CW AND VARIABLE ENERGY ION THERAPY FACILITY BASED ON A COMPACT RACETRACK FFAG

Dr. C. Johnstone, Fermilab
R. Barlow, D. Bruton, R. Edgecock, J. Taylor, D. U of Huddersfield
R. Appleby, U of Manchester

Ion Beam Therapy: Clinical, Technical and Scientific Challenges Workshop
Postgraduate Centre
Queen Elizabeth University Hospital
Birmingham, West Midlands, UK
1/18/2016

Outline

- Review of specifications for a US National Center for Particle Beam Research
- FFAG : A Conventional Accelerator
  - FFAG properties: scaling vs nonscaling
- International Effort
- Variable Energy Dual-Stage FFAG Ion Accelerator
- A FFAG-based accelerator ion facility

National Center for Particle Beam Radiation Therapy

Multi-ion capability	**p, He, Li, B, C** **O and Ne also desirable** **Fast switching between ion species (1 sec)**
Energy range	60 MeV/nucleon to 430 MeV/nucleon Depths up to 30 cm for carbon ions
Field size	At least 20 x 20 cm^2 optimally up to 40 x 40 cm^2
Real-time imaging (radiography & CT: **For tumor position verification and motion management**	For patient sizes up to 60 cm in depth.
Dose delivery rates hypofractionated regime: **Hypofractionation treatments in under one minute (ideally in one breath hold)**	20 Gy/min/ liter 7 Gy/8 sec/ liter (corresponding to 4×10^{12} p/sec for cubic liter)
Pencil beam scanning: **Fast treatment for a large variety of tumor sizes and shapes. Two extremes are considered: 30 cm x 30 cm tumor single layer in depth and a cubic volume**	Transverse scanning rate of 1-10 cm/msec Energy step time of 10-100 msec (These are present state-of-the-art)
Transverse beam size: **selectable, with stable, Gaussian profiles.**	3 mm to 10 mm FWHM
Energy step size	Protons: 2 MeV (~0.25 cm in range) Carbon: 2 MeV/nucleon (~0.1 cm in range)
Lateral targeting accuracy at the Bragg peak	Protons: ±0.5 mm Carbon: ±0.2 mm
Dose accuracy/fraction	2.5% monitored at ≥40 kHz during dose deposition

Translating into Accelerator Performance

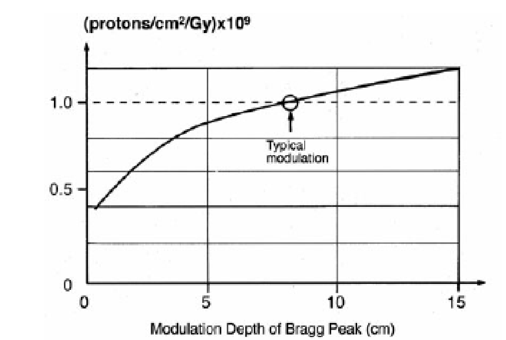


Fig. 4b: Proton fluence/Gray versus width of SOBP for 155 MeV maximum energy[4]. The proton fluence per Gray for 250 MeV maximum energy is about 30% higher than this curve and about 30% less for SOBPs with 100 MeV maximum energy.

G. Coutrakon, et. al., Proceedings 1999 PAC

Dose Delivery Rate	30 x 30 cm^2 field single layer/energy sweep step size 5 mm	10 x 10 x 10 cm^3 field 40 layers/energy steps sweep step size 5 mm
Normal Fraction: 1-2 Gy/fraction		
1 Gy/min	1/60 x 10^{12} p/sec	4/60 x 10^{12} p/sec
1 Gy/sec	1 x 10^{12} p/sec	4 x 10^{12} p/sec* (requires transverse scanning rate of 13 cm/sec and energy modulation time of 10 ms)
Hypofraction Regime:		
5-8 Gy/fraction	(5-8)/60 x 10^{12} p/sec	(5-8)/60 x 10^{12} p/sec
5-8 Gy/min	5-8 x 10^{12} p/sec	2-3 x 10^{13} p/sec*
5-8 Gy/sec	1 x 10^{12} p/sec	4 x 10^{12} p/sec*
5-8 Gy/breathhold		*requires transverse scanning rate of 13 cm/msec and energy modulation time of 10 ms
Radiobiology: up to 20 Gy/fraction		
20 Gy/min	(2)/60 x 10^{13} p/sec	8/60 x 10^{13} p/sec
20 Gy/sec	2 x 10^{13} p/sec	8 x 10^{13} p/sec*
20 Gy/breathhold	2-4 x 10^{12} p/sec	1-2 x 10^{13} p/sec* *requires transverse scanning rate of 13 cm/msec and energy modulation time of 10 ms

All FFAGS are not created equal
neither are cyclotrons and synchrotrons

Traditional – Scaling FFAGS

(MURA – electrons, 1950s and Japan – protons, present)

Magnet field follows scaling law with radius: $B \propto r^k$ k is constant (*field index*)

- **Properties:**
  - Pulsed beam, CW (continuous beam) not possible (~0.1 – 1kHz = synchrocyclotron)
  - Fixed energy - Variable energy not feasible with ions*
  - Not compact (unless scaling field gradient is very high)
    - High k values almost always present beam dynamics issues
- **Acceleration:** broad band low-gradient cavities (finemet; 0.5 – 15MHz)
  - Low low gradients compared to fixed frequency acceleration systems, more beam loss
- **Types**
  - ***Radial Sector***
    - similar to a separated sector cyclotron
    - Larger due to reverse gradients for vertical beam control
  - ***Spiral Sector –***
    - similar to a separated AVF (spiral) cyclotron
    - For higher energies can be more compact

⇨ **Recommendation: synchro-cyclotron if a degrader is implied**

*there are long-straight racetrack scaling designs which might support variable energy but these increase the size of machine considerably due to complex matching conditions and acceptance of machine is normally compromised.

FFAGs and their Variations

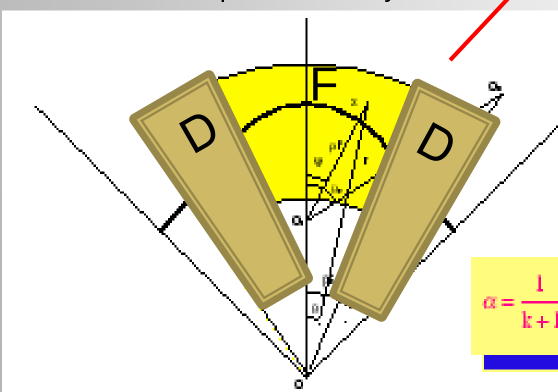
<u>Scaling FFAGs</u> (spiral or radial-sector) are characterized by geometrically similar orbits of increasing radius, imposing a constant tune (field and derivative gradient scale identically with r). Magnetic field follows the law B ∝ r^k, with *r* as the radius, and k as the constant field index.

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

Field expansion: k determines multipole order;

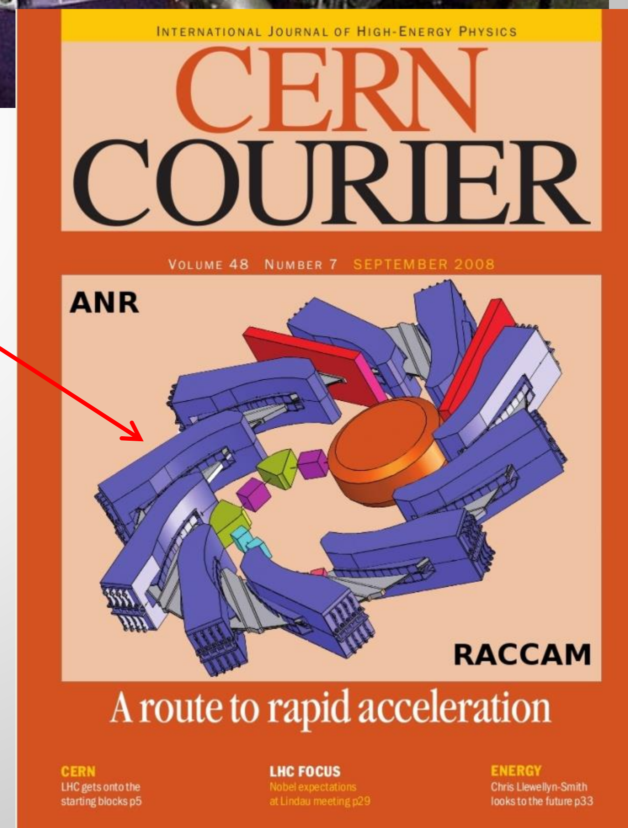
Comments: the lower the k value, the more slowly field increases with *r* and the larger the horizontal aperture, but the more linear the field composition and dynamics.

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



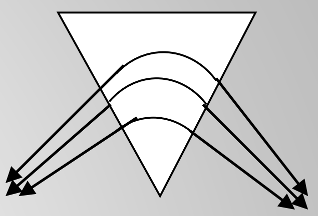
Radial Sector: example: This is a triplet DFD cell; there are also FDF, FODO and doublets. In a radial sector the D is the negative of the F field profile, but shorter.

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

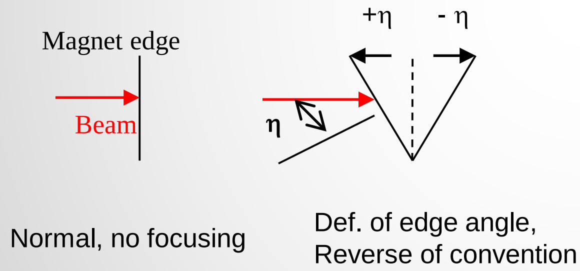


Principles of Beam Transverse Focusing: a short review

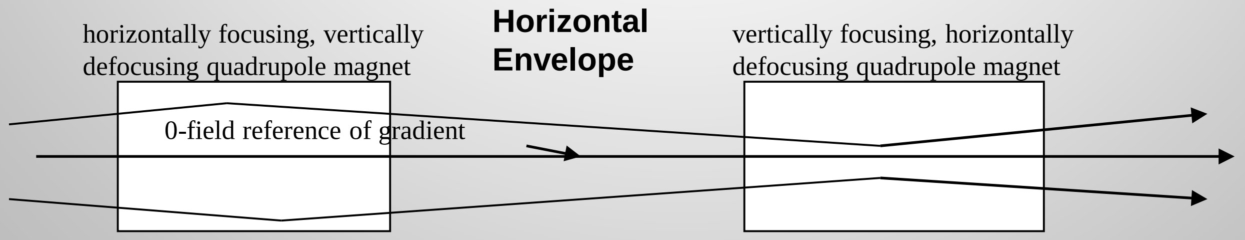
1. Centripetal focusing *(used in Cyclotrons + FFAGs)* :
   - Pathlength variation in dipole body field, bend plane only
   - Horizontally focusing or <u>defocusing</u> for FFAGs with reverse bends (radial sector).



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 innovative about a nonscaling FFAG?

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

synchrotron cyclotron

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

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.

  - For the vertical only the quadrupole gradient, $k_D l$, and the edge term are available
- The different focusing terms can be varied independently to optimize machine parameters such as footprint, aperture, and tune in a *nonscaling FFAG*

Next Generation FFAGs

New – nonscaling FFAGs (many, many variations)

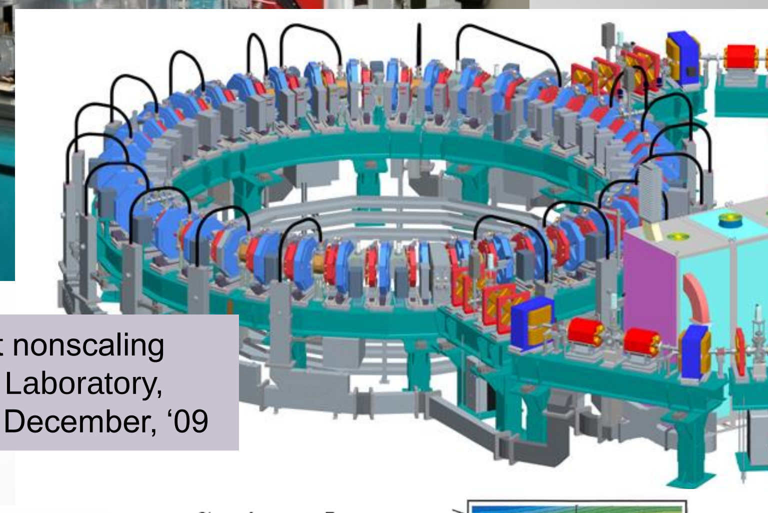
Throw out the magnetic field scaling law

Optimize to application

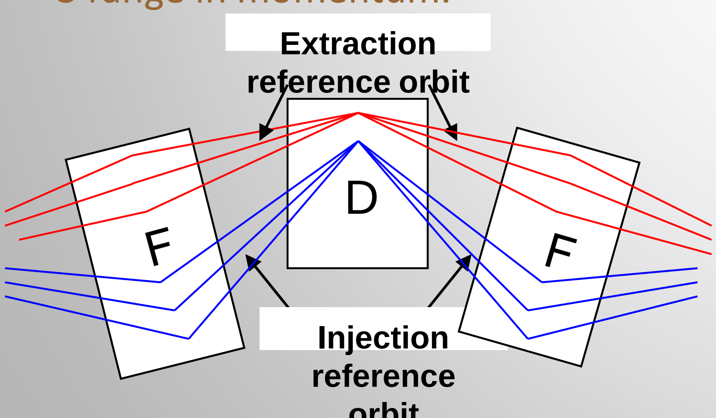
- **Properties:**
  - *CW beam like cyclotrons!* >500 MeV/nucleon ions – IMAGING WITH IONS!
  - *Variable energy* (new racetrack designs)
  - *Ultra-compact* (430 MeV/nucleon ions, 4 x 6m)
    - Robust low-loss beam dynamics – better than cyclotrons at ion energies
- **Acceleration:** Simple high-gradient, fixed frequency RF modules
- **Evolution:**
  - 1^{st} generation:
    - EMMA – designed to demonstrate rapid acceleration of unstable particles (muons)
      - Not suitable for most applications and not compact
      - Critical demonstration of new acceleration channel
    - PAMELA – close to a scaling design
      - Not compact, pulsed, variable energy difficult
  - Next generation nonscaling FFAGs
    - Developed for security applications
    - Continuous CW beam
    - Multisource injection
    - Variable energy rapid extraction (with racetrack versions)
    - Design is advanced, engineering and prototyping underway

Linear nonscaling FFAGs for rapid acceleration

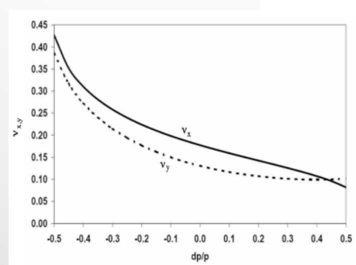
Linear-field, nonscaling FFAGs. Ultra-compact magnet aperture, proposed and developed for High Energy Physics (Neutrino Factories and Muon Colliders), relaxes optical parameters and aims only for stable acceleration. In general they are not suitable for an accelerator with a modest acceleration system and accelerate only over a factor of 2-3 range in momentum.

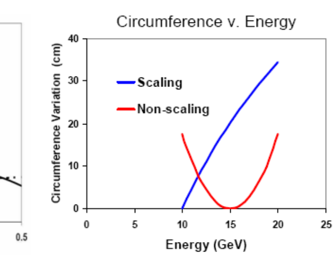


EMMA – world's first nonscaling FFAG, @Daresbury Laboratory, commissioning, late December, '09

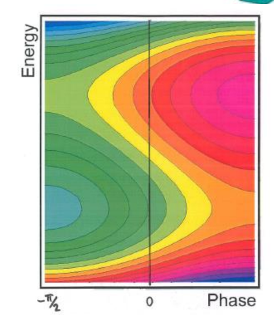


Cartoon of orbit compaction: nonsimilar orbits, nonconstant tune, resonance crossing





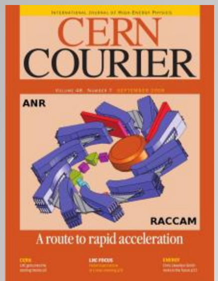
$$C(p) = C(p_m) + \frac{12\pi^2}{e^2 q^2 N L_{FD}} (p - p_m)^2$$



Characteristics– tune sweep/unit cell, parabolic pathlength on momentum (small radial apertures); serpentine (rapid) acceleration – beam "phase-slips", crossing the peak 3 times, accelerating between rf buckets

The international FFAG collaboration

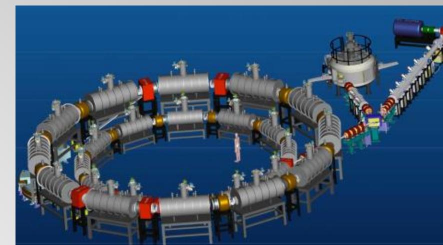
INTERNATIONAL DEVELOPMENT OF FFAGS



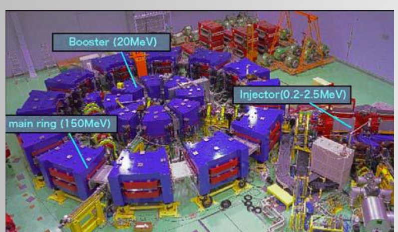
RACCAM: proton therapy
LPSC Grenoble, France

ERIT: neutron source
KURRI, Japan

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

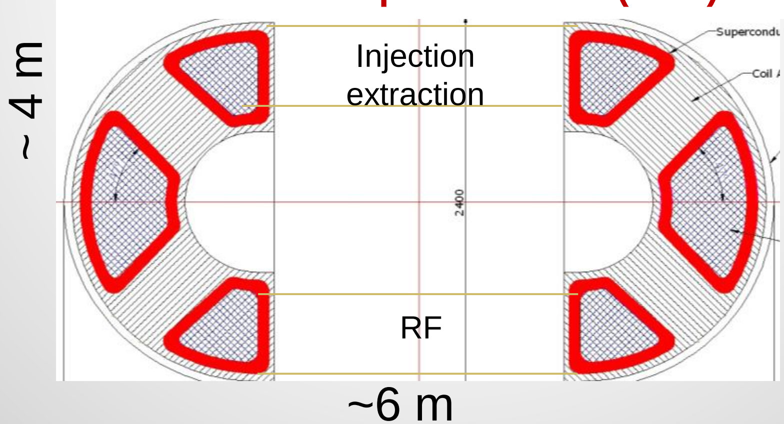


PAMELA: hadrontherapy design
Oxford, U.K.

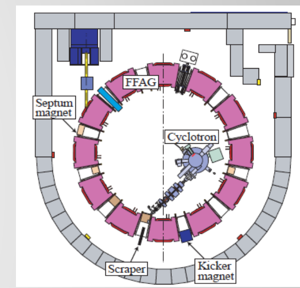


KURRI: ADS test
Kyoto U. Research Reactor
Institute, Japan

70 - 430 MeV/nucleon Ion FFAG
330 MeV pCT
1 GeV intense proton FFAG (ADS)



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



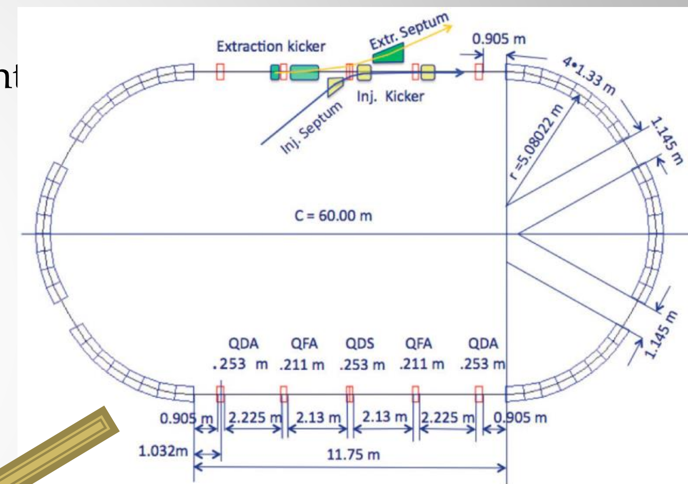
150 MeV proton, 100 Hz- kHz FFAG
KEK Japan

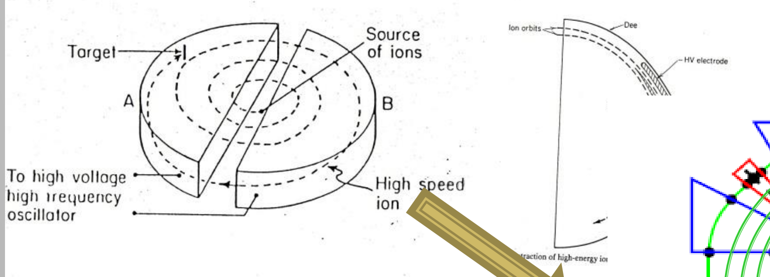
EMMA: POP muon acc demo
Daresbury Laboratory, U.K.

POP, 1st p FFAG, KEK, Japan

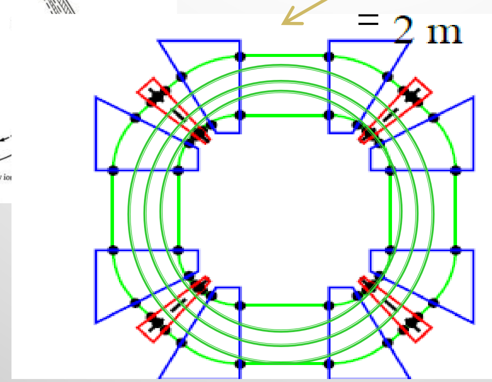
Understanding a ns-FFAG

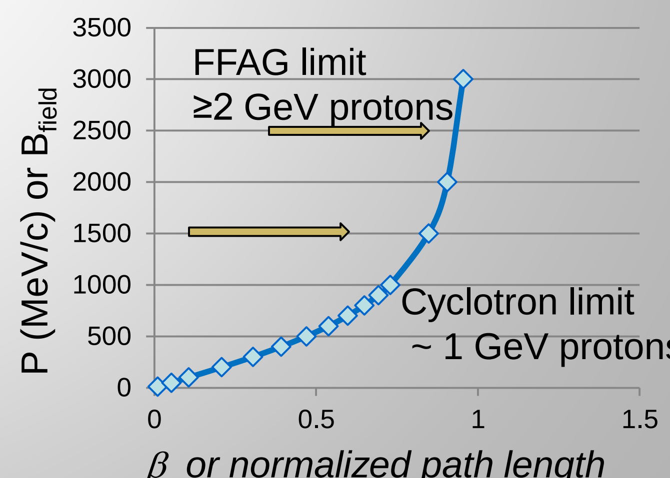
- Apply a "synchrotron" strong-focusing field profile to each "cyclotron" orbit
- Strong-focusing allows
  - Long injection/extraction or synchrotron-like straight
  - Strong RF acceleration modules
  - Low –loss profile of the synchrotron
  - DC beam to high energies in compact structure
    - 400 MeV/nucleon: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





straight = 2 m

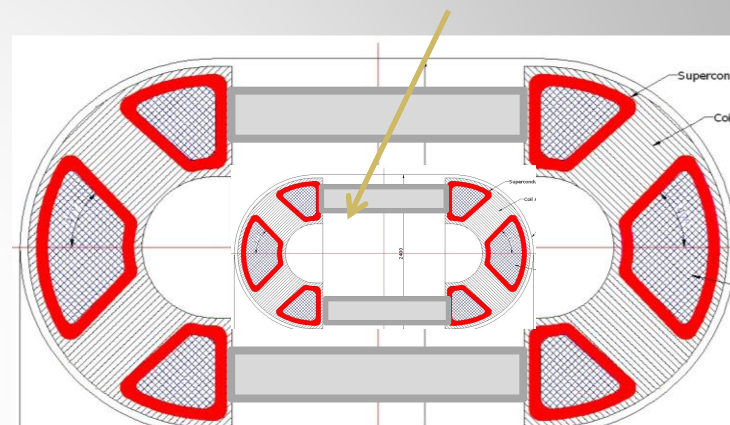




Dual-stage ion FFAG
proton FFAG with proton CT (pCT)

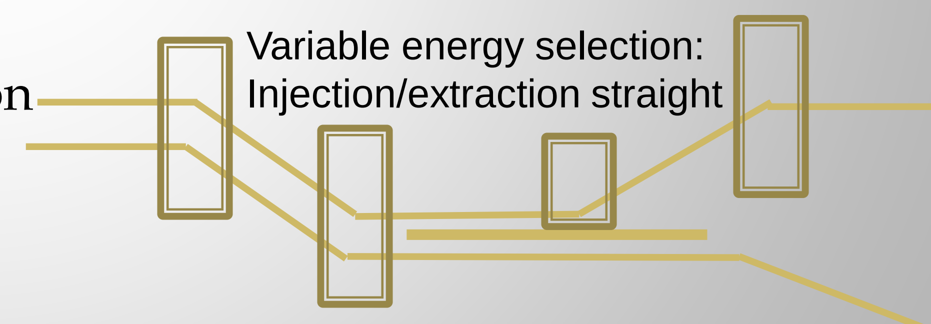
- 1st stage
  - 9-~70-90 MeV charge to mass ratio of ½
    - Fixed-frequency RF, DC beam for all ions
    - Variable energy extraction
    - Multiple ion injection/acceleration
    - Upstream injector for high-energy ring
      - Eye line, melanomas

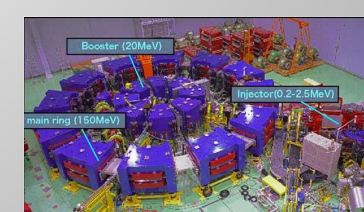
1st stage: Cyclotron or FFAG



- 2nd stage (~4 m x 5-6 m long)
  - 70/90 MeV – 430 MeV/nucleon
  - Variable energy extraction
  - Fast orbit bump magnets/extraction septum in long straight
    - CW treatment beam
    - Variable energy on scale of tens of milliseconds (~MeV steps)
    - Investigating extracted energy range

2nd stage: 70/90 – 430 MeV/nucleon ions





Accelerator is only ~10% or less the cost of the facility

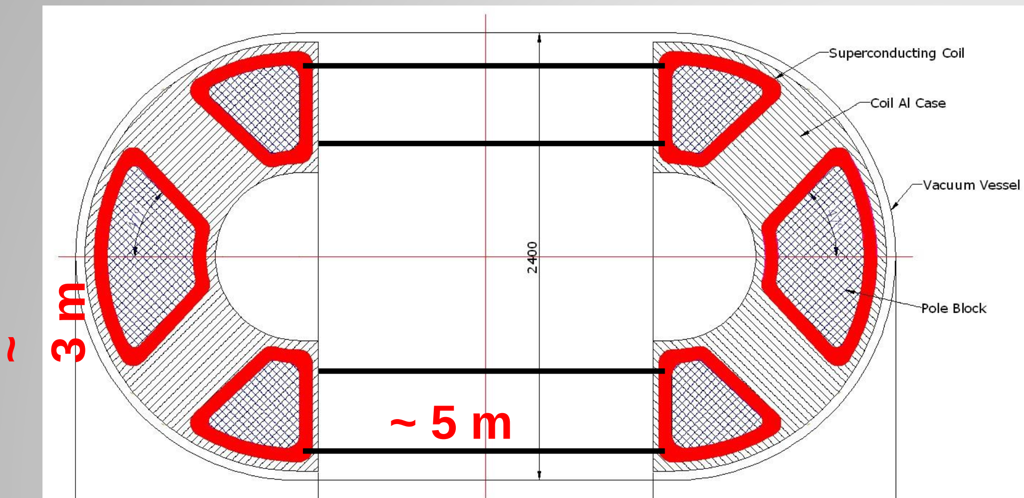
Comparison of Current Accelerator Technologies

- All ion accelerators can accommodate up to 430 MeV/nucleon carbon; fixed field use charge to mass of 1/2

Accelerator Type	Size	Dose Rate Per liter	Energy Modulation		Beam Delivery		Scan Trans/ Long
			Var/ Fixed	Acc	NC	SC	
SC Synchrotron HIMAC	40 m (diam)	5 Gy/min 0.2 Gy/sec	V	1 ms -2 sec	10 ms	100 ms	T + L in cycle
RC Synchrotron	20 m (diam)	x Cycle factor* 1.3-20 Gy/min	V	1 – 66 ms	10 ms	100 ms	L in cycle T cyc to cyc
Compact Proton Synchrotron	5 m (diam)	0.075 Gy/min 0.0025 Gy/sec	V	1 ms -2 sec	10 ms	100 ms	T + L in cycle
Hitachi	8 m	0.75 Gy/min 0.025 Gy/sec	V				
Linac/Cyclinac	40 -80m	Any rate	V	1 ms	10 ms	100 ms	Any
Cyclotron	6.3 m (diam)	5 Gy/min 0.08 Gy/sec	F	1 ms	10 ms	100 ms	T then L
FFAG (SC)	4m x 6m racetrack	Any rate	V	50 μsec	10 ms	100 ms	Any

* In principle RCS = cycle time factor x circumference factor x SC Synchrotron dose rate

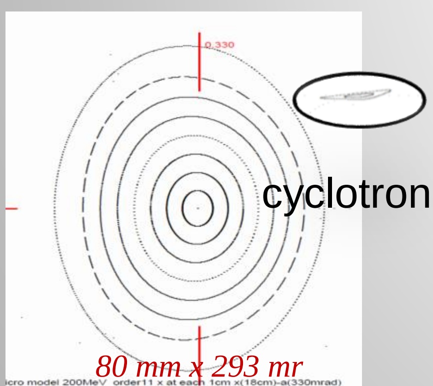
MAGNETS and modeling



Parameter	Units	Value
Number of magnets		6
Number of SC coils		12
Peak magnetic field on coils	T	7
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

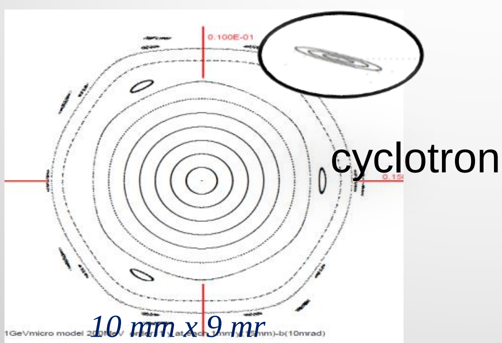
One straight section occupied by RF cavities and injection/extraction in the other

FFAG Horizontal / Vertical Stable beam area @200 MeV



$\varepsilon_H = 23{,}440\pi$ mm-mr

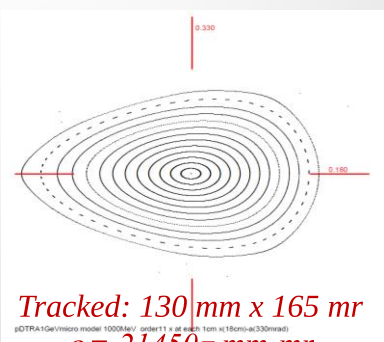
ε_{norm} = **16,059π mm-mr**



$\varepsilon_V = 90\pi$ mm-mr

ε_{norm} = **62π mm-mr**

FFAG Horizontal Stable beam area @1000 MeV vs. DA of 800 MeV Daeδalus cyclotron*



$\varepsilon = 21450\pi$ mm-mr

ε_{norm} = **38820π mm-mr**

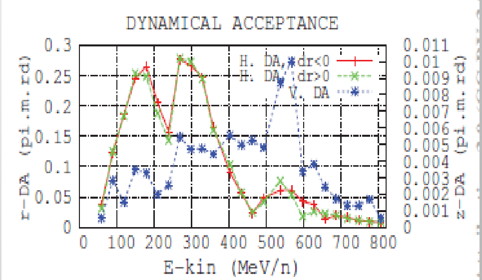


Figure 8: 500-turn DA (normalized) as a function of energy. Left axis : Horizontal DA, for either $dr < 0$, or $dr > 0$, wrt. closed orbit. Right axis : Vertical DA.

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

Tracking: Horizontal – 1 cm steps, Vertical – 1 mm steps

*FFAG vert. stable area at aperture limits.

Dual Accelerator Patient Model (PSI data*)

Below is a model-based treatment using 70 MeV as the lower limit since many nozzles (or energy degraders) only work in the 70 to 250 MeV range. (Lower energies can be obtained by plastic range shifters placed close to the skin and aperture, for example with breast, pediatric patients, and parotid tumors in the jaw.)

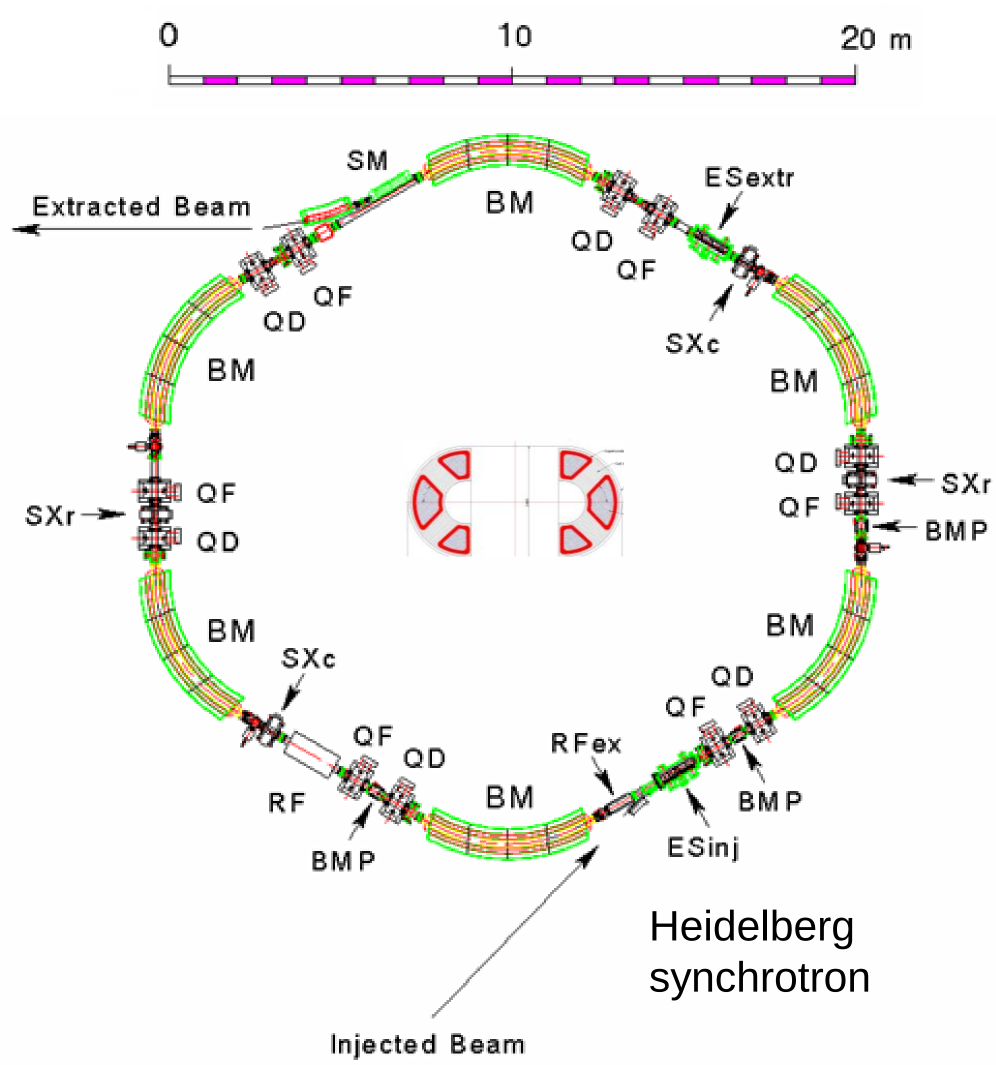
- Site Percentage Energy Range (MeV)
- Lung 9% 70 - 170
- Breast 3% 70 - 140
- CNS 15% 70 - 150 (central nervous system, i.e., base of skull & tumors around spinal vertebrae)
- Rectum 2% 70- 170 (also cervical cancers may be a few % in this energy range)
- Pediatric 8% 70 - 150
- Head & Neck 15% 70 - 150
- Prostate 45% 200-250
- Other 2%

This fits nicely with a dual energy accelerator system where $E \leq 150$ MeV can be used for roughly 50% of the patients. At PSI all patients were treated with $E < 180$ MeV excluding prostates. *

*based on discussions with G. Coutrakon, 2009.

NEXT-generation CW Accelerator!

- Isochronous or CW (serpentine channel relaxes tolerances)
- Stable tune, large energy range
- The footprint of CW FFAG accelerators is decreasing rapidly
- SC : 4 x 6-8 m
- NC: 5-6 x 8-10 m
- Multiple source injection
  - Deliver an imaging and treatment beam in a session



Heidelberg synchrotron