Status of FFAs
-
Modelling and existing/planned machines

J.-B. Lagrange
ISIS department, RAL, STFC, UK

Outline

- Introduction on FFAs
- Horizontal excursion new developments
- Vertical excursion new developments
- Summary

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Definition of FFA

(historically FFAG)

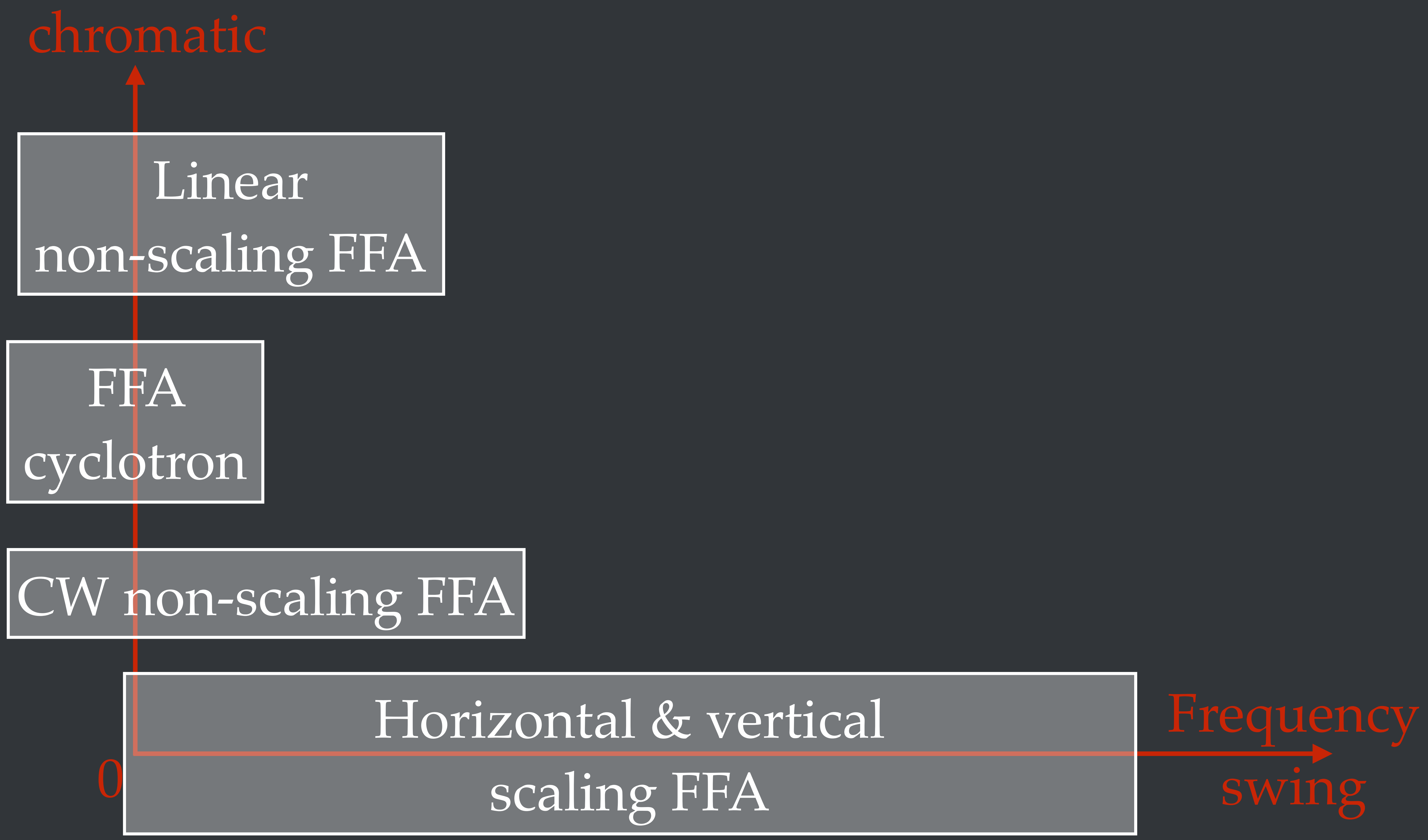
Fixed Field alternating gradient Accelerator

Static field
like cyclotrons

Strong focusing
like synchrotrons

Classification according to **how the beam is focused**, not how it is accelerated.

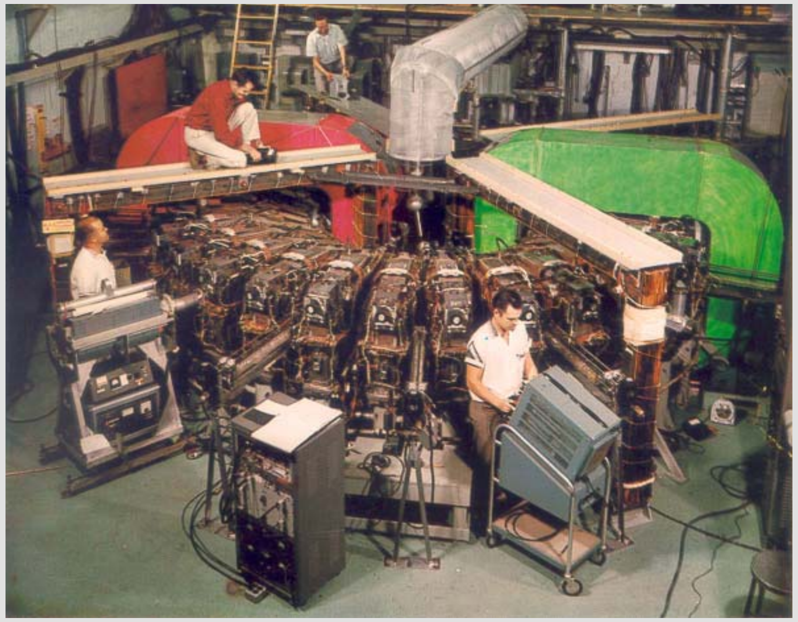
FFA classification



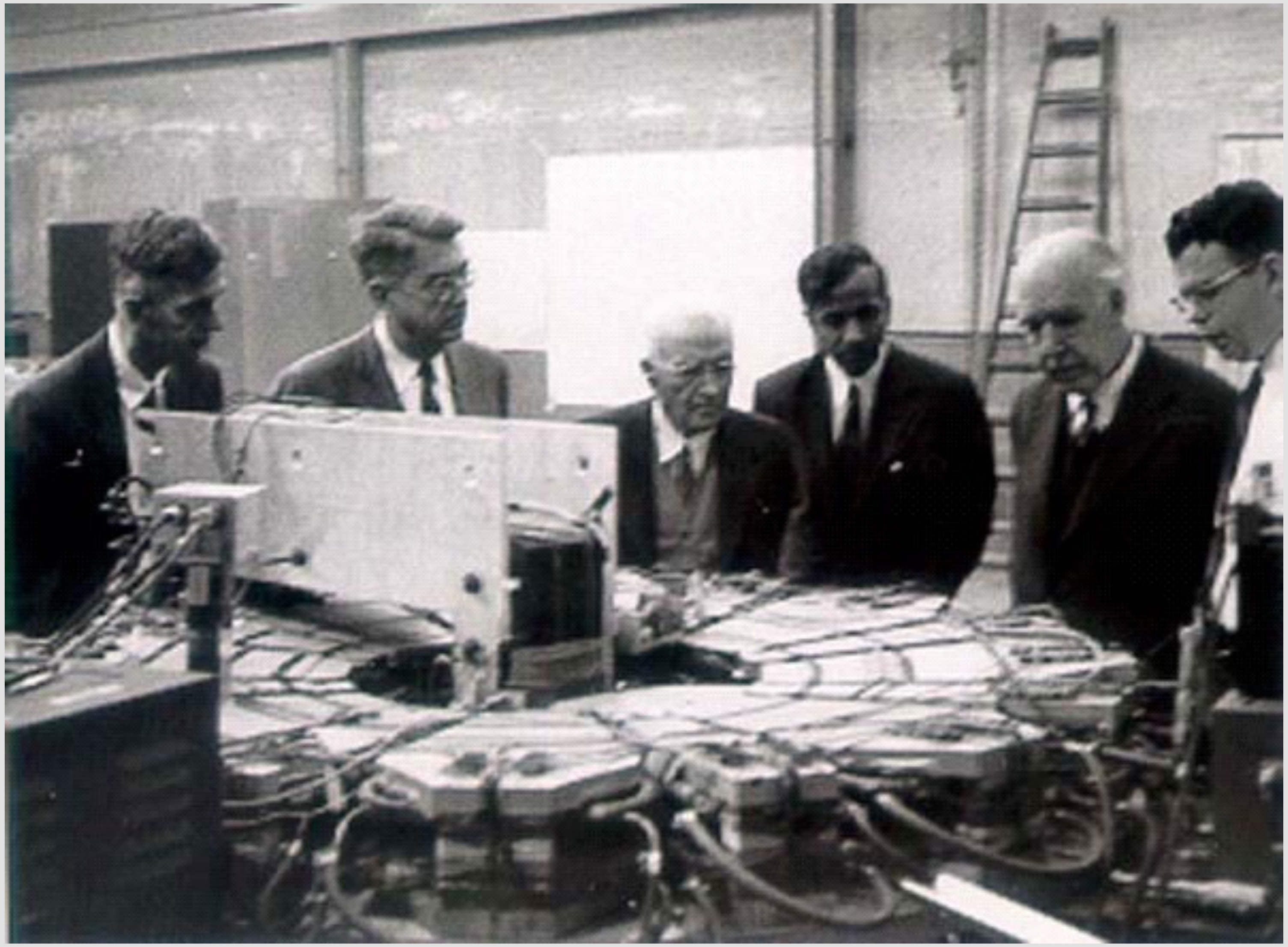
FFAs in the 1950s-1960s

First FFAs (electron) built in MURA
(Midwestern Universities Research Association).

Mark III at MURA



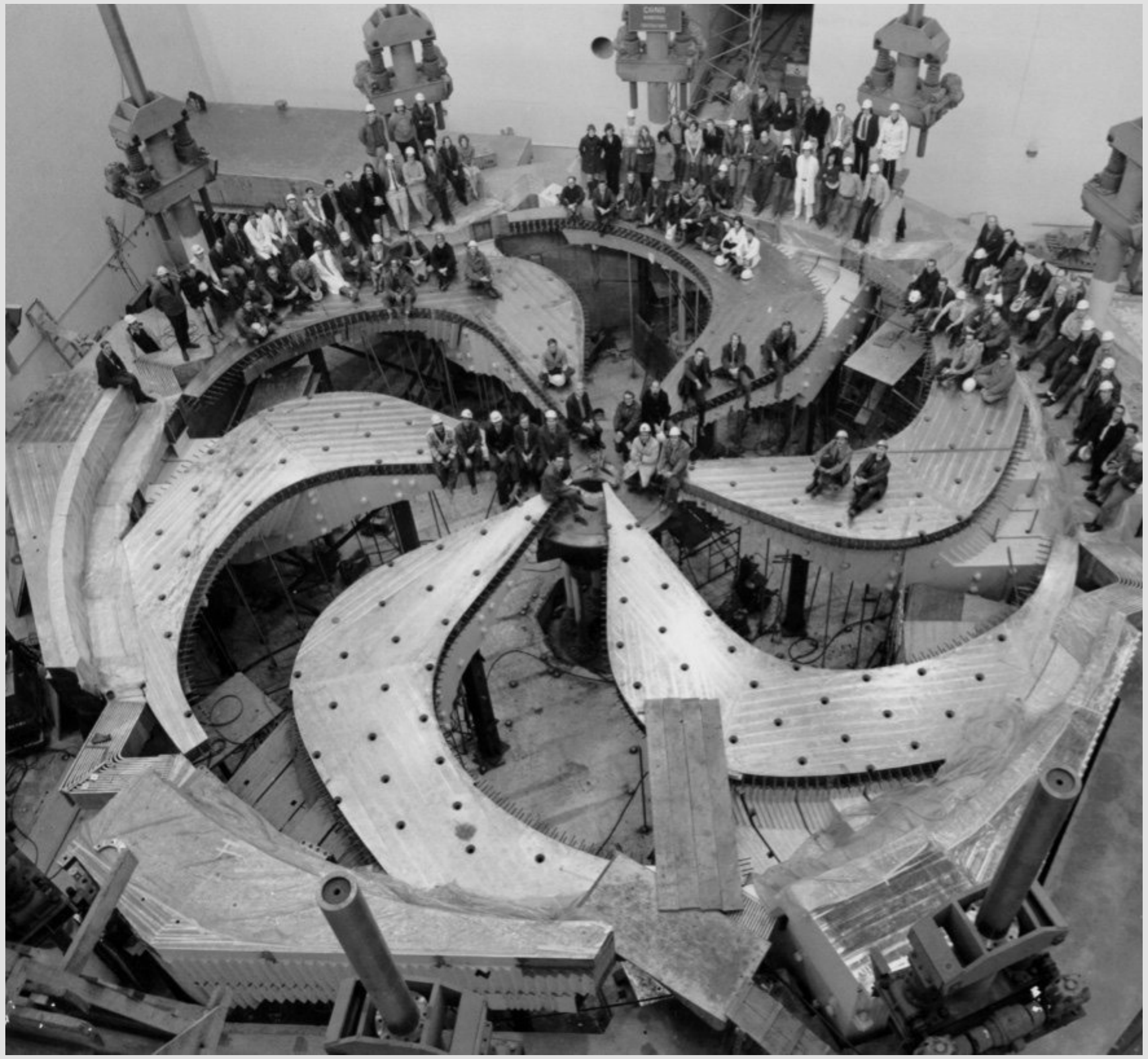
Mark V at MURA



Mark II at MURA

FFA cyclotrons

Cyclotrons benefitted from spiral sectors to go to higher energies.



TRIUMF cyclotron
520 MeV H^-

PSI cyclotron
590 MeV proton

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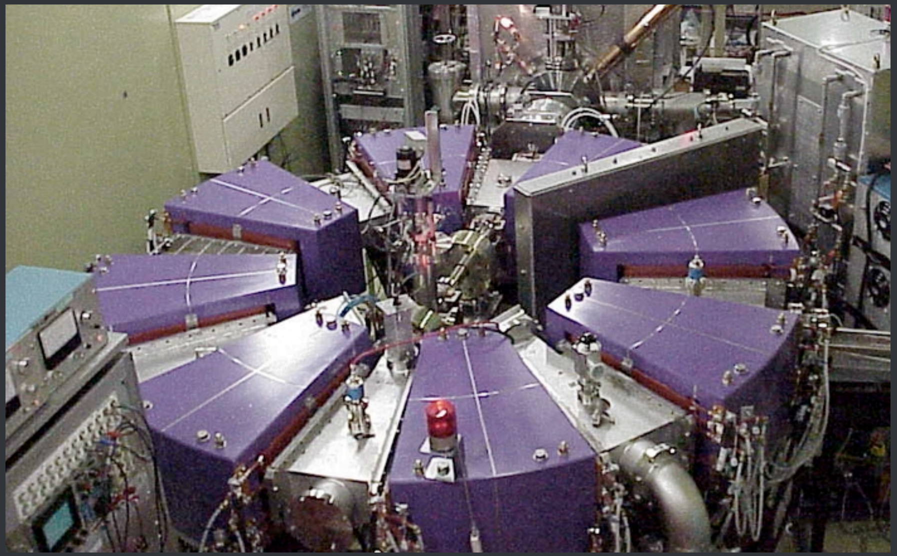
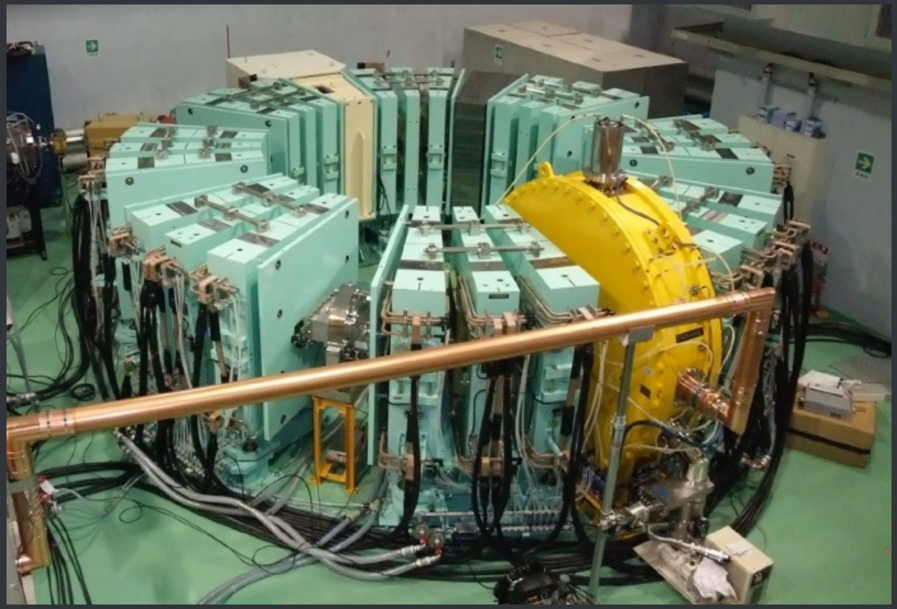
FFA synchrotrons

Revival in 2000s in Japan.



POP at KEK

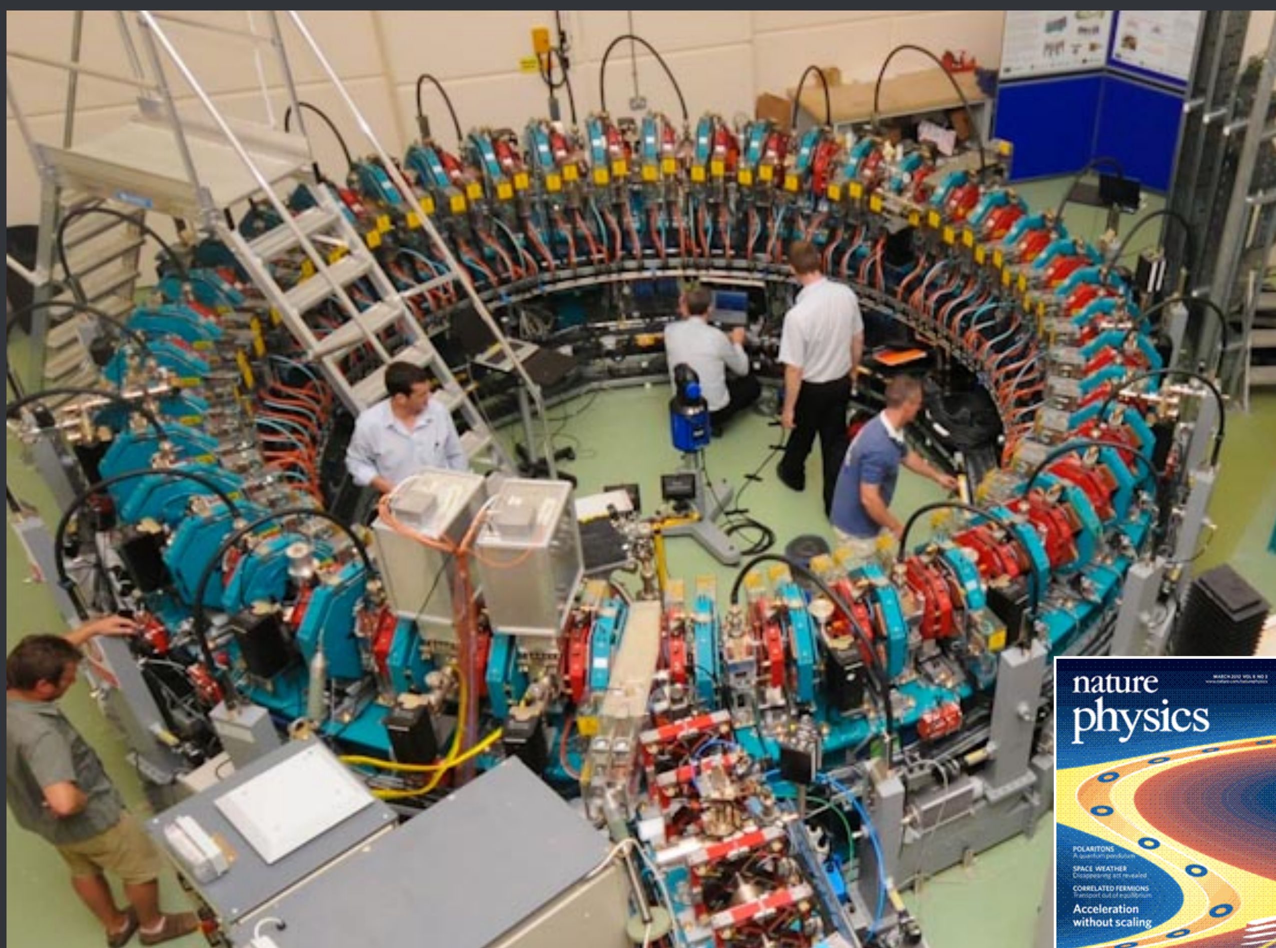


ERIT/MERIT at Kyoto University

ADS complex at Kyoto University

FFA synchrotrons

In Europe



EMMA at Daresbury Lab, UK

RACCAM project, France

FFA synchrotrons

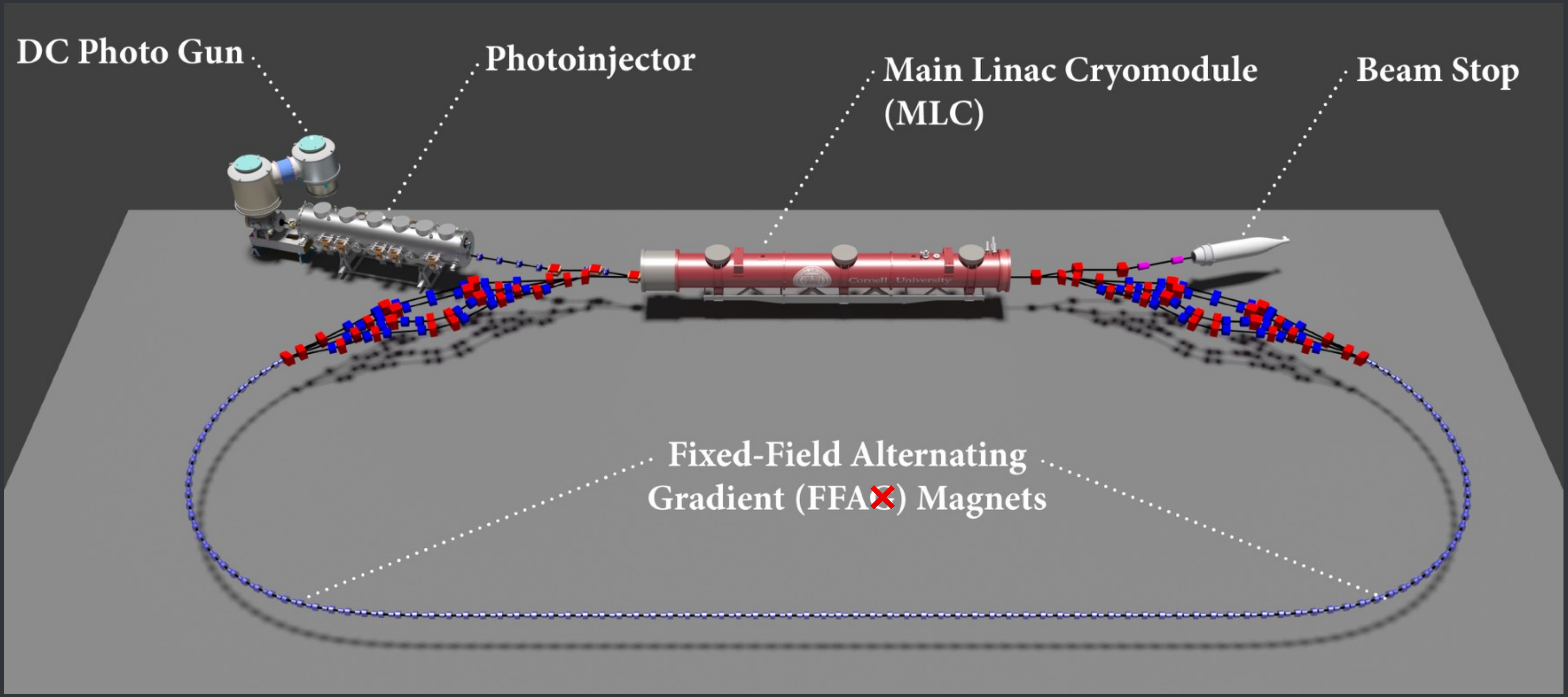
Spallation neutron source

Major upgrade of ISIS in the UK planned, with the FFA option considered.

An FFA test ring is planned at RAL to demonstrate the capability of the FFA to deliver a high-power and short pulse proton beam for spallation neutrons.

FFA arcs for ERL

In the USA



CBETA at Cornell University

Simulation codes

Synchrotron codes assuming a central orbit independent of momentum are unsuitable.

Several codes are available to model FFAs:

- OPAL,
- Zgoubi,
- SCODE,
- MUON1,
- FIXFIELD,
- FROM-ORBIT,
- etc.

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DF Spiral

Spiral FFA (cyclotrons and synchrotrons) usually consists only of 1 type of magnet to have a small circumference, but have very limited control over dynamics.

→ DF spiral cell: compromise between machine circumference size and tune flexibility.

Useful in high intensity machines!

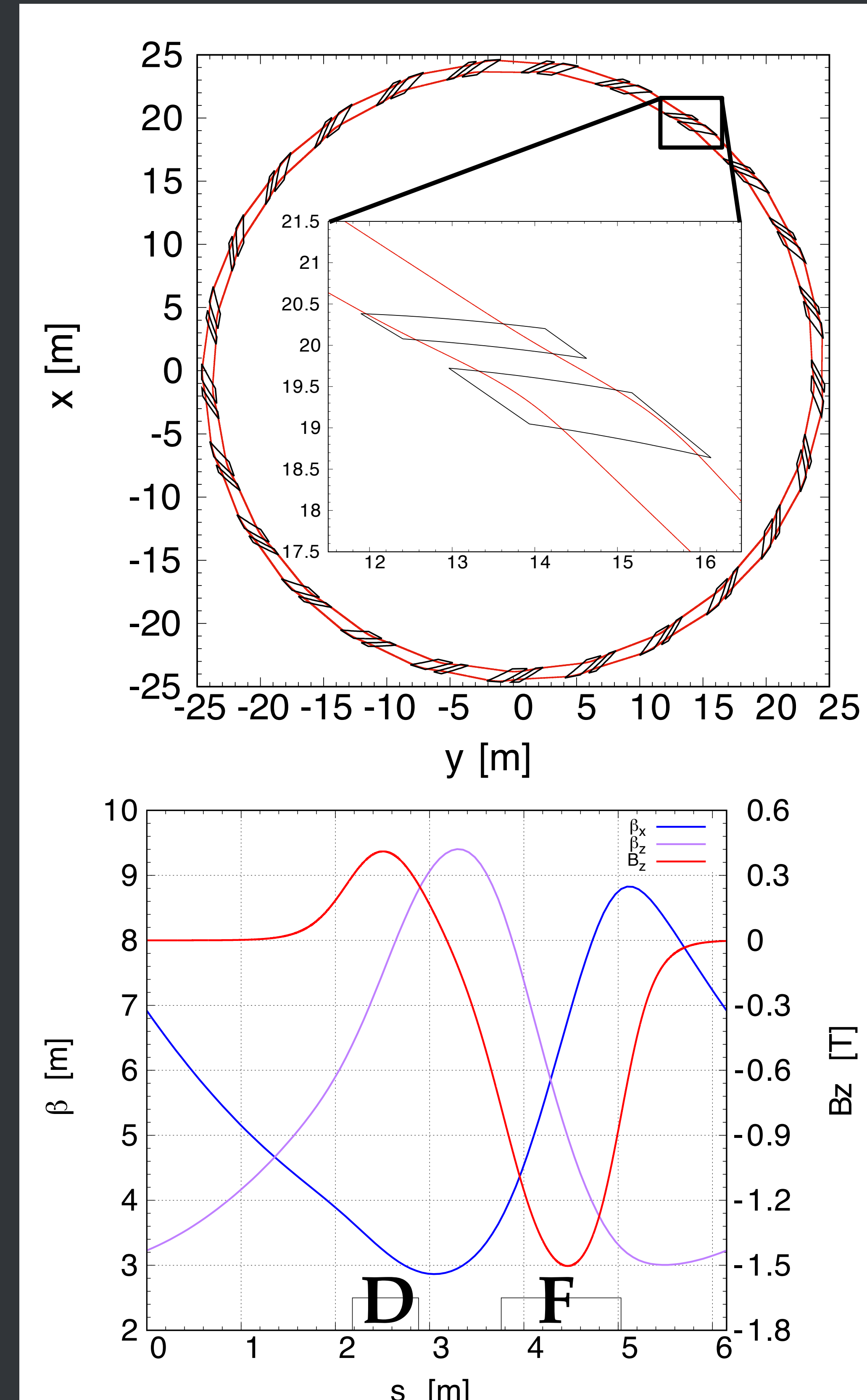
DF Spiral

Example: Upgrade of ISIS

Additional features for high intensity:

- supersymmetry multiple of 5,
- Comparable horizontal and vertical tunes

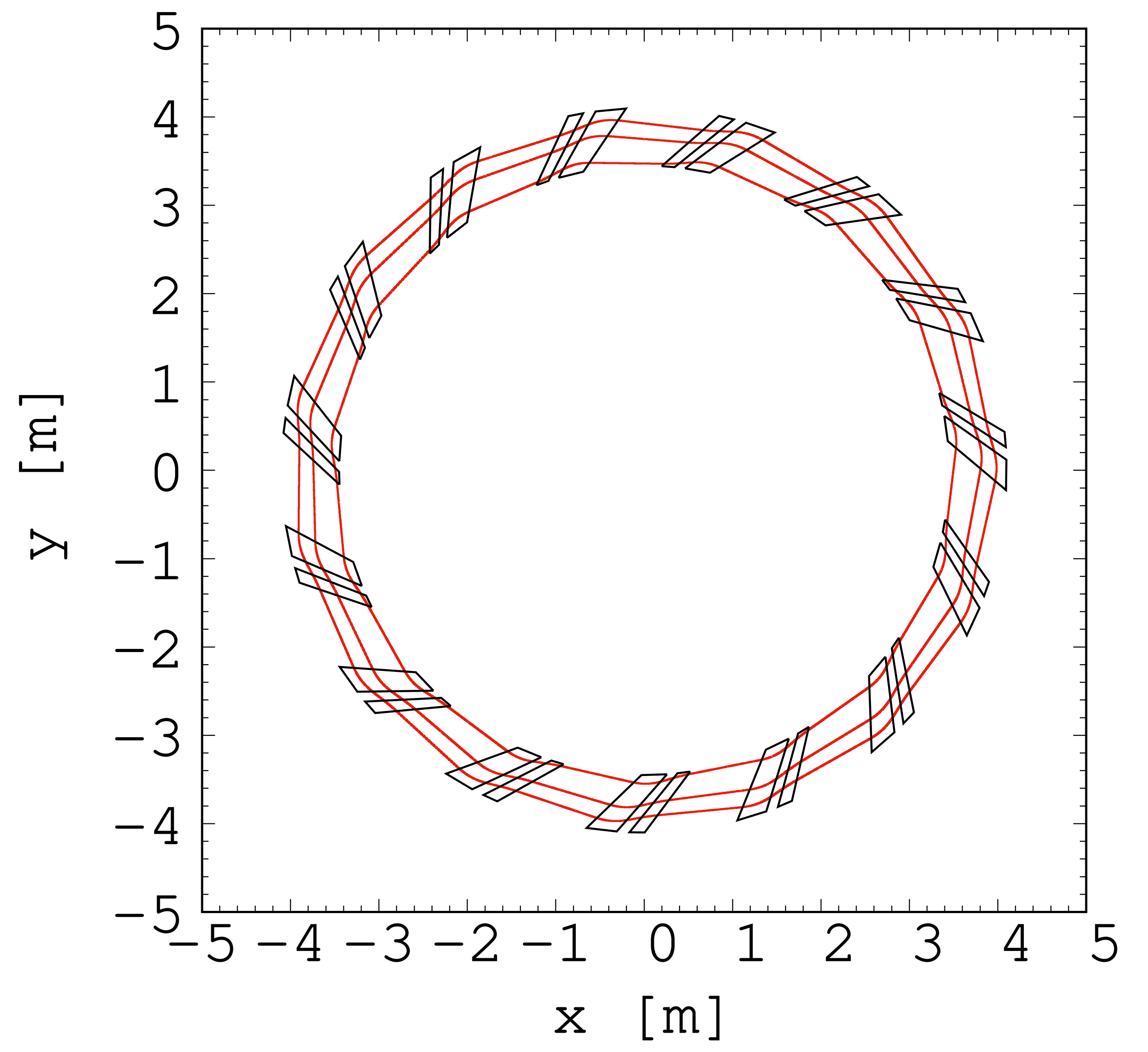
Kinetic energy	0.4 - 1.2 GeV
Reference radius	24 m
Number of cells	25
Packing factor	0.35
Straight section	3.58 m
Spiral angle	62 deg
k-index	20.6
Ratio Bd/Bf strength	-0.443
Orbit excursion	0.8 m
Cell tune (H, V)	(0.2073, 0.2098)
Ring tune (H, V)	(5.18, 5.24)
Transition gamma	4.6



Tilted sector

Spiral magnet complex to manufacture, especially for superconducting design

→ Tilted sector magnet to retain edge focussing with easier manufacturing shape (easier to arrange rectangular elements in drift spaces)



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Vertical excursion FFA

Vertical excursion FFA considered in 1955 as an ”Electron Cyclotron”, rediscovered recently.

Advantages:

- Quasi-isochronicity for relativistic particles,
- Infinite transition energy,
- Orbit radius independent of momentum, like synchrotrons,
- Geometrical arrangement of the lattice footprint independent of the scaling condition, unlike in horizontal scaling FFA,
- Rectangular shape for the main magnets and the coil geometry is simpler compared to the spiral magnet of horizontal FFA.

Vertical excursion FFA

To keep the transverse linearised equations of motion independent of momentum, the field must follow

$$B = B_0 e^{m(v-v_0)}$$

with $m = \frac{1}{B}\frac{dB}{dv}$ the vertical normalised field gradient.

⚠️ since m is a vertical gradient, there is coupling between horizontal and vertical plane.

Rectangular Field model

- In the mid-plane ($h = h_0$):

Cartesian coordinates (h,v,l)

$$B_v(h_0, v, l) = B_0 e^{m(v-v_0)} \mathcal{F}(l)$$

with m the constant normalised field gradient, and $\mathcal{F}$ the arbitrary fringe field function (*tanh* here).

- From $\left(\overrightarrow{curl}\,\overrightarrow{B}\right)_h = 0$

$$B_l(h_0, v, l) = \int_v \frac{\partial B_v}{\partial l} dv = B_0 \mathcal{F}'(l) \left(\frac{e^{m(v-v_0)}}{m} + g(l) \right)$$

with $g(l)$ an arbitrary function independent of v, must be 0 to keep the invariance of the closed orbits with momentum.

$$B_l(h_0, v, l) = \frac{B_0}{m} e^{m(v-v_0)} \mathcal{F}'(l)$$

- Because of the field symmetry, $B_h(h_0, v, l) = 0$

Rectangular Field model (2)

Cartesian coordinates (*h*,*v*,*l*)

In the mid-plane ($h = h_0$)

$$\begin{cases} B_{h0}(h_0, v, l) = 0 \\ B_{v0}(h_0, v, l) = B_0 e^{m(v-v_0)} \mathcal{F}(l) \\ B_{l0}(h_0, v, l) = \dfrac{B_0}{m} e^{m(v-v_0)} \mathcal{F}'(l) \end{cases}$$

with m the constant normalised field gradient, $\mathcal{F}$ the fringe field function (*tanh* in the models)

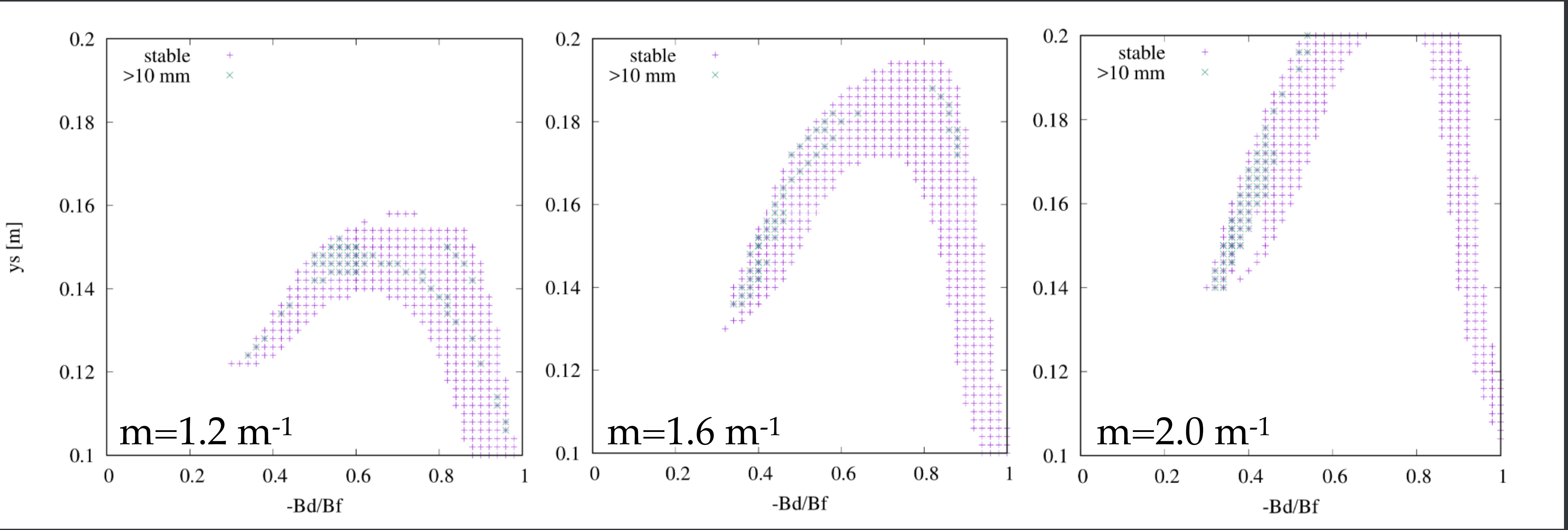
Off mid-plane extrapolation components from Maxwell equations:

$$\begin{cases} B_h(h, v, l) = \dfrac{B_0}{m} e^{m(v-v_0)} \sum_i B_{hi}(l)(h-h_0)^i \\ B_v(h, v, l) = B_0 e^{m(v-v_0)} \sum_i B_{vi}(l)(h-h_0)^i \\ B_l(h, v, l) = \dfrac{B_0}{m} e^{m(v-v_0)} \sum_i B_{li}(l)(h-h_0)^i \end{cases}$$

VFFA lattice parameters

3 key parameters in the case of rectangular magnets:

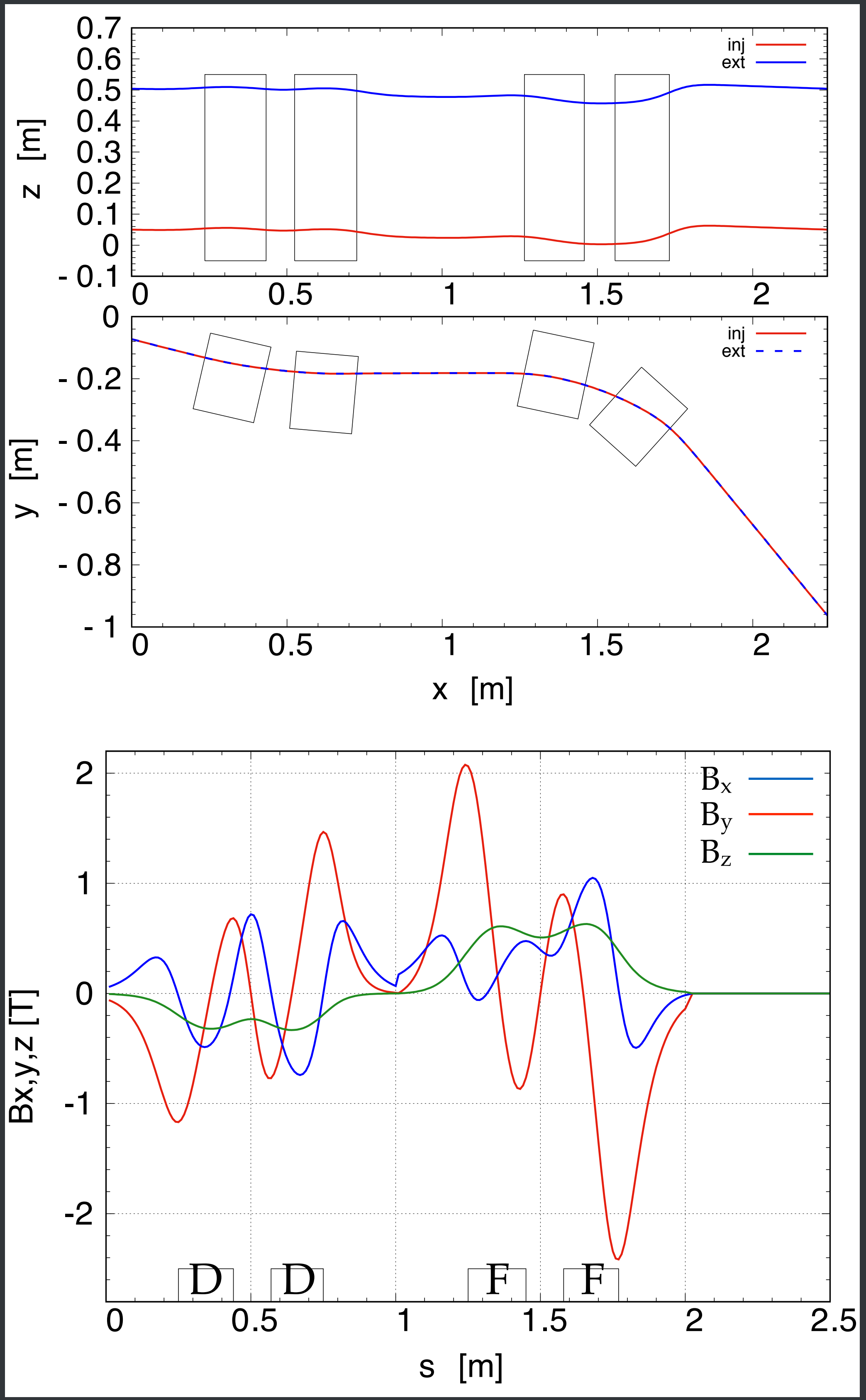
- Normalised field gradient *m*,
- F/D strength ratio,
- Magnet position in the radial direction y_s.



Vertical excursion FFA

Example: ISIS test ring

Kinetic energy	3 - 12 MeV
Reference radius	3.9789 m
Number of cells	10
Packing factor	0.32
Straight section	1.0 m (long), 0.5 m (short)
m-index	1.6 m^{-1}
Ratio Bd/Bf strength	-0.47
Orbit excursion	0.4 m
Cell tune (H, V)	(0.19, 0.16)
Transition gamma	infinite



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Summary

- FFAs have contributed to the cyclotron community for a long time, and continue to do it to this day:
  - Spiral shape to give vertical stability at high energy,
  - Addition of a reverse bend to the spiral geometry to increase control on dynamics,
  - Tilted sector geometry for easier superconducting manufacturing at high energy,
  - Isochronous acceleration of relativistic particles with vertical FFA.