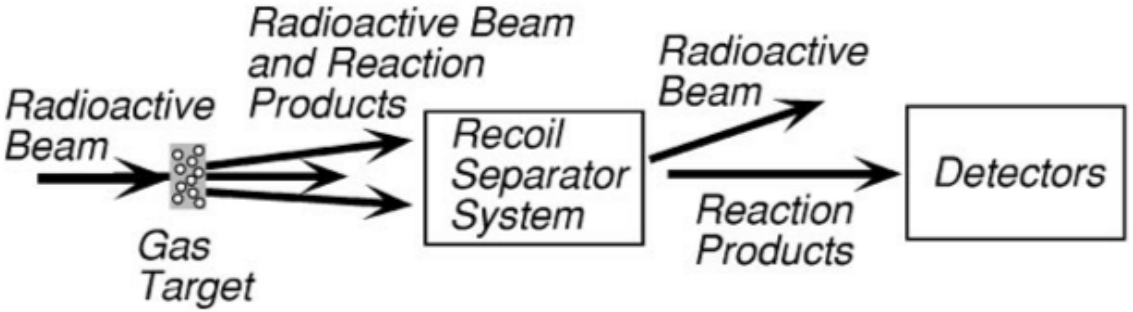
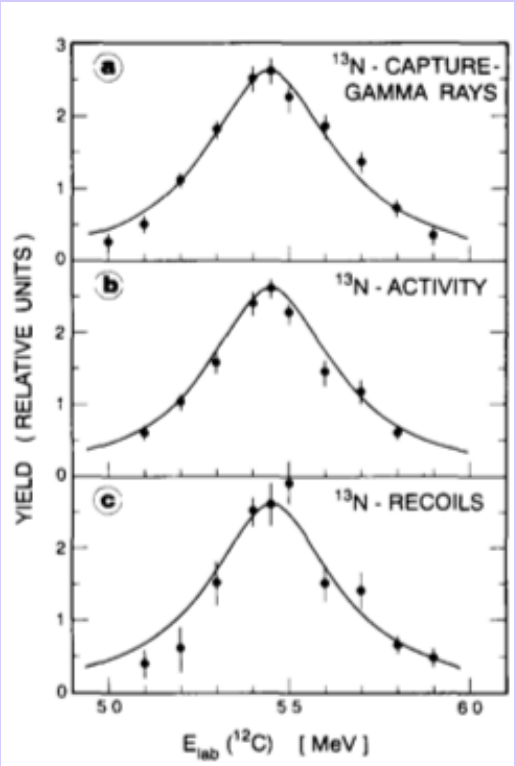
recoil separators





proof of concept with $^{12}C(p,\gamma)^{13}N$
Smith, Rolfs, Barnes NIMA306 (1991) 233

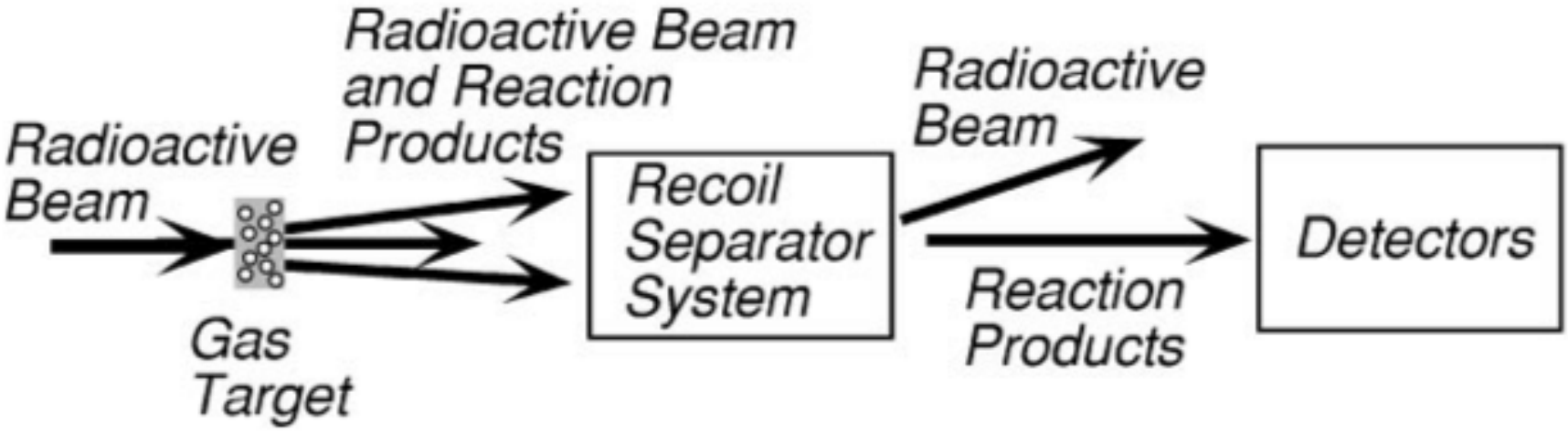
approach

- directly measure capture reactions with low-energy beams of radioactive nuclei incident on a H or He gas target

advantages

- directly obtain resonance strengths
- experiments are conceptually simple – just count the recoils
- high efficiencies possible with devices of modest acceptance
- detectors inexpensive compared to gamma arrays
- coincidence measurements possible for cleaner results

recoil separators



- radioactive beam incident on H or He gas target
- choose beam and target for an astrophysically important reaction
- directly measure **products** of thermonuclear fusion of beam and target nuclei
- heavy products are “recoils” -- need to be separated from unreacted beam particles

recoil separators

Nuclear Instruments and Methods in Physics Research A306 (1991) 233–239
North-Holland

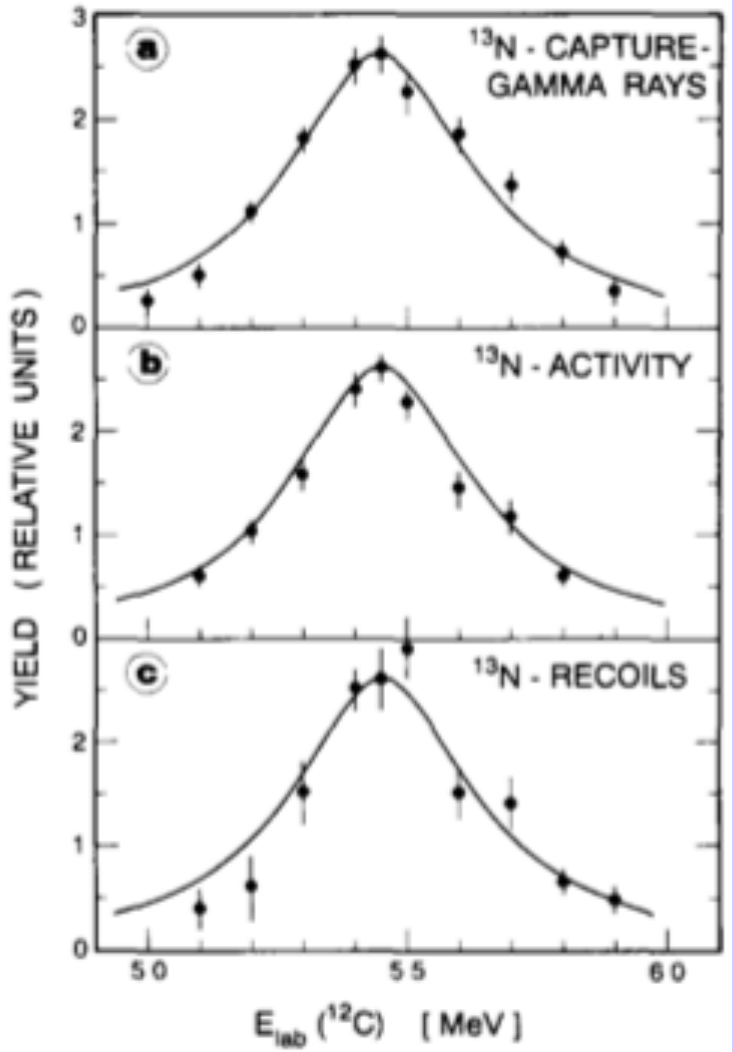
A recoil separator for use in radioactive ion beam experiments *

M.S. Smith, C. Rolfs [1] and C.A. Barnes
W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena CA 91125, USA

Received 1 March 1991

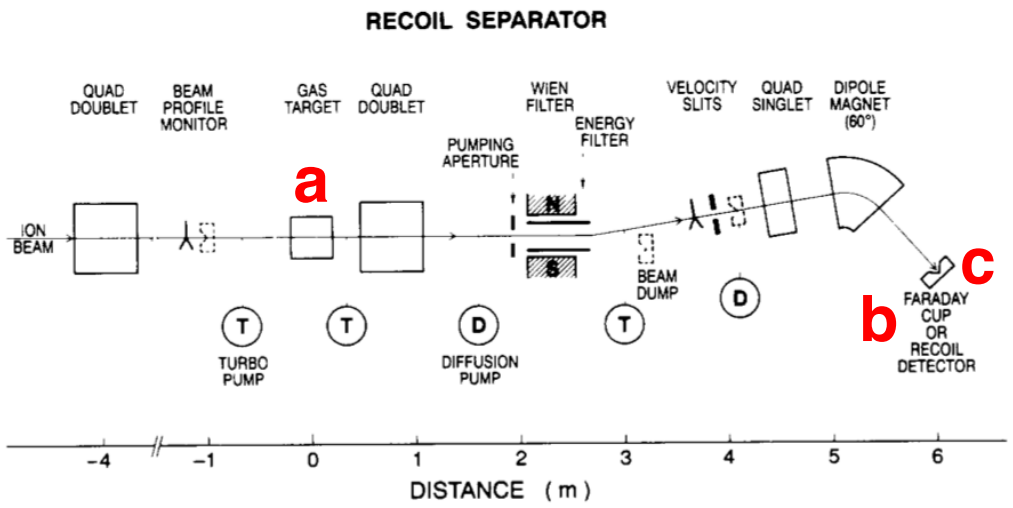
The effectiveness of a recoil separator for the measurement of radiative capture reactions at radioactive ion beam facilities has been examined. A system consisting of velocity, energy, and momentum filters was tested with the $^{1}H(^{12}C, ^{13}N)\gamma$ reaction at the $E_{cm} = 422$ keV resonance; excitation functions obtained with both the ^{13}N recoils and the capture gamma rays were compared. Projectile ^{12}C fluxes were measured directly with Faraday cups and indirectly with Rutherford backscattering into silicon detectors, while the ^{13}N recoil flux was measured directly with silicon detectors and indirectly by its residual radioactivity. A suppression of the ^{12}C beam particles by a factor of 10^{-10} was observed when the system was tuned for the recoil ^{13}N's. Possible improvements of the system are discussed.

proof of concept done with ^{12}C + p capture and small recoil separator



proof of concept with $^{12}C(p,\gamma)^{13}N$
Smith, Rolfs, Barnes NIMA306 (1991) 233

recoil separators

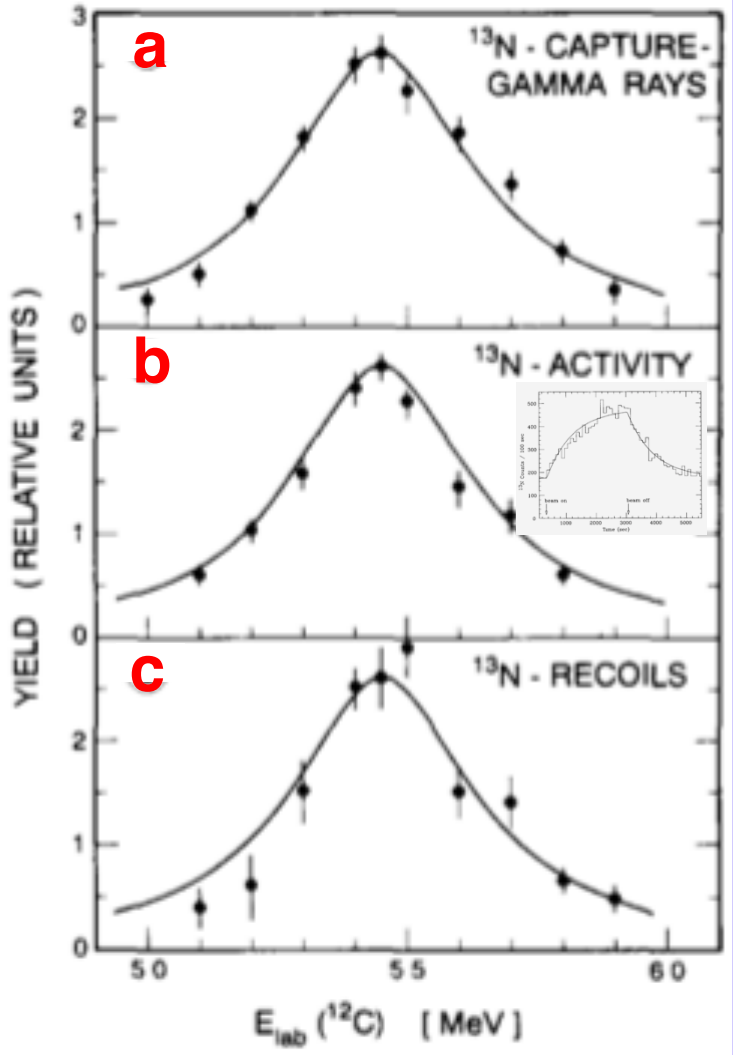


proof of concept done with ^{12}C + p capture and small recoil separator

direct detection of fusion products **c**

verified with detection of gamma rays **a**

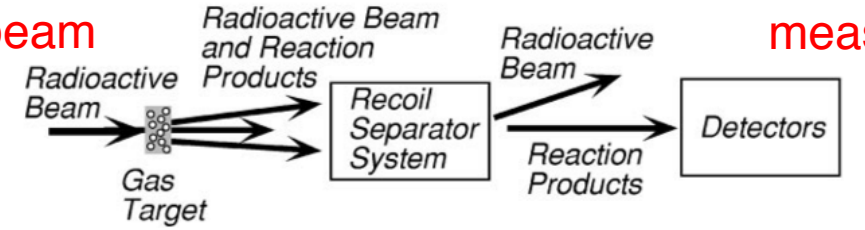
and delayed activity **b**



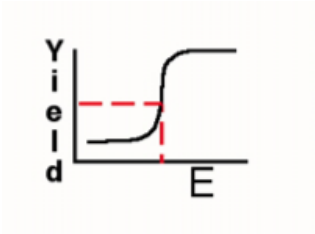
proof of concept with $^{12}C(p,\gamma)^{13}N$
Smith, Rolfs, Barnes NIMA306 (1991) 233

recoil separators - advantages

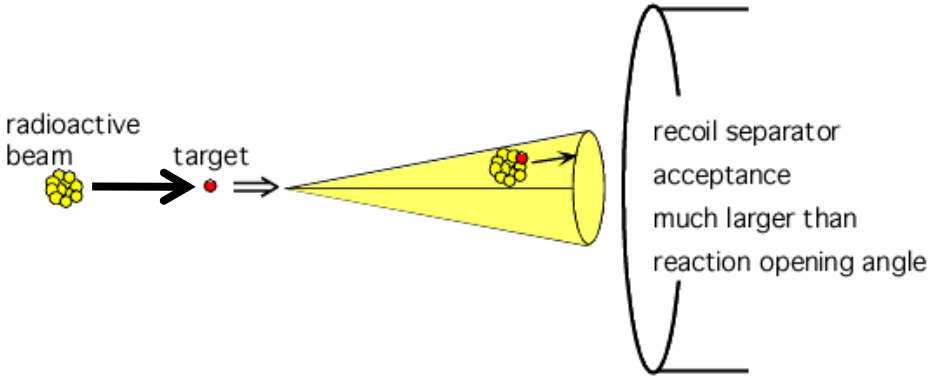
change beam energy



measure yield

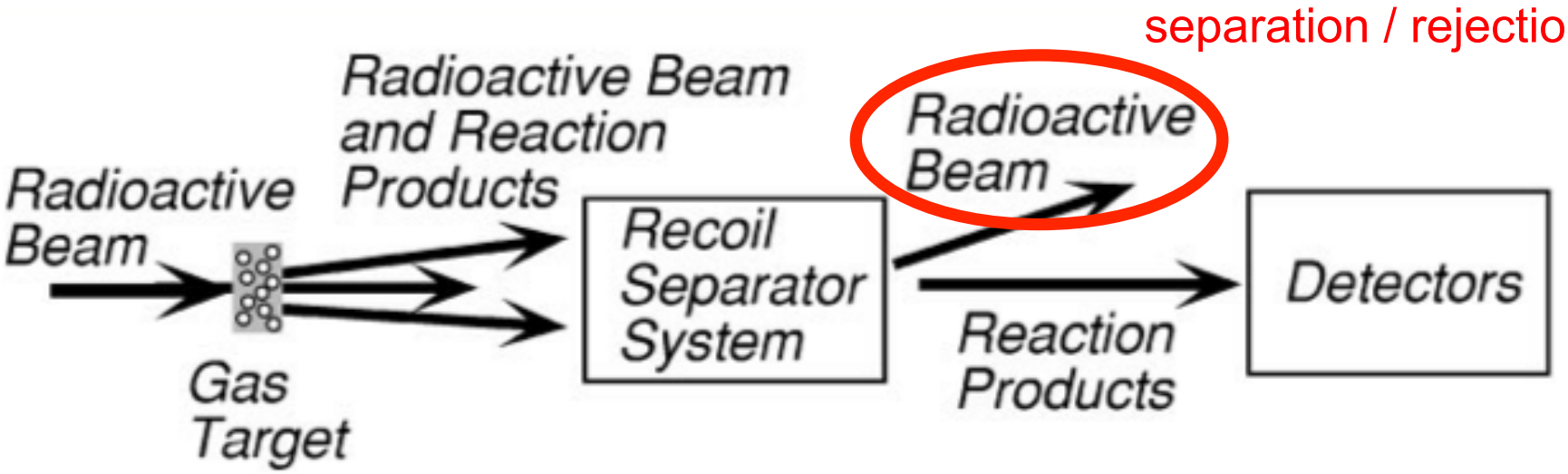


- directly obtain resonance strengths
- experiments are conceptually simple – just count recoils



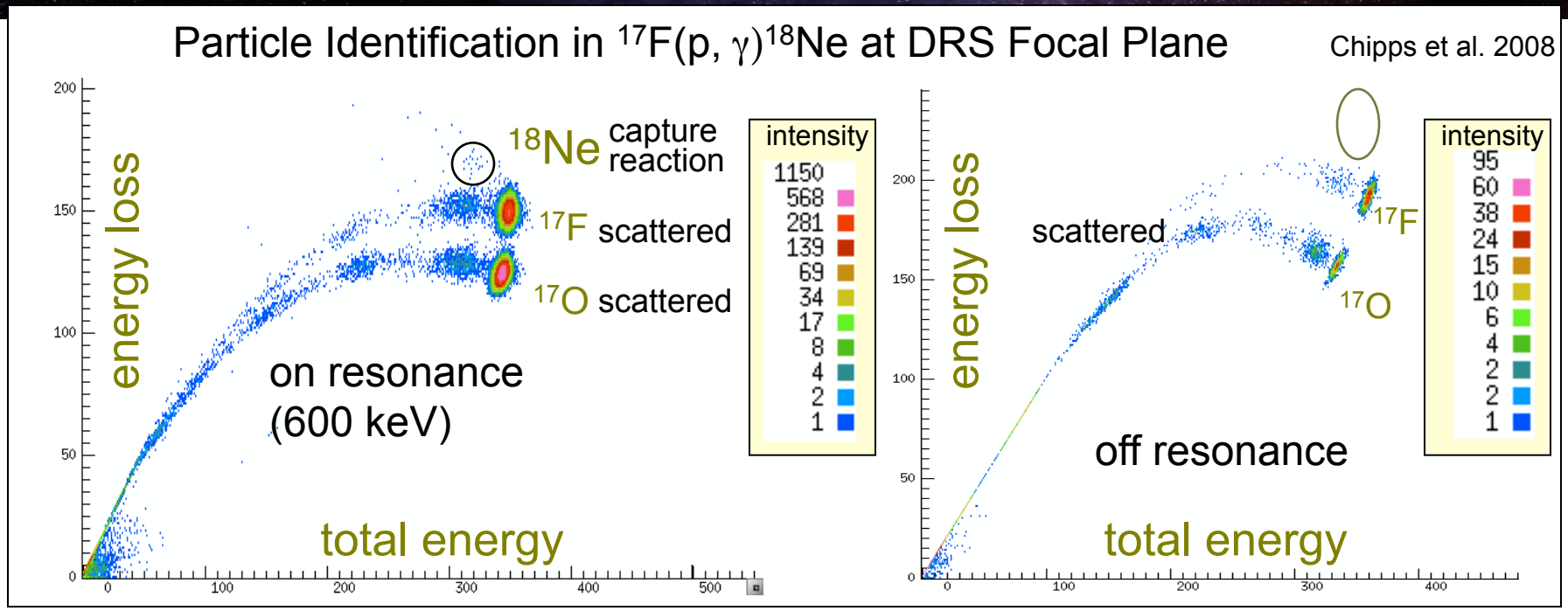
- forward focusing of recoils makes high efficiency measurements possible

recoil separators - challenges



- only 1 in ~ 10^{12} beam particles fuse with protons …**low yield, long experiments** !
- **unreacted beam particles** enter separator located along beam axis
- will reach the detectors unless actively separated and rejected [steered away]
- separation of recoils and unreacted beam particles very difficult – same momentum, small mass difference, same or similar electrical charges …

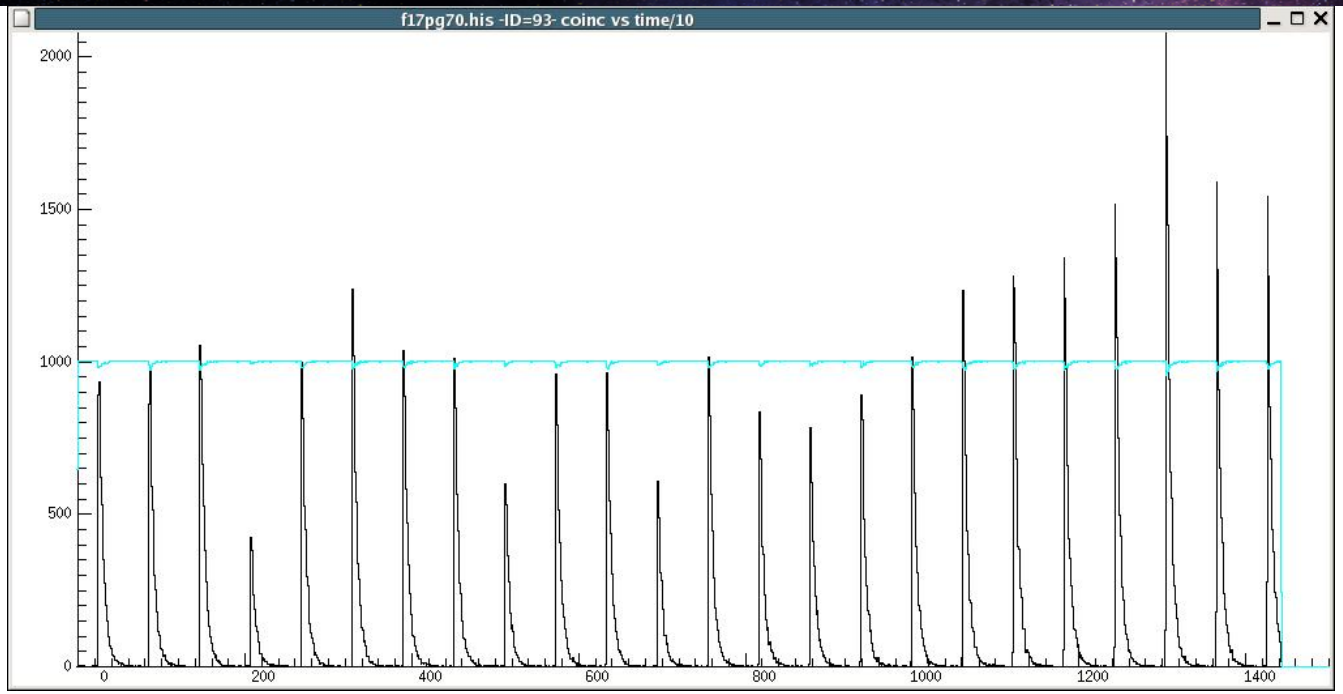
recoil separators



challenges - backgrounds

- only 1 in ~ 10^{12} beam particles fuse with protons
- all fusion reaction products **and** **unreacted beam particles** enter separator located along beam axis
- many unreacted beam particles will reach the focal plane detector after multiple scatters – signal/noise ~ 10^{-3}
- need beam rejection 10^{-10} – 10^{-12} (or more) of separator & good focal plane detector

recoil separators



"plunger" system measuring decays of implanted ^{17}F in $^{17}F(p,\gamma)\,^{18}Ne$ experiment

other challenges

- beam current & target thickness normalization
- tracking the composition in time of an impure beam
- beam intensities that are too low for capture [do (p,p) instead]
- beam intensities too low for particle – gamma coincidences

recoil separators – desired properties

- factor of 10^{10} - 10^{13} rejection of unreacted beam particles desired with separator alone -- additional rejection from focal plane detectors
- near 100 % transport efficiency of chosen recoil charge state
- mass resolution $m/\delta m$ ~ 200 or larger
- very large acceptance [large bore] of components ~30 - 50 mrad
- tuning with different ion-optical **modes** possible for different experiments
- tuning with **linear combination of fields** to change focus / mode / target location …
- devices to ensure careful preparation of beam (high purity, low emittance, negligible halo) UPSTREAM of target
- couple ion-optic code to separator set up controls
- very flexible target and focal plane areas enabling rapid change of equipment

recoil separators – associated equipment

- windowless, high-density, differentially-pumped, H / Helium gas / jet target
- focal plane detection systems for measurement of recoil
  arrival time, position, Z, energy
- charged particle detectors at target to monitor beam current & target thickness
- paddle system, harp, or other clever trick to monitor current of impure beams
- high count rate trigger detection system upstream of target
- recoil time of flight system for particle identification
- multiple position determination at focal plane to reconstruct
  [with ray tracing kinematics] recoil emission angle at target
- flexible system at target and focal plane to accommodate rapid changes
  between variety of systems

recoil separators

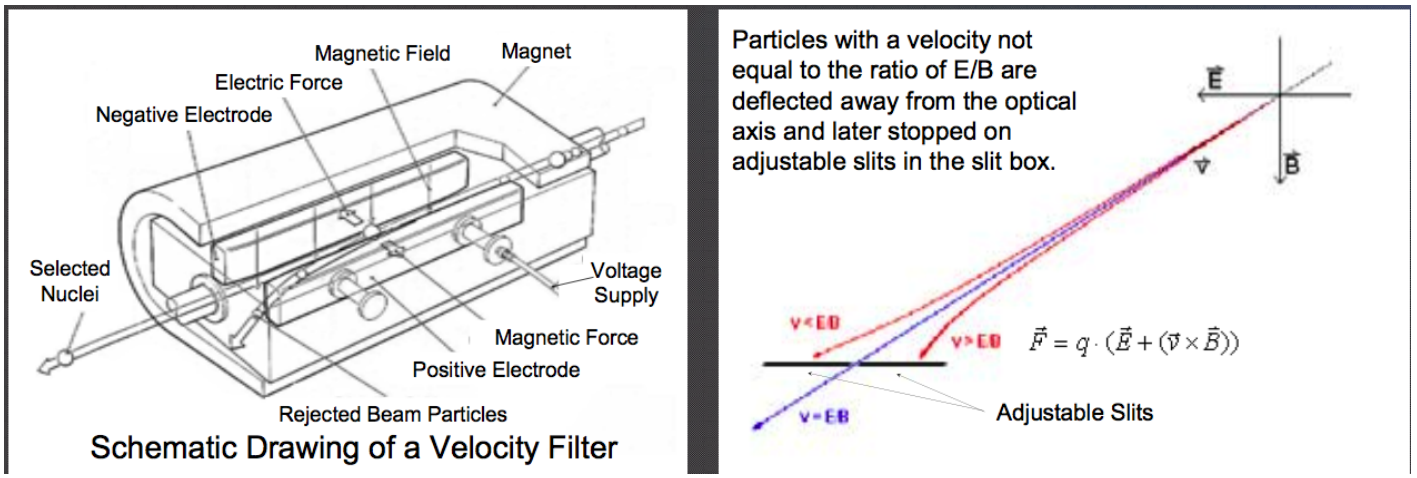
Particle Property		Separating Device
v velocity	$\propto v$	velocity filter
$B\rho$ Magnetic Rigidity	$\propto v\,(M/Q)$	magnetic dipole
$E\rho$ Electric Rigidity	$\propto v^2\,(M/Q)$	electric dipole

- properties are proportional to v and (M/Q)
- design principle: select M/Q by **combining devices** bending on

  v and v (M/Q) or v (M/Q) and v^2 (M/Q)

  velocity filter & magnetic dipole or electric dipole & magnetic dipole
- putting a number of these **filters (device pairs)** in series will increase your rejection of scattered beam (~10^3 rejection per pair)
- separators have achieved high rejections of scattered beam particles
- often a trade off between separation & efficiency – both are crucial

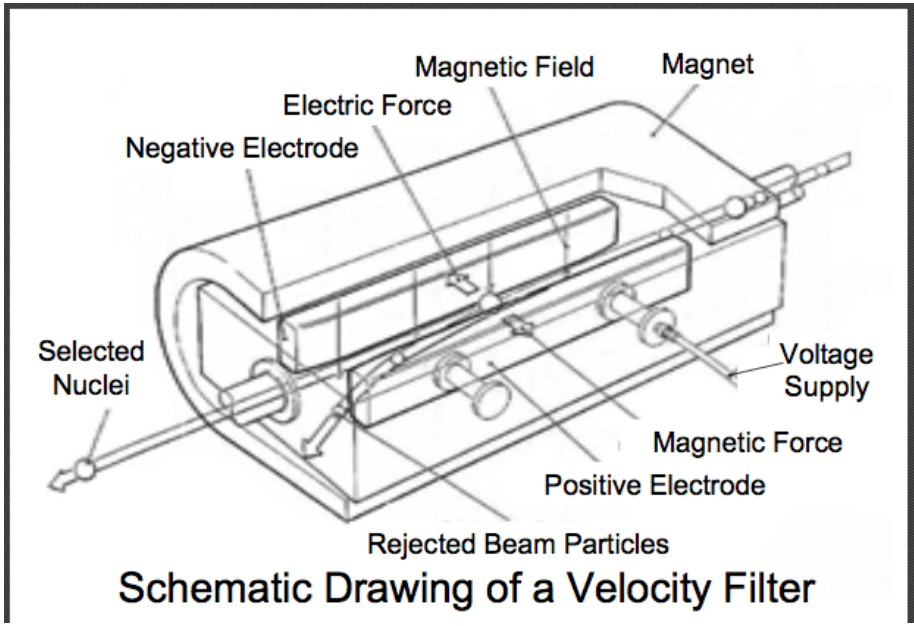
recoil separators - components



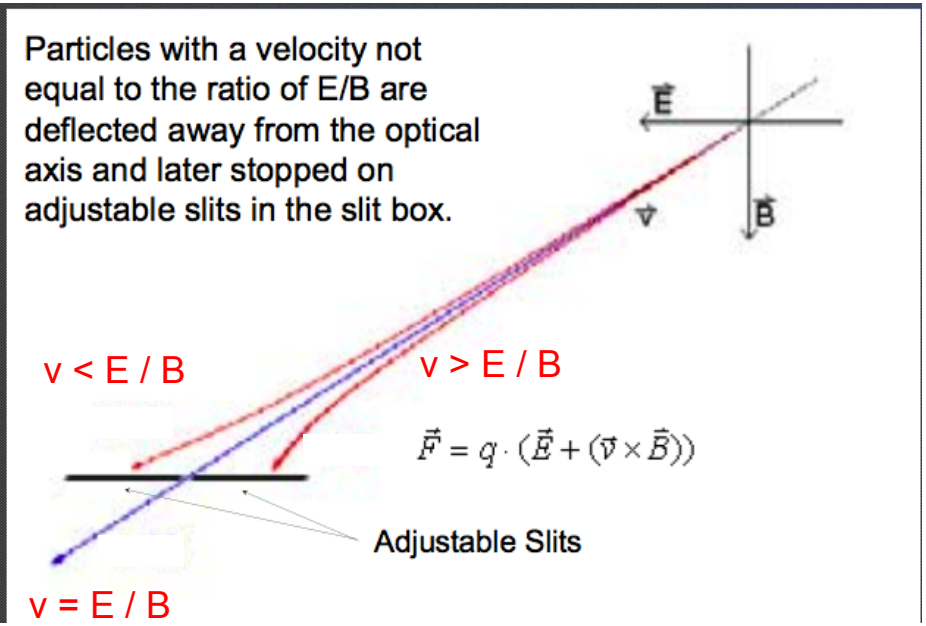
- Velocity Filters advantages
  - a straight through tune enables highly rigid beams to be used
  - variable field strengths enables unusual ion optic modes
  - tuning is NOT limited to bending the recoils around a corner

- Velocity Filters challenge
  - more expensive than dipoles
  - residual fields need to be controlled
  - sparking – depends on size of box [bigger is better] and therefore size of magnet containing the box [gets expensive quickly]

recoil separators - components

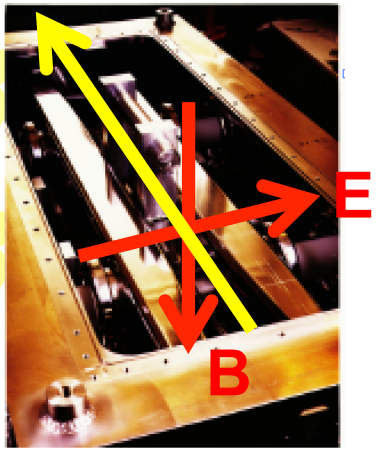


Schematic Drawing of a Velocity Filter

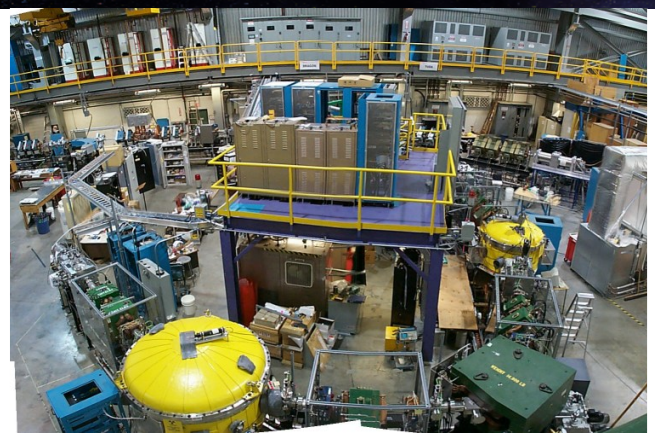


for $q\vec{E} = q\vec{v} \otimes \vec{B}$ no deflection

[$v = E / B$]



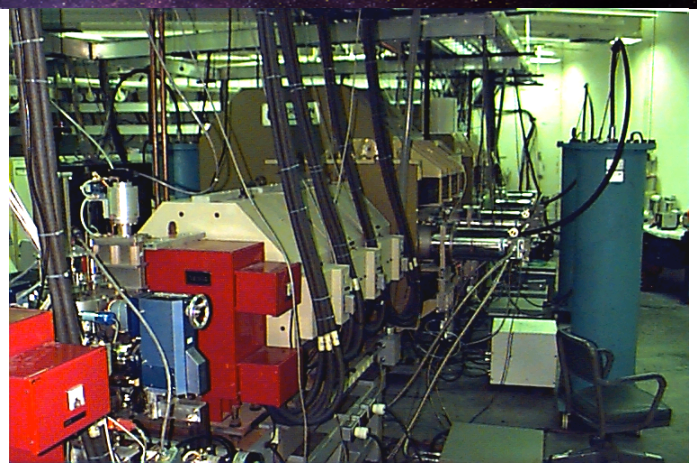
recoil separators - devices



DRAGON at TRIUMF ISAC
Used to measure $^{21}Na(p,\gamma)^{22}Mg$

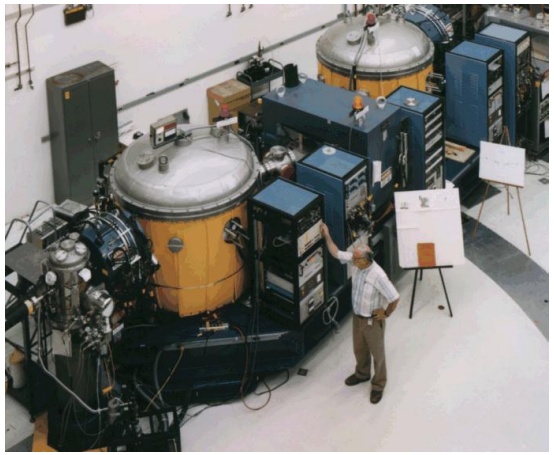
also …

- ERNA (Bochum)
- CRIB [CNS RIKEN]



DRS at ORNL HRIBF
Used to measure $^{17}F(p,\gamma)^{18}Ne$

ARES at Louvain-la-Neuve
Used to measure $^{19}Ne(p,\gamma)^{20}Na$



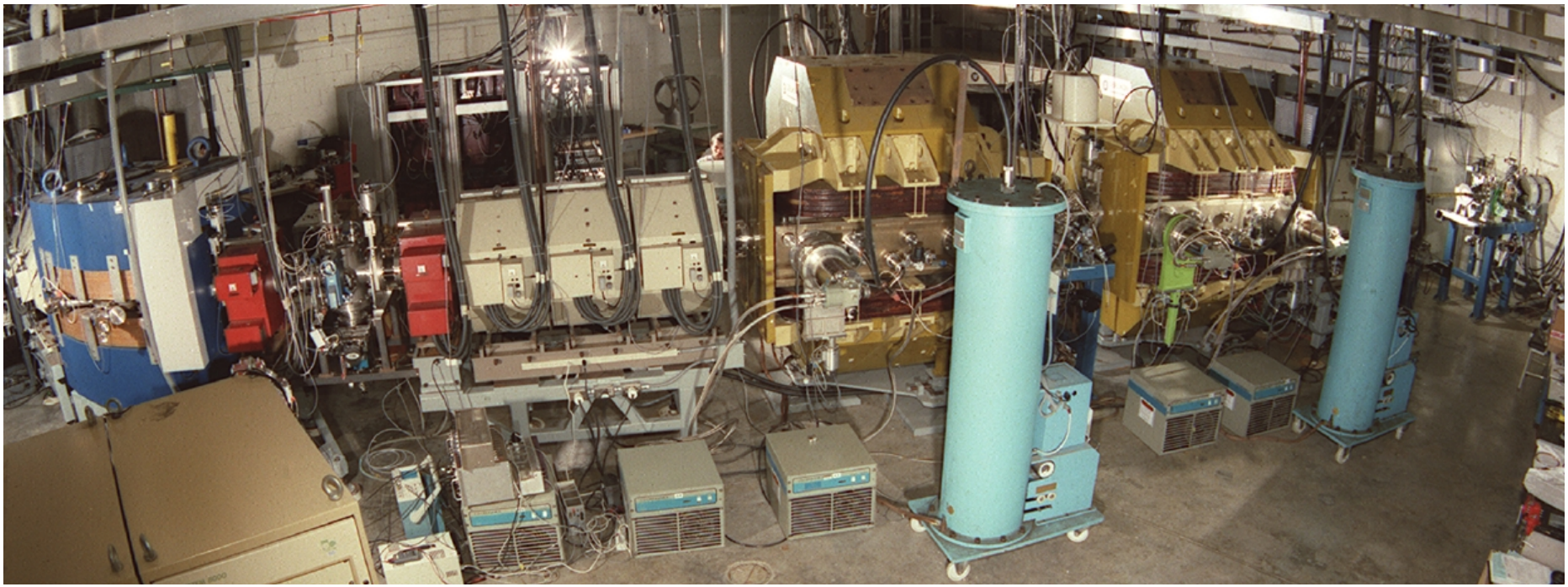
FMA at ANL ATLAS
Used to measure $^{18}F(p,\gamma)^{19}Ne$

recoil separators

- ***Caltech Recoil Separator***
  - $p(^{12}C,^{13}N)\gamma$ – Smith, Rolfs, Barnes NIM A306 (1991) 233
  - ***10^4 rejection – electric dipole alone***
  - ***10^7 rejection – velocity filter***
  - ***10^{10} rejection – vel. filter & mag. dipole***
  - (Separator Rejection Only)
- ***NABONA Separator at Naples***
  - $p(^{12}C,^{13}N)\gamma$ – Campajola et al., Z. Phys. 356 (1996) 107.
  - ***$5 \cdot 10^{10}$ rejection – mag. dipole & vel. filter***
  - (Separator Rejection only)
- ***FMA at Argonne National Lab***
  - $p(^{18}O,^{19}F)\gamma$ – Rehm et al., Phys. Rev. C. 55 (1997) R566.
  - ***10^{12} rejection – electric, mag. , elec. dipoles***
  - (Separator Rejection plus Detector Rejection)
- ***Daresbury Recoil Separator at ORNL HRIBF***
  - $p(^{12}C,^{13}N)\gamma$ – Recent HRIBF Results (unpublished) December 1997
  - ***10^{11} rejection – 2 vel. filters & mag. dipole***
  - *(not optimized)* (Separator Rejection only)

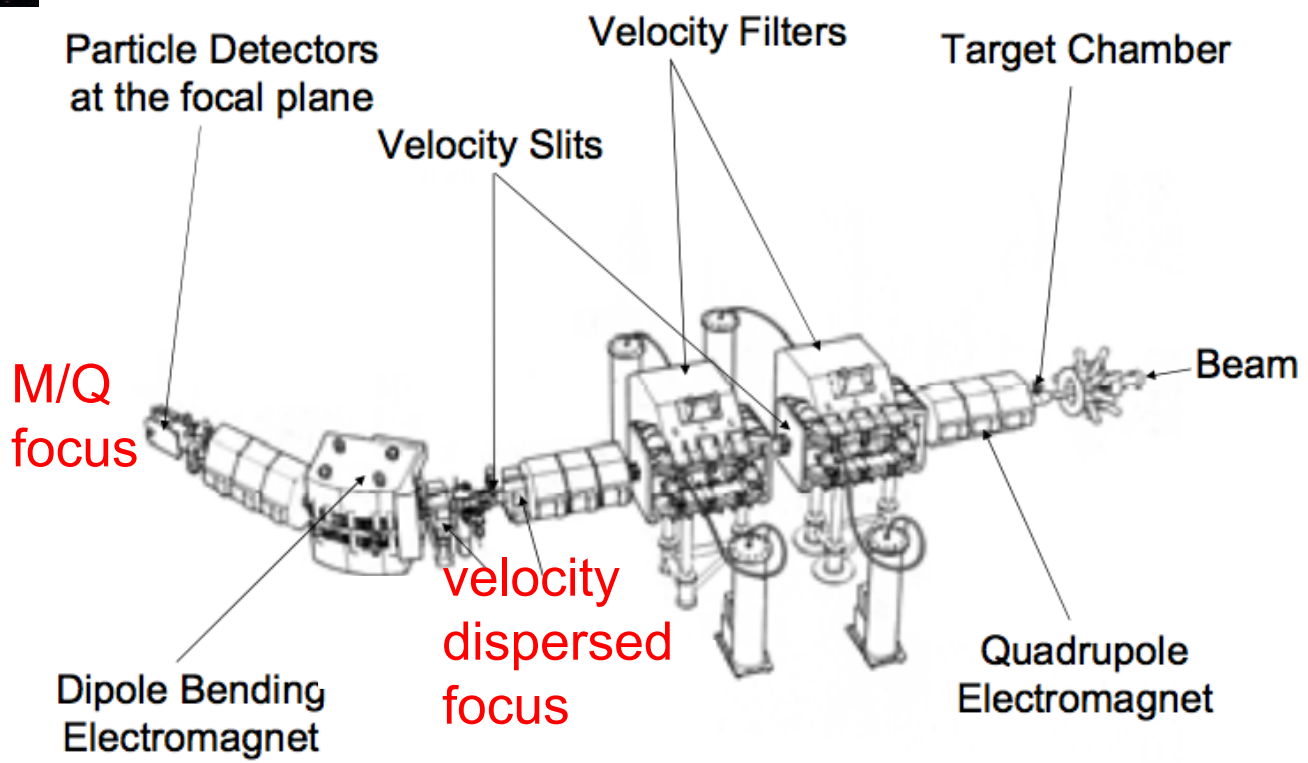
- separators have achieved high rejections of scattered beam particles
- often a trade off between separation & efficiency – both are crucial

Daresbury Recoil Separator (DRS)



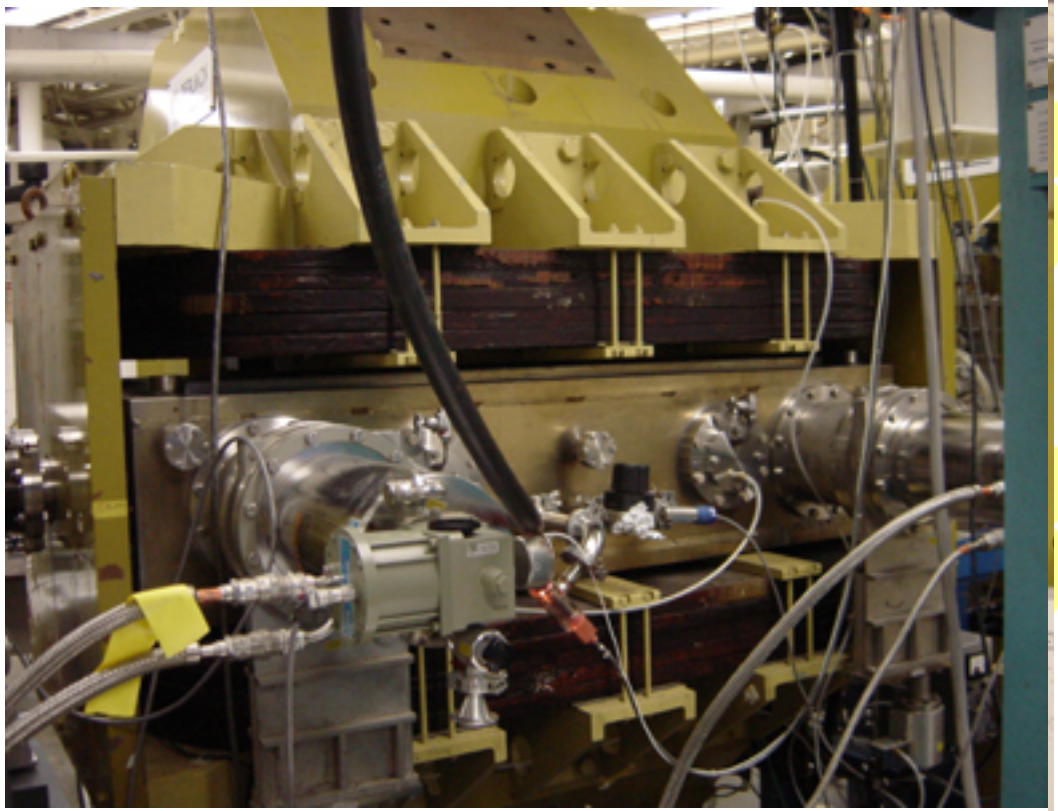
- brought over [recycled] from Daresbury Laboratory in the U.K. in 1994
- 13 m long flight path, 90 tons, 2 M$ replacement value
- installed, modified, and optimized for capture reaction measurements
- features two long velocity filters coupled to a dipole magnet

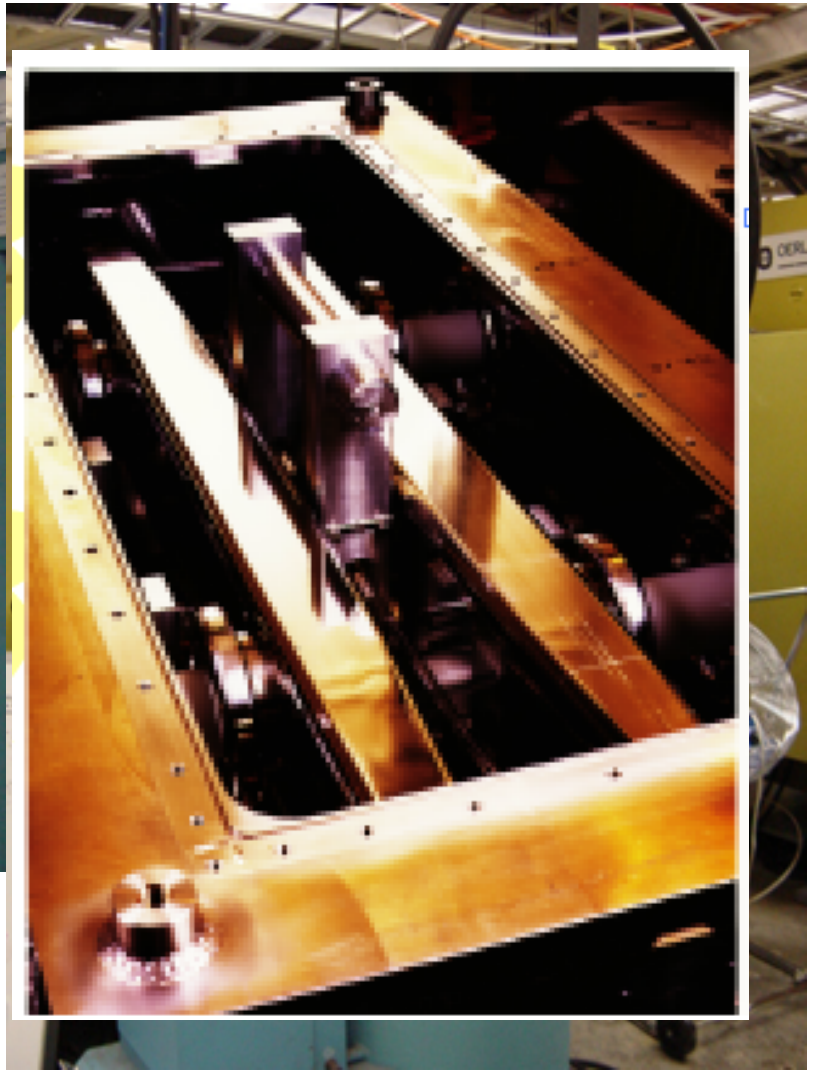
Daresbury Recoil Separator (DRS)



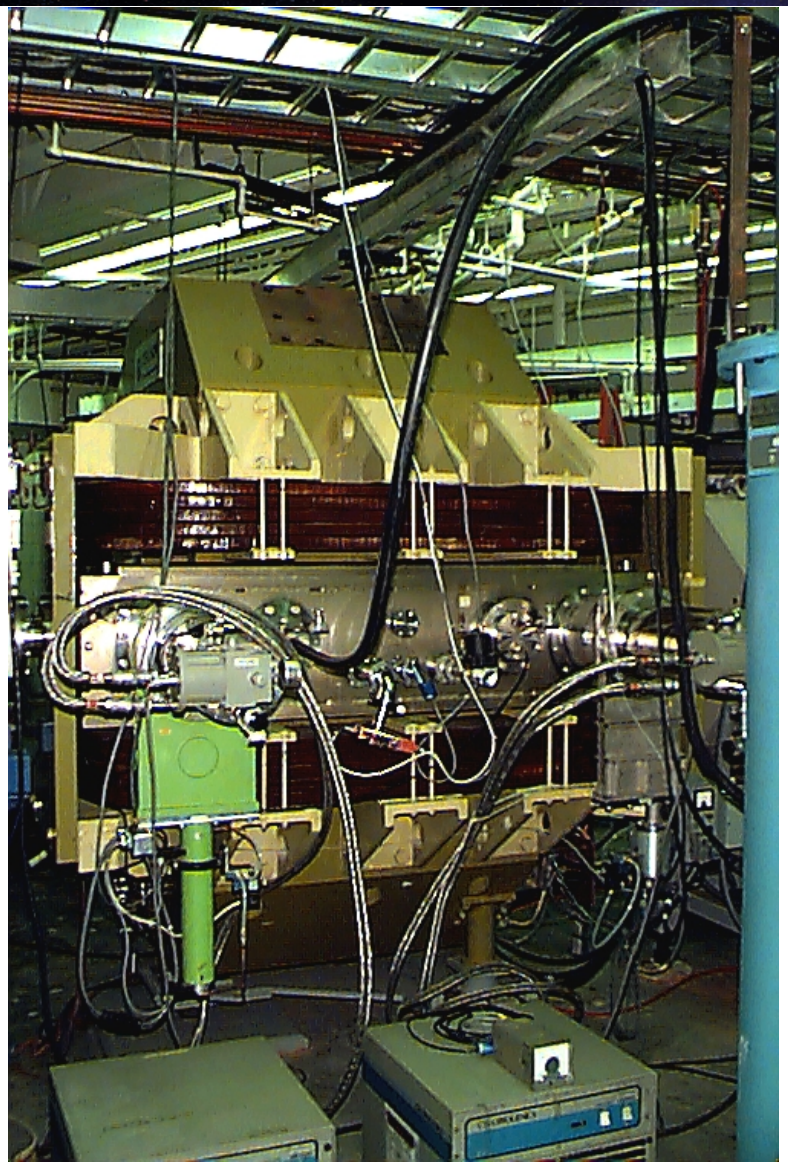
- brought over [recycled] from Daresbury Laboratory in the U.K. in 1994
- 13 m long flight path, 90 tons, 2 M$ replacement value
- installed, modified, and optimized for capture reaction measurements
- features two long velocity filters coupled to a dipole magnet

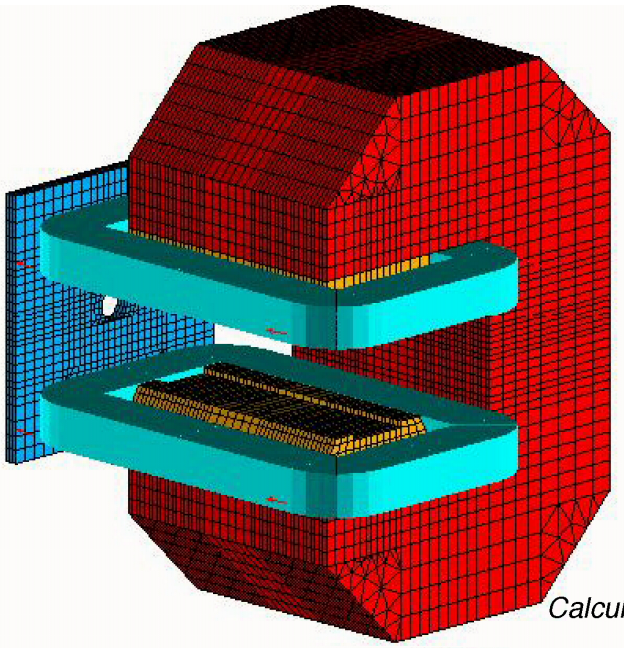
DRS Velocity Filters





DRS Velocity Filters

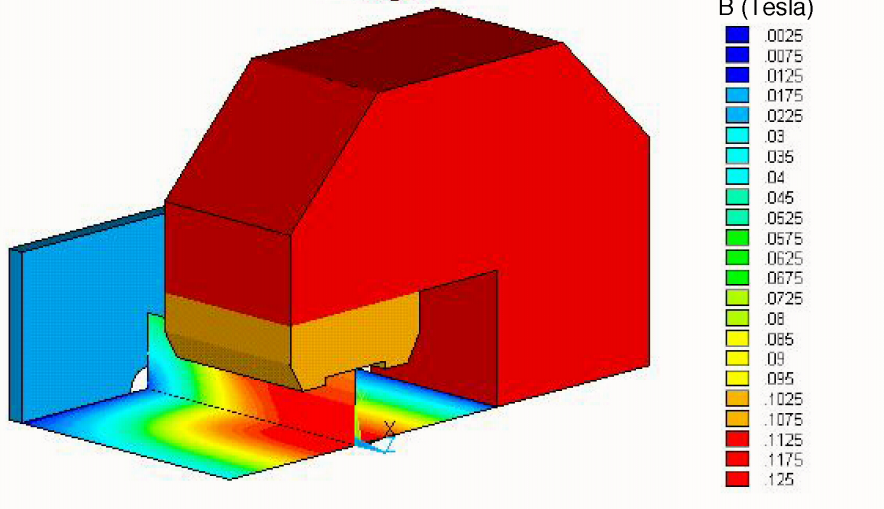




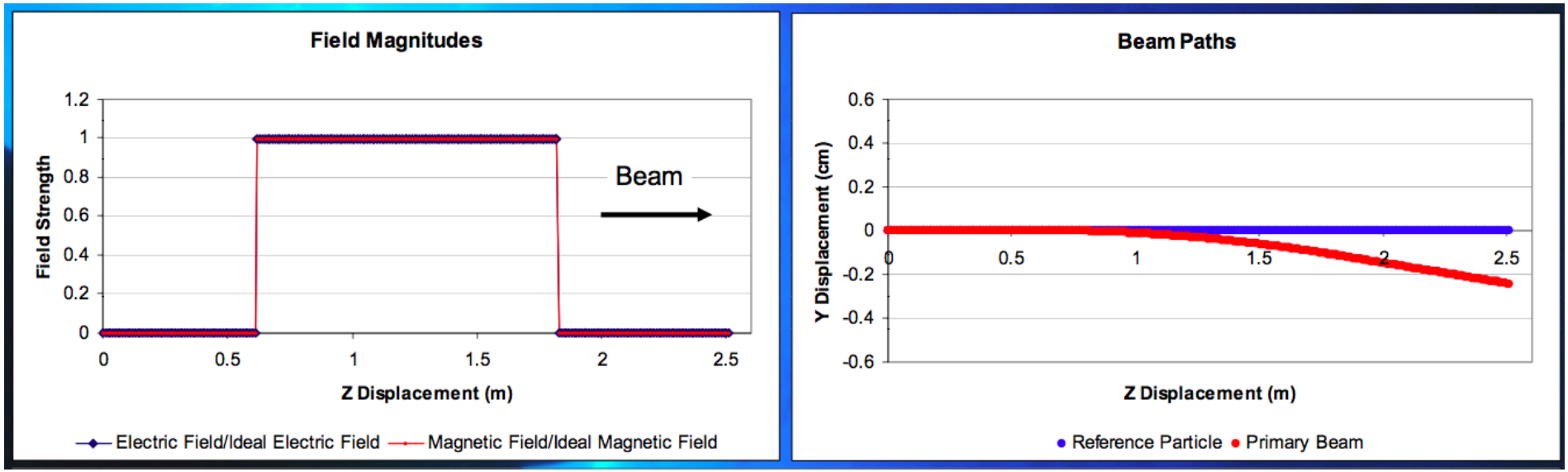
Mesh for 3-D Finite Element Field Calculations

particles

Calculated Magnetic Field



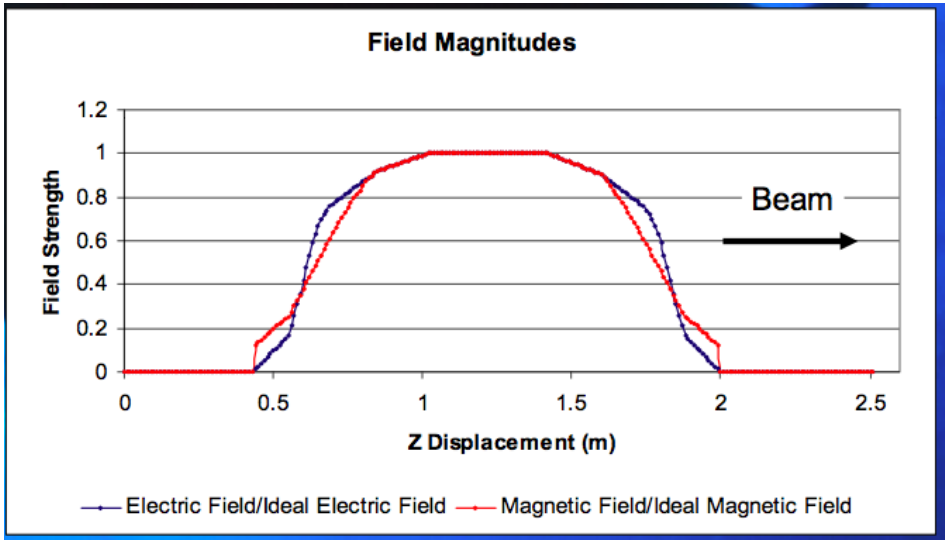
DRS Velocity Filters

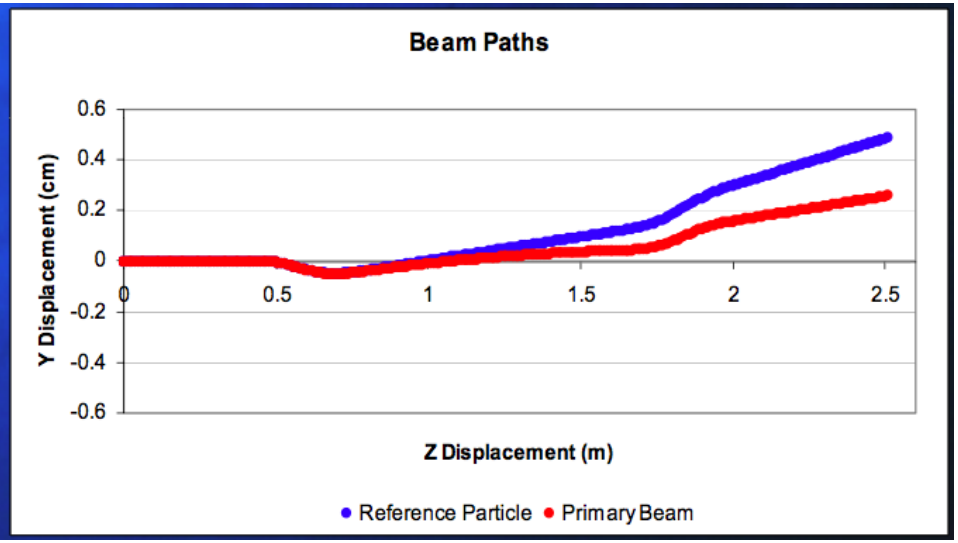


- calculate deflection of beam particles
  - in first in ideal velocity filter [E and B fields perfectly matched]

J.P. Rogers et al. 2008

DRS Velocity Filters

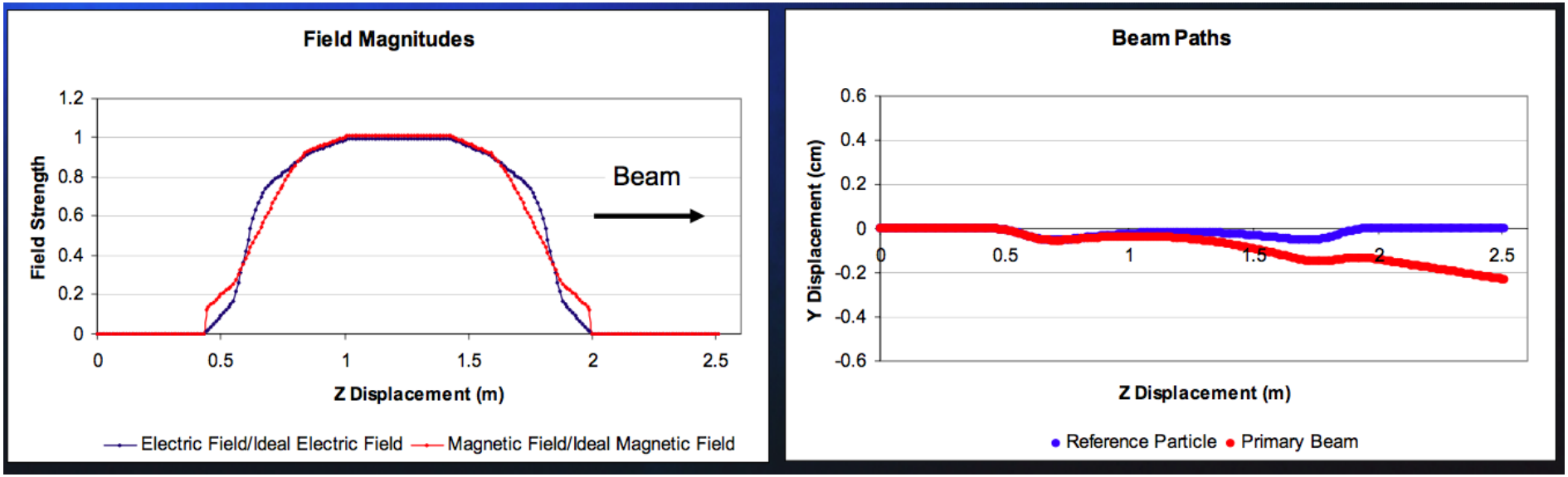




- calculate deflection of beam particles
  - in first in ideal velocity filter [E and B fields perfectly matched]
  - then with realistic fields in DRS velocity filter

J.P. Rogers et al. 2008

DRS Velocity Filters



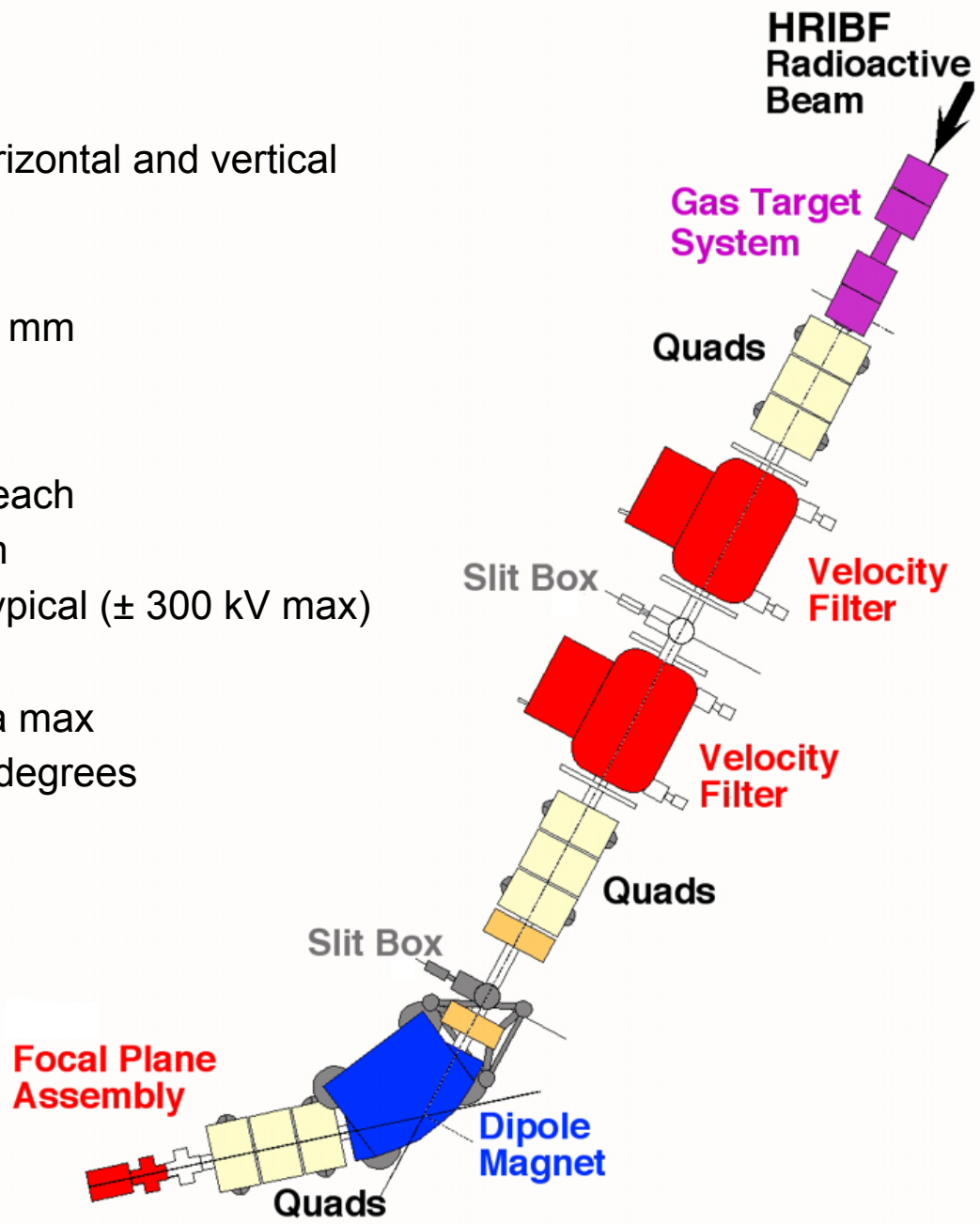
- calculate deflection of beam particles
  - in first in ideal velocity filter [E and B fields perfectly matched]
  - then with realistic fields in DRS velocity filter
  - then determine corrected fields to pass reference particles

J.P. Rogers et al. 2008

DRS

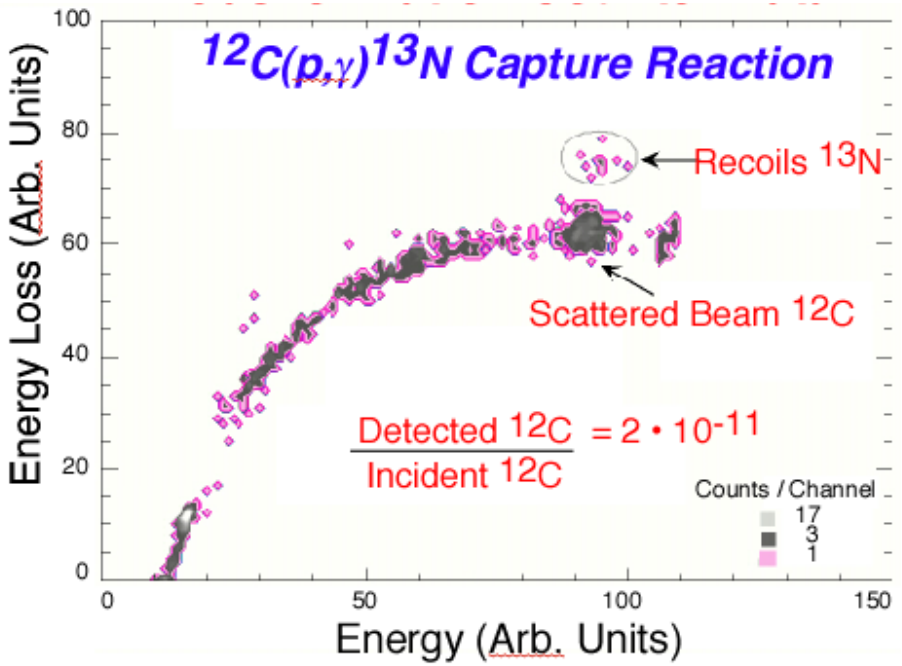
Angular acceptance: ±45 mrad horizontal and vertical
Mass/charge acceptance: ± 1.2%
Mass/charge resolution: 1/300
Mass/charge dispersion: 0.1% per mm
Energy acceptance: ± 5%
Velocity acceptance: ± 2.5%
Velocity filter length: two at 1.2 m each
Vel. filter plate separation: 100 mm
Vel. filter plate voltage: ± 150 kV typical (± 300 kV max)
Vel. filter B-field gap: 350 mm
Vel. filter B-field strength: 0.5 Tesla max
Sector magnet bending angle: 50 degrees
Overall length: 13 m
Weight: 90 tons

beam rejection: 10^{-8} – 10^{-12}

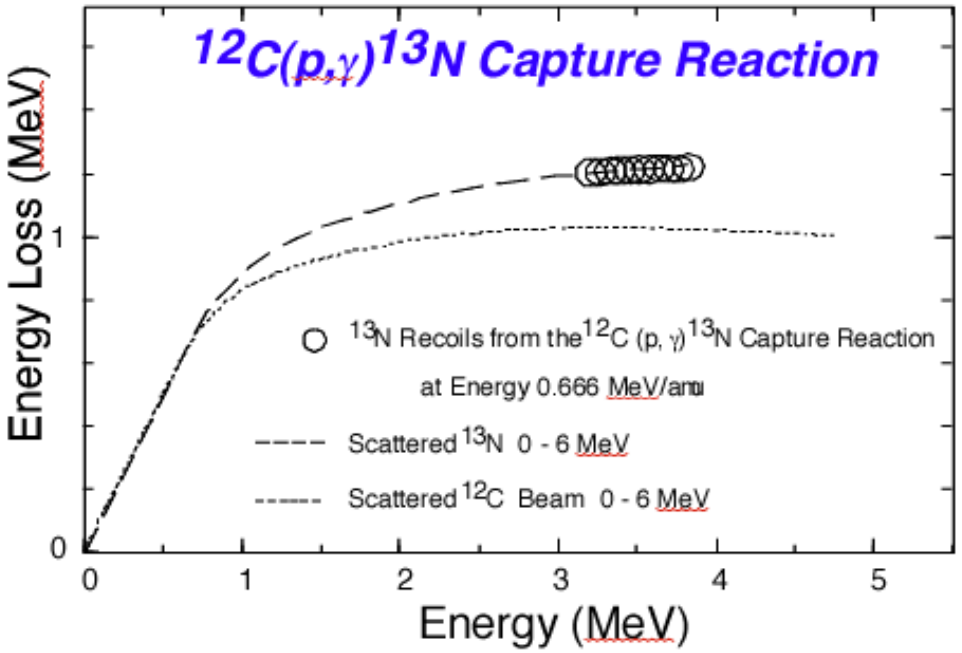


Daresbury Recoil Separator (DRS)

data



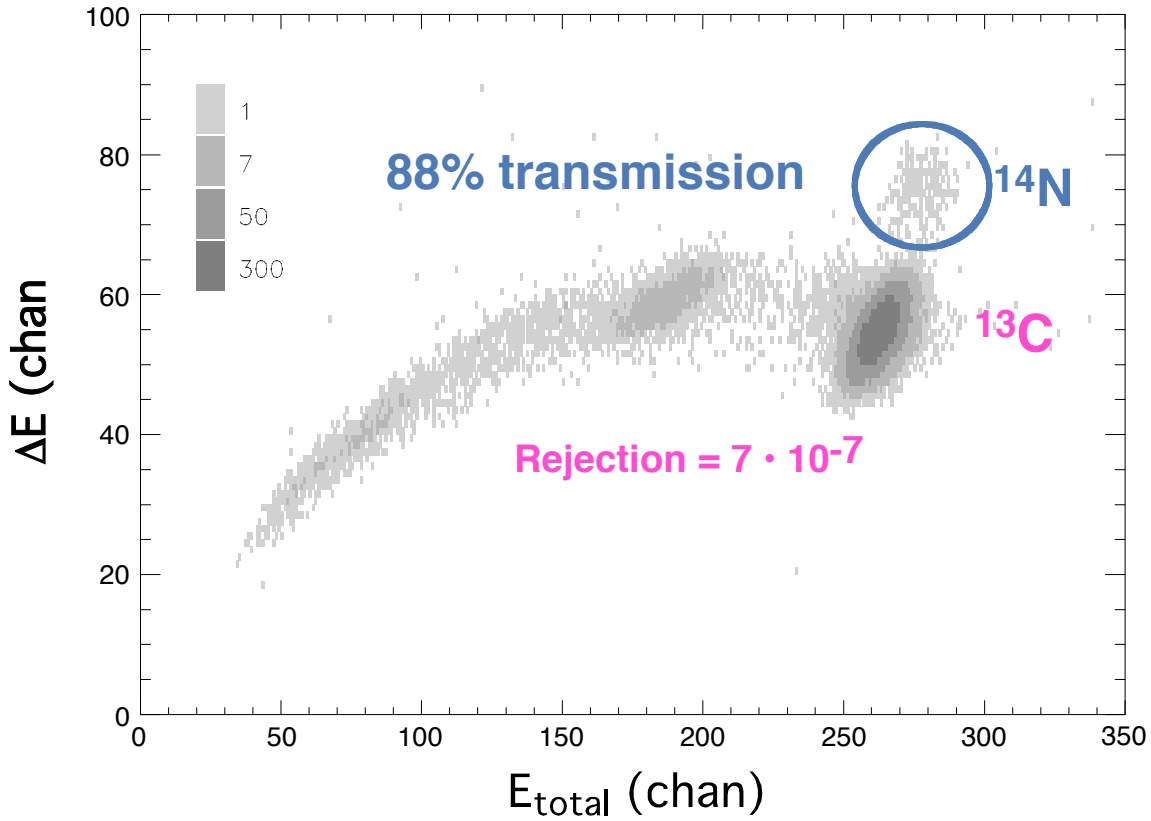
simulation



- measured capture of protons on ^{12}C as first test
- successful rejection of scattered beam by factor of 10^{11}
- focal plane detector added excellent separation of recoils, agreed with simulation
- efficiency was low, not optimized

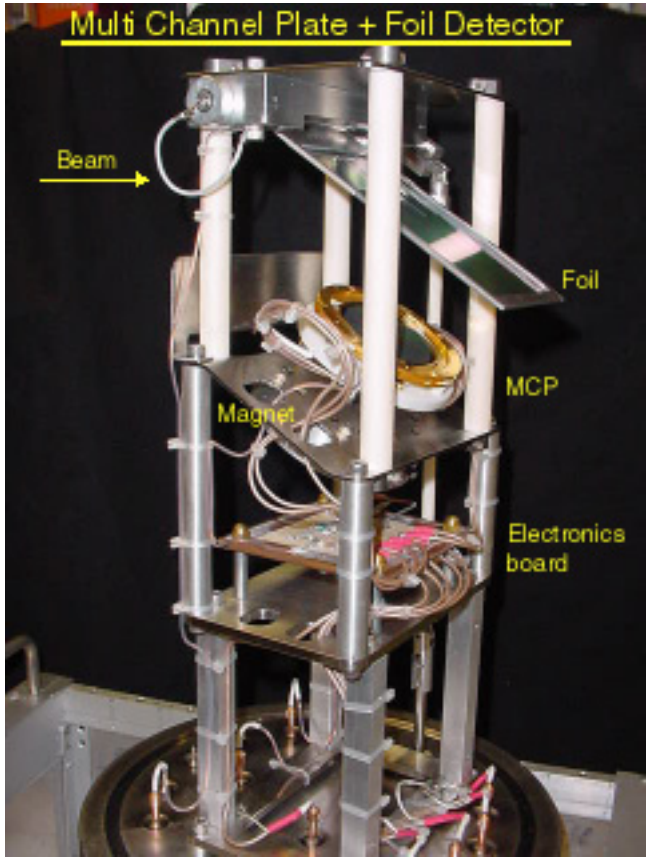
Daresbury Recoil Separator (DRS)

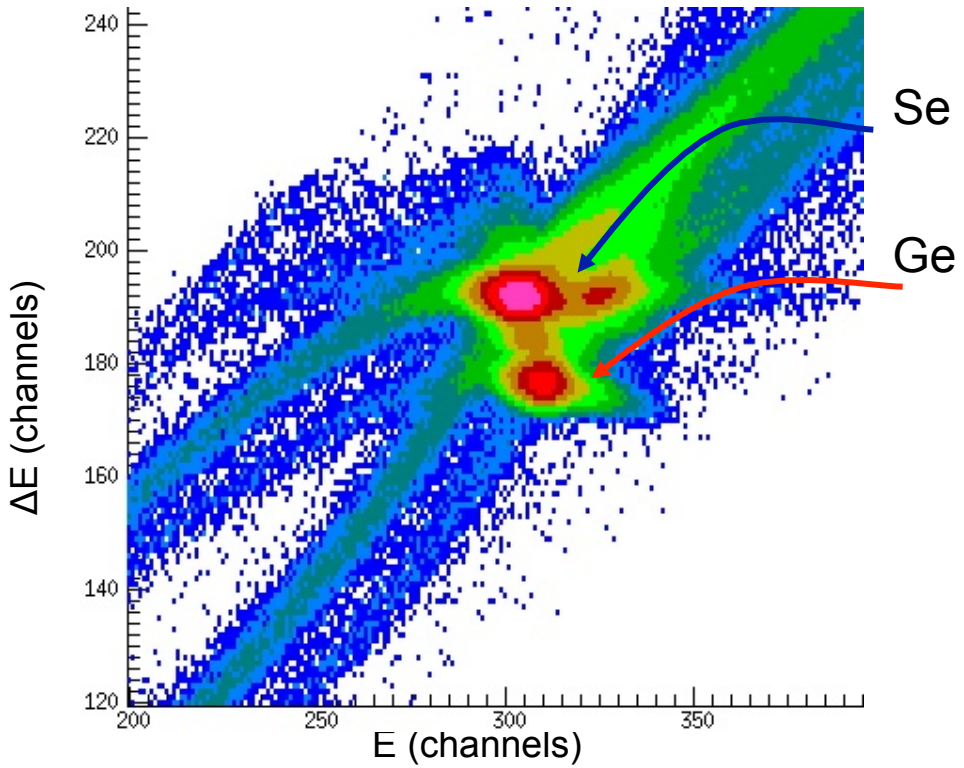
$^{13}C + p$ at $E_{cm} = 0.51$ MeV



- measured capture of protons on ^{13}C to optimize transmission
- high transmission 88 % possible with poor rejection
- other reactions measured [$^{17}O + p$, $^{24}Mg + p$ …]

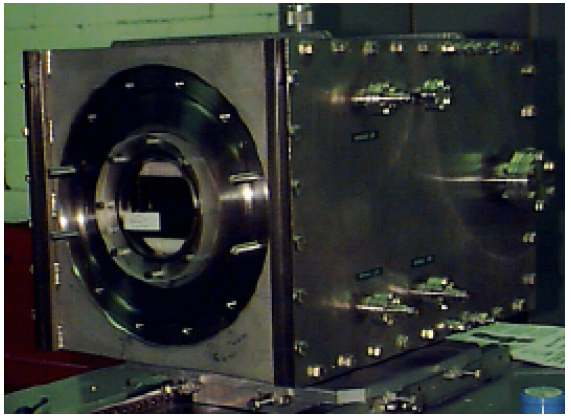
focal plane detectors

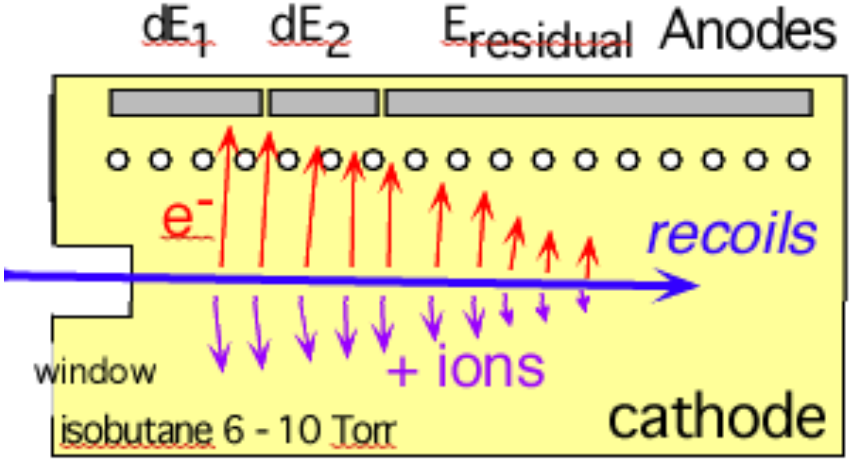


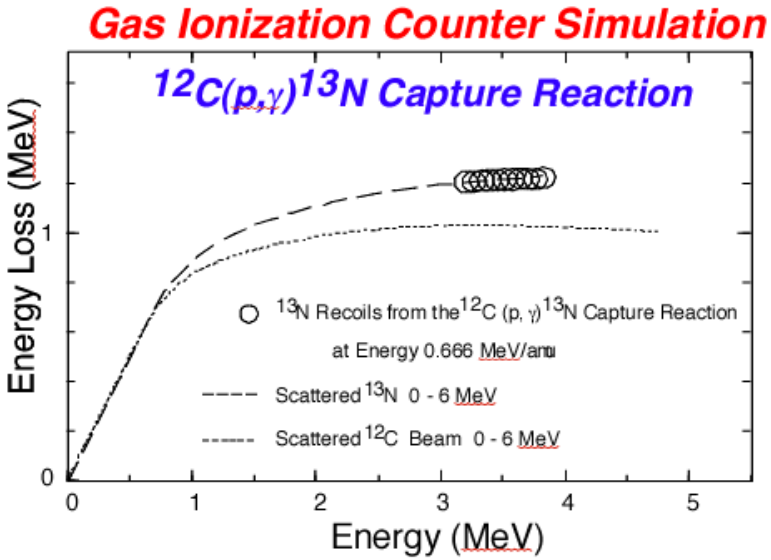


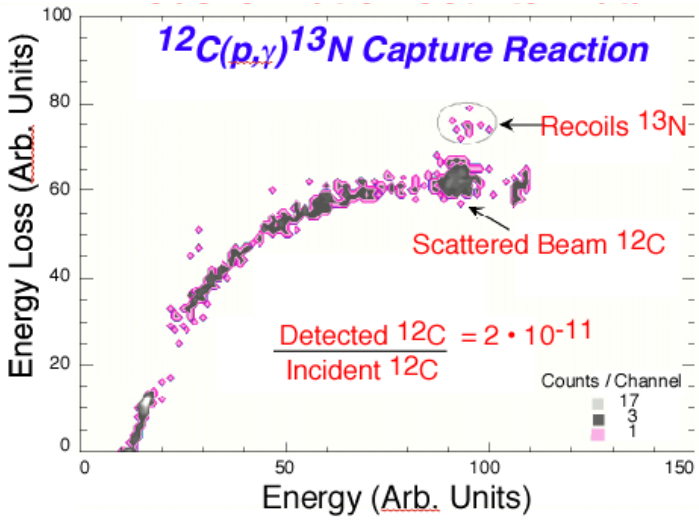
- some detectors [gas ion counters] measure energy & energy loss to identify particles
- others [micro channel plate detectors] just measure each particle for timing
- pairs of timing detectors can be used for particle identification via time-of-flight

gas ionization counters









- identify particles on basis of energy loss in gas – scales with Z
- reliably handles up to 10^4 pps
- our new detector handles up to 0.5 • 10^6 pps

gas ionization counters

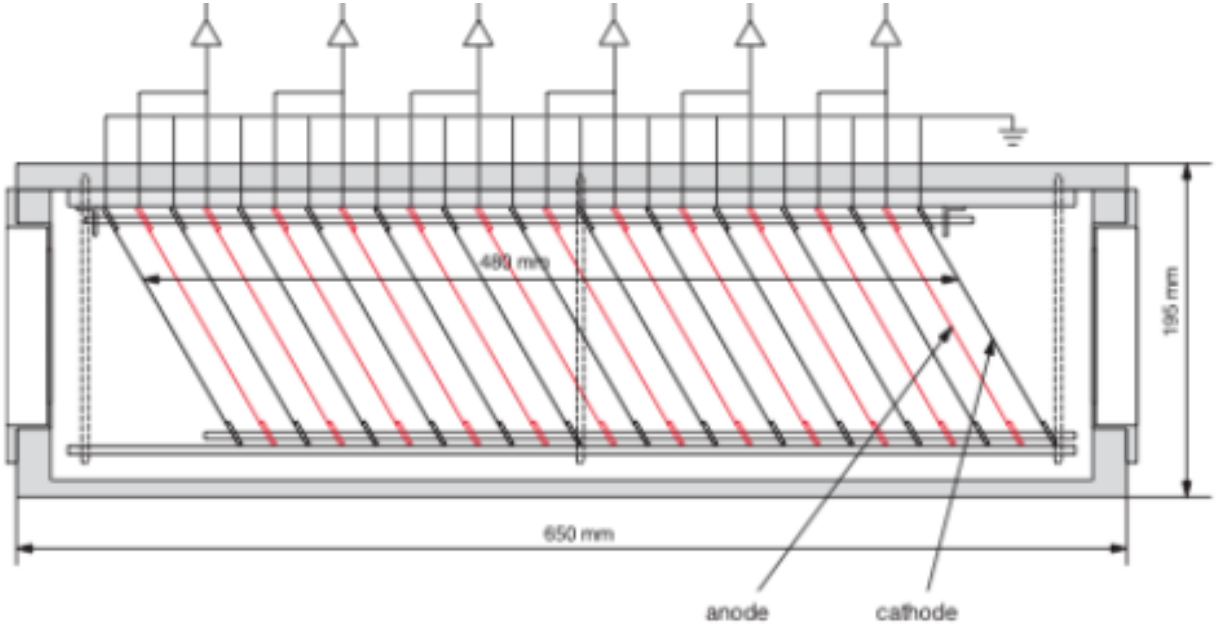
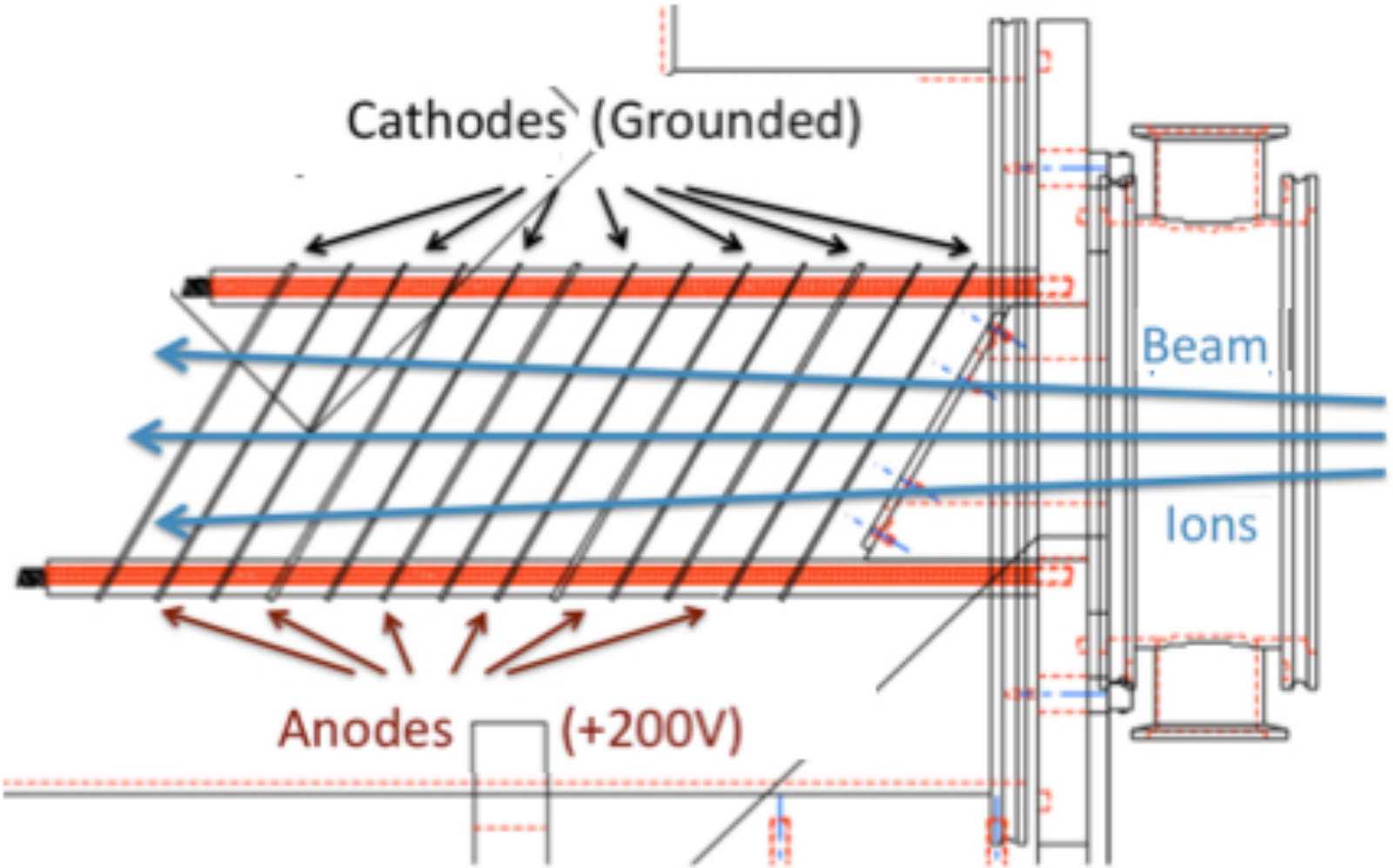


Fig. 6.5.4. Cross sectional view of a high event rate gas ionization counter built at RIKEN [Ki05]

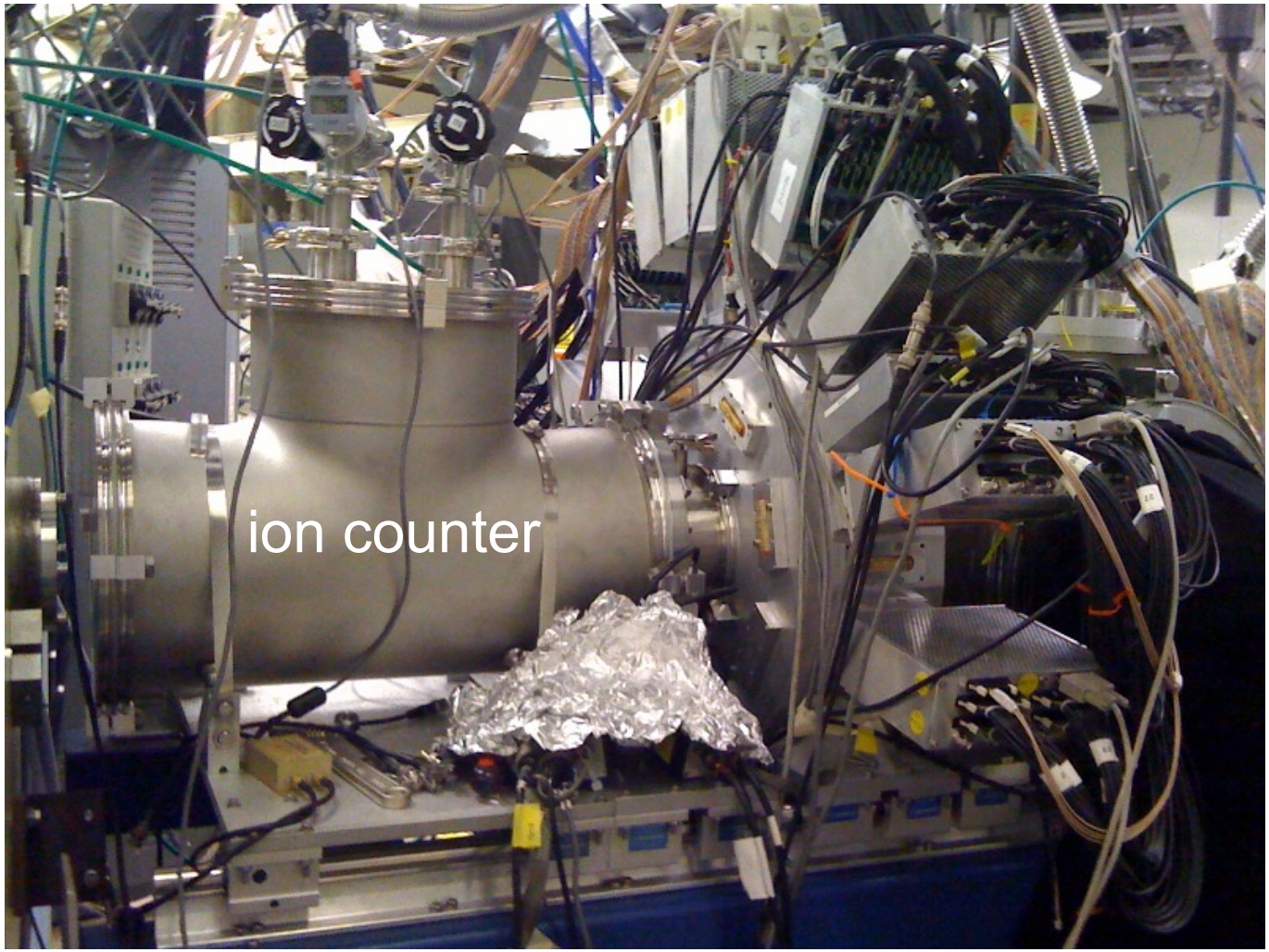
high rate gas ionization counter
- designed to handle up to 10^6 events/sec
- used for measurements with impure RIBs
- design: Kimura [Nagasaki Inst. Appl. Sci.]
  - for RIKEN, GSI measurements
- status: operating well, optimizing electronics for faster response

gas ionization counters



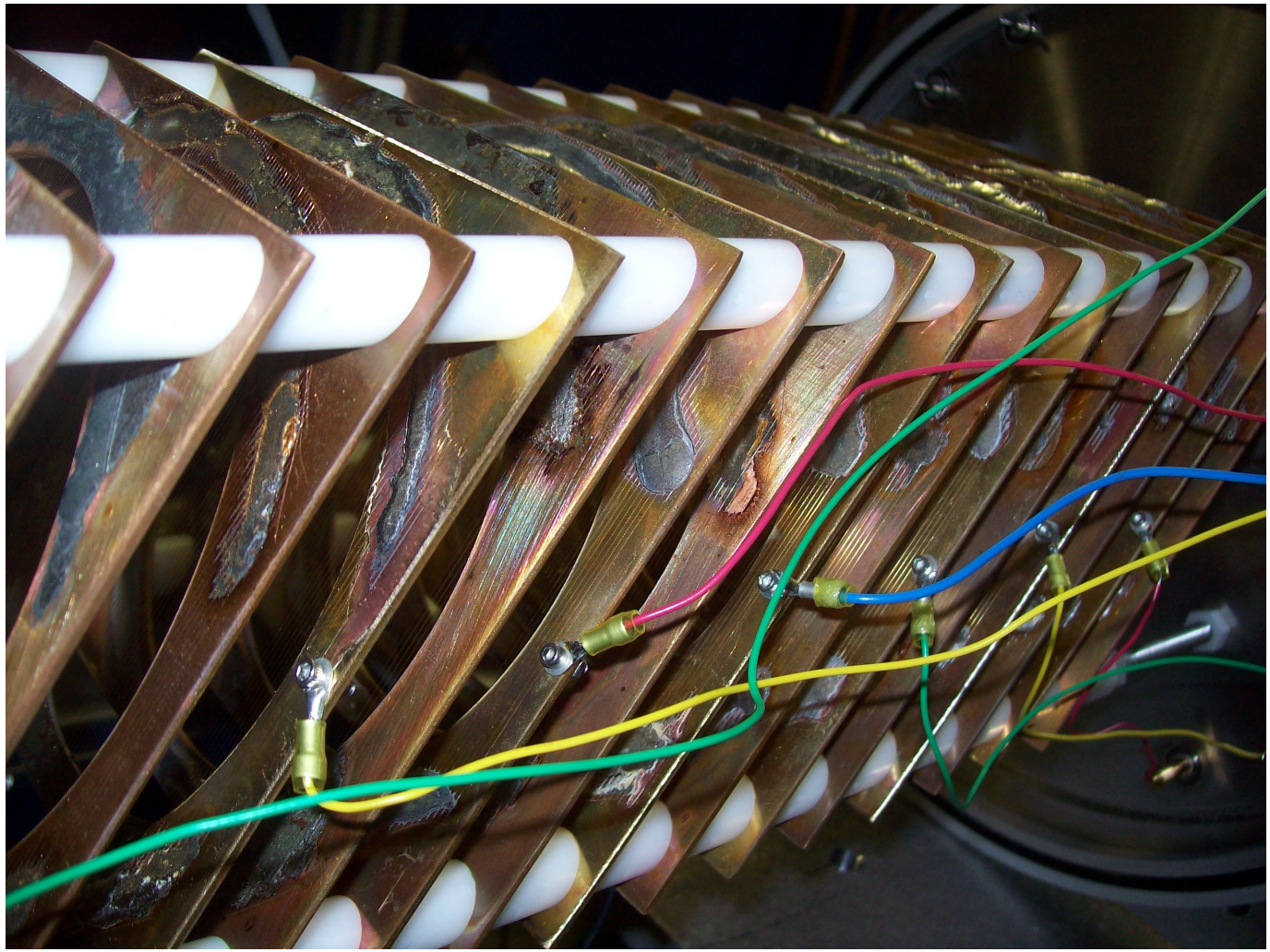
tilted foils and grids to sweep ions / electrons out of beam path
to increase event rate

gas ionization counters



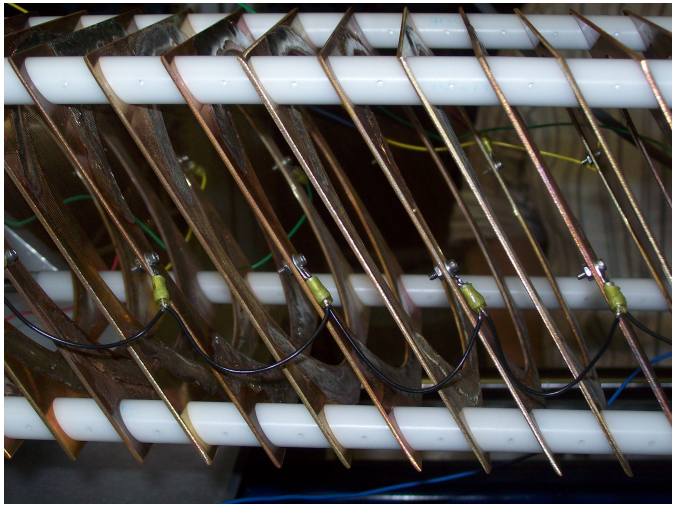
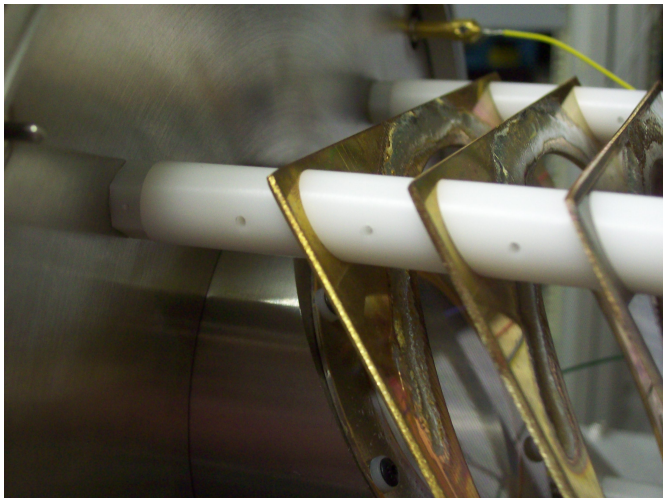
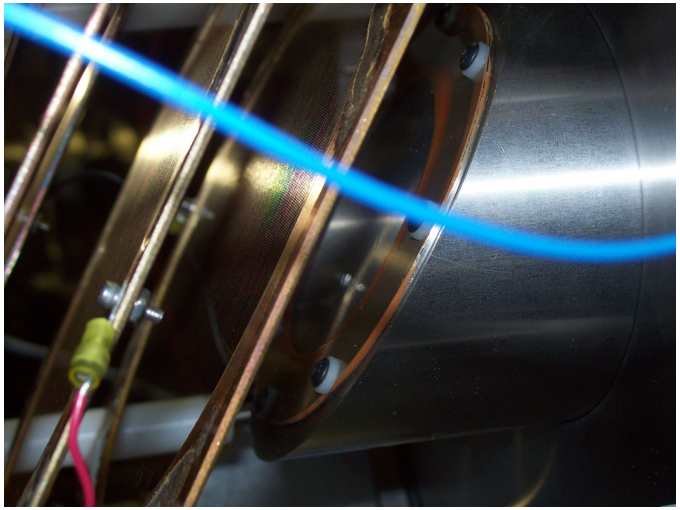
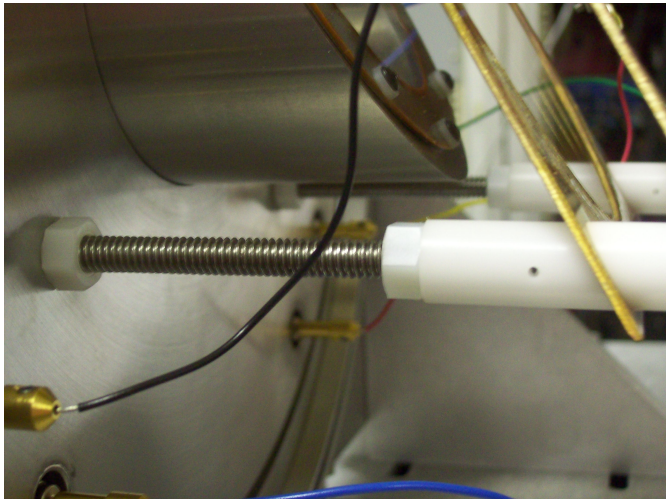
implementation behind ORRUBA Silicon strip detector system in target chamber

gas ionization counters



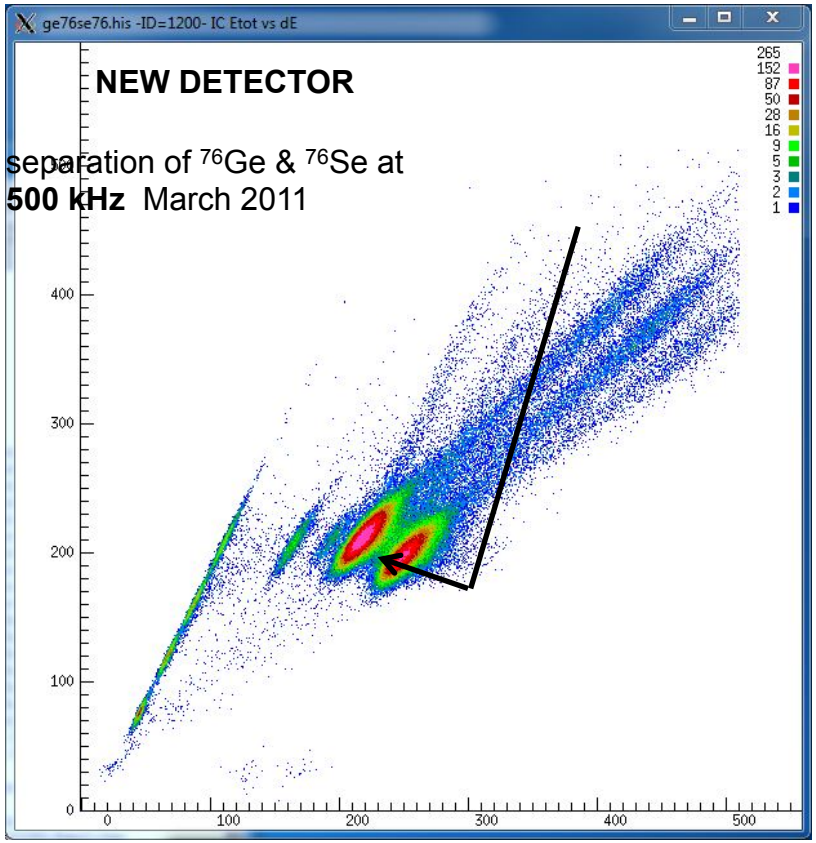
stacked wire grids

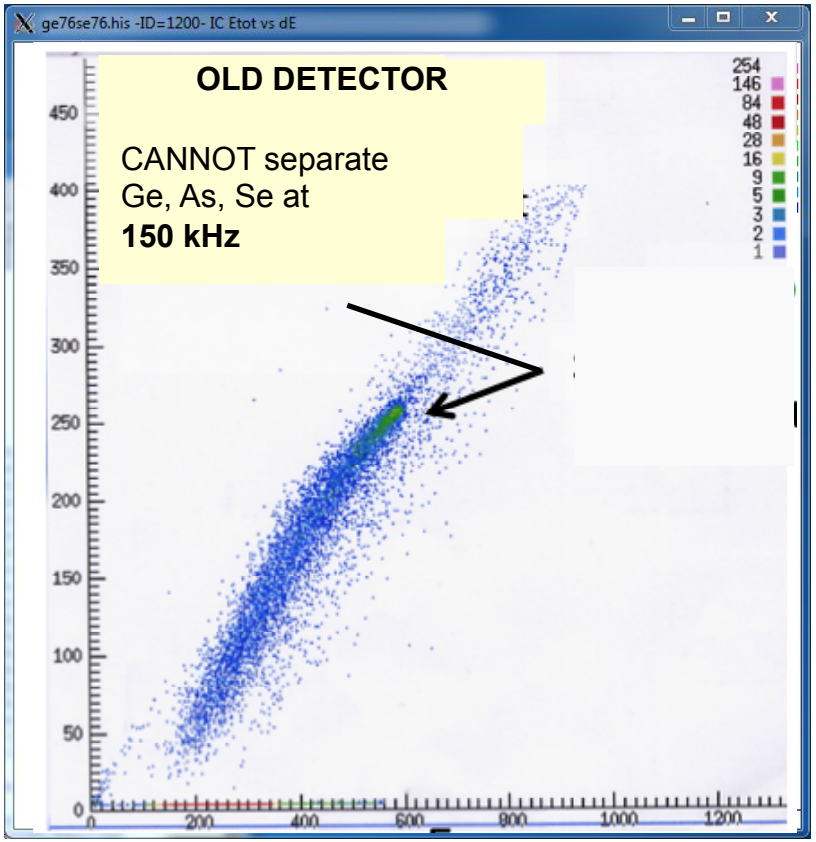
gas ionization counters

interior views

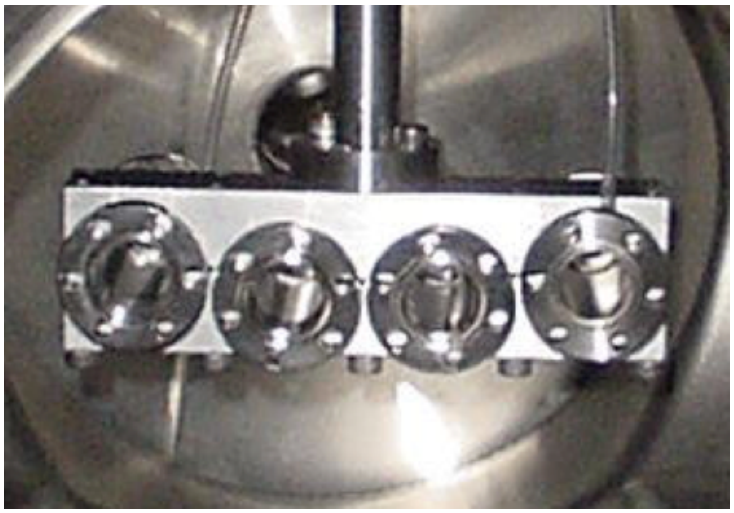
gas ionization counters

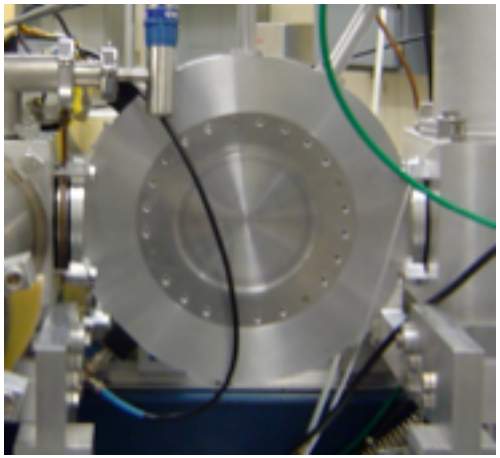


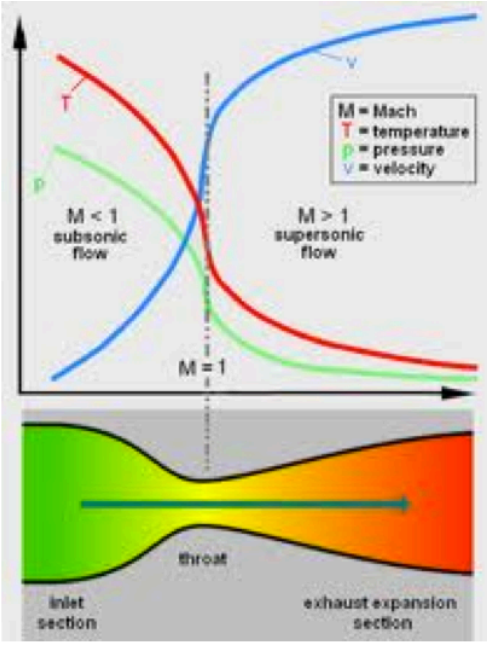


- performance: offers separation of beam and recoils at **count rates** of over 500 kHz – enabling measurements with contaminated RIBs

gas target systems







three main types:

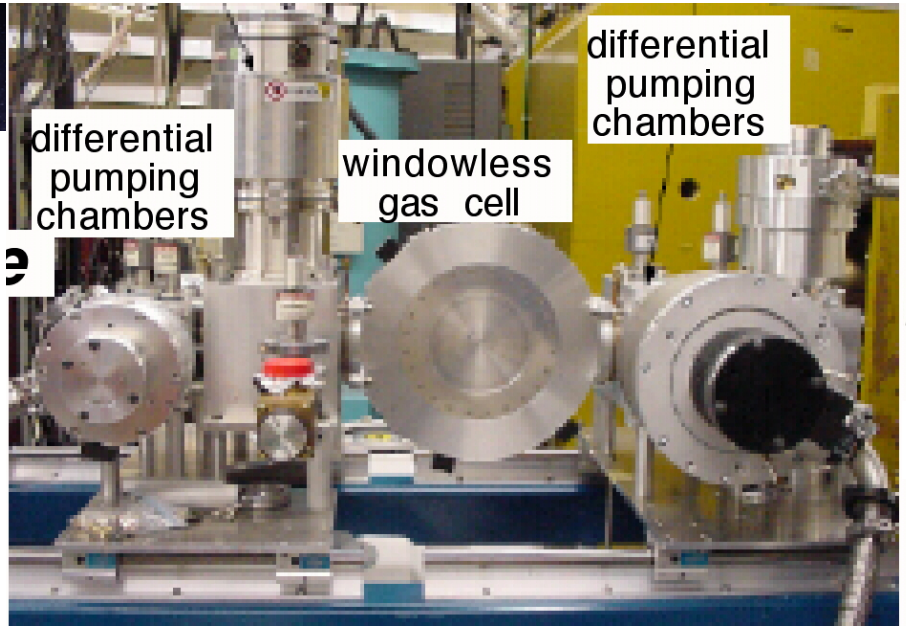
gas cell – has windows that give large backgrounds and ruin energy resolution of beam

extended windowless – no windows, gas region is extended over a 10 – 20 cm range making unsuited for some experiments

gas jet – compressed gas region good for all experiment types, hard to determine pressure, most expensive / difficult option

gas target systems

beam →

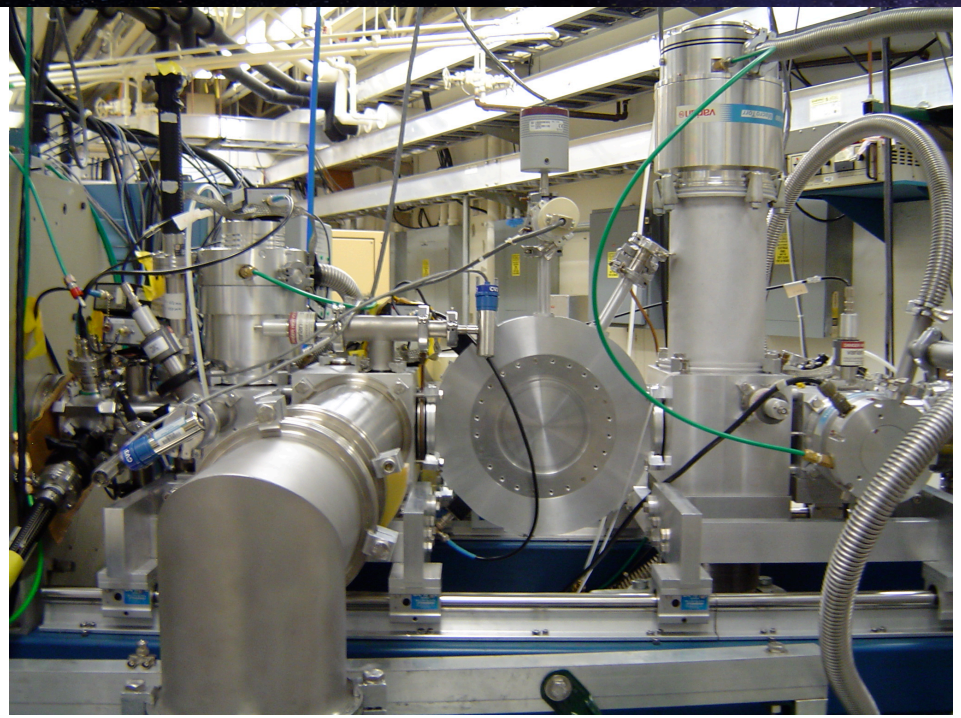


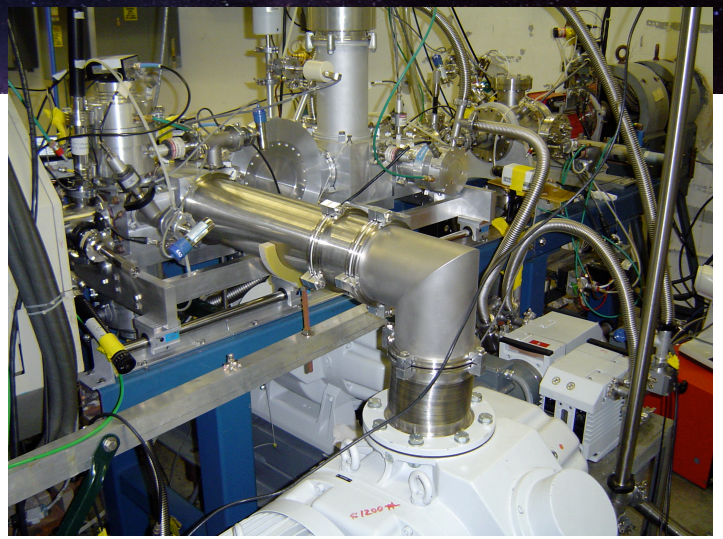
capture reaction products

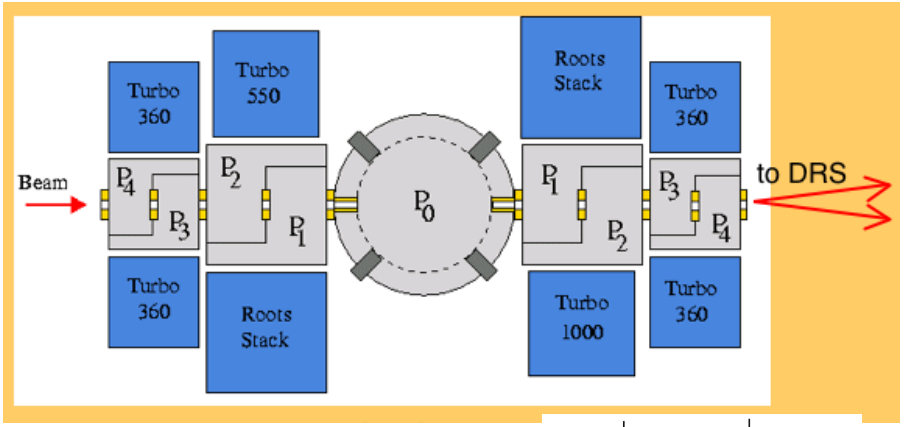
to separator

- For direct measurement of capture reactions [^{17}F(p,γ)^{18}Ne, ^{7}Be(p, γ)^{8}B]
- **Many Advantages over solid CH_2 targets**
  - increase yield by factor of ~ 3
  - composition, uniformity, thickness very stable
  - no backgrounds or resolution loss from carbon
  - reactions on helium isotopes possible [(α,γ), (3He,d)]
- ORNL: extended gas target used for over 6 years
- He gas at ~ 8 torr, 5· 10^{18} cm^{-2} , H gas at 4 – 6 torr typically

gas target systems

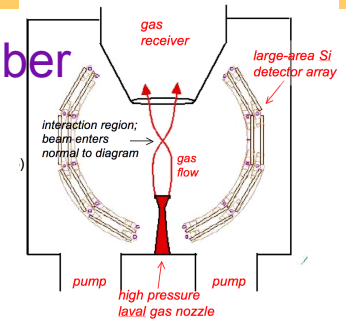




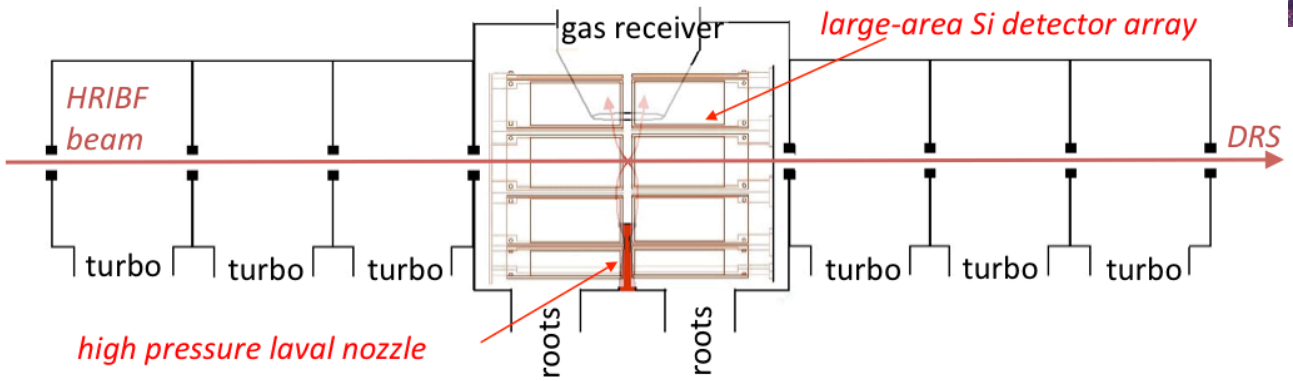


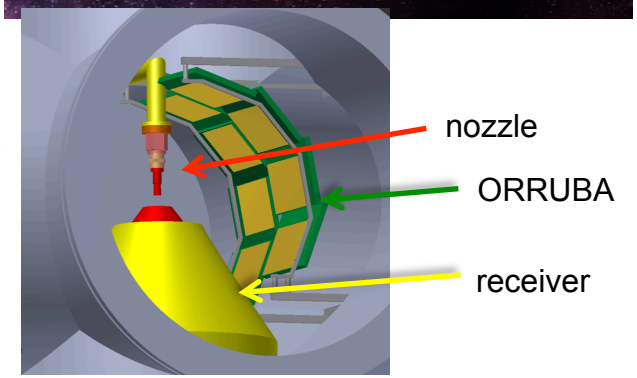
- no window to spoil energy resolution
- pressure drop of 10^7 over 30 cm
- up to 10 torr, 10^{18} cm^{-2} thickness, 15 cm long extended gas chamber
- multiple configurations utilized for maximum flexibility

- currently being transformed into a gas jet target system (higher density, few mm size, enables transfer reaction measurements)

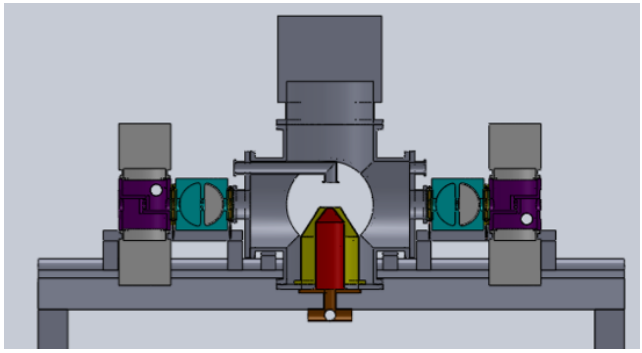


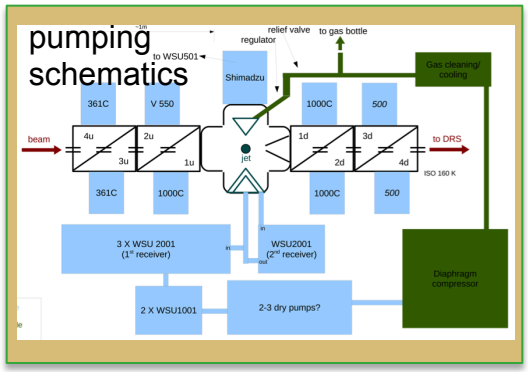
gas target systems



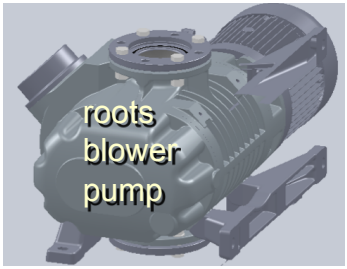


Jet diameter 4 mm
central pressure - 10 Torr
density - 10^{19} at/cm^2
gas volume - liter
system size - 4 m^2
pumps - Roots Blowers, turbos
pumping speed - 2000 m^3/hr
flow rate - 24 Nm^3/hr
weight – 8 tons





- windowless gas **jet** target system for direct, low energy measurements of (p,γ), (p,α), (^{3}He,d), (α,p) …
- standalone mode or as front end to separator for (p,γ)

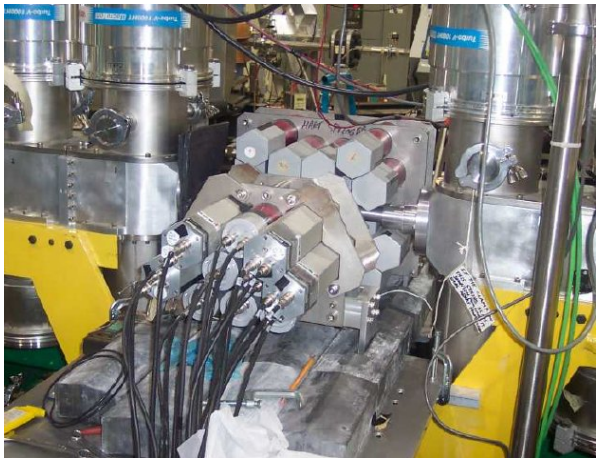


- Status: funded at over 1 M$, collaboration in place, construction in progress at ORNL, will move to ReA3 in 2013

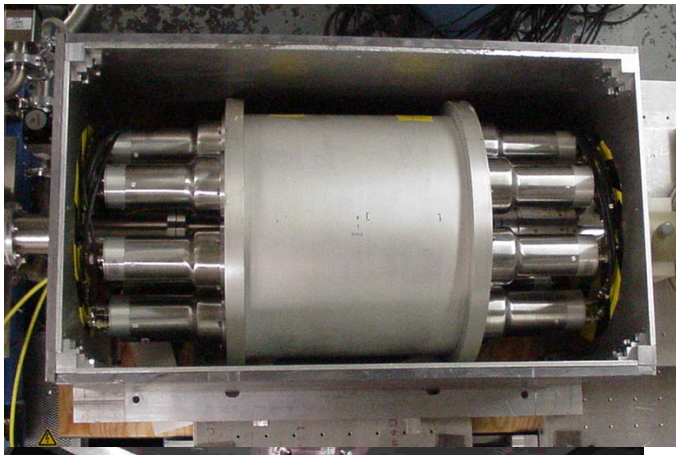
gamma ray detection systems

- excellent efficiency for gamma rays with energy ~ few MeV
- excellent performance for low multiplicity events
- geometry flexible to accommodate gas target assembly
- ability to **reject** high intensity (~MHz) background of 511 keV gammas from scattered beam particles
- large solid angle (~2π) with gas target assembly
- energy resolution equivalent to NaI or better
- fast timing (~ns) for recoil-gamma coincidences
- available for extended experiments (~month)
- examples: BGO array [ISAC]; BAF2 array [ORNL/MSU/TAMU]; GRETINA [portions…]

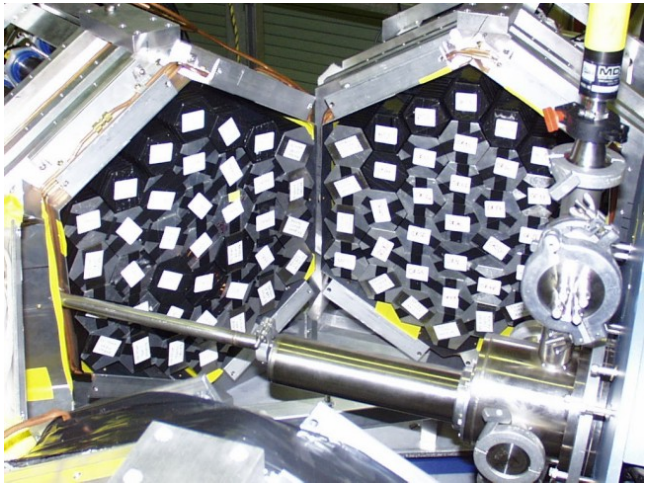
gamma ray detection systems



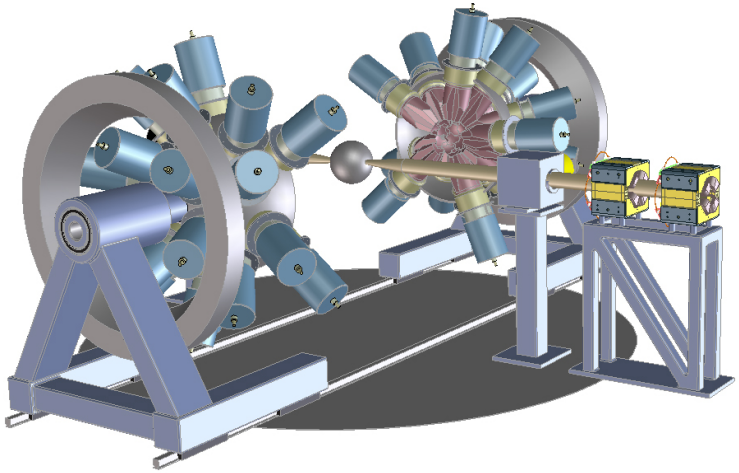
BGO Array at TRIUMF
Used to measure $^{21}Na(p,\gamma)^{22}Mg$



NaI Annulus / HPGe at LENA
Used to measure $^{14}N(p,\gamma)^{15}O$



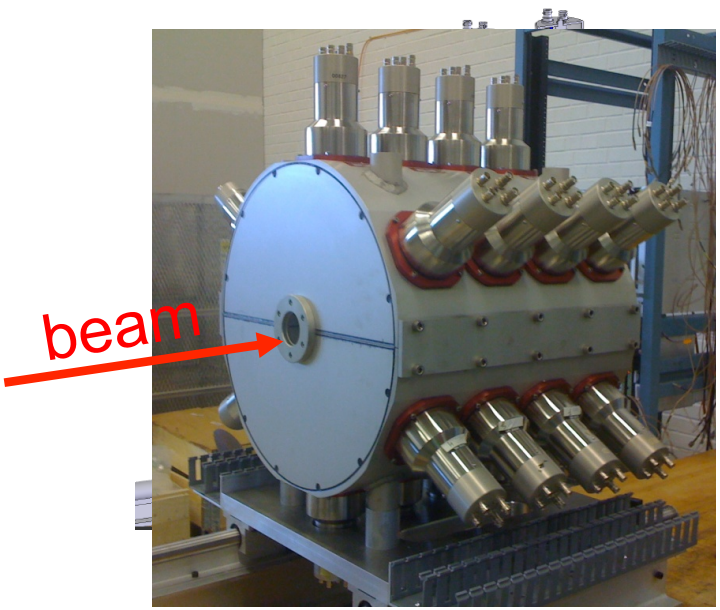
BaF2 at ORNL-MSU-TAMU

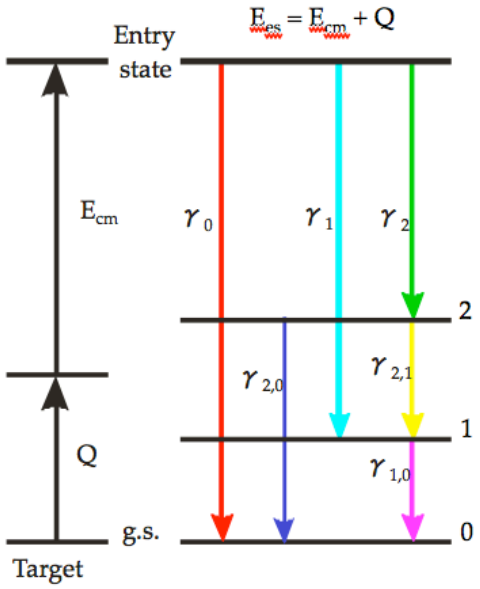


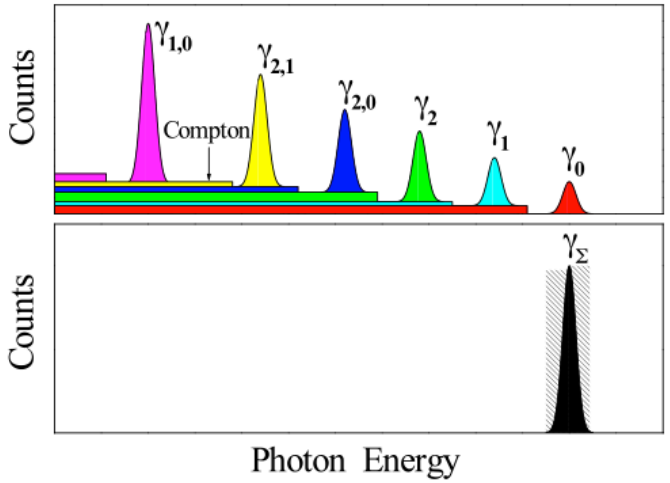
GRETA

gamma ray detection systems

SuN detector – A. Spyrou et al., Michigan State Univ.







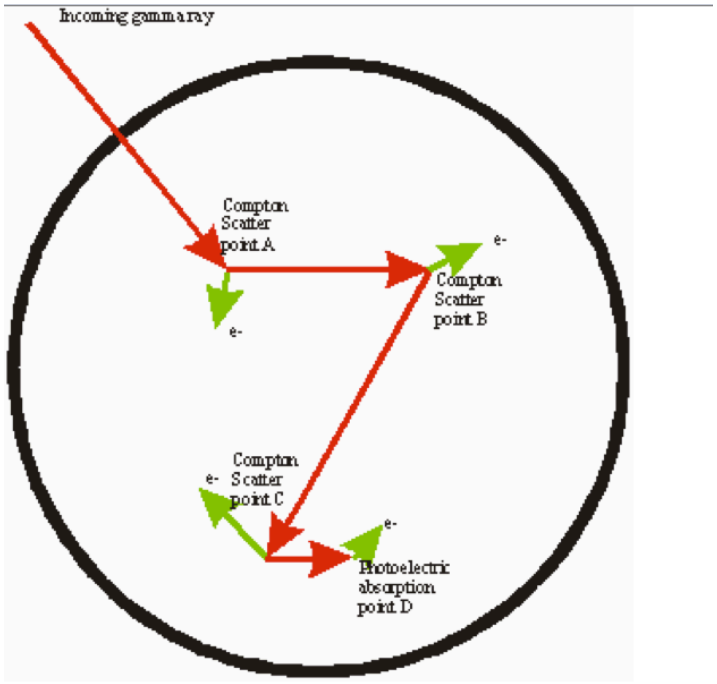
summing NaI detector for (p,γ) measurements on heavy radioactive nuclei needed for (γ,p) reactions in the p-process in supernovae

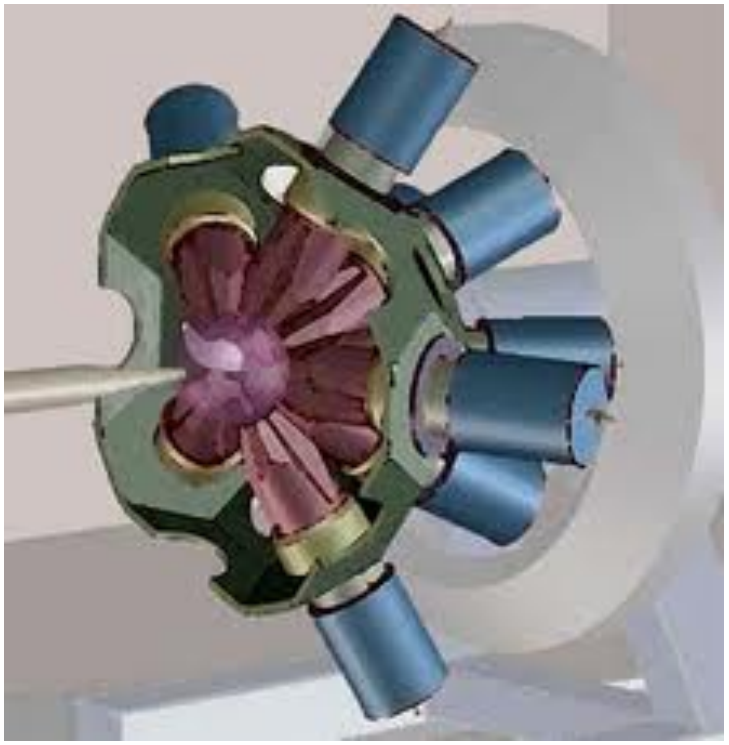
- first experiment expected to be ^{77}Br(p,γ)^{78}Kr to determine the p-process reaction ^{78}Kr(γ,p)^{77}Br

status: being commissioned at NSCL & Notre Dame

gamma ray detection systems

GRETINA





- future gamma detector array for measurements at FRIB & other facilities
- high segmentation, high resolution array
- TRACKING of gamma ray interactions – the state of the art in gamma detection
- tracking enables huge reduction in Compton scattering events & excellent Doppler corrections and background reduction by determining γ-ray path in Ge crystal

for more info

Smith_Rehm.pdf

Annu. Rev. Nucl. Part. Sci. 2001. 51:91–130

NUCLEAR ASTROPHYSICS MEASUREMENTS WITH RADIOACTIVE BEAMS*

Michael S. Smith[1] and K. Ernst Rehm[2]

[1]*Physics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6354; e-mail: msmith@mail.phy.ornl.gov*

[2]*Physics Division, Argonne National Laboratory, Argonne, Illinois 60439; e-mail: rehm@anlphy.phy.anl.gov*

Key Words nucleosynthesis, radioactive ion beams, laboratory techniques, experimental facilities

■ **Abstract** Radioactive nuclei play an important role in a diverse range of astrophysical phenomena including the early universe, the sun, red giant stars, nova explosions, X-ray bursts, supernova explosions, and supermassive stars. Measurements of reactions with beams of short-lived radioactive nuclei can, for the first time, probe the nuclear reactions occurring in these cosmic phenomena. This article describes the astrophysical motivation for experiments with radioactive beams, the techniques to produce these beams and perform astrophysically relevant measurements, results from recent experiments, and plans for future facilities.

CONTENTS

1. INTRODUCTION 92
2. MOTIVATION AND BACKGROUND 93
2.1. Nuclear Physics Information for Astrophysical Modeling 93
2.2. Unstable Nuclei in Astrophysical Environments 95
2.3. The Need for Radioactive Beams 99
3. RADIOACTIVE BEAM PRODUCTION TECHNIQUES 100
3.1. Isotope Separator On-Line (ISOL) Production 100
3.2. Projectile Fragmentation Production 102
3.3. In-Flight Production 102

1 of 41

radioactive beams: e