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HIGH POWER FIXED-FIELD RING METHODS IN ADS-REACTOR APPLICATION

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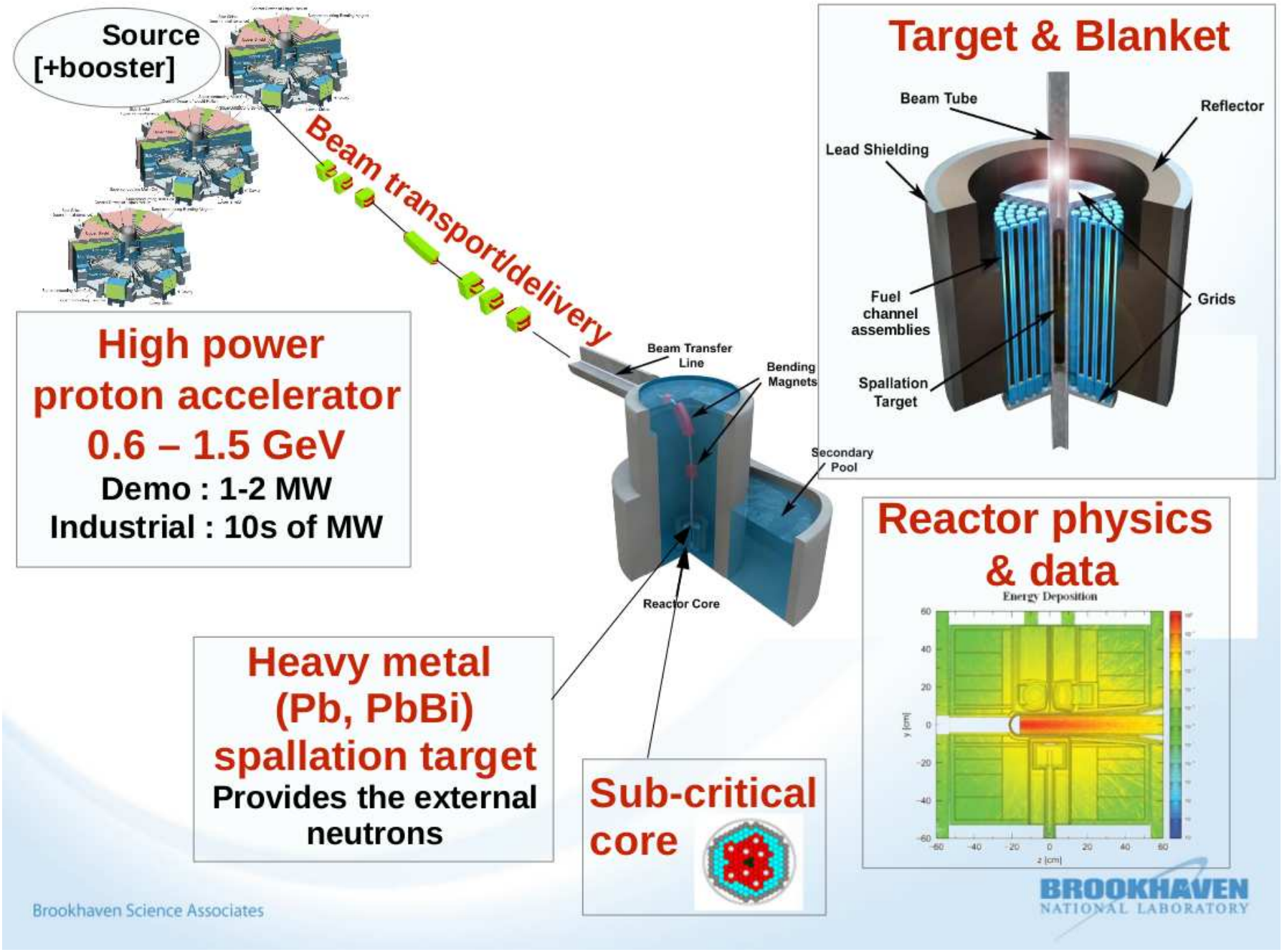
1 CONTEXT / WORKING HYPOTHESES

1.1 Subcritical reactor facility



1.2 High power proton accelerators

• **Required beam power P_B, for P_{th} reactor power :**
With beam energy $E_B \approx 1$ GeV, a handy estimate is

$$\boxed{P_B \approx \frac{1}{2}(1 - k_{\text{eff}})\, P_{\text{th}}}$$

$$P_B = E_B \frac{P_{\text{th}}}{f\, E_f} \frac{(1 - k_{\text{eff}})}{k_{\text{eff}}} \begin{cases} k_{\text{eff}} = \text{neutron multiplication factor} = \dfrac{\text{n produced}}{\text{n absorbed}} \approx 0.95 - 1^- \\ E_f = \text{fission energy} \approx 200 \text{ MeV} \\ f = \text{fraction of neutrons causing fission} \overset{1GeV-p}{\approx} \dfrac{20\text{n/incident p}}{2.5\text{n/fission}} \end{cases}$$

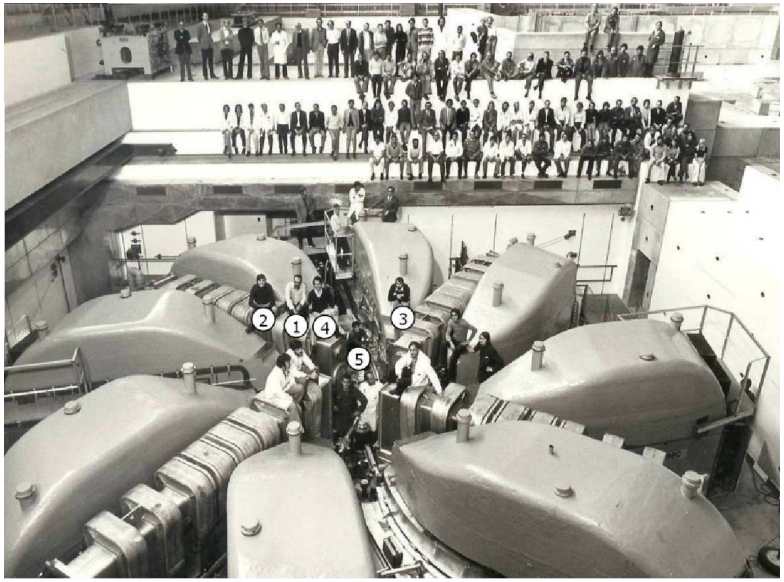
• **k_{eff} is central to the accelerator parameters, the closer it is to 1, the lower the beam power to be brought in - but, drawback, the closer the reactor core to critical.**

- Typical numbers -

	ADS thermal power	k_{eff}	Proton beam Energy / Current / Power
Demo transmuter MYRRHA:	**50-100 MW-th**	≈ 0.95	**600 MeV / 4 mA / 2.4 MW**
EFIT industrial transmuter:	**several 100 MW-th**	≈ 0.97	**800 MeV / 20 mA / 16 MW**
China's demonstrator program:	**1000 MW-th**		**1.5 GeV / 10 mA / 10 MW**

1.3 Foreseeable accelerator technologies

Reference : US ADS White Paper (2010)



- **Separate sector cyclotron**

  Paul Scherrer Institute,
  590 MeV, 1.3 MW CW beam
  First beam 1973

- **Normal conducting proton linear accelerator**

  LANSCE 800 MeV n science center linac, first beam 1972.
  Ran in 1 mA / MW range in the 1980s,
  120 Hz repetition rate, DC 7.5%.

- **Superconducting linear accelerator**

  SNS 1 GeV n science linac at ORNL,
  beam power 1.2∼1.4 MW.
  Pulsed, DC ∼6%. Accelerates H- for stripping injection into accumulator ring,
  First beam 2006

ACCELERATOR TECHNOLOGIES, FOR MULTI-MW BEAM POWER (CONT'D)

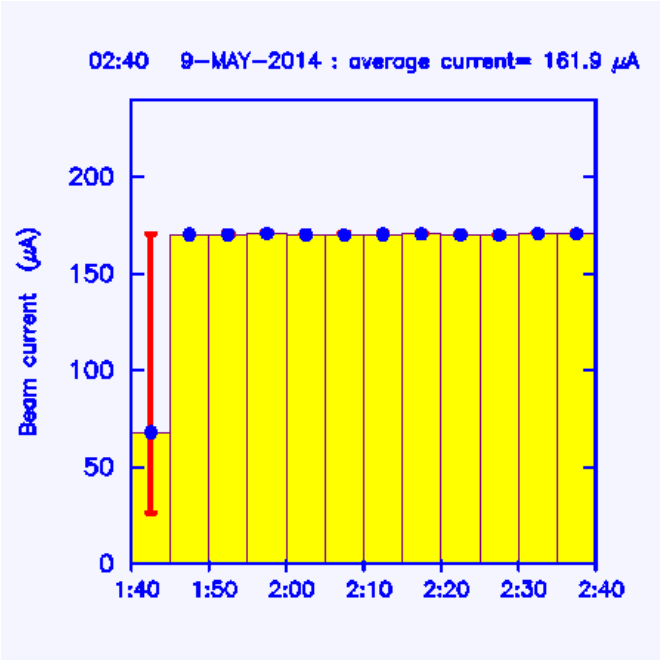
Reference : US ADS White Paper (2010)

Alternative approaches to high power include :

- **Pulsed synchrotron technology,**

Potential for ≈1 MW, for ≈1 GeV proton beam, limited by pulsed operation, few 10s of Hz, rather large ring.

Ex. : ISIS rapid-cycling synchrotron, RAL, UK. Running since 1984, 50 Hz, 800 MeV, 200 kW beam power



Beam current at ISIS TS1

- **Fixed Field Alternating Gradient (FFAG) accelerators**

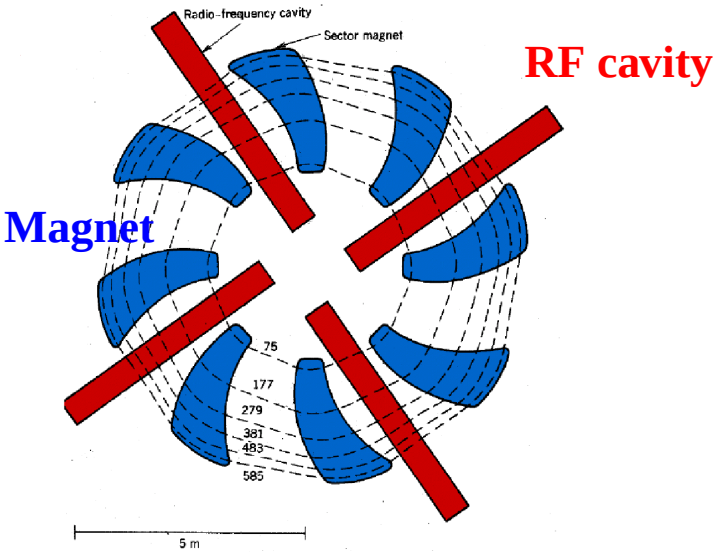
- FFAGs can have much higher repetition rate [100s of Hz].

With further development, FFAG technology may also demonstrate applicability in the 5-10 MW power range.

2 CYCLOTRONS

2.1 Principles

• **High power requires separate sectors. This allows drifts for beam manipulations: injection and extraction systems, RF cavities, beam instrumentation, etc.**



• **Fixed frequency, high-Q RF requires isochronism :**

$$T_{\text{revol.}} = 2\pi R/\beta c \;=\; \textbf{constant}$$

i.e., $R \propto \beta$**, ensured by designing**

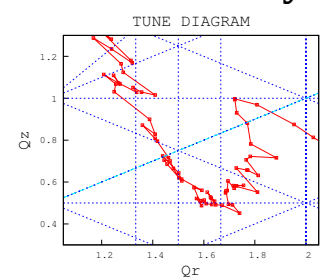
$$\boxed{\overline{B}(R) \;= B_c\,\gamma(R)}$$

• **hence a radial field index, varying with R :**

$$\boxed{k(R) \approx \frac{R}{B}\frac{dB}{dR} = \gamma^2 - 1}$$

• k **and the "flutter", F, ensure transverse stability :**

$$\begin{cases} Q_r \approx \sqrt{1+k} \approx \gamma \\ Q_z \approx -k + F^2\sqrt{1+2\,\tan\xi} \end{cases}$$



Note :

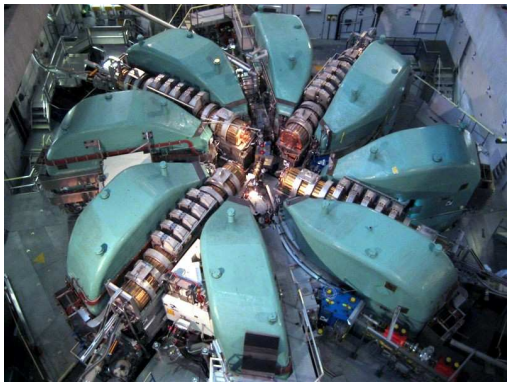
1/ (Q_r, Q_z) **changes with energy.**

2/ Weak focusing

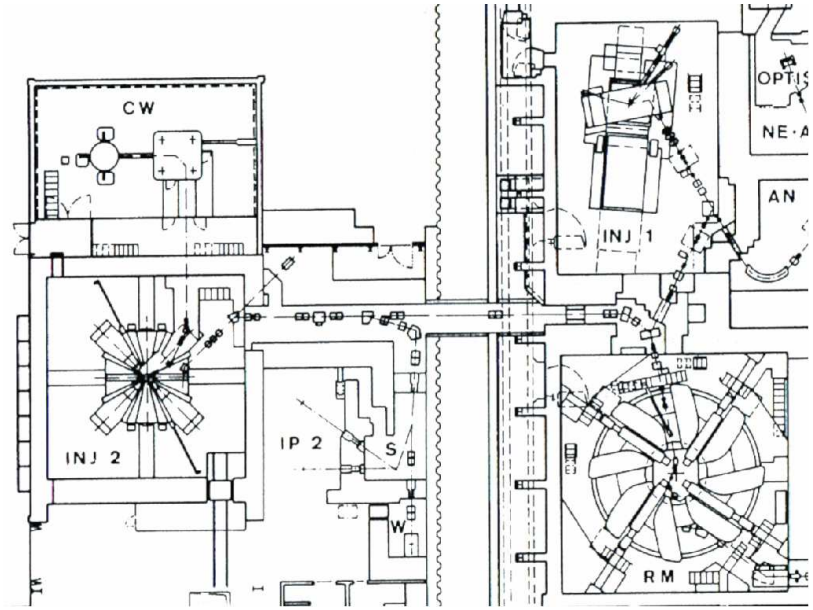
2.2 Today's practical reference, PSI cyclotron

• 590 MeV, 2.2 mA, 1.3 MW, en route for 1.8 MW.

- Beam transmission is $\approx 99.99\%$
- Availability is 85-90%, 5000 hrs/Year

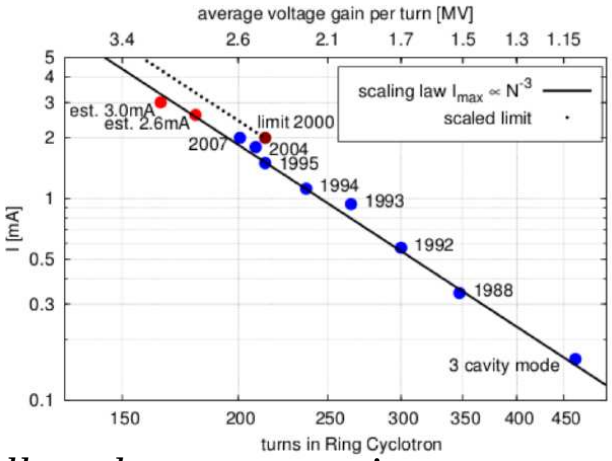


• Many upgrades, including changing the initial injector, allowed intensity increase from initial 100μA.

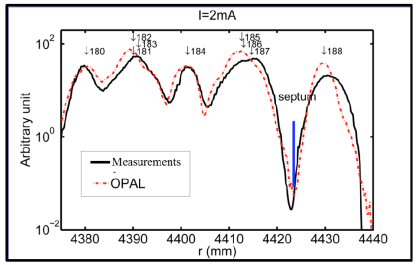


• Upgrades included RF, now $\sim$4 MV/turn
- longitudinal space charge losses scale $\propto N^3$

copper resonator for the Ring Cyclotron.



RF upgrade allows beam current increase.



[Y.J.Bi (PSI & Tsinghua Univ.), A. Adelmann]

Separation of last two turns

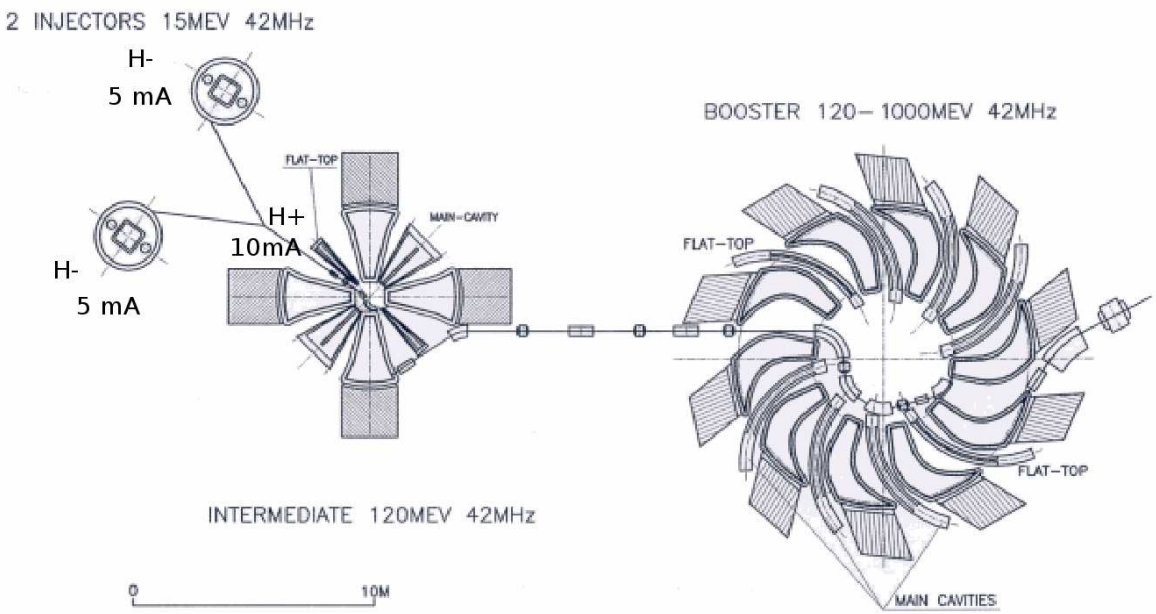
Power from plug :
goes essentially into RF system, with $\sim$34% plug-to-beam efficiency (magnets etc. add few %) [Ref. A. Adelmann, 2014].

2.3 Pushing the PSI technology beyond 1 GeV

- **1995, the energy amplifier (CERN/AT/95-44), a 3-stage cyclotron facility.**
- **Energy 1-1.2 GeV, beam current 10-15 mA CW, 10 MW range beam power**
- **Ingredients :**

- more cells for more RF (this reduces space-charge effects & losses, $\sim N^3$),
- reduced $\hat{B} = 1.8$ T for larger radius.

This favors turn separation at extraction $\Delta R_{\text{extraction}} \propto R_{\text{extract.}} \Delta E_{\text{turn}} \,/\, \beta^2\gamma^3$



MAIN RING :

- 16 m diameter

- 10 cells for more RF

- 9 mm turn separation at extraction

based on { **large ΔE at extraction**; **harmonic cavities**; **low field : $\hat{B}$=1.8 T** }

- **RF aspects, for 1 GeV/10 mA beam :**

- 3 to 6 MeV/turn from injection to extraction
- 2 harmonic cavities for space charge compensation
- Per cavity : 2.1 MW to be delivered, 1.5 MW beam power + 0.6 MW cavity loss, 3 MW electrical power

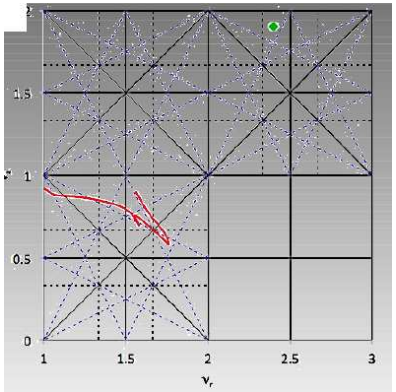
- **Magnet aspects :**

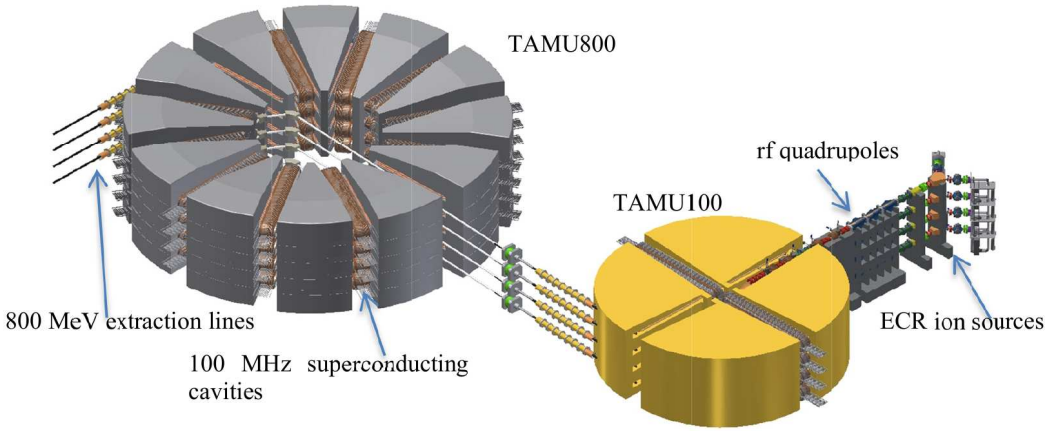
- Maximum field 1.8 T
- Power 2.7 MW
- Total weight 3200 tons

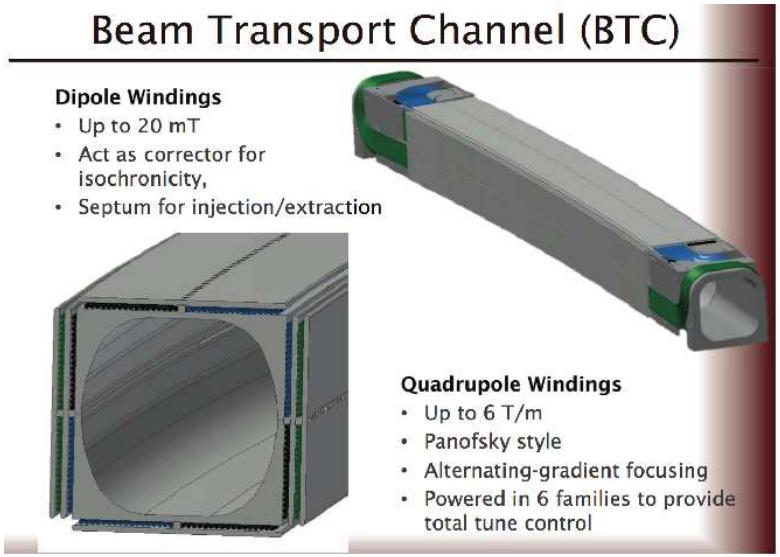
2.4 Texas A&M "TAMU" design

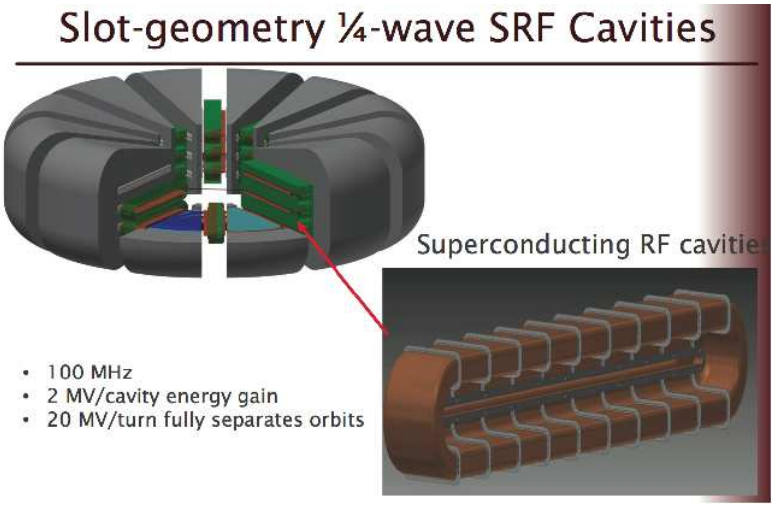
Two concepts exploited here :

- **Folded beam channel, strong focusing / constant tunes**
- **Flux coupled stacked gaps**
- **Resulting typical design : 800 MeV, 8 MW/stack, 50% efficiency**









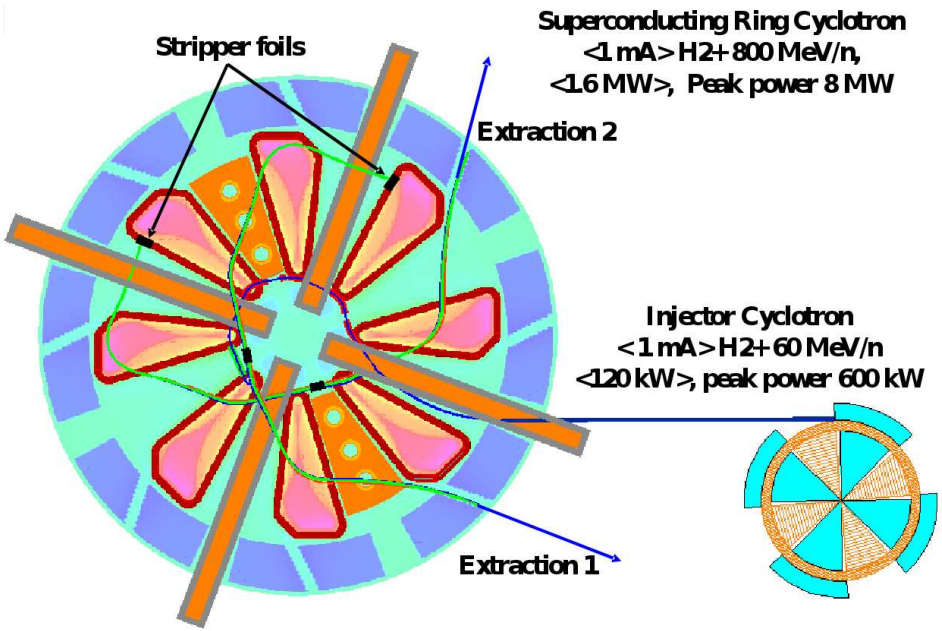
Folded, double-quarter-wave cavity structure

- **4-sector 100 MeV injector stack**
- **12-sector main ring stack**
- **10 superconducting cavities per beam for 20 MeV/turn**
- **Large turn separation allows superconducting channels**
- **Bunches in successive turns do not see each other**

2.5 The DAEδALUS H_2^+ cyclotron

"Decay-At-rest Experiment for δ_{CP} studies At the Laboratory for Underground Science"

- **After the DAEδALUS design, delivers 800 MeV, 10 mA / 8 MW proton beam.**
- **Major ingredients : acceleration of molecular H_2^+, superconducting magnets.**



- **H_2^+ stripping extraction - relaxes on turn separation thus allowing high magnetic field (compactness)**
- **Relaxes on space charge effects, weak at 5 mA H2+, i.e., 10 mA extracted proton beam**
- **Magnetic field 6 T, RF 4MV/cavity**
- **Potential for 1.5 GeV**

Power balance at the RIKEN cyclotron:

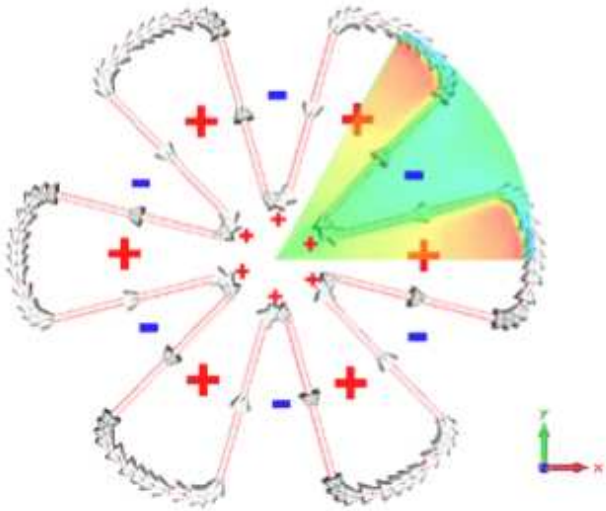
- **Helium cooling system : 1MW**
- **Power supplies for SC coils (main coils and superconducting trim coil) : 0.2 MW**
- **PS for warm trim coil : 1MW**
- **PS for injection/extraction elements : 1MW**
- **RF system : 1.5 MW**
- **Total : 4.7 MW**

Similar in design to the RIKEN K2600 SC cyclotron

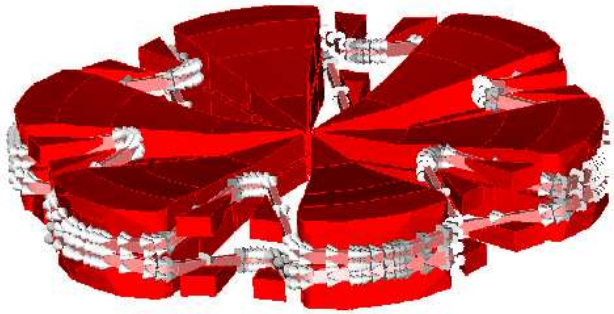
- **Diameter 19m, 3.8T field, 6 RF cavities**
- **World first SC cyclotron, first beam 2006**

2.6 AIMA Revatron

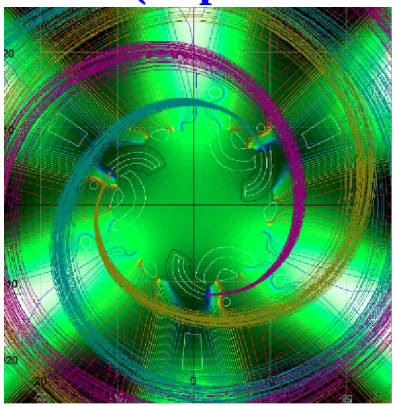
- **Concept exploited here : reversed valley field.**
- **800 MeV/u (p or H_2^+), three beams : 3 $\times$ 5 mAmp**
- **Axial injection, 60 kV/u : no injector ($\rightarrow$ compactness, cost savings, reliability)**
- **Reverse field allows direct outward extraction**

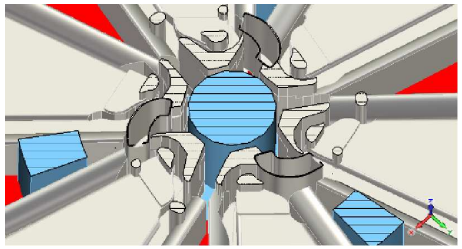


SC coils. Radius : 4.2 $\rightarrow$ 7.1 m
6 RF cavities / 12 gaps per turn,
0.15 MV $\rightarrow$ 0.45 MV per gap

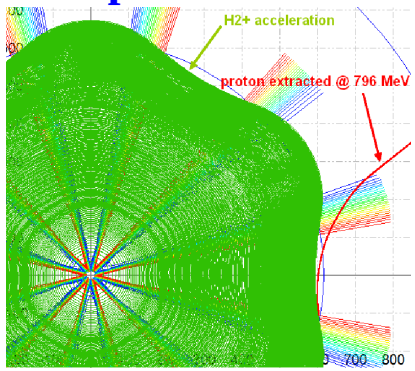


Triple injection
(3 spiral inflectors)





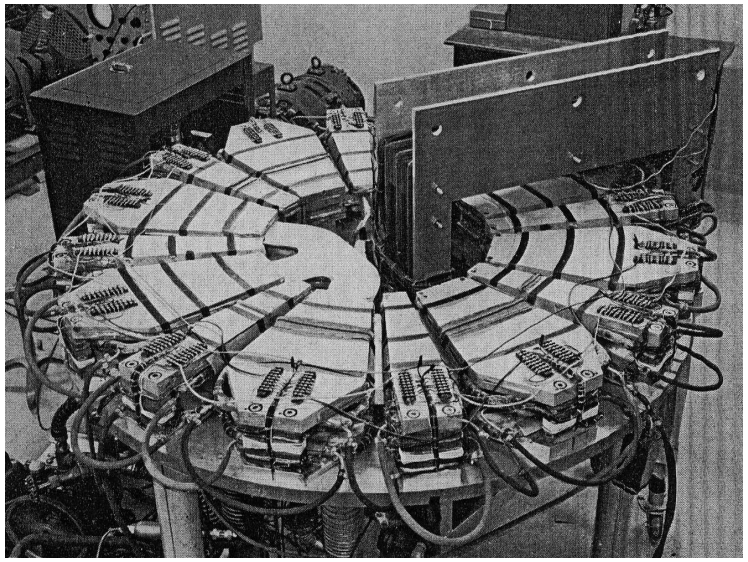
Direct extraction in reversed field valley.
Turn separation $\sim$15 mm

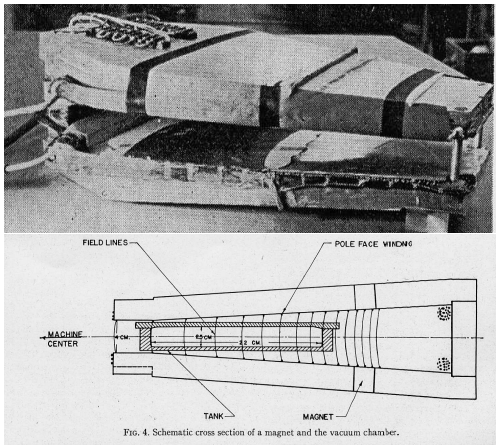


3 FIXED-FIELD ALTERNATING GRADIENT ACCELERATORS

3.1 MURA scaling FFAGs

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



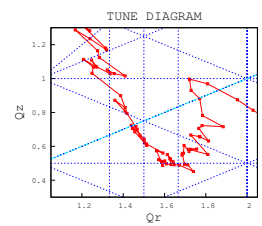


F magnet, positive field, radially focusing.

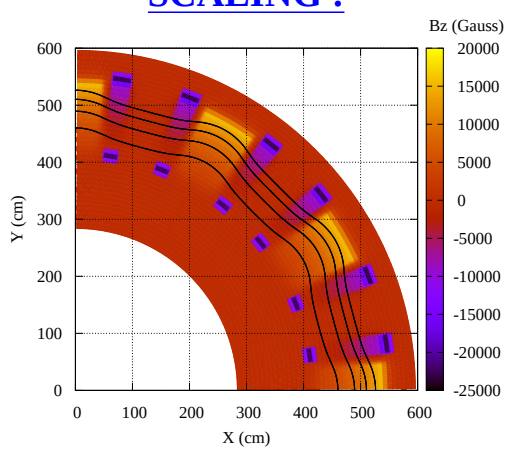
FFAG ring parameters

$E_{inj} - E_{max}$	*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**	

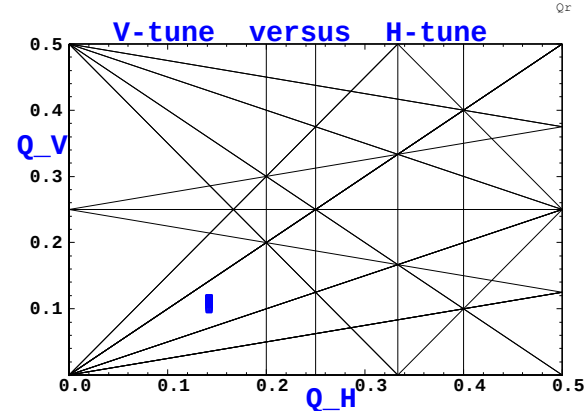
$$B = B_0 (r/r_0)^K \, F(\theta)$$



SCALING :

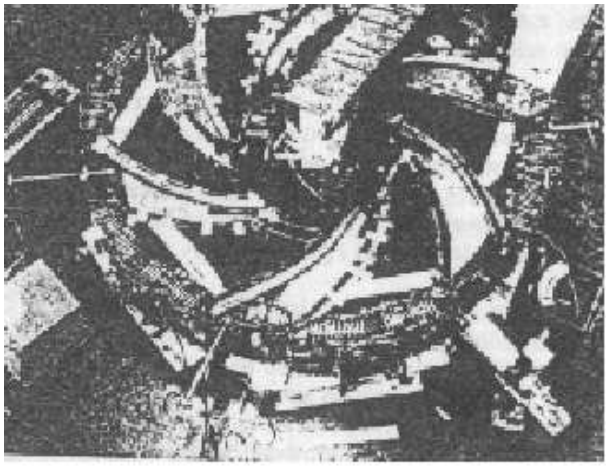


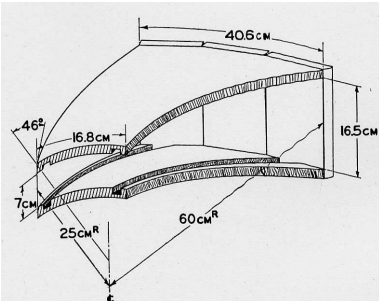
CONSTANT TUNES :



- **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

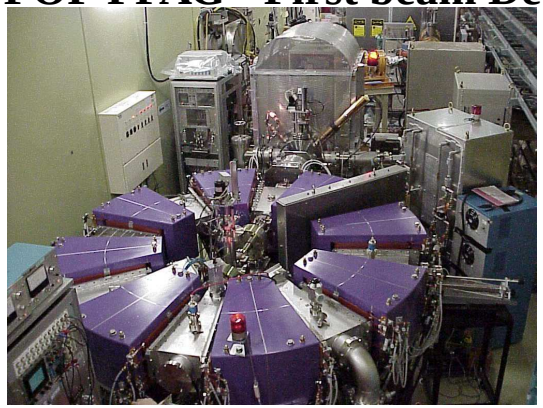
rep. rate	*Hz*	**a few 10s**

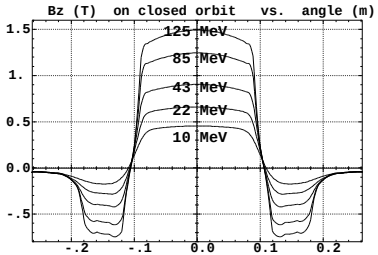
3.2 Recent proton R/D

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

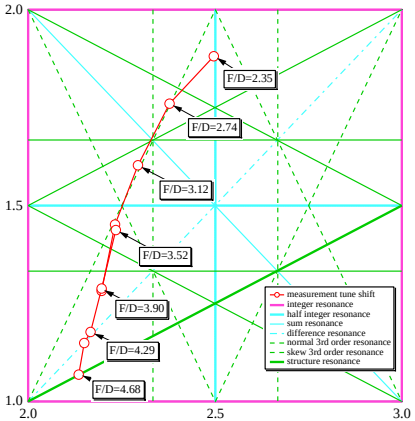
Interest: Fast acceleration (short lived muons, high average proton beam I), strong focusing (mitigates space charge effects), very large acceptance.

POP FFAG - First beam Dec. 1999

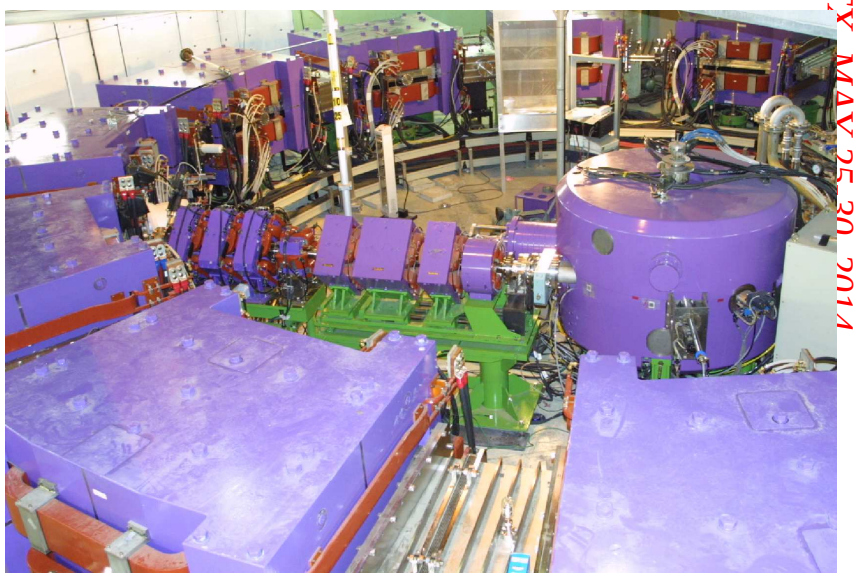




$E_{inj} - E_{max}$	keV	50 - 500
orbit radius	m	0.8 - 1.14
lattice / K		DFD $\times$ 8 / 2.5
ν_r / ν_z		2.2 / 1.25
RF swing	MHz	0.6 - 1.4
voltage p-to-p	kV	1.3 - 3
cycle time	ms	1



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

- **Mid 2000s on, KURRI KUCA**

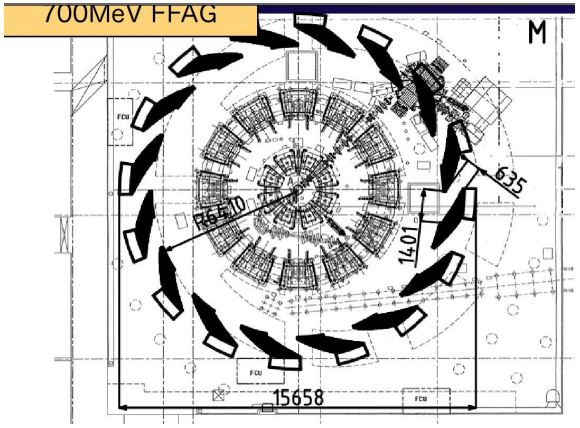
- A feasibility evaluation of ADS-R as an energy production system.

- 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

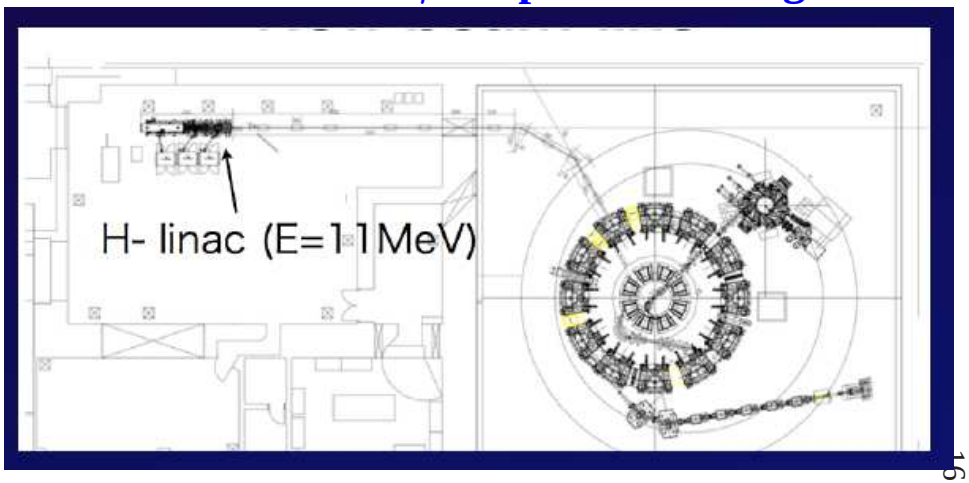
Variable energy 150-700 MeV facility, neutron flux increased by a factor 30



• Planned upgrades :

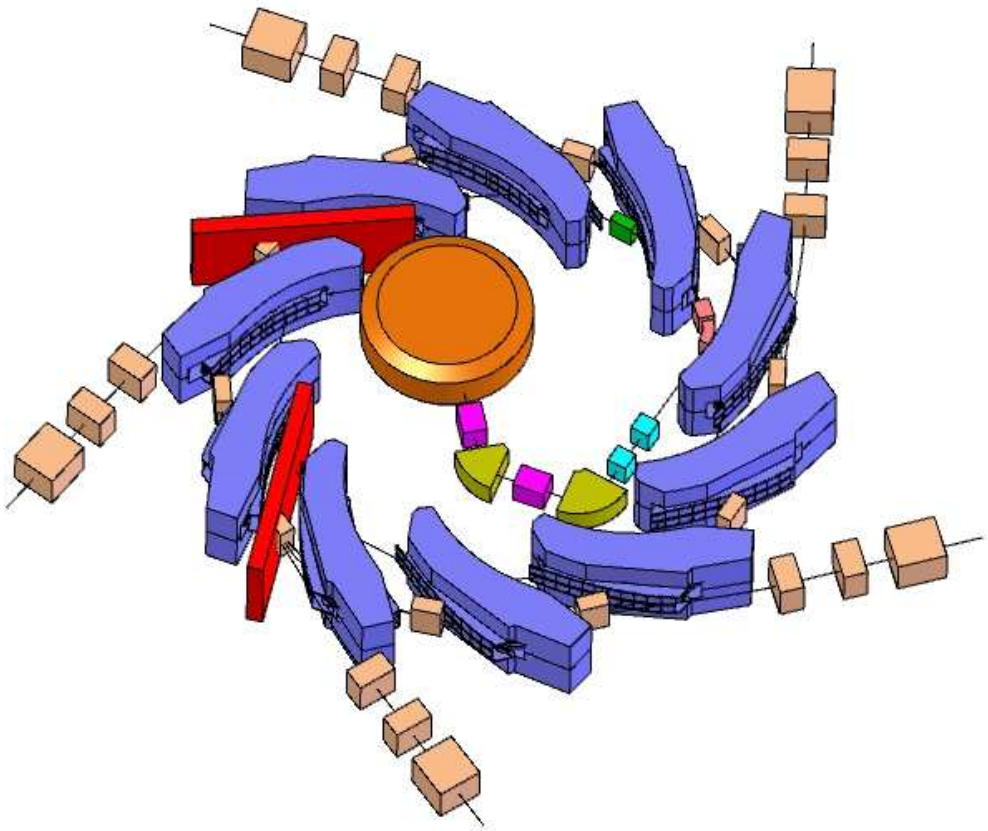
On-going : H- charge exchange injection

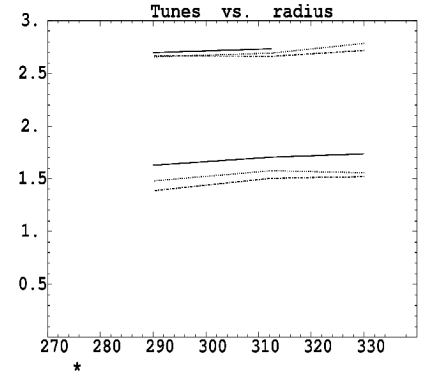
Towards 10s of μAmp current ranges

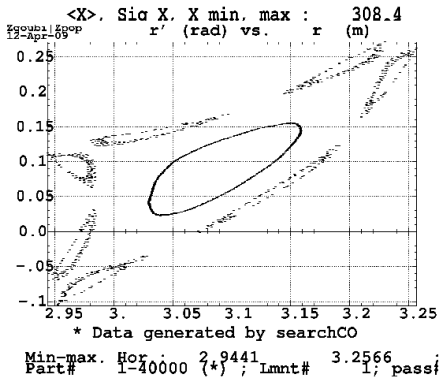


RACCAM - proton FFAG R&D

- **Working frame : Neutrino factory R/D. French ANR funding, 2006-2008, 3.5 MEU**
- **A feasibility study of a rapid-cycling, variable energy, spiral lattice scaling FFAG**
- **Found application in simultaneous multi-port hadrontherapy application [poster session, this conference]**
- **Magnet design outcomes exploited in the KURRI-KUCA 700 MeV upgrade**

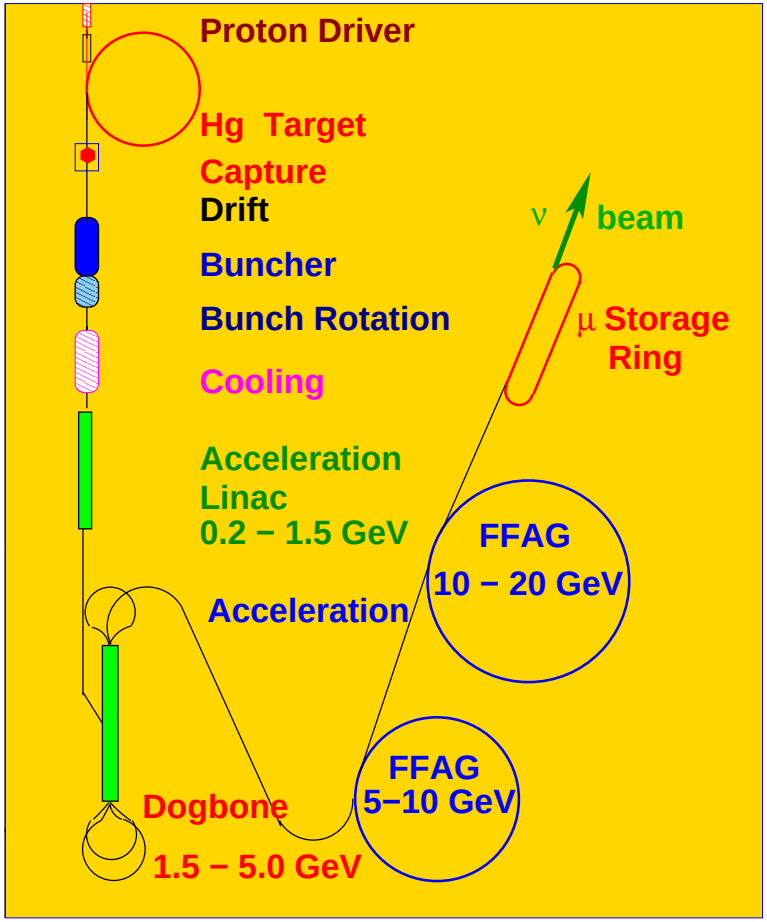


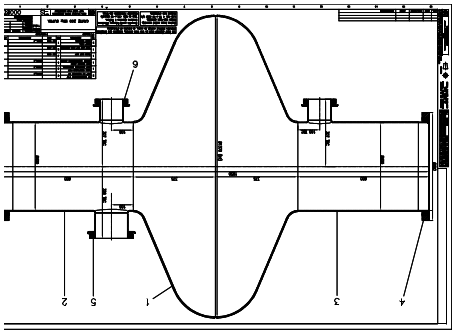




3.3 Linear FFAG, concept

- **Two concepts where introduced in the late 1990s, in the frame of the "neutrino Factory" R&D :**
  - **"linear lattice" FFAG : magnets are simple quadrupoles**
  - **"quasi-isochronous" acceleration : allows using fixed frequency RF cavities (good for CW)**
- **Well suited for the acceleration of - short-lived - muons up to 20-50 GeV**
  Compared to RLAs : many more turns, hence saving on RF cavities and systems,





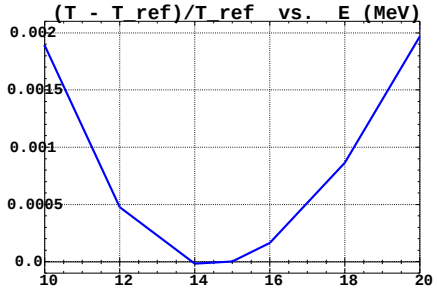
3.4 The EMMA experiment

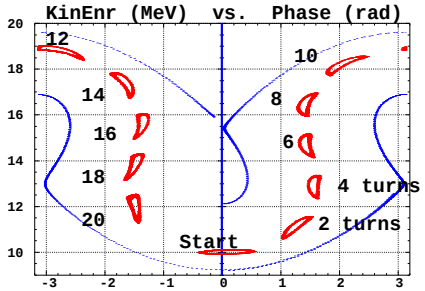
• **An experimental "Electron Model for Many Applications", to prove these concepts, in the frame of an international collaboration.**

- **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

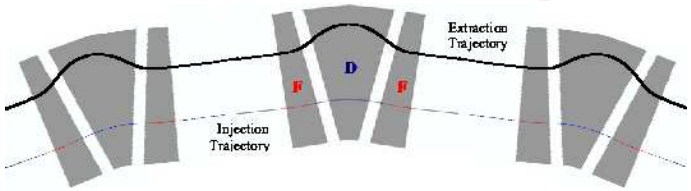




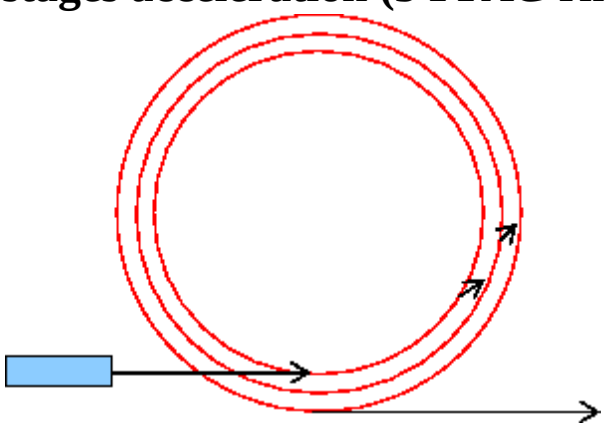
3.5 Proton driver design studies

• Linear FFAG / S. Ruggiero, BNL, 2004

• Linear FDF FFAG triplet



• 3 stages acceleration (3 FFAG rings)



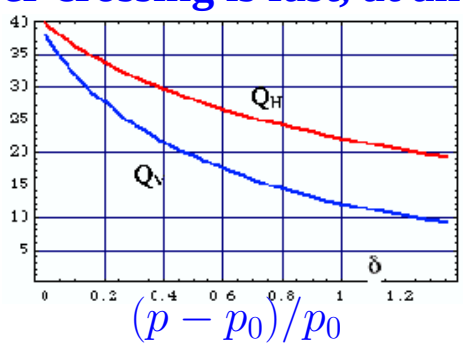
• For neutrino factory p-driver, 12 GeV design, potential for several MW

		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

• Lots of resoances to go through :

$Q_x : 40 \to 19, \quad Q_y : 38 \to 9.$

However crossing is fast, at all energy



• Consider ring 1,

- pulsed RF, using ferrite tuned cavities,
- repetition rate >100 Hz,
- assume few 10^{13}ppp

hence potential for MW beam power in GeV range.

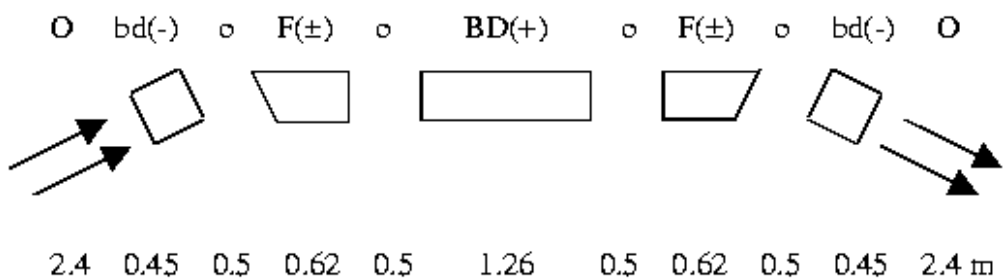
• CW acceleration based on "harmonic number jump", using fixed frequency RF systems, was investigated.

• Pumplet lattice - 2004

- 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 (two 50 Hz rings).

• Isochronism involves many variables.
It provides the advantage of on-crest acceleration.

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



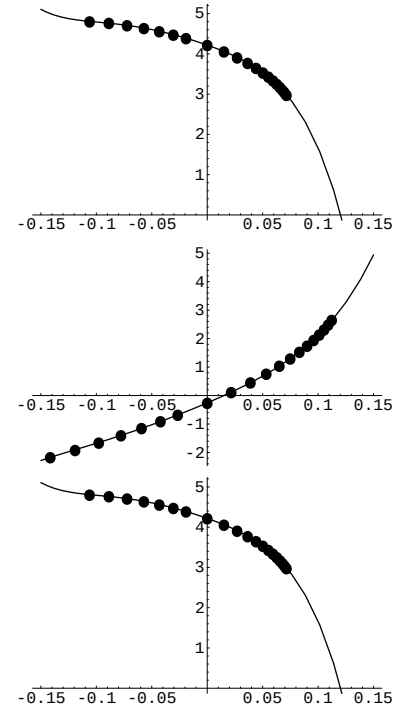
$$B_{bd}(x) = -3.456 - 6.6892\,x + 9.4032\,x^2 - 7.6236\,x^3 + 360.38\,x^4 + 1677.79\,x^5$$

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

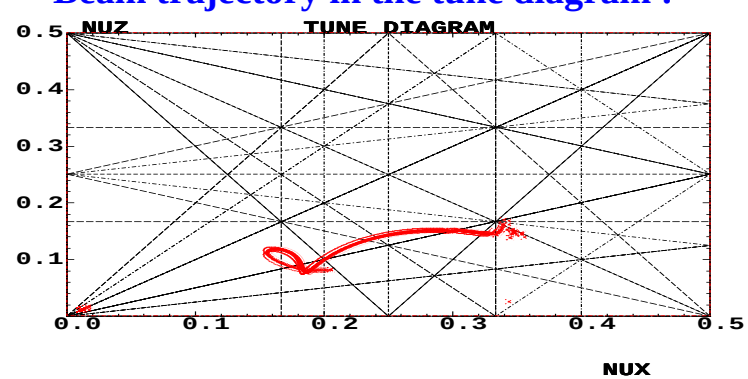
$$B_{BD}(x) = 4.220 - 9.659\,x - 45.472\,x^2 - 322.1230\,x^3 - 5364.309\,x^4 - 27510.4\,x^5$$

Allows insertion straights , with the advantages of
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.

Magnetic field in bd, BF and BD.



Beam trajectory in the tune diagram :



- **Lately, serpentine acceleration in a scaling FFAG lattice demonstrated**

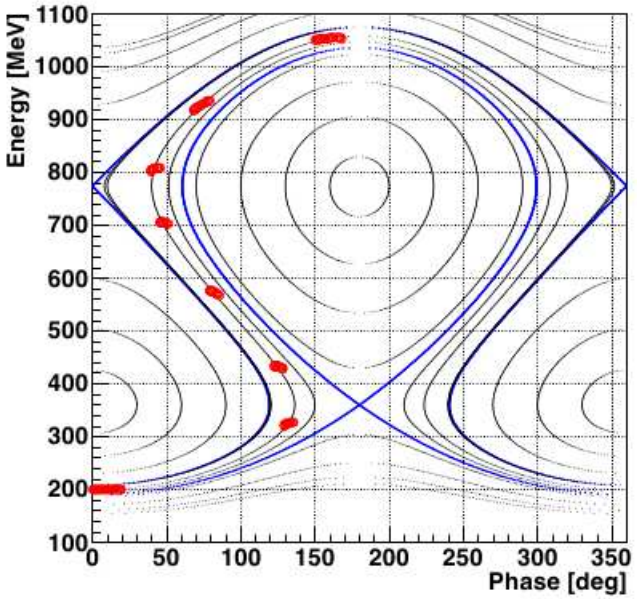
- **Allows fixed RF-frequency acceleration in variable $\beta = v/c$ regime**
  - i.e., non-relativistic beam, suitable for proton acceleration.

- **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

- **ADS equivalent**
(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)



3.6 More is going on in FFAG R&D

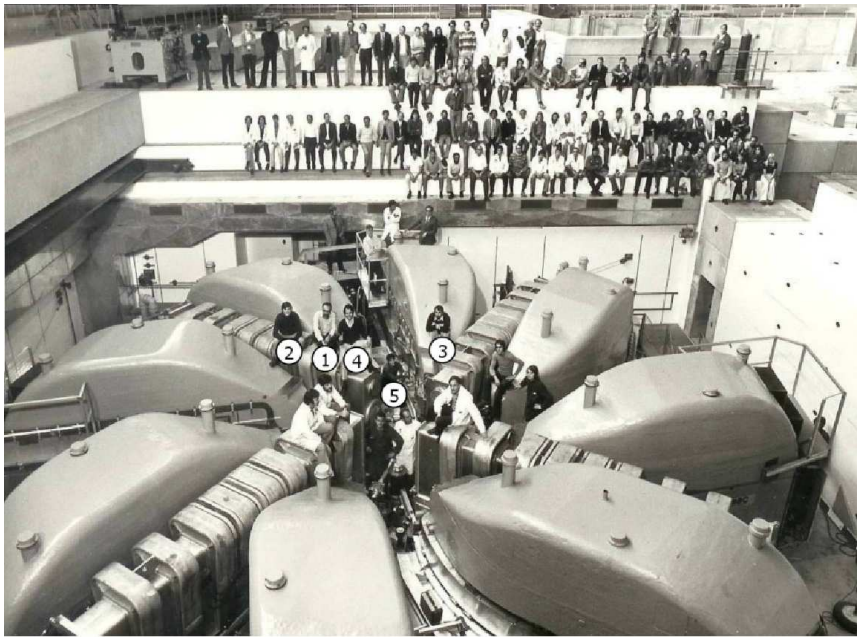
Confer FFAG workshops, PAC and IPAC conferences on JaCOW.

- **Compact, $\beta < 1$, isochronous lattices, based on radial index and magnet edge tayloring**
- **Isochronous, $\beta < 1$, lattices exploiting reverse bend optical properties**
- **Serpentine acceleration**
- **Magnet technology**
- **RF technology**
- **...**

4 MY CONCLUSION

- **In the matter of MWs , fixed-field rings still have much to say.**
- **Fixed-field rings allow alternative solution to linacs,**

potentially simpler, and producing CW beams at lower cost.



THANK YOU FOR YOUR ATTENTION