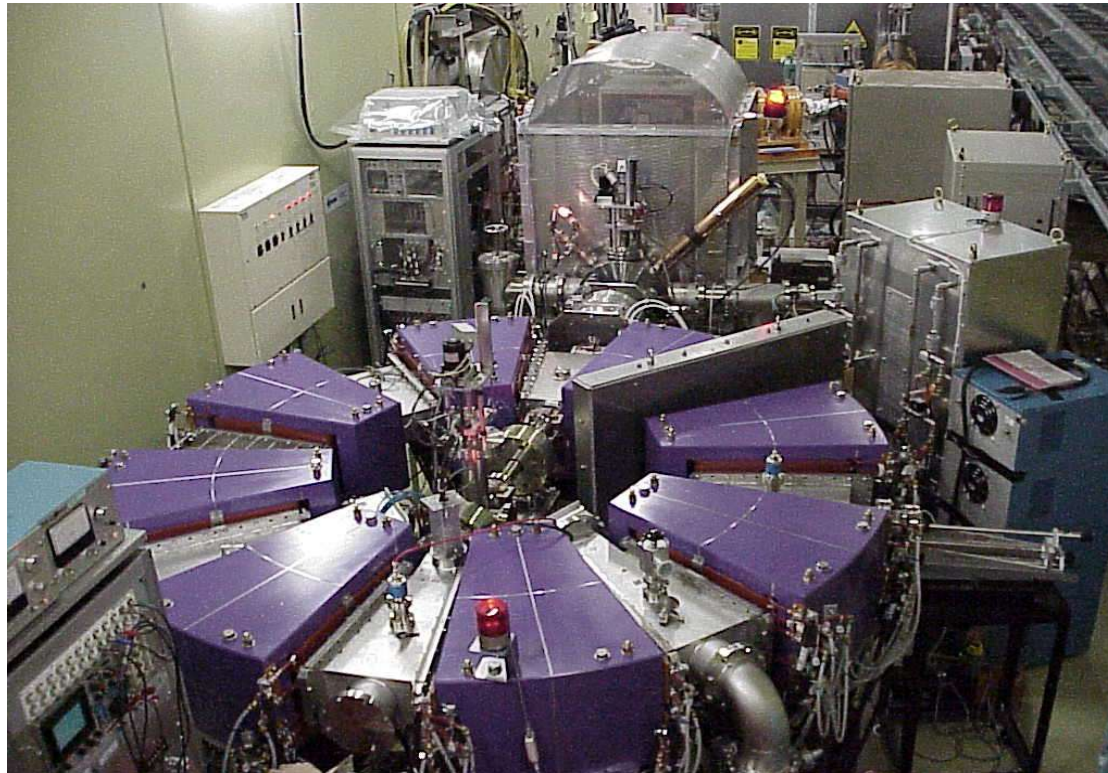


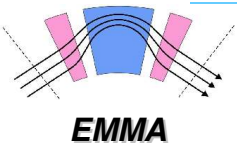
Introduction to FFAGs and a Non-Scaling Model

Rob Edgecock

CCLRC

Rutherford Appleton Laboratory



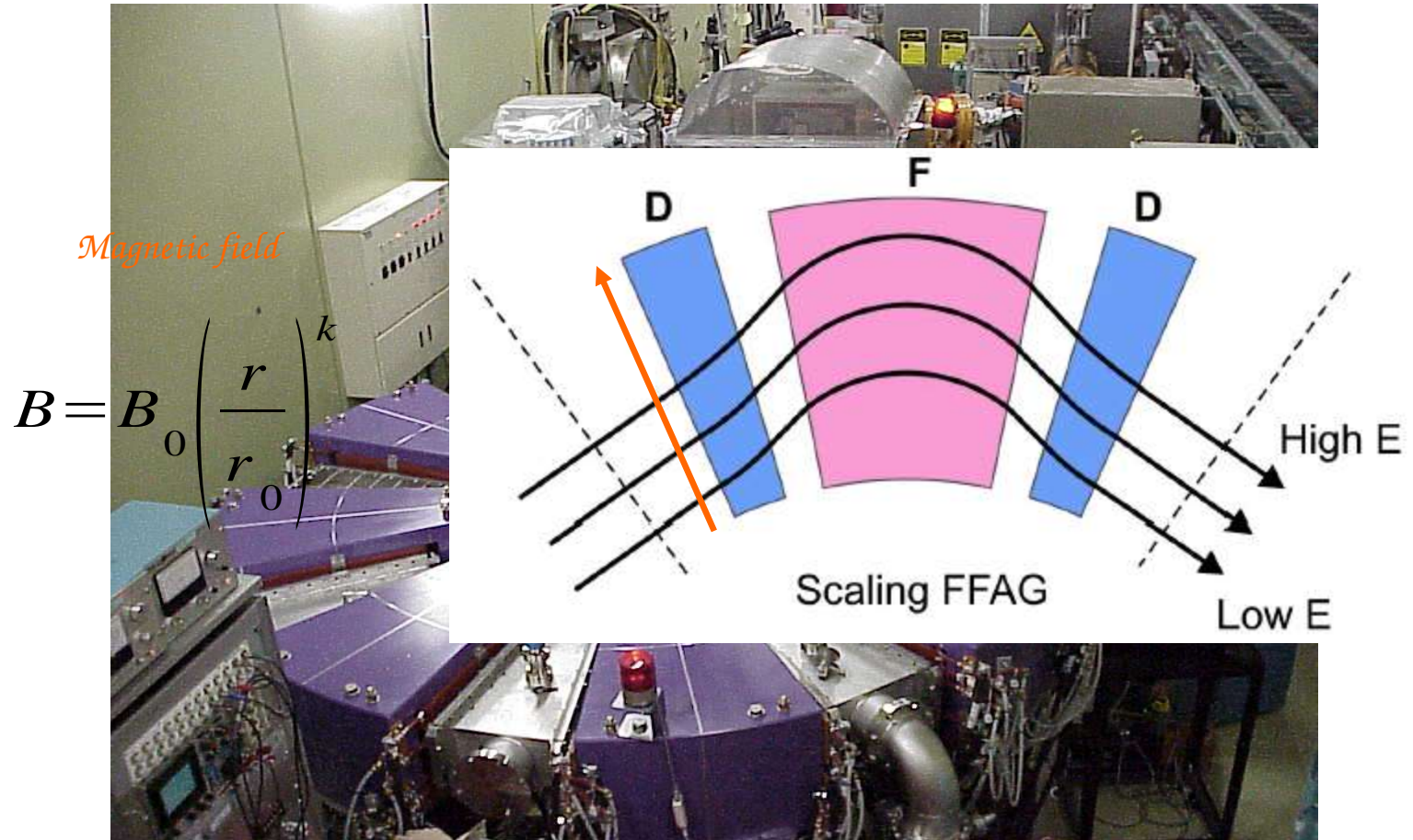


Outline

- The FFAG principle
- Brief history of FFAGs
- Developments in Japan
- Applications
- Non-scaling FFAGs
- Recent developments
- Activities in UK/Europe
- Conclusions

What is an FFAG?

Fixed Field Alternating Gradient accelerator



What is an FFAG?

Fixed magnetic field – members of the **cyclotron family**

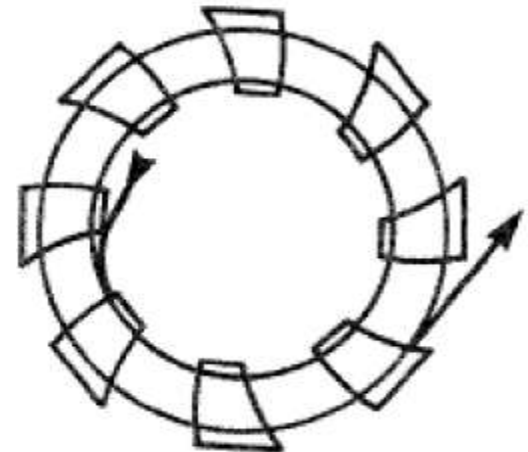
| Magnetic field variation B (θ) | Fixed RF frequency (CW operation) | Frequency modulated (pulsed beam) |
|--|--------------------------------------|--------------------------------------|
| Uniform | Classical | Synchro- |
| Alternating | Sector-focused | FFAG |



FFC + SC



SFC



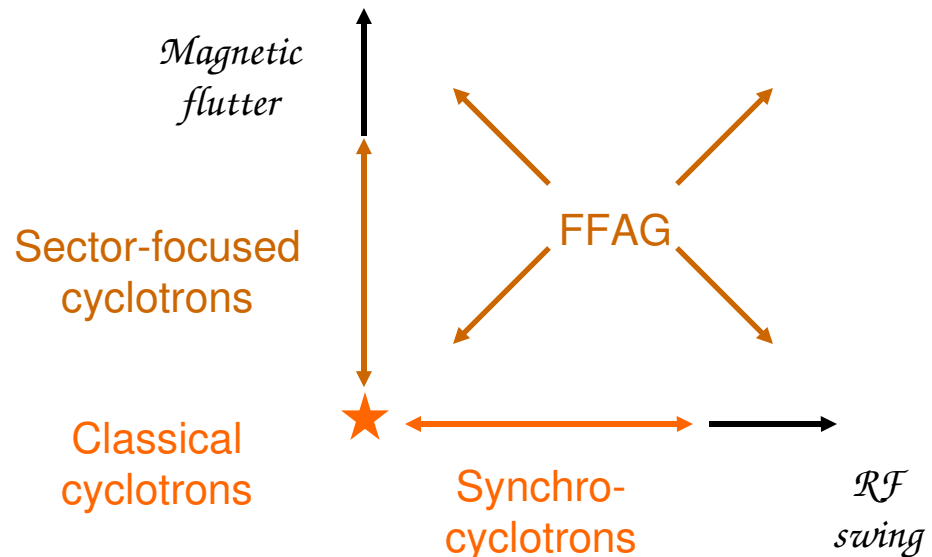
FFAG

What is an FFAG?

Fixed magnetic field – members of the **cyclotron family**

| Magnetic field variation B (θ) | Fixed RF frequency (CW operation) | Frequency modulated (pulsed beam) |
|--|--------------------------------------|--------------------------------------|
| Uniform | Classical | Synchro- |
| Alternating | Sector-focused | FFAG |

*Alternative view: cyclotrons are just
special cases of FFAGs!*



How do they work?

Magnetically: two types

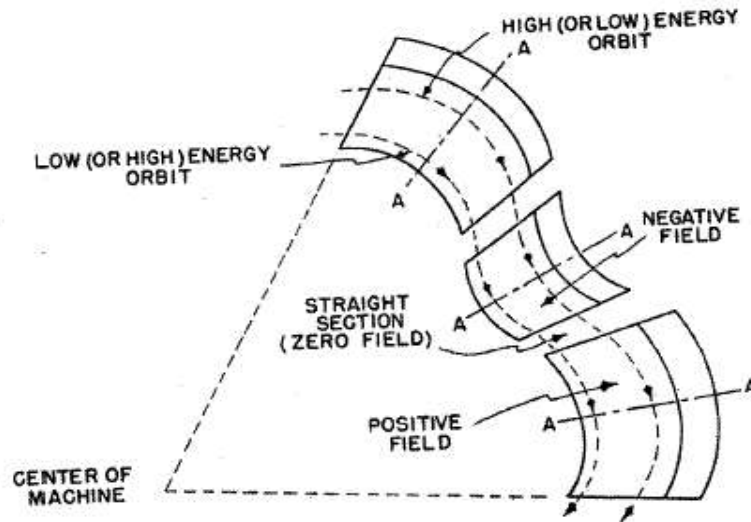


FIG. 2. Plan view of radial-sector magnets.

Radial sector FFAG

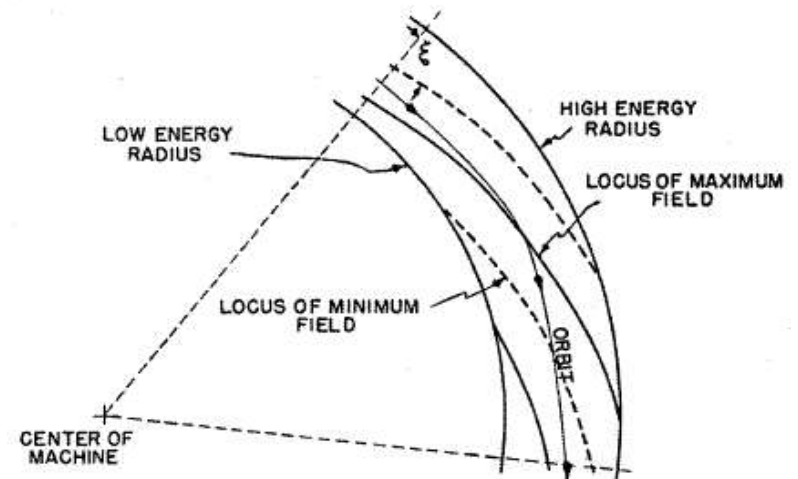
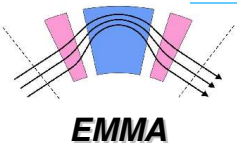


FIG. 3. Spiral-sector configuration.

Spiral sector FFAG



How do they work?

Horizontal tune

To 1st order:

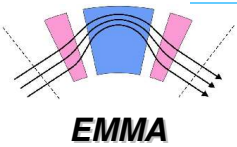
where the average field index

and

$$k(r) \equiv \frac{r}{B_{av}} \frac{dB_{av}}{dr}$$

- Note:**
- If B_{av} increases with r then $k > 0$
 - If $k > 0$ then always horizontal focussing
 - The bigger k the stronger the focussing
 - Another reason for large k

$$= \left(\frac{dp}{p} \right) / \left(\frac{dL}{L} \right) = k + 1$$



How do they work?

Vertical tune

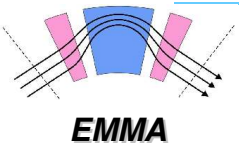
To 1st order:

where the magnetic flutter

$$F \equiv \left\langle \frac{B(\theta) - B_{av}}{B_{av}} \right\rangle^2$$

$$\frac{1}{\gamma^2} \approx -k + F(1 + 2 \tan^2 \theta)$$

- Note:**
- If $k > 0$ then vertical de-focussing
 - Real v_y requires large F and/or ε
 - For radial sector. large F from reversed fields
 - Reverse fields increase average orbit radius
 - For spiral sector, large ε - no field flip
 - More compact



A Brief History of FFAGs

- Invented in 1950s: Ohkawa in Japan, Symon in US
Kolomensky in Russia
- Interest, then and now, properties arising from FF & AG
- Fixed Field:
 - fast cycling, limited (sometimes) only by RF -
 - simpler, inexpensive power supplies - no
 - eddy-current effects, cyclical coil stress - high
 - acceptance - high
 - intensity – pulsed and continuous - low beam loss
 - and activation - easy maintenance
 - easy operation
- Strong focussing:
 - magnetic ring - beam
 - extraction at any energy - higher energies/ions
 - possible

A Brief History of FFAGs

- 1950s/60s: most extensive work at MURA



Chandrasekhar

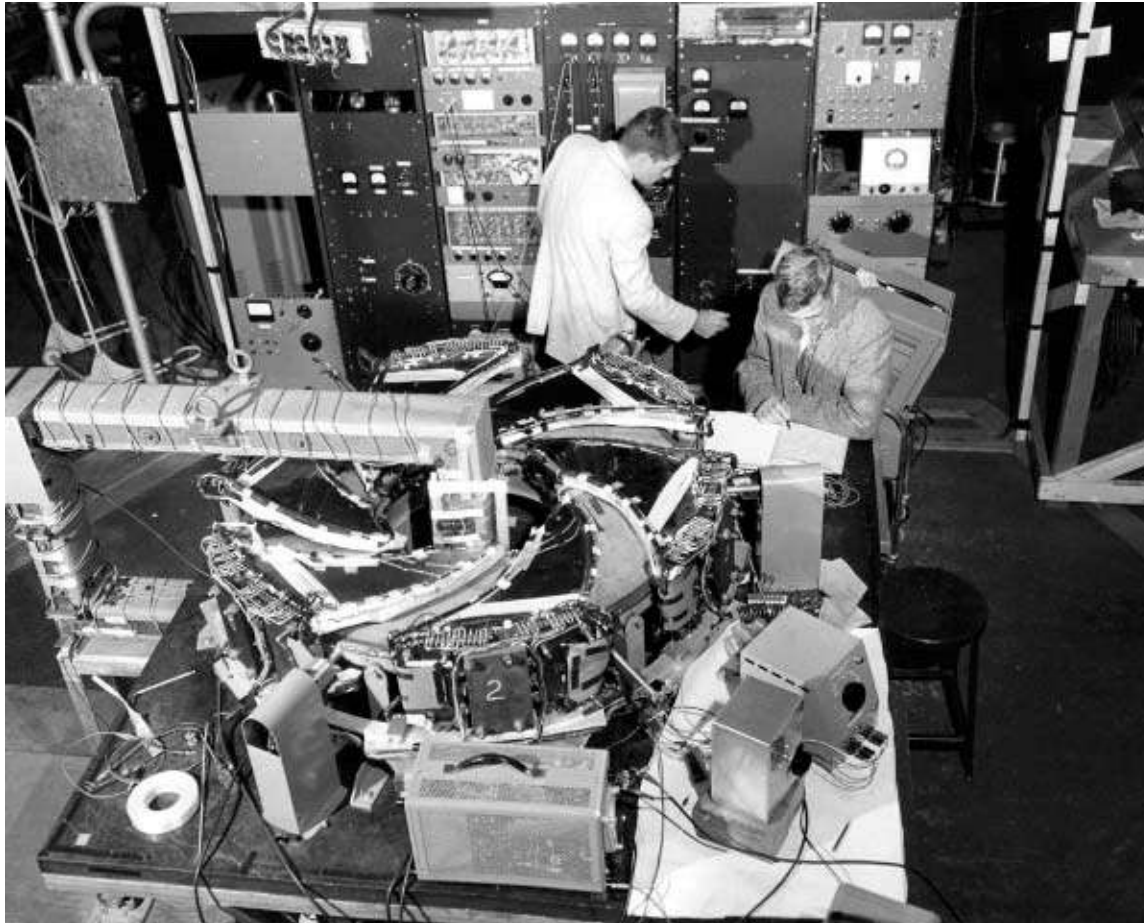
Bohr

*20 to 400 keV
machine*

*Operated at MURA
in 1956*

A Brief History of FFAGs

- 1950s/60s: most extensive work at MURA

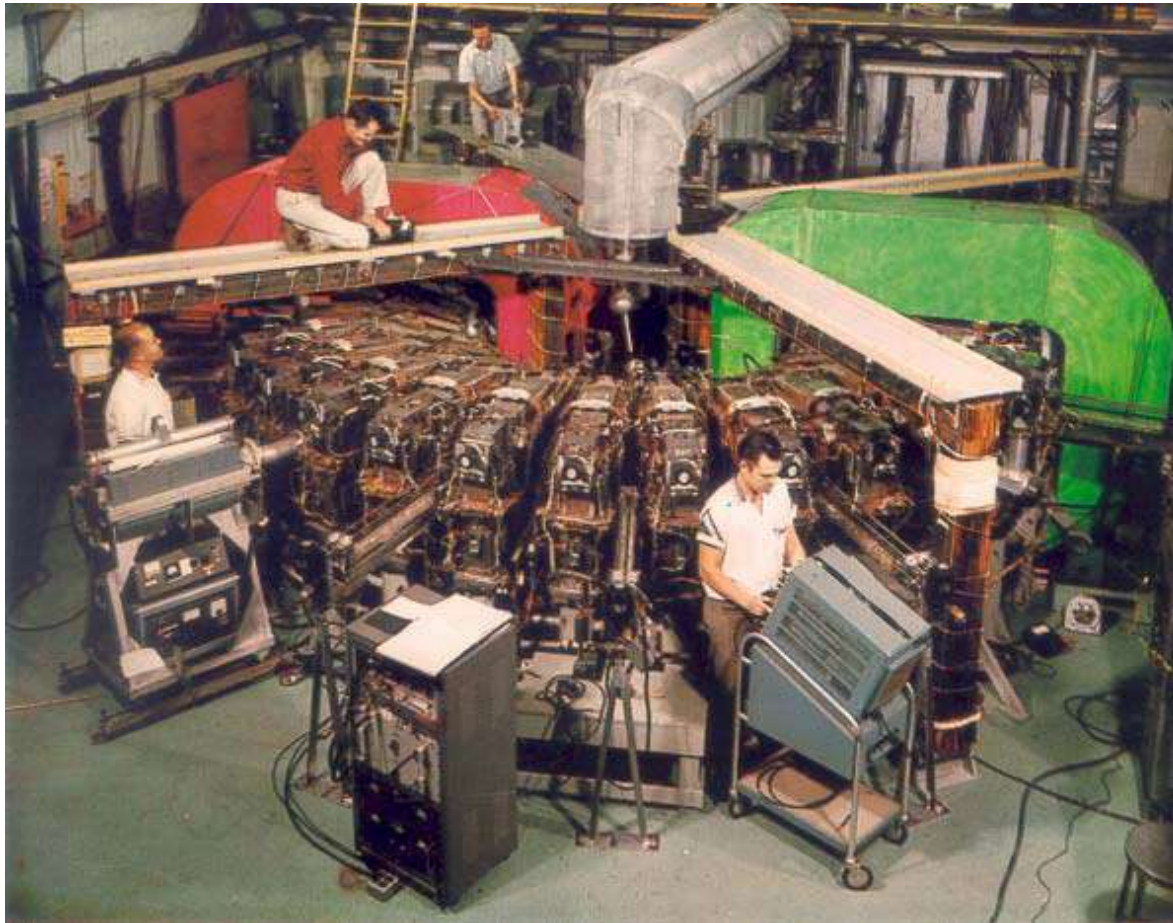


Spiral sector machine

*Operated at MURA
in 1957*

A Brief History of FFAGs

- 1950s/60s: most extensive work at MURA



*100keV to 50MeV
machine*

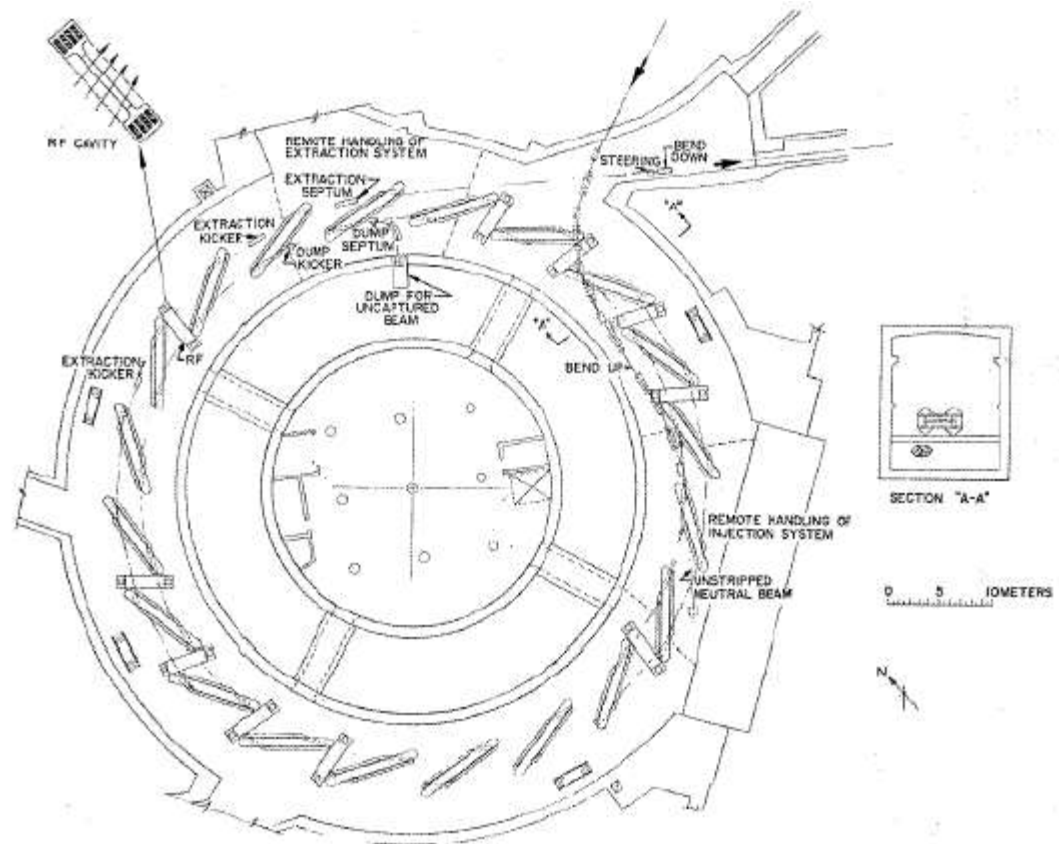
*Operated at MURA in
1961*

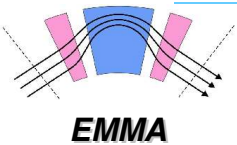
A Brief History of FFAGs

- 1950s/60s: most extensive work at MURA
- Proton proposals failed: technical complexity/energy

*200MeV to 1.5GeV neutron
spallation source*

Proposed by ANL in 1983

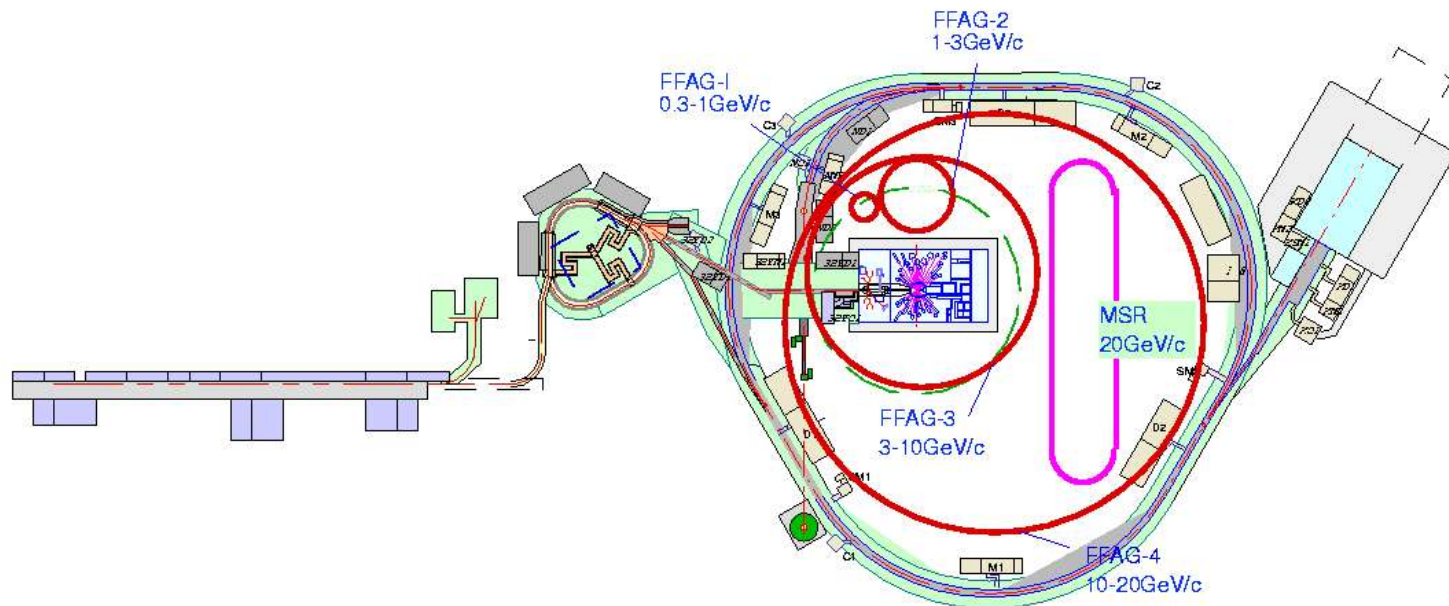




A Brief History of FFAGs

- Invented in 1950s: most extensive work at MURA
- Proton proposals failed: technical complexity/energy
- Re-invented late 1990's in Japan for muon acceleration- ideal due to high acceptance & very rapid cycling - for a Neutrino Factory

FFAG based neutrino factory



A Brief History of FFAGs



Innovations at KEK

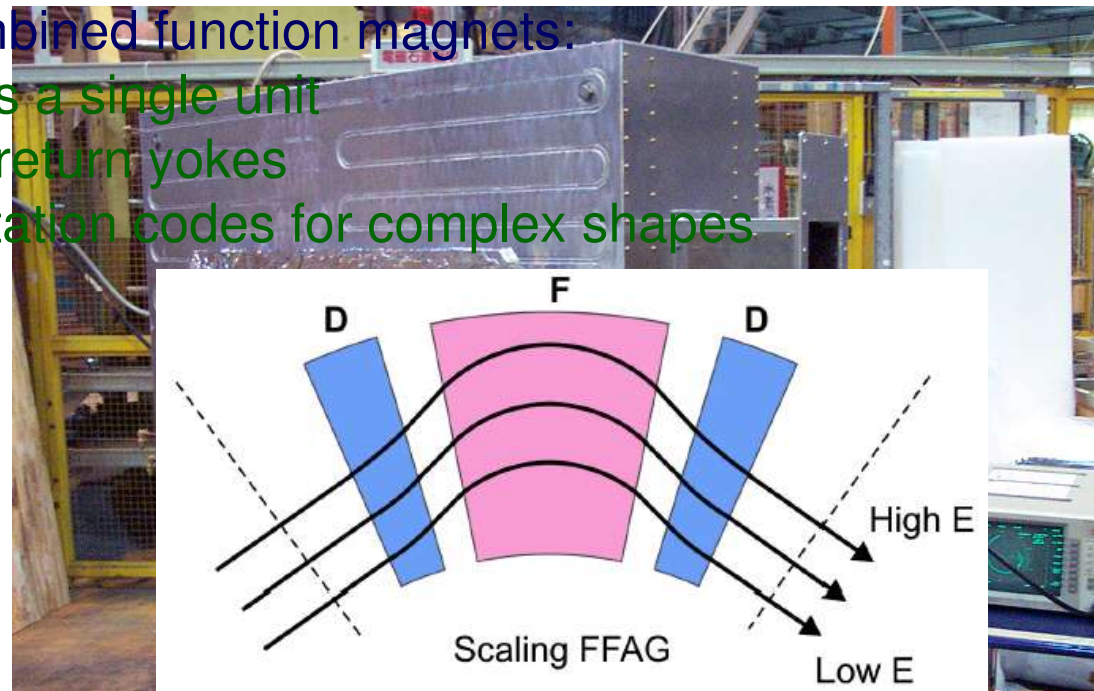
Two technological innovations made re-invention possible

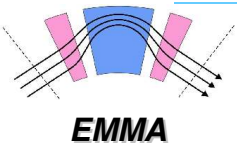
- FINEMET metallic alloy tuners:
 - modulation at $>250\text{Hz}$
 - permeability \rightarrow short cavities, high field
 - broadband operation
- Triplet combined function magnets:
 - powered as a single unit
 - D's act as return yokes
 - 3D computation codes for complex shapes

- rf

- high

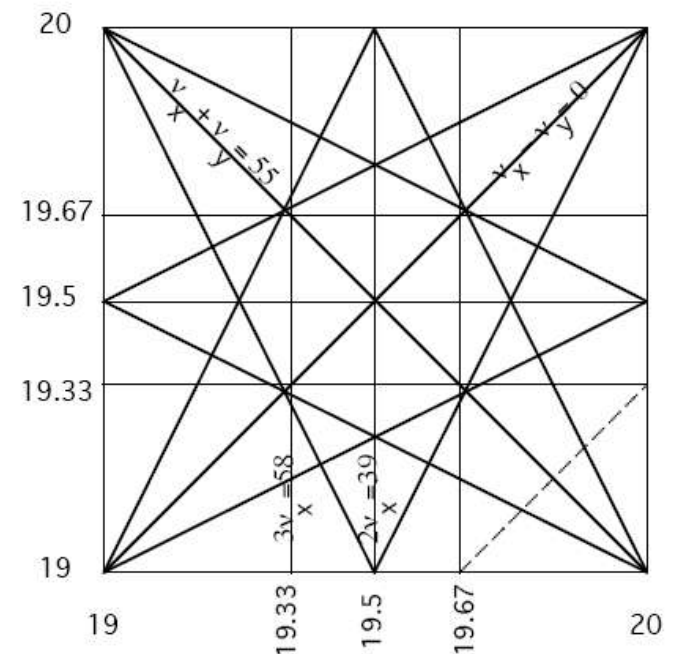
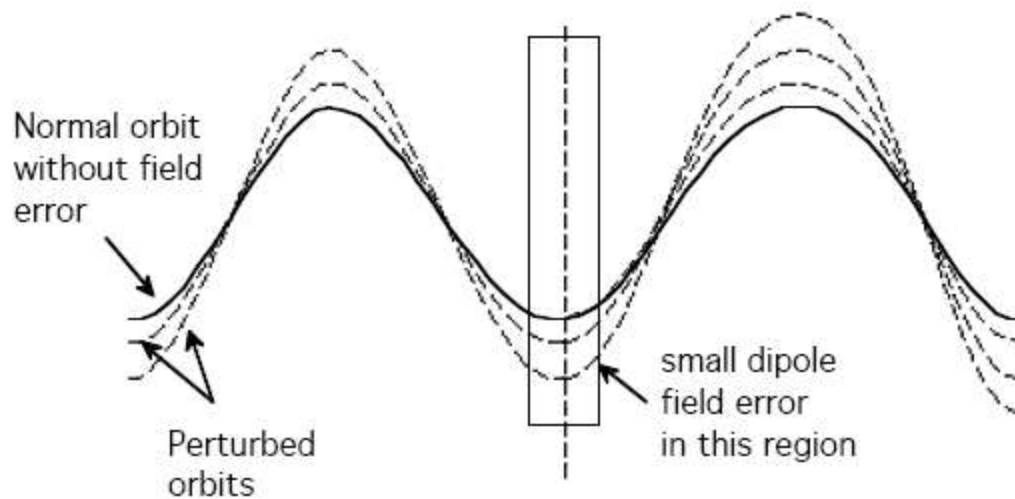
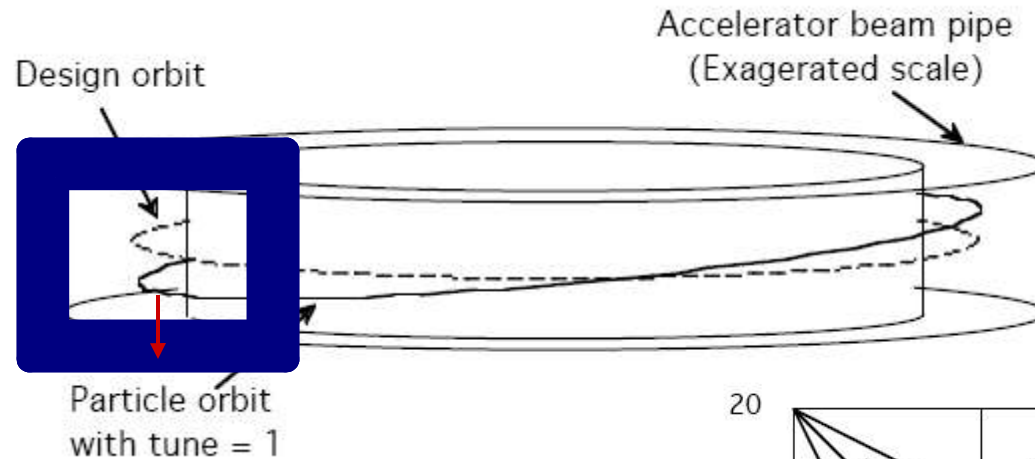
- $Q \sim 1 \rightarrow$

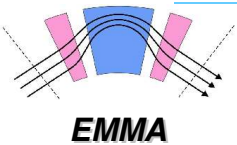




Scaling FFAGs

- Resonances big worry at MURA and in Japan





Scaling FFAGs

- Resonances big worry at MURA and in Japan: low $\Delta E/\text{turn}$
- Maintain (in principle) fixed tunes, zero chromaticity

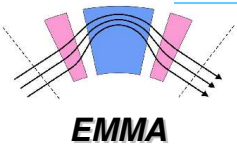
$$\frac{1}{\gamma} \approx \frac{1}{\gamma_0} + \frac{k}{\gamma_0^2} \quad \frac{1}{\gamma} \approx -k + F(1 + 2 \tan^2 \theta)$$

- Requires constant: field index
magnetic flutter
spiral angle
- Gives:
 - same orbit shape at all energies
 - same optics “ “ “ “

- FFAGs with zero chromaticity are called scaling FFAGs

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

$k=2.5$ for POP
 $k=7.5$ for 150 MeV FFAG

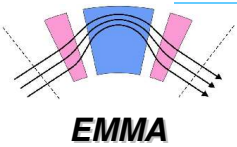


Under Development in Japan

Properties of FFAGs have created a great deal of interest
in Japan

FFAGs built or being built

| | E (MeV) | Ion | Radius (m) | k | Rep rate (Hz) | Comments/1 st beam |
|-----------------|---------|-------|------------|-----|---------------|-------------------------------|
| KEK PoP | 1 | p | 0.8-1.1 | 2.5 | | 2000 |
| KEK – p therapy | 150 | p | 4.5-5.2 | 7.5 | | 2003 |
| KURRI – ADSR | 200 | p | 4.54-5.12 | 7.6 | 1000 | 100 μ A |
| | 20 | p | 1.42-1.71 | 4.5 | | |
| | 2.5 | p | 0.60-0.99 | 2.5 | | |
| PRISM | 20 | μ | 6.5 | 5.0 | | Spiral |



ADSR

- Accelerator Driven Sub-critical Reactor
- Use thorium-232: 3x more than U, all burnt
- Doesn't make enough neutrons
- Instead, neutron spallation: 10MW, 1GeV protons
- Advantage: turn accelerator off, reactor stops!
- Later stage: combine with transmutation
- Only possible with linac or FFAGs
- Test facility under construction in Kyoto



PRISM Layout

- *Solenoid Pion Capture
- *Pion-decay and Transport
- *Phase Rotation

FFAG advantages:

synchrotron oscillation

necessary to do phase rotation

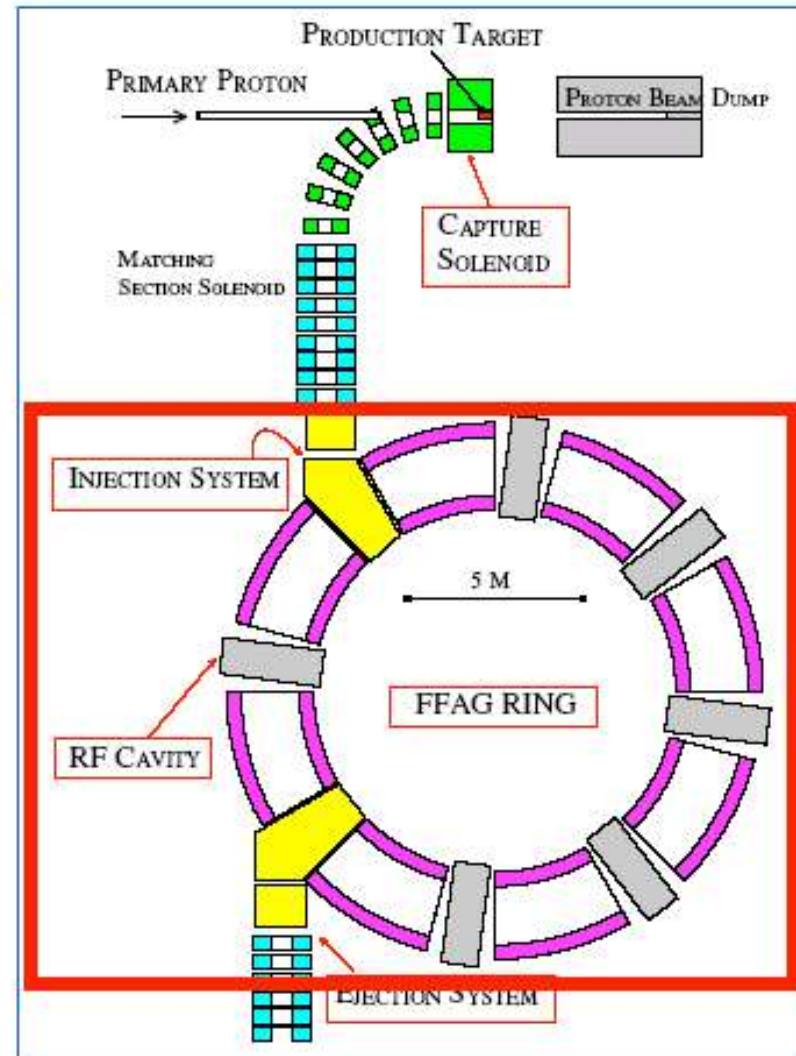
large momentum acceptance

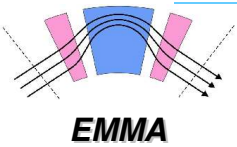
necessary to accept large momentum distribution at the beginning to do phase rotation

large transverse acceptance

muon beam is broad in space

PRISM-FFAG ring
construction has
started in JFY2003.

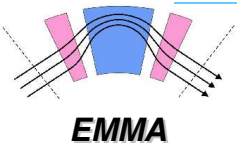




Under Development in Japan

FFAGs at design study phase

| | E (MeV) | Ion | Radius (m) | k | Rep rate (Hz) | Comments/1 st beam |
|------------------|-------------|-----------------|---------------|------|---------------|-------------------------------|
| Ibaraki facility | 230 | p | 2.2-4.1 | | 20 | 0.1 μ A, spiral |
| MEICo - Laptop | 1 | e | 0.02-0.03 | 0.8 | 1000 | Spiral |
| MEICo – Ion th. | 400 | C ⁶⁺ | 7.0-7.5 | 12 | 0.5 | Hybrid, spiral |
| | 7 | C ⁴⁺ | 1.4-1.8 | 0.7 | 0.5 | Hybrid |
| MEICo – p th. | 230 | p | 0.0-0.7 | | 2000 | Superconducting, spiral |
| NIRS Chiba | 400 | C ⁶⁺ | 10.1-10.8 | 10.5 | 200 | |
| | 100 | C ⁶⁺ | 5.9-6.7 | 10.5 | 200 | |
| | 7 | C ⁴⁺ | 2.1-2.9 | 6.5 | 200 | |
| eFFAG | 10 | e | 0.26-1.0 | | 5000 | 20-100mA, spiral |
| KURRI BNCT | 10 | p | 1.5-1.6 | | | >20mA |
| Neutrino Factory | 300-1000 | μ | 20.75-21.25 | 50 | 1000 | |
| | 1000-3000 | μ | 79.77-80.23 | 190 | 1000 | |
| | 3000-10000 | μ | 89.75-90.25 | 220 | 1000 | |
| | 10000-20000 | μ | 199.75-200.25 | 280 | 1000 | |



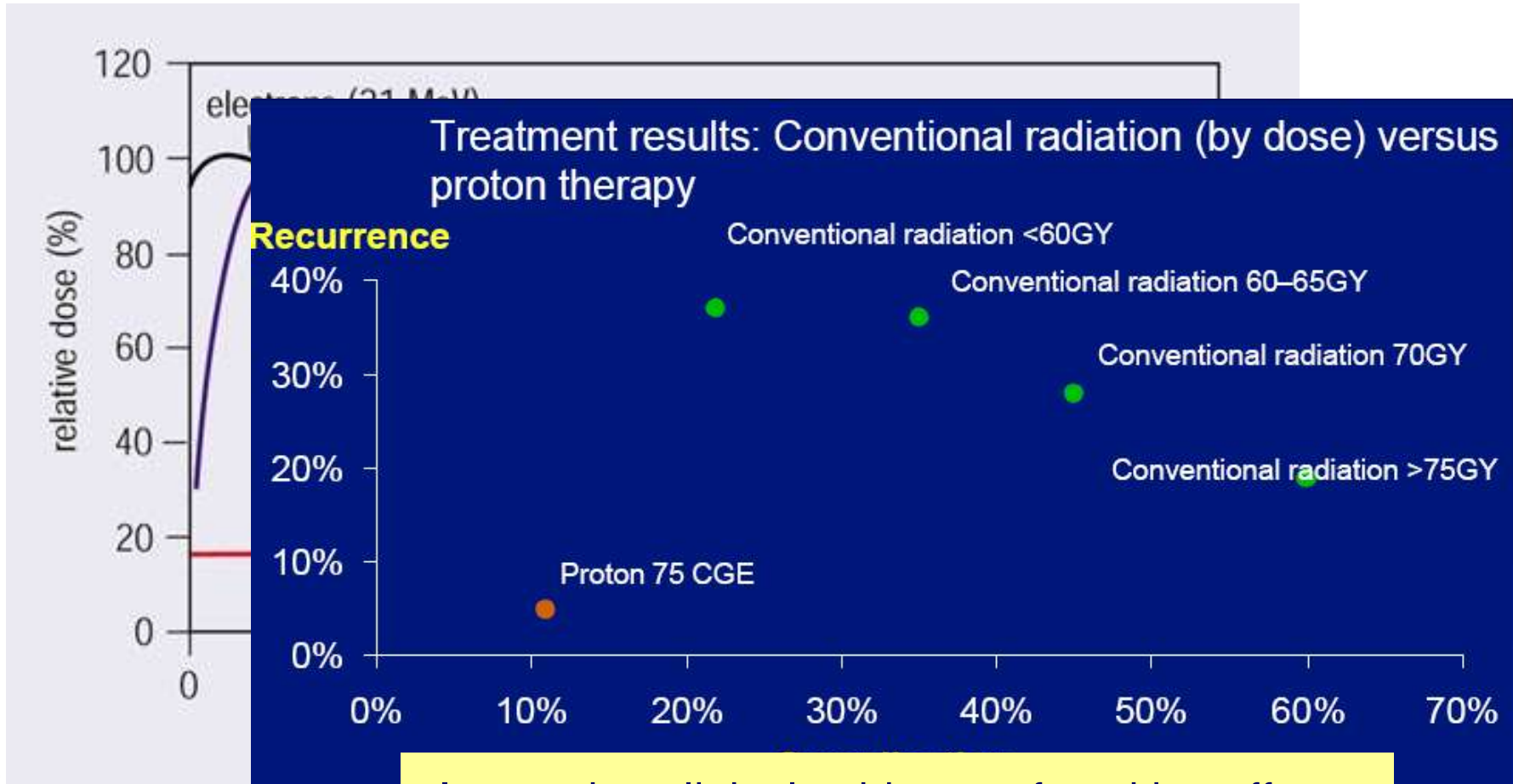
Under Development in Japan

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| | 3000-10000 | μ | 89.75-90.25 | 220 | 1000 | |
| | 10000-20000 | μ | 199.75-200.25 | 280 | 1000 | |

Hadron Therapy

Advantages over radiotherapy with X-rays



Increasing clinical evidence of positive effects of protons

Hadron Therapy

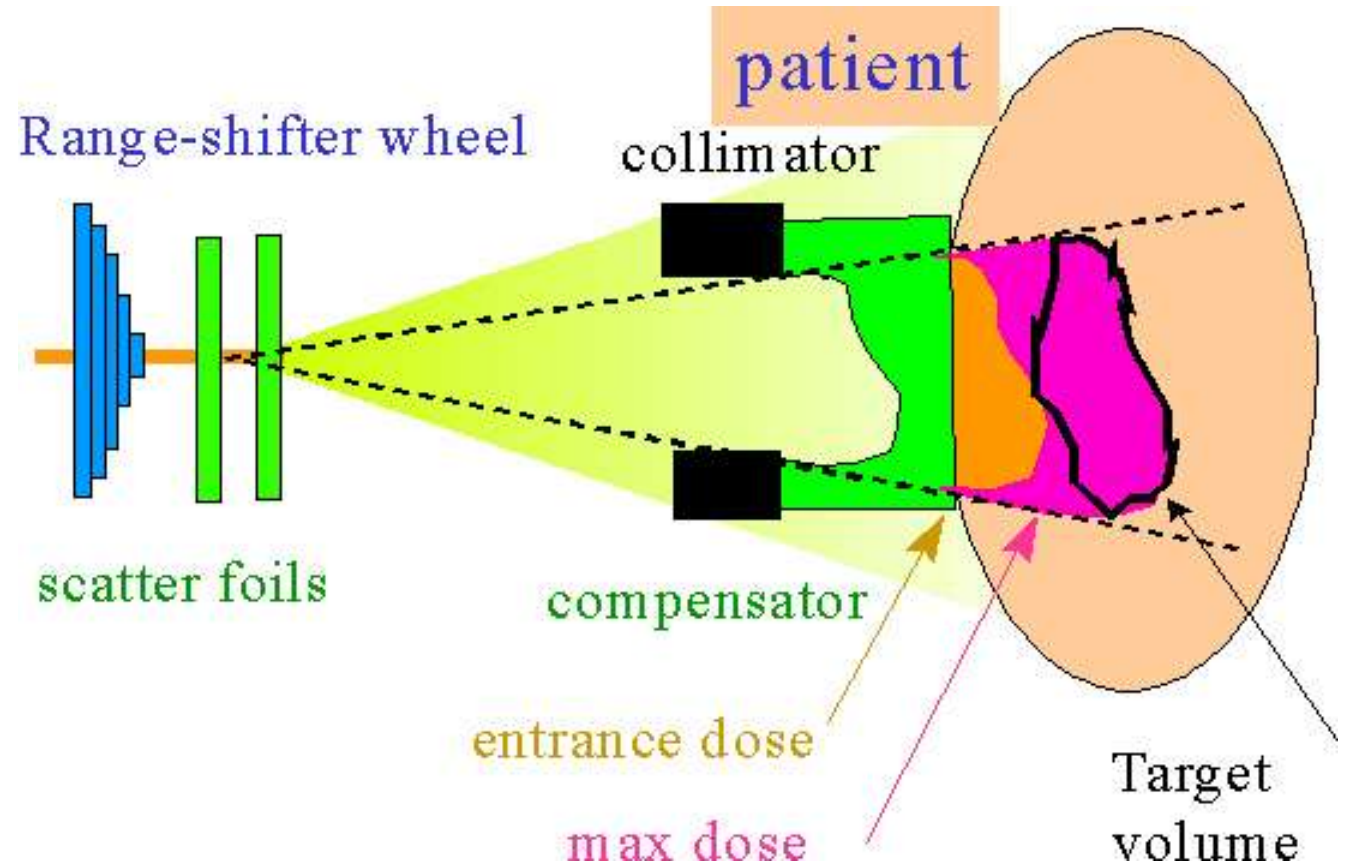
Two main types of beam:

- Protons:
 - most commonly used hadron
 - 230MeV for 30cm depth
 - cheaper/easier
 - advantages over X-rays
 - mainly cyclotrons
- Carbon ions:
 - much better Radio Biological Effectiveness
 - less damage to healthy tissue than neon
 - 425MeV/u for 30cm
 - only synchrotrons
 - expensive!
- Ideally, proton + carbon + other ions
 - best depends on tumour type and location

Hadron Therapy

Two main types of beam delivery:

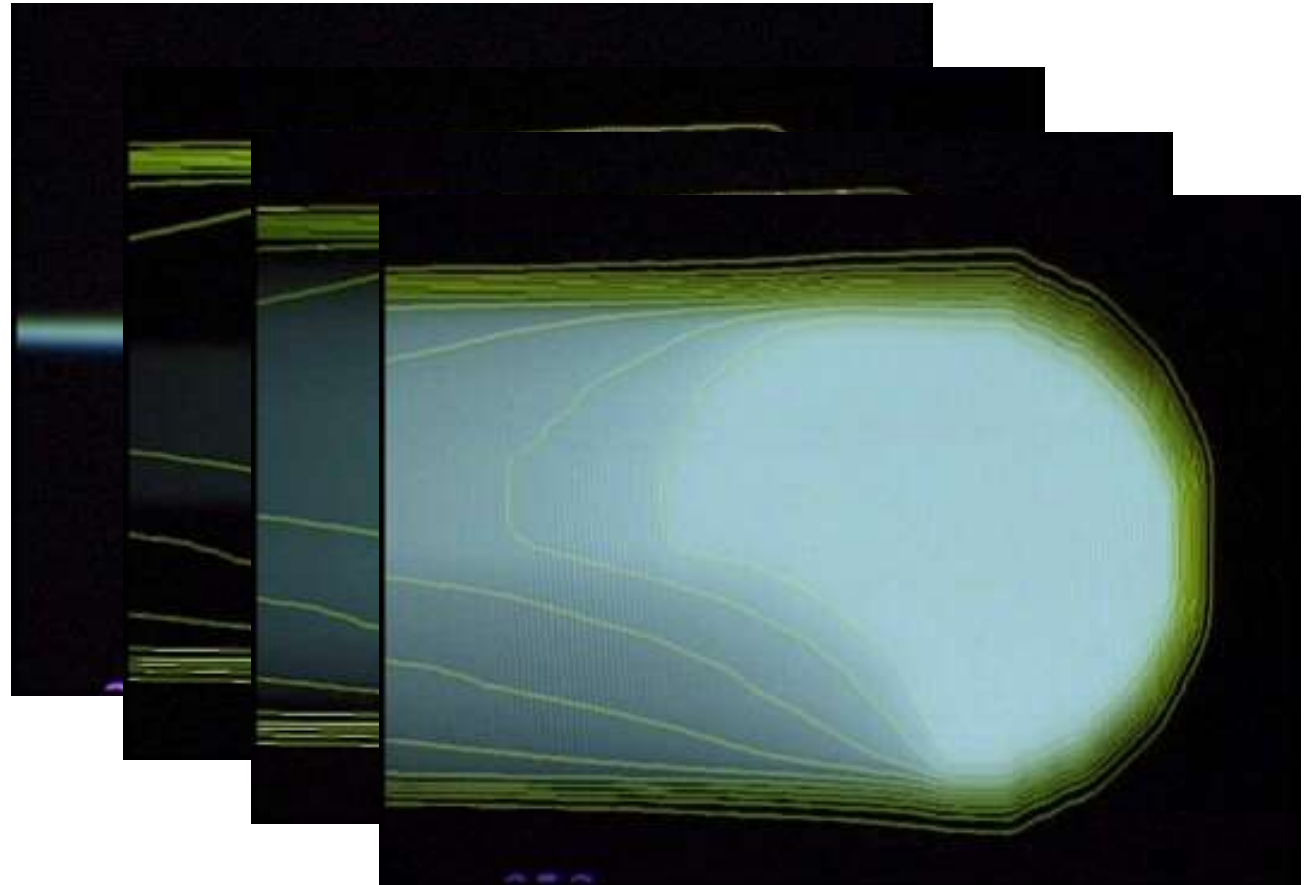
- 2D:

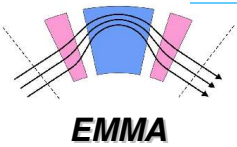


Greater than necessary damage to healthy tissue

Hadron Therapy

- 3D:
 - “range-stacking” + multi-leaf collimator - “spot”, “raster” or “pencil-beam” scanning

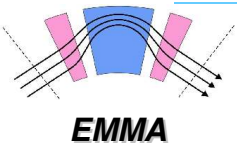




Hadron Therapy

Ideally:

- Both 2D and 3D
- For protons, carbon and other ions
- Respiration mode:
 - beam gated using sensors on patient
 - delivered at same point in breathing cycle
 - minimise damage to healthy tissue
- Simultaneous PET scanning:
 - ^{12}C
 - ^{11}C via fragmentation in tissue
 - ^{11}C has
 - positron emitter
 - sufficient quantities
 - used to correct range during treatment

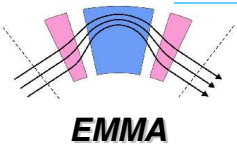


Why So Much Interest?

To extend the use of proton/ion therapy widely - in major hospitals:

Y.Mori KEK/Kyoto

- Efficient treatment patients/year
- High dose rate
>5Gy/min
- Flexibility (for various types of cancer) - Respiration mode
 - Spot scanning
 - variable energy
 - ion option
- Easy operation
- Easy maintainability activation
 - low
- Low cost
 - both construction and operation



Why So Much Interest?

To extend the use of proton/ion therapy widely - in major hospitals:

Y.Mori KEK/Kyoto

| | Synchrotron | Cyclotron | FFAG |
|-------------------------|---------------|--------------|------------------|
| ➤ Intensity (>100nA) | Low 1-16nA | Plenty | Plenty >100nA |
| ➤ Maintenance | Normal | Hard | Normal |
| ➤ Extraction eff (>90%) | Good | Poor <70% | Good >95% |
| ➤ Operation | Not easy | Easy | Easy |
| ➤ Ions | Yes | No | Yes |
| ➤ Variable energy | Yes | No | Yes |
| ➤ Multi-extraction | Possible | No | Yes |

Ibaraki Facility

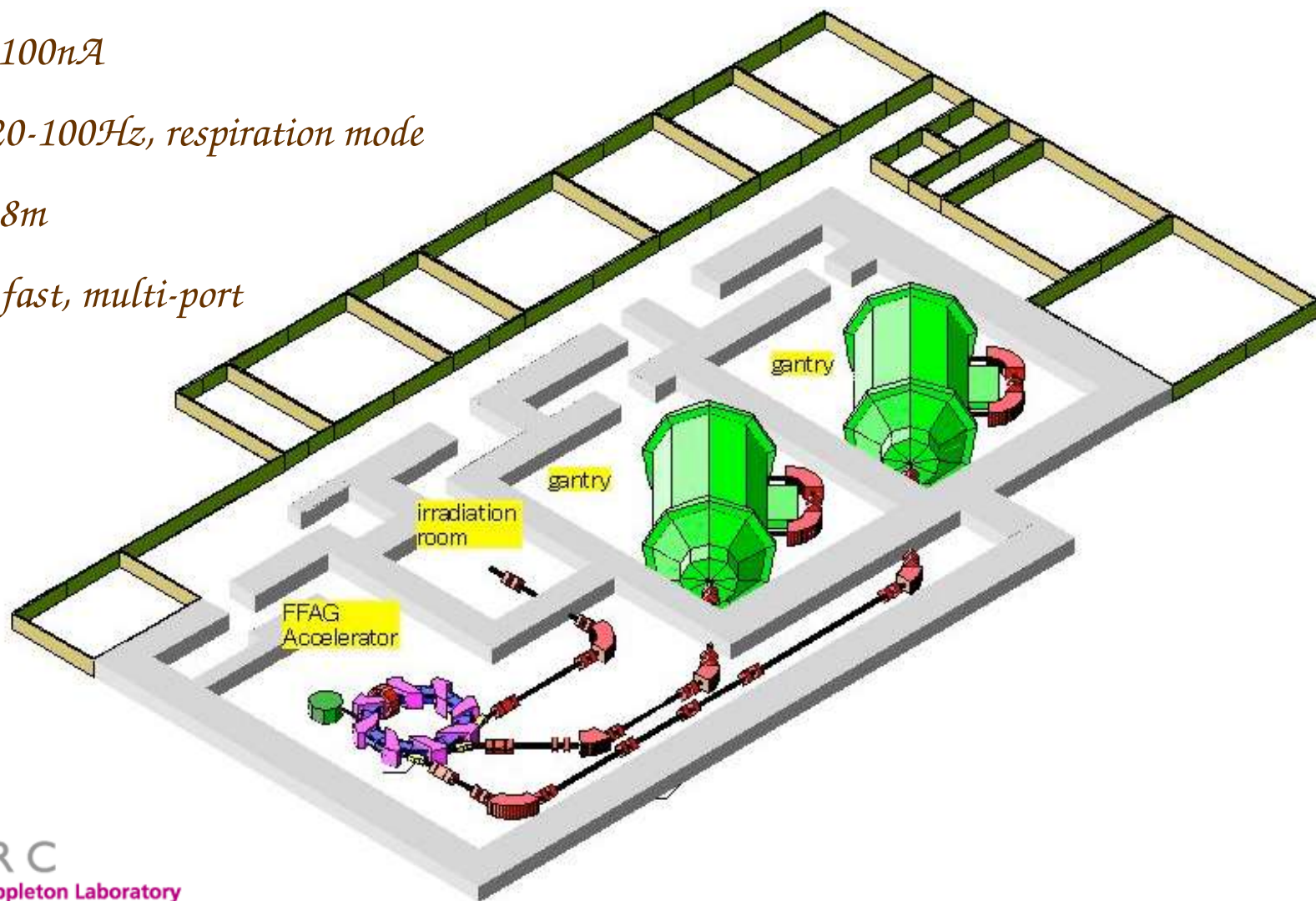
Proton energy 230MeV

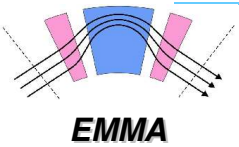
Intensity $>100\text{nA}$

Rep. Rate 20-100Hz, respiration mode

Diameter $\sim 8\text{m}$

Extraction fast, multi-port



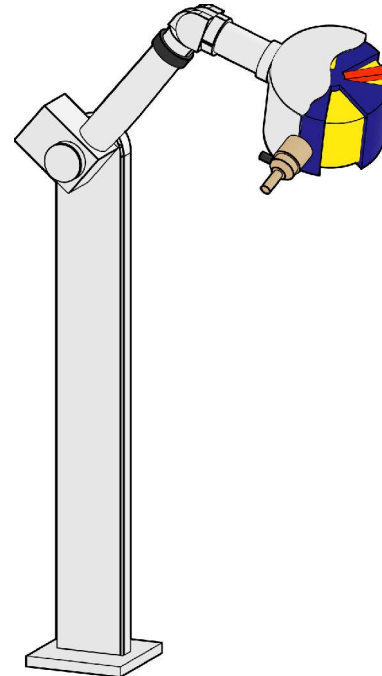


Mitsubishi - Laptop

Diameter 10cm

Energy 60 keV to 1 MeV

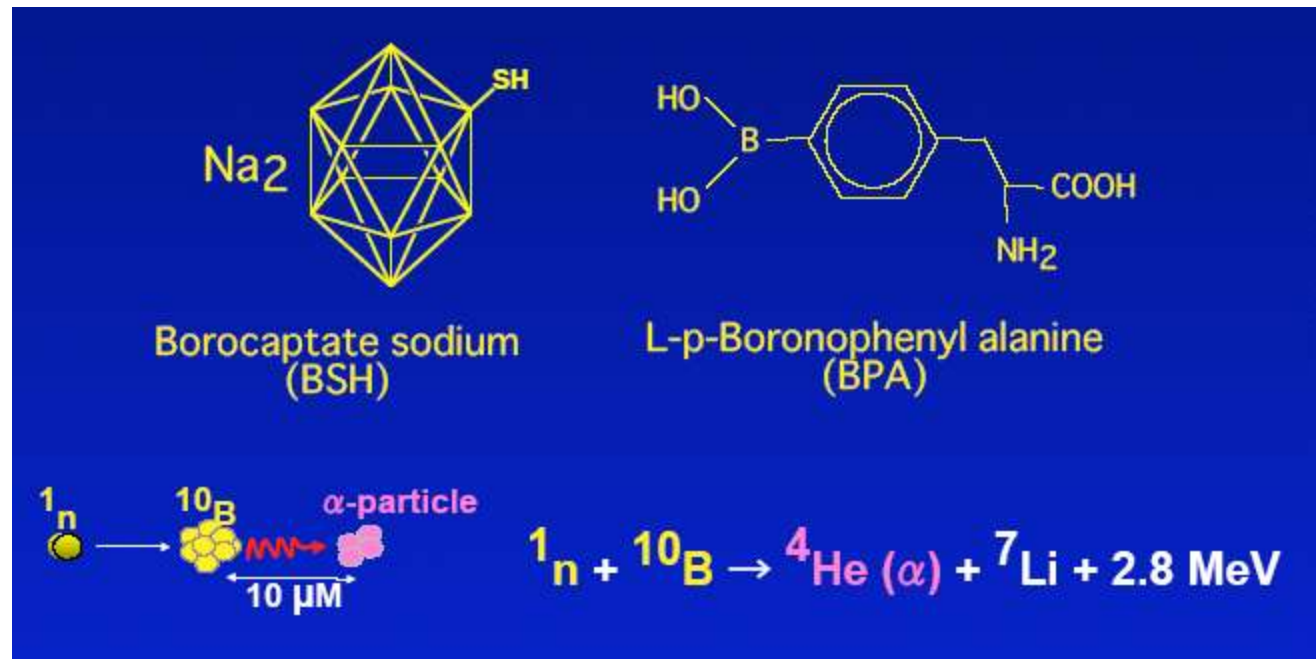
Rep. Rate 1kHz



BNCT at KURRI

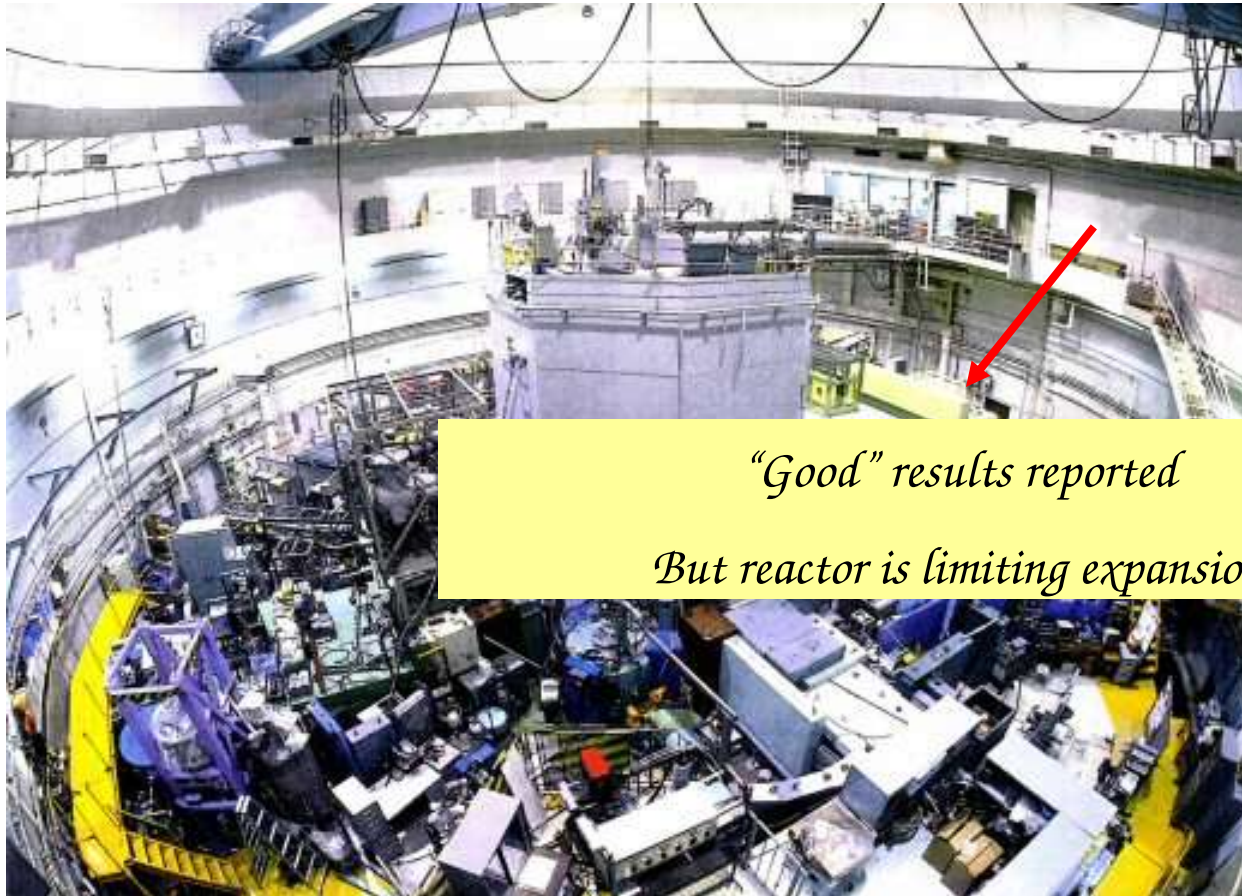
Boron Neutron Capture Therapy

- Used, for example, to treat “glio-blastoma multiforme”
- Type of brain tumour that is 100% fatal
- Afflicts 12500 people in US each year
- Use boron-10: **stable**, but fissions with a thermal neutron



BNCT at KURRI

- Problem: need a lot of thermal neutrons
 $>1 \times 10^9 \text{ cm}^{-2}\text{s}^{-1}$ at patient for 30mins
- Only source: reactor

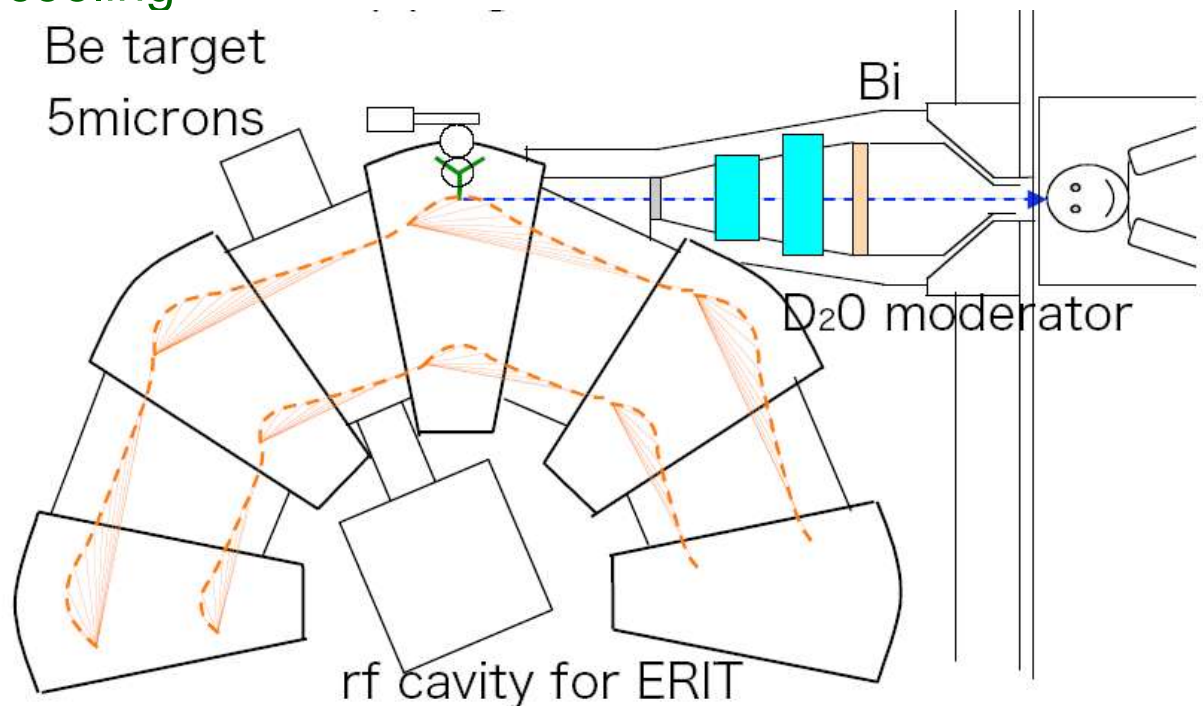


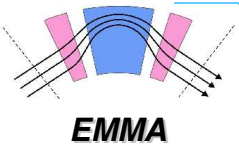
"Good" results reported
But reactor is limiting expansion



BNCT at KURRI

- Possible with accelerators
- Problem is efficiency for thermal neutrons: 1/1000
- Need: - proton energy 3-10 MeV
 - >20mA (instantaneous)
 - energy recovery
 - beam cooling





But.....

.....there are two problems:

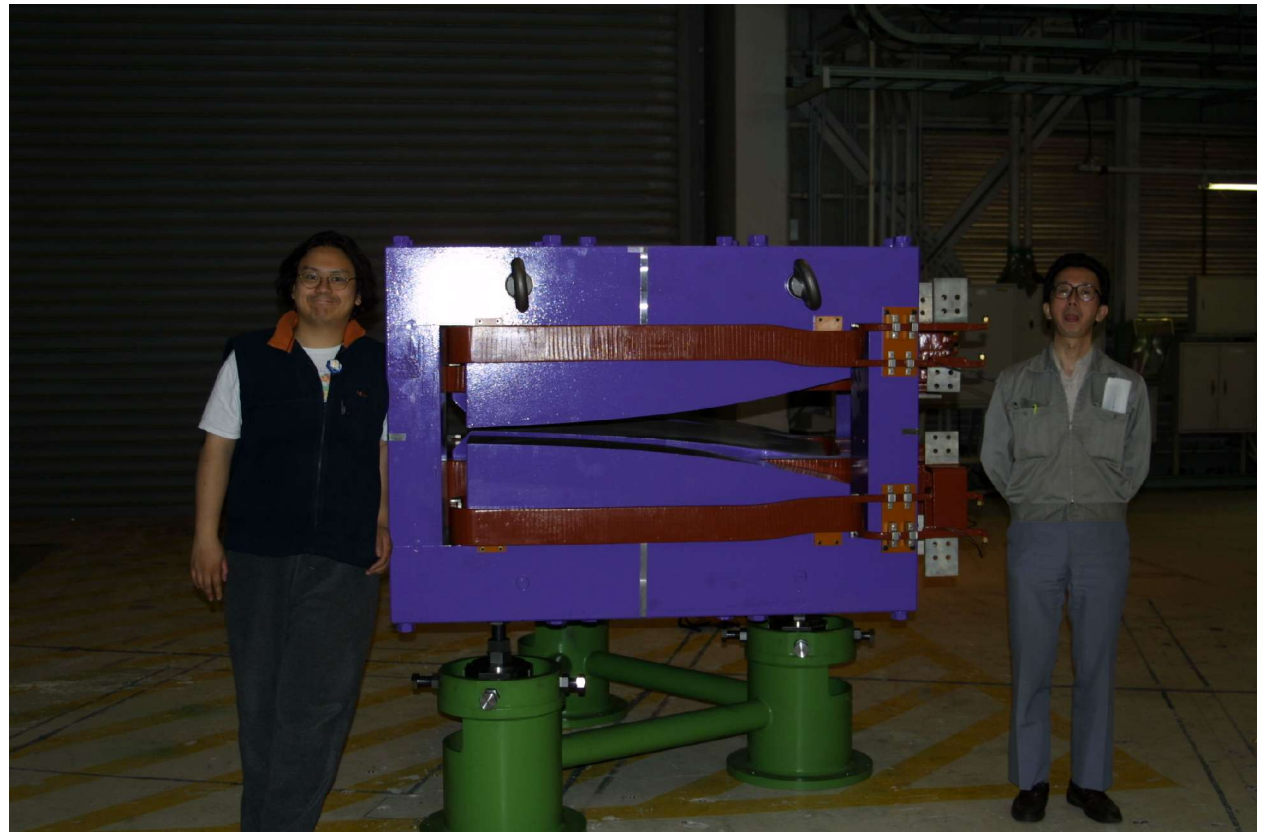
- all this is happening in Japan
- it is possible to do better

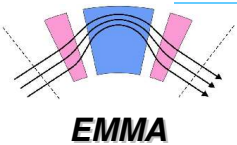
Orbit excursion $\sim 0.9\text{m}$

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

where $k=7.5$

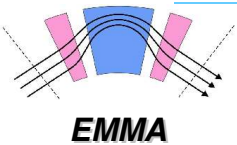
Magnets are large,
complex &
expensive!





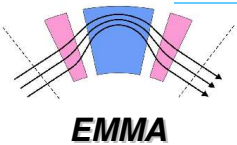
There is Another Way

- Japanese machines are called “scaling”
- There is a second type called “non-scaling”
- Originally developed for muons for a NF:
 - need rapid acceleration
 - limited number of turns
 - minimum ring circumference
 - minimum aperture



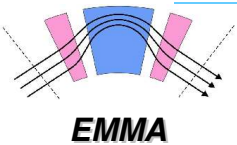
There is Another Way

- Japanese machines are called “scaling”
 - There is a second type called “non-scaling”
 - Originally developed for muons for a NF:
 - need rapid acceleration - limited
 - number of turns - minimum ring
 - circumference - minimum aperture
- ⇒ need fixed magnetic field: FFAG
- ⇒ need fixed RF frequency: isochronous as possible



There is Another Way

- Japanese machines are called “scaling”
 - There is a second type called “non-scaling”
 - Originally developed for muons for a NF:
 - need rapid acceleration - limited
 - number of turns - minimum ring
 - circumference - minimum aperture
-
- ⇒ optical parameters can vary with energy
 - ⇒ lattice can be constructed from linear elements:
 - dipoles and quadrupoles
 - ⇒ linear variation of field
 - ⇒ large dynamic aperture
 - ⇒ requires periodic structure of identical cells

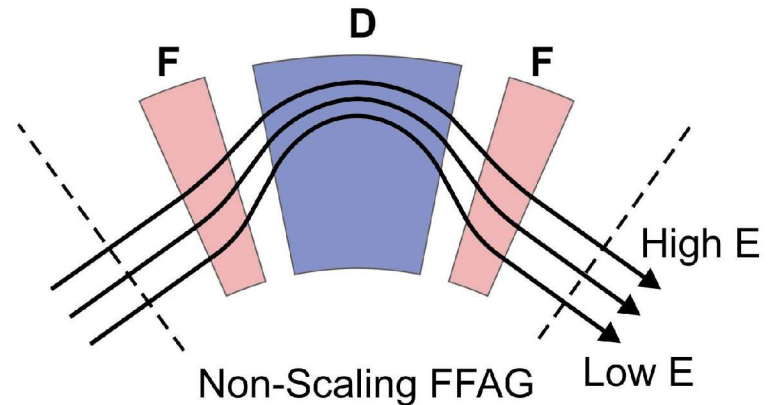
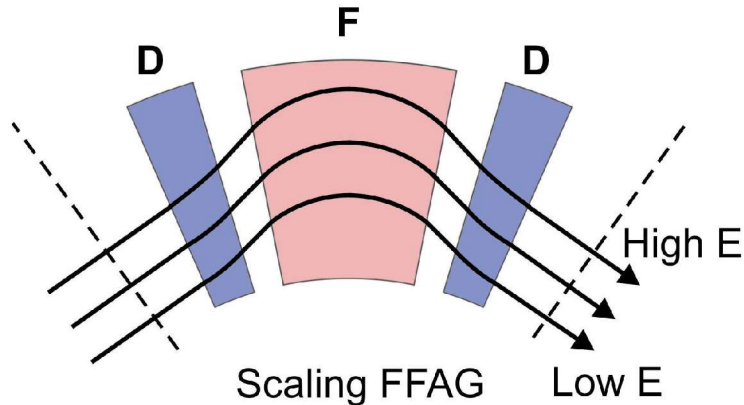


There is Another Way

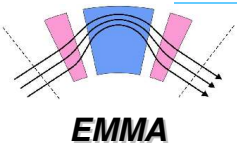
- Japanese machines are called “scaling”
- There is a second type called “non-scaling”
- Originally developed for muons for a NF:
 need rapid acceleration
 number of turns
 circumference

- limited
- minimum ring
- minimum aperture

Taking FODO cells as an example



→ opposite to scaling FFAG



There is Another Way

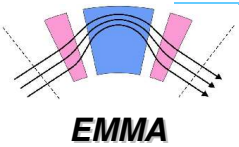
- Japanese machines are called “scaling”
- There is a second type called “non-scaling”
- Originally developed for muons for a NF:
 - need rapid acceleration
 - limited number of turns
 - minimum ring circumference
 - minimum aperture

$$= \left| \frac{dp}{p} \right| \left| \frac{dL}{L} \right|$$

⇒ maximise momentum compaction

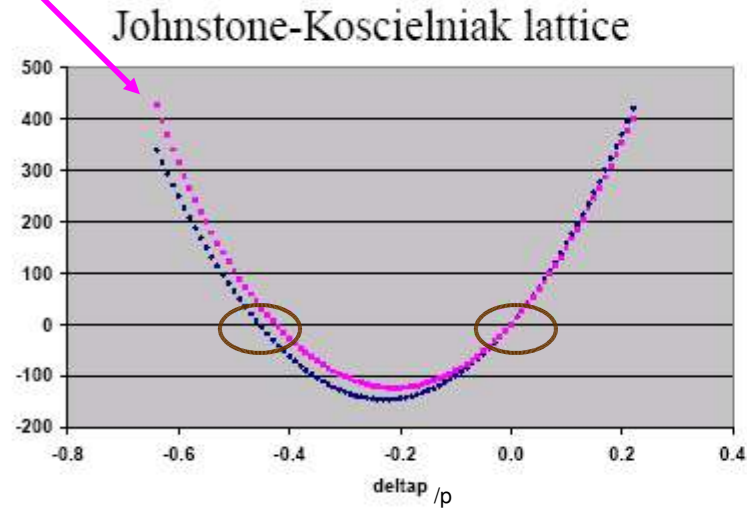
⇒ minimise path length change:

$$L_{inj} = L_{ext} \quad \& \quad L_{min} \text{ for central orbit}$$

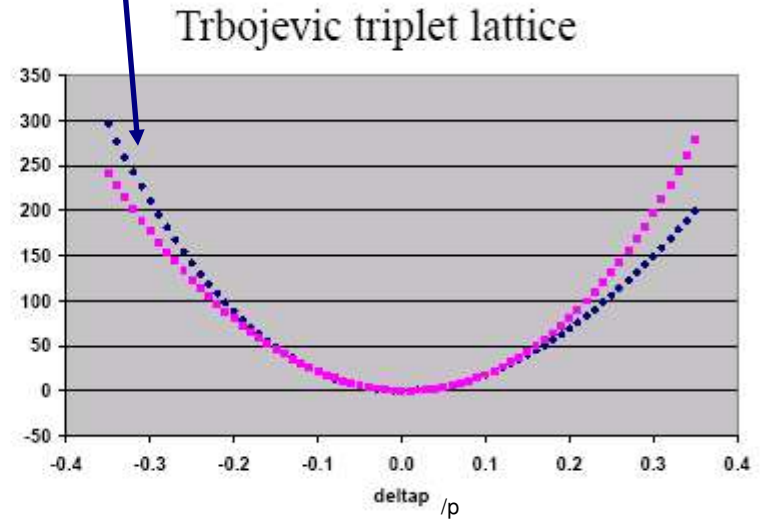


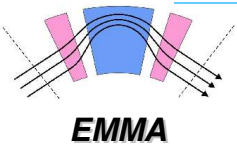
Non-Scaling FFAGs

Travel time



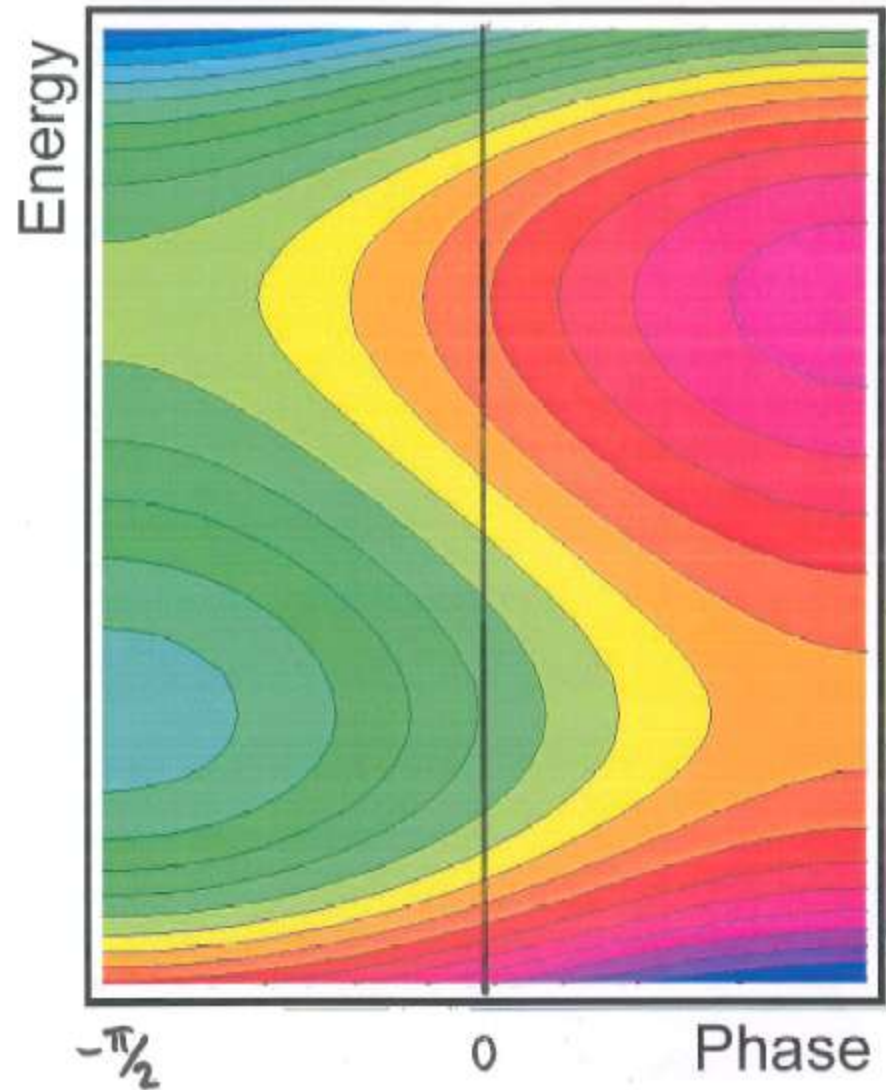
Path length

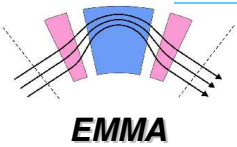




Non-Scaling FFAGs

Longitudinal phase space
Asynchronous acceleration

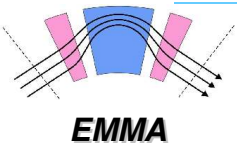




Non-Scaling FFAGs

In practice.....

- It's more complicated than that!
- FODO, doublet, triplet, etc, cells possible
- Number of lattices = number of theorists/2
- Studied for muons, electrons, protons, carbon
- Many advantages over scaling FFAGs:
 - magnet aperture is much smaller
 - can use higher frequency, ~200MHz
 - magnets are linear and much simpler
 - bigger dynamic aperture
 - bigger transverse acceptance
 - can run CW for muons
- Ideal for the Neutrino Factory



Nota Bene!!

- Orbit shape changes with energy:

⇒ tunes vary

⇒ m_x

⇒ crossing w

unique feature

be tested!

Study 2a NF

5-10 GeV

- Momentum compaction:

77 cells

⇒ bigger than ever achieved

⇒ unique feature of these machines

be tested!

⇒ **must**

- Asynchronous acceleration:

⇒ never used before

unique

“

“

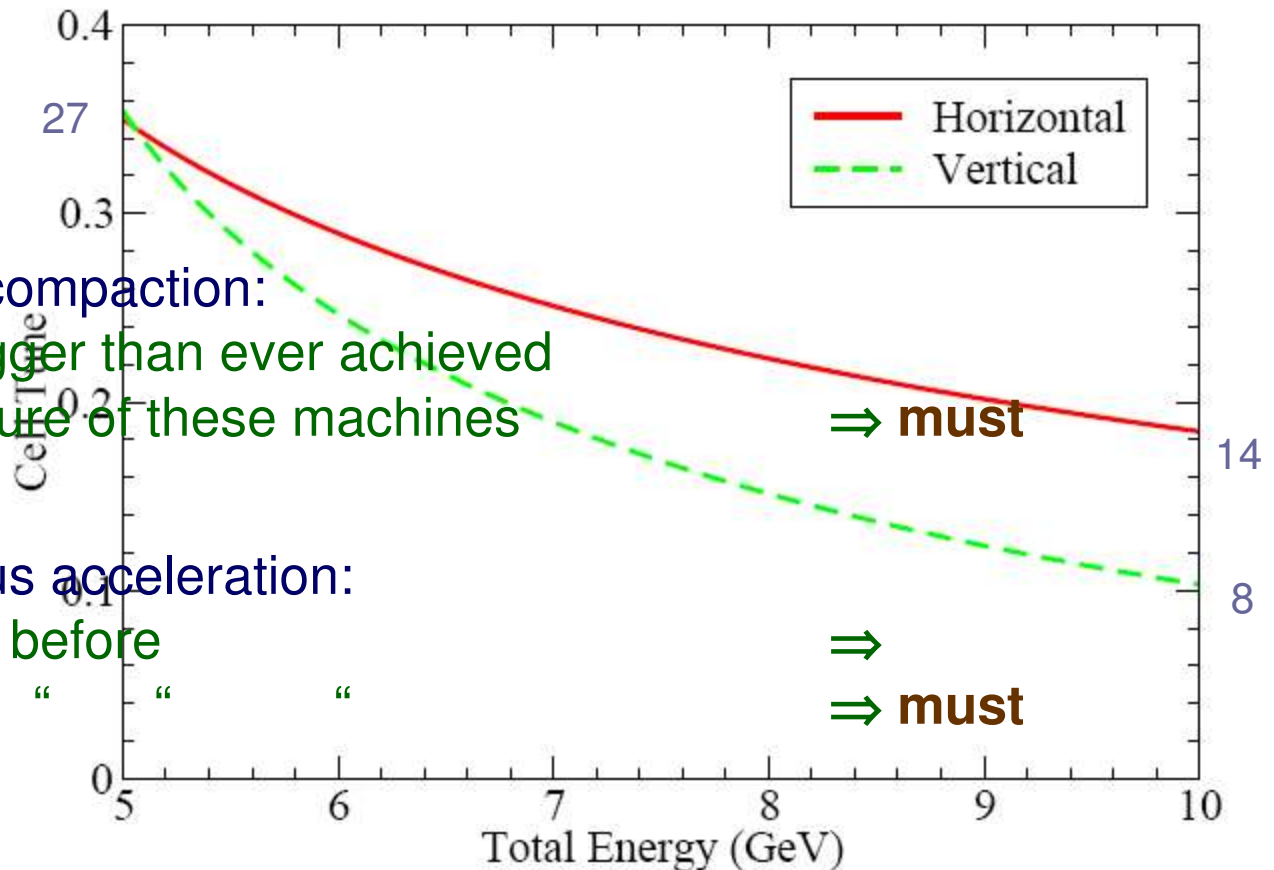
“

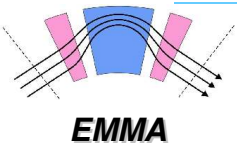
“

be tested!

⇒

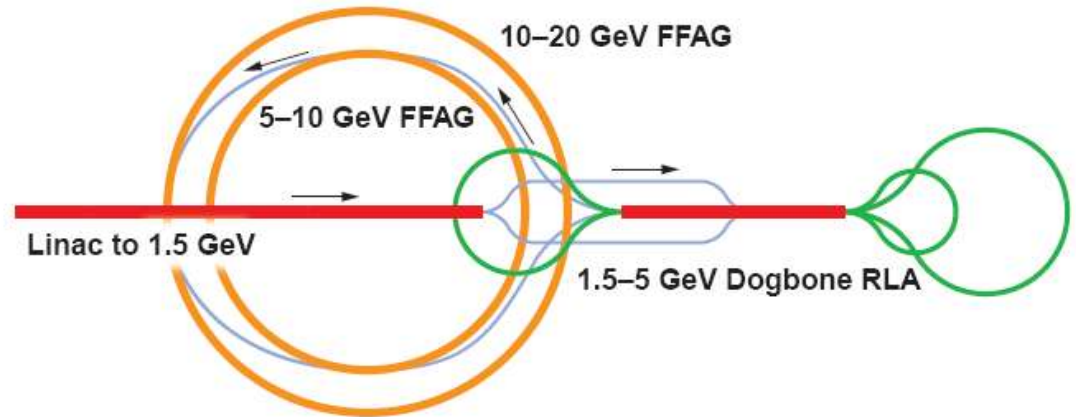
⇒ **must**



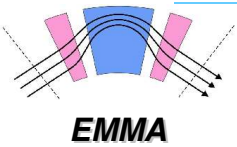


Muon Lattices

- Study 2a layout
- From Scott Berg
- 2/3 non-scaling FFAGs
- Triplet lattice
- F0D0/doublet also
- Linear magnets ~20cm



| <i>Energy (GeV)</i> | <i>Circumference (m)</i> | <i>Cells</i> | <i>Turns</i> | <i>Decay (%)</i> |
|--------------------------------|-------------------------------------|---------------------|---------------------|-------------------------|
| <i>2.5-5.0</i> | <i>246</i> | <i>64</i> | <i>6</i> | <i>6</i> |
| <i>5.0-10.0</i> | <i>322</i> | <i>77</i> | <i>10</i> | <i>7</i> |
| <i>10.0-20.0</i> | <i>426</i> | <i>91</i> | <i>17</i> | <i>8</i> |



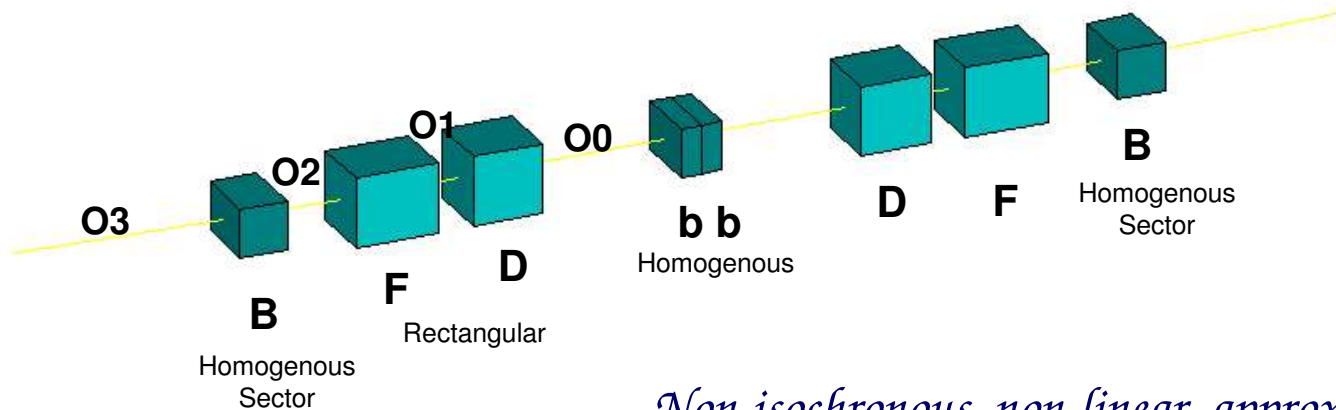
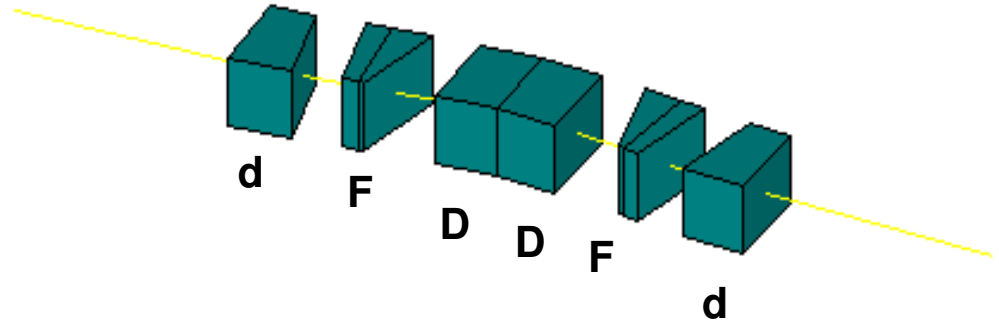
Muon Lattices

Grahame Rees

Pumplet lattice: 8-20 GeV

Isochronous

123 cells, 1255m circumference, non-linear magnets Latest version has insertions



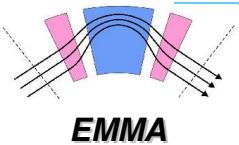
Horst Schonauer

Quadruplet lattice

10-20 GeV

Non-isochronous, non-linear, approx. constant tunes

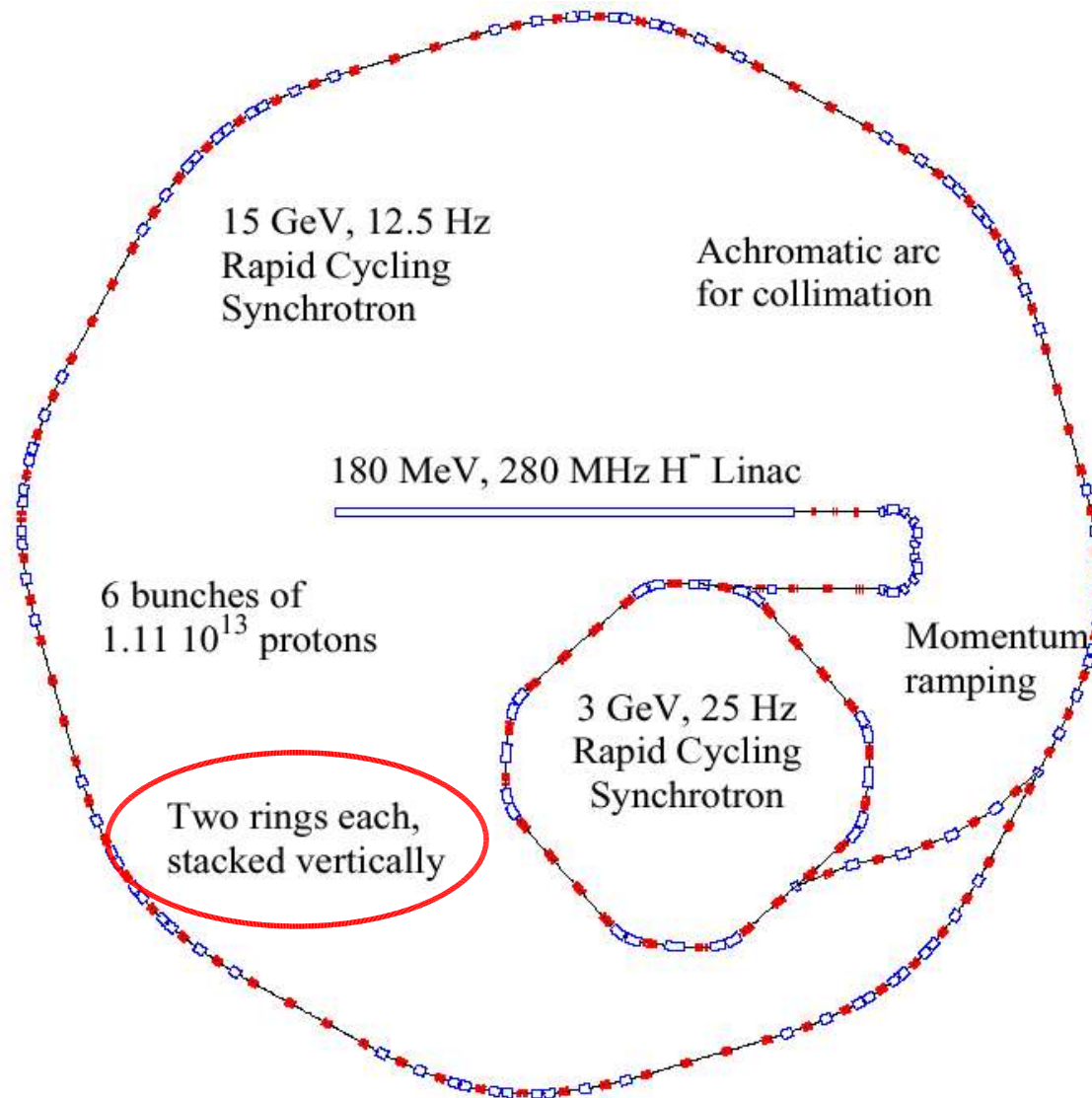
66 cells, 1258m circumference

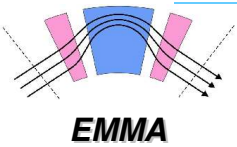


Protons

- As with scaling FFAGs, interest spreading:
 - protons: therapy, drivers
 - carbon: therapy
- Larger acceleration range desirable
- RF must be modulated
- Resonances might be a problem
- First proton designs avoided tune changes:
 - Non-linear magnets
 - compensate for tune changes
- New designs have both near linear and non-linear

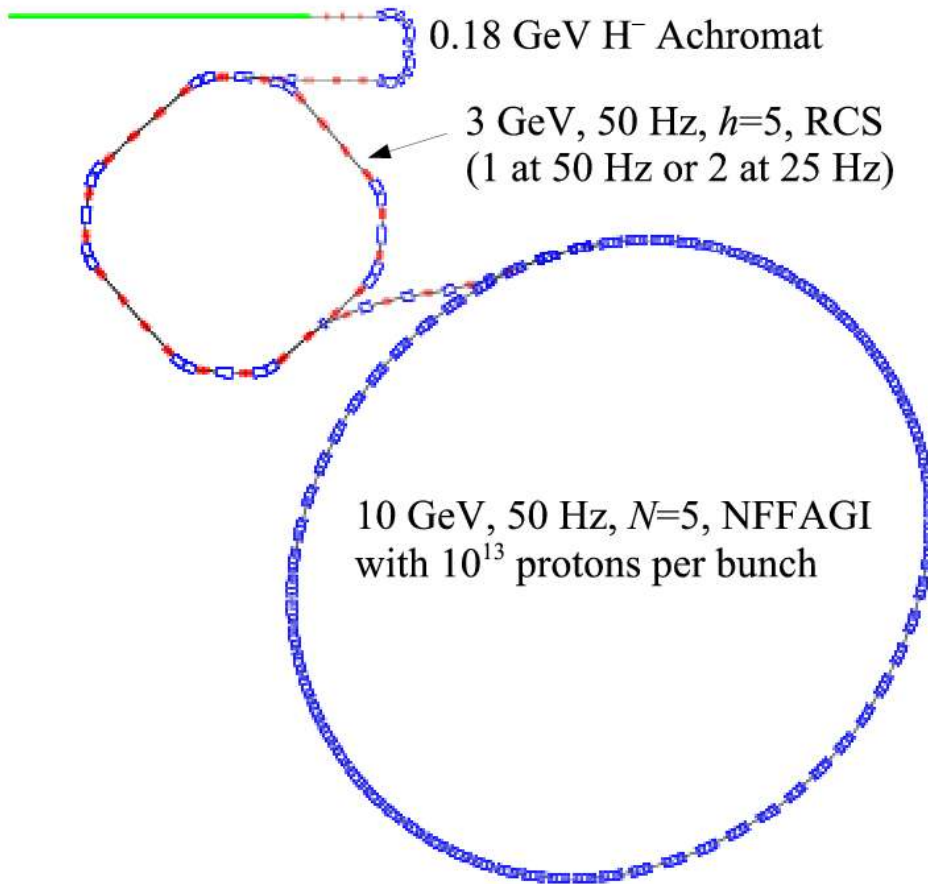
Non-Scaling FFAGs



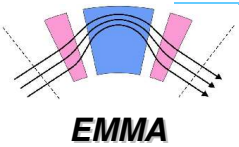


Non-Scaling FFAGs

0.18 GeV H^- Linac



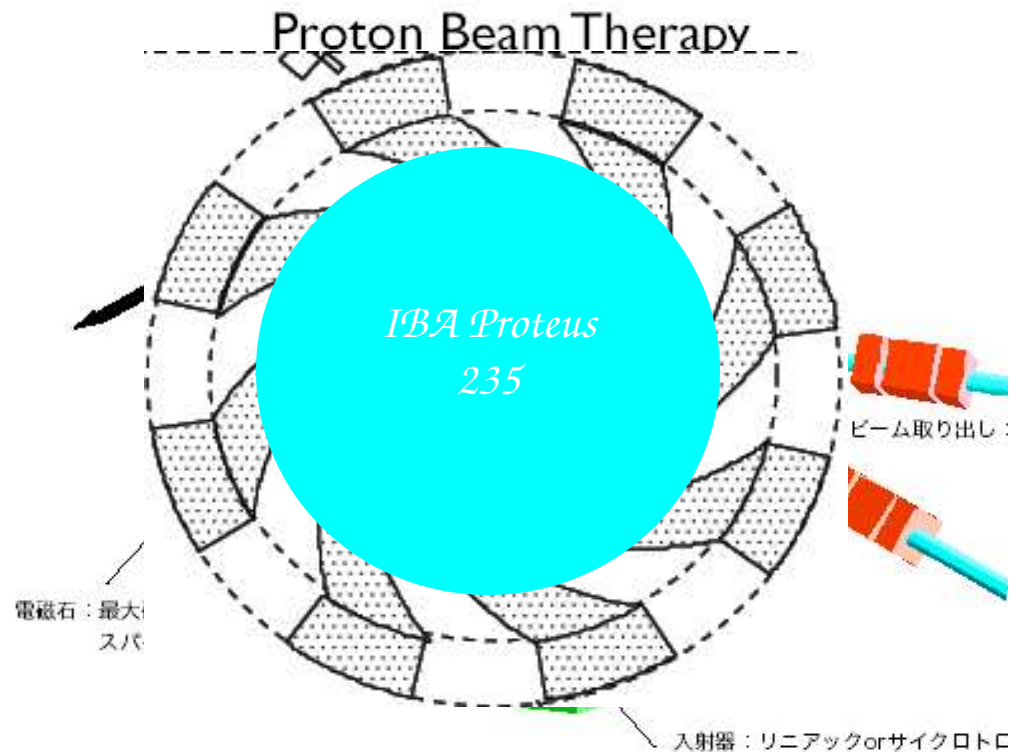
- Rees pumplet lattice
- Non-linear \Rightarrow tune variations small
- 10 GeV \sim optimal
- 50Hz \Rightarrow 0.5*target shock

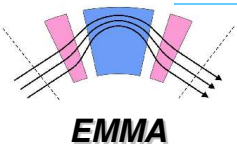


Proton Therapy

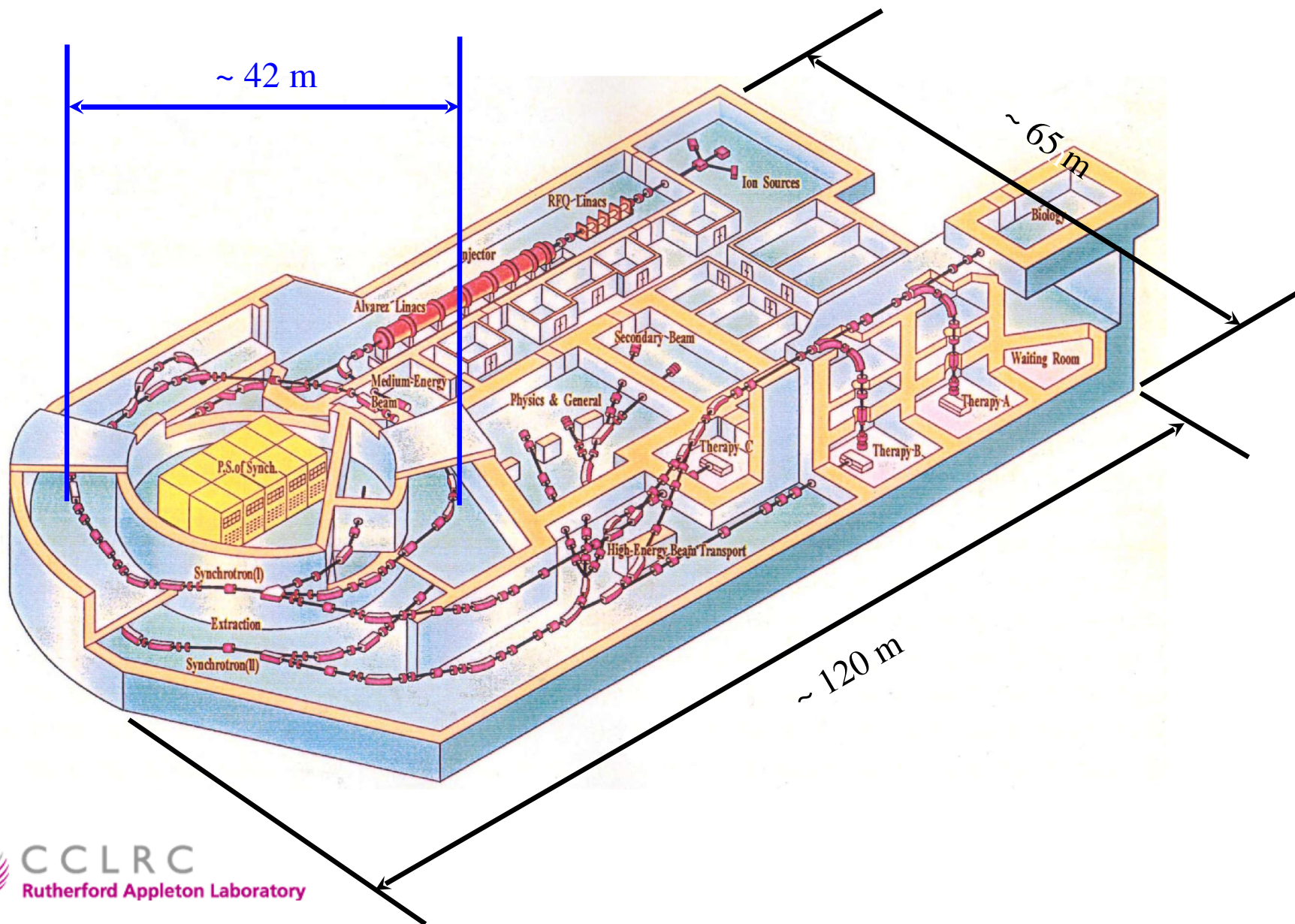
- *proton therapy*
- *20 to 250 MeV*
- *10.8m diameter*
- *8.6cm orbit ex.*
- *30 cells*
- *20 to 230 MeV*
- *8.5m diameter*
- *190cm orbit ex.*
- *8 cells*

Proton Therapy non-scaling FFAG (20 - 250 MeV)
Major bending field $B_y = 0.84$ T with fixed gradient $G_f = 18$ T/m, Circumference=34 m

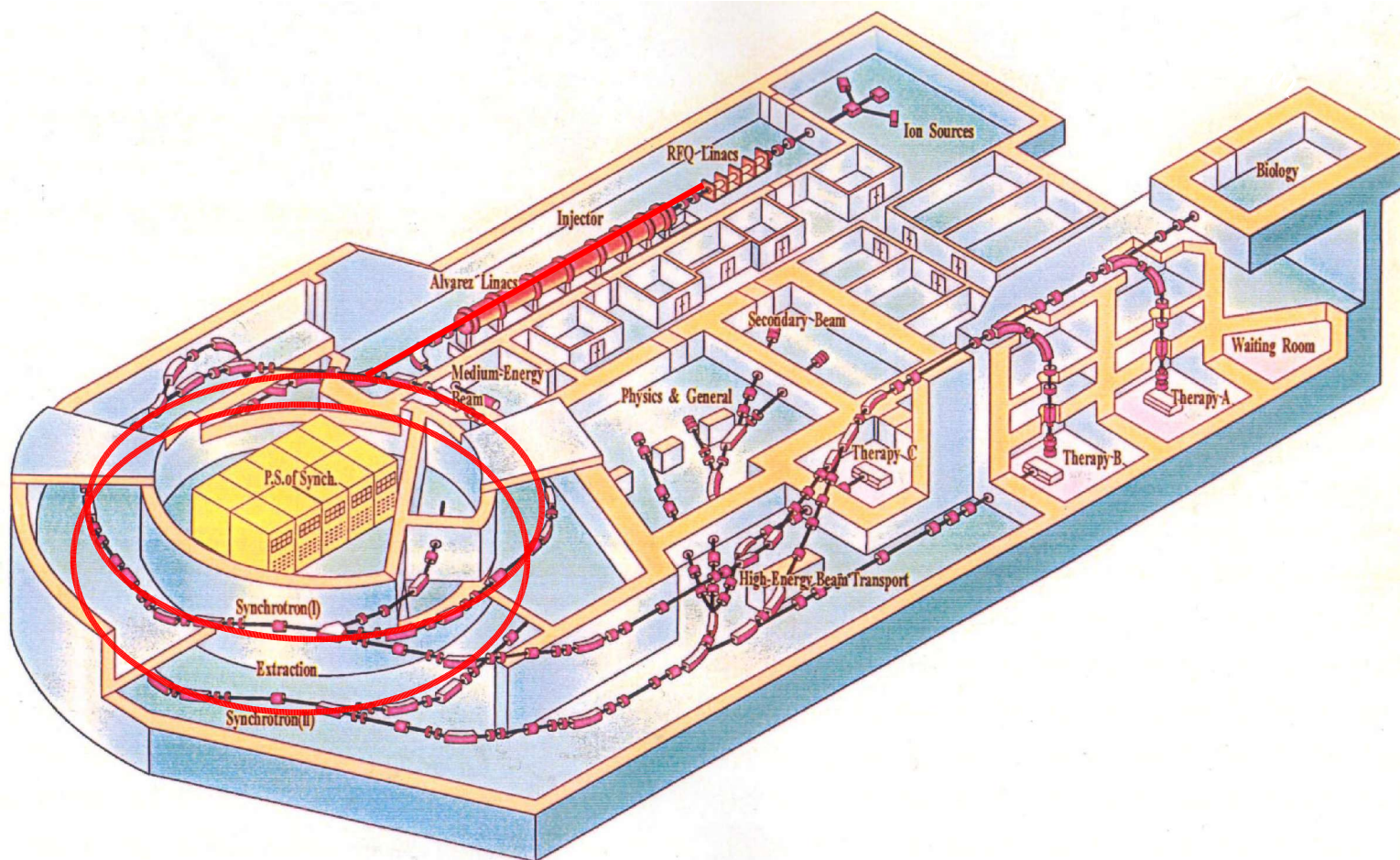


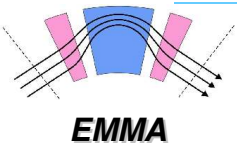


HIMAC at NIRS



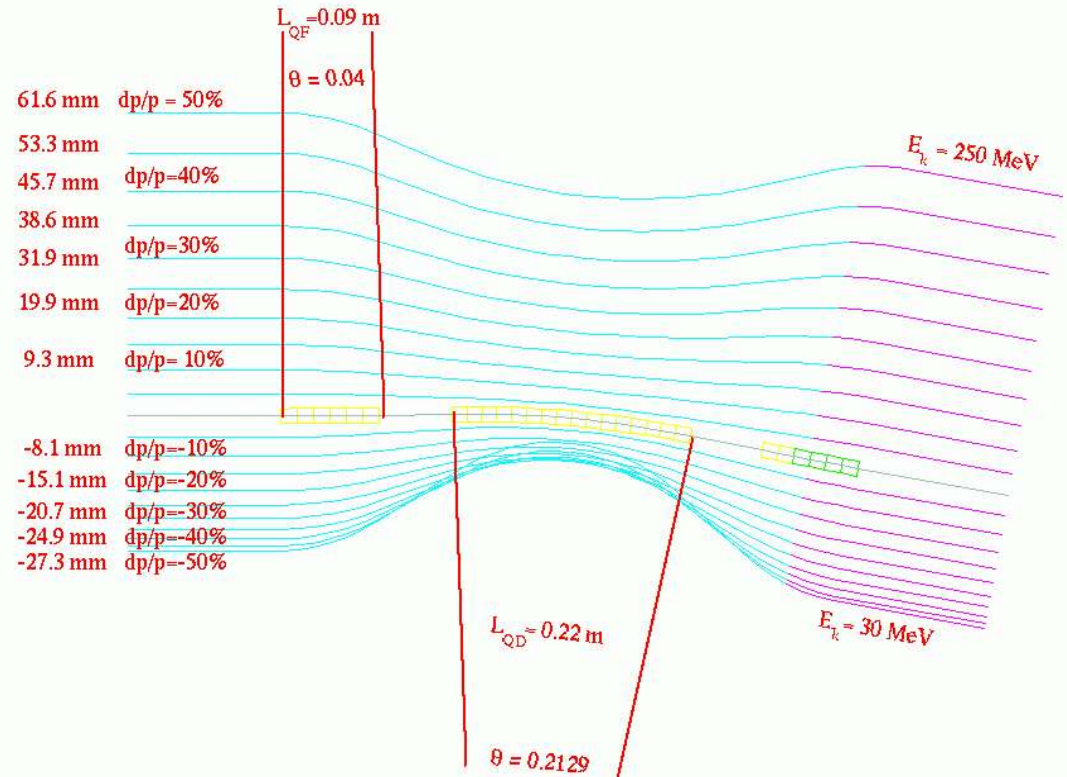
HIMAC at NIRS





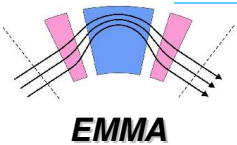
Proton & Carbon Therapy

- Diameter 21m
- Magnet aperture 65cm
- Transmission < 20%
- Low frequency ~5MHz
- Nearly linear magnets
- Diameter 9.1m
- Consists of:
 - o ECR RFQ
- FFAG1: 31 MeV p; 7.8 MeV/u C⁶⁺
- FFAG2: 250 MeV; 68 MeV/u
- FFAG3: 502 MeV/u
- Aperture 8.9cm



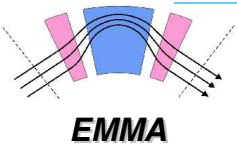
Other possibilities being investigated.

Uncertainties hampering design



“EMMA”

- Non-scaling FFAGs have three unique features:
 - multi-resonance crossings
 - momentum compaction
 - acceleration
- huge
- asynchronous
- Must be studied in detail!
- Further design work hampered
- **Must build one!**
- Proof-of-Principle non-scaling FFAG required
- Original idea: electron model EMMA
- Model of muon accelerators
- Sufficiently flexible to also model protons, ions, etc
- Perfect training facility

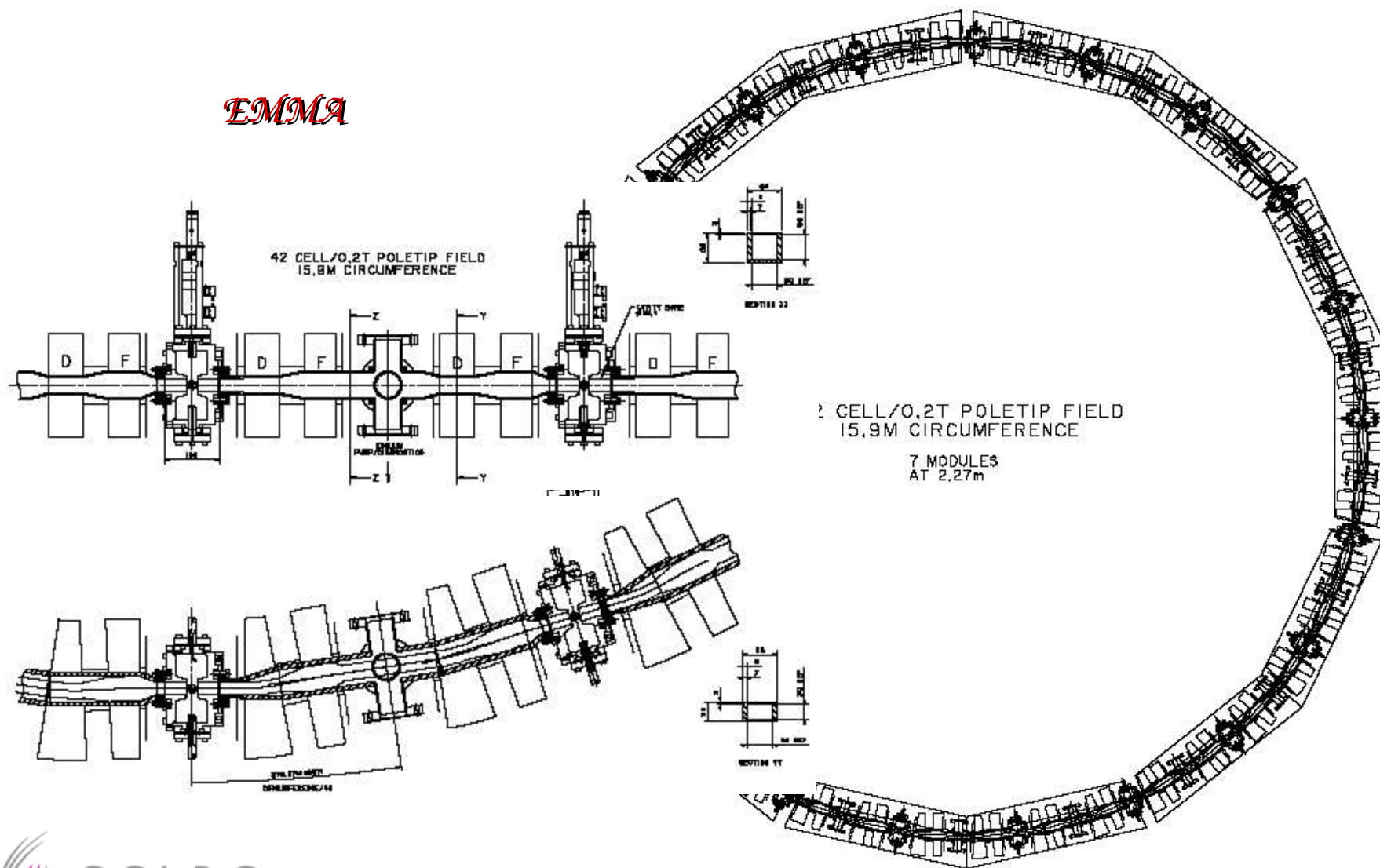


EMMA

- Baseline design done
- Selected lattice:
 - 10 to 20 MeV
 - 42 cells, doublet lattice
 - 37cm cell length
 - ~16m circumference
 - RF every other cell
 - 1.3GHz, TESLA frequency
- Specification of hardware started

Non-Scaling Electron Model

EMMA



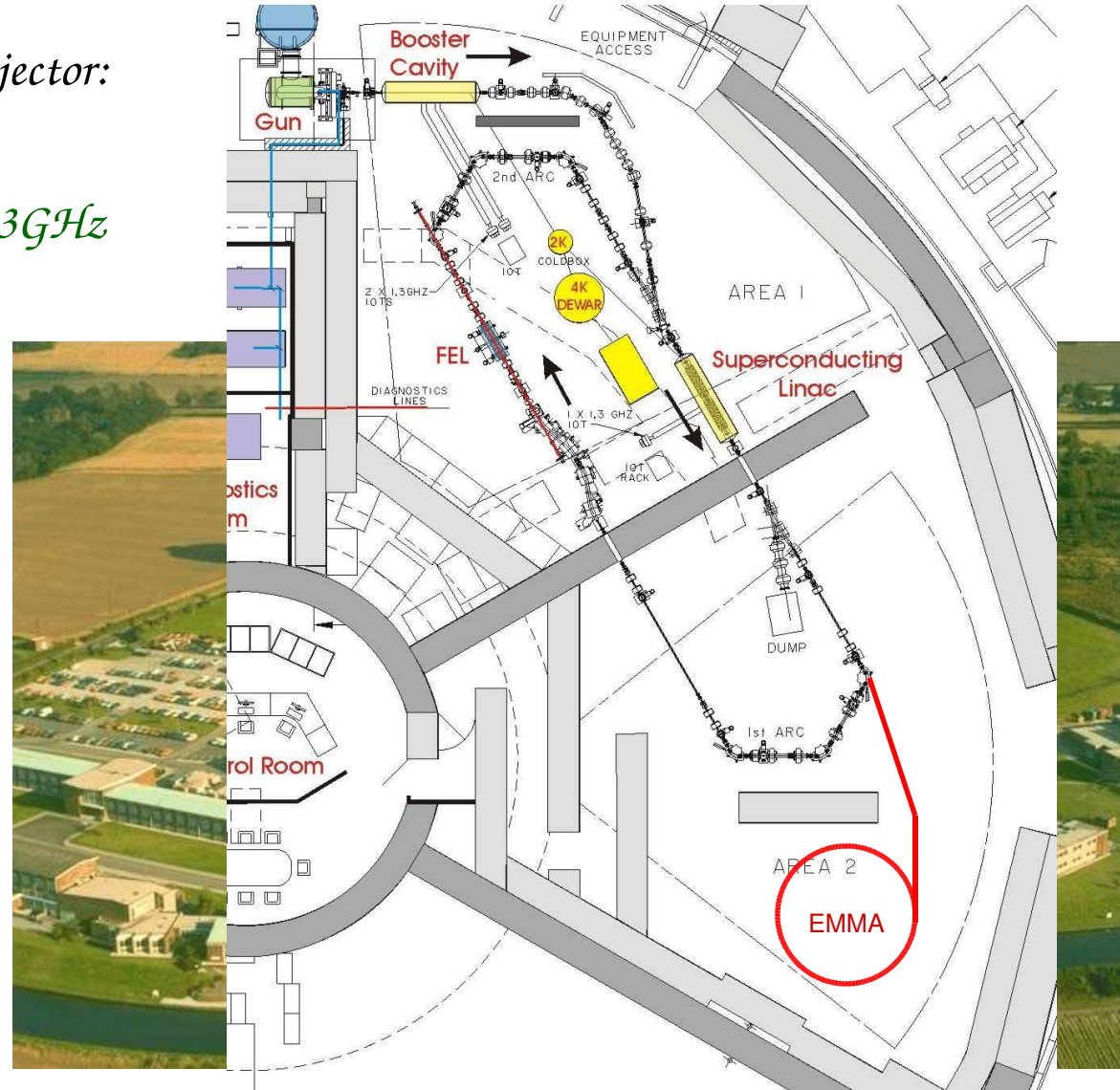
Location

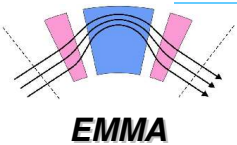
Need somewhere with flexible injector:

- variable energy
- variable bunch structure
- $\sim 1.3\text{GHz}$

Experimental hall

Infrastructure

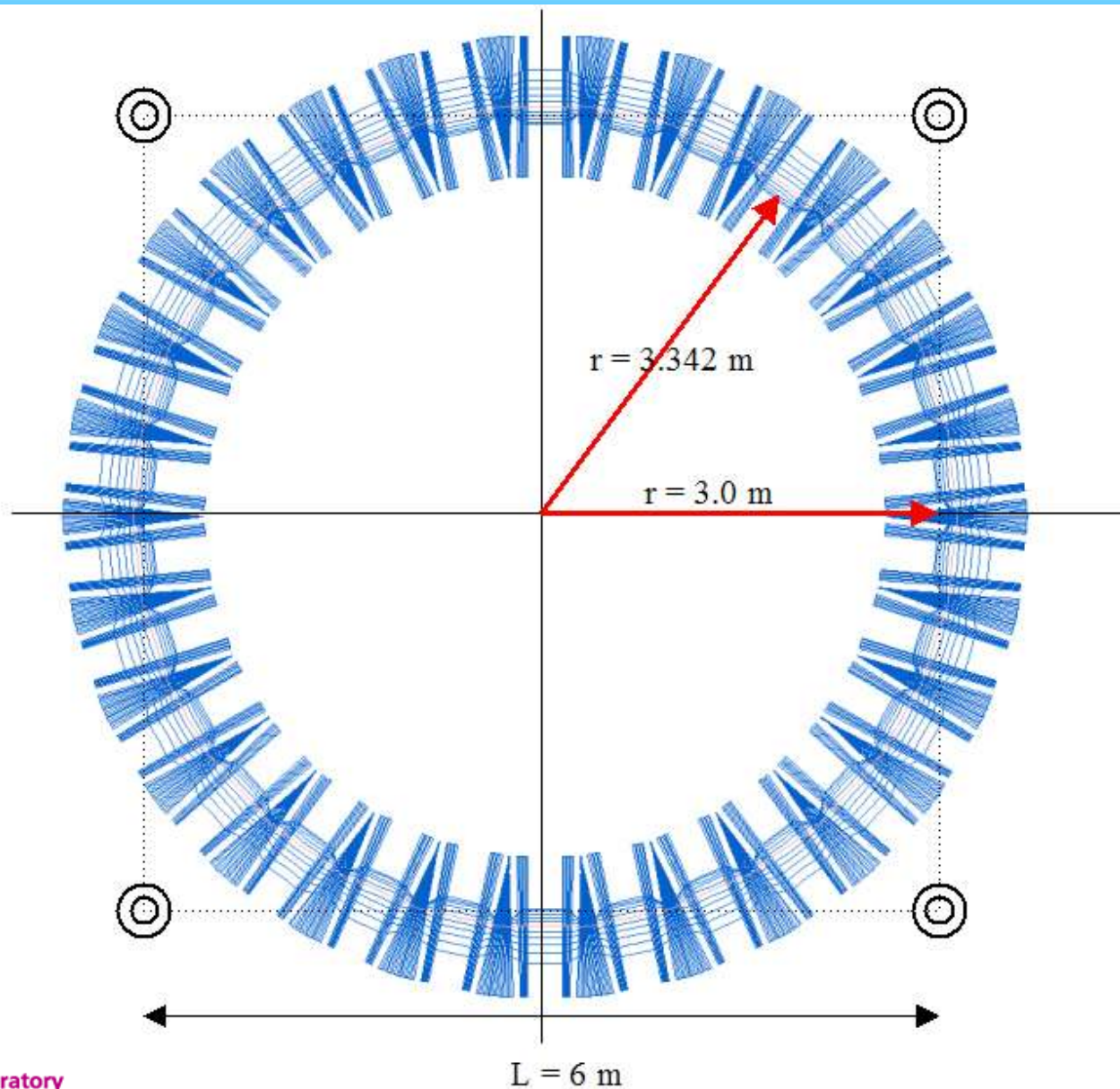


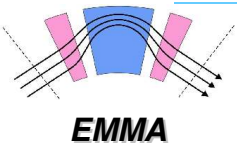


But....hot off the presses....

- Potential funding for proton non-scaling FFAG
- Proof of principle of non-scaling optics:
 - momentum compaction
 - resonance crossing
 - asynchronous acceleration
- POP for hadron therapy
- Located in new Radio-Oncology building in Oxford
- £3M “available”; same again likely
- Feasibility study just starting:
 - 18 MeV cyclotron injector (PET production)
 - 70-100 MeV non-scaling FFAG
- Consortium forming, participants welcome!
- Needs a name!

But....hot off the presses....



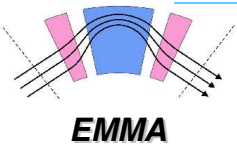


Latest Plan

- Do both!
- “Independent” funding routes:
proton: Medical Research Council &
Cancer Research UK
Technology Fund/CCLRC
- Link together in BT proposal
- Emphasis still on hadron therapy
- Complementarities:
therapy prototype;
beta
non-scaling optics;
accelerators

EMMA: UK Basic

proton:
low
EMMA: detailed study of
model of NF
training machine;
high beta



Conclusions

- FFAGs could revolutionise accelerator technology
- Much interest world-wide
- Recent focus on non-scaling FFAGs
- “Best” machine probably depends on application
- Superiority over others already being shown
- Important goals:
 - muon acceleration for NF
 - hadron therapy in the UK
- Early days: model is essential 1st step
- Demonstrate:
 - it works
 - non-scaling acceleration
 - how to optimise
- Need to build core FFAG expertise in UK

- study
- learn