INTRODUCTION TO FFAG ACCELERATORS

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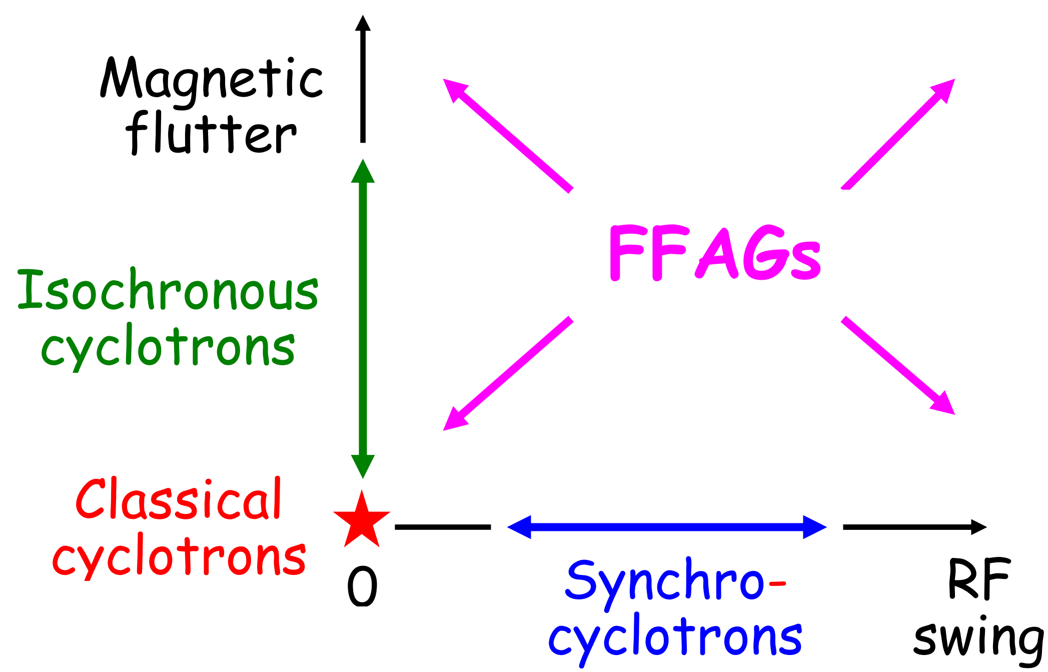
FFAGs – Fixed Field Alternating Gradient accelerators

Fixed Magnetic Field – members of the **CYCLOTRON** family[1]

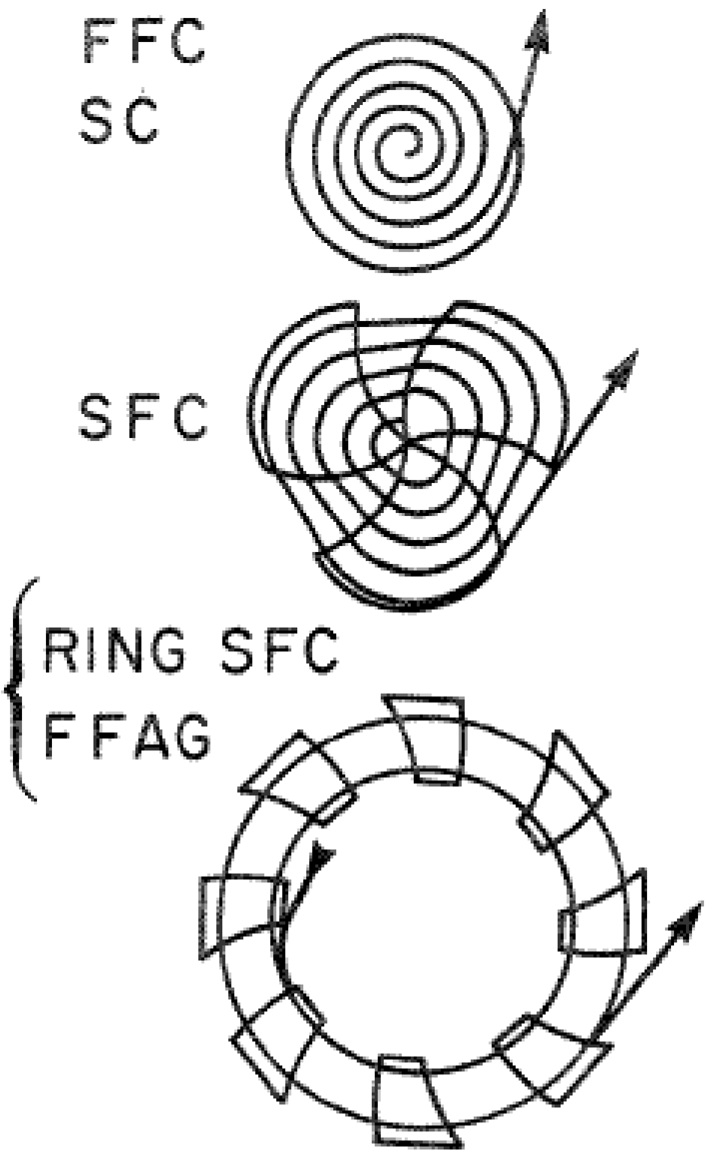
Magnetic field variation B(θ)	Fixed Frequency (CW beam)	Frequency-modulated (Pulsed beam)
Uniform	Classical	Synchro-
Alternating	Isochronous	FFAG

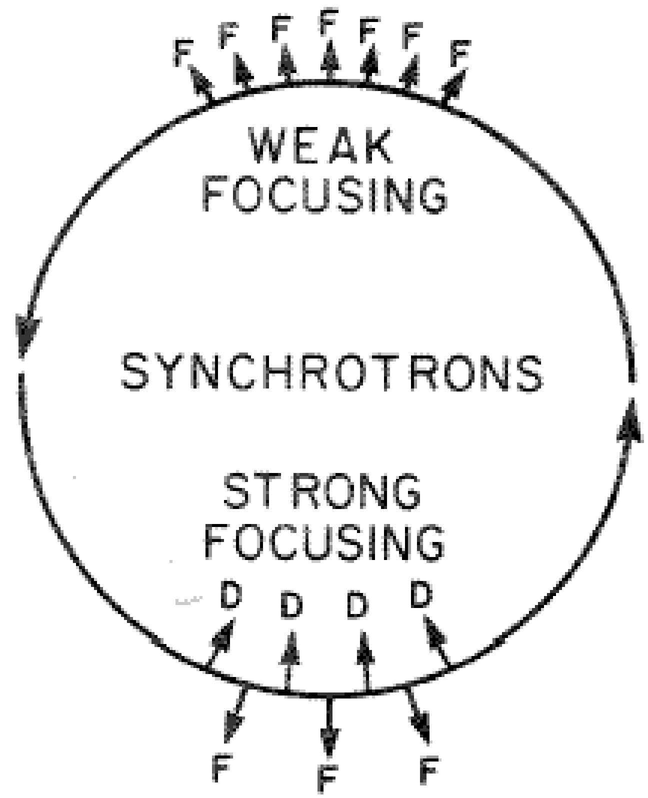
But FFAG enthusiasts sometimes express an alternative view:
– cyclotrons are just special cases of the FFAG!



1. E.M. McMillan, *Particle Accelerators*, in *Experimental Nuclear Physics*, **III**, 639-786 (1959)

THE CYCLOTRON AND SYNCHROTRON FAMILIES





FFC = fixed frequency cyclotron
SC = synchrocyclotron
SFC = sector-focused cyclotron
FFAG = fixed field alternating gradient

BASIC CHARACTERISTICS OF FFAGs

are determined by their **FIXED MAGNETIC FIELD**

- Spiral orbits
  - needing wider magnets, rf cavities and vacuum chambers (compared to AG synchrotrons)
- Faster rep rates (up to kHz?) limited only by rf capabilities
  - not by magnet power supplies
- Large acceptances
- High beam current

The last 3 factors have fuelled interest in FFAGs over 50 years!

Good reading:

- K.R. Symon, D.W. Kerst, *et al.*, *Phys. Rev.* **103**, 1837 (1956)
- C.H Prior (ed.) *ICFA Beam Dynamics Newsletter* **43**, 19-133 (2007);
- FFAG Workshops – Web links at FFAG04 and FFAG 2007.

BRIEF HISTORY

FFAGs were **proposed** by **Ohkawa, Kolomensky, Symon** and **Kerst**, (1953-5)

- and **studied** intensively at **MURA** in the 1950s and 1960s
- several **electron models** were **built** and **operated** successfully
- but no **proton FFAG** until **Mori's** at **KEK** (1 MeV 2000, 150 MeV 2003)

Now there's an explosion of interest!

- **6 more are now operating (for p, e, α)** and **3 more (e) are being built**
- **~20 designs** under study:
  - for **protons, heavy ions, electrons** and **muons**
  - many of **novel "non-scaling" design**
- with **diverse applications:**
  - ***cancer therapy***
  - ***industrial irradiation***
  - ***driving subcritical reactors***
  - ***boosting high-energy proton intensity***
  - ***producing neutrinos.***

FFAG Workshops since 1999:- Japan (x8), CERN, USA(x3), Canada, France, UK

SCALING DESIGNS - HORIZONTAL TUNE ν_r

Resonances were a worry in the 1950s, because of slow acceleration: if, at some energy, the betatron oscillation wavelength matches that of a harmonic component of the magnetic field, the ions may be driven into resonance, leading to loss of beam quality or intensity.

The general condition is $\ell \nu_x \pm m \nu_y = n$ where ℓ, m, n are integers.

So "**Scaling**" designs were used, with:

- the same orbit shape at all energies
- the same optics " " " " "
- the **same tunes** " " " " " $\Rightarrow$ no crossing of resonances!

To 1st order, the (radial tune)^2 $\nu_r^2 \approx 1 + k$ (even with sector magnets)

where the average field index $k(r) \equiv \dfrac{r}{B_{av}} \dfrac{dB_{av}}{dr}$ and $B_{av} = \langle B(\Theta) \rangle$

So large constant ν_r requires k = constant ≥ 0

$\Rightarrow$ $B_{av} = B_0 (r/r_0)^k$ and $p = p_0 (r/r_0)^{(k+1)}$

SCALING FFAGs - VERTICAL TUNE ν_z

In the vertical plane, with sector magnets and to 1st order,

$$\nu_z^2 \approx -k + F^2(1 + 2\tan^2\varepsilon)$$

where the 2nd term describes the Thomas and spiral edge focusing effects.

Note $k > 0 \Rightarrow$ vertical defocusing

$\therefore$ large constant, real ν_z requires large, constant $F^2(1 + 2\tan^2\varepsilon)$

MURA kept (1) magnetic flutter $F^2 \equiv \left\langle \left(\frac{B(\theta) - B_{av}}{B_{av}} \right)^2 \right\rangle$ = constant

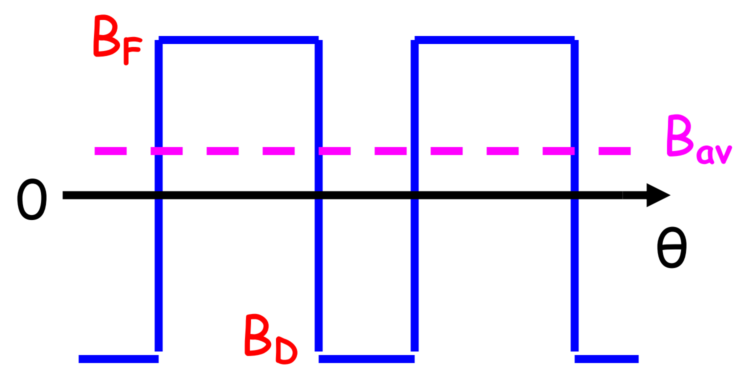
(most simply achieved by using constant profile $B(\Theta)/B_{av}$)

(2a) for spiral sectors,

spiral angle ε = constant (sector axis follows $R = R_0 e^{\Theta \cot\varepsilon}$)

(2b) for radial sectors,

$B_D = -B_F$ to boost F^2.



Note - reverse fields increase average radius:

$\Rightarrow$ >4.5x larger (Kerst & Symon '56 - no straights)

[Not so bad with straights: KEK 150-MeV FFAG has "circumference factor" 1.8]

In summary, scaling requires:-

- constant **field index**
- constant and high **flutter**, with opposing F and D fields (if radial)
- constant **spiral** angle (if spiral)

- meaning **complex wide-aperture sector magnets**

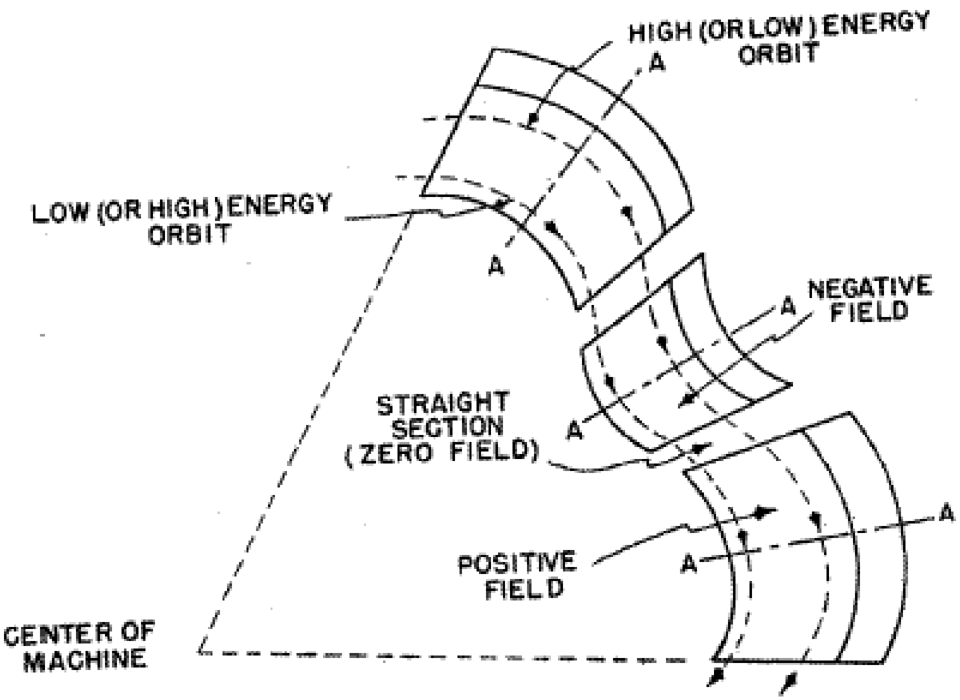


FIG. 2. Plan view of radial-sector magnets.

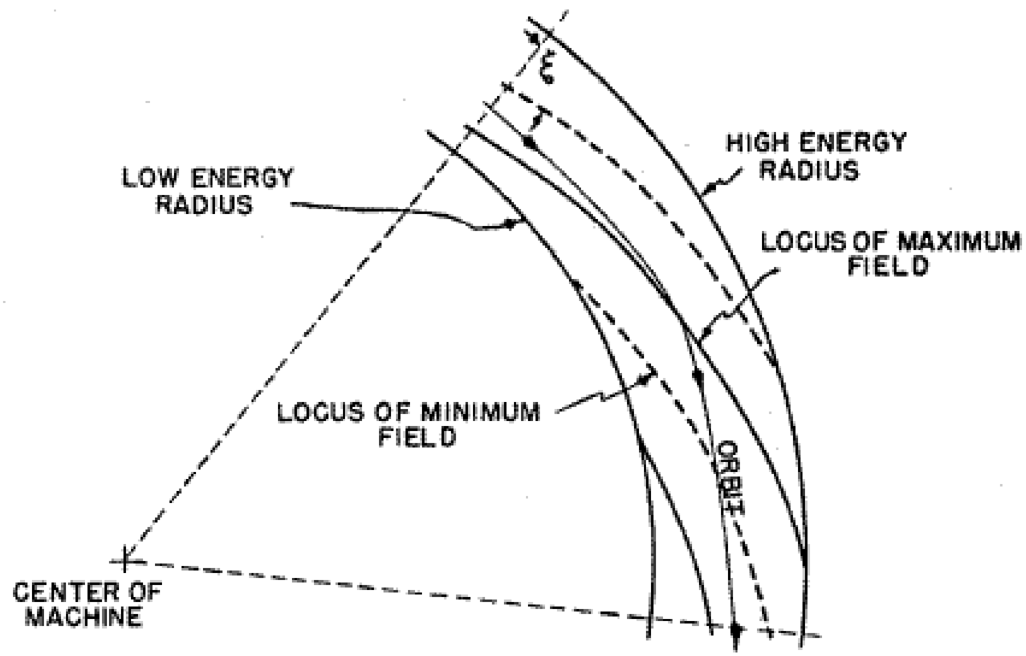


FIG. 3. Spiral-sector configuration.

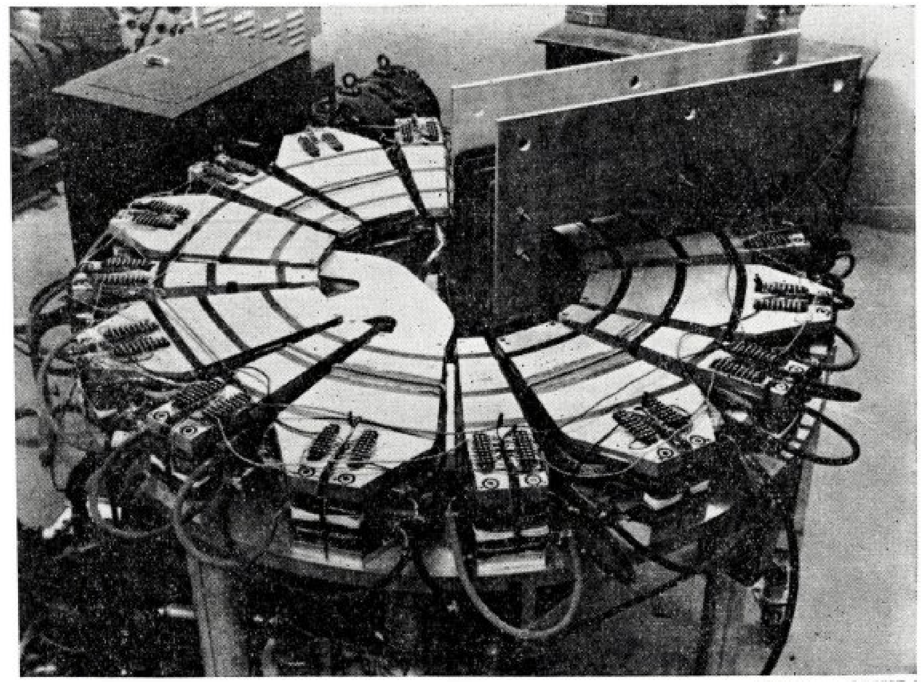
K.R. Symon, D.W. Kerst, L.W. Jones, L.J. Laslett and K.M. Terwilliger, *Phys. Rev.* **103**, 1837 (1956)

MURA Electron FFAGs

400keV radial sector →

50 MeV radial sector ↘

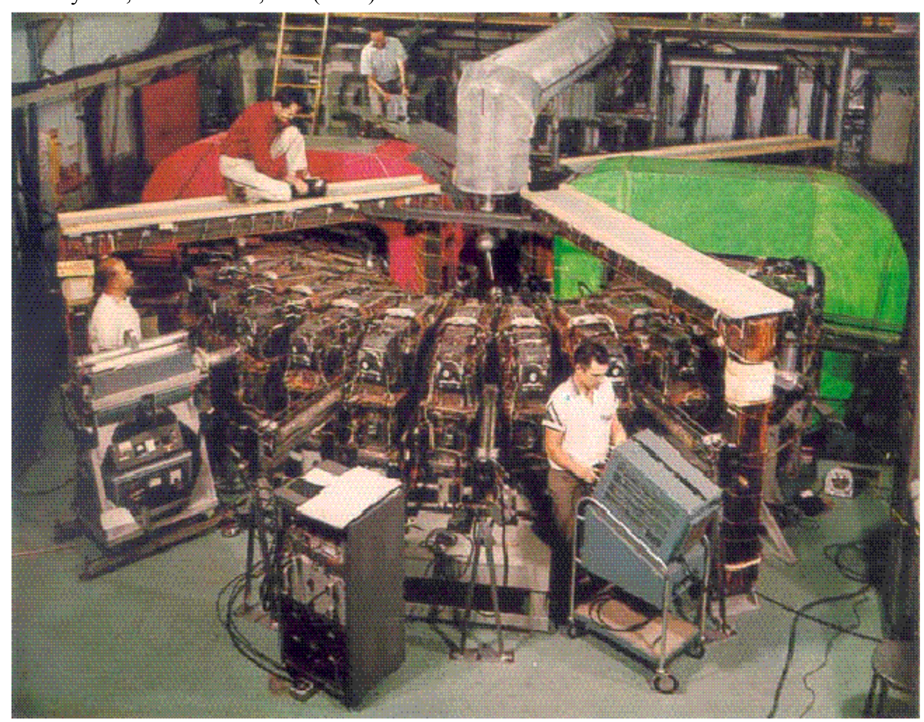
120 keV spiral sector ↓



Courtesy of MURA

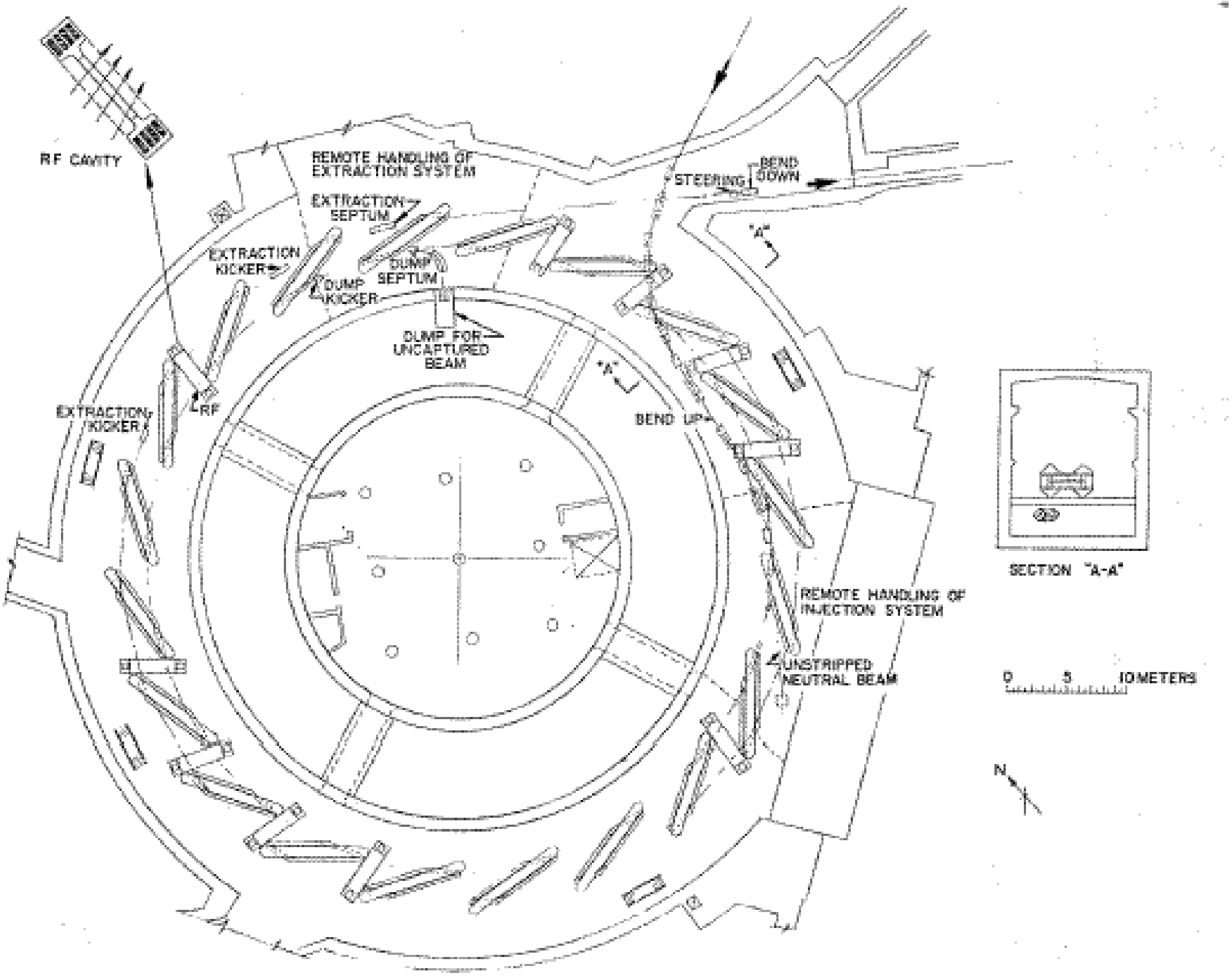
K.R. Symon, Proc PAC03, 452 (2003)

Courtesy of MURA

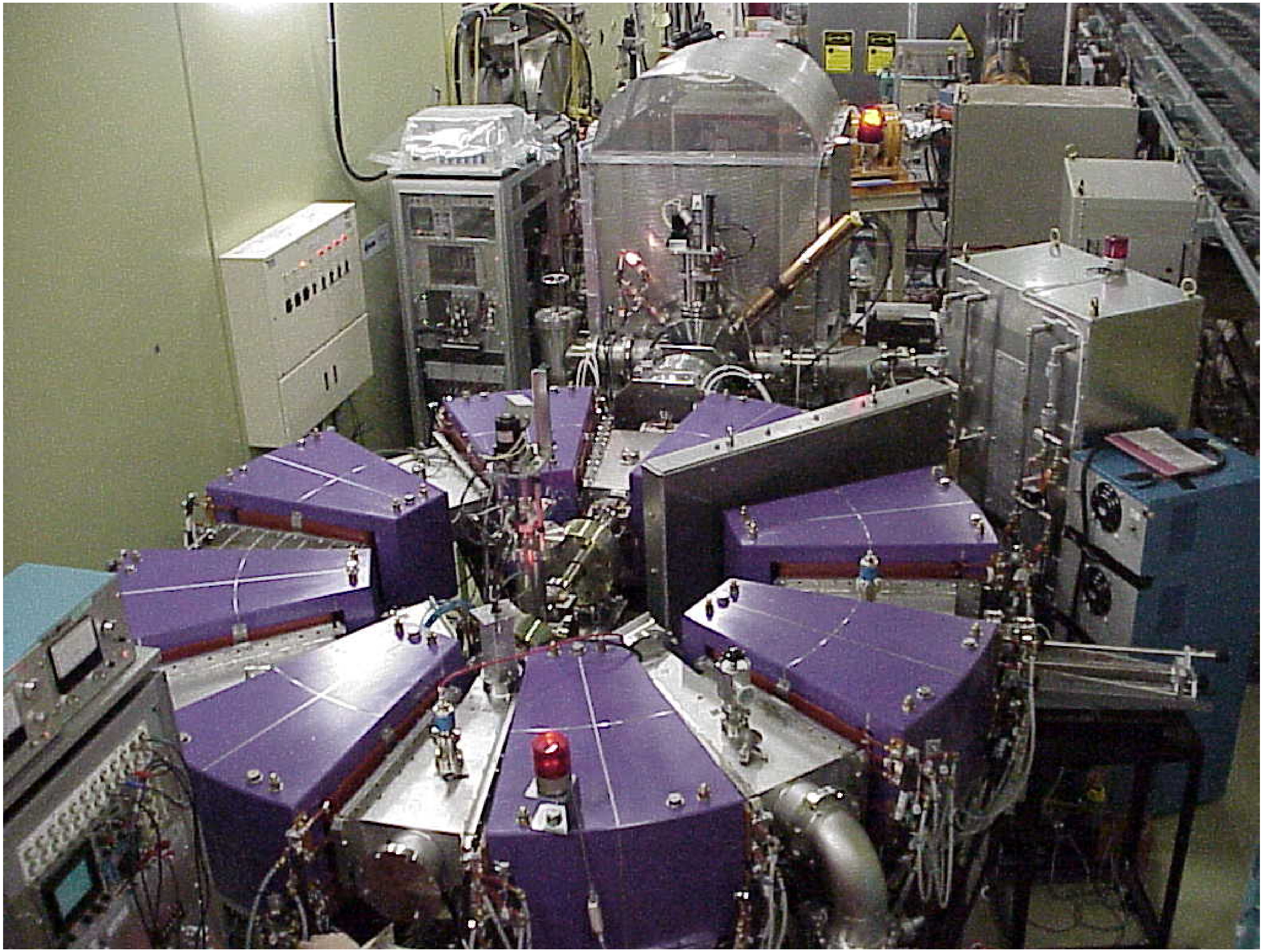


ASPUN (ANL, 1983) 1500 MeV x 4 mA

GENERAL	
NUMBER OF MAGNETS	20
SECTOR WIDTH	3.6°
FIELD INDEX, K	14
SPIRAL ANGLE	61°
ν_X	4.25
ν_Y	3.3
MAXIMUM REPETITION RATE	250 Hz
AVERAGE CURRENT	4 MA
SPACE CHARGE LIMIT	10^{14}
STACK ENERGY	1250 MEV
BUNCHES/STACK	6
RF FREQUENCY	2.11-3.09
	1.55-1.57
INJECTION	
E_{INJ}	200 MEV
$B\rho$	2.15 T-M
B	0.413 T
$\langle R \rangle_{INJ}$	25.88 M
ε_X	650 * MMMR
ε_Y	500 * MMMR
EXTRACTION	
E_{EXTR}	1500 MEV
$B\rho$	7.5067 T-M
B	1.327 T
$\langle R \rangle_{EXT}$	28.139 M

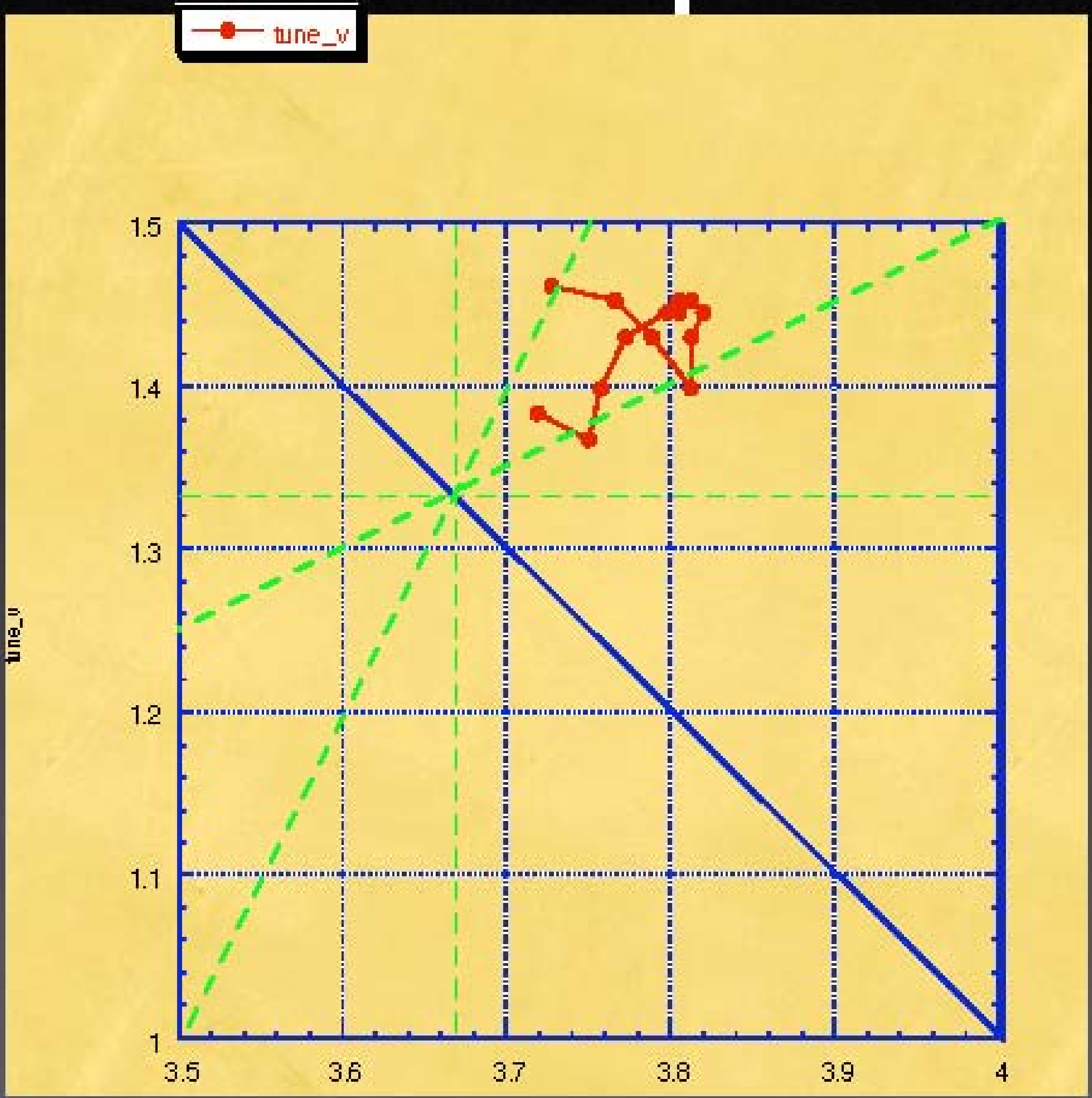


KEK Proof-of-Principle 1 MeV proton FFAG



KEK 150-MeV 12-Sector Proton FFAG

12-150MeV mode operation



criterion

1) Δ ν<0.1

2)avoid structure & linear resonaces

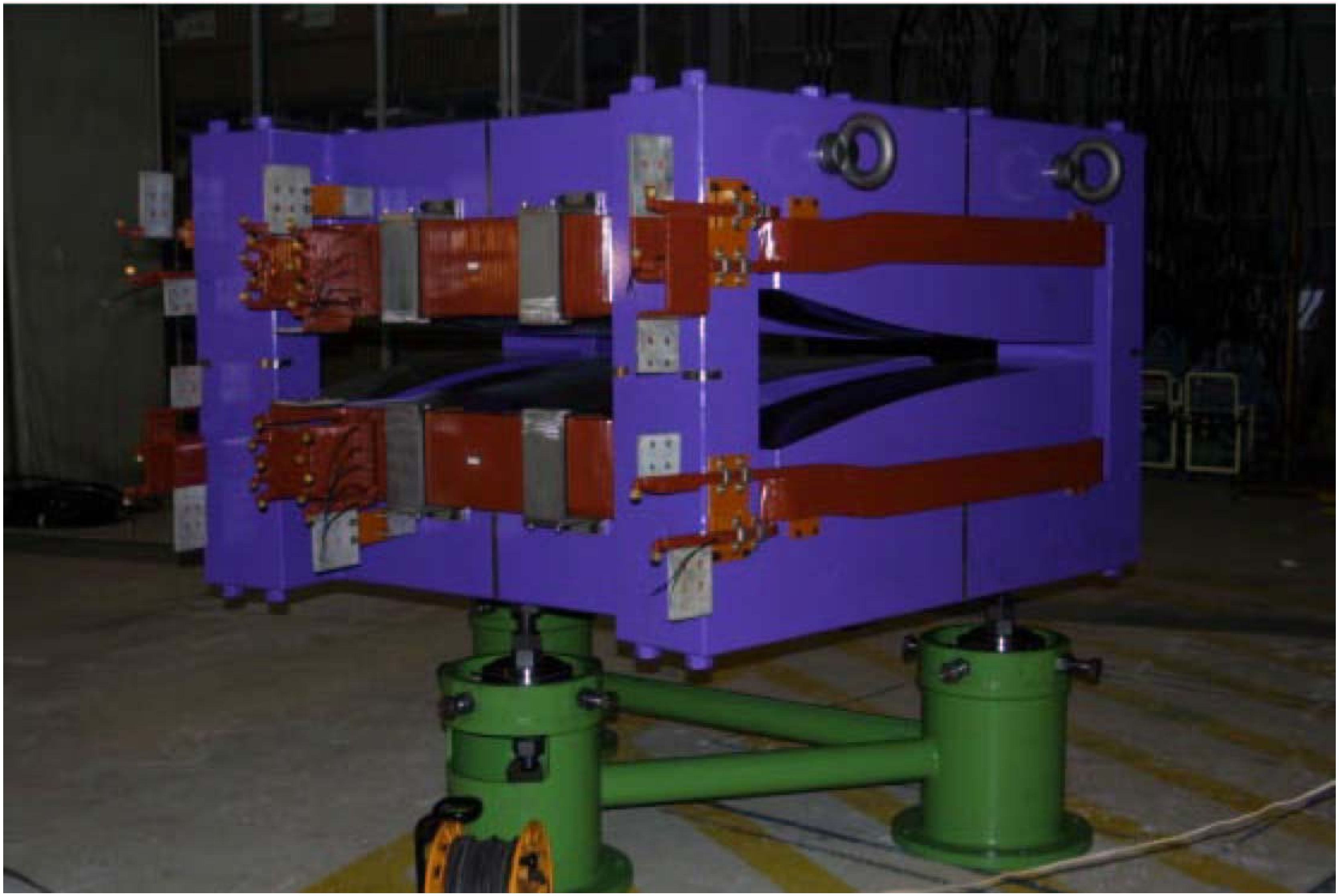
INNOVATIONS AT KEK

Mori's 1-MeV (2000) and 150-MeV **proton FFAGs** introduced two important innovations:

1. **FINEMET metallic alloy loading** in the rf cavities, allowing:
   - rf modulation at 250 Hz or more → high beam-pulse rep rates (remember the unreliable rotary capacitors on synchrocyclotrons, which operate in the same mode as FFAGs)
   - high permeability → short cavities with high effective fields
   - low Q (≅1) → broadband operation

2. **DFD triplet sector magnets:**
   - powered as a single unit
   - D acts as the return yoke, automatically providing reverse field
   - modern techniques enable accurate computation of the pole shape for constant field index *k*

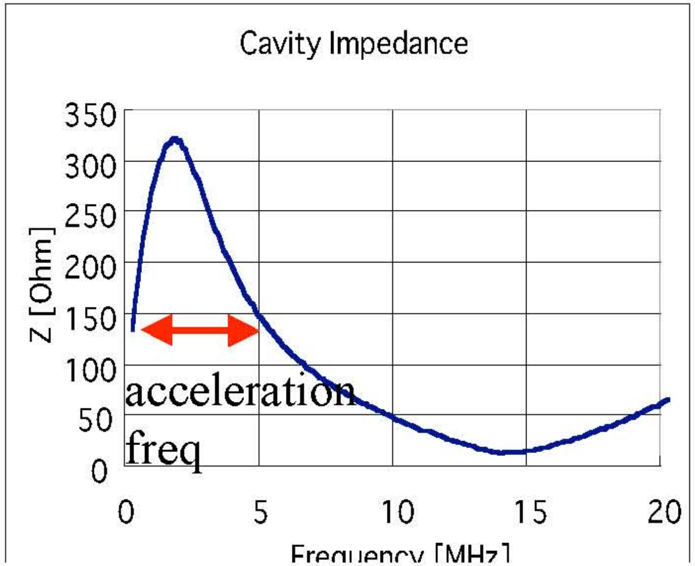
"Return-yoke-less" DFD Triplet for 150-MeV FFAG



RF system

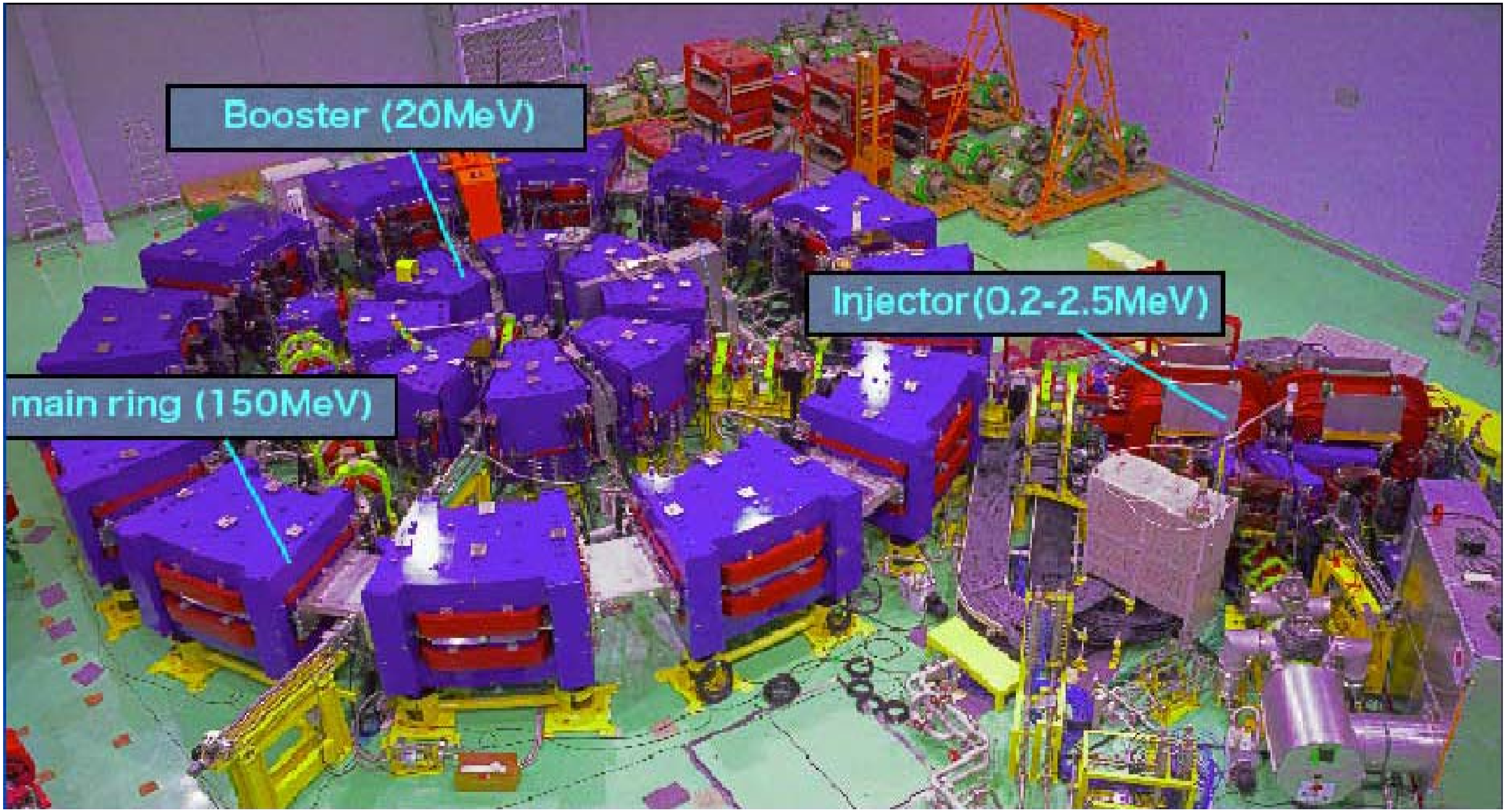
Large Magnetic Alloy (FINEMET) Cavity

Number of core	4 pieces
Outer (Inner) size	1700x950mm(980x230mm)
Core thickness	25mm
RF frequency	1.5 – 4.6 MHz
RF voltage	9kV
RF output	55kW
Power density	1W/cm3
Cooling water	70 L/min



Measured Impedance

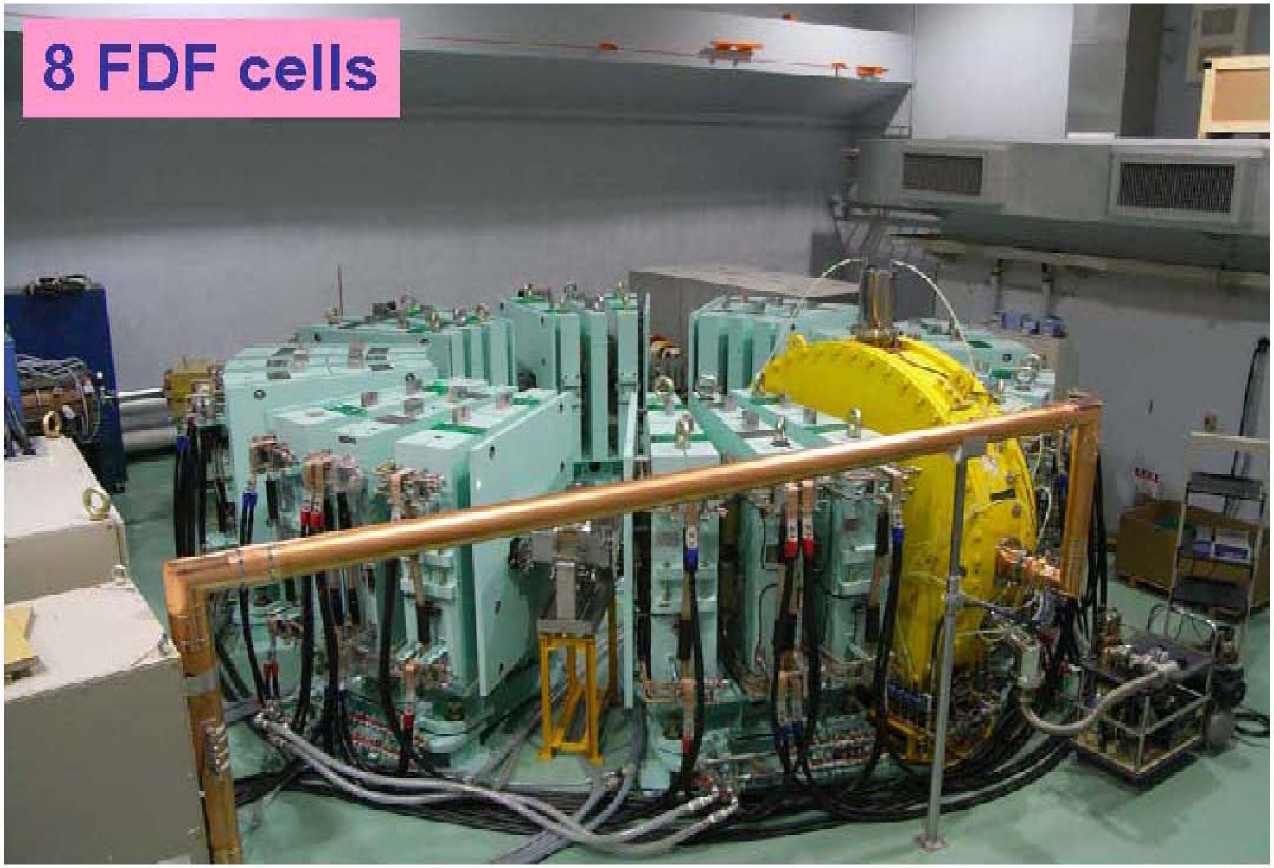
FFAG Complex at Kyoto University Research Reactor Inst.



- to test Accelerator-Driven Sub-critical Reactor (ADSR) operation

KURRI ERIT STORAGE RING FOR BNCT

(ERIT = Energy/Emittance Recovery Internal Target)



70-mA of circulating 11-MeV protons produce an intense neutron beam (>$10^9/cm^2/s$ at the patient) via the Be(p,n) reaction.

V_{rf} = 250 kV plus large FFAG acceptances (>3000 mm-mrad, ±5% $\delta p/p$) allow ionization cooling to maintain stable beam over 1000 turns.

α–PARTICLE TEST RING FOR PRISM AT RCNP OSAKA

Using 6 of the PRISM storage ring's 10 sectors
to demonstrate bunch rotation in phase space

SCALING FFAGs

- IN OPERATION OR UNDER CONSTRUCTION -

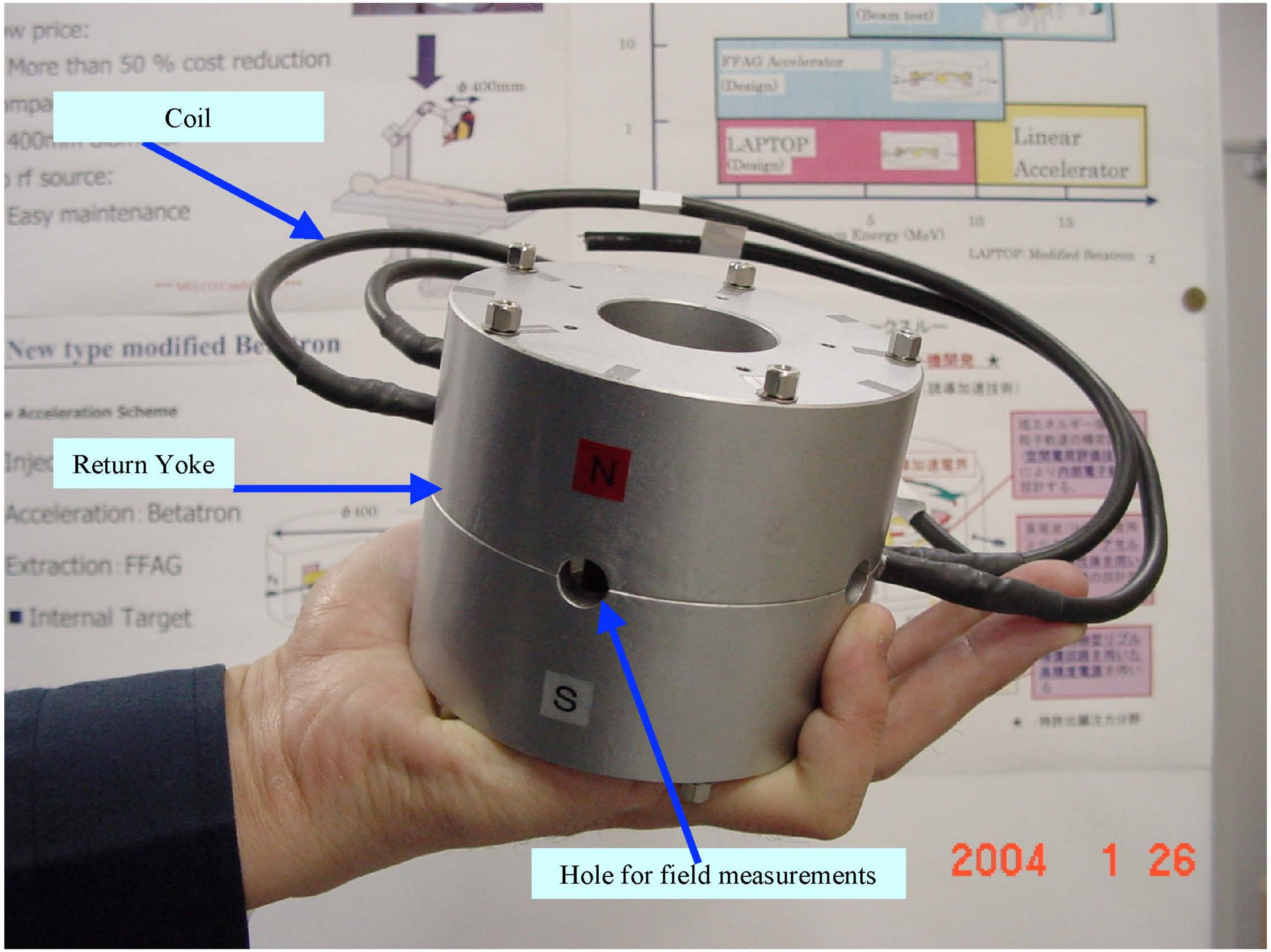
	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	1st beam
KEK - POP	1	p	8	0°	0.8-1.1	2000
KEK	150	p	12	0°	4.5-5.2	2003
KURRI - ADSR	150	p	12	0°	4.5-5.1	2006
(Accelerator-Driven	20	p	8	0°	1.3-1.9	2006
Subcritical Reactor)	2.5	p	8	40°	0.6-1.0	2008
KURRI-ERIT (BNCT)	11	p	8	0°	2.35	2008
PRISM study	0.8	α	6	0°	3.3	2008
PRISM*	20	μ	10	0°	6.5	
NHV	0.5	e	6	30°	0.19-0.44	2008
RadiaBeam Radiatron	5	e	12	0°	0.3-0.7	(2009)

* storage ring for μ bunch rotation in phase space

SCALING FFAGs - DESIGN STUDIES

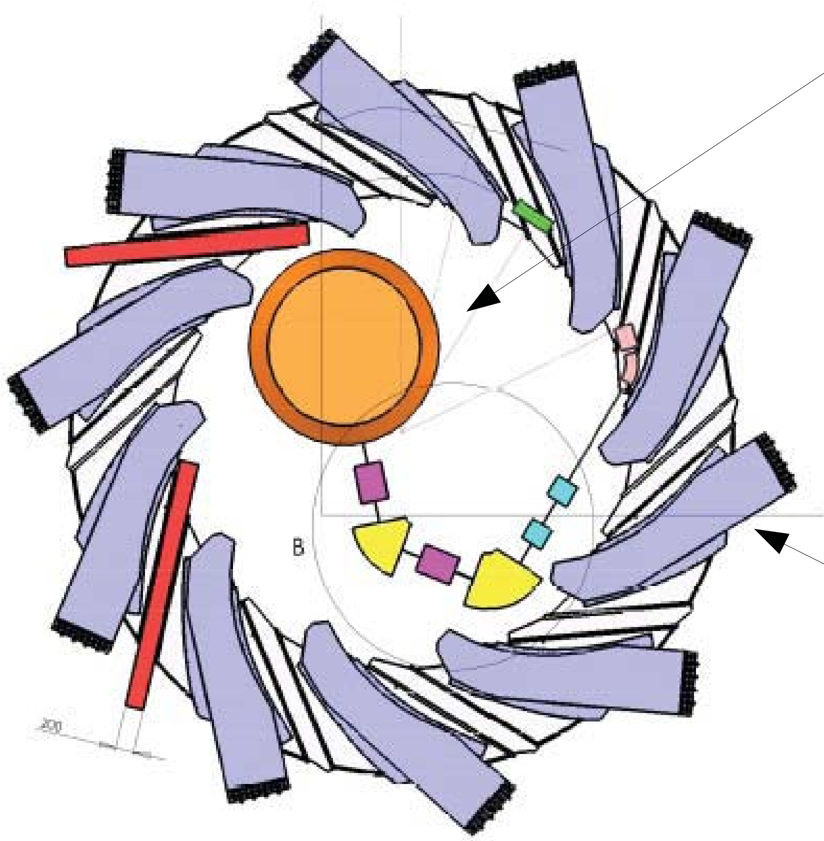
	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Rep rate (Hz)	Comments
MElCo - Laptop	1	e	5	35°	.023 -.028	1,000	Hybrid - Magnet built
eFFAG	10	e	8	47°	0.26 - 1.0	5,000	20-100 mA
LPSC RACCAM	180	p	10	54°	3.2 - 3.9	>20	Magnet sector 2008
Ibaraki Med.Acc.	230	p	8	50°	2.2 - 4.1	20	0.1 μA
MElCo - p Therapy	230	p	3	0°-60°	0 - 0.7	2,000	SC, Quasi-isochronous
MElCo - Ion Therapy	400	C^{6+}	16	64°	7.0 - 7.5	0.5	Hybrid (FFAG/synch^n)
(Mitsubishi Electric)	7	C^{4+}	8	0°	1.35 - 1.8	0.5	" " " "
NIRS Chiba	400	C^{6+}	12	0°	10.1 - 10.8	200	Compact
- Hadron	100	"	12	0°	5.9 - 6.7	"	radial
Therapy	7	C^{4+}	10	0°	2.1 - 2.9	"	sectors
Mu Cooling Ring	160	μ	12	0°	0.95 ± 0.08		Gas-filled
J-PARC	20,000	μ	120	0°	200		Δr = 0.5 m, ~10 turns.
Neutrino	10,000	"	64	0°	90		
Factory	3,000	"	32	0°	30		Q≈1 rf cavities allow
Accelerators	1,000	"	16	0°	10		broadband operation

Spiral Magnet



The present study is partially supported by the REIMEI Research Resources of Japan Atomic Energy Research Institute.

Principle of Energy Variability for RACCAM System



Variable extraction energy from
Injector – H^- cyclotron
(AIMA),
5.5-17 MeV

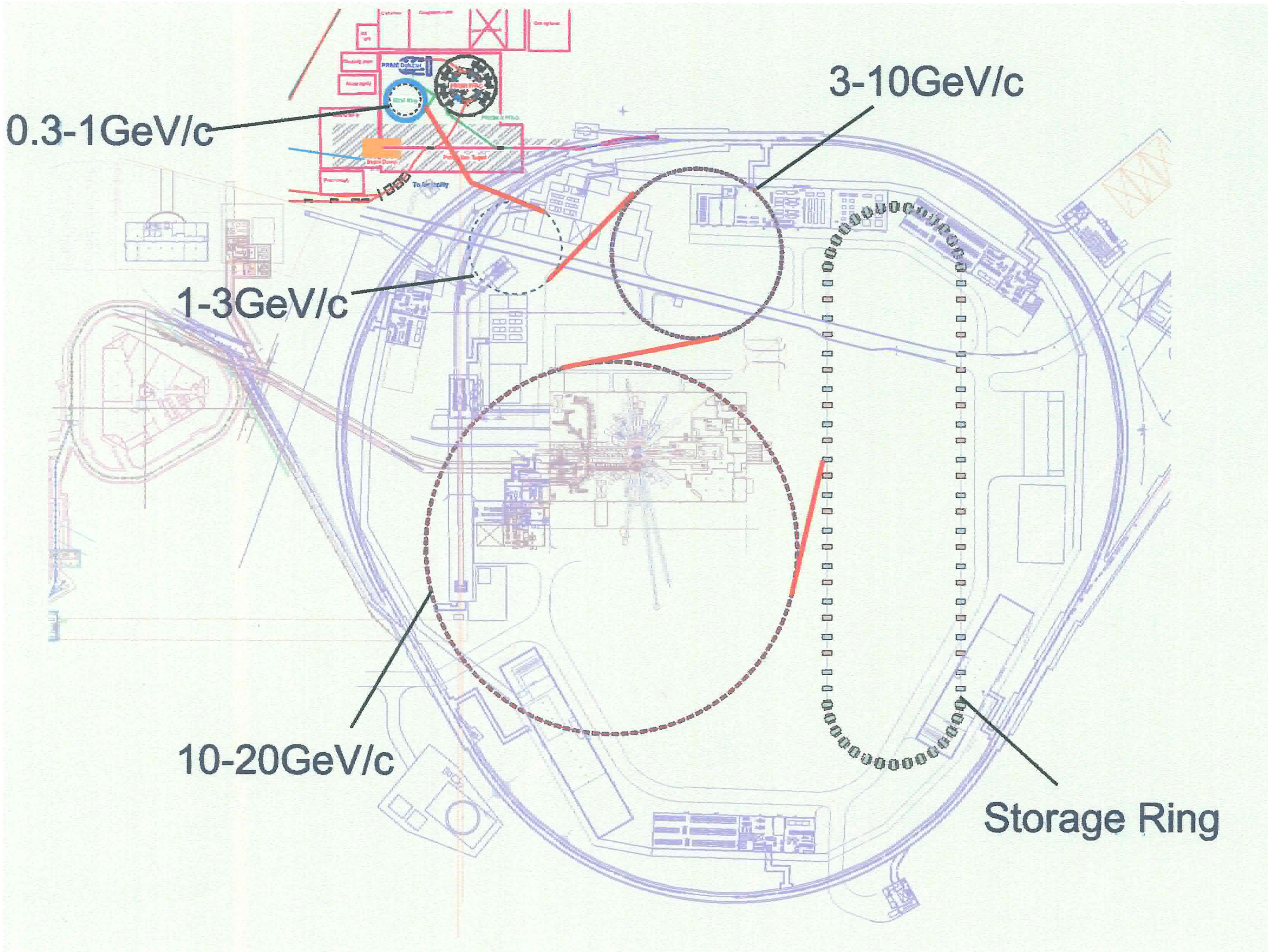
Allows variable extraction energy from
FFAG, 70-180 MeV,
i.e., 4 to 21 cm Bragg pic penetration

by varying FFAG rigidity

+

extraction kick
synchronised on turn #

Neutrino Factory : FFAG based



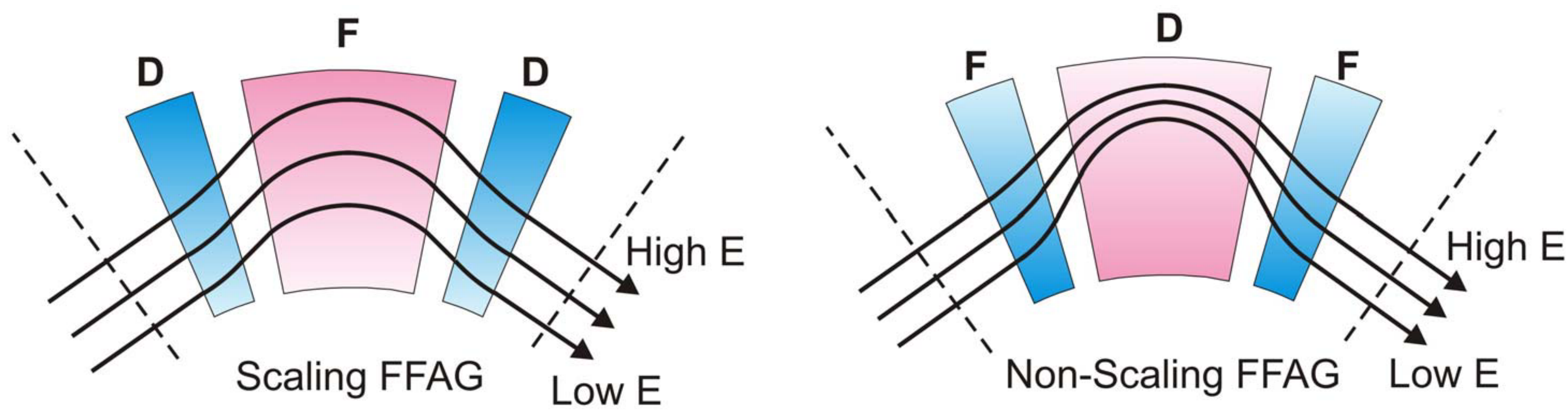
LINEAR NON-SCALING (LNS) FFAGs

FFAGs look attractive for accelerating muons in μ Colliders or ν Factories

- Large acceptance (in *r* & *p*) eliminates cooling & phase rotation stages
- Rapid acceleration (<20 turns) makes resonance crossing ignorable (Mills '97)
- Less expensive than recirculating linacs.

NON-SCALING approach first tried by Carol Johnstone (arc 1997, ring 1999)

- strong positive-bending Ds + negative Fs – i.e. negative field gradients!
- "LINEAR" constant-gradient magnets.



This leads to:

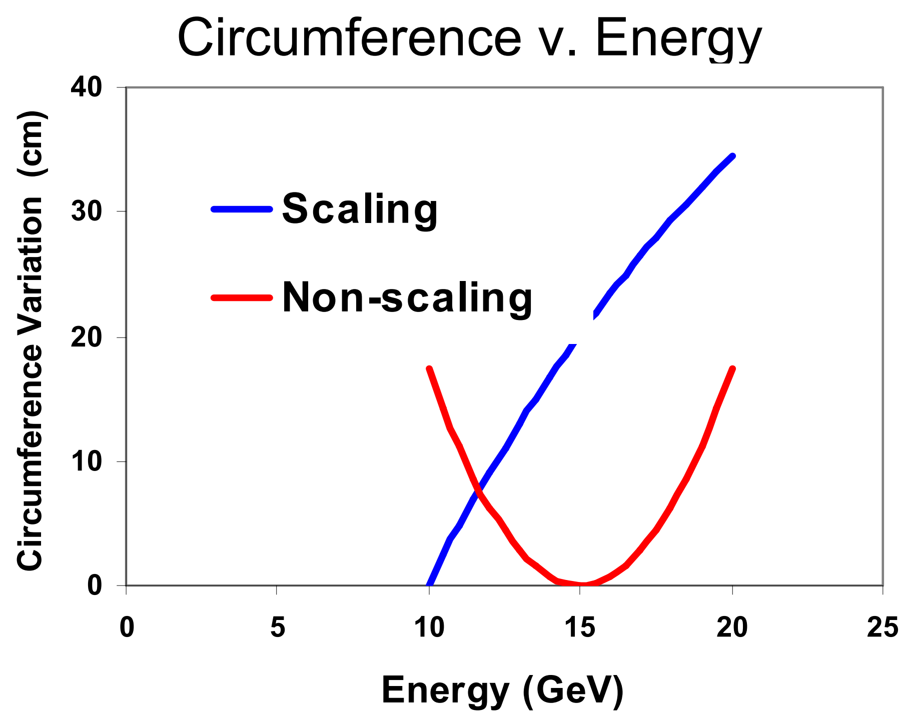
- Greater momentum compaction (& hence narrower radial apertures);
- No multipole field components to drive betatron resonances >1st order;
- Simpler construction ($B \propto r$ rather than r^k).

SCALING v. LINEAR NON-SCALING FFAGs

Note that for LNS-FFAGs, orbit circumference C varies quadratically with energy rather than rising monotonically:

$$C(p) = C(p_m) + \frac{12\pi^2}{e^2 q^2 N L_{FD}} (p - p_m)^2$$

So less variation in C and orbit period, enabling fixed rf frequency operation when $v \approx c$.

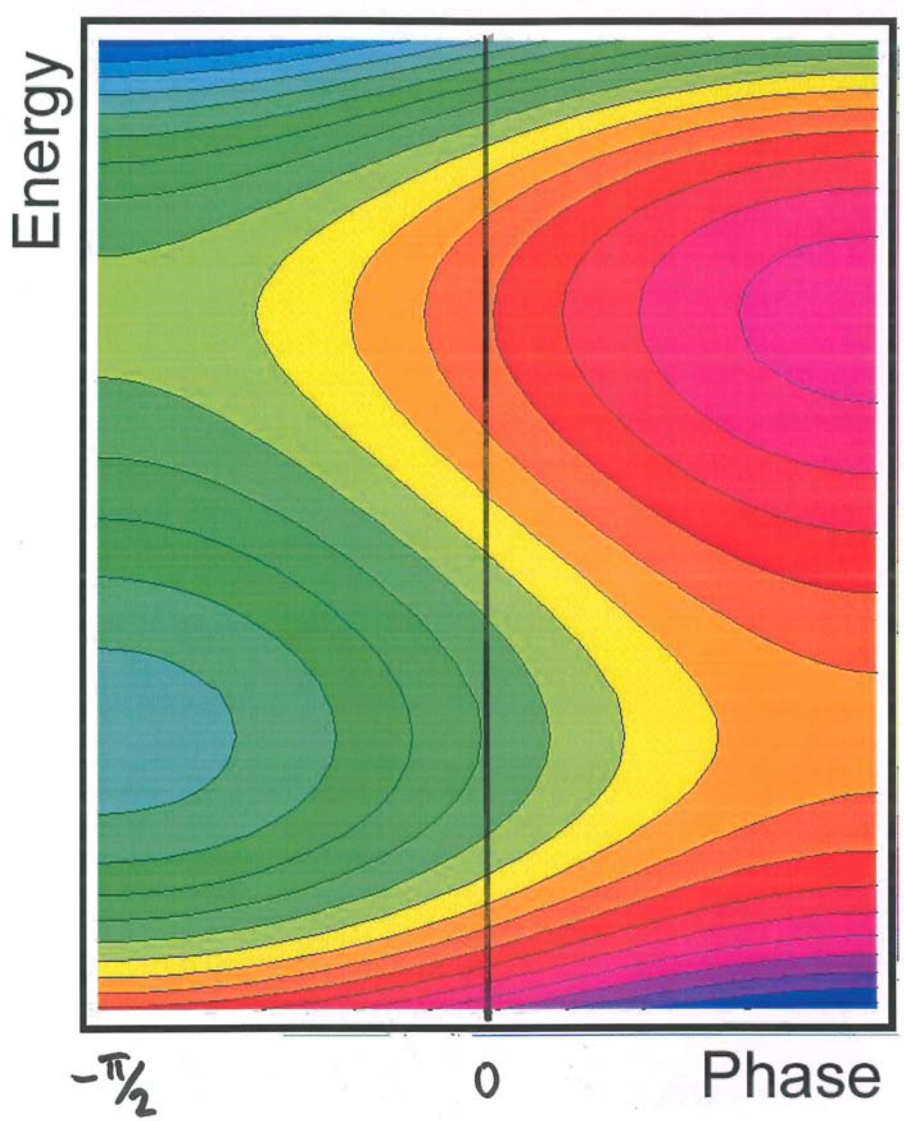


- The muons oscillate in phase across the rf voltage peak (3 crossings)
  - just as in a real, imperfectly isochronous, cyclotron!

The International Design Study for a Neutrino Factory chose LNS-FFAGs of 12.6-25 GeV and 25-50 GeV for the final stages of muon acceleration - with designs developed by a consortium led by Johnstone (FNAL), Berg (BNL), and Koscielniak (TRIUMF).

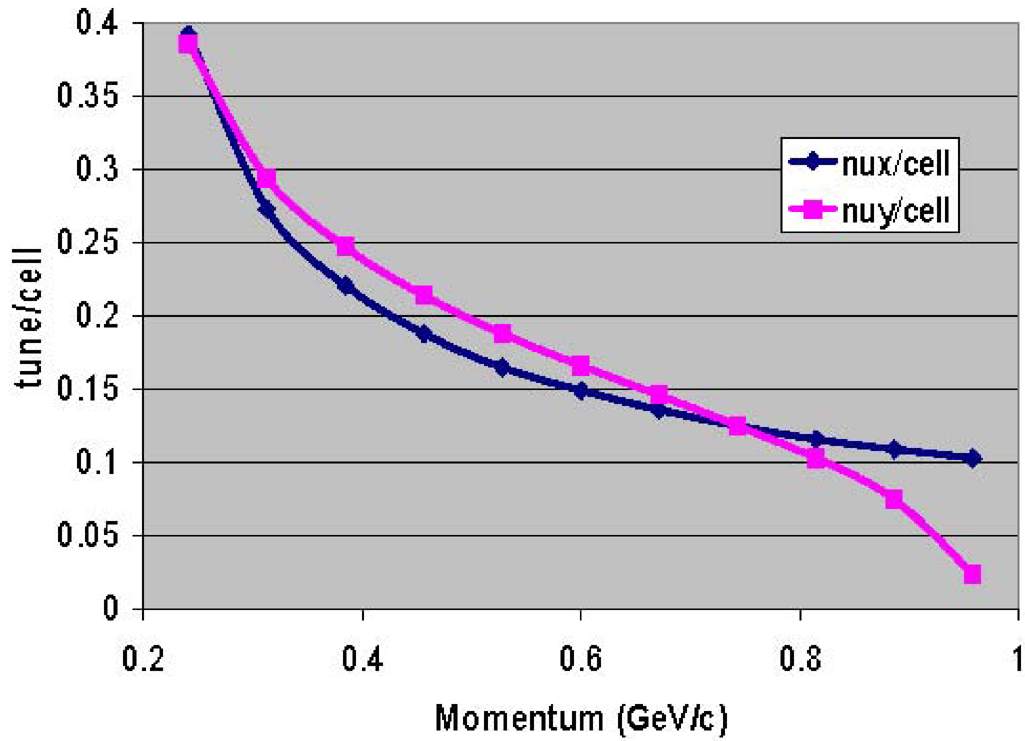
Non-linear NS-FFAGs are also being explored.

SERPENTINE ACCELERATION IN LNS-FFAGs



- Not within the buckets – but between them
- Follow the golden trail!

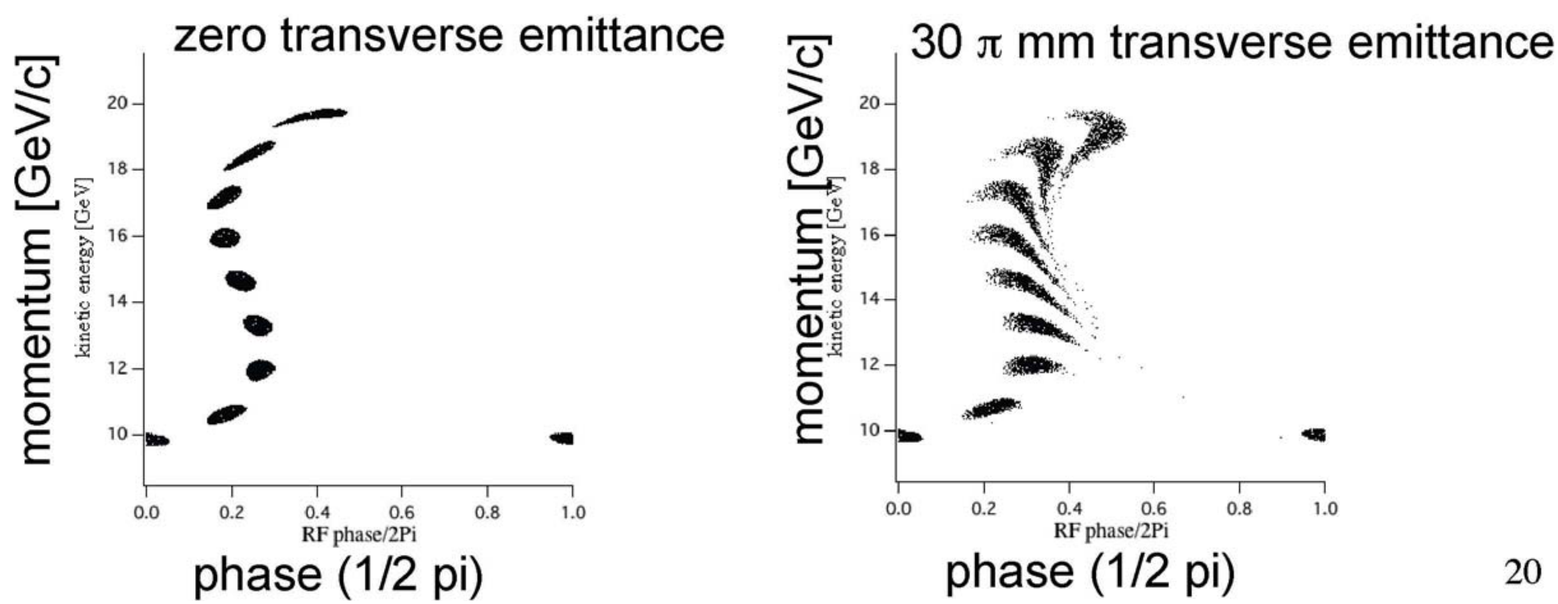
TUNES IN LNS-FFAGs



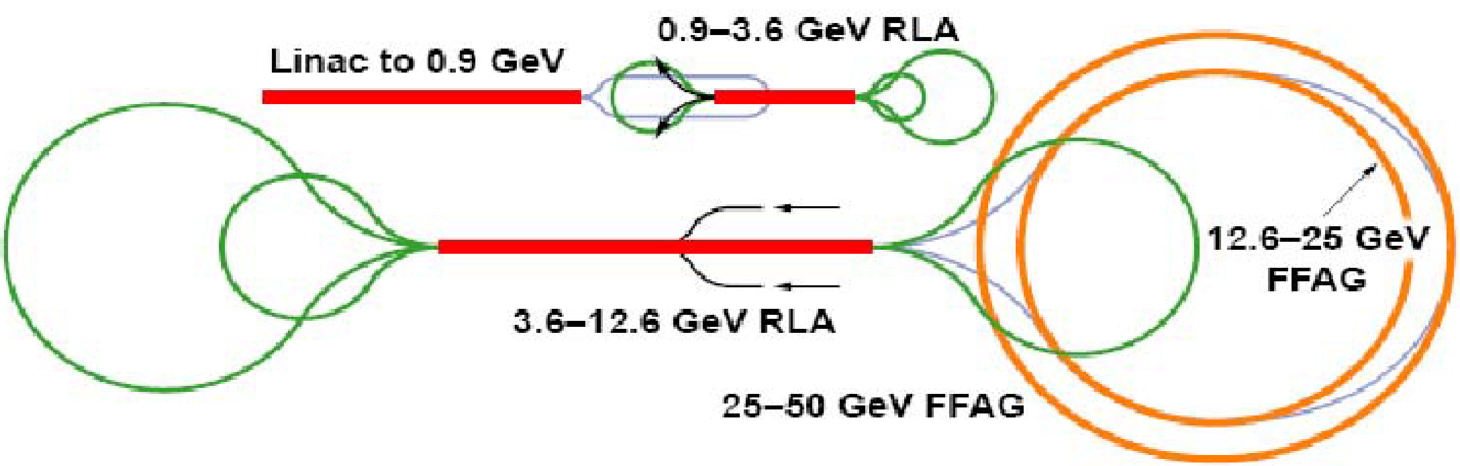
If the orbits cross the magnet ends perpendicularly:

- the tunes fall sharply with energy, crossing betatron resonances
- possibly leading to loss of beam quality/quantity
- danger lessened by rapid energy gain, but very expensive
- for muons (τ = 2 μs): expensive but essential anyhow
- for ions: just expensive

MATCHING LNS-FFAGs



Unfortunately, for large-emittance beams, the radial longitudinal coupling in LNS-FFAGs makes transfer matching difficult. Mitigation techniques exist, but the ν Factory ISS concluded that >2 LNS-FFAGs would not be practical – and opted for the more costly recirculating linacs below 12.6 GeV.



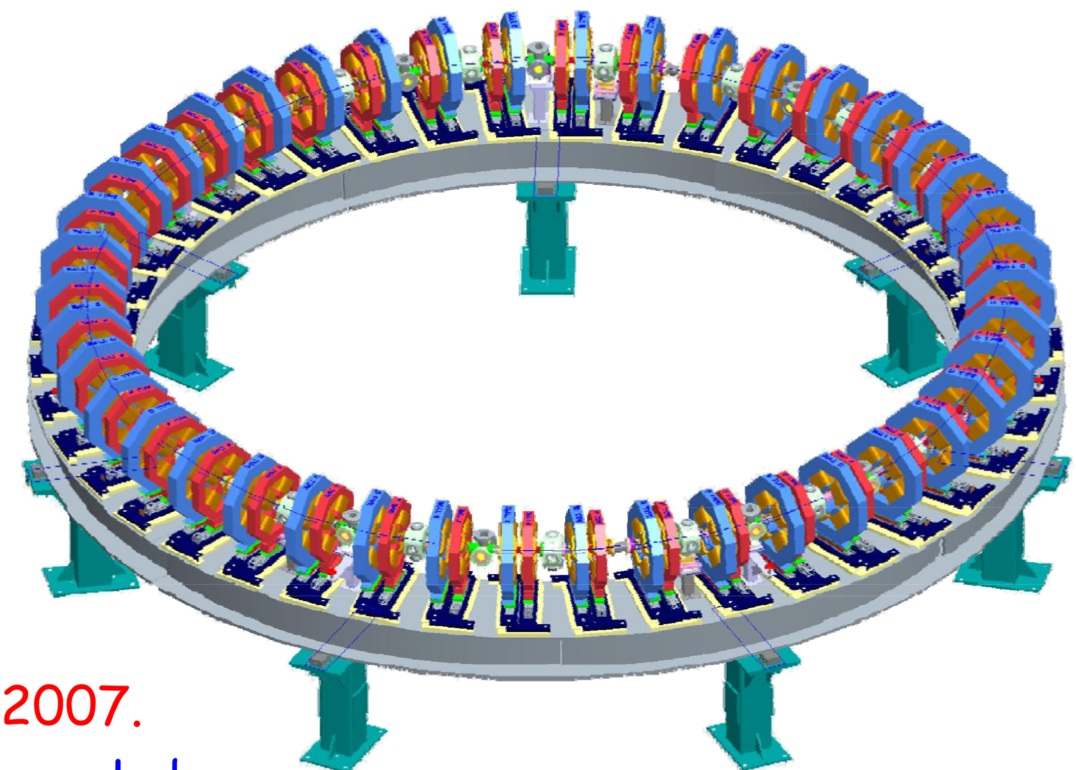
ELECTRON MODEL LNS-FFAG "EMMA"

A Proof of Principle machine for linear non-scaling FFAGs to demonstrate their two novel features:

- safe passage through many low-order structural resonances
- acceleration outside buckets.

EMMA has relativistic parameters similar to those of a 10-20 GeV muon FFAG, with a doublet lattice based on offset quadrupoles:

Energy	10-20 MeV
Circumference	16.57 m
Cells	42
N.T. Acceptance	3 mm
F quad length	5.88 cm
D quad length	7.57 cm
RF frequency	1.3 GHz
Cavities	19 x 120 kV
Injector	ALICE (7-35 MeV)



UK funding ($16M) started April 2007.
Construction under way at Daresbury Lab.

NON-SCALING LATTICES FOR HADRONS

To accelerate hadrons, where $v \ll c$, the wider range of speeds and orbit times τ requires either:

- frequency modulation, or broadband operation,
  - both requiring pulsed beam operation, or
- harmonic number jumping (HNJ) – as in microtrons
  - where the energy gain is adjusted to give $\Delta\tau$ = -integer × τ_{rf}
  - allowing cw fixed-frequency operation and higher beam intensity
  - but requiring precise variation of rf cavity voltage with radius.

With the small radial orbit spread, variable-energy extraction can be realized by timing the kicker pulse, even with fixed kicker and septum.

Three groups are actively designing NS-FFAGs for cancer treatment:

1. Keil (CERN), Trbojevic (BNL) and Sessler (LBNL)
2. Johnstone (FNAL) and Koscielniak (TRIUMF)
3. Yokoi, Peach et al. (Adams Inst.) and Machida (RAL).

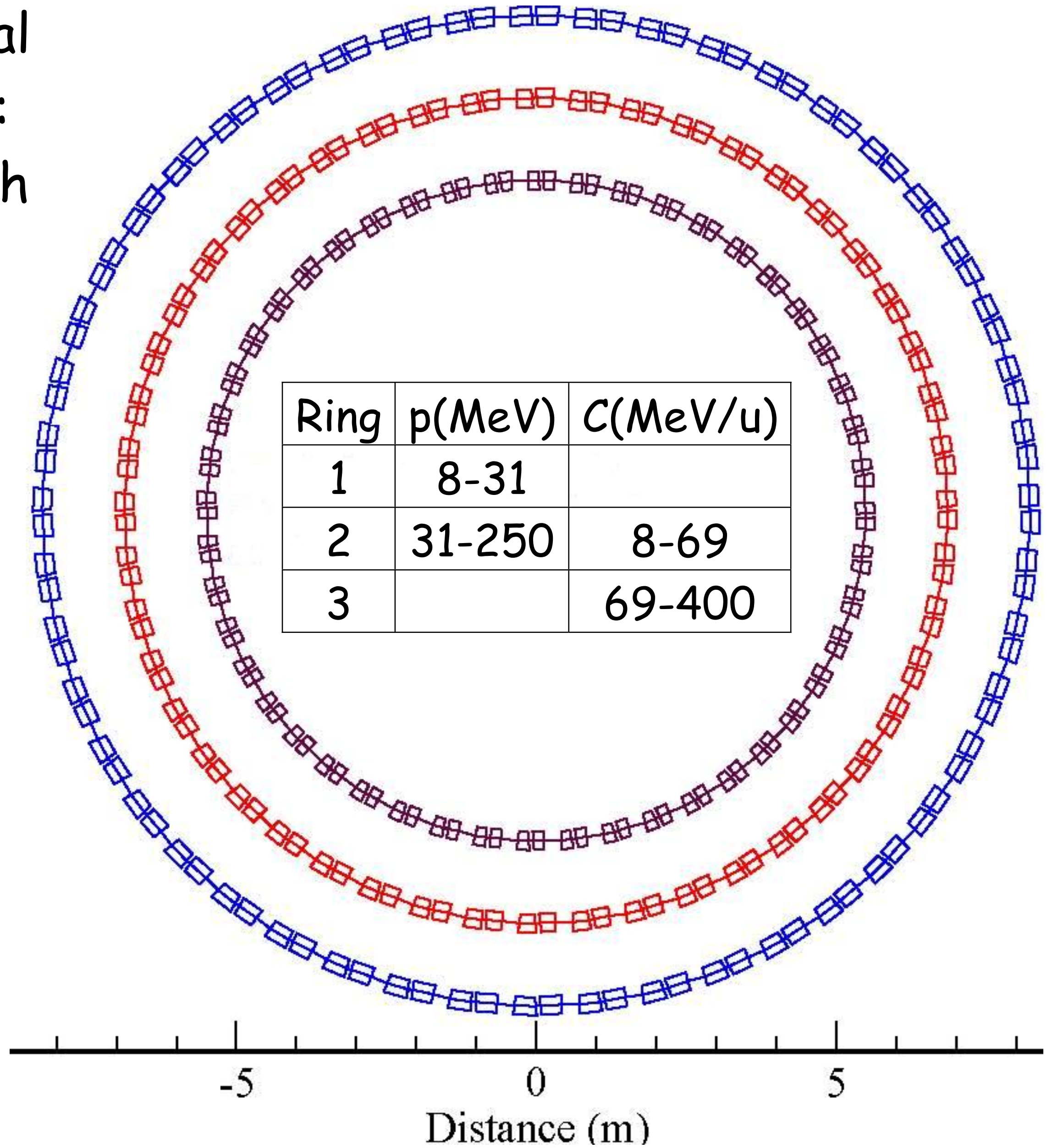
Keil-Sessler-Trbojevic LNS-FFAG Therapy Complex

The first LNS-FFAG proposal for ion beam cancer therapy:
- three concentric rings, each of 48 doublet cells.

The tunes fall with energy, crossing several n & n/2 imperfection resonances - but no intrinsic resonances below 3rd order – so good beam quality is maintained.

RF is frequency-modulated (in the range 9-25 MHz).

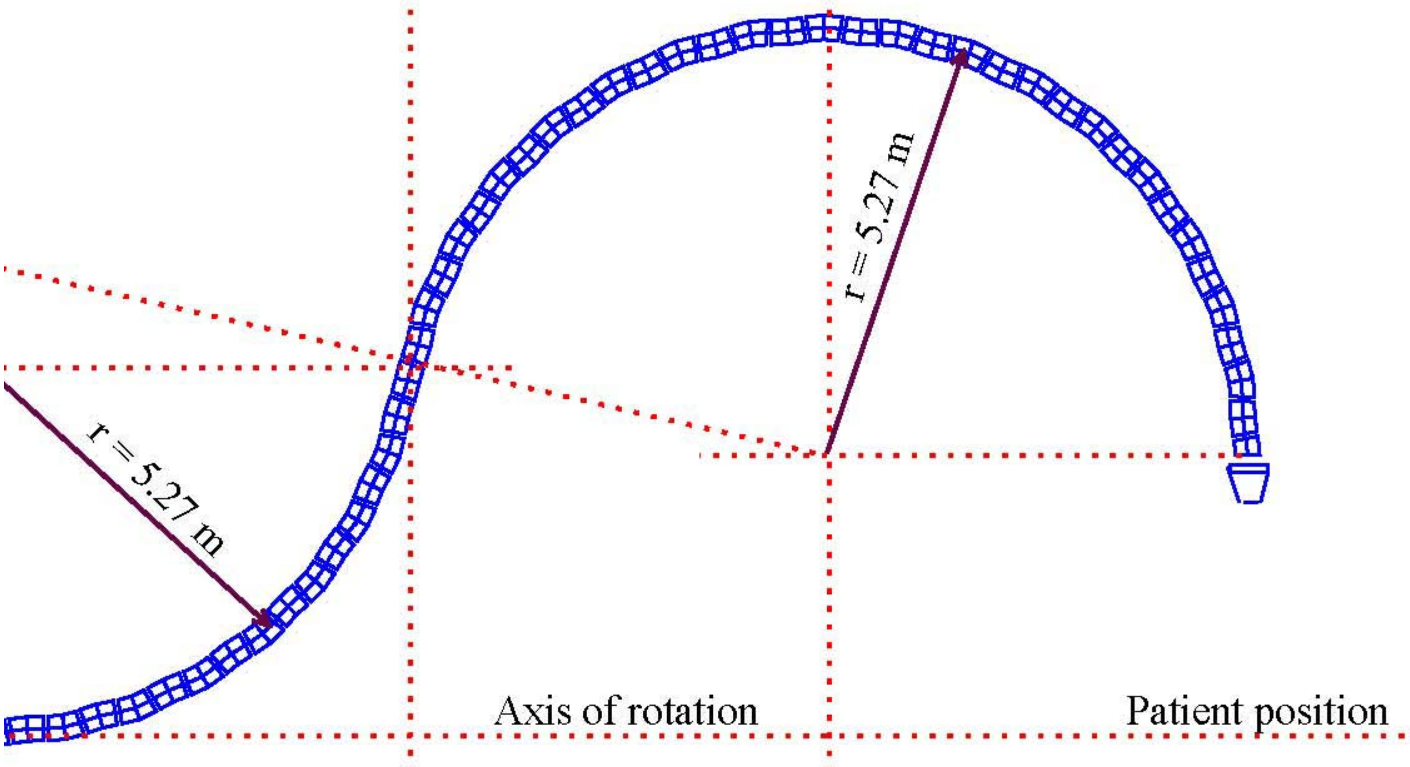
Note the small magnets (cf. NIRS 3-ring S-FFAG).



Ring	p(MeV)	C(MeV/u)
1	8-31	
2	31-250	8-69
3		69-400

Keil-Sessler-Trbojevic Lightweight FFAG Gantry

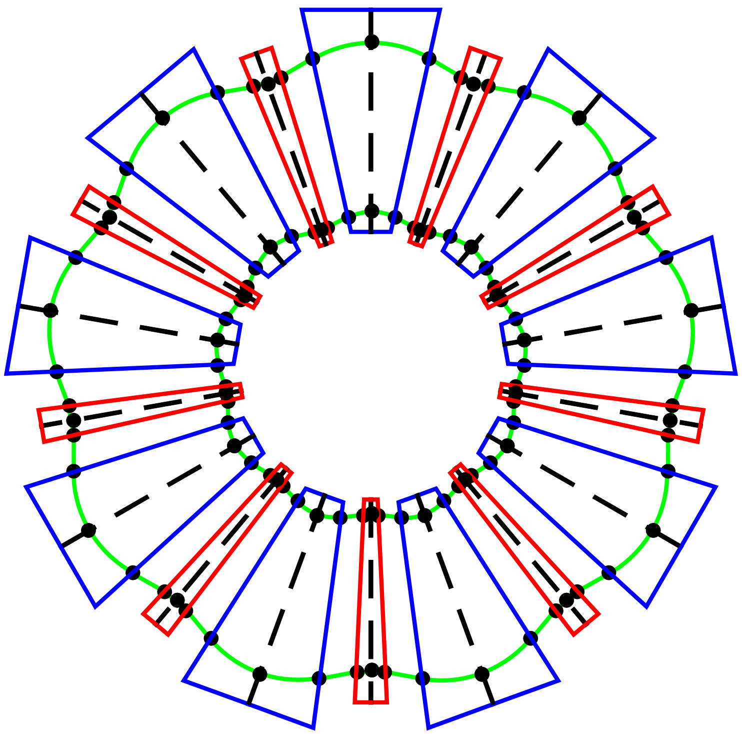
This group has also proposed a lightweight LNS-FFAG gantry, composed of superconducting magnets (either high-temperature or cryogenic) in a close-packed triplet lattice.



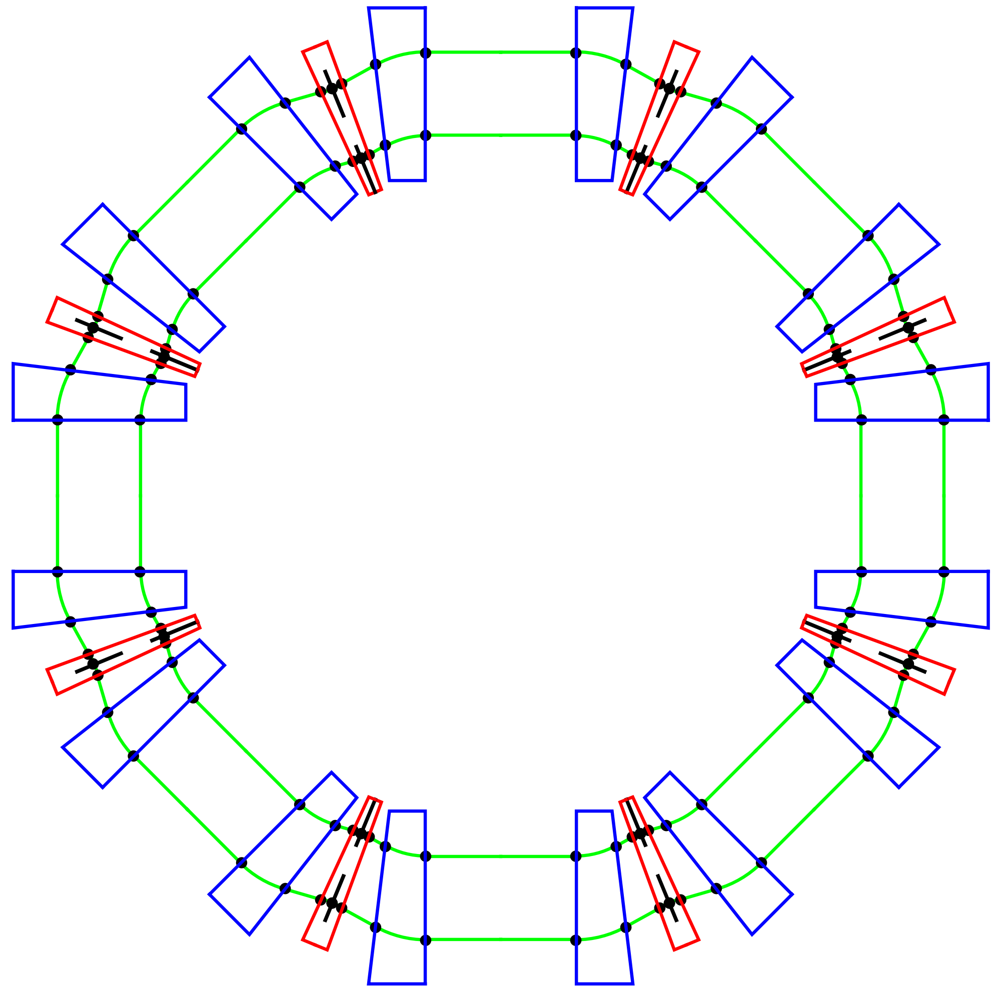
The acceptance is large enough to transmit C^{6+} ions of 150-400 MeV/u at one excitation, and protons of 90-250 MeV at another.

Johnstone-Koscielniak Tune Stabilized NLNS-FFAGs (1)

Two designs are being considered for 30-250 MeV protons
- roughly to scale



9-cell F0D0
Orbit radii 1.98-2.49 m

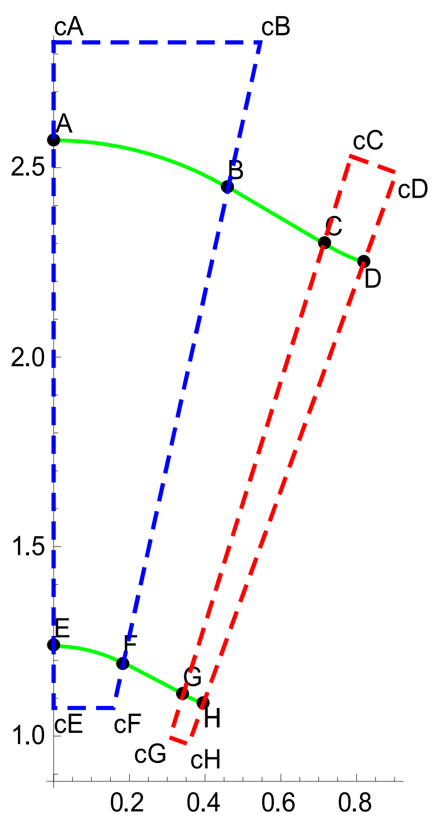


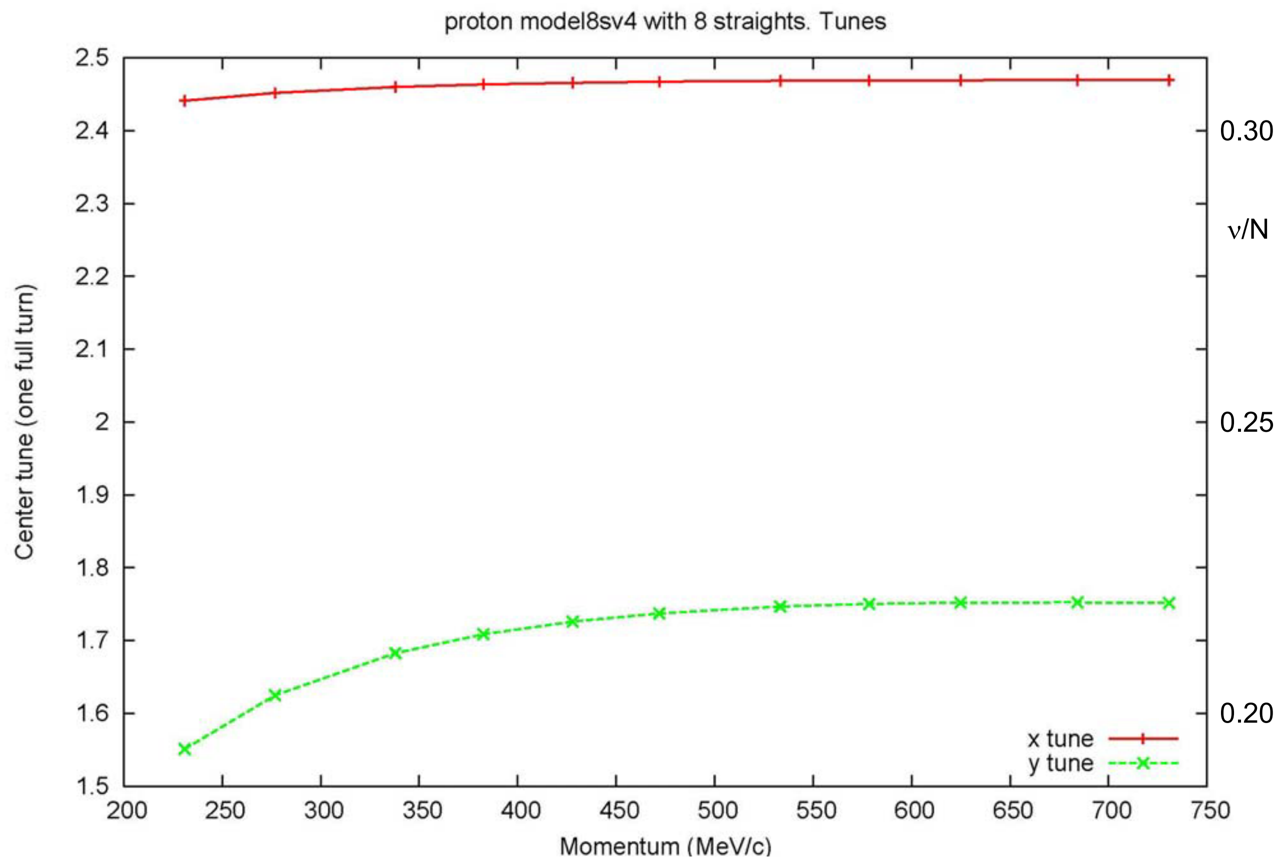
8-cell FDF Orbit radii 2.75-3.39 m

Tune Stabilized NLNS-FFAGs (2)

Tune drop-off with energy is avoided by:

- employing the "edge focusing" that occurs for non-perpendicular magnet entry/exit
- allowing a non-linear B(r) field variation





Nearly flat tunes are obtained, with large dynamic apertures.

PAMELA (Adams Inst. – Yokoi, Machida, Peach, *et al.*)

31 - 250 MeV protons

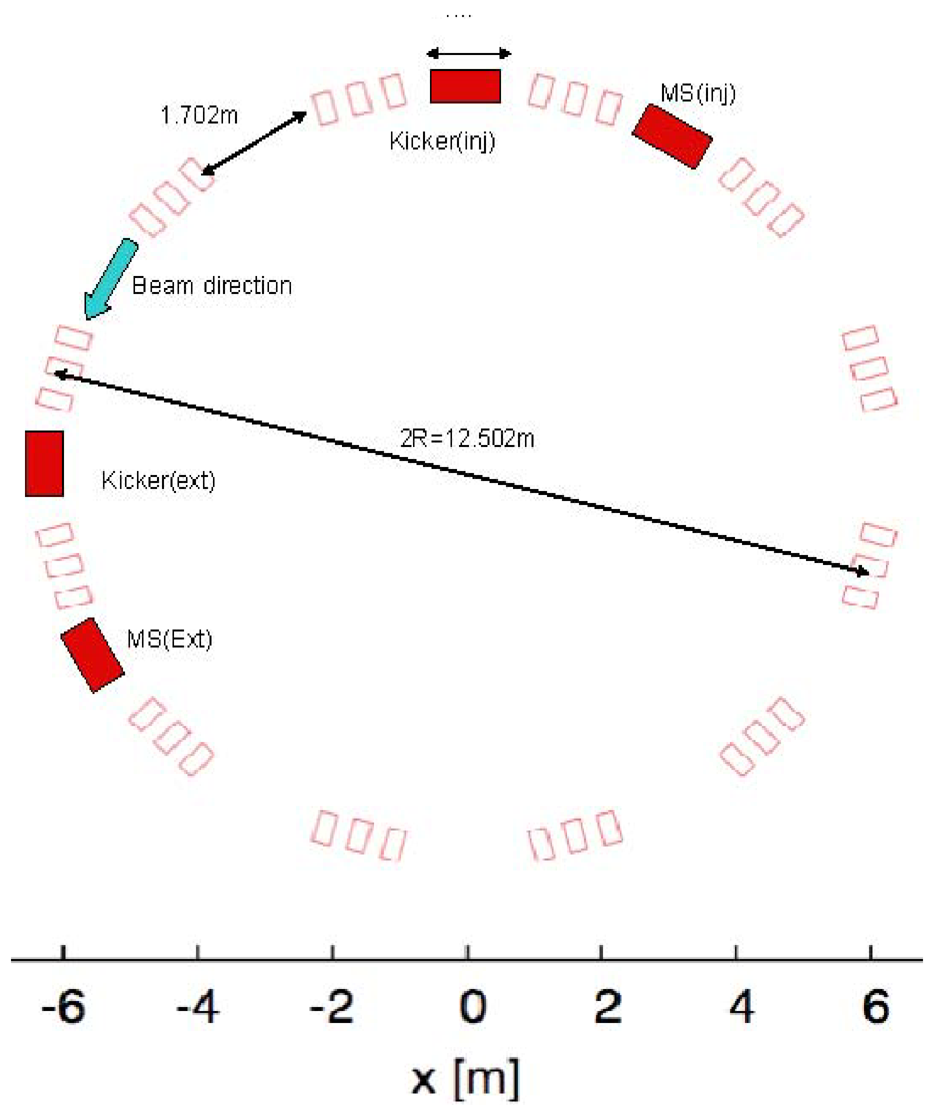
12-cell FDF

Radius ≈ 6.25 m

4-T magnets

Machida semi-scaling lattice

- High field index k (i.e. $B \sim r^k$) for small orbit excursions
- approximate r^k locally by $\Sigma b_n x^n$ with n = 0, 1, 2, 3 only
- flat tunes, good dynamic aperture



400-MeV/u C^+ version is being prepared

CURRENT FFAG CANCER THERAPY STUDIES

	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Pulse rep. rate (Hz)
SCALING						
KURRI: ERIT	11	p	8	0°	2.35	200
LPSC: RACCAM	17-180	p	10	54°	3.2-3.9	130
NON-SCALING						
Keil, Sessler & Trbojevic	8-31	p	48	0°	5.49-5.52	≤1000
	31-250 / 8-69	p / C^{6+}	48	0°	6.86-6.95	≤1000
	69-400	C^{6+}	48	0°	8.23-8.32	≤1000
Trbojevic	28-250	p	24	0°	4.18-4.42	cw (HNJ)
Johnstone *et al.* FODO	30-250	p	9	0°	1.98-2.49	
Johnstone *et al.* FDF	30-250	p	8	0°	2.75-3.39	
PAMELA (Machida lattice)	30-250 / 7-450	p / C^{+}	12	0°	≈6.25	≤1000 or cw (HNJ)

LINEAR NON-SCALING LATTICES FOR HADRONS (3)

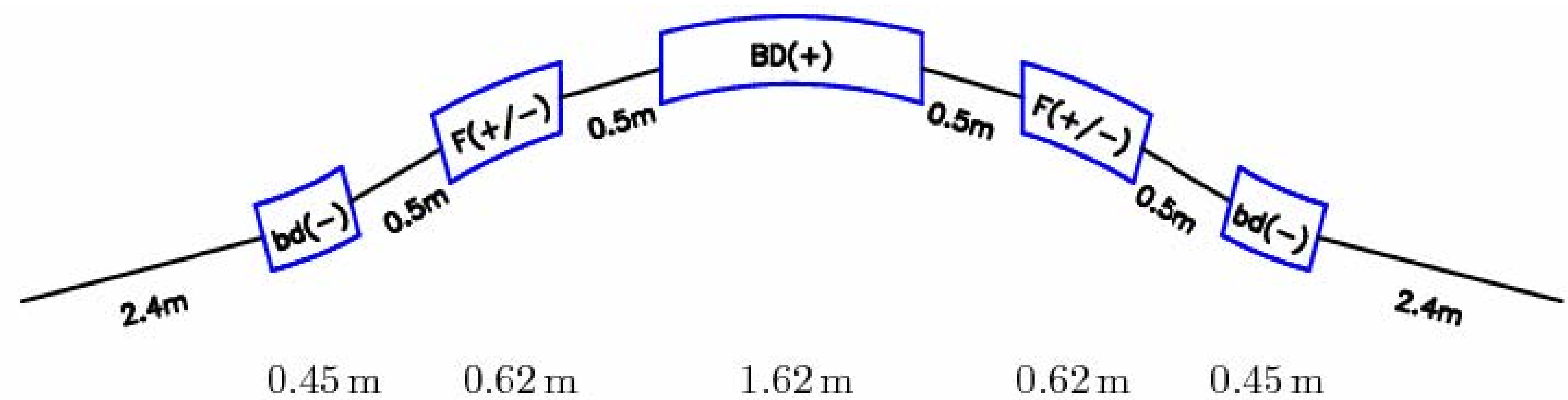
Sandro Ruggiero (BNL) has proposed a number of LNS-FFAGs using FDF triplet cells and HNJ as proton or heavy-ion drivers:

Project	Energy (GeV)	Cells	Circumf. (m)	No. of rings	Rep. rate (Hz)	Current (μA – avg.)	Power (MW – avg.)
AGS Booster replacement	0.4 – 1.5	136	807	1	2.5 - 5	33	0.05
Proton Driver I for ν Factory	0.4 -12	136	807	3	50	330	4
Proton Driver II for ν Factory	0.4 -12	136	807	3	cw	8,500	100
MINHA electron model	2-8 x 10^{-4}	48	18	Octant under construction			
Proton Driver for ADSR	0.05 – 1	80	204	2	1,000 – cw	10,000	10
U^{238} Driver for Radioactive Ions	0.015 - 0.4	80	204	2	1,000 - cw	4.2	0.4

Note that the same cell structure may be used for more than one application!

NON-LINEAR NON-SCALING LATTICES

G.H. Rees has designed several FFAGs using novel 5-magnet "pumplet" cells, in which variations in field gradient and sign enable each magnet's function to vary with radius – providing great flexibility – even allowing well-matched insertions!

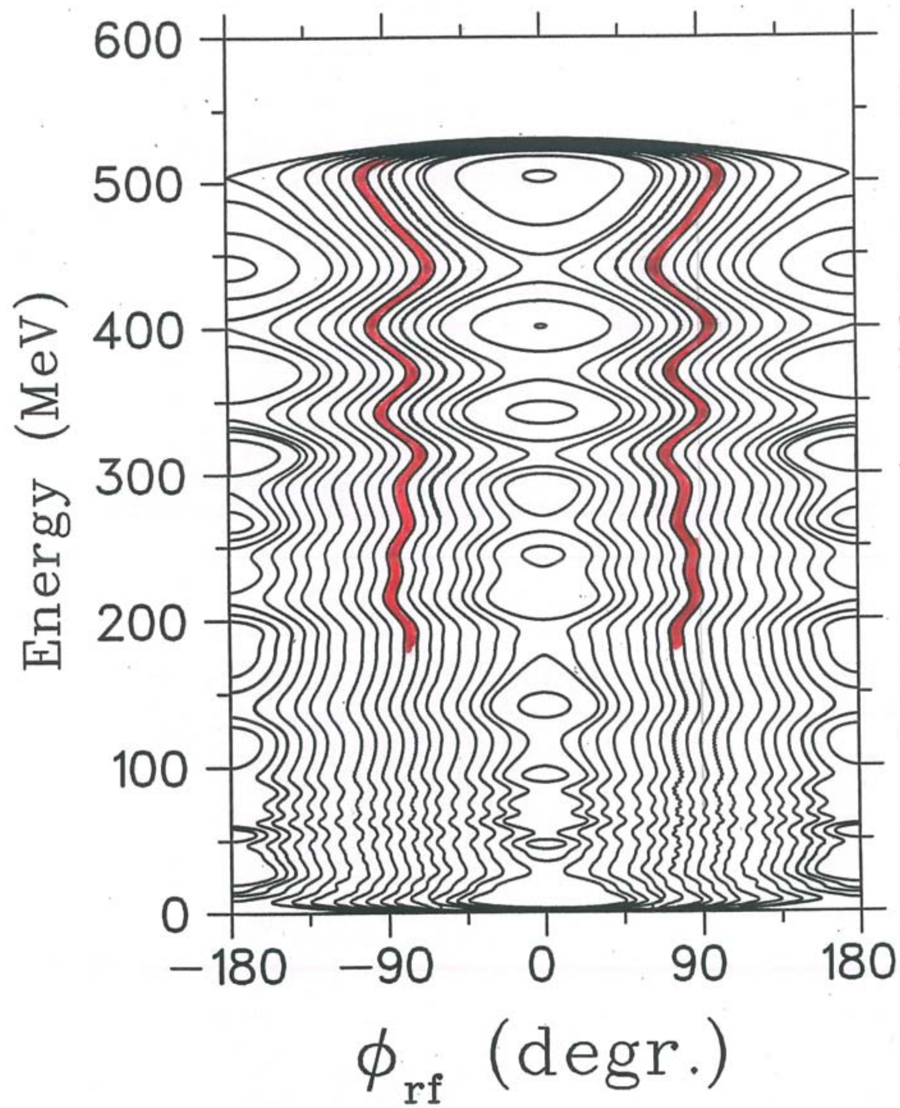


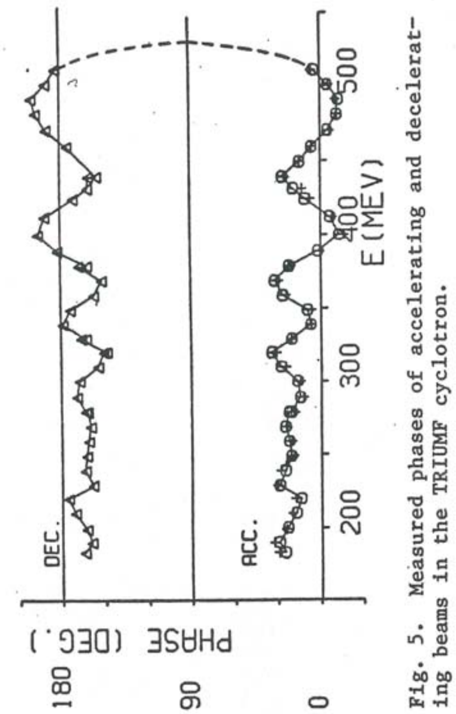
- an isochronous "IFFAG" for muons (8-20 GeV, N = 123, *C* = 1255 m, 16 turns, – as illustrated - or with insertions, N = 4 x (20 arc + 10 str.), *C* = 905 m)
- an IFFAG muon booster (3.2-8 GeV, 8 turns)
- an IFFAG electron model (11–20 MeV, N = 45, *C* = 29.3 m)
- a ν Factory proton driver (3-10 GeV, N = 66, *C* = 801 m, 50 Hz, 4 MW)
- a νF driver electron model (3.0-5.45 MeV, N = 27, *C* = 23.8 m)

SUMMARY

- Last 10 years have seen rebirth of interest in FFAGs world-wide
- 8 built, 3 under way, ~20 designs proposed
- Interest stems from applications needing the FFAG's unique characteristics:
  - high rep rate
  - high acceptance
- A whole new class of "non-scaling" FFAGs has been discovered
  - several varieties are being studied
  - perhaps scope for more?

SERPENTINE ACCELERATION IN CYCLOTRONS





Measured phase history in the TRIUMF cyclotron

- Real cyclotrons are only imperfectly isochronous
- Acceleration occurs along a serpentine path