COMPACT CW FFAGS FOR HIGH-INTENSITY APPLICATIONS

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OUTLINE

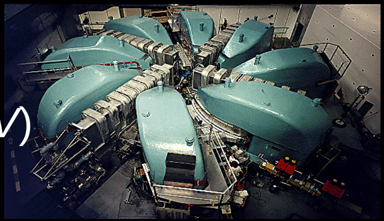
- **Motivation and Background**
  - Medical, security, energy applications
  - Isochronous or CW beam required to realize high mA currents
    - Implies next generation fixed magnetic-field accelerators
  - For medium energies – ~600 MeV – 2 GeV
    - Strong focusing for low-loss beam confinement
    - For circular machines: control of machine tunes (field gradients)
    - Isochronous (CW) strong focusing cyclotrons; i.e. FFAGs
- **These machines require high gradient acceleration for high currents**
  - Low acceleration and extraction losses
  - High gradient cavities require "drift" or component-free sections
  - Compactness further requires SCRF
- Large horizontal aperture of the FFAG, like the cyclotron, is a challenging problem for SCRF design; PSI has solved large aperture NCRF designs

APPLIED ACCELERATORS

1. *Synchrotons*
   - Pulsed magnetic fields
   - Swept-frequency accelerating systems
   - Separated components
   - Long component-free straight sections
   - Size scales with momentum/charge to mass ratio.
   - Current limited - μA
2. *Cyclotrons*
   - Fixed magnetic fields
   - DC beams, fixed-frequency accelerating system
   - Relativistic energies: swept-frequency accelerating systems
     - Synchrocyclotron.
   - Monolithic pole pieces – no straight sections
   - Very large at high energy
   - High currents (mA)
3. *Linacs*
   - Longest footprint
   - Costly – no recirculating beam or “reuse” of components
   - Ultra-high currents – 100 mA
4. *FFAGs*
   - Fixed magnetic fields
   - DC beams well into the relativistic regime
   - Compact
   - Separated components
   - Synchrotron-like dynamics allow component-free straight sections
   - High current – tens of mA

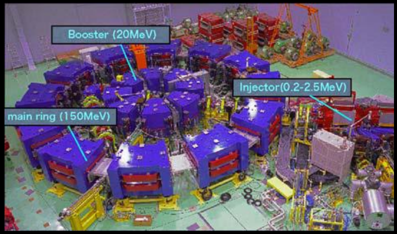
Synchrotron
Low Current (<mA)
High Energy (TeV)
Pulsed Beam

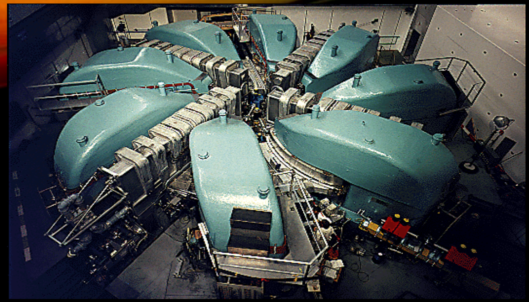
Cyclotron
High Current (<10mA)
Medium Energy (600MeV)
Continuous beam



Linac
High Current, High Energy
Pulsed or continuous beam: Large, expensive

FFAG
High Current (~20mA) , High Energy (GeV)
Continuous beam, compact





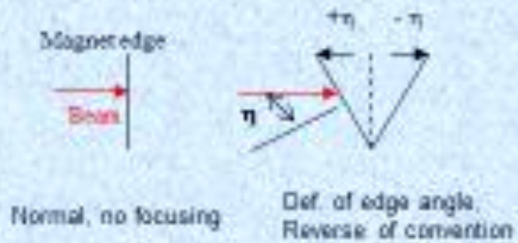
CYCLOTRONS:

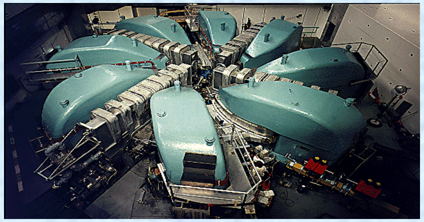
- Cyclotrons are the highest current, most compact solution, but only up ~200 MeV for protons
- As the energy becomes increasingly relativistic, orbit separation becomes smaller and smaller for CW operation
- Higher energies require separated sectors (like the 590-MeV PSI or 500-MeV TRIUMF machines) – in order to insert strong accelerating (RF) systems.
  - Stronger acceleration is required to minimize beam losses and radioactivity particularly during beam extraction
  - Fewer acceleration turns and larger between different acceleration orbits facilitate efficient extraction.
- However, once space is inserted between the magnetic sectors of the cyclotron, the footprint grows rapidly.
- At relativistic energies, above 200 MeV, cyclotrons do not scale. Field profile must be nonlinear at relativistic energies for CW operation

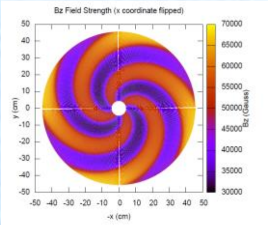
PRINCIPLES OF BEAM TRANSVERSE FOCUSING: A SHORT REVIEW

1. Centripetal focusing *(used in Cyclotrons + FFAGs)* :
   - Pathlength variation in dipole body field, bend plane only
   - Horizontally focusing or <u>defocusing</u> for FFAGs with reverse bends (radial sector).

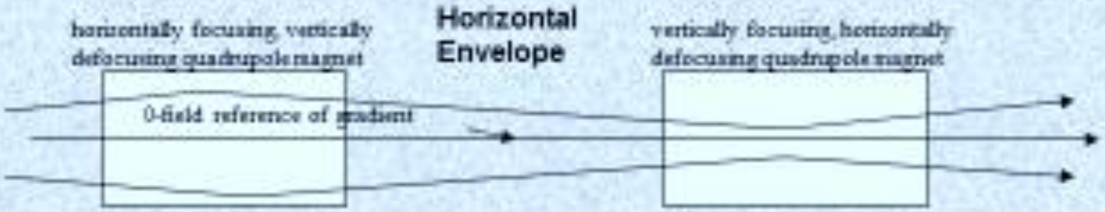
2. Edge focusing *(used in Cyclotrons + FFAGs)** :
   - Quadrupole-like: focusing horizontally, defocusing vertically, or vice versa, or no focusing depending sign of the B field and on entrance angle (defined relative to the normal to the magnet edge).







3. Field -gradient focusing *(used in Synchrotrons + FFAGs)*
   - Body gradient, fields components > dipole; AG envelope focusing:



SO WHAT IS A FFAG? NEXT GENERATION CYCLOTRON

A Fixed Field Alternating Gradient Accelerator is a ~ a cyclotron with strong synchrotron-like focusing

- The ns-FFAG combines all forms of transverse beam (envelope) confinement in an arbitrary, optimized magnet field:
  - For the horizontal, the three terms are

$$1/f_F = k_F l + \frac{\vartheta}{\rho_F} + \frac{\eta}{\rho_F}$$

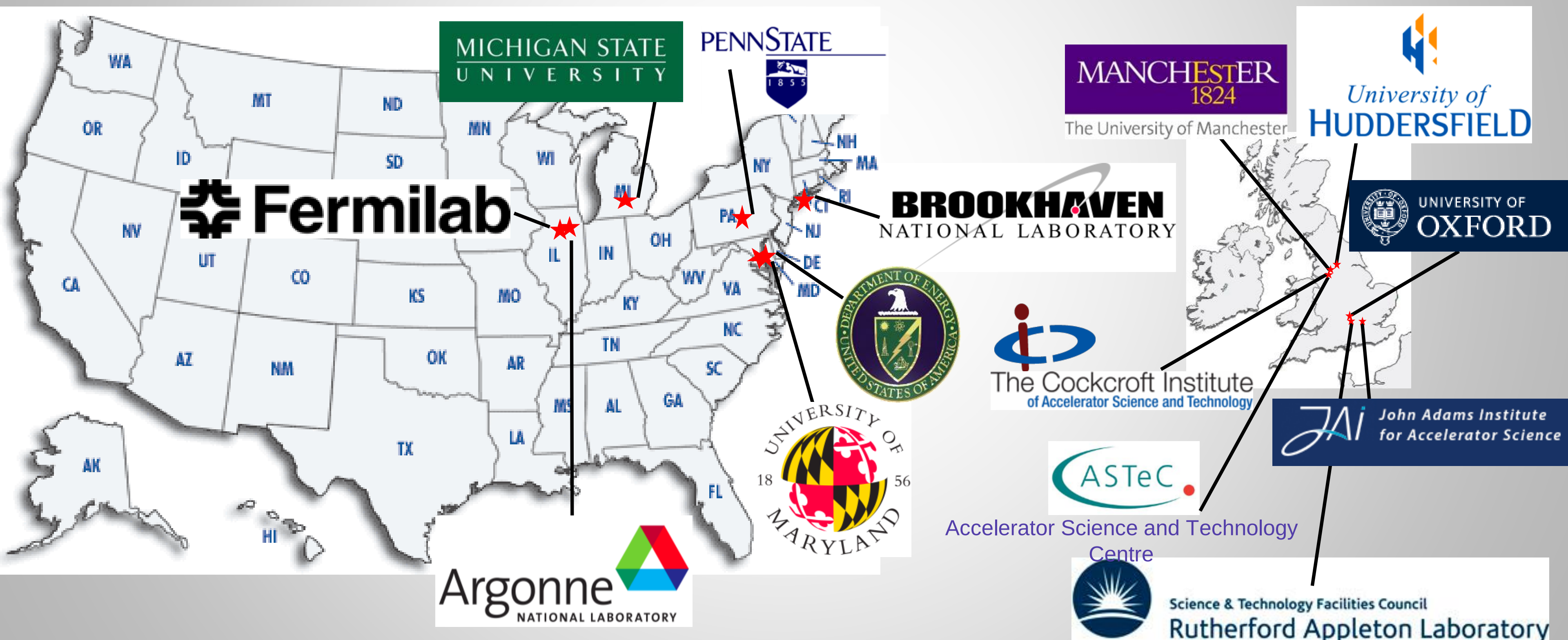
cyclotron

synchrotron

with ϑ is the sector bend angle, η the edge angle (edge angle is assume small so tangent is approximated), length, l, is the F half - magnet length and k_F is the "local" gradient for an arbitrary order field.

– *The power of the nonscaling FFAG is that the confinement terms can be varied independently to optimize machine parameters such as footprint, aperture, and tune in a FFAG AND DC beam can be supported to very high energies*

INTERNATIONAL ffAG COLLABORATION



KURRI
Kyoto University
Research Reactor Institute

OSAKA UNIVERSITY

CERN

QUICK GUIDE TO FFAGS

- Simplest Dynamical Definition:
  - FFAG is ~ a cyclotron with a gradient; beam confinement is via:
    - Strong alternating-gradient (AG) focusing, both planes: ***radial sector FFAG***
      - normal/reversed gradients alternate (like a synchrotron)
    - Gradient focusing in horizontal, edge focusing in vertical: ***spiral sector FFAG***
      - vertical envelope control is through edge focusing (like a cyclotron)
      - the normal gradient increases edge focusing with radius /momentum (unlike a cyclotron)
- Types of FFAGs:
  - Scaling:
    - B field follows a scaling law as a function of radius - r^k (k a constant;) present-day scaling FFAGs: Y. Mori, Kyoto University Research Reactor Institute
  - Nonscaling:
    - Linear (quadrupole) gradient; beam parameters generally vary with energy (EMMA FFAG, Daresbury Laboratory, first nonscaling FFAG)
    - Nonlinear-gradient; all parameters of the machine can be optimized

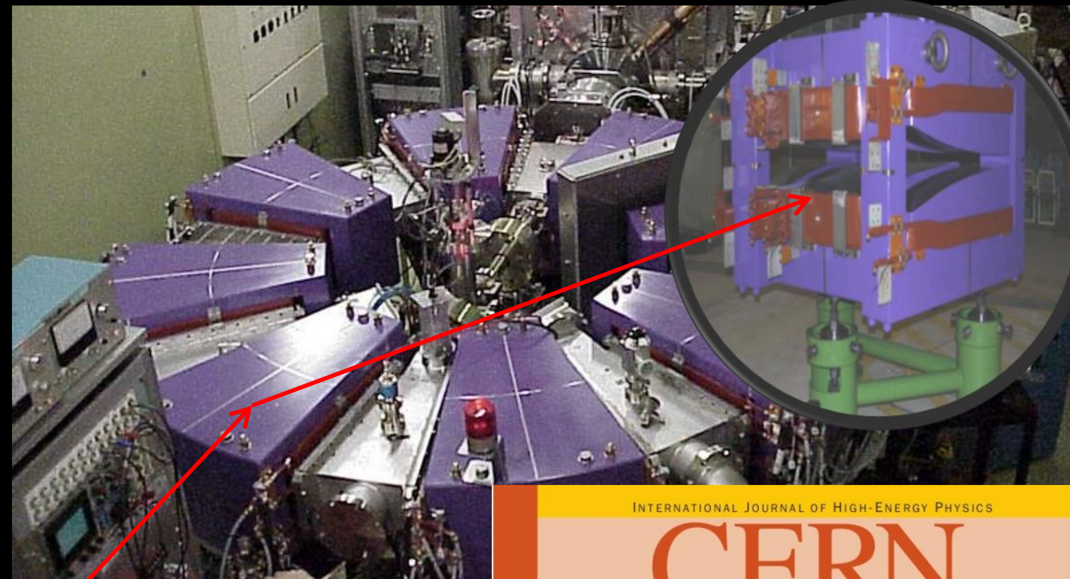
FFAGS AND THEIR VARIATIONS

Scaling FFAGs (spiral or radial-sector) are characterized by geometrically similar orbits of increasing radius, imposing a constant tune (field and derivative gradient scale identically with r). Magnetic field follows the law $B \propto r^k$, with r as the radius, and k as the constant field index.

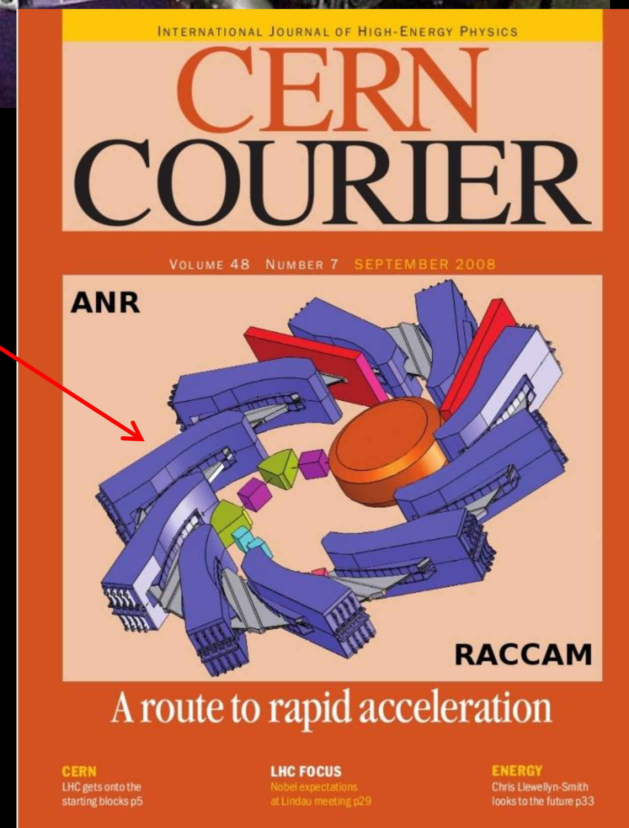
$$B = B_0\left(\frac{r}{r_0}\right)^k = B_0\left(1+\frac{k}{r_0}x+\frac{k(k-1)}{2!\,r_0^2}x^2+\cdots\right)$$

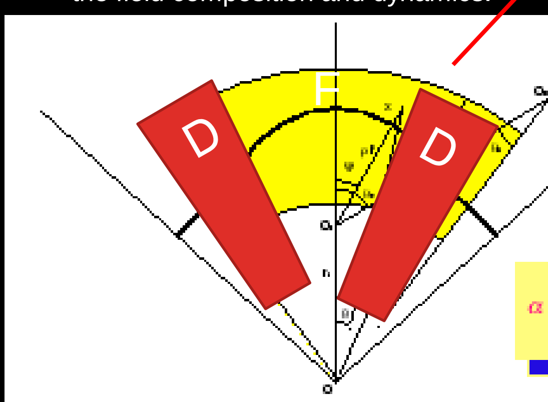
Field expansion: k determines multipole order;

Comments: the lower the k value, the more slowly field increases with r and the larger the horizontal aperture, but the more linear the field composition and dynamics.



Spiral Sector: example: more compact; positive bend field only. Vertical focusing controlled by edge crossing angle.



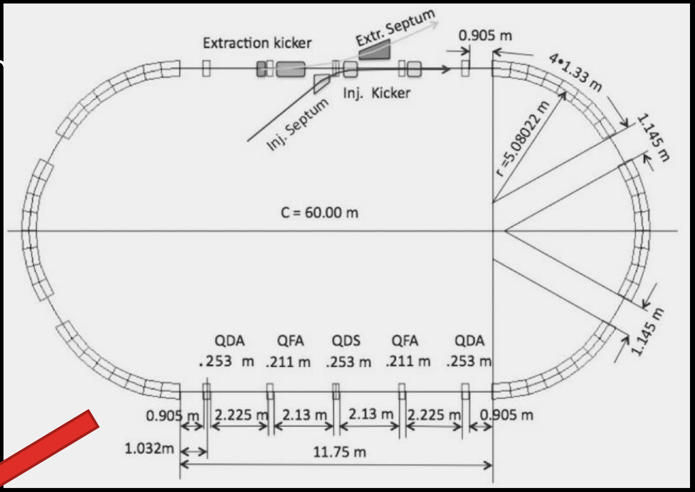


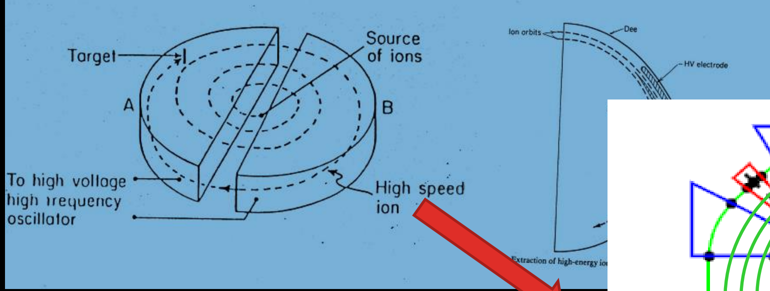
Radial Sector: example: This is a triplet DFD cell; there are also FDF, FODO and doublets. In a radial sector the D is the negative of the F field profile, but shorter.

$$\alpha = \frac{1}{k+1} \quad : \text{momentum compaction factor}$$

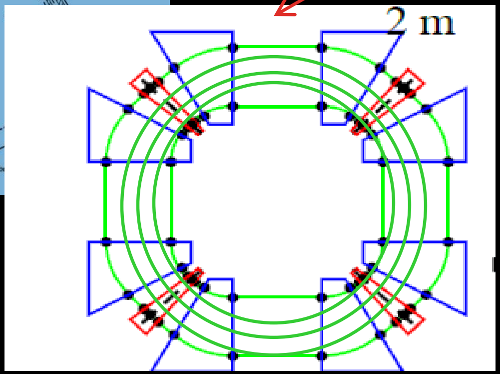
UNDERSTANDING A NS-FFAG

- Apply a "synchrotron" strong-focusing field profile to each "cyclotron" orbit; effectively eliminate reverse dipole bend
- Strong-focusing allows
  - Long injection/extraction or synchrotron-like straigh
  - Strong RF acceleration modules
  - Low –loss profile of the synchrotron
  - DC beam to high energies in compact structure
    - 400 MeV/nucleon: charge to mass of ½ (carbon)
    - 1.2 GeV protons
  - Avoidance of unstable beam regions
    - constant machine tune





straight

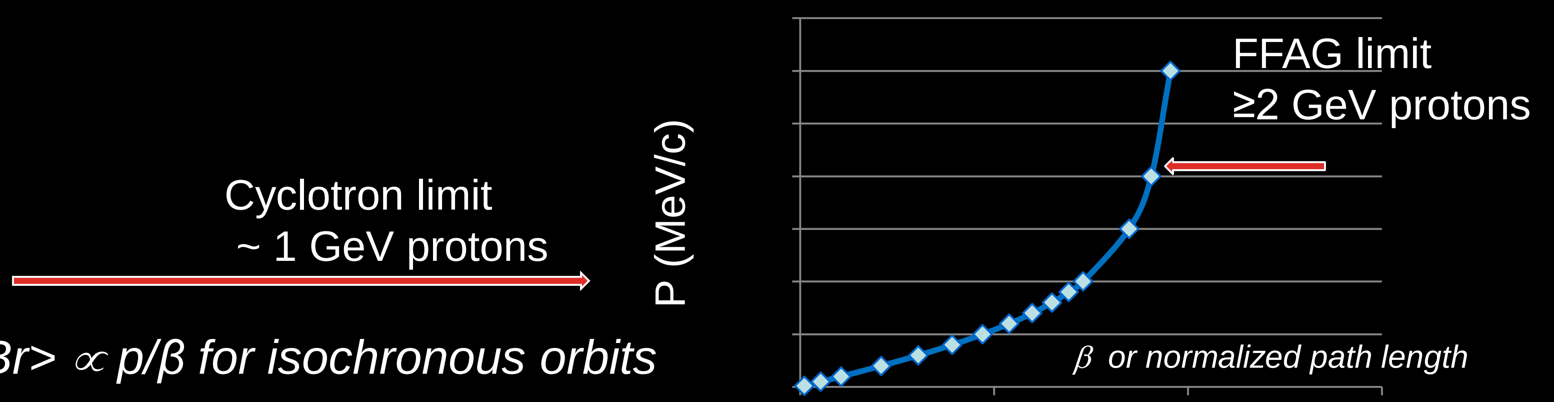


CONSTANT MACHINE TUNES AT NEAR AND FAR RELATIVISTIC ENERGIES

BEYOND CONVENTIONAL CYCLOTRON

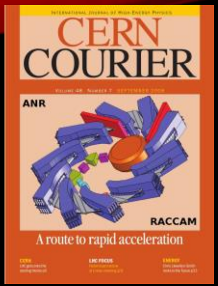
RELATIVISTIC CW (DC-BEAM) NS-FFAGS

- ✓NS FFAG can maintain isochronous orbits at relativistic energies
  - ✓Pathlength of isochronous orbits are proportional to velocity
  - ✓Orbits as a function of momentum follow, therefore the B field must scale with velocity
  - ✓At relativistic energies, momentum is an increasingly nonlinear function of velocity; therefore B field transitions from a linear slope to nonlinear, non-relativistic to relativistic as an approximate function of radius.
  - ✓THIS HAS BEEN ACHIEVED IN RECENT NONLINEAR NS FFAG DESIGNS
  - ✓Nonlinear field expansion + edge angle can constrain the tune
  - ✓Nonlinear gradient provides very strong focusing at high energy in **both** planes relative to the cyclotron



*
 $\propto$ p/β for isochronous orbits*

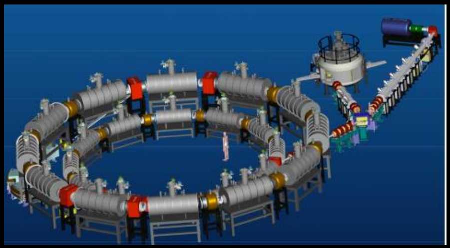
INTERNATIONAL DEVELOPMENT OF FFAGS



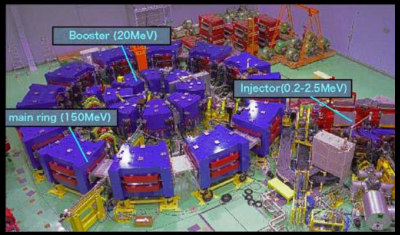
RACCAM: proton therapy
LPSC Grenoble, France

ERIT: neutron source
KURRI, Japan

PRISM: intense muon beam
Lepton flavor violation exp.
Osaka, Japan



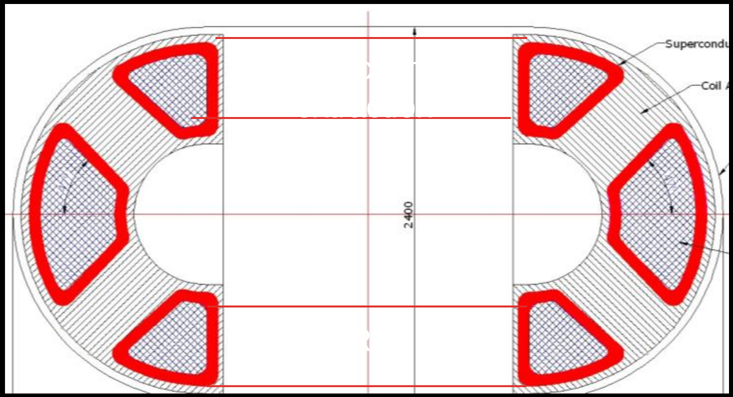
PAMELA: hadrontherapy design
Oxford, U.K.



KURRI: ADS test
Kyoto U. Research Reactor Institute, Japan

0.2 -1 GeV intense proton FFAG (ADS)
Compact Racetrack

~ 4 m



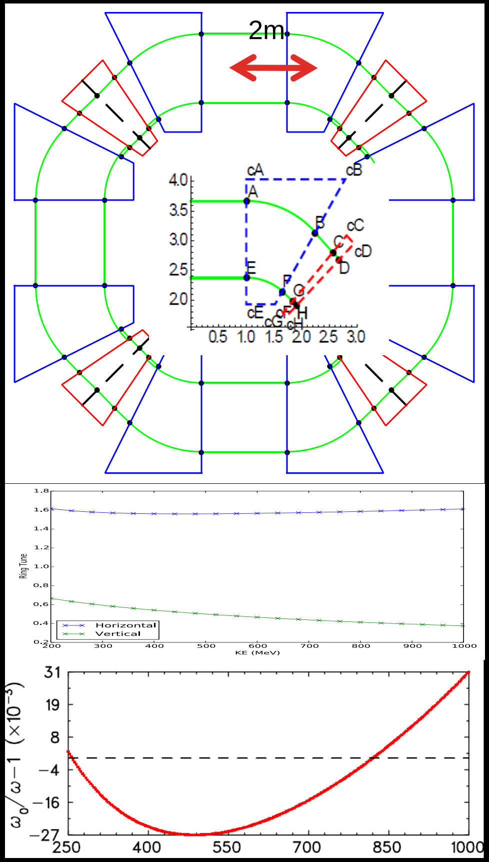
~6 m

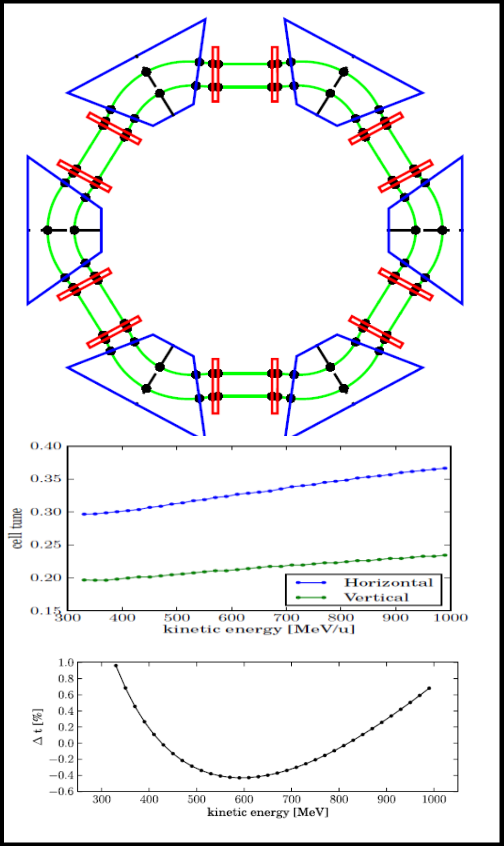
Compact CW ns-FFAG racetrack design capable of variable energy and various applications

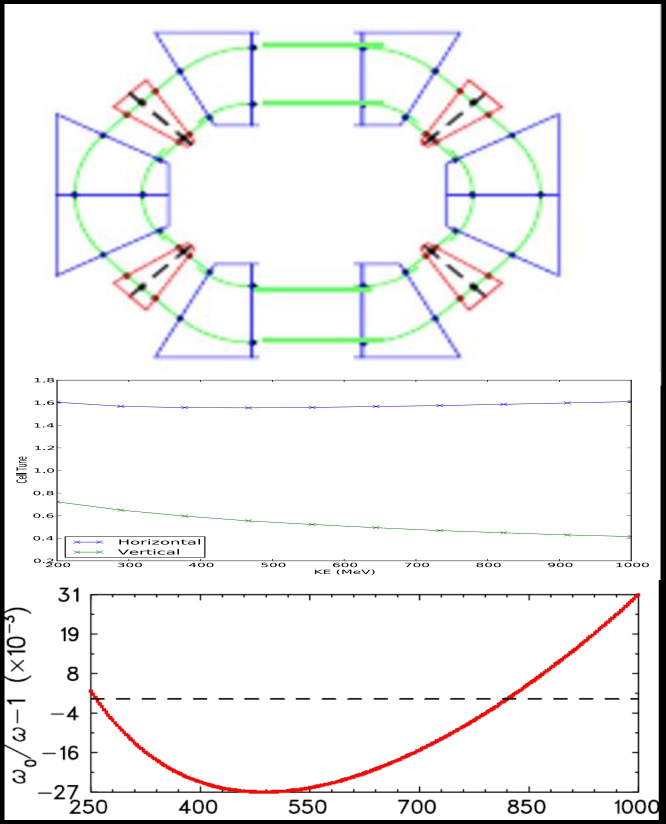
EMMA: POP muon acc demo
Daresbury Laboratory, U.K.

POP, 1st p FFAG, KEK, Japan

ADVANCED DESIGNS ISOCHRONOUS 1GEV NS-FFAG



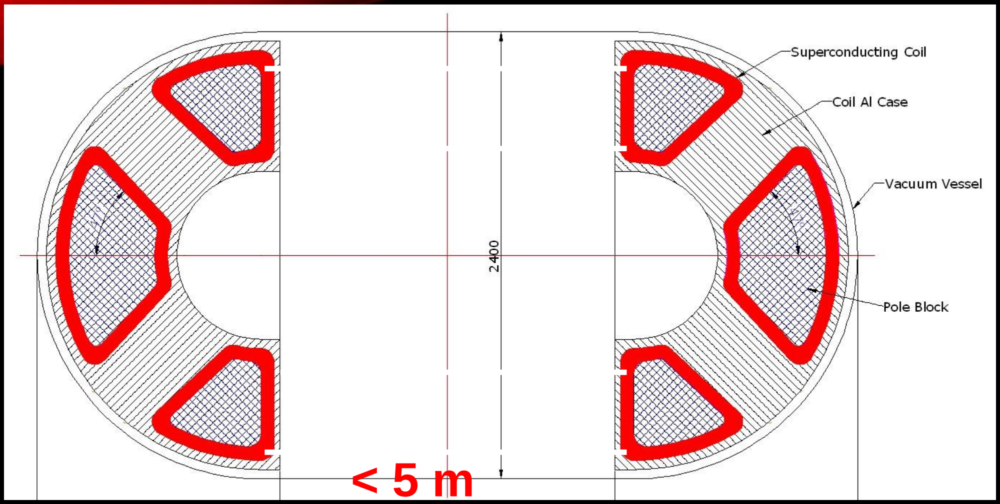




General Parameters of an initial 0. 250/0.330 – 1 GeV non-scaling, near-isochronous FFAG lattice design; peak fields are ~2-4T.

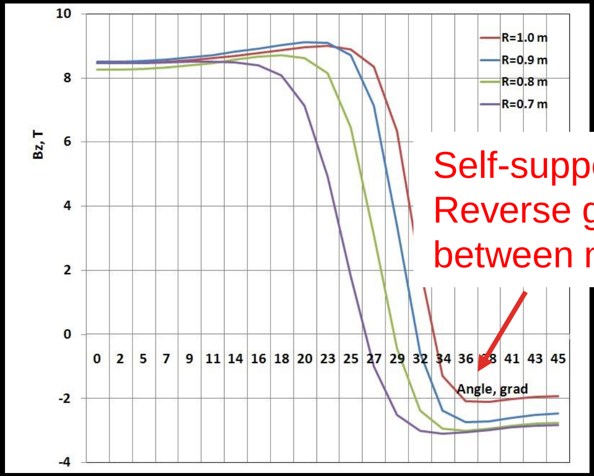
Three machines have been designed and studied
ENORMOUS DYNAMIC APERTURE
strong-focusing machine tunes

MAGNETS and modeling

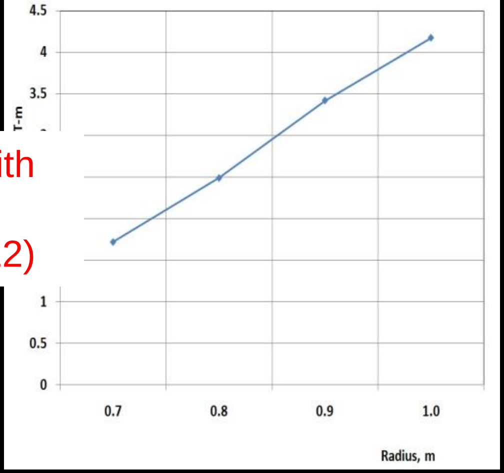


One straight section occupied by RF cavities and injection/extraction in the other

Parameter	Units	Value
Number of magnets		6
Number of SC coils		12
Peak magnetic field on coils	T	7-11
Magnet Beam Pipe gap	mm	50
Superconductor type		NbTi
Operating Temperature	K	4.0
Superconducting cable		Rutherford
Coil ampere-turns	MA	3.0
Magnet system height	M	~1
Total Weight	tons	~10



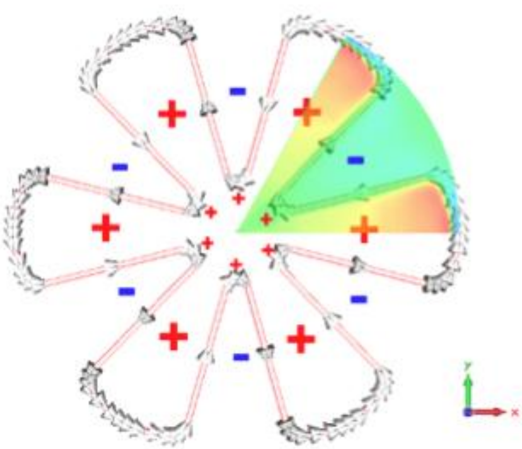
Self-supporting coils with Reverse gradient field between magnets (2012)

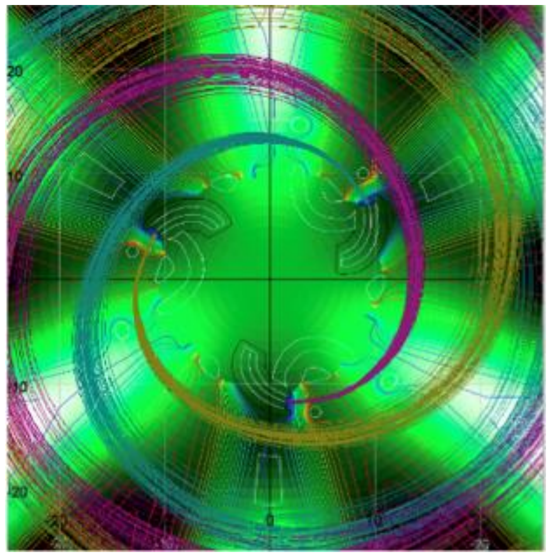


The magnetic field is relatively flat under the F-pole but the angular field length strongly depends on the radius providing the needed range from injection to extraction. The return flux provides the D or reverse gradient but needs careful optimization

The AIMA Reverse Valley B-Field Cyclotron®

Pierre Mandrillon @ ThEC13





A major advantage: The B-field configuration in the central Region allows acceleration at low energies

➔An injector cyclotron is not needed anymore !

Achieving isochronism while keeping vertical focusing at high energies is challenging: isochronism implies a large Positive radial gradient of the average B-field resulting in a strong vertical defocusing:

$$\Delta\nu_z^2 = -(\gamma^2-1) = -(d\langle B\rangle/dr)r/\langle B\rangle$$

which could be overcome by edge and spiral focusing (cf. PSI Ring Cyclotron)

$$\nu_z^2 = -(\gamma^2-1)+F^2(1+2\tan^2\zeta)$$

F^2 = Field Flutter = $(\langle B^2\rangle-\langle B\rangle^2)/\langle B\rangle$

Where ζ = spiral angle of the sector

A simpler Separate Sector Cyclotron:

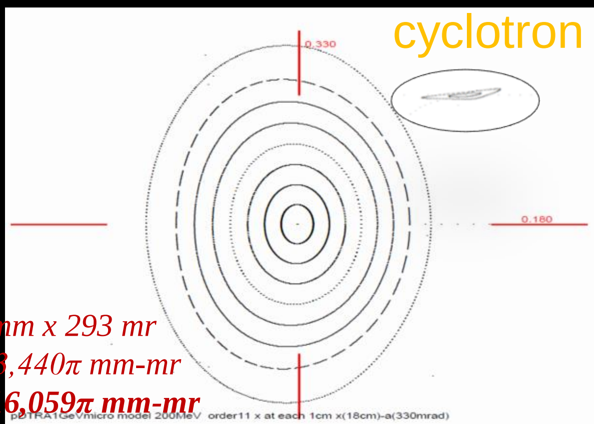
=> No spiral => Stronger Flutter

= Reverse valley B-field

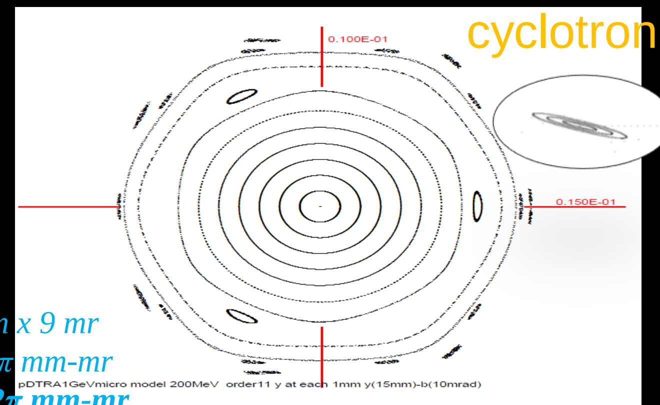
Proton extraction through stripping of H_2^+ is simple !

COMPARING DYNAMIC APERTURES

FFAG Stable beam area @200 MeV vs DA of ultracompact 250 MeV cyclotron



80 mm x 293 mr
$\varepsilon_H = 23{,}440\pi$ mm-mr
$\varepsilon_{norm} = \mathbf{16{,}059\pi}$ **mm-mr**

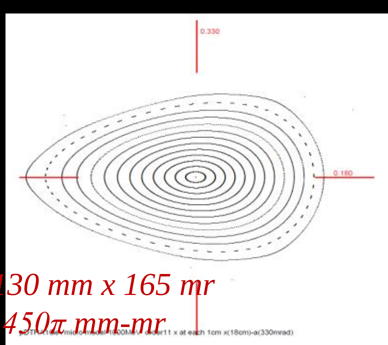


10 mm x 9 mr
$\varepsilon_V = 90\pi$ mm-mr
$\varepsilon_{norm} = \mathbf{62\pi}$ **mm-mr**

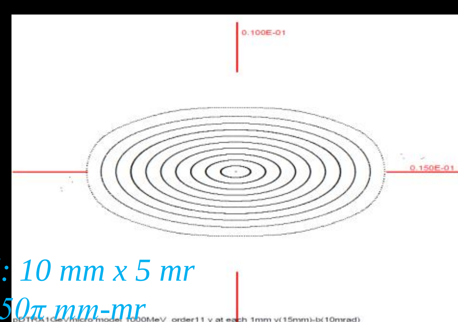
FFAG: Horizontal – 1 cm steps

FFAG: Vertical – 1 mm steps

FFAG Stable beam area @1000 MeV vs. DA of 800 MeV Daeδalus cyclotron*: factor of 4 larger for ~ a factor of 4 smaller footprint



Tracked: 130 mm x 165 mr
$\varepsilon = 21450\pi$ mm-mr
$\varepsilon_{norm} = 38820\pi$ mm-mr



Tracked: 10 mm x 5 mr
$\varepsilon = 50\pi$ mm-mr
$\varepsilon_{norm} = \mathbf{90\pi}$ **mm-mr**

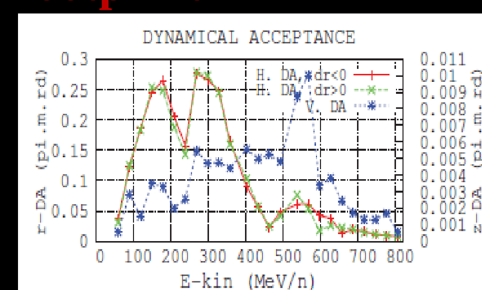
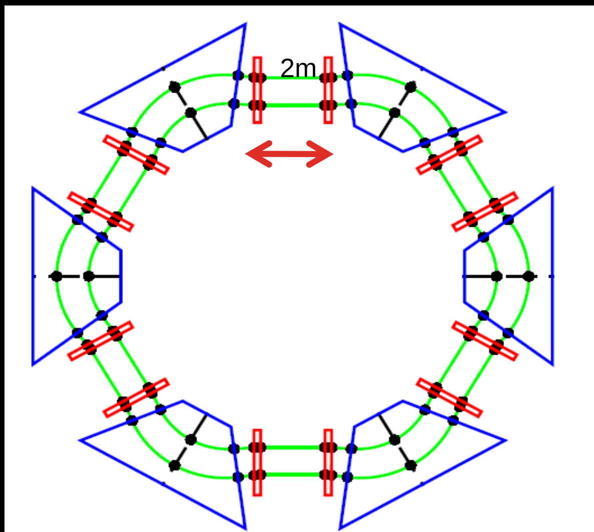


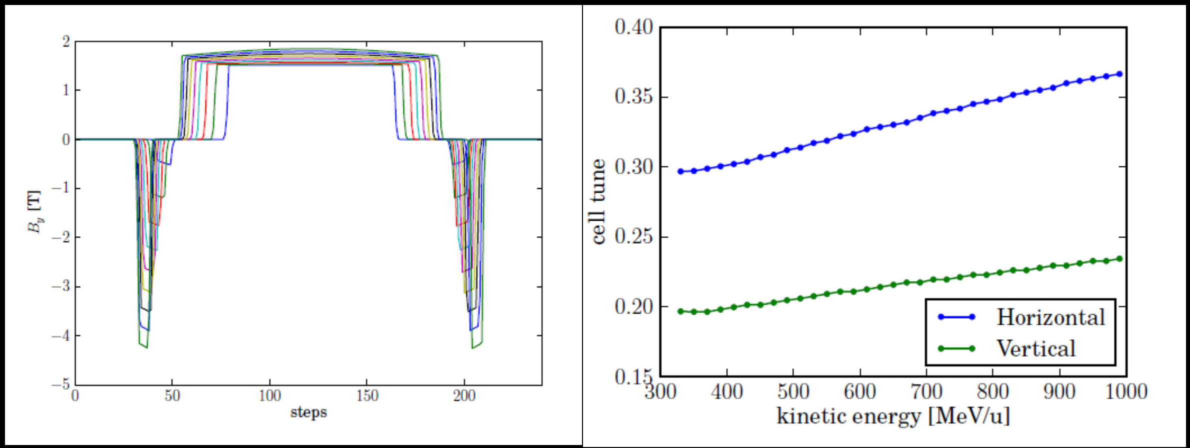
Figure 8: 500-turn DA (normalized) as a function of energy. Left axis : Horizontal DA, for either $dr < 0$, or $dr > 0$, wrt. closed orbit. Right axis : Vertical DA.

*FFAG vert. stable area at aperture limits.

*F. Meot, et. al., Proc. IPAC2012

DESIGN OF AN ISOCHRONOUS 0.3-1GEV DFD FFAG

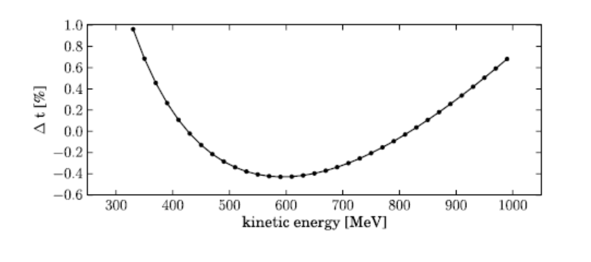




Vertical magnetic field from 0.33-1 GeV in 80 MeV steps and variation of cell tunes using OPAL in 20 MeV steps

General Parameters of an initial 0. 3 – 1 GeV isochronous FFAG lattice design (±0.5% TOF variation)

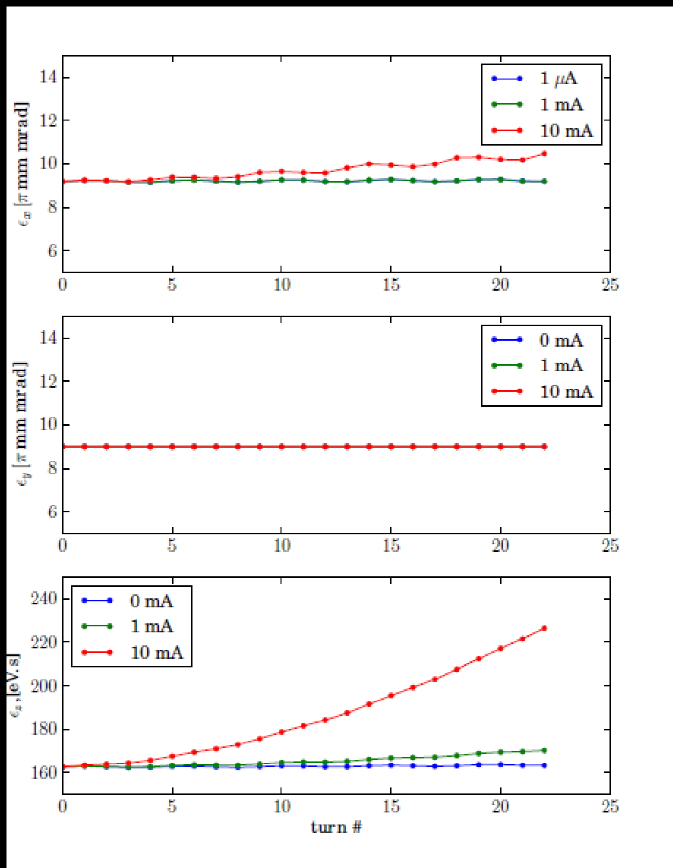
Parameter	330 MeV	500 MeV	1000 MeV
Avg. Radius [m]	5.498	6.087	7.086
ν_x/ν_y (cell)	0.297/0.196	0.313/0.206	0.367/0.235
Field F/D [T]	1.7/−0.1	1.8/−1.9	1.9/−3.8
Magnet Size F/D [m]	1.96/0.20	2.79/0.20	4.09/0.20

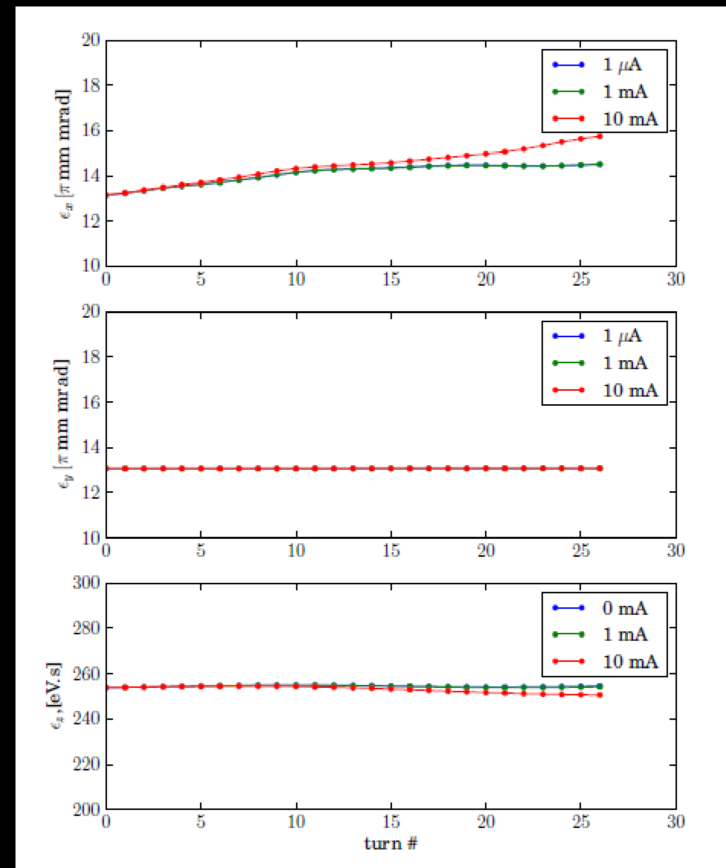


Variation cell tunes / OPAL in 20 MeV steps

Preliminary Design – a resonance is crossed at 617 MeV which needs to be addressed

SIMULATION WITH SPACE CHARGE
S. SHEEHY/A. ADELMANN

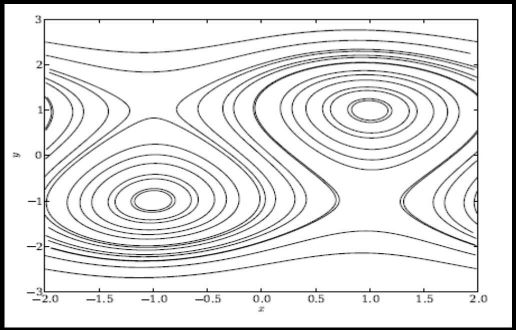




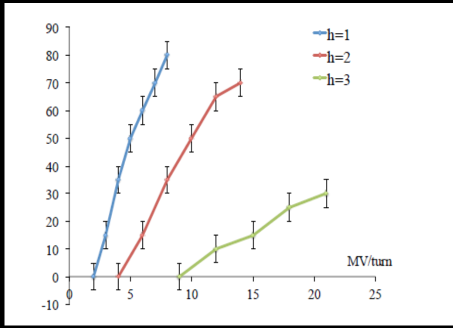
Emittance variation at 330 MeV (left) and 610 MeV (right) for fixed energy tracking (no acceleration) with space charge for 0 – 10 mA and a 100mm long single bunch

With no longitudinal focusing the bunch expands in length but space charge has little impact on transverse emittance due to strong focusing

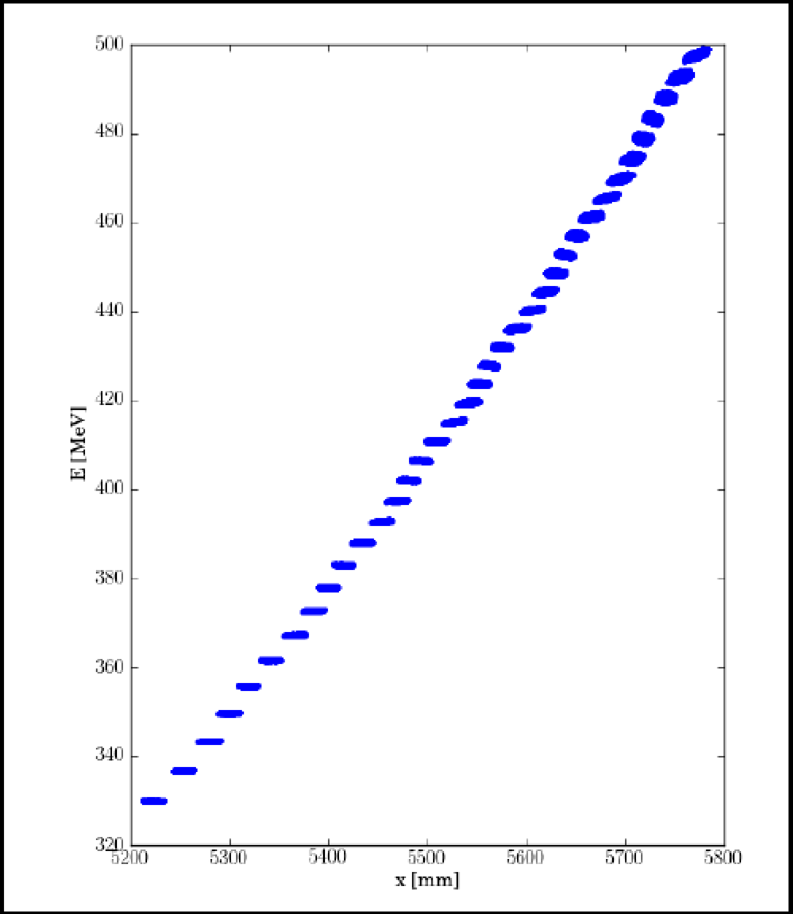
ACCELERATION WITH SPACE CHARGE S. SHEEHY/A. ADELMANN



Serpentine channel for = 4=3 contours plotted for regularly spaced values of x=y.

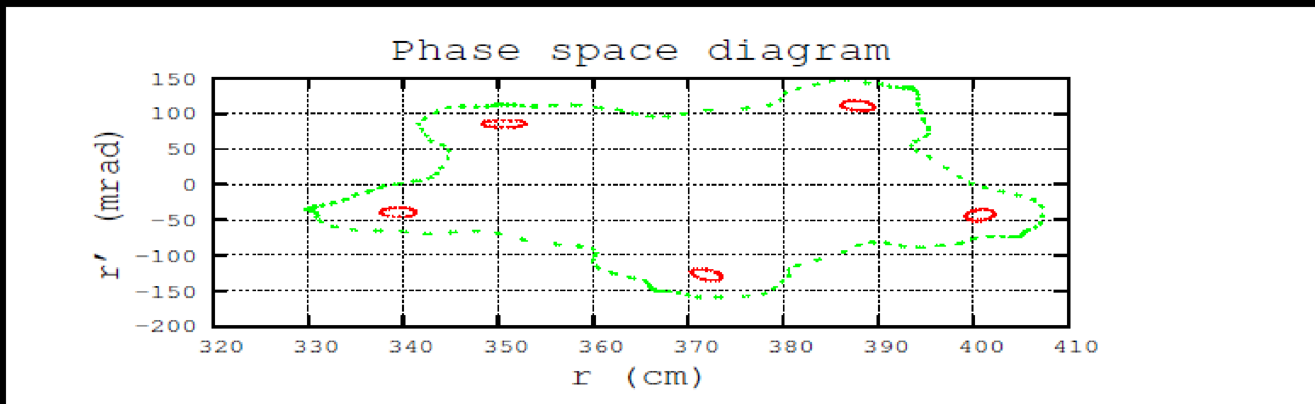


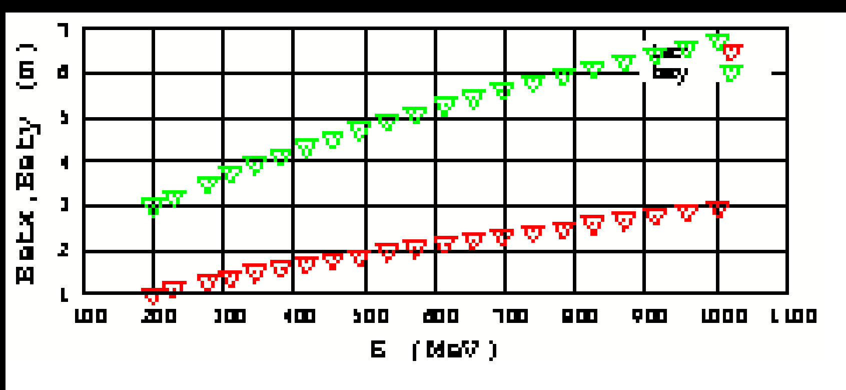
Maximum serpentine acceptance in degrees for varying voltage per turn and harmonic number.

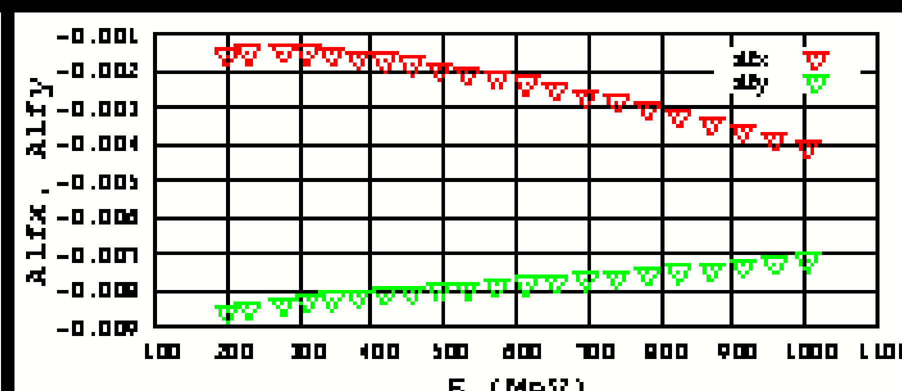


Turn-by-turn radial position vs energy for a low intensity beam in the serpentine channel accelerated to 500MeV.

ZGOUBI SIMULATIONS OF THE CIRCULAR FFAG HAJ-TAHAR MALEK







Periodic betatron functions vs energy at azimuthal angle =0. – analytical model

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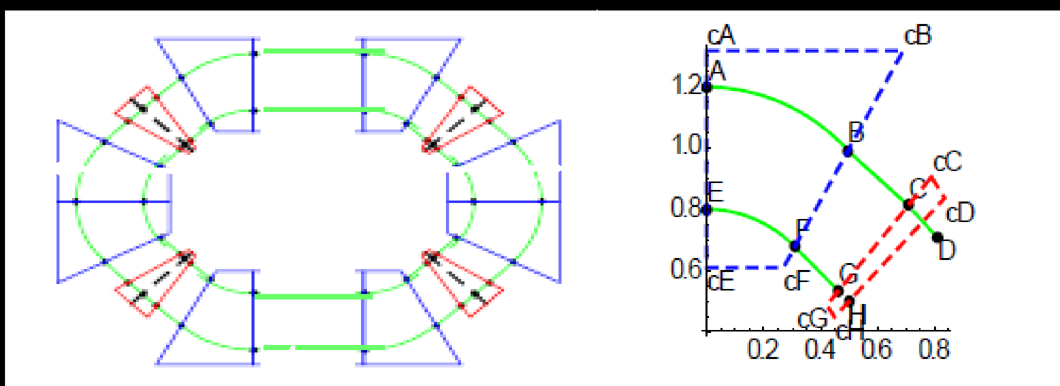
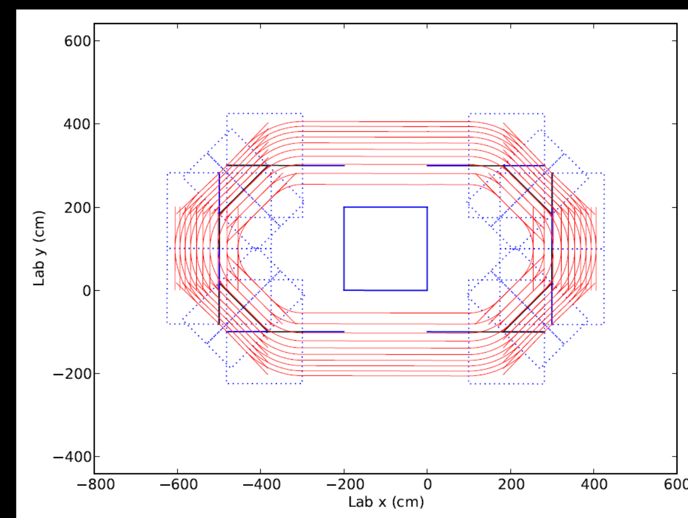
RACETRACK LAYOUT

- Start with the 2m straight, 3.7 m radius, ~2T fields
- Remove 2 m straights from sides and add to two opposing straights





Layout of racetrack FFAG for simulations and half arc layout

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PyZoubi tracks

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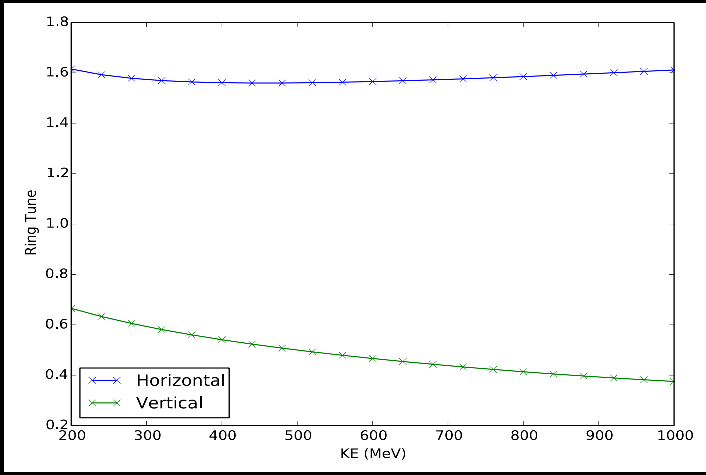
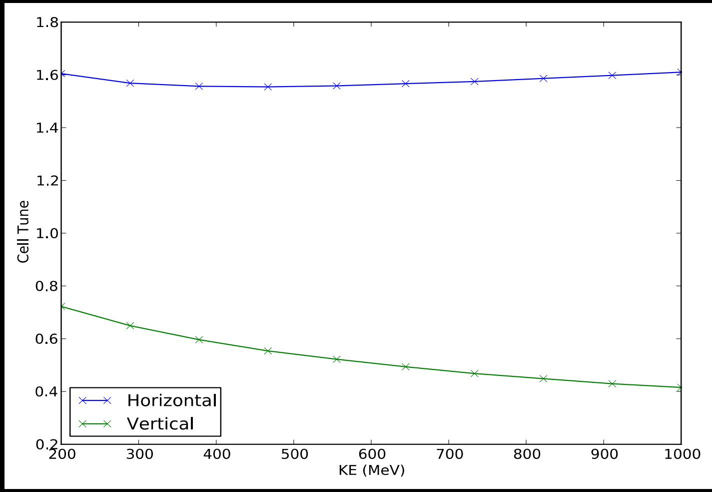
CIRCULAR VS RACETRACK SIMULATIONS USING PYZGOUBI/ R. APPLEBY





Machine tunes for the 2m ring (left) and the mini-racetrack FFAGs (right) as a function of beam energy.

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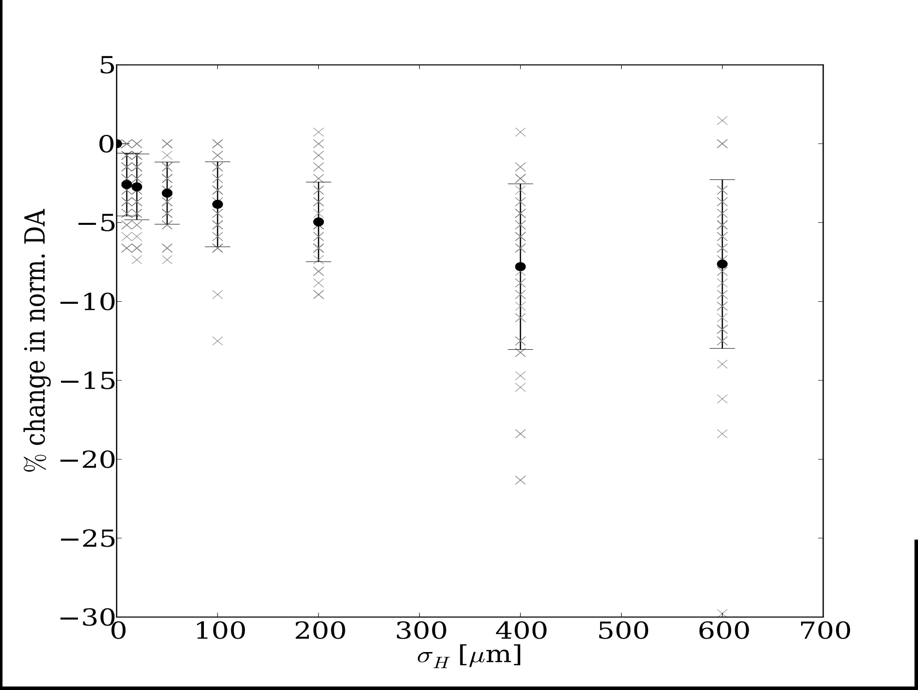
Dynamic aperture	Horizontal π.mm.mrad	Vertical π.mm.mrad
200 MeV 40 turns	74700	107
200 MeV 200 turns	72600	91
800 MeV 40 turns	156300	364
800 MeV 200 turns	155100	356

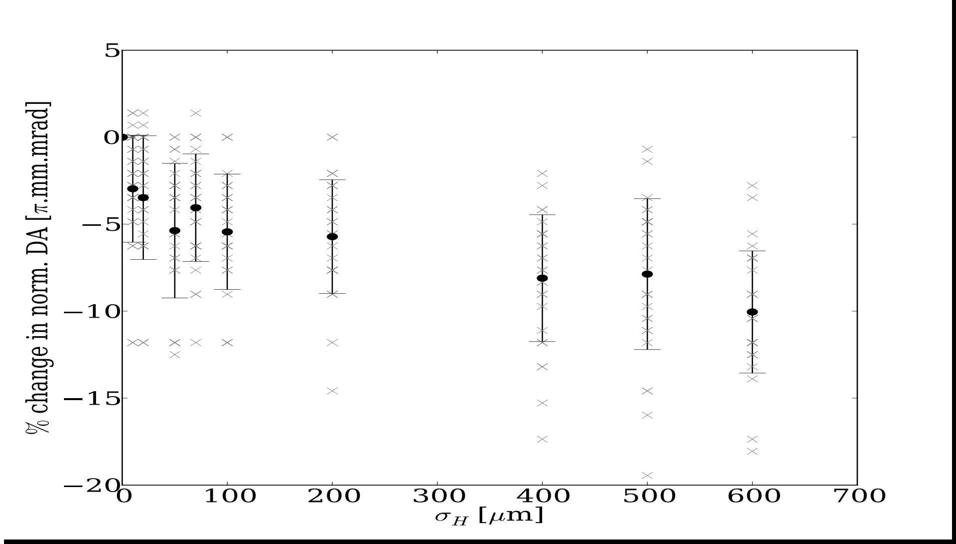
Dynamic aperture	Horizontal π.mm.mrad	Vertical π.mm.mrad
200 MeV 40 turns	25000	46
200 MeV 200 turns	23700	43
800 MeV 40 turns	63000	277
800 MeV 200 turns	63000	223

Very preliminary unnormalized DA for circular (left) and racetrack (right) computed with PyZoubi

ERROR ANALYSIS: CIRCULAR VS RACETRACK - R. APPLEBY

- Racetrack is showing similar stability to misalignments





The relative drop in dynamic aperture as a function of misalignment for the circular 2m straights FFAG (left and the 4m straights racetrack (right) computed with PyZgoubi.

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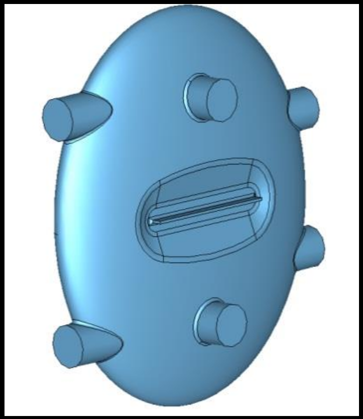
OBSERVATIONS

- DA of a FFAG ≥ cyclotron for medium energies (~100-200 MeV) and equivalent footprint
- DA aperture for these new constant-tune isochronous FFAGs are large – tens of thousands of π mm-mr (normalized)
- DA scales almost completely geometrically with size of the machine – ultracompact FFAGs show identical dynamical stability

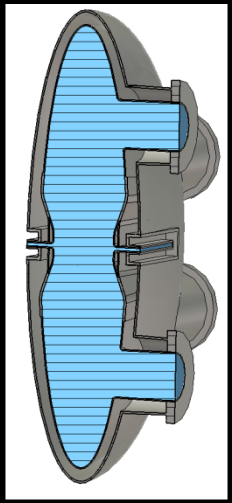
RF DESIGN SPECIFICATIONS

- Large horizontal beam aperture of 50 cm
- Cavity should operate at 150 or 200 MHz (harmonic of the revolution frequency)
- Should provide at least 5 MV for proton beam with energies 200 – 900 MeV
- Peak magnetic field should be no more than 160 mT (preferably, 120 mT or less)
- Peak electric field should be minimized
- Cavity dimensions should be minimized

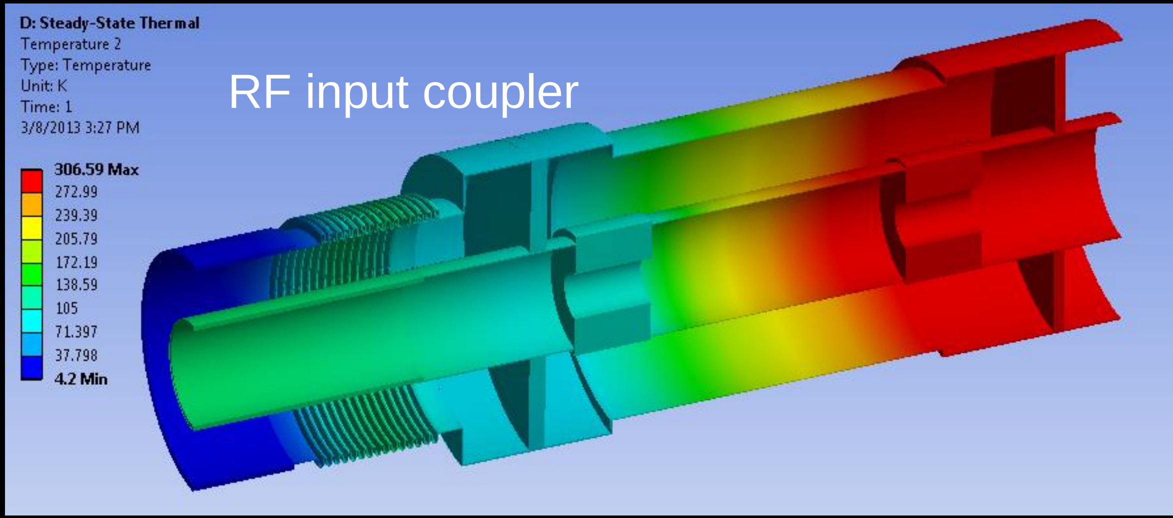
SCRF DESIGN: 10 MV/M; 50 CM X 5 CM (WXH)

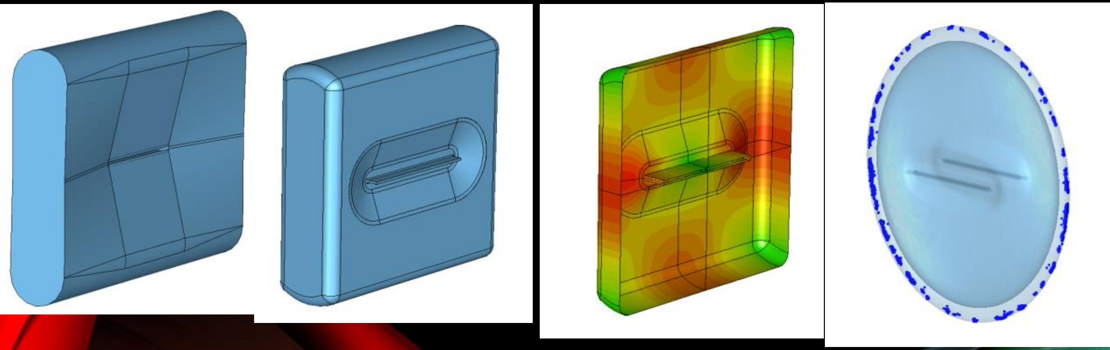


Mechanical design: port layout



Nb shell and He jacket

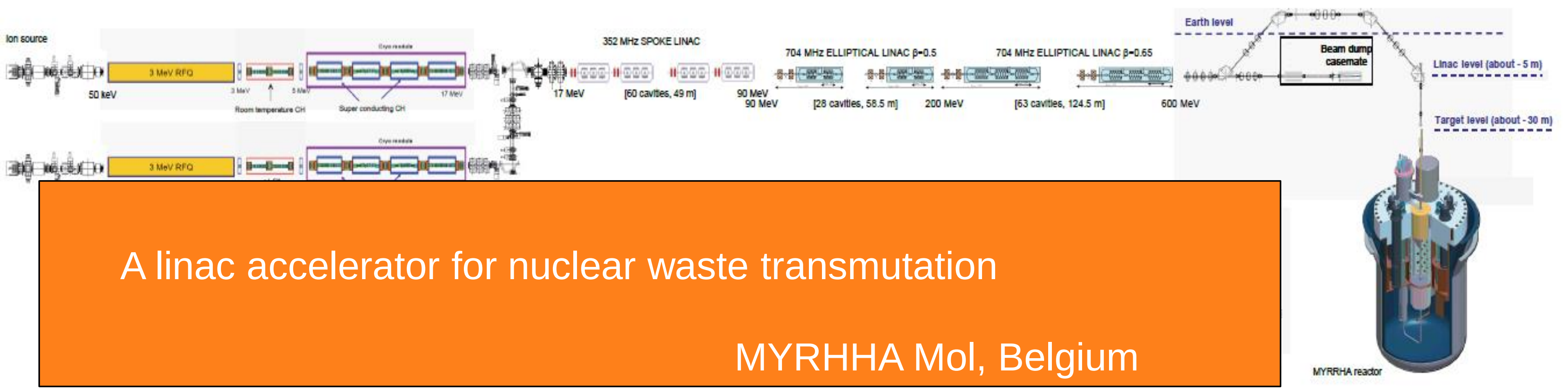




First and final optimized rectangular cavity shape (left, middle left) and surface magnetic field profile (middle right) and elliptical cavity (right).

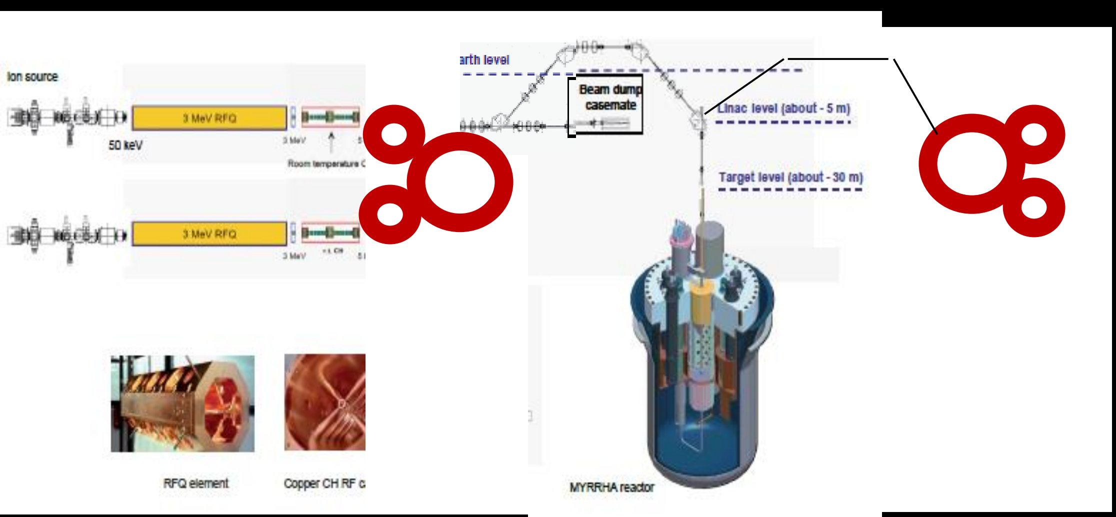
Parameter	Rectangular (Fig.1.3c) left	Rectangular (Fig.1.6) middle	Elliptical right
Frequency, MHz	200	200	200
Length, cm	100	100	120
Height, cm	104.5	92.9	142
Voltage (β=0.56, edge), MV	4.67	4.66	4.68
Voltage (β=0.78, center), MV	6.72	6.71	6.89
Voltage (β=0.86, edge), MV	5.00	5.00	5.00
R/Q (β=0.86, edge), Ohms	82.8	89.7	75.0
G, Ohms	147.9	150.2	134.2
Peak magnetic field, mT	92.1	72.7	77.2
Peak electric field,	55.2	47.0	48.1

THE FFAG ACCELERATOR FOR ADSR WASTE TRANSMUTATION



A linac accelerator for nuclear waste transmutation

MYRHHA Mol, Belgium



A FFAG high power accelerator facility

Length reduction of about 800', cost reduction of 100 in accelerator alone – more in civil

SUMMARY

- The nsFFAG has evolved to an isochronous, high energy, high current application supporting ≥20mA
- With constant strong-focusing machine tunes and optics that are independent of energy
  - Avoids resonance crossing – low acceleration losses
  - The DA aperture is 10,000 – 100,000π mm-mr depending on size and tunes
- 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
- Large aperture high-gradient cavities including SCRF have been designed; NCRF @1MV/m a PSI-like design
- Ironless, self-supported coil SC magnets are also being developed with a reverse field generated by return flux