IoP Half Day Meeting
Recoil separators, present and future design concepts
Liverpool, April 29th , 2019

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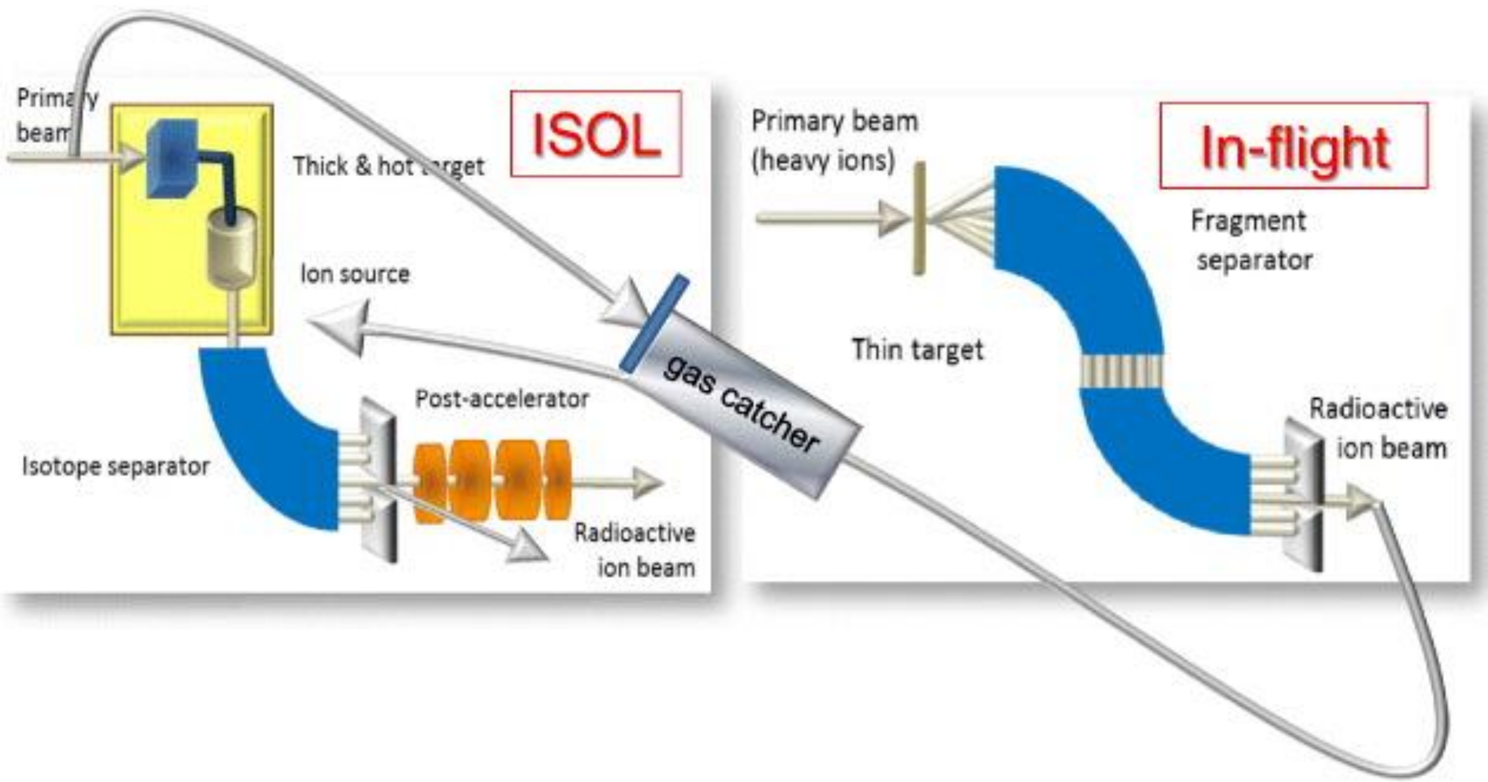
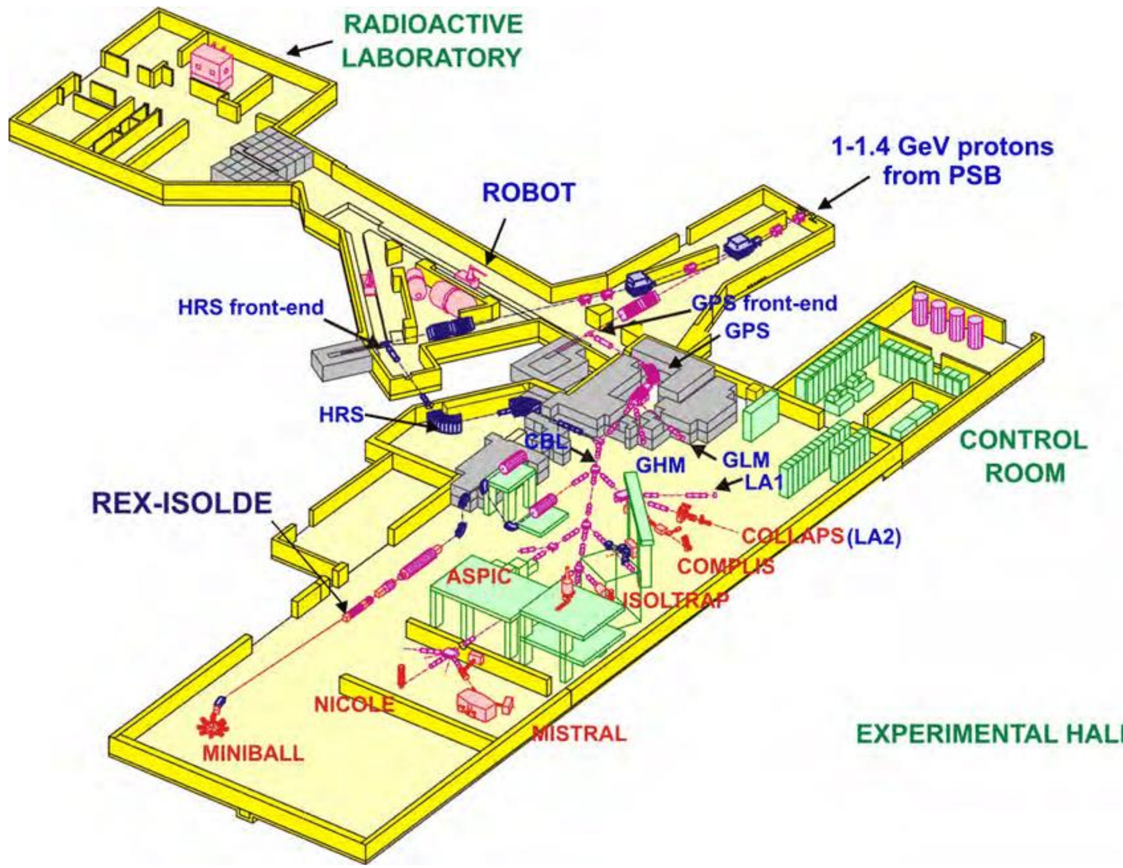
Nuclear reactions induced by exotic nuclei allow the exploration of nuclear structure at its extremes, the dynamics of stellar evolution and the limits of nuclear existence. Reaccelerated radioactive beams are currently available with energies up to around ~ 10 MeV/u from ISOL ion sources, where the beam is produced by the bombardment of thick targets by a primary particle accelerator.

High-resolution recoil separators are used to identify the reaction products, separating the primary beam from the products of interest. The singular properties of ISOL beams and the variety of physics programs impose specific design requirements.

This meeting will provide an opportunity to reinforce present collaborations and research activities across interdisciplinary lines, and to coordinate synergies and efforts for the development of a new instrument for HIE-ISOLDE.

High-resolution recoil separation is a combination of a separator itself and various detector setups at the target position and the focal plane.


ISOL
Primary beam
Thick & hot target
Ion source
Isotope separator
Post-accelerator
Radioactive ion beam
gas catcher
In-flight
Primary beam (heavy ions)
Thin target
Fragment separator
Radioactive ion beam


RADIOACTIVE LABORATORY
1-1.4 GeV protons from PSB
ROBOT
HRS front-end
GPS front-end
GPS
HRS
CBL
GHM
GLM
LA1
CONTROL ROOM
REX-ISOLDE
COLLAPS (LA2)
COMPLIS
ASPIC
ISOLTRAP
NICOLE
MISTRAL
MINIBALL
EXPERIMENTAL HALL

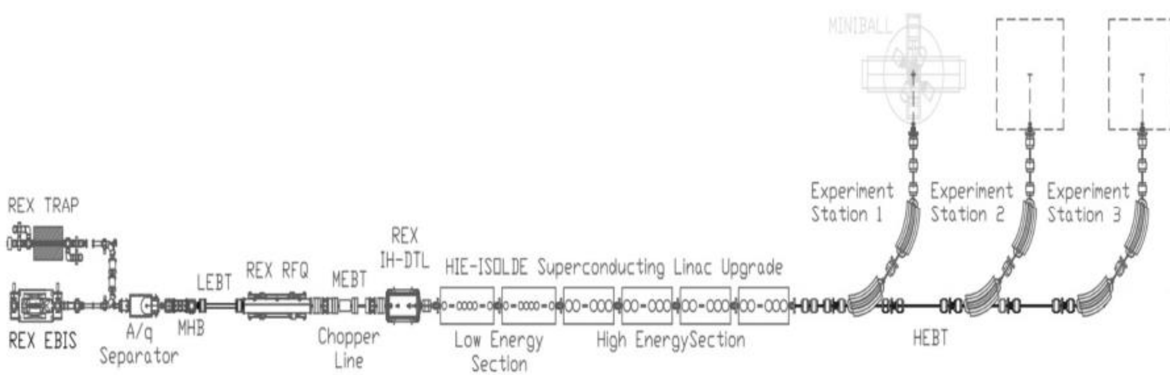
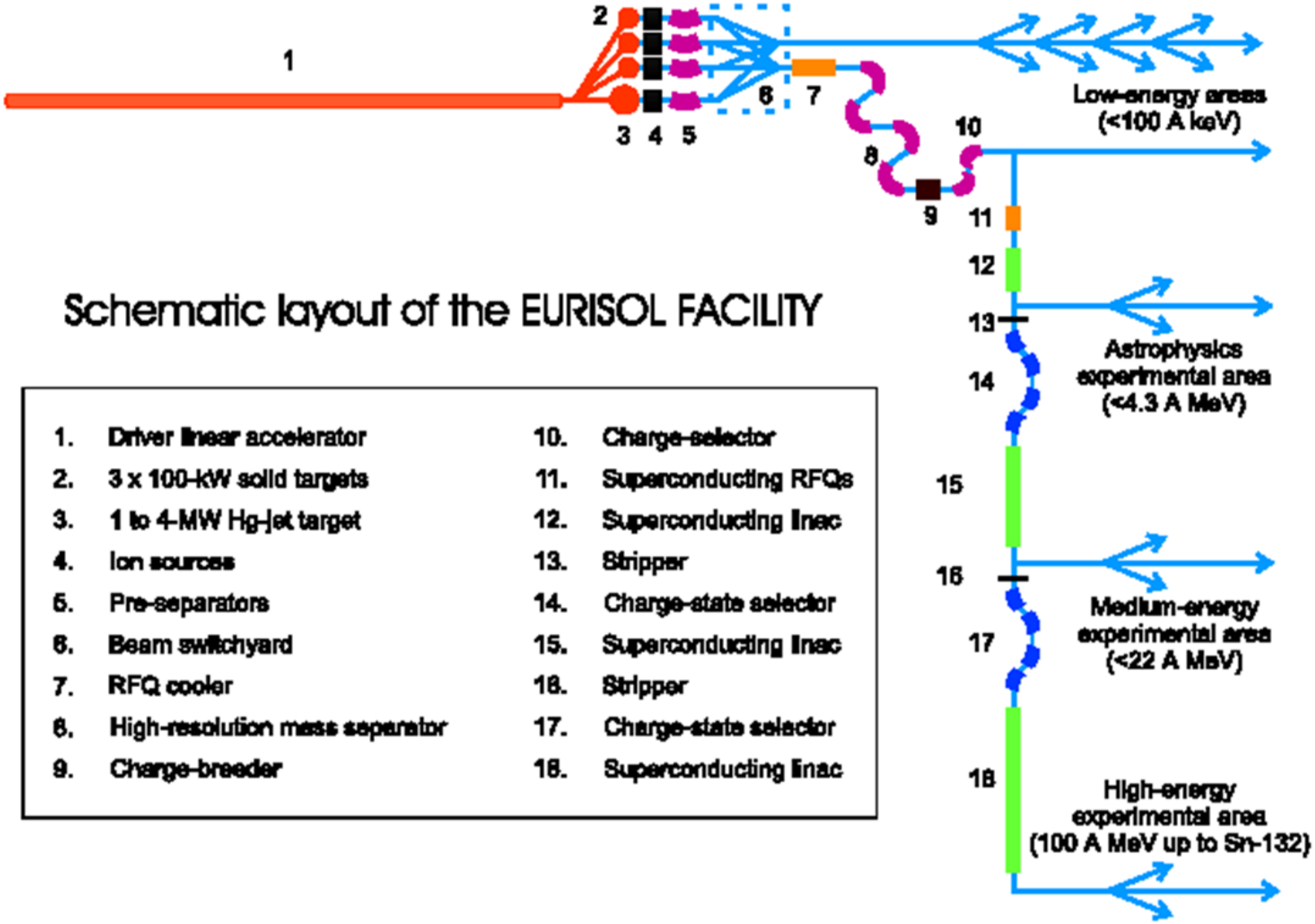

MINIBALL
Experiment Station 1
Experiment Station 2
Experiment Station 3
REX TRAP
REX EBIS
A/q Separator
LEBT
MHB
REX RFQ
MEBT
Chopper Line
REX IH-DTL
HIE-ISOLDE Superconducting Linac Upgrade
Low Energy Section
High EnergySection
HEBT

Table 9. Estimates for beam spot size, beam loss and bunch lengthening for various energies at $A/q = 4.5$ derived from MADX simulations.

Energy (MeV/u)	X-/Y- beam spot sizes (mm)	Average beam loss (%)	Bunch lengthening (ns)
0.3	6	0.3	6.3
5.9	3	<0.1	0.6
10	2.7		0.3

Initial energy (MeV/u)	Initially 3, finally 1.2
Final energy (MeV/u)	5.5 (stage 1) 10.0 (stage 2) and low energy capacity (stage 3)
A/q	3 to 4.5 (presently limited by IH1)
Intensity	<2 enA (much smaller in case of exotic beams)
Duty Factor	10% (CW with new ECR, new RFQ and new IH1 structure)
Length available	25m (including the RFQ)
Energy Variability	From 1.2 up to 10 MeV/u, maybe with deceleration

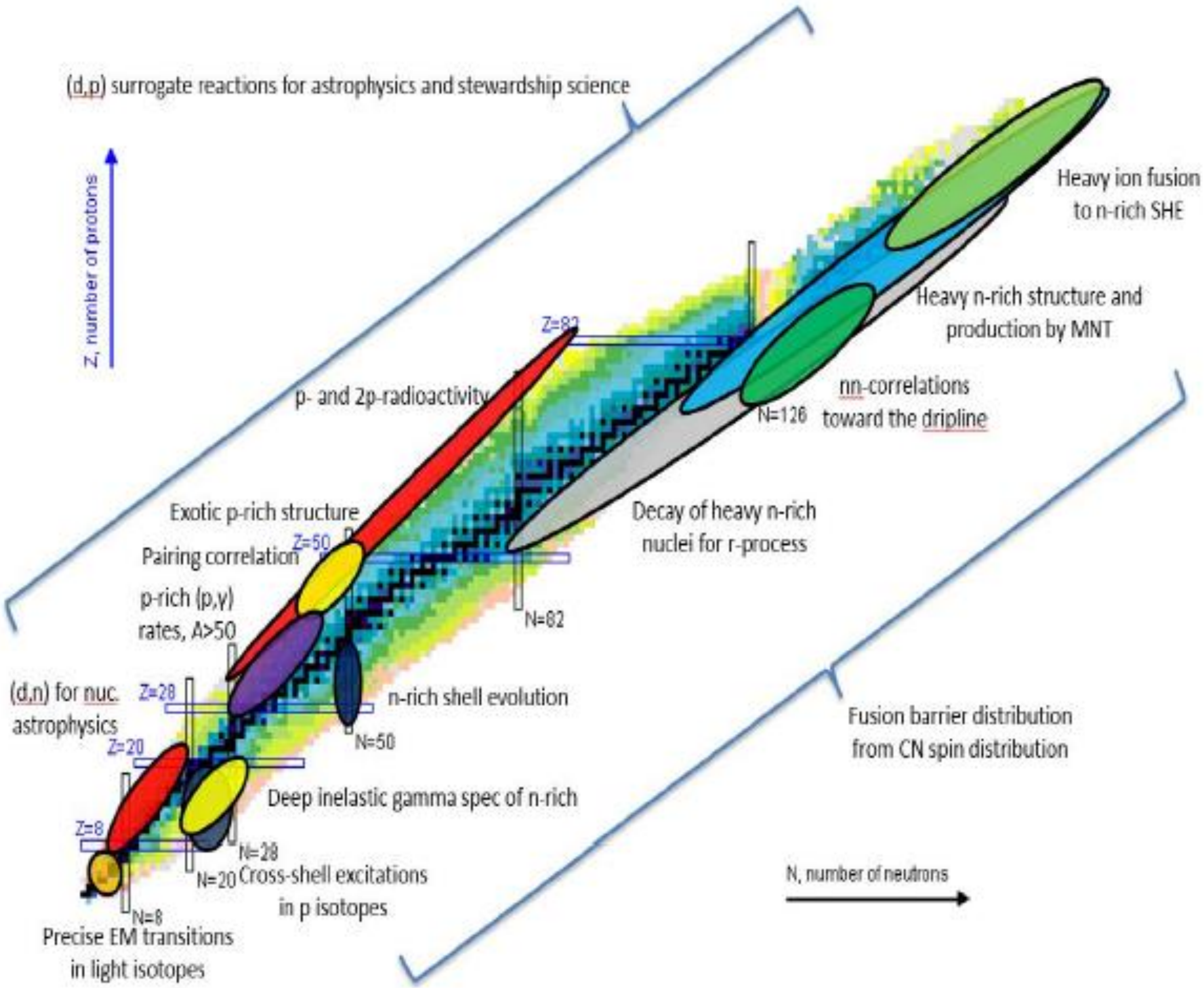
M. Huyse
at Saariselkä 2009
< 2 enA ~ < 1×10^9 pps



Schematic layout of the EURISOL FACILITY

1. Driver linear accelerator
2. 3 x 100-kW solid targets
3. 1 to 4-MW Hg-jet target
4. Ion sources
5. Pre-separators
6. Beam switchyard
7. RFQ cooler
8. High-resolution mass separator
9. Charge-breeder
10. Charge-selector
11. Superconducting RFQs
12. Superconducting linac
13. Stripper
14. Charge-state selector
15. Superconducting linac
16. Stripper
17. Charge-state selector
18. Superconducting linac

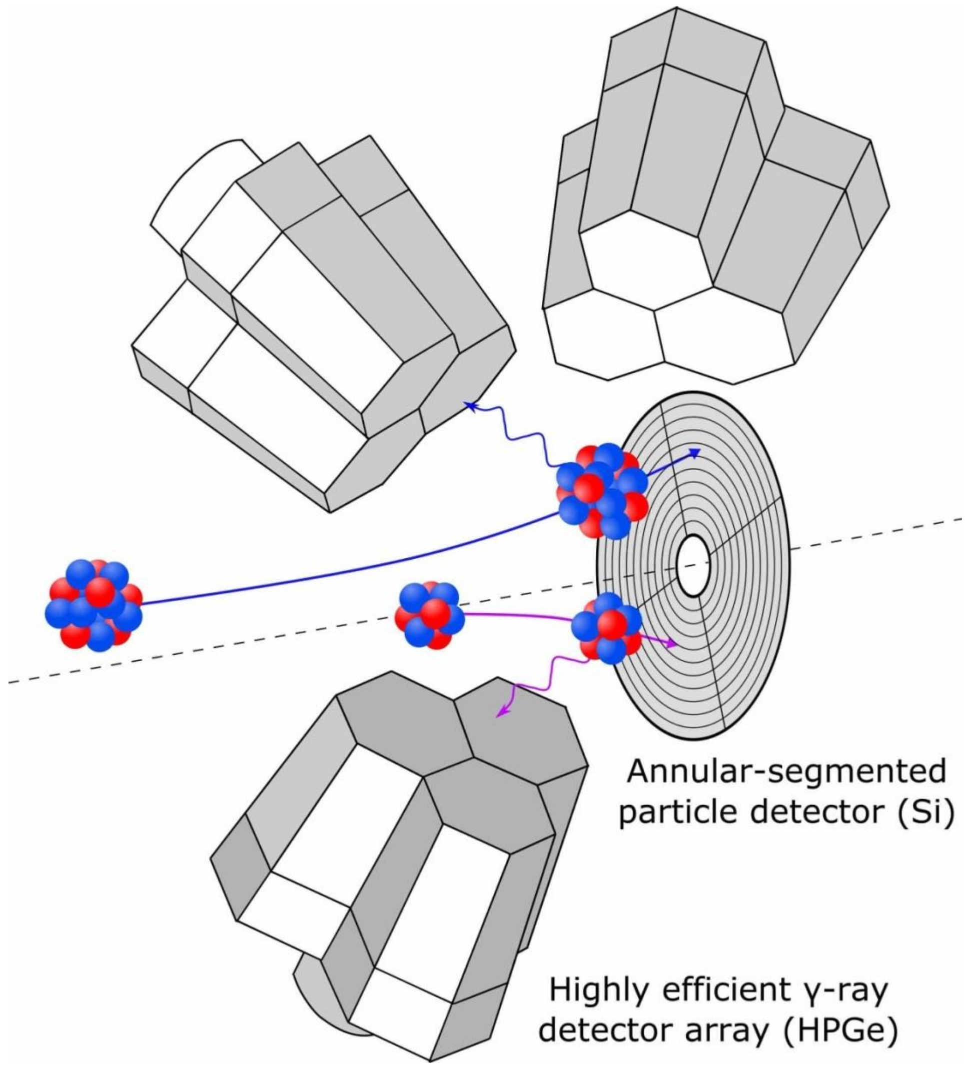
Recoil Separator for Rea12
White paper on the science case and proposed technical solution



Experiments:

- < 100 keV/A
    - Laser spectroscopic studies, mass measurements, isobar purified spectroscopy
    - COLLAP, CRIS, ISOLTRAP, IDS
- < 4 MeV/A
    - ("Safe") Coulex, MINIBALL
    - Capture reactions (p, γ), (α, γ)
- < 20 MeV/n
    - fusion-evaporation reactions
    - Transfer reactions (n,p)……
    - Deep-inelastic, multi-nucleon transfer, cluster transfer…
- 100 MeV/n
    - Spallation, fragmentation, fission

Safe Coulex experiments



- Spectrometer (in-flight separators) key features:
  - acceptance (angular, energy, momentum, m/q), resolving power, beam suppression, image size
- Small acceptance separators
  - small aberrations, image size small, physical separation
  - Examples: FMA, EMMA, MARA, (SHIP)
  - Transmission reasonable high in inverse kinematics or in symmetric cases
- Large acceptance separators
  - large aberrations, no physical separation, identification based on using large tracking detectors
  - Examples: VAMOS, PRISMA..
- Gas-filled separators
  - Charge and velocity focusing, high transmission and very good beam suppression with as-symmetric cases
  - TASCA, GARIS(I and II), BGS, RITU..

- Detector setups around the target position and around the focal plane

Dragon at Triumf for capture reactions

ΔE, E, ToF
→ A, Z

SECAR, Separator for Capture Reaction

Beam suppression
for <1 background event

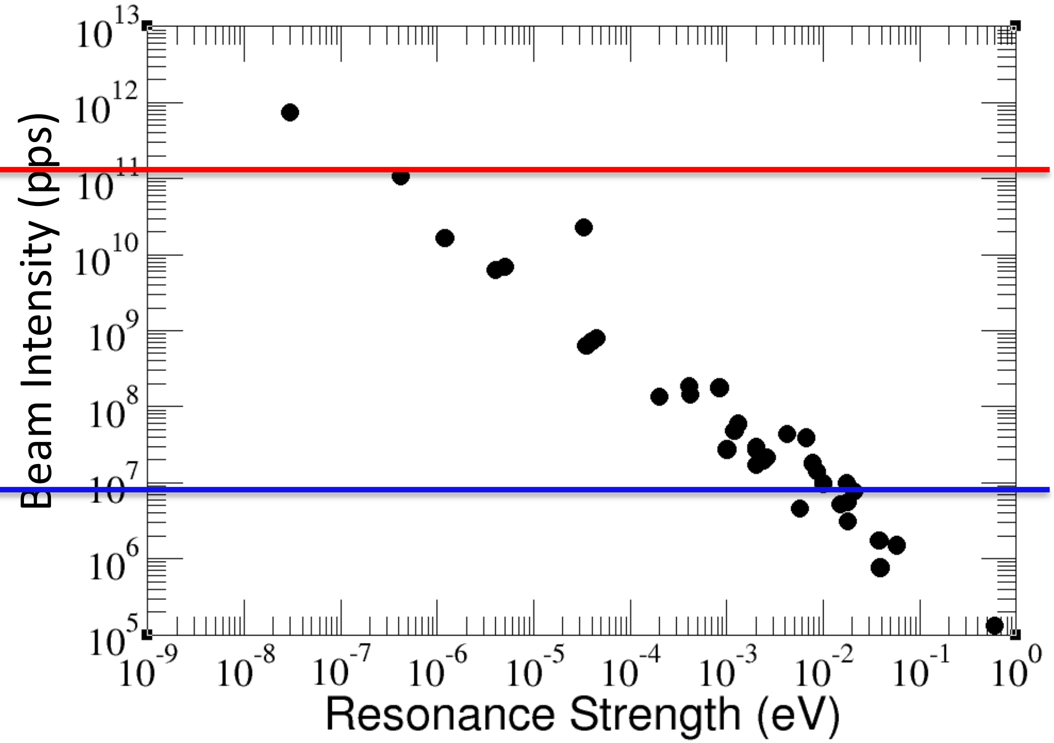
Ultimate Performance Parameter

UPP 10^{-17}

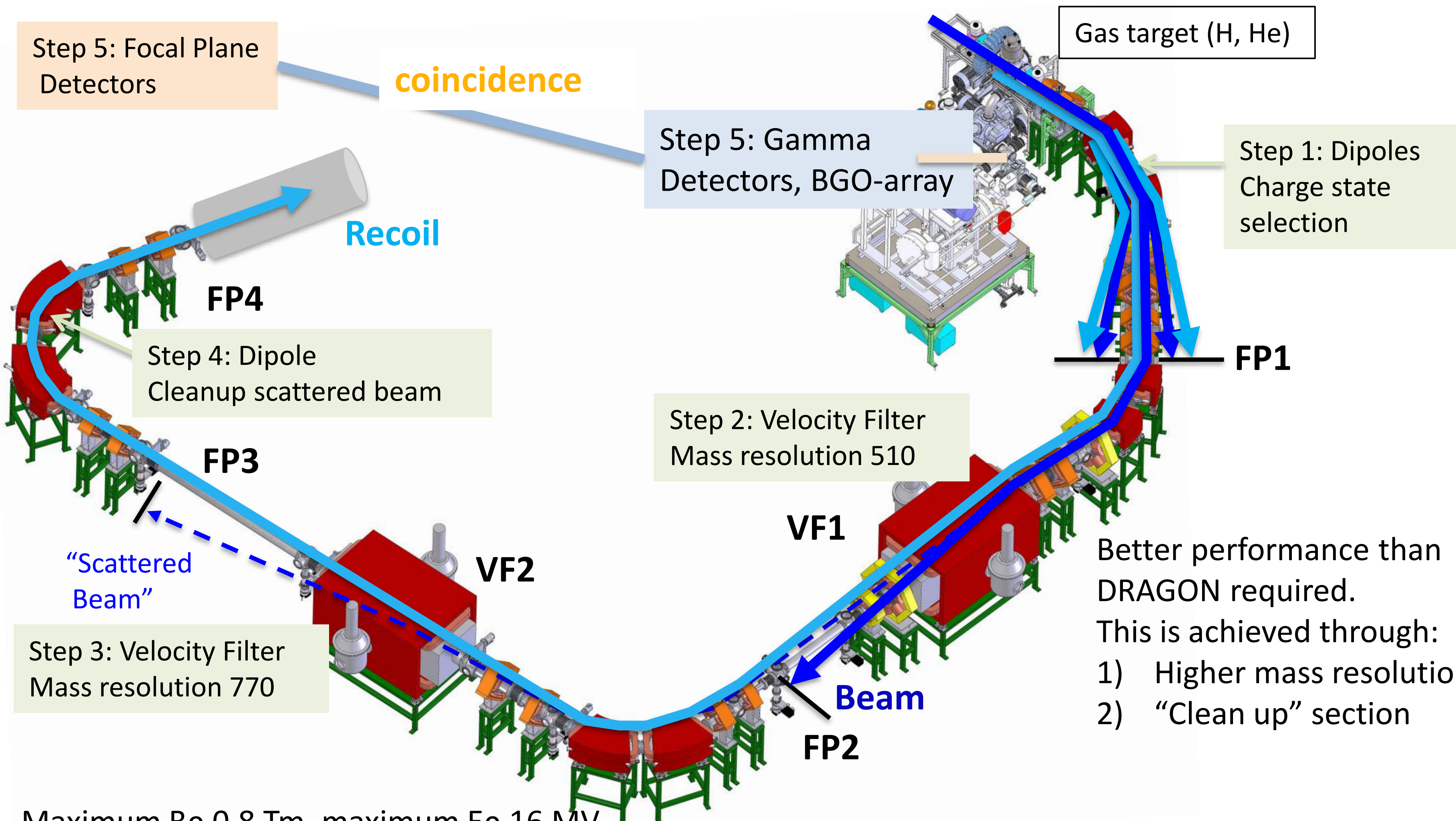
Key Performance Parameter

KPP 10^{-13}

Typical astrophysical resonances
Minimum beam intensity for 2 week measurement



SECAR, Separator for Capture Reactions



Better performance than DRAGON required.
This is achieved through:
1) Higher mass resolution
2) "Clean up" section

- Maximum Bρ 0.8 Tm, maximum Eρ 16 MV
- Angular acceptance 2.5 msr
- Energy acceptance ± 3.1 %
- m/q acceptance, one charge state

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Nuclear Instruments and Methods in Physics Research A 544 (2005) 565–576
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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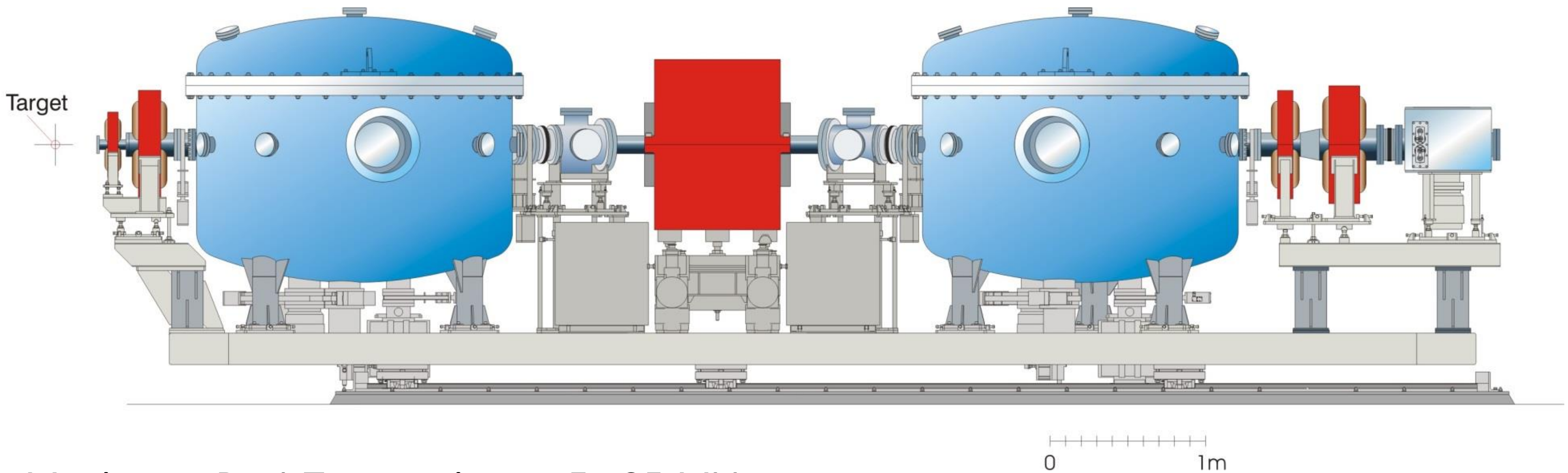
EMMA: A recoil mass spectrometer for ISAC-II at TRIUMF

Barry Davids[a,*], Cary N. Davids[b]



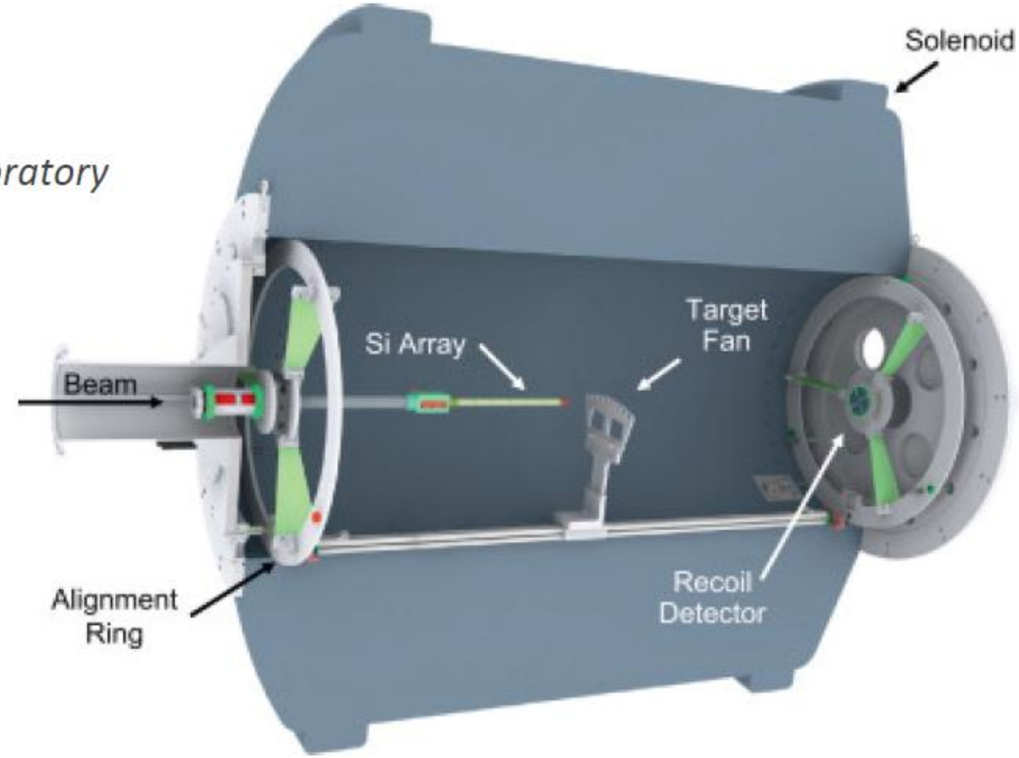
- Maximum Bρ 1 Tm, maximum Eρ 25 MV
- Angular acceptance 16 msr
- Energy acceptance ±20 %
- m/q acceptance 4 %
- Fusion evaporation studies
- Transfer studies in inverse kinematics
    - d(^{132}Sn,p)^{133}Sn, Eρ = 38 MV

HELIOS: The Helical Orbit Spectrometer at ATLAS

B.B.Back
Argonne National Laboratory

Inverse kinematics
$d(^{A}X,p)^{A-1}X$ reactions

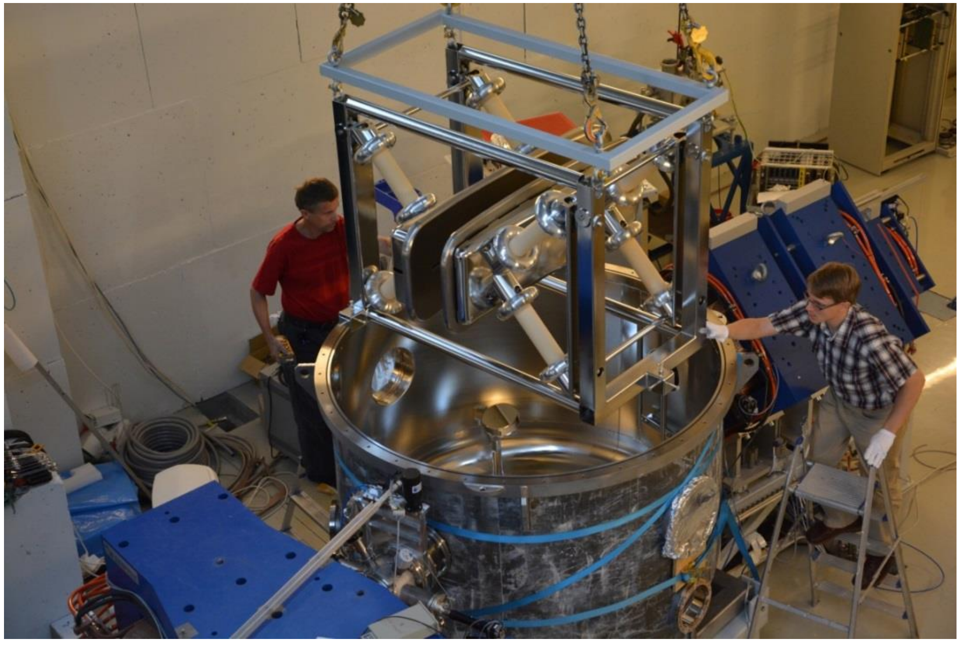
Gas targets to allow
(3He,p), (3He,d), (3He,α)

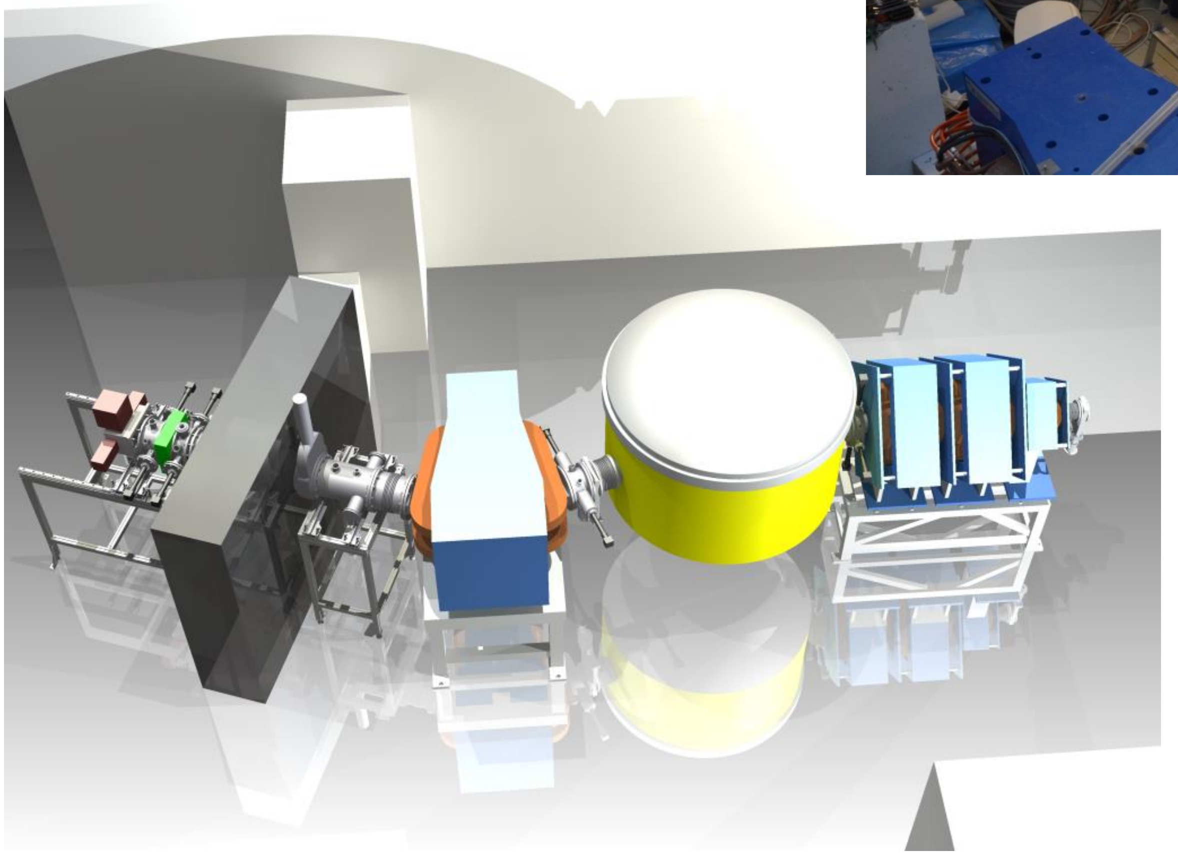


ISS, Isolde Solenoidal Spectrometer

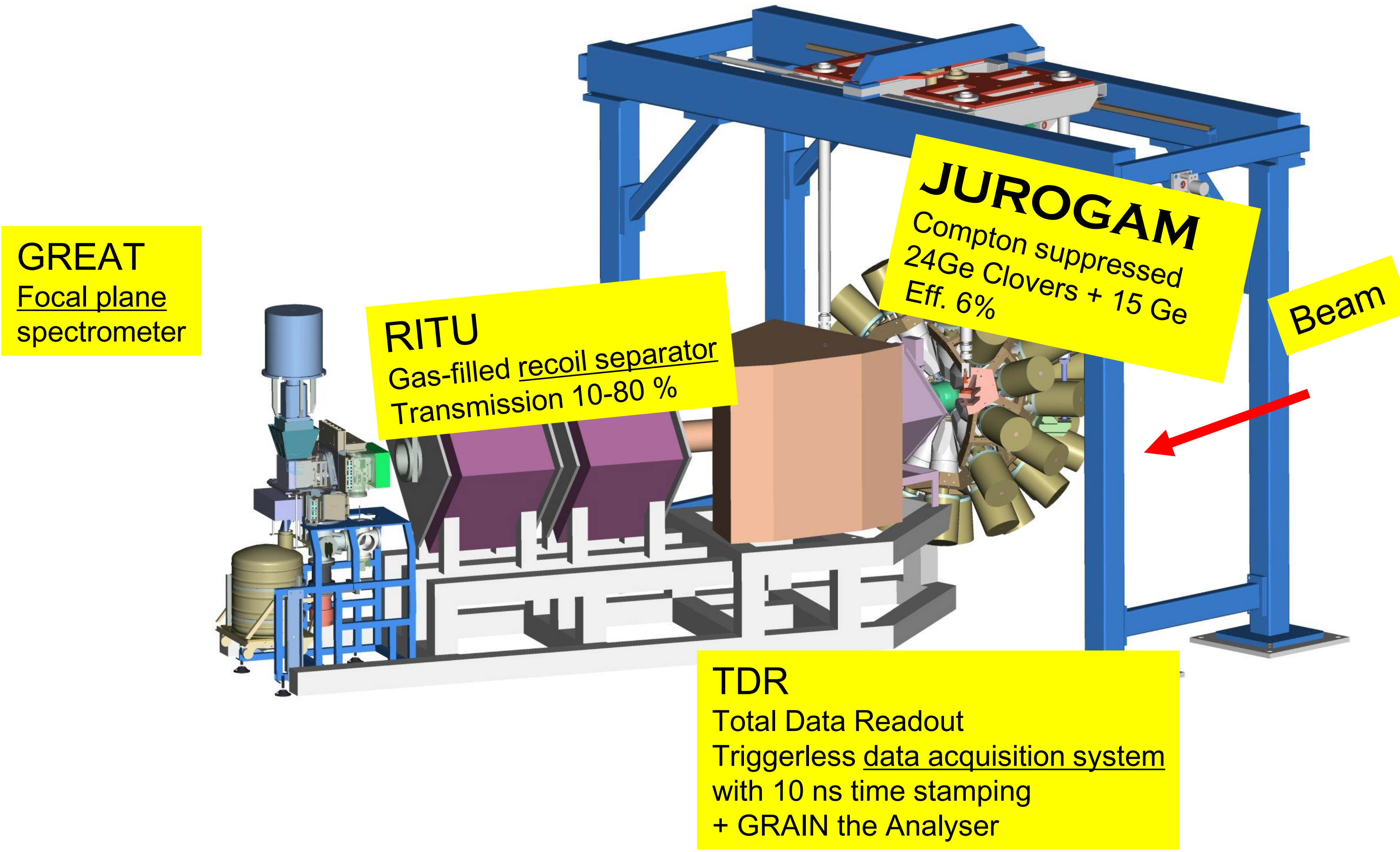
MARA at JYFL-ACCLAB

- Maximum Bρ 1 Tm, maximum Eρ 14 MV
- Angular acceptance 10 msr
- Energy acceptance +20%, -15 %
- m/q acceptance ± 7 %
- Fusion evaporation studies

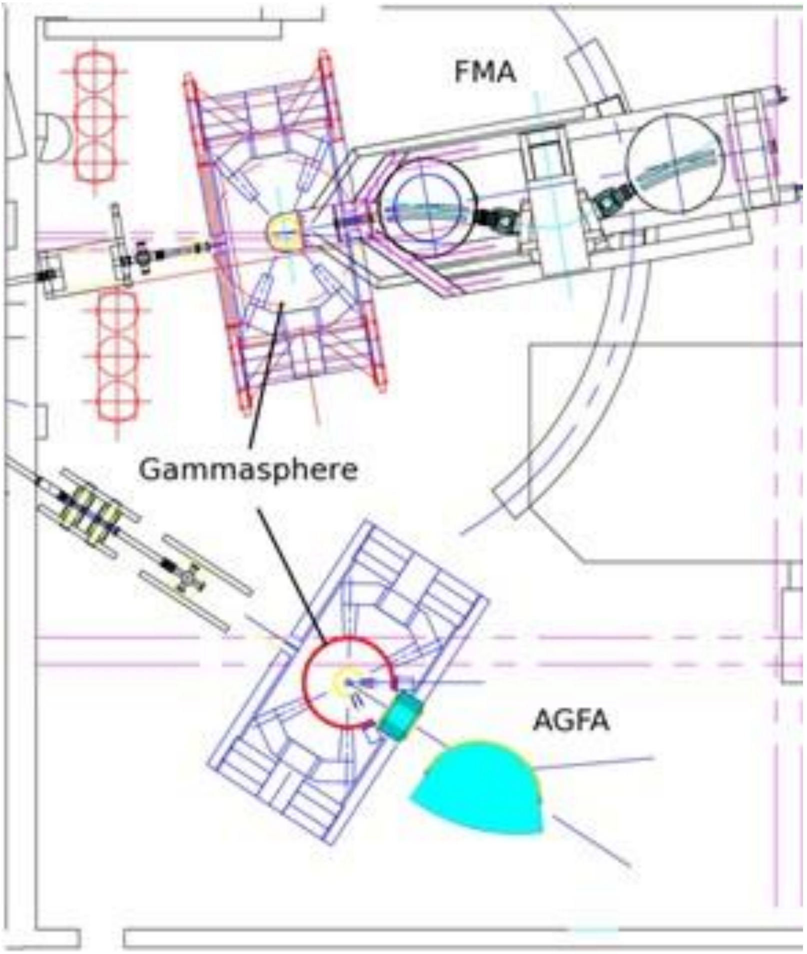




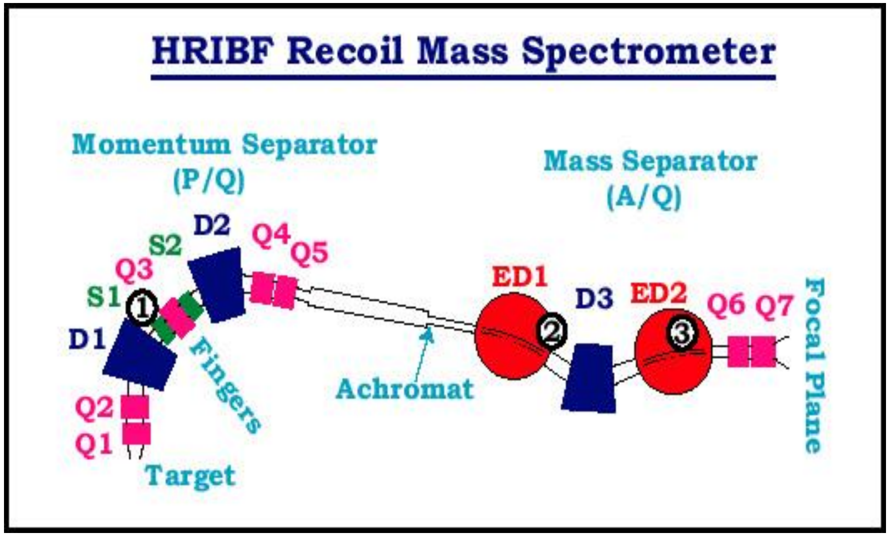
RDT Instrumentation at JYFL-ACCLAB



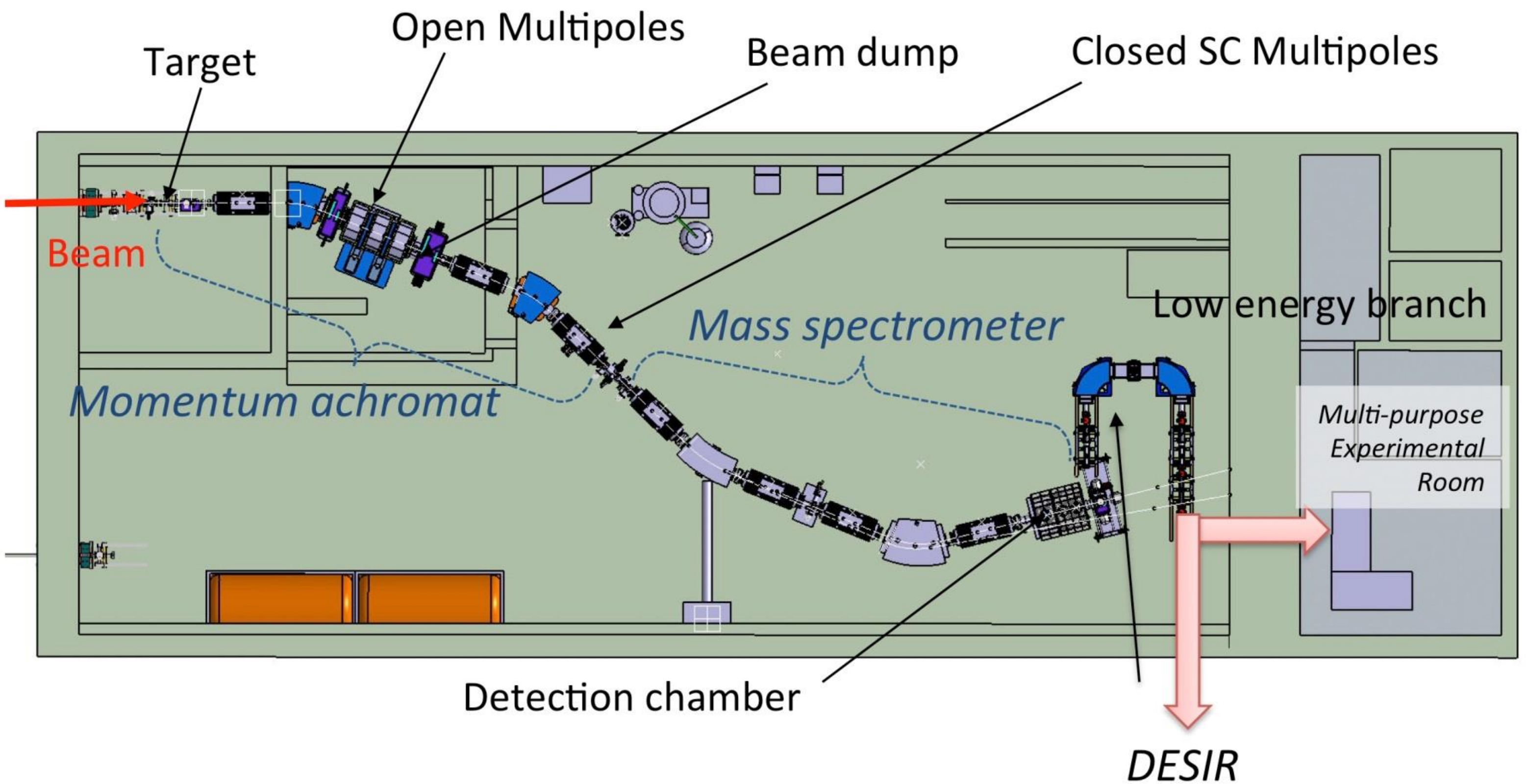
Argonne separators
ANL, USA



ORNL, USA



S3 separator at Ganil



VAMOS at GANIL

Ganil ^{238}U beam inverse kinematics

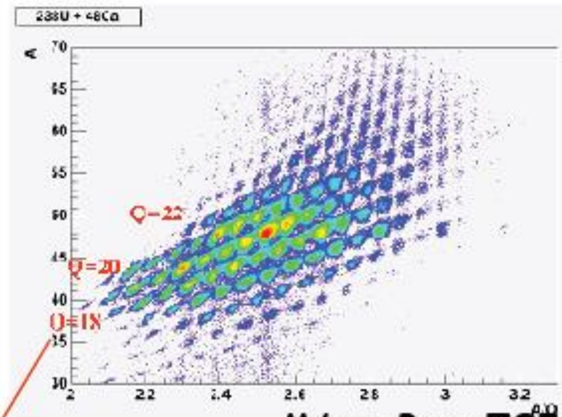
Deep inelastic transfer

$^{238}U + ^{48}Ca \rightarrow$

2- 3 pna

~1.1 V_b

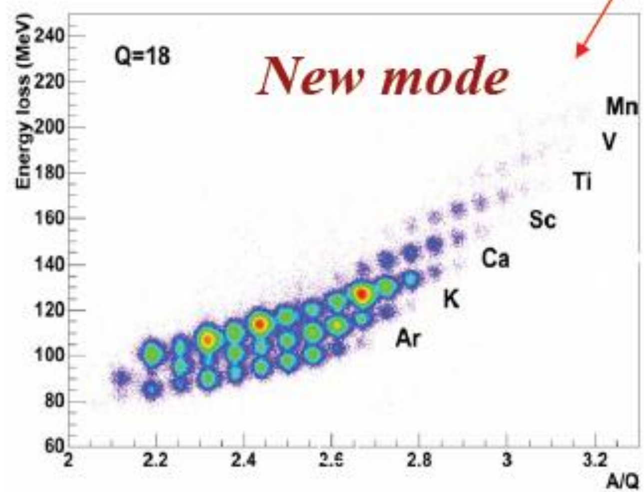
$-2p+2n$	$^{48}Ar + ^{238}Th$
$-1p+2n$	$^{49}K + ^{237}Np$
$0p+4n$	$^{52}Ca + ^{234}U$
$+1p+4n$	$^{53}Sc + ^{233}Pa$
$+2p+7n$	$^{57}Ti + ^{229}Pu$

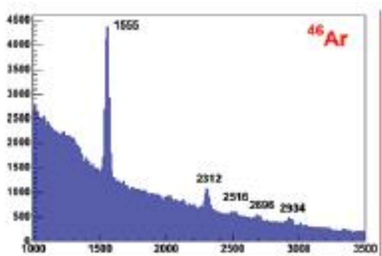


$M/q \sim B\rho \times TOF$

$M \sim E \times TOF^2$

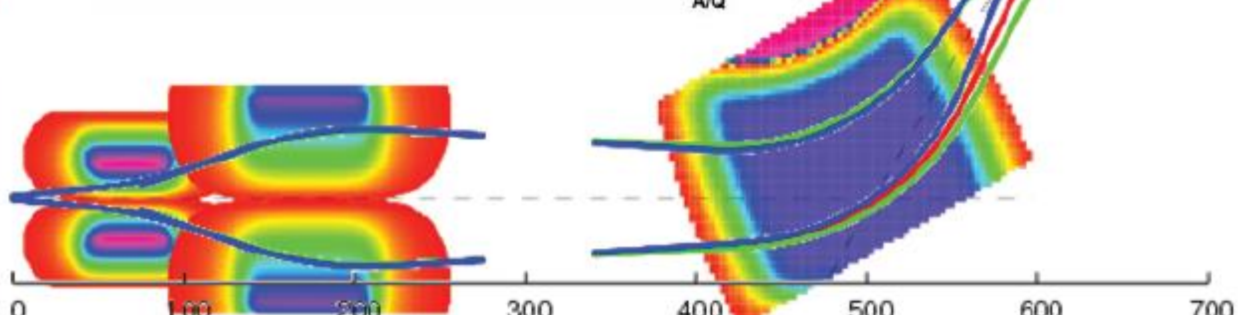
$Z \sim E \times \Delta E$





Exogam

^{238}U



PRISMA at Legnaro

PRISMA – CLARA Setup

PRISMA

Angular acceptances	$\Delta\theta \approx \pm 6^{o}$ $\Delta\varphi \approx \pm 11^{o}$
Solid angle	$\approx$ 80 msr
Distance target - FPD	7 m
Energy acceptance	± 20%
Resolving power	$p/\Delta p \approx 2000$
Mass resolution	1/200 (measured)
Energy resolution	1/1000 (via ToF)
Z resolution	$\leq$ 1/60 (measured)
Count rate capability	up to 2×10^{5} sec^{-1}

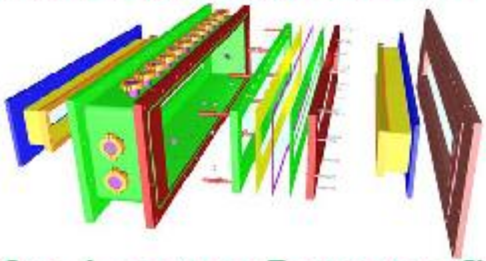
CLARA

24 to 25 Clovers setup
Efficiency ~ 3 % @ 1.3 MeV
Peak/Total ~ 45 %
Position θ = 103°-180°
FWHM ~ 10 keV
for E_{γ}= 1.3 MeV @ v/c = 10%

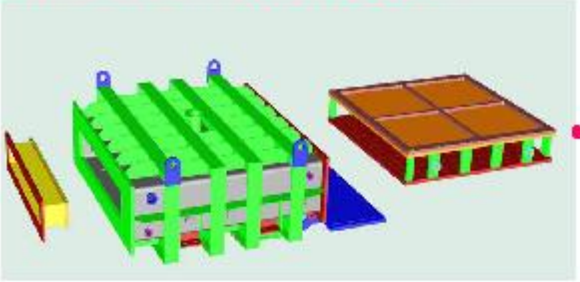
The PRISMA Spectrometer

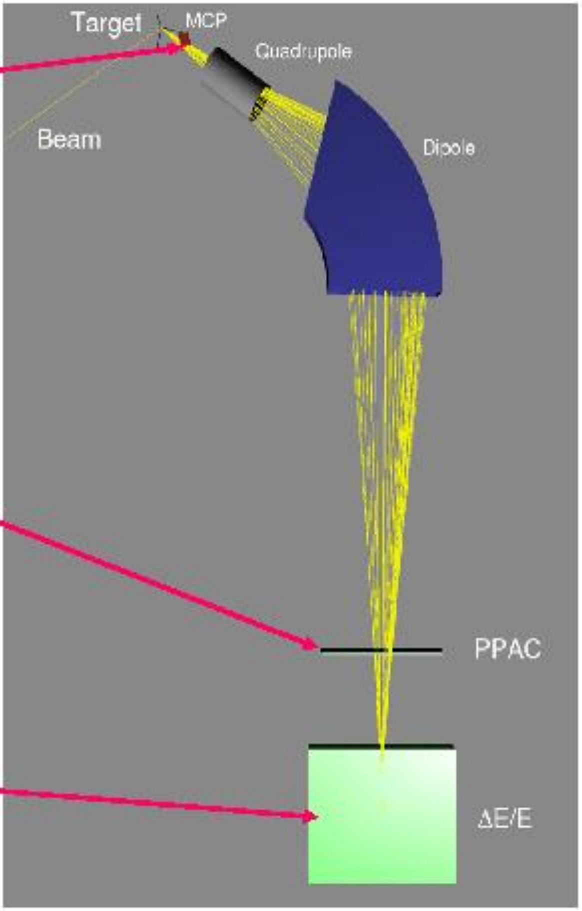
Position sensitive MCP
8 x 10 cm²

10 sections Multiwire PPAC
Active Area: 100 x 13 cm²



10 x 4 sections Ionization Chamber
Each Section: 10 x 25 cm²



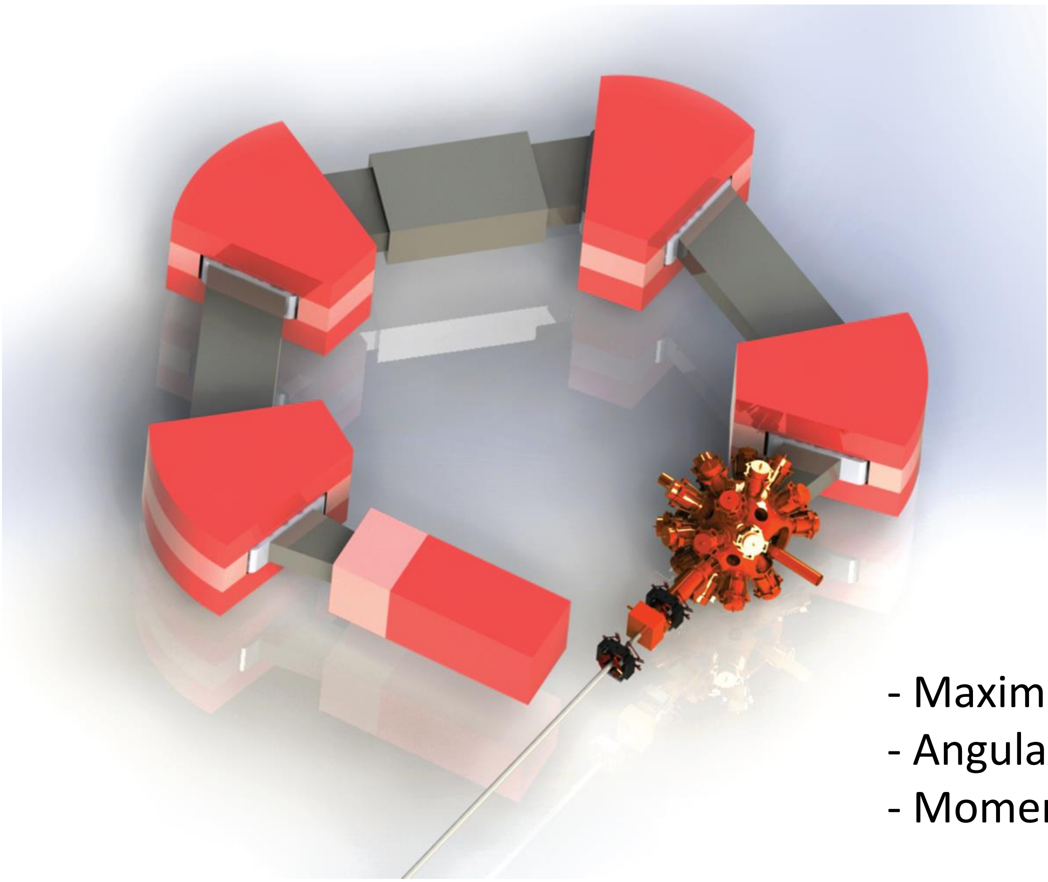


ISLA

Isochronous Separator with Large Acceptances

Recoil Separator for Rea12

White paper on the science case and proposed technical solution



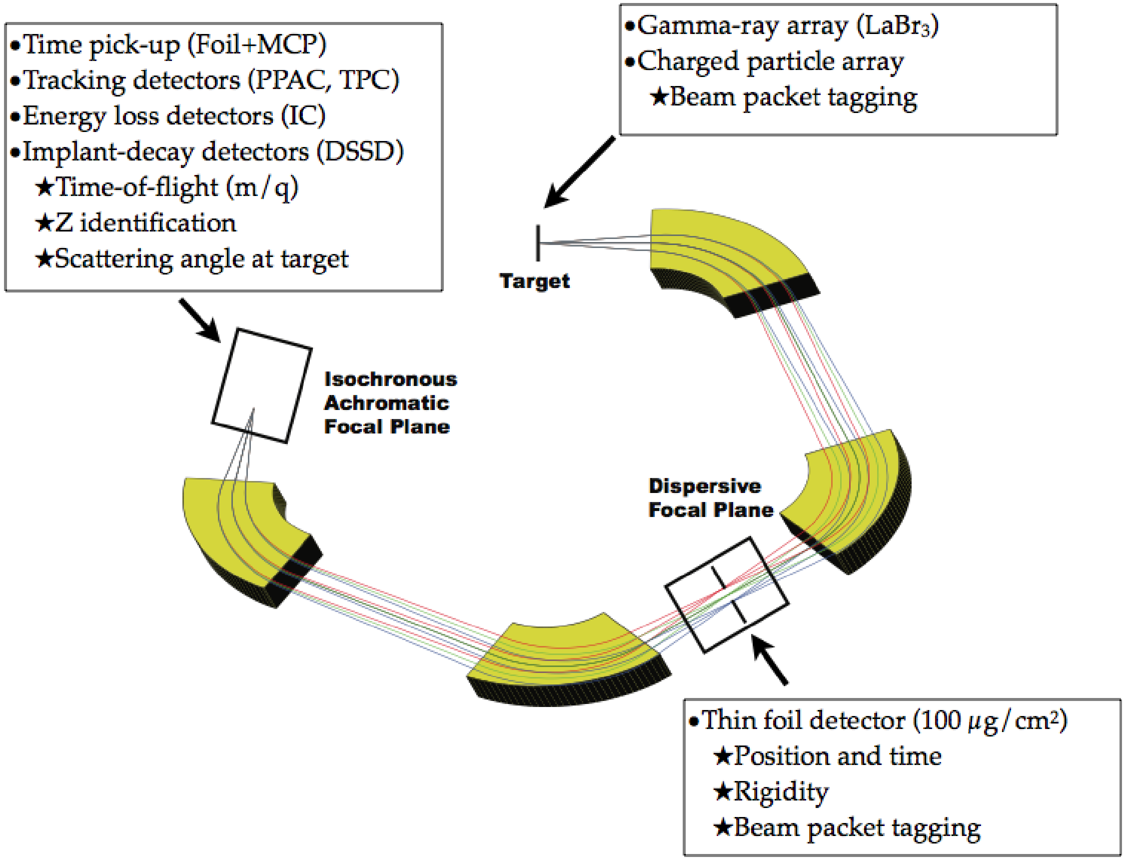
Multi-purpose separator for transfer, for deep-inelastic and for fusion evaporation reactions

Large acceptance separator with Relatively small image size (< 15 cm)

Vacuum-mode as well as gas-filled mode.

Moderate beam suppression

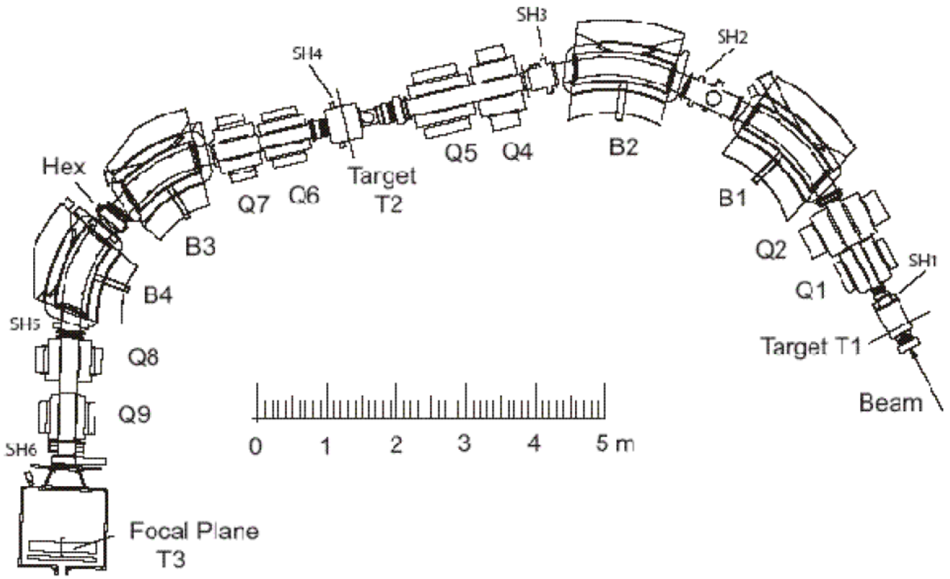
- Maximum Bρ 2.6 Tm,
- Angular acceptance 64 msr
- Momentun acceptance ± 10 %



- fusion-evaporation reactions
- high spin state population
- multi-nucleon transfer reactions to regions not accessible by fragmentation (neutron rich U isotopes, transuraniums, neutron rich nuclei below 208Pb,…)
- direct reactions such as (d,p), (d,n), (p,t)
- direct heavy ion transfer reactions such as (7Li,4He), (12C,14C), 18O,16O)

Dual Magnetic Separator for TRIμP

G.P.A. Berg[1,2], O.C. Dermois, U. Dammalapati, P. Dendooven
M.N. Harakeh, K. Jungmann, C.J.G. Onderwater,
A. Rogachevskiy, M. Sohani, E. Traykov, L.Willmann, and
H.W. Wilschut



	Fragment Separator	Gas-filled Separator
Beam rigidity Bρ	3.6 Tm (Beam line)	3.6 Tm (*Section 1*)
Product rigidity Bρ	3.0 Tm (*Section 1* and *2*)	3.0 Tm (*Section 2*)
Solid angle, vert., horiz.	±30 mrad	± 30 mrad
Momentum acceptance	± 2.0 %	± 2.5 %
Resolving Power p/dp	≈ 1000	≈ 2000 (no gas filling)
Momentum dispersion	3.9 cm/%	8.0 cm/%
Bending radius	220 cm	180 cm

THAN YOU FOR YOUR ATTENTION !