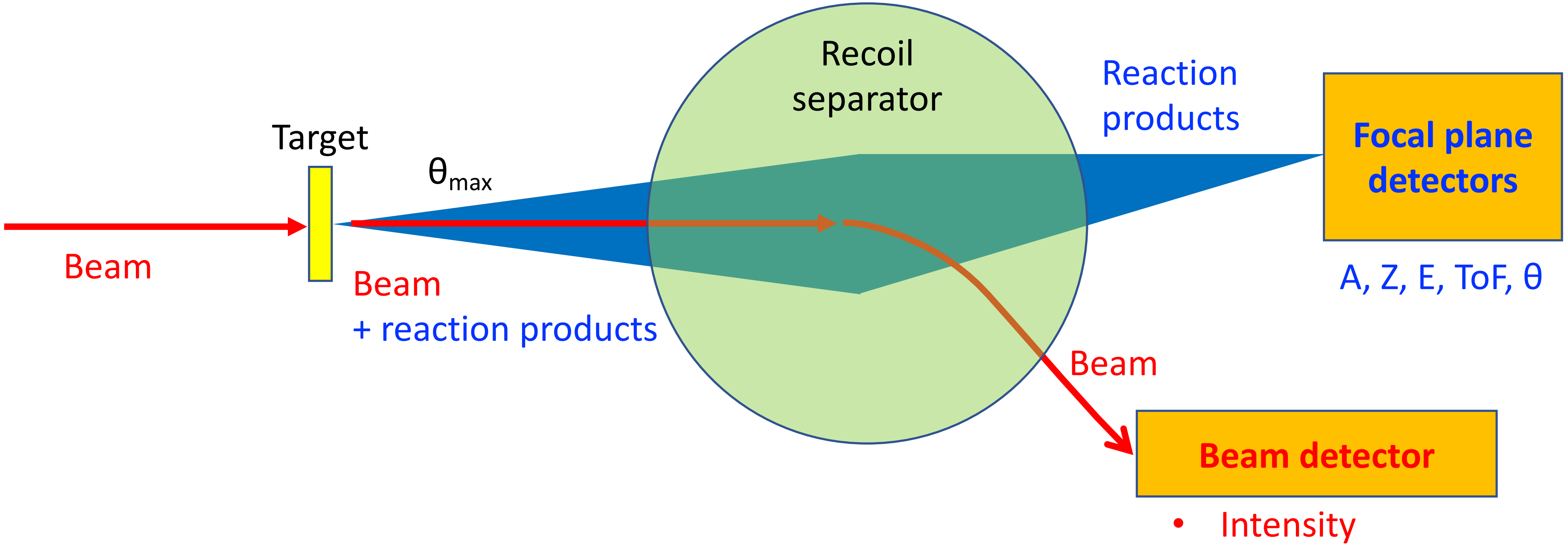
Present status of HIE-ISOLDE Superconducting Recoil Separator

I. Martel

for the ISRS Collaboration

Recoil Separators

- Use to detect forward focussed reaction products (recoils): A, Z, E, ToF, θ
- Separate them from the primary beam.



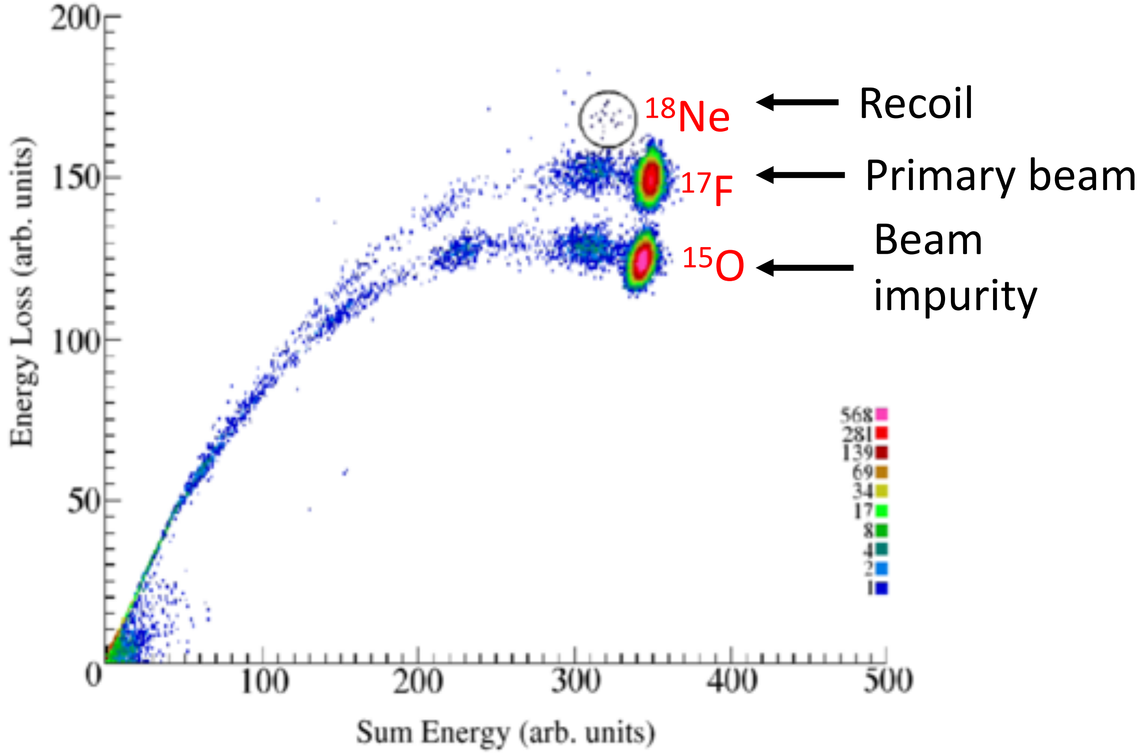
- Normally used in coincidence with other detectors systems.
- Main advantage is the very high efficiencies > 80%.
- Higher cost than particle detector systems.

- Stand alone - simpler experiments.
  - ✓ Heavy recoils
- Reactions with **γ, n** in the exit channel
- Reactiond with **particles**, **γ, n** in the exit channel
  - ✓ Reaction channel selection
- Beam impurities

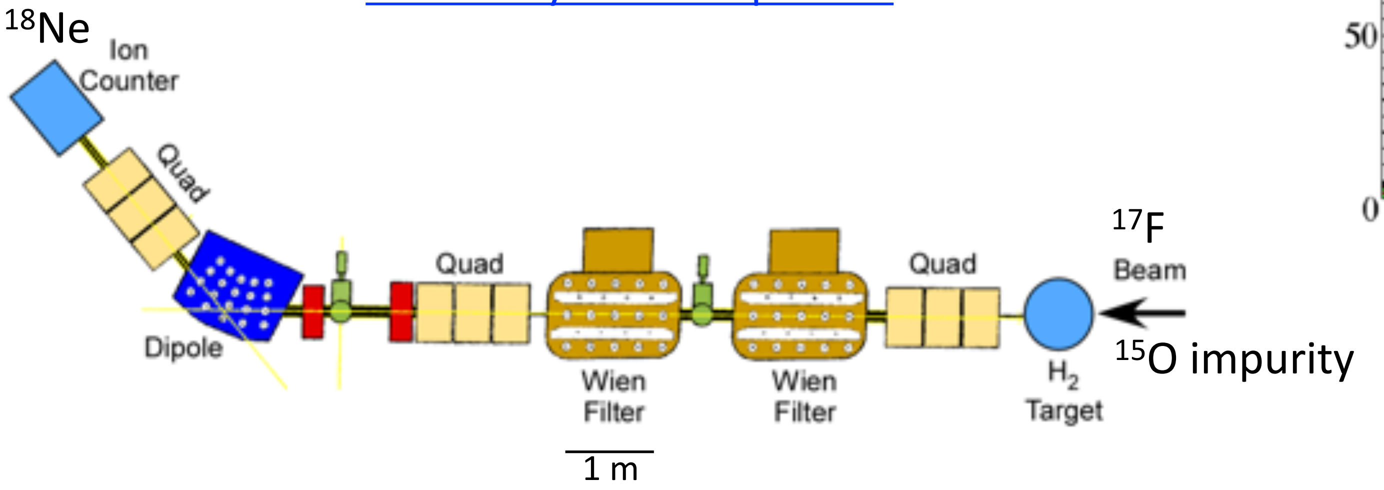
Nuclear astrophysics: Direct measurements of (*p*,γ) capture cross sections

D. W. Bardayan, *et al*. European Physical Journal A, 2009.

- Strength of the 3+ resonance in $^{17}F(p,\gamma)^{18}Ne$ - explosive nucleosynthesis
- HRIBF (Oak Ridge, USA)
- Energy and width from $^{17}F(p,p)^{17}F$ in inverse kinematics
- Beam energy – 1.1 MeV/A
- I ~ 10^7 pps
- Windowless hydrogen gas target



Daresbury Recoil Separator



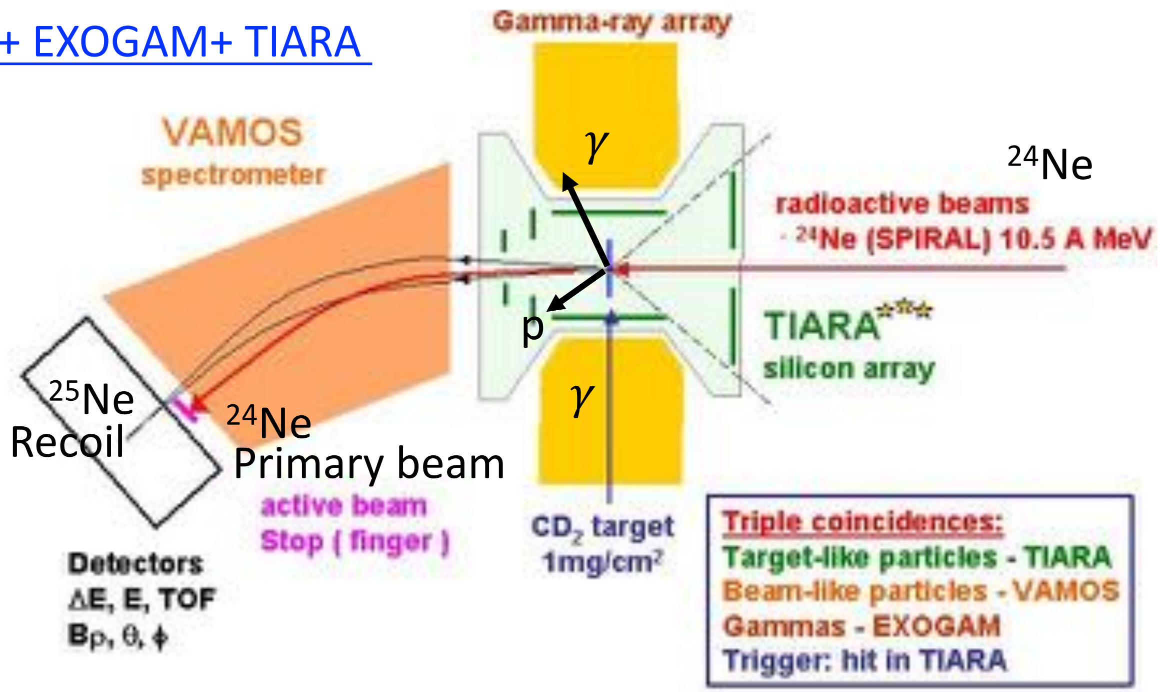
- Stand alone
- Beam impurities

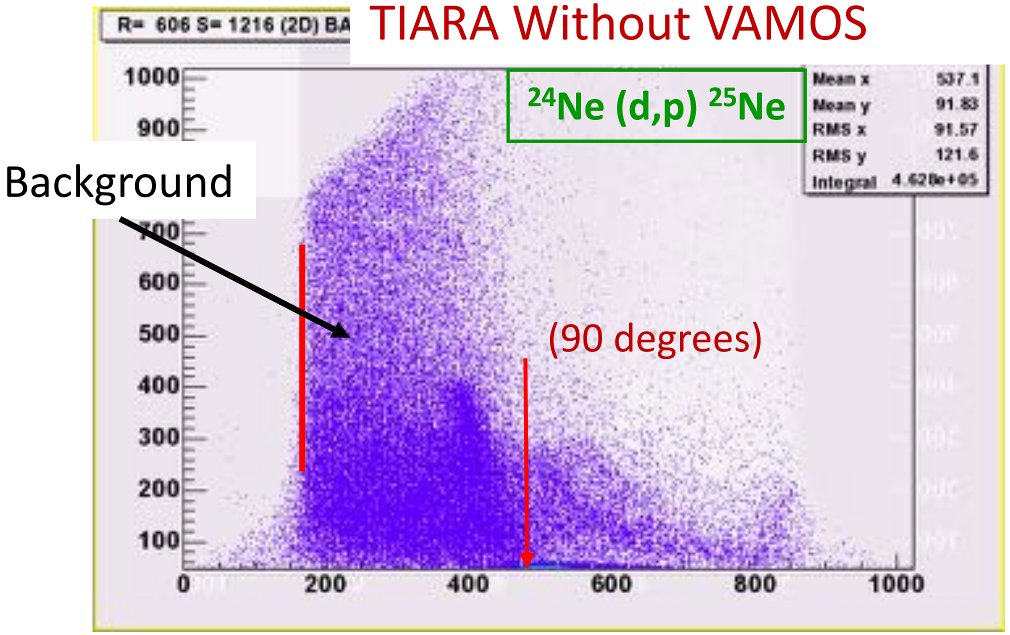
Evolution of Nuclear Shells: N=16 replaces N=20

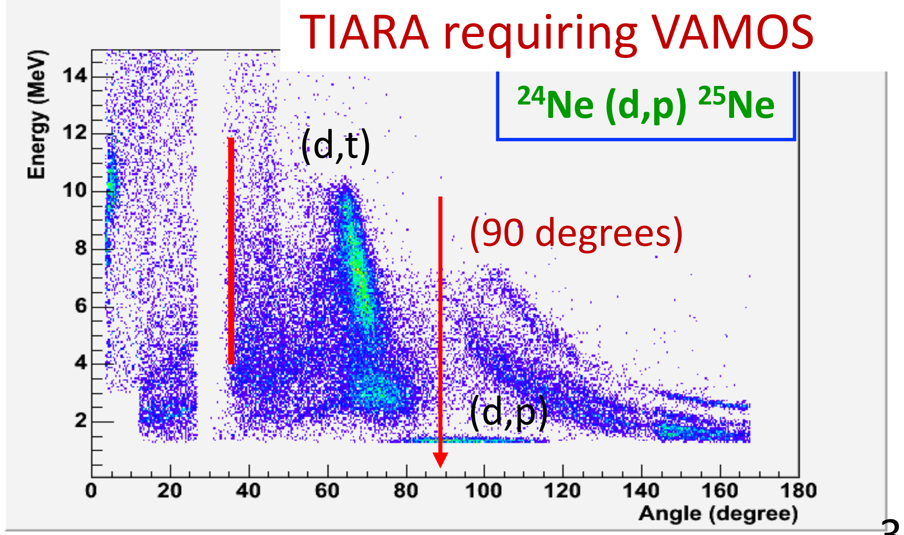
W.N. Catford *et al.*, Eur. Phys. J. **A25.1** 245 (2005).

- ^{24}Ne(d, pγ)^{25}Ne in inverse kinematics
- GANIL – SPIRAL1 (France)
- Beam energy - 10.5 MeV/A
- Target CD_2

VAMOS+ EXOGAM+ TIARA







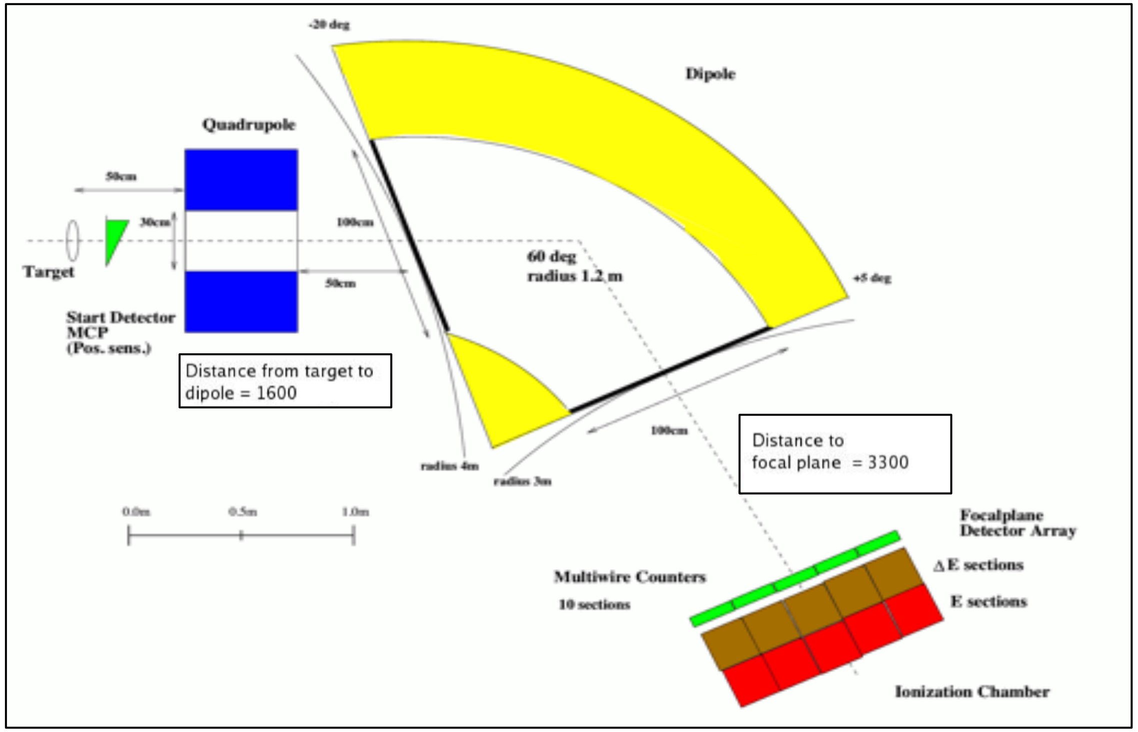
- Experiments with **particle, γ** in the exit channel
- Selection of reaction channel – background removal

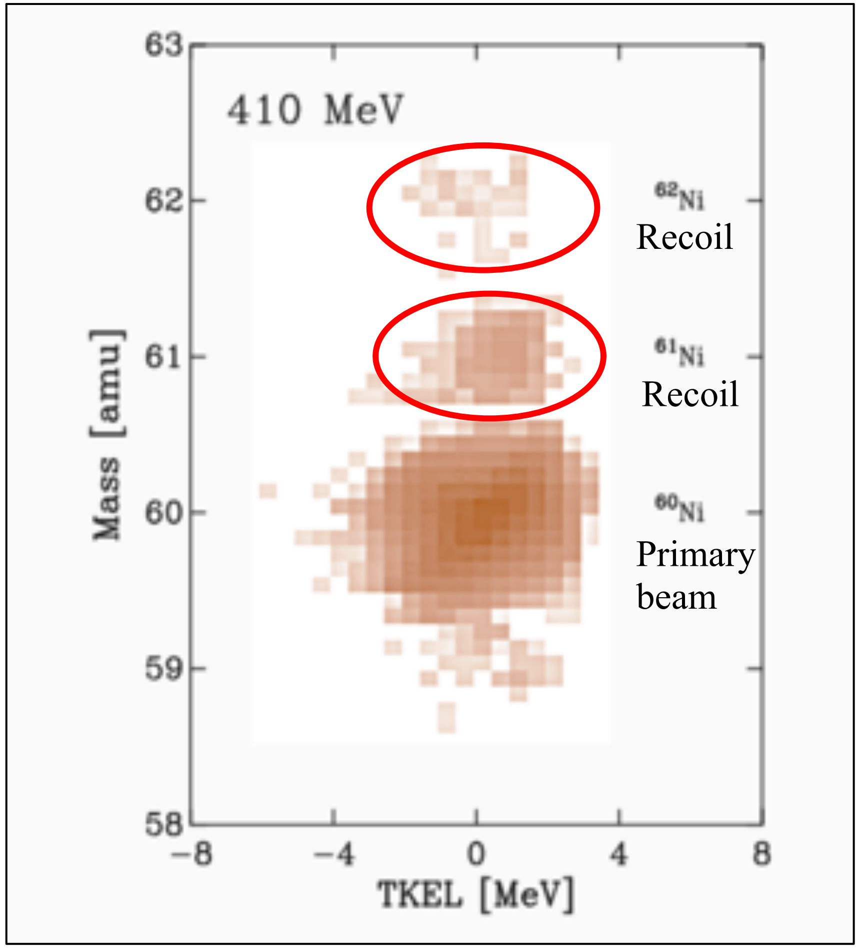
Pairing interaction with multi-nucleon transfer reactions

D. Montanari *et al.*, PRL 113, 052501 (2014)

- Dynamics of neutron transfer at Coulomb barrier
- Neutron pairing around ^{62}Ni
- ^{116}Sn(^{60}Ni , ^{62}Ni) ^{114}Sn, ^{116}Sn (^{60}Ni, ^{61}Ni) ^{113}Sn
- INFN, Laboratori Nazionali di Legnaro (Italy)
- Beam energy 3- 4 MeV/A

PRISMA spectrometer; rotated θlab = 20°





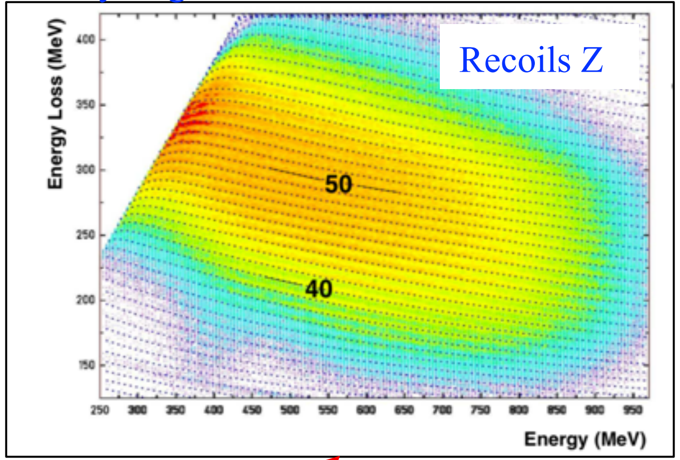
- Multinucleon transfer experiments to study neutron pairing in n-rich exotic beams.

Dynamics of Fission using multinucleon transfer reactions

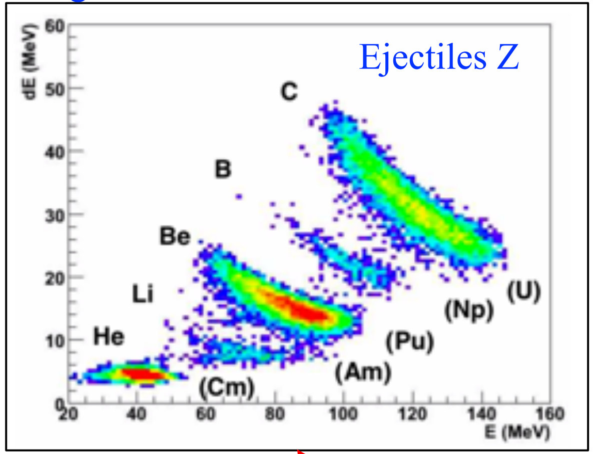
M. Caamaño et al. AIP Conference Proceedings 1175, 15 (2009)

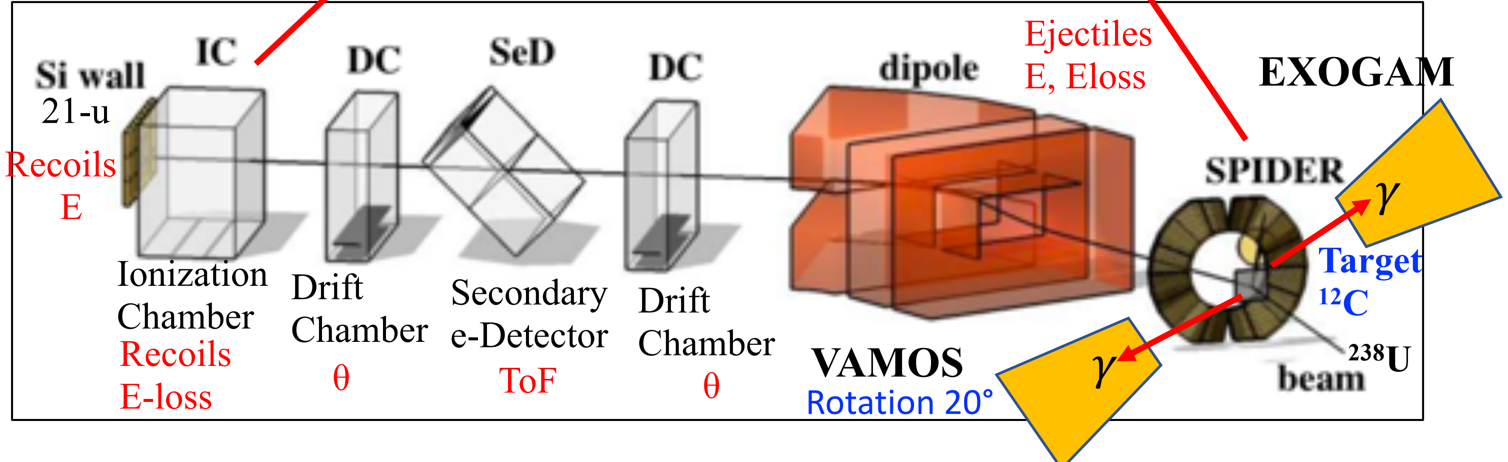
- GANIL (France)
- Fission dynamics of neutron-rich actinides → shell structure and pairing correlations at low excitation energy.
- $^{238}U + ^{12}C$ in inverse kinematics
- E = 6.1 MeV/A

Heavy fragment Z-identification: VAMOS

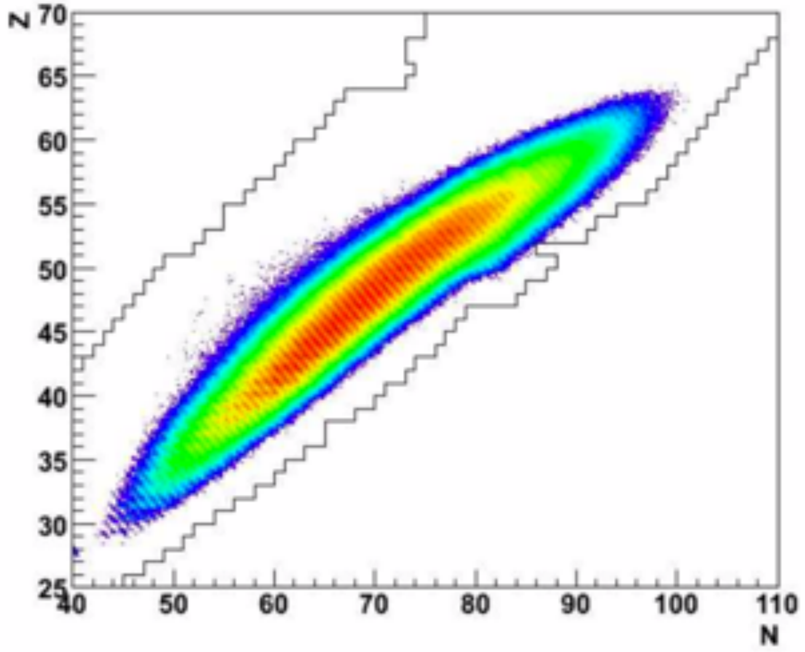


Light fragment Z-identification: SPIDER





Bρ → A/q → Full identification (Z, N)

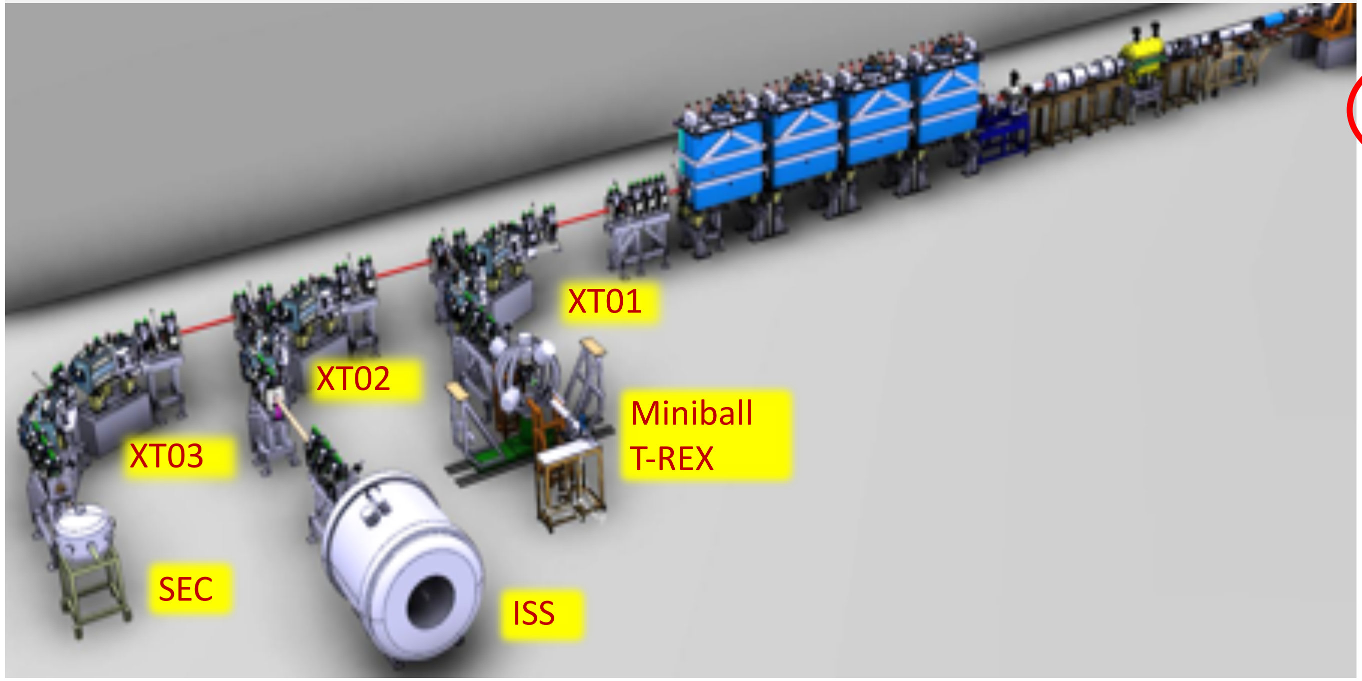


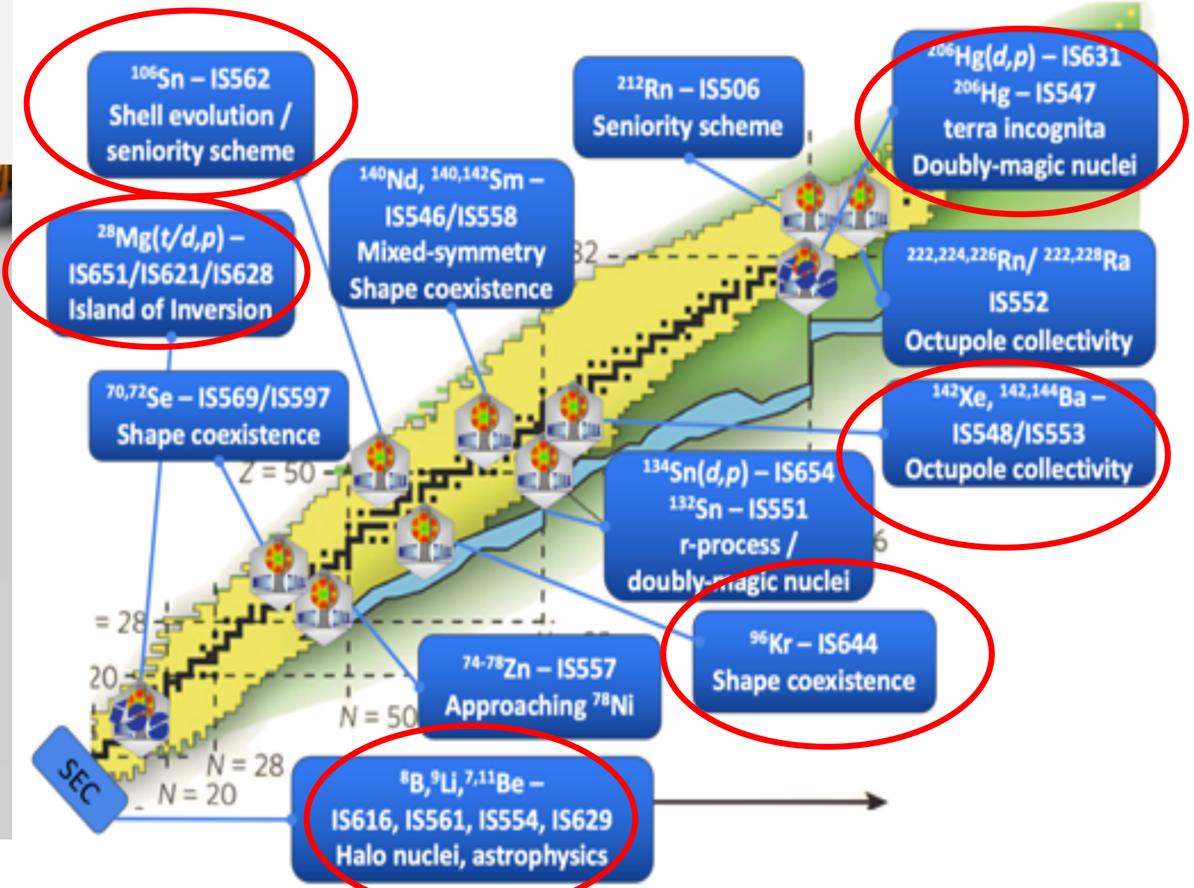
- Reactions with **particles**, **γ**
- Fission multinucleon transfer with neutron-rich exotic beams

THE HIE-ISOLDE FACILITY AT CERN

HIE-ISOLDE: very large range of radioactive beams from ^{6}He – ^{234}Ra

- > 1000 isotopes, > 70 elements
- Wide energy range 0.45 - 10 MeV/A (dep. A/Q)





Recent physics cases investigated at HIE-ISOLDE (L. Gaffney, ISOLDE EPICS Workshop 2019).

- Studies of recoil separators for HIE-ISOLDE go back to 2011.
- The HIE-Isolde Fragment Identifier - 2017, using warm magnets (HIFI).
- The ISOLDE Superconducting Recoil Separator (ISRS)– new initiative since 2019.

A Recoil Separator can bring new and exciting possibilities to the HIE- ISOLDE physics program.

HIE-ISOLDE experiments that could profit from a Recoil Separator (2018)

IS591 P377 ^{18}N: a challenge to the shell model and a part of the to r-process element production in Type II supernovae (**$^{17}N(d,p)^{18}N$).** Matta, A / Catford, W.

IS606 P440 Studies of unbound states in isotopes at the N = 8 shell closure **[$^{11}Be(t,p)^{13}Be$].** Tengblad O. / Mücher, D.

IS587 P398 Characterising excited states in and around the semi-magic nucleus ^{68}Ni using **Coulomb excitation** and one-neutron transfer. Gaffney, L./Flavigny, F./Zielinska, M./Kolos, K.

IS566 P370 Probing intruder configurations in $^{186,188}Pb$ using **Coulomb excitation.** Pakarinen, J.

IS562 P362 **Transfer Reactions** and Multiple **Coulomb Excitation** in the ^{100}Sn Region. Cederkäll, J.

IS561 P361 **Transfer reactions** at the neutron dripline with triton target. Riisager, K. / Mücher, D.

IS556 P352 Spectroscopy of low-lying single-particle states in ^{81}Zn populated in the **$^{80}Zn(d,p)$ reaction.** Orlandi, R. / Raabe, R.

IS554 P350 Search for higher excited states of $^{8}Be^{*}$ to study the cosmological ^{7}Li problem $^{7}Be(d,p),(d,d)$. Gupta, D.

IS553 P348 Determination of the B(E3,0+->3-) strength in the in the octupole correlated nuclei $^{142,144}Ba$ using **Coulomb excitation**. Scheck, M. / Joss, D.

IS551 P345 **Coulomb excitation** of doubly magic 132Sn with MINIBALL at HIE-ISOLDE. Reiter, P.

IS549 P343 **Coulomb Excitation** of Neutron-rich $^{134;136}Sn$ isotopes. Kröll, T. / Simpson, G.

IS548 P342 Evolution of quadrupole and octupole collectivity north-east of ^{132}Sn: the even Te and Xe isotopes. Kröll, T. / Simpson, G.

IS547 P340 **Coulomb excitation** of the two proton-hole nucleus ^{206}Hg. Podolyak, Z.

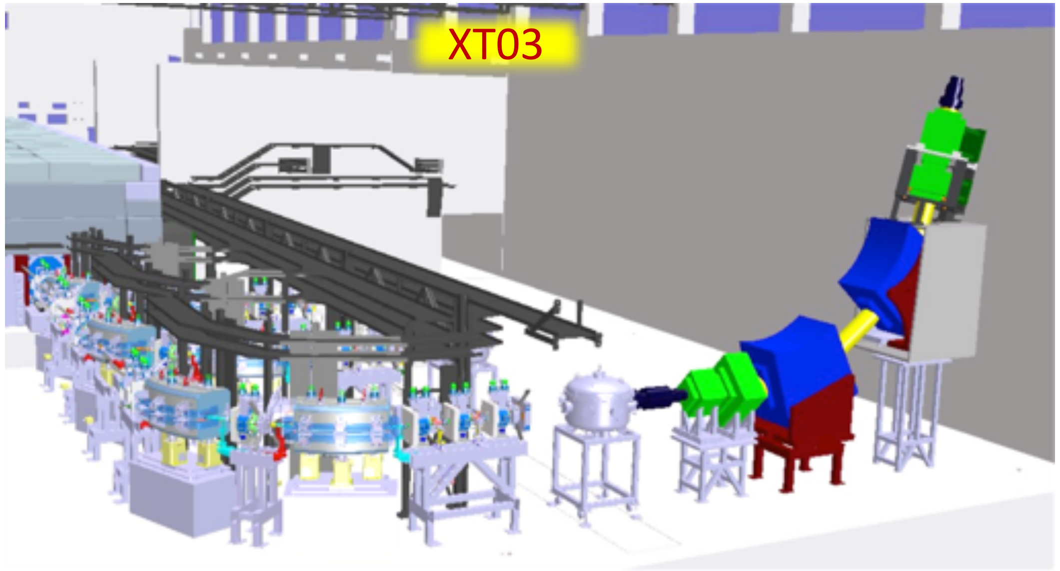
IS555 P351 Study of shell evolution in the Ni isotopes via one-neutron **transfer reaction** in ^{70}Ni Valiente Dobon, J. / Orlandi, R. / Mengoni, D.

Transfer (35%), Coulex (50%), Astrophysics (15%)

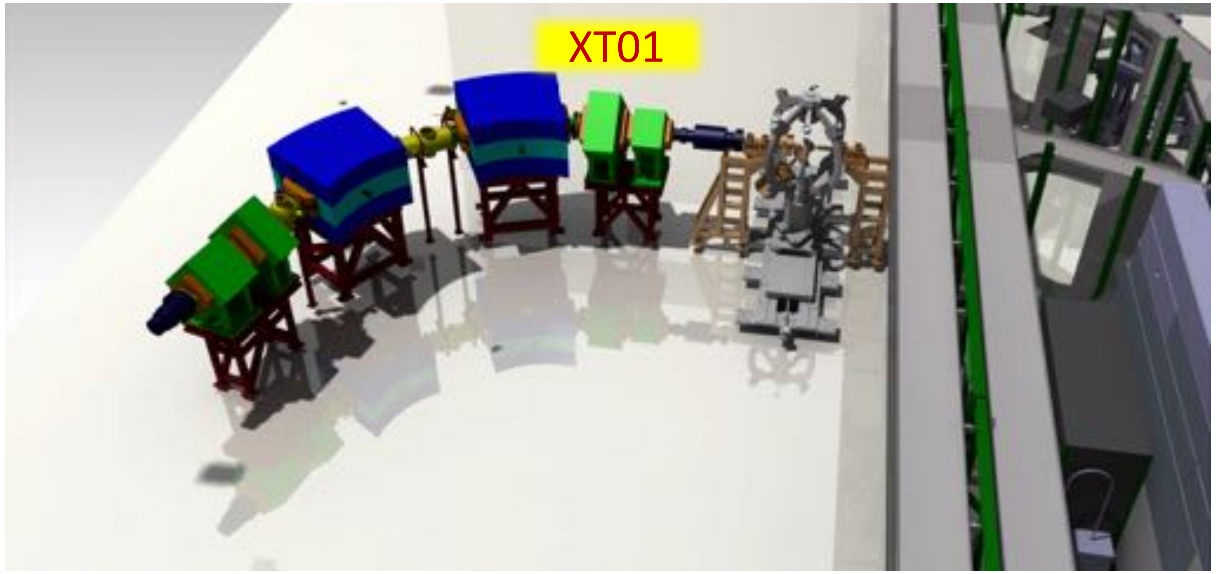
Traditional system based on warm magnets

Based on previous HIFI project

Layout for XT03 – SEC



Layout for XT01 – MINIBALL



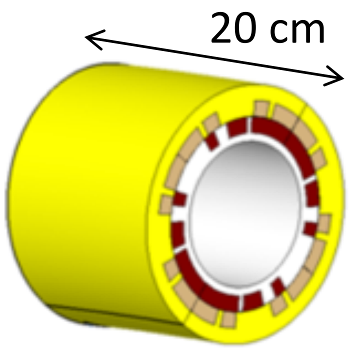
- Simpler and experienced.
- Space limitations at HIE-ISOLDE ~ 5 m x 5 m → limited resolution.
- Extension of the HIE-ISOLDE will be a great advantage.

Courtesy of J. Cederkall

Isolde Superconducting Recoil Separator: superconducting mini-storage ring

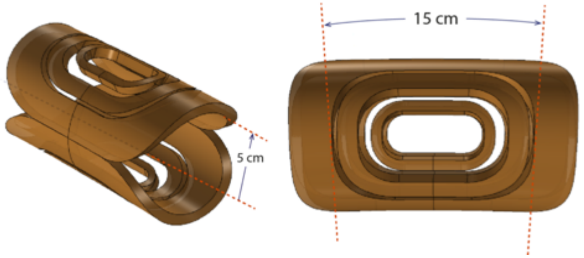
→ Use multifunction SC magnets and RF kickers to produce a compact high-selectivity recoil separator.

"Design of a superconducting Gantry for protons"
C. Bontoiu, et al., IPAC2015, doi:10.18429/JACoW-IPAC2015-WEPMN051 (2015)

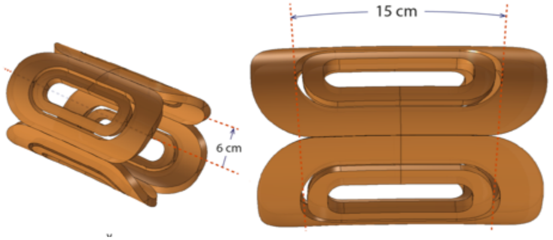


Gantry

- Protons of 175 MeV
- **Large momentum acceptance ~ 20%**
- **Combined function SC magnets for bending and focussing**
- **Non Scaling-Fixed Field Alternating Gradient (NS-FFAG)**
- R= 2.5 m
- Bmax = 2 T
- Bρ = 5.47 Tm (HIE-ISOLDE ~ 2 Tm)
- Quads gradient = 90 T/m
- **Small magnets ~ 20 cm x 15 cm**



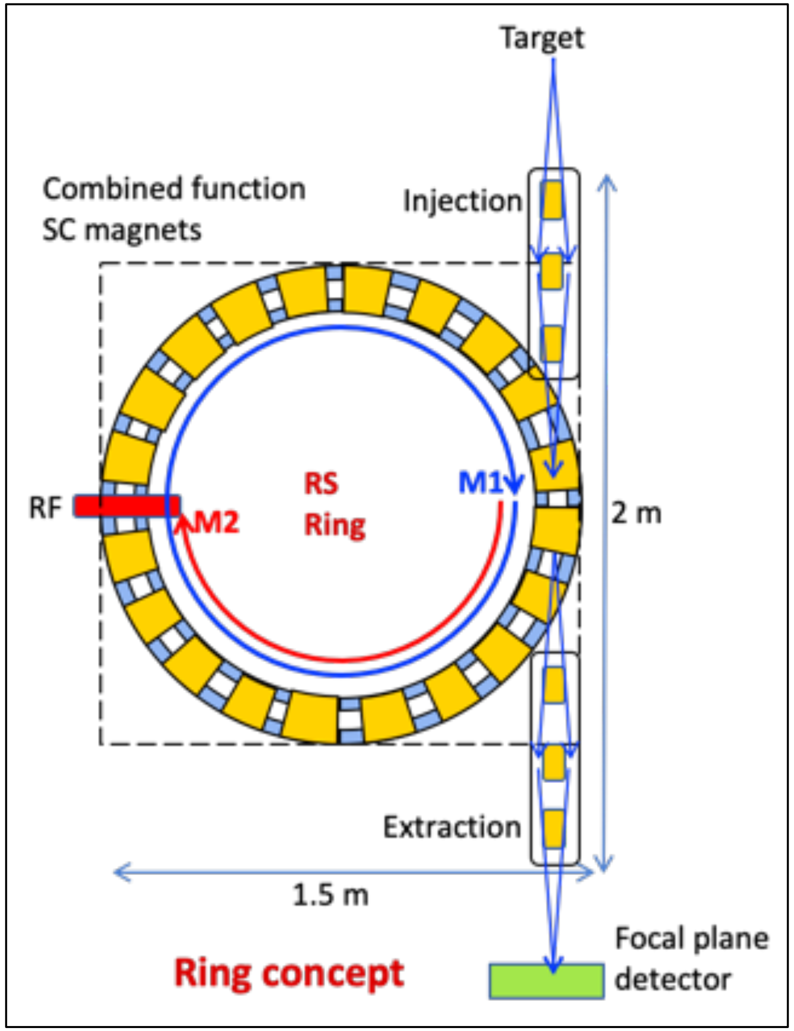
SC Dipole



SC quadrupole

Recoil separator

- Ring concept
- RF cavities → injection/ejection



Beam dynamics studies

Nuclear Inst. and Methods in Physics Research, A 969 (2020) 164048

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

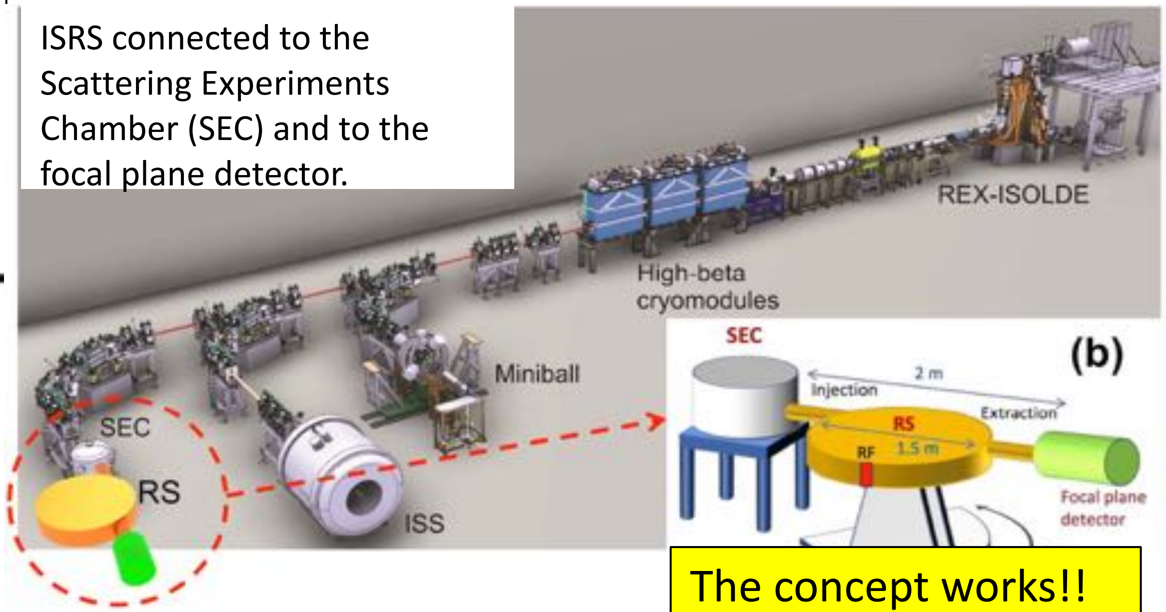
ELSEVIER

Conceptual design of a novel and compact superconducting recoil separator for radioactive isotopes

Cristian Bontoiu [b,c], Ismael Martel [a,b], Javier Resta-López [b,c,*], Volodymyr Rodin [b,c], Carsten P. Welsch [b,c]

[a] Departamento de Física Aplicada, Universidad de Huelva, 21971 Huelva, Spain
[b] Department of Physics, The University of Liverpool, L69 7ZE Liverpool, United Kingdom
[c] The Cockcroft Institute, Daresbury, Warrington WA4 4AD, United Kingdom

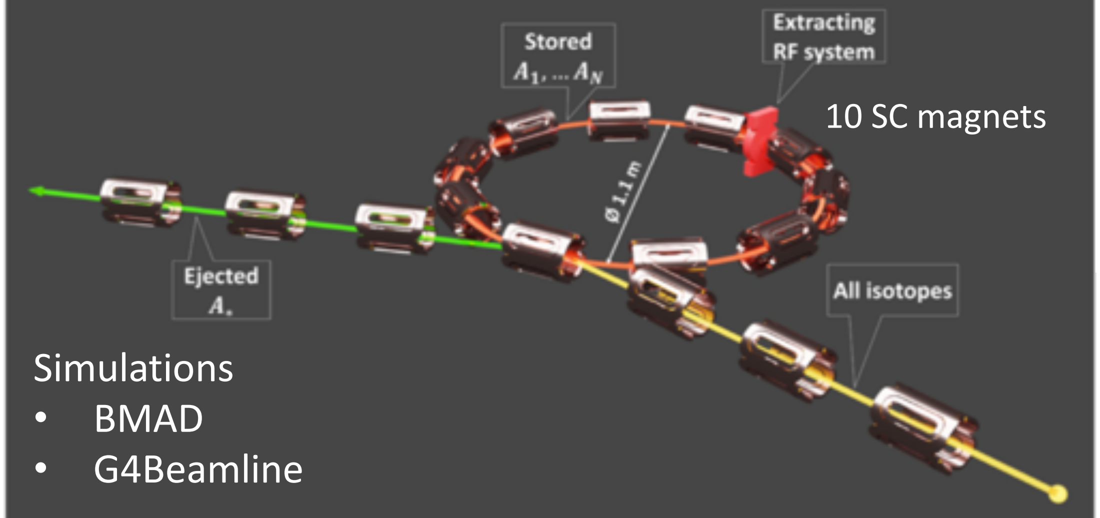
ISRS connected to the Scattering Experiments Chamber (SEC) and to the focal plane detector.



The concept works!!

- Acceptance
  - ✓ ± 115 mrad (H)
  - ✓ ± 150 mrad (V)
- Beam size $\sigma x,y$ = 1 mm.
- Pipe diameter= 200 mm
- δP ≈ ±15%
- δE ≈ (0.5 MeV/A)%

Conceptual FFAG ring layout. Diameter: 1.1 m



10 SC magnets

Simulations

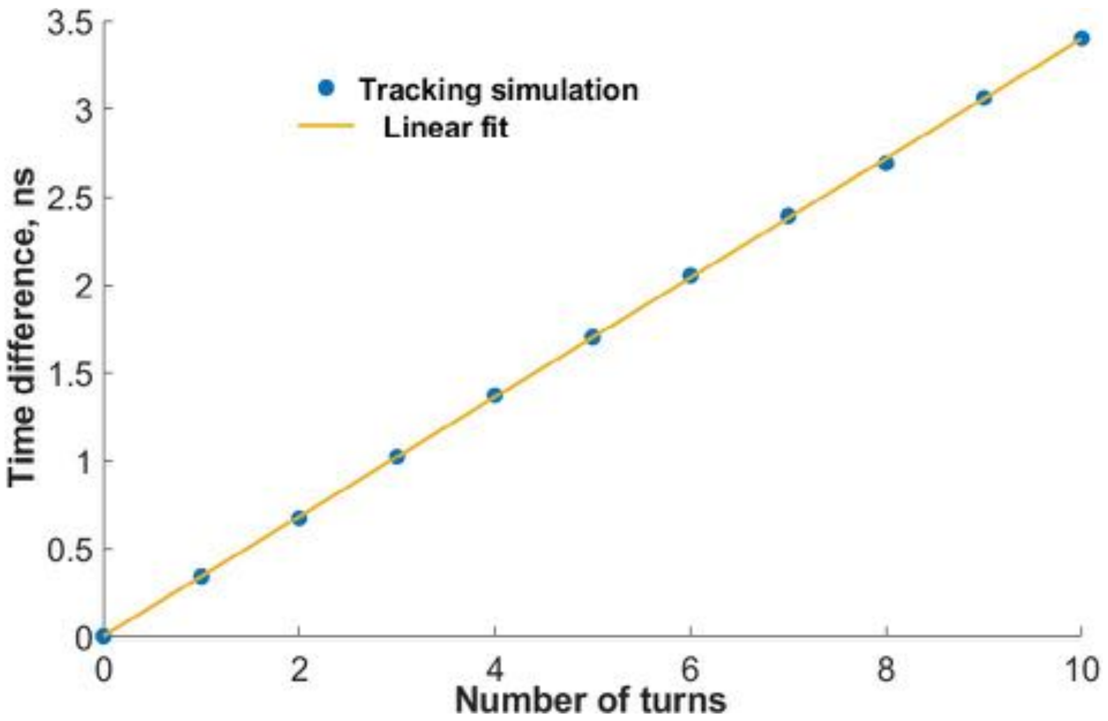
- BMAD
- G4Beamline

Optical Parameters	
Ring circumference, [m]	3.533
Injection energy up to, [MeV/u]	10
Upper limit of magnetic rigidity, $B\rho$ [T m]	2.02
Tunes, Q_x, Q_y	1.317, 2.17
Chromaticity, $\xi_{x,y}$	−6.608, −11.491
Maximum beta functions, $\beta_{x,y}$ [m]	1.2, 1.8
Maximum dispersion, D_x [m]	0.57
Revolution period, T [ns]	81

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

Challenging cases $^{2}H(^{233}Ra, ^{234}Ra)H$ @ 10 MeV/A

Test of ToF separation between ^{233}Ra - ^{234}Ra



ToF separation between the ions ^{233}Ra and ^{234}Ra as a function of the number of turns. It follows a linear function.

After 10 turns (storage $\tau \approx$ 810 ns)—ToF separation ~ 3.5 ns.

→For obtaining ToF separations of ~ 10 ns the reaction fragments must circulate typically for ≈2.3μs.

Review the ISRS configuration

- Adapt ISRS operation to time structure of HIE-ISOLDE
  - ✓ LINAC 101.28 MHz → bunch separation ~ 10 ns
  - ✓ Multi-bunch ring injection/extraction
- HIE-ISOLDE buncher study – 2 μs possible?
- Ring geometry and operation parameters
  - ✓ Available space 5 m x 5 m
- Injection/extraction process → RF kicker ~ 1.2 MHz
- Simulations: beam size, tails, emittance, etc

WORK IN PROGRESS!

Present activity of the collaboration

Based on two working groups

- Physics working group. Provides nuclear physics cases and technical specifications (PCR- Physics Cases Report).
  - ✓ Collaborators: Univ. Huelva (Spain), IPNO (France), Univ. Lund (Sweden), INFN-LNL (Italy), CENGB-Bordeaux (France), University of Liverpool (UK).

- Technical working group. Provides design studies to approach the technical specifications (CDR – Concept Design Report).
  - ✓ Collaborators: CERN (Switzerland), Univ. Liverpool (UK), Univ. Valencia (Spain), Cockcroft Institute (UK), ESS-Bilbao (Spain).
  - ✓ Discussions: Wigner RCP-Budapest (Hungary), Berkeley (USA), and other research centres. Companies: ACS (France).

- Funding. No specific funding (foreseen HORIZON EU application, 2021).
  - ✓ Activity is carried out on resources made available by the collaborators.

Physics Program

Last Physics meeting - 04.11. 2020; PCR structure:

Reaction types

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

Some proposals received so far

- Transfer reactions at ISOLDE
- Nuclear structure and dynamics close to the drip lines.
- Multi-nucleon transfer reactions to populate r-process nuclei
- Single particle transfer of n and p to single particle dominated states close to double shell closures, specifically the Sn-100 region.
- Reaction of astrophysical interest with indirect methods.

Physics cases

- Weakly bound nuclear systems and clusters
- Shape coexistence and nuclear isomerism
- Evolution of Nuclear Shells
- Isospin symmetry
- Pairing
- Nuclear astrophysics

Key nuclei

- n-, p –rich along N=Z line
- Close to the drip lines.
  - ✓ ^{17}Ne, ^{20}Mg, ^{33}K, ^{32}Ar, ^{22}Al, ^{40}Ti.
- Region around N=126 Isotopes.
  - ✓ $^{144}Xe + ^{208}Pb \rightarrow ^{151}Pm + ^{201}Re$
- Region around Sn-100

More proposals welcome!

Technical specifications

- Energy: 4 MeV/A⩽ Elab ⩽ 10 MeV/A
- Large acceptance (~ 6.5 degrees)
- Energy resolution < 100 keV
- Time resolution ~ ns (for coincidences)
- Excellent angular resolution (kinematic reconstruction/Doppler correc.) ~ 0.1 degree lab.
- Event-by-event particle identification
  - Separation of reaction products from the beam
  - Isobaric beam contaminants
  - VAMOS like spectrometer
    - ✓ ΔQ/Q ~1/70 (FWHM)
    - ✓ ΔM/M~1/200 (FWHM)
    - ✓ ΔZ/Z~1/60 (FWHM).

Ancillary detectors and special equipment

- Targets : solid (implanted) and cryogenic targets H,^{3}He,L^{4}He,^{12}C.
- Heavy targets ^{208}Pb,^{198}Pt, ^{193}Ir.
- Detectors for particle, gamma, neutron.
- Couple with a MR-TOF.

- Possible better at XT01 with existing MINIBALL and T-REX for gamma-particle coincidences.

- Long time-scale project,
  - ✓ ~ 4 years R&D - proof of concept
  - ✓ ~ 4 years detailed design + construction

- HIE-ISOLDE hall extension during LS3.

WORK IN PROGRESS!

ISRS Design study – Technical working group

Review of specifications (October – November 2020)

a) Beam dynamics

- Update of geometry for HIE-ISOLDE (J.A. Rodriguez)
- Ring dimensions 3.5 m x 3.5 m (XT03)
- Maximum space available: 5 m x 5 m (XT01)
- FFAG using Canted coils Cos Theta magnets (CCT)
- Isochronous/achromatic focal plane

b) Cryogenics

- Connection from beampipe (~4.5K) to outside (~300K)
- Common vacuum (SC magnet cryostats)
- Conduction cooled option by 4.5 K thermal LHe bath
- Cryogen free option

c) Magnets

- Q + D nested
- Beampipe diameter: 220 -300 mm
- Dipole strength: 1.5 Tm
- Quadrupole strength: 40 T/m
- Max peak field: 5 T
- **Stored energy 1.5 MJ (!!)**

d) Typical magnet geometry

- Total magnet length 500 - 800 mm, depending on final layout in the ring.
- 190 mm magnet inner diameter
- 3 straight magnets in series, bending angle 30°, R= 1 m.
- Curved option will be studied
- Max outer diameter (including shielding): 650 mm

e) Buncher. In the range of ~ MHz.

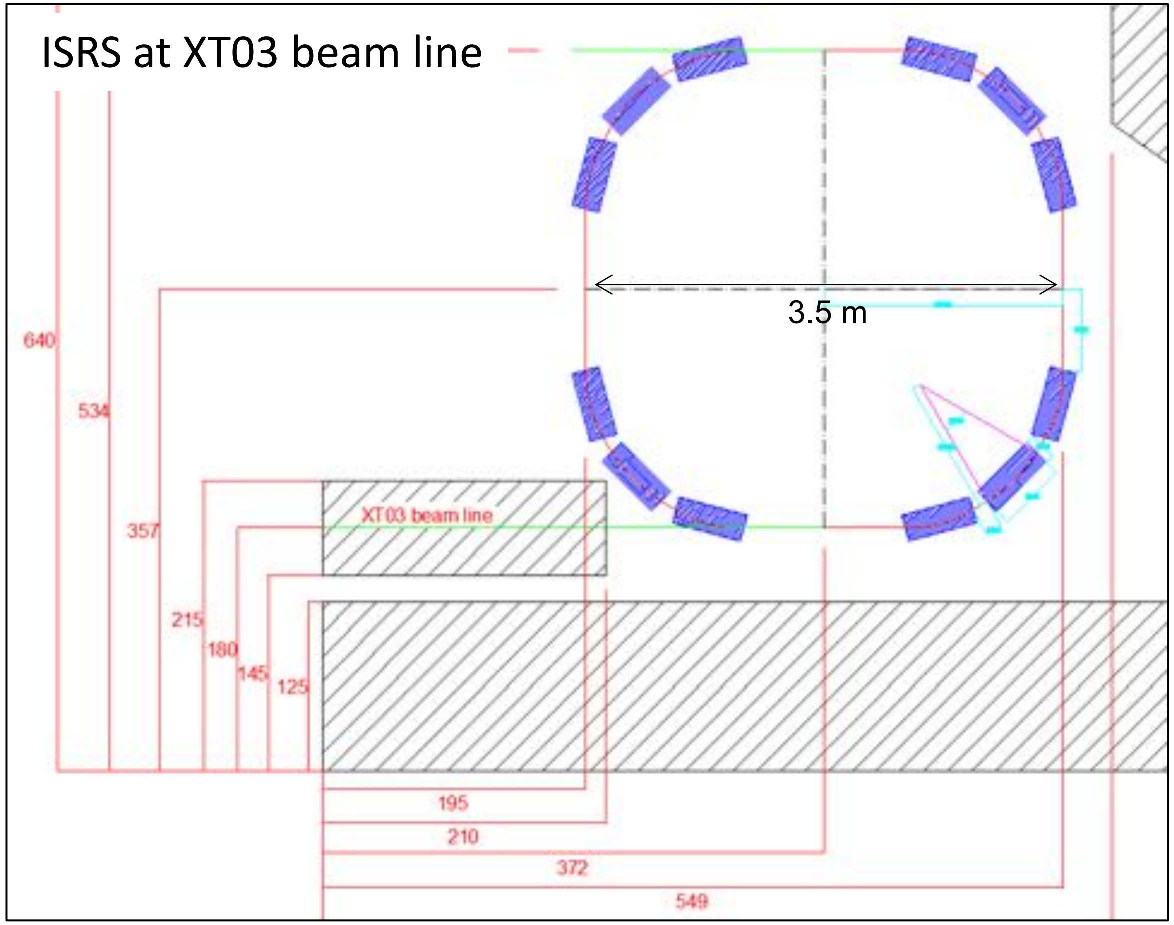
f) Magnetic shielding. To be defined.

g) Injection/extraction

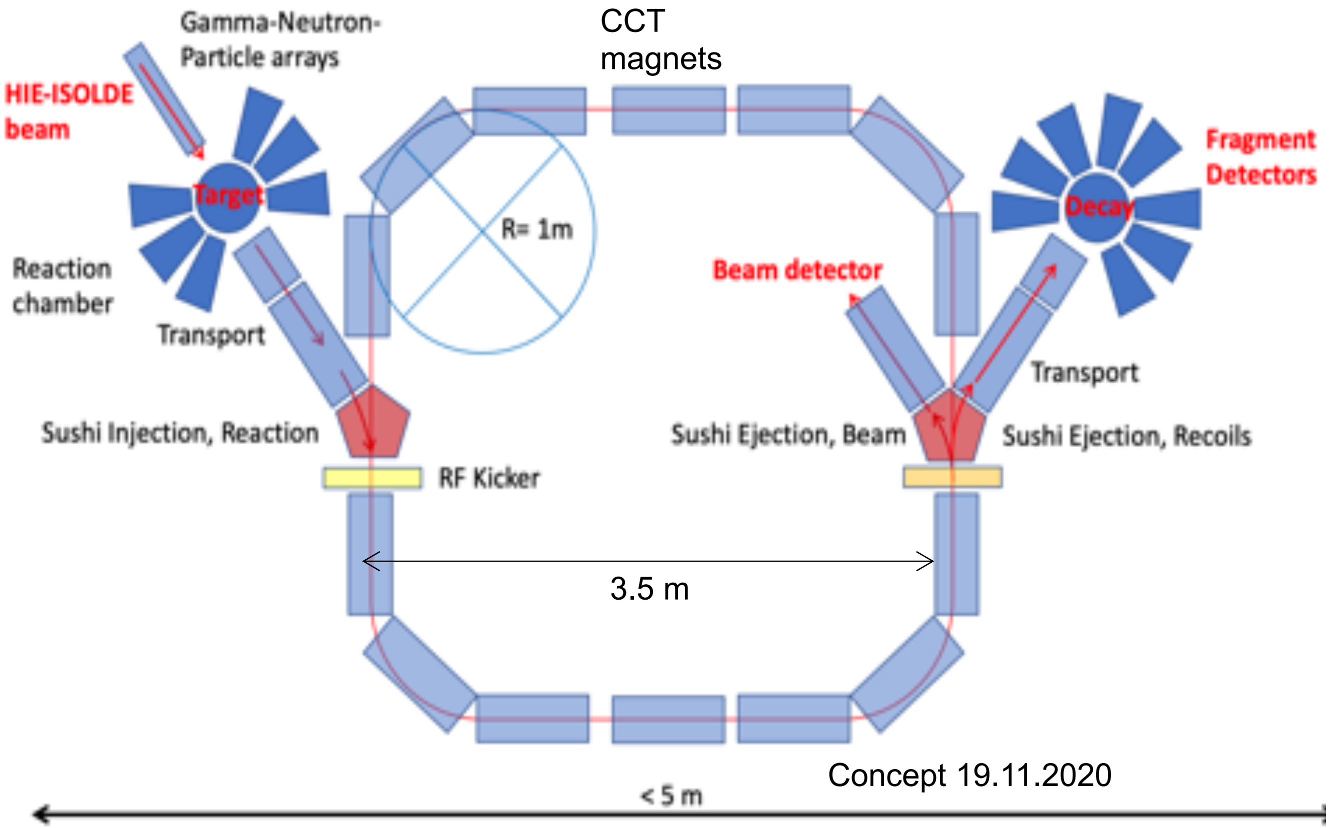
- RF Kicker + CCT magnet design a la “Sushi”

→ Superconducting septum magnet for the Future Circular Collider

ISRS Design study – Technical working group



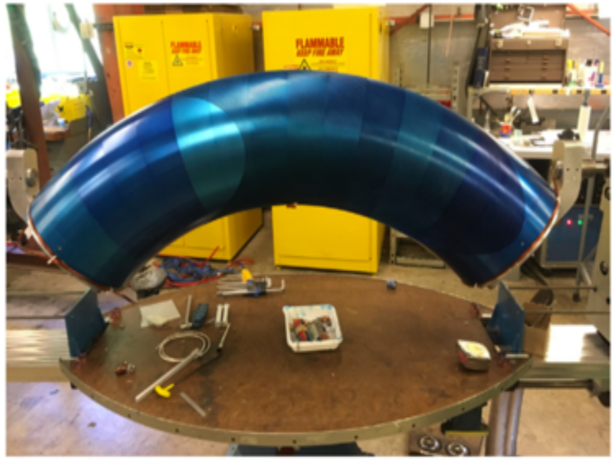
Courtesy of Jose Alberto Rodriguez, CERN BE



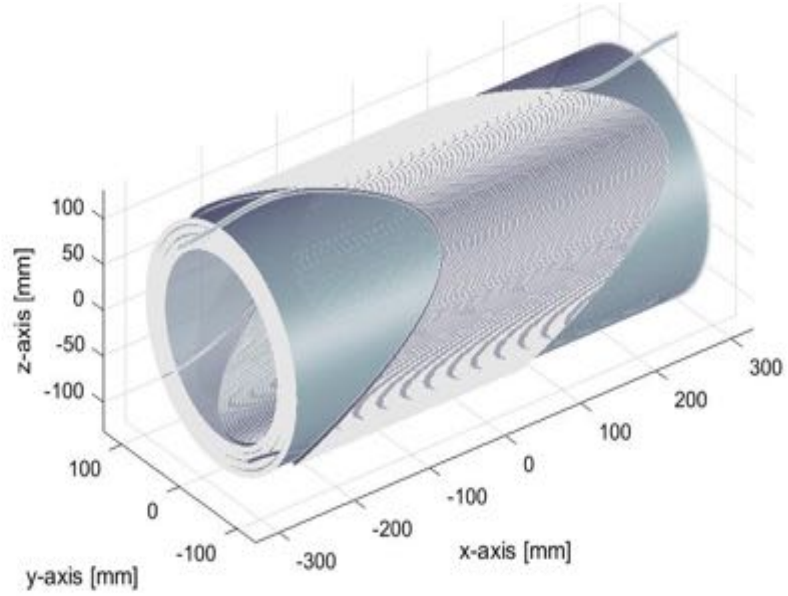
- Ring diameter 3.4 m, bending sector 1 m radius
- Maximum beam rigidity 2 T.m (~10% of margin, 2.2 T.m)

CCT magnets

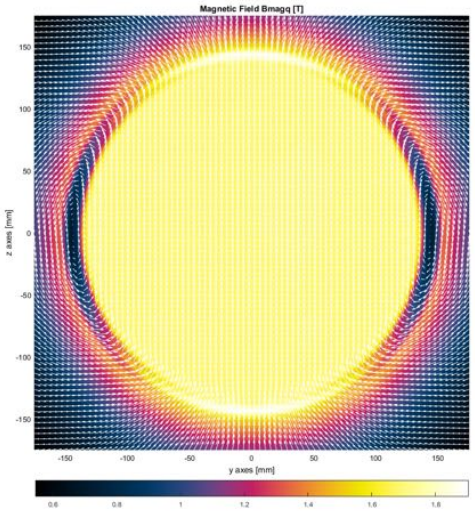
- Modulated Double Helical Coils technology with layout of Canted coil Cos-Theta. C. Goodzeit, et al. IPAC2007. 2007.
- Medium field range (2- 5 T).
- 90 deg sector of 3.3 T.m integrated field, composed of three straight coils segments each 0.5 m long.
- Curved version of the combined magnet.



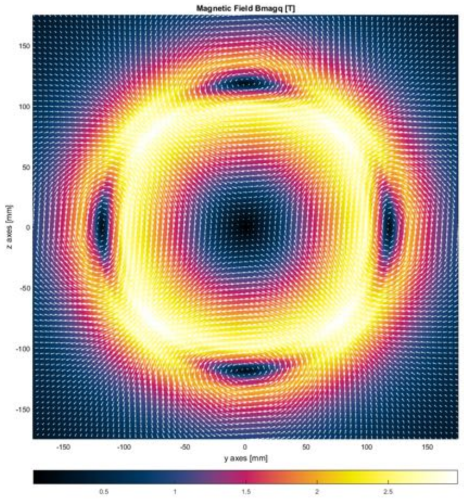
Curved CCT magnet (Berkeley model)
https://doi.org/10.1016/j.nima.2020.163414



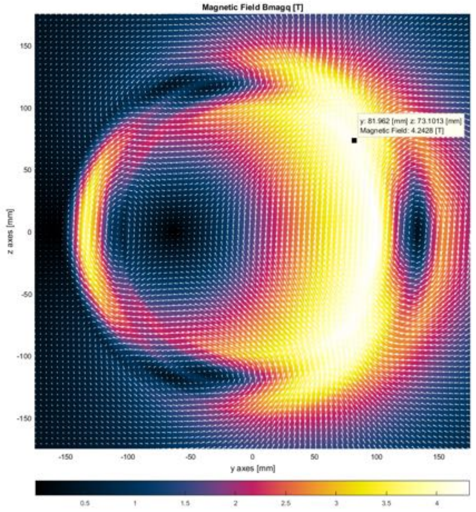
straight coil segment



Dipole



Quadrupole



Combined

Courtesy of Glyn Kirby, Arnaud Foussat CERN TE-MSC

Injection/extraction with Sushi CCT magnets

Conceptual design of a high-field septum magnet using a superconducting shield and a canted-cosine-theta magnet

Cite as: Rev. Sci. Instrum. 90, 053302 (2019); doi: 10.1063/1.5096020
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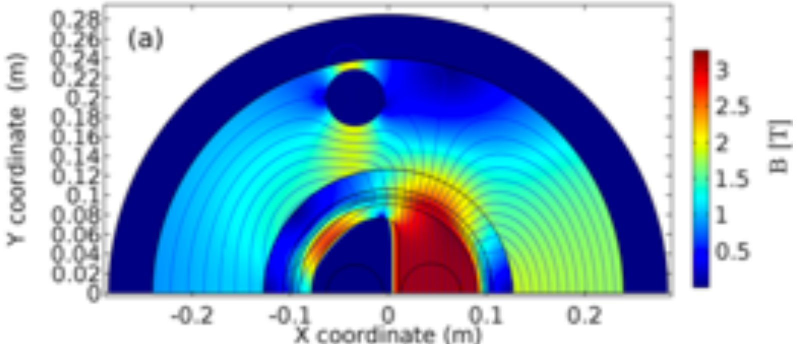
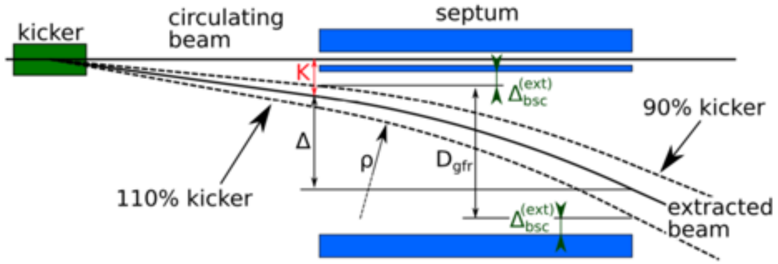
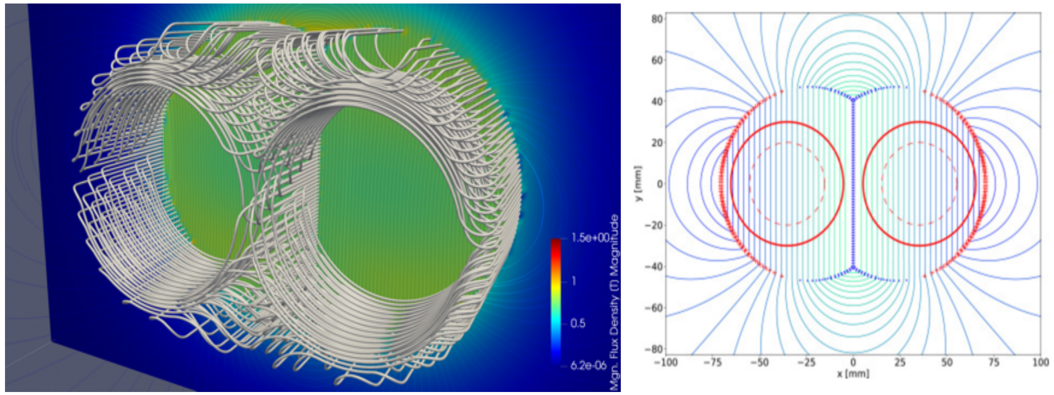
Superconducting septum magnet for the Future Circular Collider

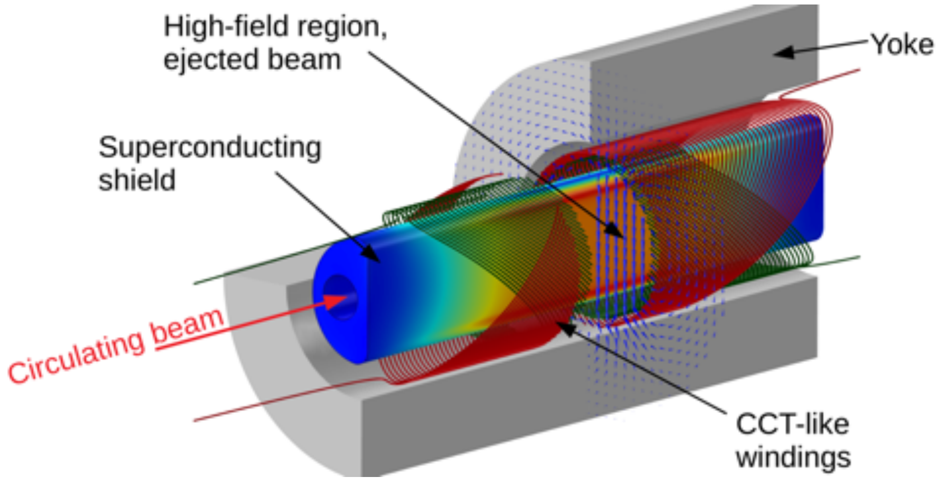






Two-dimensional conceptual design of a superconducting iron-free opposite field septum magnet

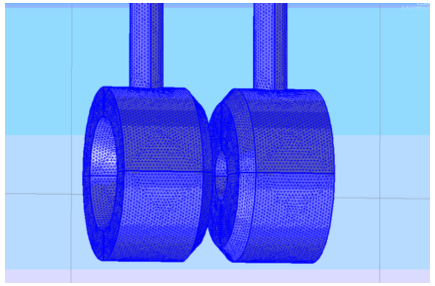
D. Barna, M. Novák, Nucl. Inst. Methd. A 959 (2020) 163521

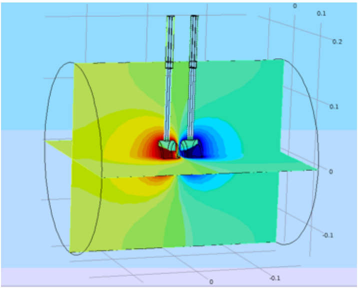


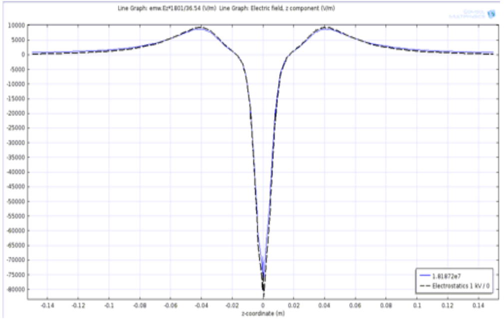
Courtesy of Daniel Barna, Wigner RCP-Budapest (Hungary)

MHB design

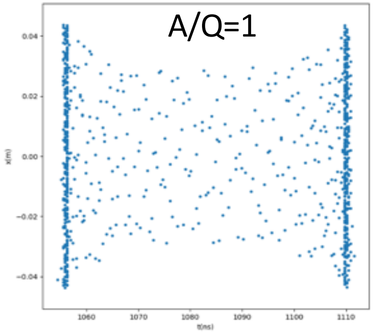
- First 2D, 3D FEM model for RF and termal calculations.

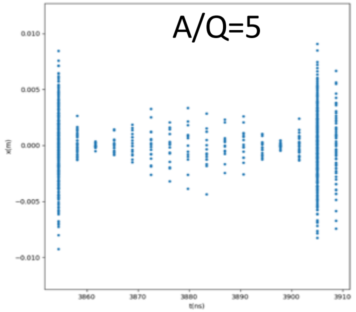






- Setup programs for 2D axisymmetric, 3D in COMSOL – ELCANO (home code) for quick parametric optimization.
- Fields exported for beam dynamics calculations with GPT code.



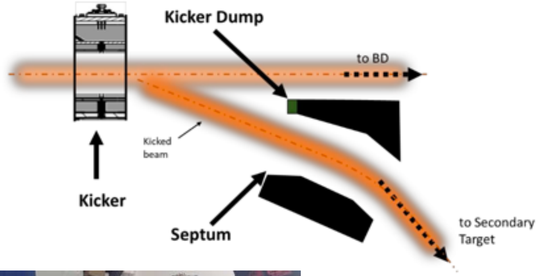


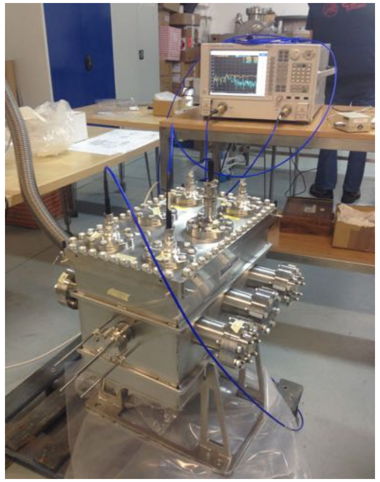
- Test-bench

WORK IN PROGRESS!

RF kicker design

- Preliminary ideas based on a fast chopper/kicker developed for European Spallation Source.
- Strip-line electromagnetic kicker





- Test-bench

Future HORIZON EUROPE application

Work Plan Structure → **proof of concept and prototyping**

WP1	**Project Coordination and Management**
WP2	**System specifications and selection of technologies**
T2.1	State of the art
T2.2	**Physics case/White book**
T2.3	Conceptual design and critical components
WP3	**Design study**
T3.1	Beam dynamics FFAG
T3.2	Beam transport (SEC, MINIBALL and ISS)
T3.3	Buncher
T3.4	Re-buncher system
T3.5	Superconducting multifunction magnets
T3.6	Magnetic probes and magnet test bench
T3.7	Injection/extraction system
T3.8	Ring cryomodule design, cryogenic system, control
T3.9	RF and LLRF systems
T3.10	Beam diagnostic systems
T3.11	Focal plane detectors
T3.12	Ancillary detectors and special equipment
T3.13	Machine and personal safety
T3.14	Budget and timeline

WP4	**Construction of prototypes**
T4.1	Beam transport
T4.2	Buncher
T4.3	Debuncher
T4.4	Injecction/extraction
T4.5	Multifunction magnets
T4.6	Magnetic probes
T4.7	Magnet test bench
T4.8	Ring cryomodules, cryogenic system, control
T4.9	Beam diagnostics
T4.10	Focal plane detector
WP5	**Prototype evaluation and test**
T5.1	Prototype testing plan
T5.2	Off-line test and data analysis
T5.3	System integration
T5.4	Commissioning at HIE-ISOLDE
T5.5	Off-line test and data analysis
T5.6	In-beam test and data analysis
WP6	**Exploitation and dissemination**

TEST AT HIE-ISOLDE
To be decided

CSIC-MADRID, SPAIN
UNIVERSITY OF HUELVA, SPAIN
UKRI-STFC, UK
CERN, SWITZERLAND
UNIVERSITY OF LIVERPOOL, UK
COCKCROFT INSTITUTE, UK
UNIVERSITY OF VALENCIA

UNIVERSITY OF LUND, LUND, SWEDEN
CENBG, BOURDEUX, FRANCE
UNIVERSITY OF WEST SCOTLAND, UK
UNIVERSITY OF AARHUS, DENMARK
UNIVERSITY OF UPPSALA/FREIA, SWEDEN
ESS-BILBAO, SPAIN

Companies

ACS, FRANCE
TTI Norte, SPAIN

Summary and conclusions

Work is progressing:

- Physics Program
- Technical design
- Horizon Europe