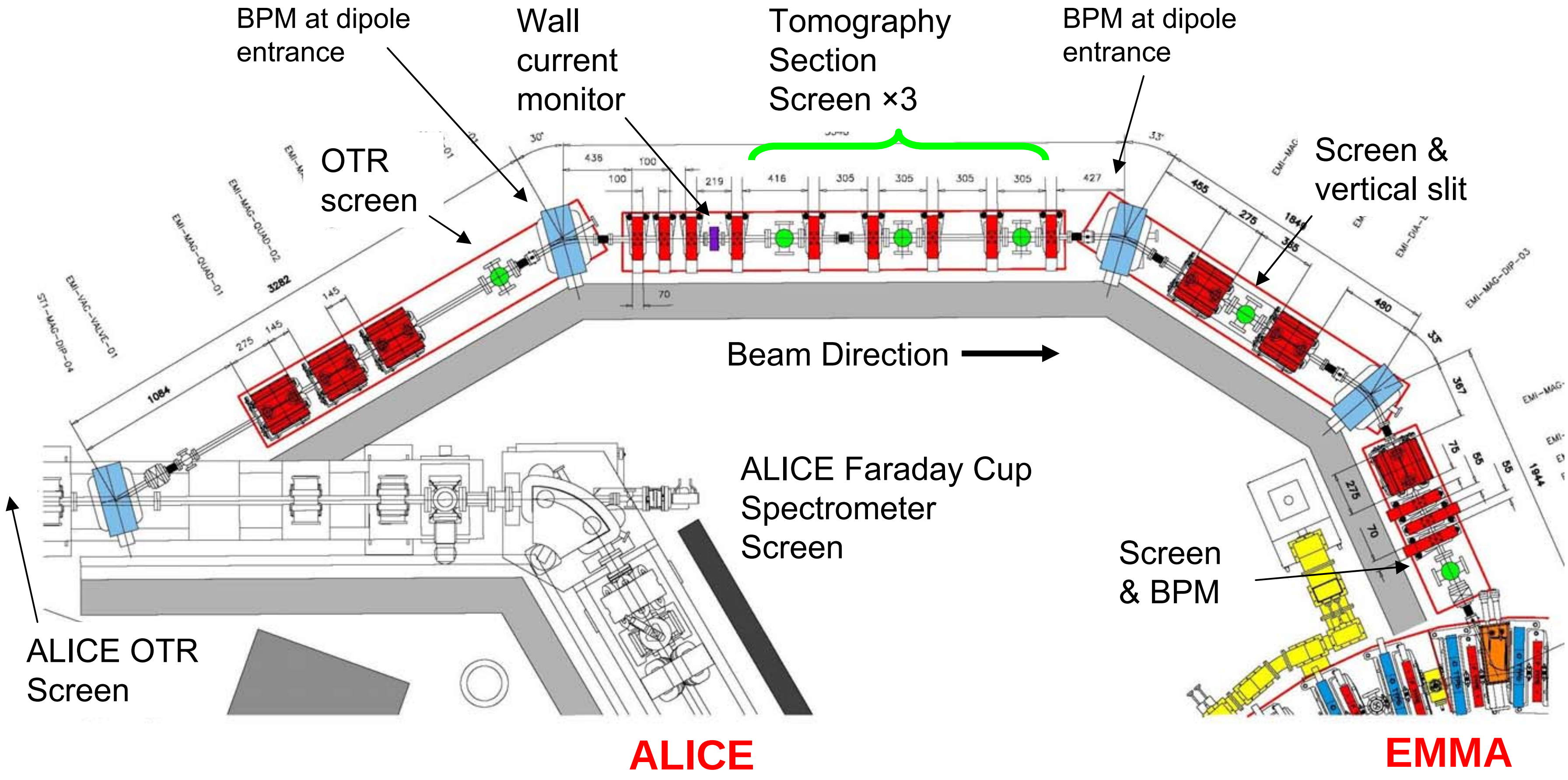
Inventory of Beam Diagnostic Devices

Measurement	Device	Number	Required resolution
Beam position	4 button BPM	2/plane/cell in ring 4 each/beam line	50μm
Beam profile & commissioning	OTR screens	2 in ring 1 each/beam line	100μm pixel size
Beam profile	Wire scanners	2 in ring 1 each/beam line	50μm
Intrinsic Emittance	Screens	3 each/beam line	5%
Beam current	Resistive wall monitor	1 in ring 1 each/beam line	2%
Phase & ToF	Resistive wall monitor	As above	5 deg
Transmission	Faraday cup	1 each/beam line	2%
Beam loss	Beam Loss Monitor	4 segments (ERLP type)	2%
Momentum*	Spectrometer	1 each/beam line	1%
Longitudinal profile	Opto-electronic (ERLP)	1 in extracted line	20keV and 5 deg

*Momentum in ring is reconstructed from BPMs and TOF from RWMs

- Ring and injection line will have full complement of diagnostics at start
- Staged approach for diagnostics in extraction line

Injection Line



BPM at dipole entrance

Wall current monitor

Tomography Section Screen ×3

BPM at dipole entrance

OTR screen

Screen & vertical slit

Beam Direction

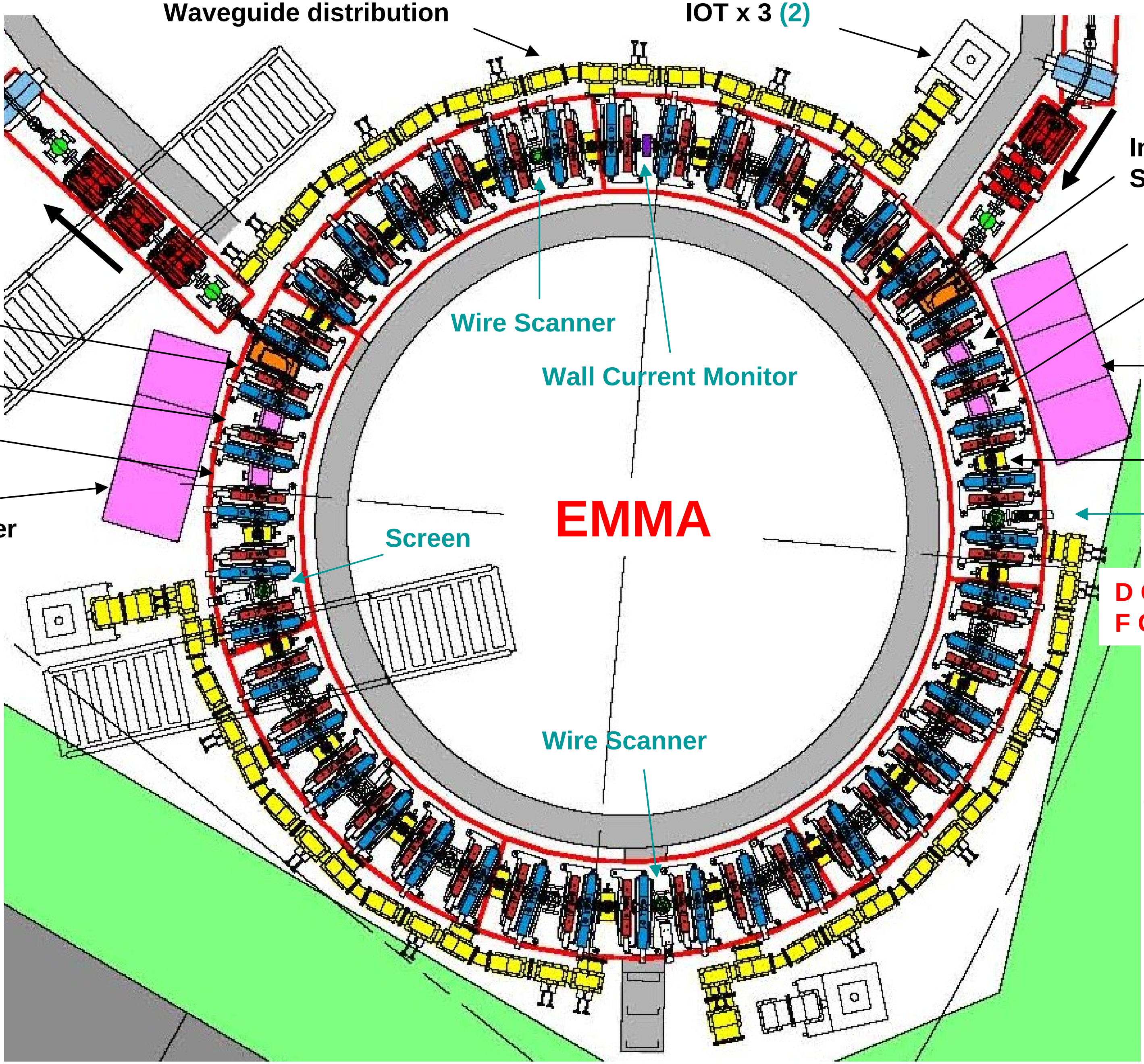
ALICE Faraday Cup Spectrometer Screen

Screen & BPM

ALICE OTR Screen

ALICE

EMMA



EMMA

Waveguide distribution

IOT x 3 (2)

Injection Septum 65°

Kicker

Kicker

Septum & Kicker power supplies

Cavities x 19

Screen

D Quadrupole x 42
F Quadrupole x 42

BPM x 82

Locations for 16 Vertical Correctors

Extraction Septum 70°

Kicker

Kicker

Septum & Kicker power supplies

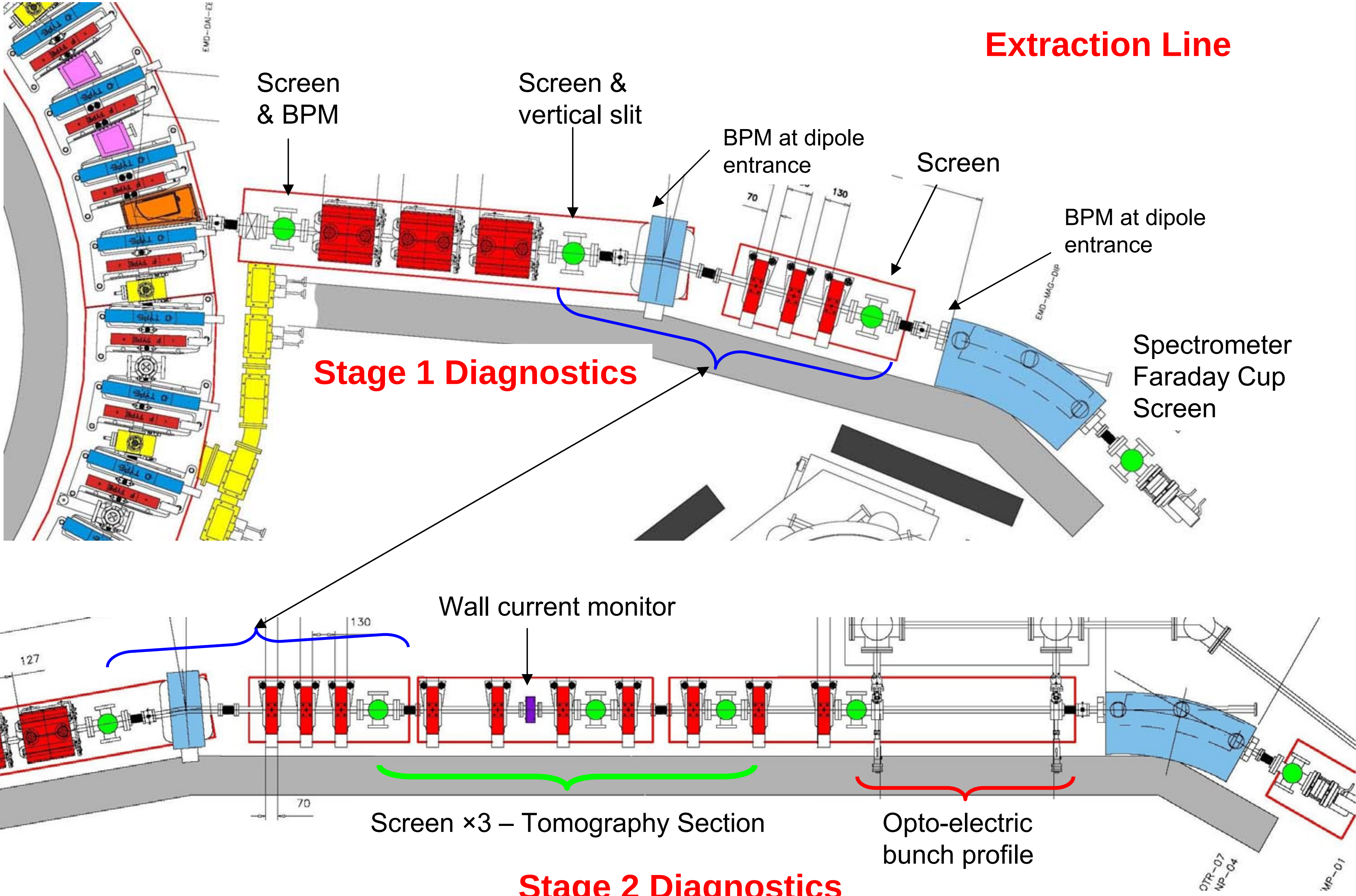
Wire Scanner

Wall Current Monitor

Screen

Wire Scanner

Extraction Line



Screen & BPM

Screen & vertical slit

BPM at dipole entrance

Screen

BPM at dipole entrance

Spectrometer
Faraday Cup
Screen

Stage 1 Diagnostics

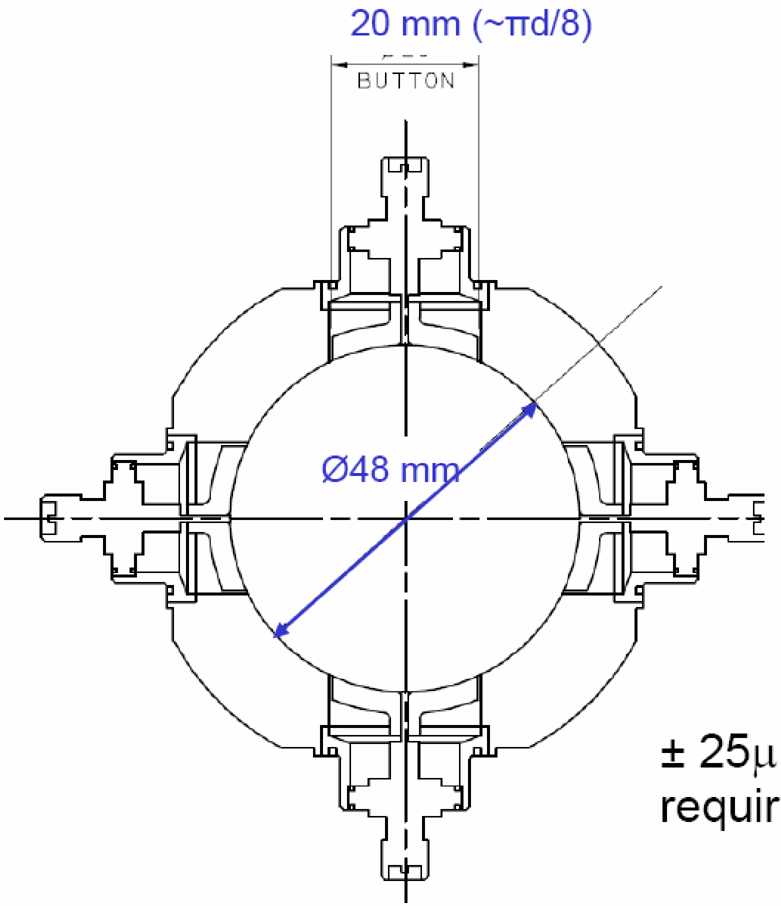
Wall current monitor

Screen ×3 – Tomography Section

Opto-electric bunch profile

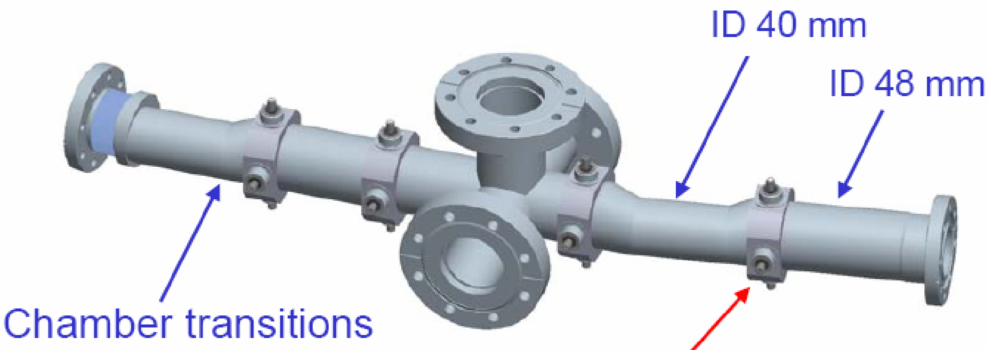
Stage 2 Diagnostics

Beam Position Monitors: the most crucial piece of instrumentation

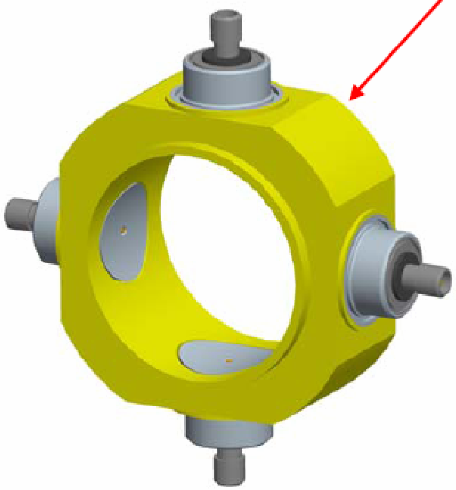


Cross-section

Standard vacuum chamber for 2 cells.
Material - stainless steel



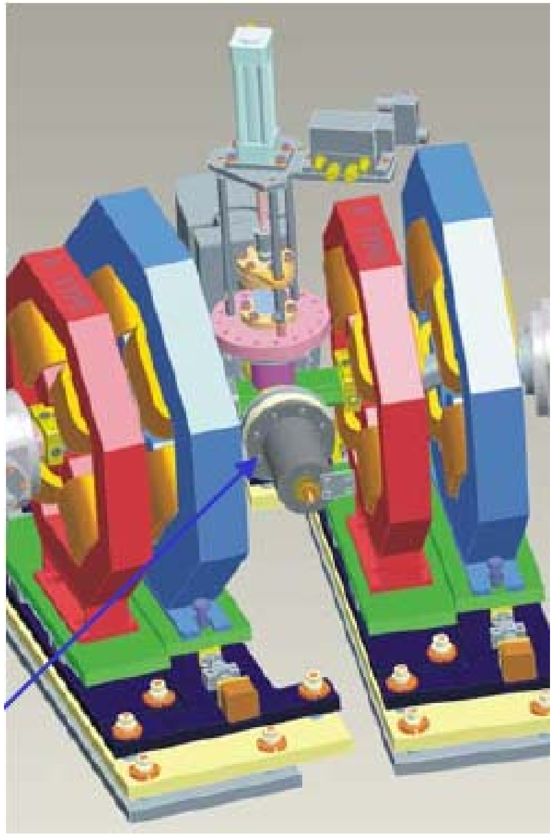
± 25μm r.m.s.
required resolution



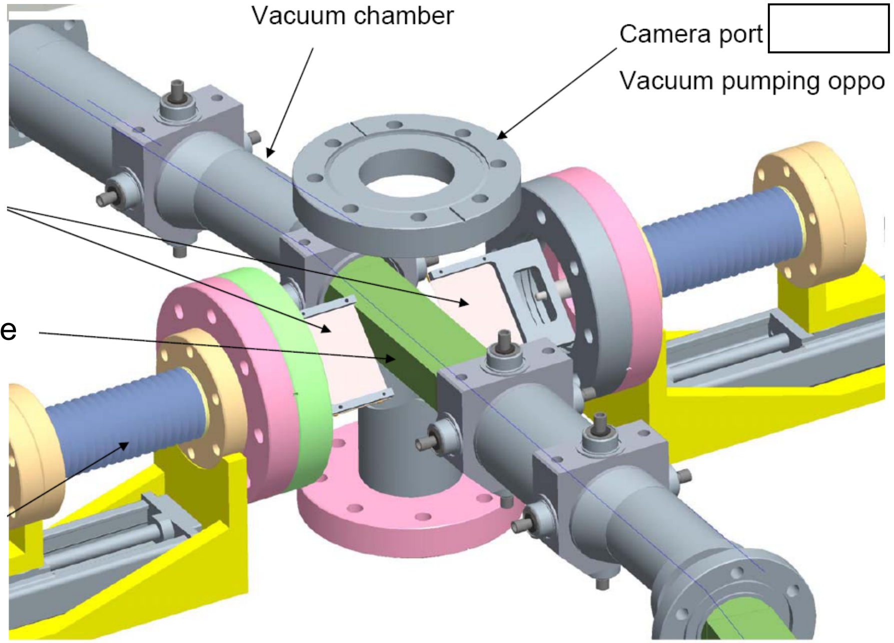
4 x BPM bodies, accurately machined and welded into vacuum chamber

Measures: closed orbits, betatron oscillations, lattice functions, tunes, as sampled at discrete locations.

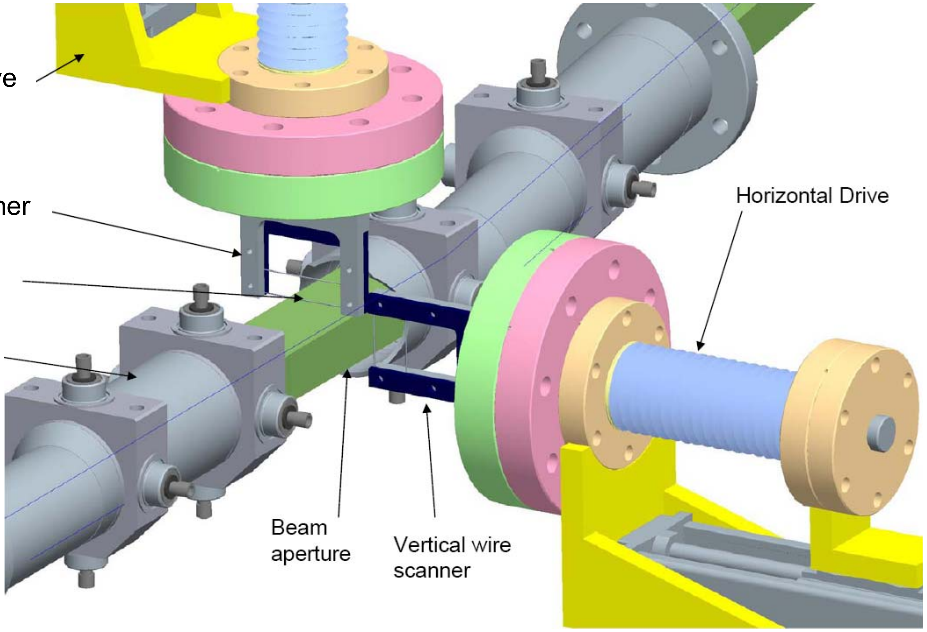
Pop in diagnostics
Screens 2/ring
Wires 2/ring

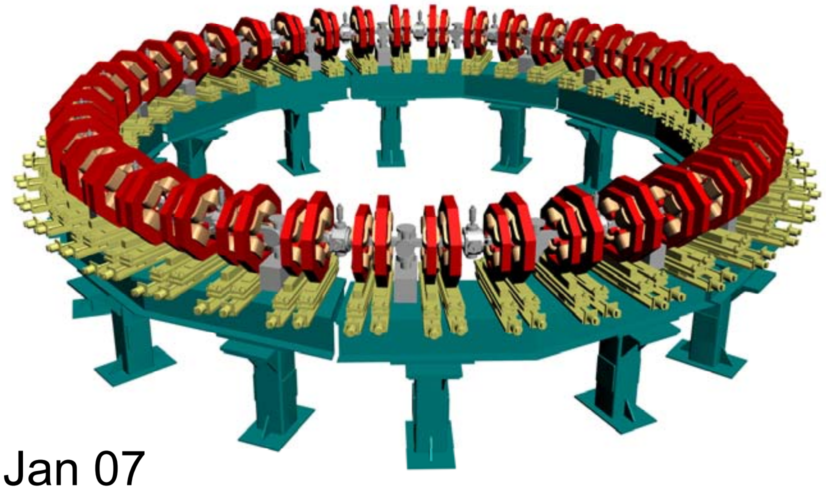


Ring OTR (Screen)



Ring Wire Scanner

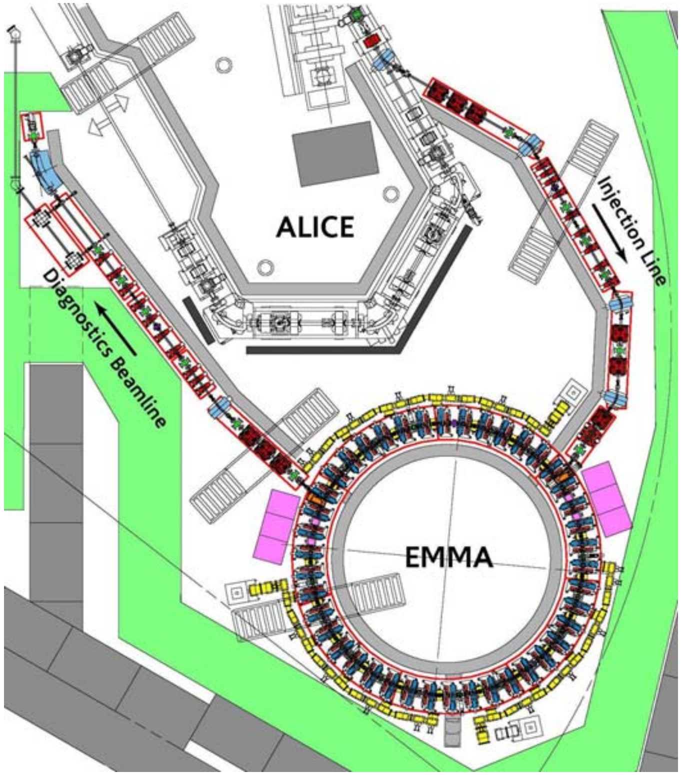




EMMA: Schedule

Design Review 1	4th Jan 07	
Design Review 2	26th Feb 07	
Design Review 3	10th – 11th Dec 07	
Major Component Design work complete	1st Jul 08	
Infrastructure upgrade	Apr 08 - Jan 09	10 months
Off line build on girders in clean conditions	Jun 08 – Mar 09	10 months
All ring DC magnets on site	1st Aug 08	
All ring cavities on site	14th Aug 08	
Fast magnets on site	30th Jan 09	
Installation in Accelerator Hall	Feb 09 – May 09	4 months
Test systems in Accelerator Hall	Jun 09 - Aug 09	3 months
Commission with electrons	Sep 09 - Nov 09	3 months
Accelerator Physics Programme	Dec 09 – Sep 2010	10 months

EMMA: Conclusions



- Construction schedule has slipped a few months
- Far more important is future of ALICE
- ALICE, formerly Daresbury Energy Recovery Linac Prototype, will be used as a variable energy injector.

BBC News 03 April 2008
Cuts in science funding mean that it may be binned as early as July, after six years of design and construction.
"Every single building block you would need for a new light source has been deployed here," said Susan Smith, head of the accelerator physics group…

- ALICE which has been in development for six years, was recently ranked as "low priority" by the STFC in a review of the UK's scientific facilities.
- Projects given this status were most at risk of being cut, said the science council, which looks after some of the largest science centres in Britain.
- Alice's fate, along with 29 other lower priority science facilities, will be announced by the STFC on 1 July.

Next Steps: write your letters of support for ALICE & EMMA