Proton Driver Efficiency Workshop, PSI, 29 Feb.-3 Mar. 2016

FFAG METHODS

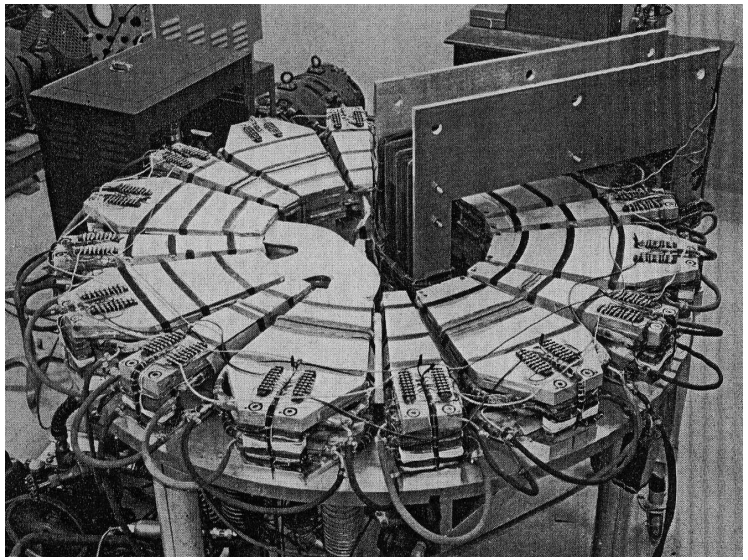
François Méot
Brookhaven National Laboratory

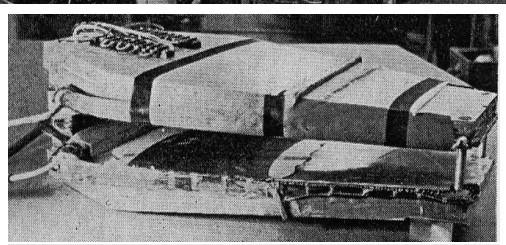
Contents

1 FIXED-FIELD ALTERNATING GRADIENT ACCELERATORS

1.1 MURA FFAGs

• The first model, radial sector FFAG, Mark II. First operation March 1956, University of Michigan.





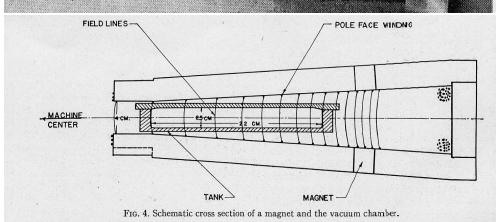


FIG. 4. Schematic cross section of a magnet and the vacuum chamber.

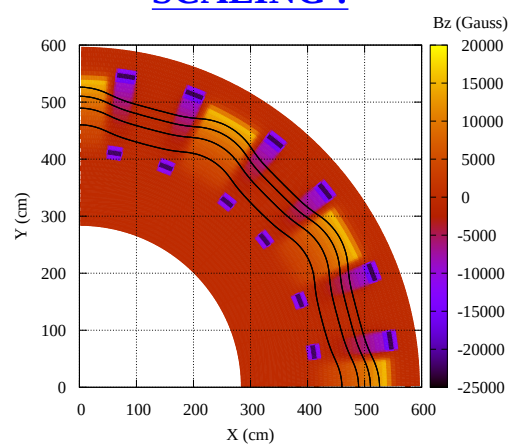
F magnet, positive field, radially focusing.

FFAG ring parameters

$E_{inj} - E_{max}$	*keV*	**25 - 400**	*small size, easy to build*
orbit radius ($\mathcal{C}/2\pi$)	*m*	**0.34 - 0.50**	*field not too low, ms lifetime*
Optics			
lattice		$\frac{D}{2}F\frac{D}{2}$	
number of cells		**8**	*16 magnets & 4.41 deg. drifts*
field index K		**3.36**	g/r =*Cst & pole-face windings*
ν_r / ν_z		**2.2-3 / 1-3**	
Magnet		**radial sector**	
Acceleration		**Induction**	
rep. rate	*Hz*	**a few 10s**	

$$B = B_0(r/r_0)^K F(\theta)$$

SCALING :



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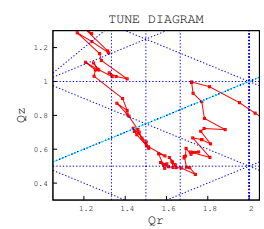
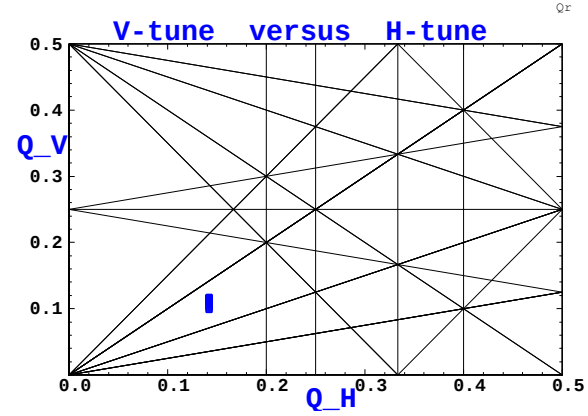
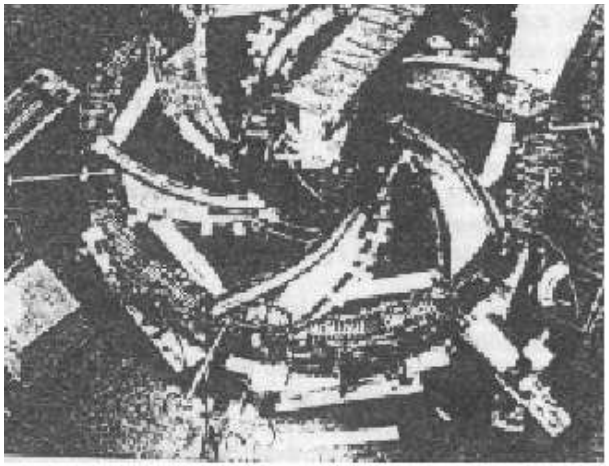
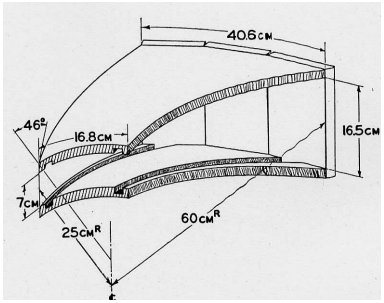




- **Second model, spiral sector FFAG, Mark V**

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





Logarithmic spiral poles

Spiral FFAG parameters

$E_{inj} - E_{max}$	*keV*	**35 - 180**
orbit radius	*m*	**0.34 - 0.52**
E_{tr} / r_{tr}	*keV / m*	**155 / 0.49**

Optics

lattice	**spiral sectors**
number of sectors	**6**
field index K	**0.7**
flutter F_{eff}	**1.1**
ν_r / ν_z	**1.4 / 1.2**

Magnet: **spiral sector**

$$B = B_0 \left(\frac{r}{r_0}\right)^K F\left(\ln \frac{r}{r_0}/w - N\theta\right)$$

Acceleration betatron and RF

rep. rate	*Hz*	**a few 10s**

1.2 Vertical variant

- **Vertical scaling optics was devised by K. Okawa (once known as the "smokatron").**
- **Re-investigated recently [S. Brooks, pr-ab]**

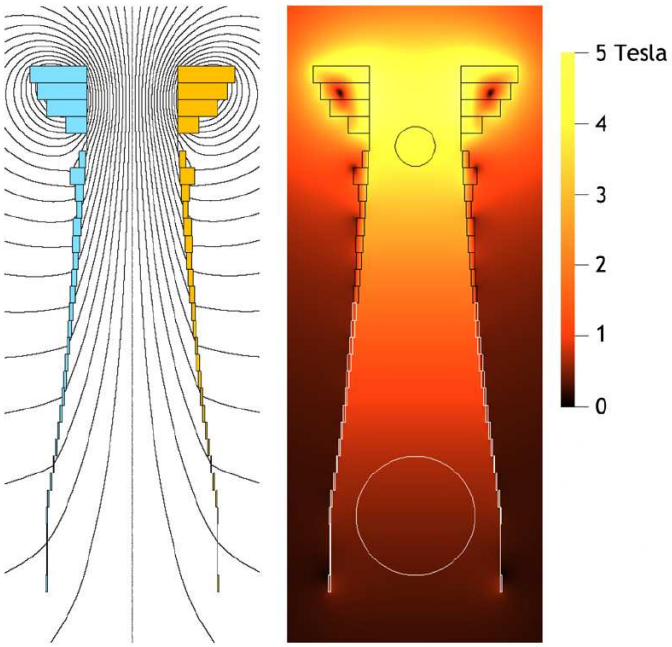
Field on closed orbit in a scaling VFFAG magnet:

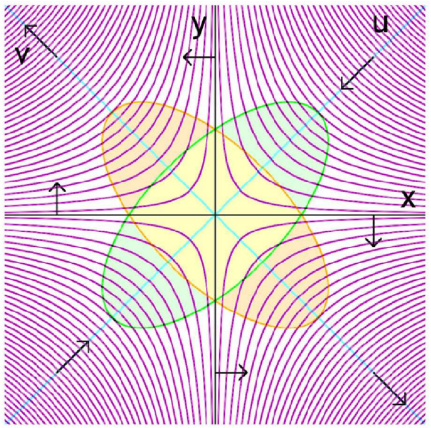
$$B_0 \exp(ky)$$

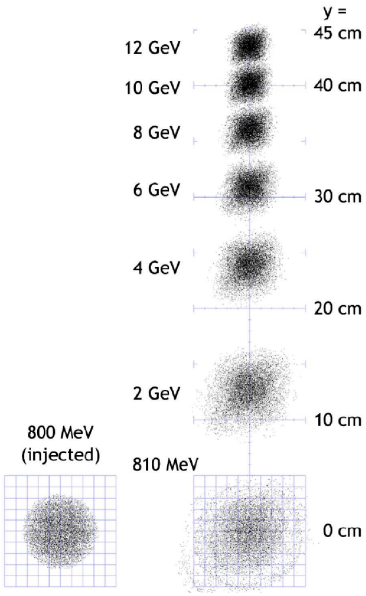
Momentum dependence of vertical orbit position:

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

Path-length is constant. Relativistic motion is isochronous.



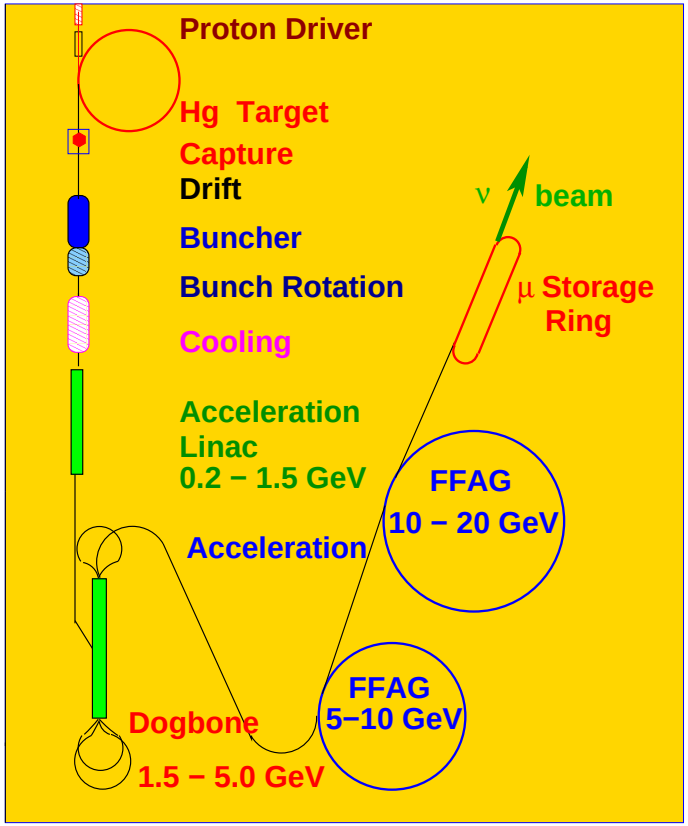




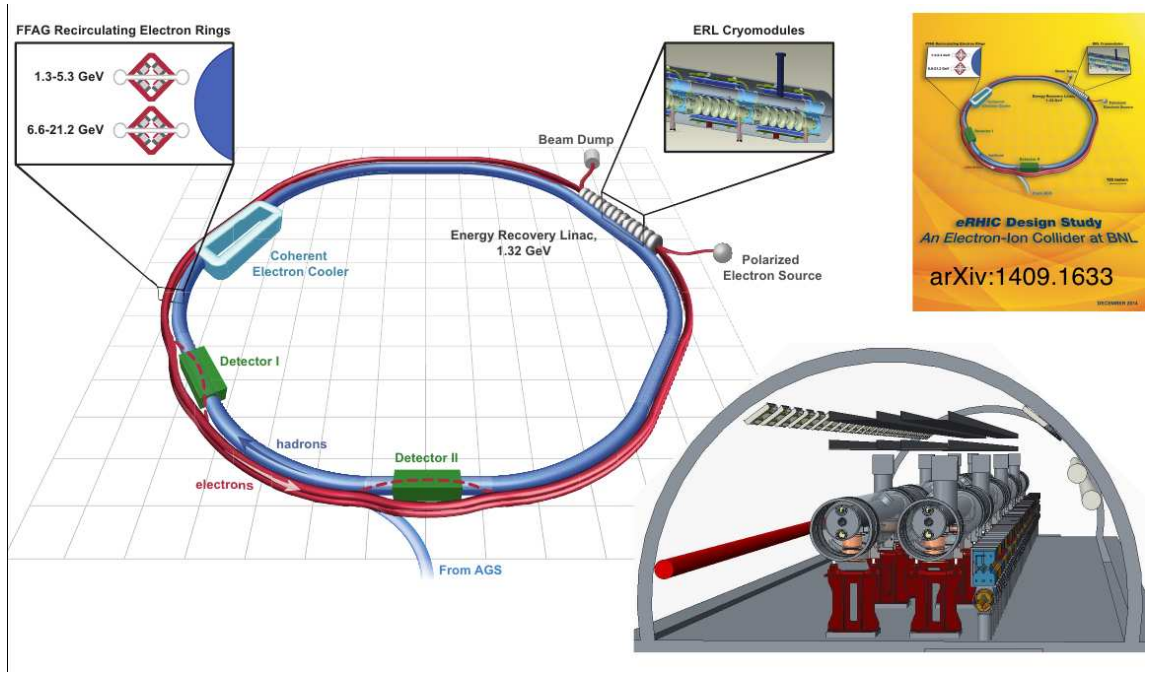
1.3 Linear FFAG

- **Two concepts where introduced in the late 1990s, in the frame of the "neutrino Factory" R&D :**
  - **"linear lattice" FFAG : magnets are simple quadrupoles (hence very large 6D acceptance)**
  - **"quasi-isochronous" optics : allows using fixed frequency RF cavities (good for CW)**

- **Linear FFAG lattice : Well suited for the acceleration of - short-lived - muons up to 20-50 GeV**



- **Today : The technology of the ERL arcs, in BNL's baseline "eRHIC" electron-ion collider design**



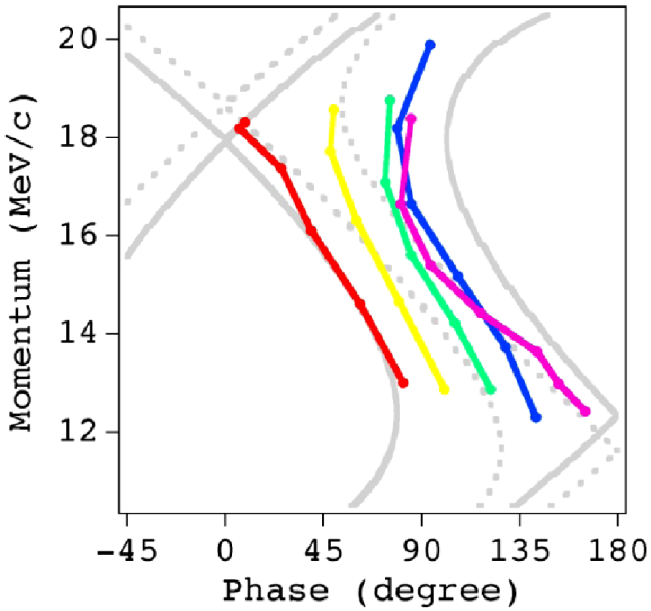
1.4 The EMMA experiment

• **An experimental "Electron Model for Many Applications", to prove these concepts, in the frame of an international collaboration.**

- **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



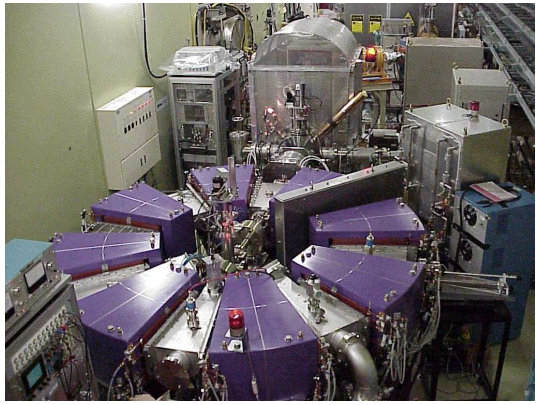
2 TOWARD HIGH POWER

2.1 Proton FFAG R&D

- **1999 - mid 2000s, working frame : Neutrino factory R&D**

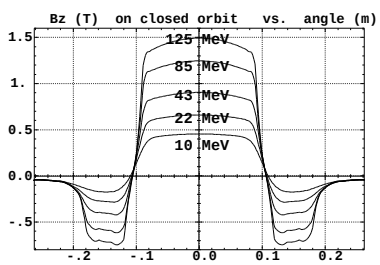
Interest: Fast acceleration (short lived muons, NuFact proton dirver design studies), strong focusing (mitigates space charge effects), very large acceptance.

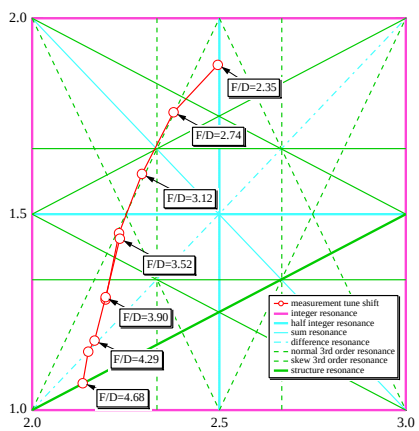
POP FFAG - First beam Dec. 1999



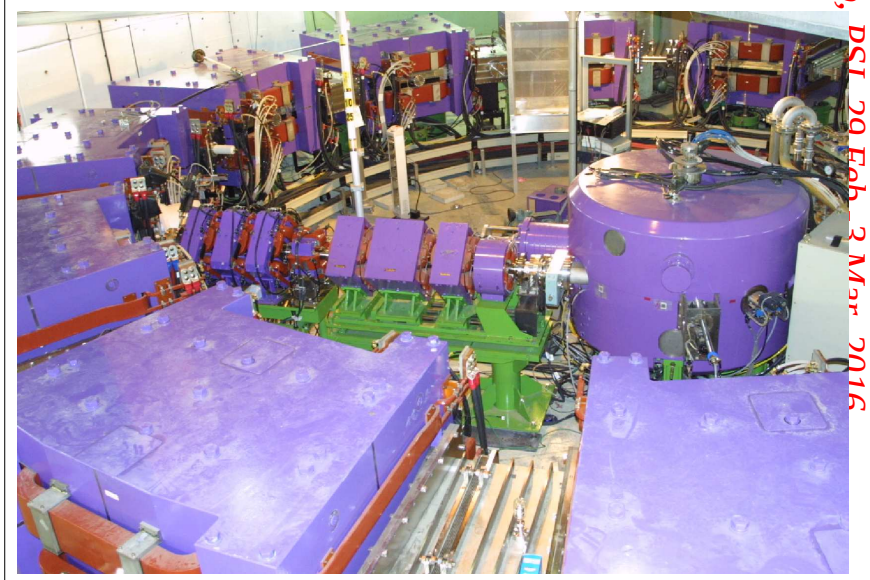
$E_{inj} - E_{max}$	keV	50 - 500
orbit radius	m	0.8 - 1.14
lattice / K		DFD $\times$ 8 / 2.5
ν_r / ν_z		2.2 / 1.25
RF swing	MHz	0.6 - 1.4
voltage p-to-p	kV	1.3 - 3
cycle time	ms	1

POP's DFD triplet cell





Medical application program 150 MeV radial sector FFAG - startup 2003



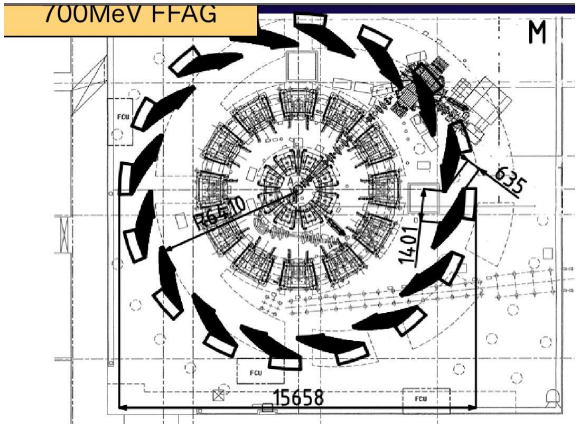
$E_{inj} - E_{max}$	MeV	12 - 150
orbit radius	m	4.47 - 5.20
lattice / K		DFD $\times$ 12 / 7.6
ν_r / ν_z		3.7 / 1.3
RF swing	MHz	1.5 - 4.5
voltage p-to-p	kV	2
rep. rate	Hz	250

2.2 KURRI KUCA

- A feasibility evaluation of ADS-R as an energy production system.
  - First coupling to 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

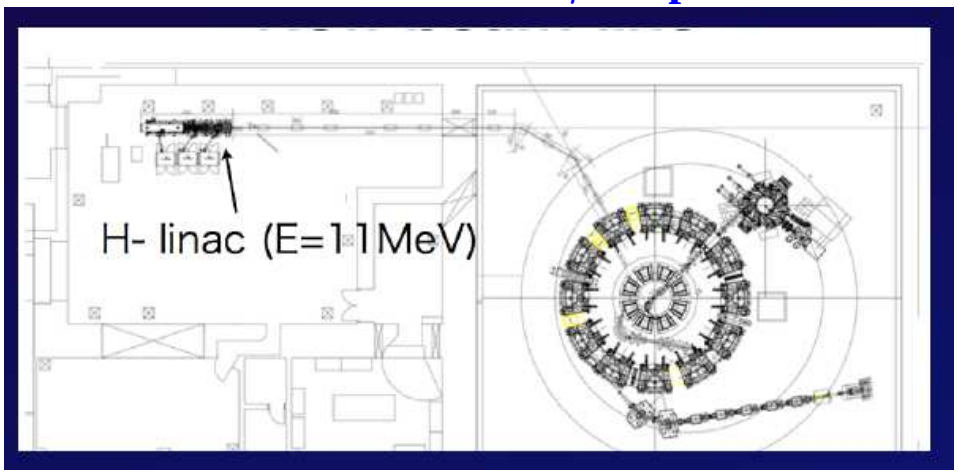
Variable energy 150-700 MeV facility, neutron flux increased by a factor 30



- **Planned upgrades :**

On-going : H- charge exchange injection

Towards 10s of μAmp



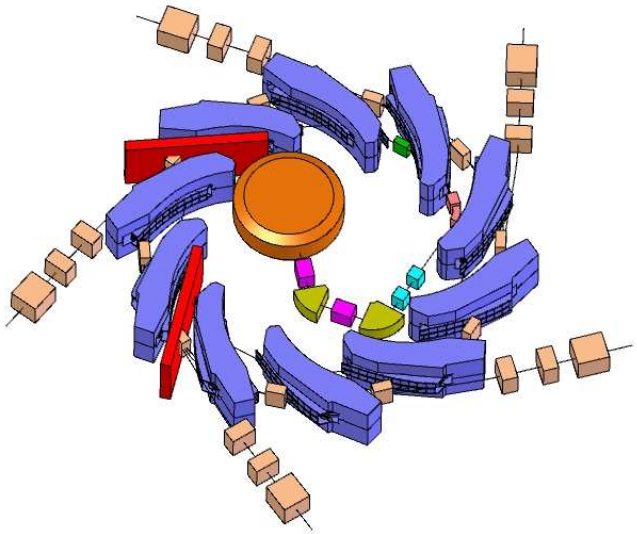
2.3 RACCAM

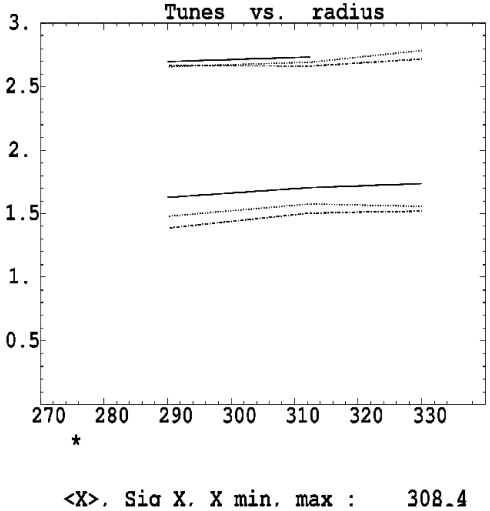
- **Working frame : Neutrino factory R/D and medical applications.**
  French ANR funding, 2006-2008. **• A feasibility study of a rapid-cycling, variable energy, spiral lattice scaling FFAG**

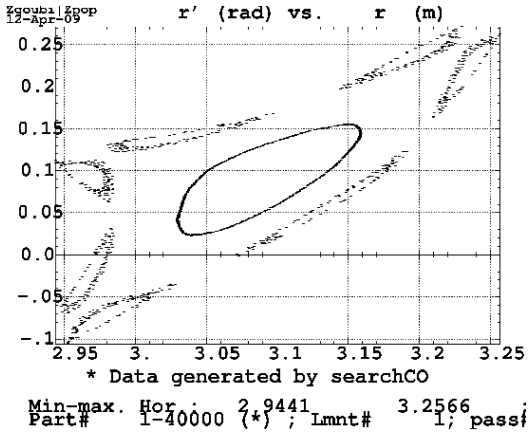
- **Magnet prototyping (SIGMAPHI Company) proved** { **spiral sector FFAG optics**, **constant tunes**, **large dynamical acceptance** }

- **Magnet design further exploited in KURRI-KUCA 700 MeV upgrade designs (previous slide)**

- **Outcome : a cost-effective multiple-beam delivery hadrontherapy installation.**



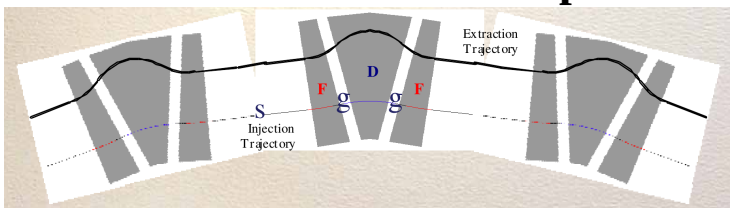


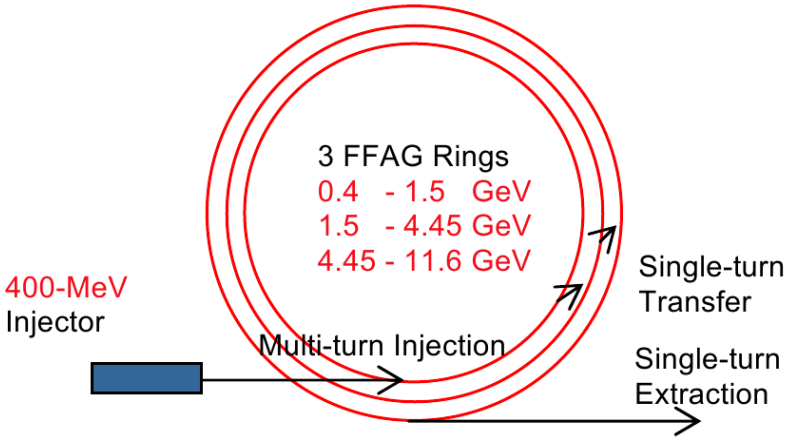


2.4 Linear lattice PD design

- **A 3-stage linear FFAG cascade, as a NuFact p-driver (S. Ruggiero, 2004)**

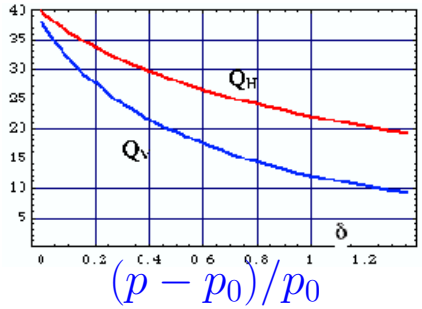
- **Linear FDF FFAG triplet**





- **Fast resonances crossing :**

$Q_x : 40 \rightarrow 19$, $Q_y : 38 \rightarrow 9$.



- **Neutrino factory p-driver parameters :**

		Ring 1	Ring 2	Ring 3
Energy, Inj.	(GeV)	0.4	1.5	4.5
Extr.	(GeV)	1.5	4.5	12
# of turns		1800	3300	3600
cycle time	ms	6	9	10
Circumf.	m	807	819	831
# cells		136	136	136
cell length	(m)	5.9	6	6.1
h		136	138	140
RF freq.	MHz	36-46	46-49.7	49.7-50.4
E gain / turn	MeV	0.6	0.9	2

- **Operation mode variant considered for ring #1, for ∼MW beam power in GeV range :**

  - broad-band, few MHz RF (JPARC style), cycled,

  - repetition rate >100 Hz,

- **Even higher rep. rate. (toward CW) based on**

  - "harmonic number jump",

  - using high frequency fixed-frequency RF.

  Requires cavity with transverse RF voltage profile.

2.5 Pumplet lattice

- A non-linear, non-scaling type of FFAG, "non-linear cyclotron", G. Rees.
- A scheme investigated for a 20 GeV, 4 MW proton driver in the neutrino factory

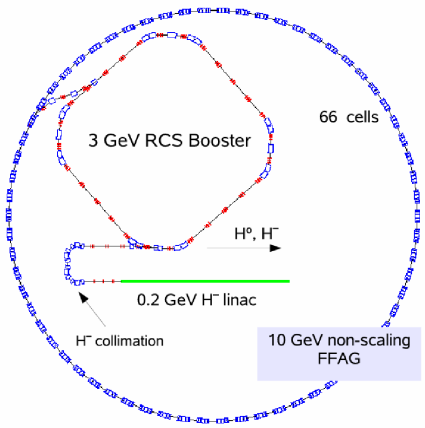
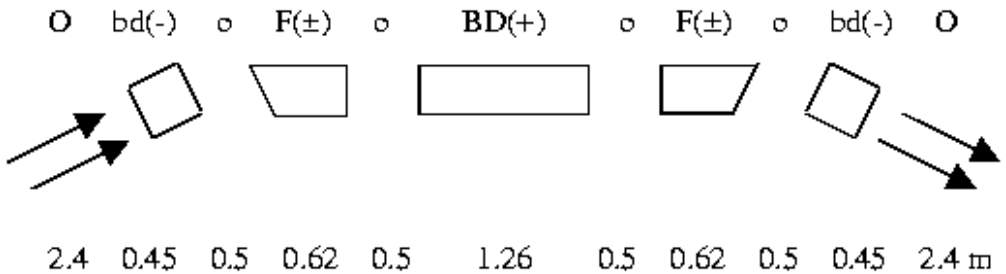


Figure1: Layout drawing of the 4 MW, NFFAG driver.

- **The many variables allow sochronism**

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

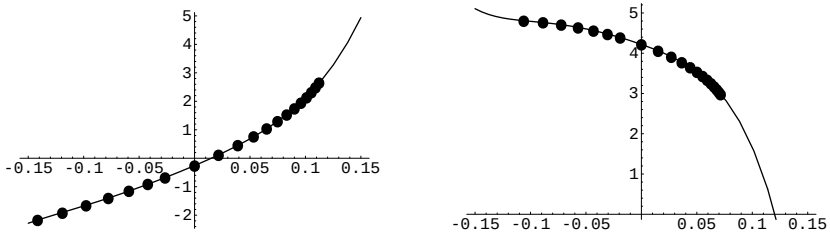


$$B_{bd}(x) = -3.456 - 6.6892\,x + 9.4032\,x^2 - 7.6236\,x^3 + 360.38\,x^4 + 1677.79\,x^5$$

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

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

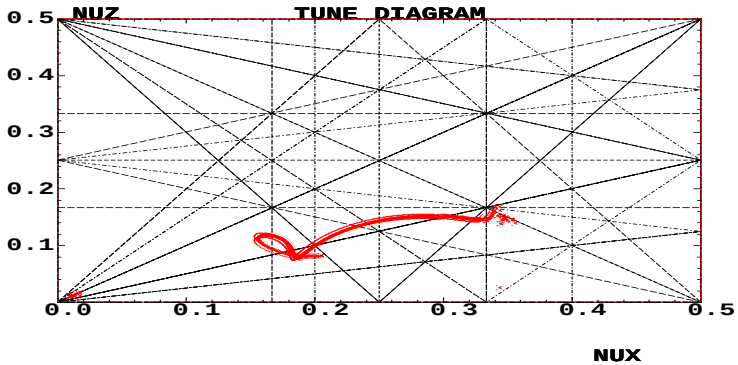
Field profile in BF and BD.



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 :



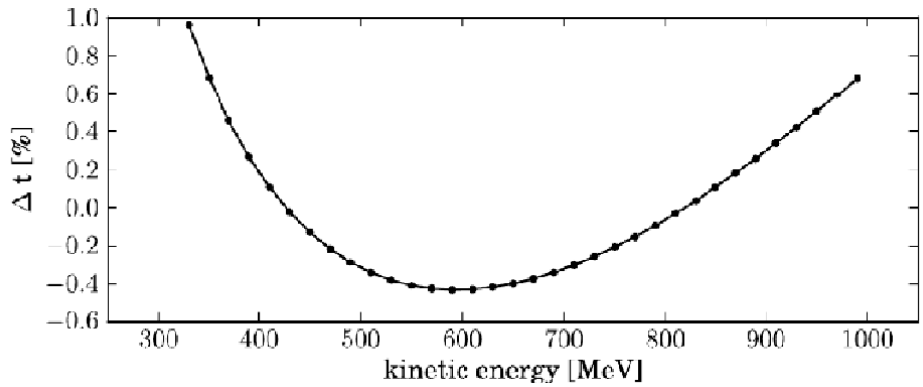
2.6 Toward CW

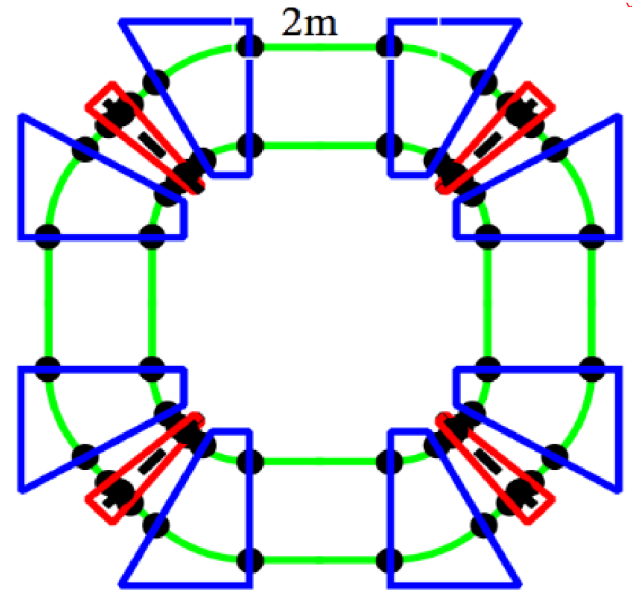
2.6.1 Quasi-isochronous optics

- **Based on SC dipoles, 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 (OPAL simulations)**

2.6.2 Serpentine acceleration in scaling lattice

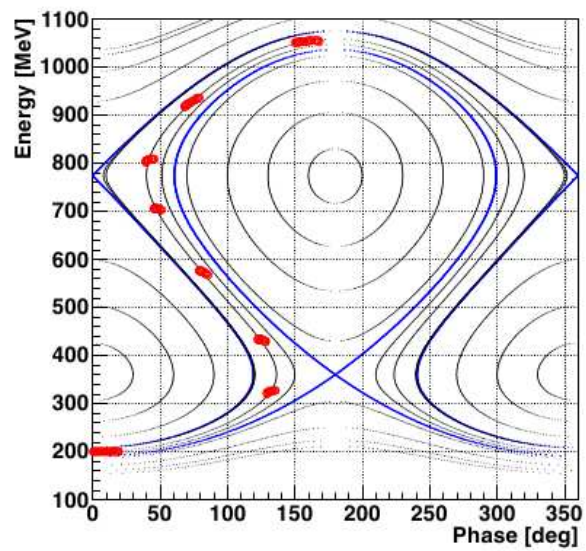
- **Allows fixed RF-frequency acceleration in variable $\beta = v/c$ regime**
  - i.e., non-relativistic beam, suitable for proton acceleration.

- **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 (Emi Yamakawa et al., 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)



3 TOWARD ENERGY EFFICIENCY

3.1 SC magnet studies

- **PAMELA Magnets, H. Witte et al.**

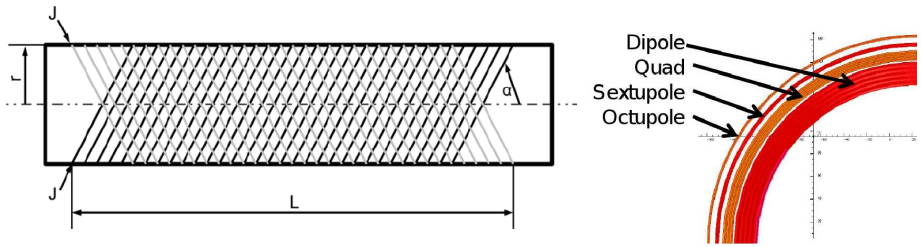


Figure 1: Double-Helix concept.

A multipole magnet. Based on tilted winding technics. Peak field up to 4 T in the useful aperture.

- **Non-scaling FFAG and their applications, D. Trbojevic, Proceedings of HB2010, Morschach, Switzerland :**

"Abstract : [...] 1 Gev NS-FFAG accelerator [...] using combined function superconducting magnets. "

- **A study for the 6-cell quasi-isochronous design :**

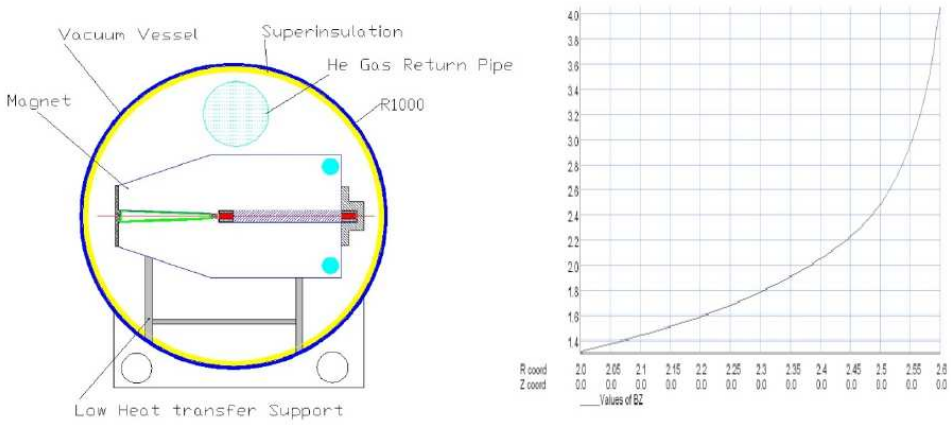


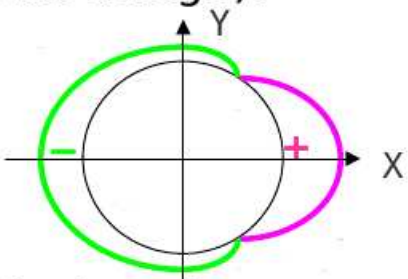
Figure 2: SC magnet and cryostate design (left) and Bz field distribution (right) in mid-plane at 300 kA current.

• One can find SC FFAG magnet investigations as far back as 1969 : Construction details for superconducting magnets for FFAG accelerators, P. Gerald, J. N. Snyder et al., IEEE (1969).

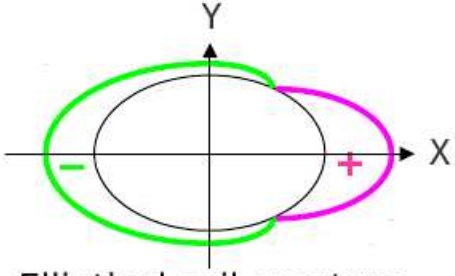
Recent investigations [FFAG workshops] :

- Scaling FFAG mag. field: $B(x) = B_0\left(\frac{R_0 + x}{R_0}\right)^k = B_0\left[1 + k\frac{x}{R_0} + \frac{k(k-1)}{2!}\left(\frac{x}{R_0}\right)^2 + \cdots\right]$

- The coils care combined to give the following current distribution (2D coil design):

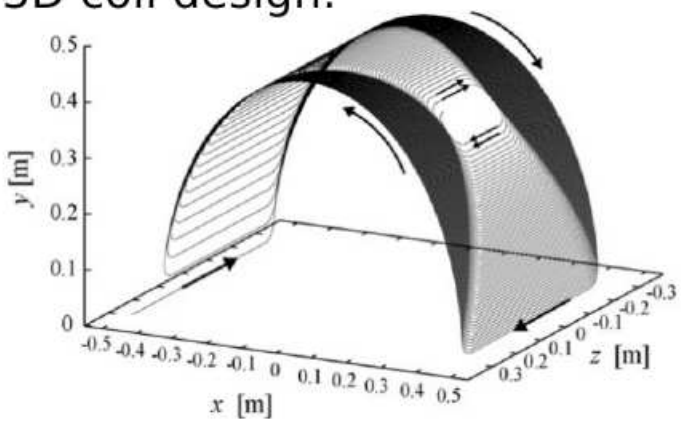


Circular coil aperture

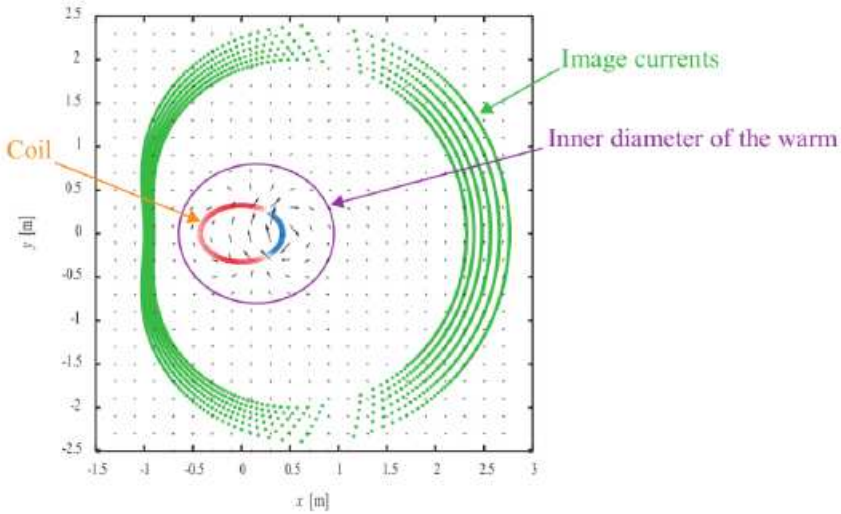


Elliptical coil aperture

- 3D coil design:



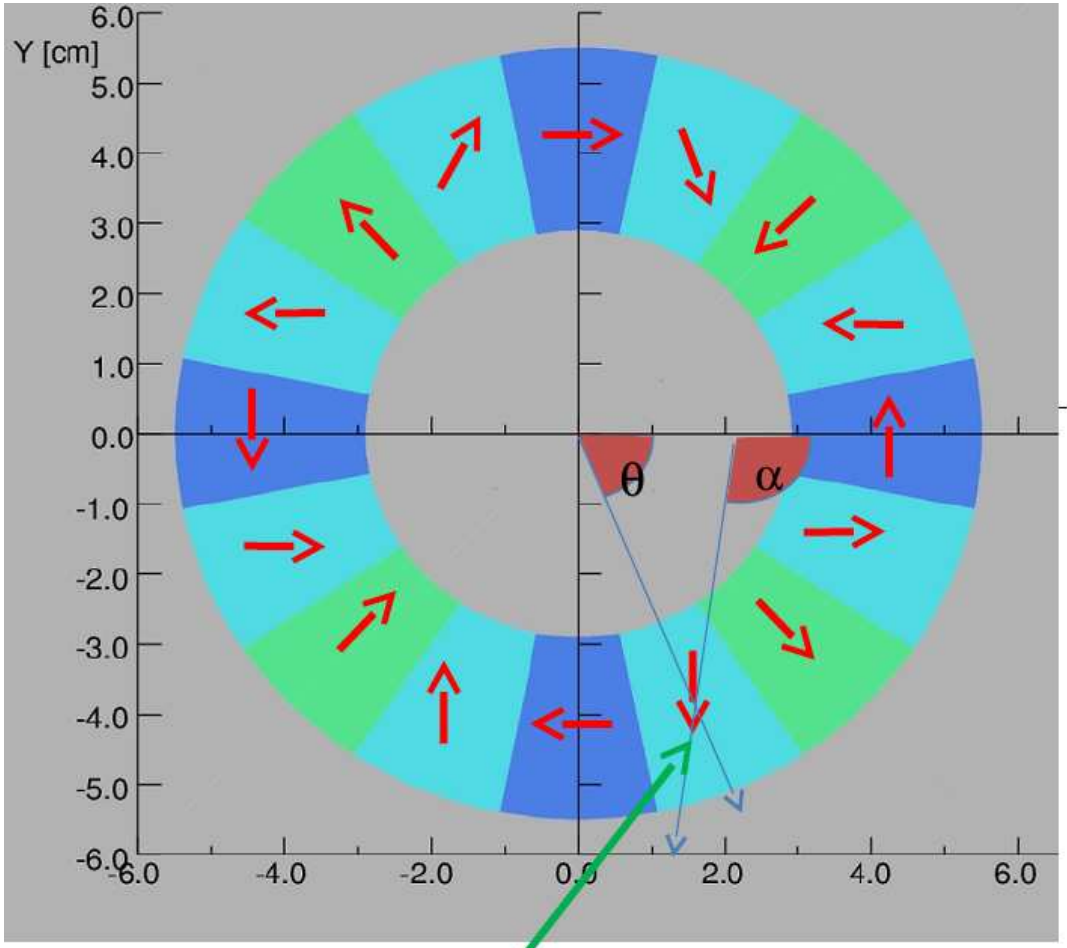
Coil configuration of the prototype coil: arrows show the direction of the current.

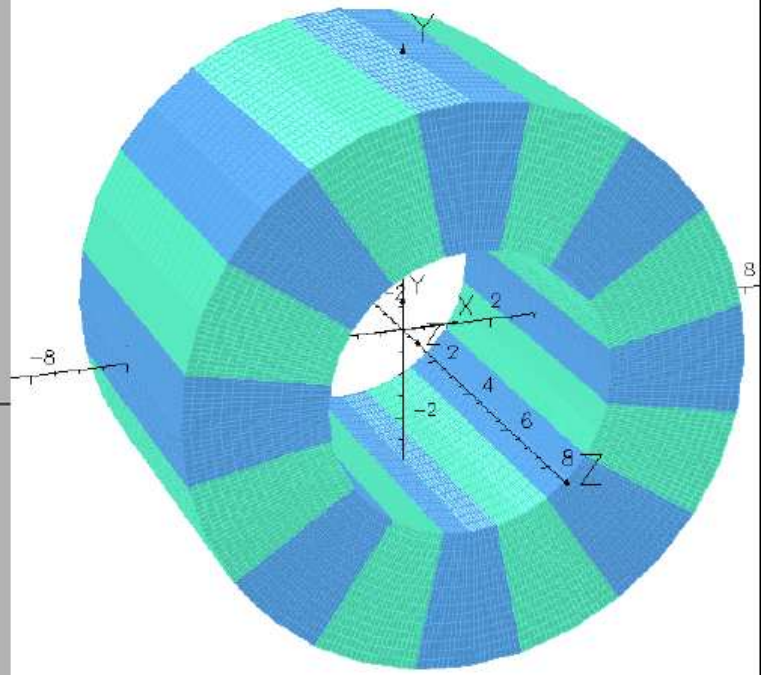


Magnetic flux in the magnet

- **Permanent magnets, an option ?**

Studied at eRHIC (N. Tsoupas) :



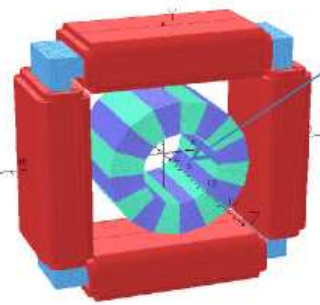


Isometric view of Magnetized Wedges

1. Small volume generate strong multipoles
2. 100 Gy does not affect NdFeB material
3. mu~1.0 allows field superposition.
4. No cross talk between mags., measured

Direction of the easy axis $\alpha=(n+1)\theta+\pi/2$

Dipole n=1
Quad n=2
Sext n=3



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3.2 SC RF studies

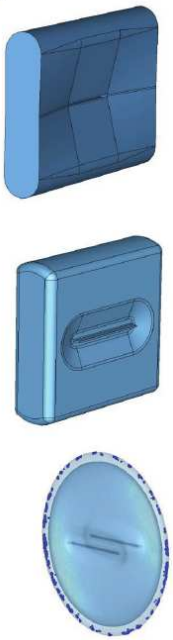
- **Objectives :**
  - **Compactness**
  - **Serpentine channel**
  - **Turn separation at extraction (low extraction losses)**
- **Challenge : large horizontal aperture of the FFAG.**

Recently : High gradient superconducting cavity development for FFAG [S.V. Kutsaev et al., Cyclotrons 2013].
Requirement is $10 \sim 20$ MV in a $\sim$2 m drift.

Comparison of different cavity geometries

Parameters of the different cavity designs.

Parameter	Rectangular top	Rectangular middle	Elliptical bottom
Frequency, MHz	200	200	200
Length, cm	100	100	120
Height, cm	104.5	92.9	142
Voltage (β=0.56, edge), MV	4.67	4.66	4.68
Voltage (β=0.78, center) , MV	6.72	6.71	6.89
Voltage (β=0.86, edge) , MV	5.00	5.00	5.00
R/Q (β=0.86, edge), Ohms	82.8	89.7	75.0
G, Ohms	147.9	150.2	134.2
Peak magnetic field, mT	92.1	72.7	77.2
Peak electric field, MV/m	55.2	47.0	48.1



4 CONCLUSION (1)

- [B. Riemer, Hih Power Targets Workshop, FNAL, May 2014]

- When isn't higher target power the right direction for higher performance?
  - Spallation sources
  - Other high-power target applications

- Integrated approaches to source design around specific instrument performance metrics, utilizing optimization techniques, can show new paths to high-performance
  - TS-2 at ISIS

5 CONCLUSION (2)

BEAM FLEXIBILITY AND ADS-Reactor APPLICATION

- A PERSONAL POINT OF VIEW -

- **In the ADS-Reactor application, do we want that :**
  - **1.5 GeV and [provision for] even more (China-ADS, Project-X, ESS) ?**
  - **H- acceleration for injection into an accumulator ring (SNS) ?**
  - **Multiple species up to U (FRIB) ?**
  - **A "multi-purpose flexible irradiation facility", including energy upgrade plans (MYRRHA) ?**

If the answer is "No" to all these questions, then, FFAG methods are certainly to be investing further, starting with component and accelerator prototyping based on existing studies and designs.

Note that we may not even want 100s of MeV beam energy upgrade flexibility (another interesting aspect of linac methods) in an ADS-Reactor accelerator system (not to say, any energy flexibility at all), however FFAG method allows foreseeing that.

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