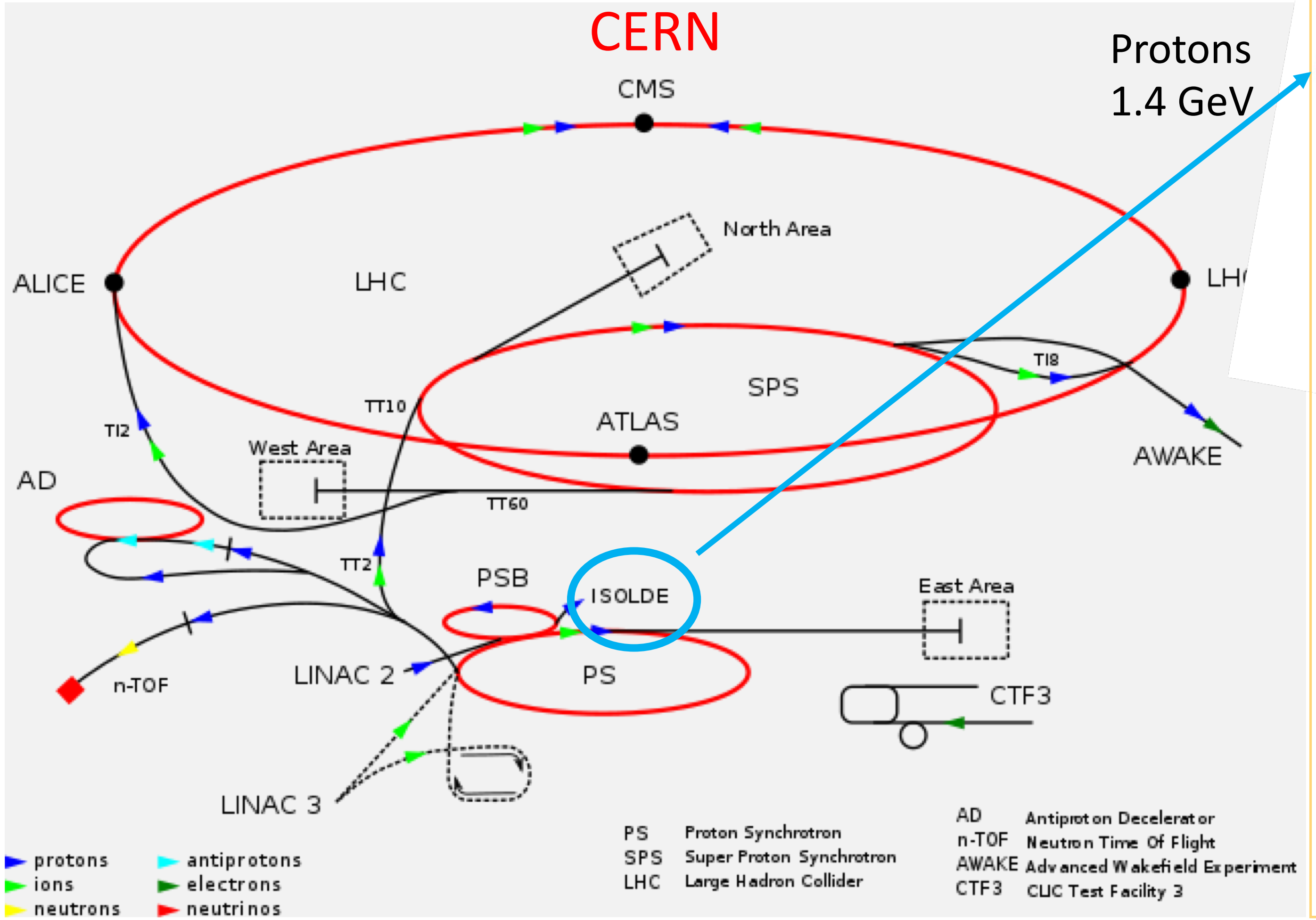
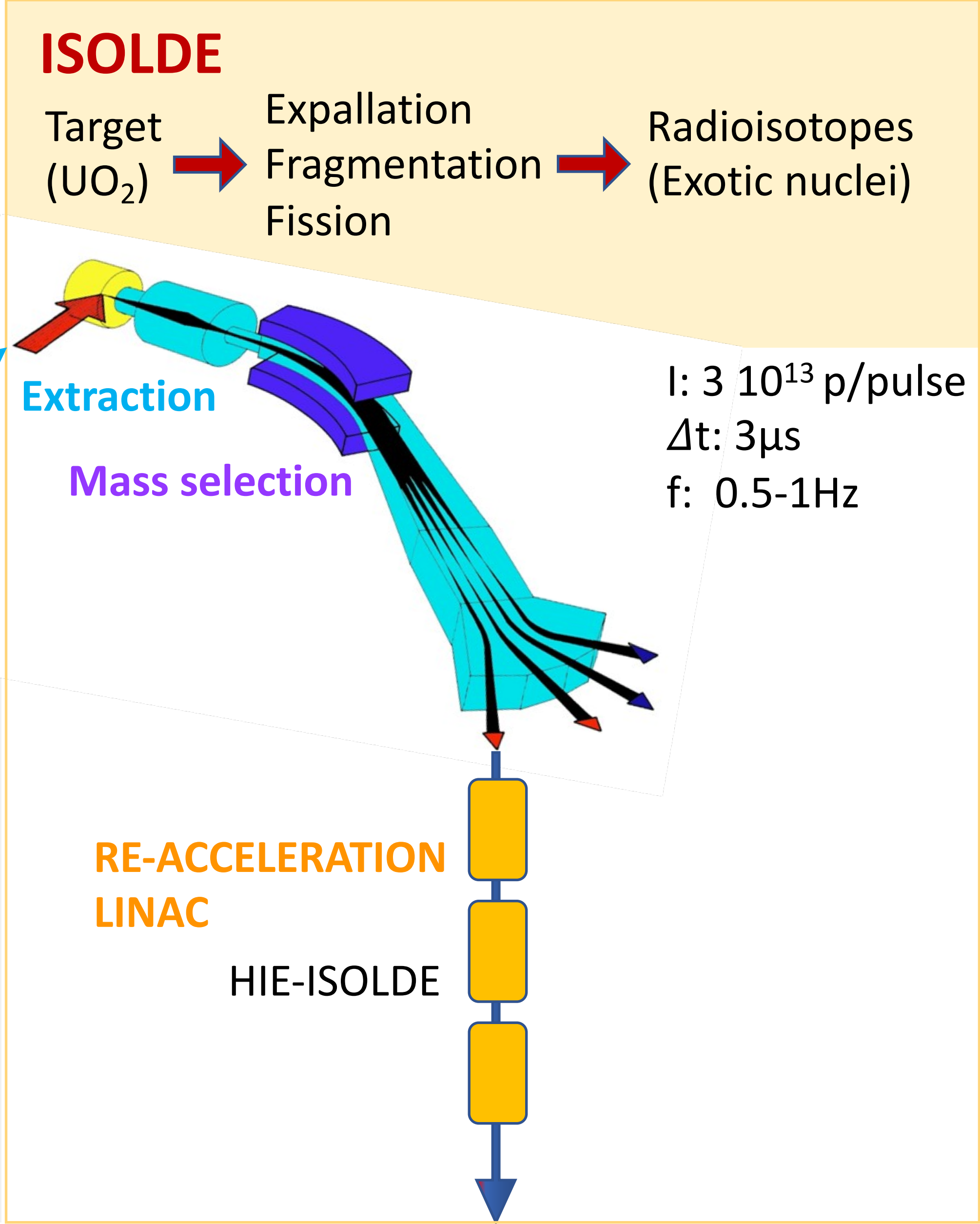
IoP Half Day Meeting: Opportunities in nuclear physics with recoil separators at HIE-ISOLDE

Research plans at HIE-ISOLDE for a future recoil separator

Ismael Martel, University of Liverpool, April 29, 2019

ISOLDE: Isotope Separation On-Line @ CERN





HIE-ISOLDE

International Nuclear Physics Conference 2010 (INPC2010) IOP Publishing
Journal of Physics: Conference Series **312** (2011) 052010 doi:10.1088/1742-6596/312/5/052010

The HIE-ISOLDE Project

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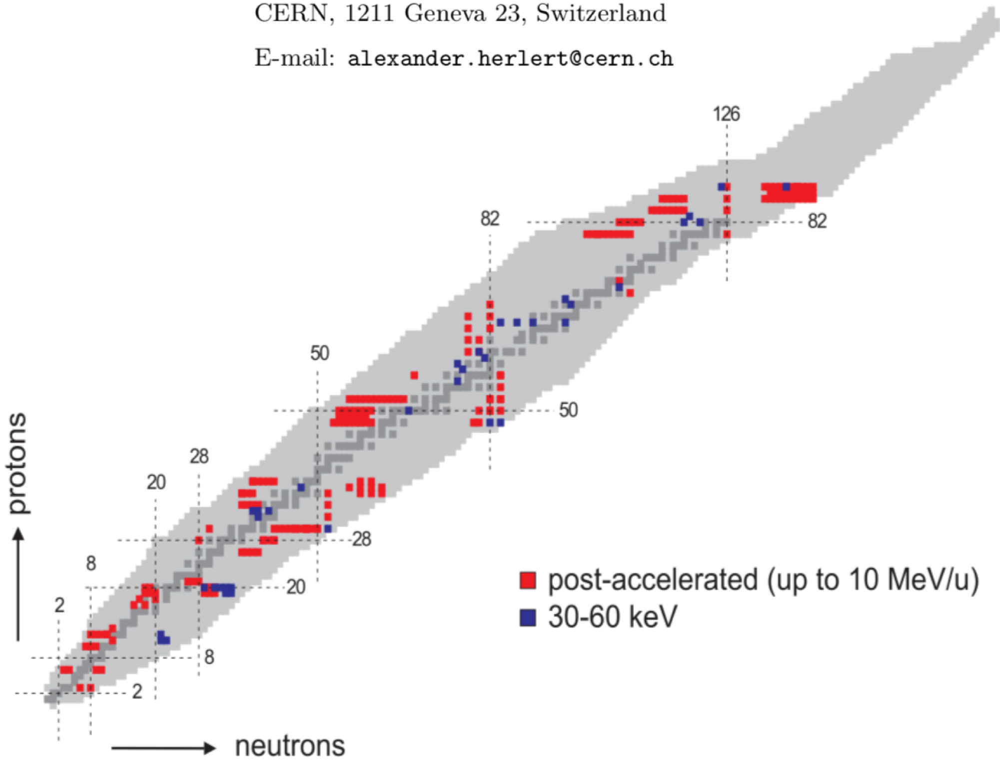
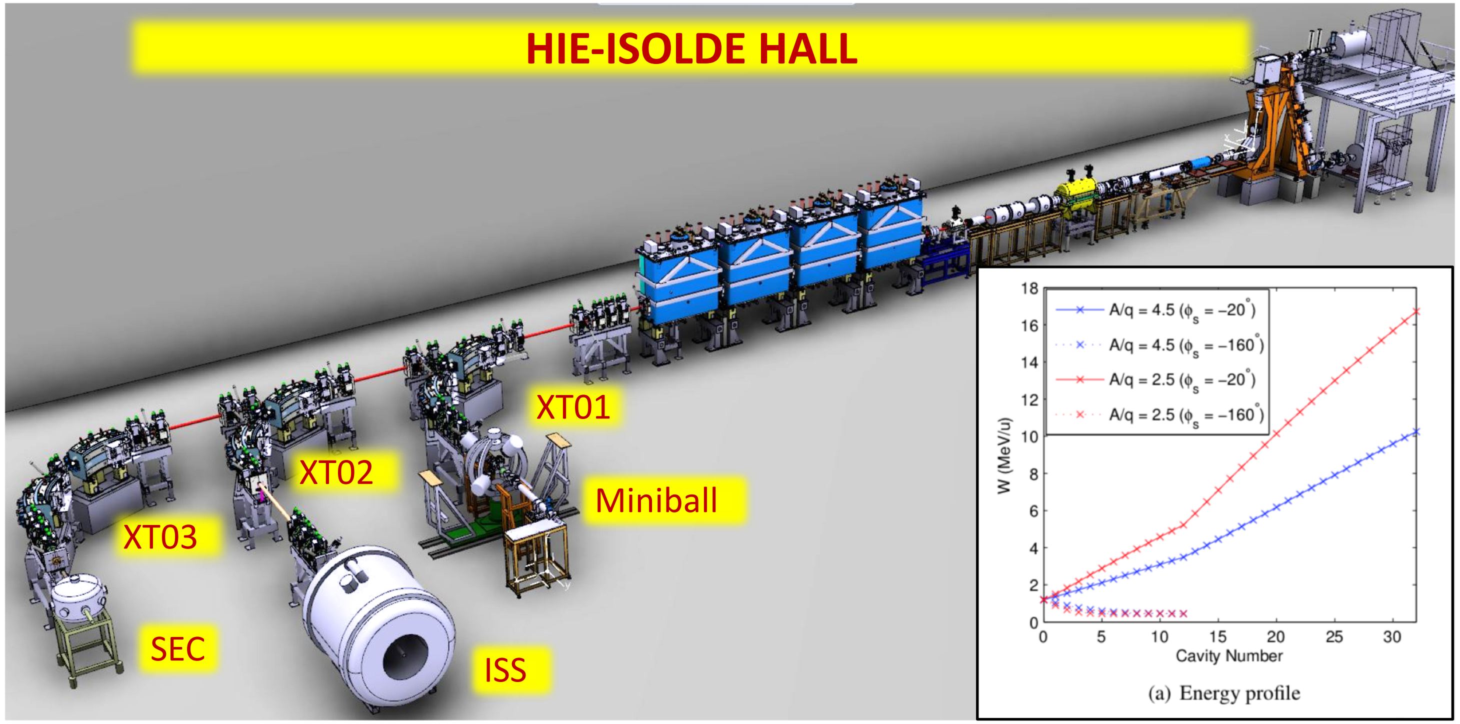


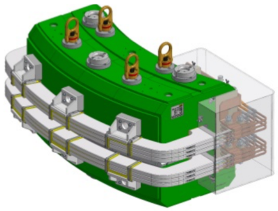
Figure 5. Isotopes requested by ISOLDE users for HIE-ISOLDE



(a) Energy profile

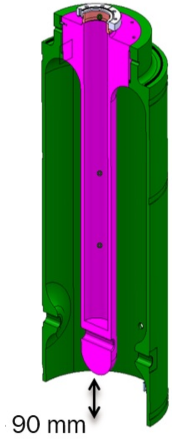
Peak field in centre [T]	1.2
Allowed integrated field error	$\pm 5 \cdot 10^{-4}$
Magnetic aperture [mm]	50
Magnetic length [mm]	1414
Bending radius [m]	1.8
Bending angle [deg]	45

Dipole



F_0 (MHz)	101.28
β_g (%)	10.3
E_{acc} (MV m^{-1}) $= V_0/L_a$	6
L_a (m)	0.3
Q_0 (at 6 MV m^{-1}, P = 10 W)	5×10^8
$\Gamma = R_s Q_0$ (Ω)	31
U/E^2_{acc} (mJ (MV m^{-1})$^{-2}$)	210
T (K)	4.5

RF cavity (QWR)



The need of recoil separators at HIE-ISOLDE: the HIFI Project

March 10-11, 2011 | Spectrometer at HIE-ISOLDE, Workshop, Lund (Sweden)

Coordinators:

Olof Tengblad, Wilton Catford, Joakim Cederkäll

Profit for proposals ~ 40%

- MINIBALL, SEC, ISS (fringe fields)

Other set-ups

- GASPARD
- ACTAR

Physics cases

- *Direct reactions studies*
- *Transfer reactions*
- *Coulomb excitation*
- *Deep inelastic reactions*
- *Fusion-evaporation reactions*
- *Astrophysics*

Approved 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.

5 Transfer (35%), 7 Coulex (50%), 2 Astrophysics (15%)

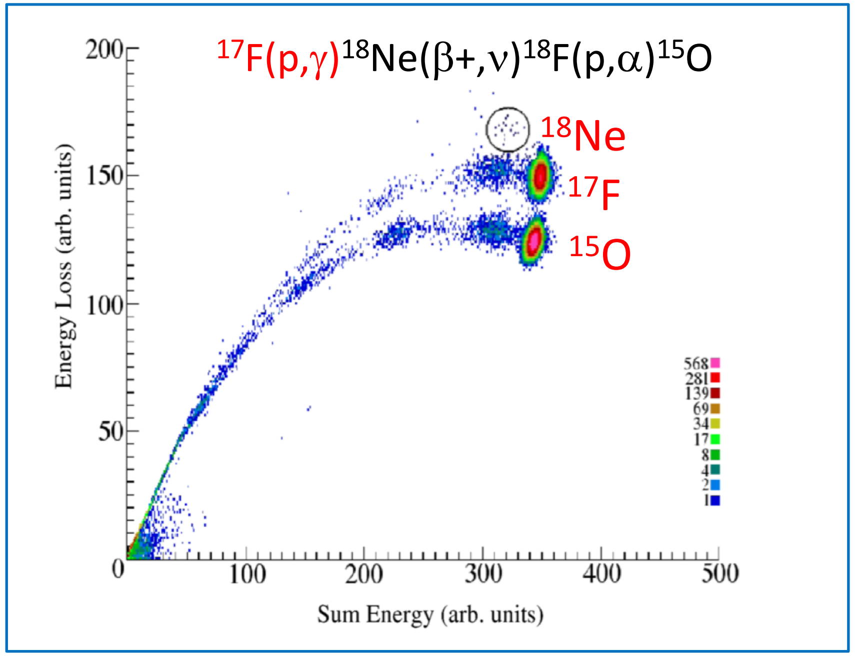
Courtesy of Olof Tengblad

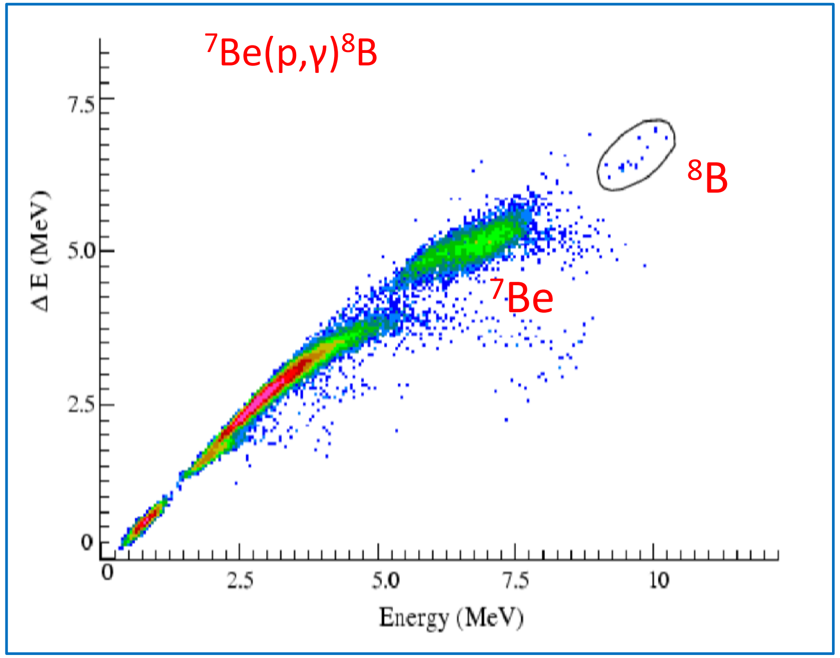
Astrophysics: Direct measurements of (p,γ) cross sections

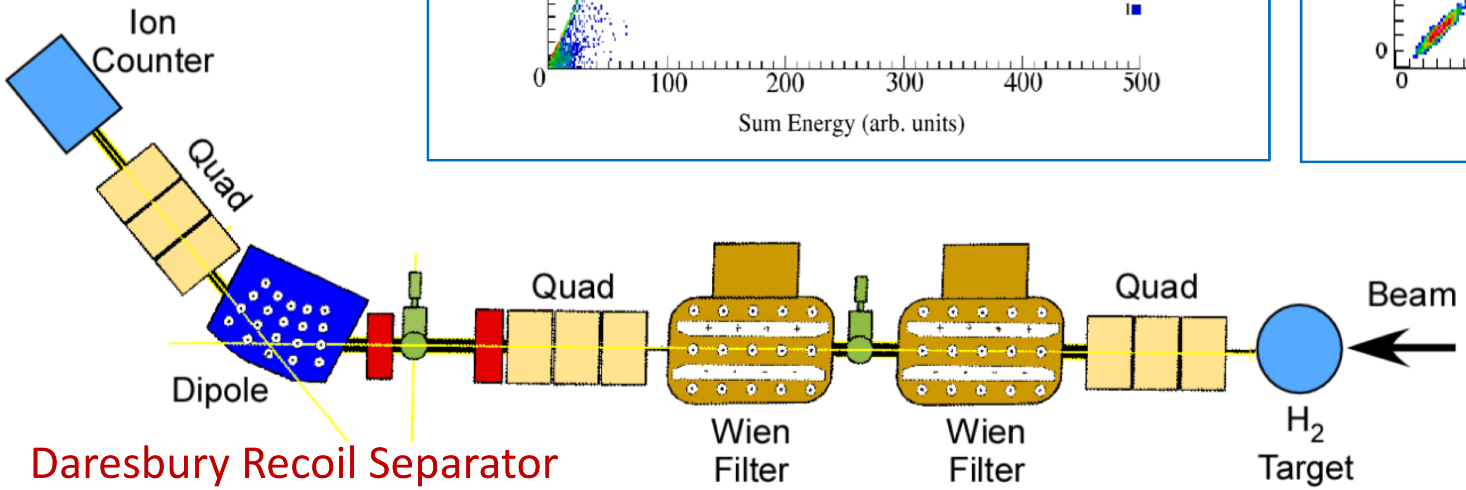
D. W. Bardayan, *et al*. European Physical Journal A, 2009.

HRIBF (Oak Ridge)

Daresbury
Recoil Separator







Daresbury Recoil Separator

Dedicated experiments with **γ, n** at exit channel

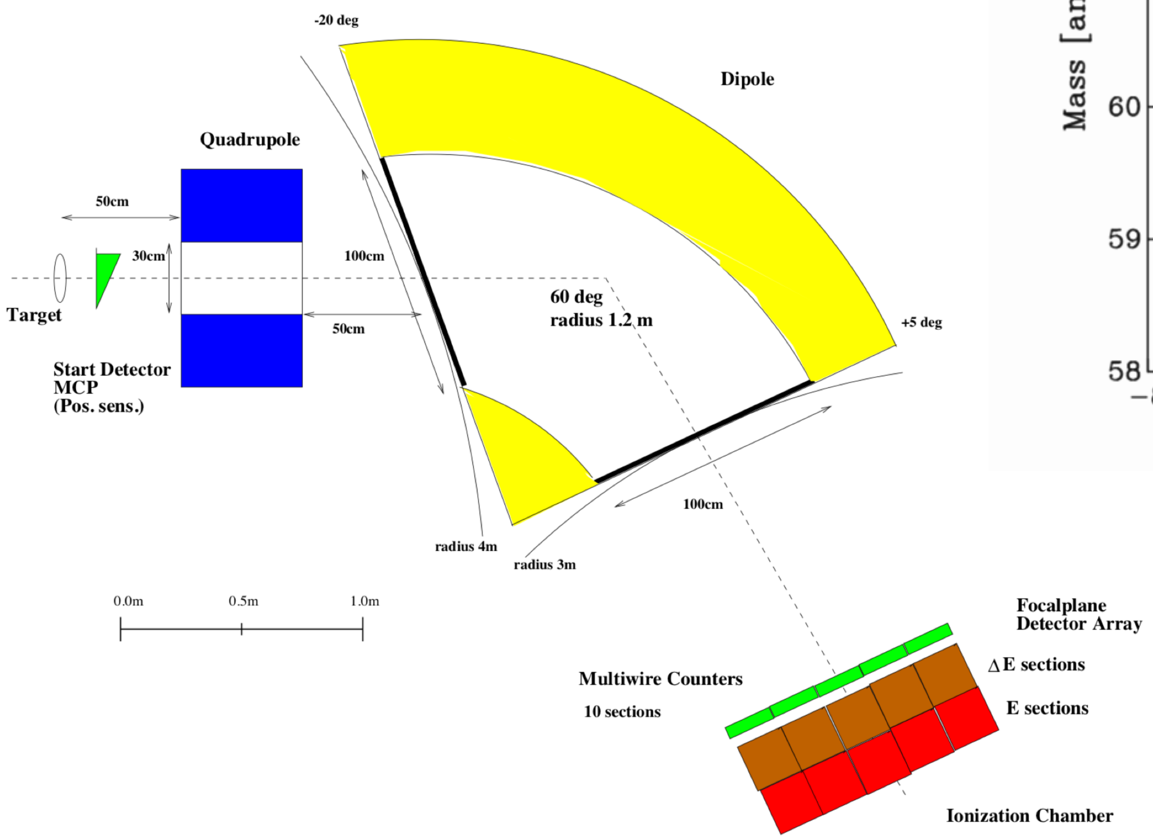
Pairing interaction: Multi-neutron transfer reactions

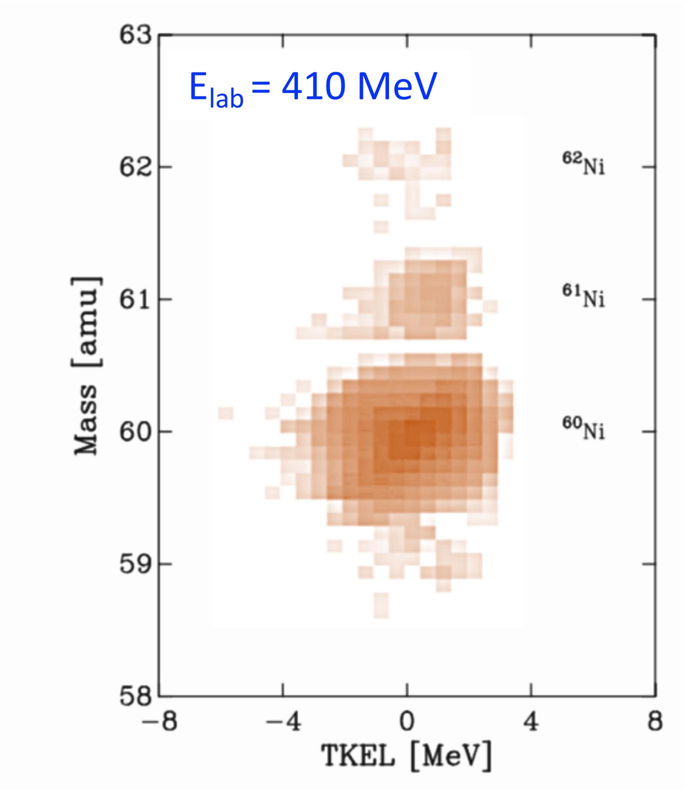
D. Montanari *et al.*, PRL 113, 052501 (2014)

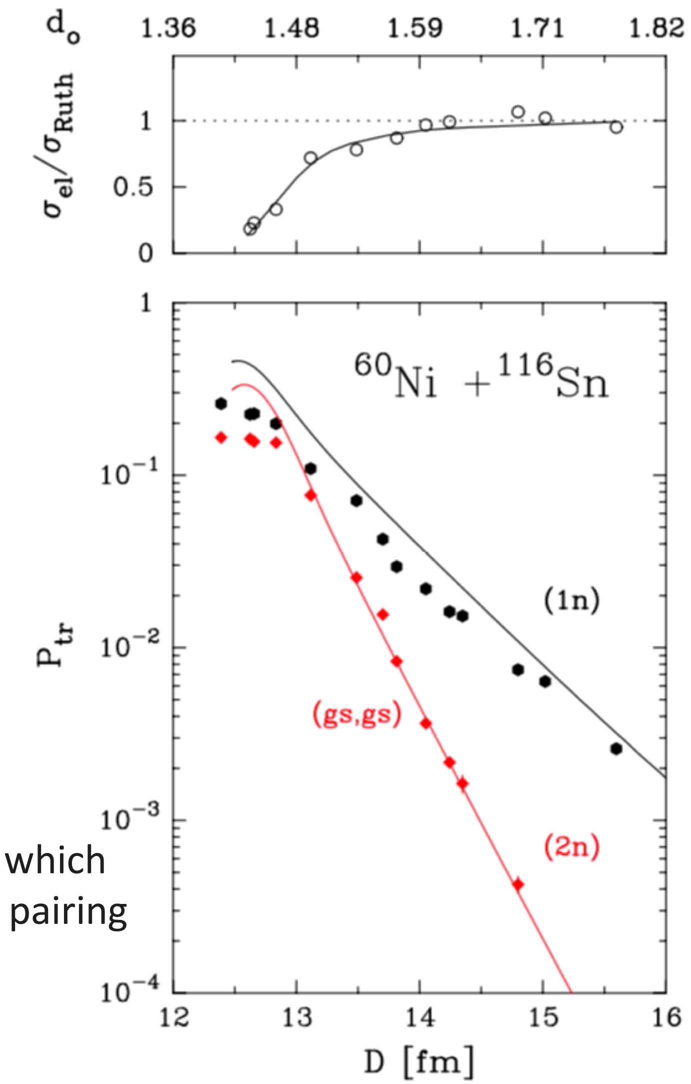
LNL (Italy), ^{116}Sn + ^{60}Ni @ E= 4.3-3.4 MeV/u

PRISMA spectrometer; θlab = 20°

Coulomb Barrier energies







Test microscopic calculations which incorporate nucleon-nucleon pairing correlations (BCS).

- Pairing gap
- 2n - SF

Dedicated multinucleon Transfer experiments

Specifications of the recoil separator

Physics		
E [MeV/u]	0.45	10
A	7	234
A/Q	2.5	4.5
P [MeV/c]	1	30
Bρ [Tm]	0.25	2.16

Timing

Slow extraction from EBIS useful for TOF

Linac f = 101.28 MHz → buncher down to ~ 10 MHz.

Multi-harmonic buncher (M. Fraiser et al. LINAC2014, THPP030)

Intensity

10^5/s for heavy beams, but 10^9/s instantaneous rate.

→ debuncher

Size of the HIE-ISOLDE hall

Separator

- Rejection: ~10^{-12}
- 100 % transport efficiency
- Mass resolution > 1/300
- Large acceptance ~ 100 mrad
- Gas-filled mode

Focal plane detector

- Position sensitivity ~ 1 mrad (scattering angle)
- Particle identification (A, Z)
- Eloss, Time of Flight, Pulse shape
- Time resolution ~ ns
- Energy resolution < 100 keV
- 100% efficiency

Simulations (HiFi)

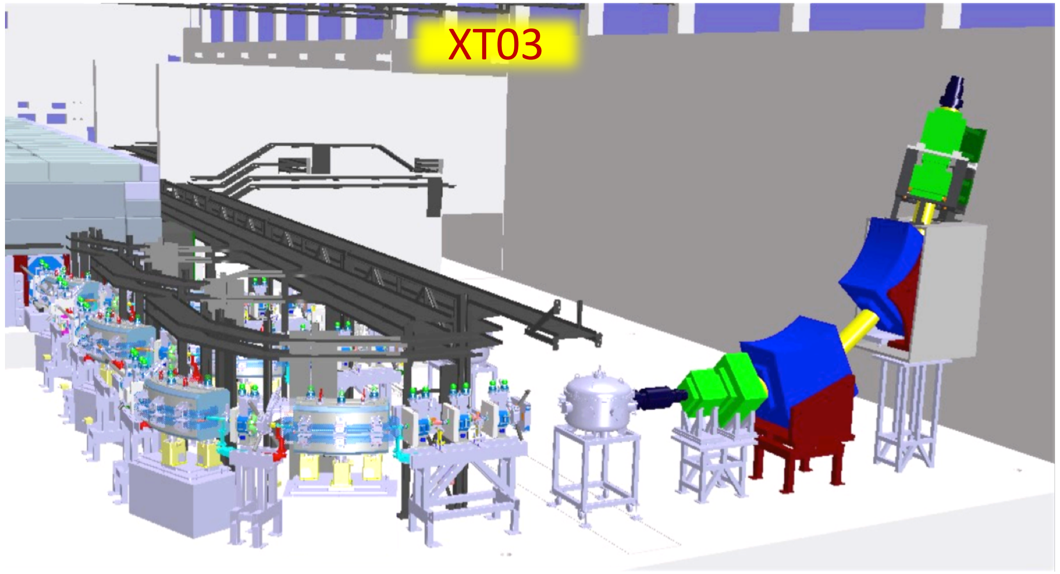
EMMA, MARA, PRISMA

- ^{9}Li(d,n)^{10}Be
- ^{22}Mg(d,n)^{23}Al
- ^{68}Ni(d,n)^{69}Ni
- ^{132}Sn(d,p)^{133}Sn
- ^{184}Hg(^{3}He,n)^{186}Pb

Traditional system based on warm magnets

- Simple and experienced.
- Little space available but could fit.
- ToF – space limitations.
- Not easy to move from one line to the other.

Layout for SEC



Layout for MINIBALL

Courtesy of J. Cederkall

Proposal for a design study using SC elements

- Explore new design concept using SC coils and RF cavities.
- Produce a compact, efficient and high-selectivity recoil separator.
- Design study including beam dynamics, mechanics, size, weight, efficiency, selectivity, construction and running costs.

SC solenoids

- Combined function magnets for bending and focussing
- High fields ~ 8 T

SC RF cavities

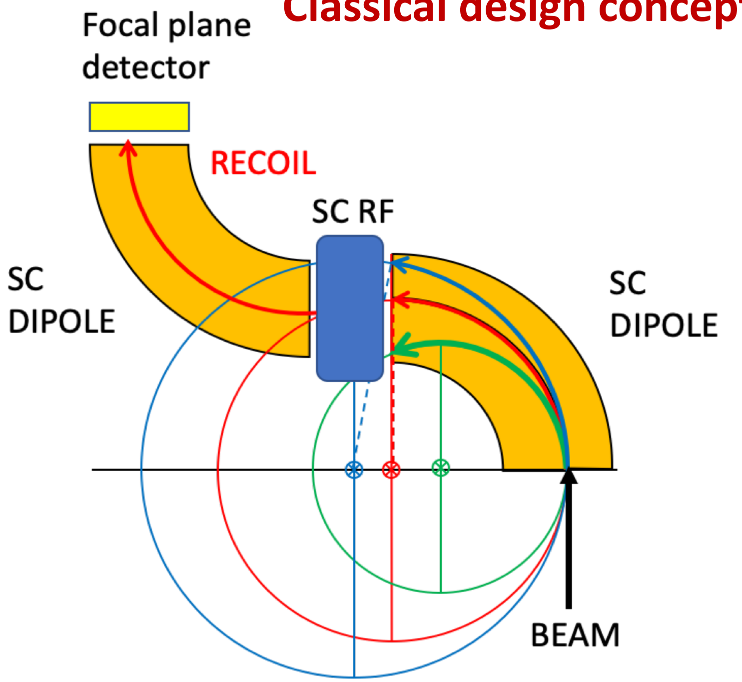
- High gradients ~ 10 MV/m
- Rebuncher ~ 10 MHz

Hight temperature SC

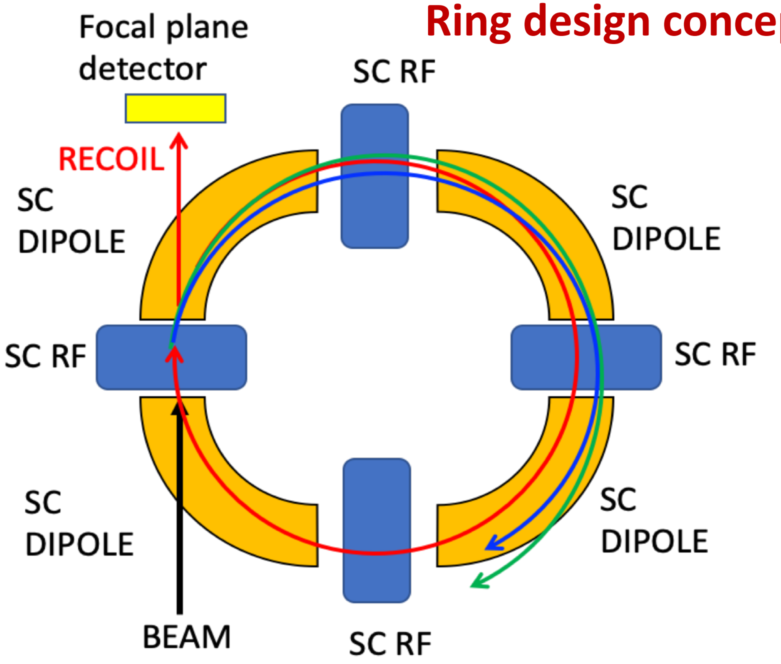
FFAG

(EMMA project at Daresbury Laboratory)

Classical design concept



Ring design concept



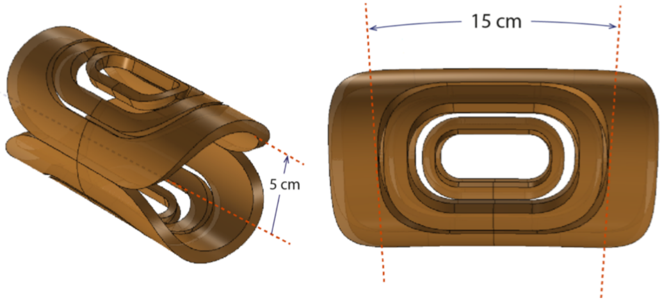
Example – Combined function magnets

"Design of a superconducting Gantry cryostat"

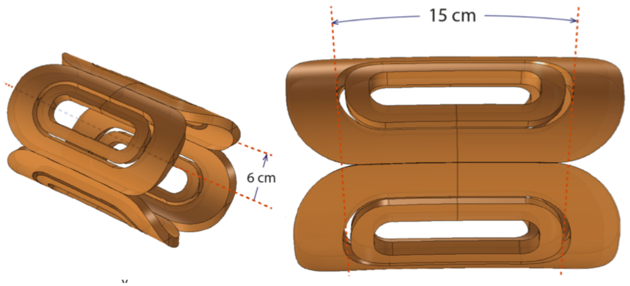
C. Bontoiu, et al., IPAC2015, doi:10.18429/JACoW-IPAC2015-WEPMN051

- Design study of a SC Gantry for protontherapy
- Protons of 175 MeV ± 20% (large acceptance); R= 2.5 m
- Bmax = 2.195 T
- Dipoles Bρ = 5.47 Tm
- Quads gradient = 90 T/m
- Small magnets Length x Diameter ~ 20 cm x 15 cm
- 36 magnets, FFAG

Specs must be scaled down for HIE-ISOLDE

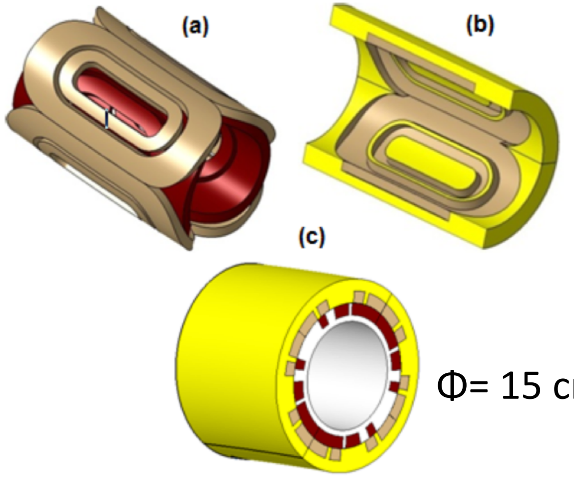


SC Dipole



SC quadrupole

Combined function magnet

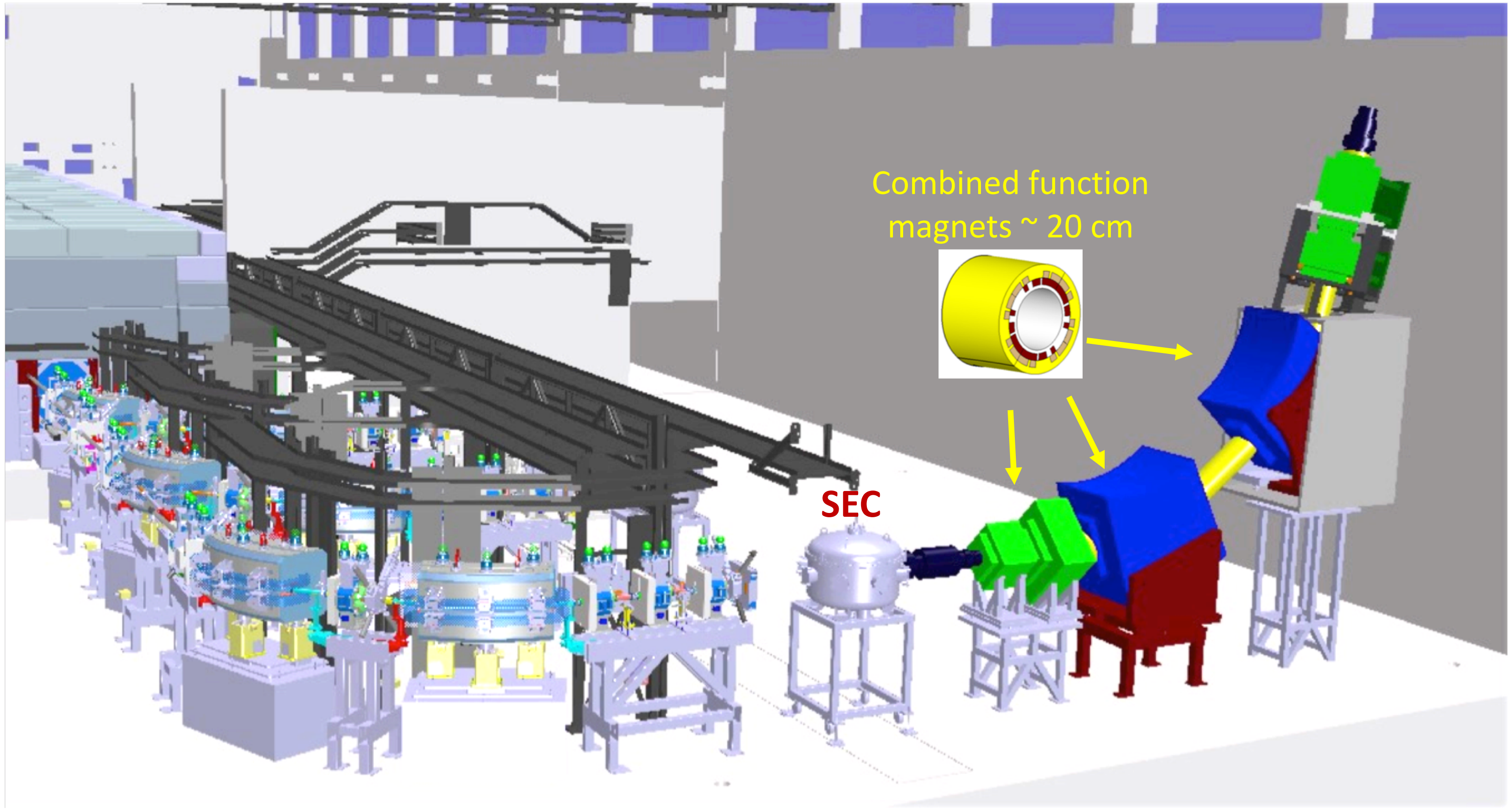


Φ= 15 cm

L=20 cm

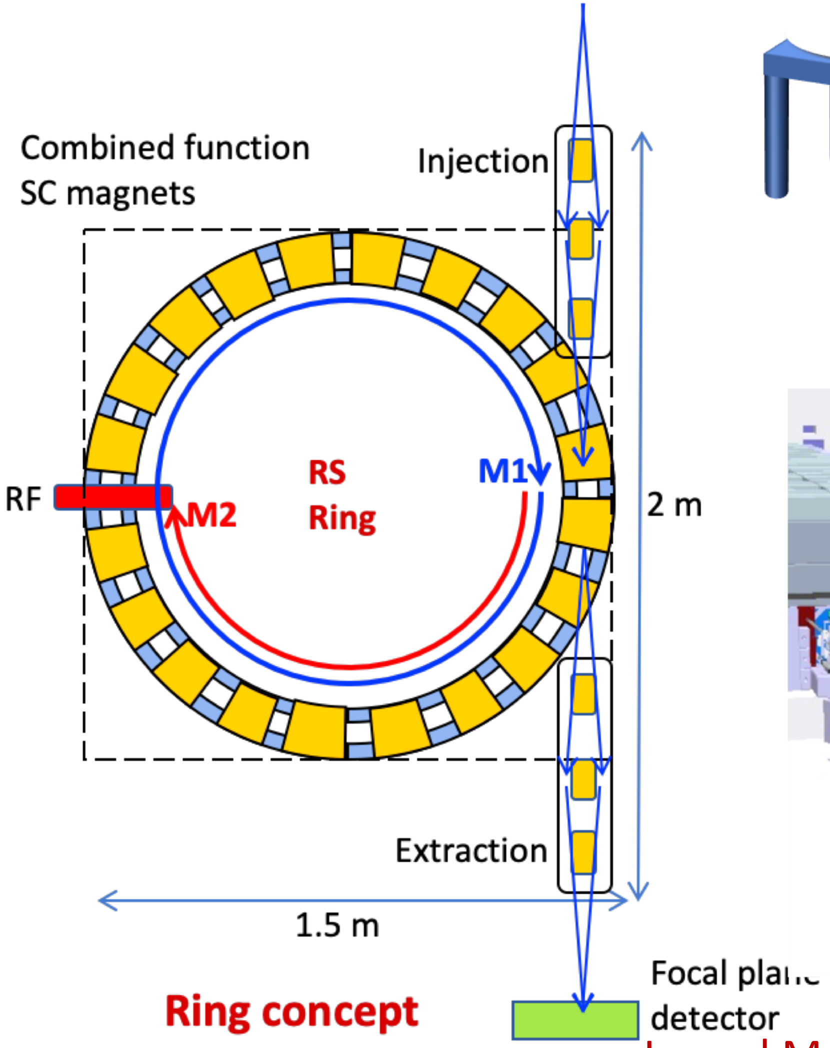
Example- Classical design concept

Reduction in size of dipoles and quadrupoles ~ factor 5.

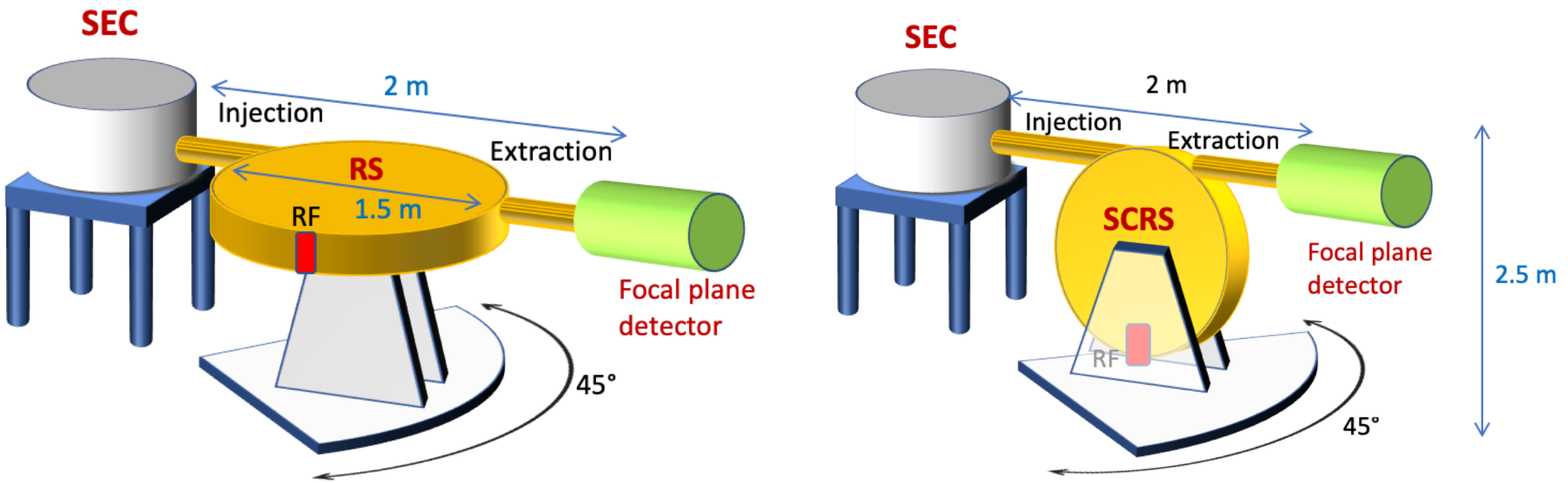


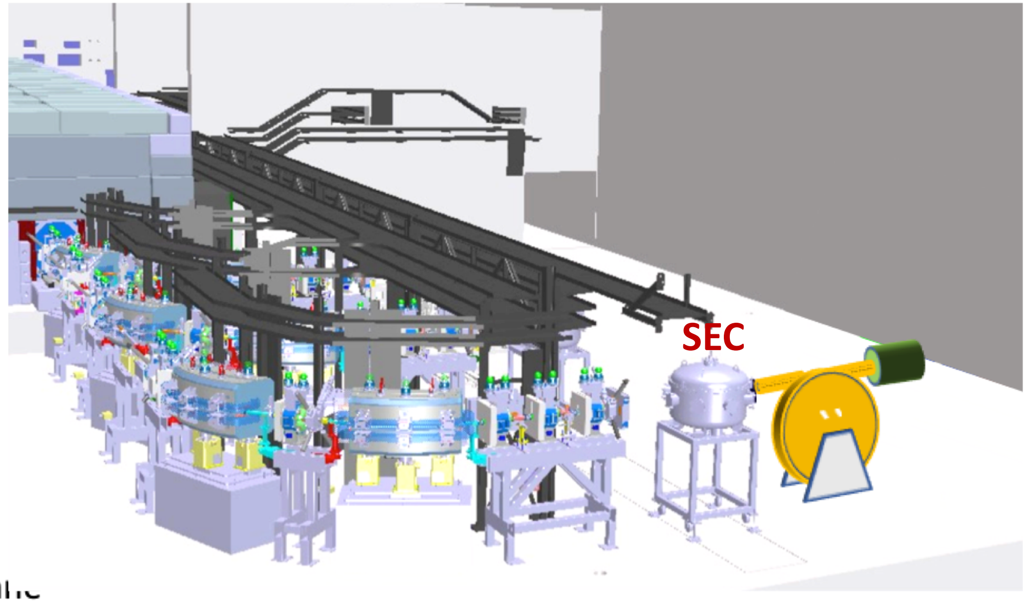
Example – Ring concept

- Remove only primary beam



Ring concept





R [m]	0.5 - 1
B [T]	2 - 6
f_0 [MHz]	10 - 40
f_k [kHz]	100 - 3000
Storage t [μs]	0.5 - 10

SC recoil separator FFGA lattice design – Zero order

J. Resta, V. Rodin, C. Welsch – Cockcroft Institute (UK) & U. Liverpool

BMAD model

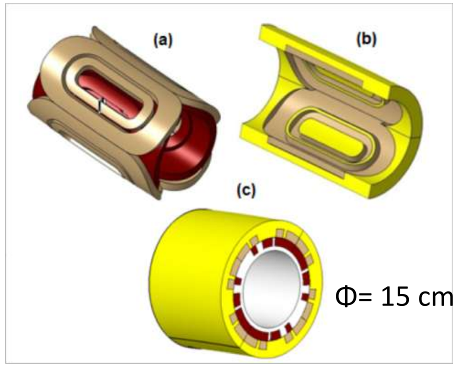
Example for ^{234}**Ra** @ 10 MeV/u
Rigidity $B\rho = 1.2$ T m
Ring circumference: 6 m
FFAG
20 magnets

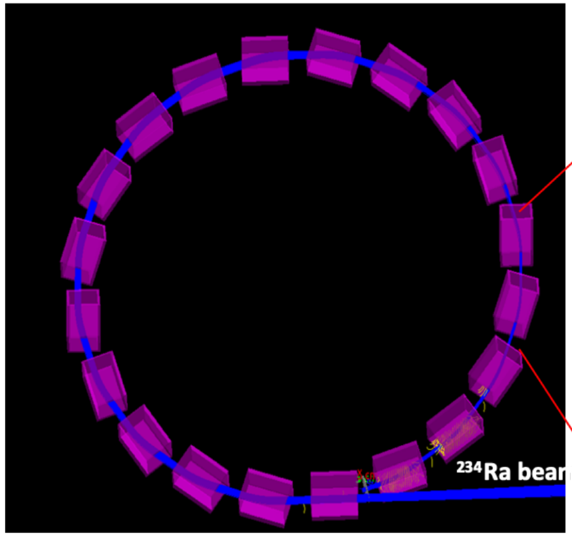
Dipolar magnetic field B=1.9 T
Bending angle ϑ=0.3 rad
Integrated quadrupolar strength KL=1.0 m^{-1}

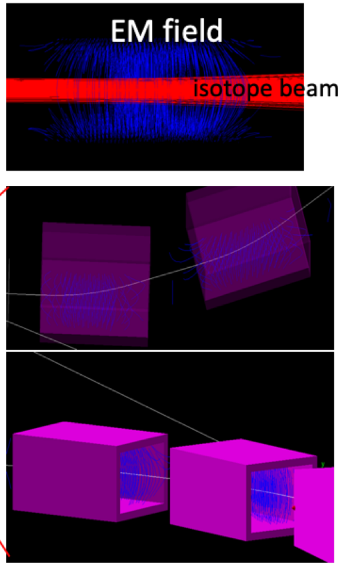
G4beamline "toy" model

Scaling the EM fields of multifunction magnets designed in the context of a superconducting Gantry cryostat [C. Bontoiu, et al., IPAC2015, doi:10.18429/JACoW-IPAC2015-WEPMN051]

Combined function magnet







- Closed and stable orbit for a 234Ra beam at 10 MeV/u.
- Still need to fully characterise the optics and study the beam dynamics of both the main beam and the reaction products.
- The work is ongoing.

Summary

- Existing physics programs would benefit from a Recoil Separator (Fragment Identifier -HiFi).
- Specific physics program could be developed
- Design study using SC coils and RF cavities to produce a compact, efficient instrument.
- Different options: warm magnets and RF cavities in ring and classical configurations.

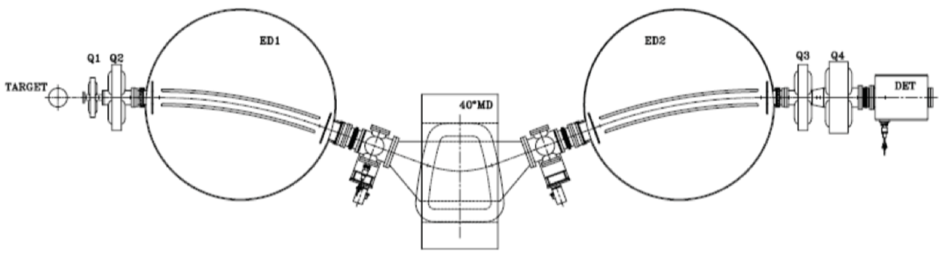
- ISCC support for launching a new design study based SC magnets and RF cavities.
- First beam dynamics calculations started.
- Studentship U. Liverpool – CERN advertised.
- Future proposal for funding to EU by international collaboration.

HIE-ISOLDE Recoil Separator (HiFi) White Book

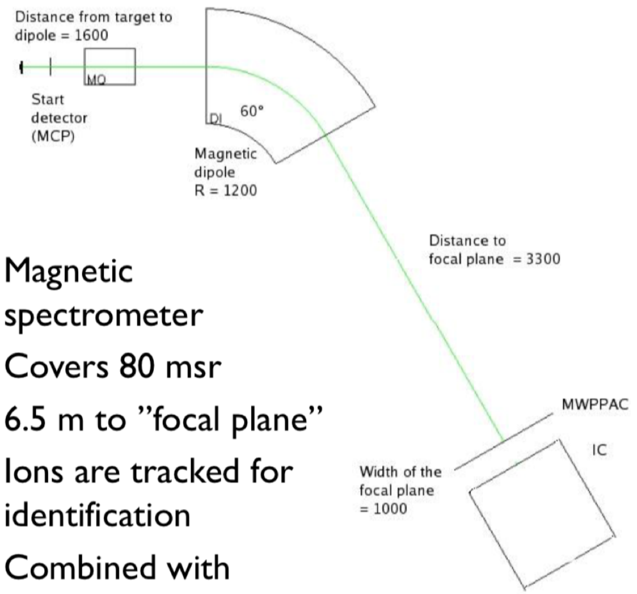
Spectrometer design for HIE-ISOLDE

EMMA@TRIUMF

B. Davids, C.N. Davids / Nuclear Instruments and Methods in Physics Research A 544 (2005) 565–576



PRISMA@LNL



- Magnetic spectrometer
- Covers 80 msr
- 6.5 m to "focal plane"
- Ions are tracked for identification
- Combined with gamma-detectors

SIMULATIONS
Test cases

^{9}Li(d,n)^{10}Be

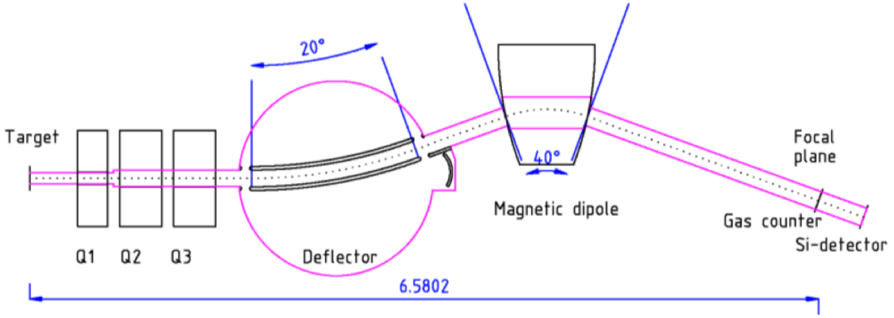
^{22}Mg(d,n)^{23}Al

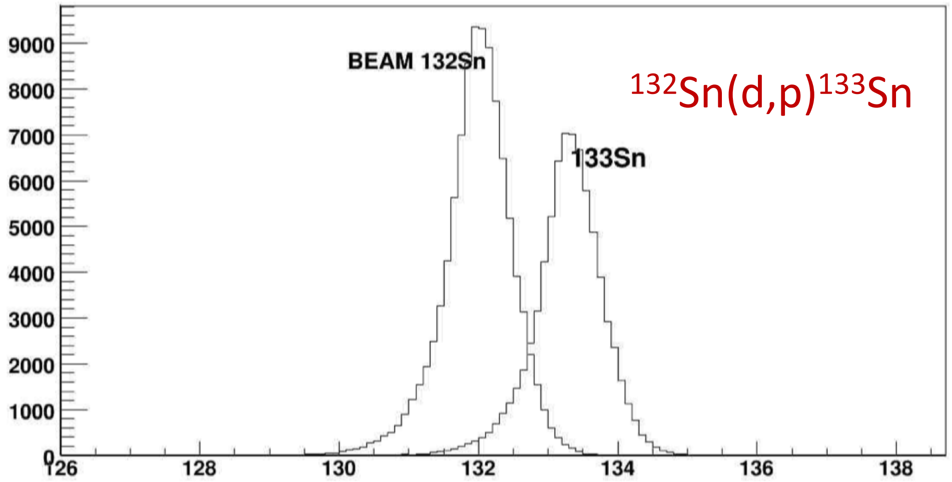
^{68}Ni(d,n)^{69}Ni

^{132}Sn(d,p)^{133}Sn

^{184}Hg(3He,n)^{186}Pb

MARA @ JYFL



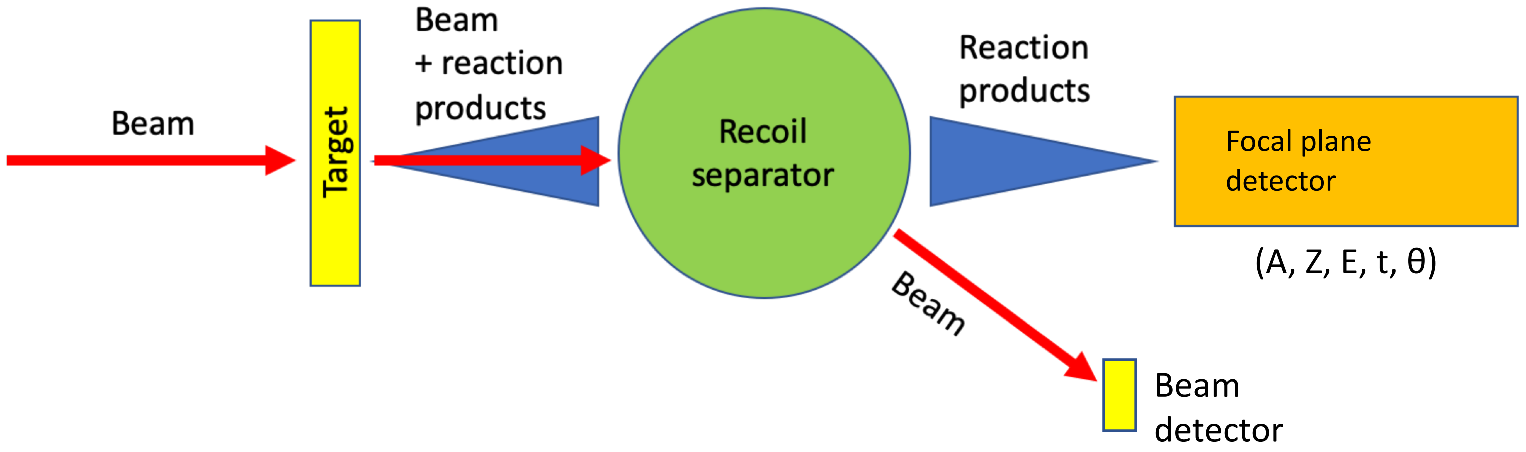


^{132}Sn(d,p)^{133}Sn

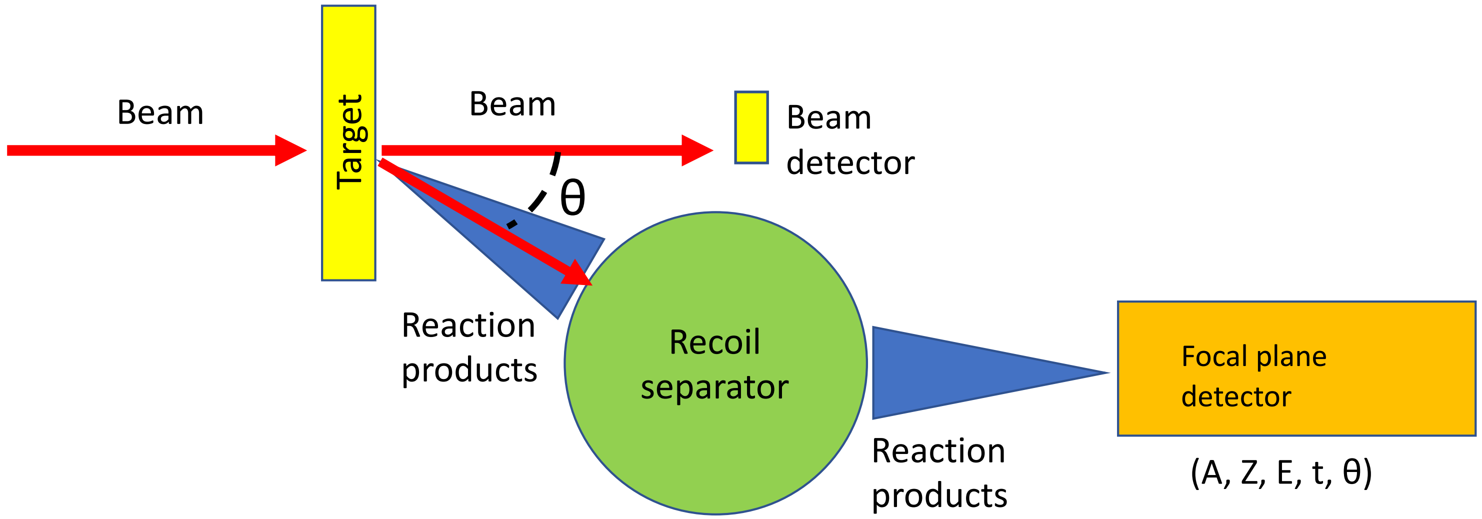
Courtesy of J. Cederkall

Recoil Separators

- Separate forward focussed reactions products (θ ~ 0°) from primary beam.



- Separate the reaction reaction products at selected angles (e.g. θ ~ grazing angle).



Principal elements

- Target and reaction chamber
- Injection and extraction system
- Separator
- Focal plane detector

Experiments

- Stand alone
- In coincidence with other systems

Advantages

- Simple experiments
- High efficiencies

Disadvantages

- Cost
- Size

Shell evolution: Study of ^{25}Ne using ^{24}Ne(d, pγ)^{25}Ne

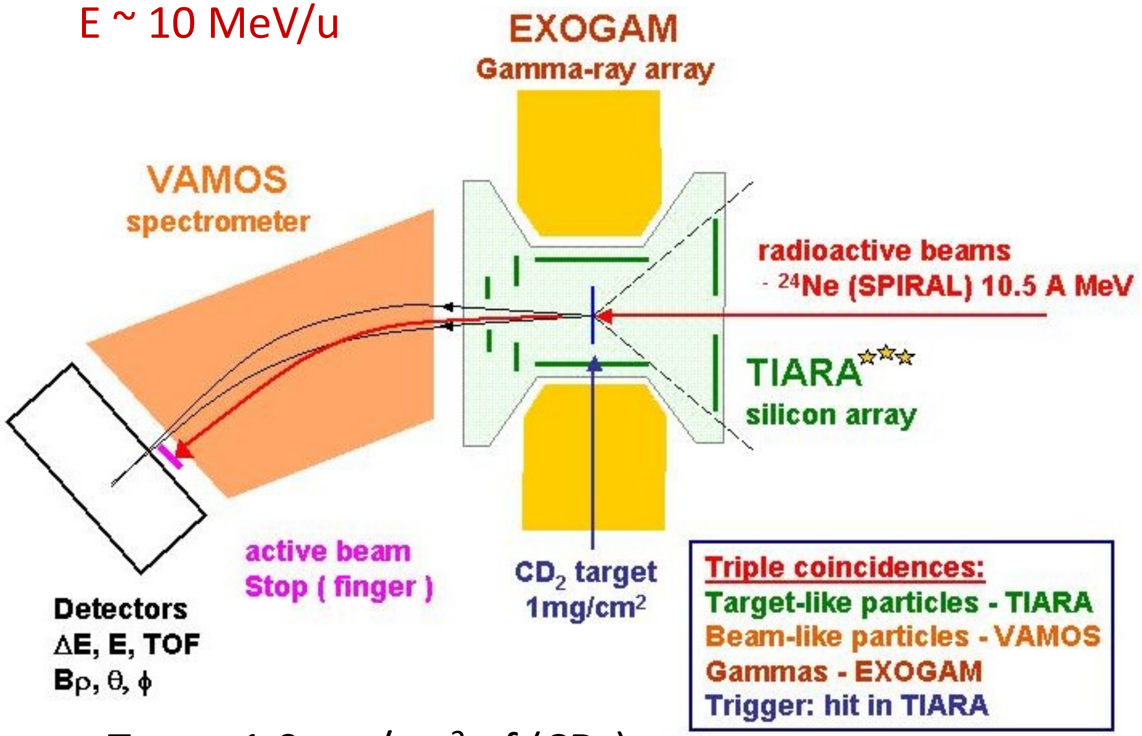
W.N. Catford *et al.*, Eur. Phys. J. **A25**, Suppl. 1, 245 (2005).

GANIL - SPIRAL

N=16 replaces broken N=20

VAMOS, θlab = 0°

E ~ 10 MeV/u



Target 1.0 mg/cm^2 of $(CD_2)_n$

Courtesy of Wilton Catford

Recoil Separator as ancillary detector

~ 10 A.MeV

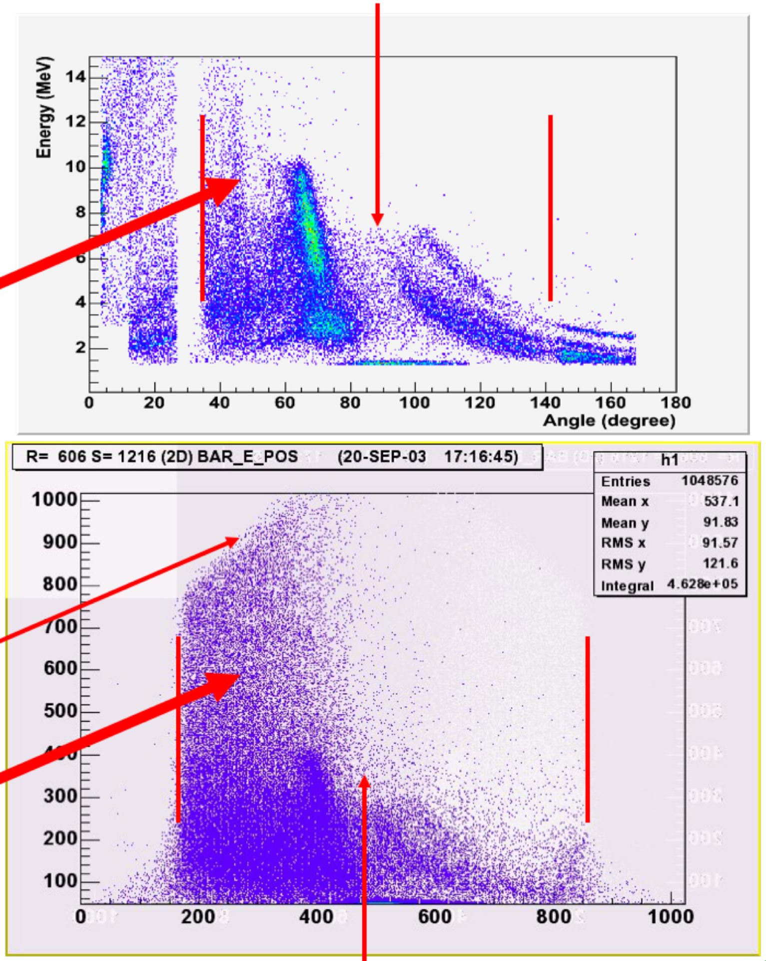
(90 degrees)

(d,t) tritons

(saturation)

Knock-on carbon elastics

BEAM



Requiring Vamos (Focal Plane Plastic)

Without Vamos Requirement

(90 degrees)

^{24}Ne (d,p) ^{25}Ne

SC recoil separator FFGA lattice design – Zero order

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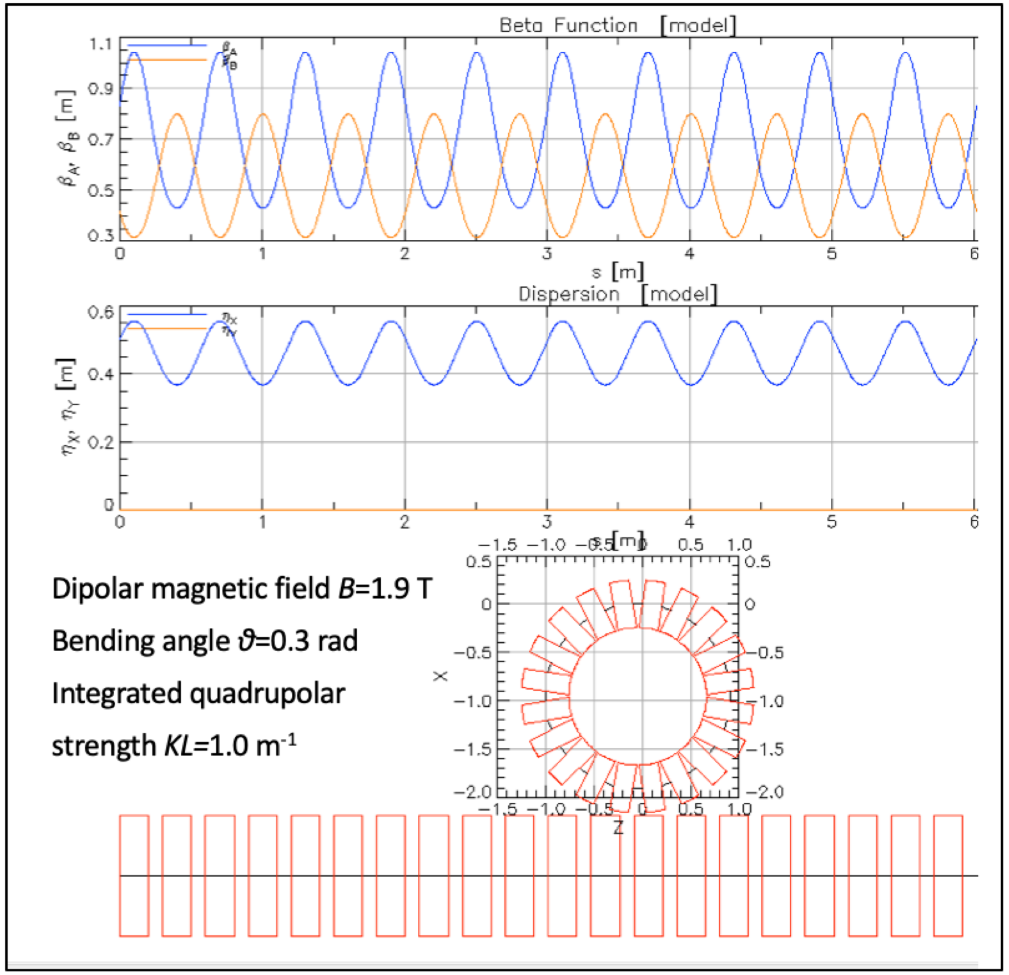
Twiss parameters



Alternating sequence of focusing and defocusing quadrupolar components