FFAGs in 2005

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& TRIUMF**

with grateful acknowledgements
to the many authors
who have lent me their slides

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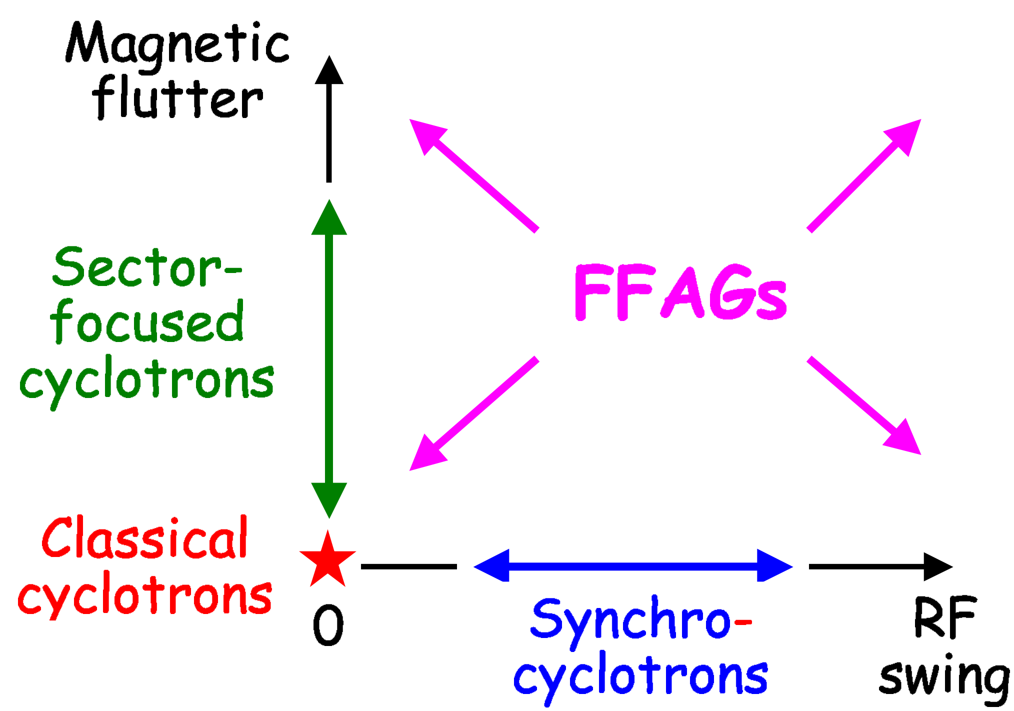
FFAGs - Fixed Field Alternating Gradient accelerators

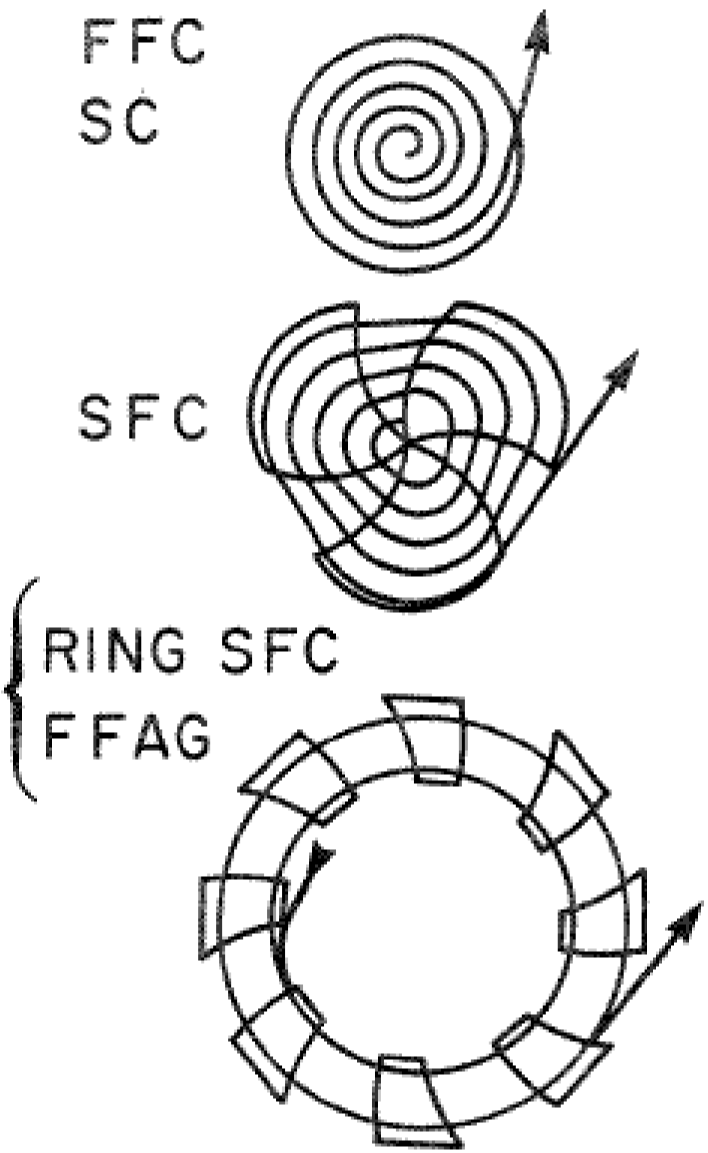
Fixed Magnetic Field - members of the CYCLOTRON family

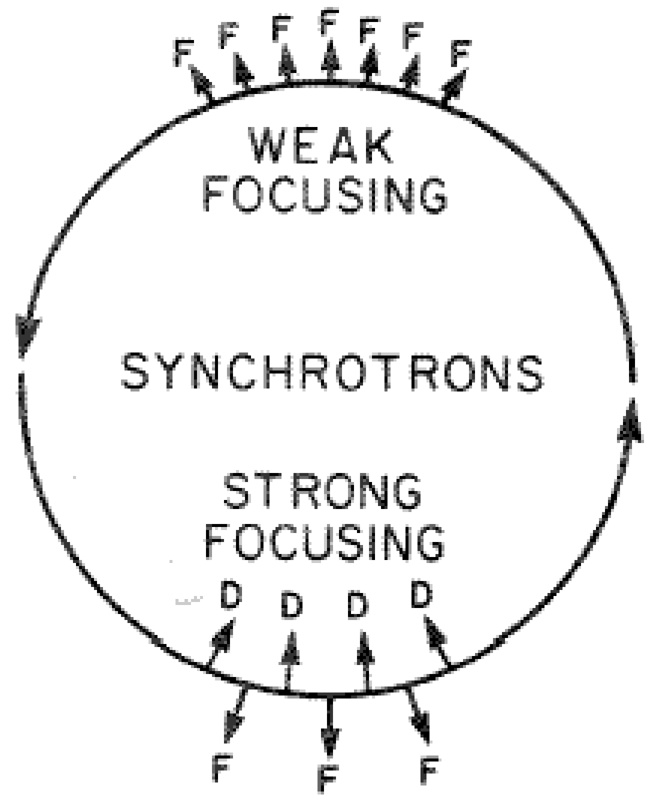
Magnetic field variation $B(\theta)$	Fixed Frequency (CW beam)	Frequency-modulated (Pulsed beam)
Uniform	Classical	Synchro-
Alternating	Sector-focused	FFAG

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



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
- Large acceptances
- High beam current

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

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!

- **3 more proton accelerators** and **a muon phase rotator** 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:- KEK (x5), CERN, LBNL, BNL, TRIUMF, FNAL

SCALING DESIGNS

Resonances were a big worry in early days, because of low ΔE/turn.

So "Scaling" designs were used, with:

- the same orbit shape at all energies
- the same optics " " " " "
- the <u>same tunes</u> " " " " "

requiring complex wide-aperture sector magnets with

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

Large and complex magnet structures!

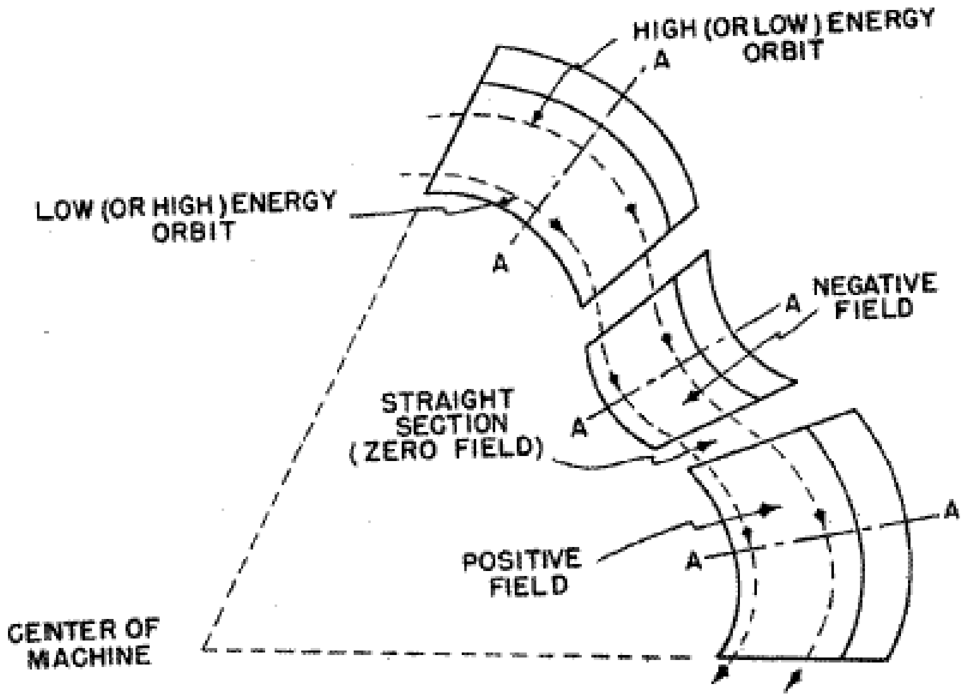


FIG. 2. Plan view of radial-sector magnets.

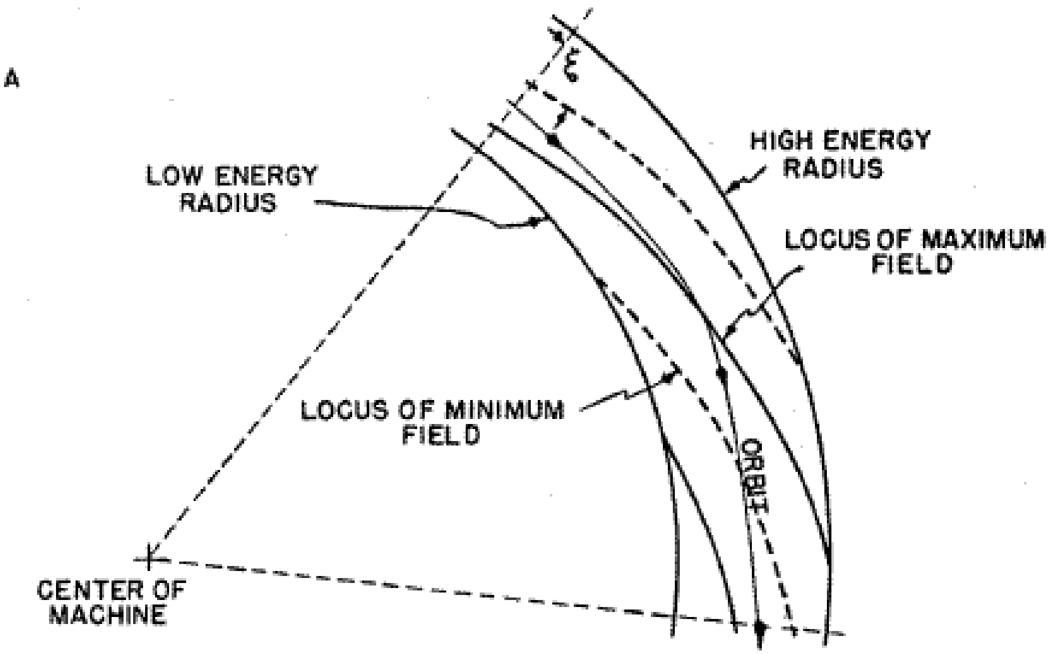


FIG. 3. Spiral-sector configuration.

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

SCALING FFAGs - HORIZONTAL TUNE ν_x

To 1st order $\nu_x^2 \approx 1 + k$

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

If B_{av} increases with r, then $k > 0 \Rightarrow$ extra horizontal focusing.

In particular, for isochronism, $\omega = eB_{av}/m$

requiring $B_{av} = \gamma B_c$

So $k = \gamma^2 - 1$ and $\nu_x \approx \gamma$

However, constant ν_x requires <u>k = constant</u> (incompatible with isochronism)

$$\Rightarrow B_{av} = B_0 (r/r_0)^k$$

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

SCALING FFAGs - VERTICAL TUNE ν_z

To 1st order $\quad \nu_z^2 \approx -k + F(1 + 2\tan^2\varepsilon)$

Note $k > 0 \Rightarrow$ vertical defocusing

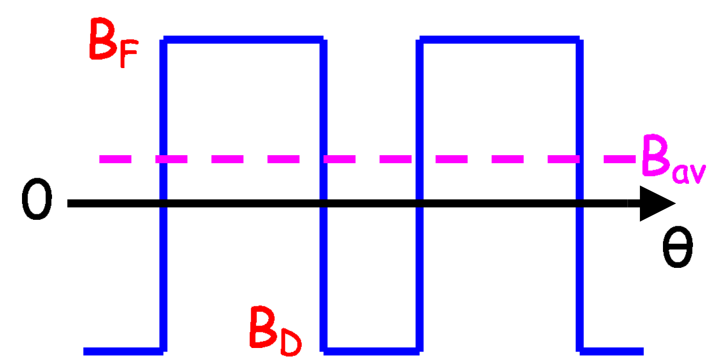
$\therefore$ constant, real ν_z requires large, constant $F(1 + 2\tan^2\varepsilon)$

MURA kept (1) spiral angle ε = constant (sector axis follows $R = R_0 e^{a\Theta}$)

(2) magnet flutter $F \equiv \langle (B(\Theta)/B_{av} - 1)^2 \rangle$ = constant

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

For high F, MURA specified $B_D = -B_F$



Note - reverse fields increase average radius:

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

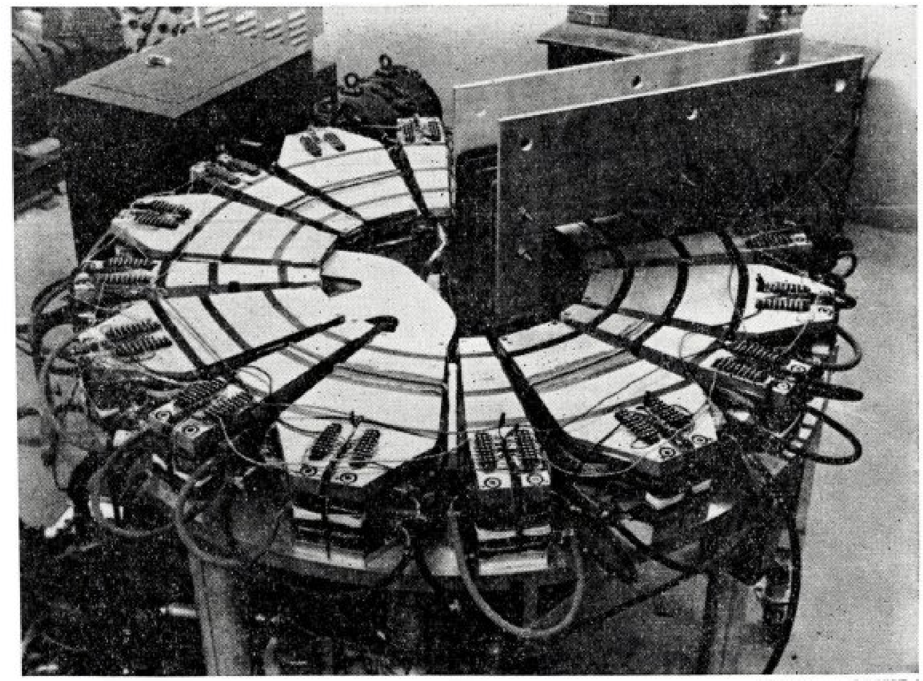
[But KEK 150 MeV FFAG, with straights, has "circumference factor" 1.8]

MURA Electron FFAGs

400keV radial sector →

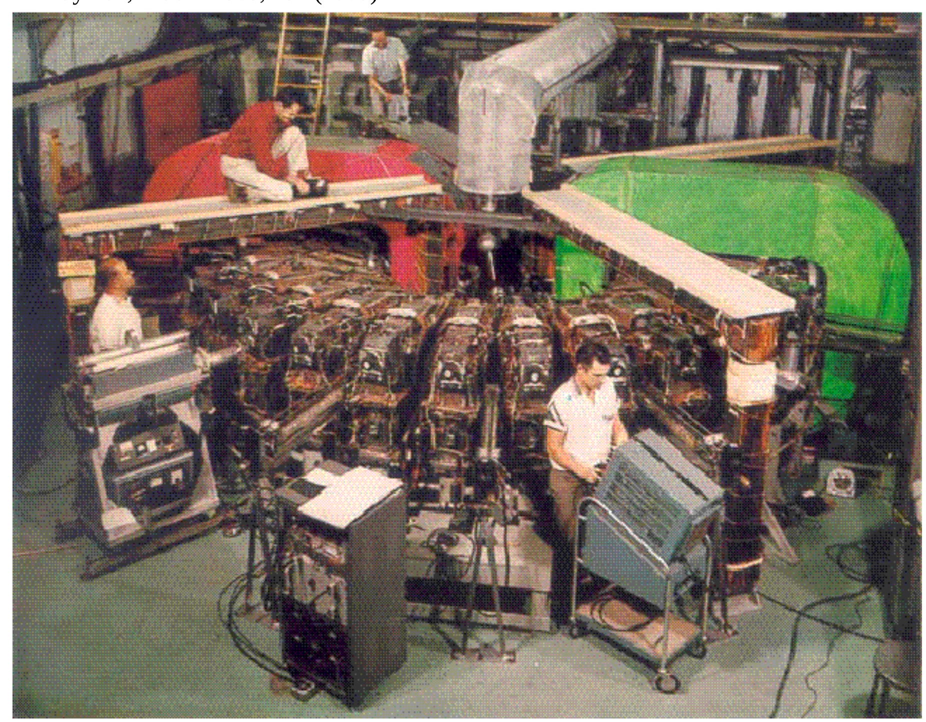
50 MeV radial sector ↘

120 keV spiral sector ↓



Courtesy of MURA

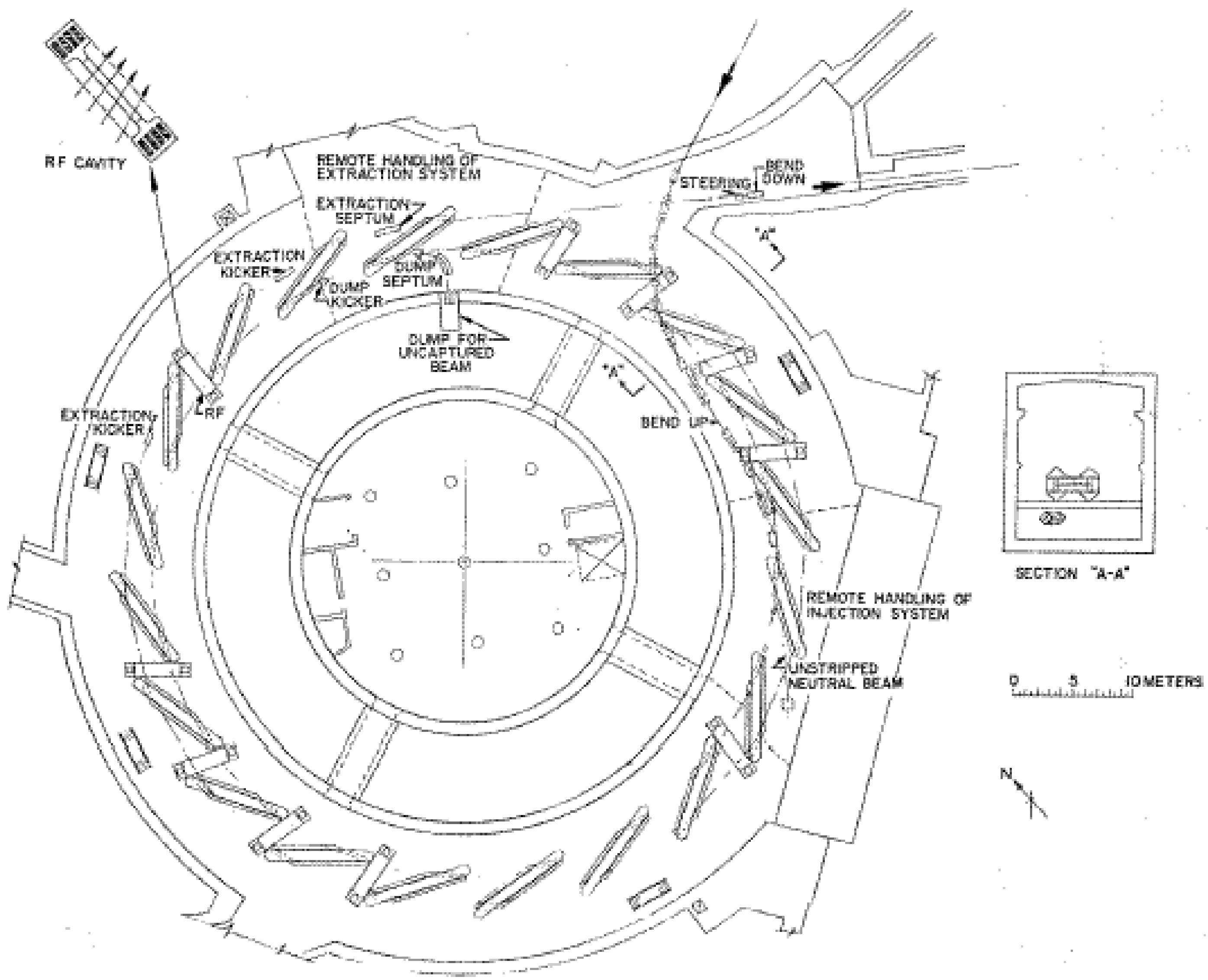
K.R. Symon, Proc PAC03, 452 (2003)



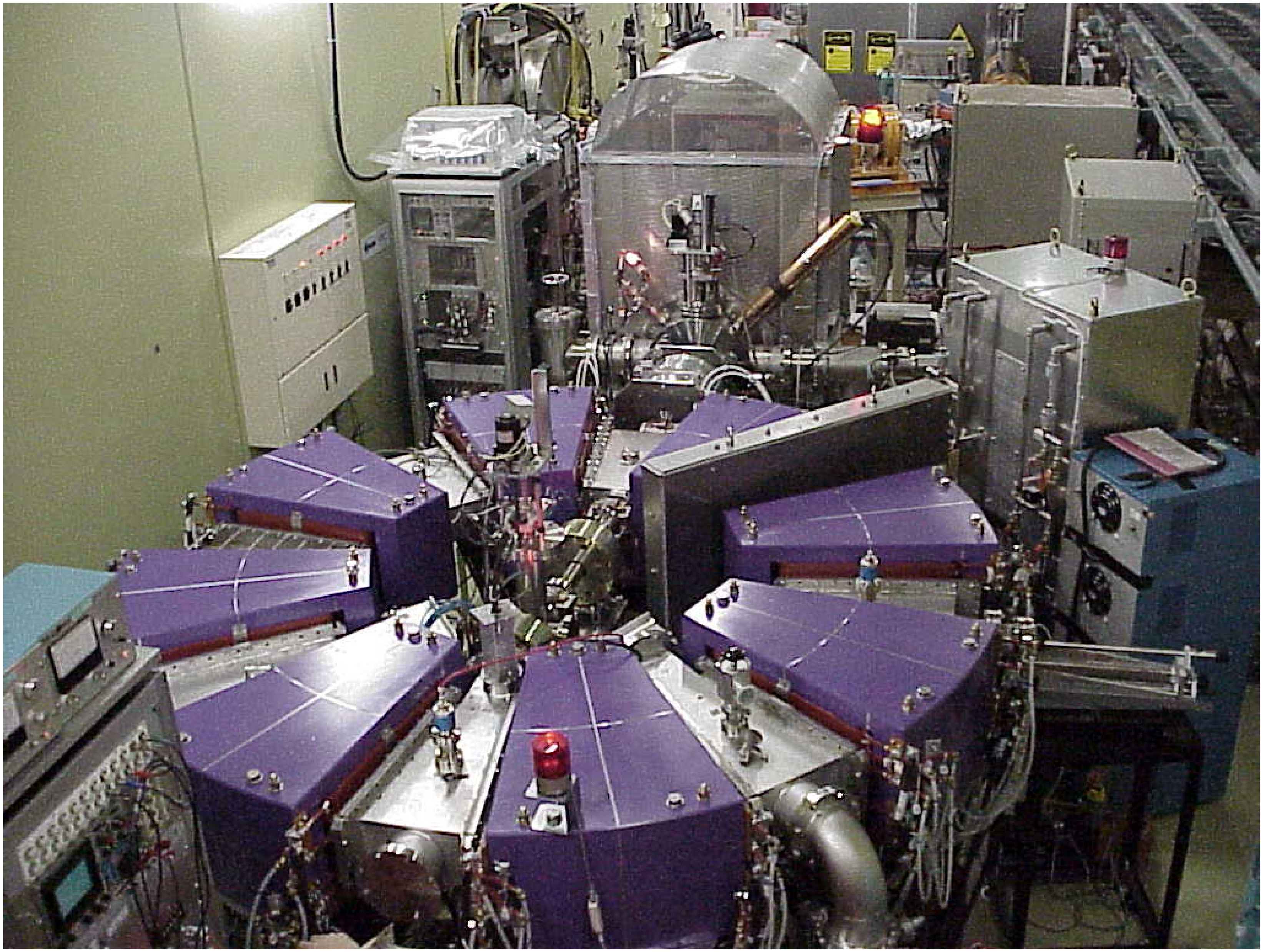
Courtesy of MURA

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 π mmmr
ϵ_Y	500 π mmmr
Extraction	
E_{EXTR}	1500 MeV
$B\rho$	7.5067 T-m
B	1.327 T
$\langle R \rangle_{EXT}$	28.139 m

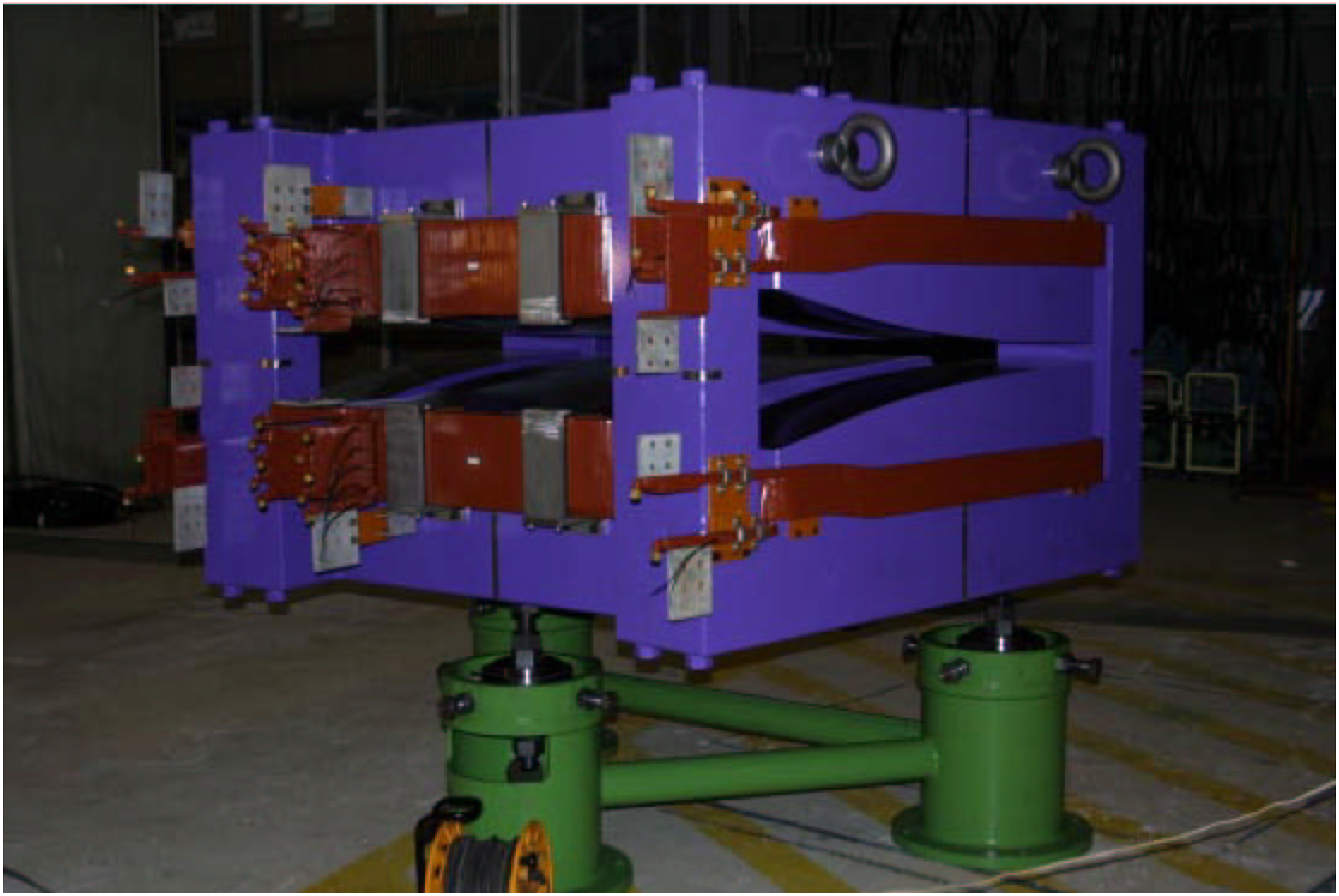


KEK Proof-of-Principle 1 MeV proton FFAG



KEK 150-MeV 12-Sector Proton FFAG

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



INNOVATIONS AT KEK

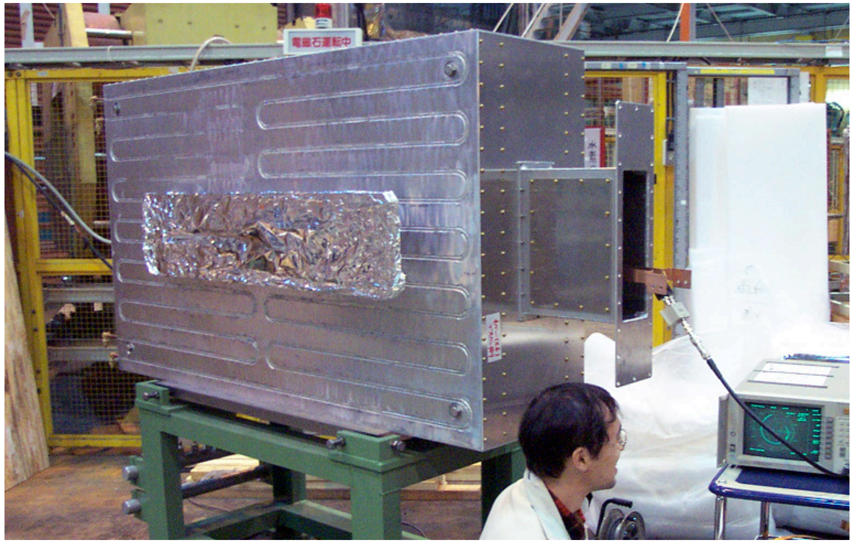
Mori's 1 MeV (2000) and 150 MeV proton FFAGs introduced two important innovations:

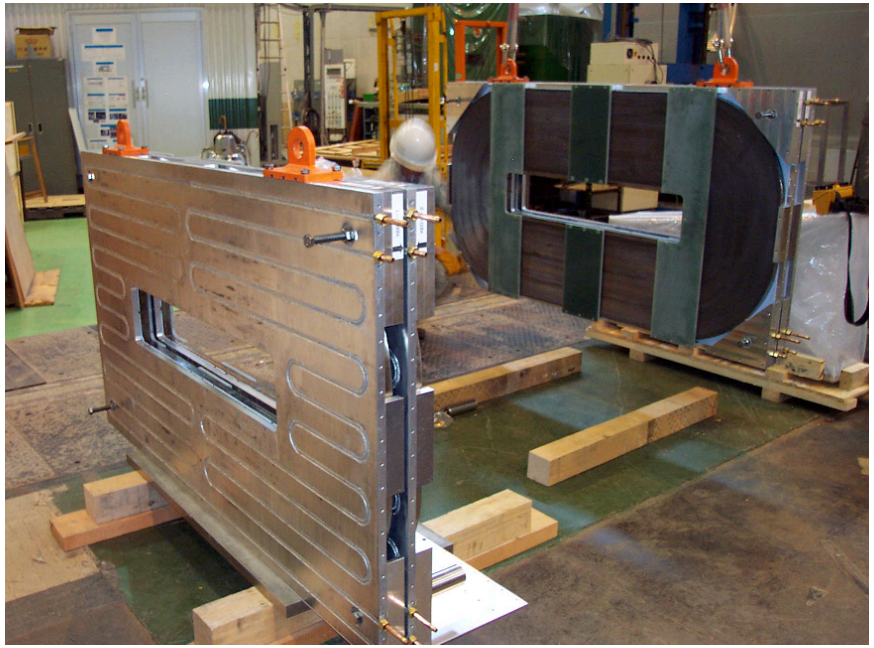
1. **FINEMET metallic alloy tuners** allowing:
   - rf modulation at 250 Hz or more → high beam-pulse rep rates (remember the unreliable rotary capacitors on synchrocyclotrons, which operate in the same mode as FFAGs)
   - high permeability → short cavities with high effective fields
   - low Q (≅1) → broadband operation - no active tuning needed

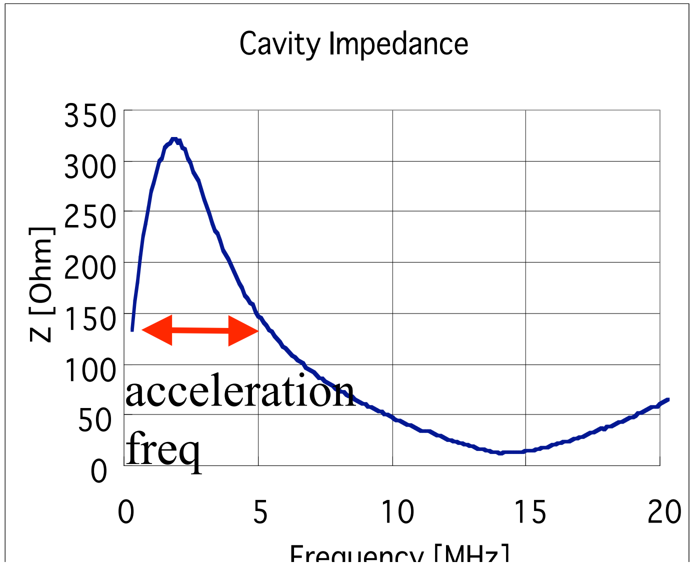
2. **DFD triplet sector magnets:**
   - powered as a single unit
   - D acts as the return yoke, automatically providing reverse field
   - modern techniques enable accurate computation of the pole shape for constant field index k

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

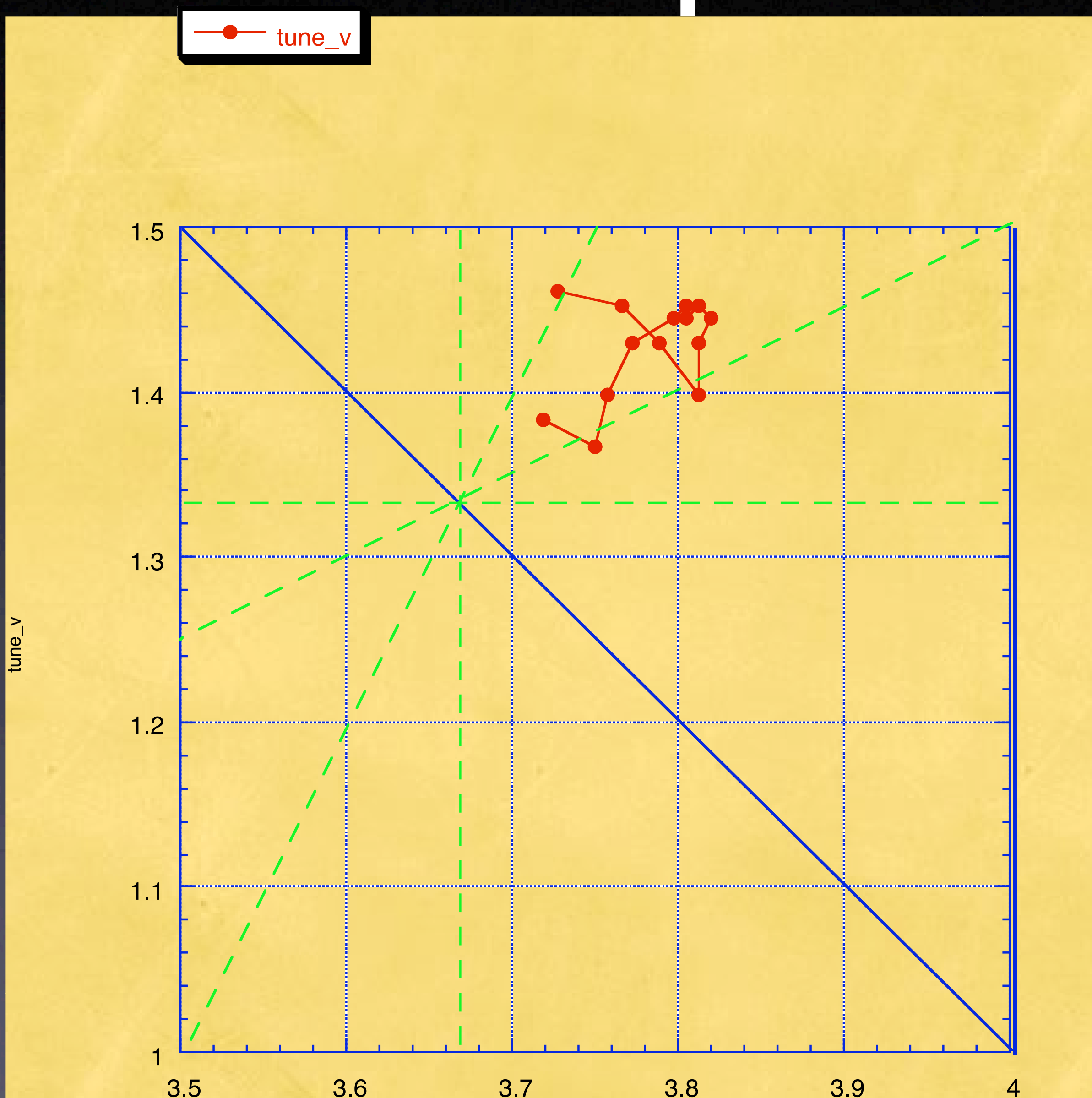






Measured Impedance

12-150MeV mode operation



criterion

1) $\Delta\nu<0.1$

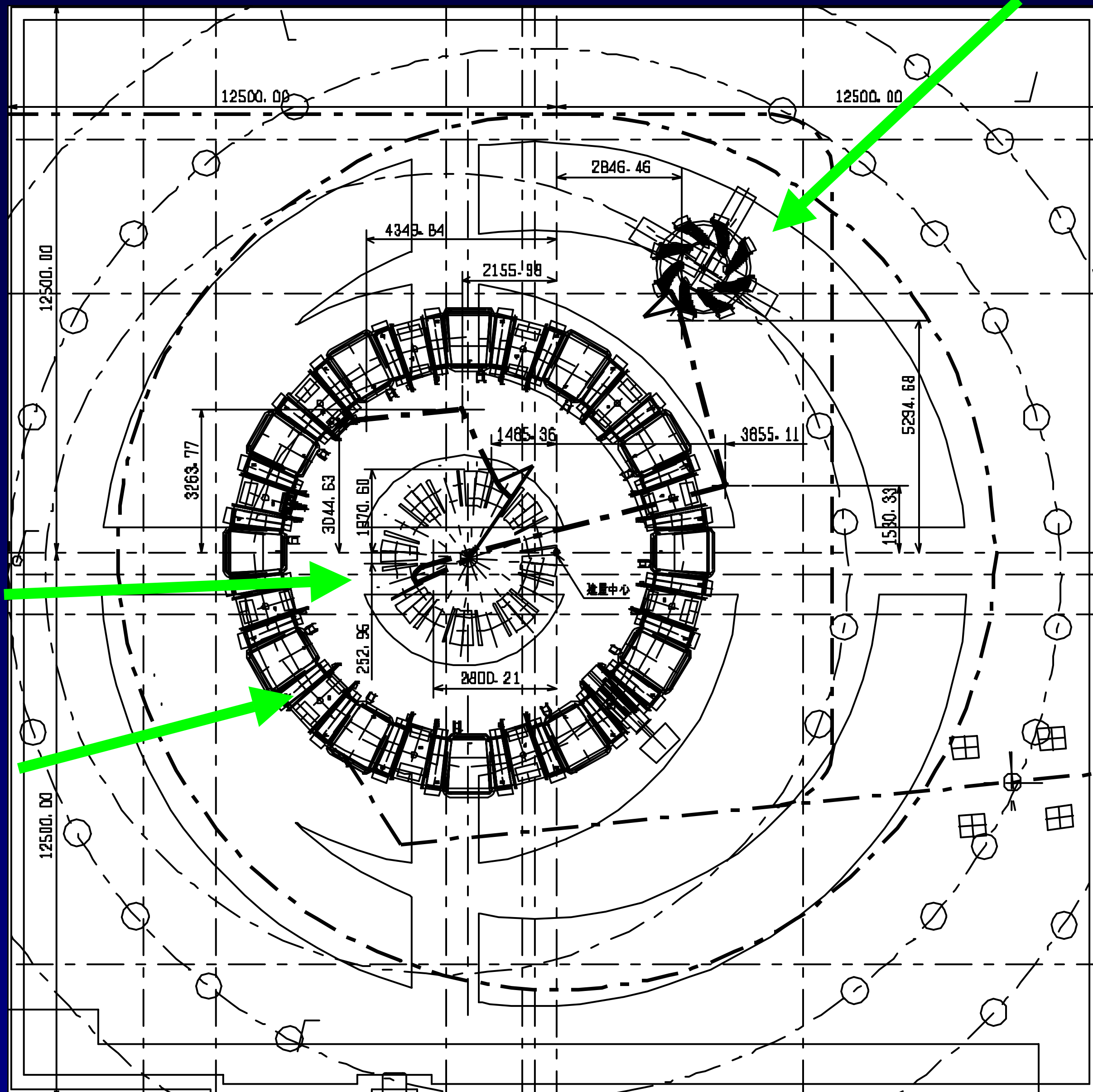
2)avoid structure & linear resonaces

SCALING FFAGs IN JAPAN

- IN OPERATION OR UNDER CONSTRUCTION -

	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Comments/ 1st beam
KEK - POP	1	p	8	0°	0.8-1.1	2000
KEK	150	p	12	0°	4.5-5.2	2003
Kyoto Univ. - ADSR	150	p	12	0°	4.5-5.1	120 Hz, 1 μA
(Accelerator-Driven	20	p	8	0°	1.3-1.9	in 2005
Subcritical Reactor)	2.5	p	8	40°	0.6-1.0	(1 kHz, 100 μA, 200 MeV later)
PRISM	20	μ	10	0°	6.5	Phase rotator

Layout


Injector
Booster
Main ring
12500.00
12500.00
12500.00
12500.00
2846.46
4348.84
2155.98
5294.68
1485.36
3855.11
3263.77
3044.63
1870.60
1580.33
252.96
2800.21

PRISM Layout

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

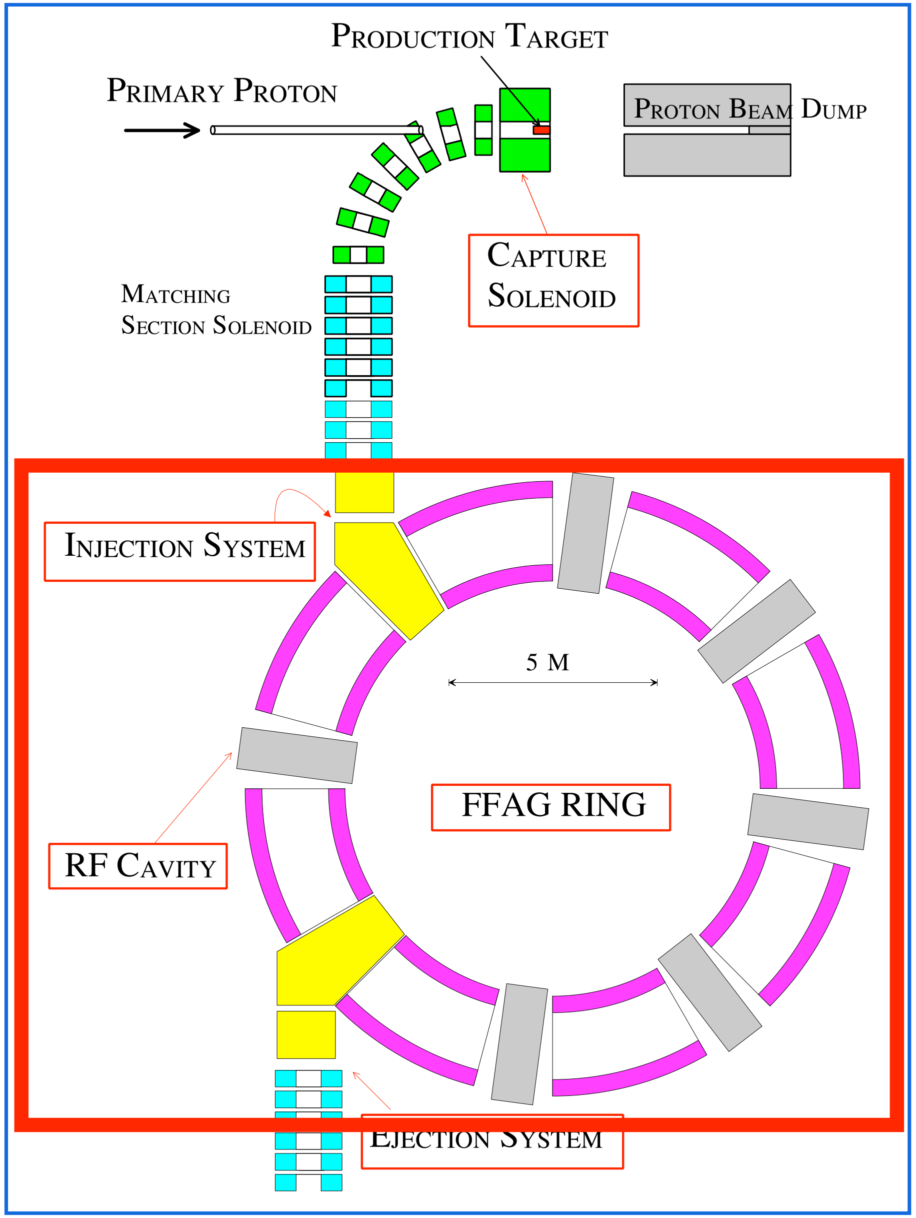
FFAG advantages:

synchrotron oscillation
necessary to do phase rotation

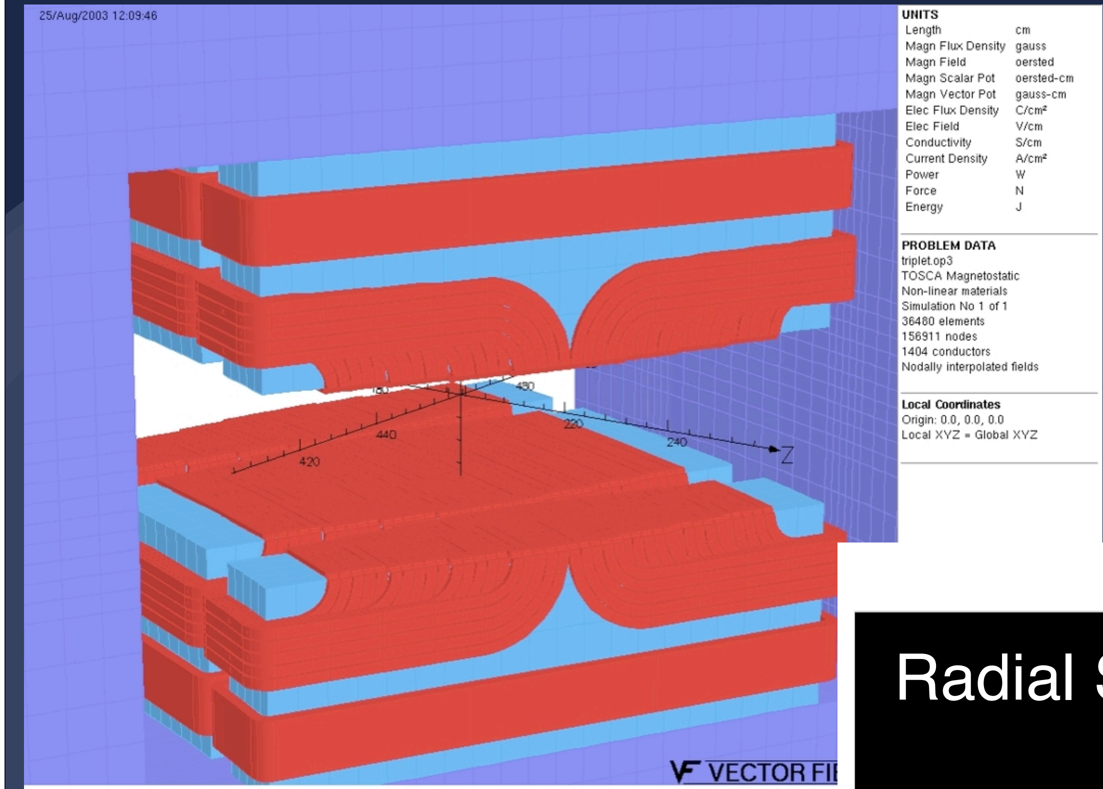
large momentum acceptance
necessary to accept large momentum distribution at the beginning to do phase rotation

large transverse acceptance
muon beam is broad in space

PRISM-FFAG ring construction has started in JFY2003.



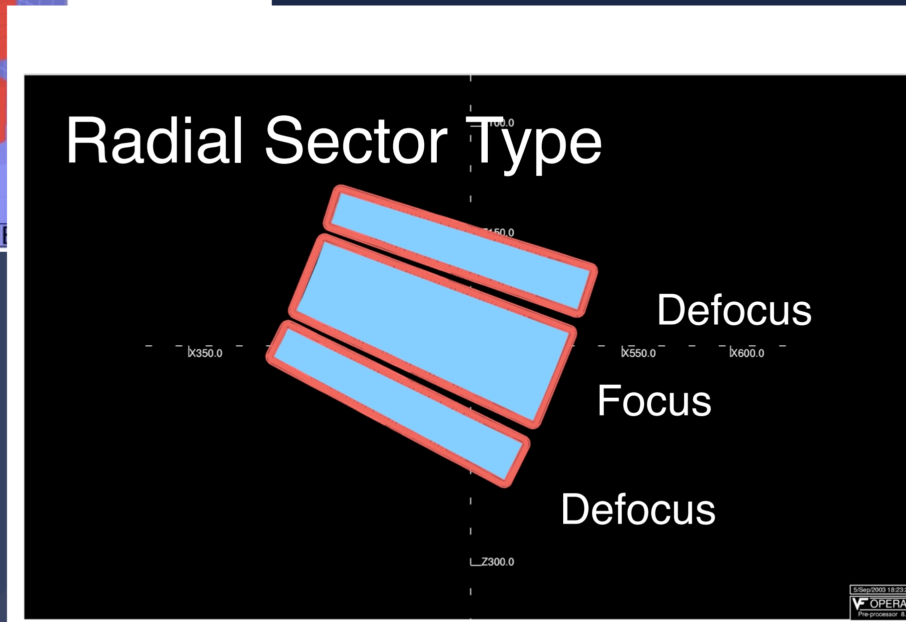
FFAG Magnet



DFD triplet magnet

FFAG field

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



SCALING FFAGs IN JAPAN - DESIGN STUDIES

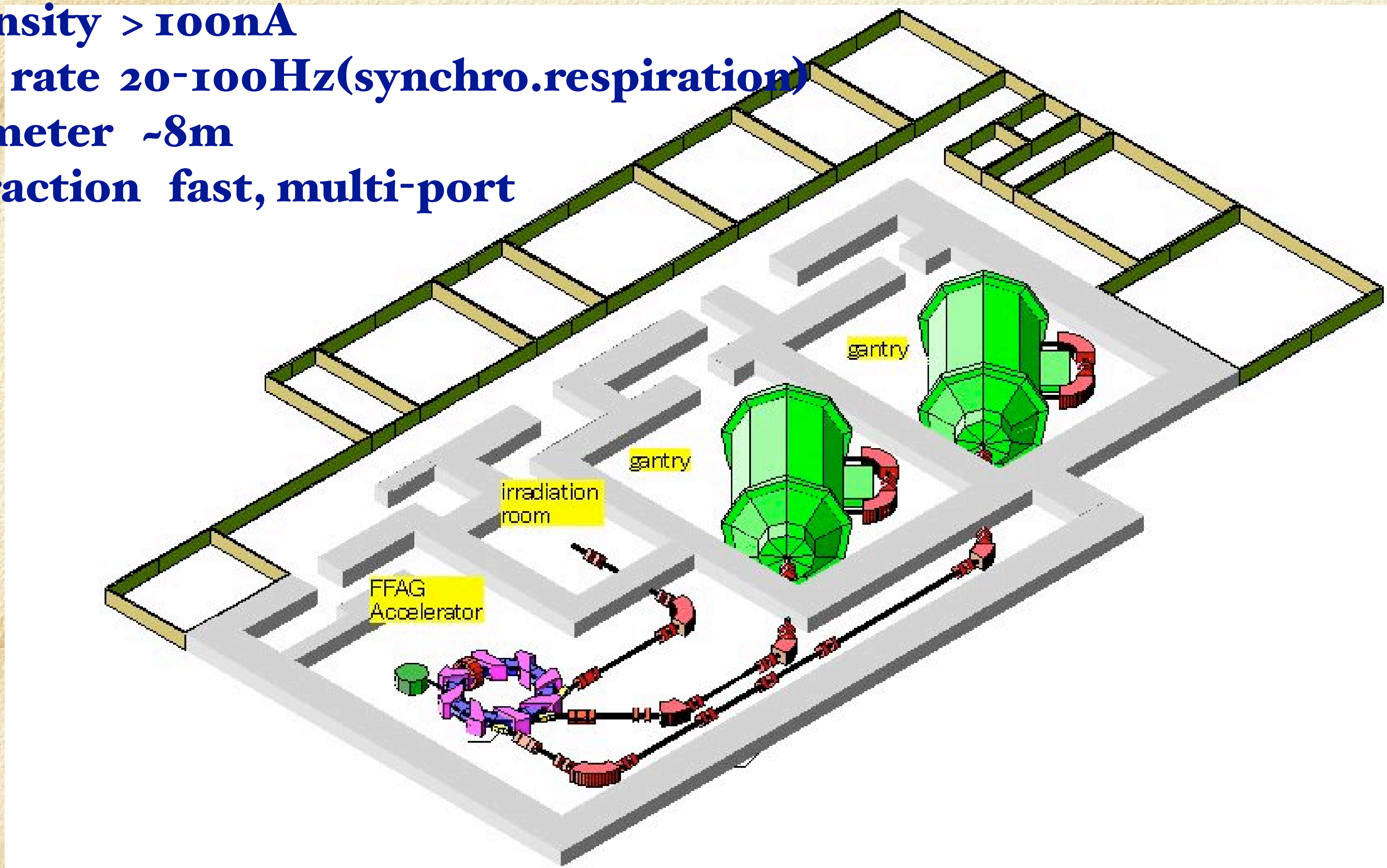
	Energy (MeV/u)	Ion	Cells	Spiral angle	Radius (m)	Rep rate (Hz)	Comments
Ibaraki Med.Acc.	230	p	8	50°	2.2 - 4.1	20	0.1 μA
eFFAG	10	e	8	47°	0.26 - 1.0	5,000	20-100 mA
MEICo - Laptop	1	e	5	35°	.023 -.028	1,000	Hybrid - Magnet built
MEICo - Ion Therapy	400	C^{6+}	16	64°	7.0 - 7.5	0.5	Hybrid (FFAG/synch^n)
(Mitsubishi Electric)	7	C^{4+}	8	0°	1.35 - 1.8	0.5	" " " "
MEICo - p Therapy	230	p	3	0°-60°	0 - 0.7	2,000	SC, Quasi-isochronous
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
J-PARC	20,000	μ	100	0°	120		Δr = 0.5 m, ~10 turns.
Neutrino	10,000	"		0°	55		
Factory	3,000	"		0°	30		$Q\approx1$ rf cavities allow
Accelerators	1,000	"		0°	10		broadband operation

Features
proton therapy accelerator

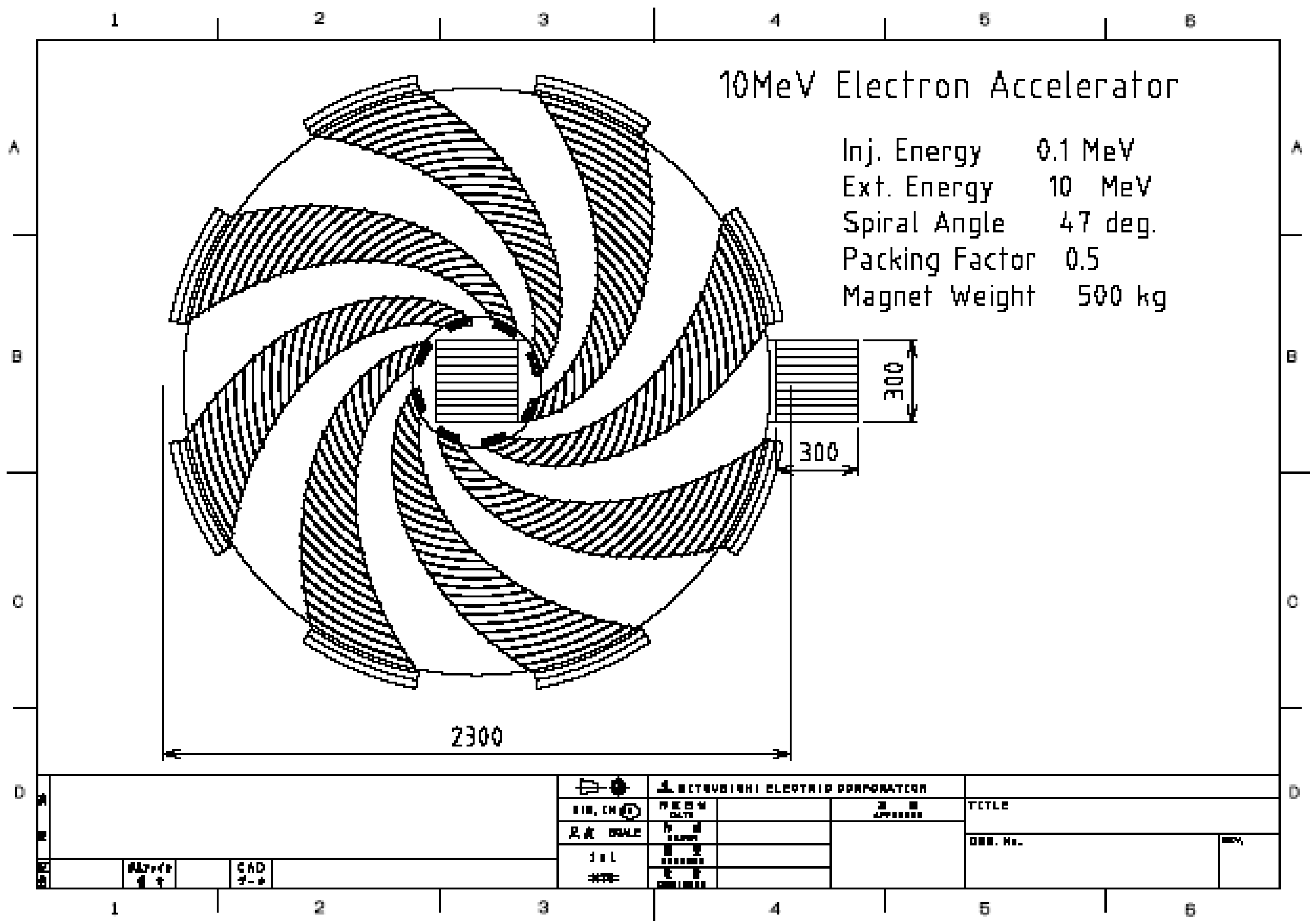
	Synchrotron	Cyclotron	FFAG
• Intensity	Low	Enough	Enough
• Maintenance	Normal	Hard	Normal
• Operation	Not easy	Easy	Easy
• Multi-extraction	Difficult	No	Yes

Hadron therapy (proton) Ibaraki Prefecture

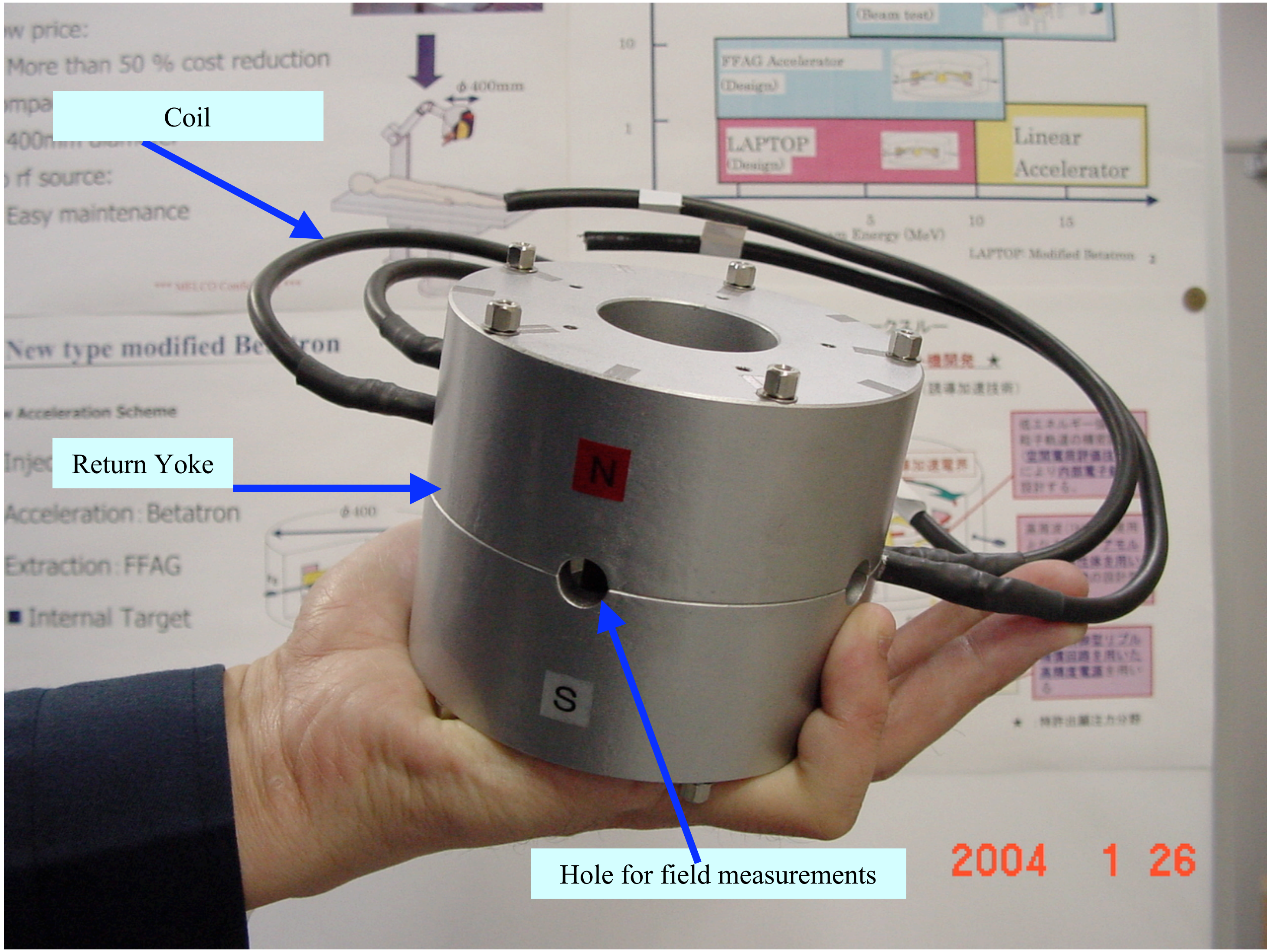
Proton energy 230MeV
Intensity > 100nA
Rep. rate 20-100Hz(synchro.respiration)
Diameter ~8m
Extraction fast, multi-port



eFFAG (10 MeV, 10-20mA, 5 kHz)

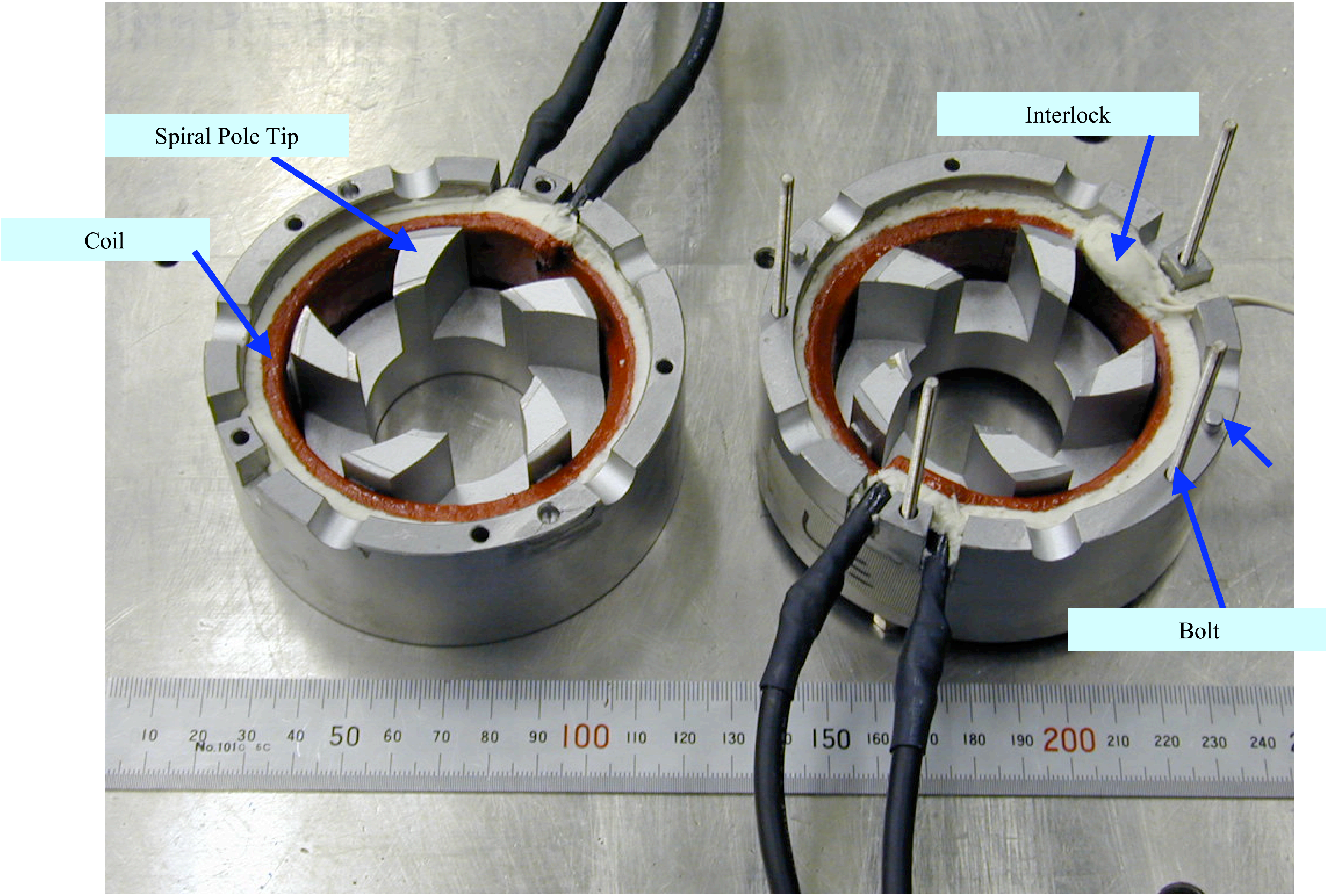


Spiral Magnet



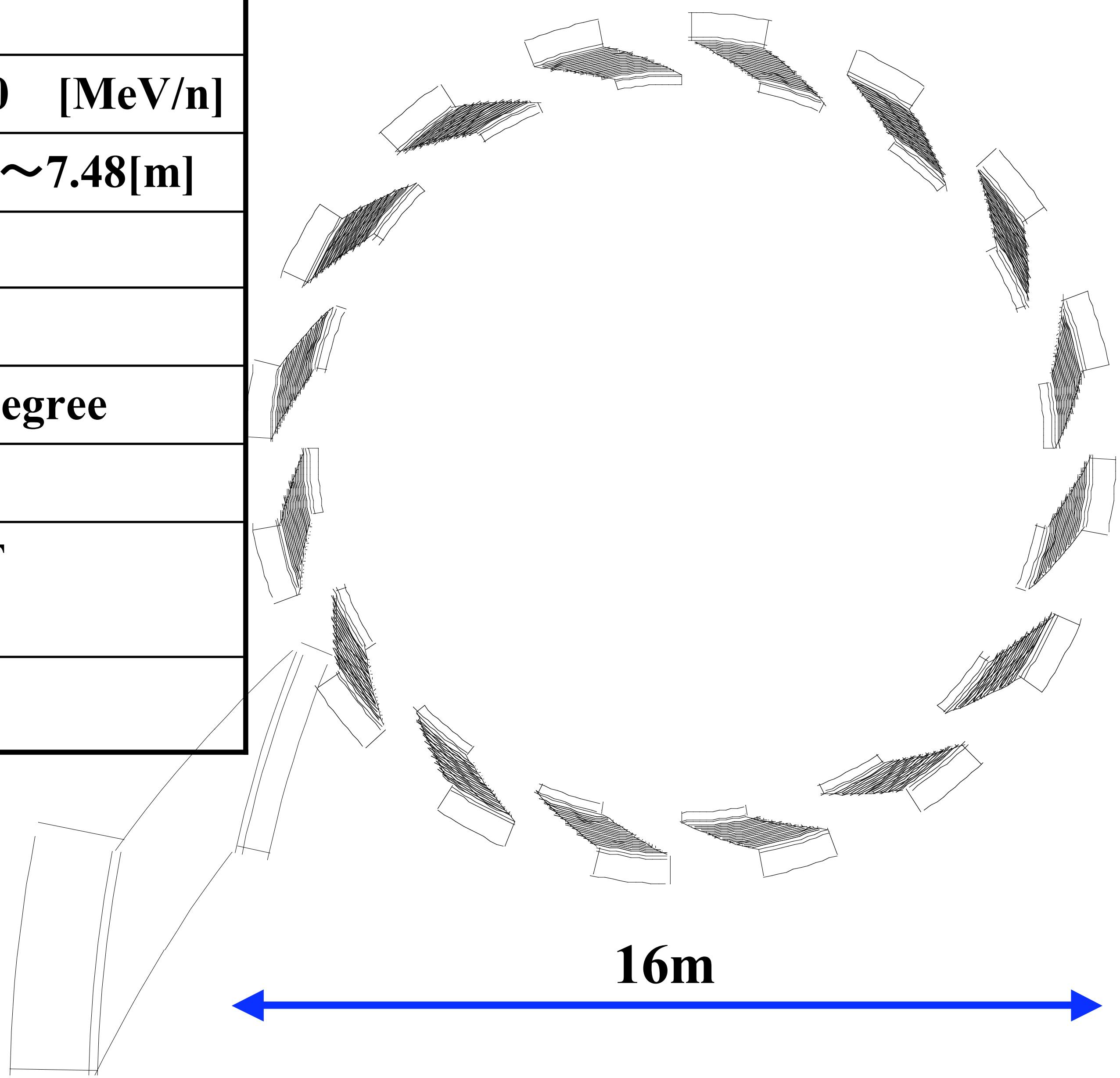
The present study is partially supported by the REIMEI Research Resources of Japan Atomic Energy Research Institute.

Spiral Magnet



C6+400MeV/n Hybrid Accelerator

Particle	C6+
Energy	4～400 [MeV/n]
Radii	7.00～7.48[m]
Cell	16
K value	12
Spiral angle	65 degree
Packing F	0.45
Maximum Magnetic Strength	1.9T
Repetition	0.5Hz

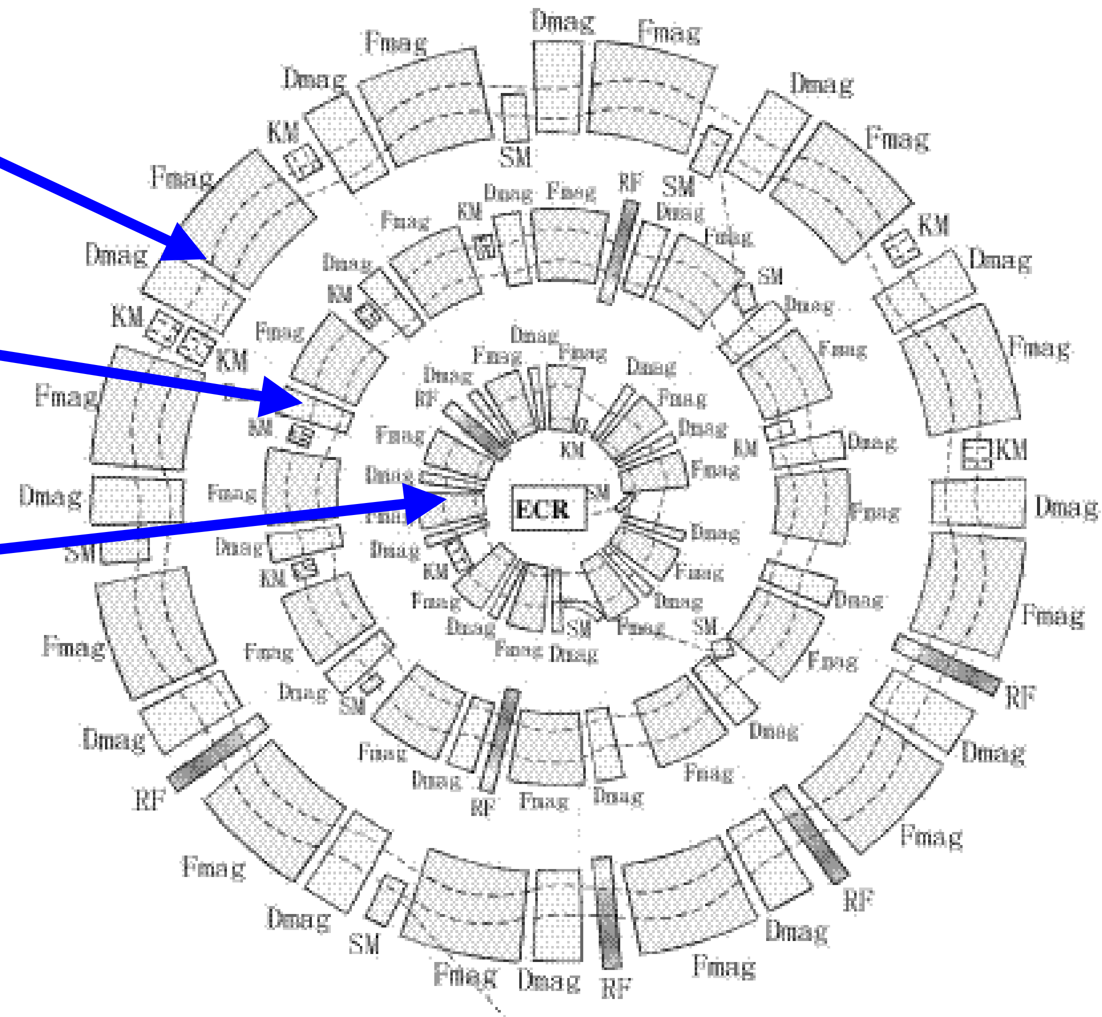


NIRS Chiba – Compact Hadron Therapy FFAG

400 MeV/u C^{6+}

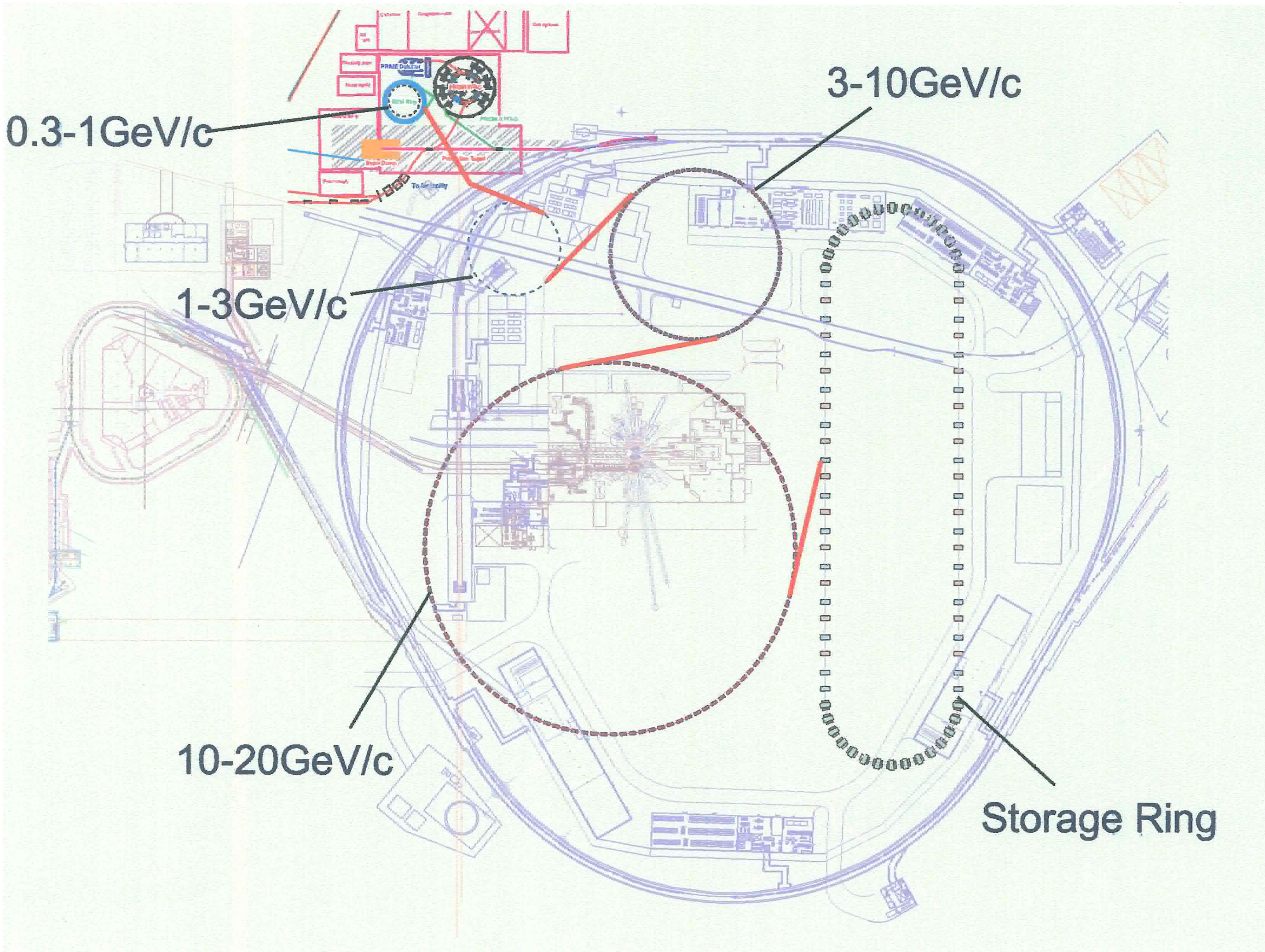
100 MeV/u C^{6+}

7 MeV/u C^{4+}



- FD0 lattices
- Radial sectors

Neutrino Factory : FFAG based



NON-SCALING 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.

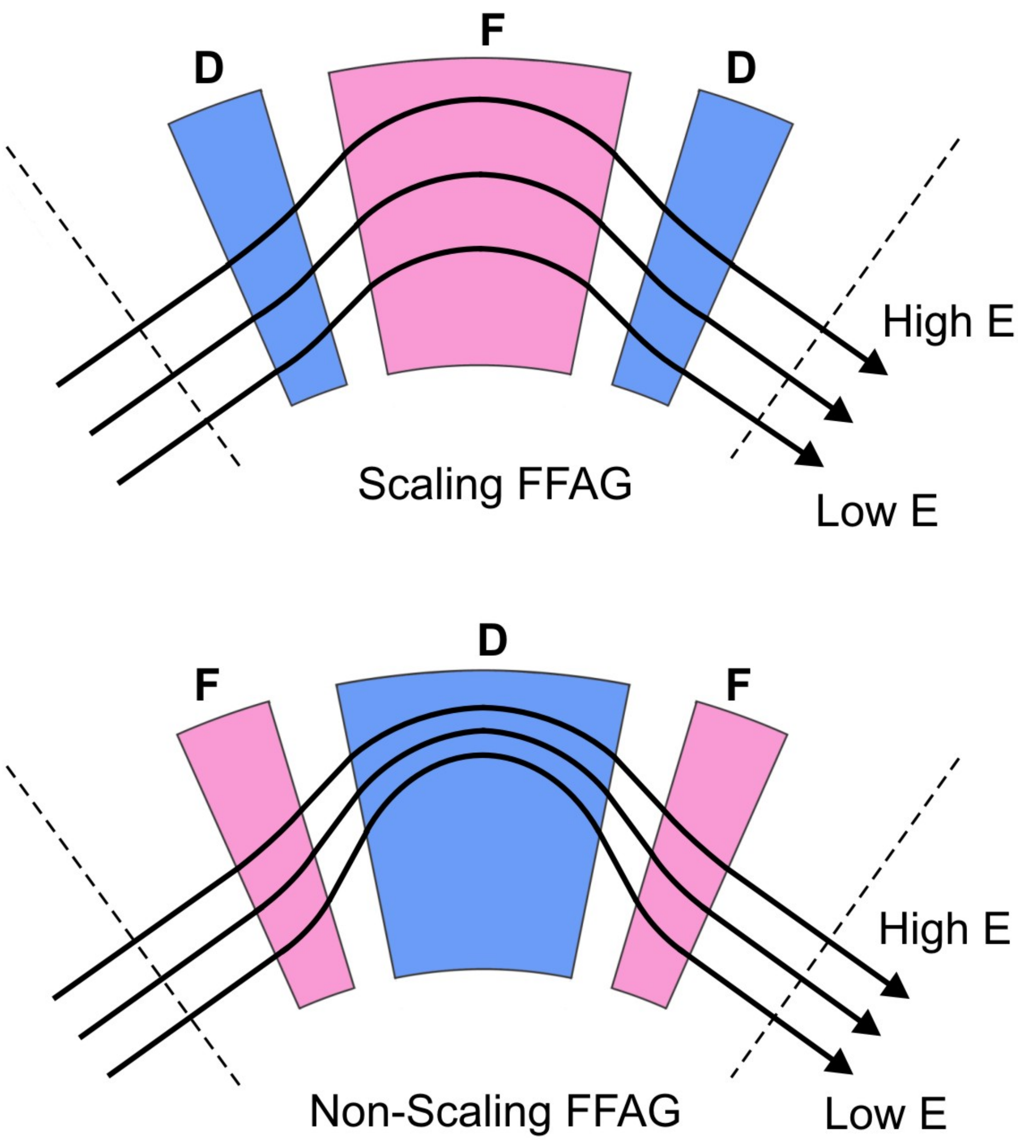
NON-SCALING approach first tried by Carol Johnstone (arc 1997, ring 1999)

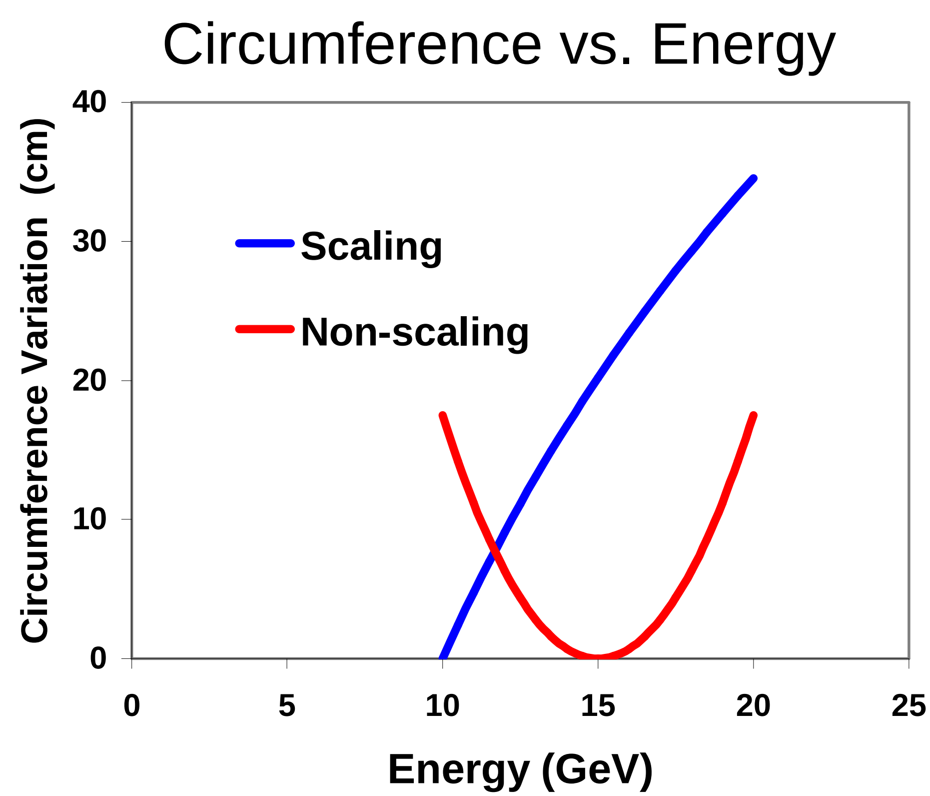
- Proposed using strong positive-bending Ds + negative Fs,
  with constant-gradient magnets
- Orbit circumference $C(E)$ varies quadratically instead of rising monotonically
  - So the variation in C and orbit period can be reduced
  - The muons oscillate in phase across the rf voltage peak (3 crossings)
    - just as in a real, imperfectly isochronous, cyclotron!

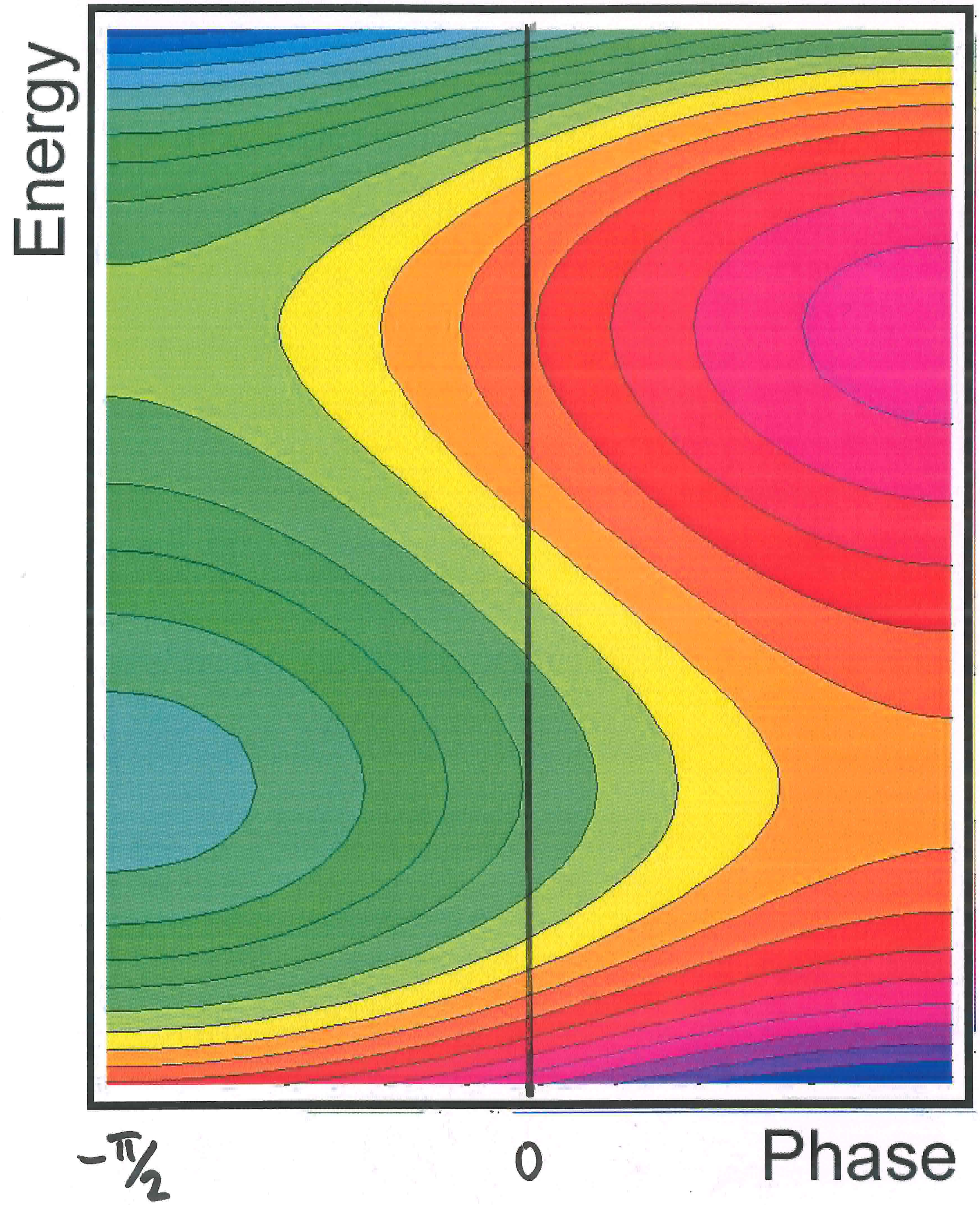
Lattice designs by
- Johnstone (Fermilab) & Koscielniak (TRIUMF)
- Berg, Courant, Trbojevic, Palmer (BNL)
- Keil (CERN) & Sessler (LBNL)

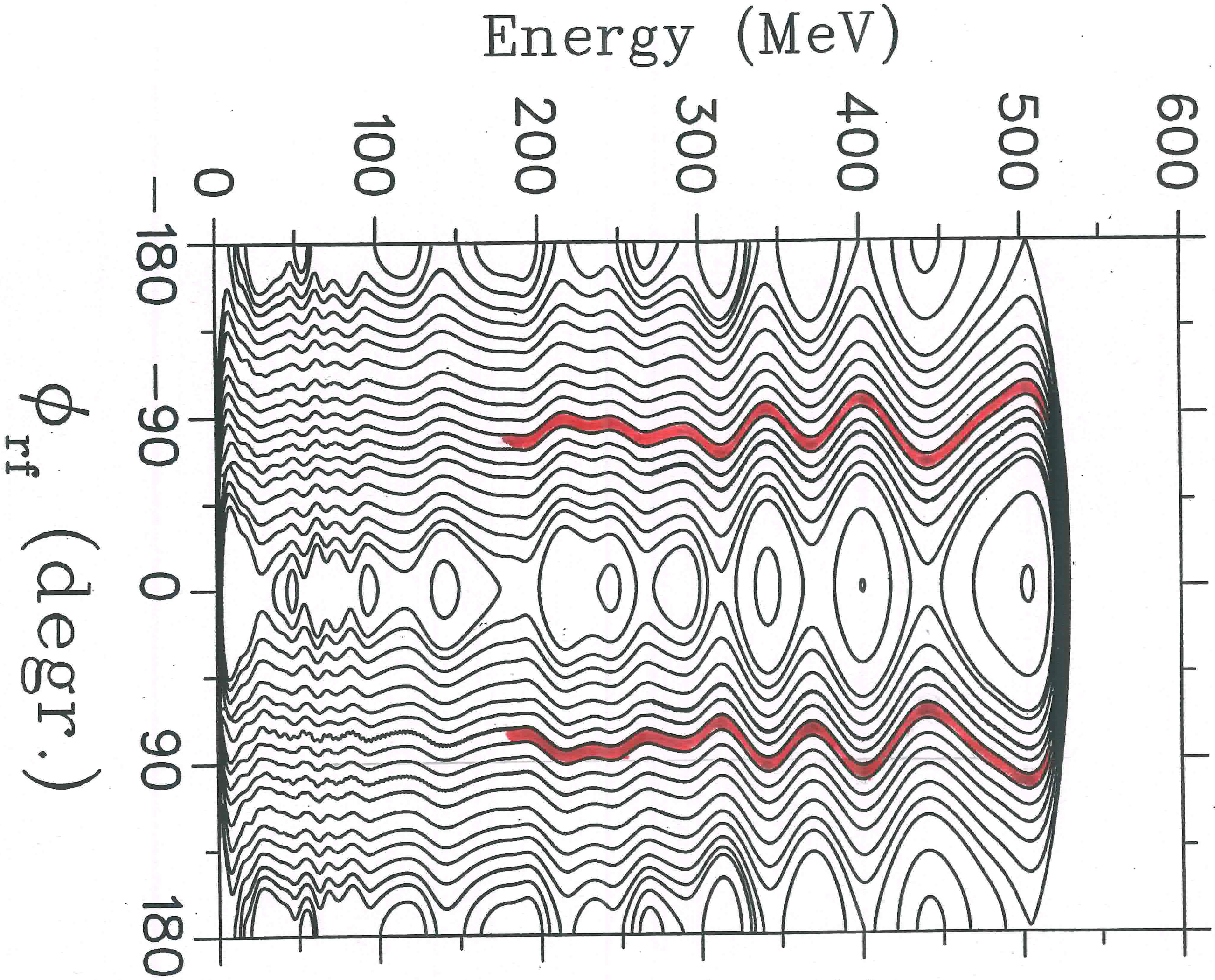
Latest cost-optimised lattices by Berg:-

2.5-5 GeV	$C = 246 \pm 0.067$ m	64 cells	6 turns	6% decay
5-10 GeV	322 ± 0.081 m	77 "	10 "	7% "
10-20 GeV	426 ± 0.095 m	91 "	17 "	8% "


D
F
D
High E
Low E
Scaling FFAG
F
D
F
High E
Low E
Non-Scaling FFAG


Circumference vs. Energy
Scaling
Non-scaling
Circumference Variation (cm)
0
10
20
30
40
0
5
10
15
20
25
Energy (GeV)


Energy
$-\pi/2$
0
Phase



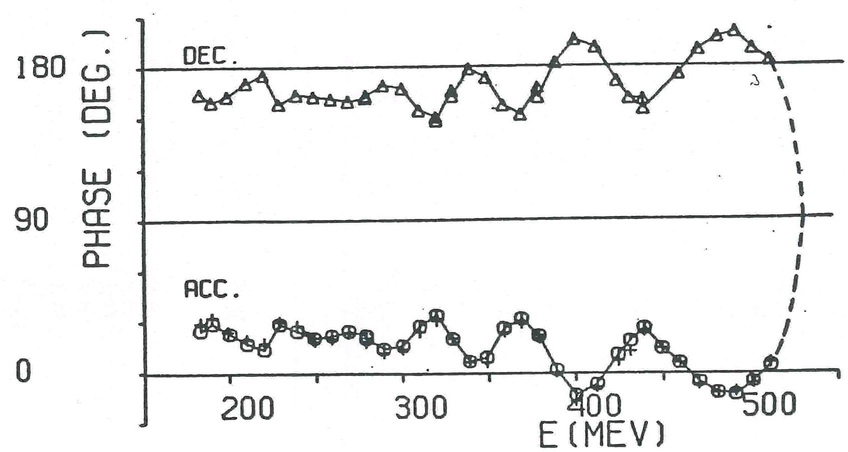


Fig. 5. Measured phases of accelerating and decelerating beams in the TRIUMF cyclotron.

NON-SCALING FFAGs FOR MUONS - II

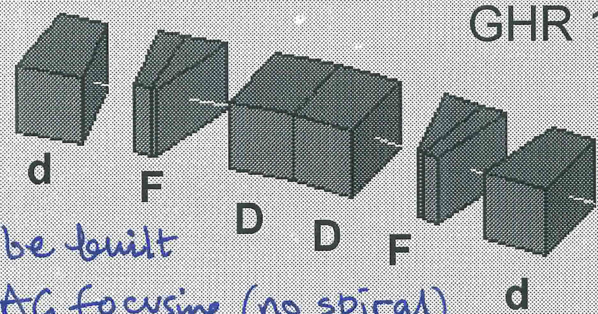
- NON-LINEAR FIELD PROFILES

Grahame Rees (RAL, 2004) Isochronous Muon Ring = MUON CYCLOTRON

GHR 123 Cell Lattice 8-20 GeV

Circumference 1255 m.

5 × 123 = 615 non-linear magnets

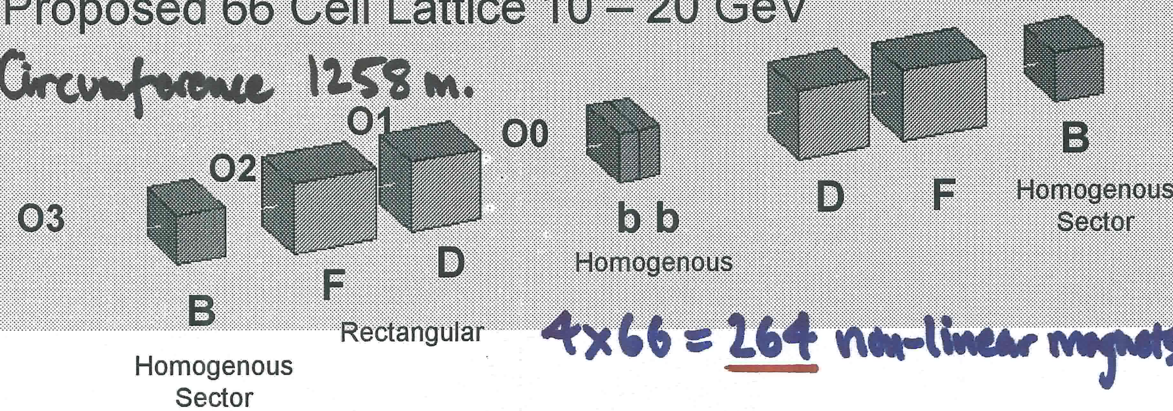


Cyclotrons can be built using Flutter + AG focusing (no spiral).

Horst Schönauer (CERN, 2004)

Proposed 66 Cell Lattice 10 – 20 GeV

Circumference 1258 m.



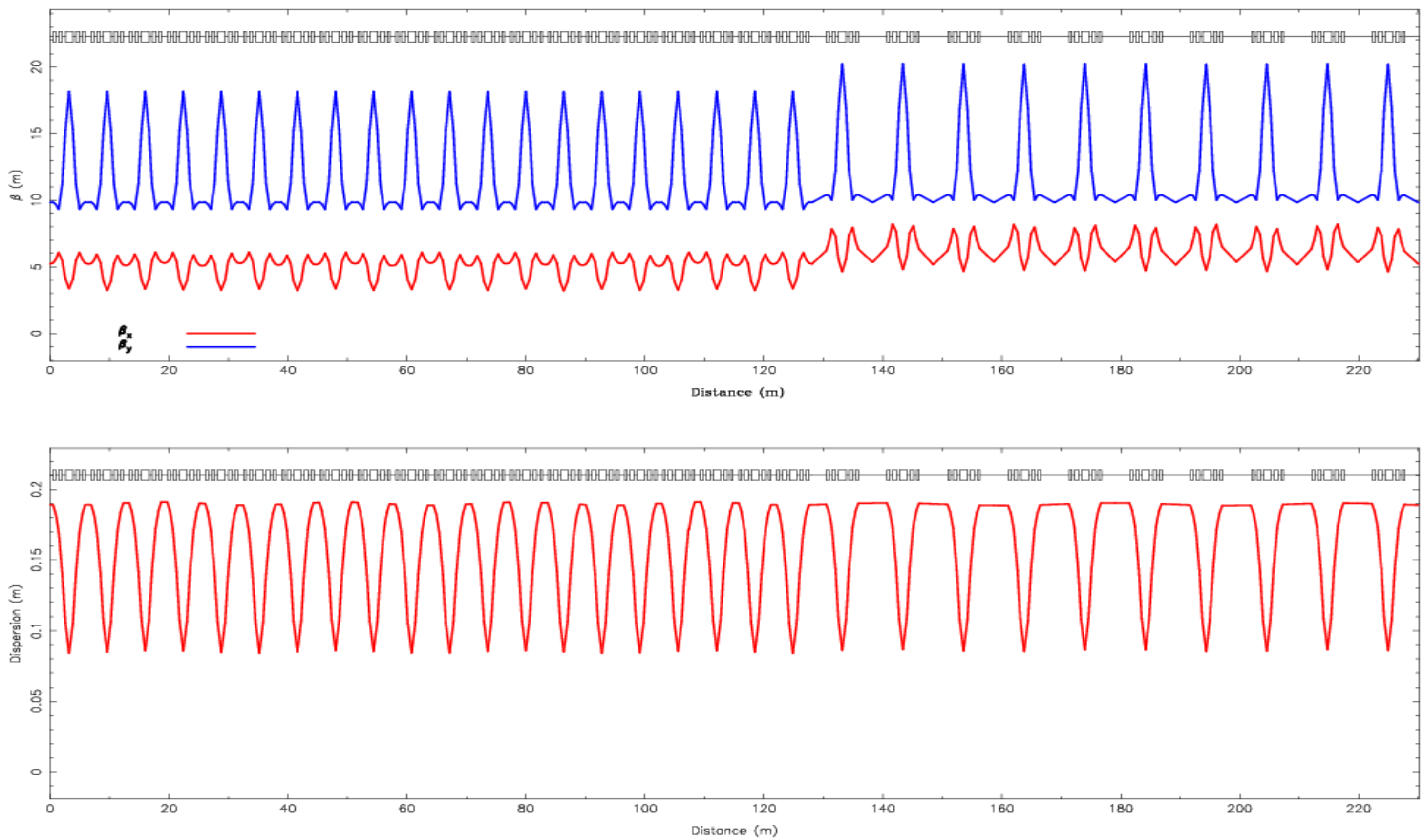
4 × 66 = 264 non-linear magnets

	Length [m]	B, Bmax [T]
Cell	19.35	
O3	3	
B	0.7	4
O2	1	
F	1.2	1.9
O1	0.5	
D	1	-2.3
O0	2	
b	0.32	-1

Reference Orbit 15 GeV **Non-isochronous**

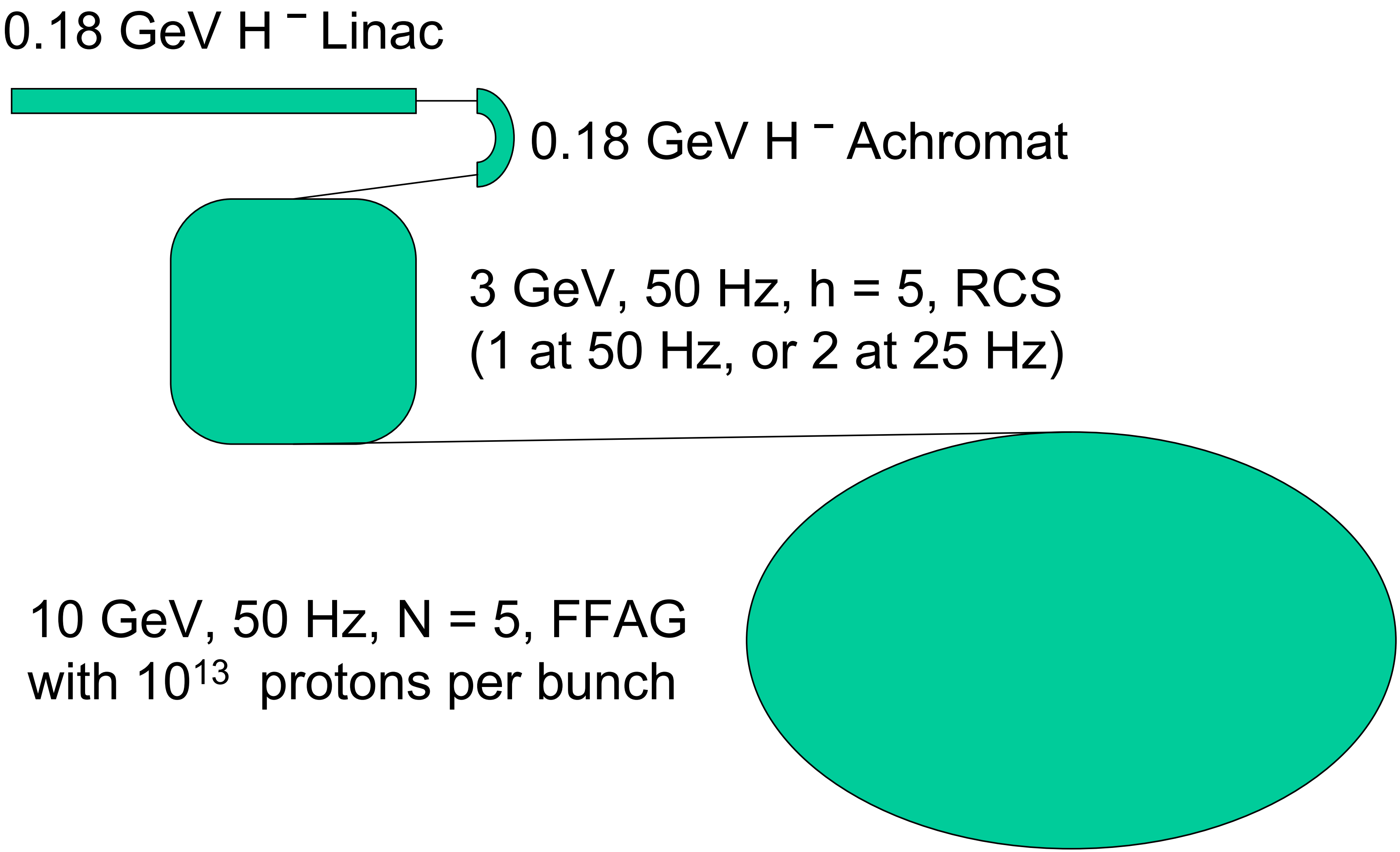
- but $\nu_x, \nu_y, \gamma_t \simeq$ constant
- so no resonance crossings.

Lattice Functions at 14.75 GeV



Rees (2005) has successfully incorporated long-drift insertions in an FFAG

4 MW, Proton Driver (Rees, 2005)



NON-LINEAR NON-SCALING LATTICES FOR HADRONS

Sandro Ruggiero (BNL) has studied low-energy proton FFAGs using non-scaling lattices with FDF cells:

- 1.5 GeV replacement for AGS Booster (R = 128 m, N = 136, 2.5 Hz, 40 μA)
- 1 GeV 10 MW proton driver (R = 32 m, N = 40, 1000 Hz, 10 mA)
- 250 MeV proton therapy FFAG.

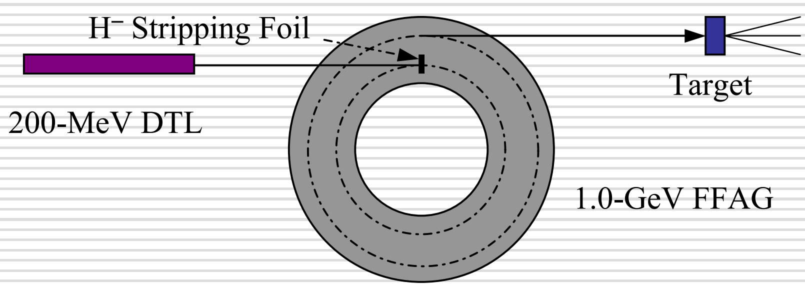
For only modest rf voltage - no resonance crossing is allowed

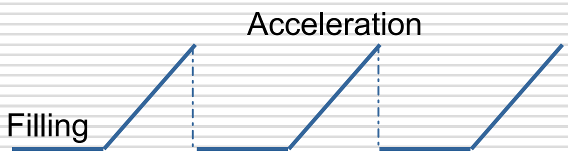
- so he keeps ν_r, $\nu_z \approx$ constant

by making the field gradient $\partial B/\partial r$ vary with r (a lot)

and with θ (a little).

1.0-GeV 10-MWatt Proton Driver





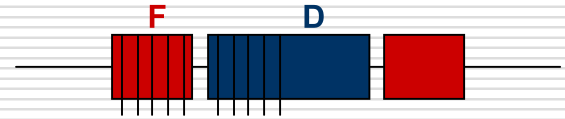
Injection Energy, U_i	200 MeV
Extraction Energy, U_f	1.0 GeV
Beam Ave. Power, $P = I\, U_f$	10.0 MWatt
Repetition Rate, F	1.0 kHz
Repet. Period, τ [illegible]	1.0 ms
Beam Ave. Current, $I = Ne\, F$	10.0 mA
Total No. Protons, N	6.25 x 10^{13}

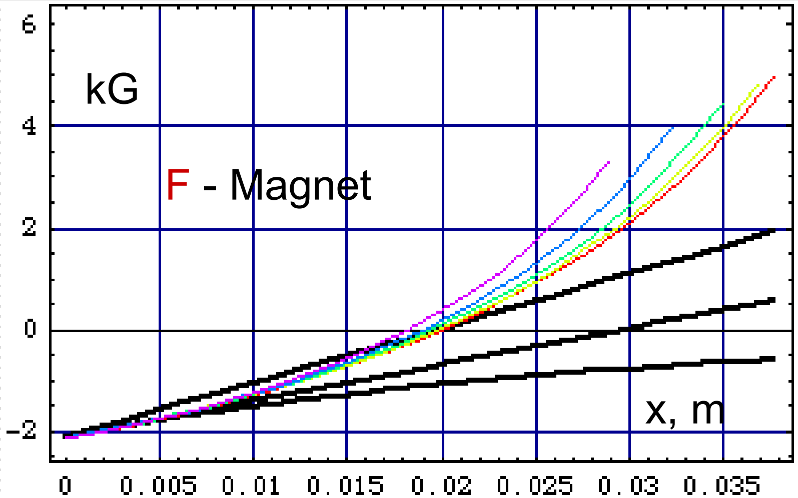
DTL Peak Current	I_L	Revol. Freq.	$f = c\, \beta_{inj} / C$
Chopping Ratio	α	Revol. Period	$T = 1 / f$
FFAG Circumference	C	No. Protons / Turn	$N_P = \alpha\, I_L\, T / e$
Injection β	β_{inj}	No. Injected Turns	$n = N / N_P = Ne / \alpha\, I_L\, T$
Acceleration Period	T_{acc}	Rep. Period	$\tau = T_{inj} + T_{acc}$

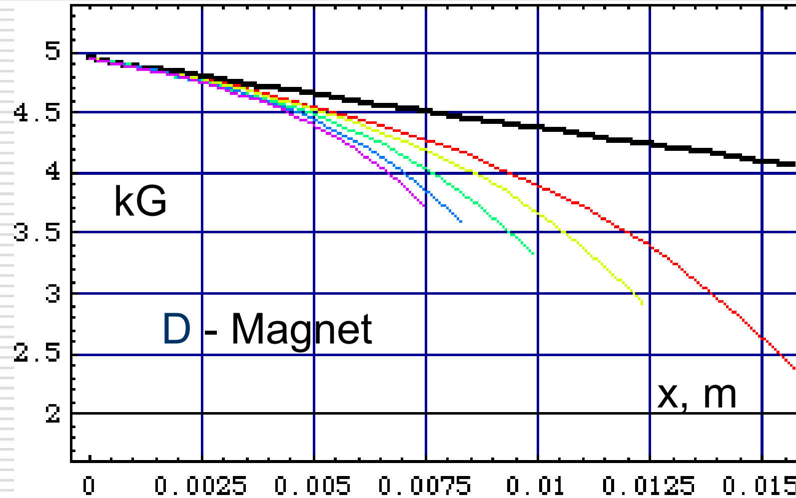
Injection Period $T_{inj} = nT = Ne / \alpha\, I_L$ --> not dependent on C and β_{inj}

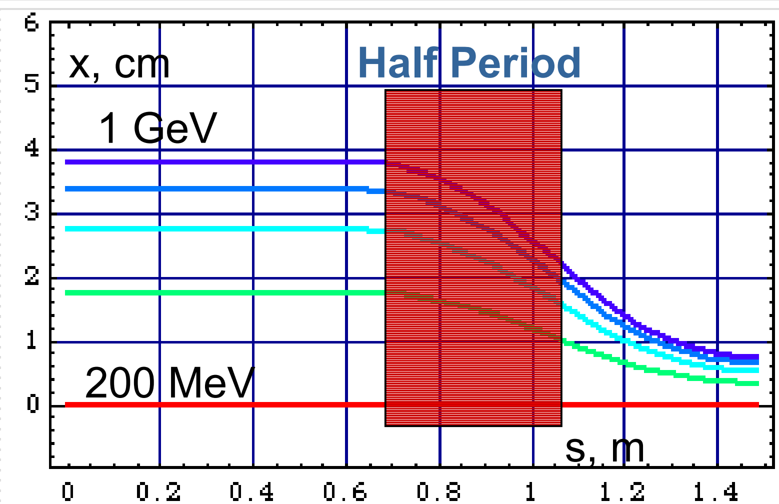
$\alpha = 0.5$ $I_L = 60$ mA --> T_{inj} = **0.333** ms & T_{acc} = **0.667** ms

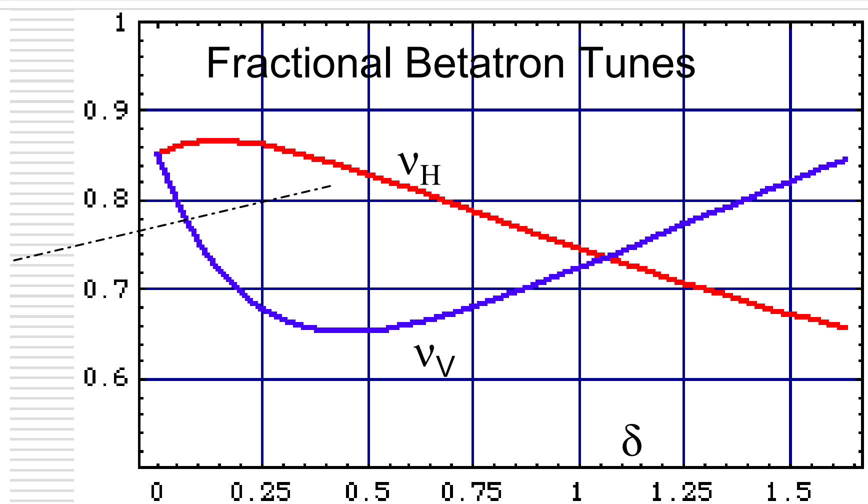
Adjusted Field Profile (AFP)



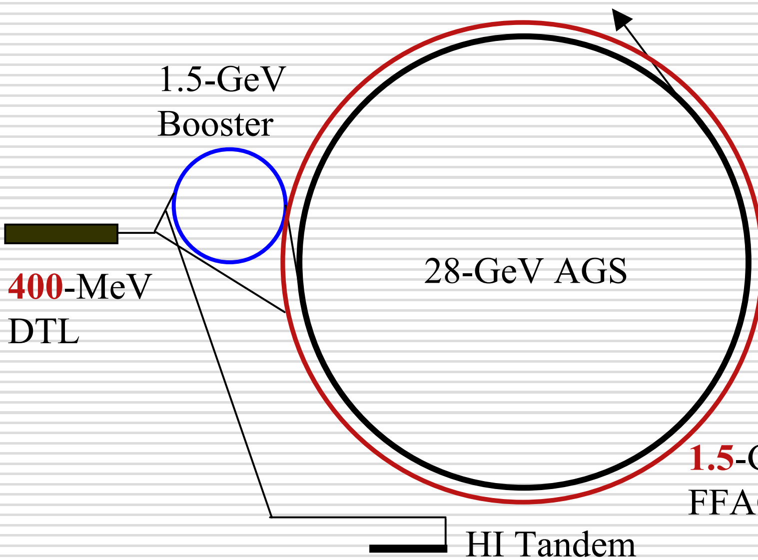








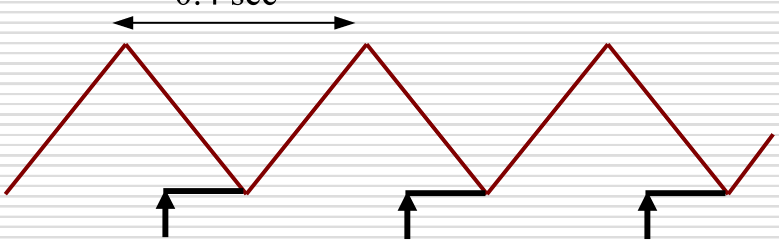
AGS Upgrade with 1.5-GeV FFAG



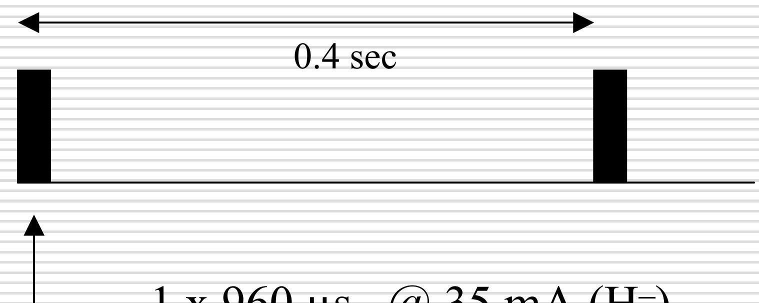
Performance

Rep. Rate	2.5 Hz
Top Energy	28 GeV
Intensity	1.0 x 10^{14} ppp
Ave. Power	**1.0 MW**
Protons, **and** HI (??)	

AGS Cycle with 1.5-GeV FFAG



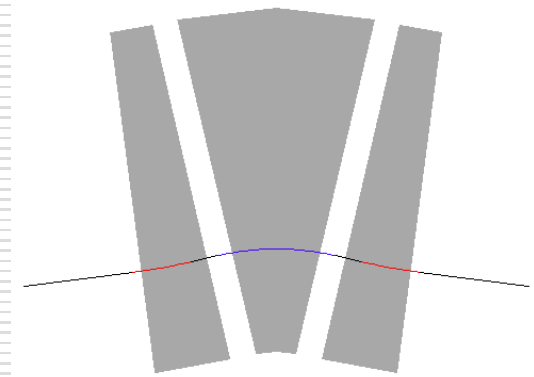
DTL cycle for Protons with 1.5-GeV FFAG

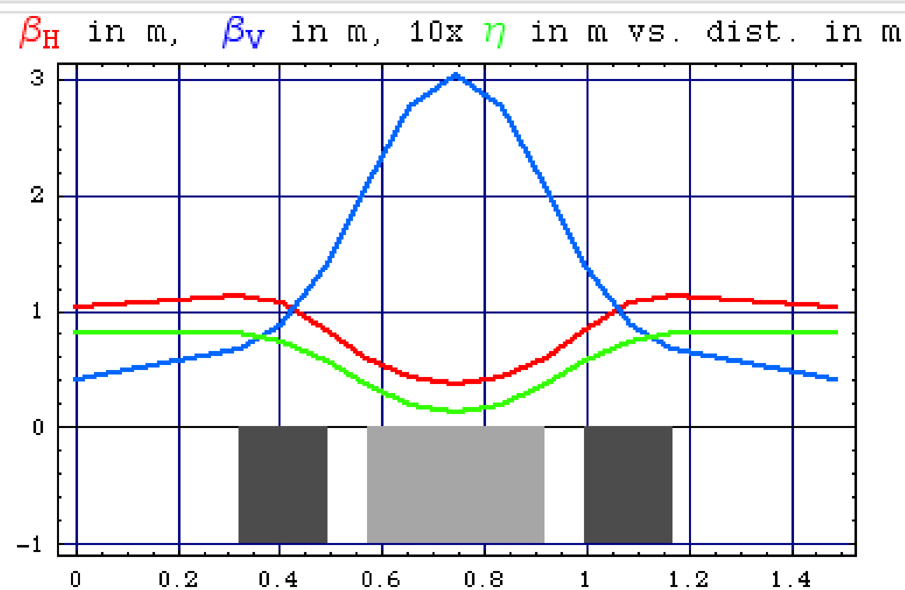


1 x 960 μs @ 35 mA (H^-)

Medical Facility -- 25-250 MeV

Circumference		35.7626 m
Number of Periods		24
Period Length		1.49011 m
Drifts: S		0.320055 m
g		0.075 m
Sector Magnet	**F**	**D**
Length, m	0.175	0.350
Field, kG	–4.06078	9.50083
Gradient, kG/m	94.9977	–87.2587
Bend Radius, m	–1.79099	0.76549
Bend Angle, rad	–97.7112	2 x 228.611
Bending Ratio (D/F)		**2.34**
Packing Factor		**0.472**
Phase Advance (H/V)	111.6°/110.8°	
Betatron Tunes (H/V)	7.44/7.39	
Transition Energy, γ_T	18.12 i	





ELECTRON MODEL FFAG

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

- Safe passage through many low-order structural resonances
- Acceleration outside buckets.

Studies have focused on an electron FFAG
- with relativistic parameters similar to one for 10-20 GeV muons - e.g:

Energy	10-20 MeV	Circumference	15.9 m
Cells	42	B_{max}	0.2T
RF frequency	1.3 GHz	F quad length	6.0 cm
Volts/cavity	19 kV	D quad length	6.8 cm

Daresbury Lab (UK) has offered lab space and a 7-35 MeV injector.

UK and EU grant applications are being submitted.

CONCLUSIONS

- Last 10 years have seen rebirth of interest in FFAGs world-wide

- 2 built, 4 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?