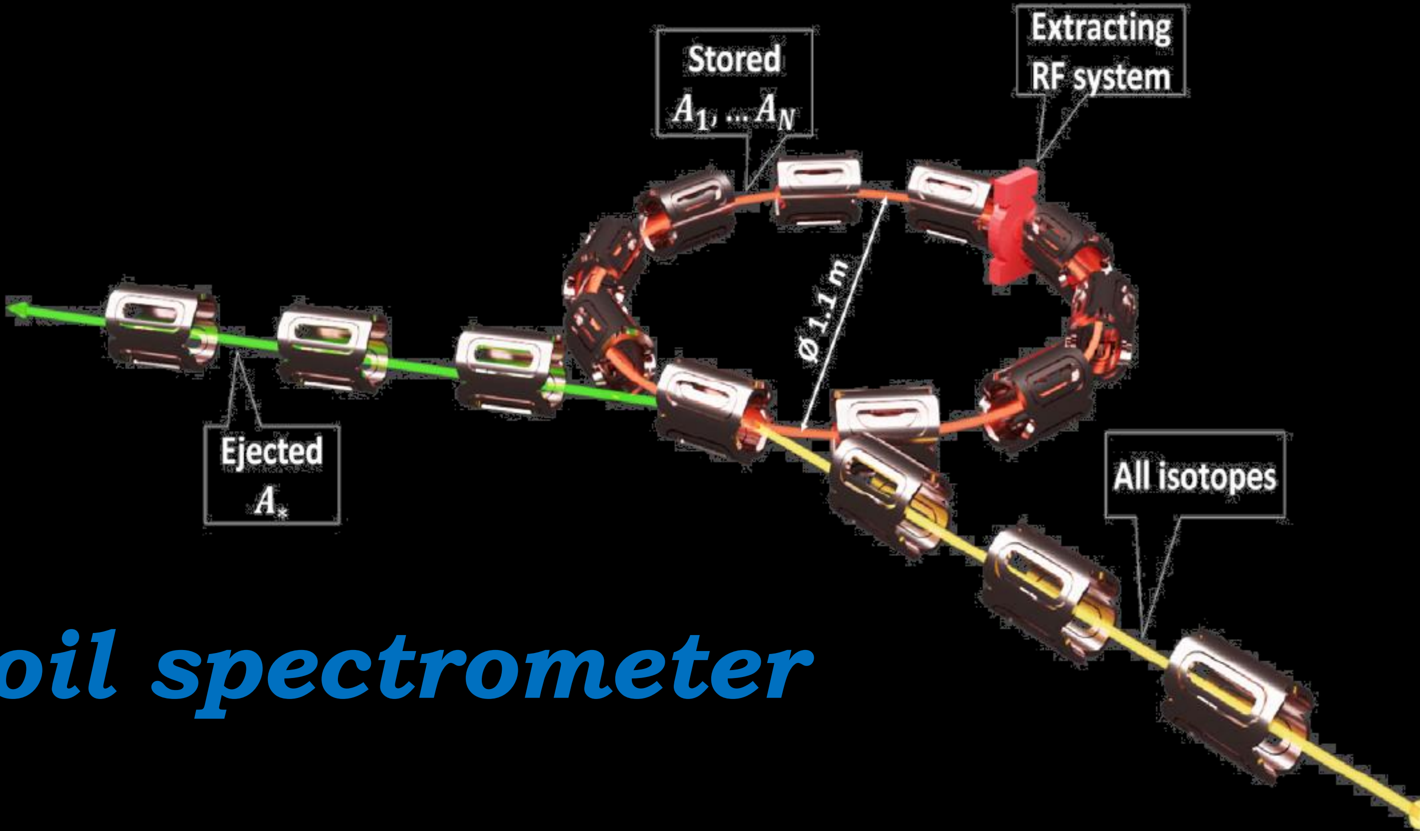


# *Mini-recoil spectrometer*

Teresa Kurtukian-Nieto
Univ. Bordeaux, CNRS, LP2I, UMR 5797, F-33170 Gradignan, France

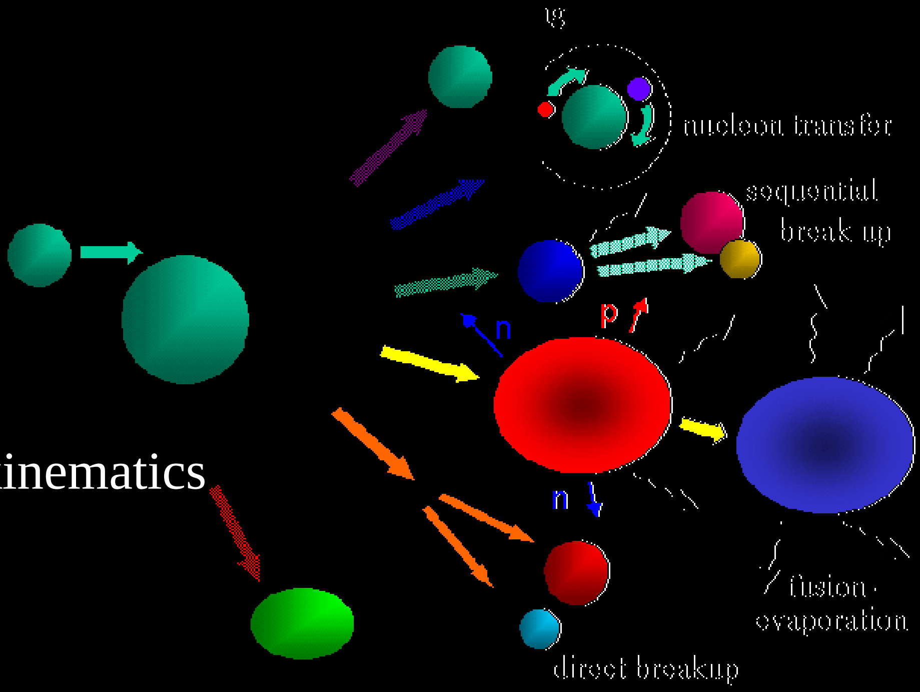
*GANIL Community Meeting*
*October 17th-21th, 2022*

# Physics opportunities

The ISRS allows an application of several reaction mechanisms to produce exotic nuclei in the energy levels of interest, decays of which can be observed by detecting particles or photons with the existing and planned detection systems

## Reaction mechanisms

- ✓ Deep inelastic reactions
- ✓ Coulomb dissociation
- ✓ Transfer reactions in inverse kinematics
- ✓ Multinucleon transfer reactions
- ✓ Fusion evaporation reactions in inverse kinematics
- ✓ Transfer, breakup and fusion reactions
- ✓ Resonant elastic scattering



# ISOLDE Recoil Separator ISRS

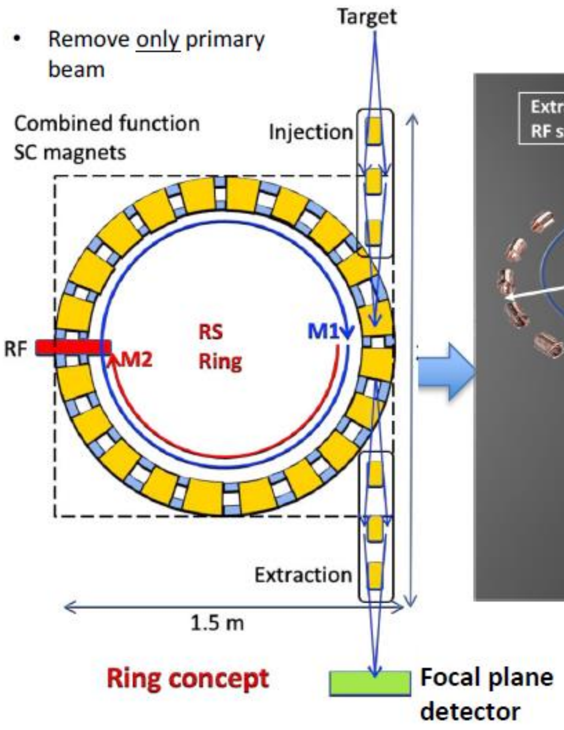
**Conceptual design**

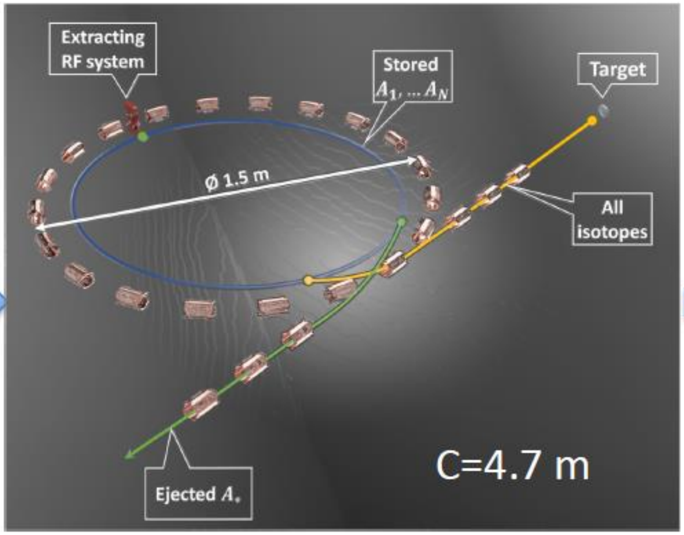
I. Martel. 84th ICC meeting.
CERN, March 2019.

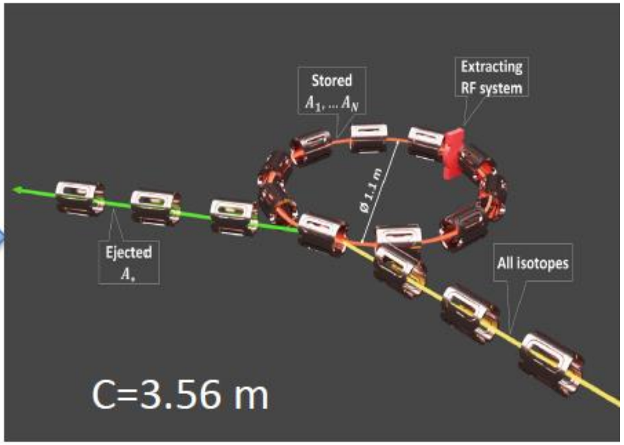
**3D G4beamline model**
**(20 multifunction magnets)**

**First optimization**
**(10 multifunction magnets)**

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

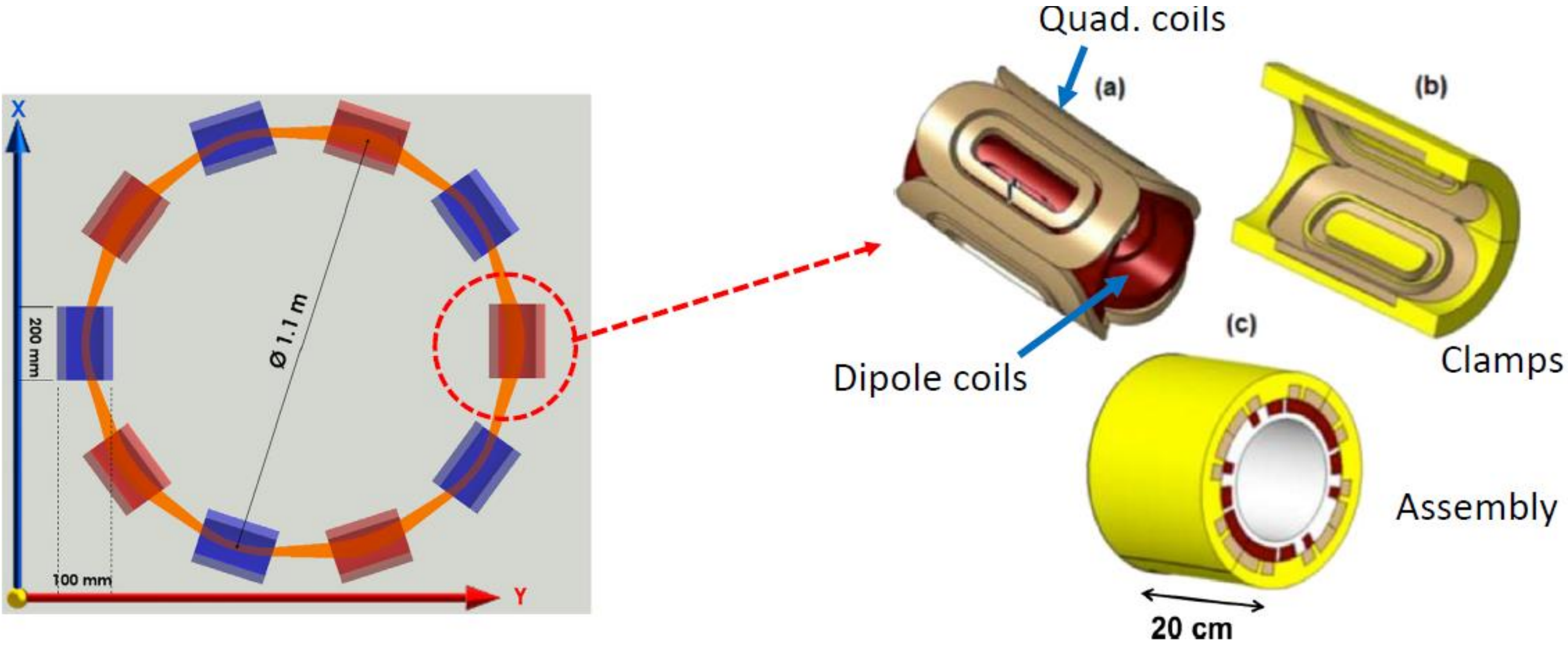






**Based on superconductor combined function magnets**
**dipolar and quadrupolar components**
**Maximum magnetic field ~ 6 T**

# Superconducting combined 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).

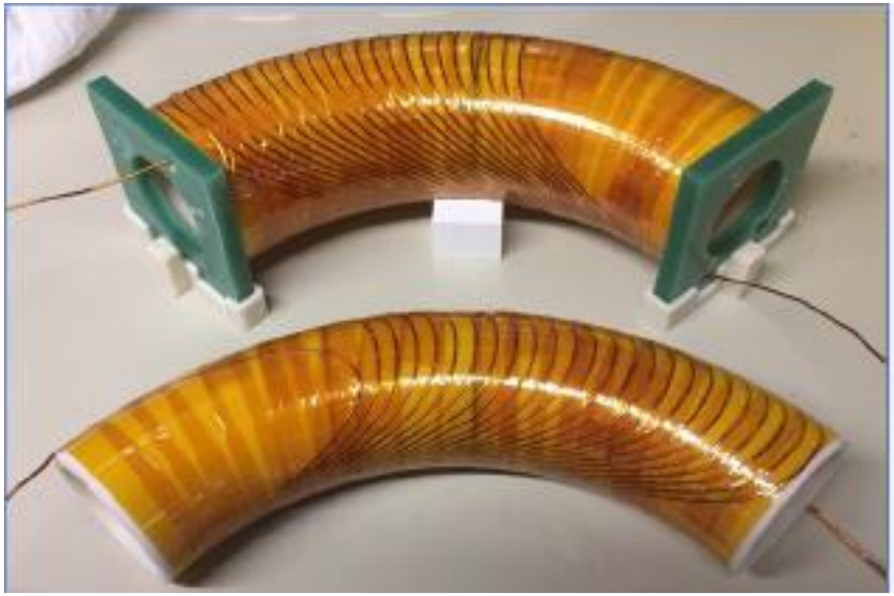
| Parameters | $^{11}$Li | $^{118}$Ag | $^{226}$Ra | $^{234}$Ra |
|---|---|---|---|---|
| Effective charge $q_{\mathrm{eff}}$ | 2.999 | 35.457 | 52.883 | 52.879 |
| Rigidity $B\rho$ [T m] | 1.67 | 1.52 | 1.94 | 2.02 |
| Deflection angle [deg] | 36 | 36 | 36 | 36 |
| Dipolar magnetic field $B_y$ [T] | 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 |

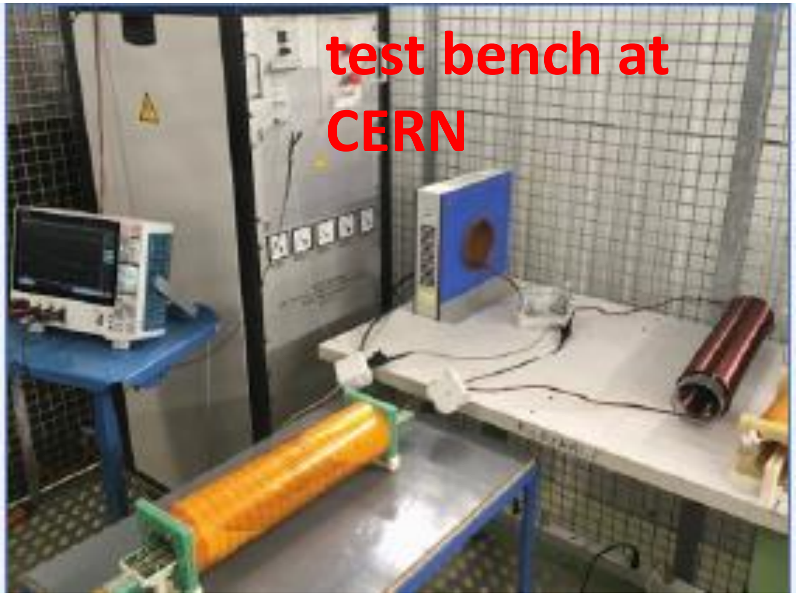
Magnets originally designed for a SC gantry for hadrontherapy

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

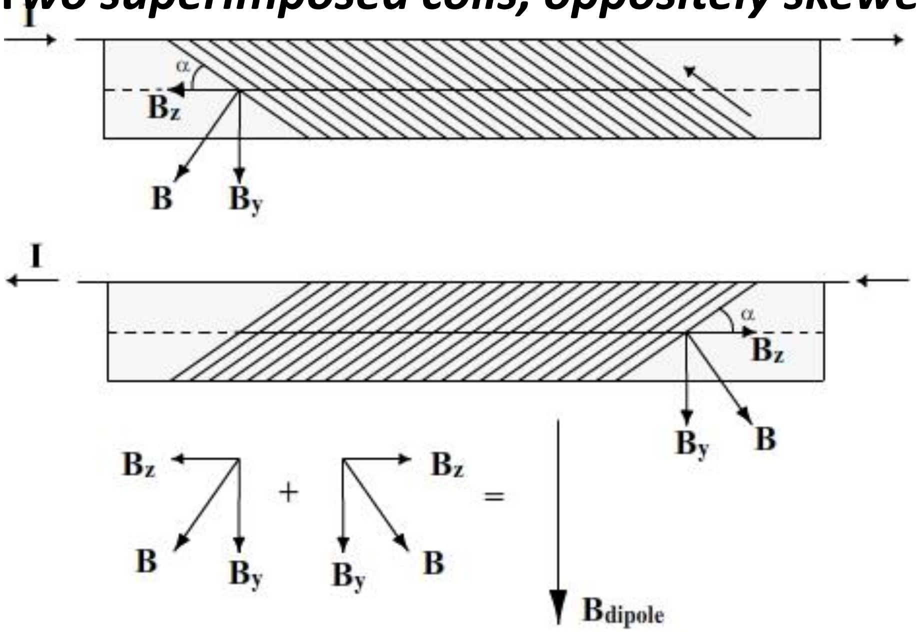
## Fixed field alternating gradient (FFAG) focus

# Canted Cosine Theta (CCT)

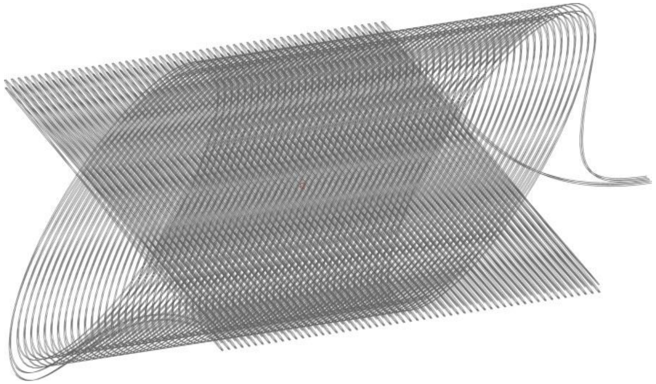



test bench at CERN

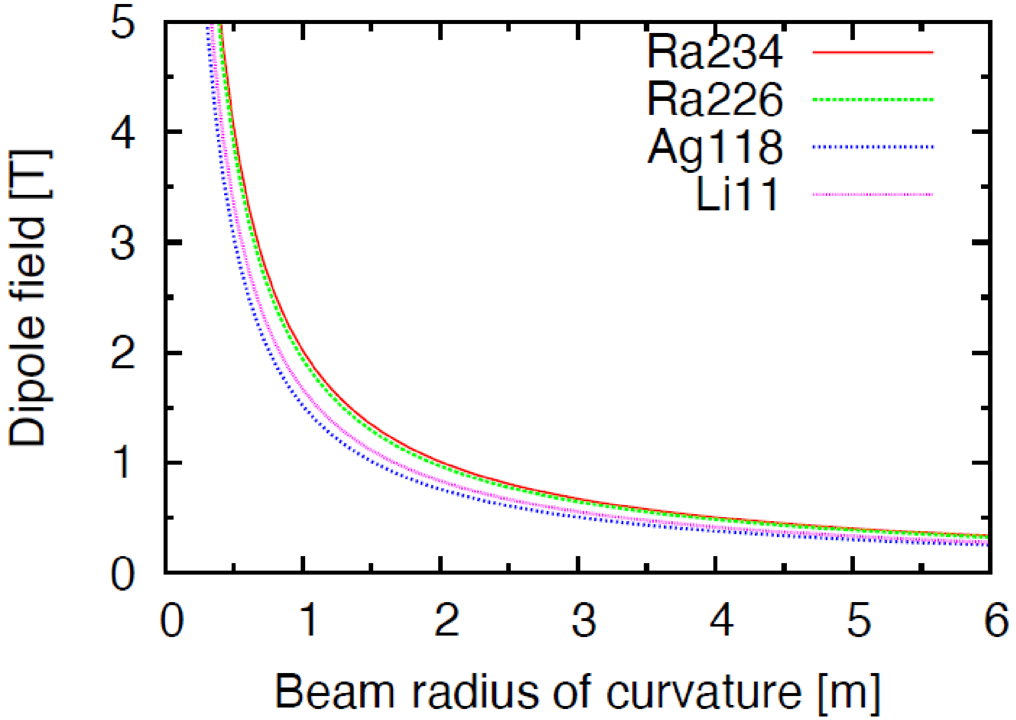
*Two superimposed coils, oppositely skewed*



*pure cosine-theta field*
*No axial field.*



# Dipole field



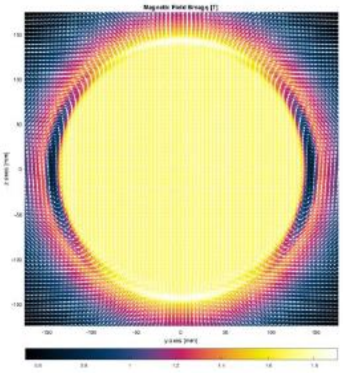
## Magnetic rigidity

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

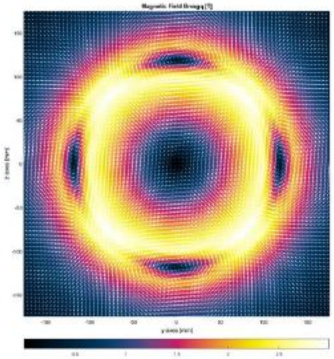
Example for different ions at 10 MeV/u kinetic energy

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

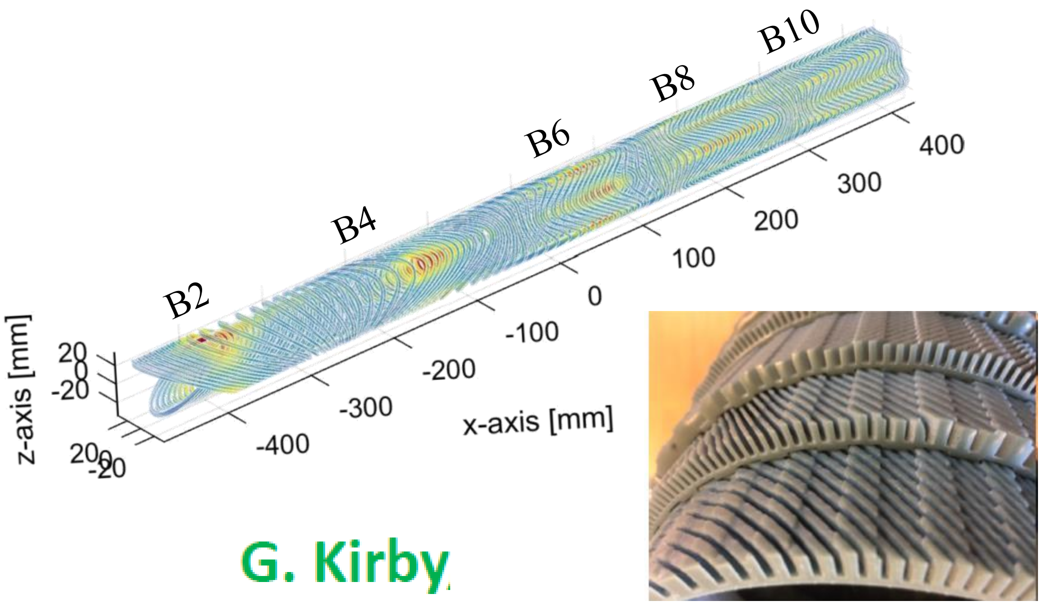
# Multifunction and high order aberrations  with CCT



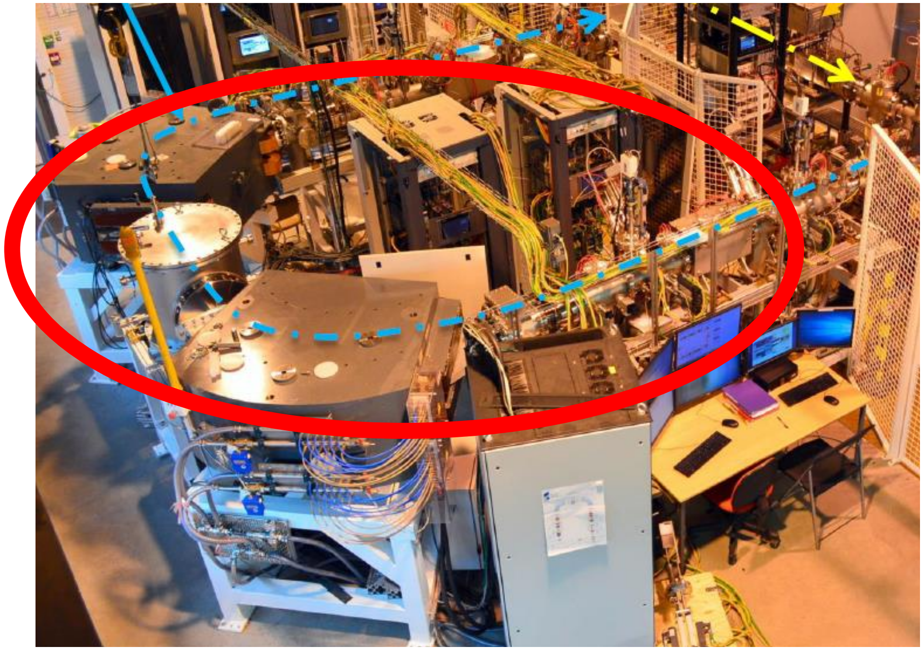
Dipole



Quadrupole



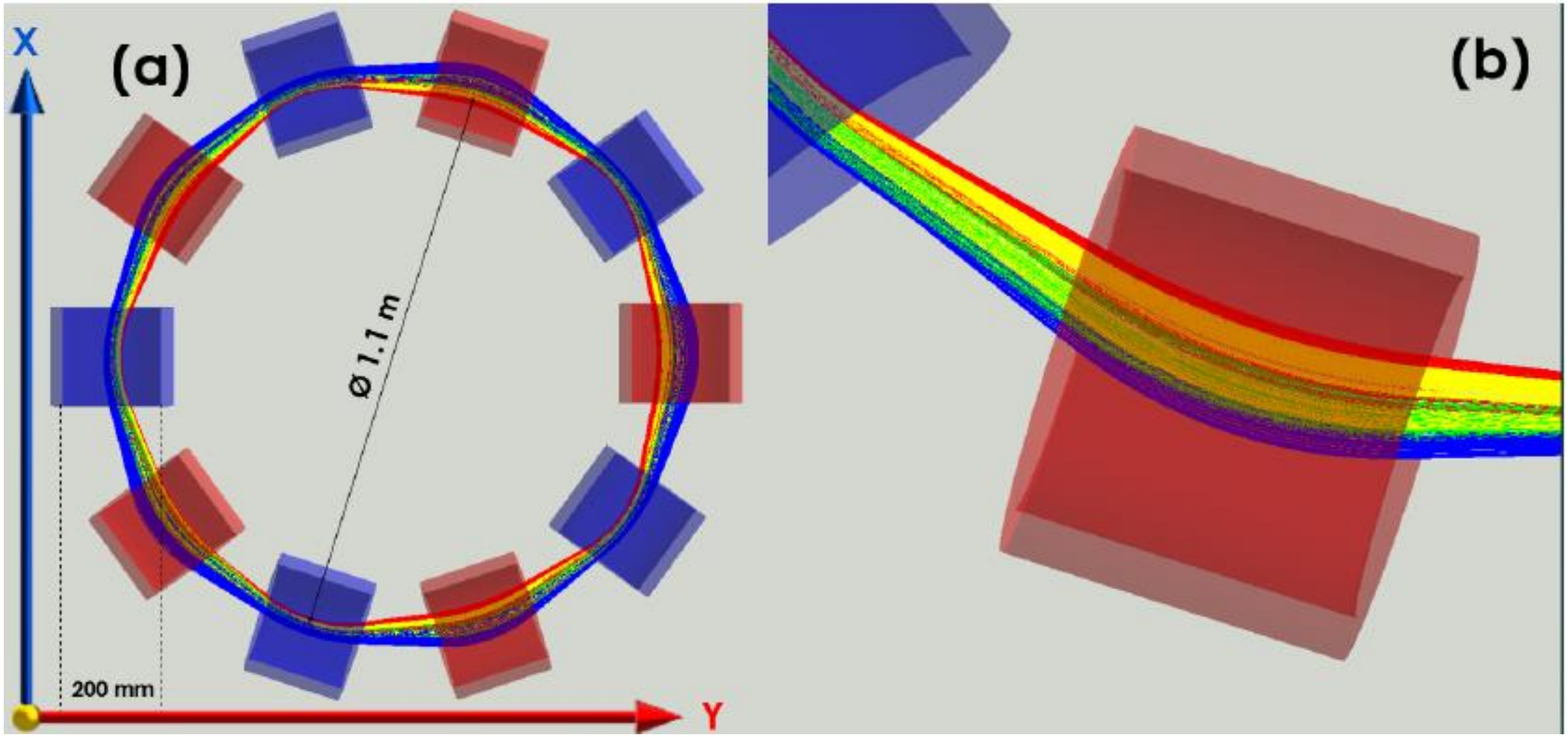
**G. Kirby**



# Ion optics

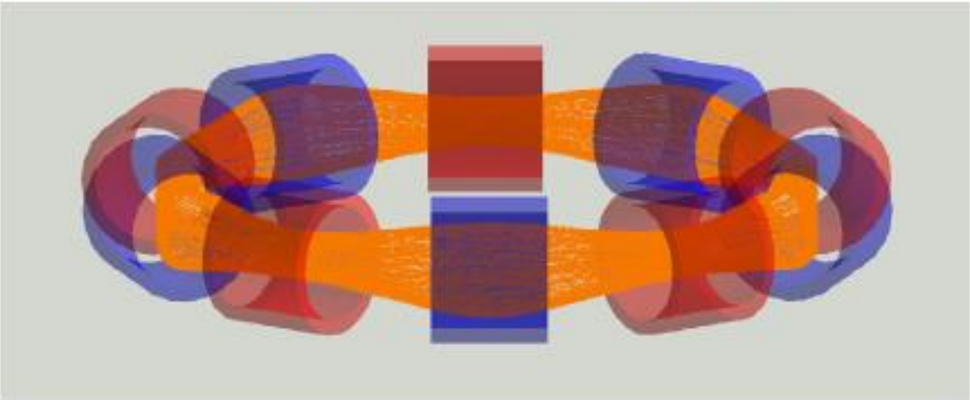
## Fixed field alternating gradient (FFAG) focus

Significantly reducing the size with respect to standard recoil separator configurations

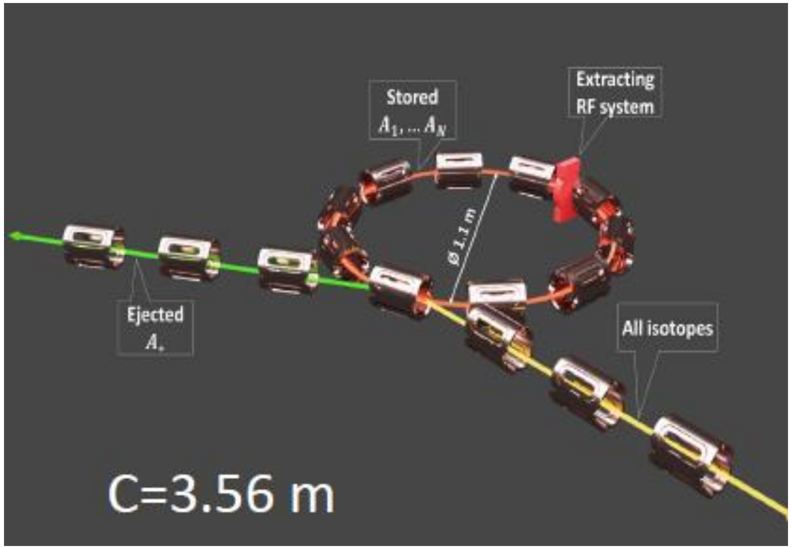


# Angular and momentum acceptance – Resolving power

Tracking of Ra226 for 300 turns

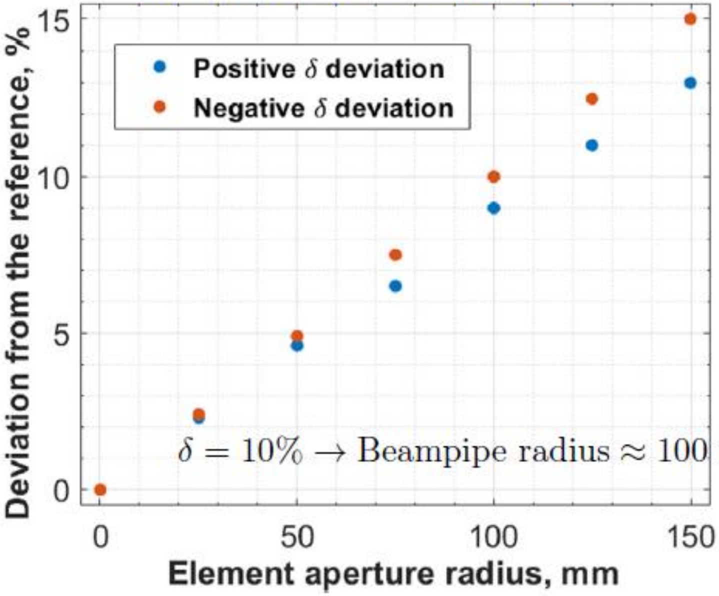


$$\mathrm{Max}(x', y') \approx (115, 160)\ \mathrm{mrad}$$



C=3.56 m

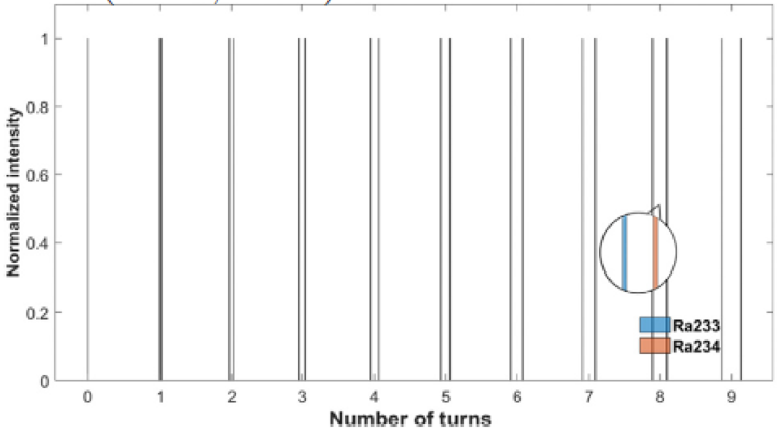
## Momentum acceptance



$\delta = 10\% \rightarrow$ Beampipe radius $\approx 100$ mm

## Mass resolving power

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



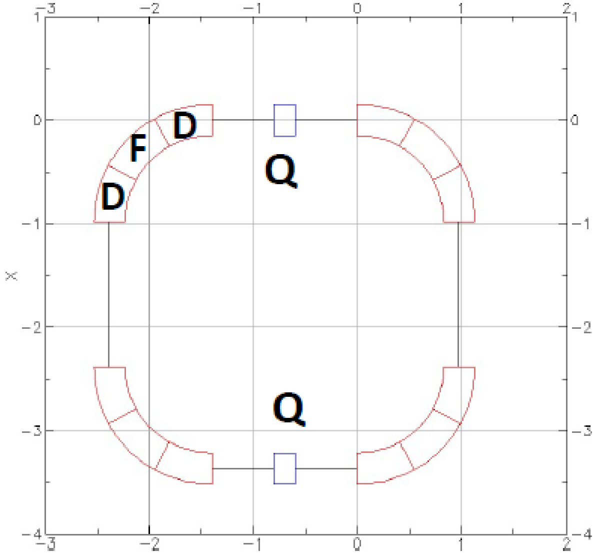
The detected intensity peaks of both Ra233 and Ra234 separate longitudinally as the number of turns increases.

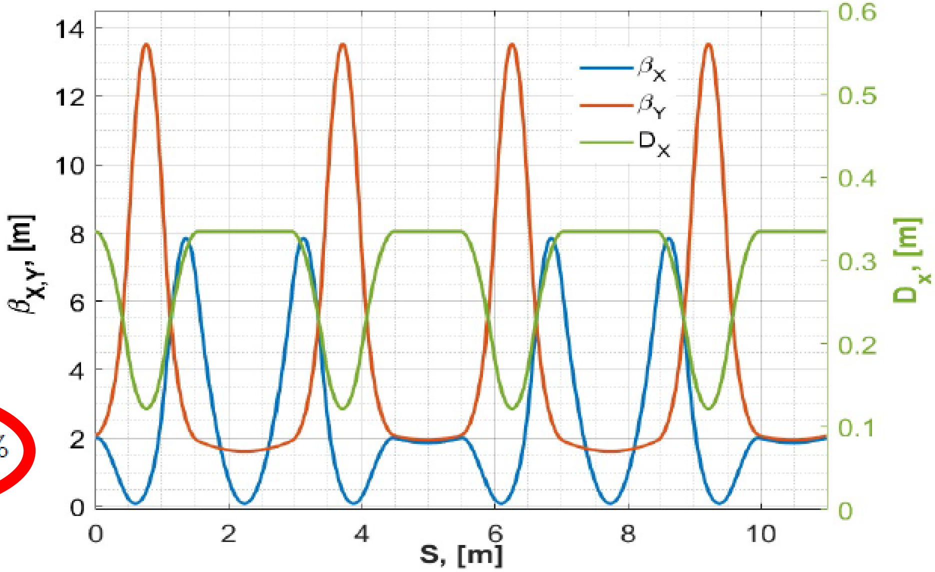
C. Bontoiu et al., NIMA 969 (2020) 164048

# High momentum acceptance desing

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

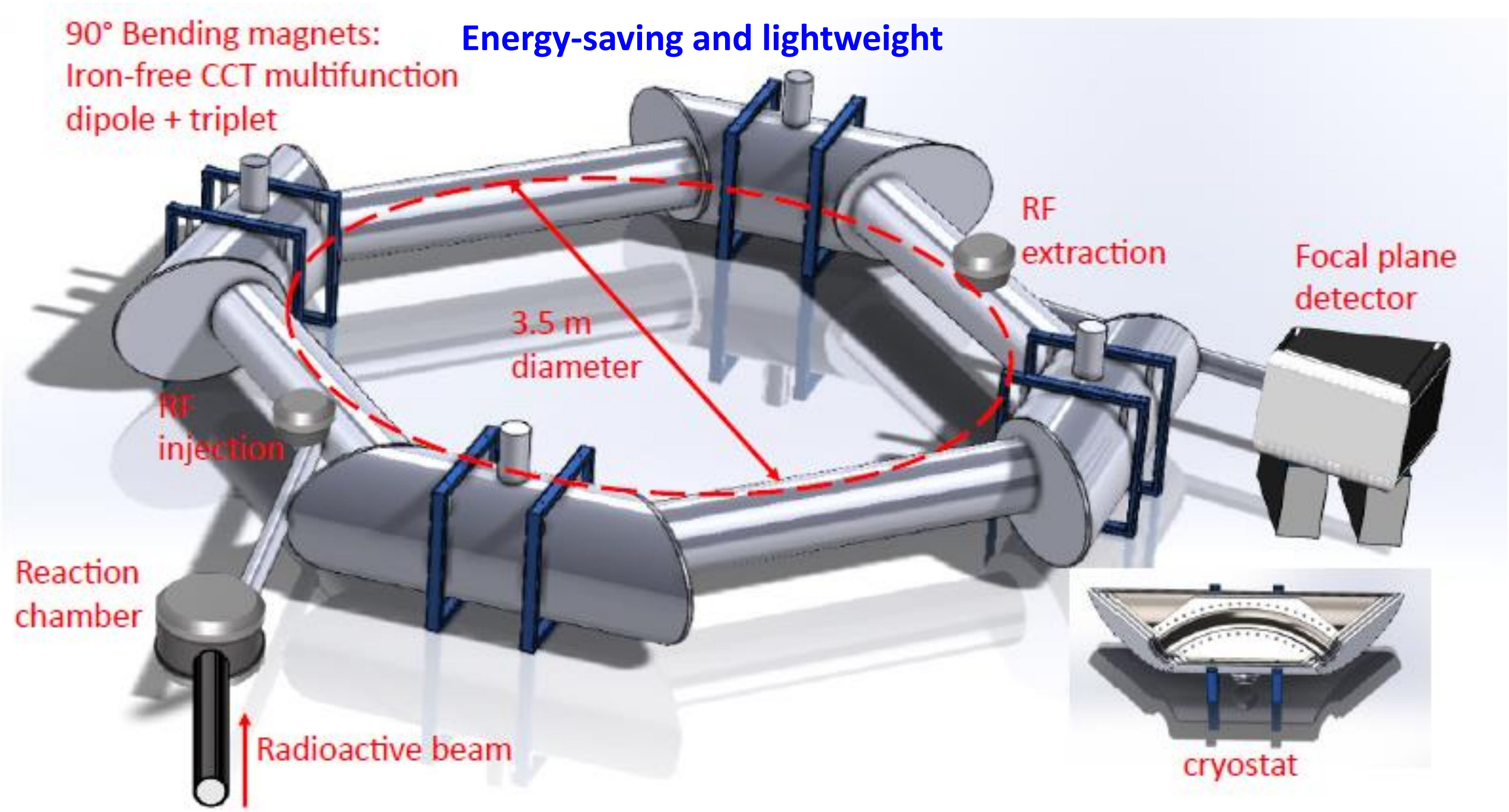
| Beam | $^{234}$Ra |
|---|---|
| Kinetic energy | 10 MeV/u |
| Rigidity, $B\rho$ [T m] | 2 |
| Maximum beta functions, $\beta_{x,y}$ [m] | 7.8, 13.5 |
| Maximum dispersion, $D_x$ [m] | 0.32 |
| **F magnet** | |
| Effective length [m] | 0.497 |
| Dipole field [T] | 2.0 |
| Quadrupole gradient [T/m] |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

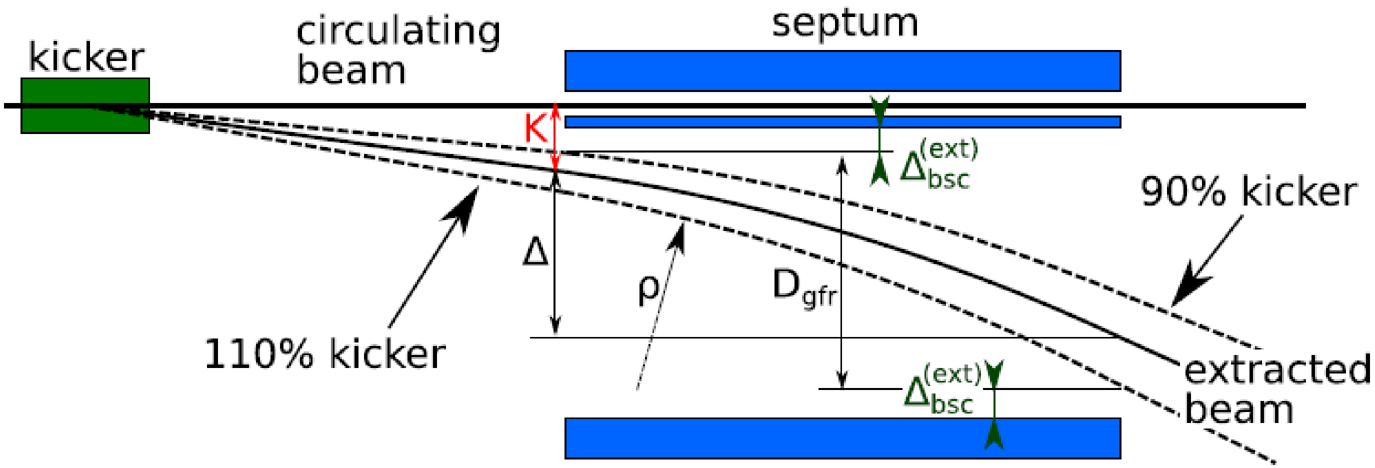
# A conceptual design of the ISRS ring showing the main subsystems



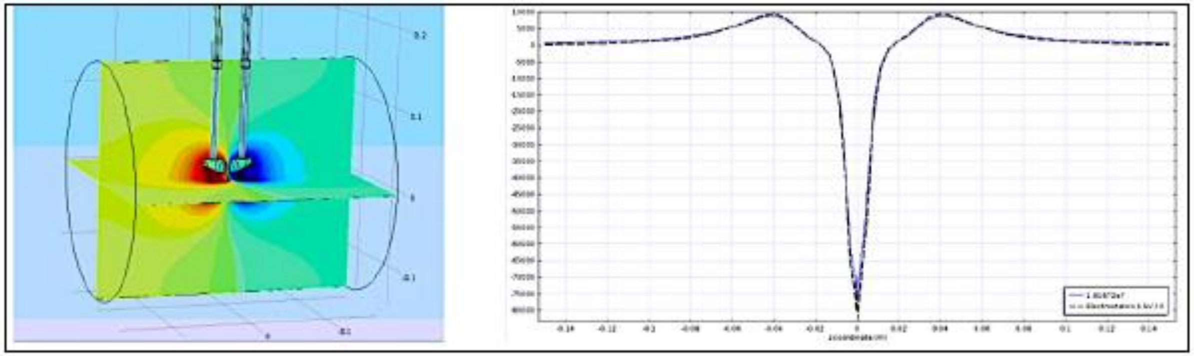
helium circulating system that re-liquefies all the evaporating helium gas and consumes far less power than conventional systems

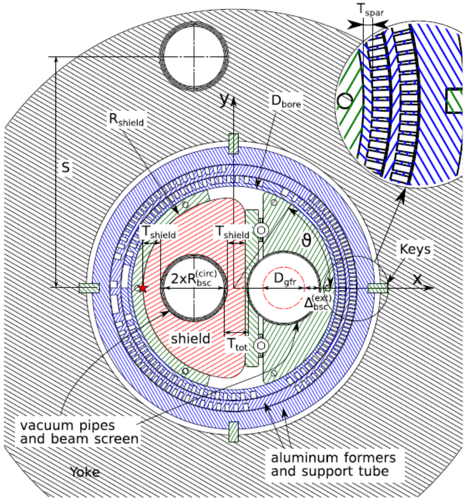
# Injection/extraction systems

SuShi (for superconducting shield) septum using a canted cosine theta-like (CCT) magnet being developed for the HiLumi LHC phase



To be studied





Dániel Barna, Martin Novák, Kristóf Brunner, et al. Rev. Sci. Instrum. 90, 053302 (2019)

# Isochronous mode

Revolution period deviation

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

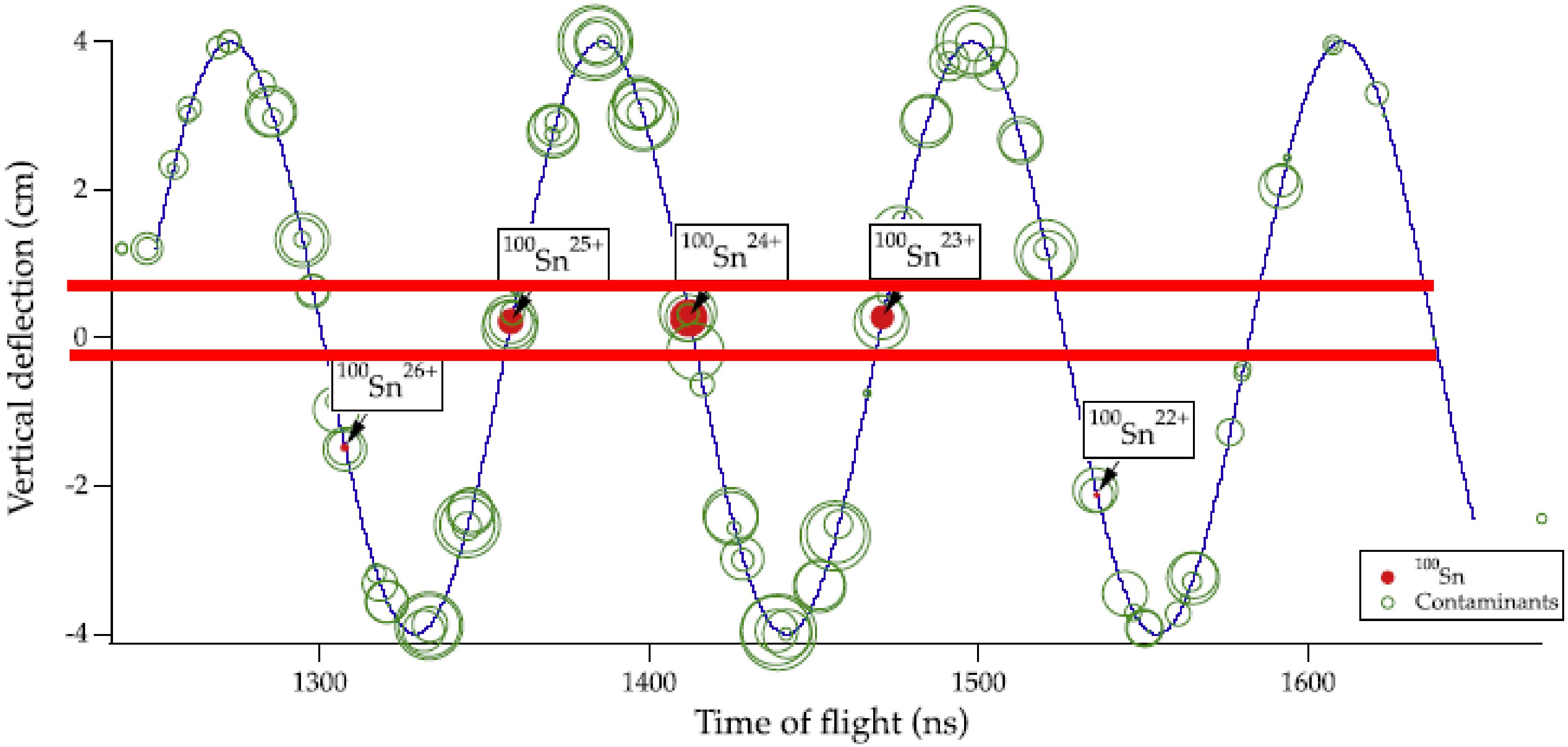
The revolution frequency becomes velocity independent if $\boxed{\gamma \rightarrow \gamma_t}$

By placing a small RF cavity at the isochronous focus, it is possible to deflect the recoils according to their m/q ratio, independent of their energy and scattering angle.

By carefully choosing the harmonic and phase used in the cavity, several charge states of the same isotope can be aligned to have the same deflection and be focused at the same location.

# Isochronous condition

$^{50}$Cr($^{56}$Ni,α2n)$^{100}$Sn at about 3.7 MeV/u, where the $^{100}$Sn ions are produced with charge states ranging from 22+ to 26+.



Nuclear Instruments and Methods in Physics Research B 317 (2013) 319–322

# Isochronous mode

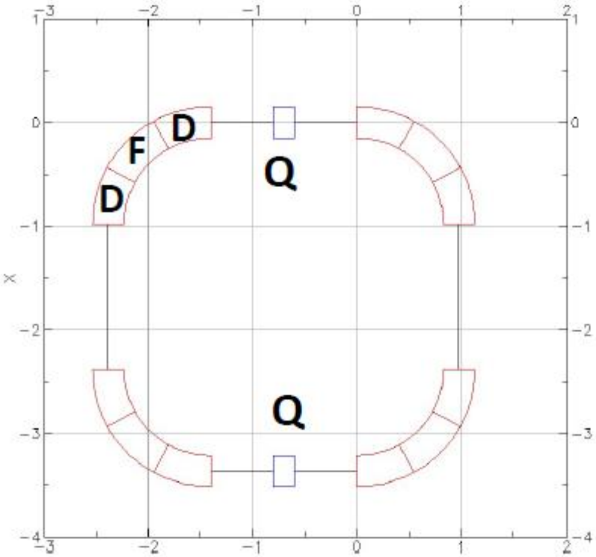
- DFD optics for non-scaling FFAG
- Matching with two additional quads. (Q). BMAD

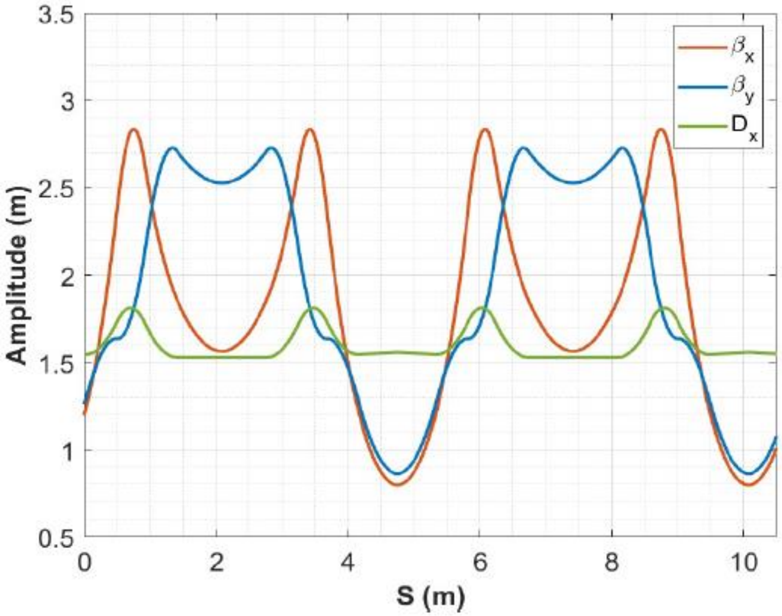
$$\alpha_c = 0.98 \quad \gamma_t = 1.0102$$

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

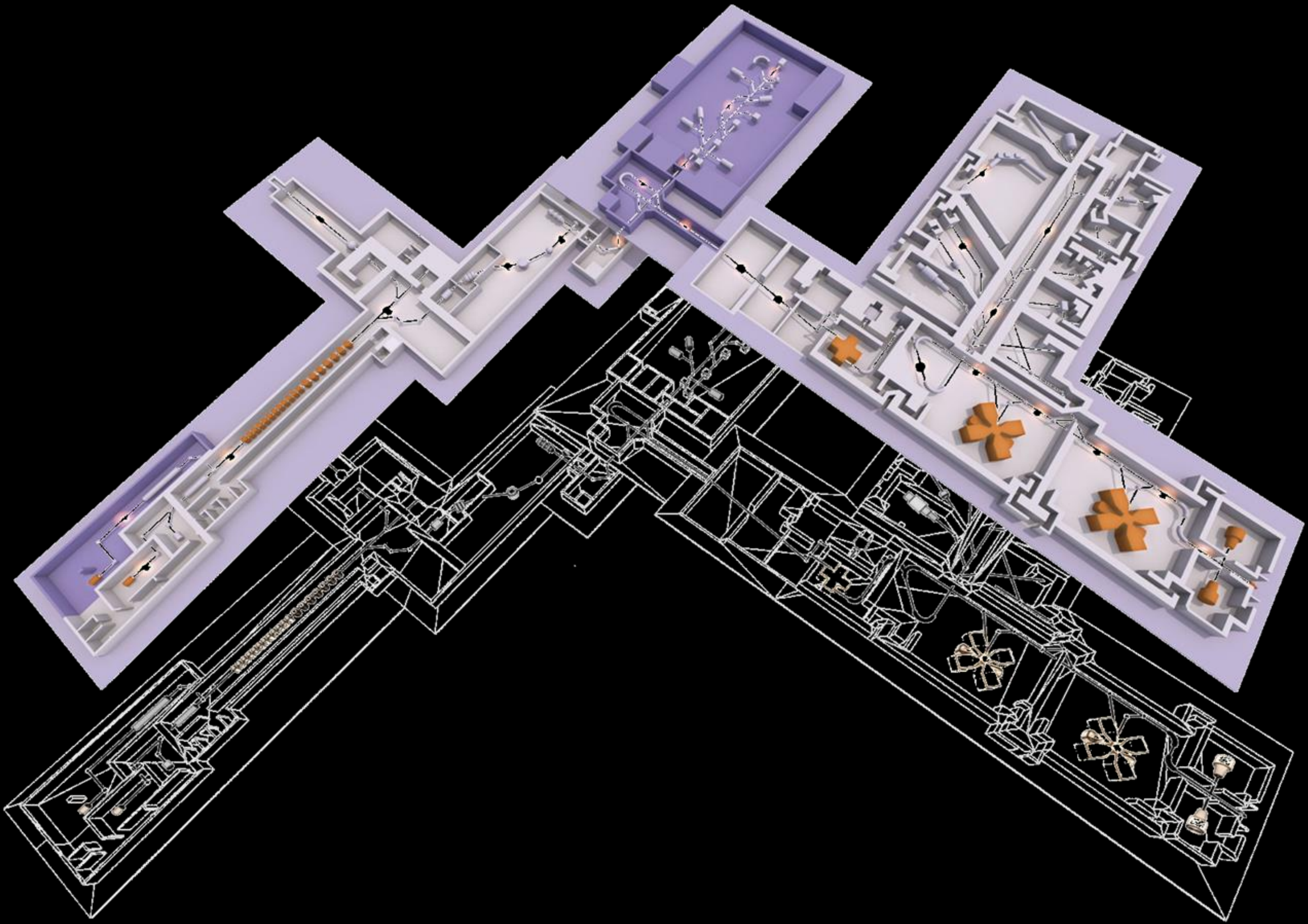
| Beam | $^{234}$Ra |
|---|---|
| Kinetic energy | 10 MeV/u |
| Rigidity, $B\rho$ [T m] | 2 |
| Maximum beta functions, $\beta_{x,y}$ [m] | 2.85, 2.72 |
| Maximum dispersion, $D_x$ [m] | 1.8 |
| **F magnet** | |
| Effective length [m] | 0.55 |
| Dipole field [T] | 2.45 |
| Quadrupole gradient [T/m] | 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:** $\Delta p/p = +/- 5.5$ %

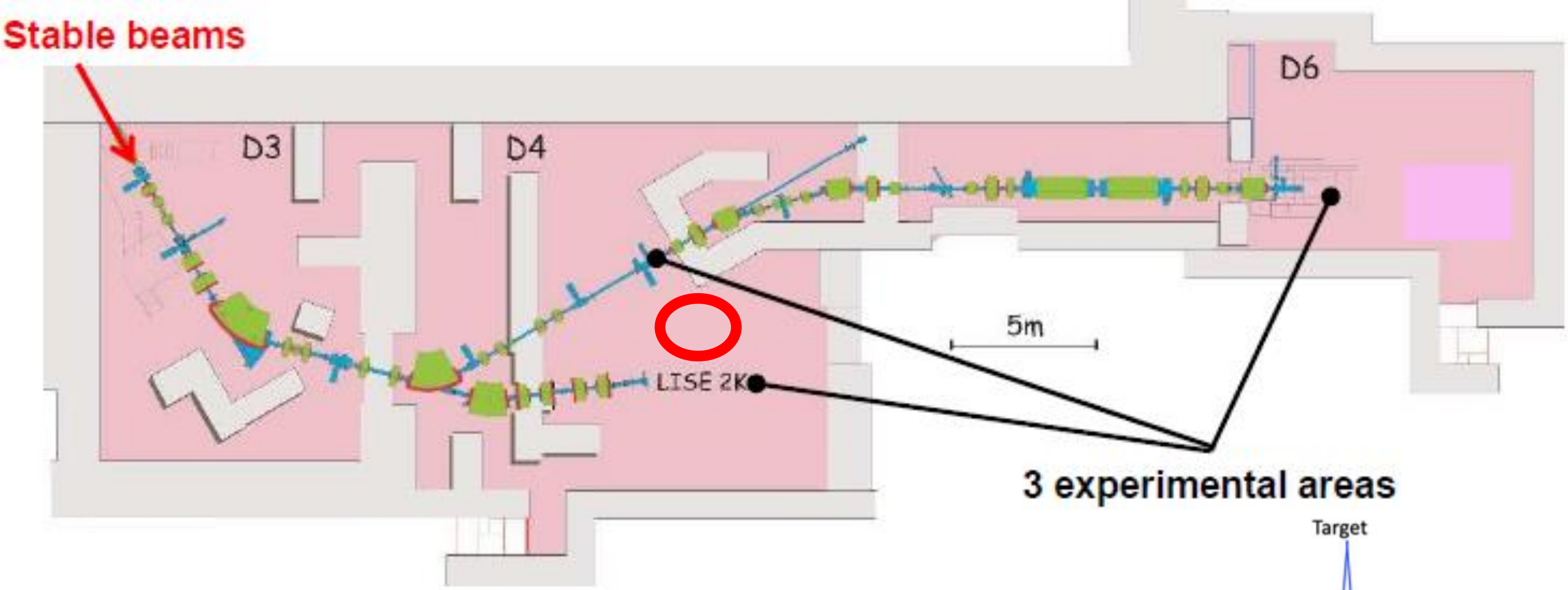




# Maybe at GANIL?

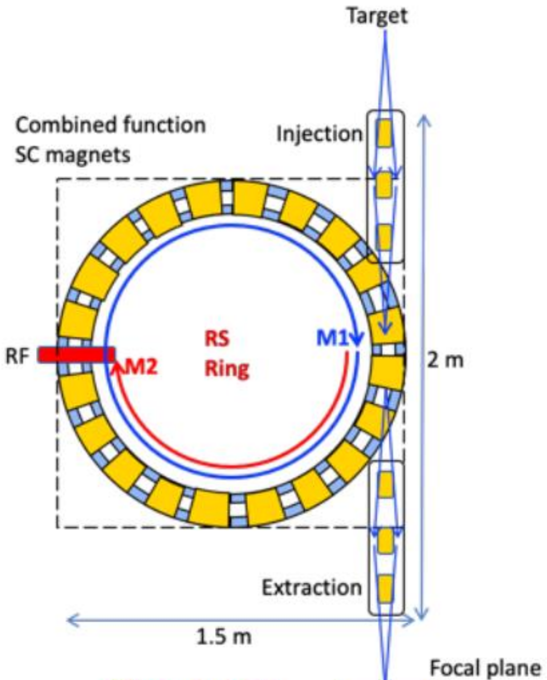


# At LISE ?



**Momentum acceptance**
**Δp/p ~30 % for 10 MeV/u**

**To be studied for other energy ranges**



Ring concept

# FFAG-SCMR advantages

- ✓ State-of-the-art iron-based magnetic systems are heavy energy-consuming. Currents up to 200 A with **20 KW energy consumption per coil are typical**, requiring cooling systems to remove the heat dissipated by ohmic losses.
- ✓ Magnet operation suffers from **nonlinearities, hysteresis, and remnant magnetization** of the iron yokes.
- ✓ The use of **SC magnets** avoids energy losses of equivalent conventional warm magnets down to **a few watts, reaching 30 times higher fields with 10 times smaller size and 1000 times reduced weight.**
- ✓ **The equivalent system of an FFAG-SCMR with similar functionalities, would be at least twenty times larger and three orders of magnitude heavier and energy-consuming**.
- ✓ **The advances in iron-free SC coils**, together with cryostat optimization, make **cryocoolers** a good option that **eliminates the need for important and expensive infrastructures to produce and distribute liquid helium** and all the associated safety and maintenance constraints. 10 €/litter…
- ✓ Adding **acceleration cavities** to the layout, the FFAG-SCMR will become a very **compact lightweight particle synchrotron accelerator**.
- ✓ **Recirculating target**

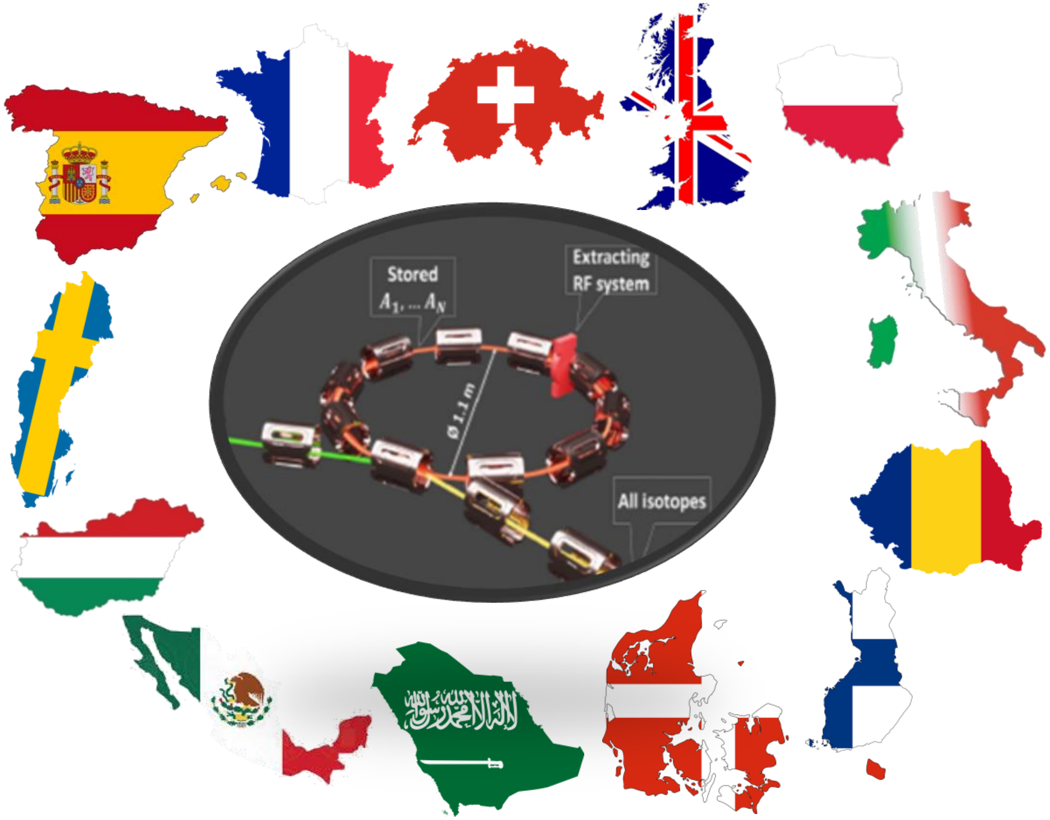
# ISRS Collaboration

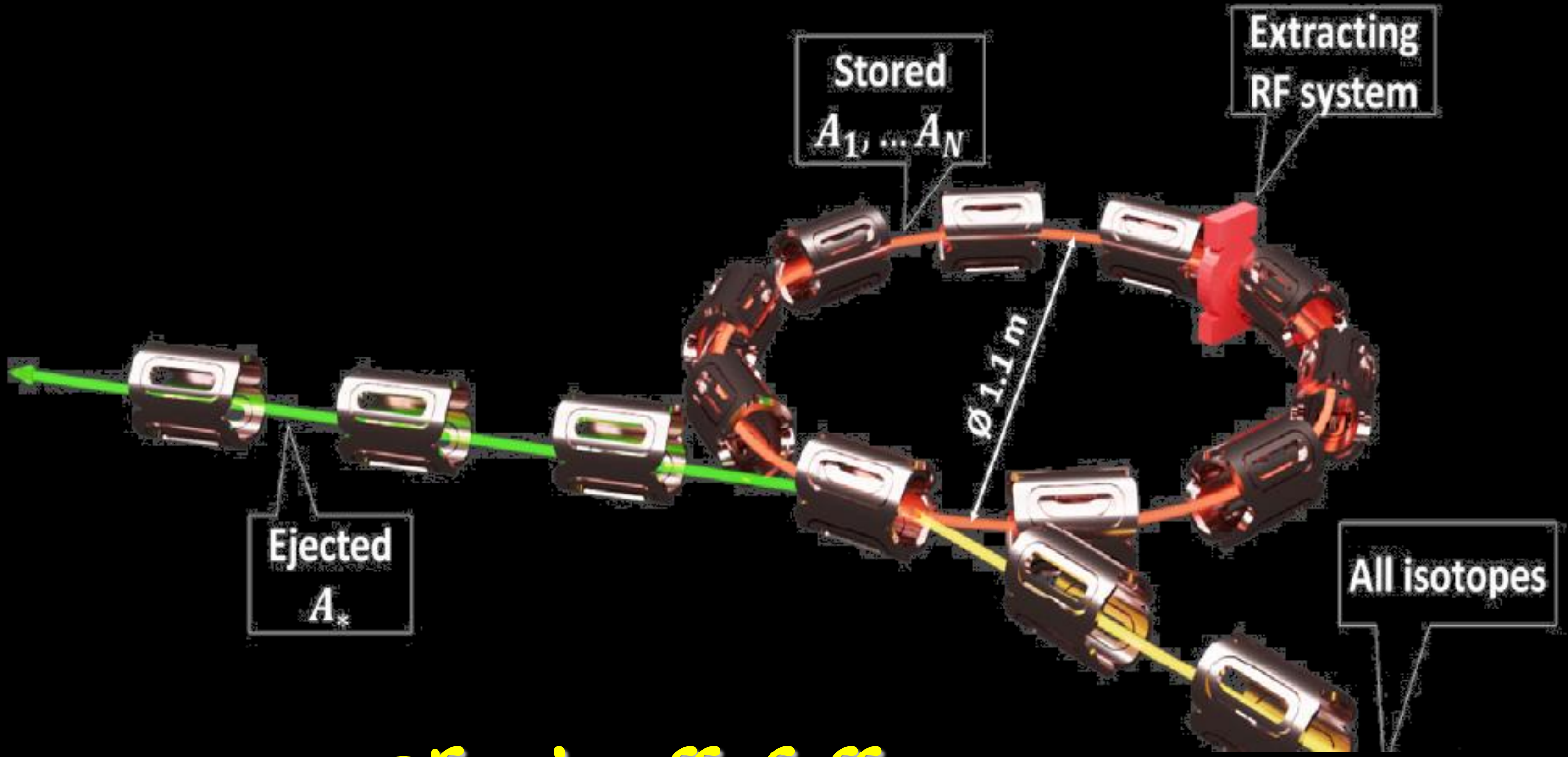
I. Martel[1], L. Acosta[2], J.L. Aguado[1], M. Assie[3], M. A. M. Al-Aqeel[4,25], A. Ballarino[9], D. Barna[5], R. Berjillos[6], M. Bonora[9], C. Bontoiu[4], M.J.G. Borge[7], J.A. Briz[7], I. Bustinduy[8], L. Bottura[9], L. Catalina-Medina[8], W. Catford[10], J. Cederkäll[11], T. Davinson[12], G. De Angelis[13], A. Devred[9], C. Díaz-Martín[1], T. Ekelöf[14], H. Felice[9], H. Fynbo[15], A.P. Foussat[9], R. Florin[26], S. J. Freeman[9,27], L. Gaffney[4], C. García-Ramos[1], L. Gentini[9], C. A. Gonzalez-Cordero[1], C. Guazzoni[29], A. Haziot[9], A. Heinz[16], J.M. Jimenez[9], K. Johnston[9], B. Jonson[16], T. Junquera[17], G. Kirby[9], O. Kirby[30], T. Kurtukian- Nieto[18], M. Labiche[22], M. Liebsch[9], M. Losasso[9], A. Laird[19], J.L. Muñoz[8], B.S. Nara Singh[20], G. Neyens[9], P.J. Napiorkowski[28], D. O'Donnell[20], R. D. Page[4], D. Perini[9], J. Resta-López[21], G. Riddone[9], J.A. Rodriguez[9], V. Rodin[4,22], S. Russenschuck[9], V.R. Sharma[2], J. Sánchez- Segovia[1], K. Riisager[15], A.M. Sánchez-Benítez[1], B. Shepherd[22], E. Siesling[9], J. Smallcombe[4], M. Stanoiu[26], O. Tengblad[7], J.P. Thermeau[23], D. Tommasini[9], J. Uusitalo[24], S. Varnasseri[9], C.P. Welsch[4], G. Willering[9].

[1]CCTH, Univ. Huelva, Spain. [2]Inst. de Física, UNAM, Mexico. [3]Univ. Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay, France. [4]Dept. of Physics, Univ. Liverpool, UK. [5]Wigner Research Centre for Physics, Budapest, Hungary. [6]TTI Norte, Santander, Spain. [7]IEM, CSIC, Madrid, Spain. [8]ESS-BILBAO, Bilbao, Spain. [9]CERN, Geneva, Switzerland.[10]Dept. of Physics, Univ. Surrey, UK. [11]Dept. of Physics, Lund Univ., Sweden. [12]Univ. Edinburgh, UK. [13]LNL INFN, Italy. [14]Uppsala Univ., Sweden. [15]Dept. of Physics and Astronomy, Aarhus Univ., Denmark. [16]Dept. of Physics, Chalmers Univ. of Technology, Göteborg, Sweden. [17]ACS, Orsay, France. [18]Univ. Bordeaux, CNRS, Gradignan, France. [19]Dept. of Physics, Univ. York, UK. [20]School of Computing, Engineering & Physical Sciences, Univ. of West Scotland, UK. [21]ICMUV, Univ. de Valencia, Spain. [22]Cockcroft Institute, Daresbury, UK. [23]Universite de Paris, CNRS, Astroparticule et Cosmologie, France. [24]Faculty of Mathematics and Science, Univ. Jyvaskyla, Finland. [25]IMIS Univ. Riyadh, Saudi Arabia. [26]IFIN-HH, Bucharest, Romania. [27]Department of Physics & Astronomy, Univ. Manchester, UK. [28]HIL, University of Warsaw, Poland. [29]Dept. Electronics, Info. and Bio., Politecnico di Milano, Milan, Italy. [30]Paul Scherrer Institute, Zurich, Switzerland.

## 72 members of 30 Institutions from 13 countries

- Spain
- UK
- France
- Italy
- Switzerland
- Poland
- Sweden
- Hungary
- Denmark
- Finland
- Romania
- Mexico
- Saudi Arabia





*That's all folks*