Recoil Separators for Nuclear Astrophysics studies

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10 years ago … in Canada

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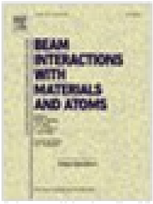


14th International Conference on Electromagnetic Isotope Separators and Techniques Related to their Applications

Recoil separators

Cary N. Davids

Recoil separators are devices which separate nuclear reaction products (recoils) leaving a target from the unreacted beam particles.

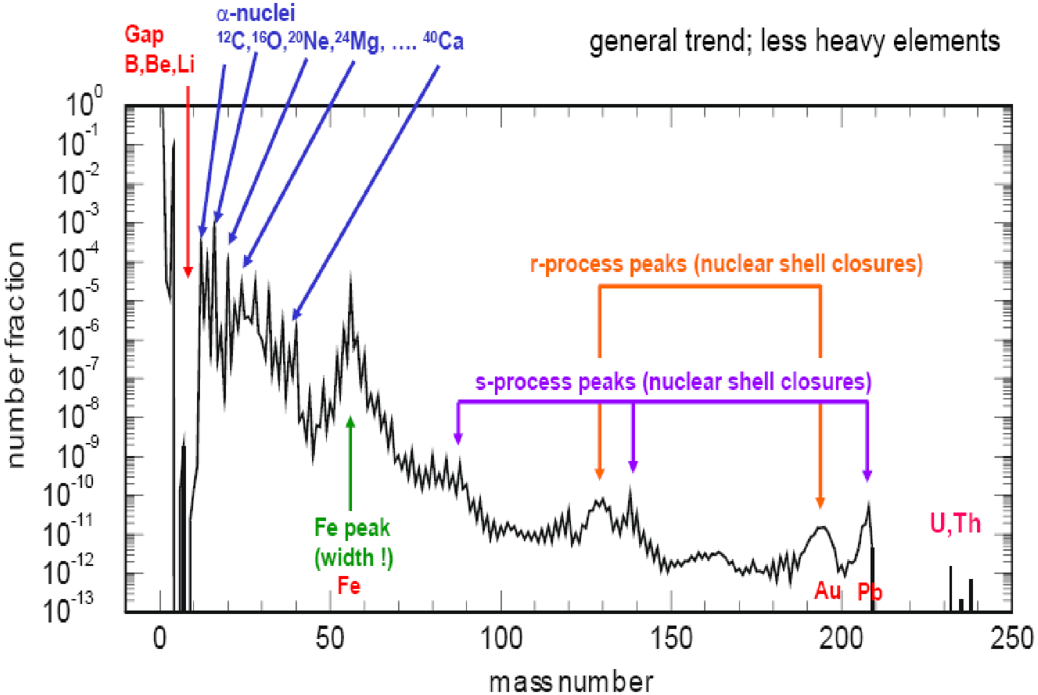
Recoil separators operating in the vacuum mode play a key role in a number of current research areas, including searches for superheavy elements, the study of nuclei far from stability and nuclear astrophysics. I will review some of these facilities, and will discuss ideas for improving the selectivity and efficiency of these devices.

Outline

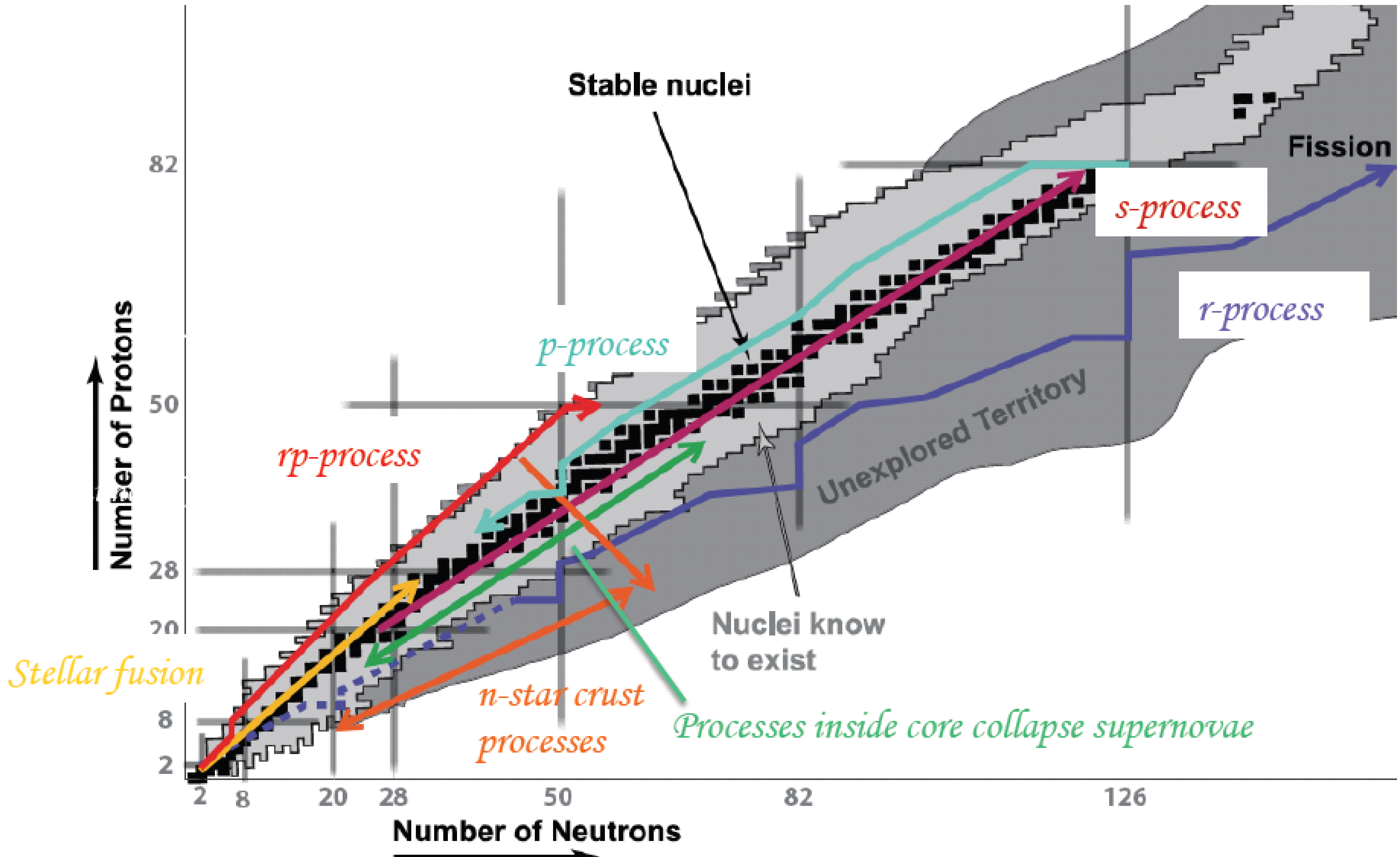
- Nuclear astrophysics
- Radiative capture kinematics
- Past, present and future of recoil separator dedicated to radiative capture
- Conclusions

Radiative capture and fusion reactions

- First step in chemical evolution of our universe
  - Big Bang nucleosynthesis
  - 500 million years later first generation of stars
  - Present star generation
- Charged particle reactions generate the seed and the fuel for nucleosynthesis processes building the elemental and isotopic abundance distribution as observed

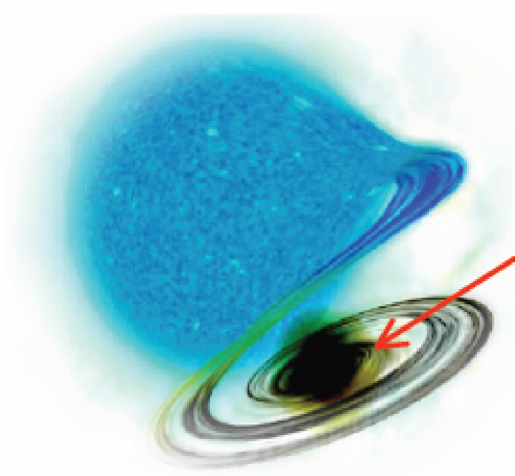


Stellar processes



From H. Schatz

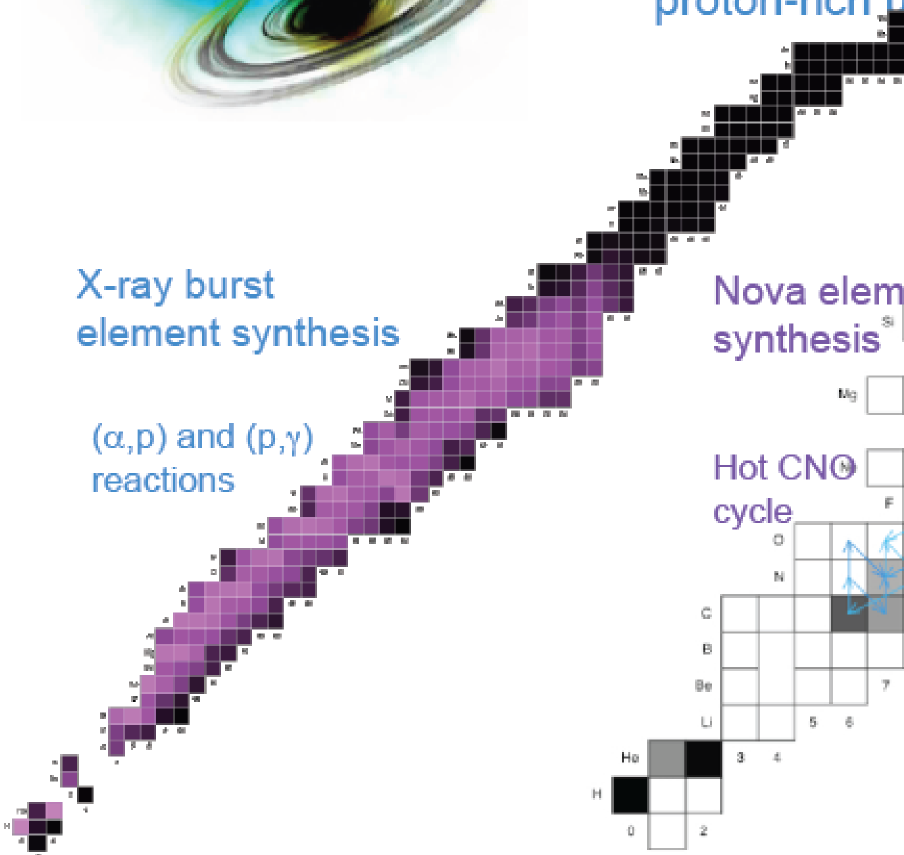
explosive nucleosynthesis - novae & X-ray bursts

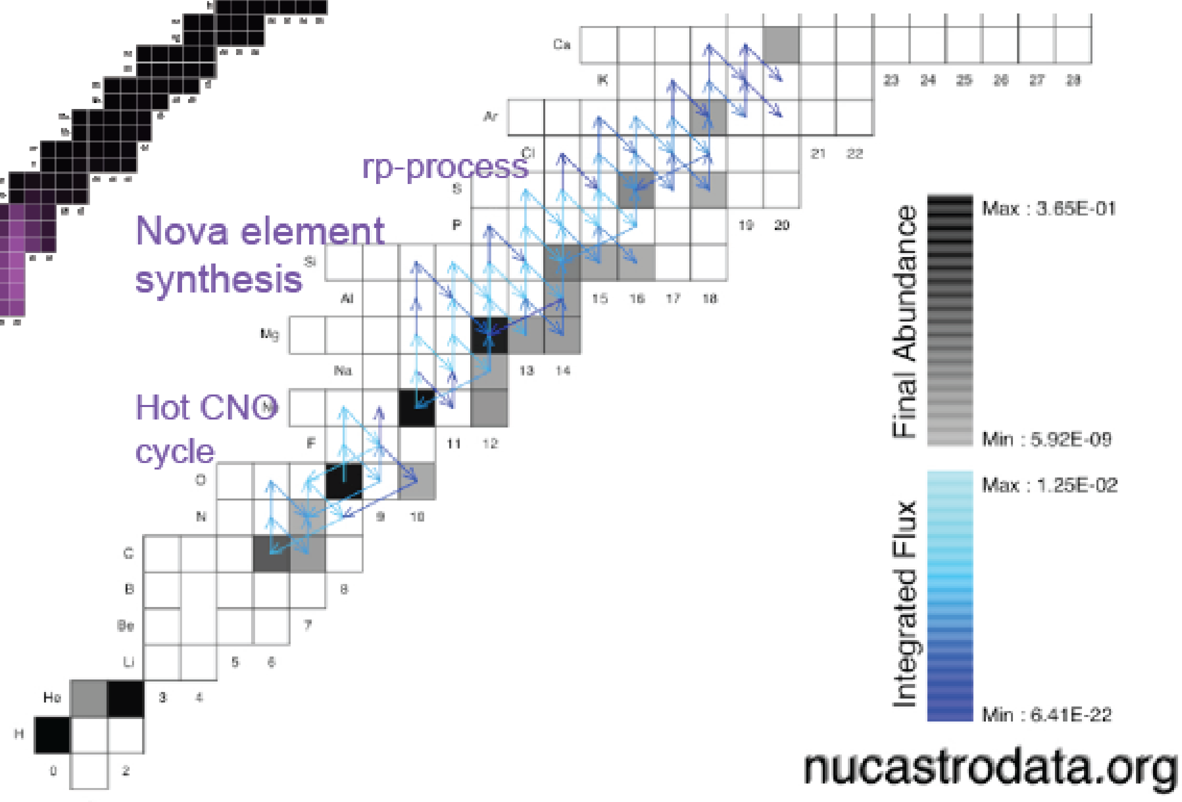


thermonuclear explosions on the surfaces of
white dwarf stars (novae)
neutron stars (X-ray bursts)

release 10^{45} ergs in visible, gamma rays, X-rays …

powered by [unmeasured] nuclear fusion reactions on proton-rich unstable isotopes





nucastrodata.org

Slide from D. Bardayan

Some interesting reactions

$^{12}C(\alpha,\gamma)^{16}O$ Holly grail of Nuclear Astrophysics, determine the ratio of $^{12}C/^{16}O$ after Helium burning as well as abundance of elements after subsequent evolution

$\Delta\theta=\pm31$mrad mrad $\Delta E=6.5\%$ (~100pμA)

$^{15}O(\alpha,\gamma)^{19}Ne$ triggers X-ray burst and contribute to determine their light curve

$\Delta\theta=\pm17$ mrad $\Delta E=3\%$ (~10^{11} part/s)

$^{13}N(p,\gamma)^{14}O$ first reaction involving radioactive beam, triggered the development of recoil separators to study radiative capture

$^{18}O(\alpha,\gamma)^{22}Ne$ populate one of the two main ingredient for production of neutron in the s-process

$\Delta\theta=\pm40$ mrad $\Delta E=7.4\%$

Radiatiative capture reaction studies

- Center of mass energies
  - (α,γ): ~0.01 MeV to ~15 MeV
    - (experimentally ~0.3 MeV to …)
  - (p,γ): ~0.01 MeV to ~4 MeV
    - (experimentally ~0.2 MeV to …)
- Direct kinematics
  - With stable ions (^{1}H and ^{4}He beams)
    - Exclusively detection of the gamma's
- Inverse kinematics
  - Coincidence between gamma's and recoil
  - Stable (to improve efficiency and signal to background ratio)
  - Radioactive beams
    - Recoil separator

Inverse kinematics

- Beam and recoil charge state distribution after target
  - ~30-50% maximum total efficiency
  - Other charge state can be source of background
    - See Dave Hutcheon talk at 15th EMIS

- $\overrightarrow{p_b} = \overrightarrow{p_R} + \Sigma\overrightarrow{p_{\gamma_i}}$
  - in first approximation recoil momentum = beam momentum

- Critical quantities:
  - $\Delta M/M$
  - Angular and energy acceptance
  - Rejection (~at least 10^{-3} * reaction rate)

Transmission requirements

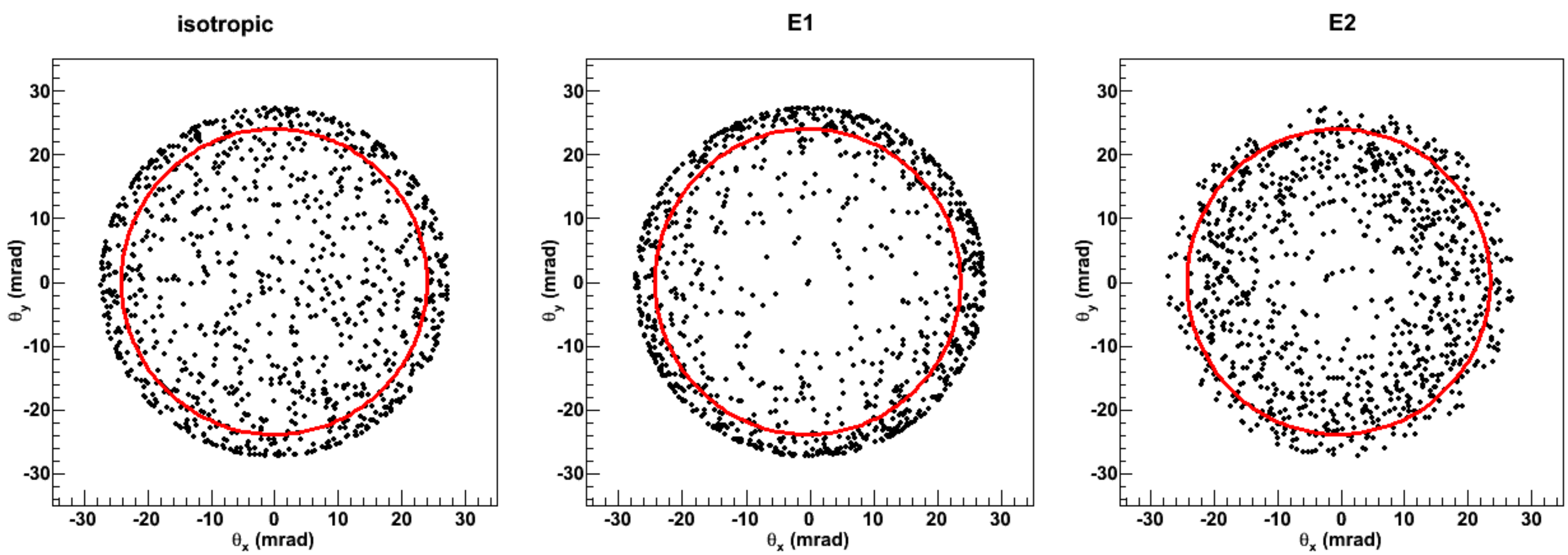


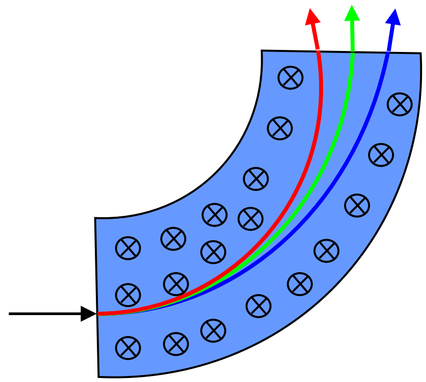
Figure 1 Distribution of recoils in the θ_x, θ_y space for $^{12}C(\alpha,\gamma)^{16}O$ ground state transition at E = 1.0 MeV. For different γ-ray angular distributions. Left: isotropic. Center: $\sin^2\theta$. Right: $\sin^2\theta\cos^2\theta$. For reference, a circle shows an angular acceptance of 24 mrad. See text for details.

For absolute cross section, full transmission of the selected charge state is needed

Attempt at FMA to study $^{13}C(p,\gamma)^{14}N$ and $^{18}O(p,\gamma)^{19}F$ and $^{18}F(p,\gamma)^{19}Ne$ but limited in transmission

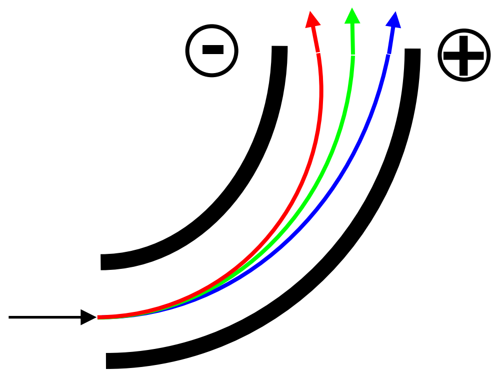
From: PoS(ENAS 6)058

Combination of two elements



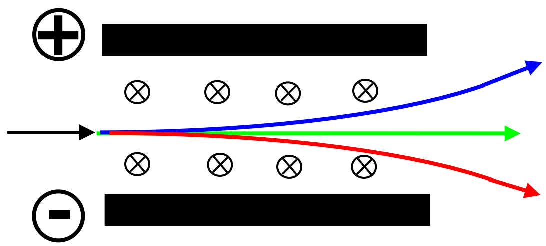
magnetic dipole

$$\frac{p}{q} = B\rho$$



electric dipole

$$\frac{2E}{q} = U\rho$$



Wien filter

$$v_0 = \frac{U}{B}$$

Dipole magnet cancels either E/Q or velocity dispersion to achieve M/Q dispersion

Drawings from D. Schürmann

Mass separation

First order spot size

The width of the recoil spot at the mass selection slits

$$x_1 = x_0(x|x) + a_0(x|a) + \tfrac{\delta E}{E}(x|\delta E) + \tfrac{\delta m}{m}(x|\delta m)$$

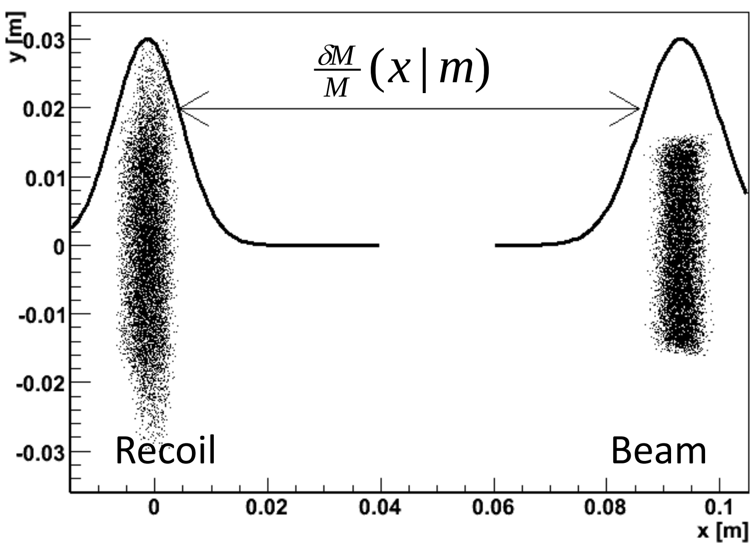
Magnification

=0 we want a focus

=0 we want an achromatic focus

$^{18}O(\alpha,\gamma)^{22}Ne$ @ 2. MeV

Spot size is due to magnification



DEDICATED DEVICES

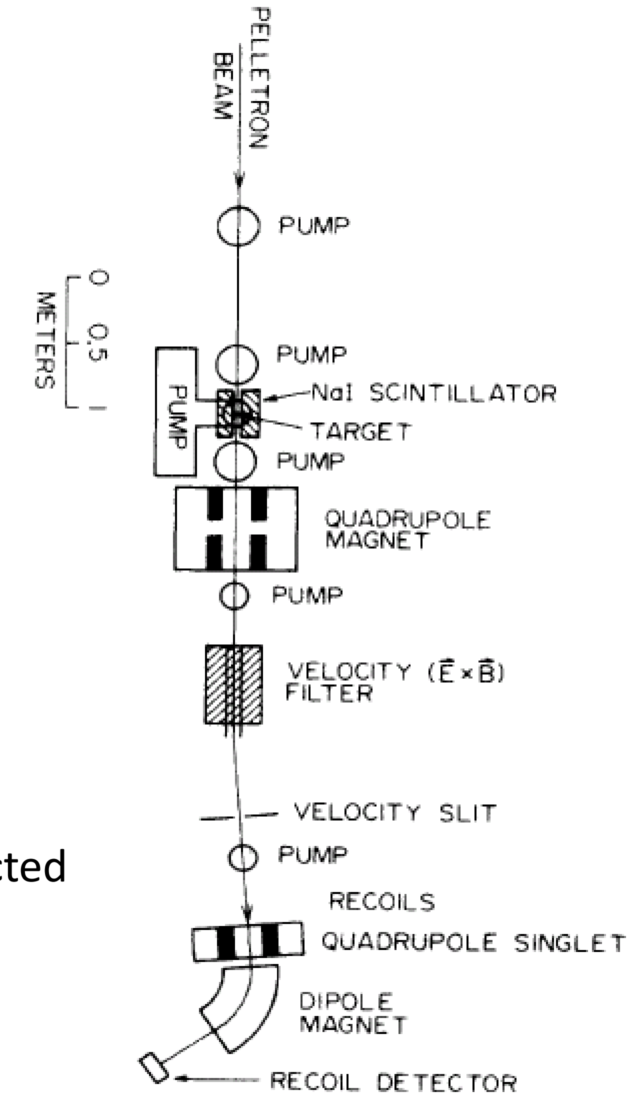
CTAG Caltech

The availability of post accelerated radioactive beams opened the door to direct cross section measurements

For example the ^{13}N beam of Louvain-la-Neuve allowed the study of $^{13}N(p,\gamma)$ in inverse kinematics

At Caltech, a recoil separator was constructed out of existing elements of the accelerator lab to demonstrate the feasibility of a recoil separator

$^{13}C(p,\gamma)^{14}N$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{12}C(\alpha,\gamma)^{16}O$

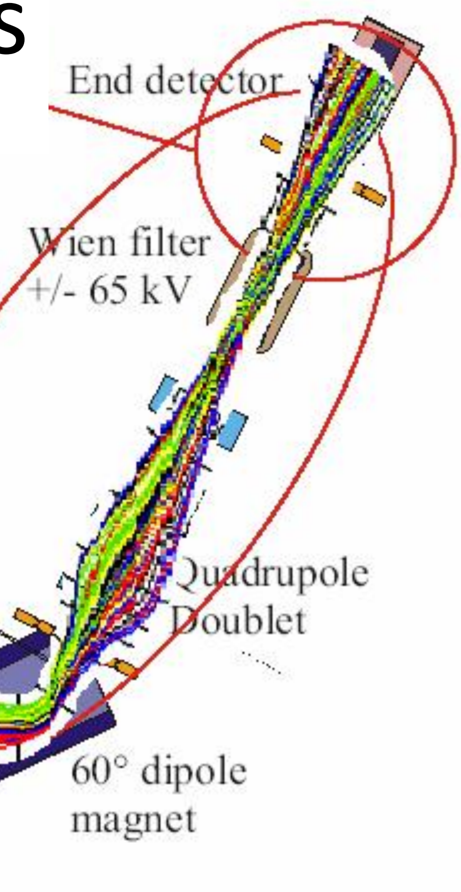


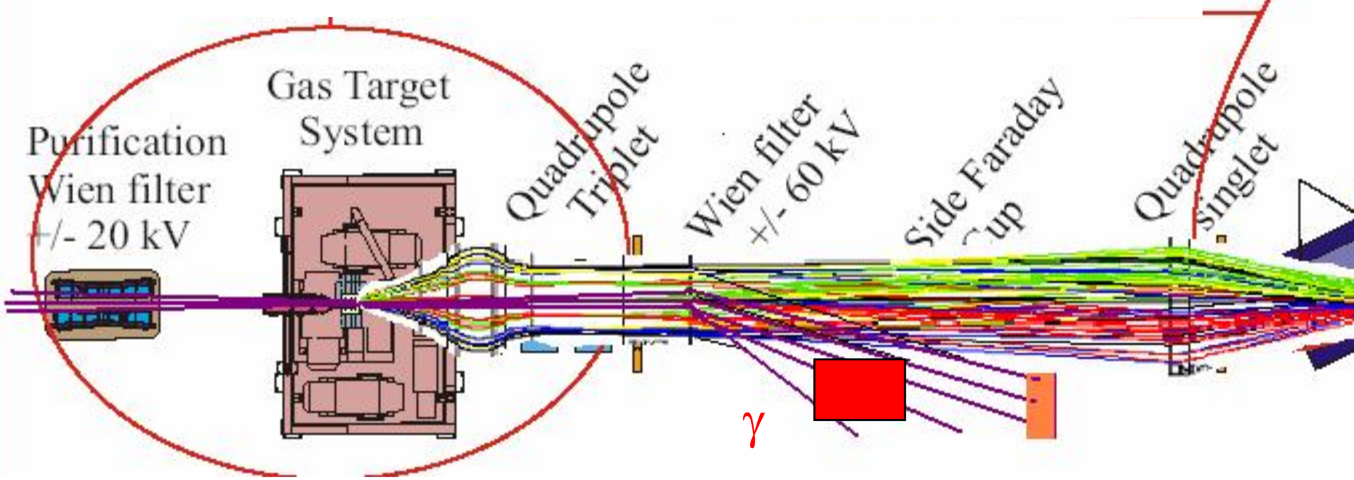
Beam undeflected

ERNA Separator

European Recoil separator for Nuclear Astrophysics

NABONA in Naples study $^{7}Be(p,\gamma)^{8}B$
Parts moved to Bochum (Germany)
Addition of Caltech Wien filter-> ERNA
Dedicated to the study of $^{12}C(\alpha,\gamma)^{16}O$





ERNA at the DTL, Bochum,

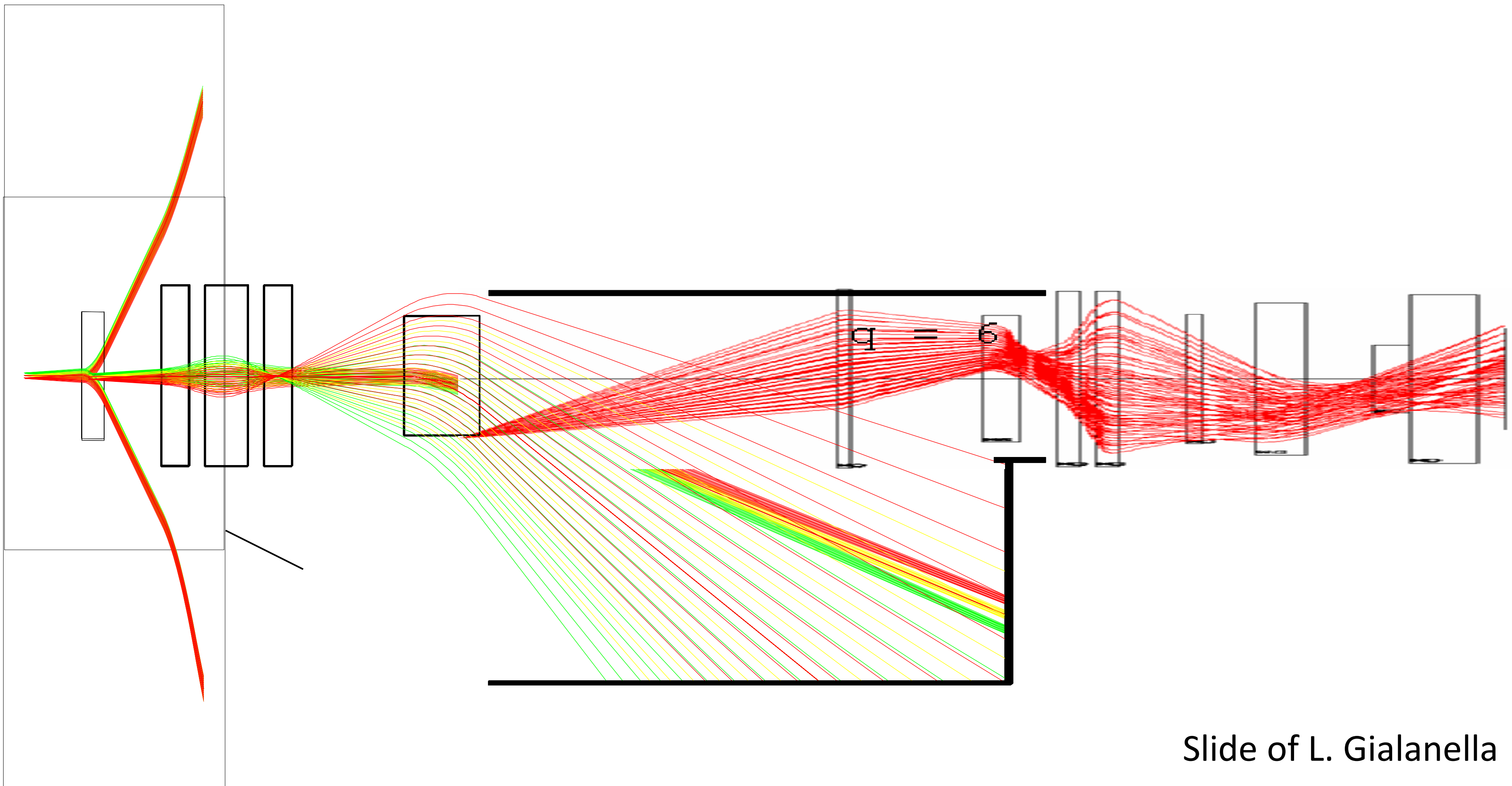
- angular acceptance ± 32 mrad
- energy acceptance ± 10%

For ^{16}O at E_{lab}=3.0 – 15.0 MeV

Adapted from a slide of L. Gialanella

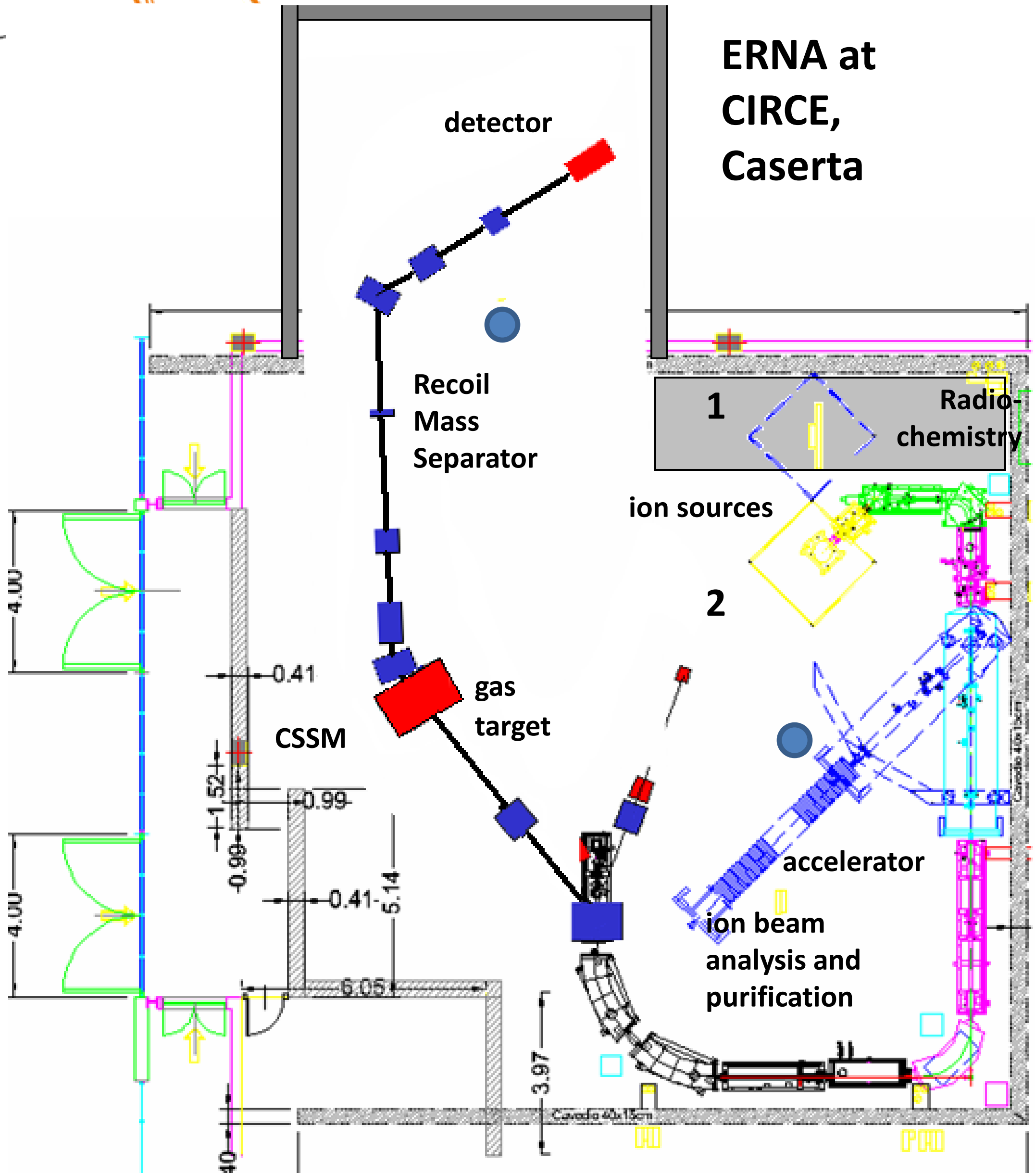
Other charge state and background

Background and leaky beams



Slide of L. Gialanella

ERNA at CIRCE, Caserta



3MV Pelletron

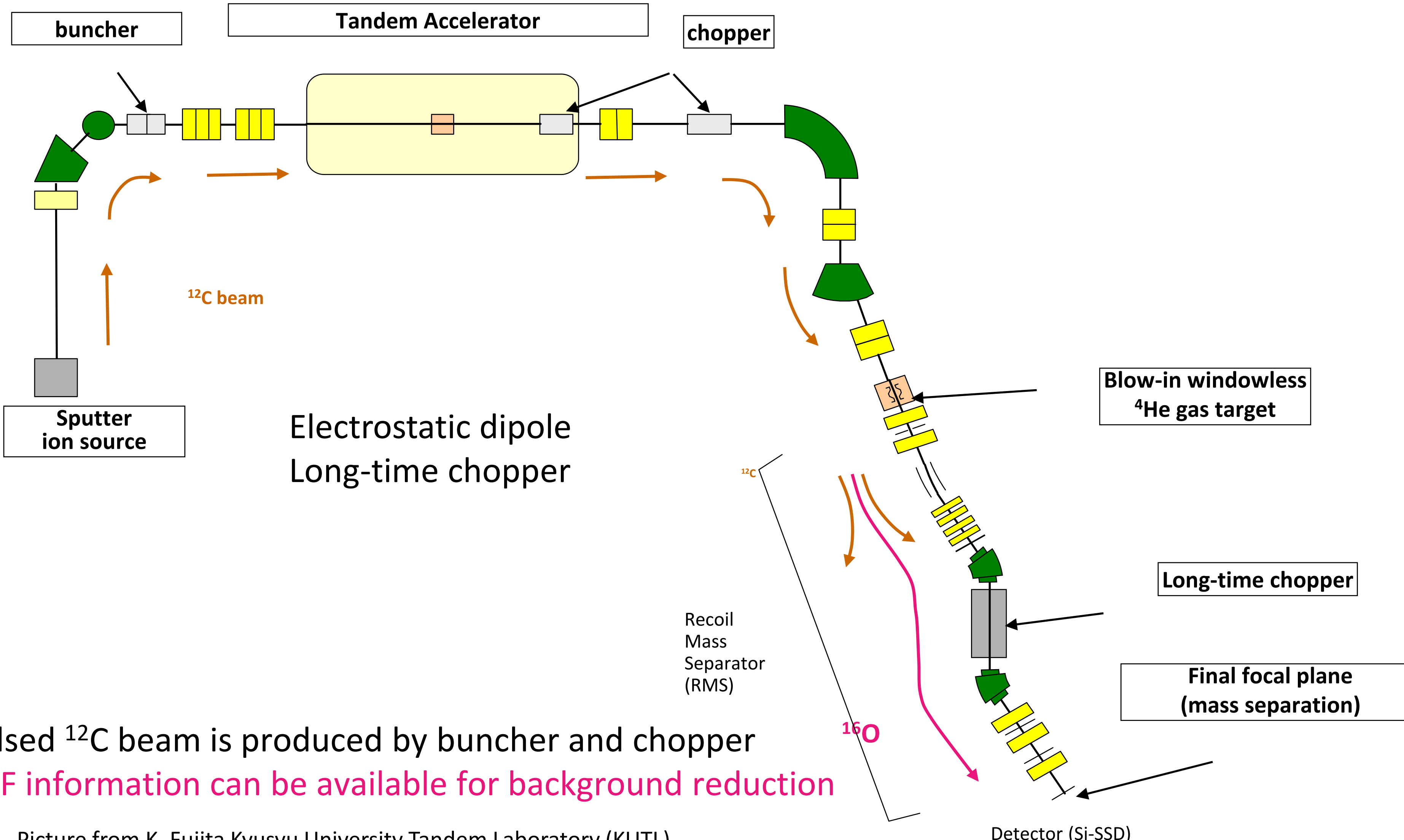
High intensity stable and radioactive ($^{7,10}Be$) ion beams (possible ^{26}Al)

Plans:

- $^{7}Be(p,\gamma)^{8}B$
- $^{12}C(\alpha,\gamma)^{16}O$
- $^{16}O(\alpha,\gamma)^{20}Ne$
- $^{33}S(p,\gamma)^{34}Cl$
- $^{14,15}N(\alpha,\gamma)^{18,19}F$
- SHE in nature

Slide of L. Gialanella

Recoil separator in Kyushu



Electrostatic dipole
Long-time chopper

Pulsed ^{12}C beam is produced by buncher and chopper

TOF information can be available for background reduction

Picture from K. Fujita Kyusyu University Tandem Laboratory (KUTL)

Recoil separator in Kyushu

$^{12}C(\alpha,\gamma)^{16}O$ at E_{CM}=2.4 MeV

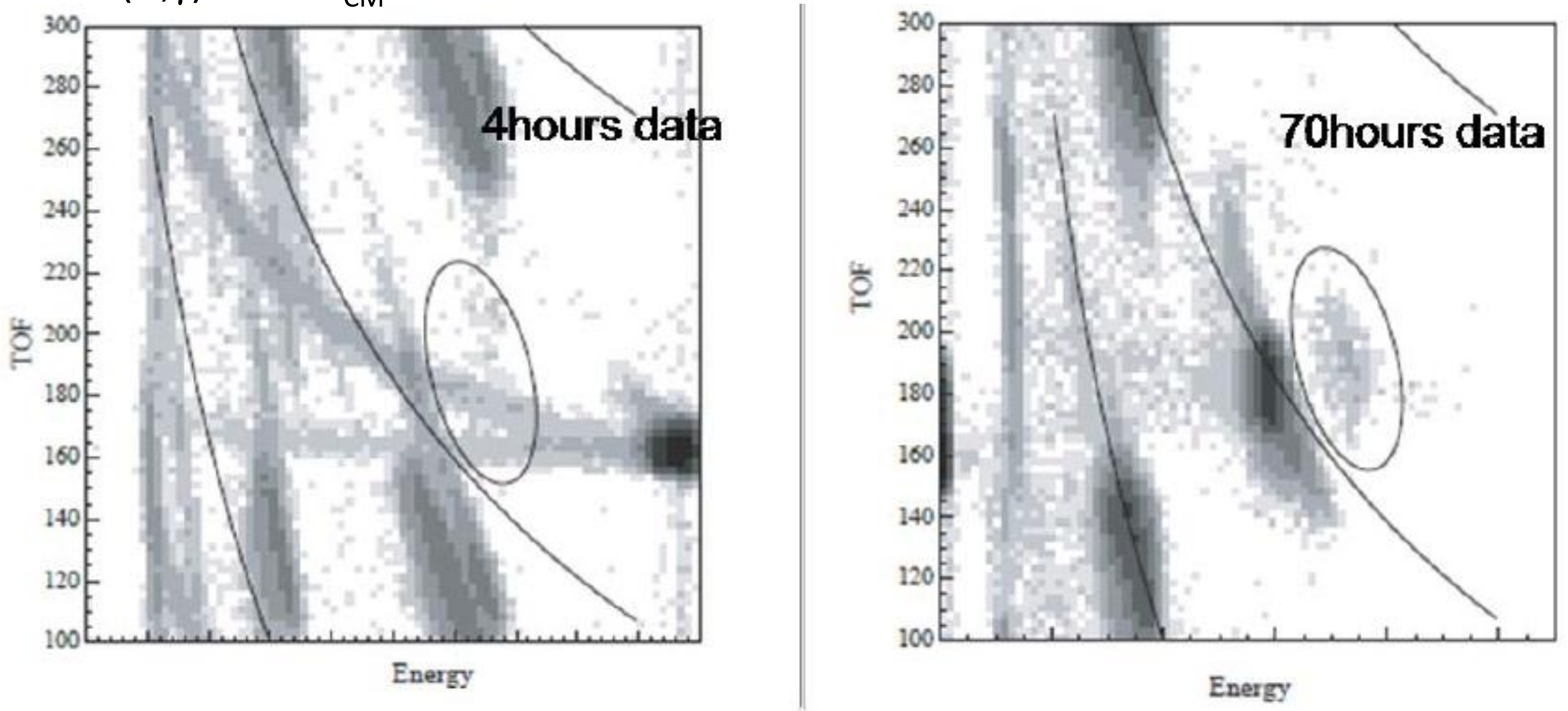


FIGURE 2. Energy – TOF spectra with (a) and without (b) the LTC.

LTC = Long Time Chopper

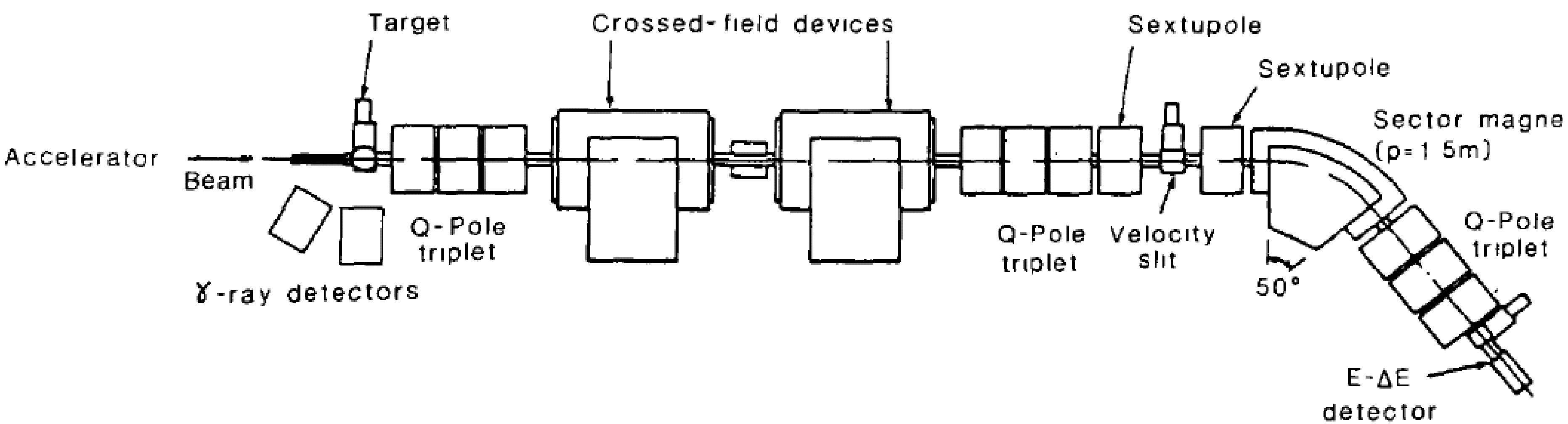
AIP Conf. Proc. 1238, 208 (2010)

Daresbury Recoil Separator DRS
ORNL - HRIBF

Angular Acceptance: 6.5 msr (+/- 45 mrad horizontal and vertical)
A/Q Acceptance: +/- 1.2 %
Velocity Acceptance: +/- 2.5 %
Energy Acceptance: +/- 5 %
A/Q resolution: 1/300
A/Q dispersion: 0.1 %/mm
Overall Length: 13 m

Radioactive beam !

Rejection ~10^8-10^{12}



MON1

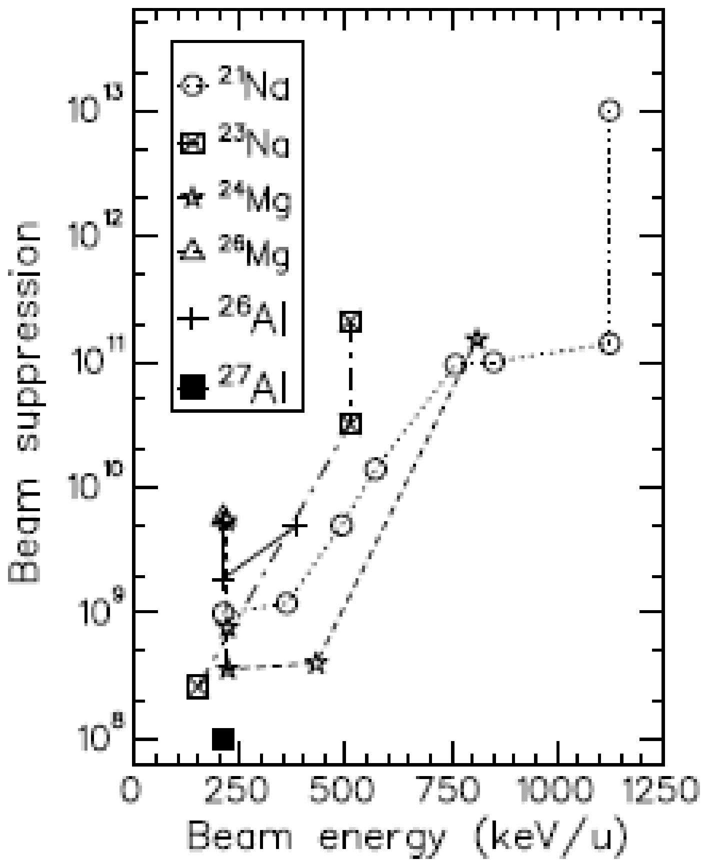


Fig. 2. Beam suppression by the DRAGON mass separator as a function of beam energy per unit mass. The separator was tuned for recoils from proton capture reactions.

NIMB 266 (2008) 4171

DETECTORS

Electric Dipole

Radioactive beam !

Two stages

Electrostatic dipoles
Rejection ~10^{10}-10^{13}

Last news:

- $^{4}He(^{3}He,\gamma)^{7}Be$

With rejection >10^{14}

- Conditioning ED up to +/-230kV

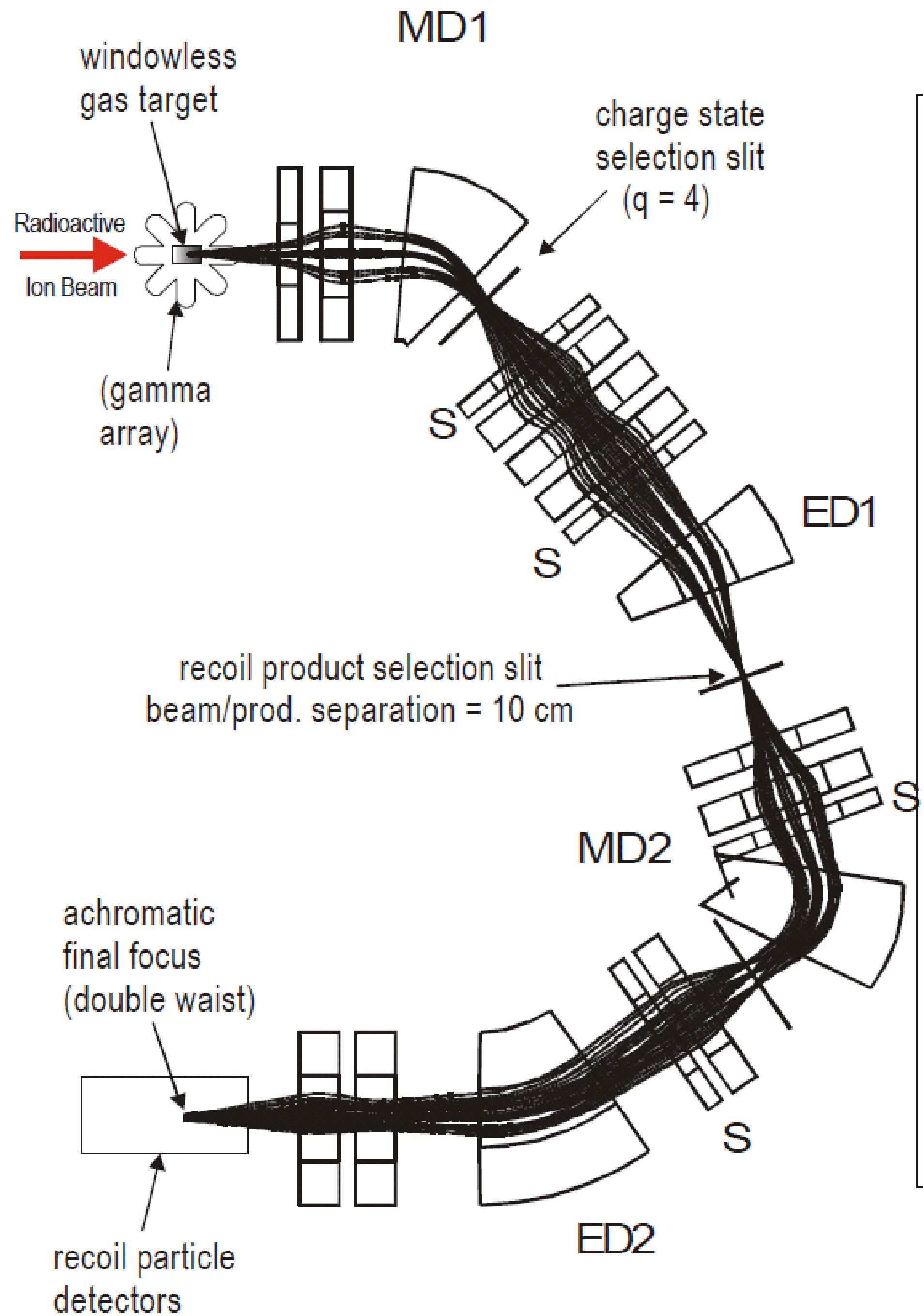
Some specs (for a $^{15}O(a,g)^{19}Ne$ tune):

Optical path length 20.4 m

Acceptance
- ang.: (+/-20 horiz. & +/- 25 vert.)
- velocity +/- 2 %

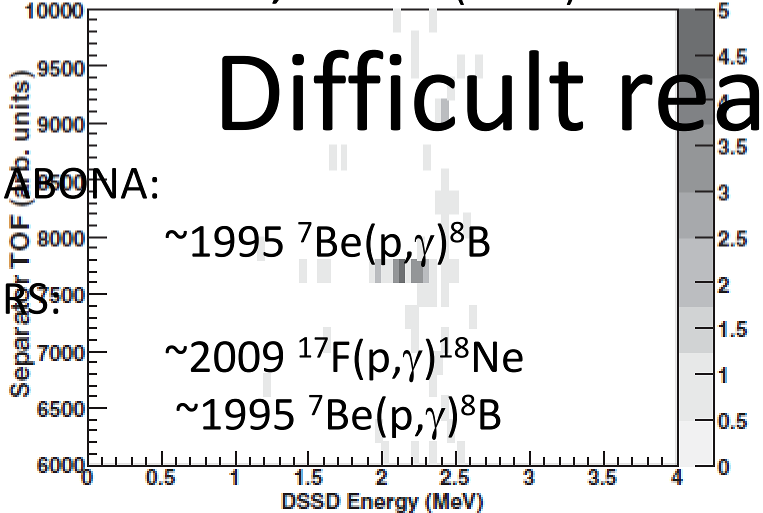
Resolving power:
200 at first stage
600 for second stage

Effective mass resolution:
~ 90 after 1st stage,
~ 200 after 2nd stage



Difficult reaction to study

PRL **96**, 252501 (2006)



NABONA:

~1995 $^{7}Be(p,\gamma)^{8}B$

DRS:

~2009 $^{17}F(p,\gamma)^{18}Ne$

~1995 $^{7}Be(p,\gamma)^{8}B$

DRAGON:

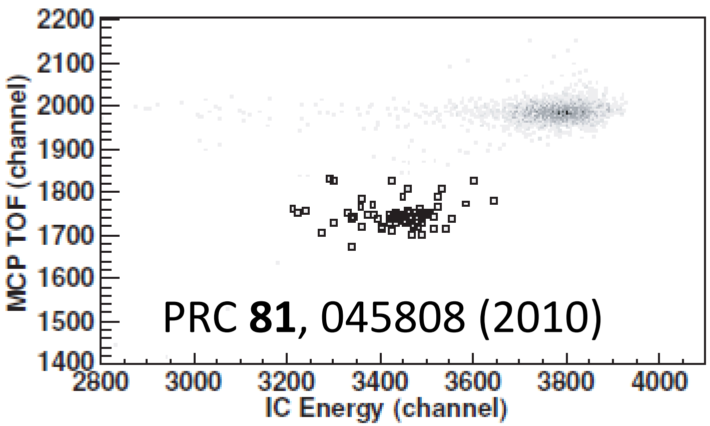
~2004 $^{21}Na(p,\gamma)^{22}Mg$

~2010 $^{23}Mg(p,\gamma)^{24}Al$

~2006 $^{26g}Al(p,\gamma)^{27}Si$

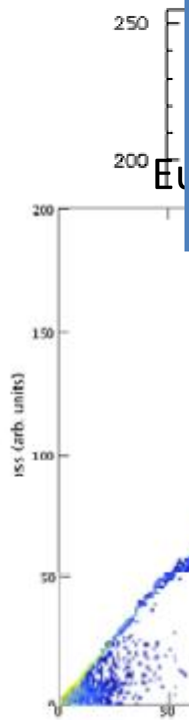
6 Radioactive beam induced radioactive capture studies in ~15 years !!!

A lot more induced by stable beams



PRC **81**, 045808 (2010)

FIG. 7. Local time-of-flight vs. total detected energy for singles recoil events at $E_{beam,lab} = 502A$ keV and $P_{targ} = 3.55$ mbar, with the gray density plot indicating all particles detected and the empty squares showing $A = 24$ recoils.



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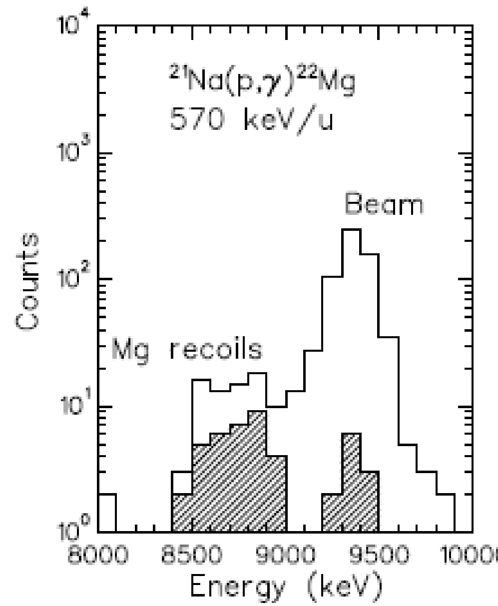
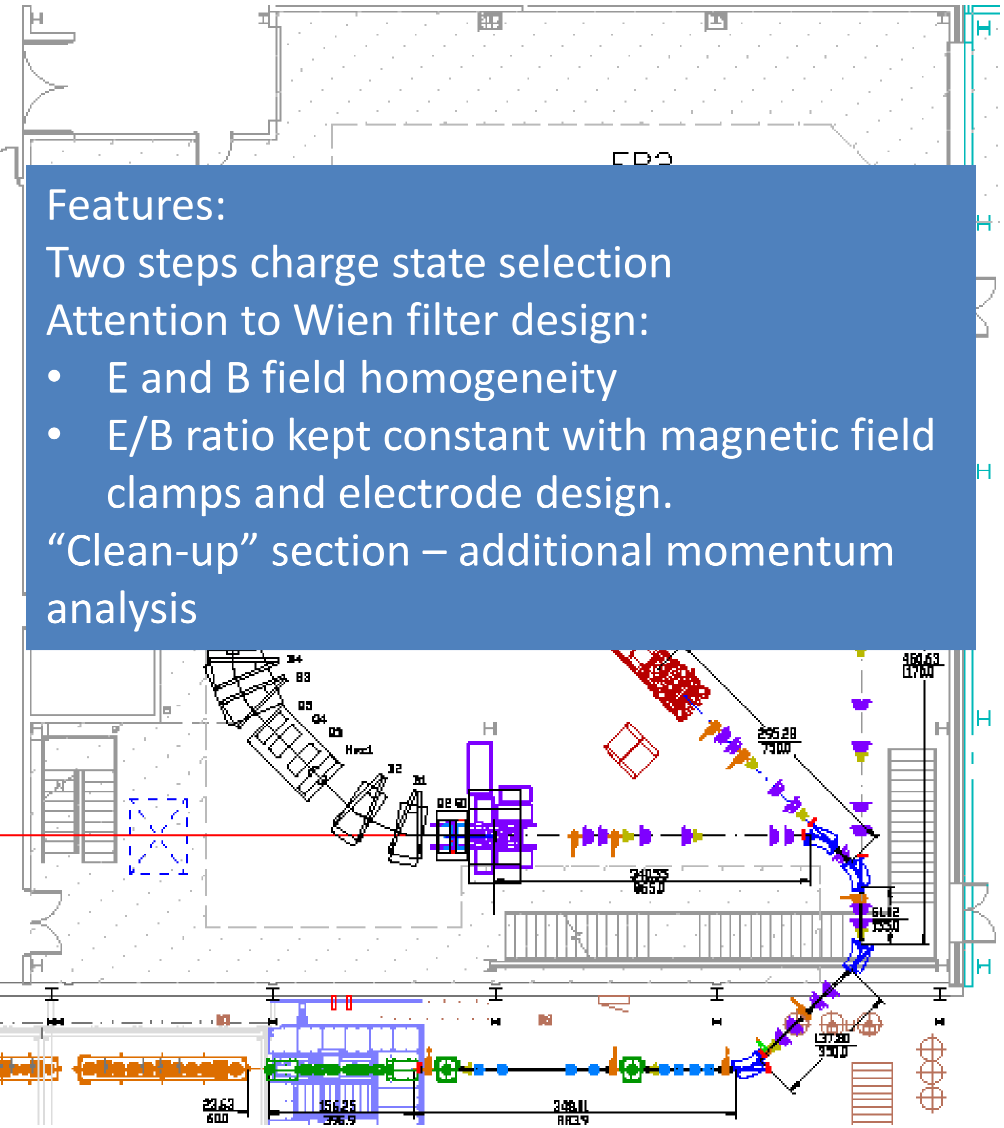


Fig. 3. Energy spectrum of recoil product and "leaky" beam for a proton capture experiment. The hatched areas indicate recoils detected in hardware coincidence with gamma rays.

SEparator for Capture Reaction



Features:
Two steps charge state selection
Attention to Wien filter design:
- E and B field homogeneity
- E/B ratio kept constant with magnetic field clamps and electrode design.

"Clean-up" section – additional momentum analysis

SECAR to be installed at ReA3

Radiative capture induced by radioactive beam

Based on design of St. George

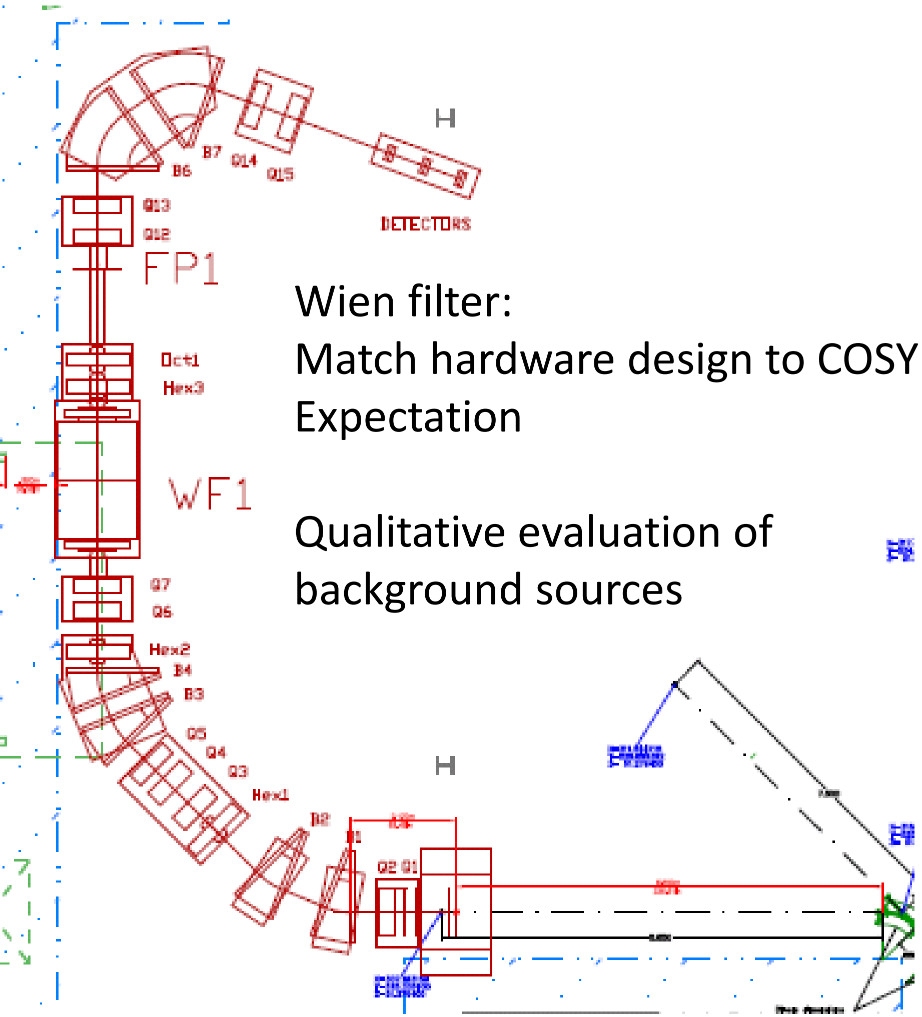
JENSA Gas Jet target: up to 10^{19}at/cm^2

Acceptance:	First stage:
θ= ±25mrad	Resolving power: 750
ΔE= ±3.1%	Mass resolution: **520**
15<A<65	
Bρ<=0.8 Tm	Second stage:
	Resolving power: 1330
	Mass resolution: **775**

Design: G.P.A. Berg, M. Couder

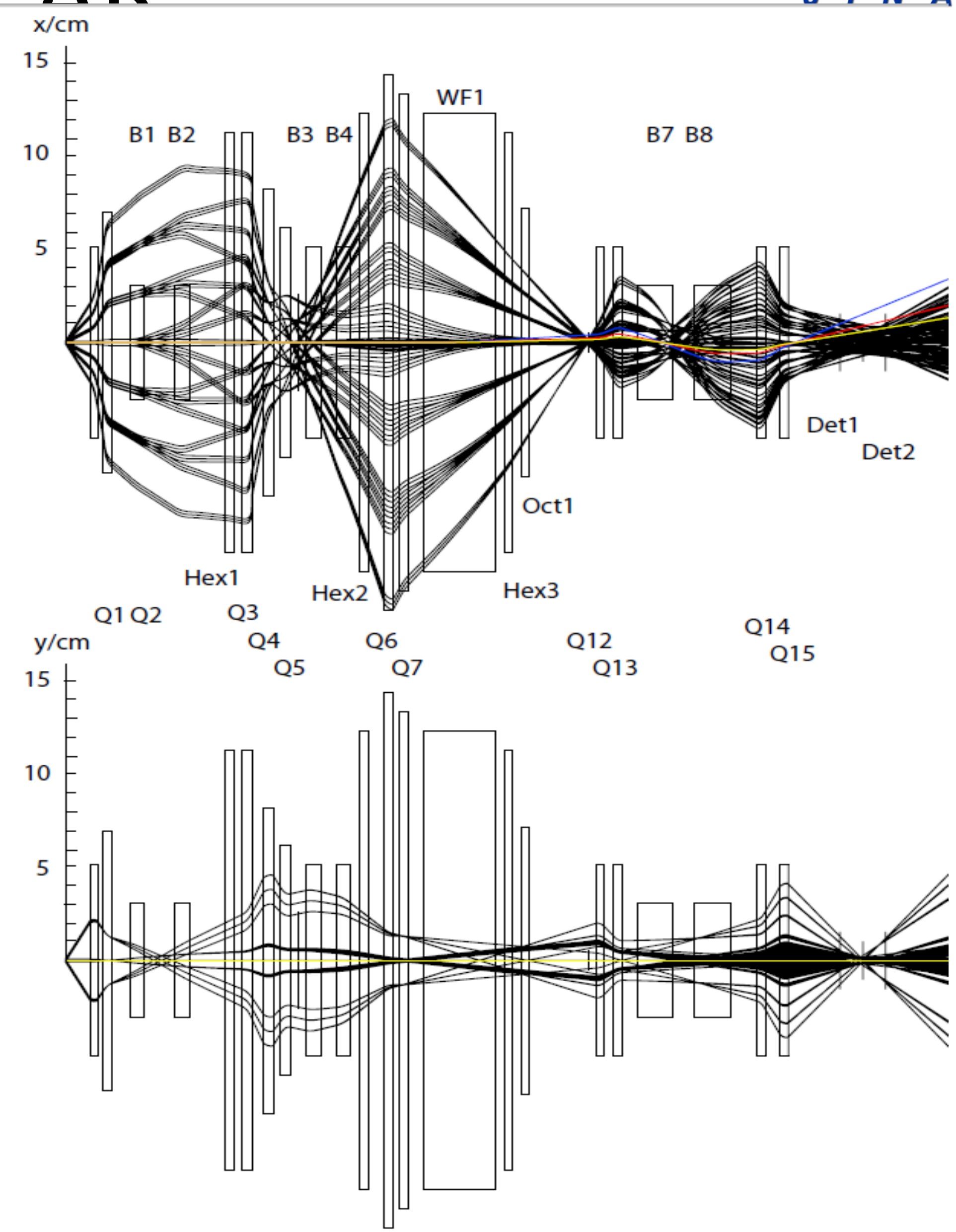
SECAR

Upgra



Wien filter:
Match hardware design to COSY Expectation

Qualitative evaluation of background sources

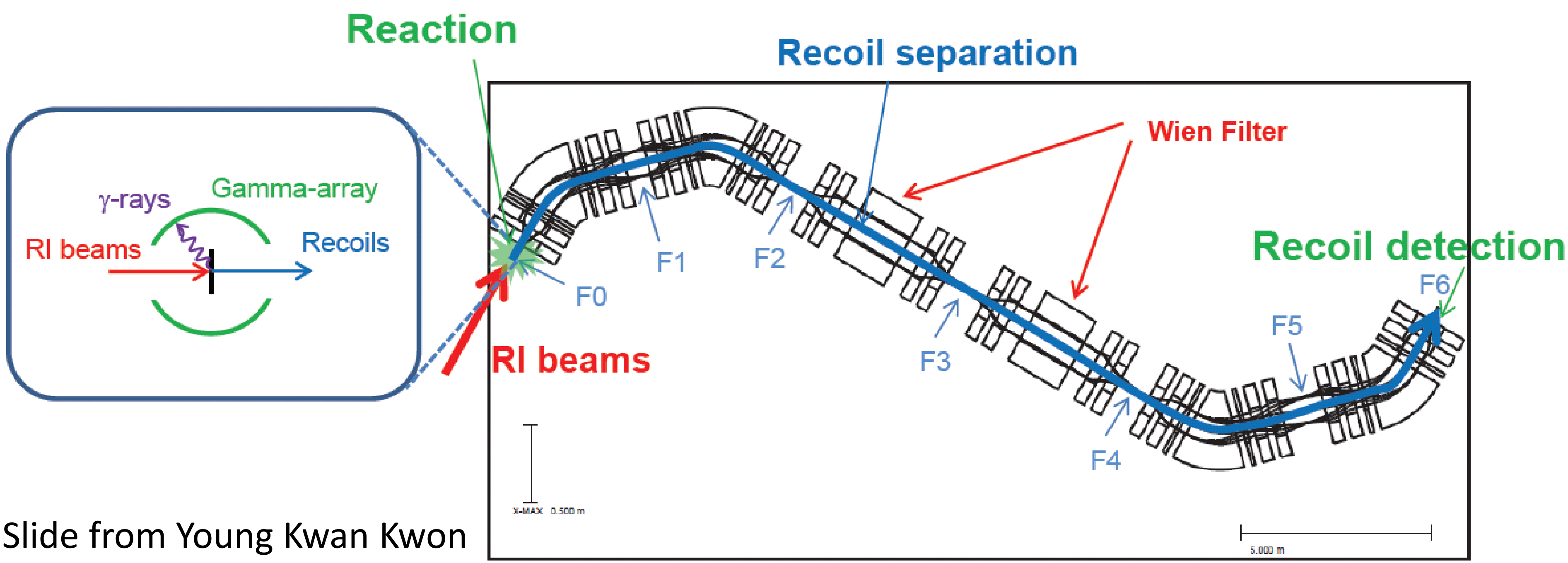


Rare Isotopes Science Project Korea

- Recoil separation with p-rich RI beams from ISOL system

  - radiative capture reactions : (p,γ), (α,γ) reactions
  - background reduction ~ 10^{-15}

  - gamma-array @ F0, recoil detection @ F6



Slide from Young Kwan Kwon

Summary

- Dedicated separator for radiative capture
  - Important tools for direct measurements of astrophysical interests
- Need stable beams to commission and tune
  - Can be used during fast beam operation
- Preliminary identification of resonance energy
- Did not mention target, detection system, diagnostics
  - They are critical
- ~25 years of separators dedicated for nuclear-astrophysics
  - Strong interaction between stable and RI Beam community
- New recoil separators are coming

Thanks !

- ERNA
  - Lucio Gialanella
  - Daniel Schürmann
- KUTL separator
  - Kenshi Sagara
- DRS
  - Daniel Bardayan
- DRAGON
  - Dave Hutcheon
- SECAR
  - Georg Berg