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High power ring methods in ADS-R application

Thorium Fuel Cycles and Nuclear Spectra Workshop

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Contents

1 The "A" in ADS-R - Ring methods

An accelerator driven system consists of

- **a high power proton accelerator that provides a beam in the spallation energy range, $0.6 - 1.5$ GeV**

- **a heavy metal, high neutron production efficiency spallation target (Pb, Pb+Bi), installed in the center of the nuclear core, provides the neutrons needed to sustain the fission process ; for instance convertion from fertile ^{232}Th to fissile ^{233}U,**

- **a sub-critical core neutronically coupled to the target. " [US OS "ADS White Paper"]**

A complete accelerator system for high power ADS applications consists of four main sections:

- **source (e.g., ECR)**

- **booster stage(s) (e.g., RFQ, linac, cyclotron, including buncher stage(s))**

- **high energy stage (linac, fixed field ring)**

- **a beam delivery system which transports the beam to the spallation target, and shapes the beam to the required size, profile, and uniformity.**

- **Beam can be protons.** **Little benefit from heavier ions, at larger accelerator cost.**

- **Required beam intensity is**

$$I[A] = \frac{P_{\rm th}[MW]}{f\,E_f[MeV]}\frac{(1-k)}{k} \approx \frac{1}{2}(1-k)\,P_{\rm th}$$

$k \approx 0.95 - 1^- =$ **neutron multiplication factor (produced/absorbed),**
$E_f =$ **fission energy** $\approx 200[MeV]$**,**
f = fraction of neutrons causing fission = nb of neutrons emitted per incident proton / nb of neutrons emitted per fission, e.g. $20/2.5$**.**

- k **is central to the accelerator parameters, the closer it is to 1, the lower the beam power to be brought in.**

- **Examples :**
  - JAEA power installation design : proton beam 1.5 GeV, 30 MW, for 800 MW-th,

  - Transmutation demonstration facility MYRRHA : 600 MeV proton, 1.5 MW beam power to a subcritical core with 85 MW thermal power.

Accelerator technologies, for 1 MW power and beyond [US ADS White Paper]

• **Separated sector cyclotron, the highest power example of which operates at the Paul Scherrer Institute in Switzerland, delivering a 1.3 MW CW beam,**

• **Normal conducting proton linear accelerator, the highest power example of which (the LANSCE linac) delivered a 1 MW pulsed beam at Los Alamos National Laboratory,**

• **Superconducting proton linear accelerator, the highest power example of which (the SNS linac) delivers a 1.1 MW pulsed beam at Oak Ridge National Laboratory.**

Alternative approaches to high proton beam power include :

• **synchrotron technology, which has the capability of achieving powers in excess of 1 MW, but is limited to pulsed operation at relatively low duty factor.**

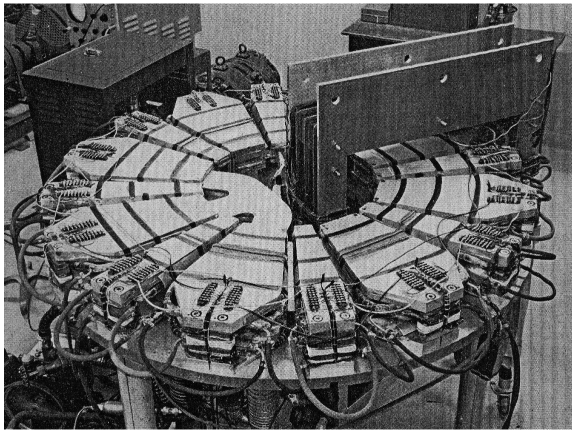
• **Fixed Field Alternating Gradient (FFAG) accelerators, actively studied at laboratories throughout the world. Synchrotrons and FFAGs have some similar intrinsic features, but the repetition rate for FFAGs can be much higher (albeit** *without the capability for true CW operation) (?)* . *While promising, FFAGs have yet to demonstrate high beam power capability.*

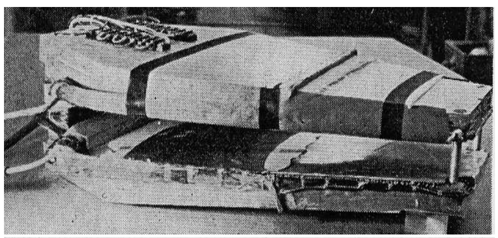
• With further development, FFAG technology may also demonstrate applicability in the 5-10 MW power range. It is worth noting that *cyclotron technology is limited to a maximum energy of 0.8-1 GeV. (?)*

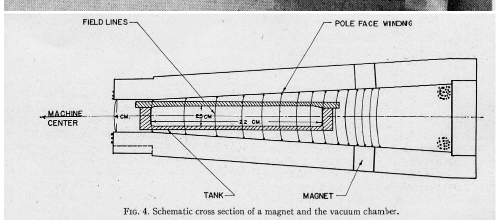
2 FFAGs

2.1 MURA electron FFAGs

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







F magnet, positive field, radially focusing.

		Machine parameters	criteria / comments
$E_{inj} - E_{max}$	*keV*	25 - 400	{ *small size, easy to build* / *field not too low, ms lifetime* }
orbit radius $(\mathcal{C}/2\pi)$	*m*	0.34 - 0.50	
Optics			
lattice		$\frac{\mathbf{D}}{\mathbf{2}}\mathbf{F}\frac{\mathbf{D}}{\mathbf{2}}$	
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	{ *varying K, resp.* B_F/B_D / *varies mostly* ν_r, *resp.* ν_z }
γ_t		≈ 2	$\sqrt{1+K}$
Magnet		radial sector	$B = B_0(r/r_0)^K\, F(\theta)$
$\theta_F,\ \theta_D$	*deg*	25.74, 10.44	*sector angles*
$r_{F,D}/\rho$		2.85, 2.59	*at center of F, D magnets*
gap	*cm*	6 - 4	g/r =*Cst*
Injection		continuous or pulsed	
Acceleration		only betatron, at first...	*for simplicity*
swing	*Gauss*	40 - 150	
rep. rate	*Hz*	a few 10's	
		... completed with RF acc., next	*split tank*
freq. swing	*MHz*	10 in [35, 75] MHz	*for RF stacking expts*
gap voltage	*V*	50	
cycle rep. rate	*kHz*	a few	*to cope with lifetime*

Second model, spiral sector FFAG, Mark V

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

Interest of spiral optics : always positive curvature, hence smaller accelerator, compared to radial sector.

Study objectives : confirm theoretical predictions - first extensive use of computers to determine magnetic field and machine parameters ; long-term orbit stability ; RF acceleration methods.

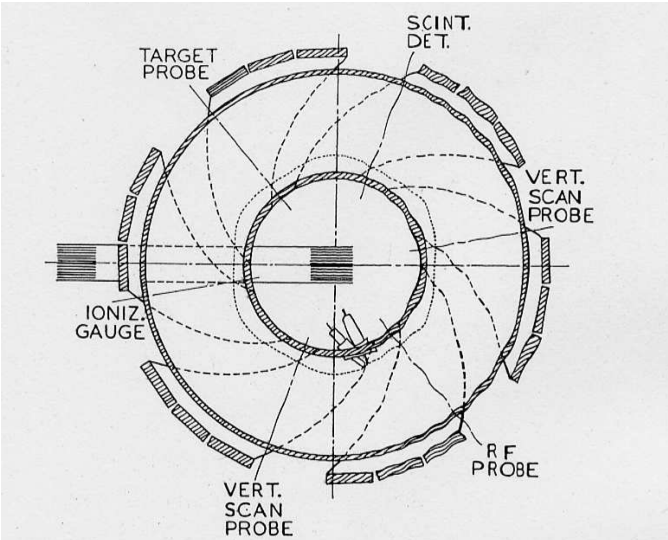
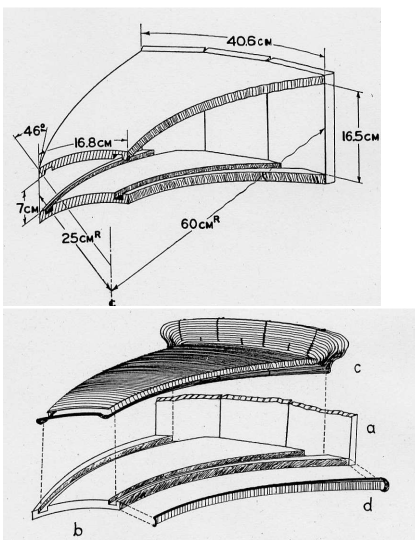


FIG. 1. Over-all view of the spiral sector model.



Logarithmic spiral poles

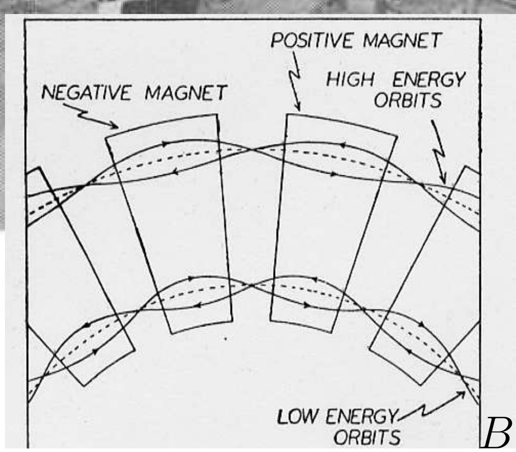
		Machine parameters	criteria / comments
$E_{inj} - E_{max}$	*keV*	35 - 180	{ *reasonable size magnets*
orbit radius	*m*	0.34 - 0.52	
E_{tr} / r_{tr}	*keV / m*	155 / 0.49	{ *RF exprmnts at* $\gamma_{tr} = (1+K)^{1/2}$
Optics			
lattice		N spiral sectors	
number of sectors		6	
field index K		0.7	{ *pole-face 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	$B{=}B_0(\frac{r}{r_0})^K F(\ln\frac{r}{r_0}/w - N\theta)$
$1/w$		6.25	$2\pi w r_0 \approx$ *ridges radial separation*
$\alpha = Arctg(Nw)$	*deg*	46	*edge to radius angle*
$r_{min} - r_{max}$	*m*	0.25 - 0.61	
gap	*cm*	16.5 - 7	g/r =*Cte*
Injection		cont. or pulsed	*e-gun + e-inflector*
Acceleration		betatron and RF	*extensive RF prog. tests*

Second radial sector, 50 MeV, 2-way "collider scheme"

Preliminary studies early 1957. The spiral sector e-model was not yet completed - this determinied the choice of radial sector : easier to design, better understood.

Study objectives : 1/ RF stacking, 2/ high circulating I, 3/ 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.



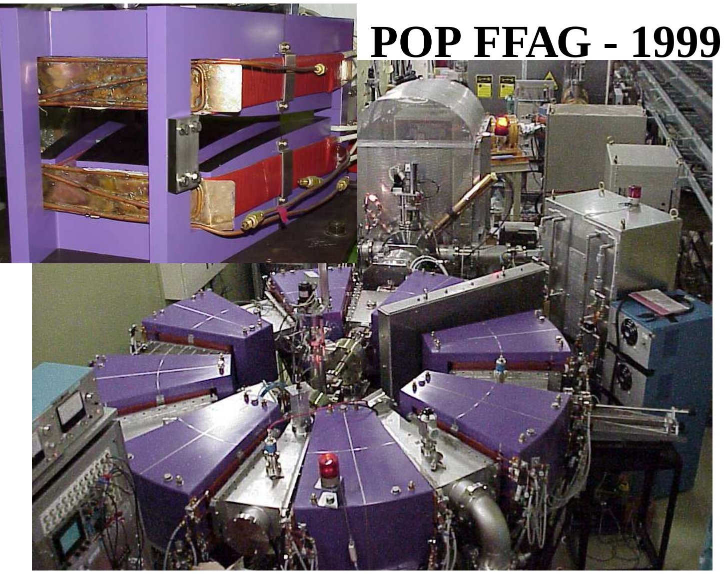
$B_F = B_D$

[Typical] data

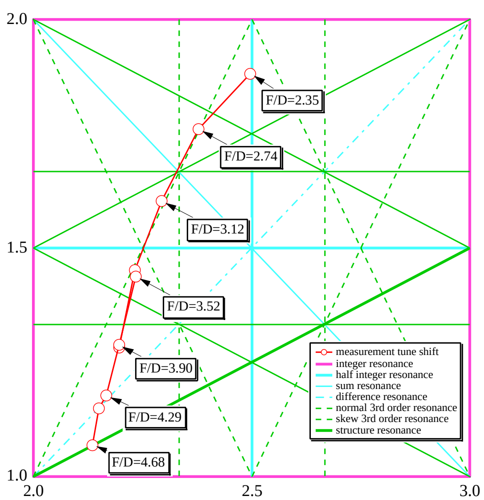
Machine parameters			criteria / comments
$E_{inj} - E_{max}$	*MeV*	**0.1 - 50**	*reasonable size & beam life-time*
orbit radius	*m*	**1.20 - 2.00**	
Optics			
lattice		**FODO**	$B \approx B_0(r/r_0)^K \cos(16\,\theta)$
number of cells		**16**	*32 magnets, 3.15 deg. drifts*
K		**9.25**	
ν_r / ν_z		**4.42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

2.2 R/D in Japan

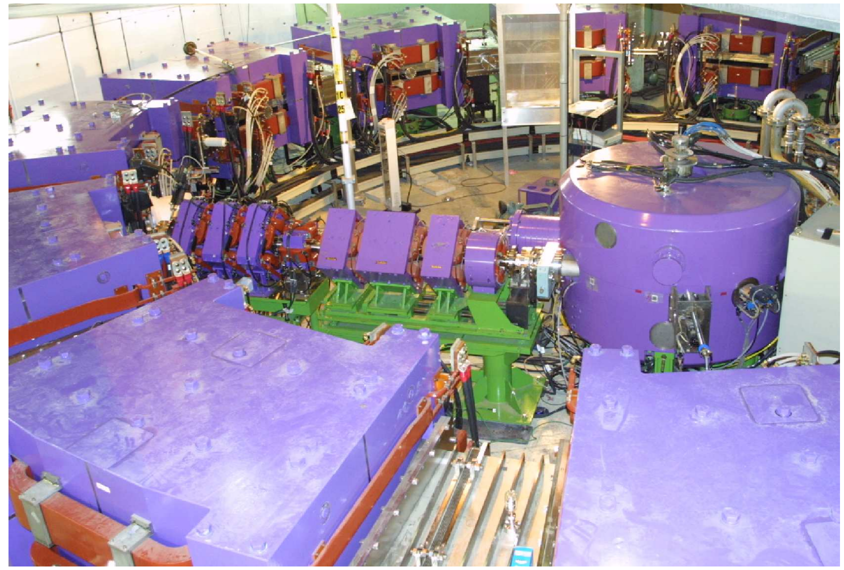
POP FFAG - 1999



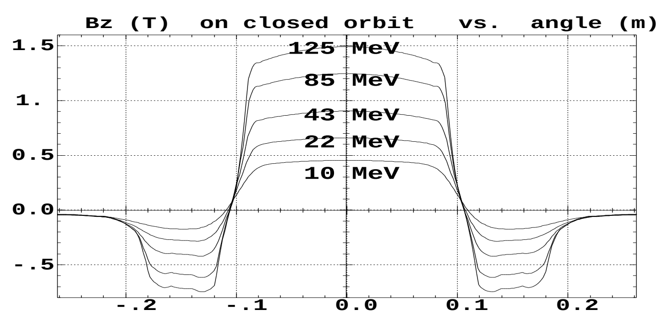
$E_{inj} - E_{max}$	keV	50 - 500
orbit radius	m	0.8 - 1.14
lattice / K		DFD $\times$ 8 / 2.5
$\beta_r,\ \beta_z$ max.	m	0.7
$\nu_r\ /\ \nu_z$		2.2 / 1.25
RF swing	MHz	0.6 - 1.4
voltage p-to-p	kV	1.3 - 3
cycle time	ms	1



150 MeV FFAG - 2003



$E_{inj} - E_{max}$	MeV	12 - 150
orbit radius	m	4.47 - 5.20
lattice / K		DFD $\times$ 12 / 7.6
$\beta_r\ /\ \beta_z$ max.	m	2.5 / 4.5
$\nu_r\ /\ \nu_z$		3.7 / 1.3
$B_D\ /\ B_F$	T	0.2-0.78 / 0.5-1.63
gap	cm	23.2 - 4.2
RF swing	MHz	1.5 - 4.5
voltage p-to-p	kV	2
rep. rate	Hz	250

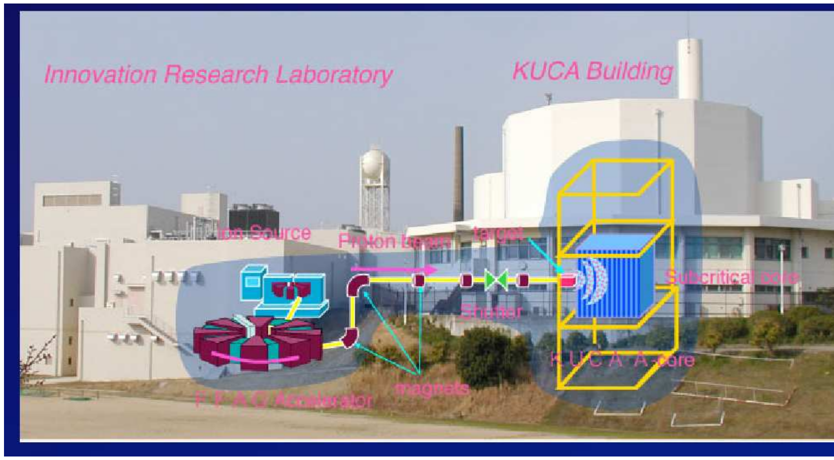


KURRI KUCA. First ADS-R connection

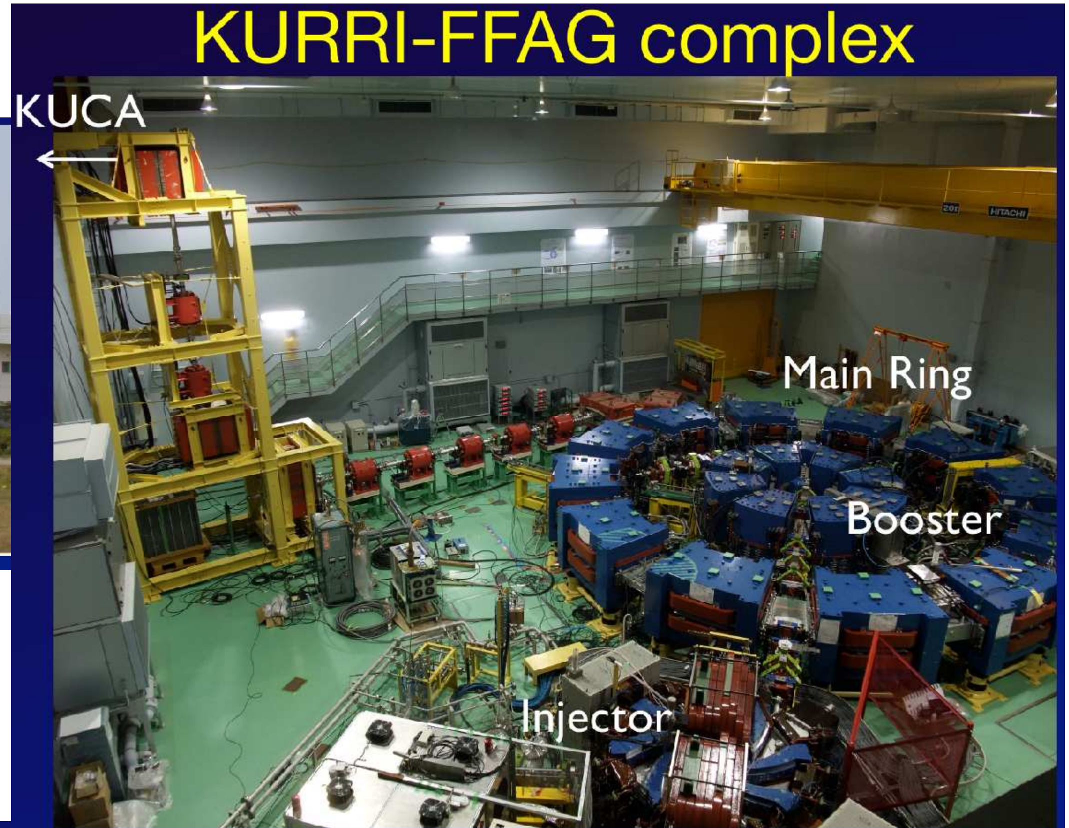
- The main purposes of this R&D :

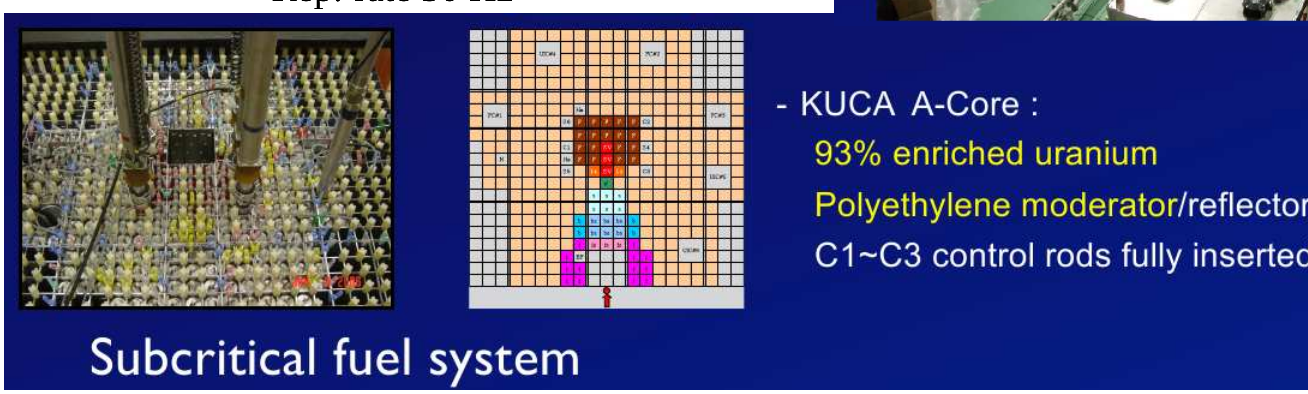
 - a basic feasibility evaluation of ADSR as an energy production device.
 - k physics : sub-criticality characteristics, neutron multiplication, fuel... Including Thorium in 2010.

$\rightarrow$ 1 GeV, spiral FFAG



Accelerator to core 2009
Core power < 10 Watt
W target D80mm/L10mm
Beam power < 0.1 Watt (100-150 MeV, 1 nA)
Rep. rate 30 Hz

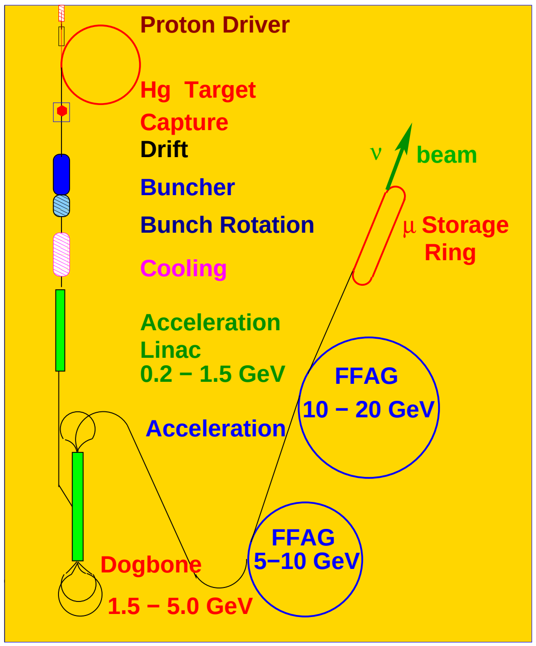


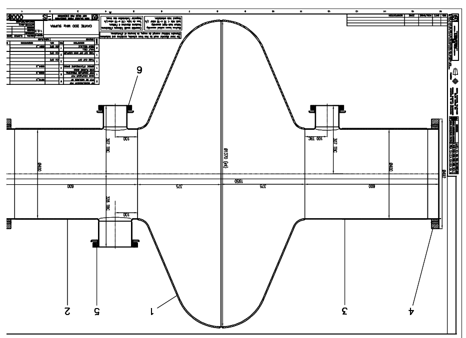


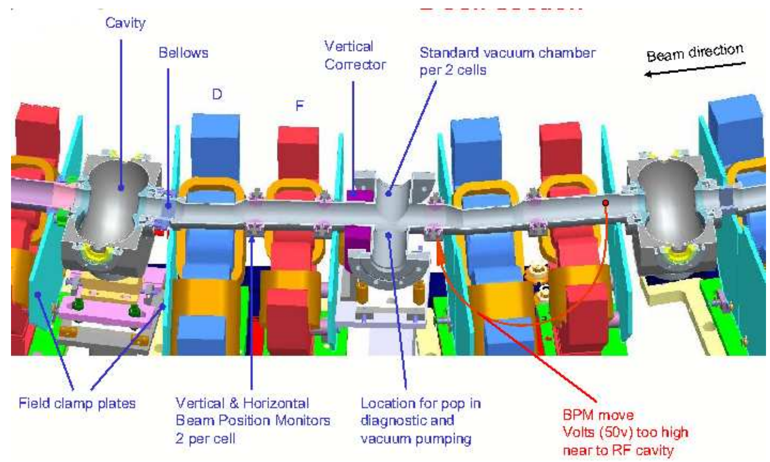
2.3 Linear FFAG

- 2 innovative concepts : linear lattice, quasi-isochronous acceleration, Johnstone/Koscielniak, 1999-2000 - introduced in the late 90's, for muons : **synchrotron-like cell - ! linear optical elements - & fixed fields**
- **Orbit position** moves in the course of acceleration, and **tunes change** unlike "scaling" FFAG
- Well suited for high energy muon acceleration in NuFact. Compared to RLA's : more turns hence less RF ; FFAG rings (2-3) are in smaller # than RLA arcs ($2\times4-5$ pass)

Typical (early) data. 6→20 GeV, 314 Cells, C≈ 2 km, B<6 T, B'<80 T/m, 10-20 MV/cell :





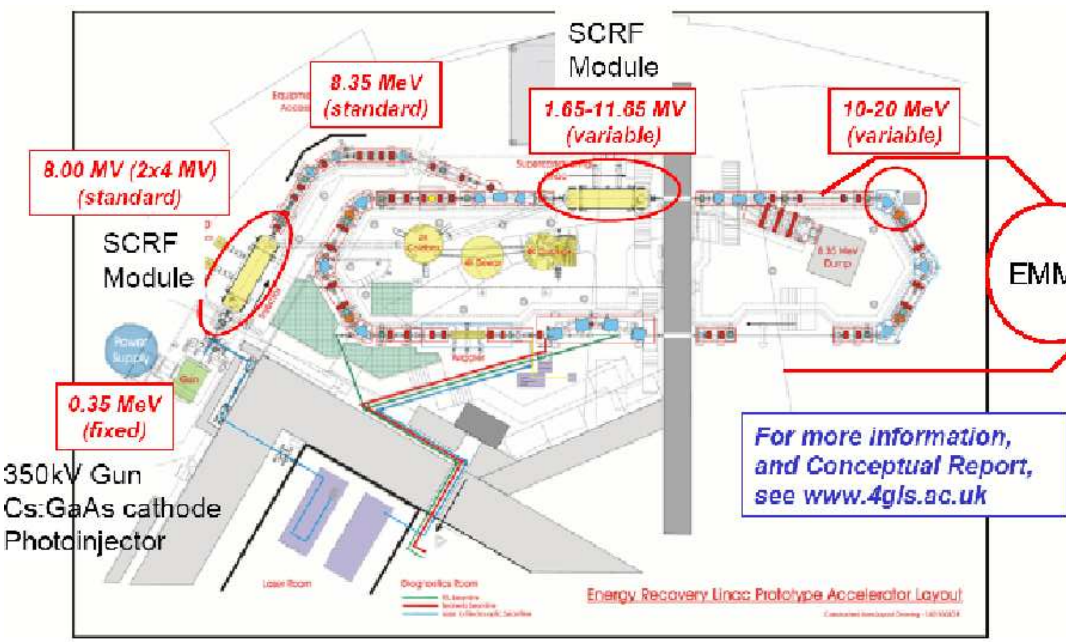


Linear, non-scaling optics induce a series of consequences :

- **large acceptance** (≈ 3 cm) ← linear fields. **Large momentum acceptance** ⇒ prone to less (no ?) cooling
- **rapid acceleration** ($\approx 2-3$ E gain over ≈ 10 turns) ← high freq./$\vec{E}$ RF, near-crest ← small δTOF over E span
- **reduced circumference** (hence μ decay loss) compared to "scaling" ← circumf. factor $R/\rho < 2$
- **magnets have reasonable size** ← reasonable horizontal beam excursion ← small D_x

EMMA - Electron Model for Many Applications

- **Launched in the frame of Neutrino Factory R&D**
- **An experimental machine**
- **International collaboration**
- **2007 : funded through "British Accelerator Science and Radiation Oncology Consortium",**
- **Construction at Daresbury Lab. started in 2007, first beam 2010**



- **Goals of EMMA experiment:**

- prove rapid, "gutter acceleration"
- investigate resonance crossing
- assess phase space, dynamic aperture
- investigate sensitivity to defects
- assess stability, operating conditions

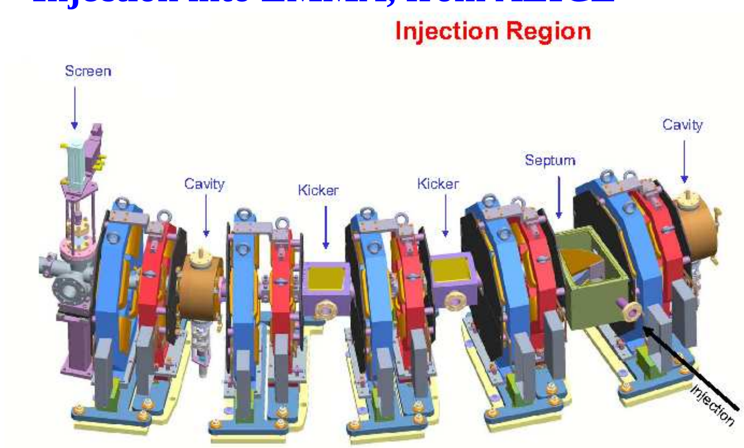
EMMA parameters

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

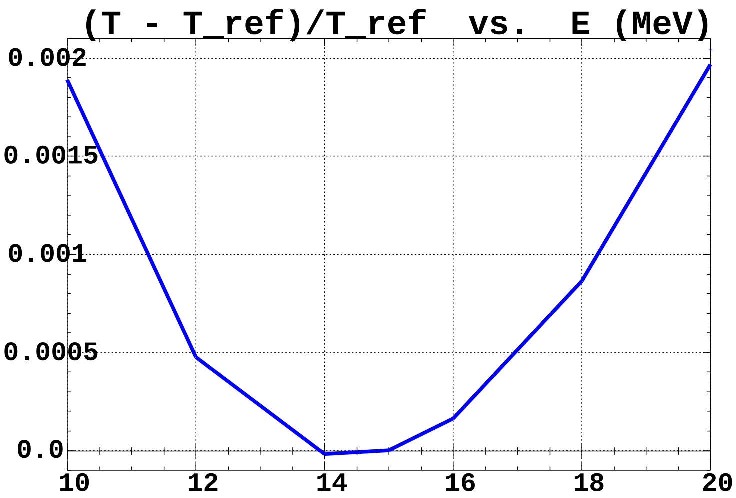
EMMA cell

- cell length	39.448cm
- length F/D	5.88 / 7.57cm
- drifts	5 / 21cm
- QF/QD/Cav. ap.	7.4 / 10.6 / 4cm
- alignement	0.25μ (1σ)

Injection into EMMA, from ALICE

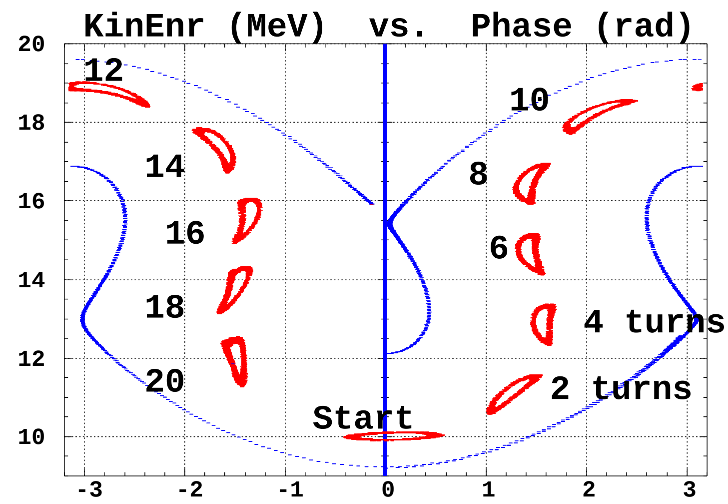


Principle of quasi-isochronous acceleration



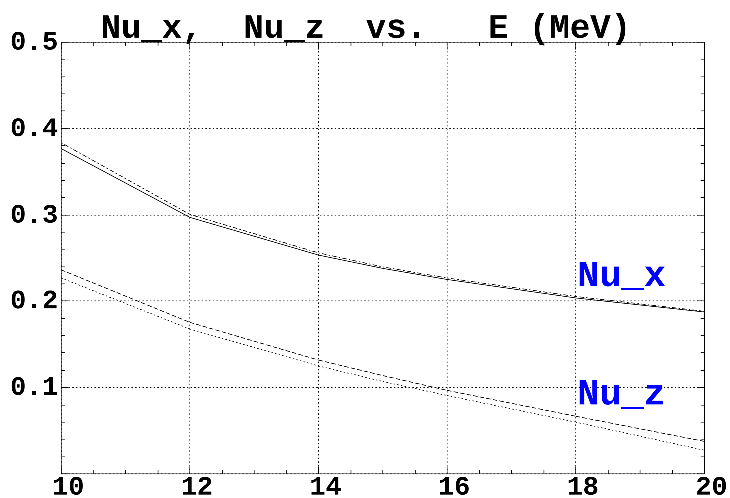
Time of flight parabola ($\gamma \approx \gamma_{tr}$)

$$\frac{\delta TOF}{TOF} \approx \left[\eta_0 \frac{\delta p}{p}\right] + \eta_1 \left(\frac{\delta p}{p}\right)^2$$



"Gutter acceleration"

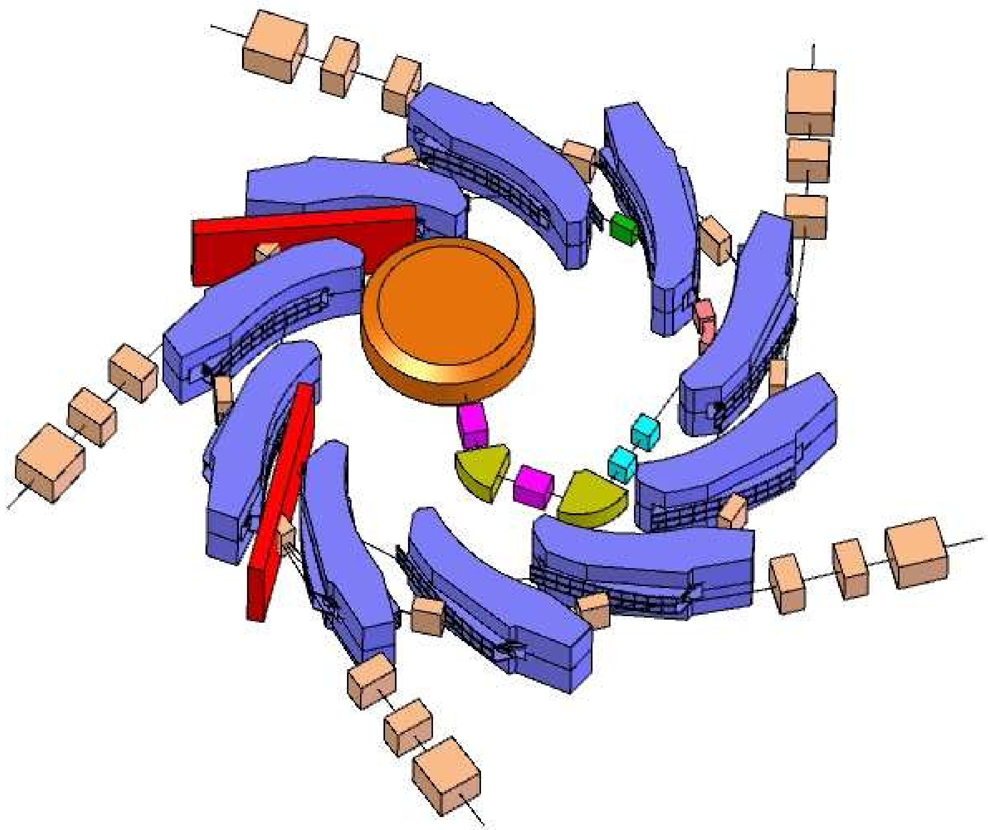
$$H \approx \sin^2 \pi\phi + [a \left(\frac{\delta p}{p}\right)^2] + b \left(\frac{\delta p}{p}\right)^3$$



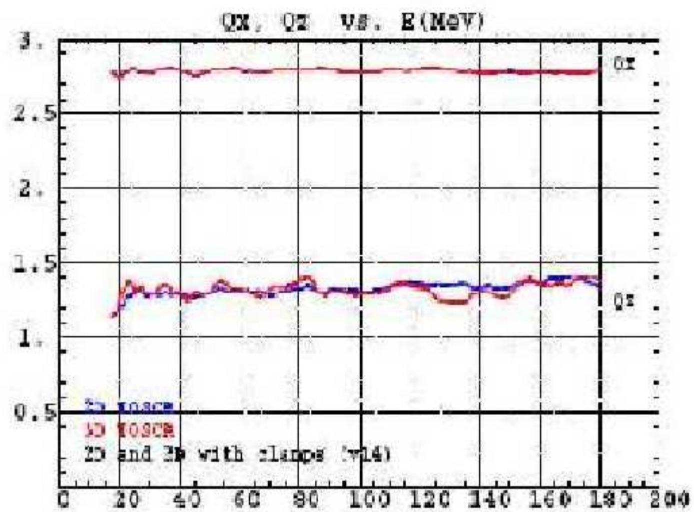
Cell tunes vary with energy

RACCAM - proton FFAG R&D

- French ANR project, 2006-2008, launched in 2005, ≈7m.y, 3.5 MEU
- A frame for collaboration in international R&D programs (EMMA, e.g.)
- A mean for magnet prototyping : focused on spiral sector optics
- Also, a medical project : hadrontherapy and biology R/D.



Master piece : spiral scaling magnet, first of the king



- Designed and built by SigmaPhi, completed April 2007
- magnetic measurements at SigmaPhi, May-November 2007
- proved scaling, industrial feasibility

- 3D design work and fabrication were a succcess : quasi-invariant optics (constant tunes) achieved

- A follow-on : 1 GeV proton driver, KURRI, 2010s

2.4 Proton driver prospects

- **Linear FFAG / S. Ruggiero, BNL, 2004**
  - **For neutrino factory p-driver**, 12 GeV design, 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

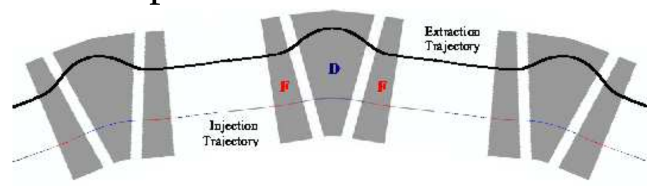
Note : Ring 1, pulsed RF, 10^{14}ppp, rep. rate 100 Hz

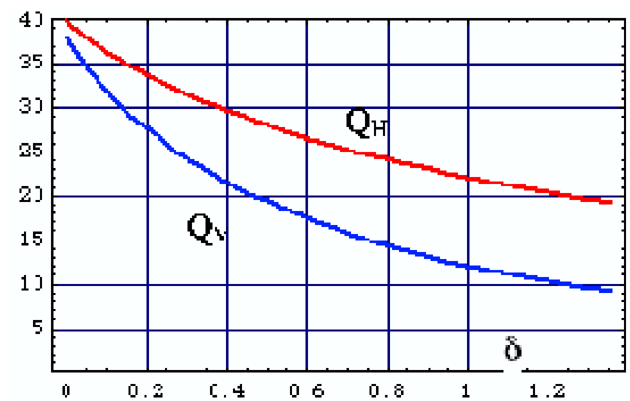
$\rightarrow$ potential for MW beam in GeV range.

- CW acceleration based on "harmonic number jump" foreseeable

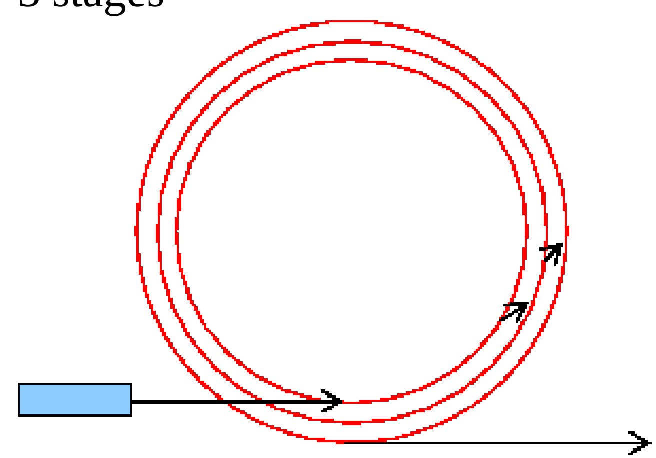
- Refs: (BNL) C-A/AP/208, C-A/AP/218, C-A/AP/219.

- FDF triplet





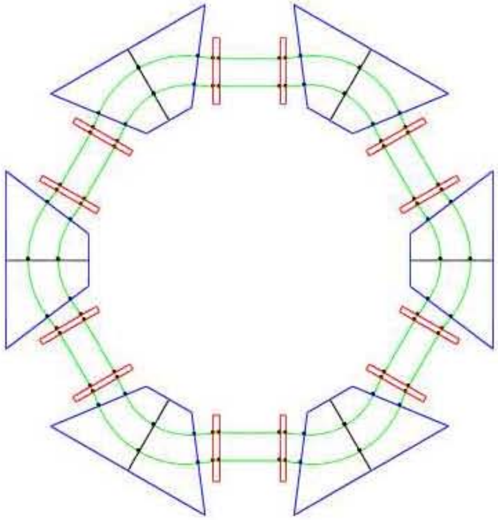
- 3 stages



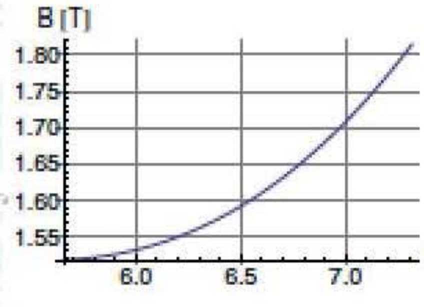
• Non-linear, quasi-isochronous ns-FFAG

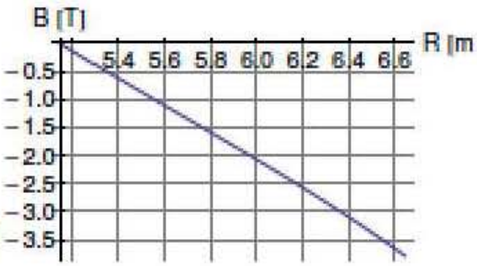
- The main driver behind this design was to achieve better *isochronicity* but the tune variation also improved compared to previous designs.
- Non-linear magnets with radial profile

Parameter	330 MeV	500 MeV	1000 MeV
Avg. Radius [m]	5.498	6.087	7.086
ν_x/ν_y (cell)	0.297/0.196	0.313/0.206	0.367/0.235
Field F/D [T]	1.7/−0.1	1.8/−1.9	1.9/−3.8
Magnet Size F/D [m]	1.96/0.20	2.79/0.20	4.09/0.20

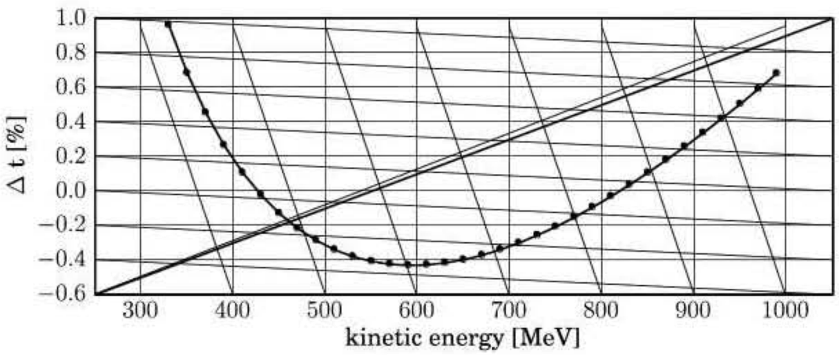


- Total tune variation = 0.42 (H) / 0.234 (V)





Field profiles from C. Johnstone, IPAC'12, THPPR063



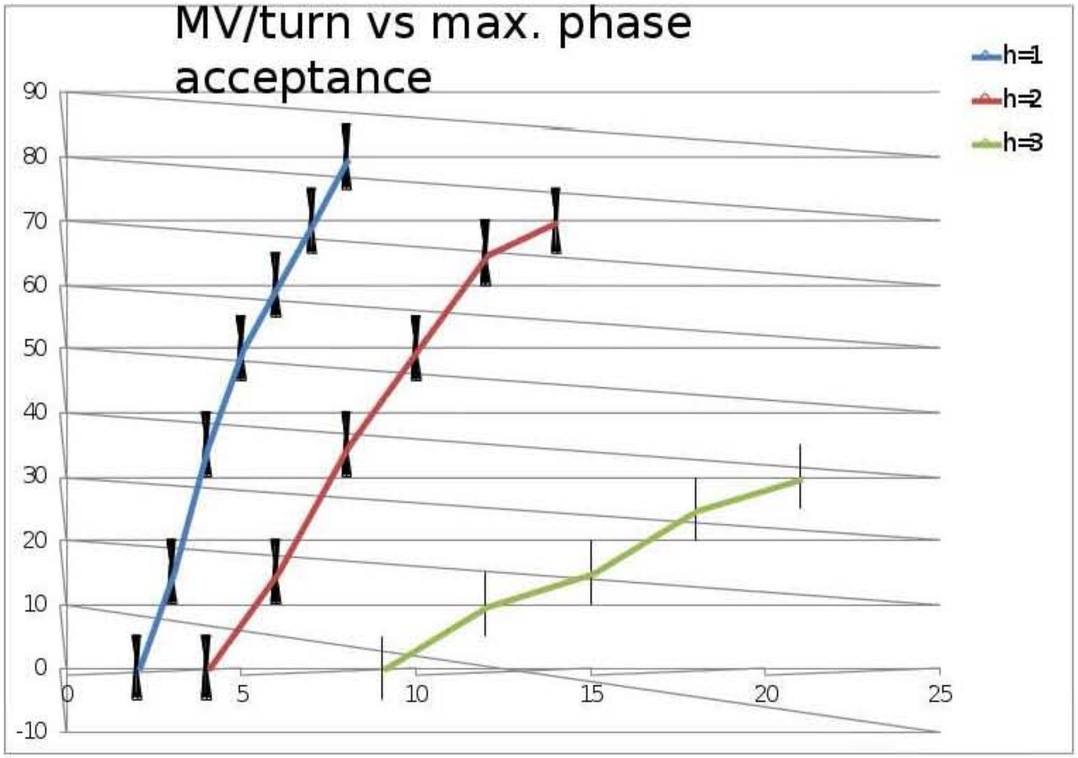
S. Sheehy

Serpentine acceleration

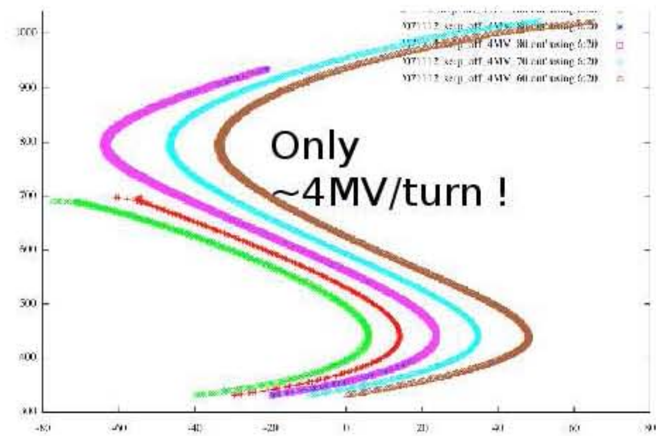
- Not 'perfectly' isochronous
- Phase slip during acceleration is still too large for cyclotron-like acceleration
- BUT what about the serpentine channel?

$$f_{RF} = \frac{1}{T_{min} + \delta T/4}$$

$$\delta E = \frac{\omega\, \delta T\, \Delta E}{16}$$



Serpentine channel acceleration available at ~3.7 MeV/turn for h=1



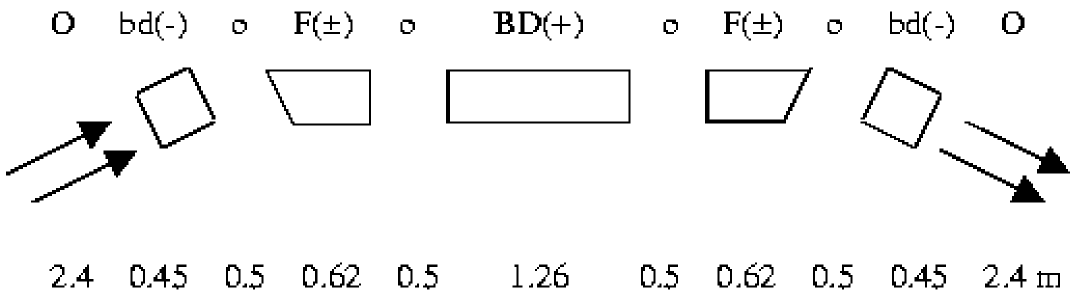
For space charge reasons a higher harmonic cavity may be needed – to be studied

• Pumplet lattice

A non-linear, non-scaling type of FFAG, “non-linear cyclotron”, G. Rees.

It has the advantage of on-crest acceleration.

Ex.: lattice for 8 to 20 GeV / 16 turns / 123 cell ring.



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

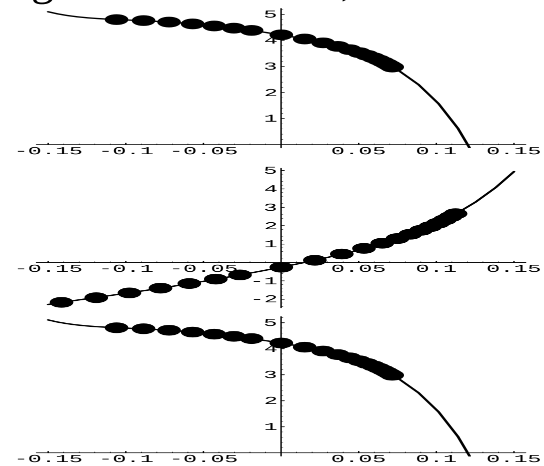
$$B_{BF}(r) = -0.257 + 16.620\,r + 29.739\,r^2 + 158.65\,r^3 + 1812.17\,r^4 + 7669.53\,r^5$$

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

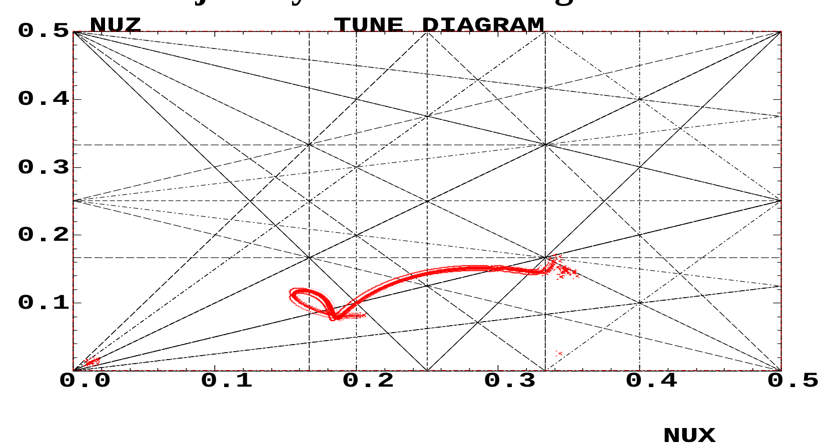
Allows insertion straights , with the advantages of

1. reduced ring circumference,
2. easier injection and extraction,
3. space for beam loss collimators,
4. RF gallery extending only above the insertions, not above the whole ring,
5. 4-cell cavities usable, thus reducing, by a factor of four, the total number of rf systems.

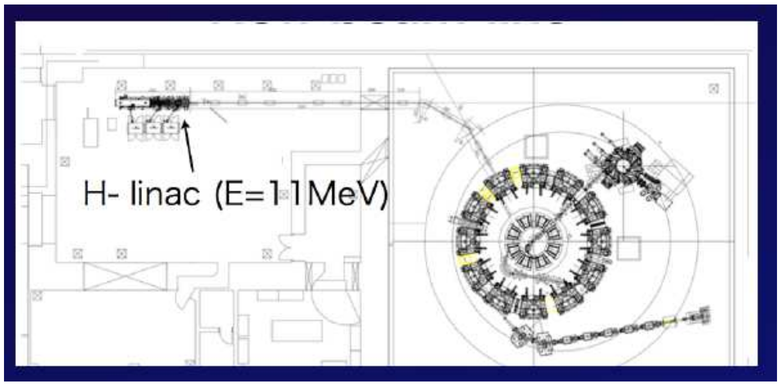
Magnetic field in bd, BF and BD.

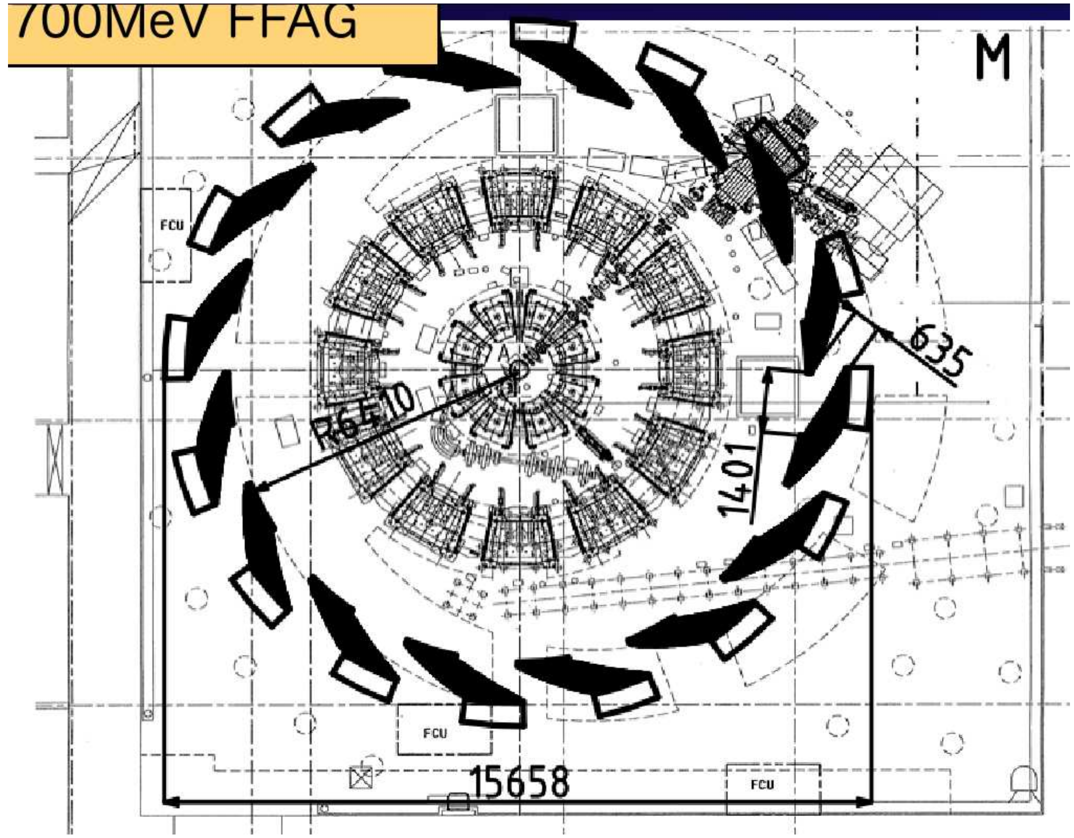


Trajectory in the tune diagram :



• **Spiral scaling lattice - KURR-Institute**





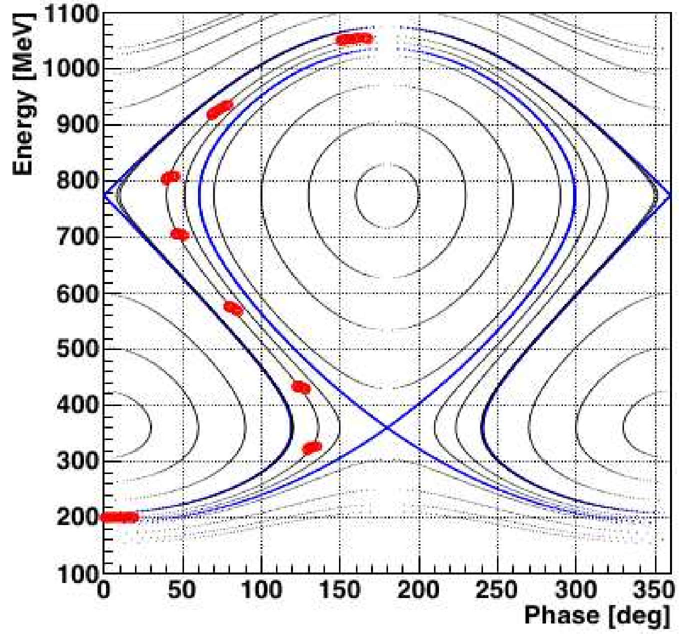
H- charge exchange injection.
Variable energy 150-700 MeV. n flux x30.
Will reach space charge limit 12μA at 150 MeV.

• Serpentine acceleration in a scaling lattice

• **Allows fixed RF-frequency acceleration in non-relativistic regime.**

• **ADS equivalent, Emi Yamakawa, FFAG 2012**

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)

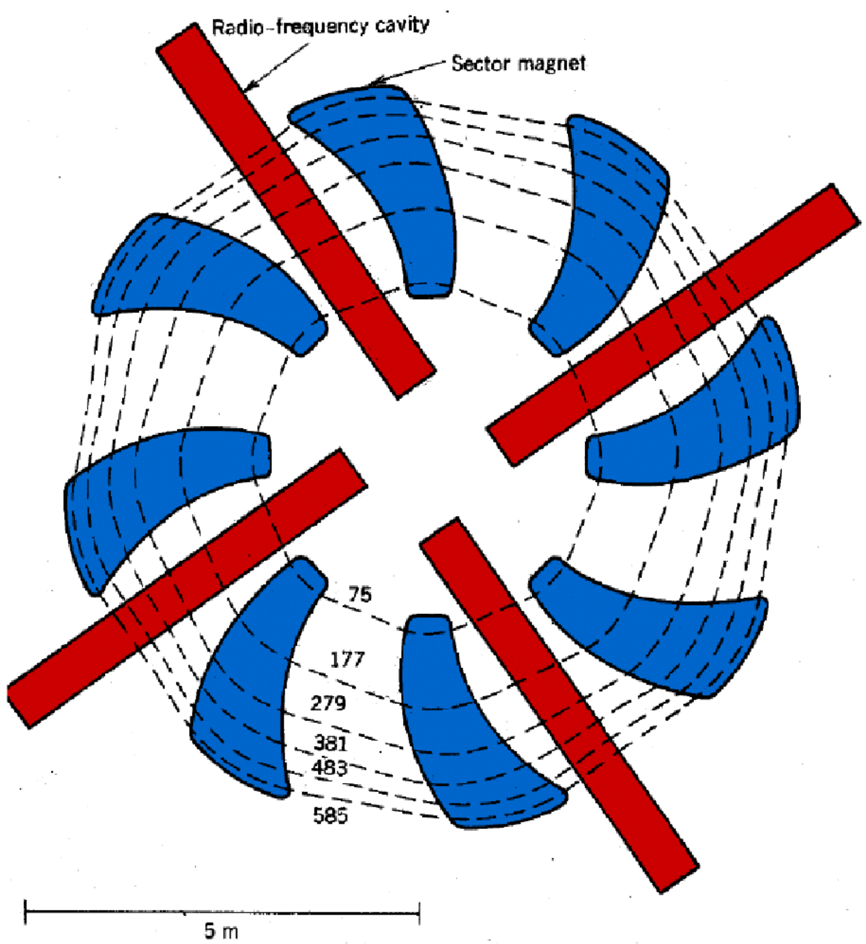


• **Experimental demonstration with electron FDF lattice (2012) :**

- 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

3 Cyclotrons

3.1 Principles



Isochronism : $R \propto \beta$, $B \propto \gamma$

$E_k/A = K(Q/A)^2$, $k = \frac{R}{B}\frac{dB}{dR} = \gamma^2 - 1$

$Q_r = \sqrt{(1+k)} \approx \gamma$, $Q_z \approx (-k + F^2\sqrt{(1 + 2\,tan\xi)})$

• High power requires separated sector technology,
so allowing room (drifts) for beam manipulations :
- injection (also high poower !)
- extraction
- acceleration
- longitudinal manipulaiton
- monitoring
etc.

• Main concern : beam loss.

• Limiting factor : beam loss at extraction, whereas

turn separation
$\Delta R/R \propto \Delta E_{\rm turn} \;/\; \beta^2\gamma^3$

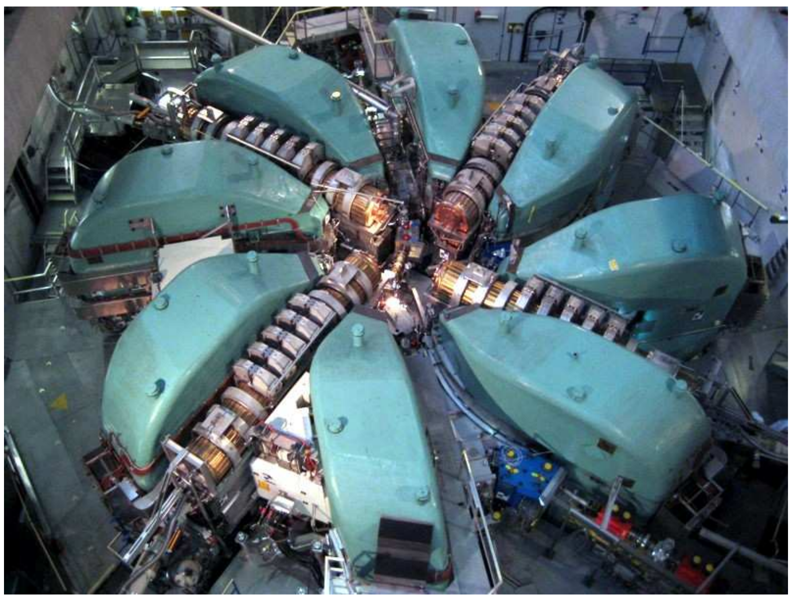
• Hence, receipes :
- large R (low B)
- maximize $\Delta E \;/\; turn$
- orbit oscillations at extraction

3.2 The archetype of a high power ring : PSI cyclotron

590 MeV beam, 1.3 MW, en route to 1.8 MW, in a continuous effort, over the years, to raise the current for the experiments.

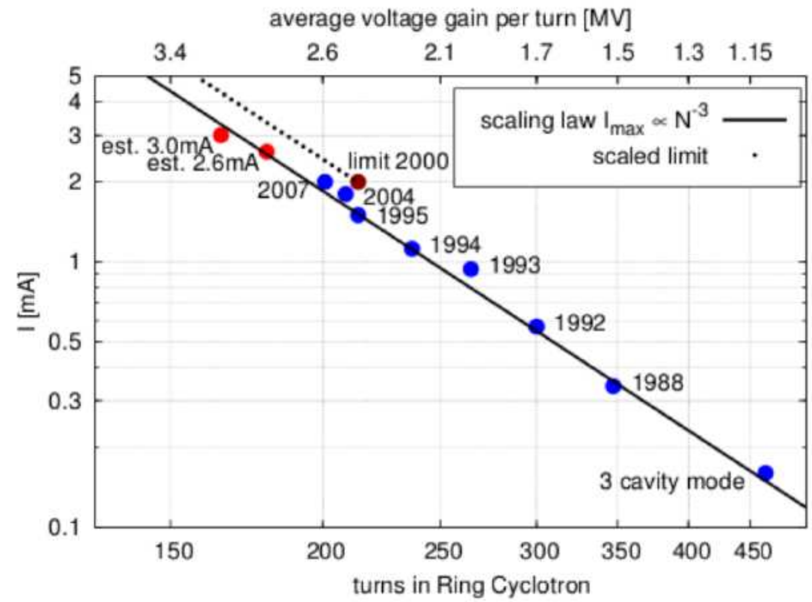
• Most important aspect of the control of the facility : beam losses, now $\approx 10^{-4}$.

• Availability is 85-90%, 5000 hrs/Year.



• Key to low beam loss is turn separation at extraction. Main “knob” is RF voltage - close to 4 MV/turn.

• Longitudinal losses with space charge scale $\propto 1/n^3$, current increase over the years follows, from RF upgrade.

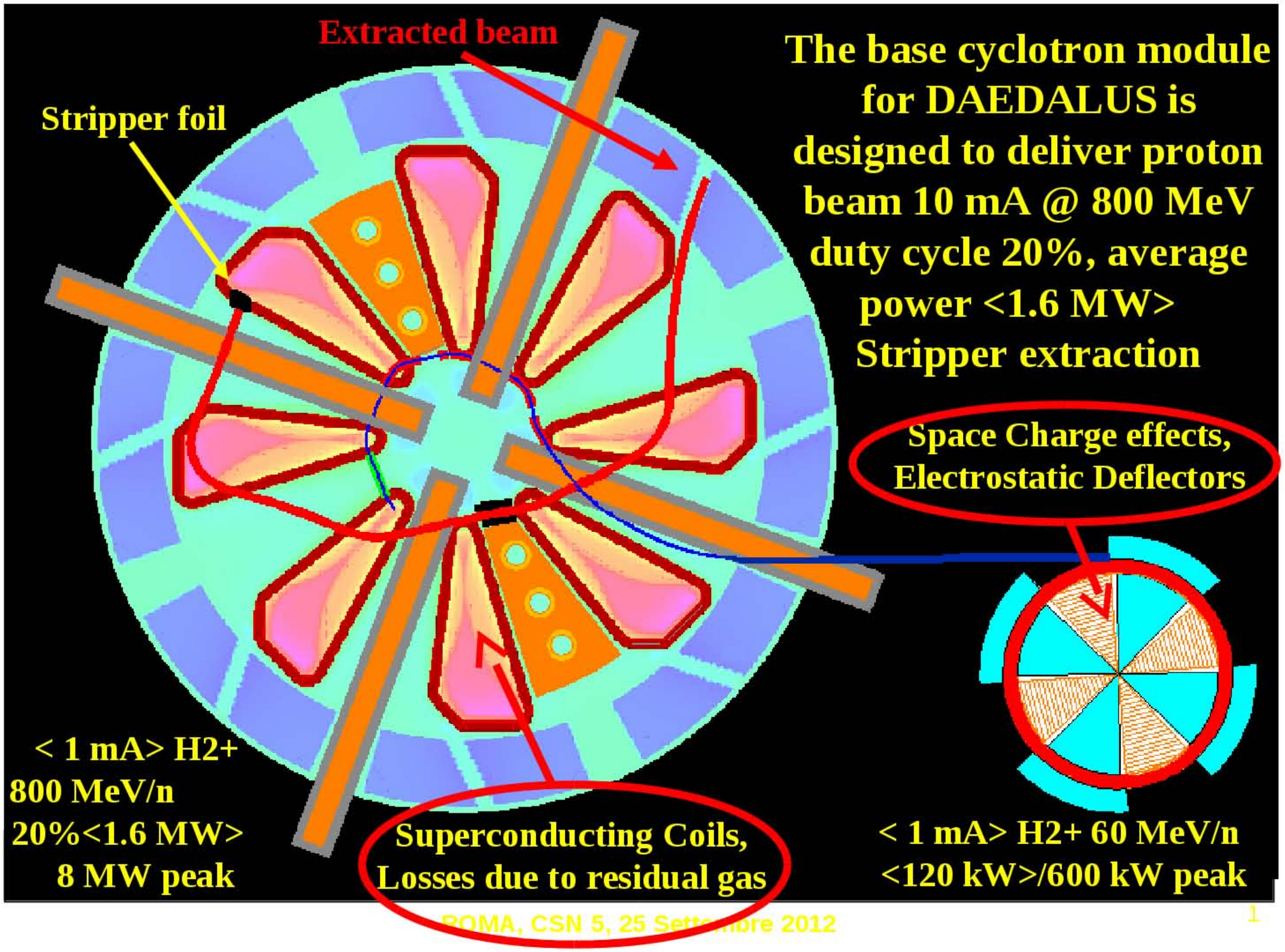


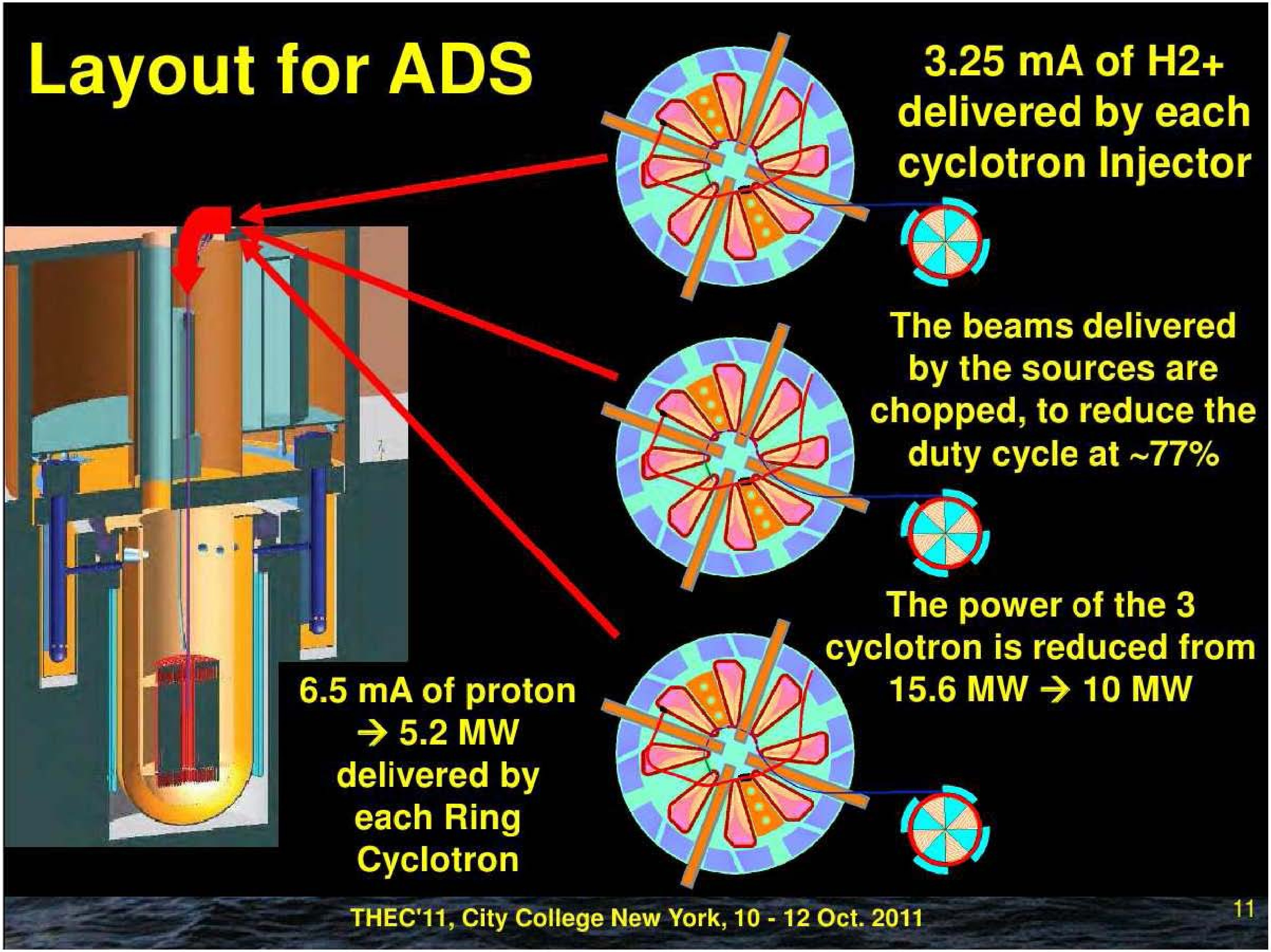
copper resonator for the Ring Cyclotron.

3.3 Molecular H2 cyclotron

- **Two specificities :**

- stripping extraction - relaxes on turn separation thus allowing high field, SC technology ,
- "2-in-1". Relaxes on space charge effects. Namely, negligible at 5 mA (eq. 10 mA p)





A possible trip-safe scheme : injectors work at $< 2/3$ duty cycle. In case of failure, or maintenance, remaining two sources ensure full power.

4 MY CONCLUSION

- **In matter of megawattS , cyclotrons and other FFAGs cannot be said to have said their last word !**

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• Bibliography

PAC and IPAC conferences.

Cyclotron Conference.

FFAG Workshops.

US “ADS White paper” :
H. At Abderrahim et al.,
Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production,
http://science.energy.gov//media/hep/pdf/files/pdfs/ADSWhitePaperfinal.pdf(2010)

Thank you for your attention