Fixed Field Alternating Gradient Accelerators and Muon Beams

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Contents

Bibliography:

◇ JACoW: https://www.jacow.org/Main/Proceedings - lookup "FFA[G] muon"
◇ FFAG workshops, 1999-present:
https://www.bnl.gov/ffaworkshop/events/

1 Introduction

- **Muon beams require fast acceleration:**

Getting a muon bunch from downstream a pion production target

- to an experiment or a storage ring

- possibly via (long) cooling sections

- and/or via an accelerator cascade

- **This requires distance ... that may take a life time!**

a meere 2.197μs if just resting ...

• **Short life time requires**

- **taking muons to high γ as fast as possible, if high energy muon beams needed (NF/10GeV, nuSTORM/5GeV, muon collider/5TeV beams)**
- **bunch manipulations to be quick, if low energy (PRISM phase rotator/70MeV/c, muon cooler ring/300MeV/c, ...)**

• **Technologically this requires**

- **fixed magnetic field - if any magnetic field required!**
- **lots of RF**

• **The idea of using the mid-1950s FFAG accelerator technology for fast acceleration thrived from the 1990s on with the Neutrino Fatory and muon collider projects,**

◇ **with remarkable innovations:**

- **linear FFAG, non-scaling FFAG, scaling FFAG beam line, ...**
- **quasi-synchronous serpentine acceleration ...**

• **A period known as "The Rebirth of the FFAG"**

¿ Why FFAG technology ?

• They are ring accelerators: that saves on (expensive) RF systems

¡ this is why ring accelerators have been invented ! ... a century ago

• They don't require ramping magnetic fields to accelerate, thus such thing as dB/dt limiting the acceleration rate is a non-concern;

- for instance: acceleration to 590 MeV in PSI FFA (cyclotron) takes 180 turns

- main limitations are: amount of RF; beam dynamics principles

• FFAG optics is strong focusing optics

→ beams manipulated have minimal transverse dimensions (∼ synchrotrons)

→ magnetic and RF systems have minimal aperture

• FFAG optics has large dynamical acceptance → efficient use of aperture

¿ Why FFAG technology ? (cont'd)

• In its 1950s 'scaling' version, FFAG optics is zero-chromatic: optics does not depend on momentum

→ large momentum acceptance,

→ allows manipulation and/or acceleraton of beams featuring large momentum spread (*cf.* PRISM)

• In its 1990s 'non-scaling' version, FFAG optics

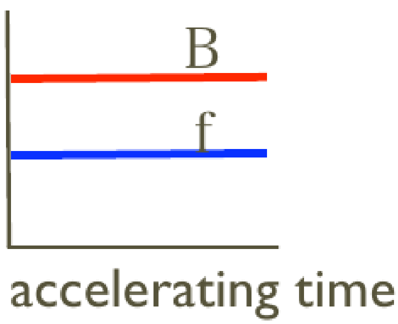
- has a very large dynamical acceptance
- very compact radial excursion (cm vs. meter)

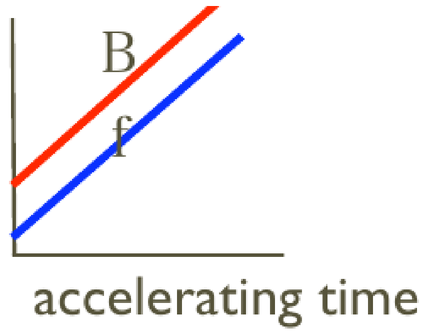
→ much smaller magnets - simple quadrupoles

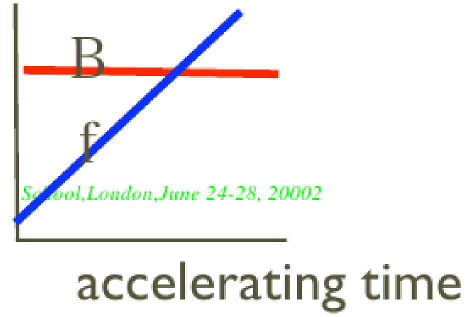
• In both techniques, 'serpentine' quasi-isochronous acceleration

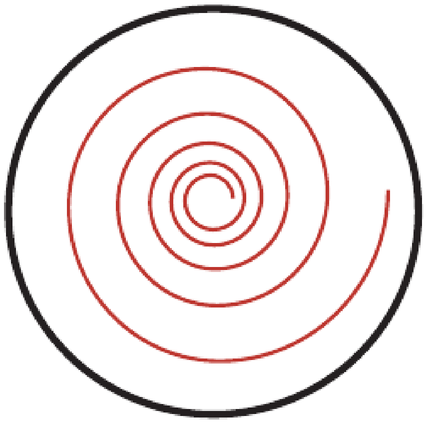
- has been demonstrated
- has the potential for cyclotron-style CW acceleration.

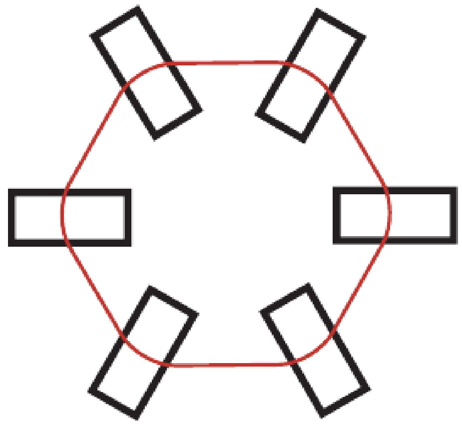
Principle

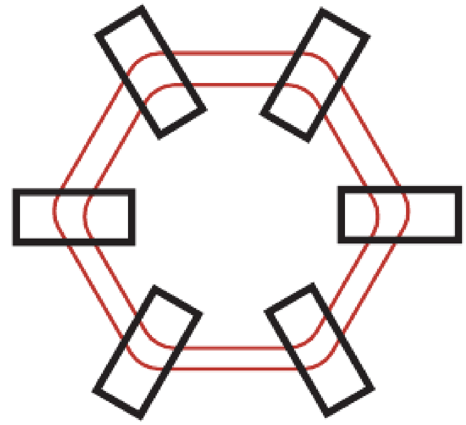






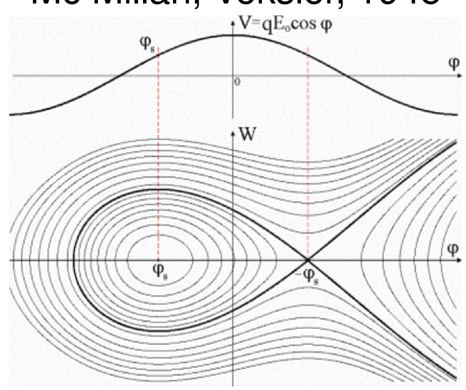






CW (High $\overline{I}$)
Limited max. Energy
Invented by
Ernest O. Lawrence,
1930

Slow acceleration (Low $\overline{I}$)
Reduced 6D acceptance
Principle of “phase stability”
Mc Millan, Veksler, 1945

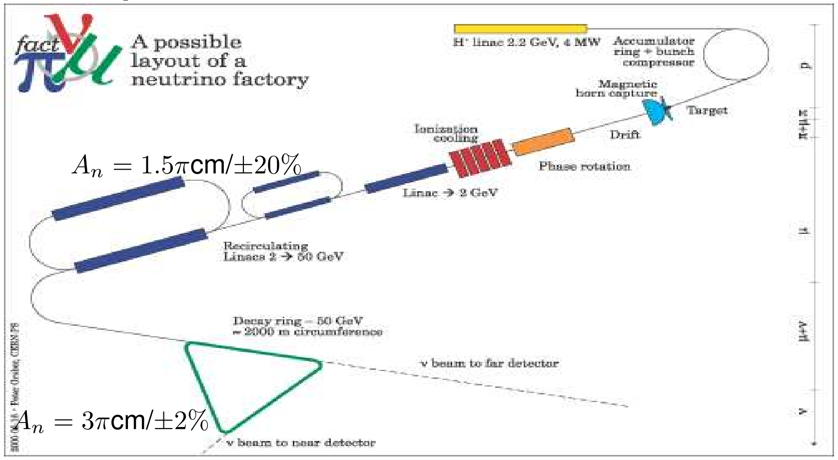


Fast acceleration (High $\overline{I}$)
Huge 6D acceptance
Versatility / beam
manipulations
An invention by
Symon/Okawa/Kolomensky
1954

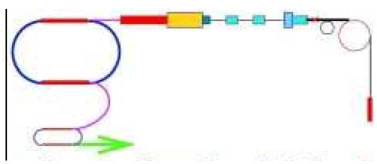
2 The Neutrino Factory; Muon Collider - Rebirth of the FFAG

It has triggered a strong activity in the domain of FFAG design, and lead to the development of new concepts.

Europe NuFact



US NuFact



Study 2 Costs ….

Muon Collaboration

- Study I, II ν-Factory – feasible but too expensive
- Biggest cost item: acceleration (~600M$)

Table A.1: Construction Cost Rollup per Components for Study-II Neutrino Factory. All costs are in FY01 dollars.

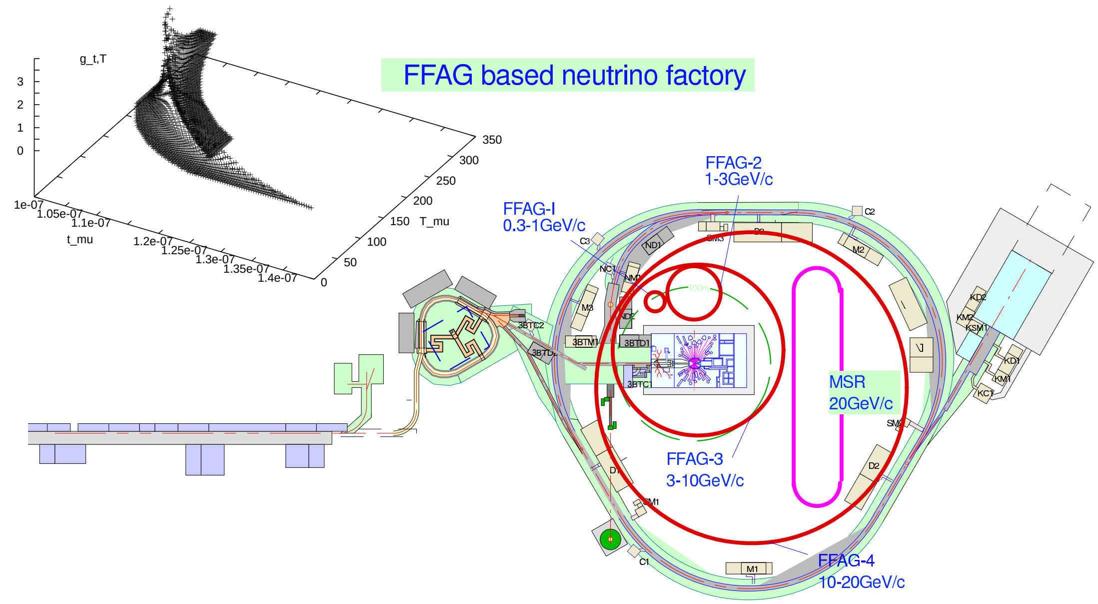
System	Magnets ($M)	RF power ($M)	RF cav. ($M)	Vac. ($M)	PS ($M)	Diagn. ($M)	Cryo ($M)	Util. ($M)	Conv. Facil. ($M)	Sum ($M)
Proton Driver	5.5	7.0	66.1	9.8	26.6	2.2	28.5		21.9	167.6
Target Systems	30.3			0.8	3.5	8.0	18.8		30.2	91.6
Decay Channel	3.1			0.2	0.1	1.0	0.2			4.6
Induction Linacs	35.0		90.3	4.4	163.3	3.0	3.6		19.5	319.1
Bunching	48.8	6.5	3.2	2.7	2.1	5.0	0.3			68.6
Cooling Channel	127.6	105.6	17.7	4.3	4.8	28.0	9.5		19.5	317.0
Pre-accel. linac	46.3	68.4	44.1	7.5	3.0	6.0	13.6			188.9
RLA	129.0	89.2	63.4	16.4	5.6	4.0	28.9		19.0	355.5
Storage Ring	38.5			4.8	2.2	29.0	4.8		28.1	107.4
Site Utilities								126.9		126.9
Totals	**464.1**	**276.7**	**284.8**	**50.9**	**211.2**	**86.2**	**108.2**	**126.9**	**138.2**	**1,747.2**

The Europe and the two US NuFact studies propose to accelerate muons up to the storage energy (20 or 50 GeV) by means of one or two 4- or 5-pass RLA's. RLA's are complicated machines (spreaders, combiners), hence expensive.

Japan NuFact at JPARC

J-Parc: 50-GeV, $3.3\,10^{14}$ ppp at 0.3 Hz (15 μA) / 0.75 MW
Four muon FFAG's : 0.2-1 GeV, 1-3, 3-10 (SC), 10-20 (SC).
No cooling, compact (R≈200m)

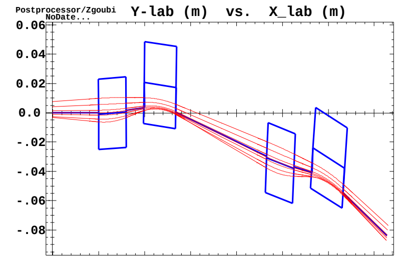
30ns/300±50% MeV bunch

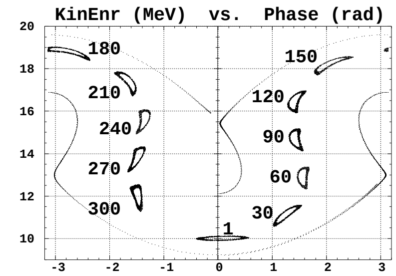


Acceleration rate is lower than RLA, requires larger distance, but, acceptance is larger both transversally (twice : DA $3\ \pi$cm norm. at $\delta p = 0$) and longitudinally (≈ 5 eV.s). Hence achieve comparable production rate : $\approx 10^{20}$ muon decays per year (1 MW p power).

US-Study-2a : the linear FFAG bifurcation

- FFAG based on linear optical elements (quadrupoles)
- orbits no longer scale, tunes are allowed to vary with energy





This has a series of consequences :

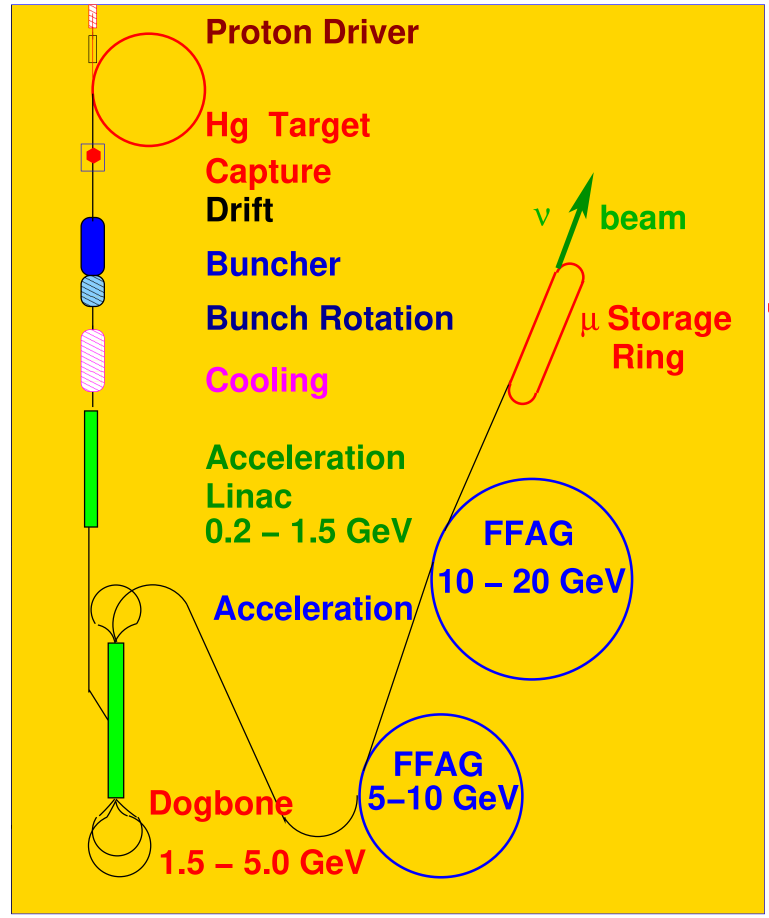
- $R/\rho < 2$ - this decreases the machine size compared to classical (scaling) FFAG

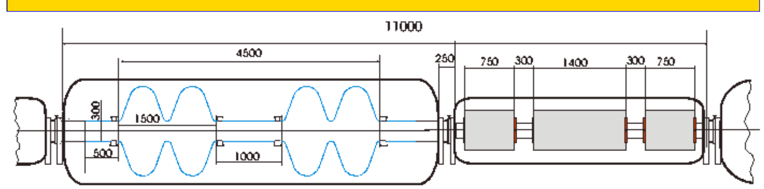
- horizontal beam excursion is reasonable (small D_x)
$\rightarrow$ **magnets apertures are much smaller**

- yields **large transverse acceptance** $\leftarrow$ fields are linear (3πcm achieved)

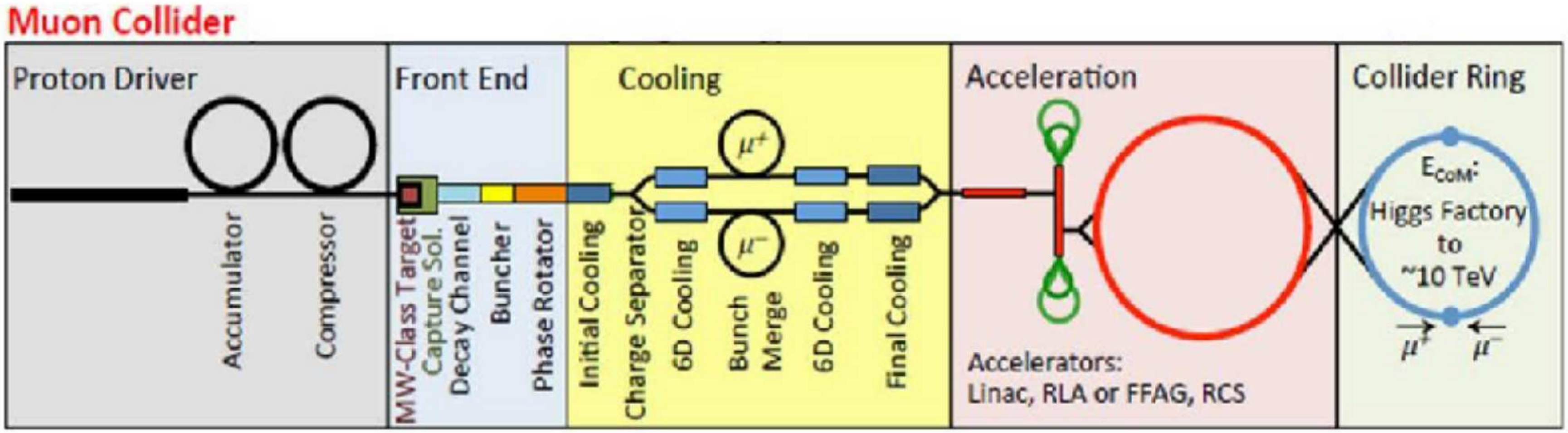
- small δTOF over energy span, allows **fast acceleration** high gradient RF (200 MHz type SCRF cavities)

- Above 5 GeV, non-scaling linear FFAG method yields **lower cost/GeV than RLA**.





Muon collider $\mu^+ \leftrightarrow \mu^-$



- **FFA options:**

- Proton beam production

- Fast acceleration of muons: compact rings with lots of RF, or compact RLAs

(pulsed synchrotron is the baseline)

- vertical FFA collider ring lattice

FLASH BACK

3 MURA electron FFAGs

• Motivations for "MURA", in the early 1950s

Midwest Universities Research Association

- Stimulate accelerator R/D for high energy physics, and build accelerators ! in the Midwest

- Explore alternate routes to AG synchrotrons, high intensities

• A major contribution to accelerator science [?]

(i) beam stacking,

(ii) Hamiltonian theory of longitudinal motion,

(iii) colliding beams (in itself a quite old idea),

(iv) storage rings (independently invented by O'Neill),

(v) spiral-sector geometry used in isochronous cyclotrons,

(vi) lattices with zero-dispersion and low-β sections for colliding beams,

(vii) multiturn injection into a strong-focusing lattice,

(viii) first calculations of the effects of nonlinear forces in accelerators,

(ix) first space-charge calculations including effects of the beam surroundings,

(x) first experimental measurement of space-charge effects,

(xi) theory of negative-mass and other collective instabilities and correction systems,

(xii) the use of digital computation in design of orbits, magnets, and rf structures,

(xiii) proof of the existence of chaos in digital computation, and

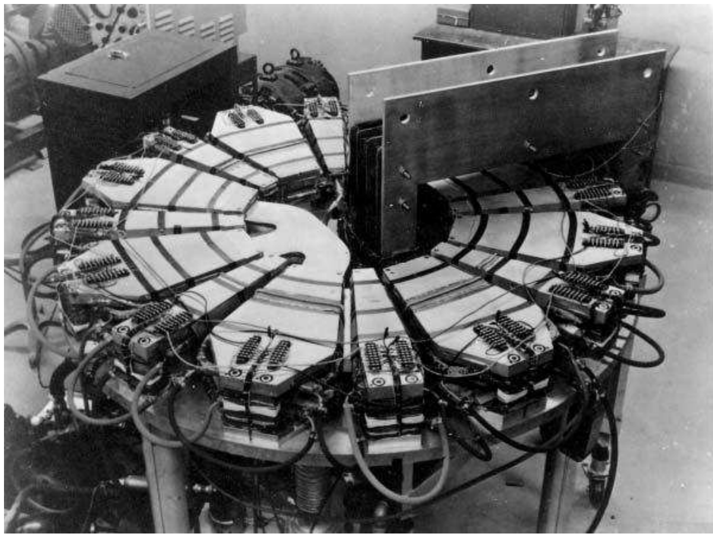
(xiv) synchrotron-radiation rings

• The first model, radial sector FFAG, "MARK I"

◇ **Main features : fixed field ring, $B = B_0(r/r_0)^K \mathcal{F}(\theta)$, strong focusing, scaling gap**

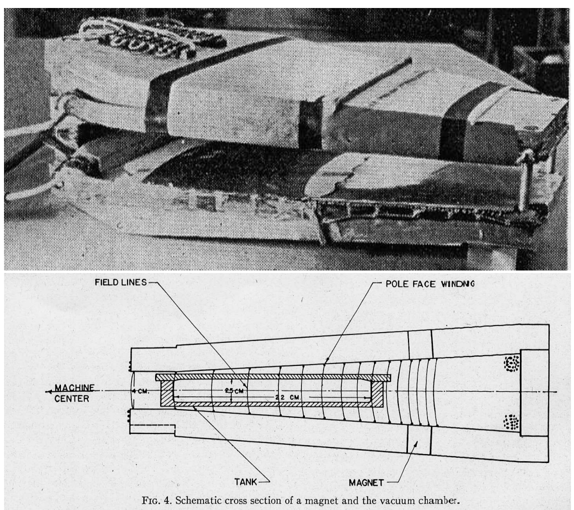
◇ **Objectives : demonstrate the FFAG principle. Studies included optics, injection, RF manipulations, effects of misalignments, exploring resonances.**

◇ **First beam 1956.**



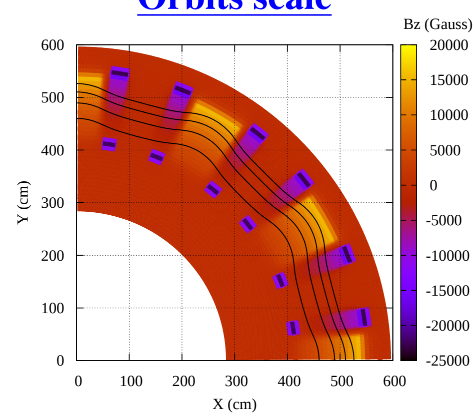
FFAG ring parameters

$E_{inj} - E_{max}$	*keV*	**25 - 400**	{*small size, easy to build* {$B\rho/10^{-3} : 0.54 \rightarrow 2.52$
orbit radius ($\mathcal{C}/2\pi$)	*m*	**0.34 - 0.50**	
Optics			
lattice		**FD**	
number of cells		**8**	*4.41 deg. drifts*
field index K		**3.36**	$g \propto r$ *& pole-face windings*
ν_r / ν_z		**2.2-3 / 1-3**	
Magnet	**radial sector**	$B = B_0(r/r_0)^K F(\theta)$	
θ_F, θ_D	*deg*	**25.74, 10.44**	*sector angles*
Acceleration	**Started with betatron yoke...**		
swing	*Gauss*	**40 - 150**	
	... added RF system, later		
freq. swing	*MHz*	**10 in [35, 75] MHz**	
gap voltage	*V*	**50**	

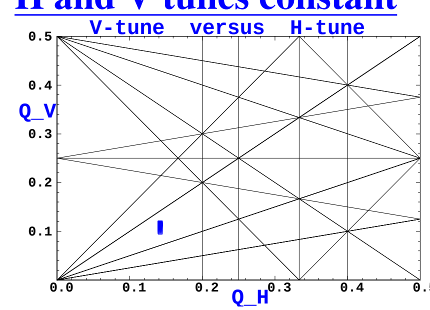


F magnet, $B > 0$, H-focusing
scaling gap g∝r

Orbits scale



H and V tunes constant

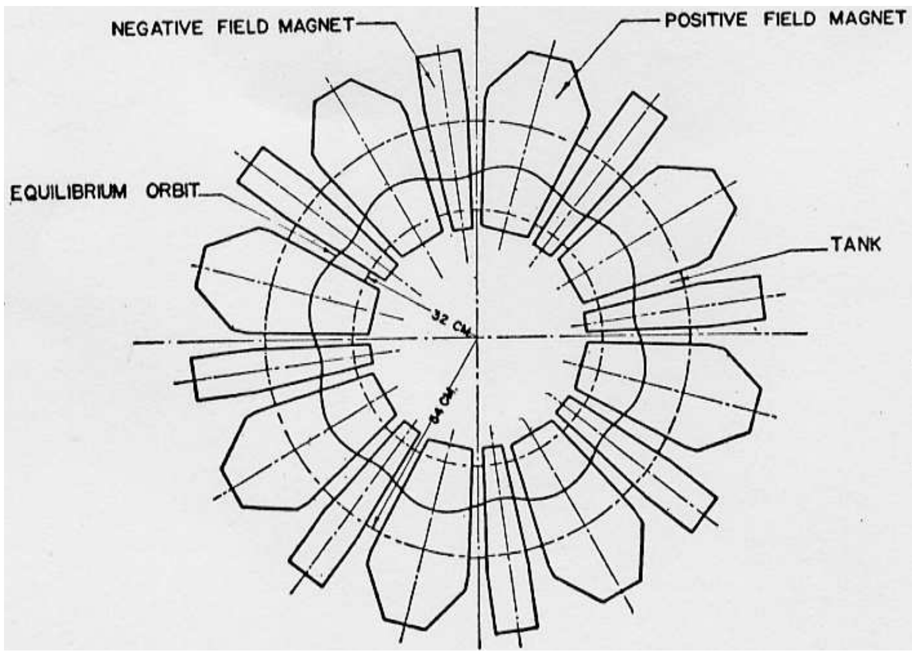


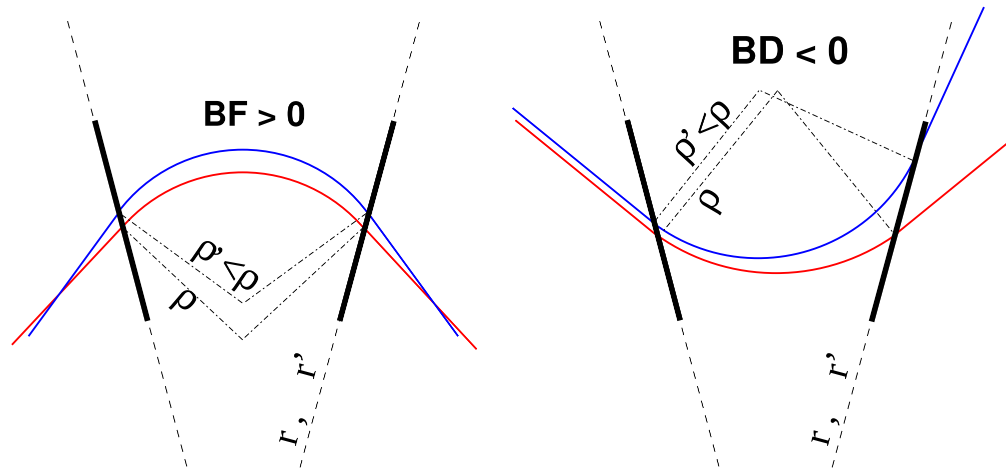
• **Basic theory**

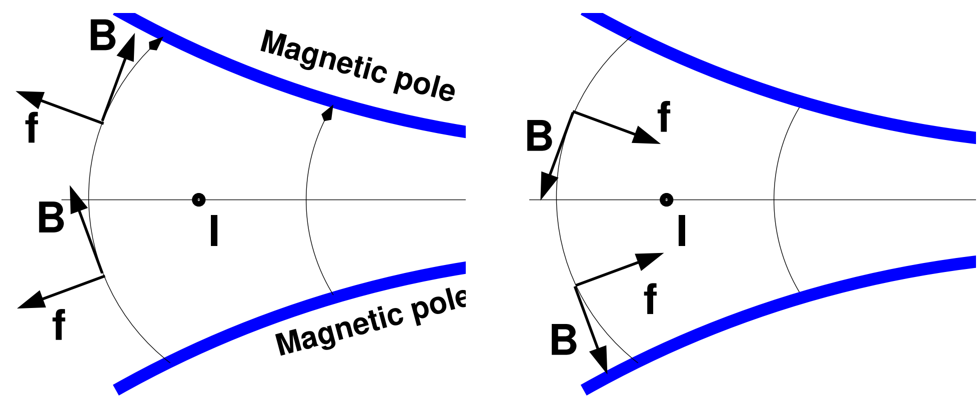
◇ **Combined function optics**

• **A rule that yields the orientation of $\vec{F}$:**

• $Id\vec{l}$ **,** $\vec{B}$ **and** $\vec{F}$**, in that order, form a direct triedra**







(in this sketch I assume field obtained from pole shaping, just for simplicity)

• Solution of the motion across a combined function magnet

◇ **A reference trajectory can be defined, characterized by** $B_0\rho_0 = \frac{p_0}{q}$

◇ **The equations of small amplitude motion** $(x = \rho - \rho_0, y)$ **of a particle, in the Serret-Frenet frame attached to that reference curve, are derived from the Lorentz force equation**

$$\frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}$$

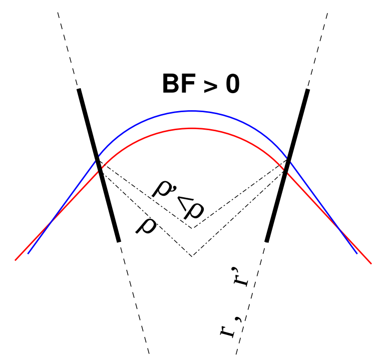
using a transverse expansion of the magnetic field $\vec{B}(s)$ **along the trajectory :**

$B_x = -n\frac{B_0}{\rho_0}y$ ***[+ non-linear terms],*** $\quad B_y = B_0(1 - n\frac{x}{\rho_0})$ ***[+ non-linear terms]***

◇ **In expanding** $\vec{B}$ **the field index has been introduced :**

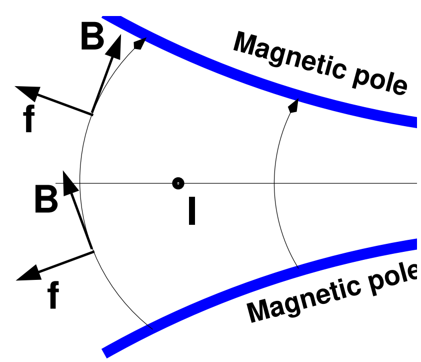
$$n = -\frac{\rho_0}{B_0}\frac{\partial B}{\partial x}$$

The FFAG index $K = \frac{r}{B}\frac{\partial B}{\partial r}$ **(of** $B = B_0(\frac{r}{r_0})^K$ **) relates to** n **by** $\boxed{K \approx -nr/\rho}$**.**



◇ **Calculations (found in text books) lead to the linear approximation :**

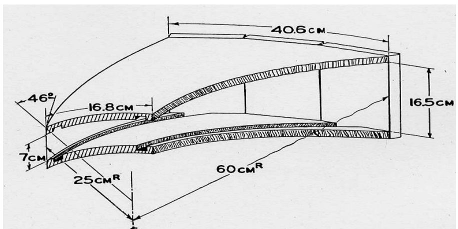
$$\left|\begin{array}{l} \frac{d^2x}{ds^2} + \frac{1-n}{\rho_0^2}x = \frac{1}{\rho_0}\frac{\Delta p}{p} \\ \frac{d^2y}{ds^2} + \frac{n}{\rho_0^2}y = 0 \end{array}\right.$$



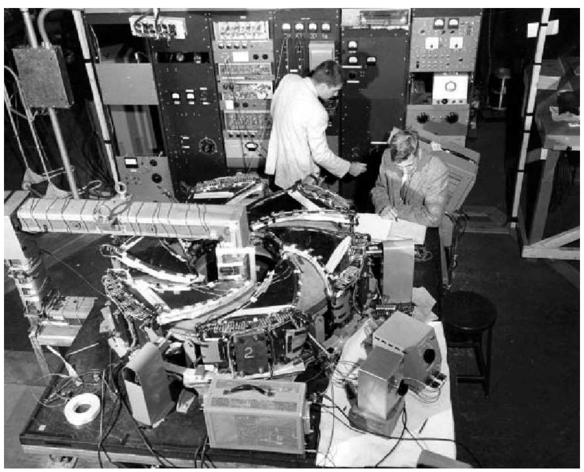
• Second model, spiral sector FFAG, "MARK V" - Thomas Focusing

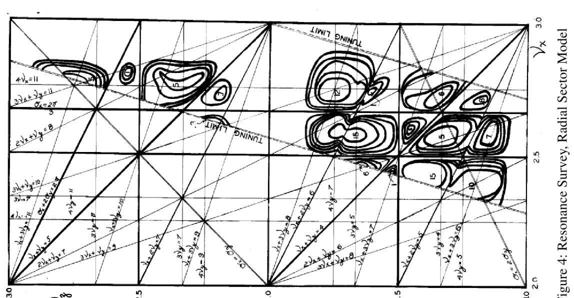
◇ **The idea in the spiral FFAG was to avoid the "wrong sign" curvature and bring the circumference factor $C = R/\rho$ close to 1. The wedge angles provides the vertical focusing.**
◇ **R&D objectives : spiral FFAG POP - first extensive use of computers to determine magnetic field and machine parameters ; long-term orbit stability ; RF acceleration methods.**

First operation Aug. 1957 at the MURA Lab., Madison.



Spiral dipole, $B > 0$,
H-focusing
scaling gap g∝r





MARK V PARAMETERS

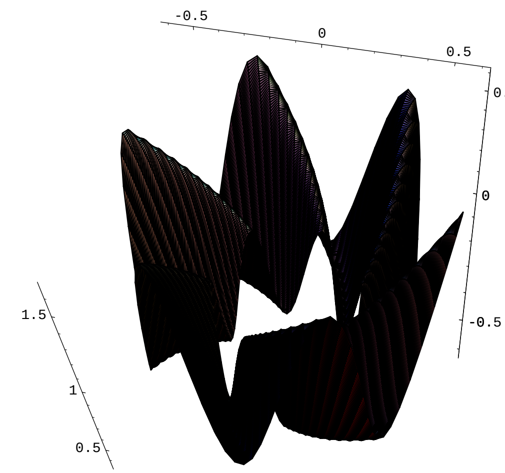
$E_{inj} - E_{max}$	*keV*	**35 - 180**	{ *reasonable size magnets*
orbit radius	*m*	**0.34 - 0.52**	**spiraling orbit**
E_{tr} / r_{tr}	*keV / m*	**155 / 0.49**	{ *RF exprmnts at* $\gamma_{tr} = (1+K)^{1/2}$
Optics	**strong focusing, scaling**		
lattice		**N spiral sectors**	
number of sectors		**6**	
field index K		**0.7**	{ *coil windings, tunable 0.2-1.16*
flutter F_{eff}		**1.1**	*tuning coils / 0.57 - 1.60*
ν_r / ν_z		**1.4 / 1.2**	*tunable*
β_r / β_z	*m*	**0.45-1.3 / 0.6-1.4**	*min-max*
Magnet	**spiral sector,** $B = B_0(\frac{r}{r_0})^K \mathcal{F}(N(\tan\zeta \ln\frac{r}{r_0} - \theta))$		
ζ	*deg*	**46**	*edge to radius angle*
gap	*cm*	**16.5 - 7**	g/r =*Cte*
Injection		**cont. or pulsed**	*e-gun + e-inflector*
Acceleration		betatron and RF	*extensive RF tests*

• On the optics in the spiral FFAG

◇ The following form for the field preserves the scaling property in an N-periodic spiral FFAG:

$$B(r,\theta)|_{z=0} = B_0 \left(\frac{r}{r_0}\right)^K \ \mathcal{F}\left(N(\tan\zeta \times \ln\frac{r}{r_0} - \theta)\right)$$

$\mathcal{F}$ is the axial modulation of the field ("flutter"). One can for instance think of
$\mathcal{F} = 1 + f \sin\left(N(\tan\zeta \ln\frac{r}{r_0} - \theta)\right)$, $f \approx 0.25$.

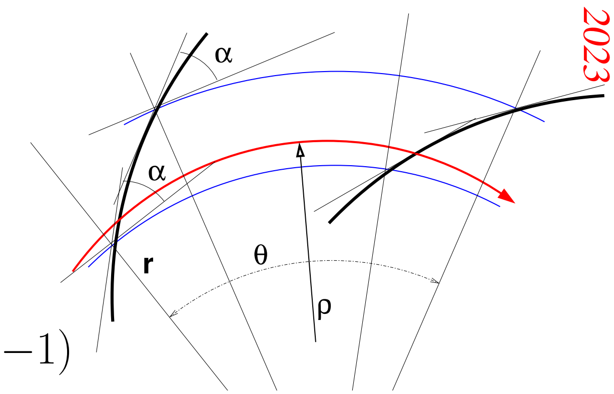


- The logarithmic spiral edge $(r = r_0 \exp((\theta - \theta_0)/\tan\zeta)$ ensures constant angle between spiral sector edges and radius.
- The in and out wedge angles are different, V-defocusing, and V-focusing (larger), overall effect is vertical focusing.

◇ Effect field fall-off extent on vertical focusing

$$\begin{pmatrix} x \\ x' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ \frac{\tan\epsilon}{\rho} & 1 \end{pmatrix} \begin{pmatrix} x_0 \\ x'_0 \end{pmatrix}, \begin{pmatrix} y \\ y' \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ -\frac{\tan(\epsilon-\psi)}{\rho} & 1 \end{pmatrix} \begin{pmatrix} y_0 \\ y'_0 \end{pmatrix},$$

where $\psi = \frac{I_1\cdot\lambda\cdot(1+sin^2(\epsilon))}{\rho\cdot cos(\epsilon)}$, with $I_1 = \int \frac{B_z(s)\cdot(B_0 - B_z(s))}{\lambda\cdot B_0^2}\cdot ds$, λ is the fringe field extent.

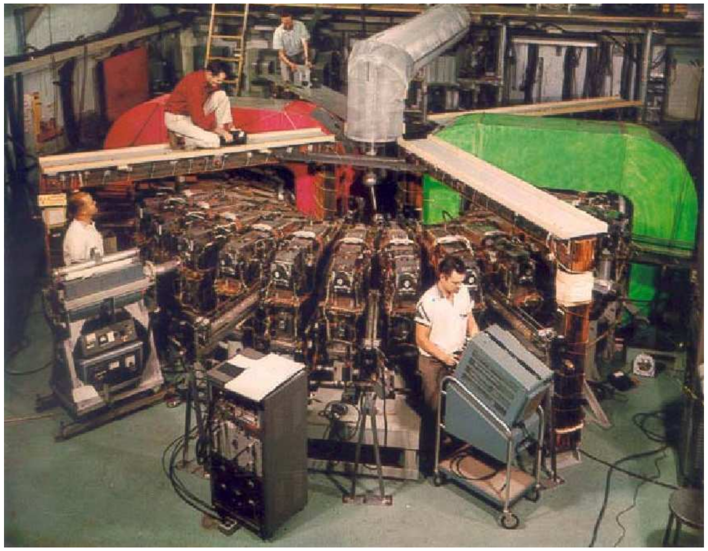


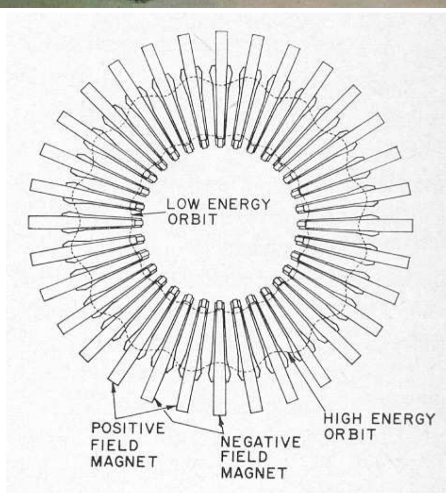
◇ Expansion of the equations of motion around the scalloped orbit in the linear approximation yields the approximate tunes

$$\nu_r \approx \sqrt{1+K}, \quad \nu_z \approx \sqrt{-K + F^2(1 + 2\tan^2\zeta)} \quad (F = \frac{\overline{B^2}}{\overline{B}^2} - 1 \xrightarrow{hard-edge} \frac{R}{\rho} - 1)$$

• Second radial sector, 50 MeV, 2-way

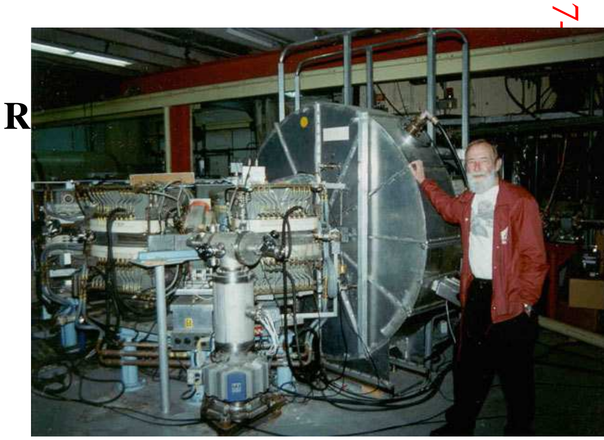
◇ **Preliminary studies early 1957.**
◇ **Study objectives : RF stacking, high circulating I, 2-way storage.**
◇ **First start Dec. 1959, 2-beam mode, 27 MeV ; disassembled in 60, magnets corrected ; second start Aug. 61, single beam, 50 MeV.**





FFAG parameters

$E_{inj} - E_{max}$	*MeV*	**0.1 - 50**	*reasonable size & beam life-time*
orbit radius	*m*	**1.20 - 2.00**	$B\rho$: $0.001 \rightarrow 0.17$ **(T.m)**
Optics			
lattice		**FODO**	$B \approx B_0(r/r_0)^K \cos(16\,\theta)$
number of cells		**16**	*32 magnets, 3.15 deg. drifts*
K		**9.25**	
ν_r / ν_z		**4.42 / 2.75**	
Magnet	**a single type, radial sector**		
θ**, core**	*deg*	**6.3**	
peak field	*T*	**0.52**	*at* r_{max}
gap	*cm*	**8.6**	
power	*kW*	**100**	
Injection	**e-gun + e-inflector**		
Acceleration		**betatron core or R**	
swing	*MHz*	**20 - 23**	
harmonic		**1**	
voltage p-to-p	*kV*	**1.3 - 3**	
cycle rep. rate	*Hz*	**60**	



• **Potentially allows two-way $\mu^+ - \mu^-$ acceleration!**

• **Ended up injector to the first dedicated light source storage ring - by MURA, Tantalus.**

4 Mid-1960s to 1990s - not much happened

- **After MURA, reduced activity. On alternative proposals in high power proton beam projects mostly.**

◇ ESS accelerator facility should serve two target stations, a 5MW 50 Hz and a 1MW 10Hz.

Structure : a 1.33GeV H- Linac followed by 2 accumulator rings that compress the beam pulse to 0.4μs (H- injection, 1000 turns), 2.5MW throughput each, 2.3e14ppp, 25Hz, radius 26m, Iav in each ring=63A.

Alternative FFAG scheme (early 1990's) : 0.4 GeV H- Linac followed by either 1.6 or 3 GeV FFAG.

Finally rejected, considered difficult option : injection (drifts too short), large magnets, high cost.

	beam power	MW	5	
	top E	GeV	3	
	ppp	GeV	2 10^{14}	
	rep. rate	Hz	50	. users' specif
	$< I >$	mA	1.7	
	max. radius	m	45	
injection				. multiturn, charge exchange
	E	MeV	430	. space charge tune shift constraint
	# of turns		260	. 320 μs
extraction				. single turn, fast kicker
	power gain with FFAG		7	. favors lower intensity (hence higher top E and – stronger magnets
FFAG optics				
	DFD triplet, K		21	. feasibility of the magnets was demonstrated / $\gamma_{tr} > \gamma_{max}$
	straight section length	m	10	. considered too short for injection
	number of sectors		20	
	ν_r / ν_z		5.8 / 2.8	
	radial excursion	m	2.7	. yields "very massive magnets"
	$B_{D,min}$ / $B_{F,max}$	T	-2 / 4	. SC magnets considered - MAFIA calculations performed.
RF				
	freq	MHz	0.8 - 1	
	voltage ($\times$10 cavities)	kV	20	

◇ Fermilab proton driver

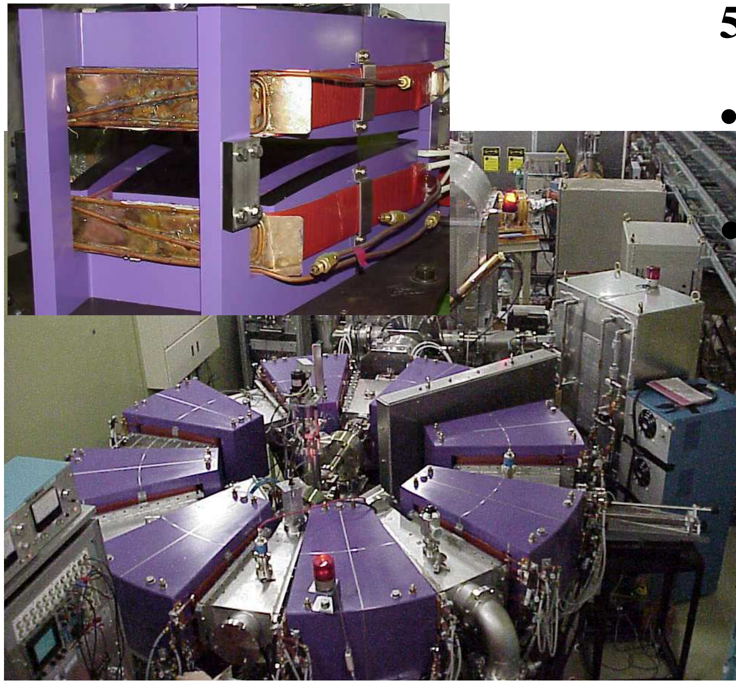
[W. Chou, P.F. Meads, FFAG03]

Two options 1 : synchrotron, Linac
Possible option 3 : FFAG, because it is supposed to feature large acceptance, high repetition rate.
Two optics explored : spiral (issue of RF space) and radial (magnets and β_V too big).

An additional drawback was : difficult to install in existing accelerator complex.

		p-Driver	FFAG radial sector	
Energy	GeV	8		. FFAG : need more than one ring ?
$E-injection$	MeV	600		
beam power	MW	0.5		
p/bunch		$3\ 10^{11}$		
circumference	m	474		
optics			DFD	
# of sectors			32	
K value			120	
radial extent	m		4.55	
rep. rate	Hz	15	105	. $\times 7 \rightarrow$ Needs new Linac
b/pulse (RF harmonic)		84	12	
p/pulse		$2.5\ 10^{13}$	$3.6\ 10^{12}$	. synchrotron $\xrightarrow{1/7}$ $FFAG$
RF frequency	MHz	53	7.5	. FFAG needs bunch rotation for inj. into 5
RF peak power	kW	200		
$< I >$	μA	60		. 7 times lower circulating current in FFAG
$\beta\gamma\epsilon_{x,z}$	10^{-6}m.rad	40 π		
$\beta\gamma\epsilon_l$	eV.s	0.2		
# of injections to MI (inj. time 400 ms)		6	42	. an advantage of Option 2 compared to Op
cost estimates	M$	230	130	. rough, for a 0.8-2.5 GeV, 5 MW design

BACK TO THE FUTURE



5 Proton Prototyping

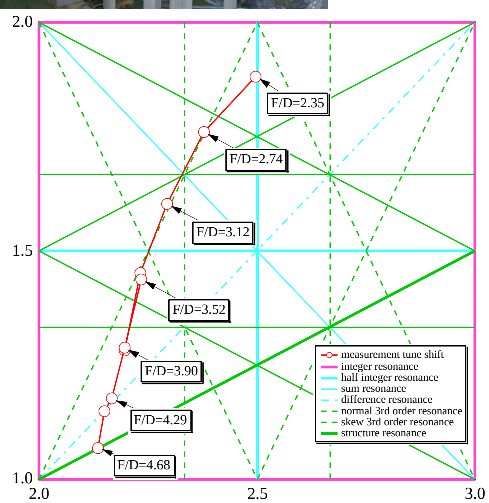
- **R/D at KEK: NuFact muon beams, p-driver, medical application ...**

- **POP - Proof of principle, the first proton FFAG**

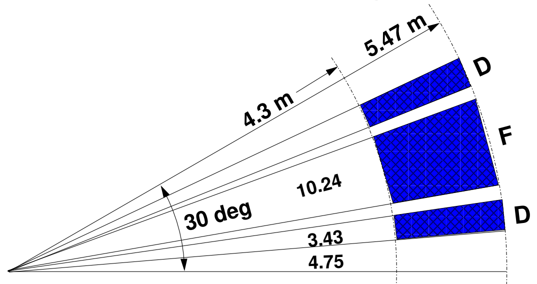
First beam Dec. 1999.

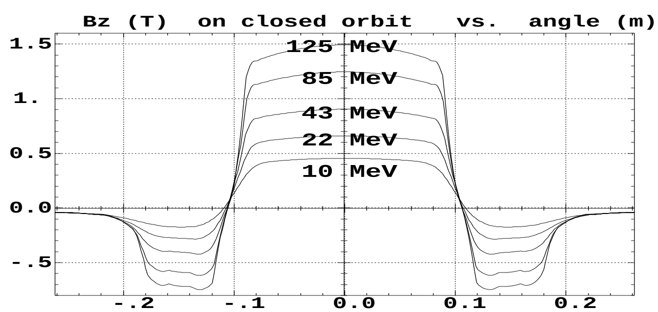
[Typical] data

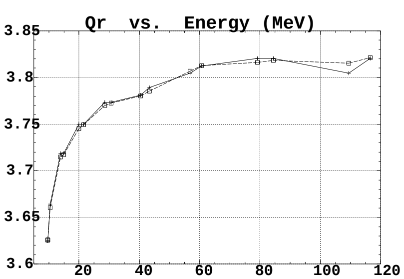
$E_{inj} - E_{max}$	**keV**	**50 - 500**	
orbit radius	**m**	**0.8 - 1.14**	
Optics			
lattice		**DFD**	
number of cells		**8**	
K		**2.5**	$(B = B_0(r/r_0)^K \mathcal{F}(\theta))$
$\beta_r,\ \beta_z$ **max.**	**m**	**0.7**	
$\nu_r\ /\ \nu_z$		**2.2 / 1.25**	*tunable via* B_F/B_D *ratio*
Magnet		**high field, non-linear gradient**	*sector triplet*
$\theta_D\ /\ \theta_F$**, core**	**deg**	**2.8 / 14**	
$B_D\ /\ B_F$	**T**	**0.04-0.13 / 0.14-0.32**	$r_{inj} \rightarrow r_{max}$
gap	**cm**	**30-9**	$gap = g_0(r_0/r)^K$
Injection		**multi- or single-turn**	{ *electrostatic inflector* + *2 bumpers*
Extraction		**massless septum** **exprmnt**	
Acceleration			
Amorphous MA cavity		**broad band, high $\vec{E}$ RF** ; **2-beam accel.**	
swing	**MHz**	**0.6 - 1.4**	
harmonic		**1**	
voltage p-to-p	**kV**	**1.3 - 3**	
cycle time	**ms**	**1**	*fast acceleration*
rep. rate	**kHz**	**1**	*high average current*
$\dot{B}$	**T/s**	**180**	

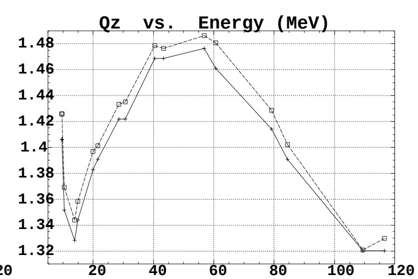


"return yoke free" magnet









• The 150 MeV ring at KEK

First operation 2003.

[Typical] data

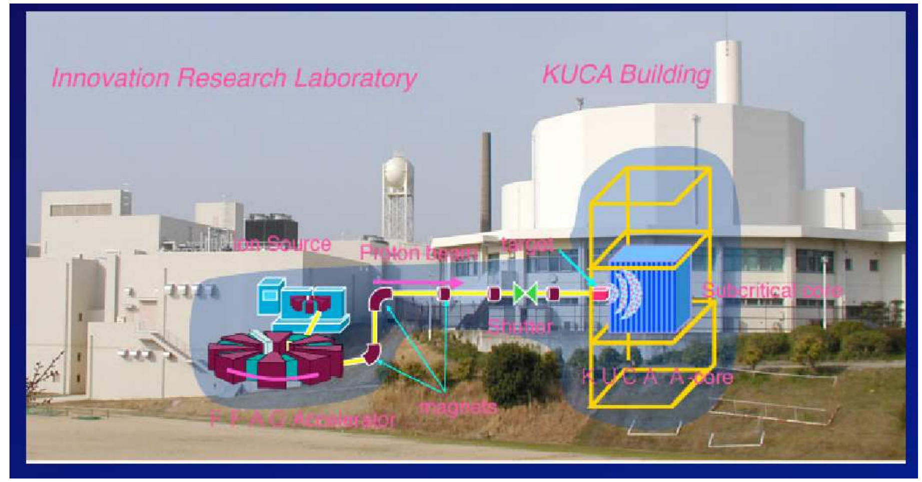
$E_{inj} - E_{max}$	**MeV**	**12 - 150**	
orbit radius	**m**	**4.47 - 5.20**	
Optics			
lattice		**DFD**	*9.5 deg. drift*
numb. of cells		**12**	
K		**7.6**	$(B = B_0(r/r_0)^K \mathcal{F}(\theta))$
β_r / β_z **max.**	**m**	**2.5 / 4.5**	
ν_r / ν_z		**3.7 / 1.3**	*tunable via* B_F/B_D *ratio*
$\alpha,\ \gamma_{tr}$		**0.13, 2.95**	$1/(1+K),\quad (1+K)^{1/2}$
$\mathcal{R}/\rho\|_{E_{max}}$		**5.4**	
Magnet	**Return yoke free magnet**		
θ_D / θ_F	**deg**	**3.43 / 10.24**	
B_D / B_F	**T**	**0.2-0.78 / 0.5-1.63**	$r_{inj} \to r_{max}$
gap	**cm**	**23.2 - 4.2**	*at* r_{inj} - r_{max} $(gap = g_0\left(\frac{r_0}{r}\right)^K)$
Injection		**multi-turn**	{ *B-septum + E-septum + 2 bumpers*
Extraction		**single-turn**	**fast kicker (1kG, 150 ns)**
Acceleration	*Amorphous MA,*	**broad band, high gradient RF**	
swing	**MHz**	**1.5 - 4.5**	
harmonic		**1**	
voltage p-to-p	**kV**	**2**	
ϕ_s	**deg**	**20**	
ν_s		**0.01 - 0.0026**	
$\dot{B}$	**T/s**	**300**	*fast acceleration*
rep. rate	**Hz**	**250**	*high average current*

KURRI KUCA - 2005 to Present

An ADS-R experiments, proton driver R/D

- **First coupling to an ADS-R core, March 2009, 100 MeV beam**
- **Thorium-loaded ADS-R experiment, March 2010 : 100 MeV, 30 Hz, 5 mW**

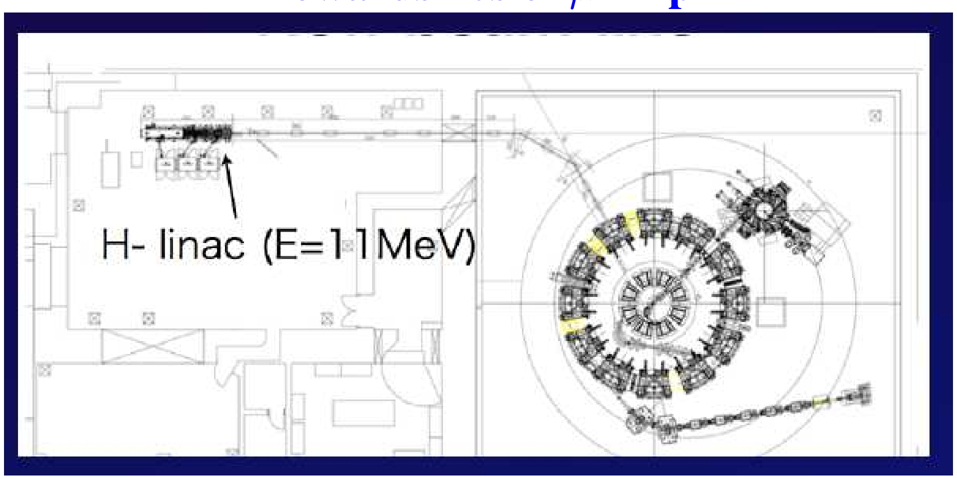
100-150 MeV proton, repetition rate 20-50 Hz



- **Upgrades :**

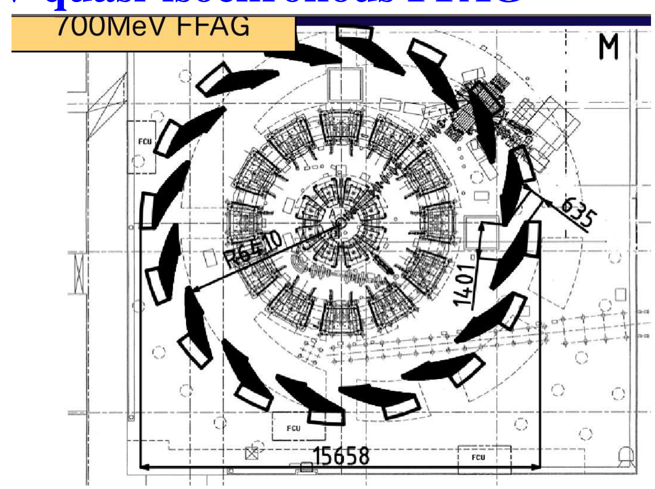
On-going : H- charge exchange injection

Towards 10s of μAmp

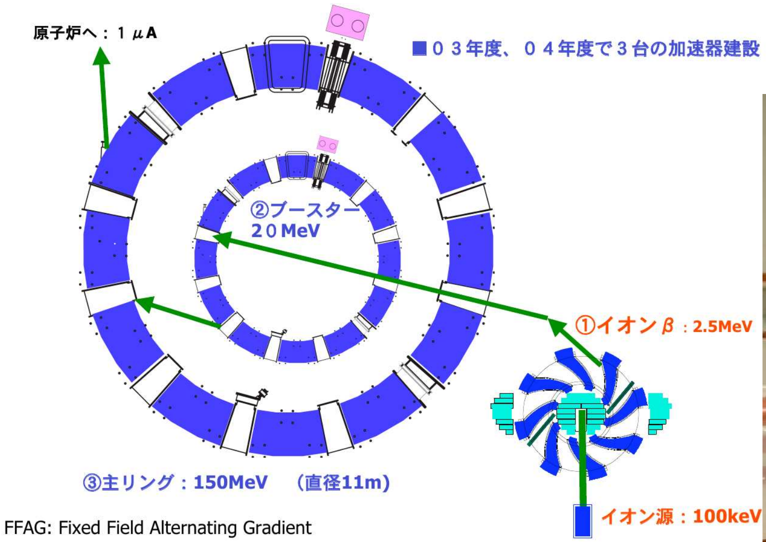


Planned : neutron flux increased by a factor 30.

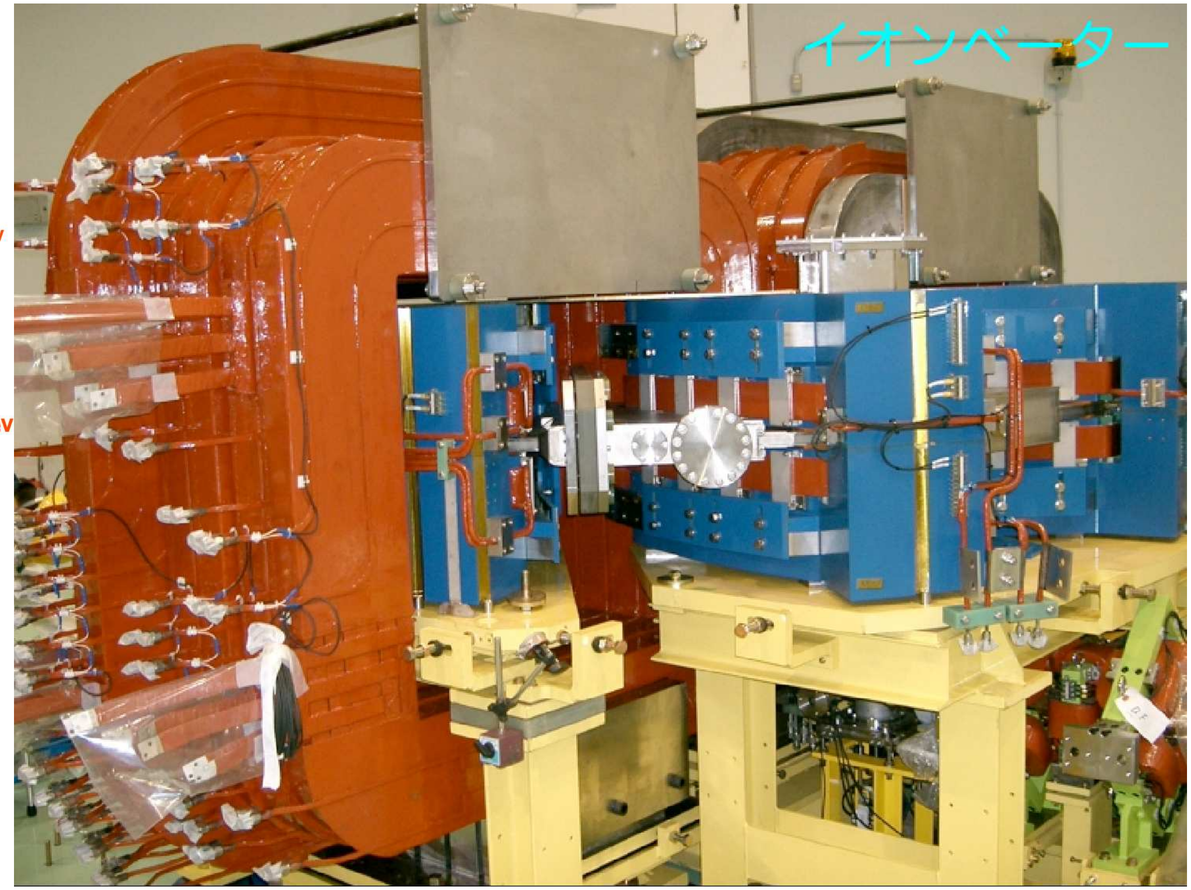
Options : additional 700 MeV spiral lattice FFAG, or 400 MeV quasi-isochronous FFAG



KURRI KUCA 3-ring cascade



100keV	2.5MeV	20MeV
2.5MeV	20MeV	150MeV
Spiral	Radial DFD	Radial DFD
Induction	rf	rf
8	8	12
2.5	4.5	7.6
coil	pole	pole
5.00	2.84	2.83
0.60m	1.42m	4.54m
0.99m	1.71m	5.12m

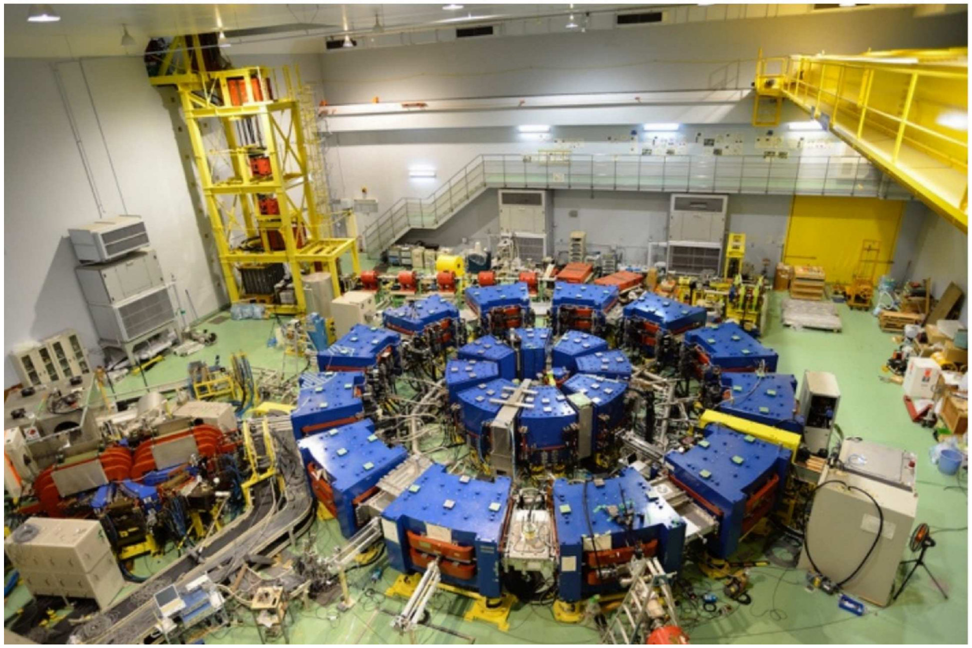


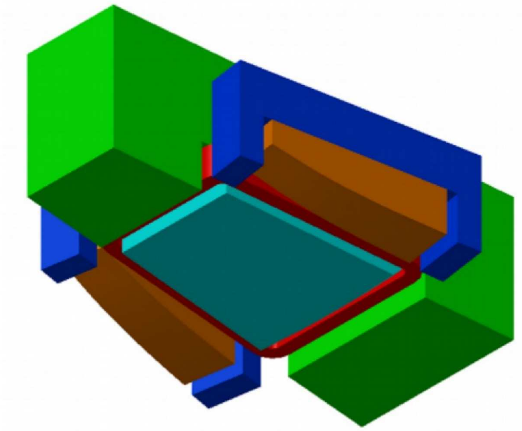
The magnet gap is non-scaling : parallel faces. Pole face windings control the r-dependence of the vertical tune.

ADS/reactor facility at KURNS (cont'd)

- **Today: muon beam plans**

KURNS 150 MeV FFAG main ring upgrade to 400 MeV for pion production (PP-Ring).





Ref.: https://accelconf.web.cern.ch/ipac2019/papers/moprb021.pdf

ERIT

- "Energy Recovery Internal Target", at KURRI, Kyoto University.

◇ A compact proton storage ring for the production of 10 MeV BNCT neutrons
◇ High neutron flux is needed at patient : $\approx 2\,10^{13}$neutrons in 30 minutes for typical tumor volume
◇ Today, a 5-10 MW reactor is used, there is needed for hospital environment compliant equipment : ERIT

Injector (425 MHz RFQ + IH-DTL)

H-, kinetic energy 11 MeV
Peak/average beam current 5 mA / $> 100\mu$A
Repetition rate 200 Hz, d.c. 2%

FFAG ring

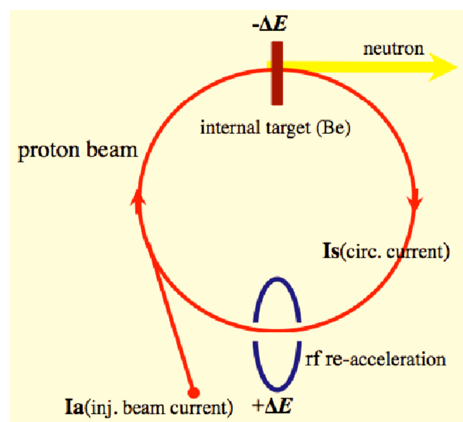
FDF lattice, 8 cells
H- injection on internal Be target $(5-10\mu$m thick)
proton energy 11 MeV
circulating current 70 mA

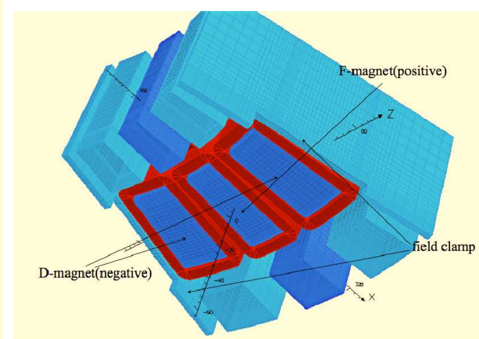
ERIT system

Beam survival 500-1000 turns
Target lifetime $>$ 1 month
ΔE / turn 70 keV

RF cavity

Operated CW, 100 kW input power
RF voltage / frequency 250 kV / 18.1 MHz
Harmonic number 5



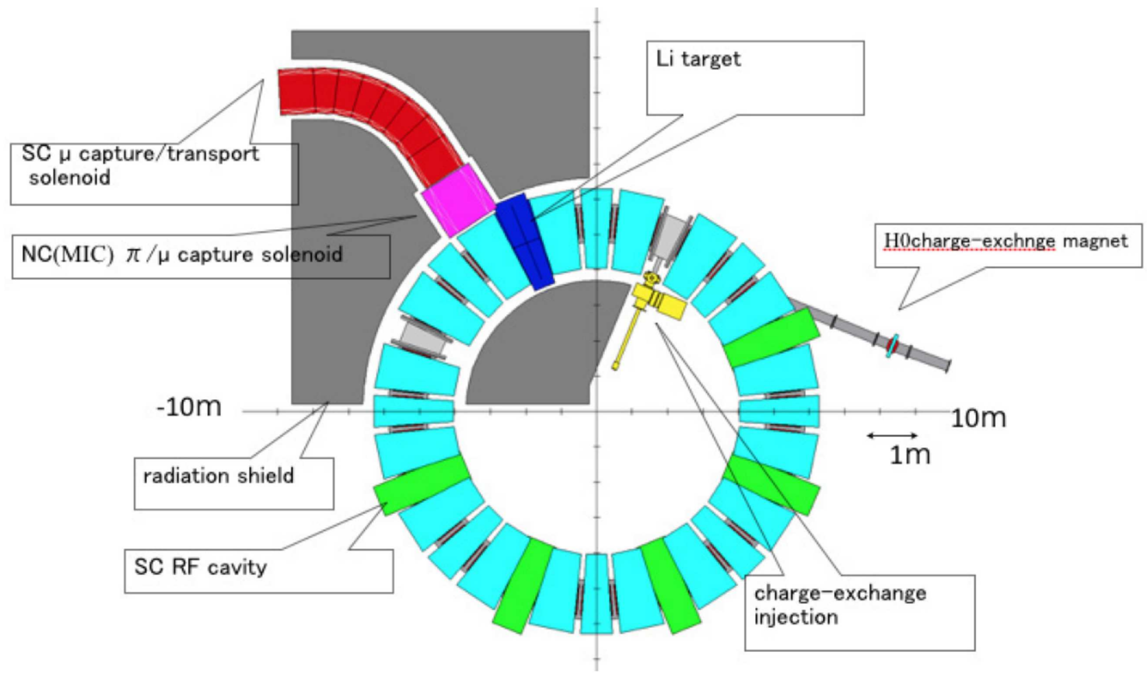


- **An intense negative muon source MERIT (Multiplex Energy Recovery Internal Target)**

◇ **An evolution of ERIT**

◇ **Muon beams for transmutation of long-lived fission products from nuclear plants.**

Ring configuration	H−FFAG
Energy range(MeV)	500-800
Magnetic rigidity(T.m)	3.633 -4.877
Lattice	FDF
Average radius(m)	5.044-5.5
Magnetic field(T):F	1.96-2.41
Magnetic field(T):D	1.71-2.11
Number of cell	8
Geometrical field index	2.43
Cell tune:H	0.212
Cell tune:V	0.180
Beta function(m) @SS:H	2.5
Beta function(m) @SS:V	2.8
Dispersion function(m)	1.5



Ref.: Y. Mori, et al.: Intense Negative Muon Facility with MERIT ring for Nuclear Transmutation. Proc. 14th Int. Conf. on Muon Spin Rotation, Relaxation and Resonance (μSR2017)

PRISM

- A muon bunch phase rotator

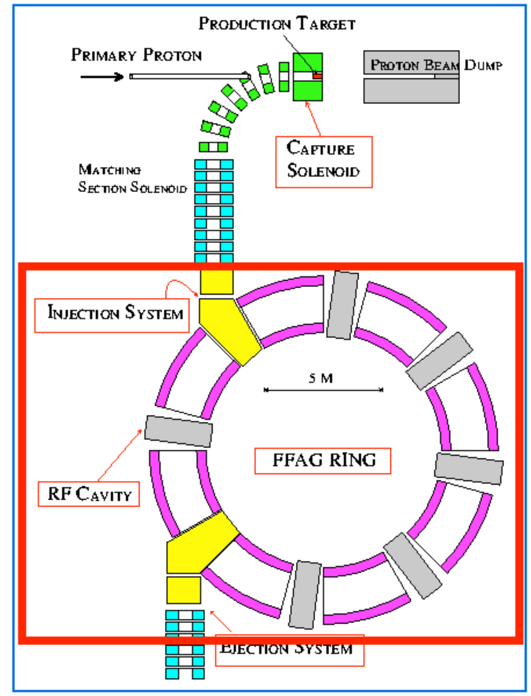
◇ An R/D program started in 2003

◇ FFAG used as phase rotator, for momentum compression

p=68MeV/c +/-20% down to +/-2% in 6 turns

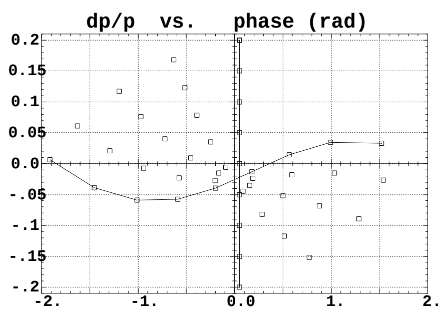
Advantage of FFAG optics : large geometrical acceptance, zero chromaticity

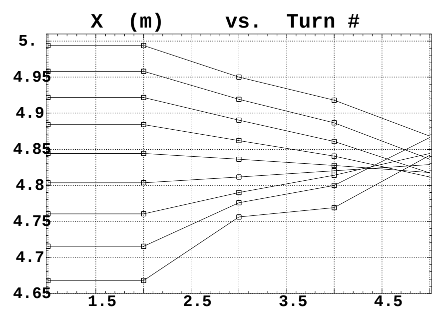
A difficult task : injection and extraction

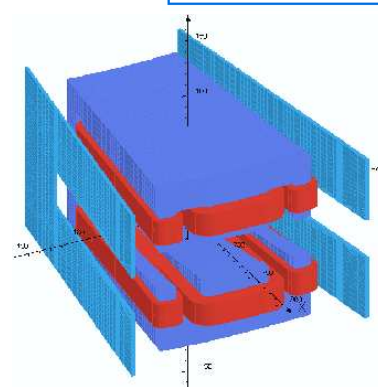


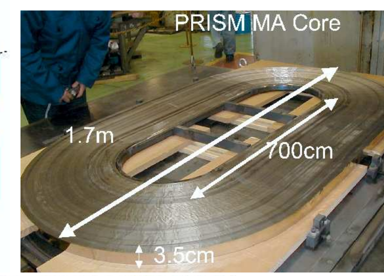
◇ FFAG ring characteristics :

- DFD lattice 14t triplet yoke, 120 kW/triplet
- K, B_F/B_D variable → quasi-decoupled ν_x, ν_z adjustments
- H / V apertures : 1 / 0.3 m
- acceptance : 4 π cm.rad × 0.65 π cm.rad
- RF : 5-gap cavity, 33 cm gap, 150-200 kV/m, 2MV/turn, saw-tooth waveform









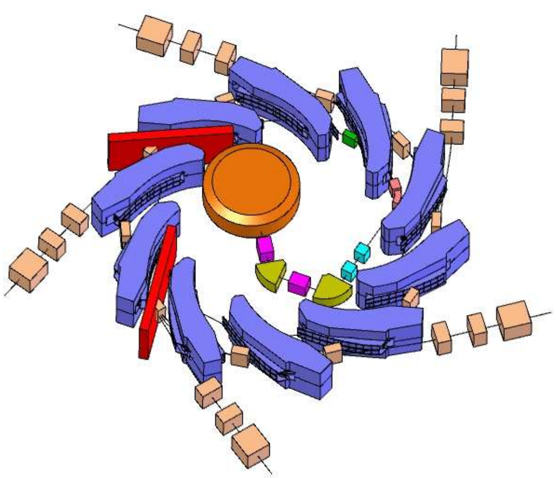
◇ 2005: downsized to 6 cells for POP,
- central orbit radius 3 meter
-2.1 MHz (h=5) RF, gap voltage 33 kV peak
- operated using 100 MeV/c alphas from an ^{241}Am source.

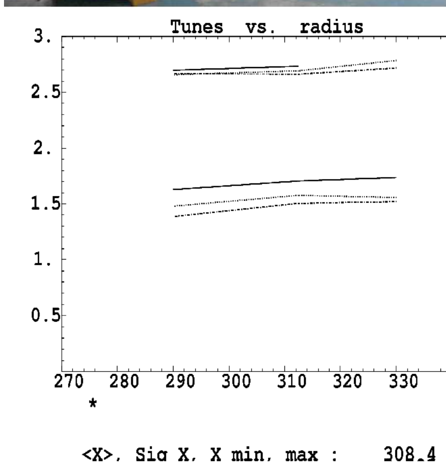
RACCAM

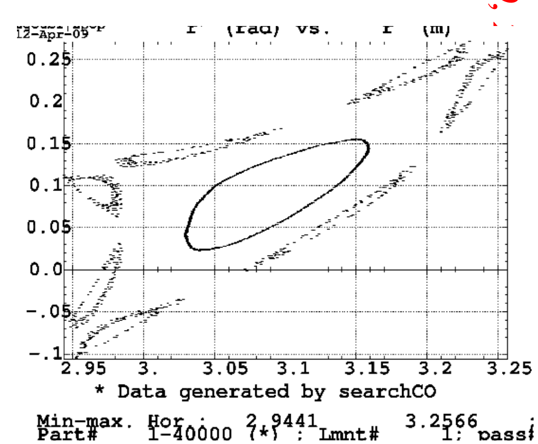
- Working frame : Neutrino factory R/D and medical applications.
  French ANR funding, 2006-2008.
- A feasibility study of a rapid-cycling, variable energy, spiral lattice scaling FFAG
- Magnet prototype (built by SIGMAPHI) proved { gap shaping spiral sector / scaling FFAG field, including flutter }

Tracking in measured field maps (3D Hall-probe, by SIGMAPHI) proved { constant tunes / large dynamical aperture }

- Outcome :
  - demonstration of gap shaping scaling spiral dipole feasibility. First of the kind.
  - a cost-effective multiple-beam delivery hadrontherapy installation.







Straight S-FFAG line

◇ **Scaling FFAG accelerators can be designed not only in a ring shape, but also with no overall bend.**
◇ **This requires a mid-plane guide field of the form**

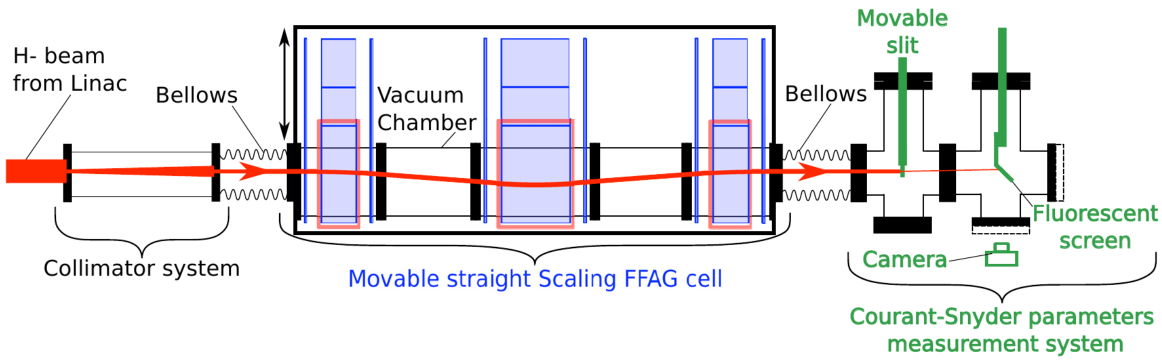
$$B_y(x,s) = B_0 e^{m(x-x_0)} F(s)$$

◇ **Similarly to the cylindrical (r,θ) case, B_0 is some reference field value, taken at some arbitrary reference x_0, $F(s)$ is a flutter function.**
$m = \frac{\rho}{B\rho}\frac{\partial B}{\partial x}$ **is the normalized field gradient.**

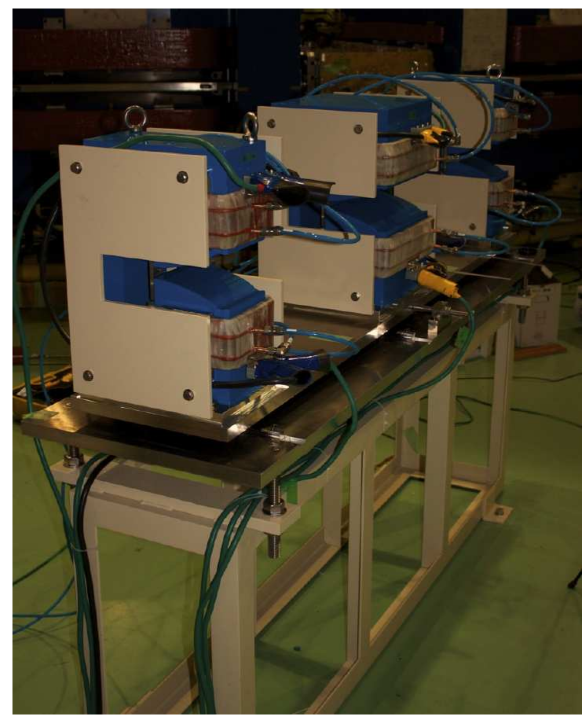
The experiment used the 11 MeV linac (injector of the 150 MeV FFAG). The FDF cell is moved horizontally (bellows) to match the incident beam momentum to the proper FFAG orbit.

The experiment measured the orbit location, optical functions including phase advances, for various momenta, and showed good agreement with outcomes of tracking in field maps.

TUPPC022 Proceedings of IPAC2012, New Orleans, Louisiana, USA



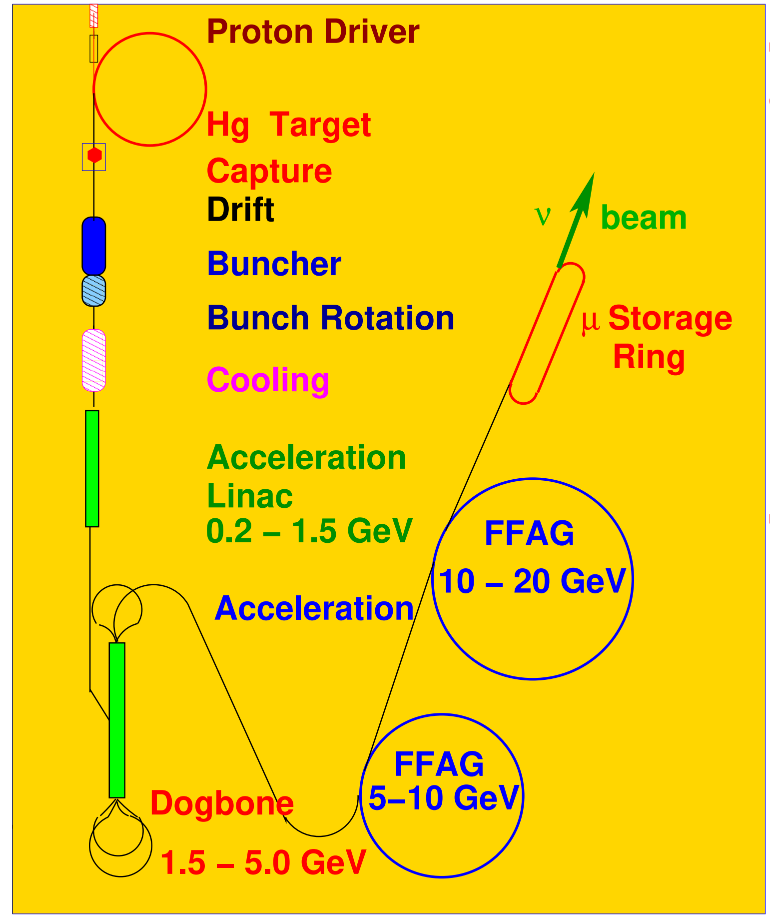
Type	FDF
m-value	11 m^{-1}
Total length	4.68 m
Length of F magnet	15 cm
Length of D magnet	30 cm
Max. B Field	0.35 T
Horizontal phase advance	87.7 deg.
Vertical phase advance	106.2 deg.

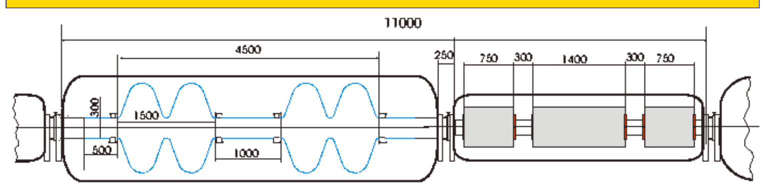


6 EMMA

Back to the neutrino factory, US-Study-2a : based on linear FFAG

- FFAG based on linear optical elements (quadrupoles)
- orbits no longer scale, tunes are allowed to vary with energy





This has a series of consequences :

• $R/\rho < 2$ - this decreases the machine size compared to classical (scaling) FFAG

• horizontal beam excursion is reasonable (small D_x)
$\rightarrow$ magnets apertures are much smaller

• yields large transverse acceptance $\leftarrow$ fields are linear (3πcm achieved)

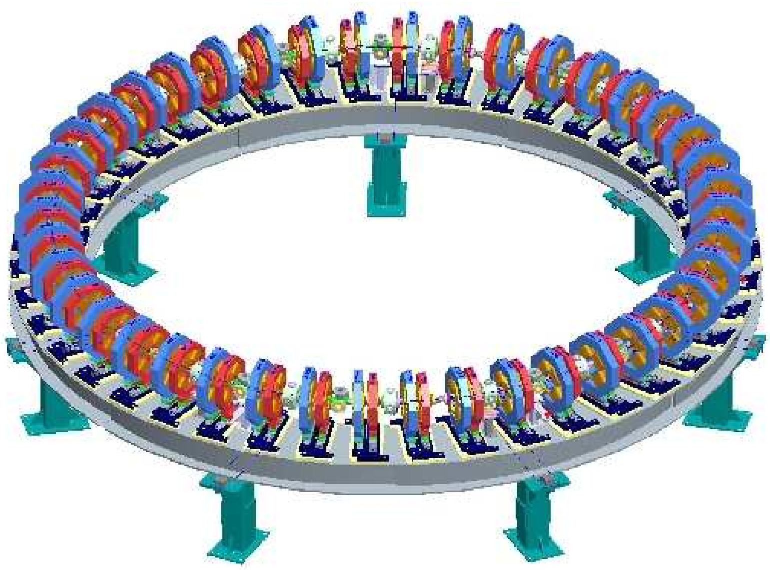
• small δTOF over energy span, allows fast acceleration high gradient RF (200 MHz type SCRF cavities)

• Above 5 GeV, non-scaling linear FFAG method yields lower cost/GeV than RLA.

• The EMMA experiment.

◇ **An experimental model to investigate the new concept of "linear FFAG" :**

- **linear magnets (quadrupoles) ⟶ yields huge acceptance**
- **fixed field ⟶ yields fast acceleration**
- **fast acceleration ⟶ requires a lot of RF, and fixed frequency, gutter acceleration**



A model of Study IIa FFAG
10 to 20 MeV
42 cells, doublet
pole-tip fields ≈ 0.2 *T*
apertures $\approx \phi 40$ *mm*
37cm cell length
16m circumference
1.3GHz RF
1 cavity every other cell

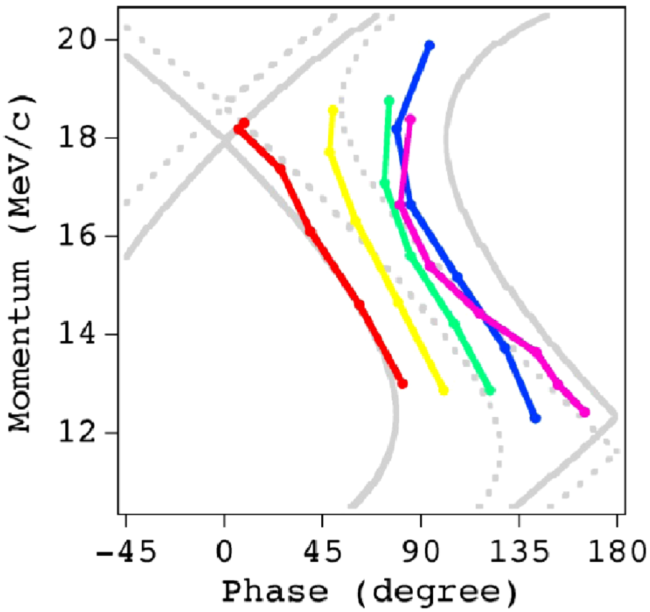
- **Launched in the frame of Neutrino Factory R&D**
- **An experimental model of muon accelerators**
- **International collaboration :**
  BNL, CERN, FNAL, LPSC, STFC, J.Adams Inst., Cockcroft Inst., TRIUMF
- **Recollection :**
  1999 : principle of linear FFAG optics, FNAL
  2001 : first e-model meeting, BNL
  2006 : project funded by "British Accelerator Science and Radiation Oncology Consortium",
  3.5 years : 04-2007 / 09-2010, £5.6M budget
- **Construction started at Daresbury, 04/2007, first beam planned summer 2009**

Beam due Autumn 2009

- Construction at Daresbury Lab. started in 2007
- Commissioning started in 2010
- "Serpentine" acceleration demonstrated in 2011

EMMA parameters

Energy range	*MeV*	10 - 20
number of turns		<16
circumference	*m*	16.568
Lattice		F/D doublet
No of cells		42
RF frequency	*GHz*	1.3
No of cavities		19
RF voltage	*kV/cav.*	20 - 120
RF power	*kW/cav.*	<2
Rep. rate	*Hz*	1-20



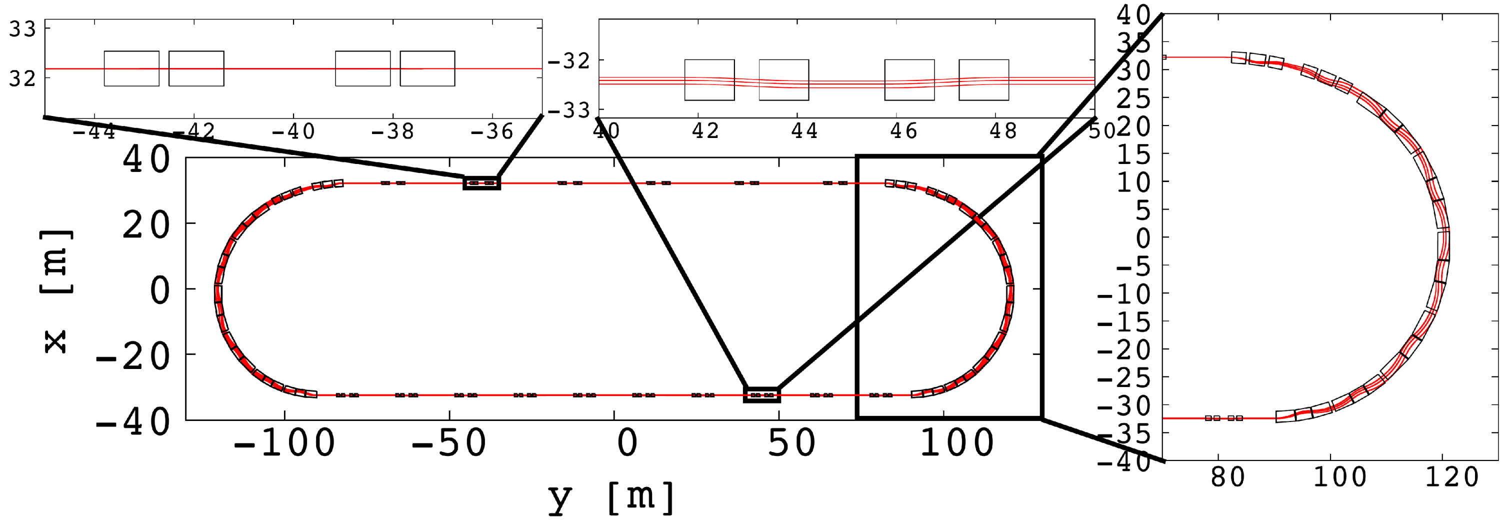
7 And more FFAG design studies

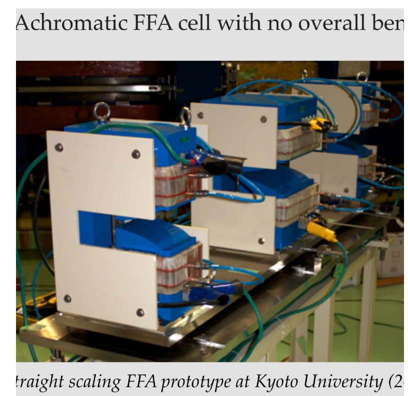
A *very limited* excerpt of what can be found in our Labs... See the bibliography for more, in particular the FFAG workshops.

• nuSTORM FFAG decay ring, J.-B. Lagrange et al. [IPAC2016]

◇ Neutrinos from STORed Muon beam (nuSTORM), the simplest implementation of a neutrino factory : pions are directly injected into a racetrack storage ring, where the circulating muon beam is captured.

FODO **FFA** **FFA arc** **FFA straight**





◇ The racetrack nuSTORM FFAG lattice with zoom on the straight section (top left) and on the arc section (right).

◇ The muon flux is key to successful neutrino experiment, so, FFAG optics allows ring with large momentum acceptance, $\sim \pm 20\,\%$.

- **Vertical FFAG [S. Brooks, PRST AB 16, 084001 (2013)]**

◇ **Vertical scaling optics was devised by K. Ohkawa (once known as the "smokatron"),**

◇ **Re-investigated recently [S. Brooks, prst-ab]**

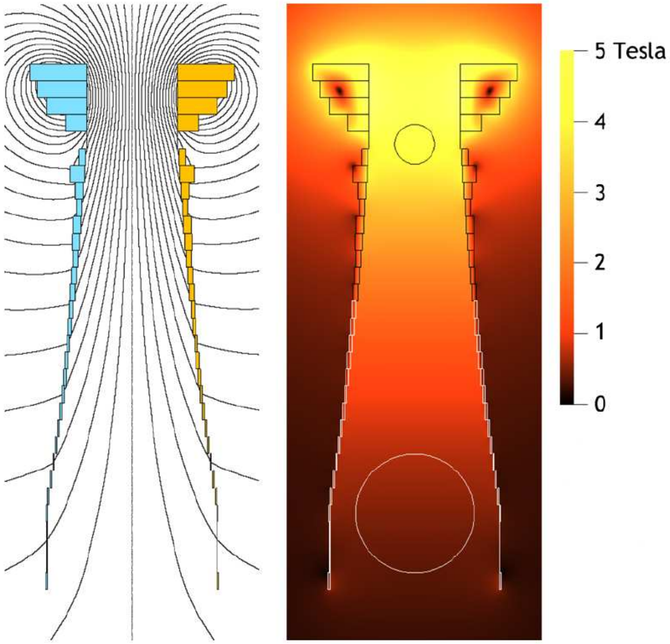
Field on closed orbit in a scaling VFFAG magnet:

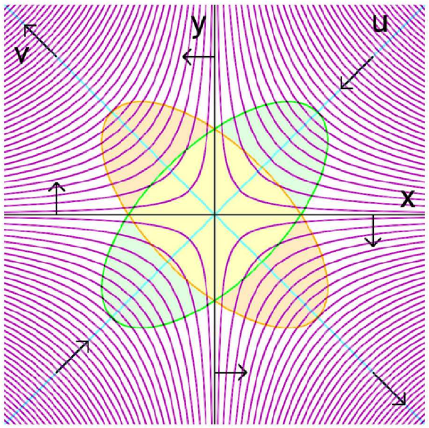
$$B_0 \exp(ky)$$

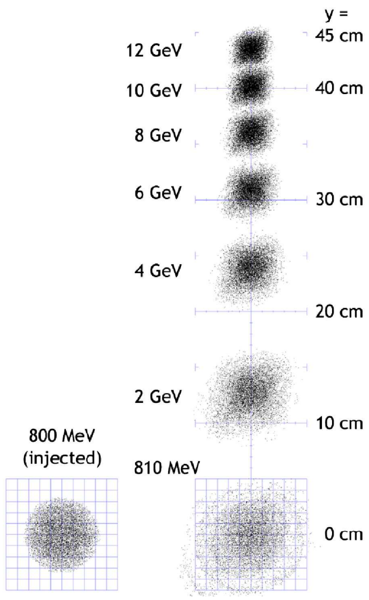
Momentum dependence of vertical orbit position:

$$y = \frac{1}{k} \ln \frac{p}{p_{inj}}$$

Path-length is constant. Relativistic motion is isochronous.







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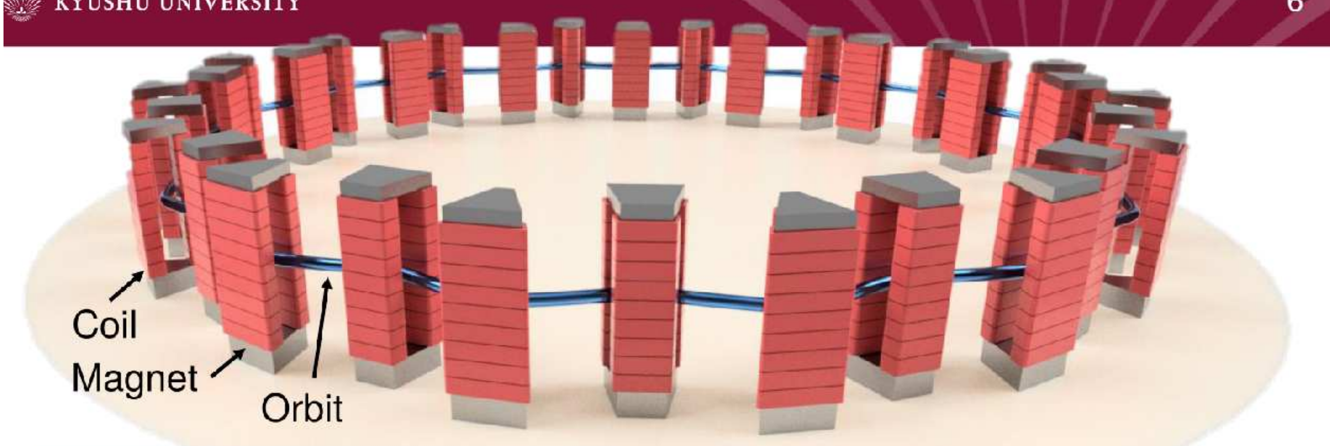


vFFA electron model

Focusing system	F-D Singlet
Number of cell	16
Magnet	Sector
Injection energy	20 [keV]
Maximum energy	40 [keV]
Radius	1.0 [m]

Development and Proof-of-Principle Experiment of the vFFA electron model is goal in our study.

Muon collider based on v-FFA lattice

- acceleration: VFFA allows isochronous acceleration $\rightarrow$ CW beam delivery
- collider ring: short bunch + spreads out muon decay products along arcs)

Ref.: Machida et al.: Application of the FFA concept to a muon collider complex. IPAC2021, Brazil

• Pumplet lattice [G. Rees, RAL]

- An isochronous lattice. Candidate for muon acceleration, muon storage ring.
- A scheme investigated for a 20 GeV, 4 MW proton driver for the neutrino factory

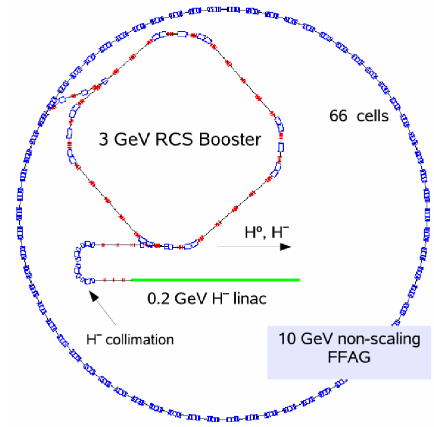
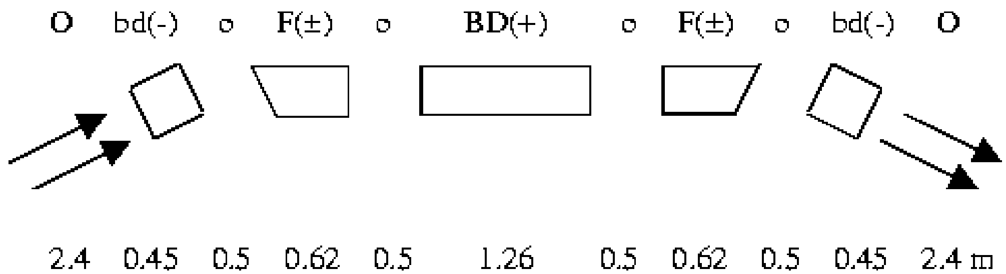


Figure1: Layout drawing of the 4 MW, NFFAG driver.

◇ The many knobs (field non-linearities) allow isochronism

Lattice for 8 to 20 GeV / 16 turns / 123 cell ring :

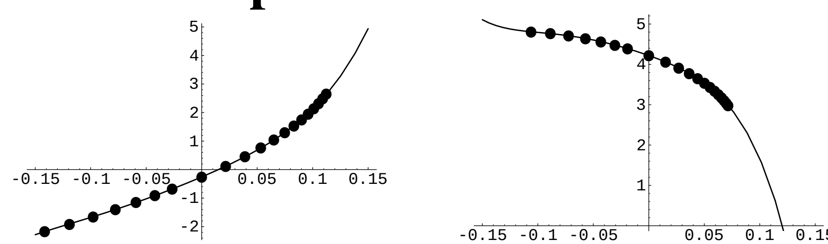


$$B_{bd}(x) = -3.456 - 6.6892\,x + 9.4032\,x^2 - 7.6236\,x^3 + 360.38\,x^4 + 1677.79\,x^5$$

$$B_{BF}(r) = -0.257 + 16.620\,r + 29.739\,r^2 + 158.65\,r^3 + 1812.17\,r^4 + 7669.53\,r^5$$

$$B_{BD}(x) = 4.220 - 9.659\,x - 45.472\,x^2 - 322.1230\,x^3 - 5364.309\,x^4 - 27510.4\,x^5$$

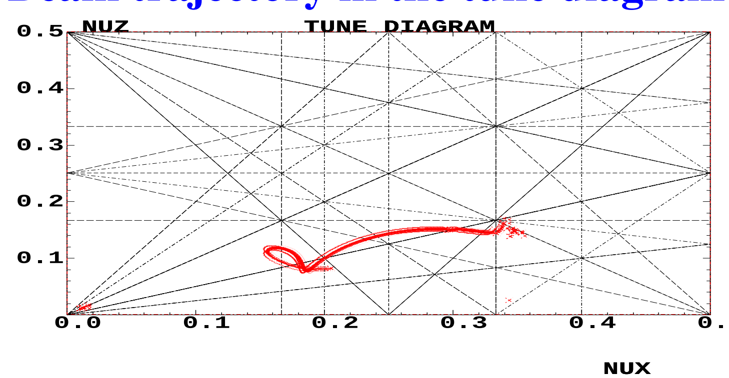
◇ Field profile in BF and BD :



Allows insertion straights - advantages :

1. easier injection and extraction,
2. space for beam loss collimators,
3. RF gallery extending only above the insertions, not above the whole ring,
4. 4-cell cavities usable, thus reducing, by a factor of four, the total number of rf systems.

◇ Beam trajectory in the tune diagram :



• Toward CW [C. Johnstone, FNAL]

Quasi-isochronous optics,

◇ **based on SC dipoles and featuring**

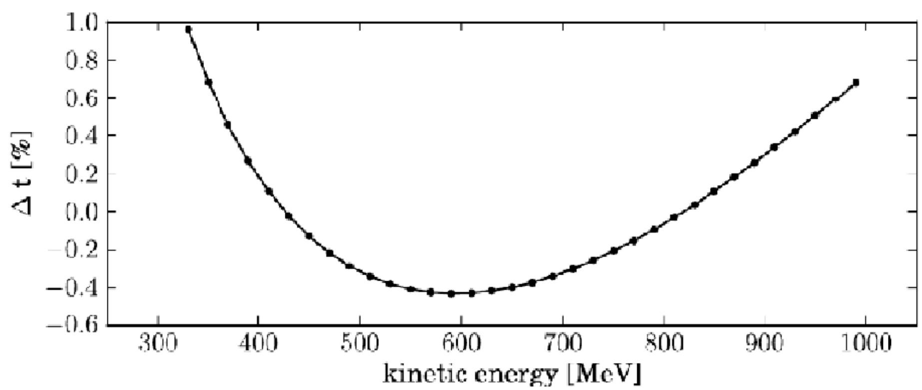
- alternating-gradient with non-linear radial field profile

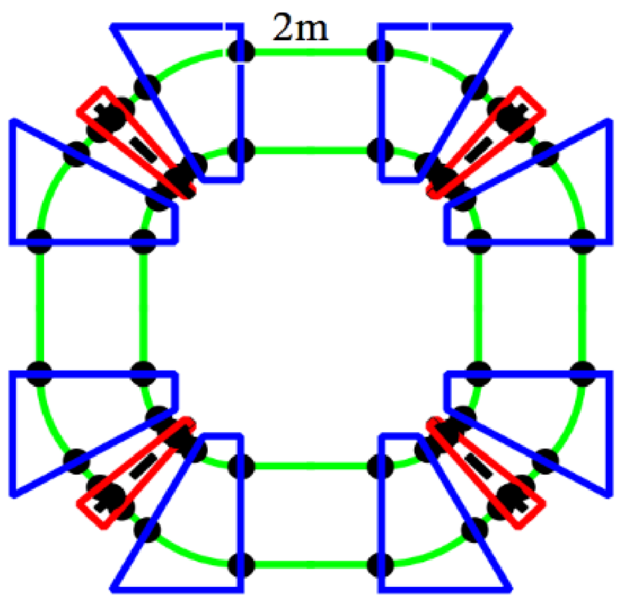
- optimized magnet-edge contour

◇ **Allows near-crest (serpentine) acceleration, based on SCRF**

◇ **Principle 6-cell lattice used for numerical beam dynamics studies :**

0.33 to 1 GeV at a rate of 10∼20 MV/turn





◇ **Numerical beam dynamics studies show**

- large transverse dynamical acceptance

- currents in 20 mA range with no transverse beam growth doable (OPAL simulations)

• **Serpentine acceleration in scaling lattice, FFFFAG [E. Yamakawa et al., KURRI]**

◇ **The lattice $\gamma_{\mathrm{tr}} = \sqrt{1+K}$ is set to be in the acceleration range : beam γ is accelerated in transition region, time of flight is parabolic**

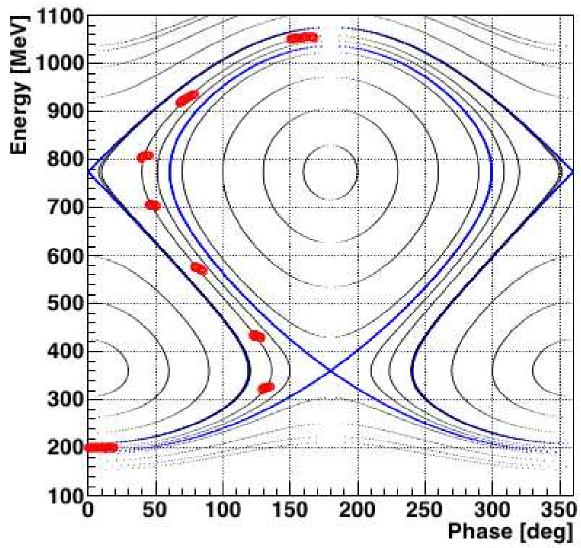
◇ **This allows using fixed RF-frequency acceleration in variable $\beta = v/c$ regime**
- i.e., case of non-relativistic beam, suitable for proton acceleration.

◇ **Experimental demonstration performed with an electron prototype (Japan, 2012):**

- small e-beam ring
- 160 keV $\rightarrow$ 8 MeV
- F-D-F scaling triplet lattice at transition gamma (764 keV)
- RF freq. 75 MHz (h=1), 750 kV/gap

◇ **An ADS equivalent has been designed (NIM A 716 (2013))**

k-value	1.45
Equivalent mean radius at 200 MeV [m]	3
Equivalent mean radius at 1 GeV [m]	5.9
Stationary kinetic energy below transition [MeV]	360
rf voltage [MV/turn]	15 (h=1)
rf frequancy [MHz]	9.6(h=1)



THANK YOU FOR YOUR ATTENTION