FUTURE ACCELERATORS: FROM GREEN ENERGY TO CANCER THERAPY: AND BOB

This is ~~EMMA~~ BOB. She's going to save the world (and cure cancer)

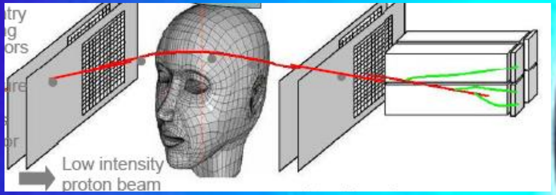
Best Of Britain

"No, not the engineer in the lab coat. Rather, the ~~Electron Model of Many Applications~~ in which she's standing - a remarkable new technology which could change everything about the way we live." — *The U.K. Daily Mail (2011)*

Dr. C. Johnstone, Fermilab

Bob Says: "THE future of the World is in ACCELERATORS!"

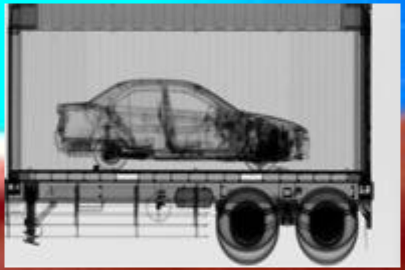
CANCER THERAPY and IMAGING:
$100 Billion Market



RADIOISOTOPES:
$ 40 Billion Market

ENERGY CRISIS:
$ Trillion Market

HOMELAND SECURITY:
$80 Billion Market



"This is my slide edited by an accelerator physicist!"

Conventional Applied Accelerator Types

1. **Synchrotons** *(multi-GeV - TeV energies)*
   - Pulsed with ramping magnetic fields (0.5-50Hz)
   - Swept-frequency accelerating systems
   - Separated components
   - Current limited by size
   - Variable energy
2. **Cyclotrons** *(low – medium energies - 1 GeV limit)*
   - Fixed magnetic fields
   - CW beams, fixed-frequency accelerating system
   - Higher energies: swept-frequency accelerating systems
     - ***Very large at high energy for low-loss CW beam***
     - ***Synchrocyclotron for low-loss compact applications.***
   - High currents (mA for CW beam)
   - Fixed energy
3. **Linacs** *(any energy)*
   - Longest footprint
   - Most costly – no multipoass through components
   - Ultra-high currents – 100 mA
   - Variable energy
     - constant beam properties synchrotron speeds
4. **FFAGs** *(low to high - ~2 GeV)*
   - Fixed magnetic fields
   - CW beams well into the relativistic regime
   - Ultra-compact non-scaling designs
   - High current – tens of mA
   - Variable energy with long straight sections

Synchrotron

Low Current (<mA)

High Energy (TeV)

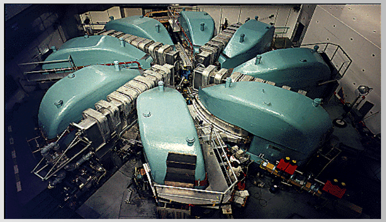
Pulsed Beam

Cyclotron

High Current (<A)

Low Energy (600MeV)

Continuous beam



Linac

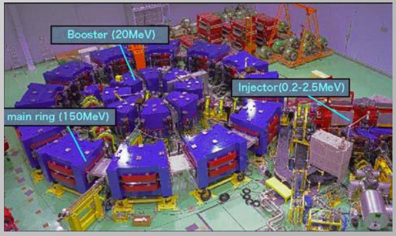
High Current, High Energy

Pulsed or continuous beam: Large, expensive

FFAG

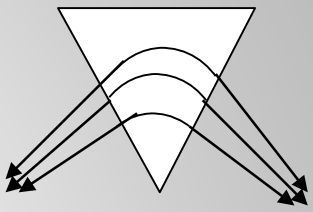
High Current (<A) , High Energy (few GeV)

Continuous beam, compact

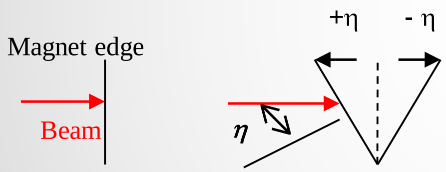


Principles of Transverse Beam Focusing

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).



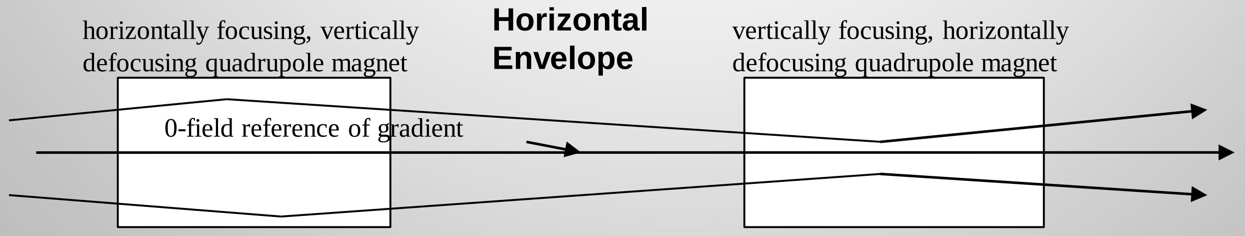
2. Edge focusing *(used in Cyclotrons + FFAGs)** :
   - Quadrupole-like: focusing horizontally, defocusing vertically, or vice versa, or no focusing depending sign of the B field and on entrance angle (defined relative to the normal to the magnet edge).



Normal, no focusing

Def. of edge angle,
Reverse of convention

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



Accelerators and beam control

1. Centripetal *(Cyclotrons + FFAGs)* :
   - bend plane only, horizontally defocusing or focusing
     - Strength ∝ **θ/ρ** (bend angle/bend radius of dipole field component on reference orbit)
2. Edge focusing *(Cyclotrons + FFAGs)* :
   - Horizontally focusing / vertically defocusing, vice versa, or no focusing depending on field at entrance and entrance angle
     - Strength ∝ **tan η/ρ** , (or ~ **η/ρ** for reasonably small edge-crossing angles)
3. Gradient focusing *(Synchrotrons + FFAGs)* :
   - Body gradient, fields components > dipole:

$$B = a + bx + cx^2 + dx^3 + \dots \qquad B' = b + 2cx + 3dx^2 + \dots$$

     - Linear field expansion, constant gradient
       - Synchrotrons + linear-field nonscaling FFAGs (muon accelerators)
     - Nonlinear field expansion up to order k, magnitude of gradient increases with r or energy:
       - Scaling FFAGs
     - Arbitrary nonlinear field expansion, magnitude of gradient increases with *r* or energy:
       - Nonlinear Non-scaling FFAGs

Edge crossing angles are kept deliberately small in large multi-cell synchrotron rings. This term becomes increasingly important for and causes problems in small synchrotron rings.

So What is a FFAG

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

synchrotron   cyclotron

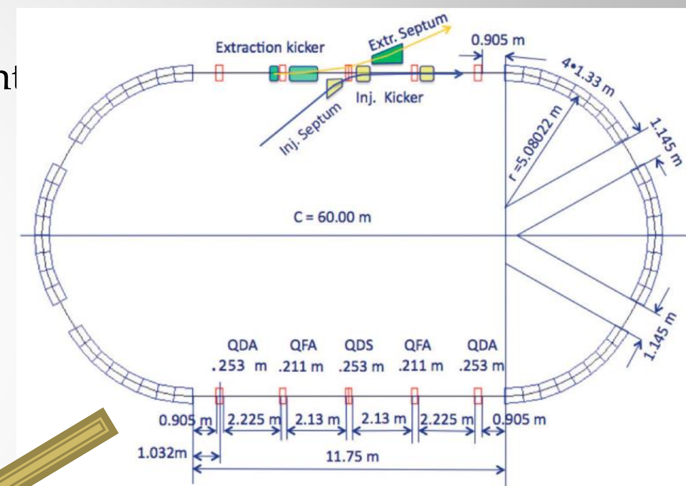
$$1/f_F = k_F l + \frac{\vartheta}{\rho_F} + \frac{\eta}{\rho_F}$$

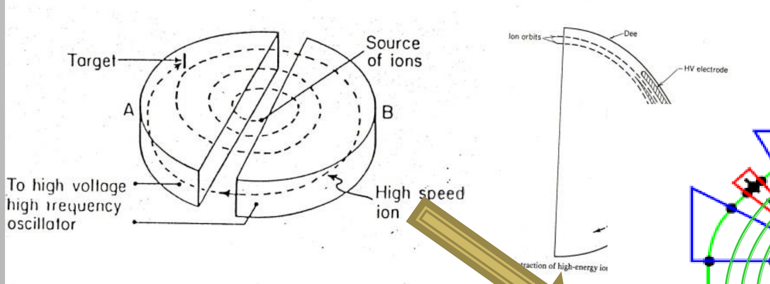
with ϑ is the sector bend angle, η the edge angle (edge angle is assume small so tangent is approximated), length, l, is the F half-magnet length and k_F is the "local" gradient for an arbitrary order field.

- *The power of the 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*

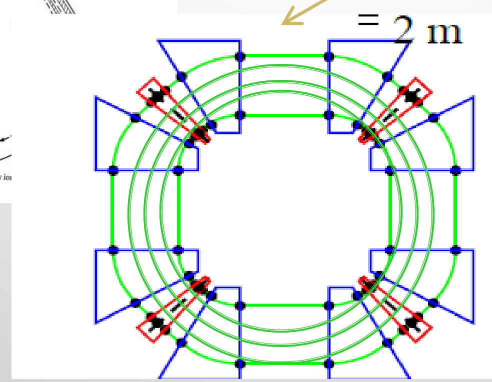
Understanding a ns-FFAG

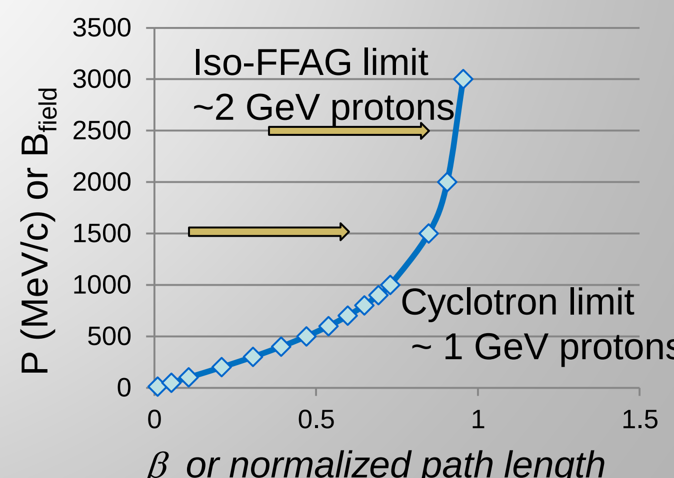
- Apply a "synchrotron" strong-focusing field profile to each "cyclotron" orbit
- Strong-focusing allows
  - Long injection/extraction or synchrotron-like straights
  - Strong RF acceleration modules
  - Low –loss profile of the synchrotron
  - CW beam to high energies in compact structure
    - 400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



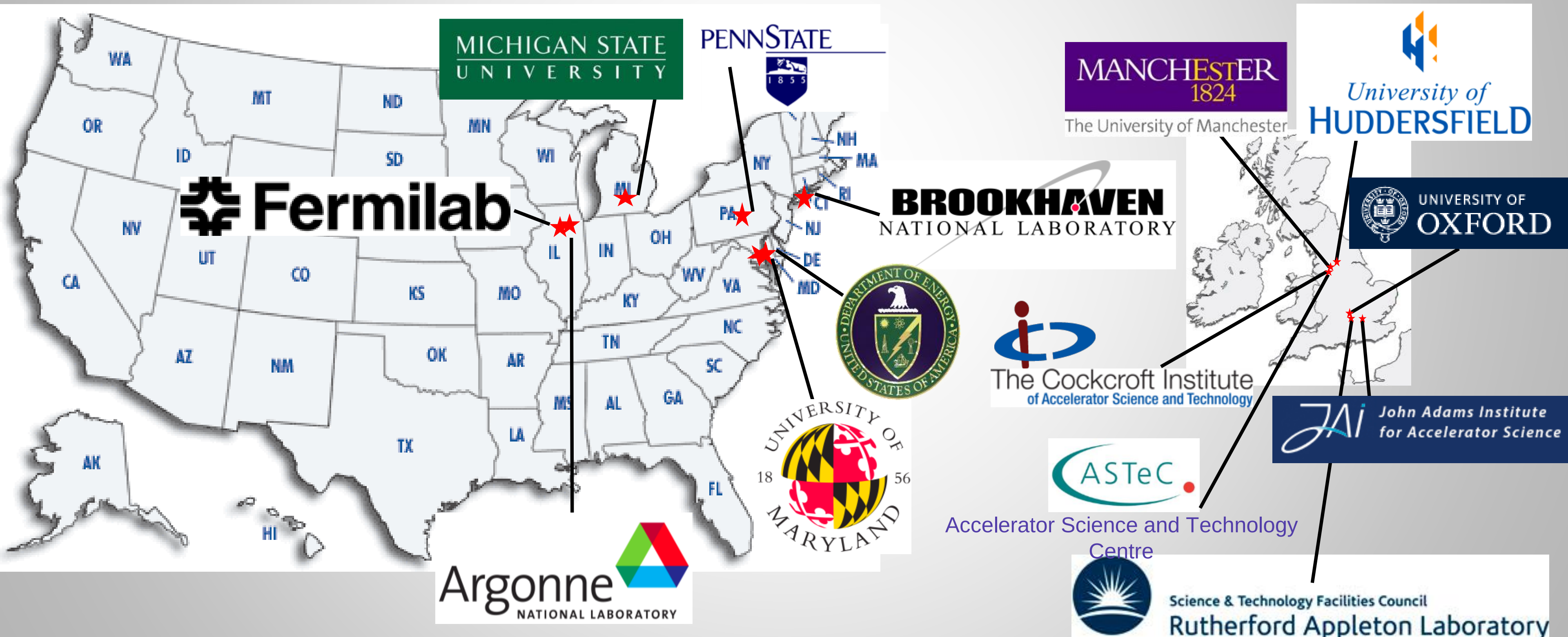


straight = 2 m





The international FFAG collaboration



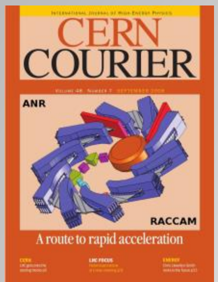
KURRI Kyoto University Research Reactor Institute

KYOTO UNIVERSITY FOUNDED 1897 KYOTO JAPAN

OSAKA UNIVERSITY

CERN

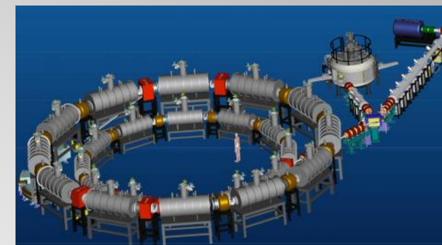
INTERNATIONAL DEVELOPMENT OF FFAGS



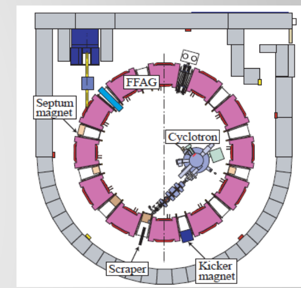
RACCAM: proton therapy
LPSC Grenoble, France

ERIT: neutron source
KURRI, Japan

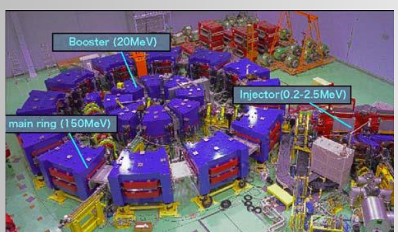
PRISM: intense muon beam
Lepton flavor violation exp.
Osaka, Japan



PAMELA: hadrontherapy design
Oxford, U.K.

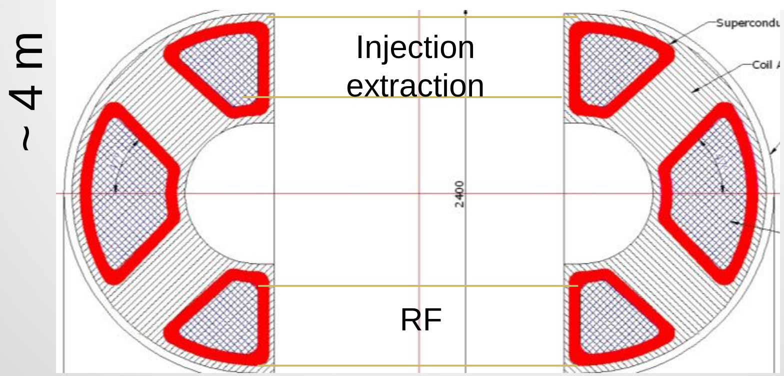


150 MeV proton, 100 Hz- kHz FFAG
KEK Japan



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

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



~6 m

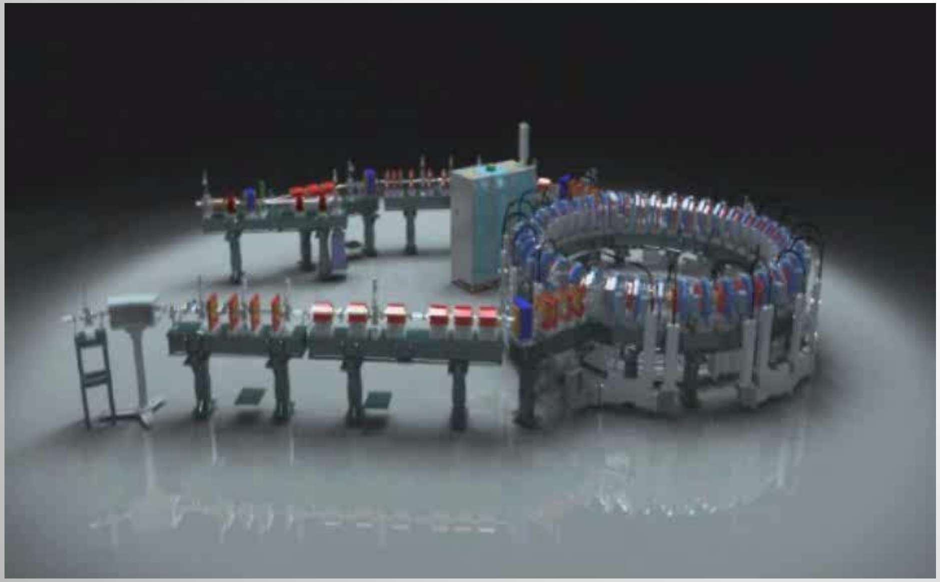
Compact CW ns-FFAG racetrack design capable of variable energy and various applications

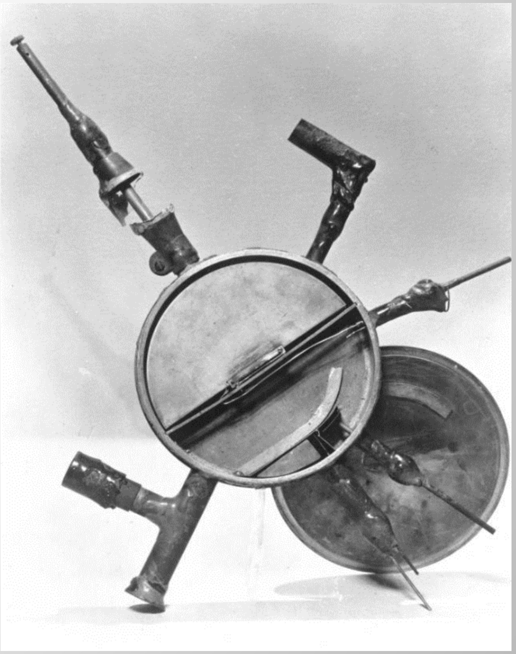
POP, 1st p FFAG, KEK, Japan

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

BOB (previously EMMA)

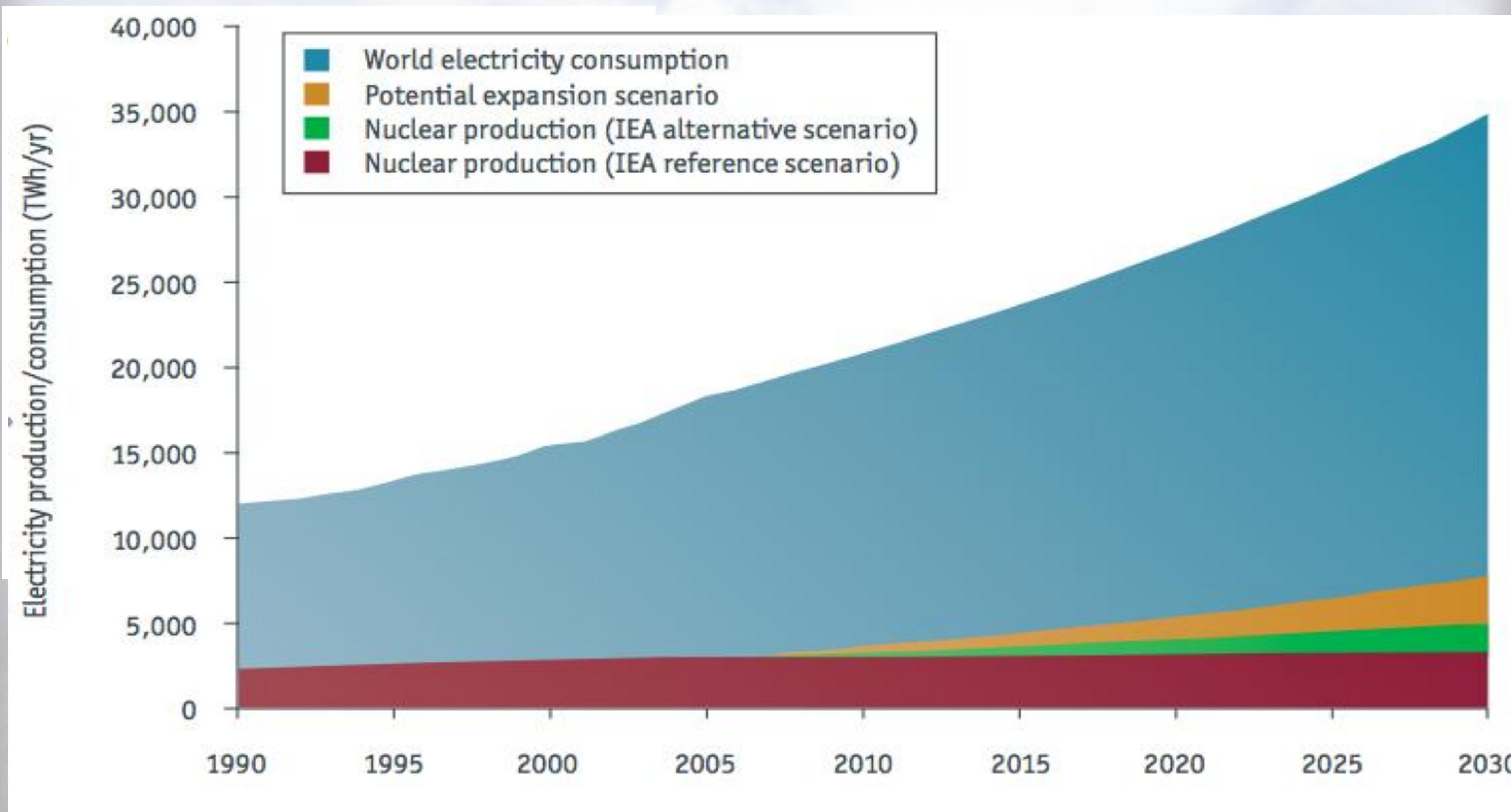
- Enormous advances in FFAG technology since the first machine at Daresbury ≅ first cyclotrons
  - Well maybe not quite





The Energy Crisis

The world is already in an energy crisis, worsening rapidly as fossil fuels deplete and their devastating impact on climate change increases:



“Premise”

“A reactor needs an accelerator like a fish needs a bicycle…”

University of HUDDERSFIELD

FFAG Driven Nuclear Reactor

Accelerator Driven Subcritical Reactor
Meltdown Impossible! No Proliferation!

World Electric Power Production is Currently Around ~ 5000 Gigawatts

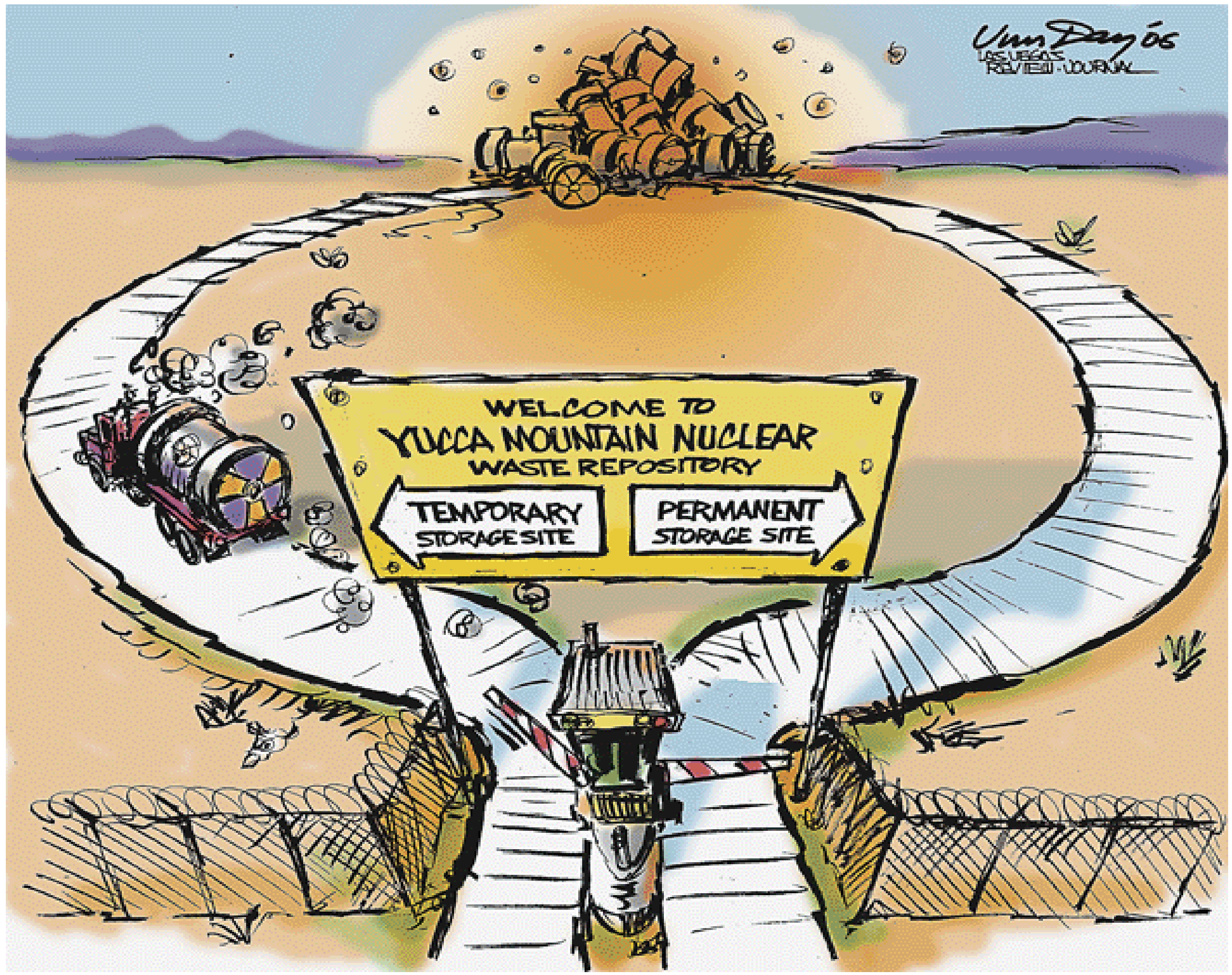
Power Usage is Projected to Double as BRIC Countries Develop

Once the Reality of Clean (Green), Safe Nukes is Established, **revolutionize the Entire World Power Market**

A 1 Gigawatt FFAG Driven Reactor Would Require 3 FFAGs for Redundancy at ~$80M each (assumes profit)
The Potential LINAC Competition costs $100s of Millions More

Hey this is my joke

Waste management: there is no such thing



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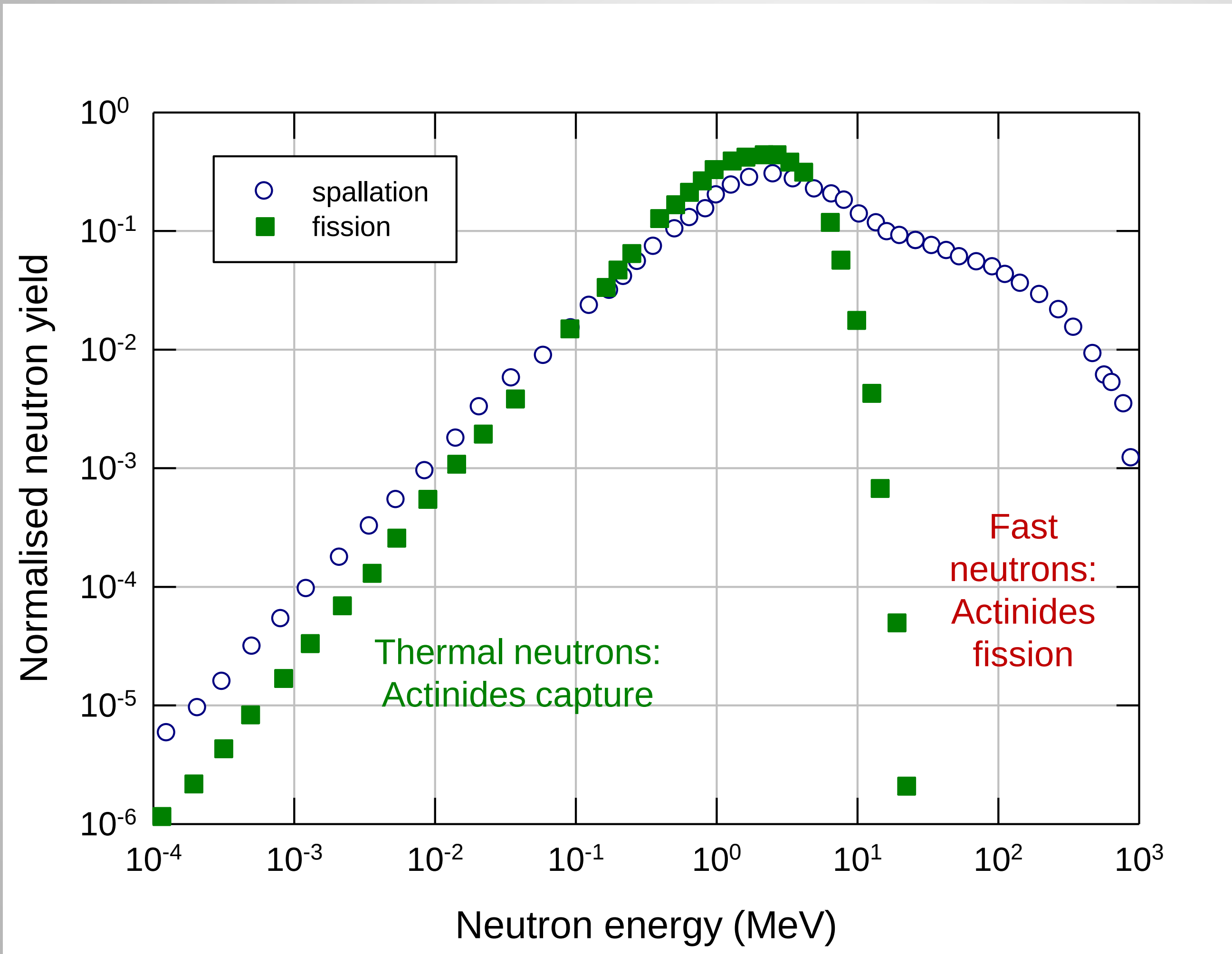
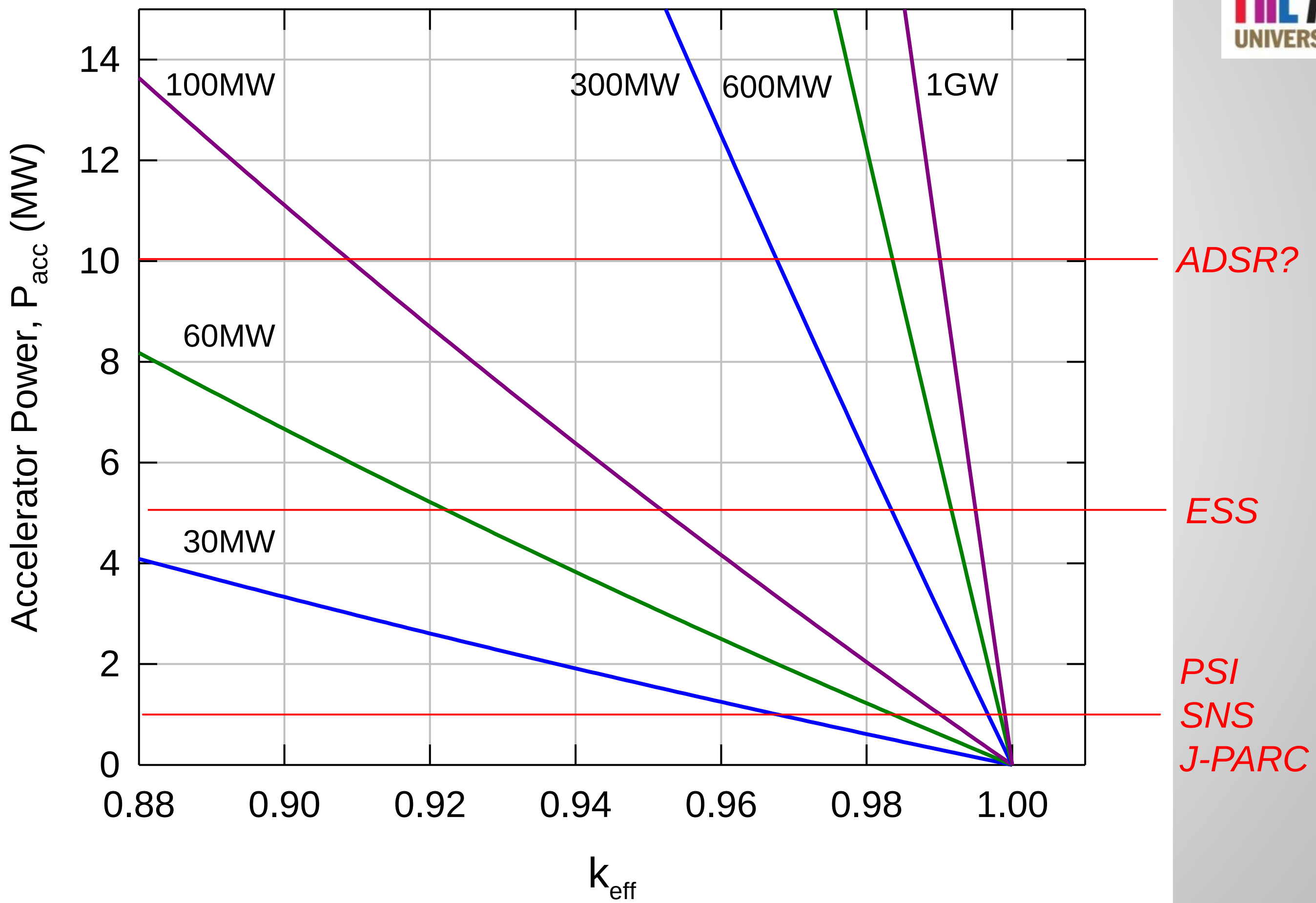
Spallation neutron vs fission neutrons



THE AWARDS
UNIVERSITY OF THE YEAR

Nuclide	fiss/abs Thermal	fiss/abs Fast
^{239}Pu	63%	79%
^{240}Pu	0.34%	43%
^{241}Pu	23%	82%
^{242}Pu	1.4%	36%
^{237}Np	1.9%	17%
^{238}Np	91%	84%
^{239}Np	3.9%	19%
^{241}Am	1.3%	12%
^{242}Am	83%	84%
^{242}Cm	8.9%	33%
^{244}Cm	6.0%	32%
^{246}Cm	18%	53%

ADSRs : accelerator power

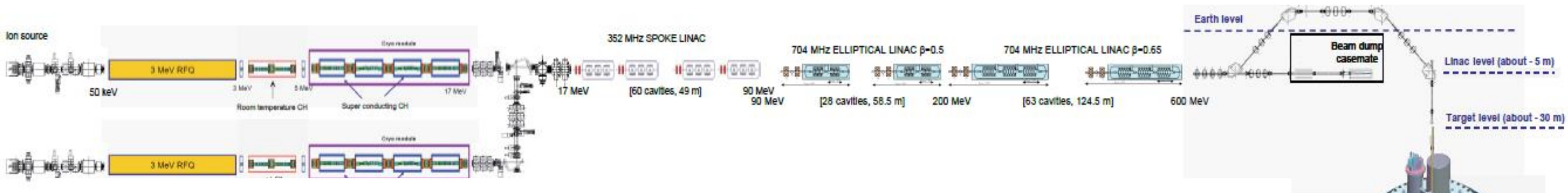


"My Conclusion"

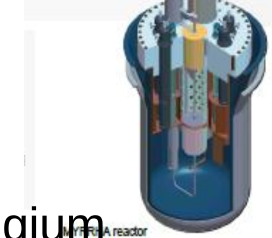
"A fish needs a bicycle…"

University of HUDDERSFIELD

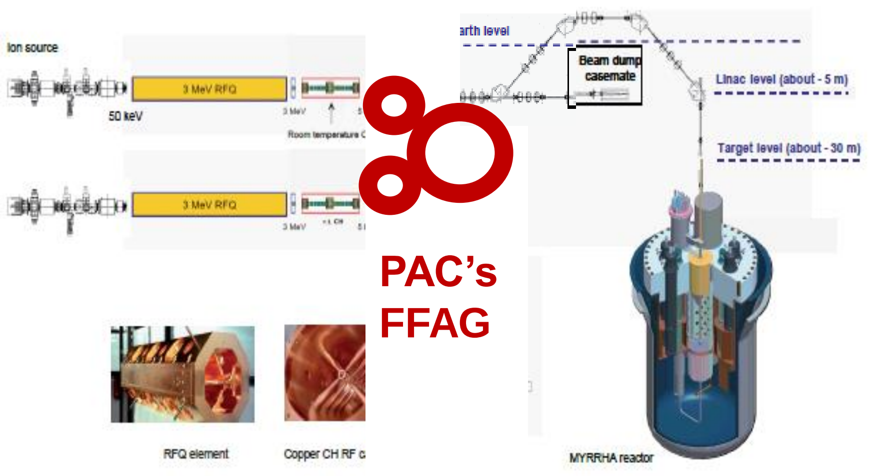
The FFAG vs MYRHHA Linear Accelerator for ADSR waste transmutation



A linac accelerator for nuclear waste transmutation



MYRHHA Mol, Belgium



PAC's FFAG

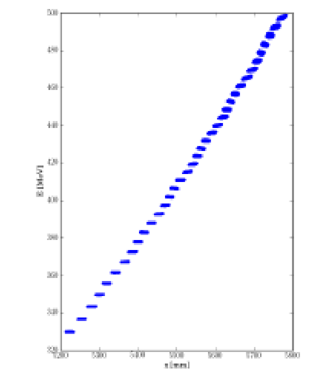


Figure 12: Turn-by-turn radial position vs energy for a low intensity beam in the serpentine channel accelerated to 500 MeV.

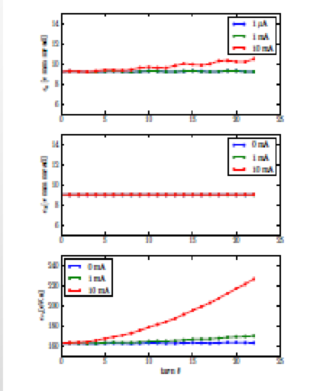


Figure 10: Emittance variation at fixed energy at 330 MeV for a 100 mm long beam at varying average beam current.

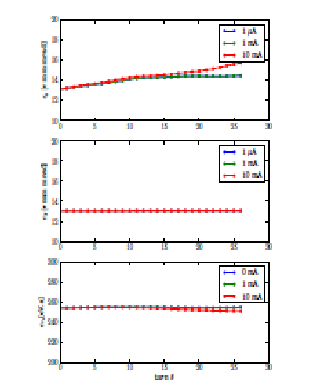


Figure 11: Emittance variation at fixed energy at 610 MeV for a 100 mm long beam at varying average beam current.

A FFAG 1 GeV high power accelerator facility

S. Sheey, high current OPAL simulations, AccApp13 paper – operates at 20 mA as a storage ring

The Looming Radioisotope Shortage

Most medical imaging radioisotopes have short lives,

- must reach patient within 110 minutes for Alzheimer's scan

Many isotopes can be manufactured in the hospital

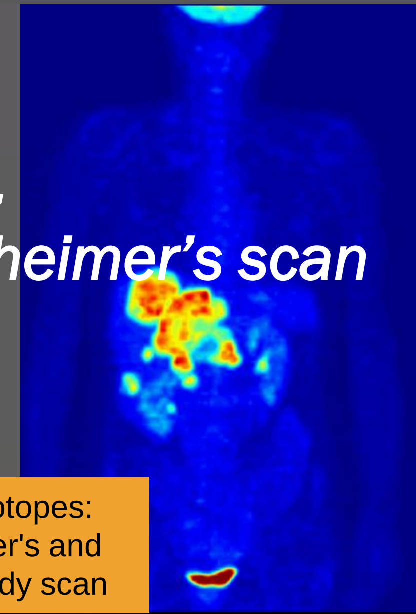
- using accelerators!

80% of procedures use ^{99m}Tc (from ^{99}Mo)

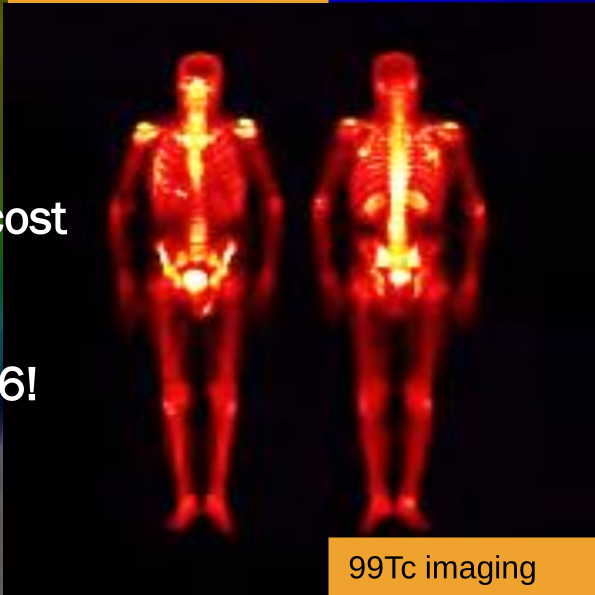
(bone scans, nuclear stress tests)

^{99}Mo produced in <10 aging reactors worldwide,

- Transport causes large loss in activity and increased cost
- 2009 world ^{99}Mo crisis due to reactor failures
- Main supply (Chalk River, Canada) shuts down by 2016!
- Target (weapons-grade uranium) soon not available



PET isotopes: Alzheimer's and whole body scan



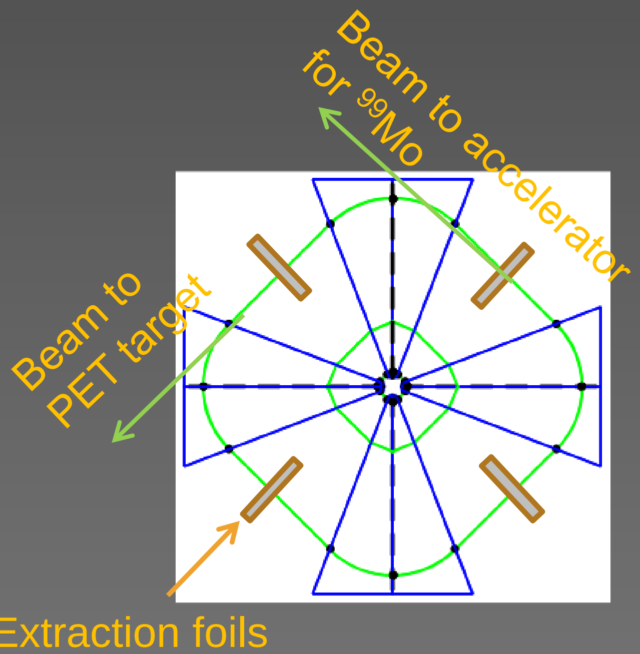
99Tc imaging

PIP: FFAG for Radioisotope Production
The Huddersfield Accelerator Project

Supporter

PET and ^{99}Mo isotopes can be produced with new accelerator and target technologies (no uranium).

IDEAL FOR THE HOSPITAL ENVIRONMENT!



PET isotope FFAG (<2m diameter)
Multiple target stations and isotopes
Injector for $^{99}Mo(^{99}Tc)$ stage

Worldwide demand for PET and ^{99}Tc isotopes increasing 10%/year

^{99}Tc crisis by 2016!

- ➢ First high-current compact proton accelerator will corner ^{99}Tc market.

- ➢ Linacs : costly, large
- ➢ Cyclotrons : high losses (stripping extraction and highly radioactive

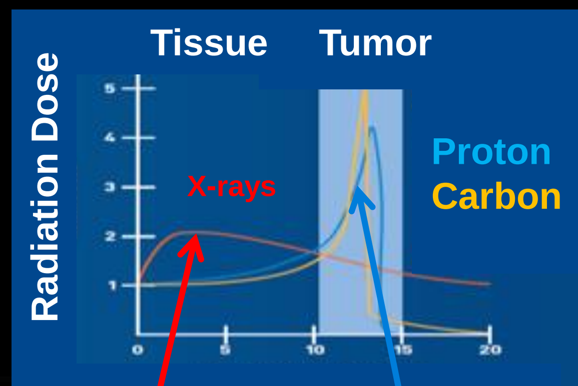
- ✓ **FFAGs** :
  - ✓ more target stations,
  - ✓ efficient production and use of hospital space
  - ✓ critical isotopes- combined PET/^{99}Tc system.

PROTON/ION VS. X-RAY CANCER THERAPY

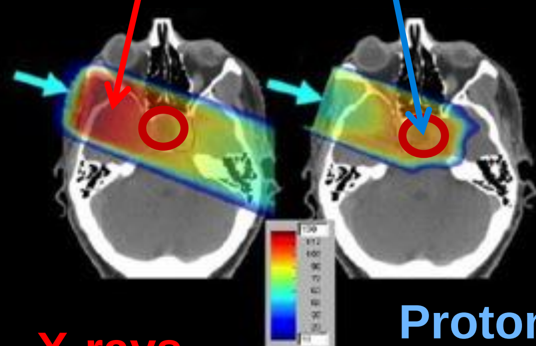
- 2/3 of cancer patients treated with radiation therapy: >95% with X-rays

X-Rays: radiation poisoning

Protons/Ions: no radiotoxic side effects



Higher radiation dose to healthy brain than tumor!



X-rays

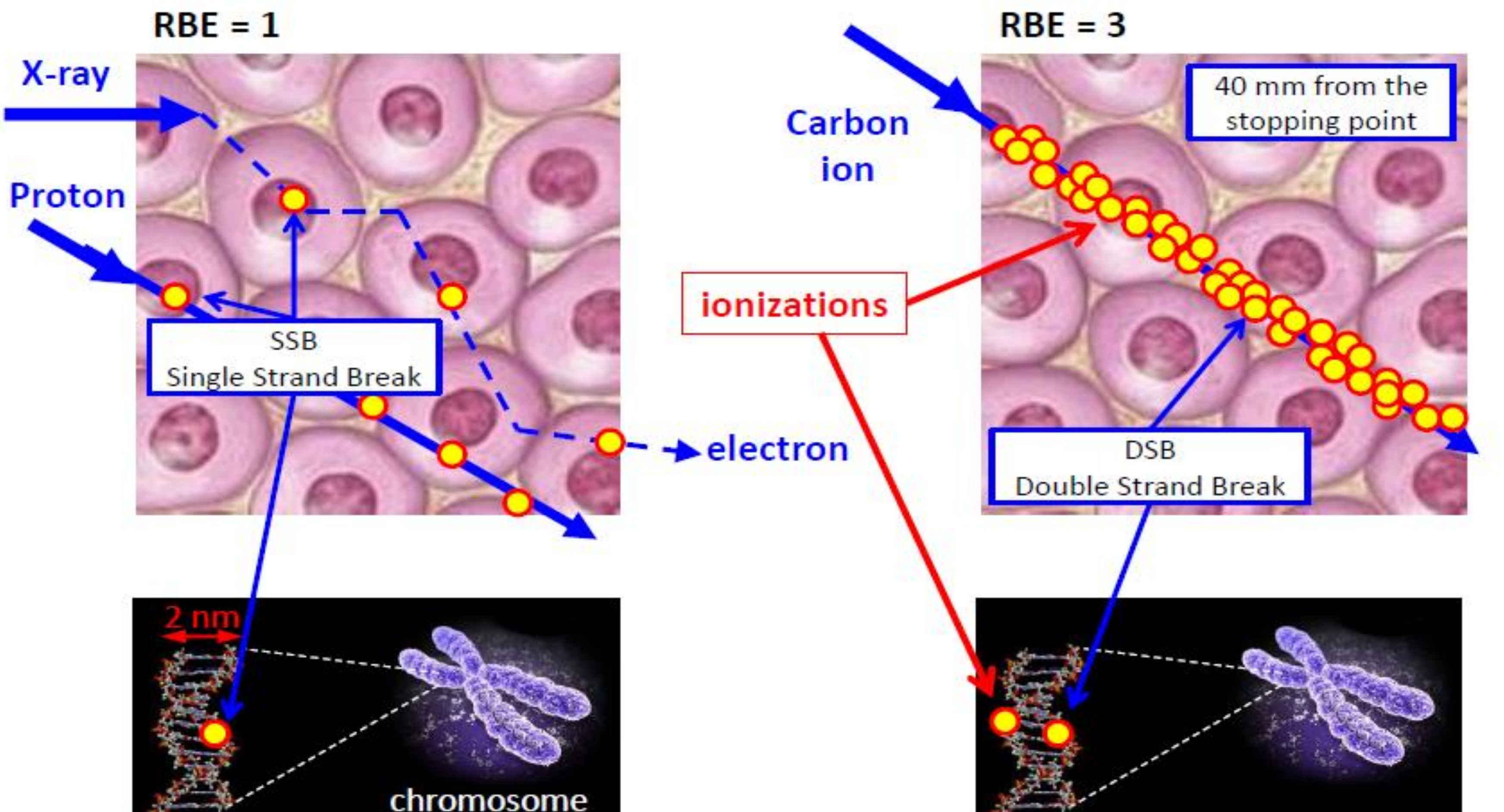
Proton
Carbon

Proton/carbon therapy targets tumor precisely NOT healthy tissue!
Critical for pediatric cancers

Why heavier ions vs protons

Radiobiological efficiency (RBE) of carbon ion beams

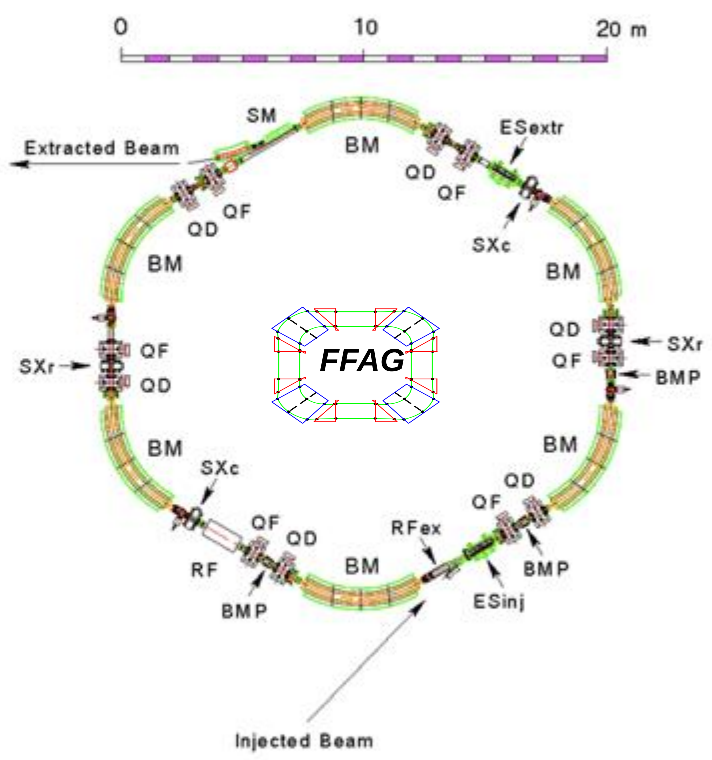
Better control of radioresistant tumours



Courtesy of U. Amaldi

FFAG PROTON/ION CANCER THERAPY

5000 electron linacs for X-ray cancer therapy worldwide



The carbon/ion synchrotron
vs ion FFAG (430 MeV/nucleon)

- ✓ Use of proton therapy is expanding rapidly and several ion therapy centers under construction
- ➢ Carbon/Ion Therapy required for radio-resistant tumors and both proton or ion therapy for X-ray therapy treatment failures
- ✓ The demand for ultra compact particle therapy accelerator technology is projected to be *~500-1000 units.*
  - ✓ *Only Competition is the large synchrotron. Issues with cyclotrons at these energies for ions.*

ACCELERATORS FOR HOMELAND SECURITY

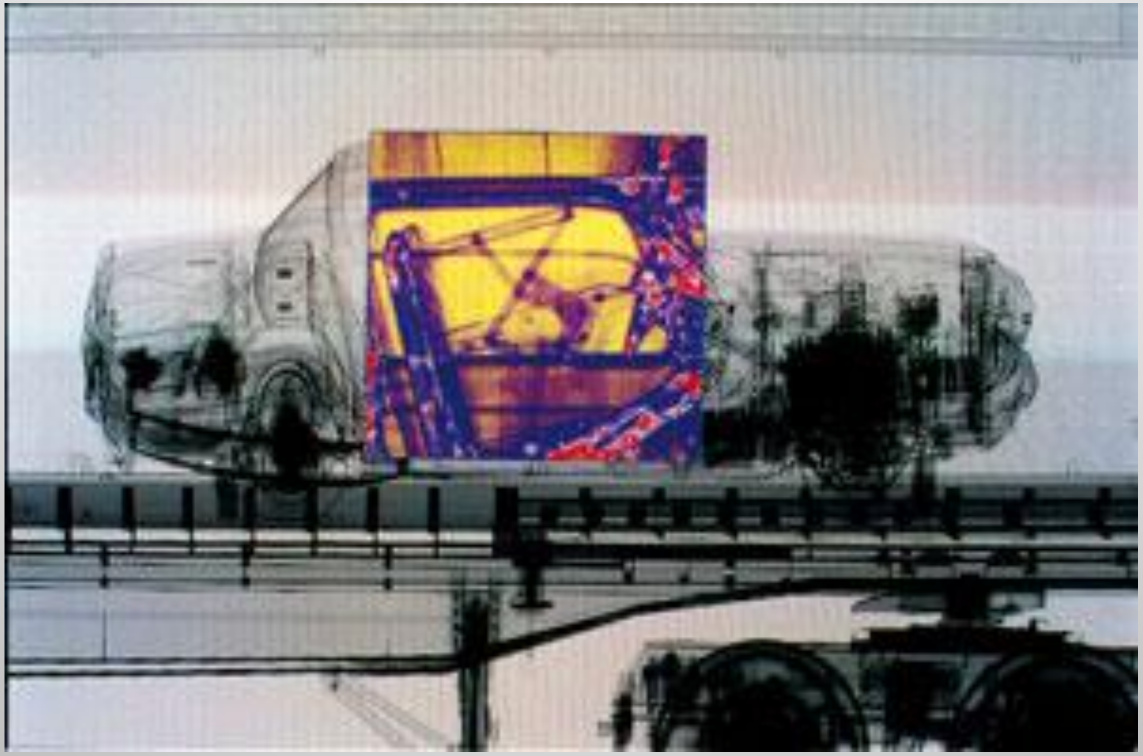
Accelerators can scan shipping containers for weapons material

There are a ~*1000 Ports of Entry* in the world, over 300 in the U.S.

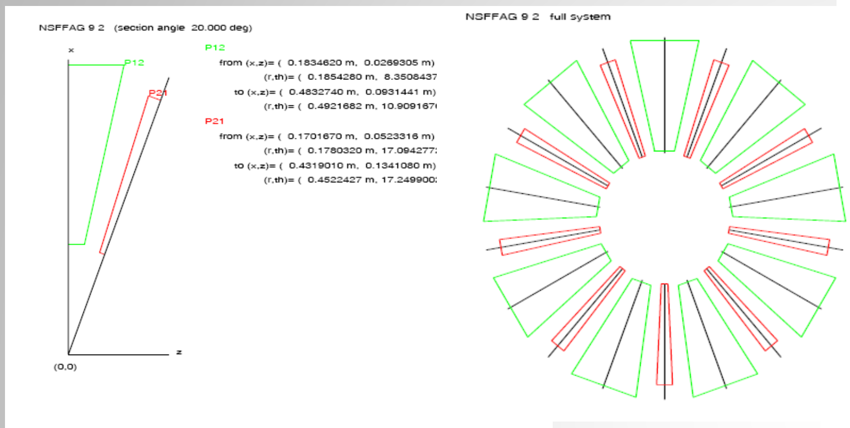
High-energy, high current proton and high current electron FFAG accelerators can scan cargo and detect nuclear weapons material.

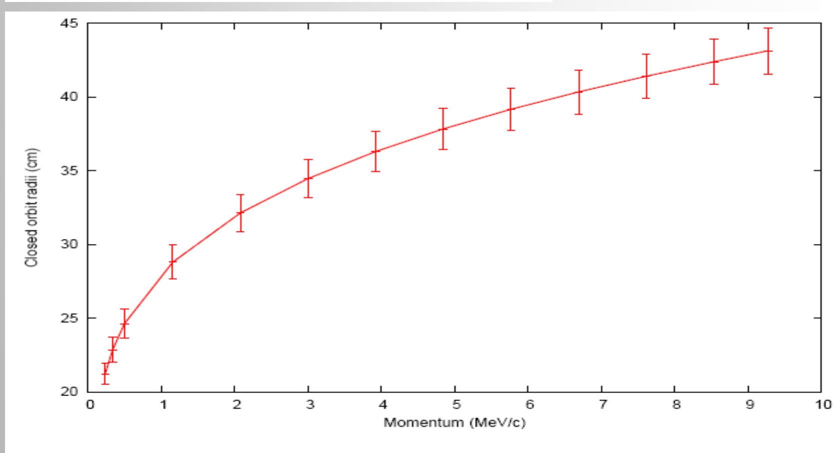
Transmission Radiograph with NRF

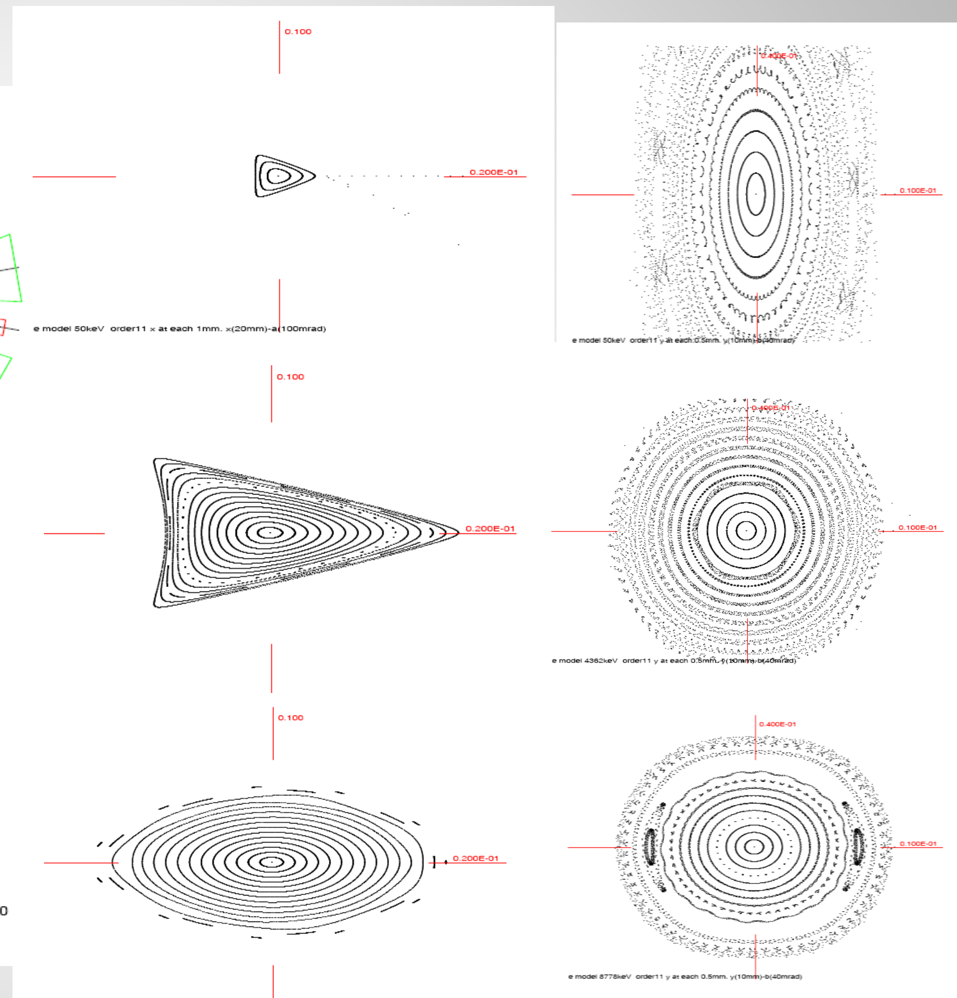
- Nuclear resonance lines are now “missing” from spectrum and can be identified.
- Photon spectroscopy combined with transmission provides 2D isotopic composition to the radiograph.



Simulation: COSY Results: Electron Ring



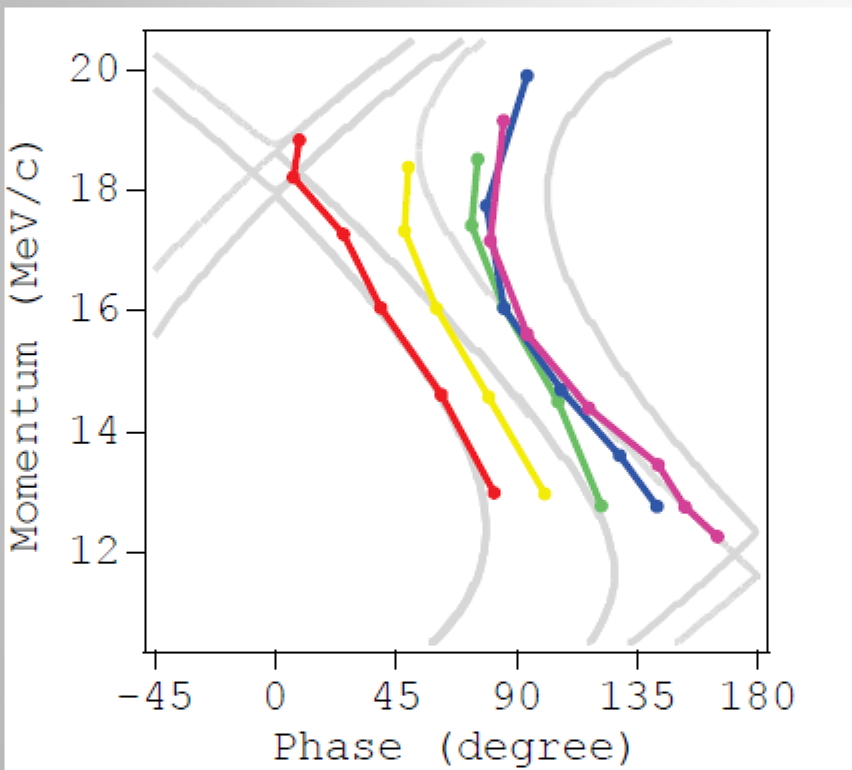


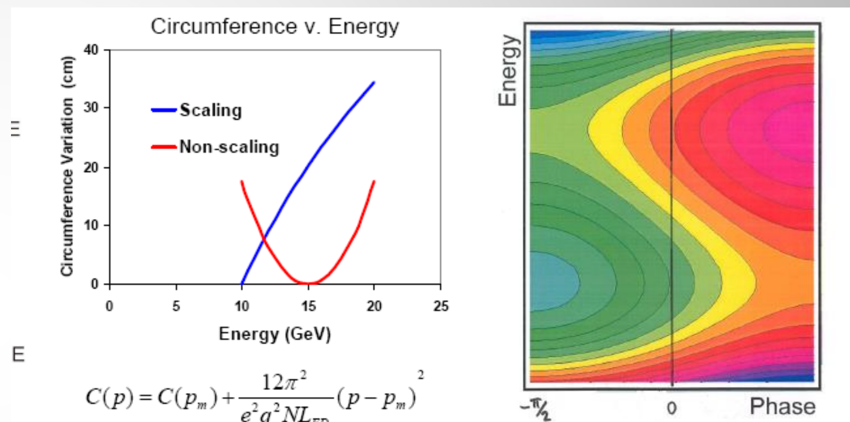


COSY results and tracking at 3 energies: 50 keV, 4.4 MeV, and 9 MeV machine. Except for the tune change required at horizontal injection, the DA is very large.

Serpentine channel: quasi-isochronous Acceleration in a nonscaling FFAG

- Acceleration in serpentine channel





$$\delta T \sim \frac{2}{h}\frac{V_{min}}{\Delta E} \sim \frac{1}{turns}$$

example

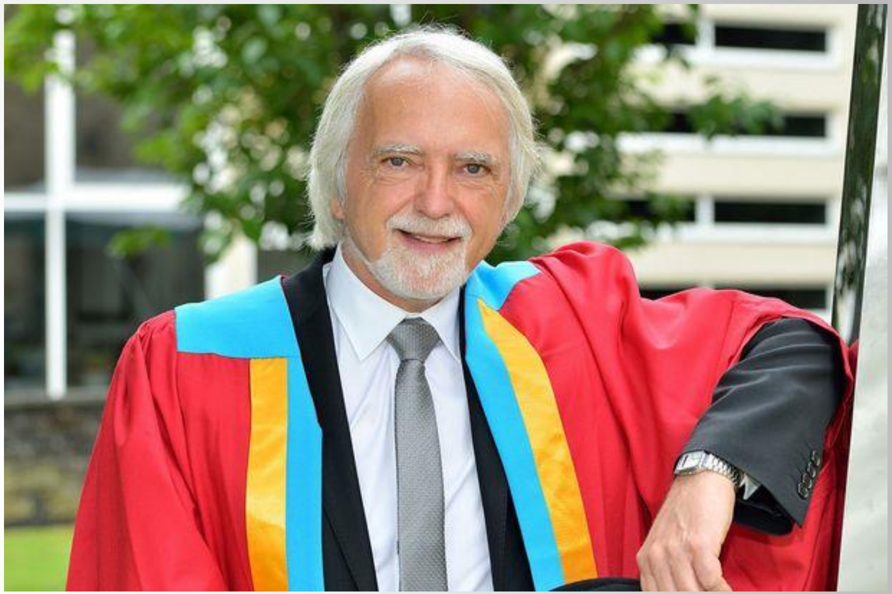
The machine which takes 100 turns to the top energy needs 1% level of isochronous.

Longitudinal phase space trajectories of beams with five different initial phases in EMMA. All of these cases clearly demonstrate acceleration within the serpentine channel.

In Memoriam

- Bob has been one of the strongest advocates of accelerator applications
  - huge supporter of FFAGs and recent advances
- One question Bob - now that you're emeritus – do you need a new job?

- There might be openings back in the states



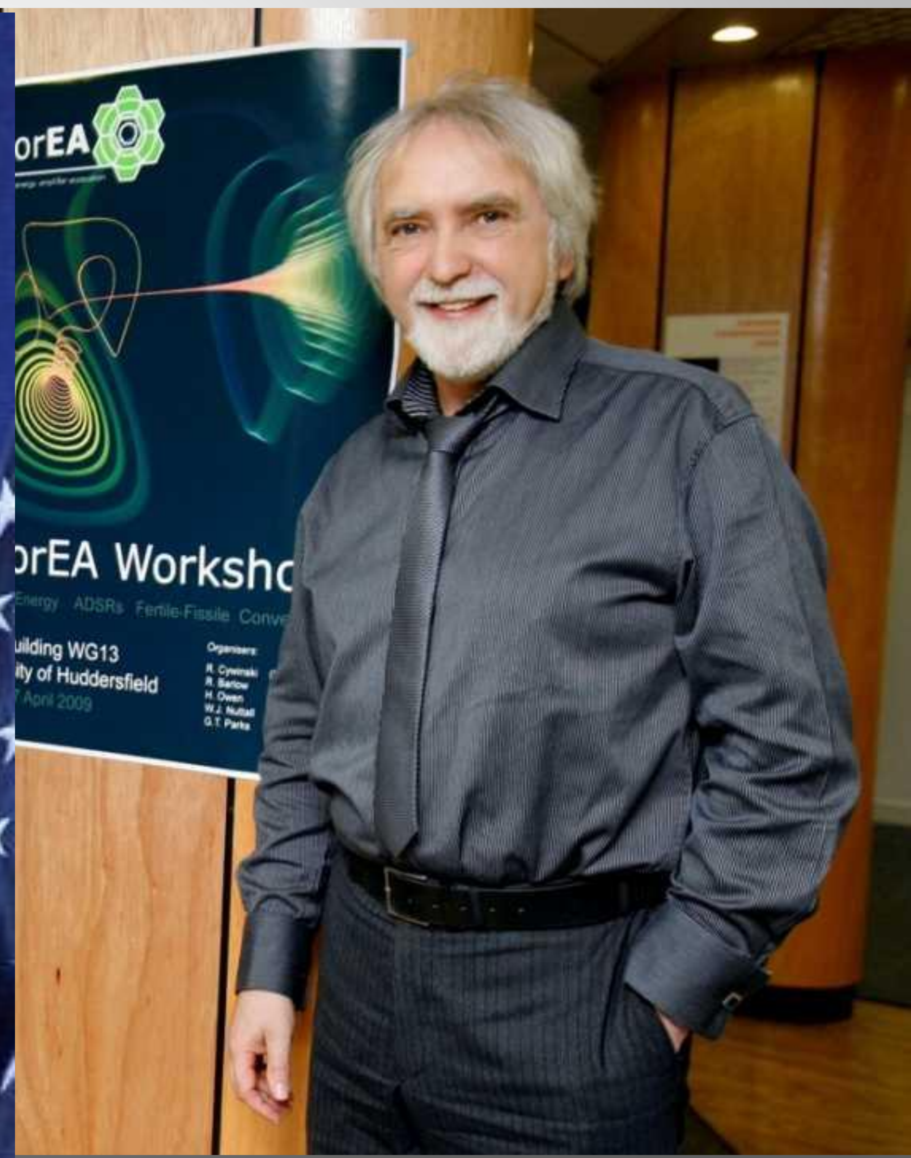
Breaking News

Trump's Energy Amplifier

Donald Trump has purchased a Nobel Prize from ebay and the rights to ADSR trademark; hehas renamed it The Trump Amplifier.

Trump has als proposed buying Mexico as the prototype site.

Bob - about that job in the states



THANK YOU BOB!