Optics and Beam Dynamics Studies for the ISRS

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Financiado por la Unión Europea
NextGenerationEU

ISRS Meeting
29th November, 2022

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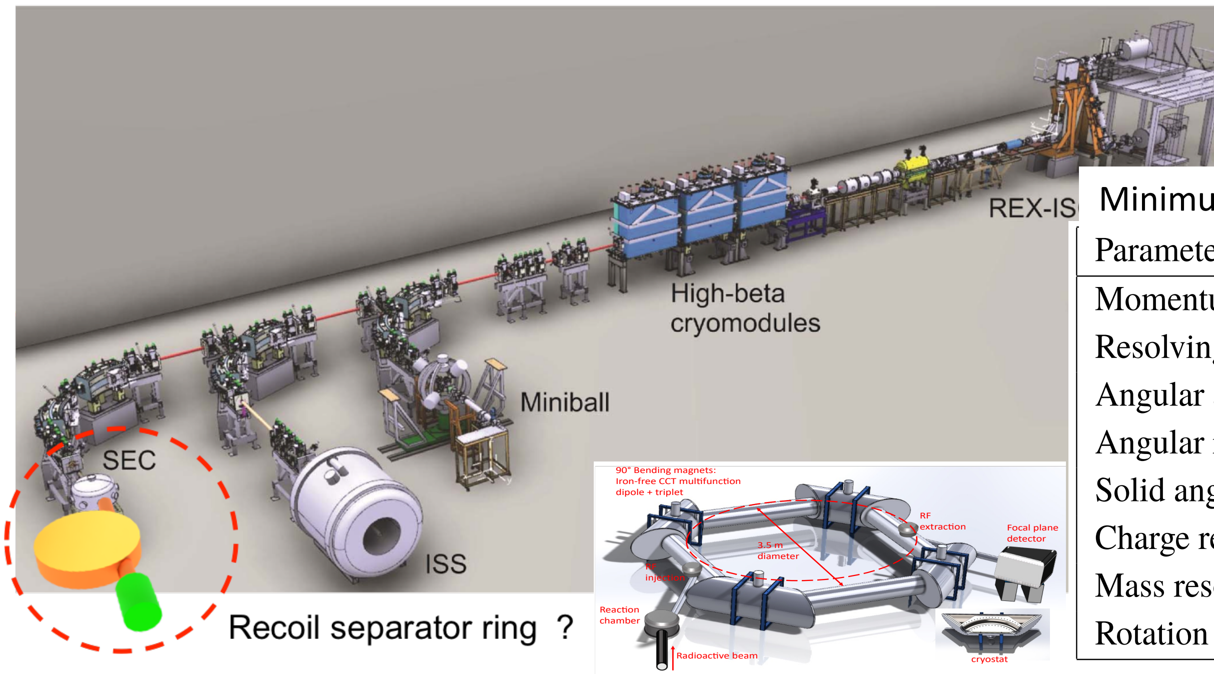
GENERALITAT VALENCIANA
Conselleria d'Innovació, Universitats, Ciència i Societat Digital

Introduction

The HIE-ISOLDE facility at CERN

- Very large range of radioactive beams from ^{6}He – ^{234}Ra
- 1000 isotopes, > 70 elements
- Wide energy range 0.45 – 10 MeV/u   (depending on A/Q)



Minimum spectrometer requirements

Parameters	Values
Momentum acceptance	±10%
Resolving power $p/\Delta p$	2000
Angular acceptance	±10°
Angular resolution	0.1°
Solid angle	100 msr
Charge resolution $\Delta Q/Q$	1/70 (FWHM)
Mass resolution $\Delta M/M$	1/250 (FWHM)
Rotation	0 – 70°

A compact recoil separator can bring new and exciting possibilities to the HIE-ISOLDE physics program

The ISOLDE Superconducting Recoil Separator (ISRS) – new initiative since 2019

Preliminary studies

Conceptual design

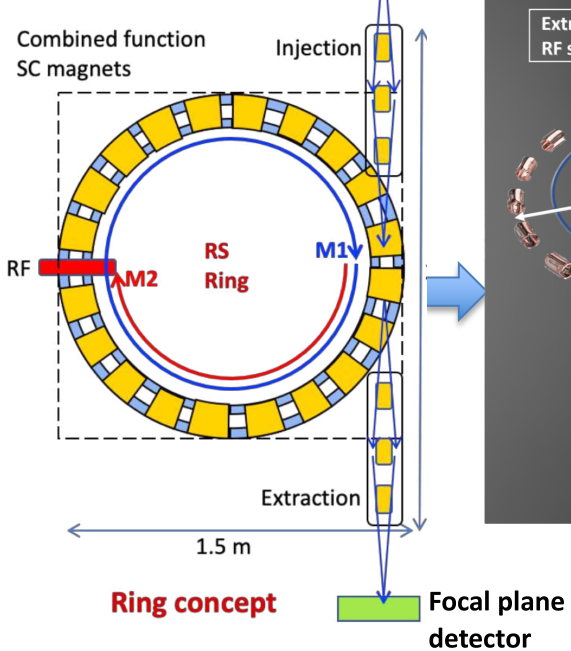
I. Martel. 84th ICC meeting. CERN, March 2019.

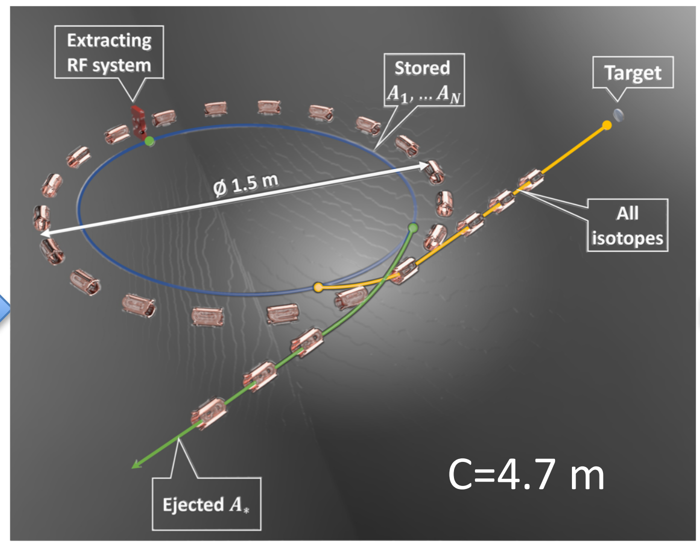
3D G4beamline model (20 multifunction magnets)

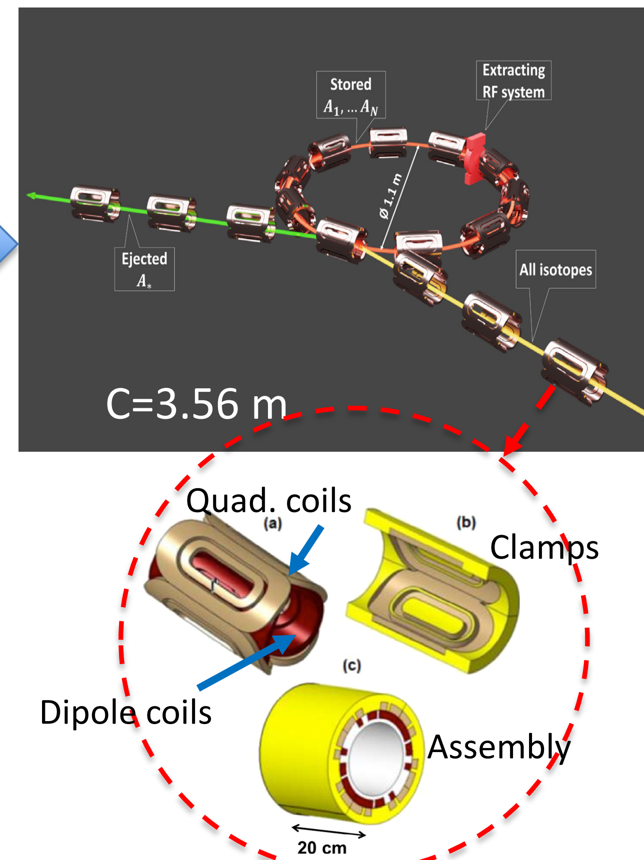
First optimization (10 multifunction magnets)

C. Bontoiu et al., NIMA 969 (2020) 164048

- Remove only primary beam

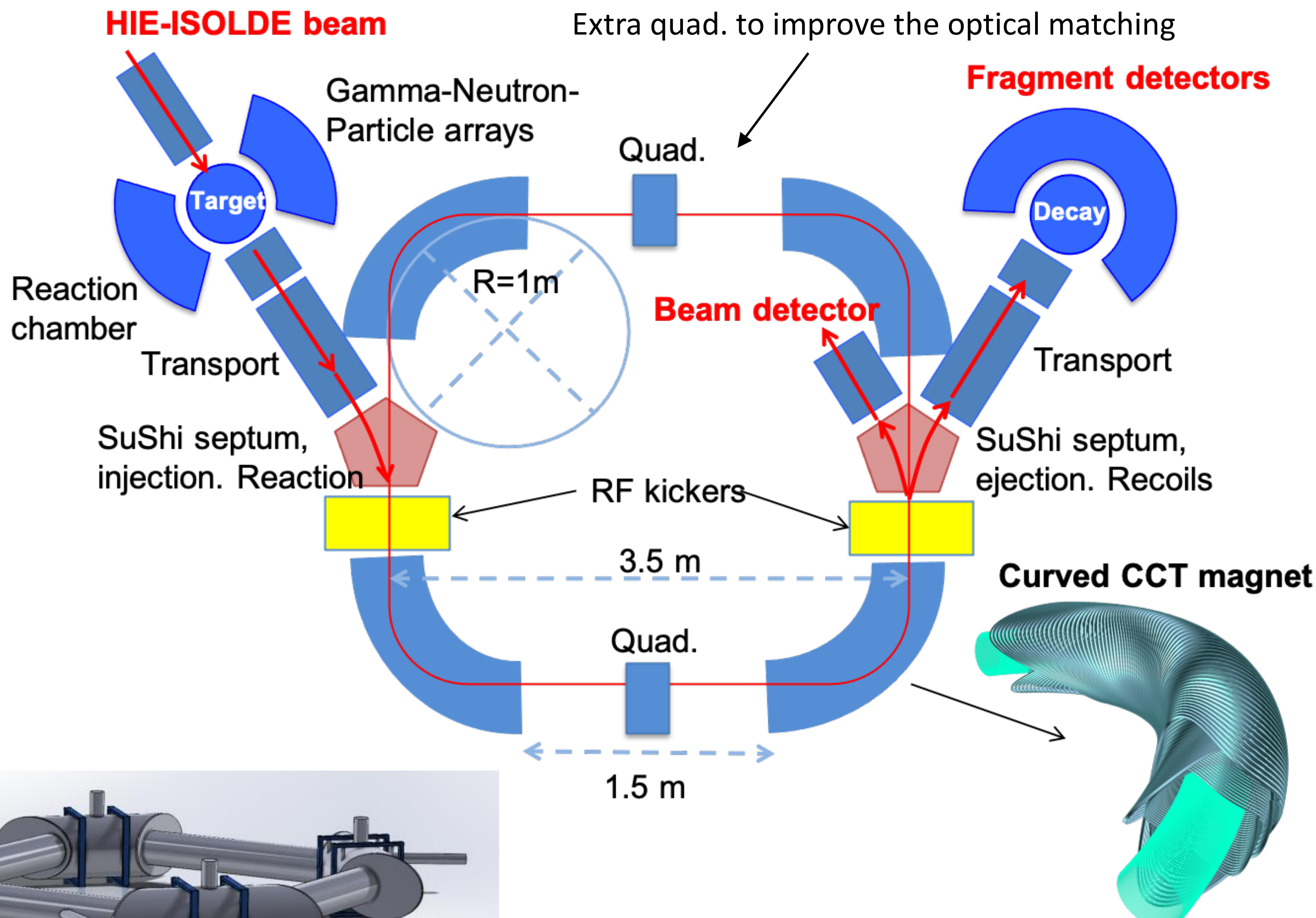


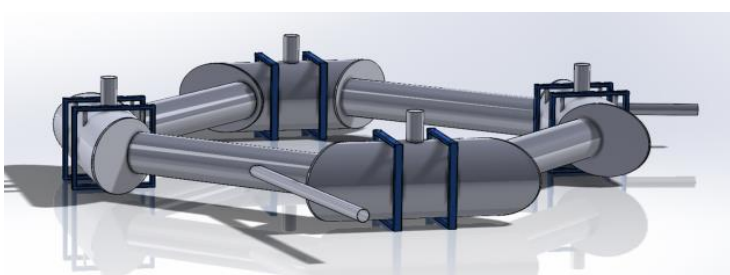




Based on short combined function magnets: dipolar and quadrupolar components. Maximum magnetic field ~ 6 T

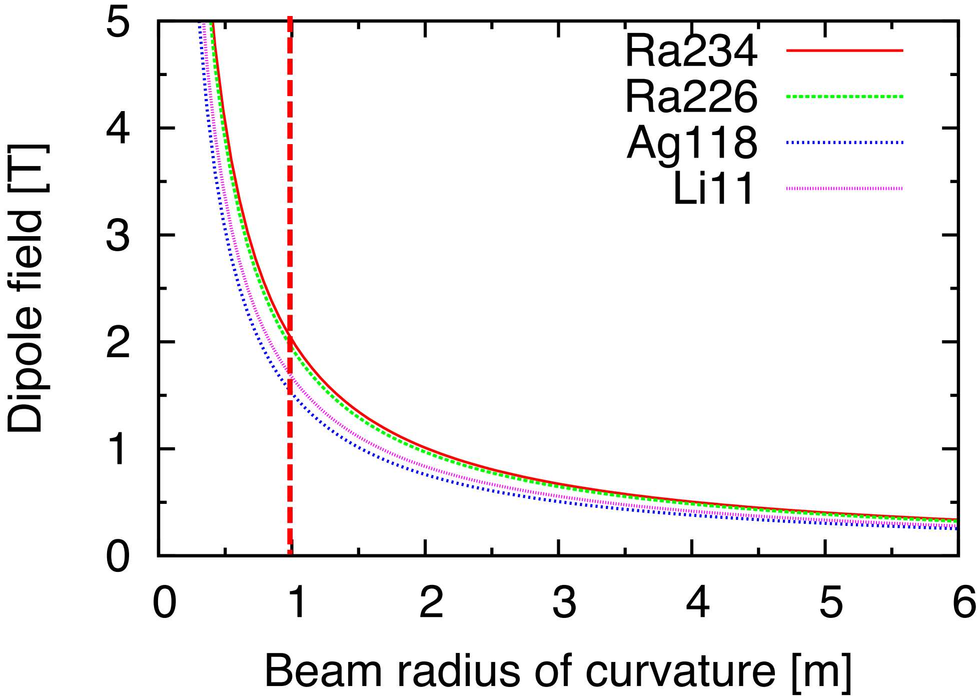
ISRS conceptual design. Recent studies





- 4 Curved Canted-Cosine-Theta (CCT) magnets

Dipole field



Magnetic rigidity

$$B\rho[\mathrm{T\,m}] = \left(\frac{3.3356}{q_{\mathrm{eff}}}\right) \cdot A \cdot P[\mathrm{GeV/c}]$$

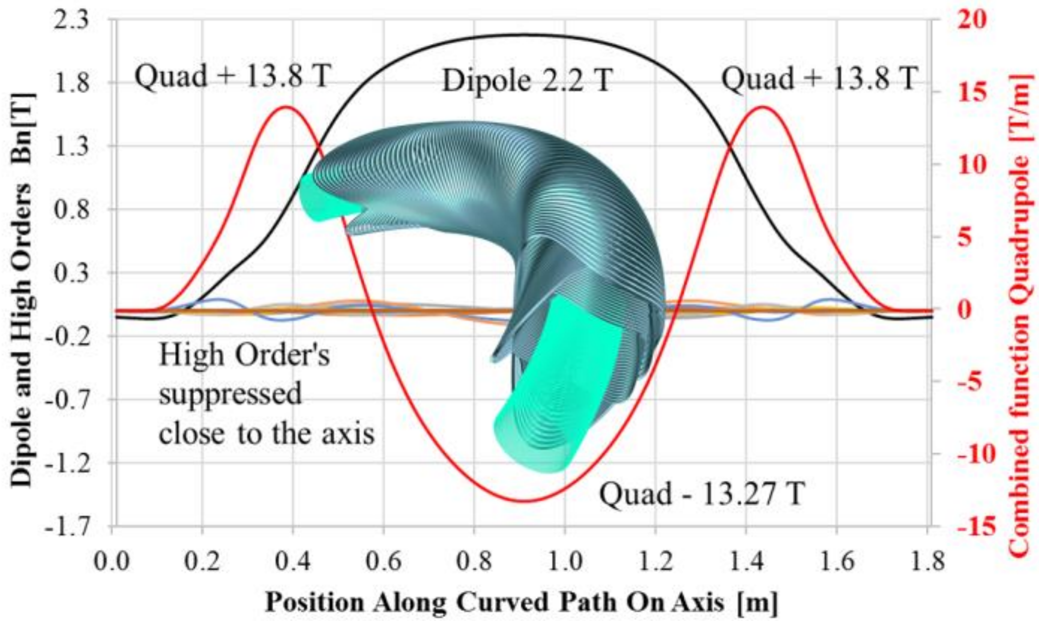
Example for different ions at 10 MeV/u kinetic energy

Parameters	^{11}Li	^{118}Ag	^{226}Ra	^{234}Ra
Effective charge q_{eff}	2.999	35.457	52.883	52.879
Rigidity $B\rho$ [T m]	1.67	1.52	1.94	2.02

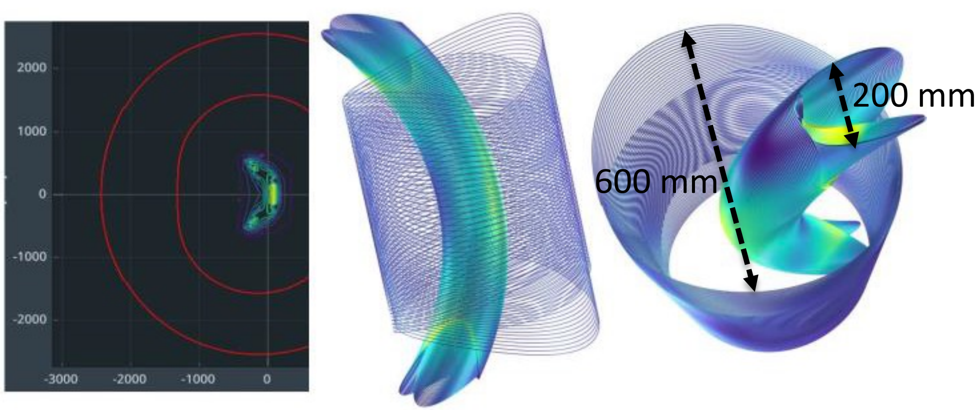
Magnets

G. Kirby et al., IEEE Trans. Appl. Supercond. 32(6) 4004105 (2022)

- **Bent CCT nested dipole and quad. magnet**
- Synergy with CCT magnets for gantries
- 200 mm beam aperture
- Curvature of 1 m
- 90 deg. bend
- Two layer coil has both 2.2 T dipole and ~ 14 T/m (maximum) quad. in a single conductor pack



- The quad. consists of three sections rotated by +/- 45 deg. to make a FDF (DFD) triplet focusing/defocusing configuration
- Stray field shield that replaces the classic iron yoke



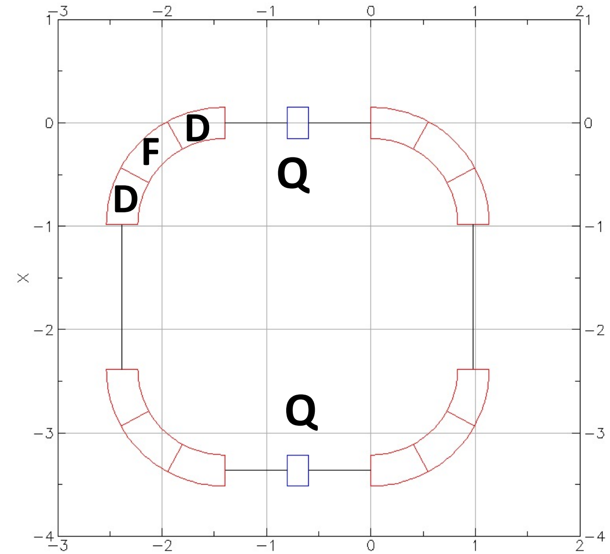
High momentum acceptance mode

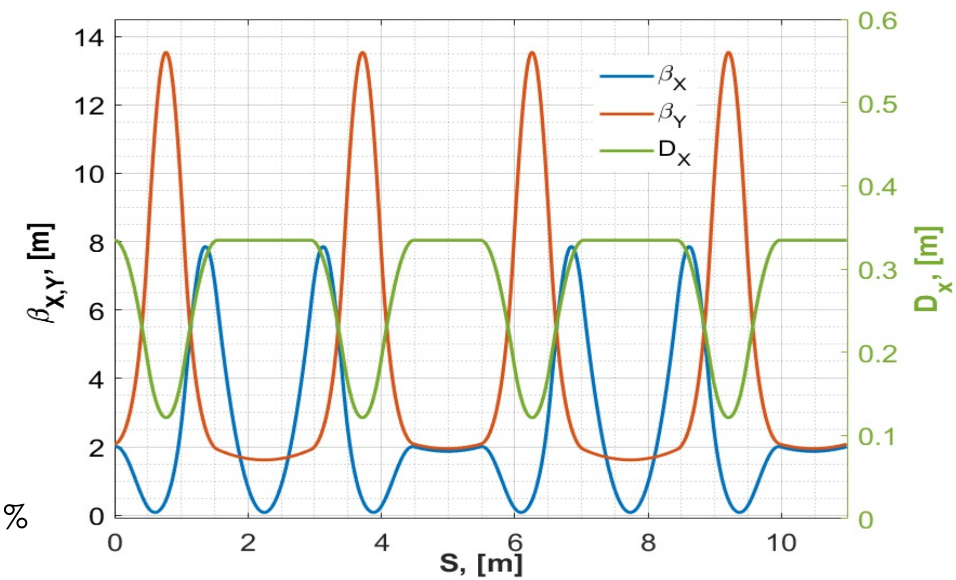
- FDF optics for non-scaling FFAG
- Lattice with sbend magnets. BMAD code

$$\alpha_c = 0.12 \quad \gamma_t = 2.92$$

$$\gamma = 1.0107 \; (^{234}\mathrm{Ra\ at\ 10\ MeV/u})$$

Beam	^{234}Ra
Kinetic energy	10 MeV/u
Rigidity, $B\rho$ [T m]	2
Maximum beta functions, $\beta_{x,y}$ [m]	7.8, 13.5
Maximum dispersion, D_x [m]	0.32
F magnet	
Effective length [m]	0.497
Dipole field [T]	2.0
Quadrupole gradient [T/m]	12.3
D magnet	
Effective length [m]	0.55
Dipole field [T]	2.11
Quadrupole gradient [T/m]	-13.1





Expected max. momentum acceptance: $\Delta p/p = +/-31.25\ \%$

Isochronous condition

Revolution period deviation

$$\frac{dT}{T} = -\frac{df}{f} = \frac{1}{\gamma_t^2}\frac{d(m/q)}{m/q} - \left(1 - \frac{\gamma}{\gamma_t^2}\right)\frac{dv}{v}$$

$$\gamma_t = 1/\sqrt{\alpha_c}$$ Transition point

$$\alpha_c = \frac{dC/C}{d(B\rho)/(B\rho)} = \frac{1}{C}\oint \frac{D_x(s)}{\rho(s)}ds$$ Momentum compaction factor

The revolution frequency becomes velocity independent if $\gamma \rightarrow \gamma_t$

In our case, how to match an isochronous mode? Increasing $D_x(\mathrm{s})$ to increase $\boldsymbol{\alpha}_c$ and, therefore, to decrease $\boldsymbol{\gamma}_t$ w.r.t. the high momentum acceptance optics mode

Isochronous mode

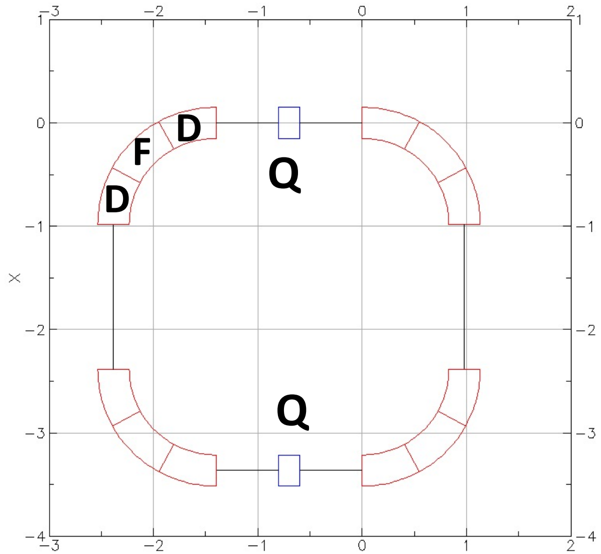
- DFD optics for non-scaling FFAG
- Matching with two additional quads. (Q). BMAD

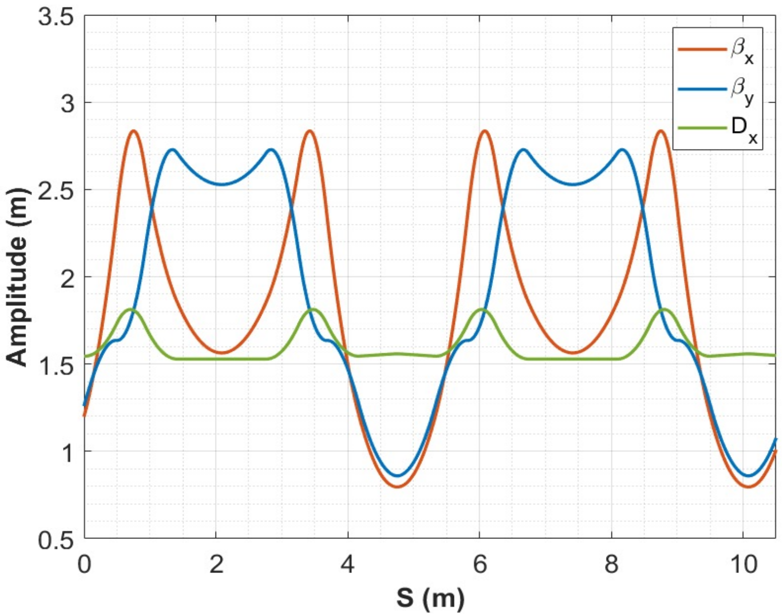
$$\alpha_c = 0.98 \quad \gamma_t = 1.0102$$

$$\gamma = 1.0107 \ (^{234}\text{Ra at } 10 \text{ MeV/u})$$

$$\gamma \approx \gamma_t$$

Beam	^{234}Ra
Kinetic energy	10 MeV/u
Rigidity, $B\rho$ [T m]	2
Maximum beta functions, $\beta_{x,y}$ [m]	2.85, 2.72
Maximum dispersion, D_x [m]	1.8
F magnet	
Effective length [m]	0.55
Dipole field [T]	2.45
Quadrupole gradient [T/m]	2.531
D magnet	
Effective length [m]	0.497
Dipole field [T]	2.133
Quadrupole gradient [T/m]	-2.967
Additional quads. Q	
Quadrupole gradient [T/m]	0.423



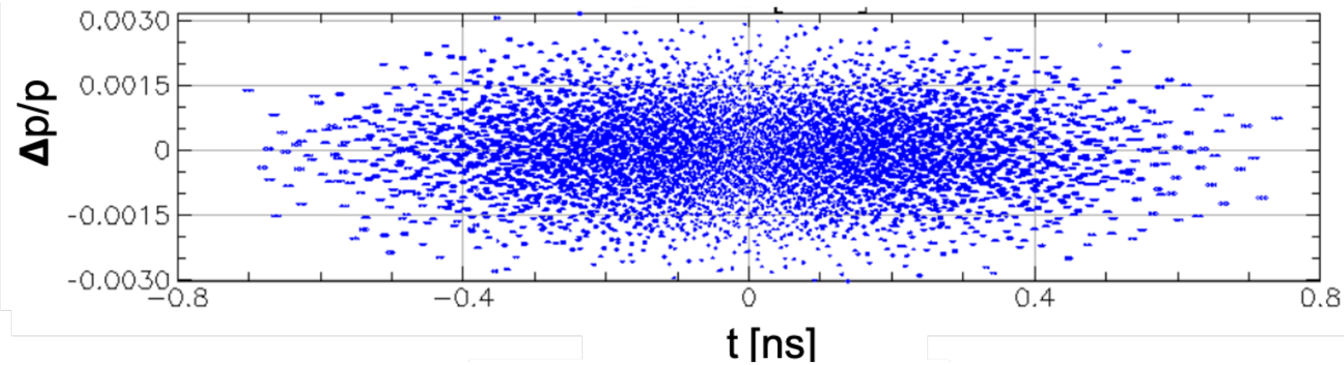


Expected max. momentum acceptance: $\Delta p/p = +/-5.5$ %

Beam tracking studies

Let's study the lattice performance by means of tracking simulations, injecting the following particle distribution:

Initial longitudinal phase space

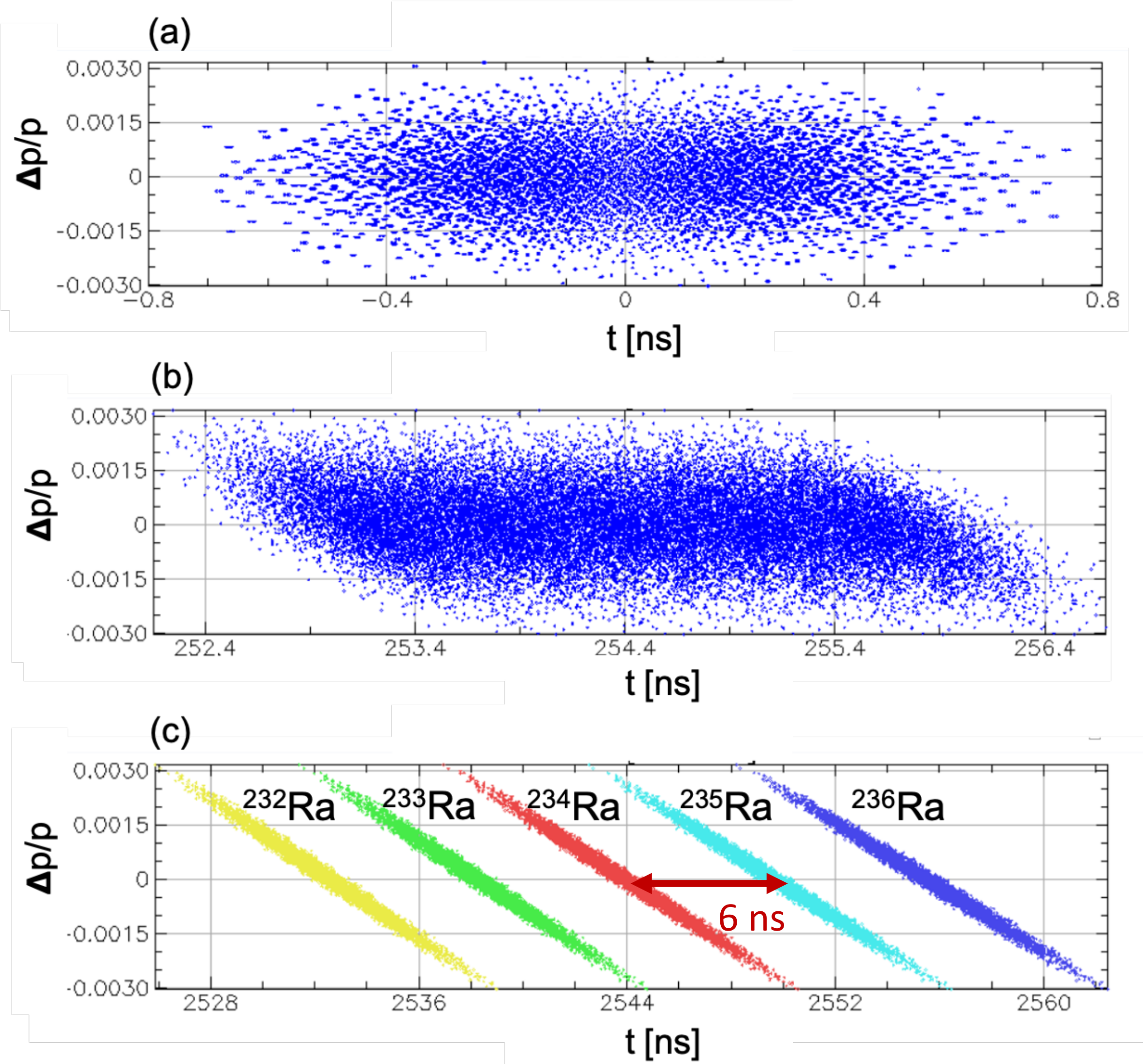


Initial parameters

Gaussian distribution
5 isotopes of radium: 232Ra, 233Ra, 234Ra, 235Ra, 236Ra
5000 macroparticles per isotope
234Ra in reference orbit
Kinetic energy = 10 MeV/u
Transverse emittance (x,y) = 5 x 10^{-6} m-rad
RMS longitudinal size $\boldsymbol{\sigma}_z$ = 0.01 m
RMS Momentum spread $\sigma_{\Delta p/p}$ = 0.01%

Beam tracking studies

For the high momentum acceptance mode (non-isochronous)



Initial longitudinal phase space

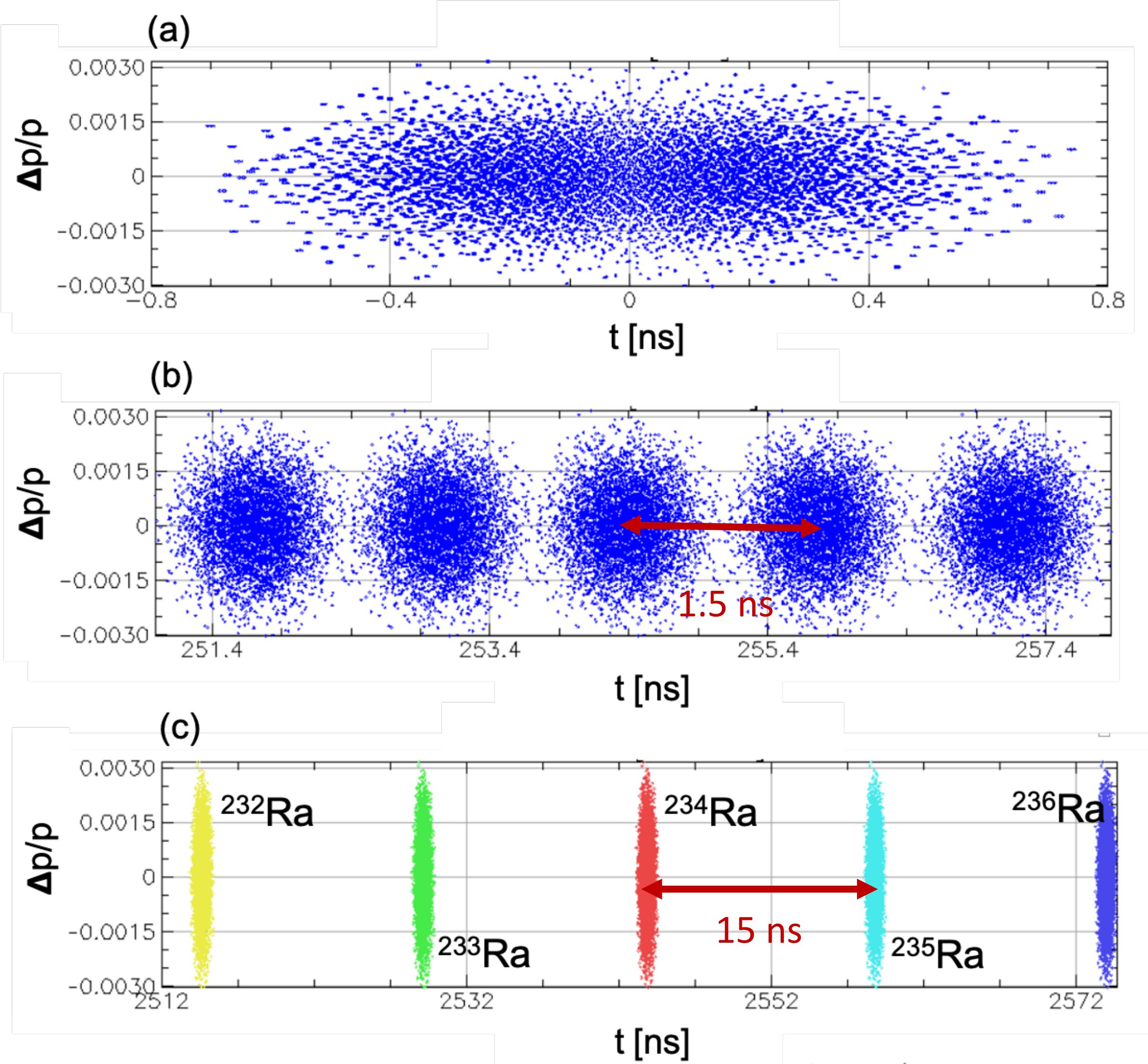
1 turn (254.4 ns)

10 turns (2544 ns)

It doesn't separate isotopes beyond 6 ns. After several turns they stay at the same position

Beam tracking studies

For the isochronous mode



Initial longitudinal phase space

1 turn (254.4 ns)

10 turns (2544 ns)

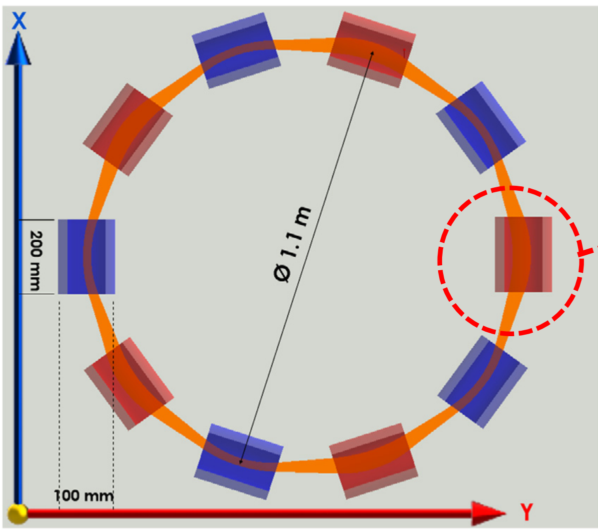
Outlook

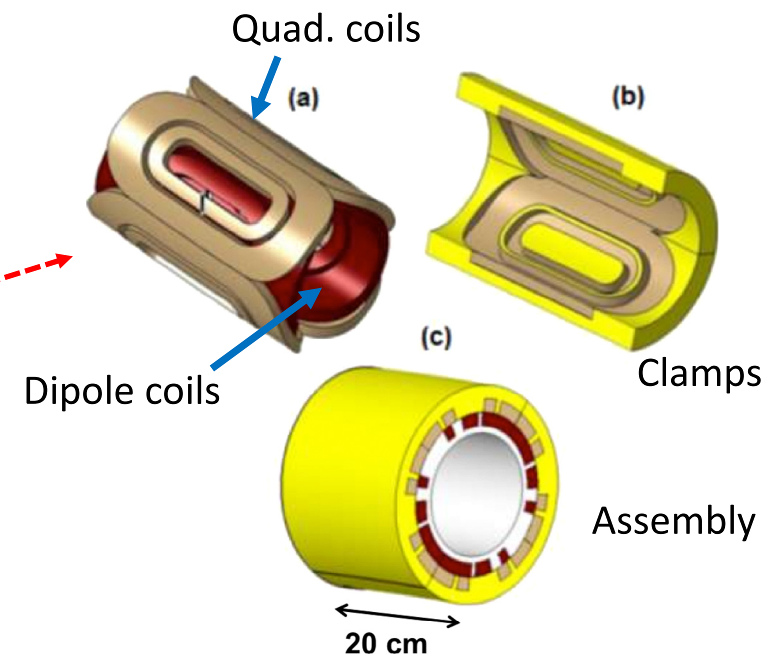
- A new concept of compact recoil separator is proposed: The Isolde Superconducting Recoil Separator (ISRS)
- Optics layout based on innovative CCT curved magnets (strong synergies with medical gantries); non-scaling FFAG ring
- Versatile optics, different operation modes: isochronous, high momentum acceptance, etc. Currently investigating different operation modes and their potential application.
- Fine tuning of the magnets and the optics lattice will provide very large solid angles > 100 msr and momentum acceptances $\Delta p/p > 20\%$ (high momentum acceptance mode).
- Ongoing studies to get a better balance between isochronicity and momentum acceptance.
- Beam dynamics simulations are being carried out to investigate the performance of the current design and to optimise the layout
- Plans to perform tracking simulations considering realistics 3D magnetic field maps including higher order harmonics
- Injection/extraction are very challenging for heavy isotopes in such a compact lattice. Under investigation.

Back-up

Preliminary studies (2019)

SC combined function magnets





Summary of magnet parameters for operation mode with light isotopes (e.g. ^{11}Li) and heavy isotopes (e.g. ^{118}Ag and ^{226,234}Ra nuclides).

Parameters	^{11}Li	^{118}Ag	^{226}Ra	^{234}Ra
Effective charge q_{eff}	2.999	35.457	52.883	52.879
Rigidity $B\rho$ [T m]	1.67	1.52	1.94	2.02
Deflection angle [deg]	36	36	36	36
Dipolar magnetic field B_y [T]	5.26	4.77	6.13	6.35
Quadrupolar strength KL [m^{-1}]	5	5	5	5
Quadrupolar gradient G [T/m]	41.86	37.98	48.77	50.5

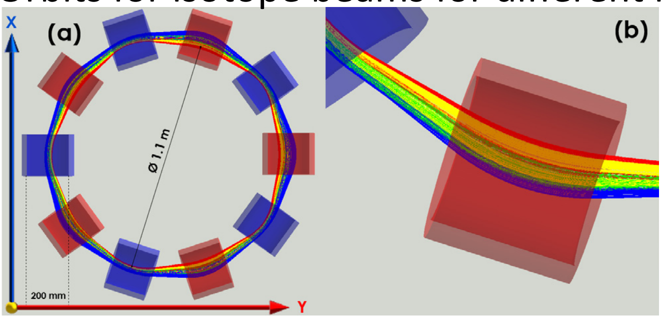
Magnets originally designed for a SC gantry for hadrontherapy

C. Bontoiu et al., IPAC2015, TUPWI014
C. Bontoiu et al., IPAC2015, WEPMN051
C. Bontoiu et al., NIMA 969 (2020) 164048

Preliminary studies (2019)

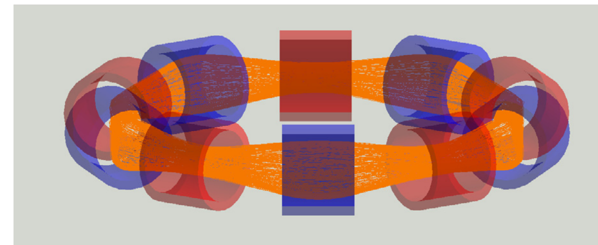
Beam dynamics.

Orbits for isotope beams for different momentum ranges



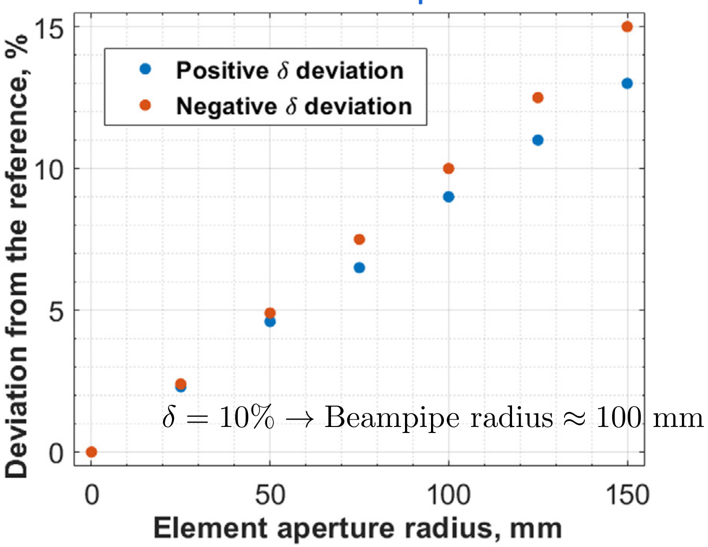
Angular acceptance

Tracking of Ra226 for 300 turns



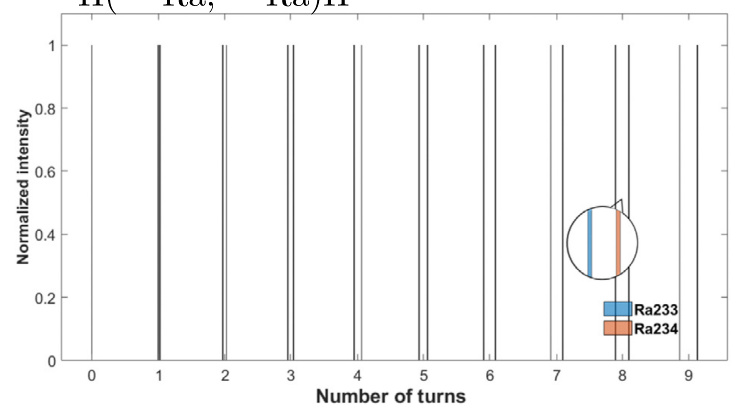
$\mathrm{Max}(x', y') \approx (115, 160)$ mrad

Momentum acceptance



Mass resolving power

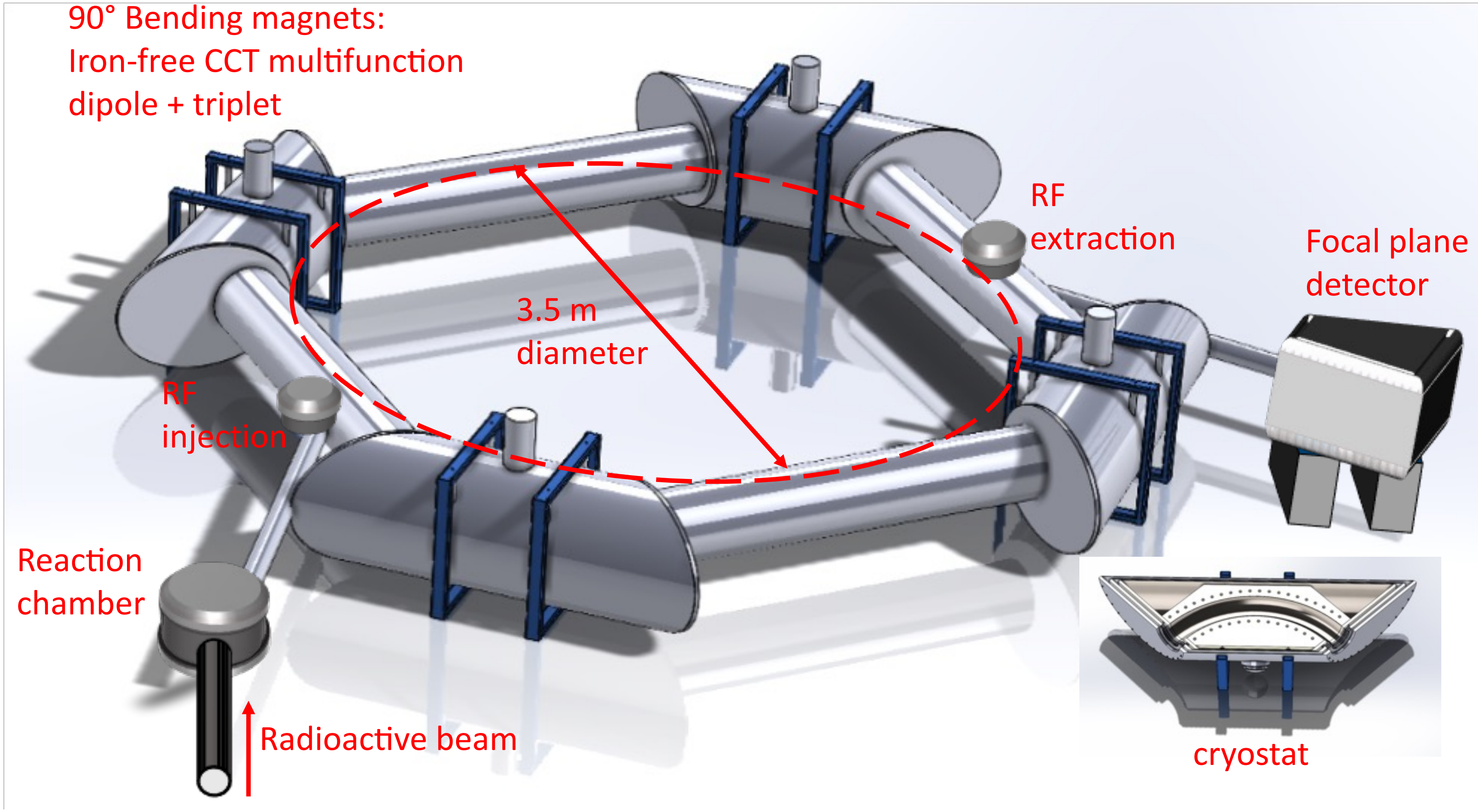
$^{2}\mathrm{H}(^{233}\mathrm{Ra}, ^{234}\mathrm{Ra})\mathrm{H}$



The detected intensity peaks of both Ra233 and Ra234 separate longitudinally as the number of turns increases.

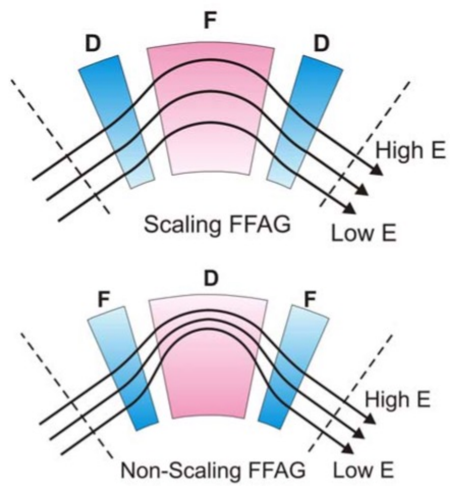
C. Bontoiu et al., NIMA 969 (2020) 164048

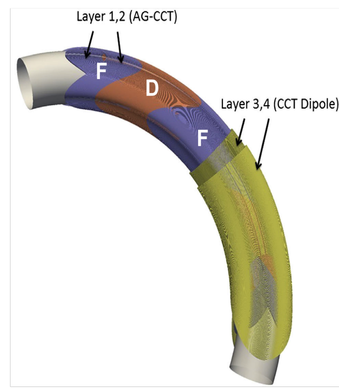
Current ISRS layout



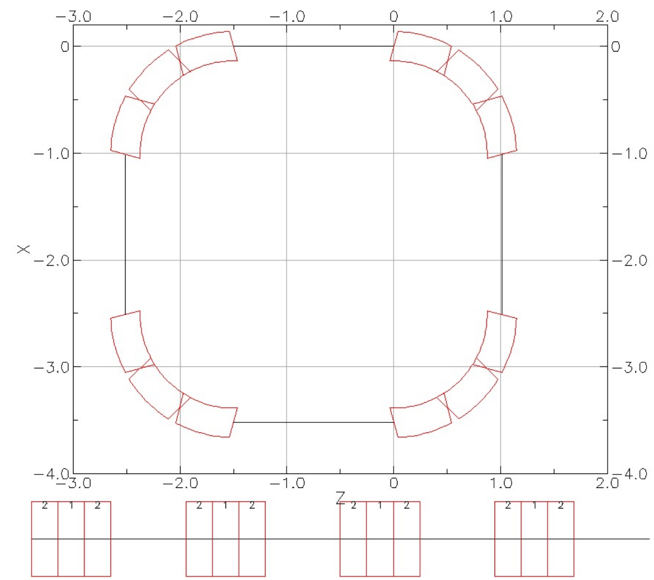
FFAG optics

- DFD or FDF focusing triplet for FFAG lattice
- Combined function magnets as rbends

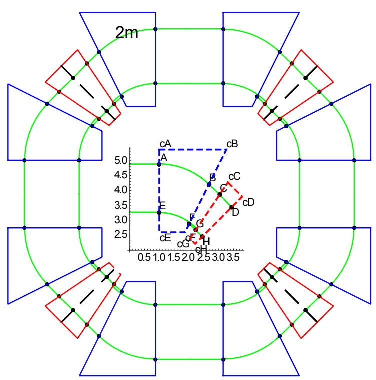




ISRS footprint



ISRS lattice presents similarities with non-scaling FFAG lattice by C. Johnstone et al.



C. Johnstone et al., “Isochronous (CW) Non-Scaling FFAGs: Design and Simulation”, AIP Conference Proceedings 1299 (2010) 682