A Multi-ion CW FFA for Medical Radioisotope Production

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Abstract

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An isochronous separated-sector cyclotron with a focusing field gradient has been designed to accelerate light ions with a charge-to-mass ratio of ½ up to 15-20 MeV/u, extendable to 30 MeV/u. The design can support a host of applications for therapy, radiobiology, material science, and instrumentation development. The light ions species, which can include a mixed ion beam, can be dynamically chosen to provide a range of characteristic signals appropriate for specific material identification and all medical radioisotopes can be produced. With large turn-to-turn orbit separation and a novel extraction channel, low-loss beam extraction is supported without the need for charge-changing through a foil. The design concept is optimal for production of radioisotopes such as alpha emitters and theranostic radiopharmaceuticals and is scalable in gross physical parameters to realize a smaller, lighter potentially transportable system to advance new approaches in security applications. In addition to the FFA design principles, the FFA is especially suited for internal isotope production targets which will be presented briefly.

This work was supported by the US Department of Energy, under SBIR grant DE-SC0020009.

Theranostics and radioisotope production

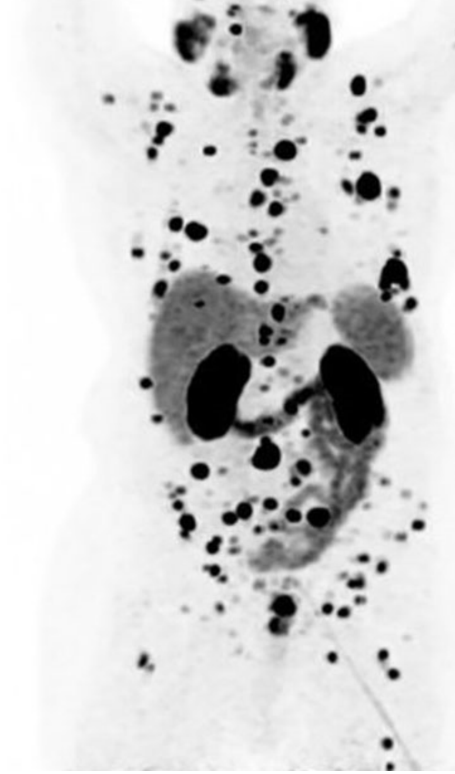
Theranostic radiotherapy combines radioisotopes for diagnostics and therapy.

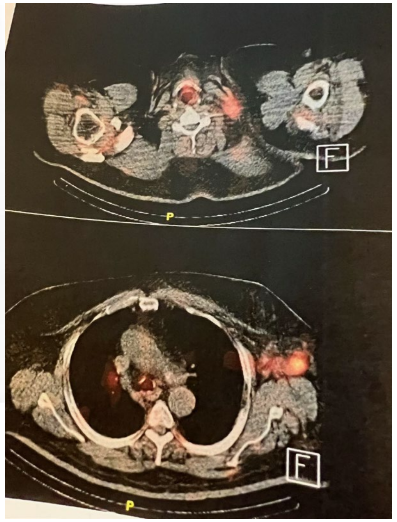
- *Antibody which specifically attaches to prostate cancer cells, called Prostate Specific Membrane Antigen (PSMA), is radiolabeled with Ga-68 or Lu-177.*
  - Ga68 lights and identifies metastasized prostate cancer cells in a diagnostic PSMA PET scan.
  - Lu177 is a β-emitter when administered after a scan kills the cancer cells.
    - Lu177 is also a low energy γ-emitter which can be used in a diagnostic SPECT scan and is one of the true theranostic radioisotopes.
    - A stronger therapeutic radioisotope is Ac225 which can be used in place of Lu177 (more side effects).
- *Lu177 and Ac225 can be produced by deuteron and proton radioisotope accelerators, respectively.* ***A commercial radioisotope facility is planned for the Ion Campus Complex to produce Lu177 and Ac225***

Lu177 is currently produced in reactors and there is a global shortage –

most common medical radioisotopes are produced in nuclear reactors. Currently there is not a commercial high-current ion radioisotope production accelerator.

PSMA PET scan (Ga-68) showing metastatic prostate cancer

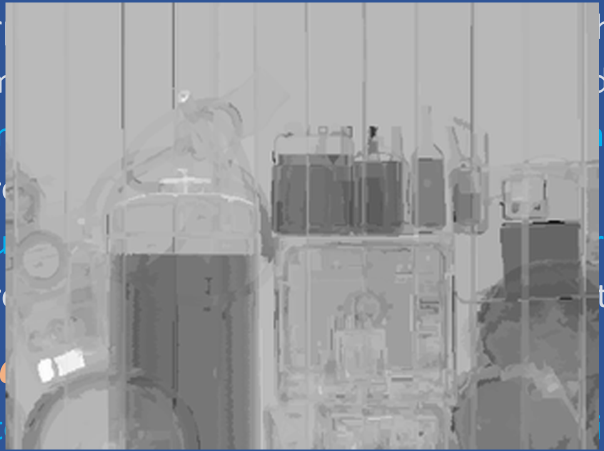


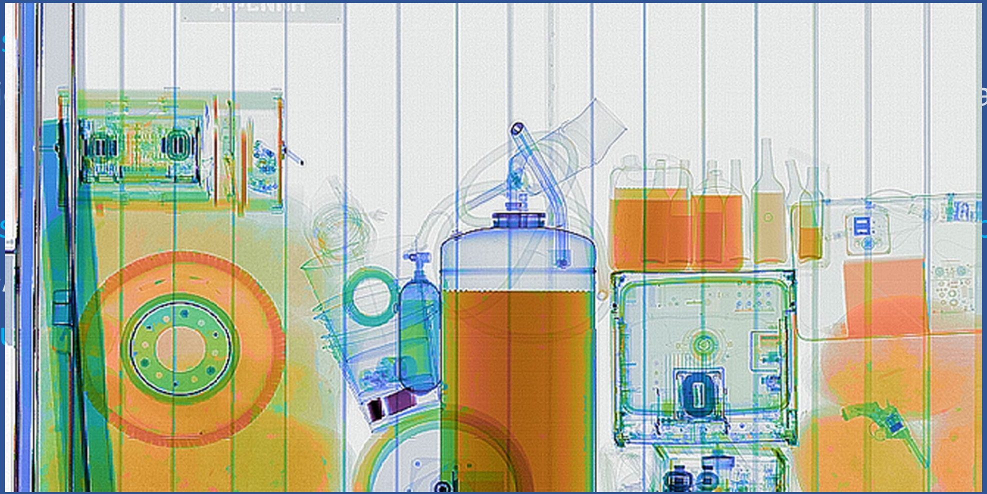


SPECT scan (Lu177) showing metastatic prostate cancer

Applications of a Light Ion, (Q/A ≅ 1/2) ISO-FFGA

- ***The capability to produce high current, low loss, extracted external beams, of different ion species, is an enabling technology for nuclear security, Isotope production, medical, and material science applications***
- ***Nuclear Security***
  - Interrogation and radiography using high-energy, monoenergetic gammas (produced via excitation of nuclear states)
    - Absor hibiting a strong dependence on Z – identifying Special Nuclear Materials
    - Gamm d transmission (Nuclear Resonance Fluorescence – spectroscopy & timing)
  - Fast monoer s on targets
    - Neutr
  - Simultaneou ron beams
    - Neutr trons indi al)
- ***Isotope Produ***
  - Medical Isot oisotopes py
    - ^{225}Ac is produced using a proton (H-, H_2^+) beam and ^{211}
  - Isotopes for material science, nuclear medicine, imaging, secu
    - Wide range of ion beams with Q/A ~ ½, fast switching
- ***Radiobiology***
  - Cell irradiation by different light ions - measure RBE vs LET and tumor/normal tissue damage response



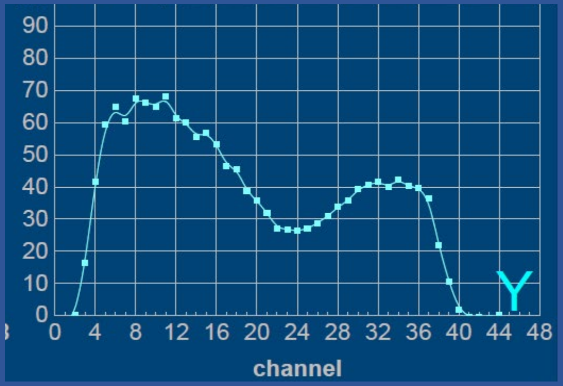


Base Design Specifications

- ***Gross specifications for a broad application base design concept***
- *Beam Specifications*
  - q/m=1/2 Ion beams supported: H_2^+(p), D^+ , He^{2+},Li^{3+},B^{5+},C^{6+},N^{7+},O^{8+}, Ne^{10+}, S^{16+} , Ca^{20+}
    - 15-20 MeV/u for high-energy gamma and neutron secondary production
    - High current, up to 1 mA for protons, (implies continuous wave (CW) or high duty-factor operation)
  - Multi-ion capability
  - Low loss extraction into an external beamline (allows locally shielded target vault, lower radiation dose for machine maintenance)
  - Individual turn extraction capability – overlapping turns not extracted for timing resolution (for imaging)
    - High acceleration gradient (specification is 400 keV/turn)
- *Operational Specifications*
  - High, >90% machine reliability (specification given for most medical, commercial, and security applications)
    - Turnkey or least low overhead operation (fixed field, fixed frequency machines lowest overhead << synchtrotrons)
  - Normal conducting for reliability, high currents *(SC quenching is not sustainable in a security, medical , or commercial isotope facility)*
- *Gross Parameters*
  - Small footprint– w/o charge changing extraction - depends on turn-to-turn separation requirement and current
    - Space charge effects start to dominate and increase beam size ~500 μA
  - Transportability – size and weight (different current regimes for degree of compactness)
    - Variants for different applications

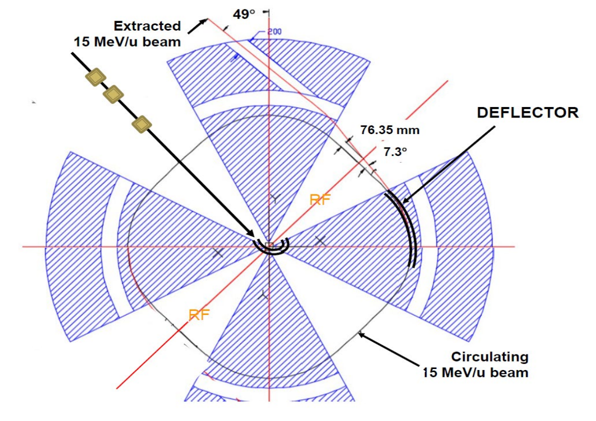
Injection Subsystems

- ***Injection occurs at ≥0.5 MeV/u to eliminate the lossy central region***
- *Pre-accelerator and Injection Line*
  - Tandem eliminated due to contamination from different ion charge states
  - Variable-frequency ion RFQ chosen; ≤1% tunable frequency range needed
    - HZB RFQ has been acquired accelerates Q/A > 0.15 with (85-120 MHz, tunable)
  - Beam from the RFQ is transported and re-bunched
    - Enters inner region of FFGA between sector magnets
    - A "booster" CW DTL appears required for clean injection (~4 MeV/nucleon)



HZB ion beams – two species due to incomplete stripping in tandem

- *Injection into FFGA – preliminary design*
  - Injection into the ring initiated between sector magnets
    - 3 inflectors, ~5MV/cm , 15 mm plate separation.
    - Injection occurs at 0.28 m radius in the base design
    - Ring center outer radius~0.1 m
    - Magnetic shielding and end mirror plates will be needed

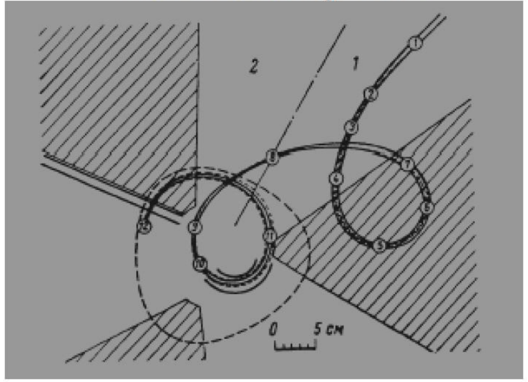


Notational sketch of injection line into the central region of the FFGA ring

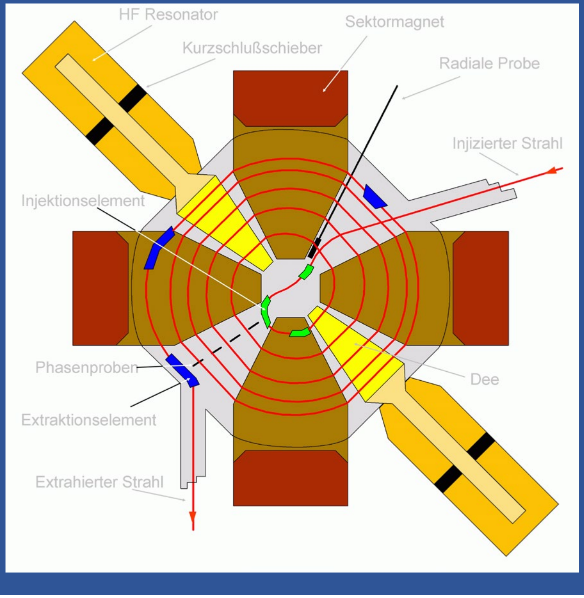
The Injection Issues

- ***Injection occurs at 0.5 MeV/u to eliminate the lossy central region***
- *RFQ ~ 2 x frequency of the ring; enormous momentum spread*
  - Operate buncher at cyclotron frequency
  - Bunch rotation – reduce momentum spread by ~ half
- *Fringe fields in the inner region of the ring*
  - Careful Shielding Design
    - Mirror plates at magnet ends!
    - Larger ring (yuck}
  - Longer injection magnet length
  - Higher Injection energy
    - Two RFQs (HZB injection approach)
    - Add a CW DTL
  - Larger ring (existing ion cyclotrons)

Horizontal Injection



Injection in the presence of uncorrected fringe fields

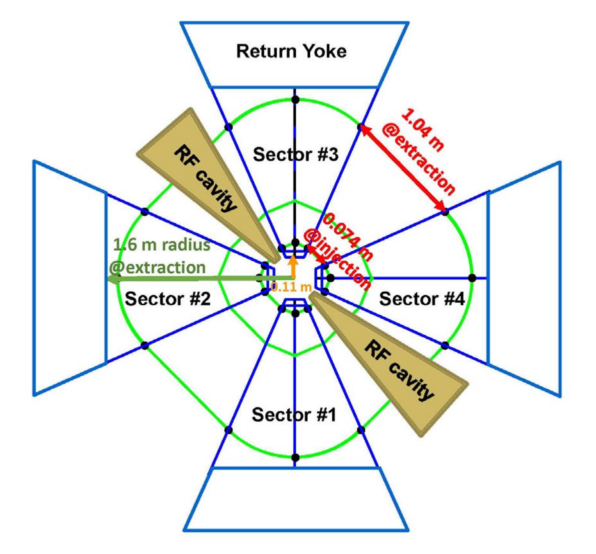


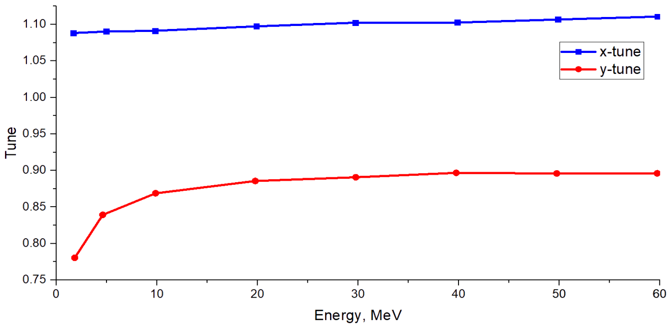
HZB ion injection

The FFGA ring (Fixed Field Gradient Accelerator)

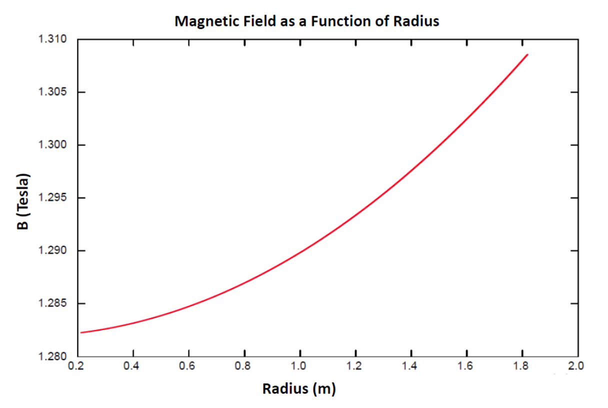
- ***Separated Sector FFA with a radial field gradient***
- ***Machine Layout***
  - 4 separated sectors with opposing high-gradient cavities
  - Meter component-free straight at 15 Mev/u facilitates low-loss extraction
  - Radial field gradient serves the same purpose as an azimuthally-varying field
    - Nonlinear radial gradient up to sextupole;
    - Provides 97° horz and ***a strong 80° vert phase advance***
    - Near 90° mitigates "odd parity" transverse "kicks" from opposing cavities
    - Linear edge limits the highest order feeddown– to octupole
    - Vertical tune falls as fringe fields overlap near injection energies
  - Acceleration uses 8th harmonic for Q/A of ½ (~45 MHz)
    - At 400 keV/turn, at extraction orbits are separated by 0.8 cm center to center

Layout of Ring



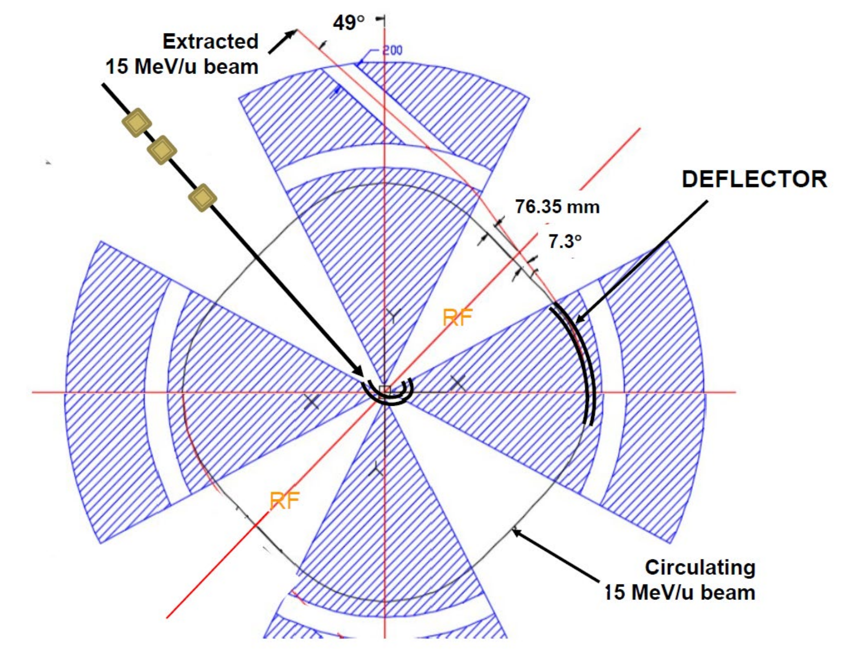


Nonlinear radial field gradient (lright) Machine tunes (right) for He^{2+} (left) predominately dipole at nonrelativistic energies; higher energies, radial gradient increases



Extraction

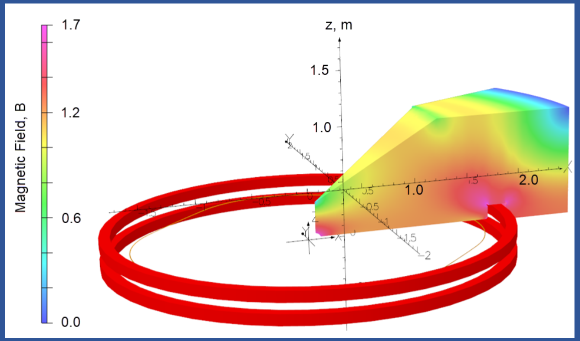
- ***Extraction occurs at 15 MeV/u. At this energy no extraction septum is required.***
- *Extraction System*
  - A meter-long 6.6 MV/m electrostatic deflector, 15 mm plate separation
    - On extraction orbit @1.6 m radius in upstream sector magnet
    - 90° upstream of extraction channel entrance
    - Betatron oscillation peaks at entrance to downstream sector magnet
  - 76 mm of radial displacement is achieved at downstream sector magnet
    - Beam enters and crosses the low-field, between-coil region
  - Extraction occurs through a 200 mm bore in the return yoke
    - Extraction system designed/modeled using TOSCA OPERA
- *Extraction line*
  - Extraction optics are known starting from the FFGA ring
    - External target beamline under design
    - Dispersion from the ring is high
  - To cleanly isolate and extract only the last acceleration turn
    - Radial collimation is required at low energy in the ring
    - Could exploit high dispersion from ring in external beamline for narrow dp/p
    - Space charge will broaden and flatten extracted beam



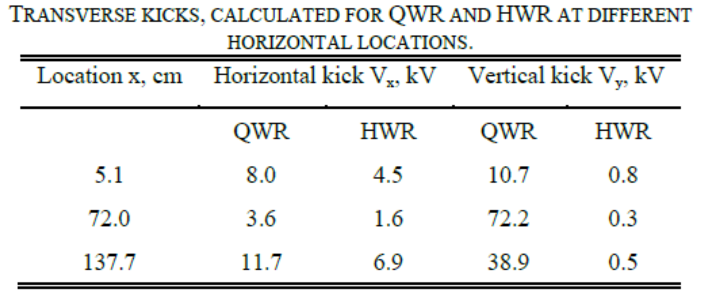
Layout of extraction from OPERA model and TOSCA tracking through return yoke

Magnets and RF

- ***Magnets and RF have been designed using OPERA to match the design lattice performance***
- *Magnet System Design*
  - All 4 sectors are excited by a coil fitted in top and bottom slots
    - The integrated field of the magnets matches the integrated design field
    - Integrated coil current is 18,500A (925A in water-cooled Cu coils)
    - Power consumption estimated to be 31.4kW
    - Further optimization can significantly reduce current magnet weight (42 tons)
  - Magnet gap is currently 40 mm although 50 mm is also dynamically stable
- *RF Cavity Design*
  - Two opposing HWR cavities, 200 keV/turn/cavity – HWR chosen for optics stability
    - Size and field uniformity dictated TEM-class double-gap coaxial line geometry
    - 45 MHz (8th harmonic), RF losses below 20 kW



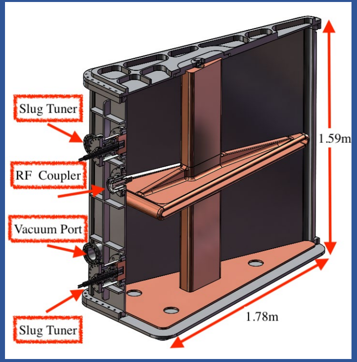
Half of a sector magnet showing flux density in iron core using OPERA3D

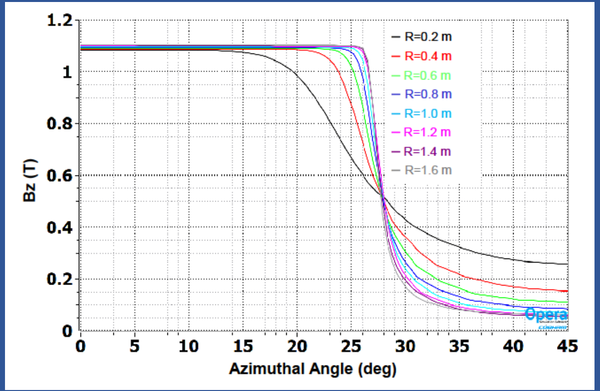


TRANSVERSE KICKS, CALCULATED FOR QWR AND HWR AT DIFFERENT HORIZONTAL LOCATIONS.

Location x, cm	Horizontal kick V_x, kV		Vertical kick V_y, kV	
	QWR	HWR	QWR	HWR
5.1	8.0	4.5	10.7	0.8
72.0	3.6	1.6	72.2	0.3
137.7	11.7	6.9	38.9	0.5

Engineering design of HWR cavity

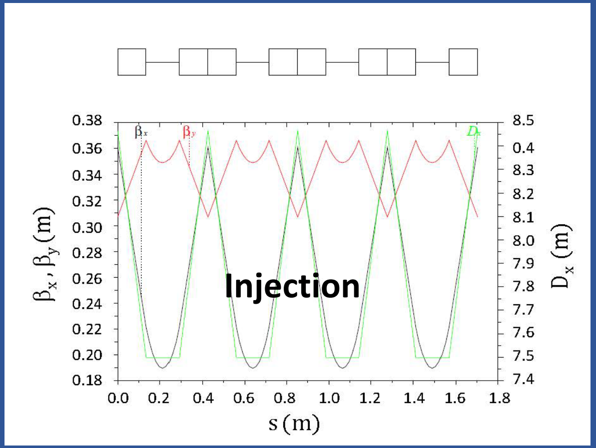


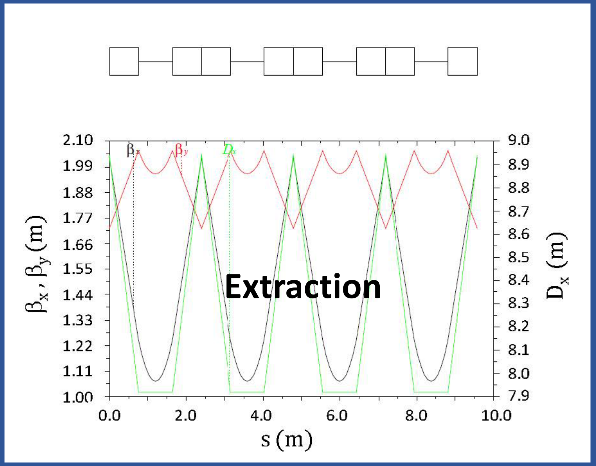


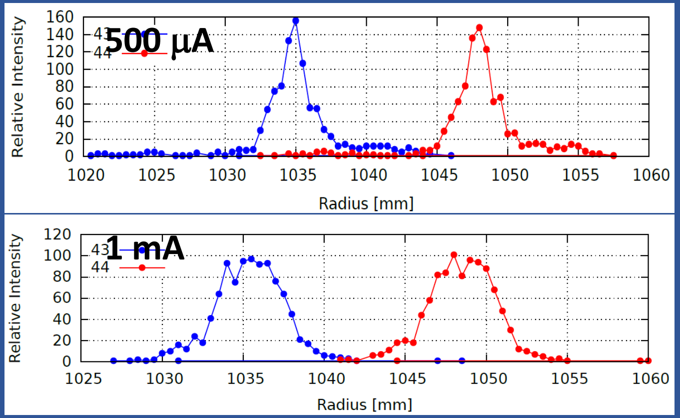
Field versus azimuthal angle at different radii in ½ of a sector magnet

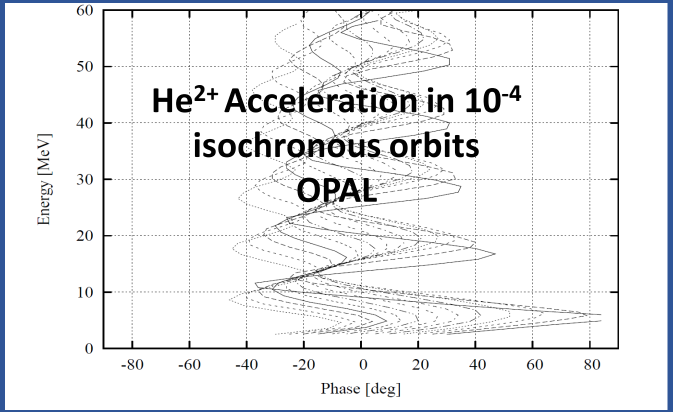
Performance Simulations

- ***Performance modeling of the conservative base design are presented***
- *Lattice Design*
  - Adiabatically increasing Courant Snyder functions (MADX)
    - Emittance depends on extraction turn separation
- *Acceleration (~75 acceleration turns)*
  - 10^{-4} to 10^{-5} isochronism required for low-loss acceleration (OPAL)
    - 10^{-3} to 10^{-4} achieved in magnet design to date
- *Space Charge*
  - 500µA to a mA on H_2^+ injected 5π mm-mr geometric emittance (σ=2mm, OPAL)



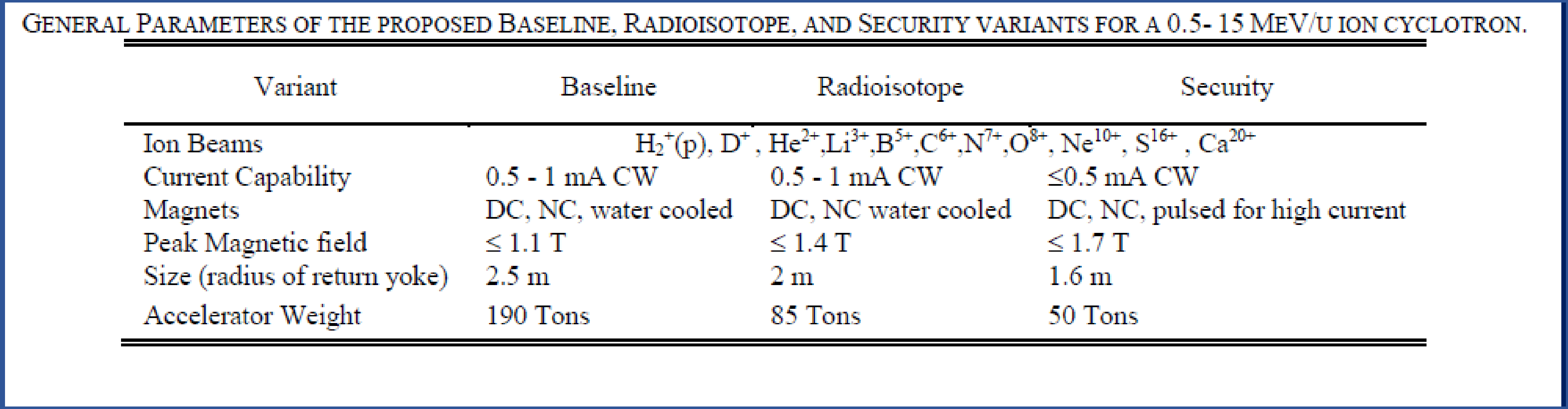






Scaled Variants for Different Applications

- ***Three scaled variants with decreasing footprint and weight are proposed adapted to specific applications***
- *Baseline design for prototype is ultra-conservative technology*
  - Targeted application is ion radiobiology where size/transportability is less of an issue
- *Radioisotope – high currents for radioisotope production (source dependent)*
  - Ultra-high >90% machine reliability, turnkey (specification for almost all medical, commercial, and security applications)
- *Security – transportable for cargo scanning*
  - Smallest, lightest based on a 1.7 T peak field (consistent with existing machines) – transportable in a standard cargo container
    - Potentially ramp magnets for second-level beam pulses to reduce total power consumption and achieve higher fields



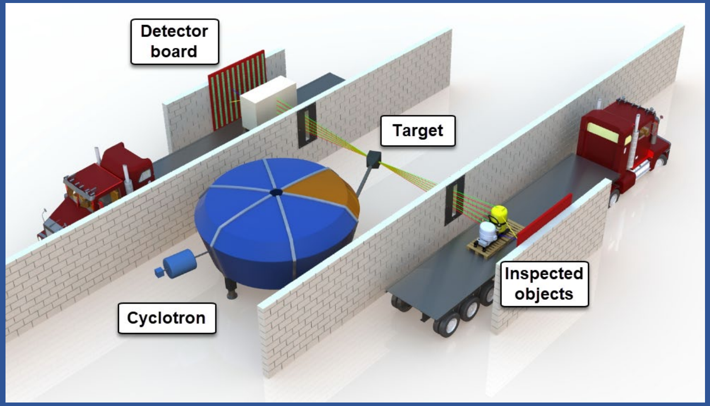
GENERAL PARAMETERS OF THE PROPOSED BASELINE, RADIOISOTOPE, AND SECURITY VARIANTS FOR A 0.5- 15 MEV/U ION CYCLOTRON.

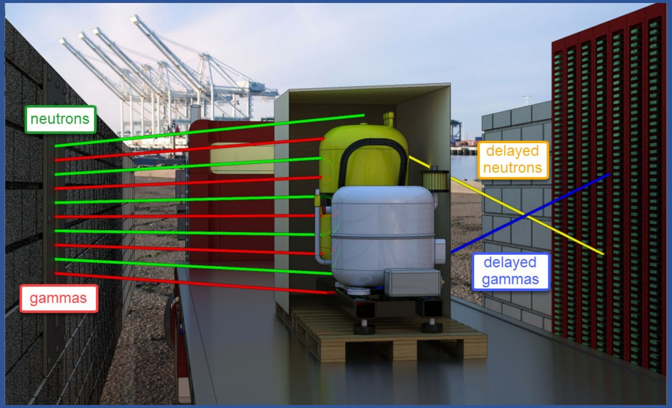
Variant	Baseline	Radioisotope	Security
Ion Beams	H_2^+(p), D^+ , He^{2+},Li^{3+},B^{5+},C^{6+},N^{7+},O^{8+}, Ne^{10+}, S^{16+} , Ca^{20+}		
Current Capability	0.5 - 1 mA CW	0.5 - 1 mA CW	≤0.5 mA CW
Magnets	DC, NC, water cooled	DC, NC water cooled	DC, NC, pulsed for high current
Peak Magnetic field	≤ 1.1 T	≤ 1.4 T	≤ 1.7 T
Size (radius of return yoke)	2.5 m	2 m	1.6 m
Accelerator Weight	190 Tons	85 Tons	50 Tons

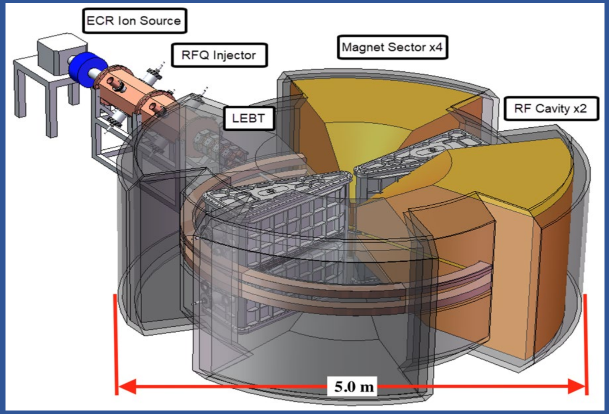
Summary: Ions for Isotopes and Security

- ***A multipurpose base gradient-field FFA has been designed, scalable to specific targeted applications***
- ***General Properties***
  - Accelerates ions from H_2^+ up to Ca^{20+} for Q/A near ½
    - Lower q/m can generate lower energy beams
  - mA for protons, currents depend on ion source/isotope
  - External beams for separate target vault
  - Supports injecting multi-specie ions, rapid switching
    - using small 1% level RF frequency changes RFQ/cyclotron
- ***Medical Applications (diagnostic and theranostics)***
  - Produces all medical radioisotopes currently produced in accelerators
  - Generation of monoenergetic gammas and fast neutrons

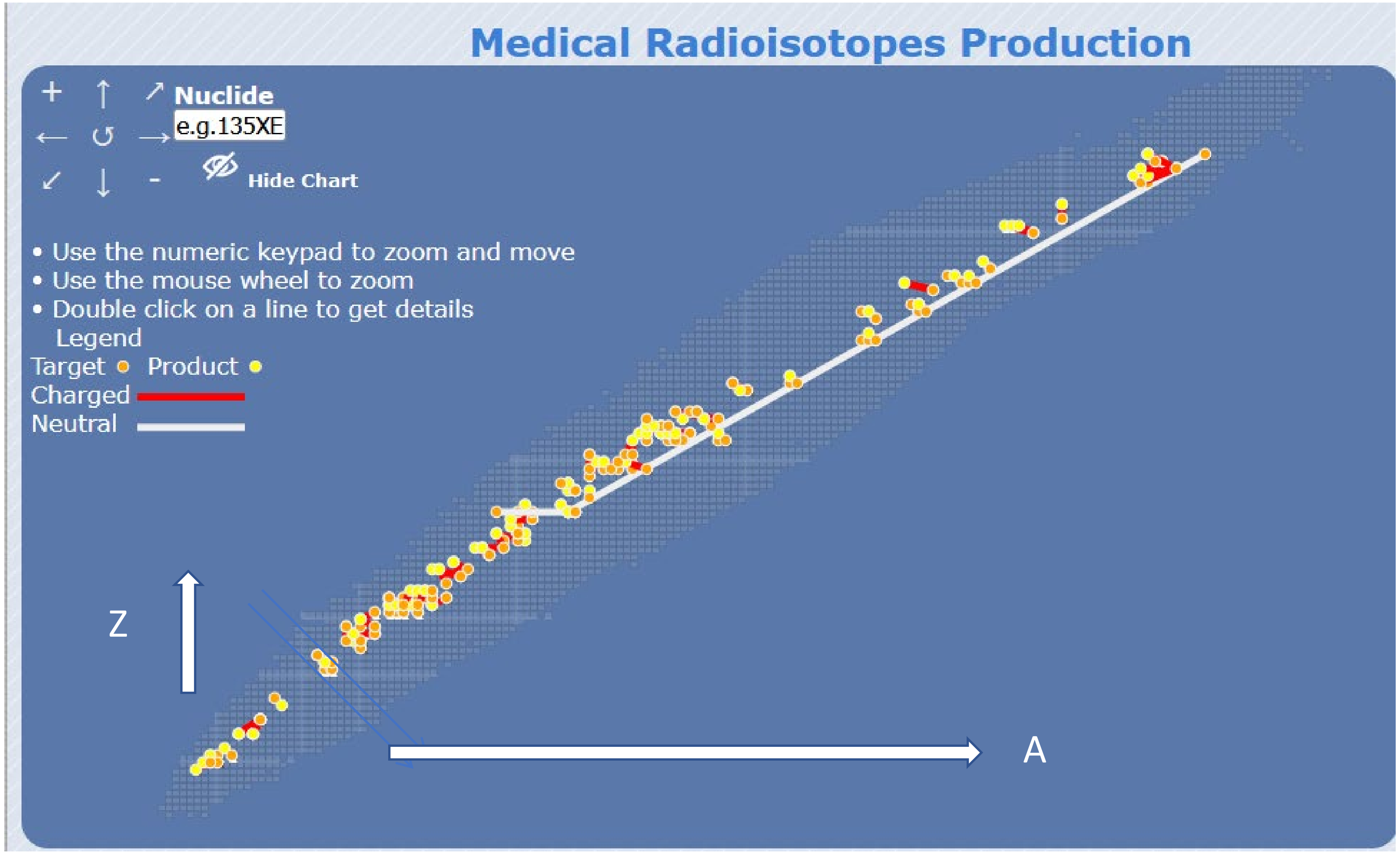
Energy per nucleon	**q/A**	**harmonic**	**Ions**
2.6 MeV	1/6	24	TBD B^{2+}, C^{2+}, $^{30}Si^{5+}$, $^{36}Ar^{6+}$, Co^{10+}, Cu^{11+}, Kr^{14+}, Xe^{22+}
6 MeV	1/4	16	He^{1+}, B^{3+}, C^{3+}, O^{4+}, Ne^{5+}, Si^{7+}, S^{8+}, Ca^{10+}, $^{36}Ar^{9+}$, V^{13+} Co^{15+}, Cu^{16+}, Kr^{22+}, Xe^{33+}
10.7 MeV	1/3	12	B^{4+}, C^{4+}, N^{5+}, O^{5+}, Ar^{6+}, Al^{9+}, Ne^{7+}, Cl^{12+}, Si^{10+}, V^{17+}, Co^{20+}, Cu^{21+}, Kr^{29+}, Xe^{44+},
24 MeV	1/2	8	H_2^+, He^{2+}, N^{7+}, O^{8+}, Ne^{10+}, Si^{14+}, $^{32}S^{16+}$, $^{36}Ar^{18+}$, Ca^{20+}







Accelerator isotope production:
IAEA Nuclear Data Services compilation



Medical Radioisotopes Production

- Use the numeric keypad to zoom and move
- Use the mouse wheel to zoom
- Double click on a line to get details

All medical radioisotopes tabulated for accelerator production can be produced using this ion accelerator: Z/A= ½ & 15 MeV/nucleon.

Rapid-cycling FFGA Storage Rings with Internal Targets: ERIT

Proceedings of EPAC08, Genoa, Italy **TUOBM04**

FFAGS FOR THE ERIT AND ADS PROJECTS AT KURRI

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M. Inoue, SLLS, Shiga, Japan
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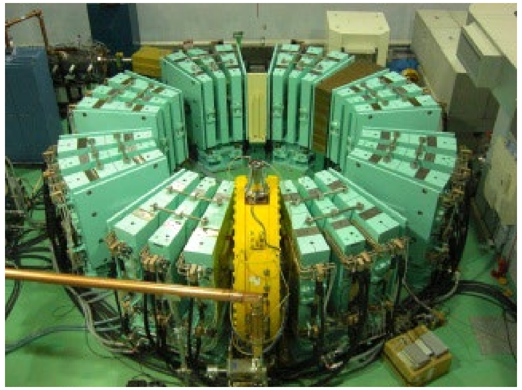
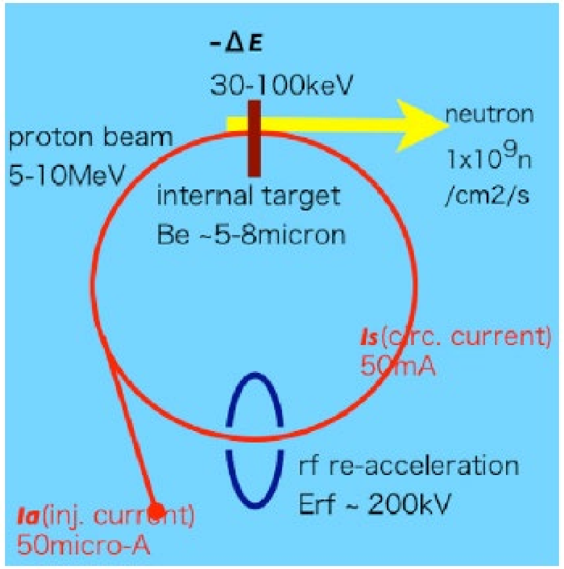
M. Muto, FFAG-DDS Research Organization, Tokyo, Japan



ERIT: neutron source KURRI, Japan

In Kyoto University Research Reactor Institute (KURRI), we have two FFAG accelerator projects; FFAG storage ring with Energy/emittance Recovery Internal Target (ERIT) and FFAG accelerator complex to study Accelerator Driven Sub-critical reactor (ADS). The FFAG ERIT has shown that the FFAG accelerator can be a high intensity neutron source with internal target, because of its large energy acceptance.

When neutron is produced by interaction with an internal target, the neutron flux can be comparable to the nuclear reactor. In this scheme, however, the incident proton beam is lost very quickly due to the interaction with the target atoms turn by turn through the energy loss and emittance blow up. These deleterious effects can be cured by ionization cooling [9, 10]. The transverse emittance reaches equilibrium because of ionization cooling which is invoked in the ERIT scheme.



ERIT: Experimental configuration with target

Recirculating CW-accelerators for Internal Production Targets

Proceedings of IPAC2017, Copenhagen, Denmark TUPVA133

THIN INTERNAL TARGET STUDIES IN A COMPACT FFAG*

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C. Johnstone, Particle Accelerator Corporation, Batavia, USA

Simulations show that target thickness doesn't have a significant impact on yields as the total average thickness traversed by the beam is independent of target thickness. ***The dynamic apertures of the machine are very large so the limiting factor for beam survival is the physical aperture.*** Increasing the vertical aperture would improve beam survival but is limited by magnet engineering constraints and the effect it would have on the magnet fringe fields.

Dynamic aperture	Circular FFA Horizontal π.mm.mrad	Circular FFA Vertical π.mm.mrad	Racetrack FFA Horizontal π.mm.mrad	Racetrack FFA Vertical π.mm.mrad
200 MeV 40 turns	74700	107	25000	46
200 MeV 200 turns	72600	91	23700	43
800 MeV 40 turns	156300	364	63000	277
800 MeV 200 turns	155100	356	63000	223

ICFA Beam dynamics Newsletter #76, April, 2019, pgs. 143-161

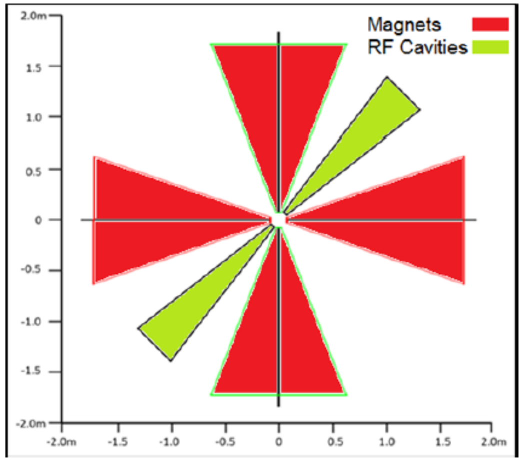
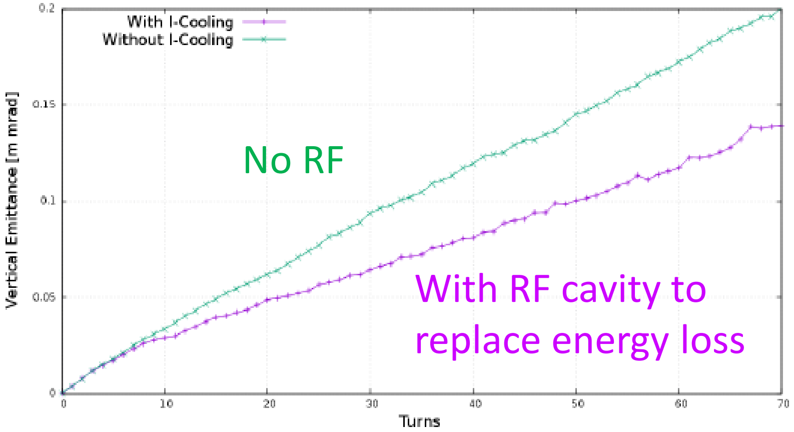


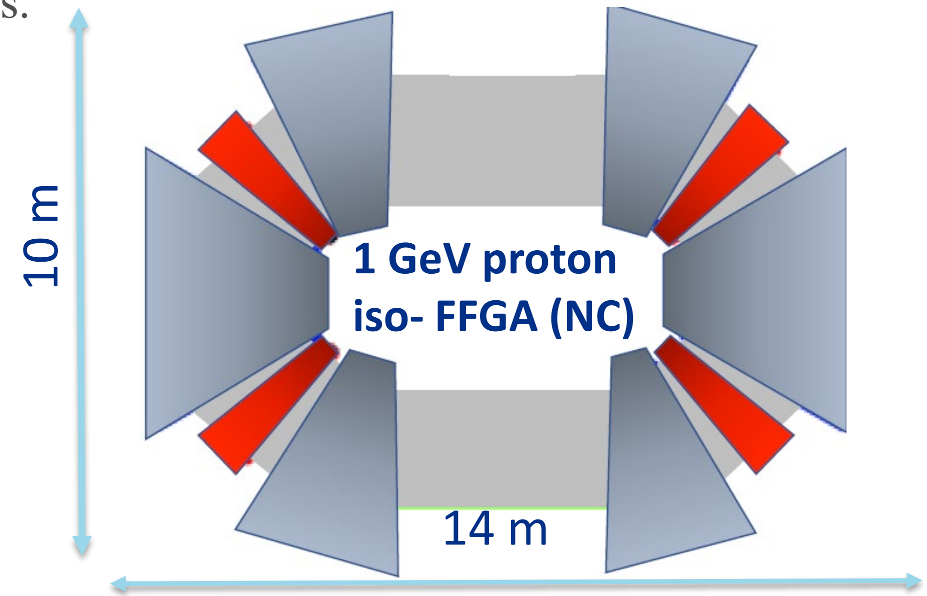
Figure 1: Layout of machine design featuring separat sector magnets and RF cavities.



No RF

With RF cavity to replace energy loss

Figure 6: Emittance growth with and without ionisation cooling showing the emittance suppression effect.



10 m

1 GeV proton iso- FFGA (NC)

14 m