Compact CW Recirculating Electron Accelerator – eFFAG (3–9 MeV)

Dr. C. Johnstone

Acknowledgements: Passport Systems, Particle Accelerator Corp

Introduction – Outline

- Primary Application presented: Cargo scanning
  - Compact, mobile, economical system
- Purpose
- Physics of cargo interrogation
  - Radiography (transmission through cargo of photon and neutron beams)
  - Neutron induced reactions
  - Photon induced reactions
- The role that accelerators play
  - Photon generation
    - Hadron induced reactions
    - Bremsstrahlung
    - Monochromatic photon sources
- Important characteristics of electron accelerators
- Novel approaches to accelerators

Identified Threats easily transported in containers

- Explosives
  - Examples of extensive damage
    - Oklahoma, Lebanon, Lockerbie, Halifax (1917)
  - Important elements: N, O, Cl, Na, S, K, P (and fulminates)
- Toxic Substances
  - Mustard gas ($C_4H_8Cl_2S$), Sarin ($C_4H_{10}FO_2P$), Phosgene (CCl_2O), etc.
- Dirty Bombs
  - ^{137}Cs, 69Co, etc.
  - Shielding materials Pb, W, Fe, etc.
- Special Nuclear materials (SNM)
  - ^{235}U, 239Pu, 237Np
- Weapons of Mass Destruction
  - ^{235}U, 239Pu, 237Np, Explosives, Tamper materials, etc.

Cargo interrogation

- examination must be performed rapidly
- non-intrusive
  - Therefore must involve penetrating radiation; i.e. neutrons and/or photons
- requires an electron or neutron particle accelerator
  - Only photon-producing electron accelerators are considered here
- One alternative: cosmic muons have been used to identify
  - SNM such as ^{235}U and ^{239}Pu
  - heavy metal shields such as lead or tungsten (through multiple scattering differences)
  - the technique does not identify specific isotopes
  - Does not provide comprehensive identification of explosives and toxic substances

Threat-based materials can be detected using photons via nuclear reactions

BEAM

MEASURED PARTICLE

Photons:

Photons

Transmission

Nuclear Resonance Fluorescence

Effective Z measurement

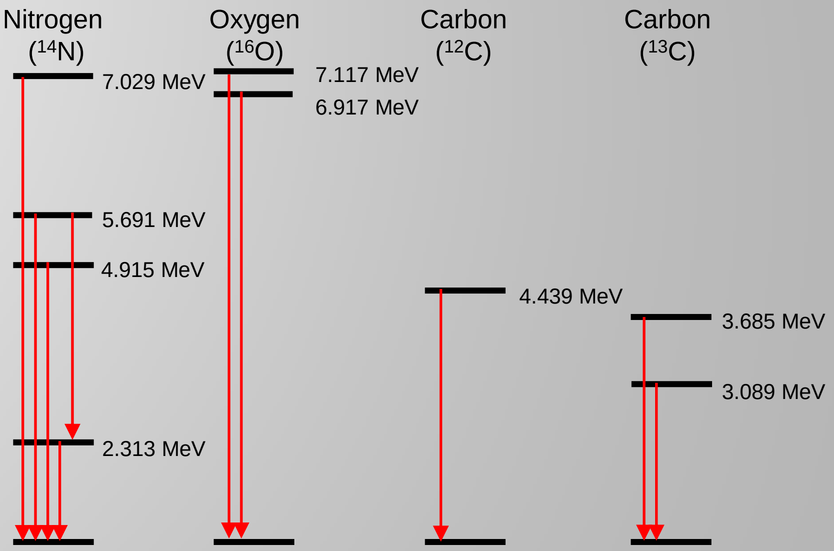
Neutrons:

Photon Induced Fission
(Prompt Neutrons)

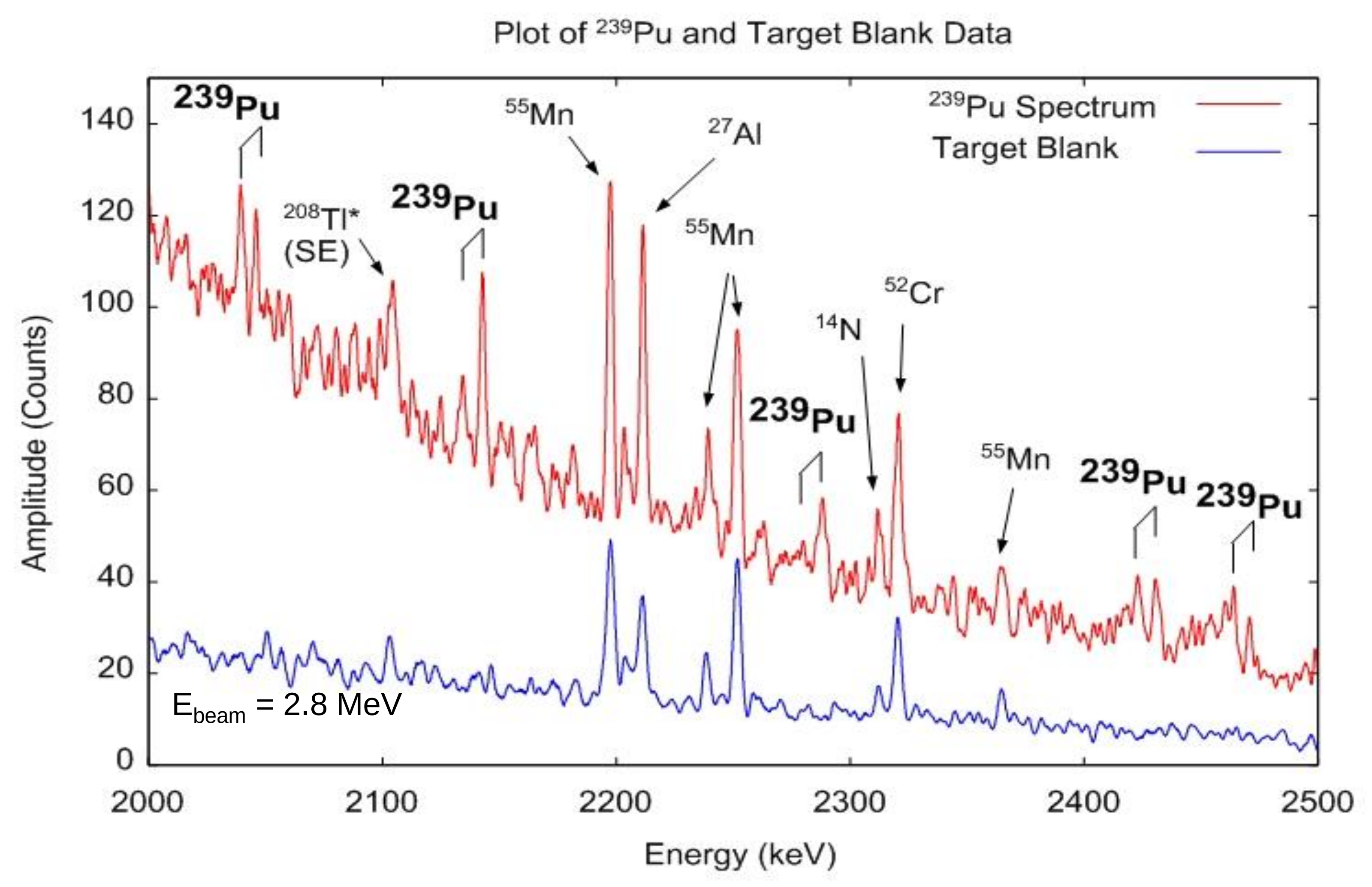
Identification of Nuclear States

Nuclear Resonance Fluorescence

- *Broad spectrum bremsstrahlung* photons produced by a 5-9 MeV electron accelerator are collimated and scan the container
- *Different nuclear species* are resonantly excited by specific photon energies and then re-emit photons when the “excited” state decays. The photons are Doppler-shifted and therefore not re-absorbed.
- *Using photon spectroscopy* the contents can be identified and a 3-D image reconstructed with proper detector arrays



NRF Spectrum from ^{239}Pu

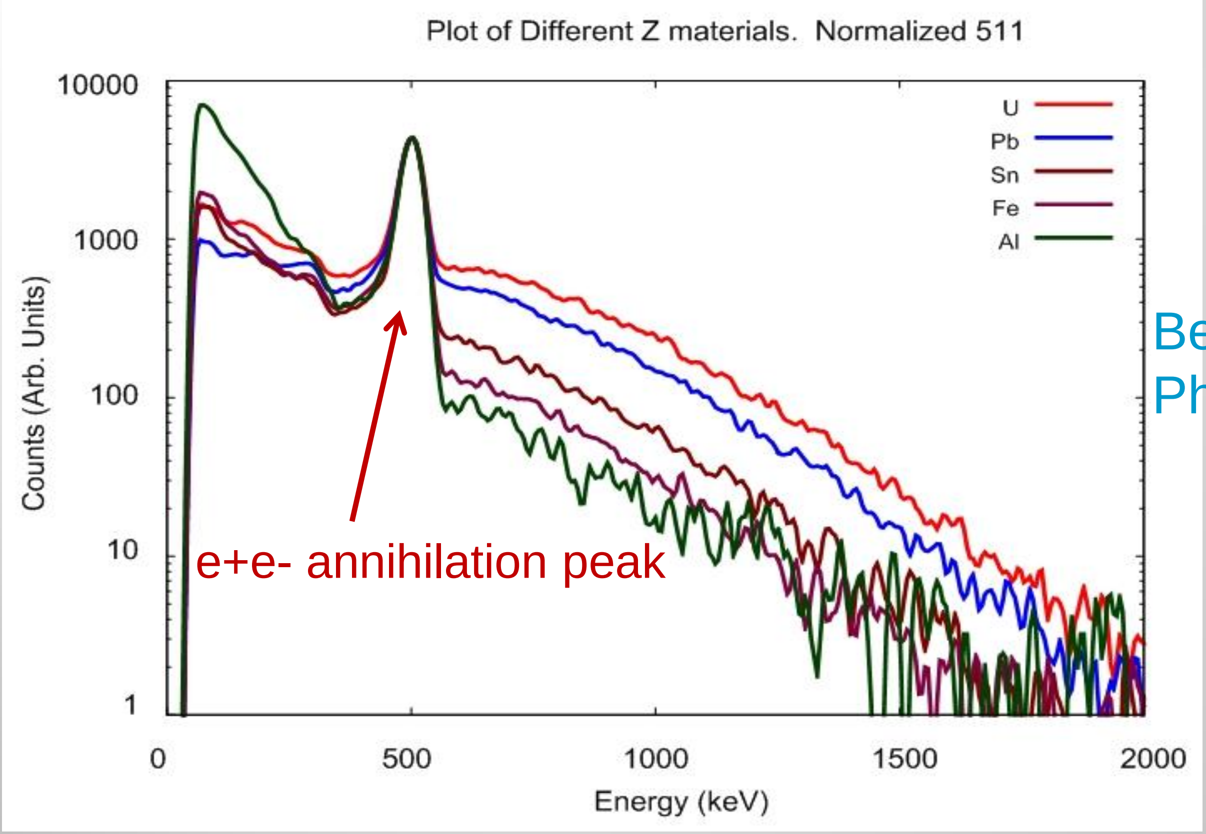


Measurements performed with LLNL

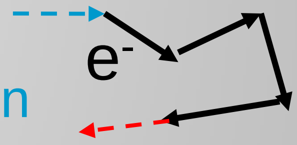
Exploiting NRF and non-resonant backgrounds

- Photons emitted by NRF
  - 1-8 MeV (hence a high energy electron accelerator/photons are required)
  - Nearly isotropic
    - Detect back-emitted photons
    - Reduction in background (forward Compton scattering)
- Effective Z measurement
  - Non-resonant background from multiple processes
    - Multiple processes again require high energy incident photons
  - Simple count of back-angle photons
  - Count proportional to Z^{α} to when normalized to annihilation peak

Effective Z Determination



e+e- annihilation peak



Compton

Pair Production

Coulomb

Scattering

Beam

Photon

e^-

Back-Angle Photon

Fast detection of high Z contents

Single Compton Scatter with Ebeam = 5 MeV

- E_{photon} (120º) = 320 keV
- E_{photon} (180º) = 240 keV

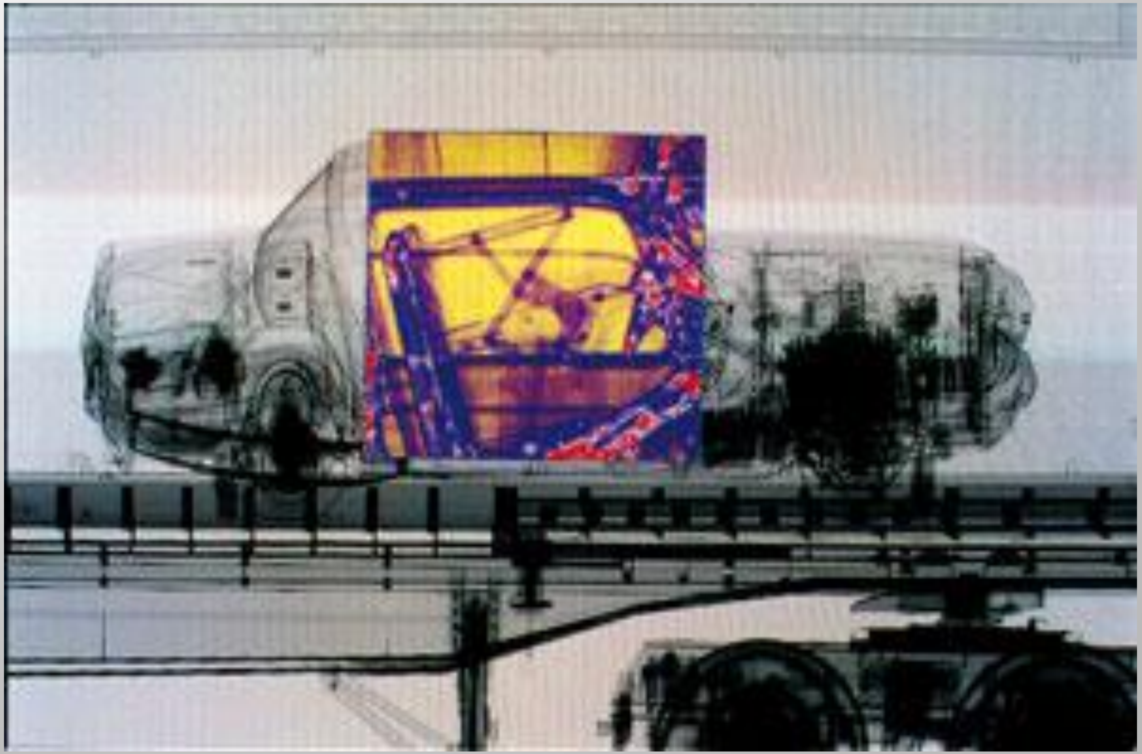
Pair Production → e+e- annihilation (~Z^2)

- E_{photon} = 511 keV

Transmission Radiograph with NRF

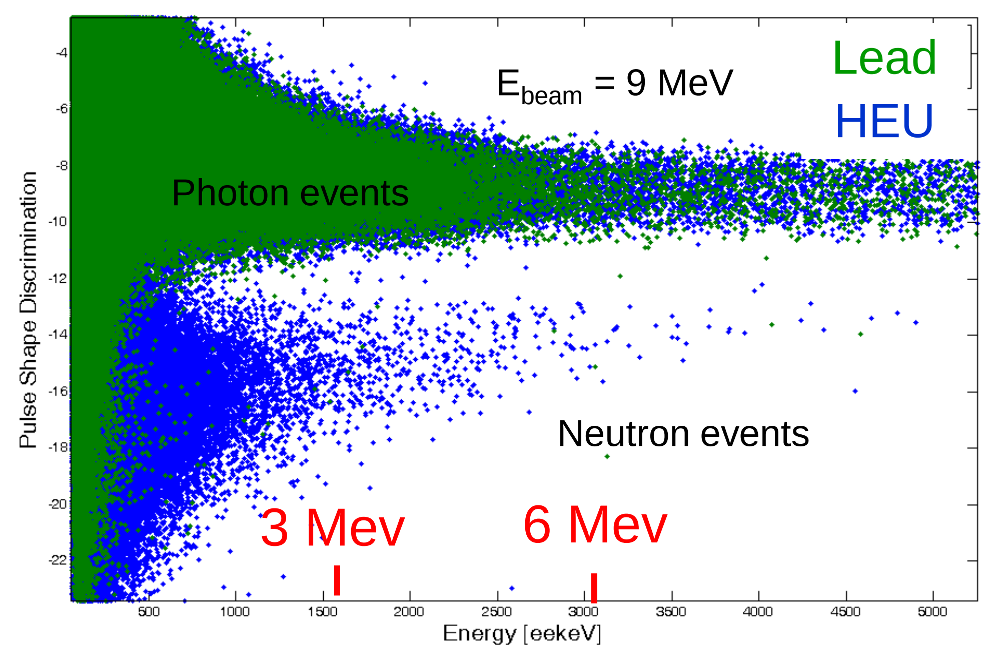
Nuclear resonance lines are now "missing" from spectrum and can be identified.

Photon spectroscopy combined with transmission provides 2D isotopic composition to the radiograph.



Prompt Neutrons from Photofission

- Prompt, high energy neutrons provide unique signal for fissile material and actinides
- Photon events are distinguished from neutrons by pulse-shape discrimination
- Neutron energy distribution independent of incident photon energy



Summarizing criteria

- Energy of photons: ~ 3 – 9 MeV
  - 3 MeV: NRF signatures for SNM is generally below this energy
  - 6 MeV: Good yield for effective Z and good penetration for radiography
  - 9 MeV: NRF from oxygen; well above photofission thresholds for actinides, increased penetration; excellent yield effective Z determination
- Intensity: Adjustable from zero to several mA
  - Must dynamically adjust to different cargo loadings to minimize dose
- Continuous time distribution (high duty cycle) desirable
  - Single photon/neutron counting
  - Signal to Noise

List of References

Muon Radiography; Detecting Nuclear Contraband, Brian Fishbine, Los Alamos Research Quaterly, Spring 2003

Gamma-ray and Neutron Radiography as Part of a Pulsed Fast Neutron Analysis Inspection System- J. Rynes, J. Bendahan, T. Gozani, R. Loveman, J. Stevenson and C. Bell; Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, **Volume 422**, Issues 1-3, 11 February 1999, Pages 895-899: And references therein.

Imaging and Radiography with Nuclear Resonance Fluorescence and Effective-Z (EZ-3D^{TM})Determination; SNM DetectionUsing Prompt Neutrons from Photon Induced Fission; William Bertozzi, Richard Hasty, Alexei Klimenko, Stephen E. Korbly, Robert J. Ledoux and William Park; **CP1099**, Application of Accelerators in Research and Industry:20th International Conference, edited by F.D.McDaniel and B.L. Doyle; AIP Conference Proceedings **1099**

W.Bertozzi, J. A. Caggiano, W. K. Hensley, M. S. Johnson, S. E. Korbly, R. J. Ledoux, D. P. McNabb, E. B. Norman, W. H. Park, and G. A. Warren, Phys. Rev. C **78** 041601(C) (2008)

C. P. Sargent, W. Bertozzi, P. T. Demos, J. L. Matthews, and W. Turchinetz, *Prompt Neutrons from Thorium Photofission*, Phys. Rev. **137**, B89 - B101 (1965)

Higher energy, higher intensity accelerators are required

- Low duty cycle RF LINACs traditionally used for transmission radiography (measurement of energy deposition for photons ≥ MeV)
  - duty cycle is typically limited to a value of approximately 10^{-3} (microsecond beam pulses at ~300 Hz rates)
- Innovative technologies that provide material discrimination capabilities rely on single event counting and spectral analysis require much higher duty cycles
- Higher duty cycle DC beams can be obtained from electrostatic machines, but require a large footprint limiting their mobility and broad application.
- High initial and operating costs for commercial high duty cycle machines (e.g. IBA Rhodotron)

Applied accelerator types

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)

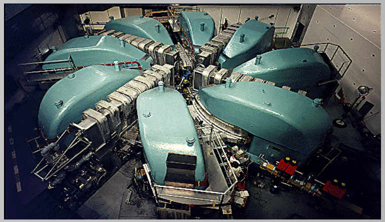
Pulsed Beam

Cyclotron

High Current (<A)

Low Energy (600MeV)

CW beam



Linac

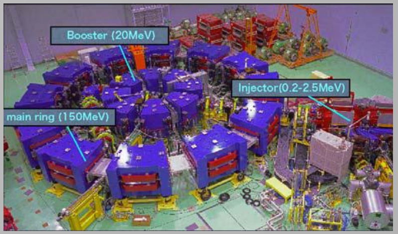
High Current, High Energy

Pulsed or continuous beam: Large, expensive

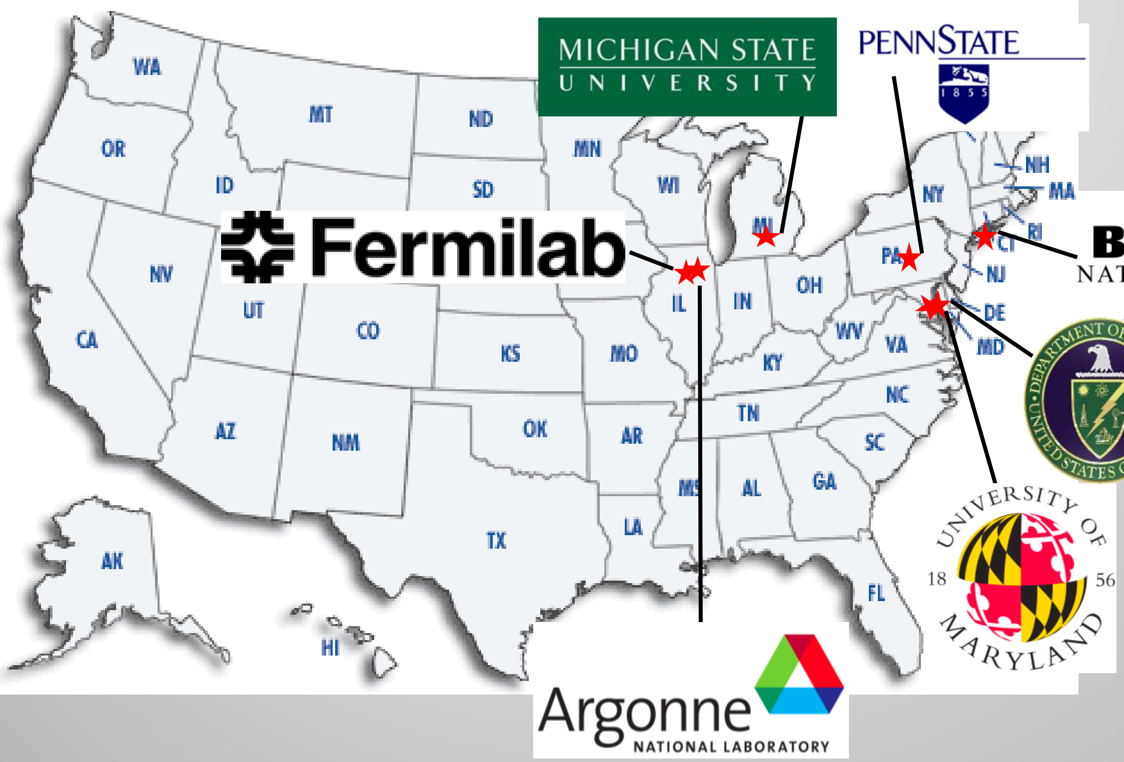
FFAG

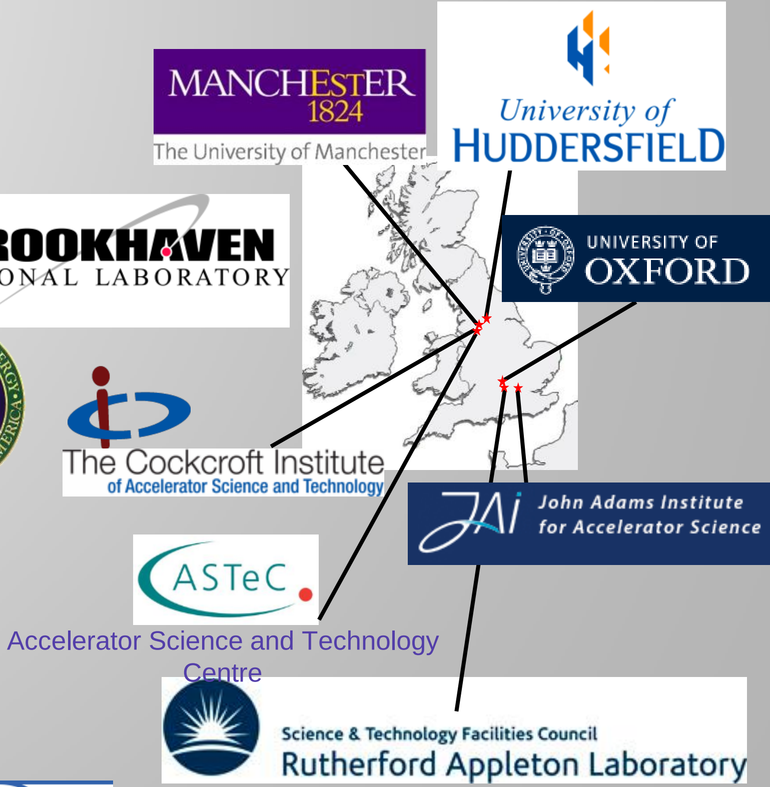
High Current (<A) , High Energy (few GeV)

CW beam, compact



The international FFAG collaboration





KURRI Kyoto University Research Reactor Institute

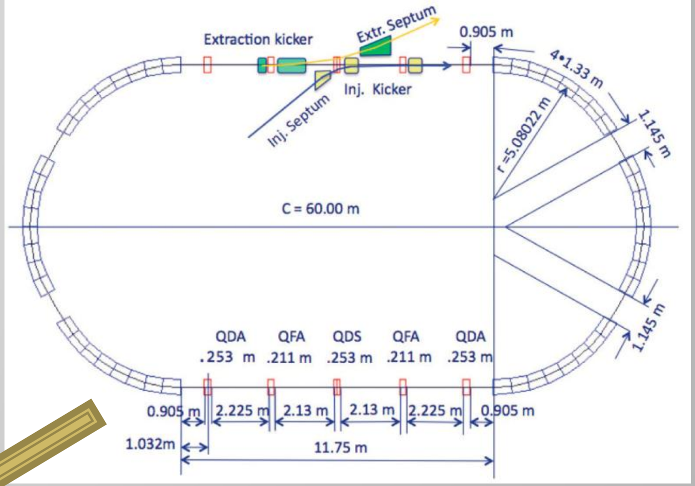
KYOTO UNIVERSITY

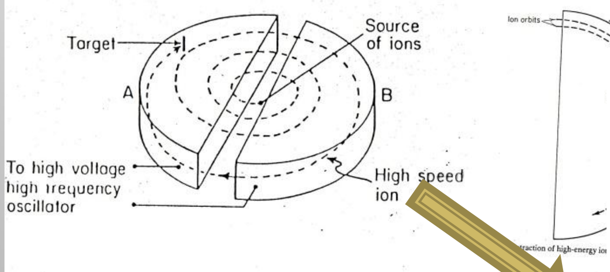
OSAKA UNIVERSITY

CERN

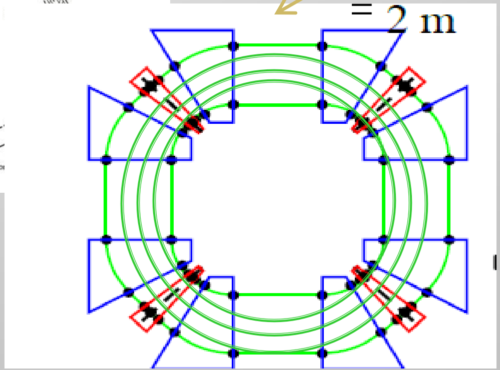
Next generation high duty cycle Accelerators

- Apply a “synchrotron” strong-focusing field profile to each “cyclotron” orbit
- Strong-focusing allows
  - Strong RF acceleration
  - Low –loss profile of the synchrotron
  - CW beam to high energies in compact structure
  - Avoidance of unstable beam regions
    - constant machine tune





straight = 2 m



CONSTANT MACHINE TUNES AT NEAR AND FAR RELATIVISTIC ENERGIES

UNLIKE A CYCLOTRON

Focusing in Conventional Accelerators

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

$$1/f_F = \overbrace{k_F l}^{\text{Synchrotron and linac}} + \overbrace{\frac{\vartheta}{\rho_F} + \frac{\eta}{\rho_F}}^{\text{cyclotron}}$$

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 FFAG

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)

A cyclotron is a dipole-only FFAG with no reverse gradients

Types of FFAGs:

Scaling:

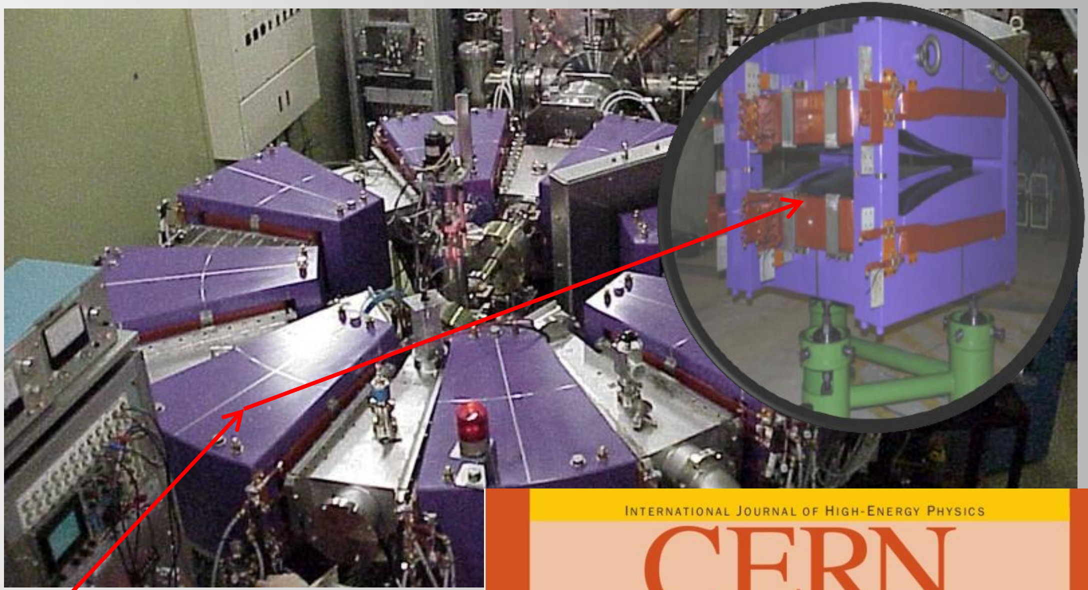
- B field follows a scaling law as a function of radius - r^k (k a constant;) present-day scaling FFAGs: Y. Mori, Kyoto University Research Reactor Institute

Nonscaling:

- Linear (quadrupole) gradient; beam parameters generally vary with energy (EMMA FFAG, Daresbury Laboratory, first nonscaling FFAG)
- Nonlinear-gradient; beam parameters such as machine tune can be fixed (as in a synchrotron)

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 ∝ r^k, with *r* as the radius, and k as the constant field index.

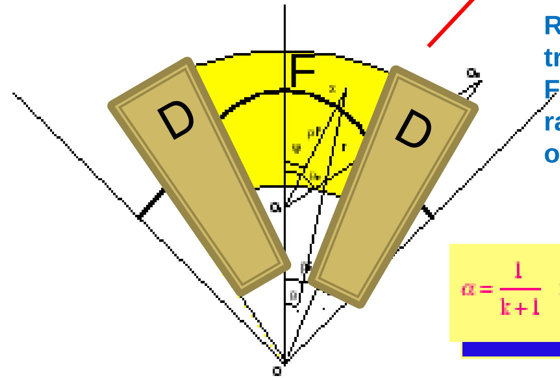


Spiral Sector: example: more compact; positive bend field only. Vertical focusing controlled by edge crossing angle.

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

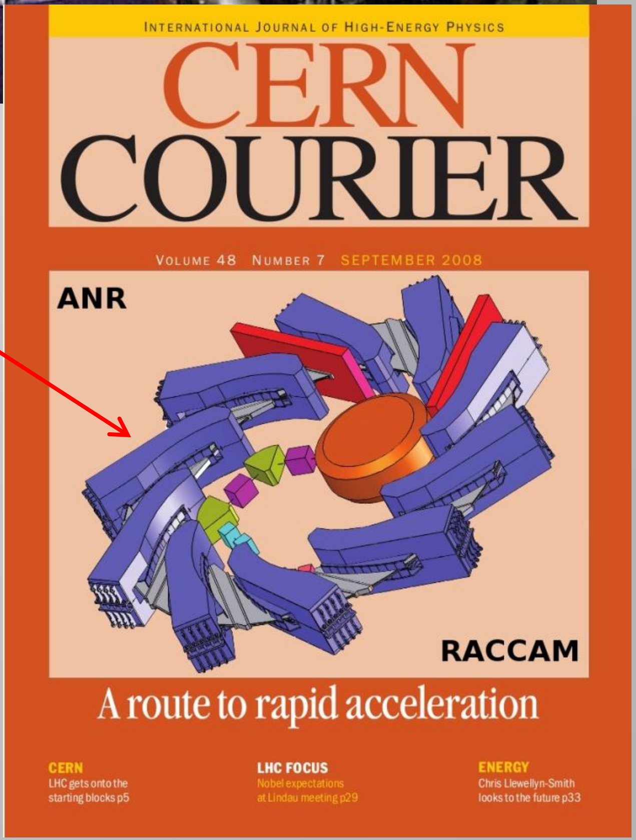
Field expansion: k determines multipole order;

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.



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.

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


INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

CERN COURIER

VOLUME 48 NUMBER 7 SEPTEMBER 2008

A route to rapid acceleration

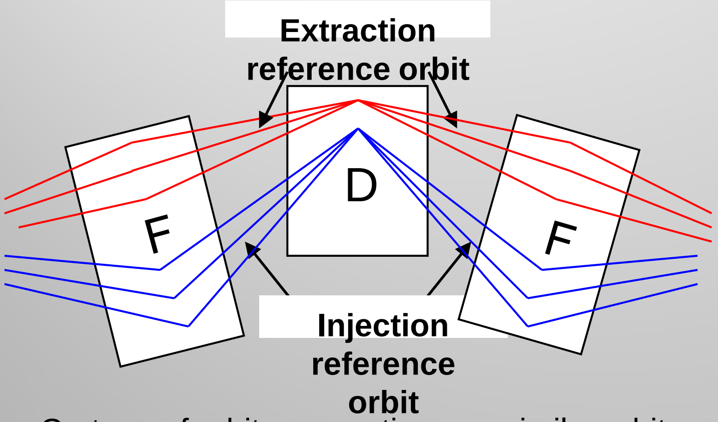
CERN
LHC gets onto the starting blocks p5

LHC FOCUS
Nobel expectations at Lindau meeting p29

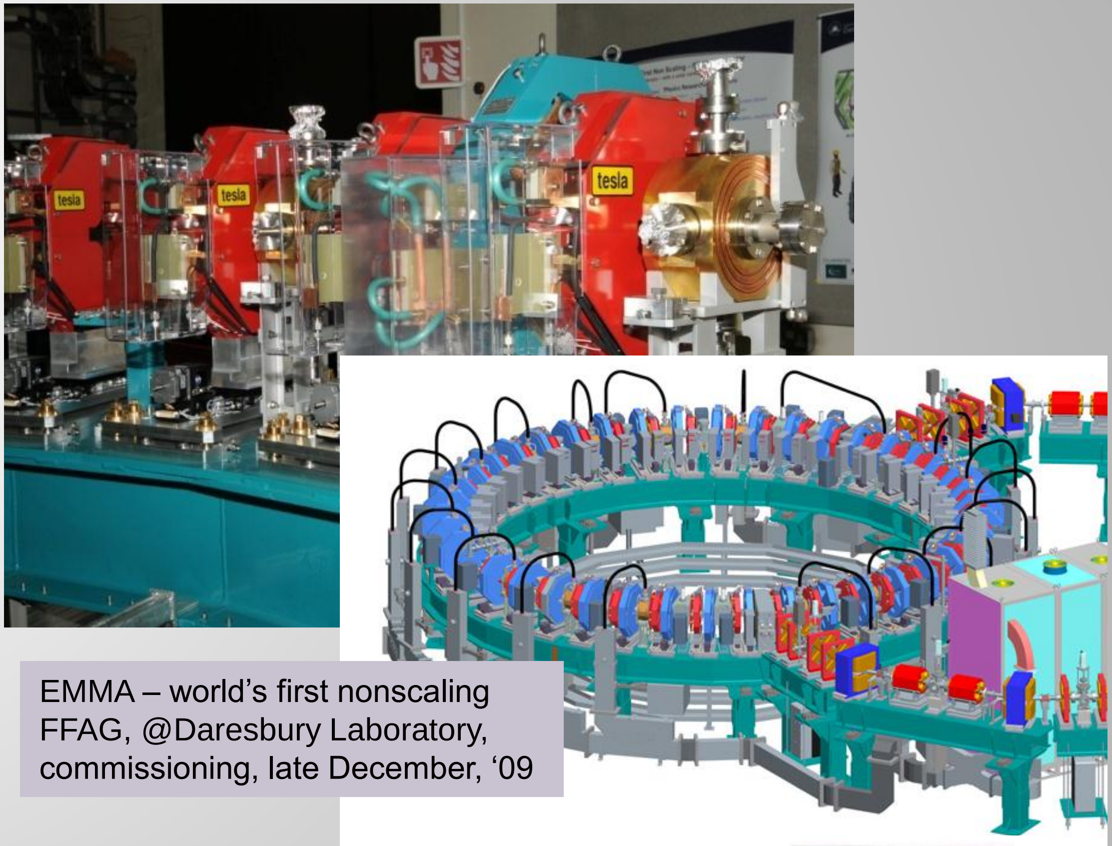
ENERGY
Chris Llewellyn-Smith looks to the future p33

Linear nonscaling FFAGs for rapid acceleration

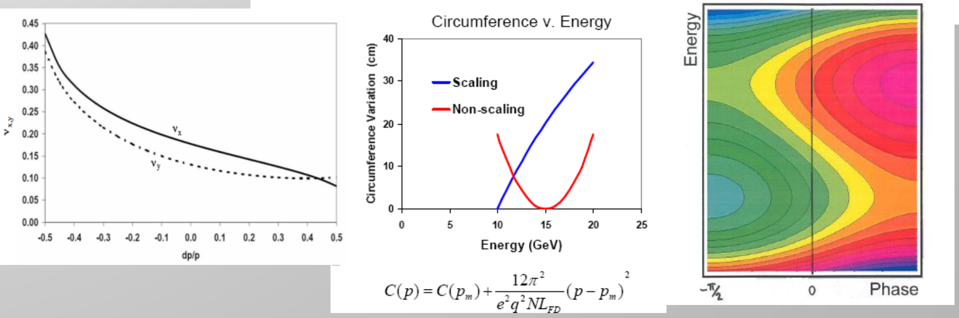
Linear-field, nonscaling FFAG. Ultra-compact magnet aperture, proposed and developed for High Energy Physics (Neutrino Factories and Muon Colliders), relaxes optical parameters and aims only for stable acceleration. In general they are not suitable for an accelerator with a modest acceleration system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



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



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



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

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

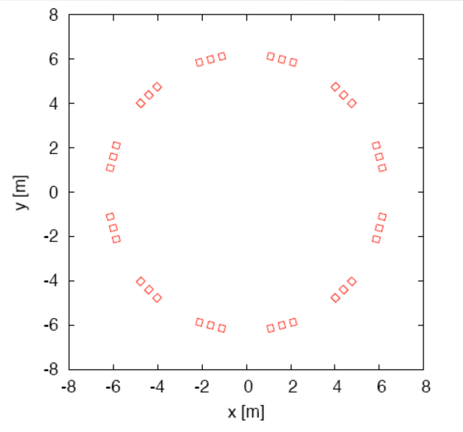
Tune-stable nonscaling FFAGs for slower acceleration

Tune-stable, nonscaling FFAGs

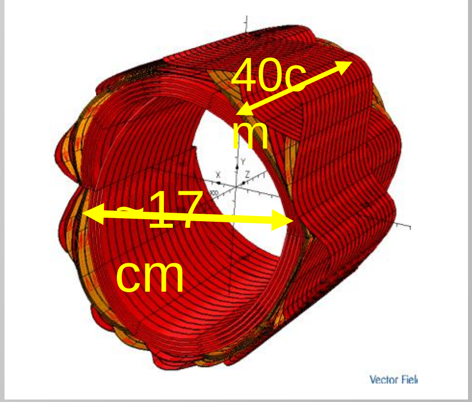
- Tune is strongest indicator of stable particle motion – allowing particles execute periodic motion eventually returning to the same transverse position relative to a reference orbit. Constraining the tune can be sufficient to design a stable machine.
- Release of other linear optical parameter allows flexibility and optimization both in cost and complexity of the accelerator design; i.e. simpler magnets, strong vertical focusing, for example
- ***Tune Stable Nonscaling FFAGs have either linear or nonlinear field profiles and/or edge contours***

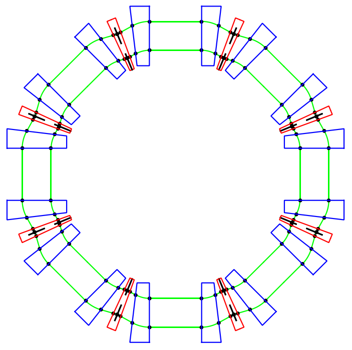
Two lattice approaches

1) Machida version - which uses a scaling law truncated at decapole, rectangular magnets , (not discussed here, see PAMELA project) and
2) Johnstone version – The most general form of a radial sector : allowing independent, unconstrained field and edge profiles between two combined-function magnets.

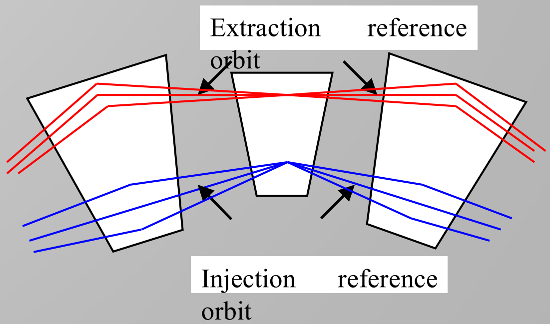


1

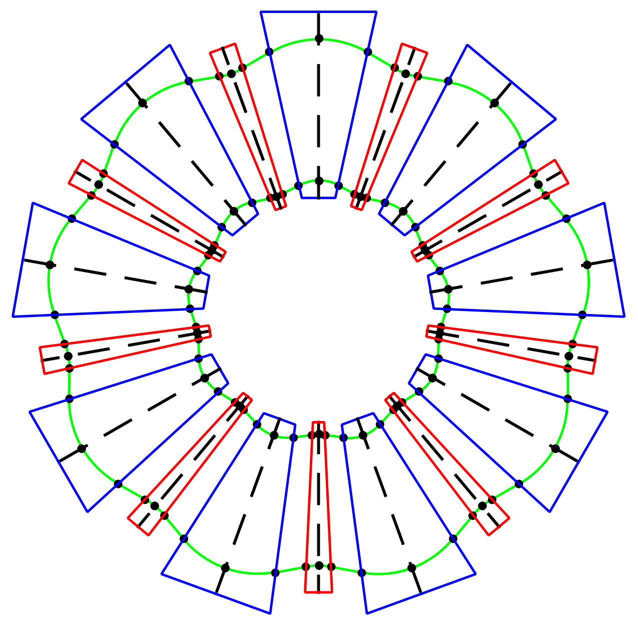




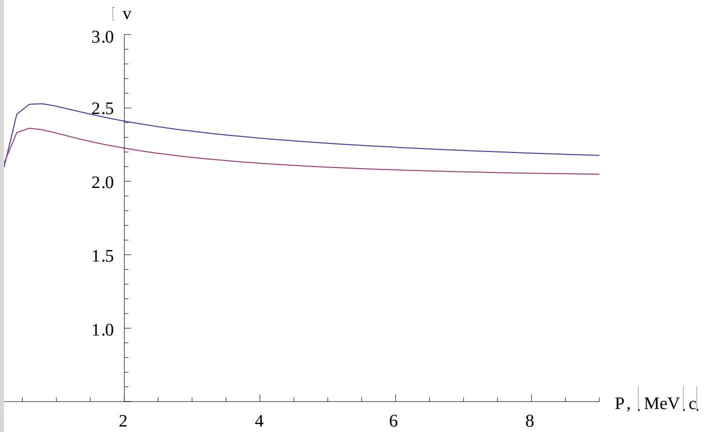
2



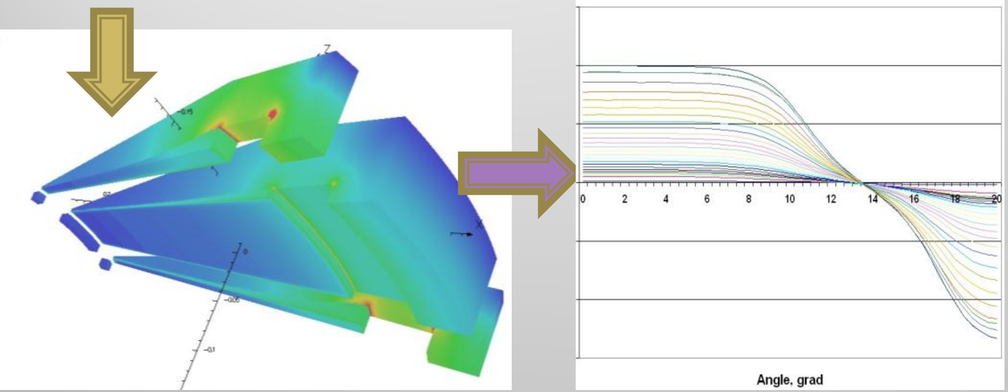
A 50 keV to 9 MeV Compact eFFAG



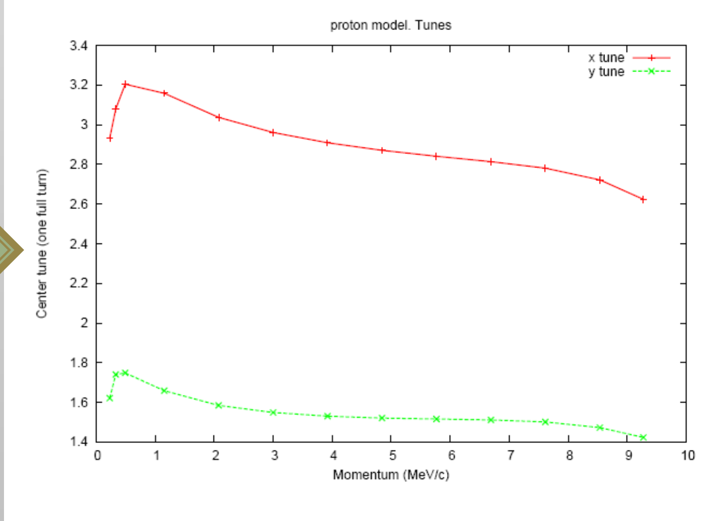
Full 9-MeV ring with injection and extraction orbits displayed. Outer radius <50 cm



COMPARISON Tune Results:
hard edge vs. extendedfFringe field



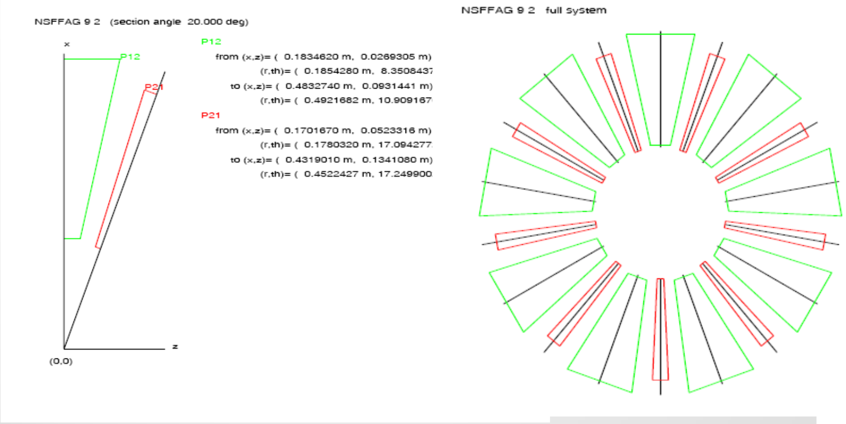
TOSCA Magnet Design and Field profiles.

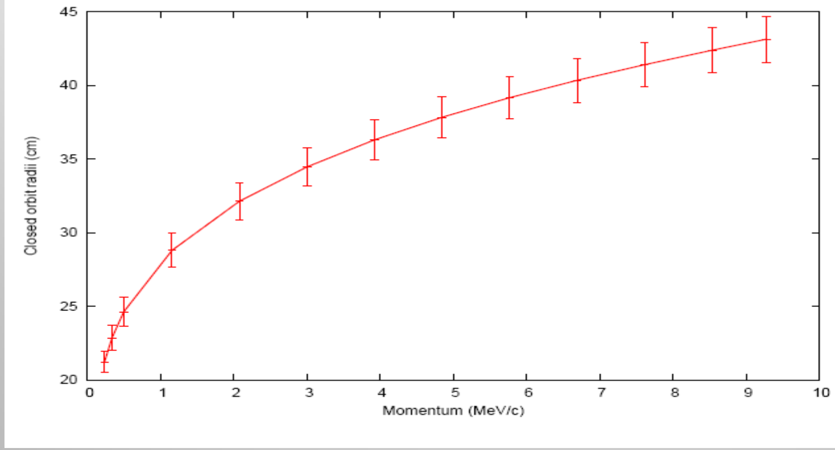


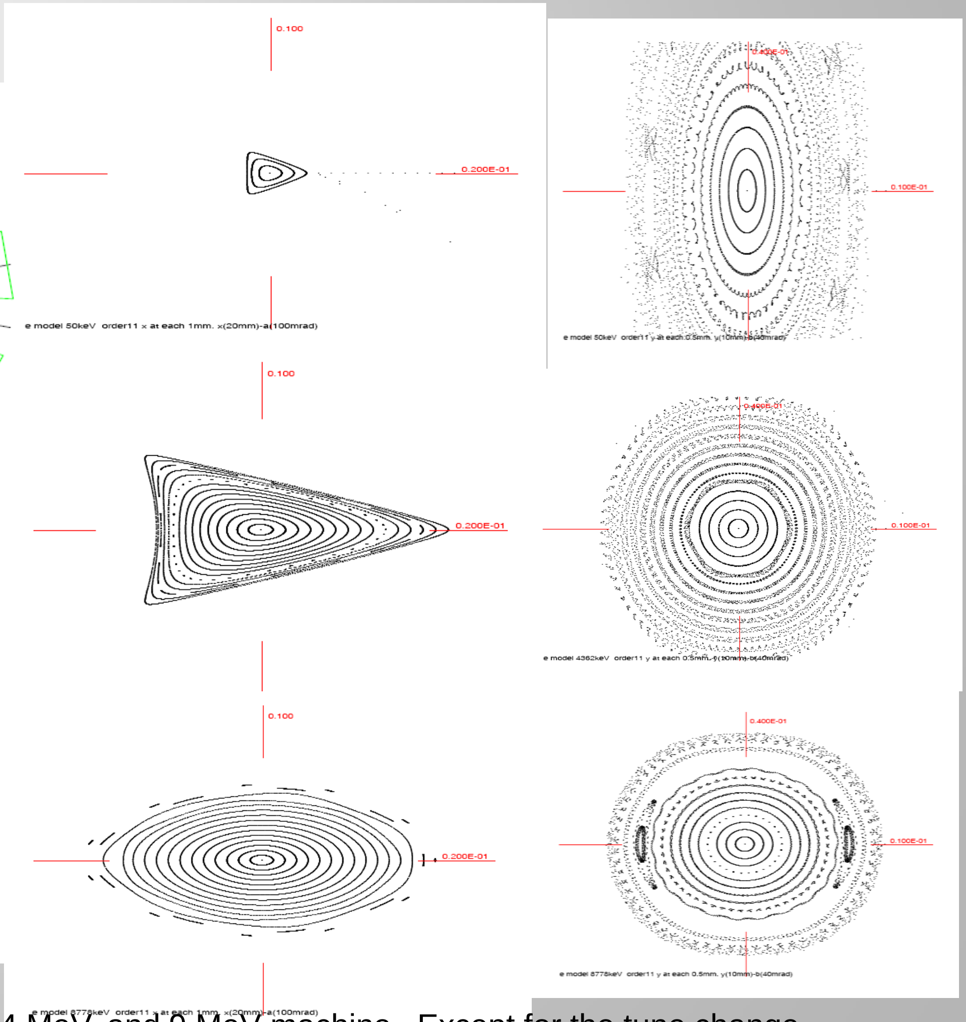
COSY INFINITY Tune Results

Originally designed for induction acceleration (~kHz cycle time)

Simulation: COSY Results: Electron Ring



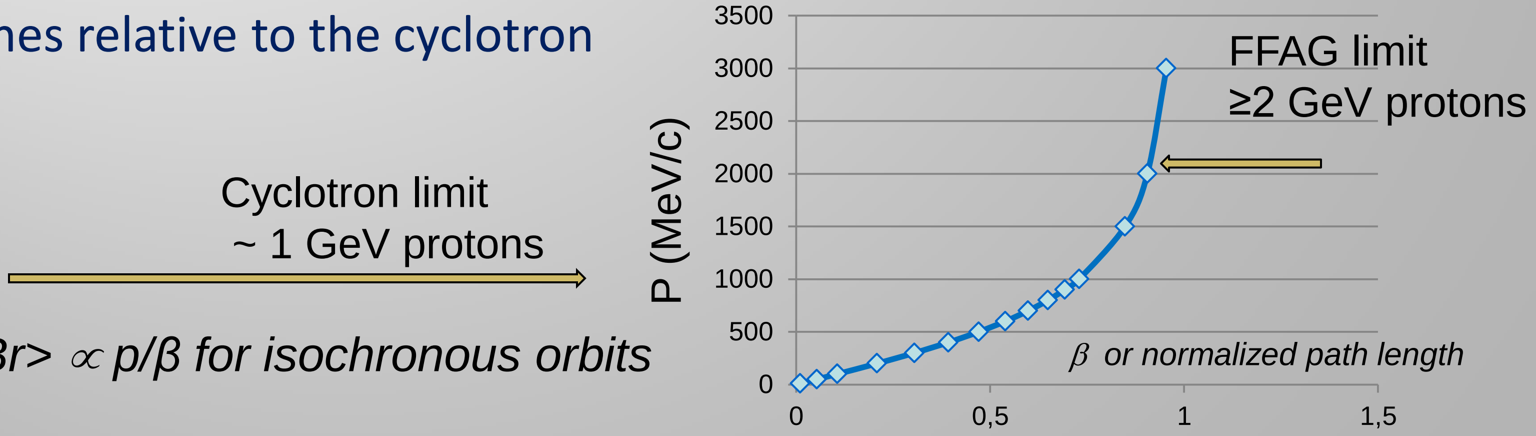




COSY results and tracking at 3 energies: 50 keV, 4.4 MeV, and 9 MeV machine. Except for the tune change required at horizontal injection, the DA is very large.

Relativistic CW (DC-beam) 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



*
 ∝ p/β for isochronous orbits*

The significance of CW Accelerators

A CW accelerator implies:

Fixed magnetic fields

- 50 Hz is the ~ practical technical limit for pulsed magnet systems
  - Stored power and expense of pulsed supplies can be commercially prohibitive

The simplicity of fixed-frequency rf

- the rotational frequency of orbits is a constant at all energies

Consequences of non-isochronous orbits

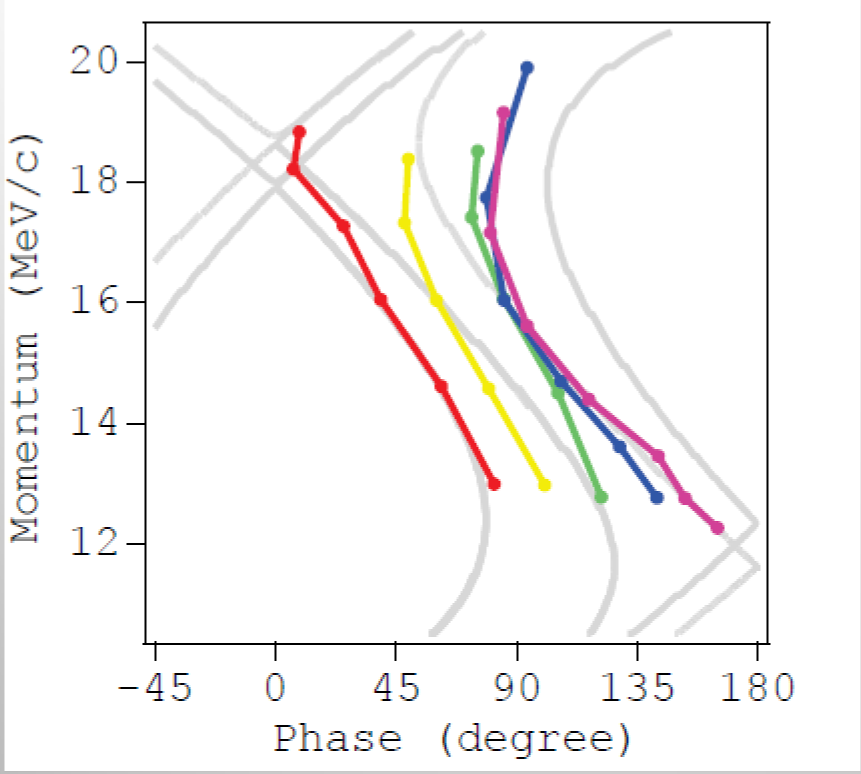
Beam is pulsed at the rf sweep rate, not continuous

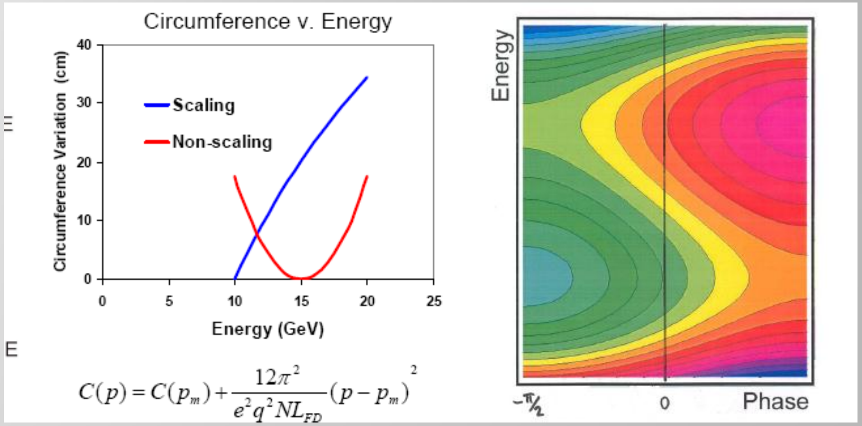
Swept-frequency rf (rf timing is changed to match the revolution time of the beam – the synchrotron and synchro-cyclotron)

- 50-100 Hz sweep rate for rf frequencies ≥ tens of MHz
- KHz sweep rate for broad-band rf (~MHz)
  - slow acceleration, high power consumption

Serpentine channel Acceleration in a nonscaling FFAG

Acceleration in serpentine channel





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

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

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.

Serpentine CW acceleration in 50 keV – 9 MeV eFFAG

To be isochronous, constant revolution time

$$\langle R_{ext}\rangle / \langle R_{inj}\rangle = \beta_{ext} / \beta_{inj}$$

For this design

$$\langle R_{ext}\rangle \sim 43\ cm,\ \beta_{ext} = 0.4127$$

$$\langle R_{inj}\rangle \sim 19\ cm,\ \beta_{inj} = 0.9985$$

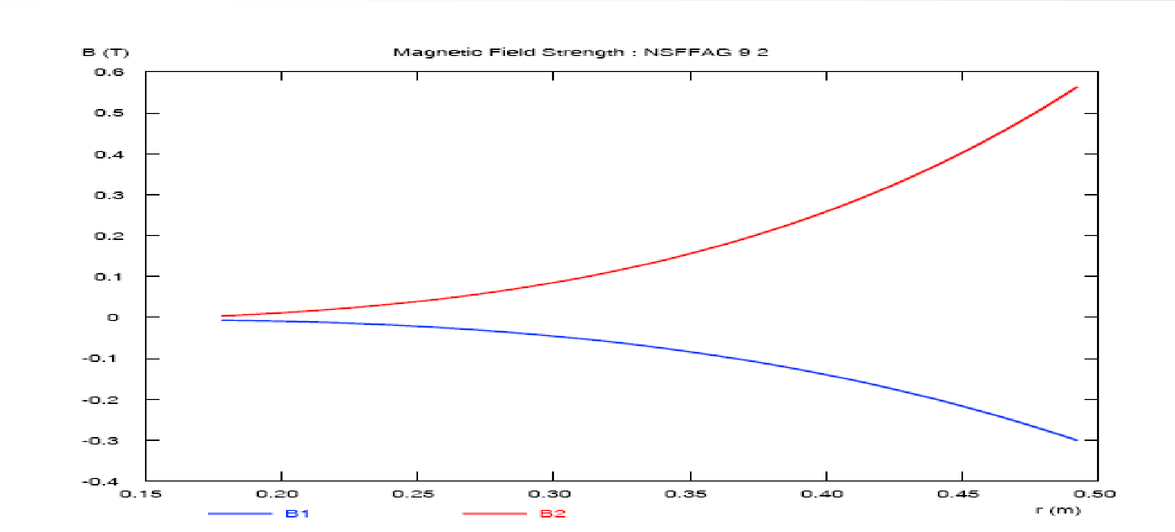
$$\beta_{ext} / \beta_{inj} = 0.4133$$

$$\langle R_{ext}\rangle / \langle R_{inj}\rangle = 0.4418$$

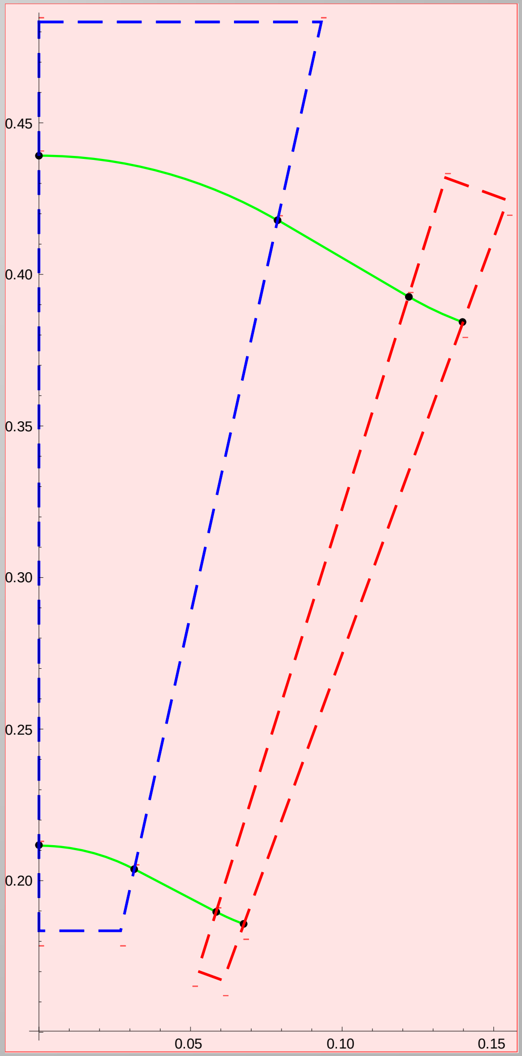
Isochronous to ***~±1-2%***

Conclusion: serpentine channel can be used for 50-100 turn acceleration as designed

Magnetic components and fields for a half cell



Magnetic field profile F and D



Half cell injection and extraction orbits

RF acceleration system and estimated output power

- A single 100-200 keV cavity gives 45-90 acceleration turns
  - Single Dee Cavity as in cyclotron
  - Dummy Dee on other side
- Can use the serpentine channel for acceleration
- Duty cycle: *1ns/10 ns ~10%*
  - Factor of 100 increase
- Space charge limited to ~10^9 electrons/RF micro bunch
- For fundamental, 100 MHz cavity (10 ns bunch spacing)
  - 1.6 mA, ~140 kW CW beam

Innovation: permanent magnets

The level of specified magnetic fields (<0.4 T) permits the use permanent magnets. Permanent magnets have the following advantages:

- Do not need power supplies;
- Do need a cooling system and water;
- Low magnet system cost and simple industrialization;
- No hysteresis effects, remnant fields, degaussing, etc.;
- More field concentration under magnet poles;
- Magnets without coupling to AC fields.

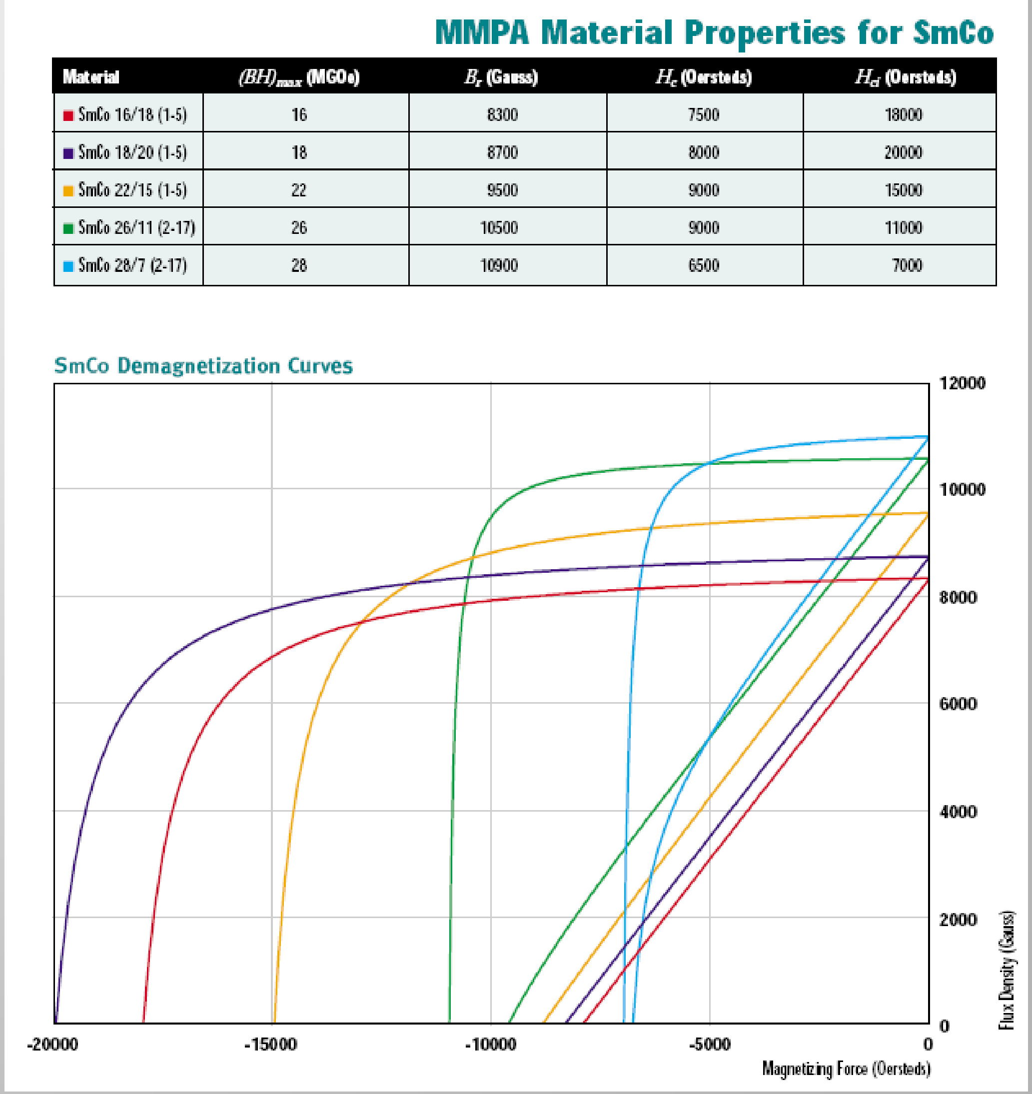
However the following issues require control or resolution

- Magnets calibration;
- Thermal effects control;
- Adjust or correct the field.

For this magnet system, permanent magnets based on: ceramic ferrites, SmCo5 or NdFeB permanent magnets could be used.

SmCo chosen for permanent magnet material

- Although NdFeB magnets B fields up to 1.35 T.
  - have lower temperature stability than SmCo
  - must be rust protected by thin Ni coating.
- SmCo with B fields just over 1T.
  - most stable to the temperature change and radiation.
  - Used in linear accelerators.
  - high energy concentration in a small volume

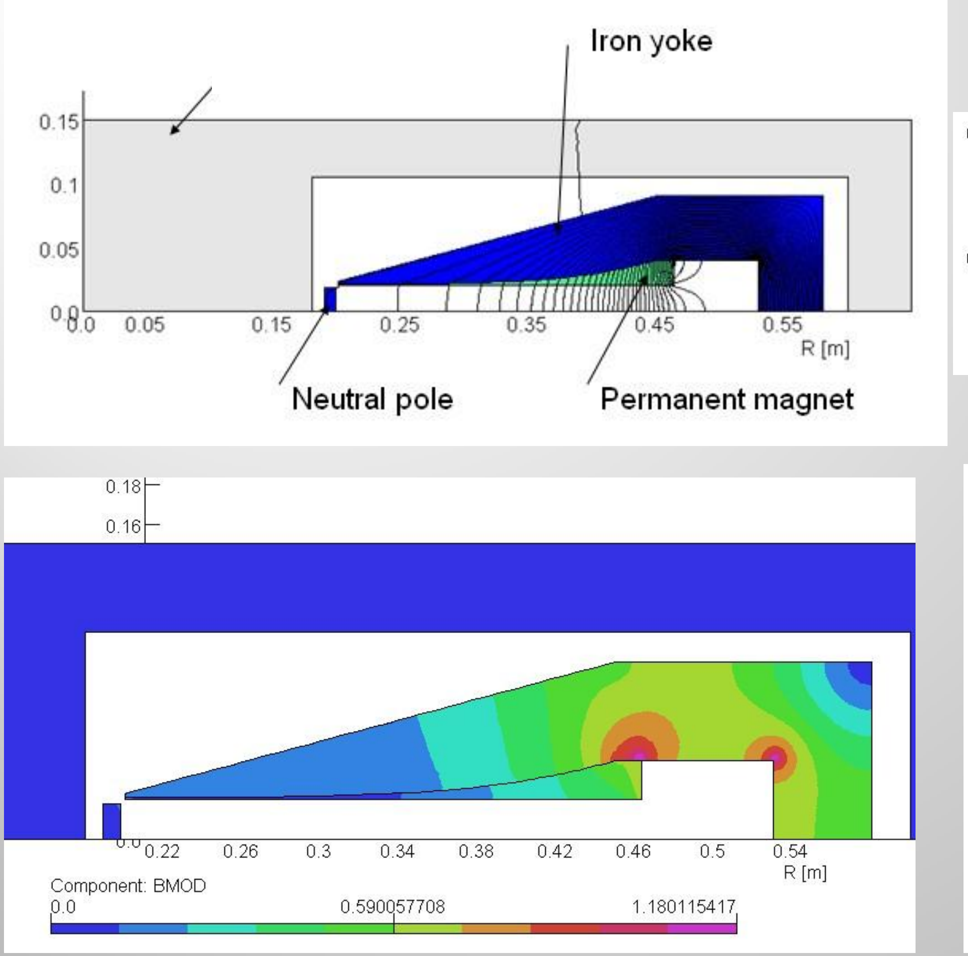


MMPA Material Properties for SmCo

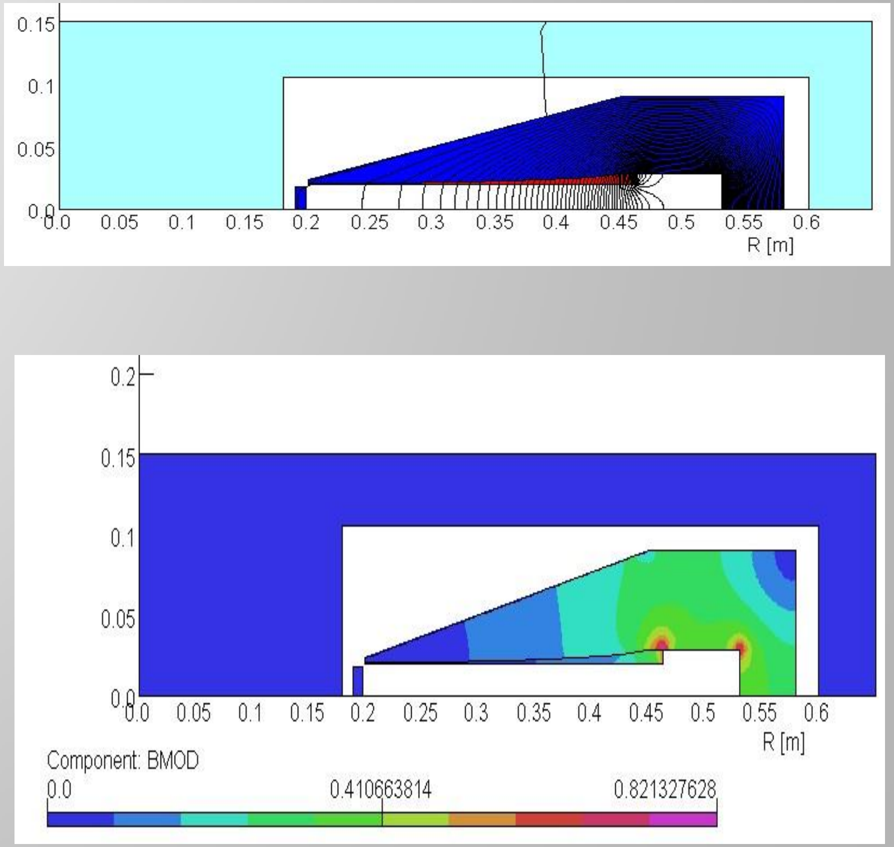
Material	$(BH)_{max}$ (MGOe)	B_r (Gauss)	H_c (Oersteds)	H_{ci} (Oersteds)
🟥 SmCo 16/18 (1-5)	16	8300	7500	18000
🟪 SmCo 18/20 (1-5)	18	8700	8000	20000
🟧 SmCo 22/15 (1-5)	22	9500	9000	15000
🟩 SmCo 26/11 (2-17)	26	10500	9000	11000
🟦 SmCo 28/7 (2-17)	28	10900	6500	7000

SmCo Demagnetization Curves

F and D Magnet design and fluxes

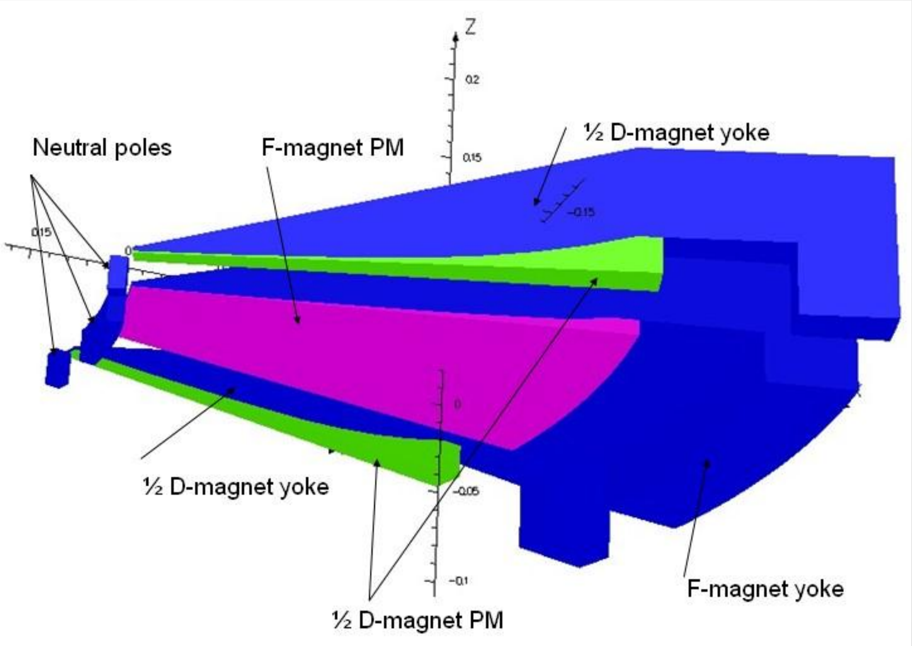


D-magnet geometry and flux lines (top) and flux density in poles (bottom)

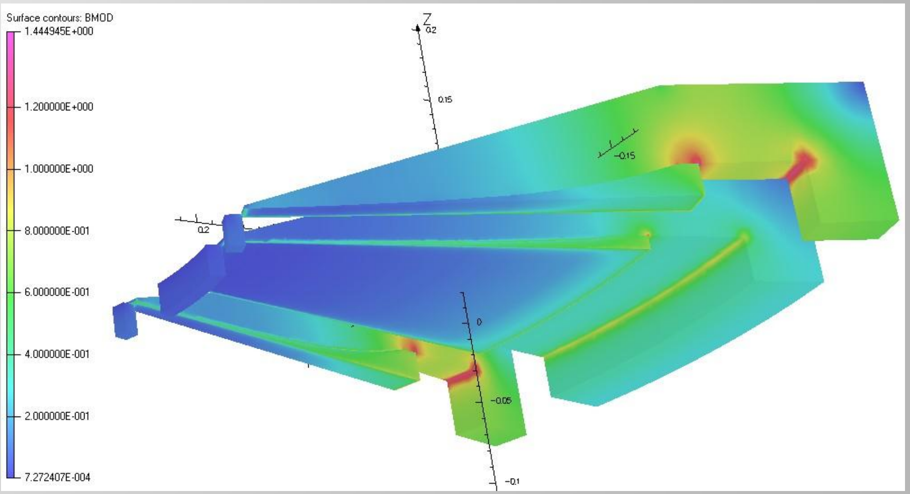


F-magnet geometry and flux lines (top) an
flux density in poles (bottom)

Overview of magnet system

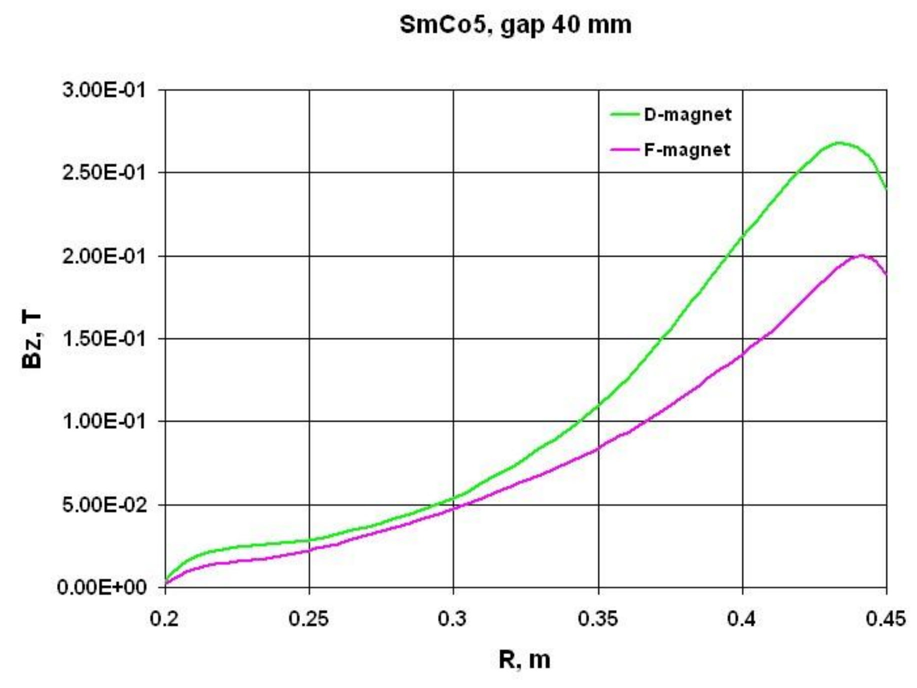


One cell of 3D Model geometry view (upper part from middle plane).

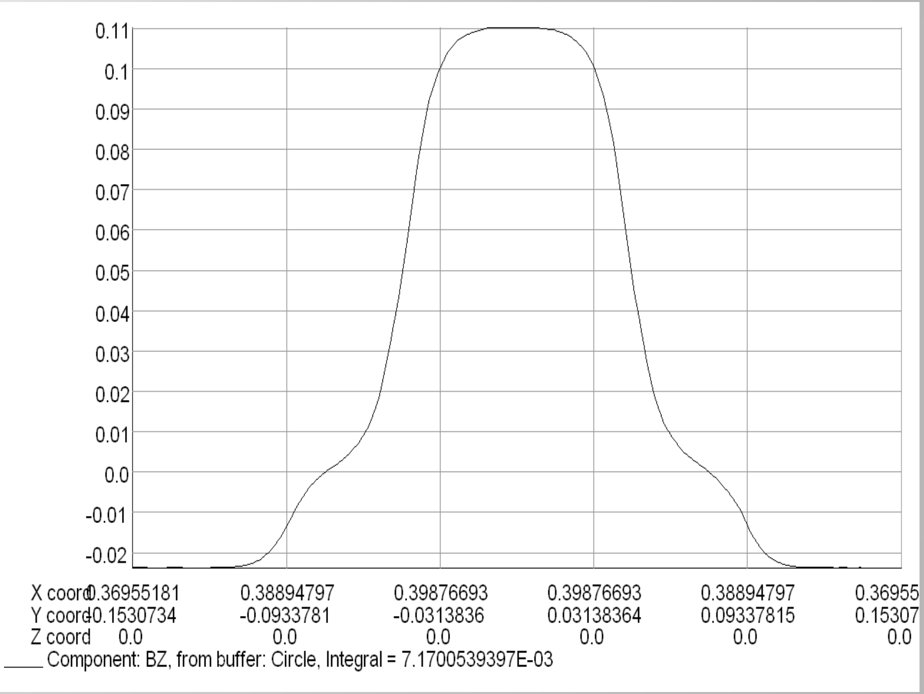


Flux density distribution in the magnet yoke and SmCo5 PM material.

Magnetic field profiles



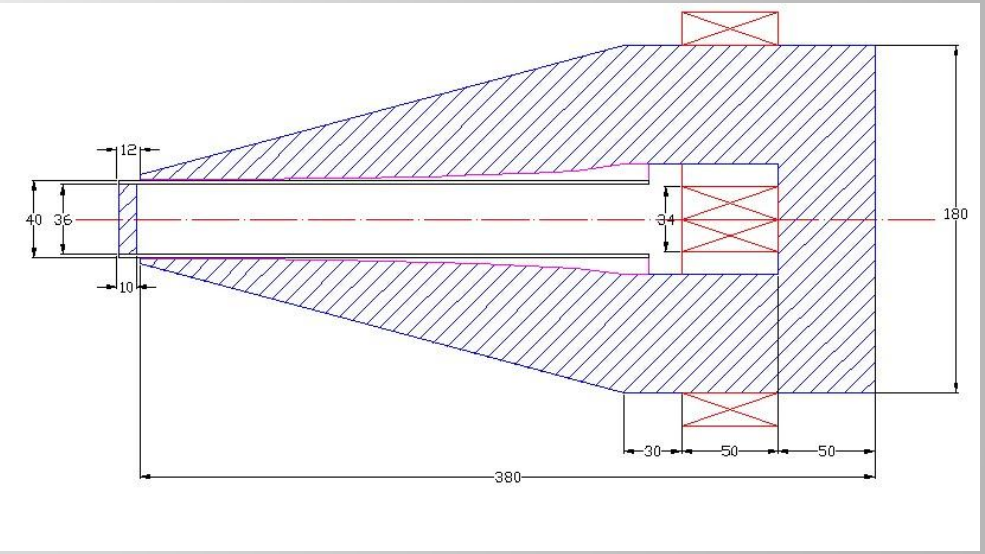
Bz field distribution in radial direction for the D and F magnet vertical center planes (SmCo5, 40 mm gap)

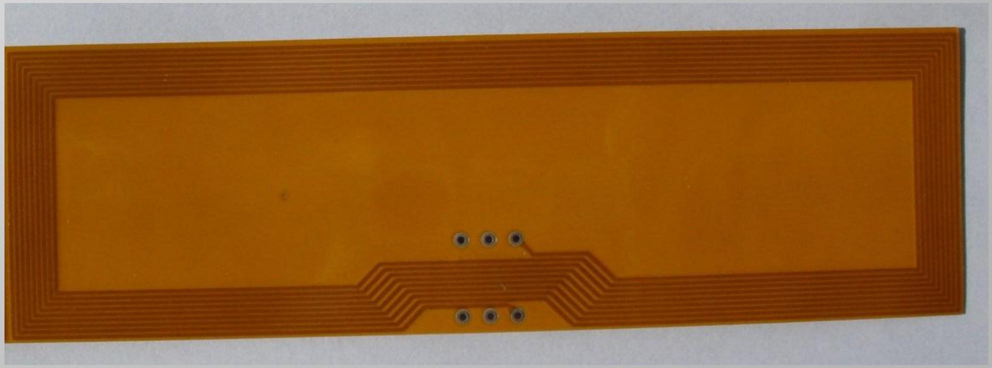


Bz field in the middle plane on arc +/-22.5º with radius 0.4 m (extraction).

Correction coils

- The main correction coils mounted on the return yokes and installed through the magnet air gap.
- They correct the field peak value.
- There may be installed also pole coils for fine field tuning at injection radius.
    - For this, a printed board technique could be used as shown





Strong market case for compact CW effags

Compact, 1m diameter, transportable

High current – 1-2 mA projected

No power supplies

Inexpensive components