Applications of FFAG accelerators

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Disclaimer

- This review is not intended to be comprehensive and the author recognizes that there are many FFAG applications that are not covered here.

- The views and opinions expressed in this article are those of the authors and do not necessarily reflect the official policy or position of any agency of the U.S. government.

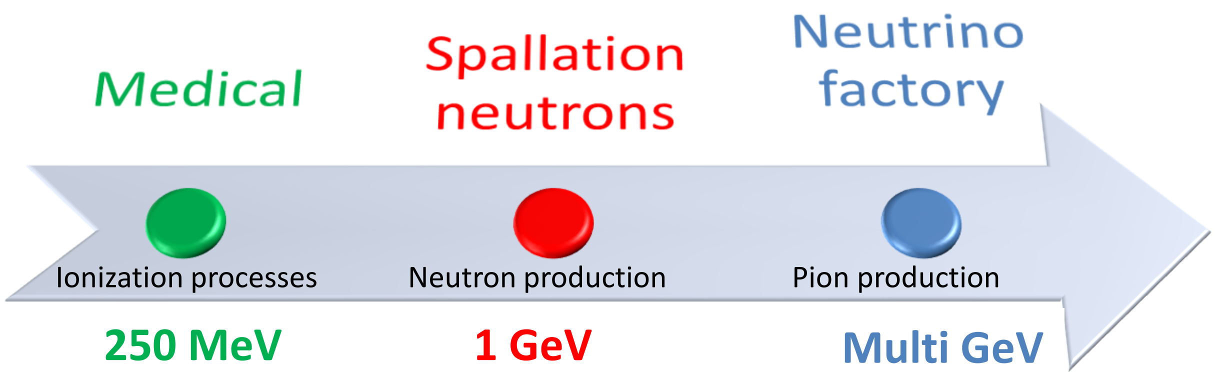
Overview

- Classification of the applications.
- 1st scaling FFAG PoP
- 1st non-scaling FFAG PoP: EMMA
- Applications: - Medical / Energy / Science.

Main specifications of the accelerator application

- **Beam species**: protons, electrons, heavy ions, (neutrons, muons, neutrinos).

- **Beam energy** (for protons):



Why such a wide variety?

- **Beam intensity**: high power brings difficulties and should be considered in the preliminary design phase.

1) 1st scaling FFAG PoP

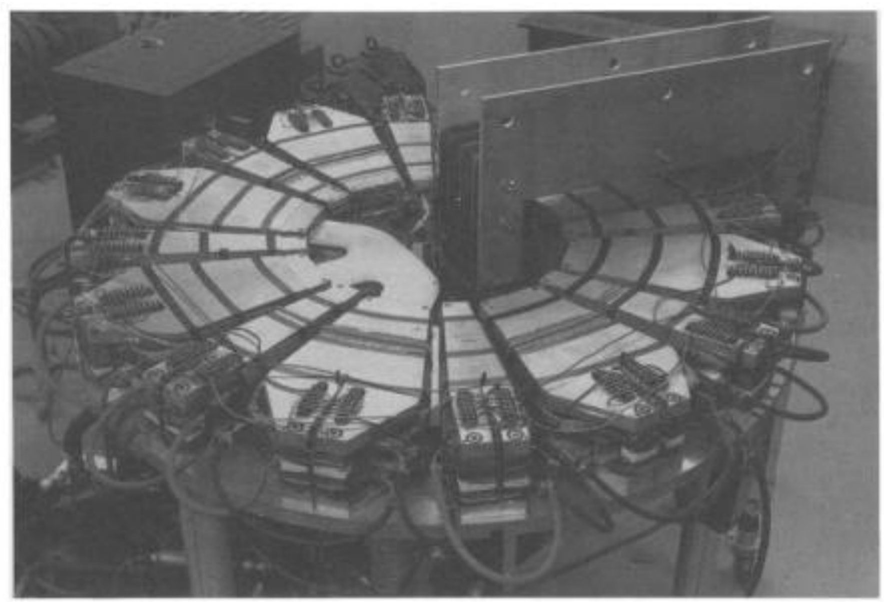
PoP for electrons

- The FFAG principle was devised in the mid-1950s, following the discovery of the alternating gradient in 1952.

- The idea was developed independently by T. Ohkawa in Japan, K. Symon in the United States and A. Kolomensky in Russia.

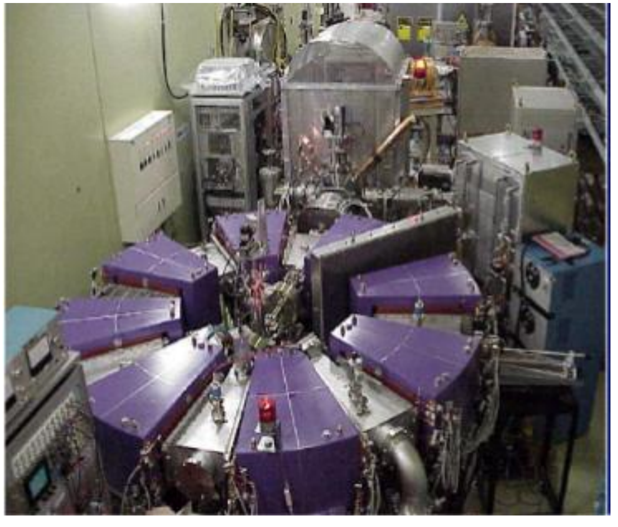
- Three electron prototypes, the third and last one a 50 MeV two-way ring, were constructed. They were called “scaling” FFAGs.

MURA electron model in 1956.

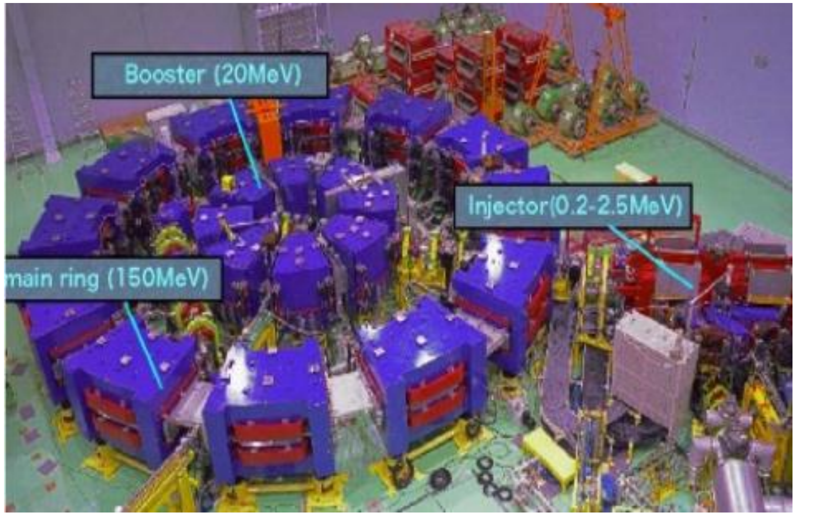


PoP for protons

- The interest of the FFAG method was revived in Japan in the late 1990s: a proton prototype was built based on a radial sector Defocusing-Focusing-Defocusing dipole triplet.



PoP machine 500 keV machine, 2.5 m diameter, operated in 1999 in KeK.



Proton driver of the KURRI KUCA ADS-Reactor experiment.

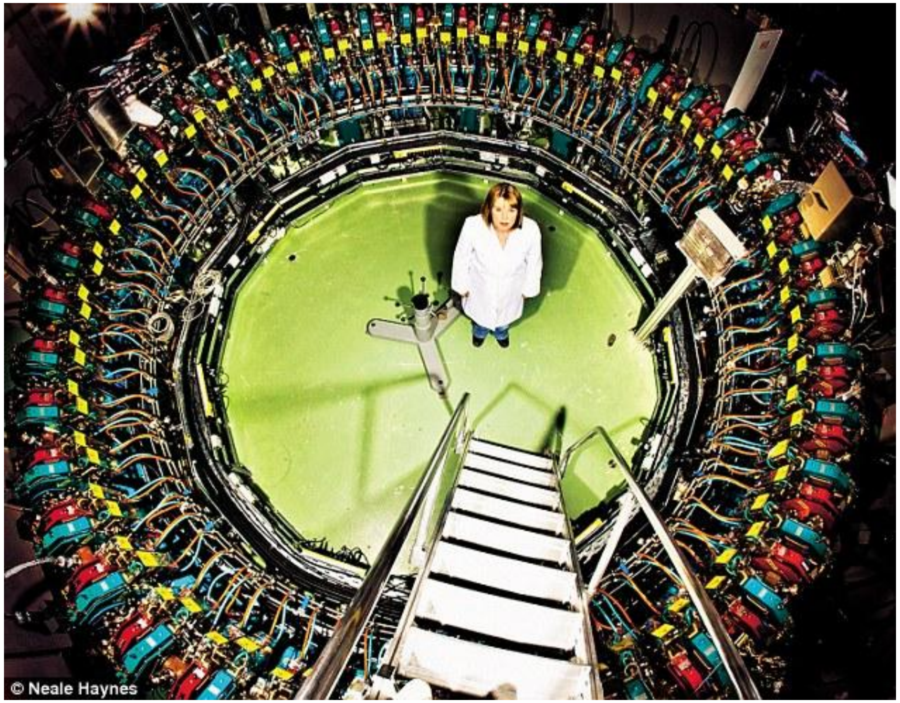
2) 1st non-scaling FFAG PoP: EMMA

EMMA

- EMMA is the Electron Machine for Many Applications: demonstrator of the linear non-scaling FFAG technology.

- Construction at Daresbury laboratory, UK started in 2007, commissioning in 2010.

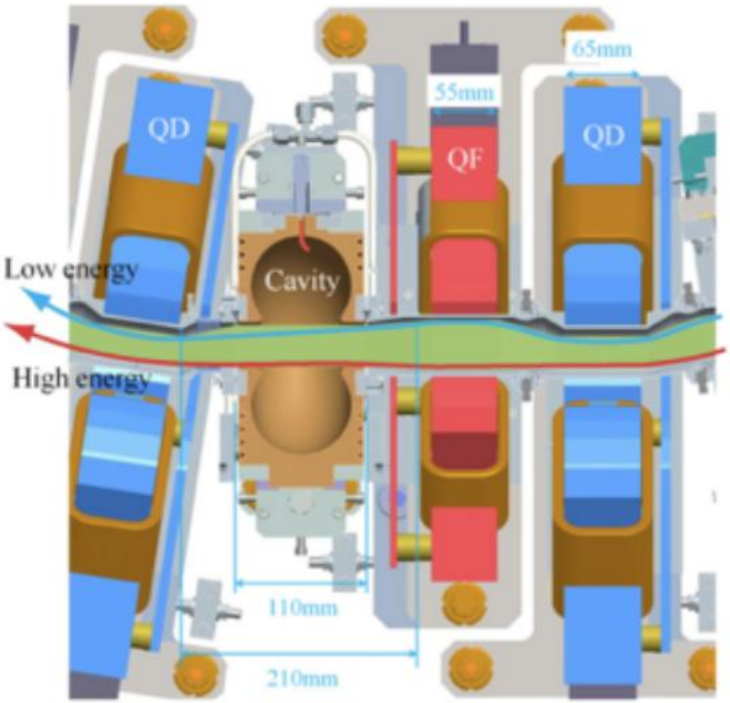
- More information can be found in **[1][2].**

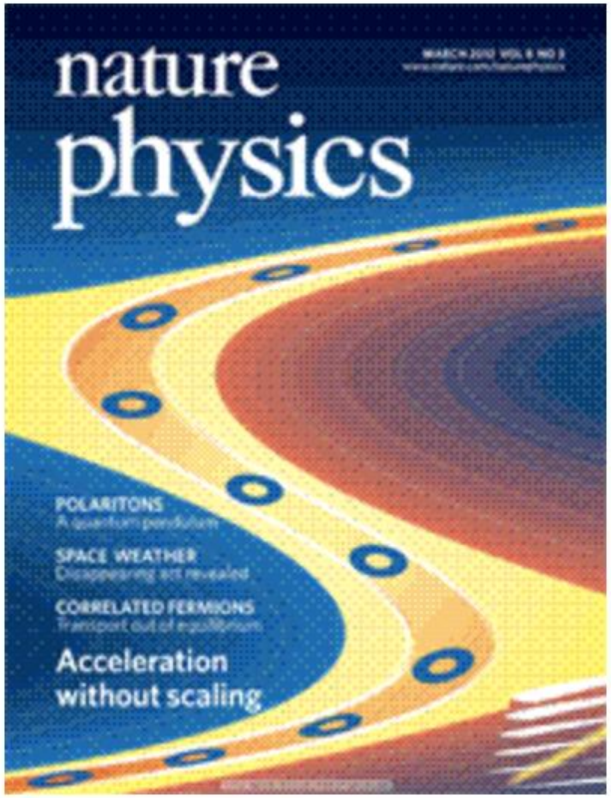


Energy range	10 -> 20 MeV
Number of turns	< 16
Circumference	16.56 m
Lattice	F/D doublet
Nb of cells	42
RF frequency	1.3 GHz
Nb of cavities	19
RF voltage	20-120 kV/cav
Rep rate	1-20 Hz

However, can an EMMA-like ring work for protons?

EMMA





- ❑ One key finding of EMMA is that no beam blowup is observed despite resonance crossing.

- ❑ The concept is presently exploited in the design of the eRHIC electron ion collider.

3) Applications:

3.1) Medical applications

3.2) Energy applications

3.3) Fundamental science

3.1) Medical Applications

Hadron therapy

- Proton energies up to 250 MeV.
- Flexibility and reliability are of utmost importance within a hospital environment.
- Because of the limited space, circular accelerators are the best choice: synchrotrons and cyclotrons are the most widely employed.

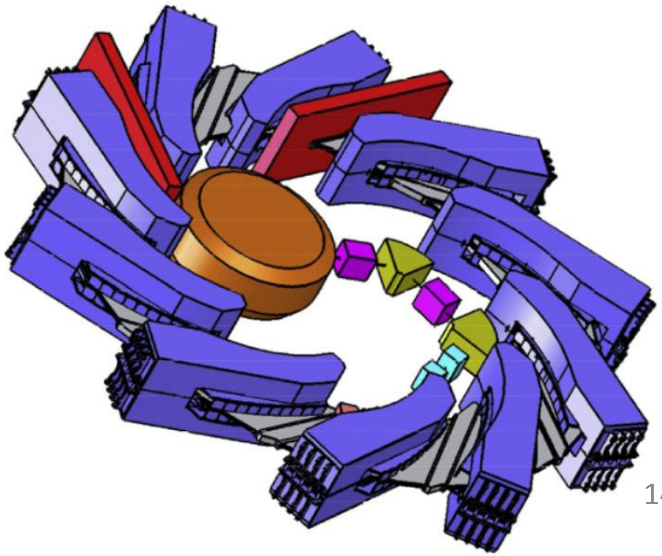
  What can FFAG bring?

  - Potential for CW acceleration
  - Repetition rates in the kHz range
- An additional challenge is how to make cheaper and smaller size gantries?

GSI Heidelberg gantry.

RACCAM

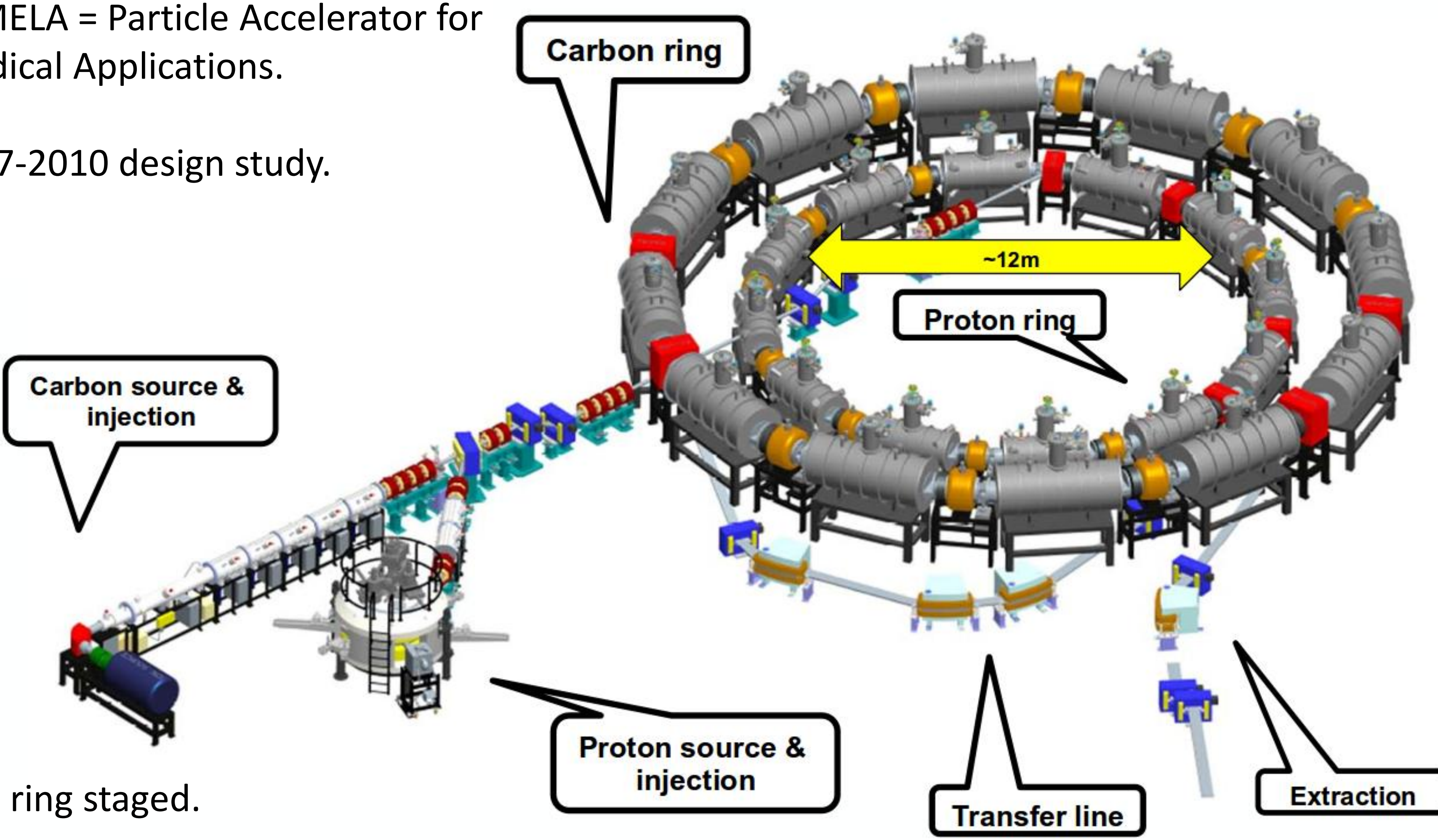
- RACCAM = Recherche en ACCélérateurs et Applications Médicales
- Proton FFAG for medical application: French ANR funding, 2006-2008, 3.5 Meuros.
- A feasibility study of a rapid-cycling, variable energy, spiral lattice scaling FFAG.
- Designed to accelerate beams from 5.55 MeV to 180 MeV (variable energy range).
- Multi-room treatment center based on the normal-conducting scaling FFAG magnet technology.
- Prototype Magnet built and measured.



PAMELA

PAMELA = Particle Accelerator for Medical Applications.

2007-2010 design study.



Two ring staged.

1kHz repetition rate.

PAMELA

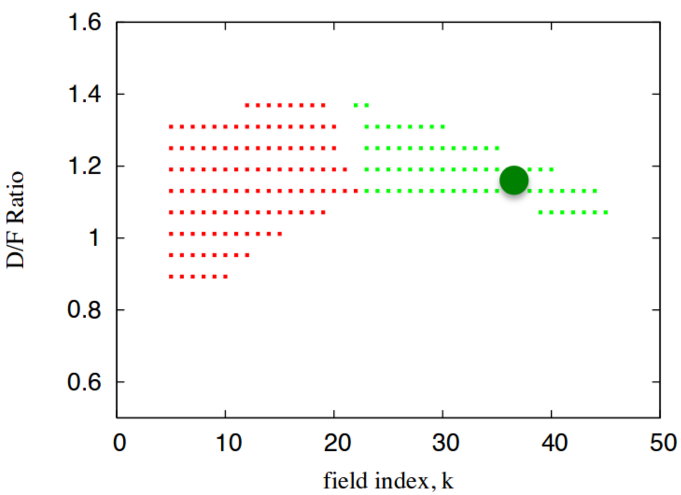
- ❑ Non-linear FFAG design: the concept is based on a radial sector FDF triplet in which the second stability region is chosen so that $\frac{\varphi_x}{2\pi} > 0.5$ (large k-value).

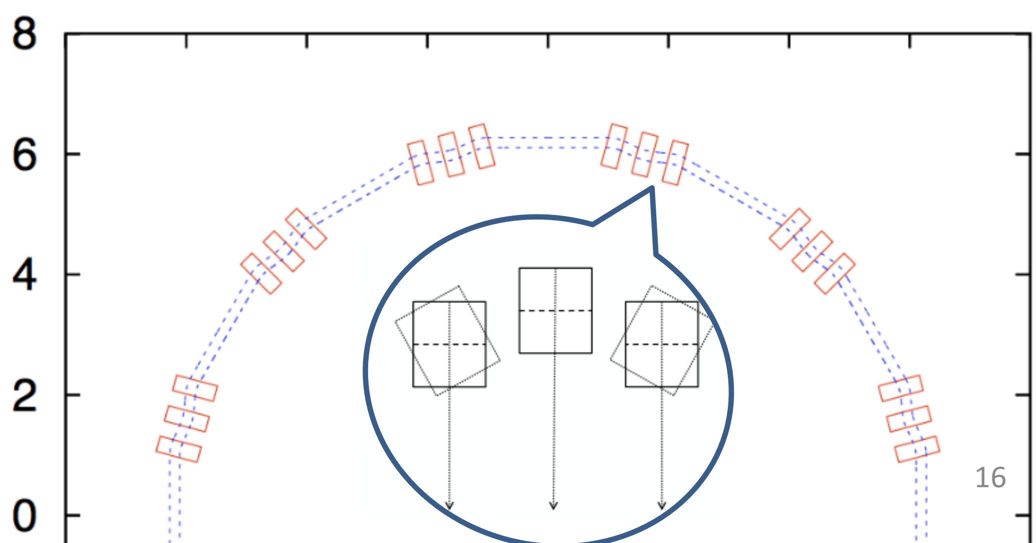
⇨ The orbit excursion is reduced by a factor of ~ 5 compared to the first stability region.

- ❑ The magnets were shaped in a rectangular way and aligned in a straight line rather than along an arc to simplify the construction.

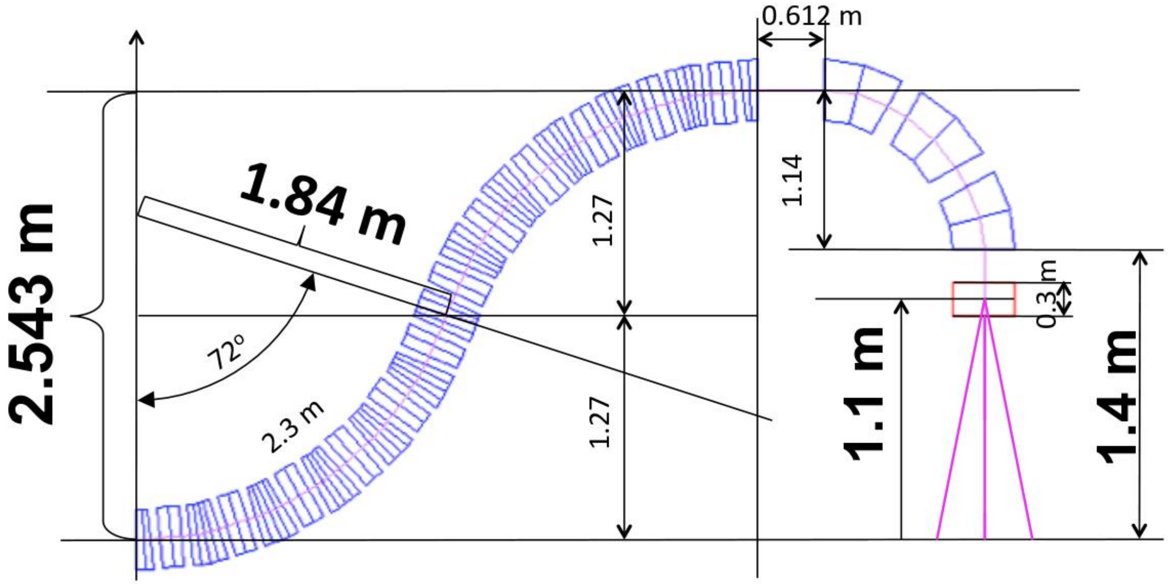
- ❑ The field of a scaling FFAG was decomposed into its multipoles, truncated to low order, and the tunes stabilized:

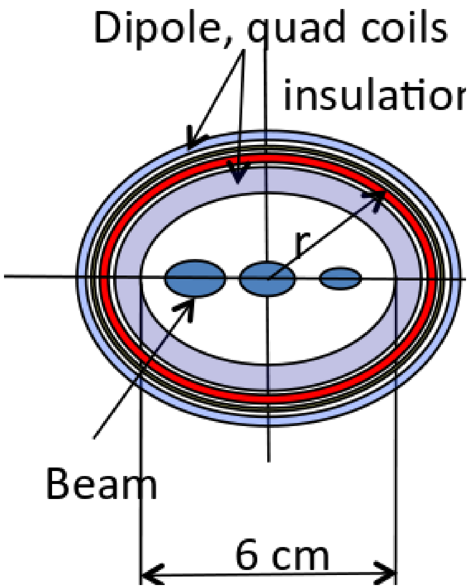
$$B = B_0\left(\frac{R}{R_0}\right)^k \times F(\theta) = B_0\left[1 + k\frac{x}{R_0} + \frac{k(k-1)}{2!}\left(\frac{x}{R_0}\right)^2 + O\left(\frac{x^3}{R_0^3}\right)\right]$$





FFAG gantries





FFAG magnets sequentially arranged along the beam tube of the gantry.

Reducing the size and weight of the carbon gantry (135 tons → 2 tons) with fixed field.

3.2) Energy Applications

Energy applications

- Need for a powerful source of neutrons to split the actinides and accommodate any type of fuel, i.e spent fuel.

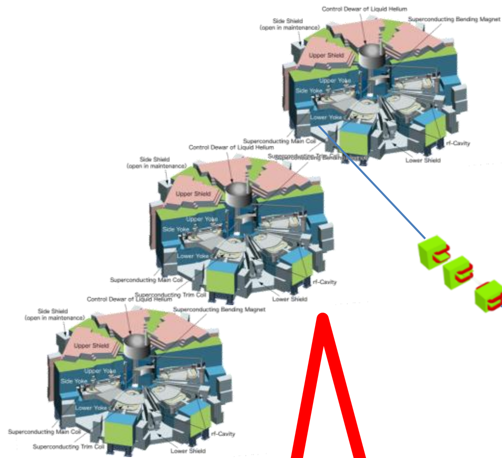
- Cost of producing neutrons is lower with a particle accelerator than with other techniques.

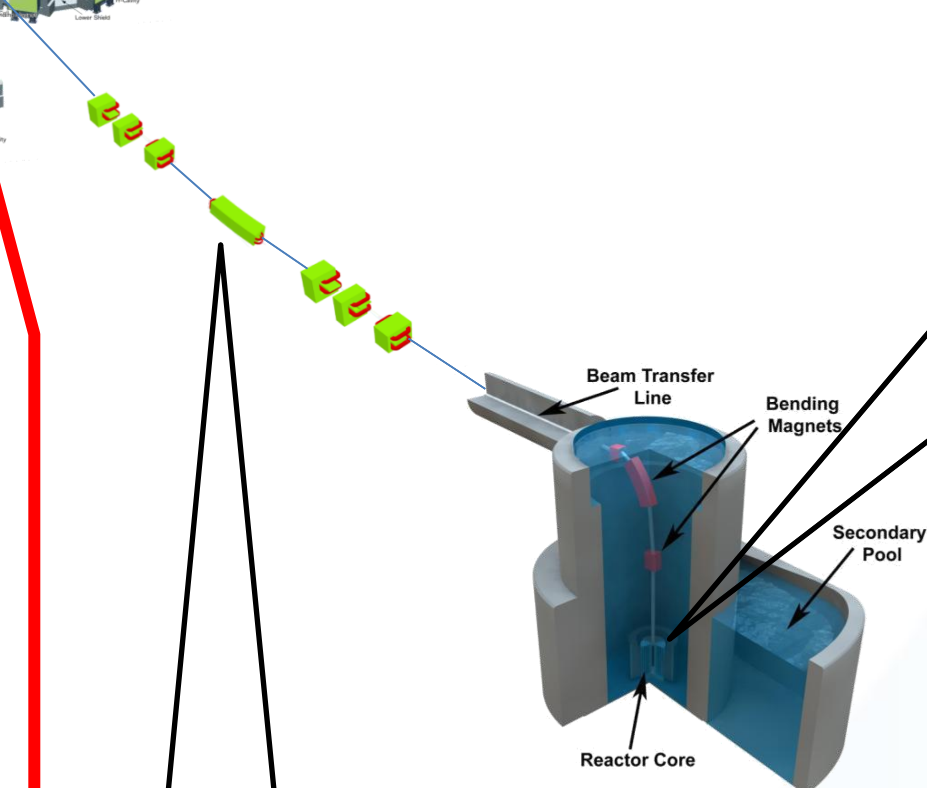
➡ Accelerator Driven Subcritical Reactor (ADSR) is a hybrid technique combining a particle accelerator with a sub-critical core.

- The accelerator could be linear or circular.
- The reactor could be thermal or fast.

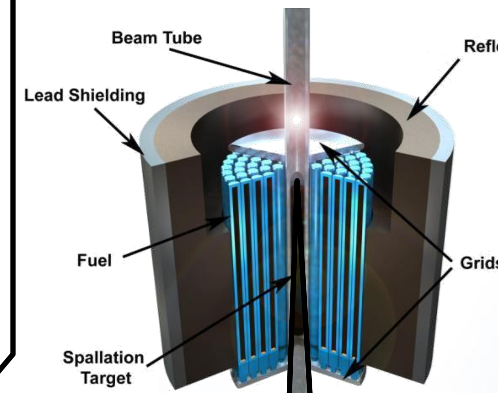
What are the potential missions of ADSR?

ADSR concept



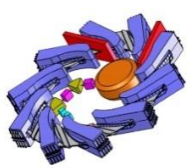


Target & Blanket

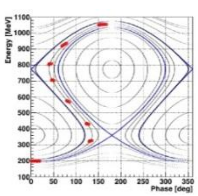


Accelerator

Multiple-ring



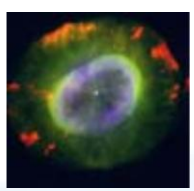
Fixed Field accelerators



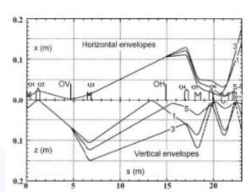
Serpentine/ CW methods

Beam transport

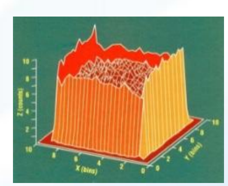
Space charge



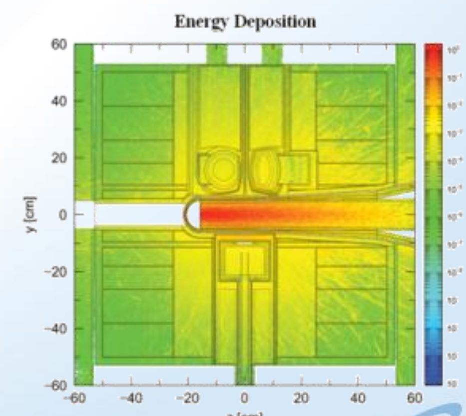
Halo control



Beam uniformization



Neutronics & data



ADSR missions

- **There exists three potential missions of ADSR:**

1) Accelerator Transmutation of Waste (ATW): the goal is to eliminate the most offending isotopes (fission products and minor actinides) of nuclear spent fuel prior to storage in an underground repository. The ADSR is a net burner.

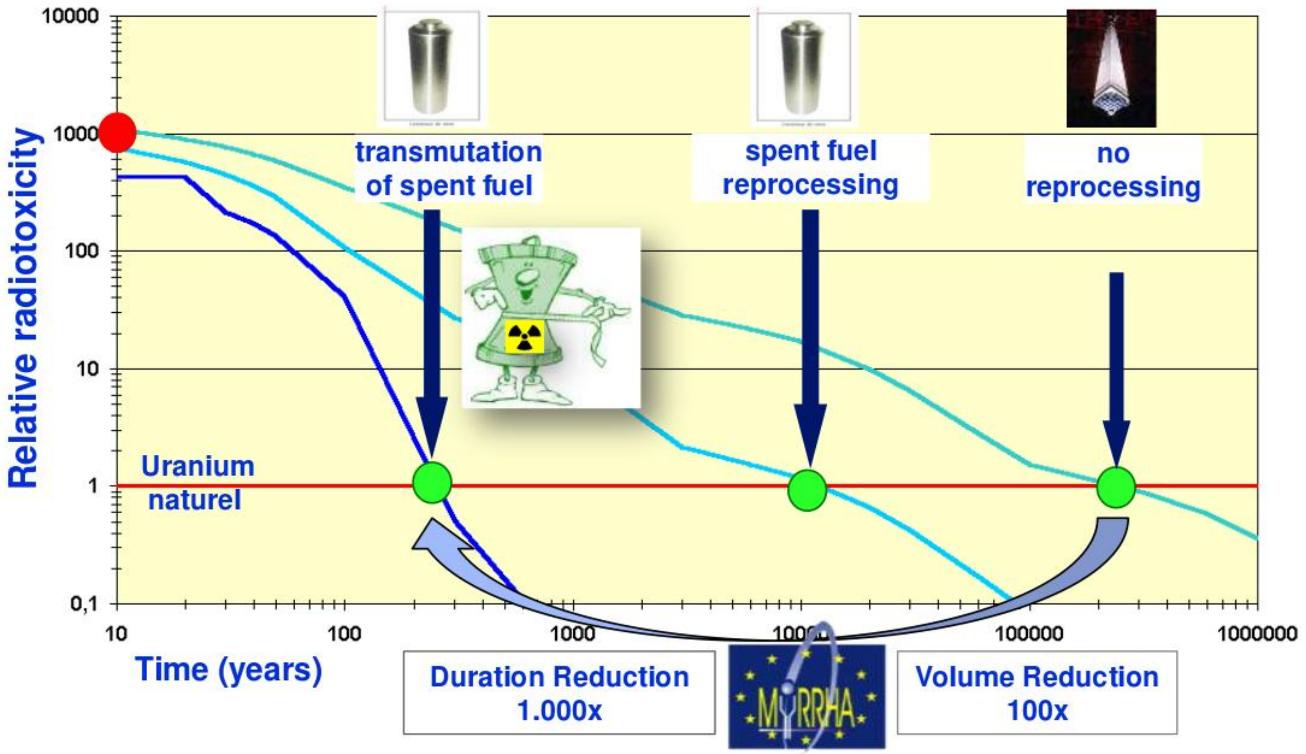
2) Fissile pre-breeder for critical reactor fleet: the goal is to produce fissile material to be used for critical reactor fleet. The ADSR is a breeder. This is seen as a solution to the uranium scarcity problem (although it is not yet the case!). The process can be summarized by the following chain of transformations:

$$\left\{ \begin{array}{l} {}^{238}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{239}_{92}\mathrm{U} + \gamma \rightarrow {}^{239}_{93}\mathrm{Np} + {}^{0}_{-1}\beta \\ \qquad \rightarrow {}^{239}_{94}\mathrm{Pu} + {}^{0}_{-1}\beta \\ \\ {}^{232}_{90}\mathrm{Th} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{233}_{90}\mathrm{Th} + \gamma \rightarrow {}^{233}_{91}\mathrm{Pa} + {}^{0}_{-1}\beta \\ \qquad \rightarrow {}^{233}_{92}\mathrm{U} + {}^{0}_{-1}\beta \end{array} \right.$$

3) Energy Amplifier: The ADSR is a breeder and burner at the same time. The fertile material is provided in the fuel or in a breeder blanket surrounding the core or in both.

Best missions of ADSR: ATW

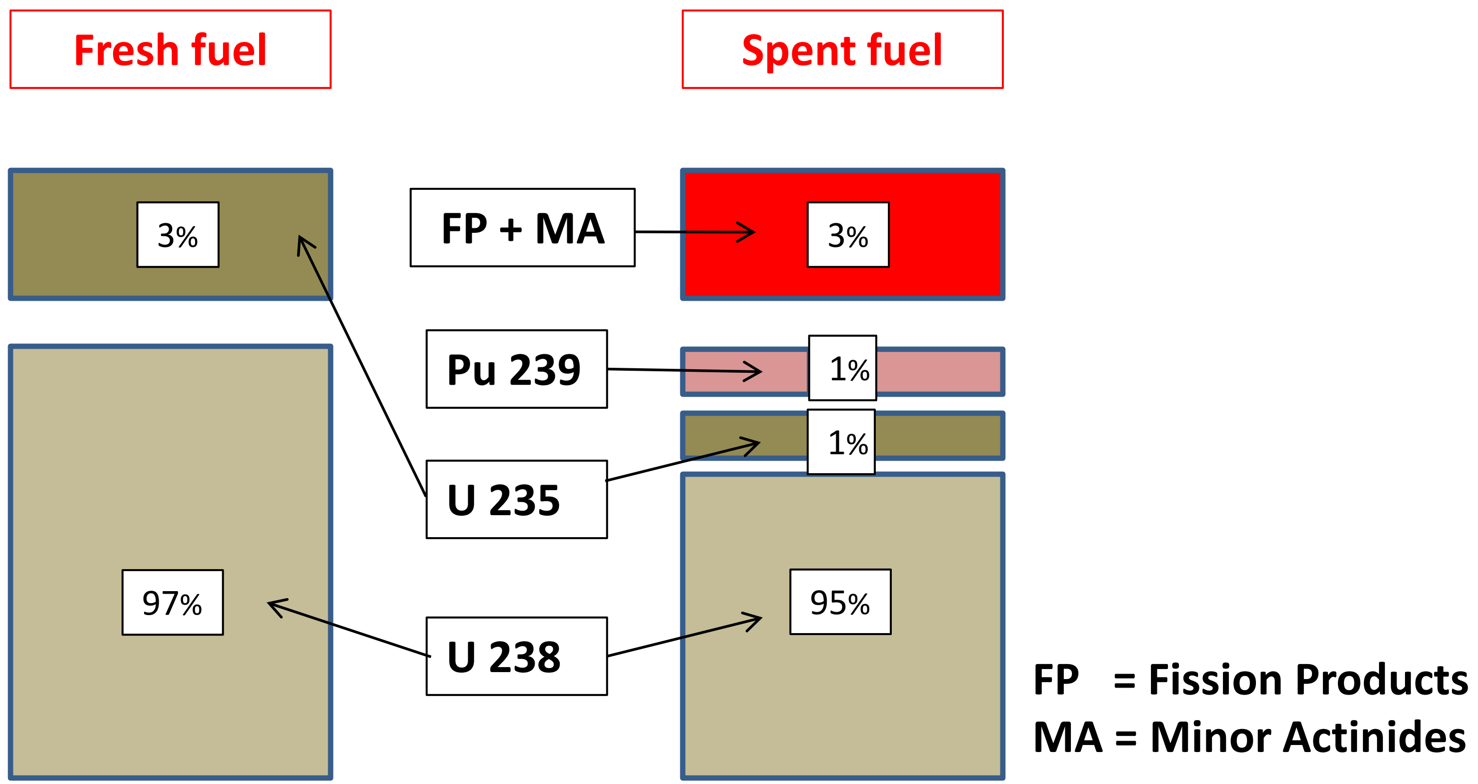
- The Accelerator Transmutation of Waste is generally considered as the best mission of an ADSR. Why?



Transmutation helps reduce the size of the repository by two orders of magnitude as well as the time of storage.

Best missions of ADSR: higher fuel usage

- Flexibility is the main advantage of running a nuclear reactor in a subcritical mode: almost any fuel composition can be accommodated:

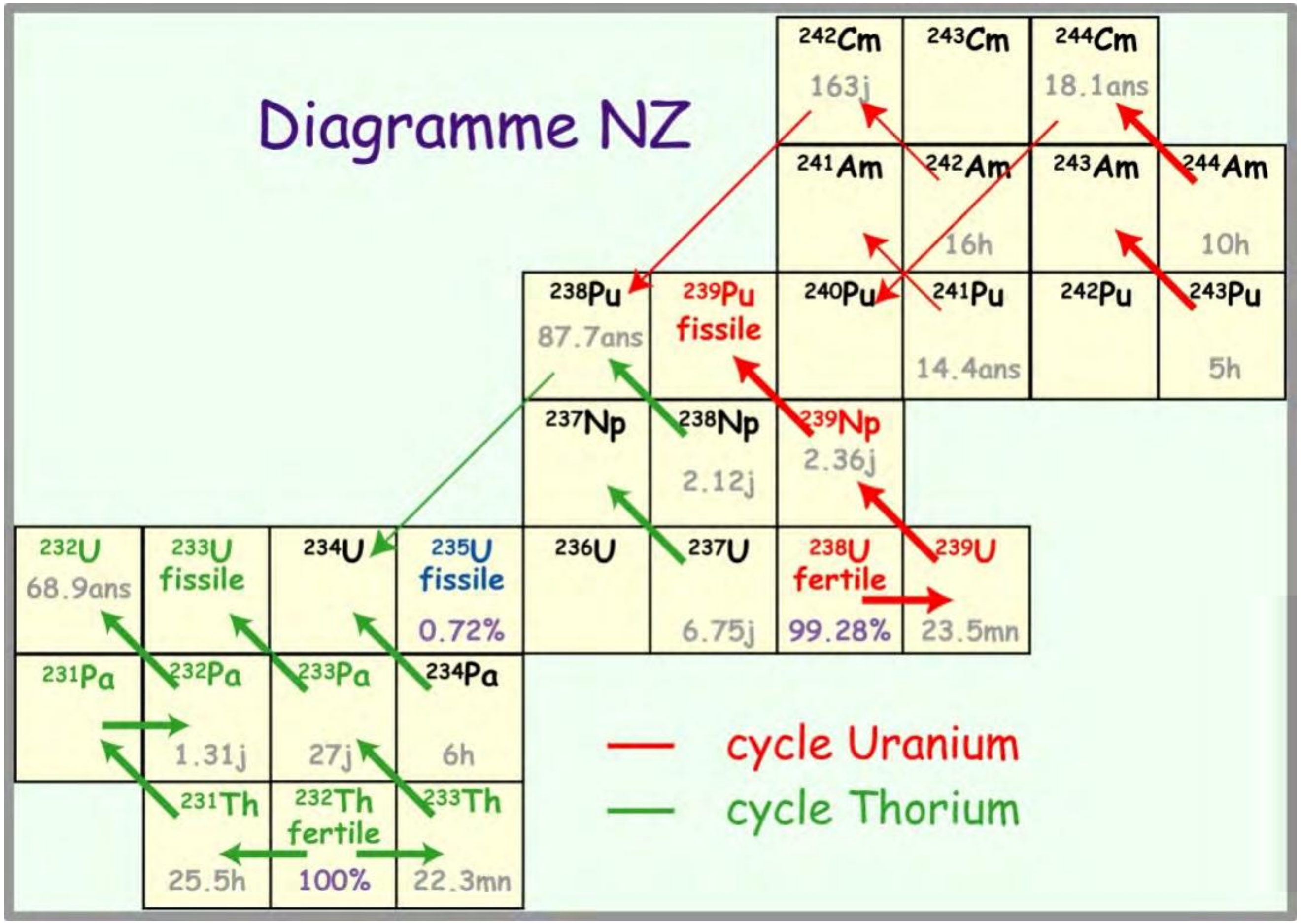


⇨ **Highly inefficient use of the fuel resources in critical Light Water Reactors.**

ADSR and thorium fuel cycle

- In particular, ADSR is associated with Thorium, because the latter has no naturally occurring fissile isotopes.

Z



j = day
ans = years

N

Accelerator parameters for ADSR (1/4)

- ❑ The sub-critical core is mainly characterized by two parameters:

- The neutron effective multiplication factor defined as:

$$k_{eff} = \frac{number\ of\ neutrons\ in\ one\ generation}{number\ of\ neutrons\ in\ previous\ generation}$$

- The average number of neutrons produced per fission ν (~2-3)

- ❑ Derive the formula:

$$\boxed{P_{th}(MW) = E_f(MeV) \times I(A) \times \frac{\mathrm{N_0}}{\nu} \times \frac{k_{eff}}{1 - k_{eff}} + (P_{dh})}$$

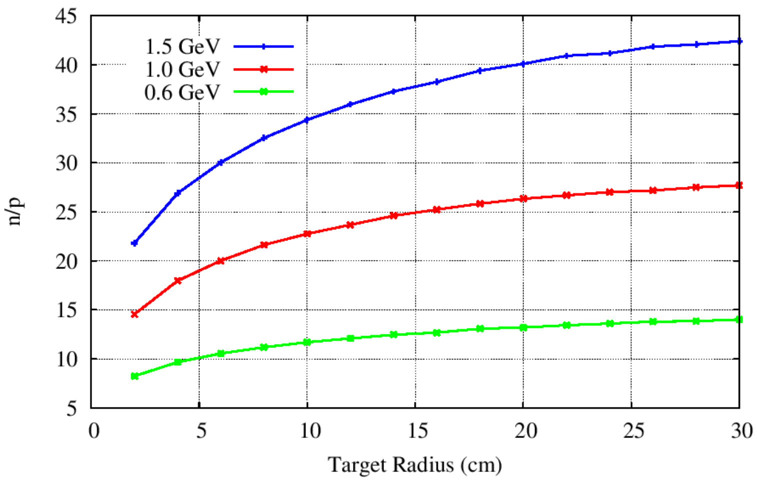
where $E_f(MeV) \sim 200\ MeV$; I is the beam current, ν is the number of neutrons produced per fission (~2-3) and N_0 is the number of neutrons per proton (n/p).

The accelerator parameters are determined by the required thermal power of the reactor core.

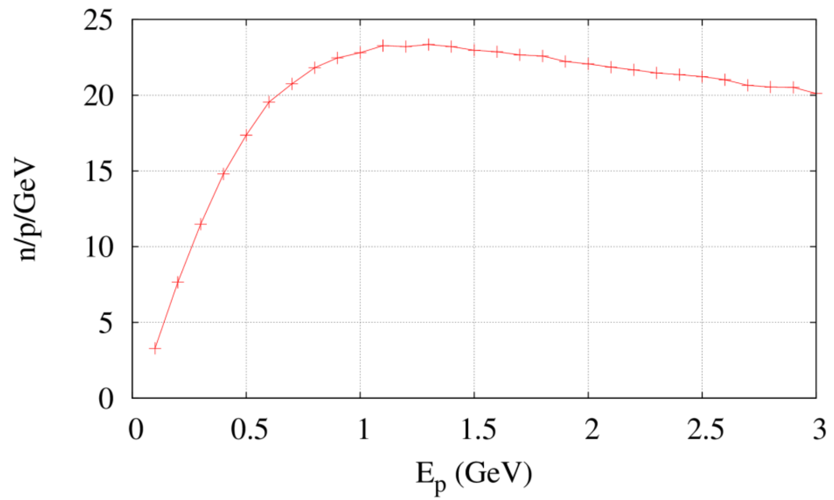
Accelerator parameters (2/4)

<u>What's the optimal energy?</u>

$$P_{th}(MW) = E_f(MeV) \times I(A) \times \frac{N_0}{\nu} \times \frac{k_{eff}}{1-k_{eff}} + (P_{dh})$$



Target multiplicity on a cylindrical lead target.



Neutron cost as a function of the energy.

Neutron cost saturates at around 1 GeV.
Shielding of the high energy cascade neutrons is problematic.
Material damage problems.

⇨ The optimal energy should be in the [0.5,1] GeV range. Can be achieved by FFAG ✓

Accelerator parameters (3/4)

What's the optimal current?

$$P_{th}(MW) = E_f(MeV) \times I(A) \times \frac{\mathrm{N_0}}{\nu} \times \frac{k_{eff}}{1 - k_{eff}} + (P_{dh})$$

- Considering a core thermal power of $\approx 1000\ MW_{th}$ and a proton beam energy of 1 GeV, which yields 20 n/p on a lead target,

$$\begin{cases} \mathrm{E_p} = 1\mathrm{GeV} \ \Rightarrow \ N_0 \sim 20 \\ P_{th} = 1000\ \mathrm{MW_{th}}\ ,\ \nu \sim 2.5\ ,\ k_{eff} = 0.95 \text{ and } E_f \sim 200\ MeV \end{cases}$$

one obtains $I \sim 32\ mA \Rightarrow P_{beam} \sim 32\ MW \Rightarrow P_{grid}$???????

⇨ **Energy efficiency of the installation can become problematic.**

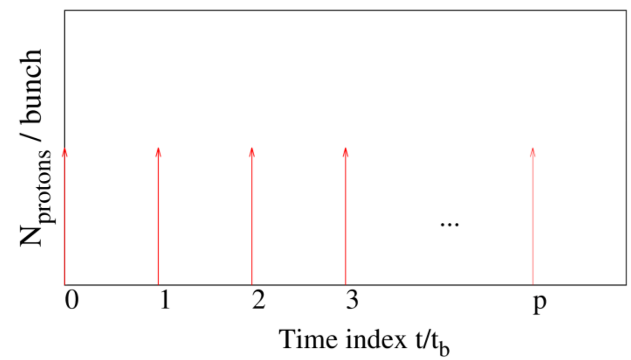
Accelerator parameters (4/4)

<u>What's the optimal beam Time-Structure?</u>

- Defining the equivalence between two beams in terms of average current,

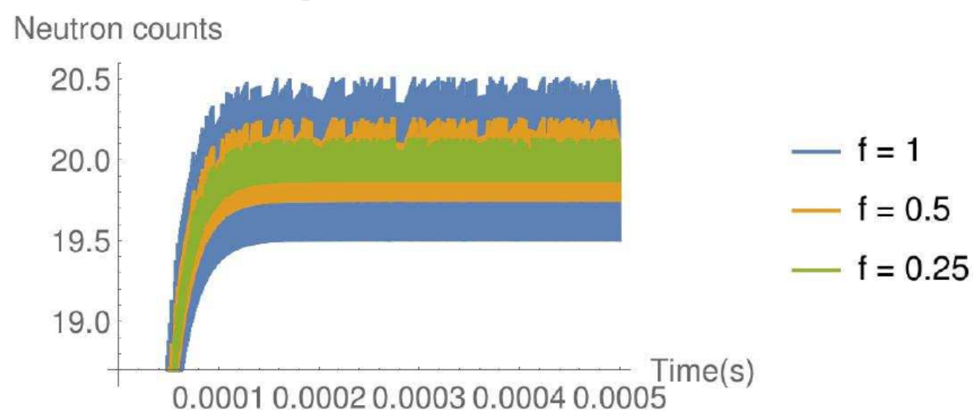
$$\begin{cases} N_s \\ t_b \end{cases} \text{is equivalent to} \quad \begin{cases} f \times N_s \\ f \times t_b \end{cases}$$

where f = time structure scale factor



- This yields $\frac{N(t)}{N_s} = f \exp\left[-\frac{t - E(\frac{t}{f t_b}) f t_b}{\tau_1}\right] \times \frac{1 - \exp\left[-\left(E(\frac{t}{f t_b}) + 1\right)\frac{f t_b}{\tau_1}\right]}{1 - \exp(-\frac{f t_b}{\tau_1})}$

⇨ **CW beams with high repetition rate must be employed. Can be achieved by FFAG ✓**

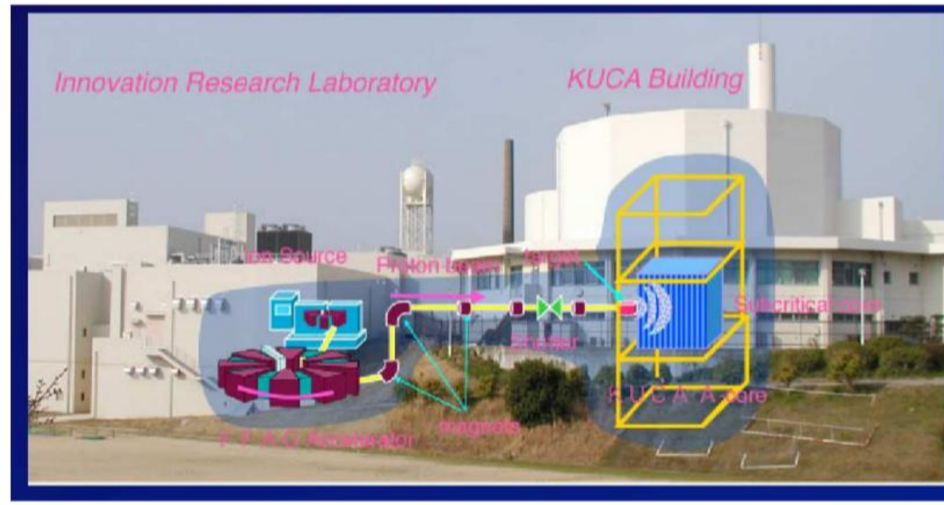


[Effect of the Beam Time Structure on the Neutronics of an Accelerator Driven Subcritical Reactor, IPAC16].

Time variation of the neutron population for various values of the scale factor f.

FFAG for ADSR: KURRI KUCA

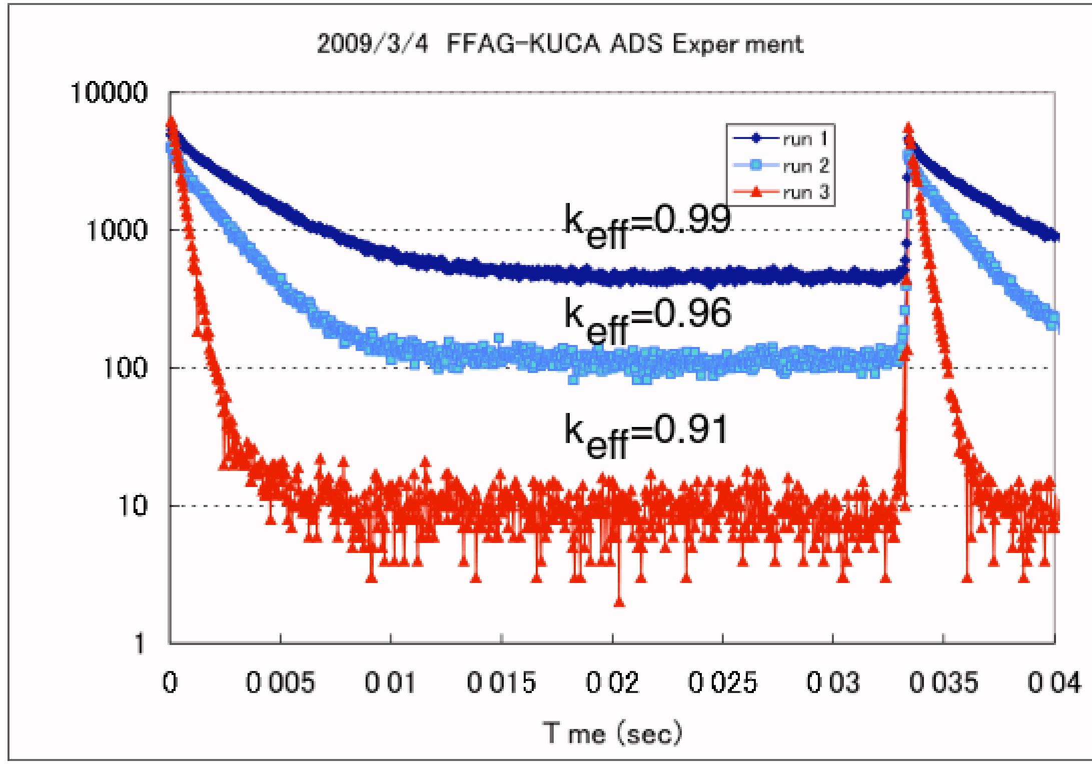
100-150 MeV proton, repetition rate 20-50 Hz



- A zero power ADS-Reactor.
- First-coupling to ADSR core, March 2009, 100 MeV proton beam.

FFAG for ADSR: KURRI KUCA

- Thorium-loaded ADSR experiment, March 2010.
- Very short proton beam of the accelerator is injected (10ns).
- It follows a chain multiplication of the fission neutrons in the core.
- Interruption of the proton beam yields an exponential decay such as: $n(t) \propto \exp(-t/\tau)$ where $\tau \ \propto \frac{1}{k_{eff}-1}$



Neutron rate as a function of time for different effective multiplication factors.

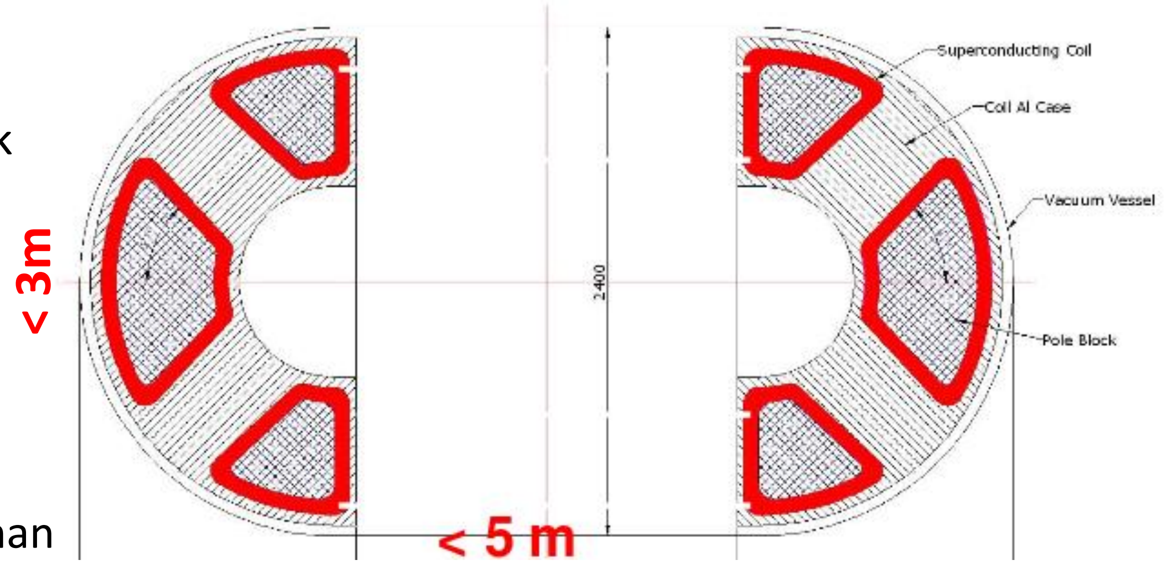
FFAG for ADSR

- ❑ A wide variety of FFAGs can be explored for high power applications.

- ❑ Of particular interest are the NS-FFAG that has evolved to an isochronous, high energy, high current design.

- ❑ Compact CW ns-FFAG racetrack design capable of variable energy and various applications.

- ❑ “In the relativistic regime, the FFAG becomes more compact than the separated sector cyclotron and more stable if designed properly. The racetrack is the most compact”. C. Johnstone.



0.2 -1 GeV intense proton FFAG for ADS.

3.3) Fundamental science

Neutrino Factory

- The Neutrino Factory is a proposed accelerator complex intended to measure the <u>properties of neutrinos</u>. The latter are extremely weakly interacting particles.
- The phenomenon of neutrino oscillations implies that the standard model of particle physics is incomplete.
- Examining the properties of the neutrino will provide an information about their weak-interaction properties.
- In such a facility, the neutrinos are produced from the decay of muons.
- International design study reports provide the details of the physics, schedule as well as the costs of the project.
- However, these designs are evolving too quickly …

Neutrino Factory

- <u>Conceptual design of the neutrino factory (as of 2014):</u>

  - pions are produced by the interaction of high energy protons with a target.

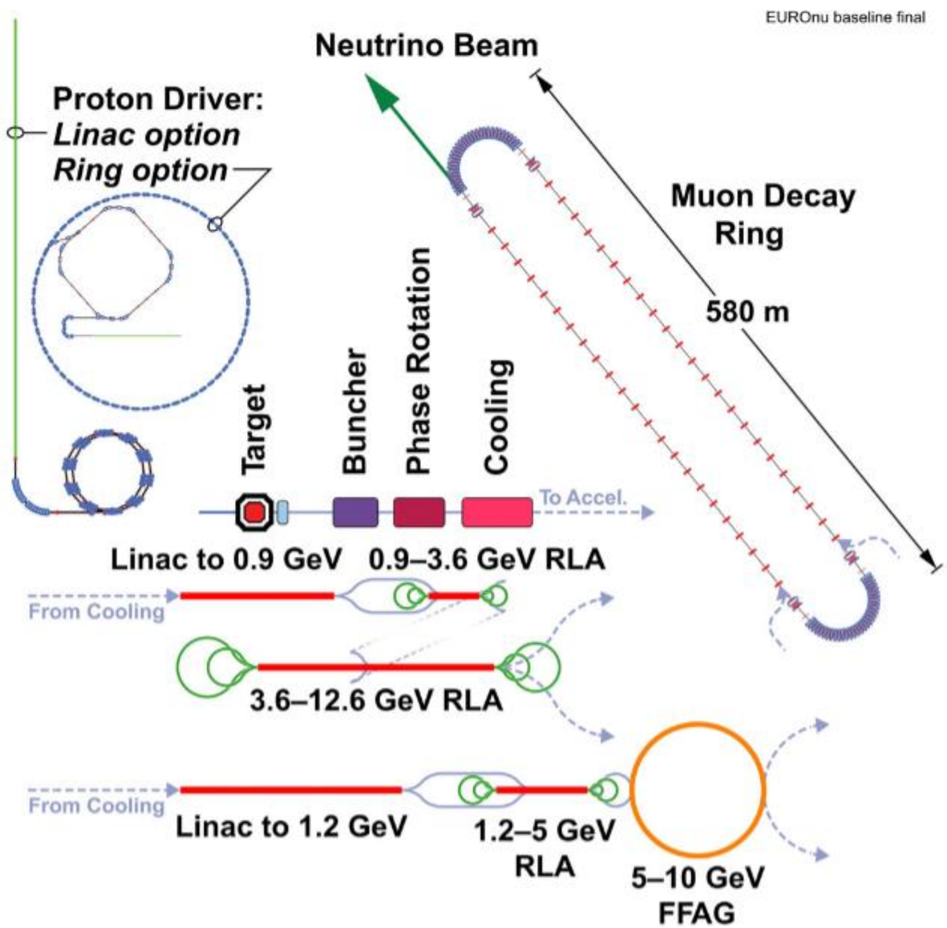
  - pions are captured in a high field solenoid and transported to a solenoid-focusing decay channel where muons are produced.

  - the latter have a large energy spread and a large transverse emittance:
Bunching ⇨ Phase Rotation ⇨ Ionization cooling (MICE experiment at RAL).

  - A sequence of accelerators is used to accelerate the beam to its final energy of 12.6 GeV.

  - The beam is injected into one racetrack-shaped decay ring (straight sections point at a detector (at 1500~2500 km distance))

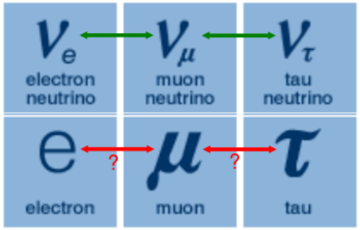
RLA = Recirculating Linear Accelerator.



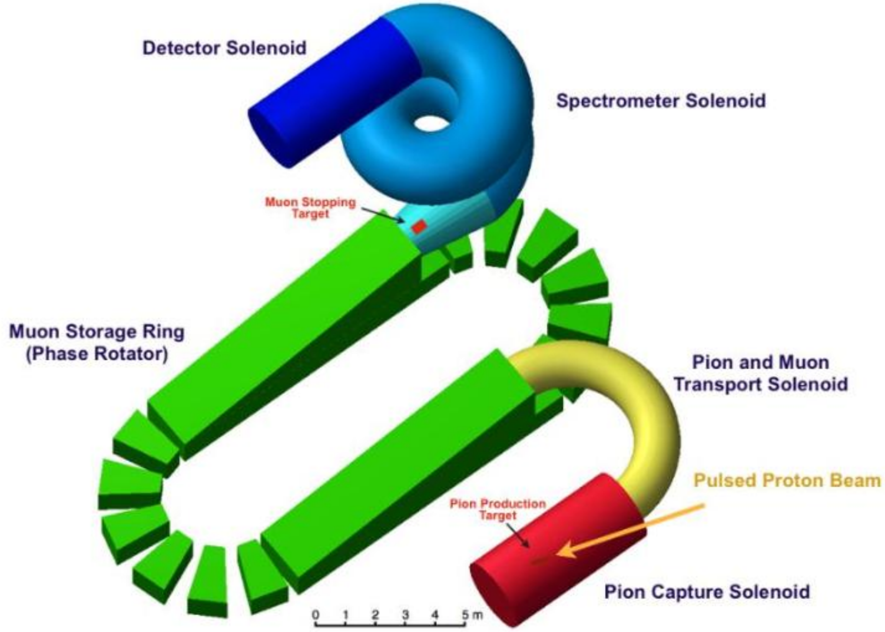
Schematic baseline of the accelerator facility for the neutrino factory.

PRISM

- Purpose of the experiment: measure muon to electron conversion ratio with a sensitivity less than 10^{-18}.



- The PRISM (Phase Rotated Intense Slow Muon beam) project was proposed in order to realize a low-energy muon beam with a high-intensity, narrow energy spread and high purity.
  ⇨ A scaling FFAG is proposed since it provides a large transverse and large longitudinal acceptance.



Conceptual layout of the PRISM accelerator and experimental system.

PRISM

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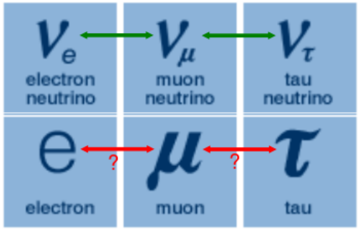

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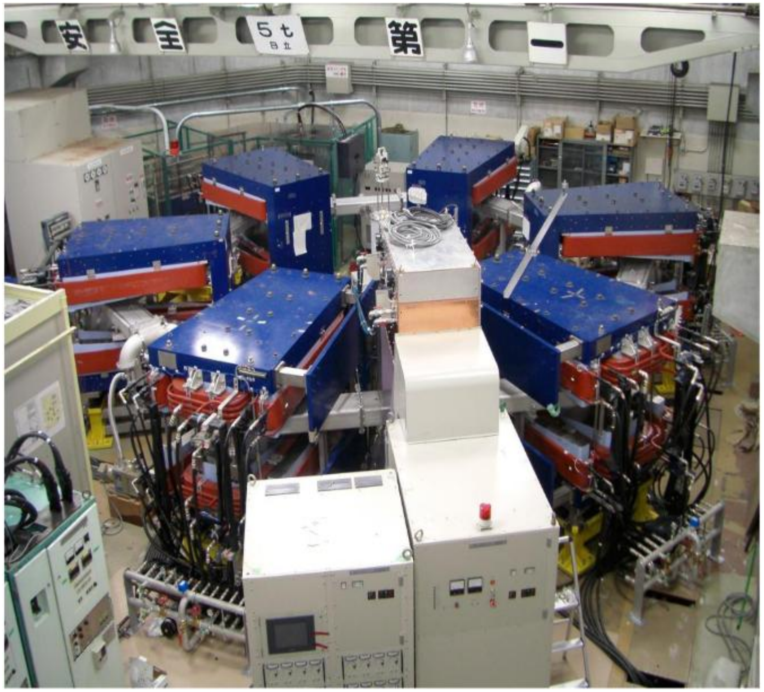
Feasibility study performed.

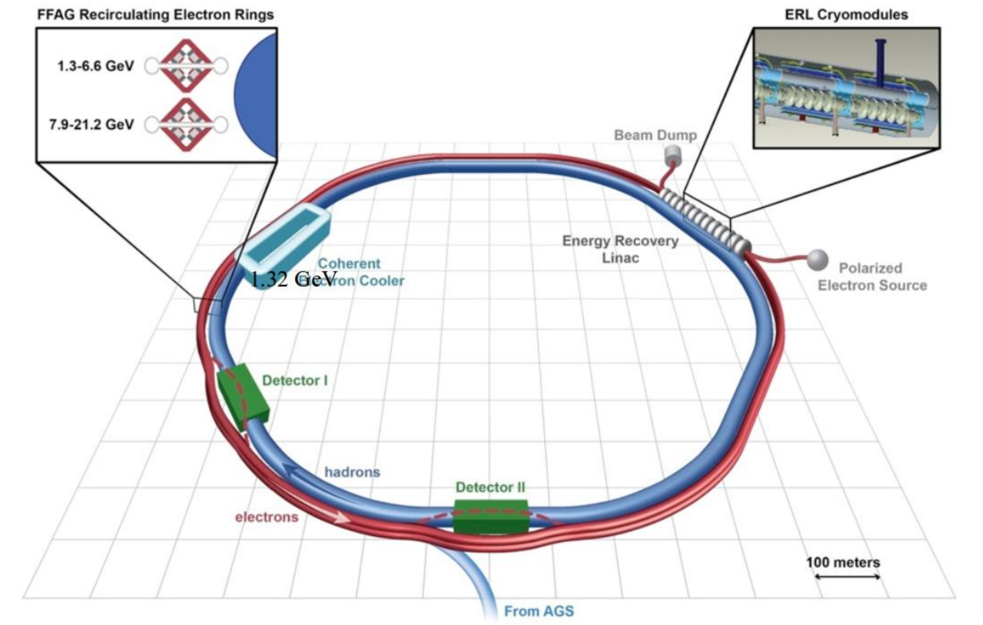
6-cell scaling FFAG ring assembled at RCNP in Osaka to perform phase rotation demonstration experiment using alpha particles (2003-2009). Demonstration done.



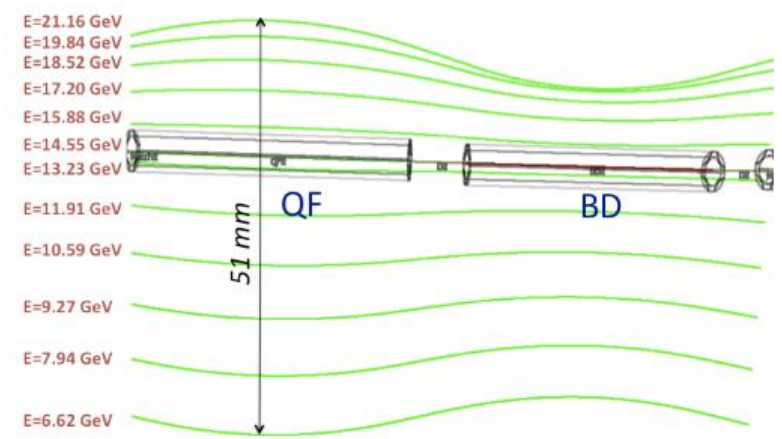
Electron-Ion collider eRHIC

- Add an electron ring to the existing \$2.5B RHIC (including the tunnel and the cryo facility).

- The NS-FFAG for eRHIC is made of identical cells in the arcs that follow the shape of the RHIC tunnel.



2 FFAG magnets transporting up to 16 beams.



Orbits in the high energy FFAG arc.

- 5 paths in FFAG1 & 12 paths in FFAG2
- Major objective: probing the nucleon's spin structure, 3D imaging of the nucleons, etc.

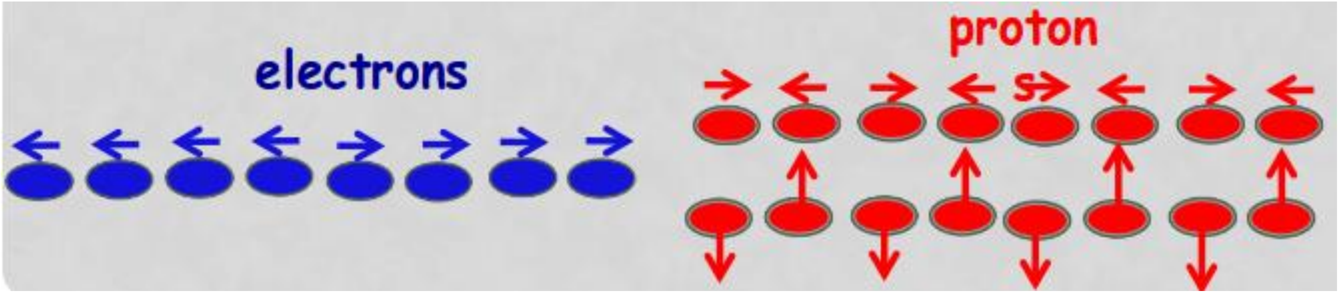
Why FFAG for eRHIC

- Until 2013, eRHIC has been designed with individual recirculation passes. So, what are the main arguments for using FFAG? (V. Ptitsyn)

  - <u>construction cost saving</u>: FFAG beam lines (instead of separate) that allow to reach higher electron beam energy at the same cost.

  - <u>operation cost saving</u>: potential for using permanent magnet technology.

- Dejan Trbojevic: campaigning for NS-FFAG eRHIC for so many years.



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