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

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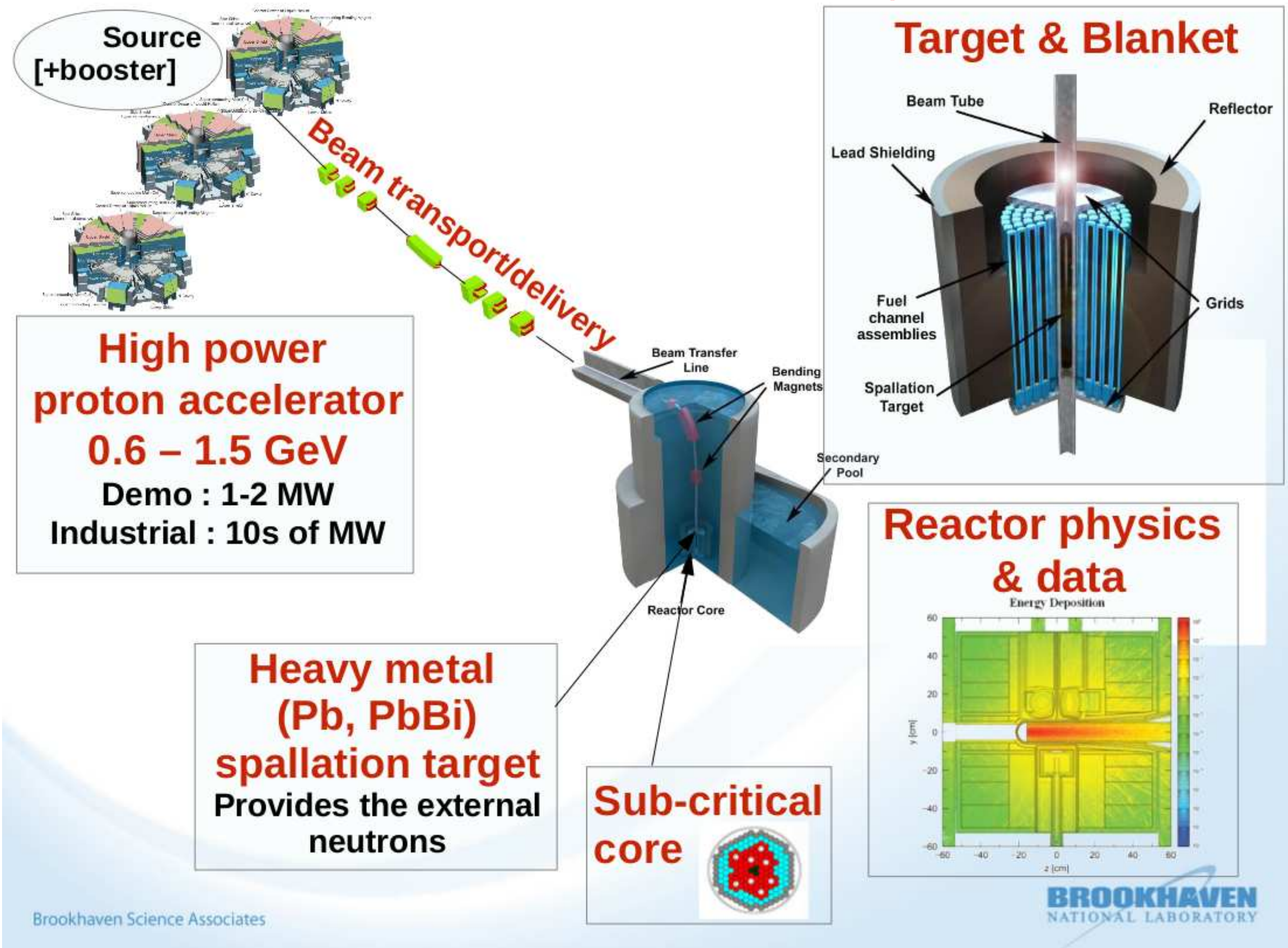
Contents

1 SUBCRITICAL REACTOR FACILITY

Primary interest (Roger Barlow's presentation): incineration of long-lived minor actinides from reactor park. Can not compete as "Energy Amplifier".

- **Principle scheme:**

Fuel: 238U $\rightarrow$ MAs Np, Am, Cm...
and/or: 232Th



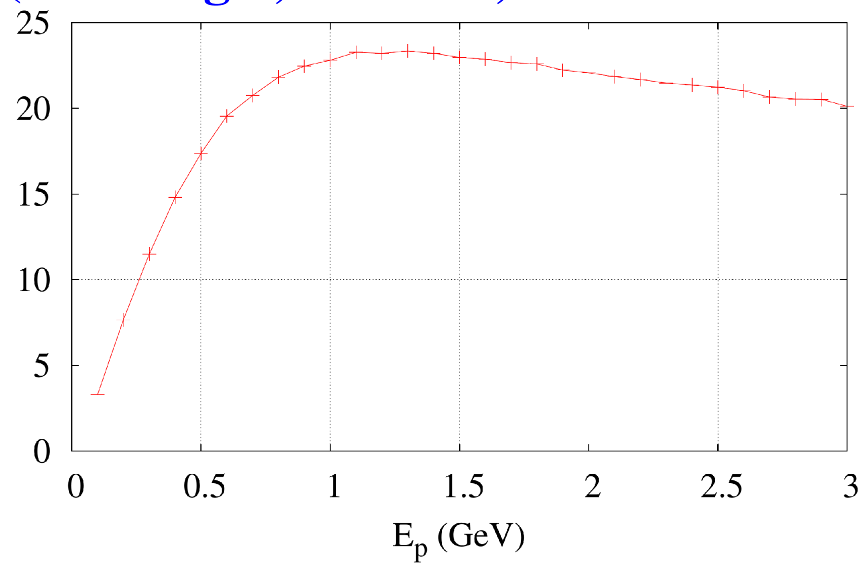
- **Required beam power P_B to generate the necessary source-neutron rate yielding P_{th} reactor power :**

with beam energy $E_B \approx 1$ GeV, a handy estimate is

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

$$P_B = E_B \frac{P_{\text{th}}}{f\, E_f} \frac{(1 - k_{\text{eff}})}{k_{\text{eff}}} \begin{cases} k_{\text{eff}} = \begin{cases} \text{neutron multiplication} \\ \text{factor of the reactor} \end{cases} = \frac{\text{n produced}}{\text{n absorbed}} \approx 0.95 \sim 0.98 \\ E_f = \text{energy released per fission} \approx 200\ \textbf{MeV} \\ f = \text{fraction of neutrons causing fission} \overset{1GeV-p}{\approx} \frac{\textbf{20n/incident p}}{2.5\text{n/fission}} \end{cases}$$

neutron yield per incident proton
(lead target, L=60cm, diameter 20cm)



- **Reactor's k_{eff} is central to the accelerator parameters.**
  The closer to 1 (*closer reactor core to critical*), the lower the beam power needed.

- **Power demand by accelerator system :**

$$P_A = \frac{P_B}{\eta_A} \approx \frac{1 - k_{\text{eff}}}{2\eta_A} P_{\text{th}}$$

η_A = **accelerator's plug-to-beam power conversion efficiency**

For the record, plug-to-beam efficiency (*facilities not optimized in that aim*) **:**
PSI : 13% [M. Seidel, 2015]
SNS : 8 % [J.Galambos, Priv. comm., 2015]
ESS goal: 18%

- Typical figures -

	Reactor: *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 transmutation:	**400 MW-th**	≈ 0.97	**800 MeV / 20 mA / 16 MW**
China's demonstrator program:	**1000 MW-th**		**1.5 GeV / 10 mA / 15 MW**

BEAM PARAMETERS (CONT'D)

ADS-Reactor systems are still in early development stage, with many unresolved questions, including [3]:

- **an integrated Accelerator–Window[-less]–Target–Blanket system, in which beam current connects to target cross-section, which in turn determines**
  - **neutron loss in target volume,**
  - **shielding requirements upstream of target (beam delivery line: hardened beam line components),**
  - **current density (A/cm^2) at the window, possibly plasma-window,**
  - **blanket size.**

  Typical required beam current stability $\pm 1\%$;

- **beam energy**
  - **can be traded against beam current for a given power, thus impacting on all of the above: smaller target cross section etc.**
  - **determines energy of proton knock-on neutrons which**
    - **if beam points downwards: traverse bottom shield, contaminate ground,**
    - **beam points upwards: cause sky shine.**

  Typical required beam energy stability $\pm 2\%$;

BEAM PARAMETERS (CONT'D)

- **beam power** determines fluency of high energy neutrons and leakage protons: impact on fuel and structural material survivability.
- **beam shape and size** correlated to target, window aperture: circular or rectangular (raster scan or else), typically several 10s of millimeters.

  Typical required size stability $\pm 10\%$.
- **Beam time structure**:
  - pulsed: possibly if linac p-driver; for sure from synchrotron - $\sim$50s-Hz mitigate thermo-mechanical stress
  - CW for multi-MW: from cyclotron, bunch trains possibly from linac.
- **Beam reliability** is paramount:
  - core power drops down to decay heat levels each time the beam is lost, causing thermal stress induced on core
  - getting reactor back to nominal power takes hours.

BEAM PARAMETERS (CONT'D)

Add to that, possibly,

- **Multiple-beam configurations.**

  Ex.: case of Th based blanket,

  - need initial excess of spallation neutrons as $k_{\mathrm{eff}} \ll 1$

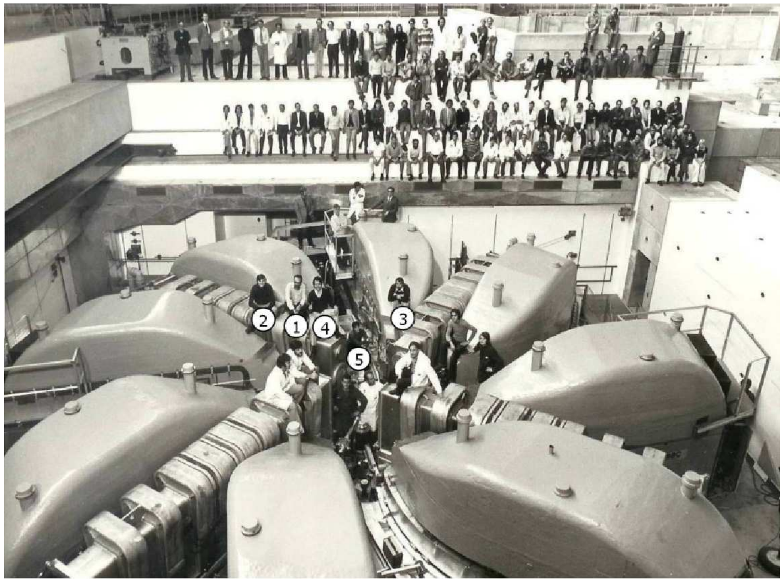
  - $\Rightarrow$ 3 beam tubes, Φ15 cm in Ref. [7],

  - with time, beam power needed decreases as concentration in U-233, thus k_{eff}, increases

- **Re-visit the question of ion species ?**

  ***Cf.* Ref. [6] study: 7Li beam, 0.3 A GeV, and Be core target: smaller accelerator, lower plug-power?**

- **Modular ADS-Reactor waste burner? $\sim$100 MW-th range, beam power $\sim$10-fold lower, on-site avoids transportation.**

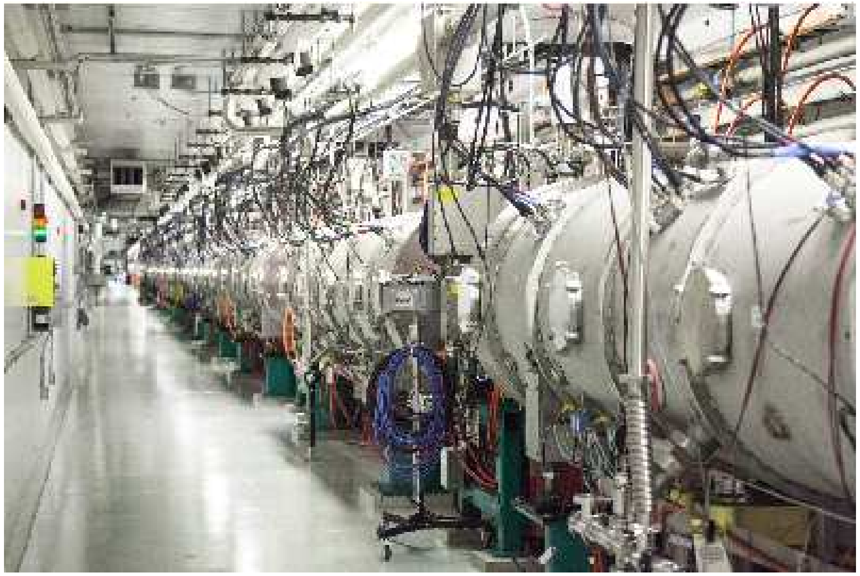


- **Separated sector cyclotron**

Paul Scherrer Institute, first beam 1973,
590 MeV, 1.3 MW CW beam,
upgrade on the way to 1.8 MW.

- **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 2006,
today beam power 1.2$\sim$1.4 MW.
60 Hz-pulsed, DC $\sim$6%. Accelerates H- for stripping injection into accumulator ring.

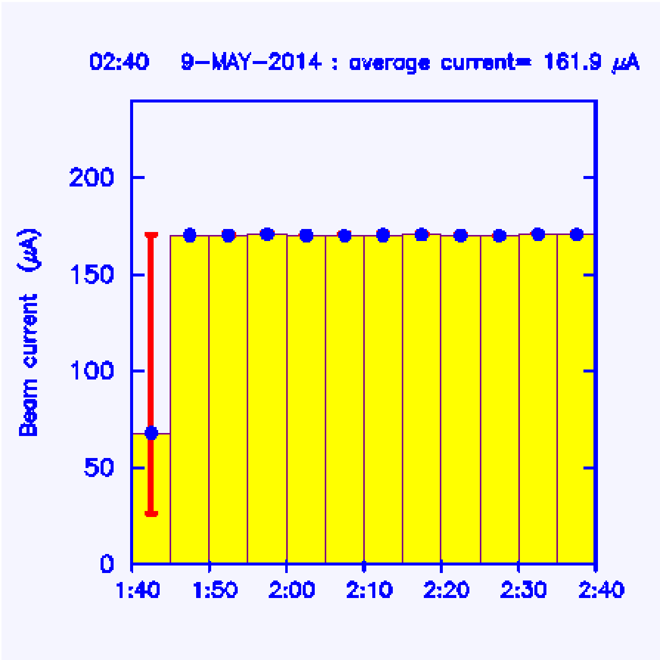
Reference : US ADS White Paper (2010)

Alternative approaches to high power include :

- **Synchrotron technology,**

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

Ex.-1 : ISIS rapid-cycling synchrotron, RAL, UK. Running since 1984,
50 Hz, 800 MeV, 200 kW beam power



Beam current at ISIS TS1

Ex.-2 : Neutrino Factory, proton driver, energy 3∼5 GeV optimal, 4 MW, 50 Hz rep. rate → parallel synchrotron schemes.

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

- FFAGs potentially have repetition rate in 100s of Hz range - synchro-cyclotron.

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

3.1 Push Cyclotron Technology

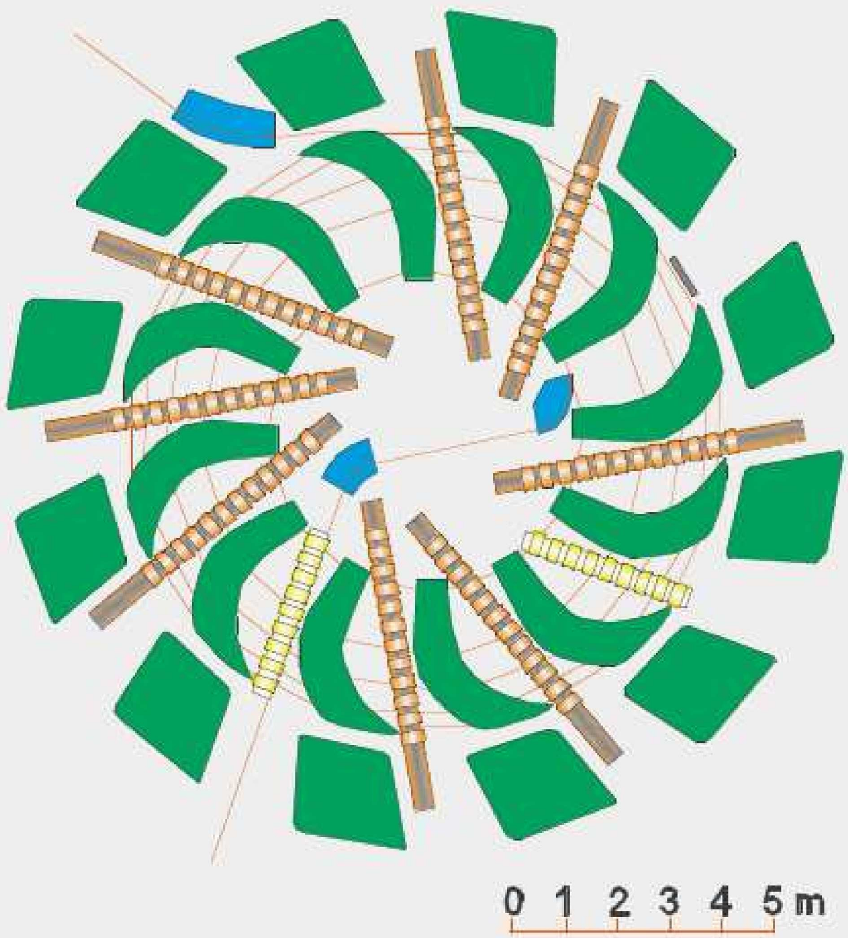
I'll be short, here:

- **Limitations of High-Power Cyclotrons, C. Baumgarten, yesterday;**
- **Luciano Calabretta's talk, today.**

- **Just two instances, to transition to FFAGs...**

Pushing PSI technology to 10 MW (1/2)

[1997, Th.Stammbach et al]



parameters	1 GeV Ring	PSI Ring
Energy	1000 MeV	590 MeV
Injection energy	120 MeV	72 MeV
Magnets	12 (B_{max} = 2.1 T)	8 (B_{max} = 1.1 T)
Cavities	8 (1000 kV)	4 (800 kV)
Frequency	44.2 MHz	50.63 MHz
Flat tops	2 (650 kV)	1 (460 kV)
Injection radius	2.9 m	2.1 m
Extraction radius	5700 mm	4462 mm
Number of turns	140	186
Energy gain at extraction	6.3 MeV	2.4 MeV
DR/dn	11 mm	5.7 mm
Turn separation	7 s	7 s
Space charge limit	10 mA	2.2 mA (3.0 @ 4 MV/turn)
Beam power	10 MW	1.3 MW

Note : redundancy of resonators opens up the way to compensation of failed resonator.

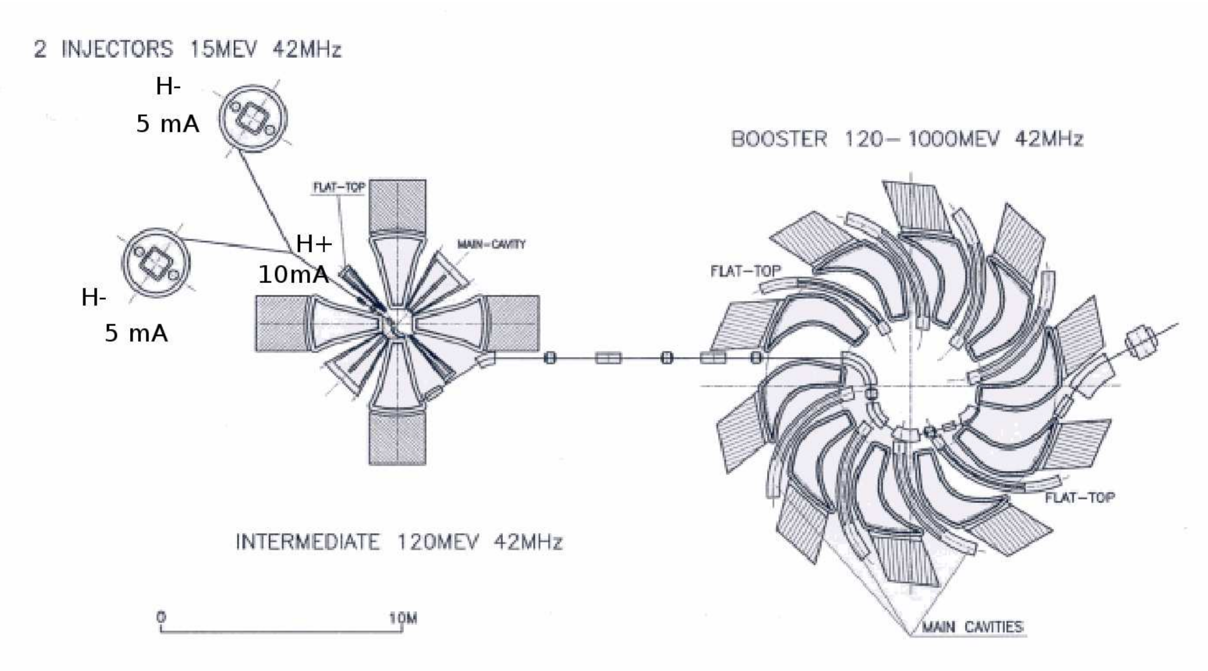
Pushing PSI technology to 10 MW (2/2) (CERN/AT/95-44 / Mandrillon)

- **Energy 1-1.2 GeV, beam current 10-15 mA CW, 10 MW**
- **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 : B̂=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

RIKEN SC Cyclotron: K2600

See *"Operational experience with the RIKEN RIBF accelerator complex"*, Hiroki Okuno, yesterday.

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

Power balance at the RIKEN cyclotron:

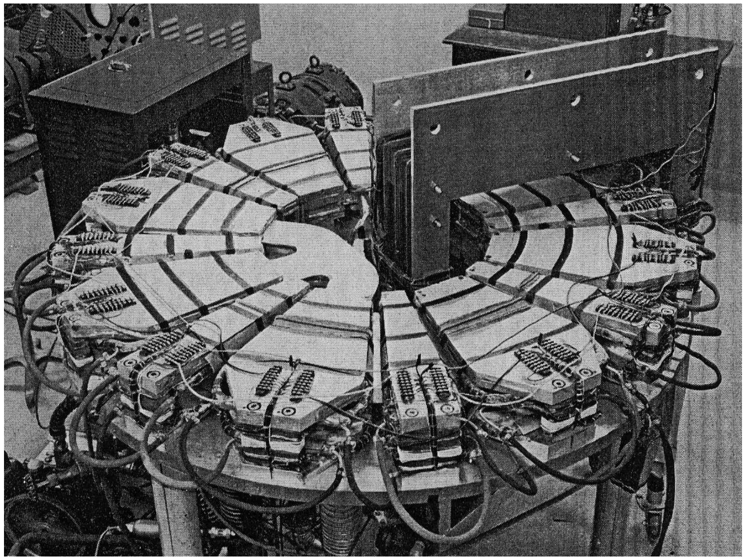
- **Helium cooling system : 1MW**
- **Power supplies for SC coils (main coils and superconducting trim coil) : 0.2 MW**
- **PS for warm trim coil : 1MW**
- **PS for injection/extraction elements : 1MW**
- **RF system : 1.5 MW**
- **Total : 4.7 MW**

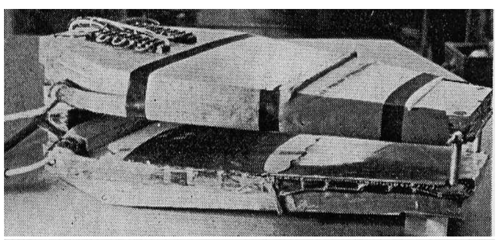
- I'll be quick the next 15 slides:

- See this quick tour of the topic as a guidance, for whoever is interested in digging into one or the other of the techniques addressed.

3.2.1 MURA Scaling FFAGs, 1950s

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





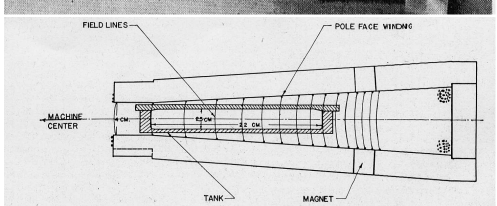


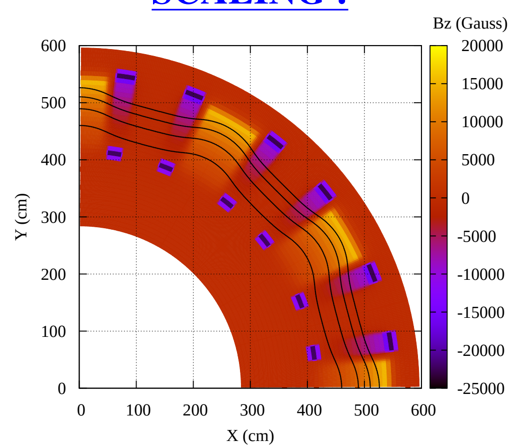
Fig. 4. Schematic cross section of a magnet and the vacuum chamber.

F magnet, positive field, radially focusing.

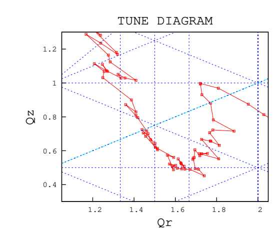
FFAG ring parameters

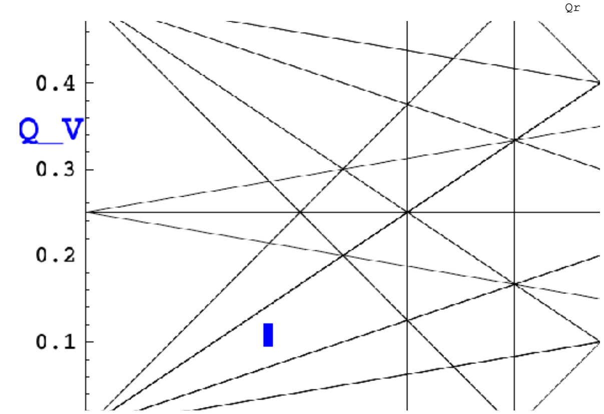
$E_{inj} - E_{max}$	*keV*	**25 - 400**	*small size, easy to build; field not too low, ms lifetime*
orbit radius ($\mathcal{C}/2\pi$)	*m*	**0.34 - 0.50**	
Optics			
lattice		$\frac{D}{2}F\frac{D}{2}$	
number of cells		**8**	*16 magnets & 4.41 deg. drifts*
field index K		**3.36**	g/r *=Cst & pole-face windings*
ν_r / ν_z		**2.2-3 / 1-3**	
Magnet		**radial sector**	$B = B_0(r/r_0)^K F(\theta)$
Acceleration		**Induction**	
rep. rate	*Hz*	a few 10s	

SCALING :



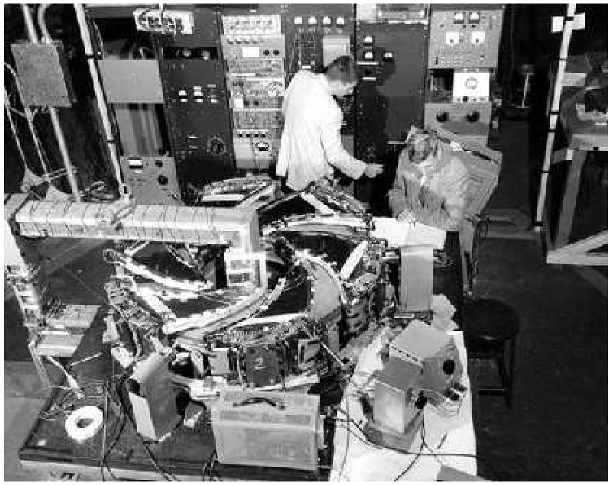
CONSTANT TUNES :

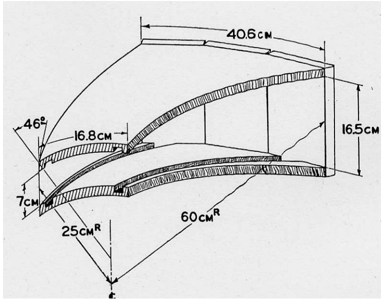




• **Second model, spiral sector FFAG, Mark V**

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





Logarithmic spiral poles

Spiral FFAG parameters

$E_{inj} - E_{max}$	*keV*	**35 - 180**	{ *reasonable size magnets*
orbit radius	*m*	**0.34 - 0.52**	
E_{tr} / r_{tr}	*keV / m*	**155 / 0.49**	{ *RF exprmnts at* γ_{tr}

Optics

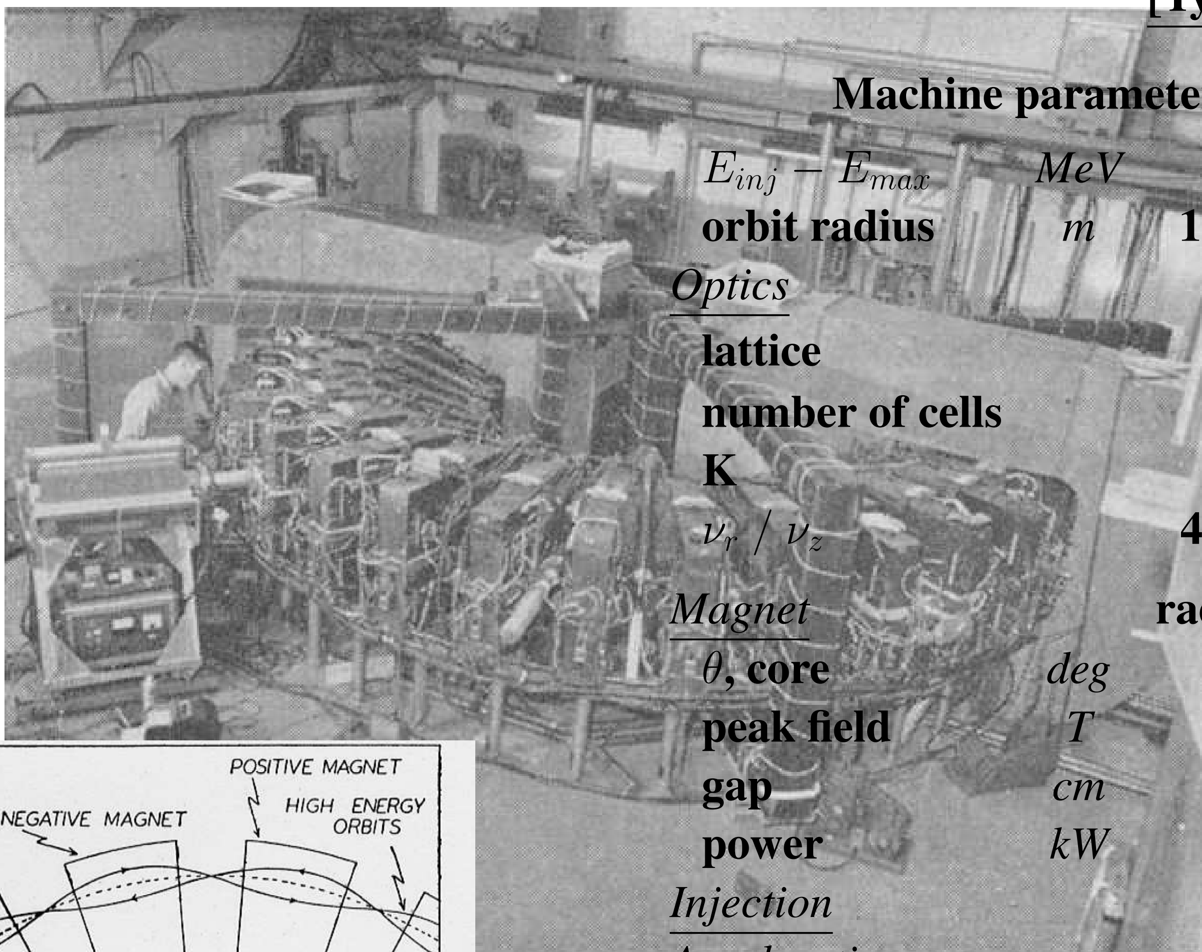
lattice	**spiral sectors**	
number of sectors	**6**	
field index K	**0.7**	{ *pole-face windings tunable 0.2-1.16*
flutter F_{eff}	**1.1**	*tuning coils / 0.57 - 1*
ν_r / ν_z	**1.4 / 1.2**	*tunable*

Magnet: **spiral sector** $B=B_0(\frac{r}{r_0})^K\,F(\ln\frac{r}{r_0}/w - N\theta)$

Acceleration betatron and RF

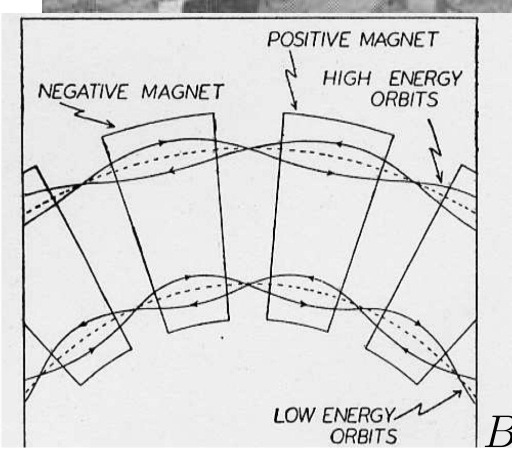
• "Collider ring", 50 MeV

Start up Dec. 1959, 2-beam mode, 27 MeV ; disassembled in 60, magnets corrected ; second start Aug. 61, single beam, 50 MeV.



[Typical] data

Machine parameters			
$E_{inj} - E_{max}$	*MeV*	**0.1 - 50**	
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**	

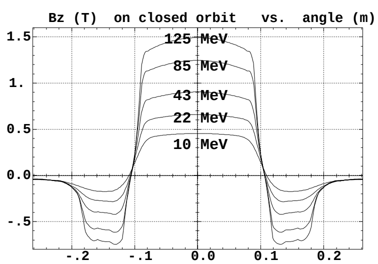


$B_F = B_D$

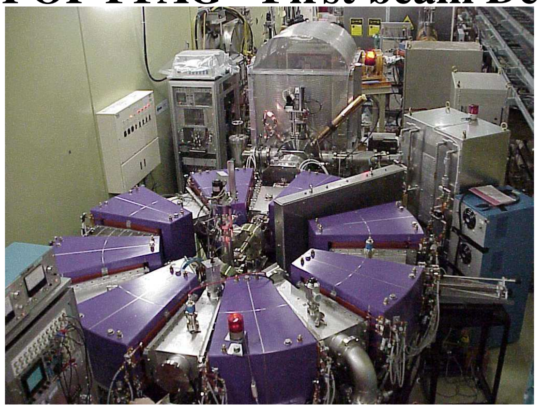
3.2.2 Proton and ADS R/D, 2000s

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

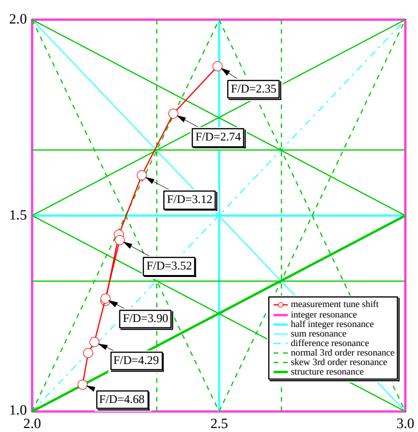
Interest of the FFAG method : Fast acceleration (short lived muons - and/or high average I), strong focusing (mitigates space charge effects), very large acceptance (beam may be big)



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

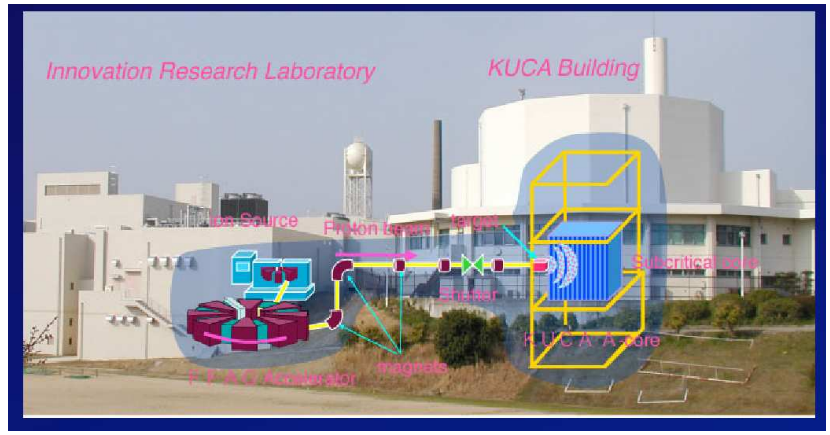
$E_{inj} - E_{max}$	MeV	12 - 150
orbit radius	m	4.47 - 5.20
lattice / K		DFD $\times$ 12 / 7.6
ν_r / ν_z		3.7 / 1.3
RF swing	MHz	1.5 - 4.5
voltage p-to-p	kV	2
rep. rate	Hz	250

● **KURRI (KUNST) KUCA ADS-Core R/D**

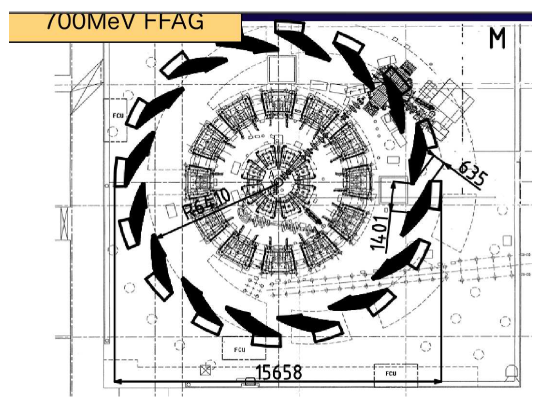
- A feasibility evaluation of ADS-R as an energy production system.
ADS-R core irradiation program.

- **- 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



Upgrade plans: variable energy 150-700 MeV facility,
neutron flux increased by a factor 30

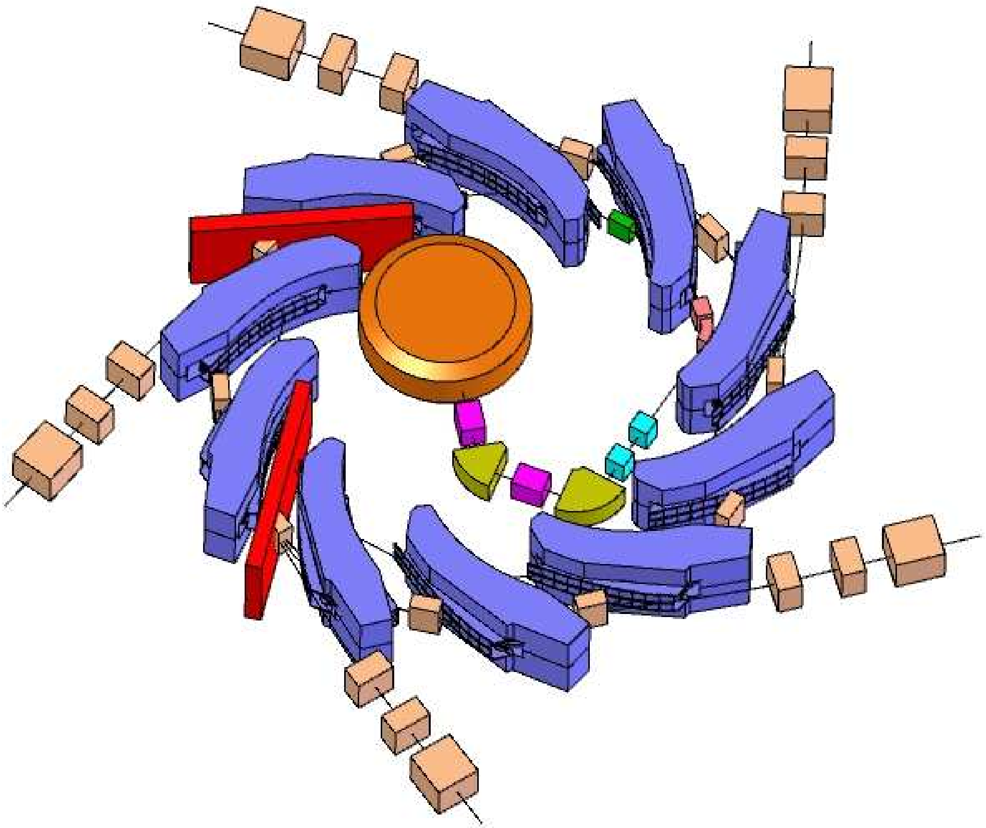


• **RACCAM Spiral Design - Magnet Prototyping**

• **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**



• **Towards High-Energy CW: Quasi-Isochronous "Serpentine" Acceleration Demo**

• **Allows fixed RF-frequency acceleration in variable $\beta = v/c$ regimen in a zero-chromaticity FFAG lattice**

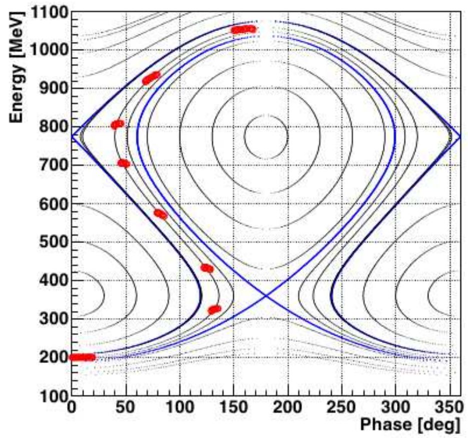
- i.e., non-relativistic beam, suitable for proton acceleration.

• **Experimental demonstration with an electron ring prototype (Japan, 2012):**

- small electron 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)



"Gutter acceleration"

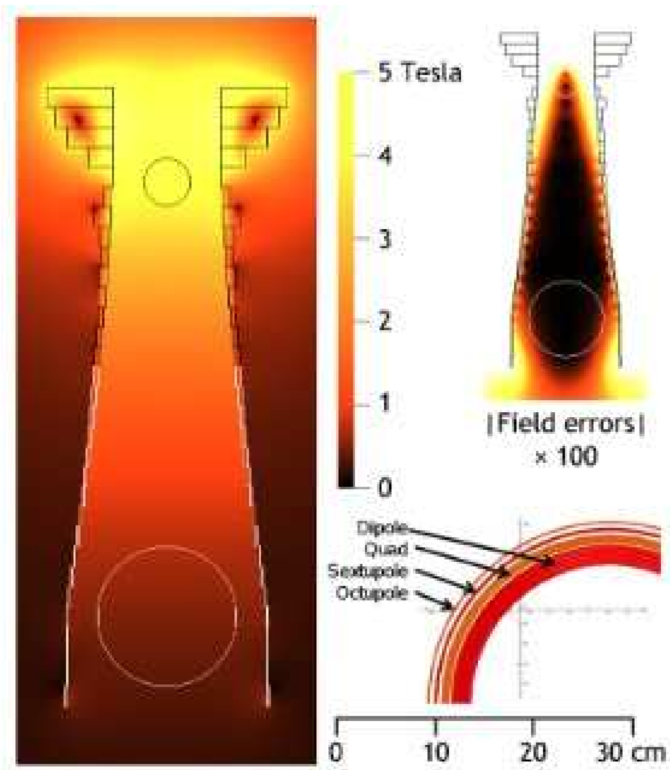
$$\mathbf{H} \approx \sin^2 \pi\phi + \left[\mathbf{a}\left(\frac{\delta \mathbf{p}}{\mathbf{p}}\right)^2\right] + \mathbf{b}\left(\frac{\delta \mathbf{p}}{\mathbf{p}}\right)^3$$

• **Vertical FFAG**

More on V-FFAG and proton-driver application, by J-B Lagrange tomorrow.

• **Goal of this R/D: developments toward complete isochronism.**

Sub-relativistic orbits can be made isochronous by deviation from vertical (at lower energies, into bowl shape)



Field within the magnet gap :

$$B_y = B_0 \exp(k\,y)$$

Refs:

FFAG Helicoidal, Etude de la Stabilité Bétatron, G. Leleux et al., CEA Saclay, Rapport S.O.C. 70 (19 juillet 1959);

J-B Lagrange et al., this workshop; S. Brooks, PRST-AB 16 (2013);

3.2.3 Linear FFAG Concept, Prototyping

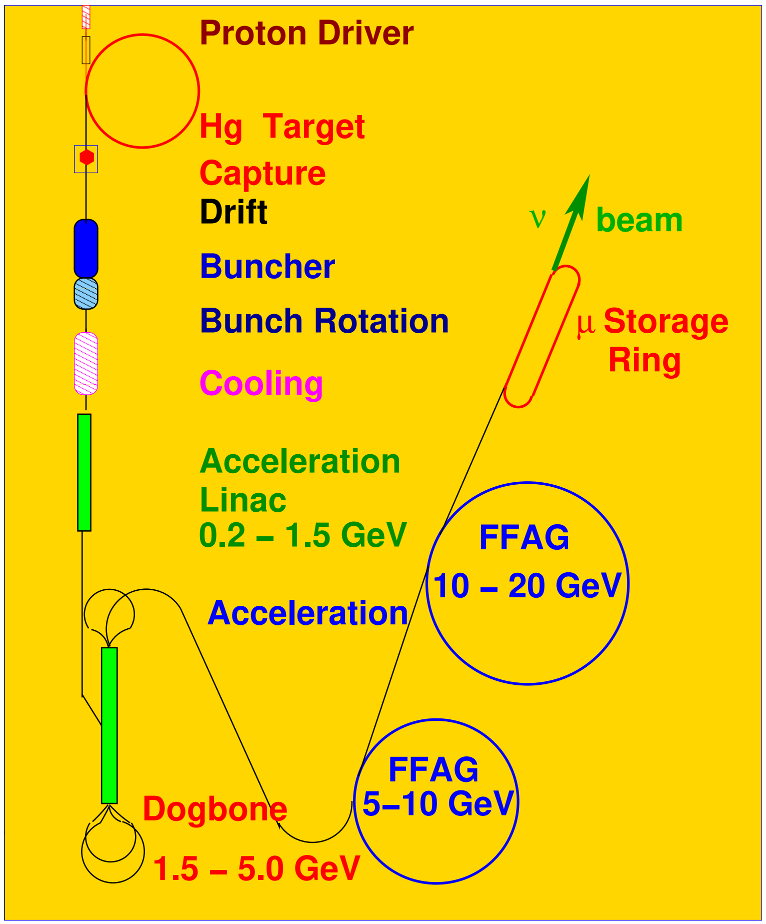
- **Two concepts introduced in late 1990s, in the "neutrino Factory" R&D framework:**

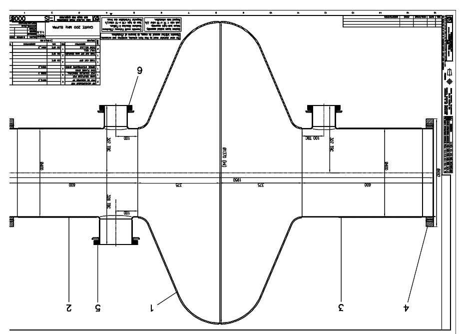
- "linear lattice" FFAG : magnets are simple quadrupoles

- "quasi-isochronous" acceleration by near transition γ lattice design: 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,

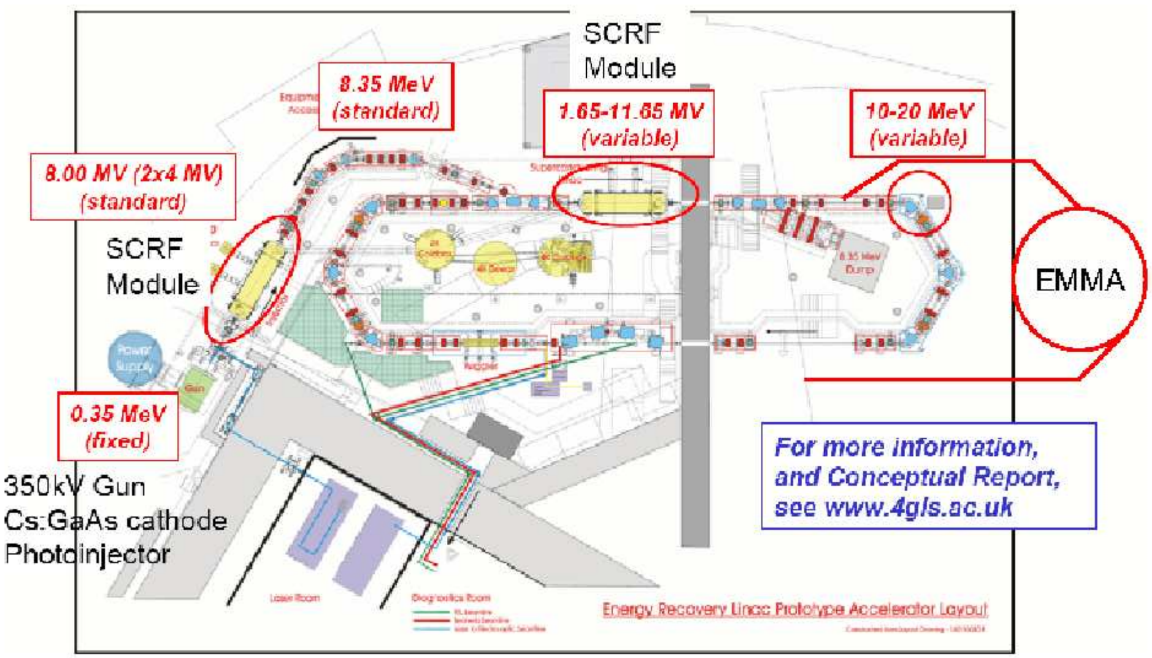




• **EMMA Ring Prototype**

An experimental “Electron Model for Many Applications”, to prove these concepts; an international collaboration.

- **Construction at Daresbury Lab. started in 2007**
- **Commissioning 2010**
- **Quasi-isochronous acceleration and fast resonance crossing demonstrated in 2011**



• **Goals of EMMA experiment:**

- prove rapid, “gutter acceleration”

- investigate resonance crossing

- assess phase space, dynamic aperture

- investigate sensitivity to defects

- assess stability, operating conditions

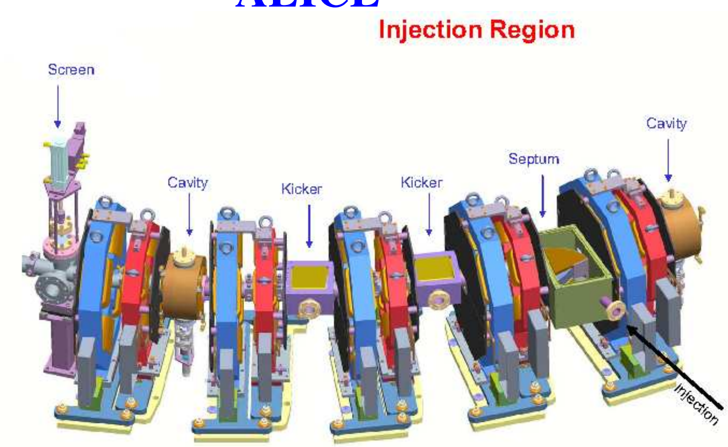
EMMA parameters

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**

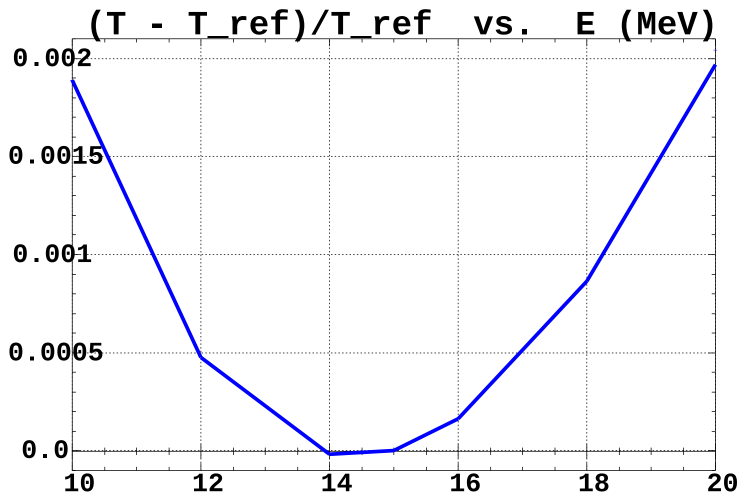
EMMA cell

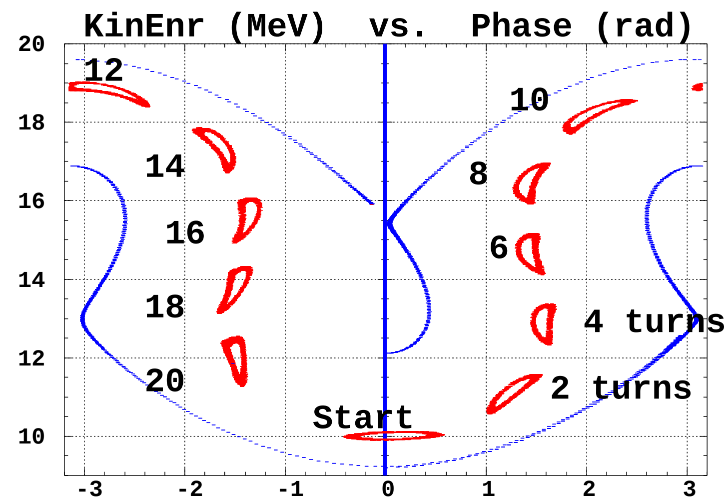
- cell length	**39.448cm**
- length F/D	**5.88 / 7.57cm**
- drifts	**5 / 21cm**
- QF/QD/Cav. ap.	**7.4 / 10.6 / 4cm**
- alignment	**0.25μ (1σ)**

Injection into EMMA, from ALICE



Principle of the quasi-isochronous - "serpentine" - 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"

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

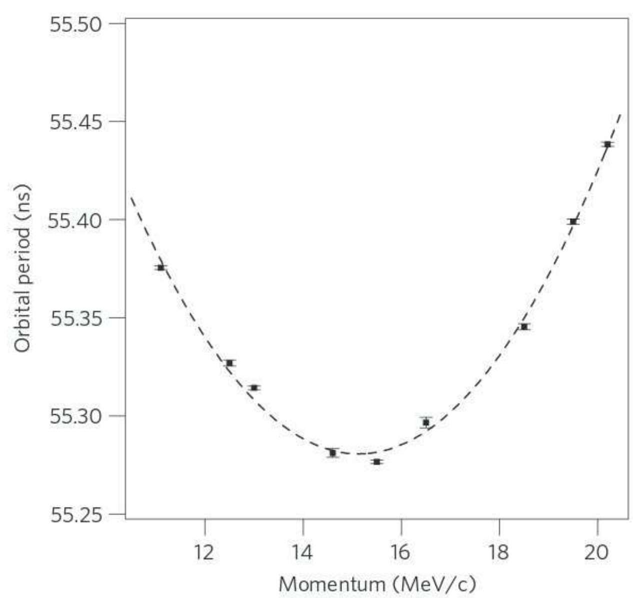
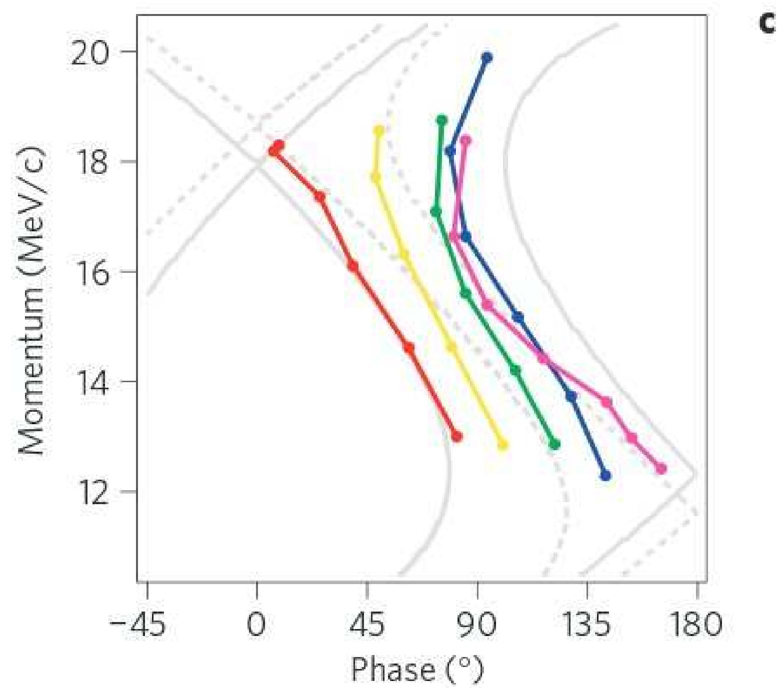
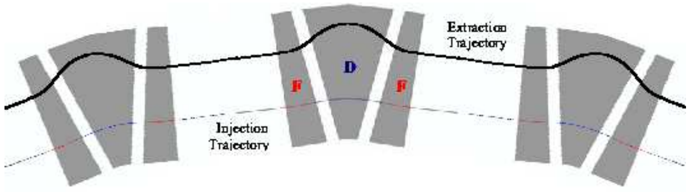


Figure 1 | Orbital period in the EMMA ring as a function of momentum,



3.2.4 Linear FFAG: Proton Driver Design Studies

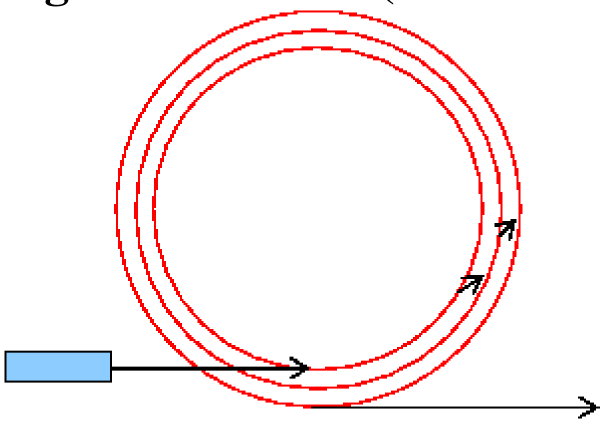
- **FDF FFAG cell / S. Ruggiero, BNL, early 2000s**



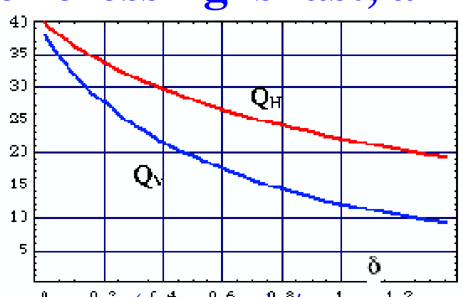
- **For neutrino factory p-driver, 12 GeV design, potential for several MW**

		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

- **3-stage acceleration (3 FFAG rings)**



- **Lots of betatron resonances crossed :**
  $Q_x : 40 \rightarrow 19$, $Q_y : 38 \rightarrow 9$.
  However crossing is fast, all the way



$(p - p_0)/p_0$

- **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.

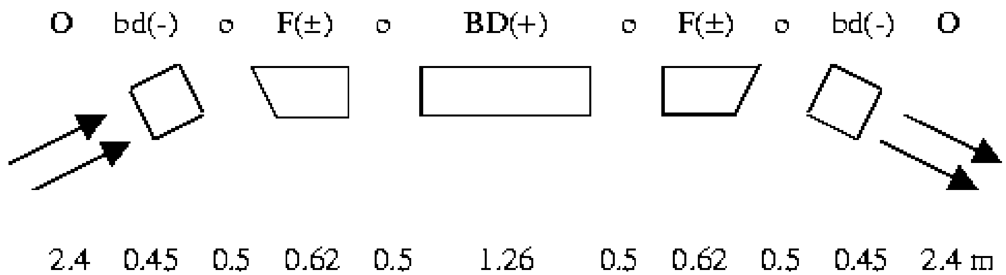
- **CW acceleration based on "harmonic number jump", using fixed frequency RF systems, was investigated.**

• **Pumplet lattice / Graham Rees, 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 :

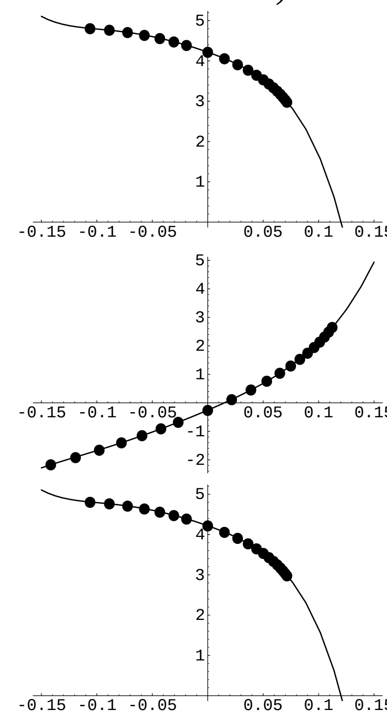


$$B_{bd}(x) = -3.456 - 6.6892\,x + 9.4032\,x^2 - 7.6236\,x^3 + 360.38\,x^4 + 1677.79\,x^5$$

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

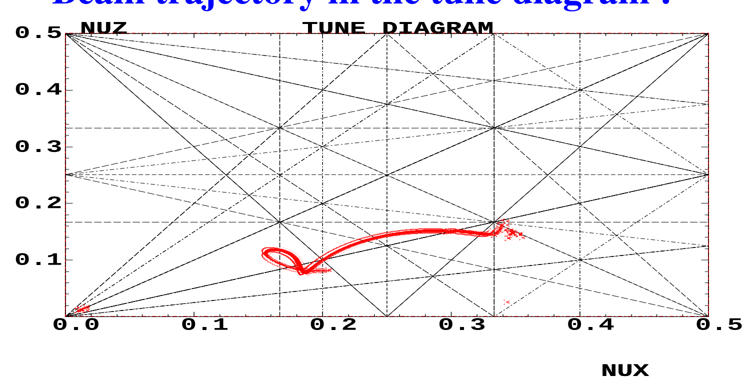
$$B_{BD}(x) = 4.220 - 9.659\,x - 45.472\,x^2 - 322.1230\,x^3 - 5364.309\,x^4 - 27510.4\,x^5$$

Magnetic field in bd, BF and BD.



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.

Beam trajectory in the tune diagram :



Snowmass'21 Workshop, PSI, 7-9 Sept. 2021

- **Toward CW high energy FFAG**

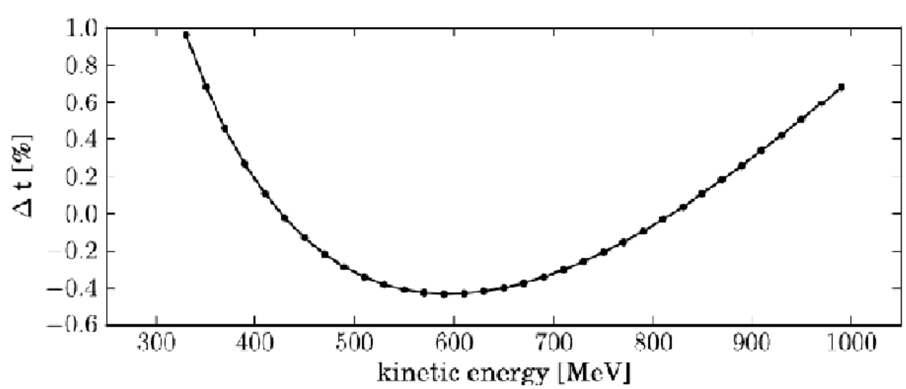
- **Quasi-isochronous, DFD triplet, lattice design**
  - **- non-linear radial field profiles, alternating gradient bends,**
  - **- optimized magnet-edge contour**

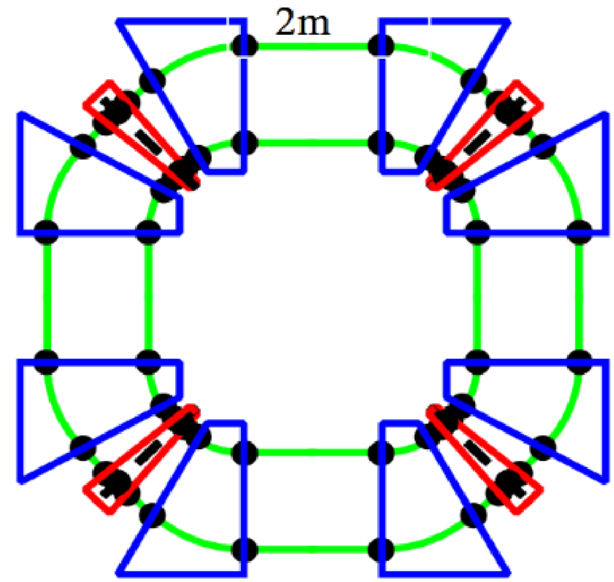
- **Features small tune variation over acceleration cycle**

- **Allows near-crest acceleration using fixed-frequency RF**

- **Numerical beam dynamics studies show huge transverse dynamical acceptance. OPAL simulations indicate feasibility of 20 mA current with no transverse beam growth.**

- **Principle 6-cell lattice used for numerical beam dynamics studies.**
- **0.33 to 1 GeV acceleration.**





Regarding ADS-R application: devising MW scale designs from these techniques, to start with.

Reliability

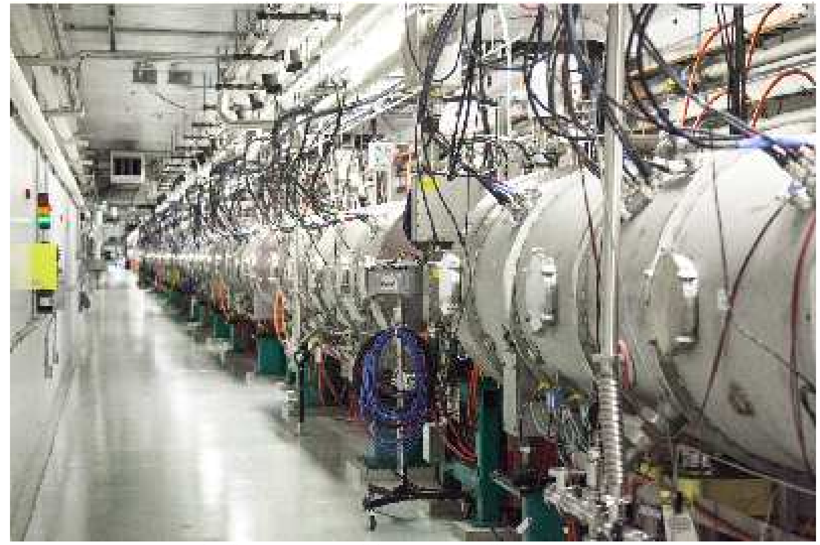
- **FFAG methods and technologies (magnets, RF, instrumentation) are cyclotron style, very conservative, this is a good starting point.**

- **Regarding achieving required reliability at lowest cost from linacs, I am not convinced, at all:**
  - **Such extremely complex accelerator installations as light sources do reach near 100% reliability, have stored beams over days, non-stop. Large colliders store beams over day-scale durations.**
  - **However this does not come for free:**
    - **large periods of maintenance (weeks, months), yearly - this is something we may not want at an ADS**
    - **extremely complex construction, operation and maintenance, and costs accordingly.**

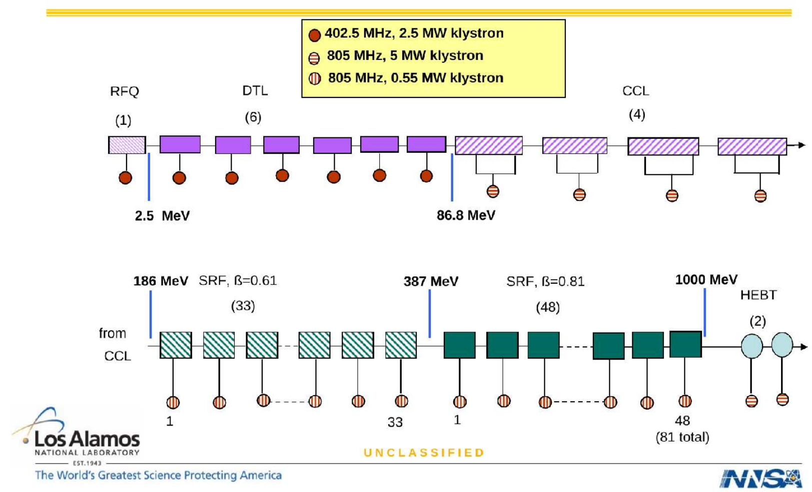
• I have in mind: high power linacs go by pair :

If I buy 1, I actually get 2 long strings of high power linear accelerators and other RF cavities of all possible sorts, of which I need to ensure ADS-R grade reliability.

• And redundancy adds on top of that.



Layout of Linac RF with NC and SRF Modules



Confer SNS:

- 100-something RF cavities,

- 81 klystons,

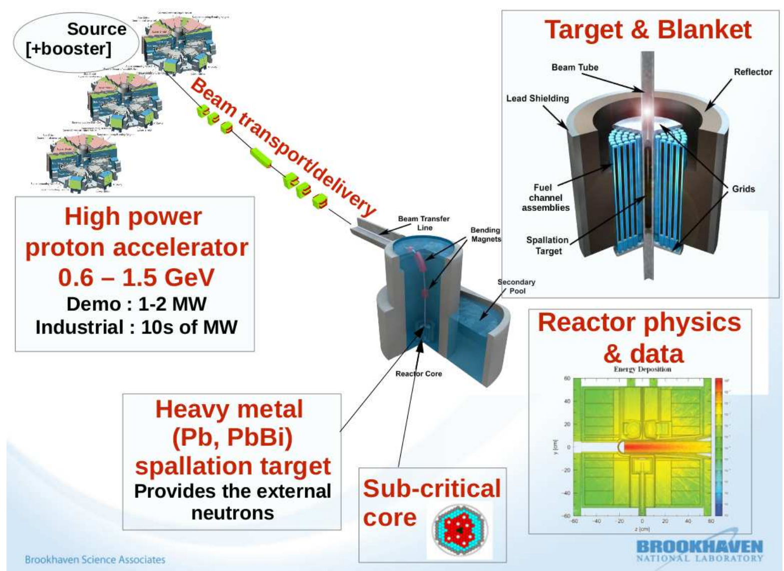
- 100s of power supplies of all sorts...

Corollary:

Linacs are claimed to lend themselves well to fault-tolerant designs:

- redundant cavity design: if one fails then adjust others to overcome,
- double the injector,
- and so on

It looks like, given the cost of a high power CW linac installation, there is room for a highly redundant multiple FFAG or cyclotron installation. A point worth taking a closer look at $\Longrightarrow$ Luciano.



Beam flexibility

In the ADS-Reactor application, is any of these needed :

- **Multi-GeV for many applications (Project-X, China-ADS) ?**
- **H^- acceleration for stripping injection in accumulator ring (SNS)?**
- **Multiple species: whatever particle from p to U (FRIB) ?**
- **A "multi-purpose flexible irradiation facility", including energy up-grade plans (MYRRHA) ?**
- **100s MeV beam energy flexibility for whatever reason?**
- **All of the above ?**

6 CONCLUSION

If the answer is "NO" to all of these questions - previous slide -, then, fixed-field ring methods, are certainly worth considering very closely, and actively R&D'ed further towards ADS-R grade reliability.

Voilà

THANKS FOR YOUR ATTENTION

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