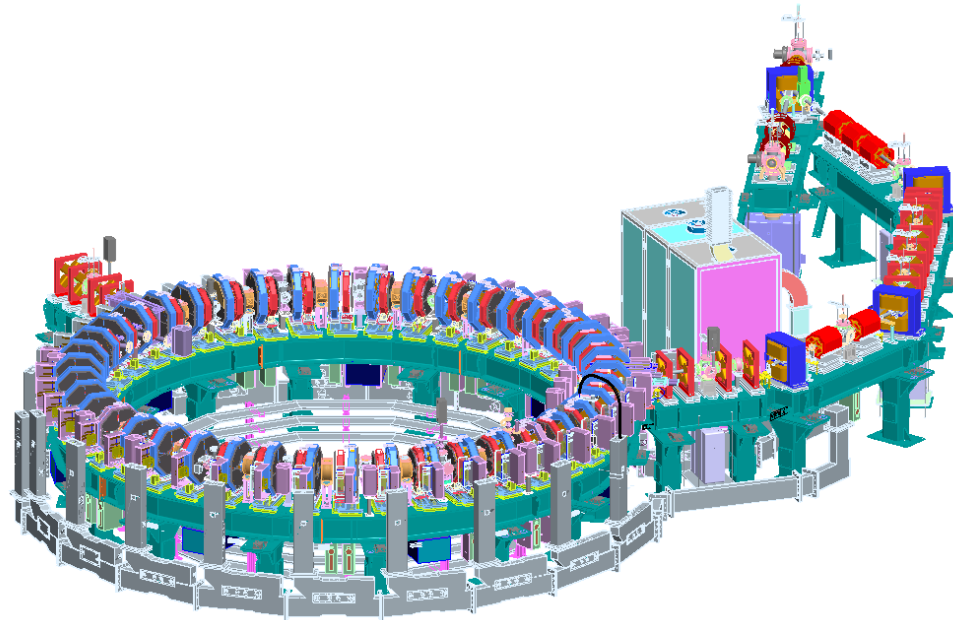


# Commissioning of the EMMA non-scaling FFAG

**Rob Edgecock**  
**STFC Rutherford Appleton Laboratory**  
**For the EMMA Collaboration\***



\*BNL, CERN, CI, FNAL, JAI, LPSC Grenoble, STFC, TRIUMF



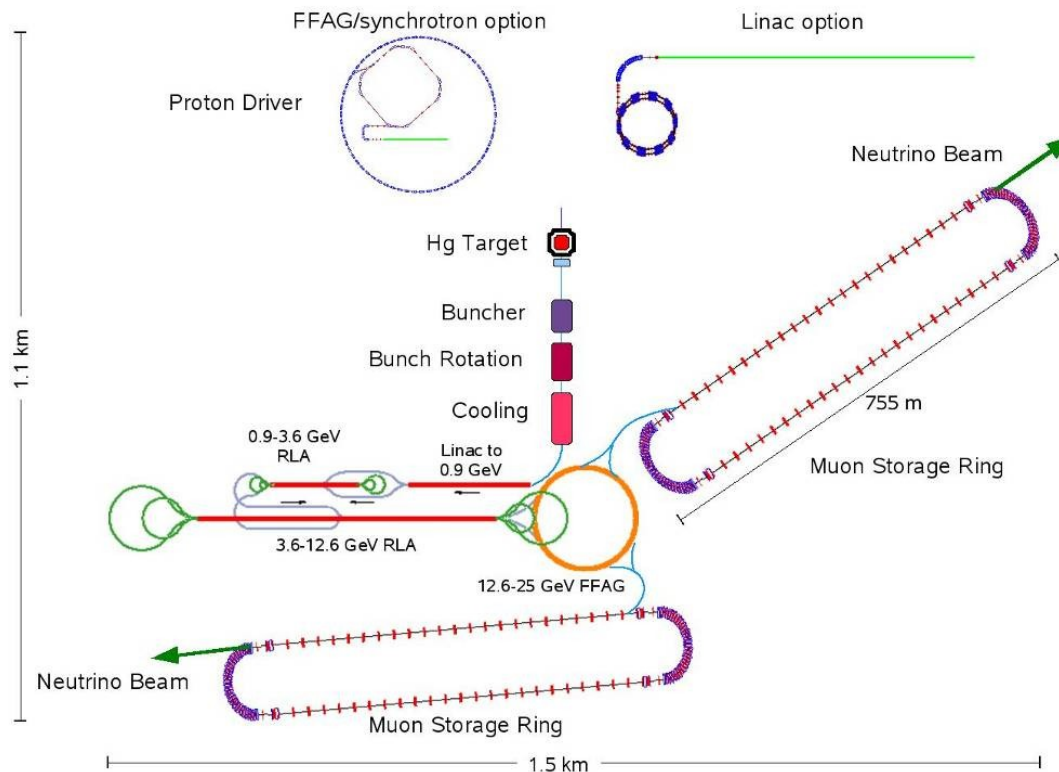
# Outline

- **Introduction**
- **Motivation for EMMA**
- **EMMA design**
- **Construction**
- **Commissioning**
- **Next steps**
- **Conclusions**

# Introduction

- Linear non-scaling FFAGs:**
  - invented 1997/9
  - for muon acceleration in a Neutrino Factory

$$B = B_0 \left( 1 + \frac{k}{r_0} r \right)$$

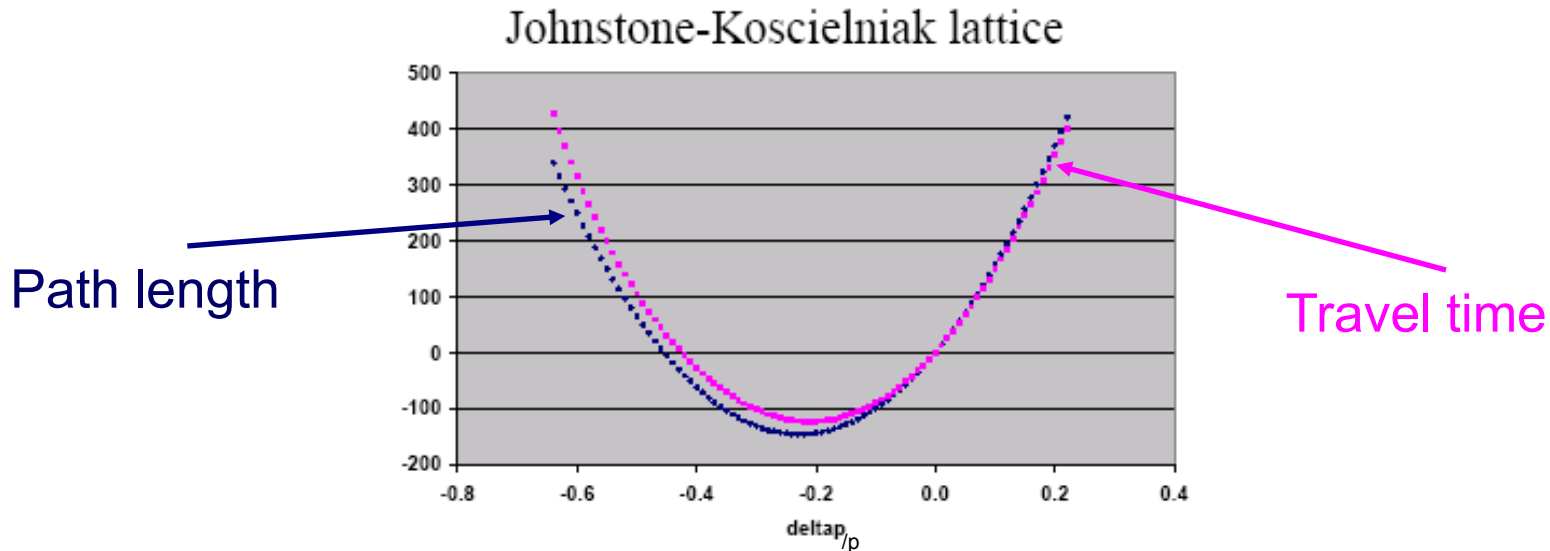


Neutrino Factory

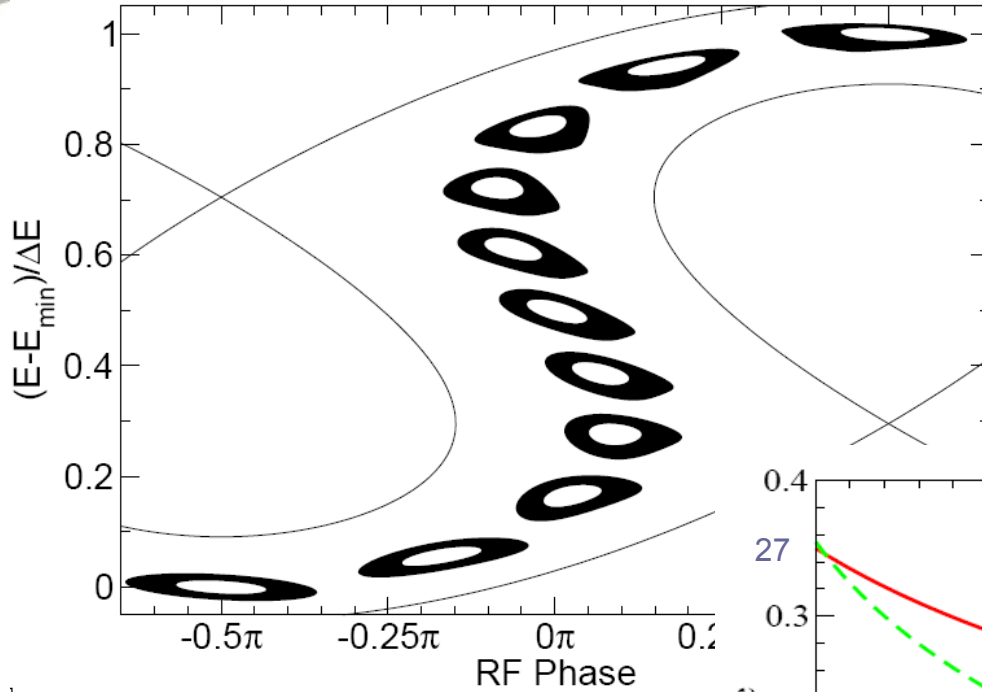
# Introduction

- **Linear non-scaling FFAGs:**
  - **invented 1997/9**
  - **for muon acceleration in a Neutrino Factory**
  - **large dynamic aperture**
  - **small orbit excursion – higher frequency RF**
  - **CW acceleration**

$$B = B_0 \left( 1 + \frac{k}{r_0} r \right)$$

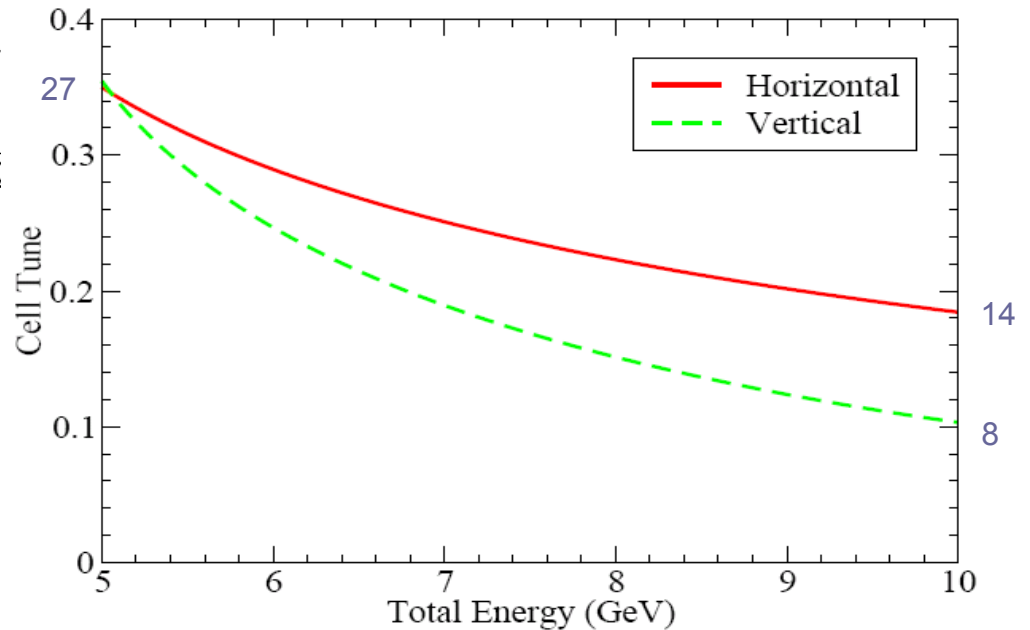


# Introduction



**Serpentine, bucketless,  
asynchronous, etc  
acceleration**

**Fast resonance  
crossings**





# Motivation for EMMA

- **Realised early on:**
  - **Other potential applications:**
    - **hadron therapy**
    - **ADSR**
    - **other high power proton beam applications**
  - **One or two issues:**
    - **tiny momentum compaction**
    - **unique longitudinal dynamics**
    - **possible transverse dynamics problems**
    - **resonance crossings**
    - **constraints on construction**
    - **standard tracking codes not applicable**
    - **purpose built codes need benchmarking**
- **Must build one!**
- **Hence, EMMA**

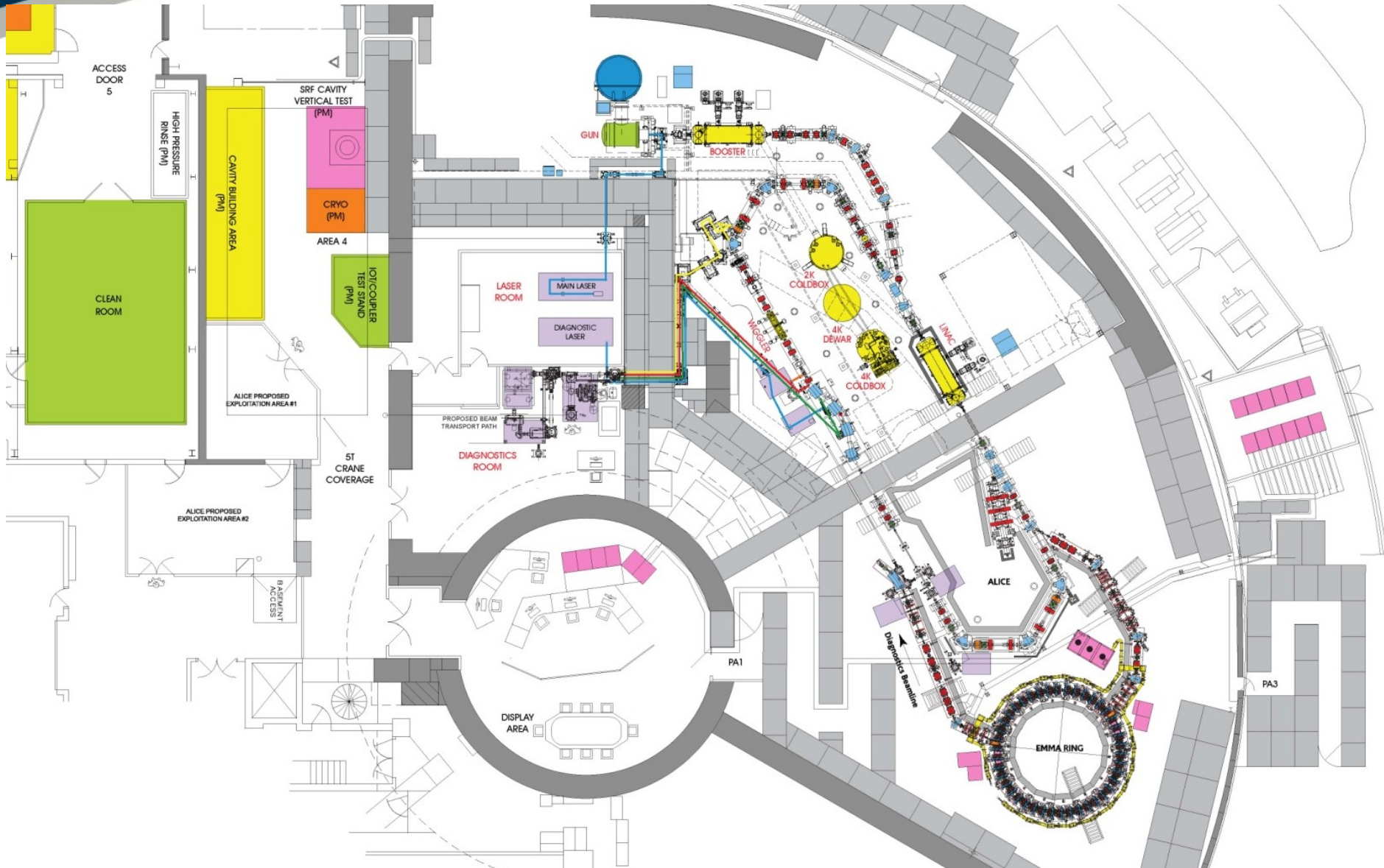


# EMMA Design

- **Simplest to build linear non-scaling machine**
- **Main parameters taken from muon accelerator:**
  - **electrons, 10-20MeV**
  - **linear magnets, cw RF**
  - **42 cells, doublet lattice**
- **In addition**
  - **very flexible**
  - **injection into full muon acceptance**
  - **lots of diagnostics**
  - **need flexible (10-20 MeV) injector with hall space**
  - **small**
  - **not too expensive!**



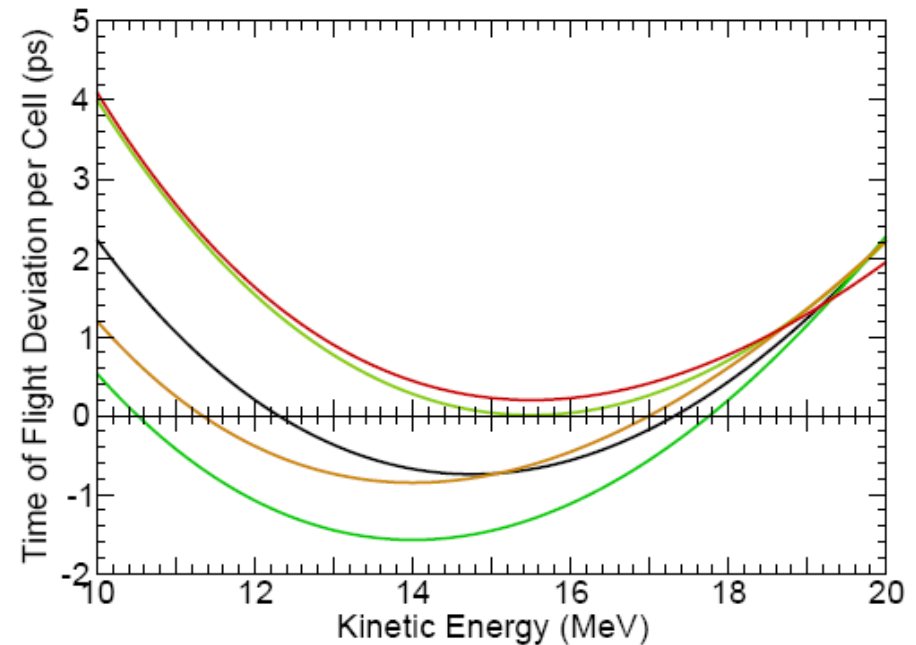
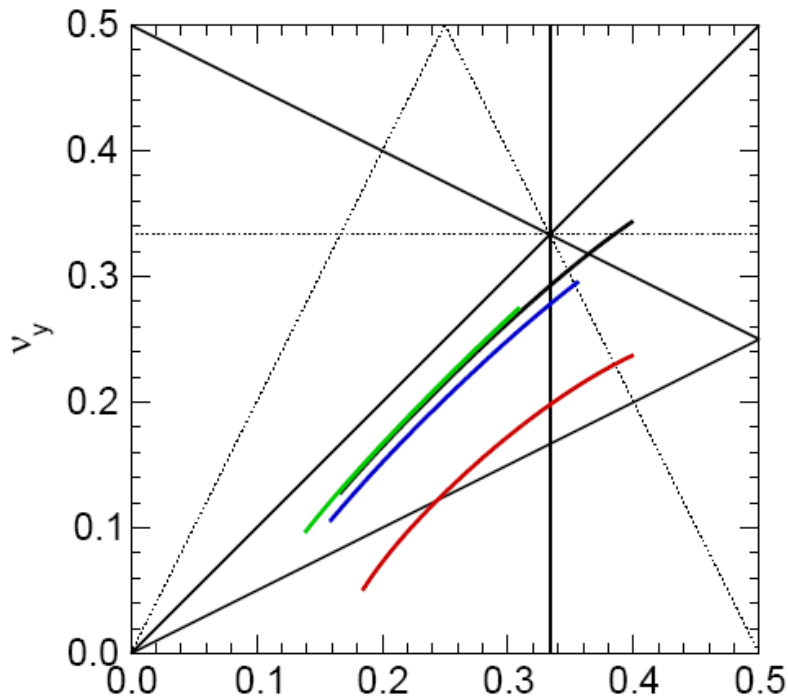
# EMMA Location





# EMMA Specifications

- **Driven by experimental nature**
- **8 lattices to explore long. & trans. dynamics**



## Requires:

- indep. dipole & quadrupole fields
- sufficient magnet aperture
- RF frequency: -4.0 to 1.5MHz
- RF gain: ~20kV to 180kV/cavity

# EMMA Design

**42 “identical” cells, ~40cm long**

**Ring ~16.5m circumference**

**Very compact**

**7 girder**

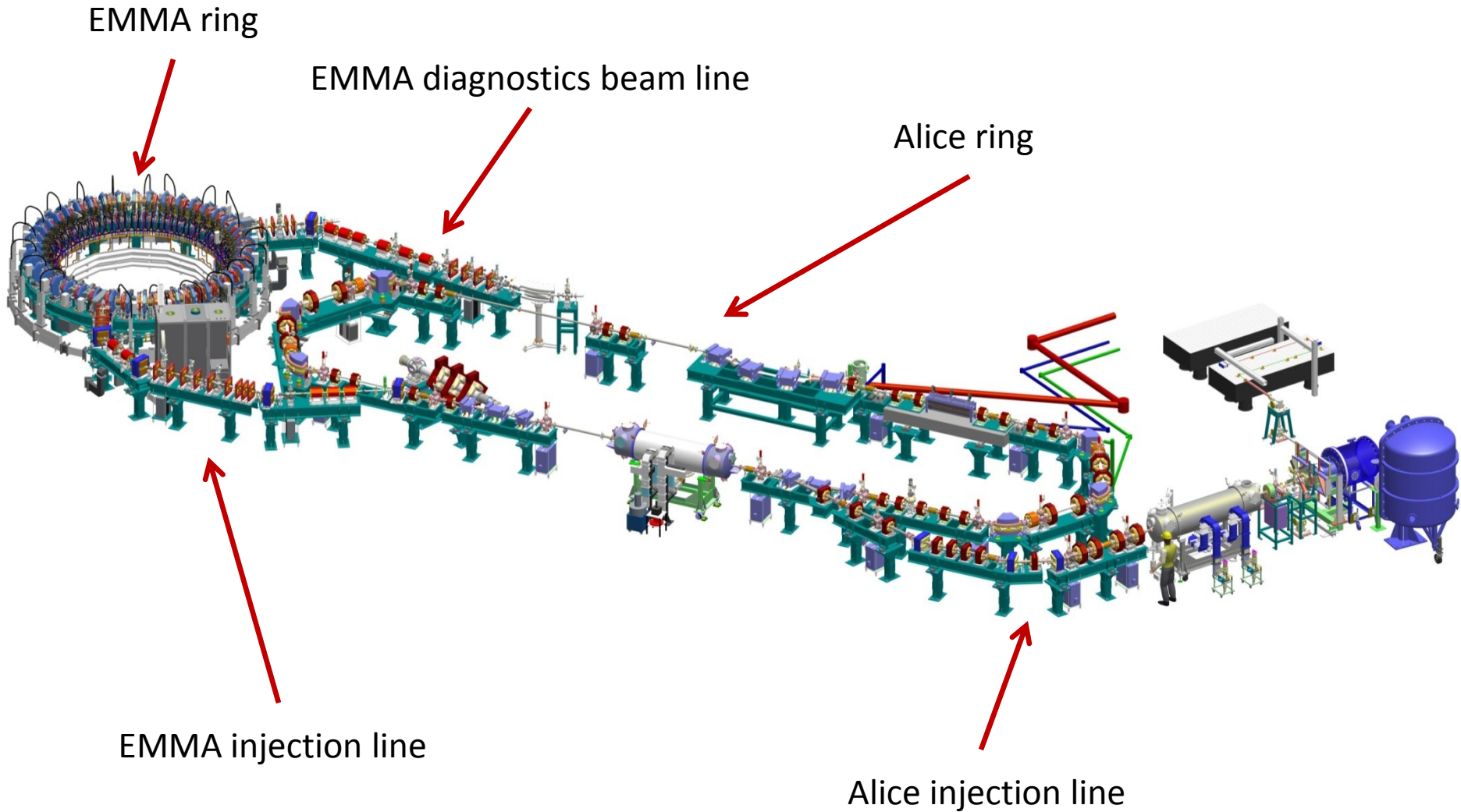




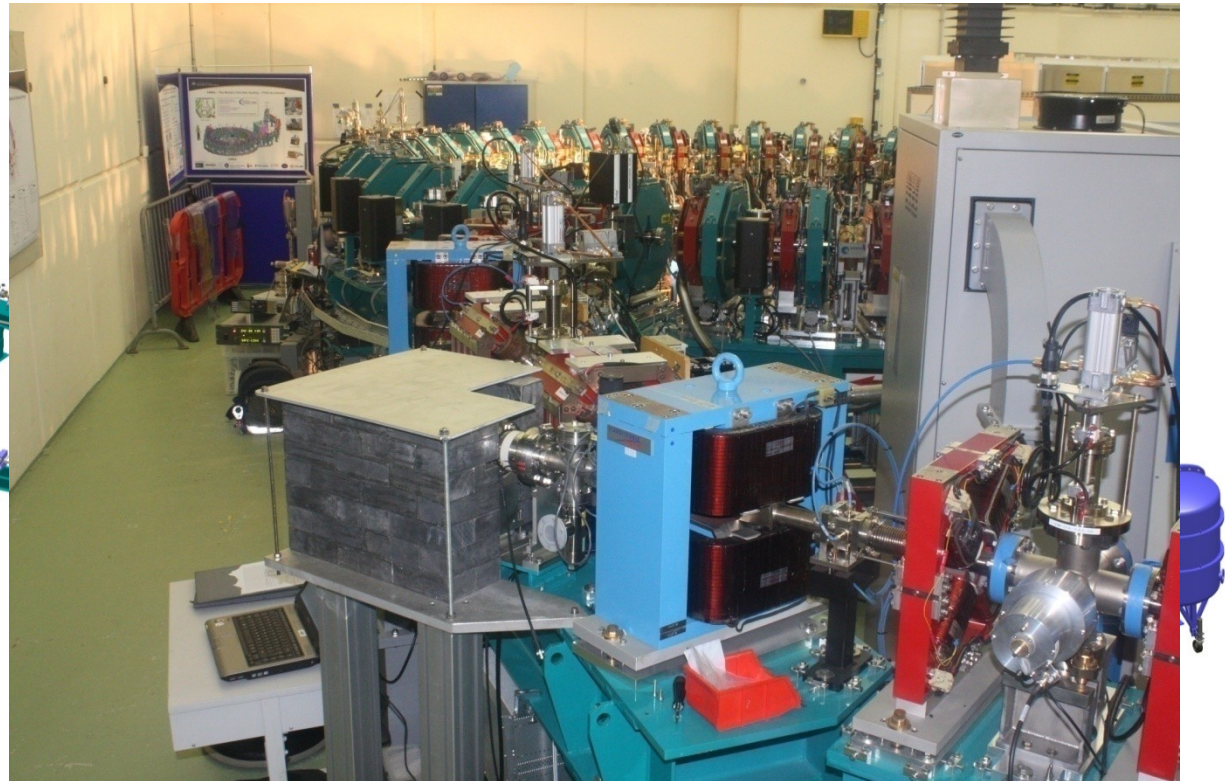
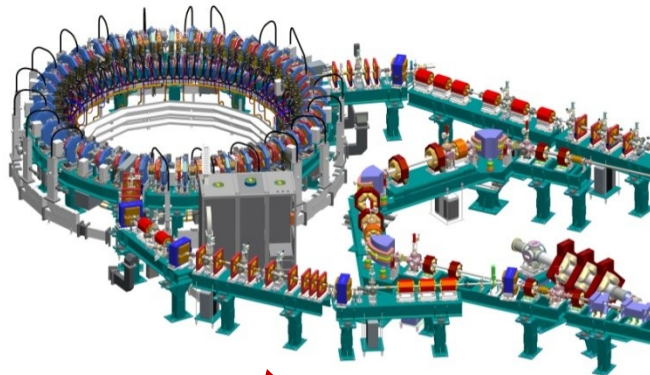
# EMMA Design



# Status of Construction



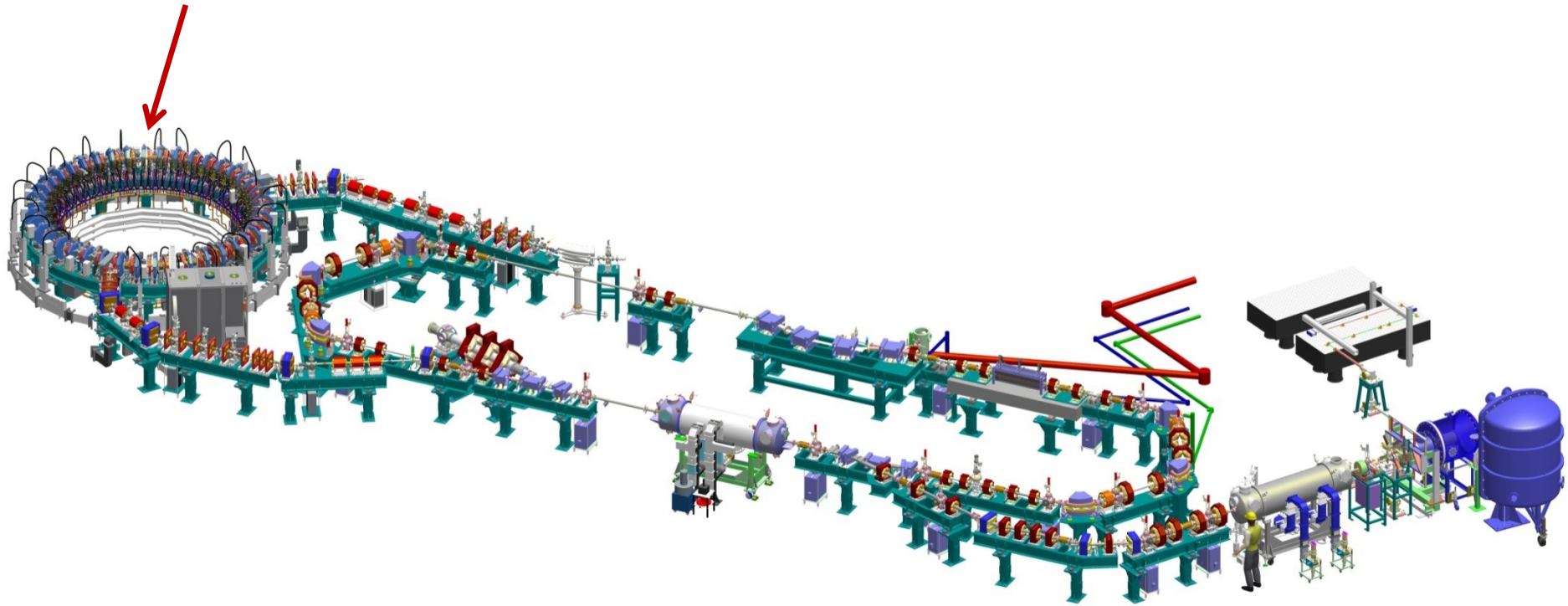
# Status of Construction



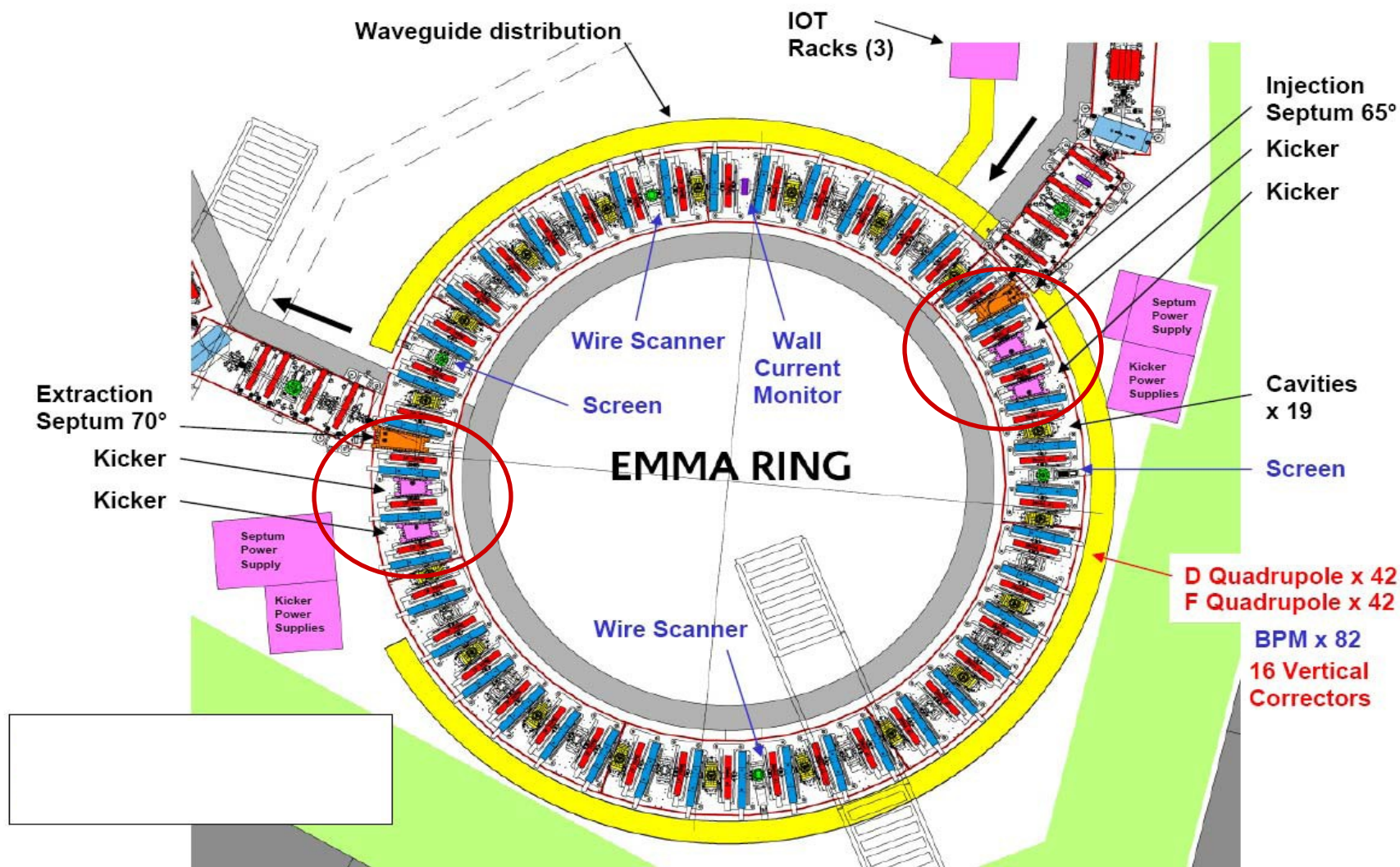
EMMA injection line - Completed March 2010  
- First beam: 26<sup>th</sup> March

# Status of Construction

EMMA ring



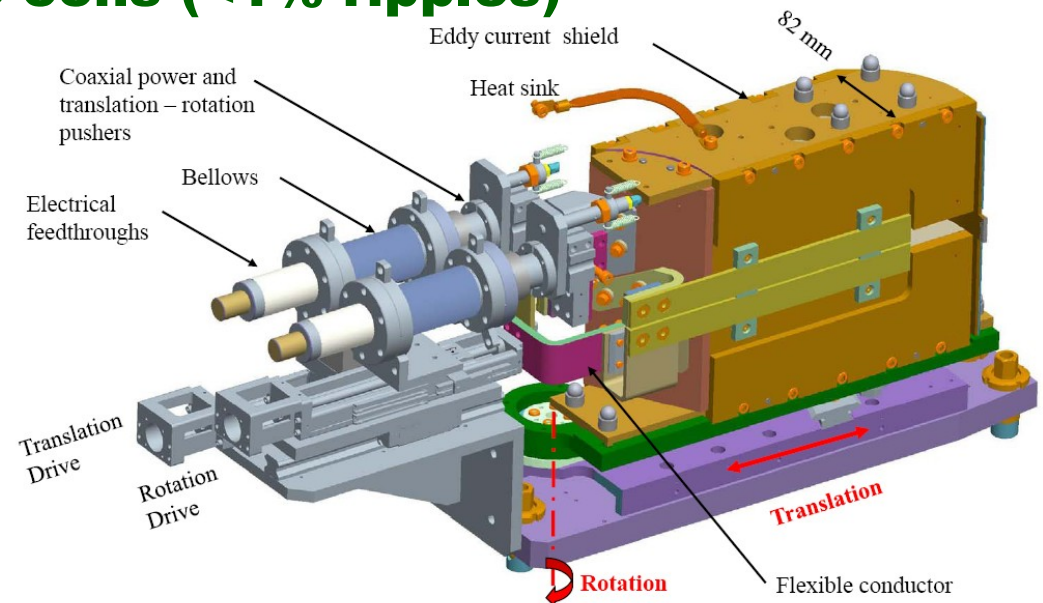
# EMMA Ring



# Injection & Extraction

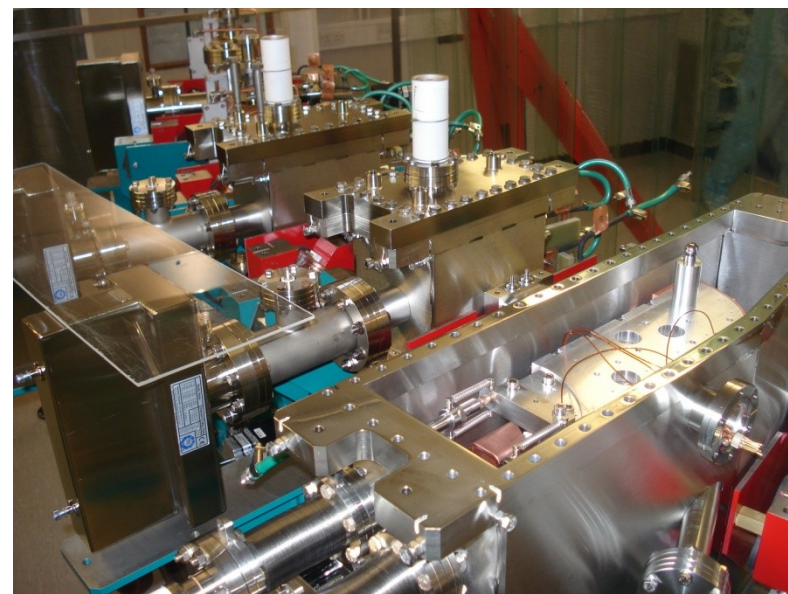
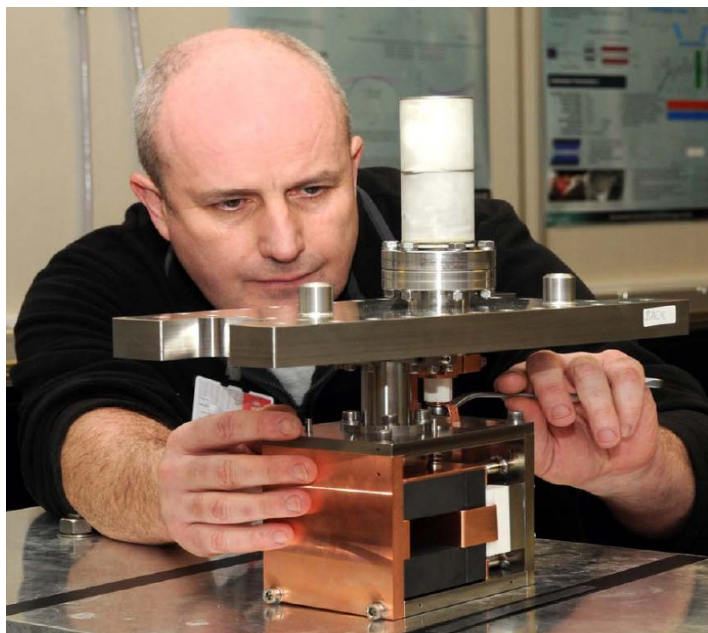
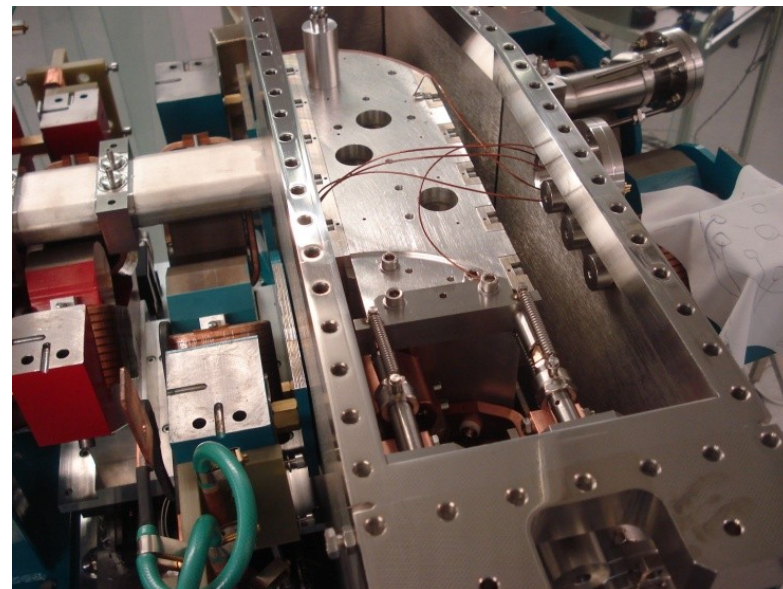
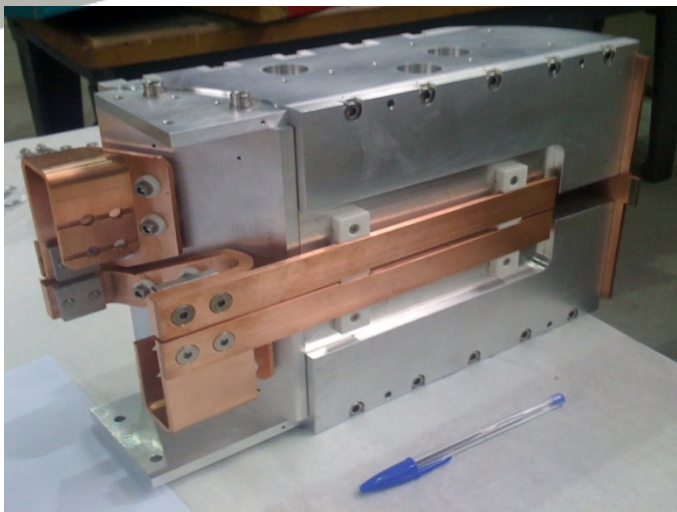
## Requirements

- **Injection of:**
  - all 8 lattices
  - all energies between 10 and 20 MeV
  - into  $3\pi$  m mrad
- **Minimal impact on next turn:**
  - leakage field from septum < 0.01%
  - kickers off before 55ns (<1% ripples)
- **Slot length: ~10cm**



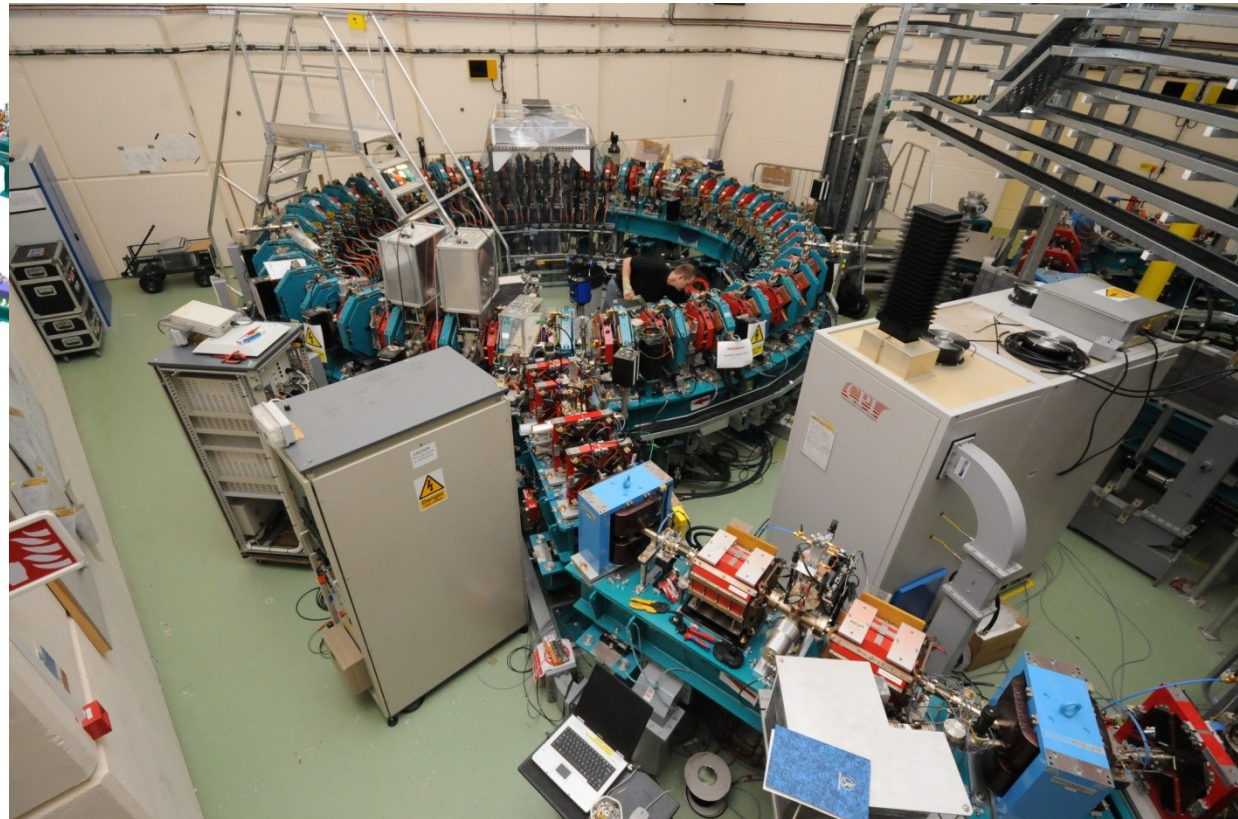
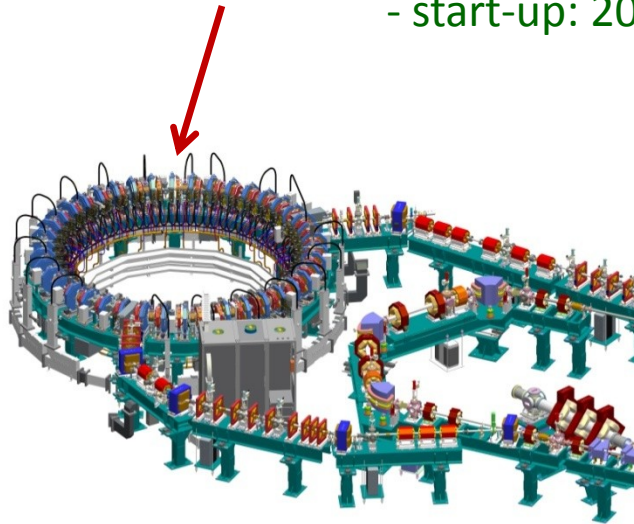


# Injection & Extraction

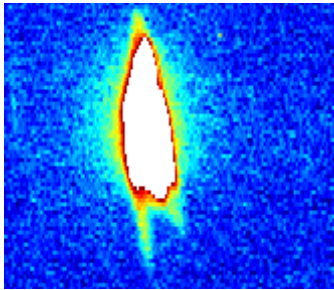


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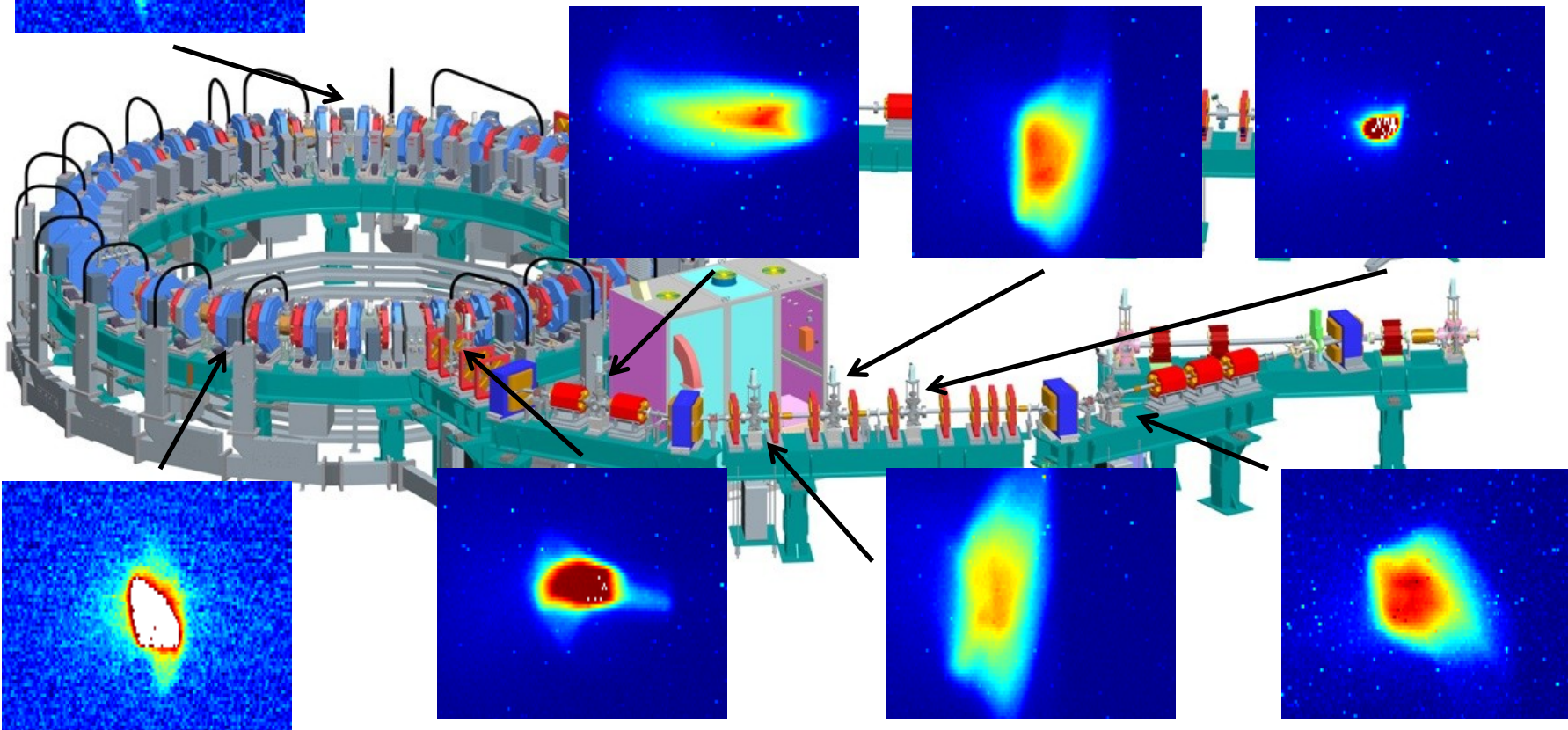
EMMA ring - “completed” on 18th June 2010  
- start-up: 20<sup>th</sup> June



# Status of Construction



12:05Z 12/3/2006





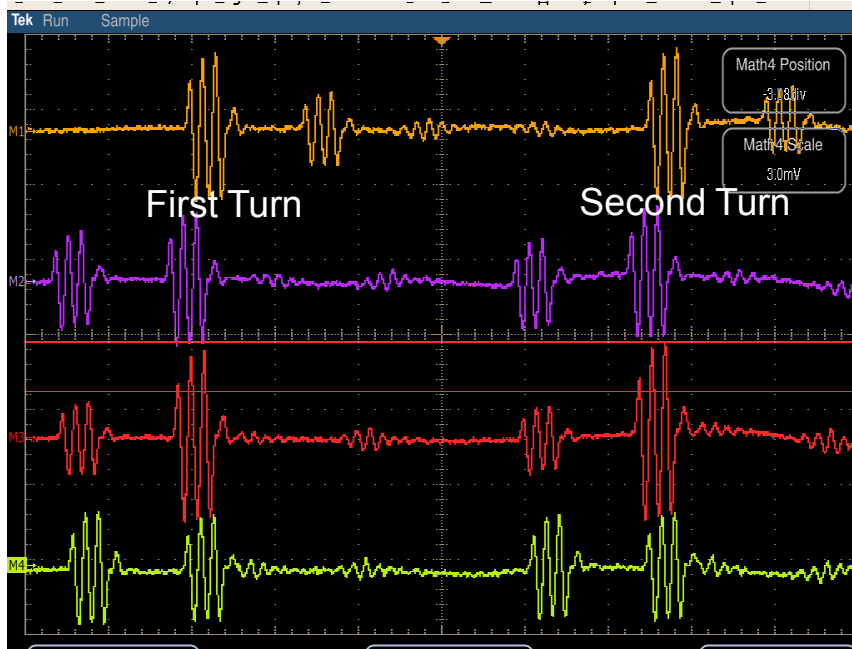
# Status of Construction

EMMA ring

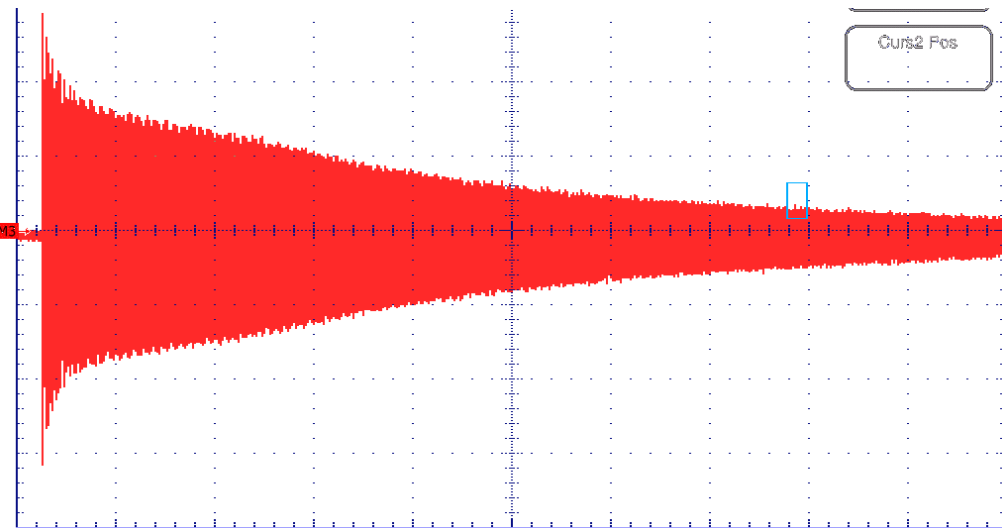
- “completed” on 18th June 2010
- start-up: 20<sup>th</sup> June
- ring complete: end of July 2010
- 1<sup>st</sup> commissioning period: Aug to Oct



# 1<sup>st</sup> Commissioning



16<sup>th</sup> August 2010  
15 MeV Beam  
Magnets set for 18 MeV

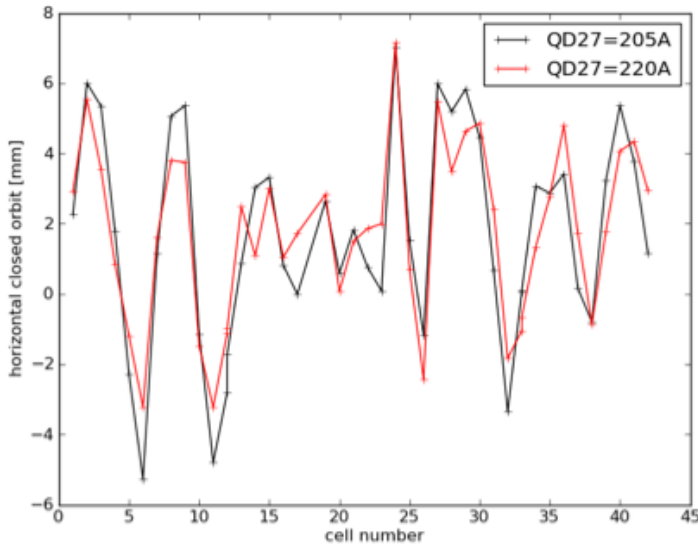


24<sup>th</sup> August 2010  
12 MeV Beam  
Magnets set for 18 MeV  
No RF

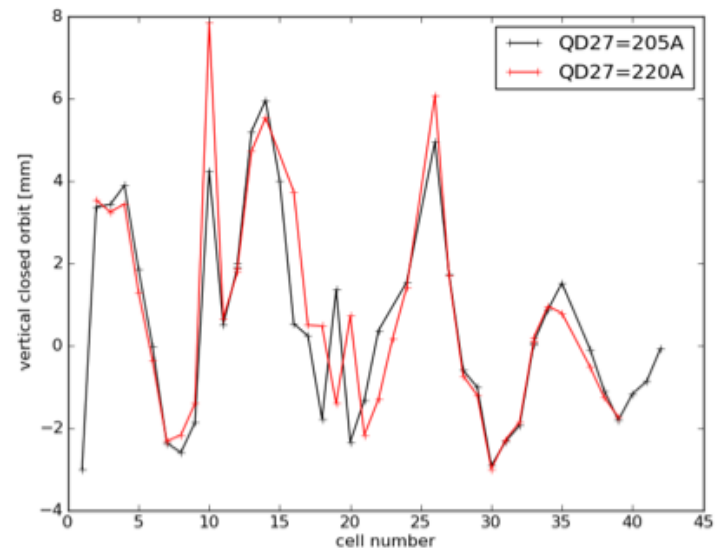
# Acceleration

- **Demonstrating accel. in FF machine not so easy!**
- **Need to look for orbit changes:**
  - **ToF**
  - **Tune**
- **Some evidence obtained before Oct shutdown, but:**

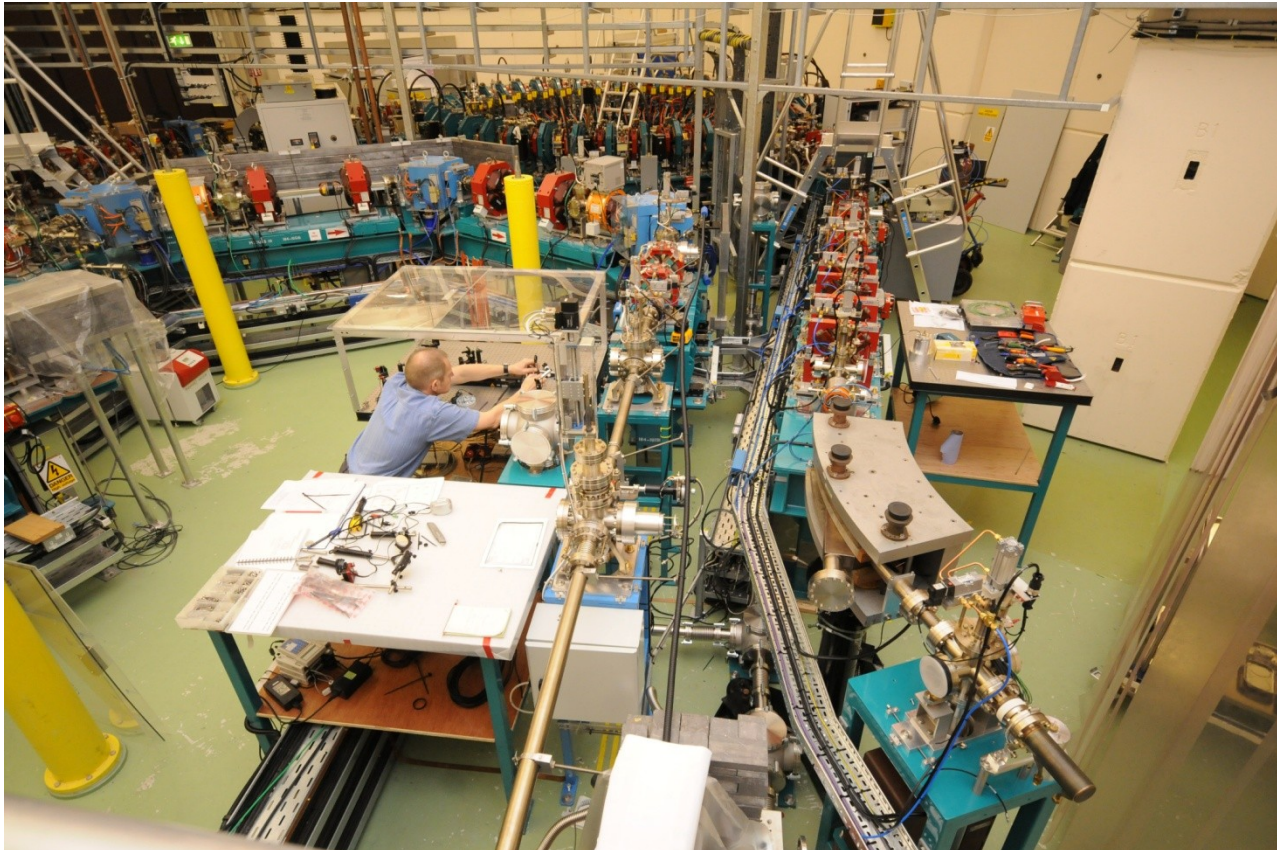
Horizontal Closed Orbit



Vertical Closed Orbit



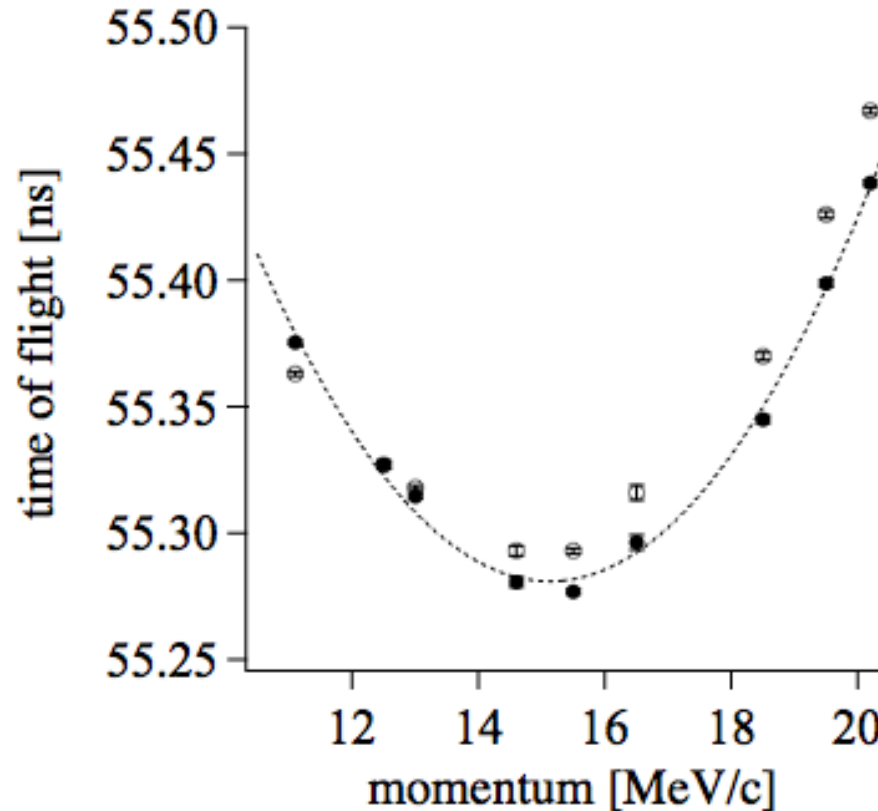
- **During Oct-Feb shutdown biggest error found & fixed:  
- some ring magnets mis-aligned**
- **Extraction line also completed**



## 2<sup>nd</sup> commissioning period

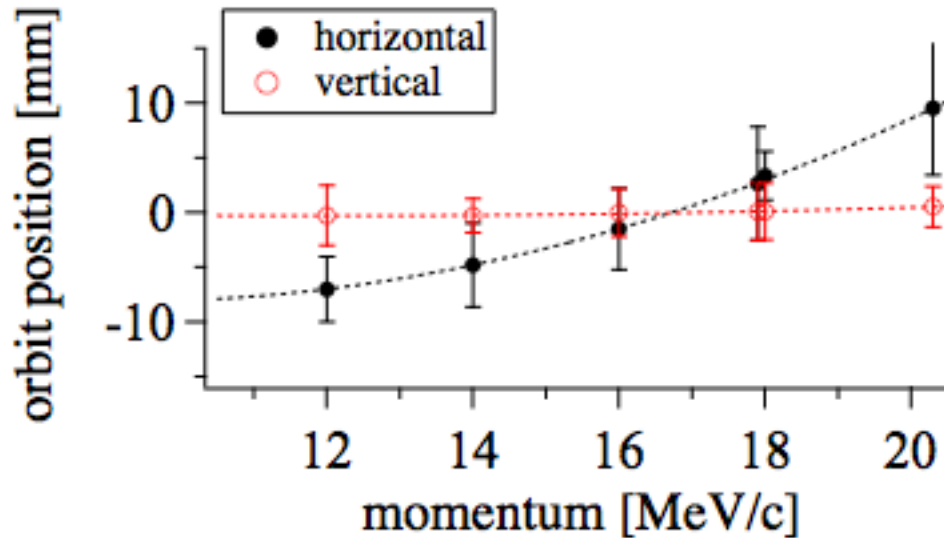
- **Real energy: 12 MeV**
- **Measurements at equivalent energies**

Time of flight

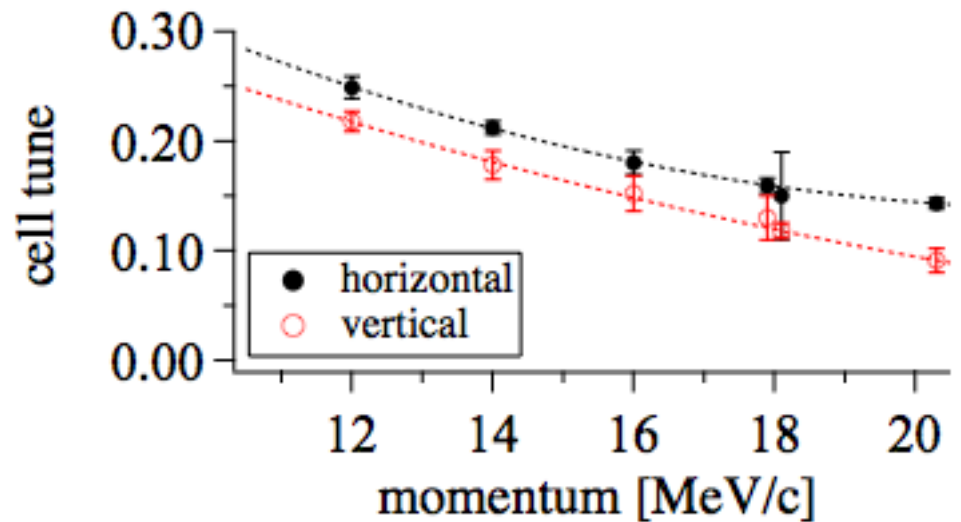




# 2<sup>nd</sup> commissioning period

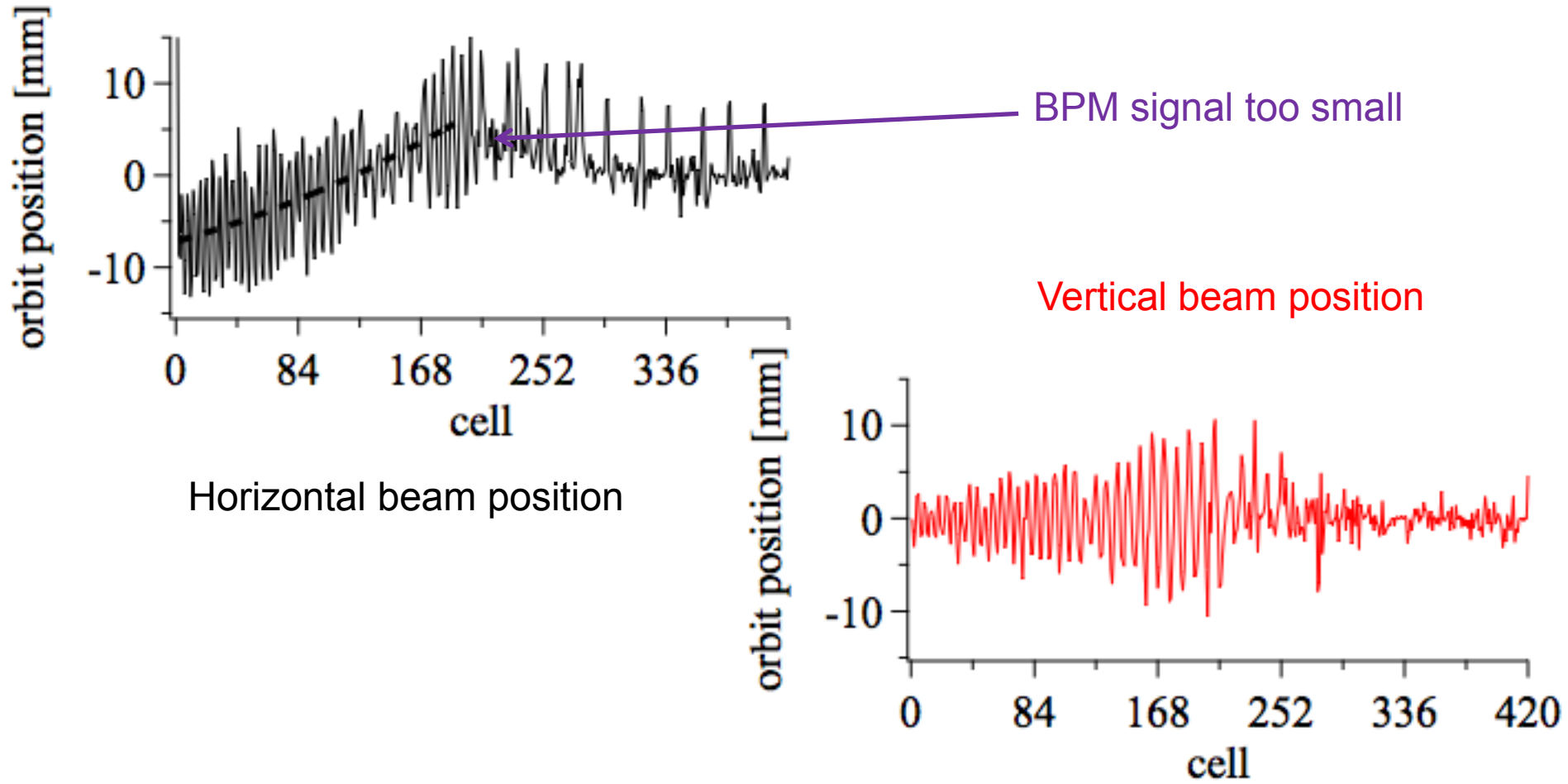


Tunes



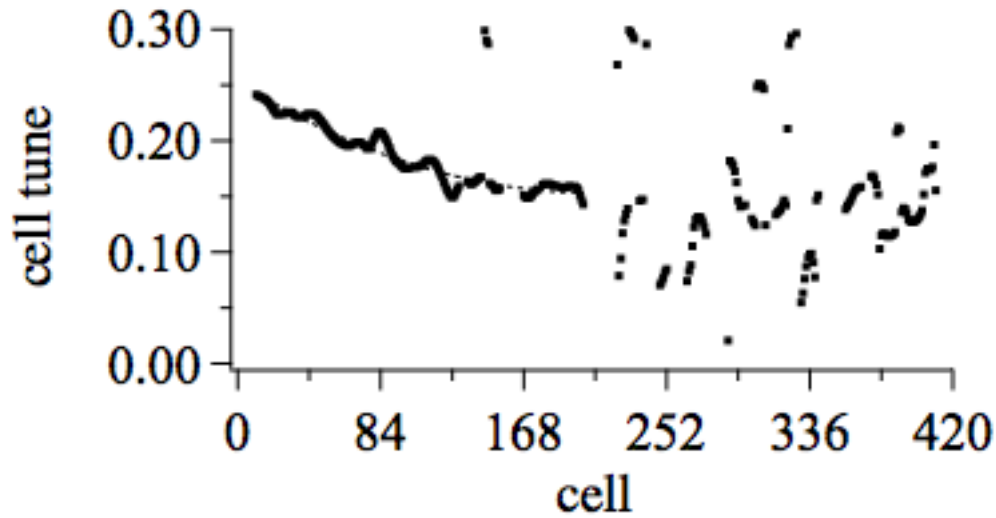
# Acceleration

- **RF set to 2.1 MV**
- **Global phase suggests acceleration of 1.9 MV**

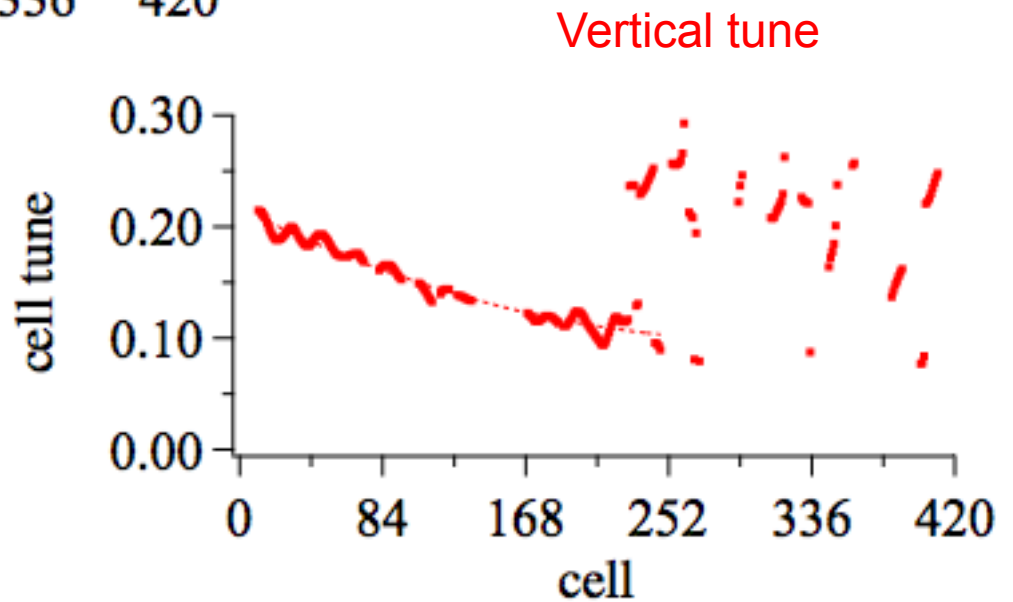




# Acceleration

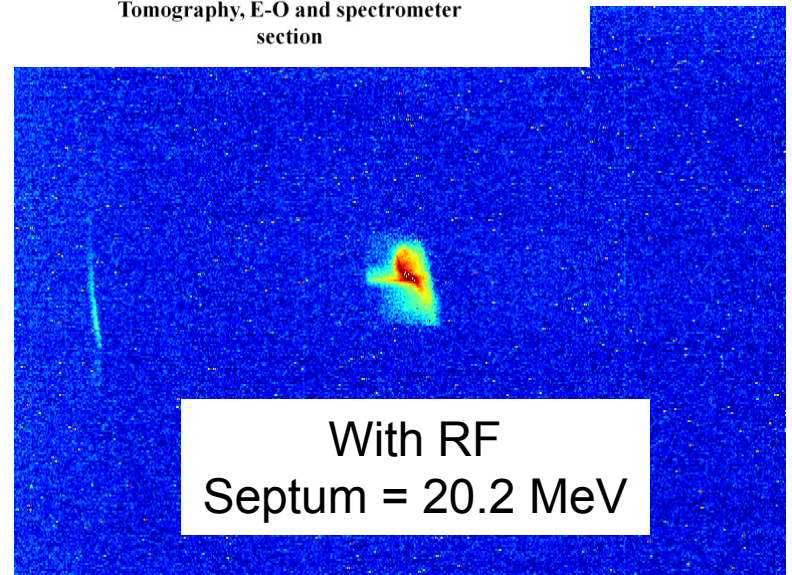
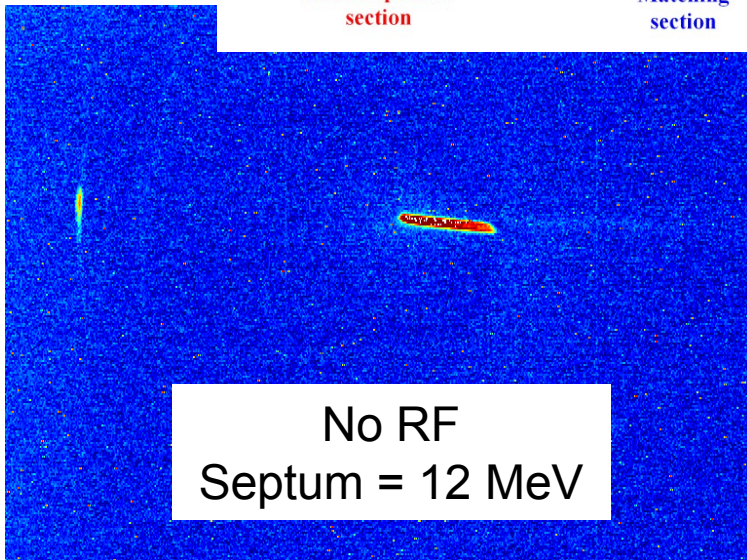
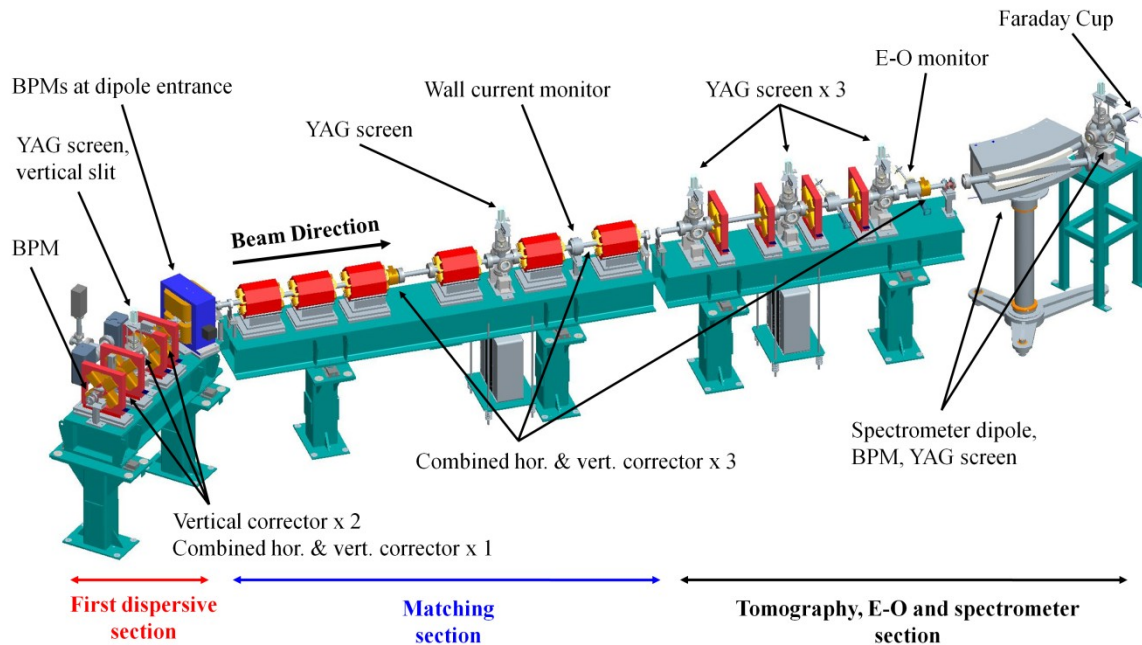


Horizontal tune



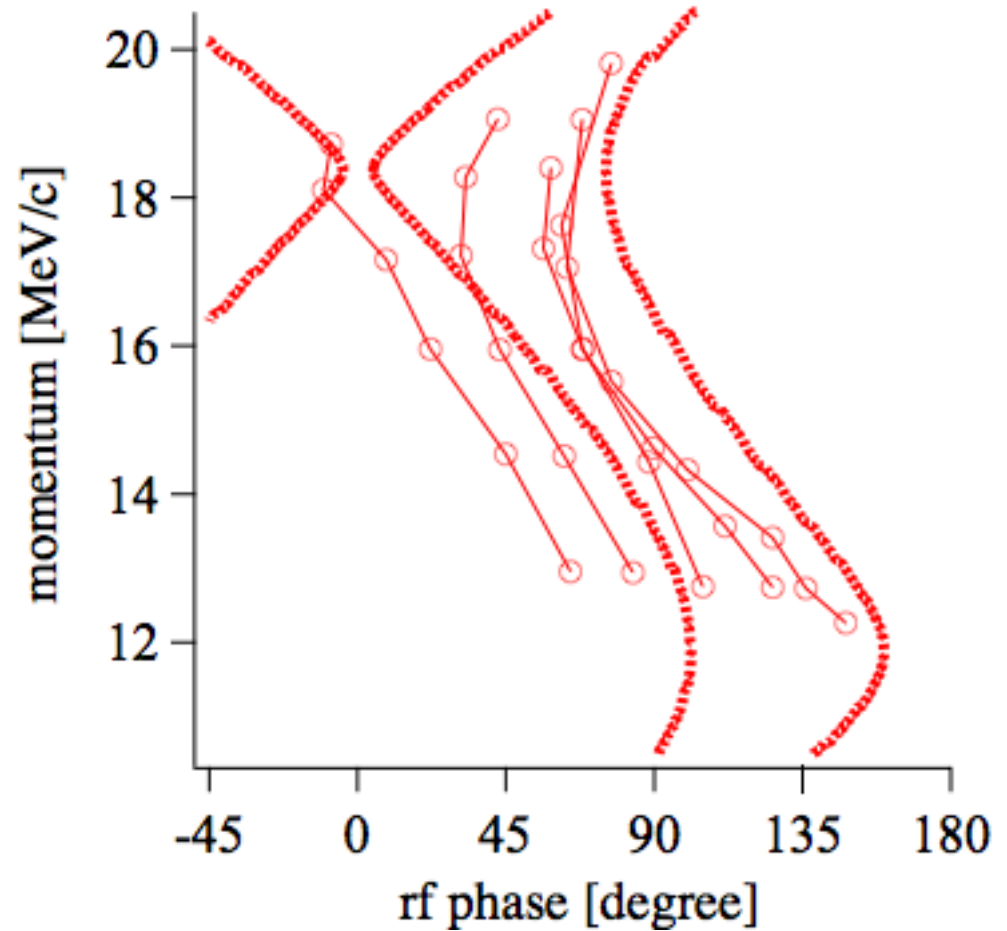
Vertical tune

# Extraction line



# Acceleration

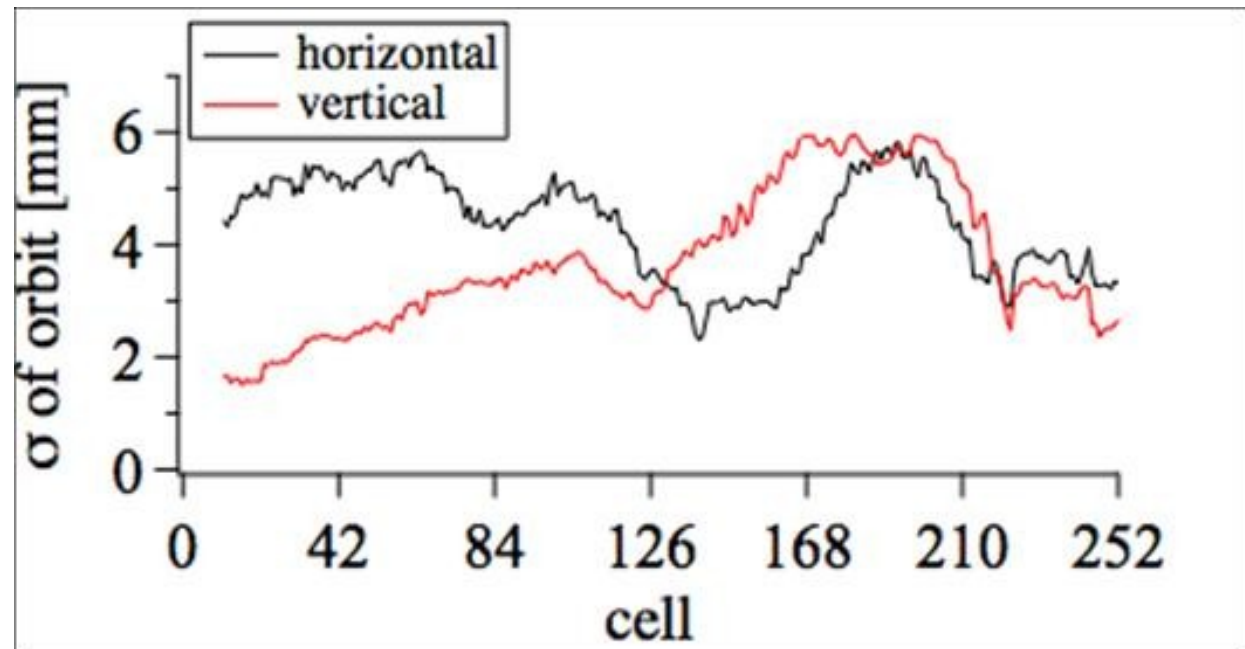
Serpentine acceleration  
works!



# Acceleration

- **During acceleration:**
  - **both horizontal and vertical cell tunes change by  $> 0.1$**
  - **ring tune changes  $> 4.2$**
  - **4 integer tunes crossed**

The  $\sigma$  of beam orbit oscillations



# Conclusions

- **EMMA works!**
  - many turns without RF
  - serpentine acceleration demonstrated
  - many integer tunes crossed
- **NS FFAGs look feasible for muon acceleration in NF!**
- **Full EMMA experimental programme starting soon**
- **Work towards other applications continues:**
  - charged particle therapy
  - ADS
- **Paper on acceleration in preparation**