TRIUMF

Canada’s national laboratory
for particle and nuclear physics
and accelerator-based science

The DRAGON facility

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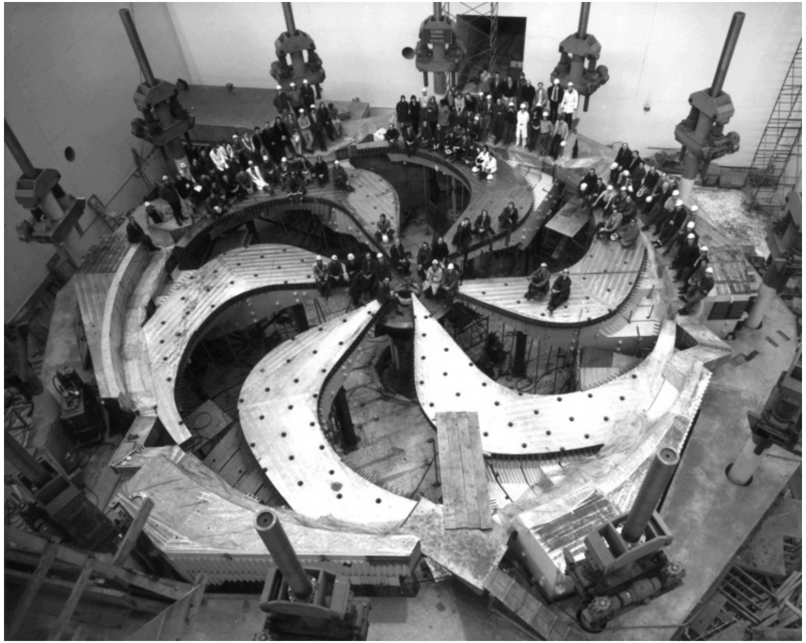
Nuclear Astrophysics at Rings and Recoil Separators – GSI, Darmstadt
March 13th, 2018

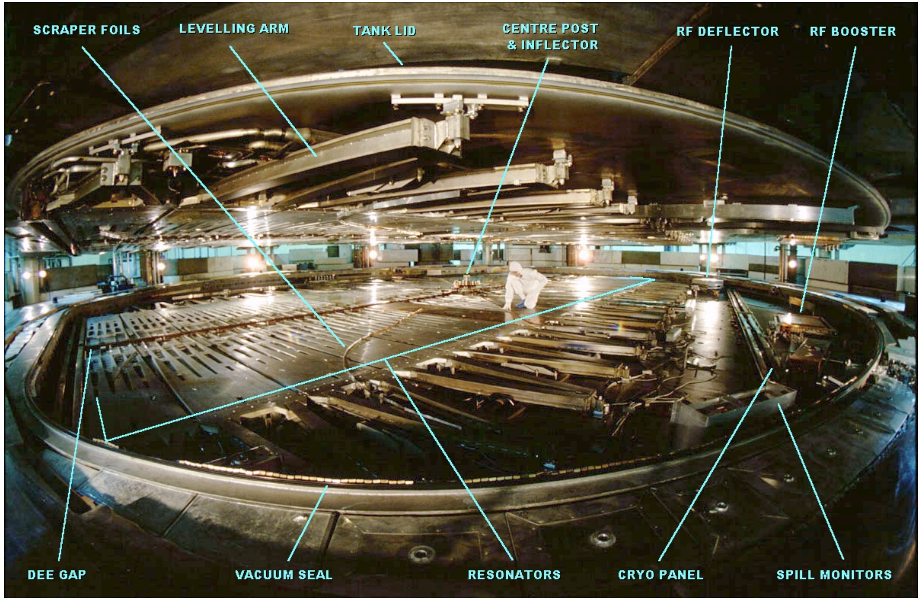
Outline

I. DRAGON introduction
II. Gas target & inverse kinematics
III. Separator specifications
IV. Particle Detection & Identification
V. Summary/Outlook

I. Introduction

TRIUMF facility

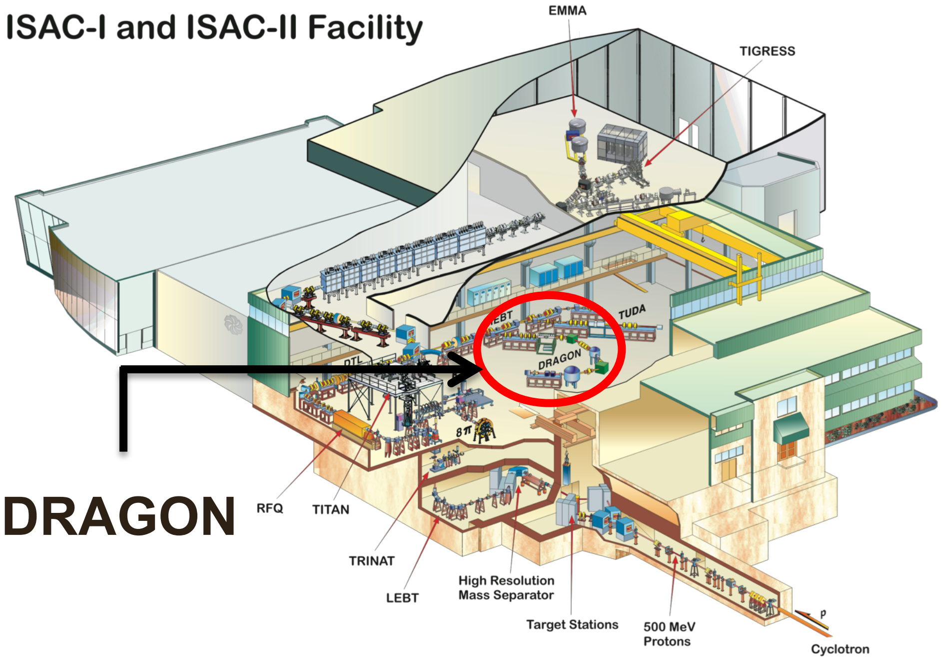




- Production of rare ion beams
- Irradiation of thick production target with proton beam
- Generated in sector-focused H^- cyclotron

500 MeV proton beam
Up to ~100 μA

TRIUMF ISAC facility



- Beams reaccelerated through 35 MHz RFQ with A/q<30
- 105 MHz variable energy DTL ($3 \leq A/q \leq 6$)
- Energies between 0.15 MeV/u & 1.5 MeV/u
- Low-energy regime well suited for reaction studies for novae & X-ray bursts

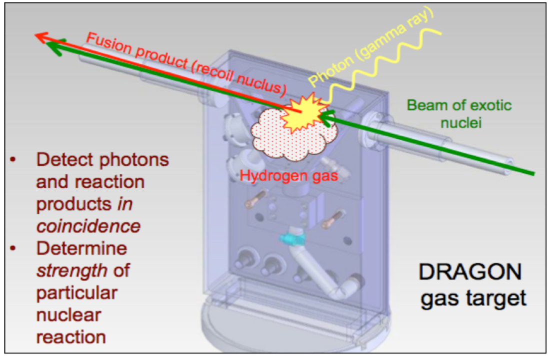
TRIUMF DRAGON – Detector of Recoils And Gamma-rays Of Nuclear reactions

① Windowless gas target

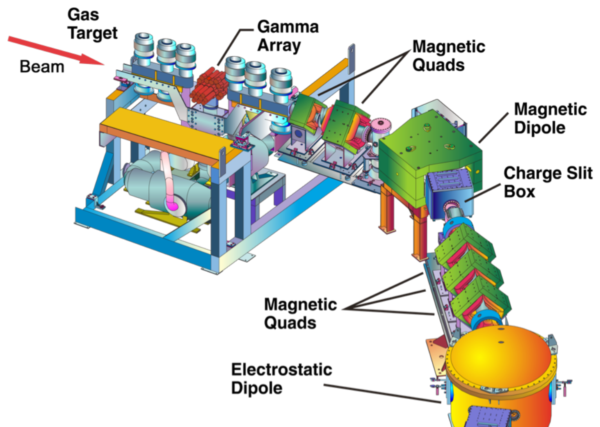
② BGO γ-detection array

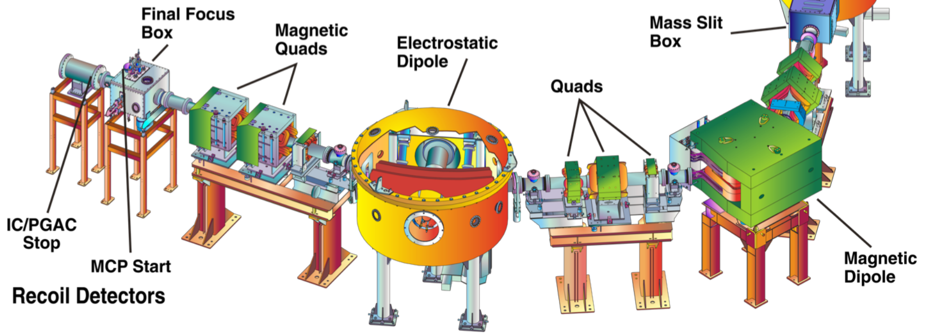
③ MEME mass separator

④ Recoil detection system



- Detect photons and reaction products *in coincidence*
- Determine *strength* of particular nuclear reaction





$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

#reactions per incident ion

DRAGON – Detector of Recoils And Gamma-rays Of Nuclear reactions

① Windo

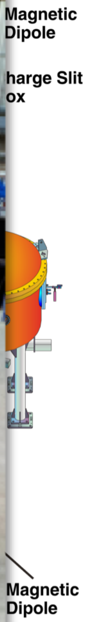
② BGO γ

③ MEMI

④ Recoil

Y(

#reactio
incider



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II. *Gas target and inverse kinematics*

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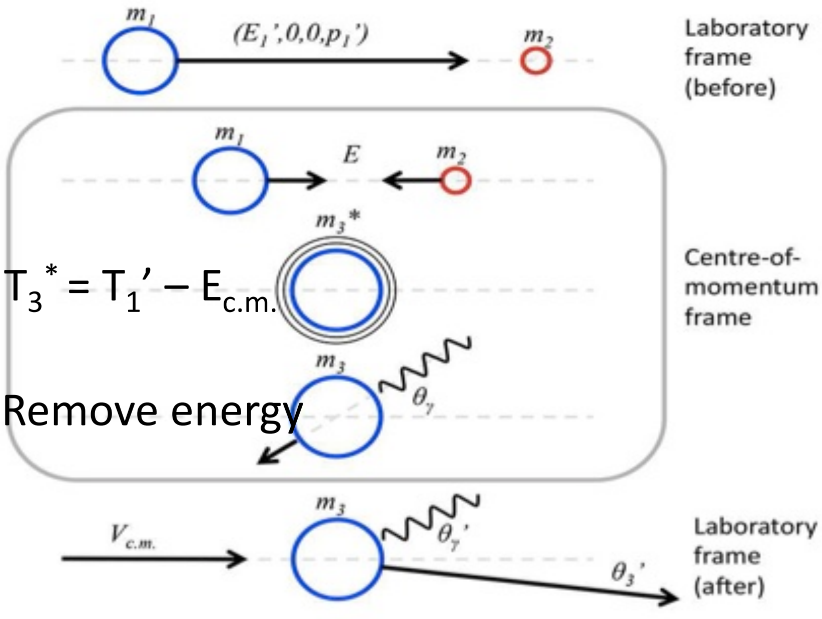
Radiative capture in inverse kinematics



$T_3^* = T_1' - E_{c.m.}$

Remove energy

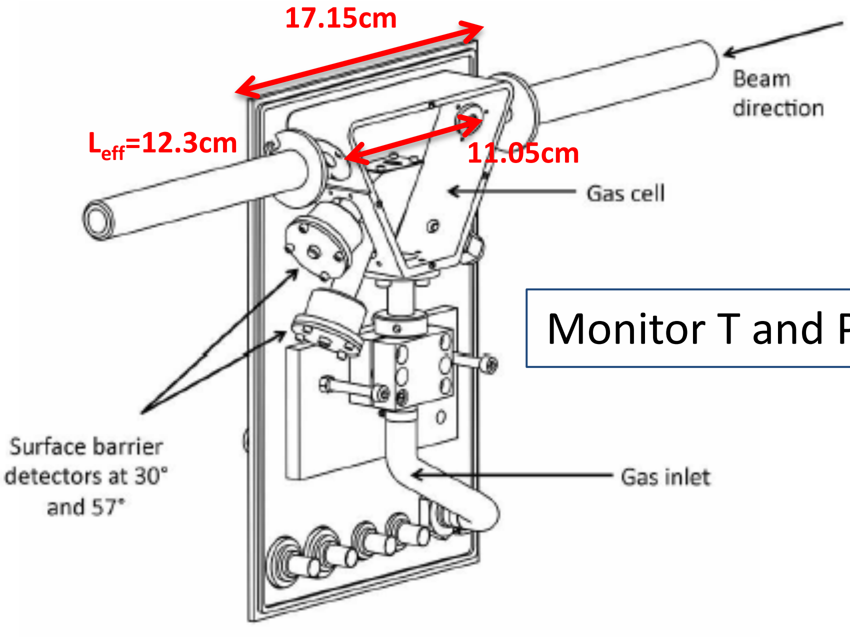
$$N_A\langle\sigma v\rangle = 1.54\times10^{11}(\mu T)^{-3/2}\,\omega\gamma\cdot\exp\left(-11.605\frac{E_R}{T_9}\right)$$

- (p,γ) and (α,γ) reactions
- Mainly resonant capture:
  A + b = C + γ
- σ in μb range

Important consideration:

If ratio m_{beam}/m_{target} is large, recoil energy can only be relatively small amount lower than beam energy!

DRAGON gas target



Monitor T and P!

Extended target

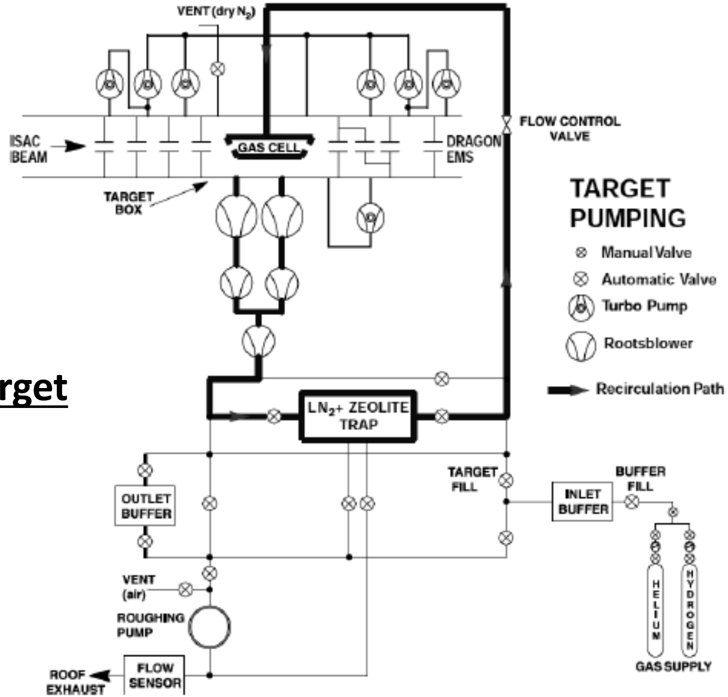
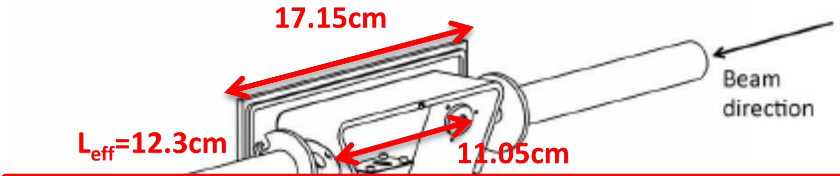
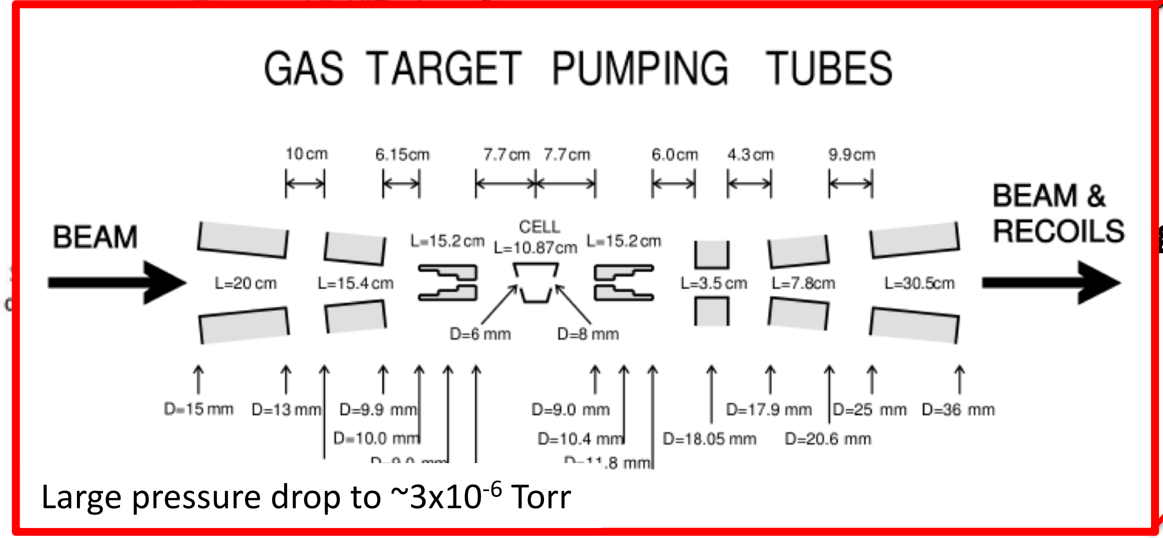


Figure from D. Hutcheon et. al., Nucl. Instr. Meth. A 498,, 190 (2003)

- Windowless, differentially pumped, recirculating **gas target** (H_2 or He)
- 1-10mbar (pumping constraints)
- LN_2 cooled zeolite cleaning trap

DRAGON gas target





Large pressure drop to ~$3x10^{-6}$ Torr

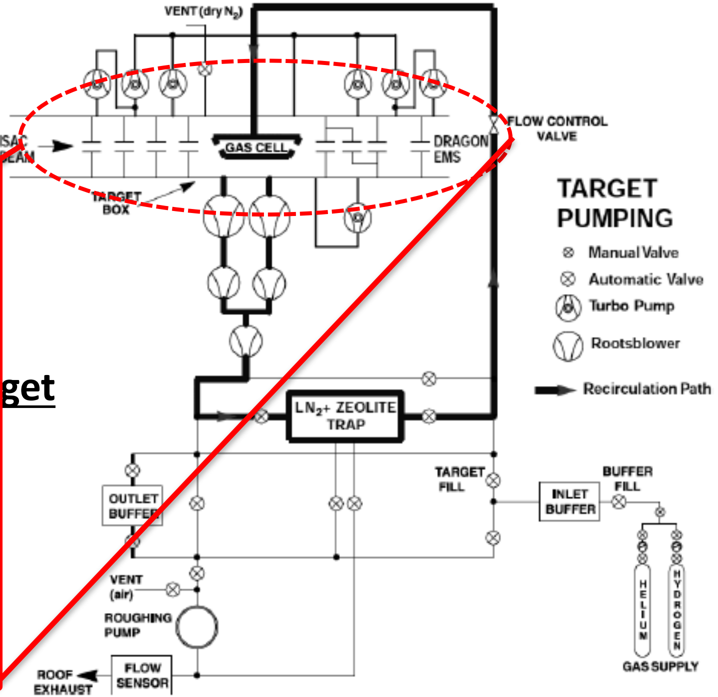


Figure from D. Hutcheon et. al., Nucl. Instr. Meth. A 498,, 190 (2003)

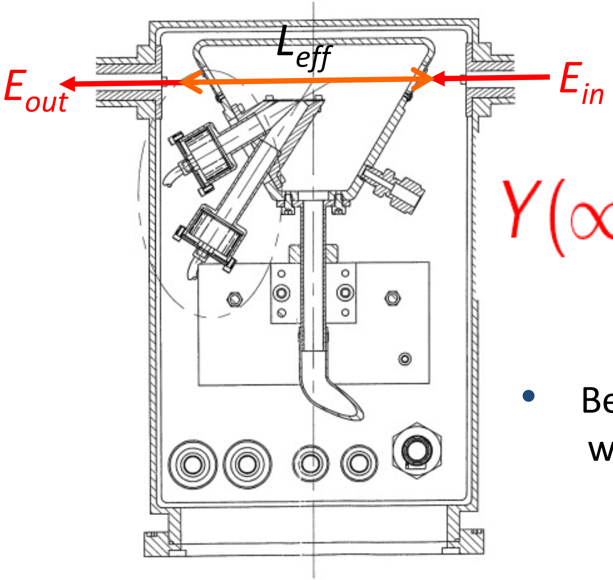
get

(H_2 or He)

- 1-10mbar (pumping constraints)
- LN_2 cooled zeolite cleaning trap

DRAGON gas target

- Extraction of cross section & resonance strength requires knowledge of **stopping power** of heavy ions in H or He
- SRIM code shows 20-30% deviation from experiment
- Stopping power measurement requires knowledge of **effective length**



$$Y(\infty) = \frac{\lambda^2}{2}\frac{M+m}{m}\epsilon^{-1}\omega\gamma$$

- Beam energy can be measured with 0.1-0.2 % accuracy (**ΔE & stopping power ~5%**)

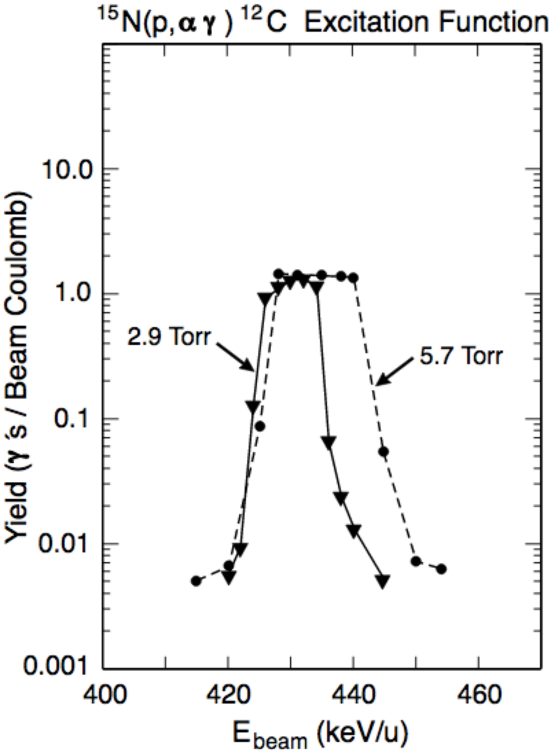


Figure from D. Hutcheon et. al., Nucl. Instr. Meth. A 498,, 190 (2003)

DRAGON gas target – DON'TS!

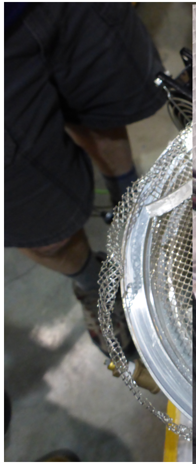
We learned the hard way…

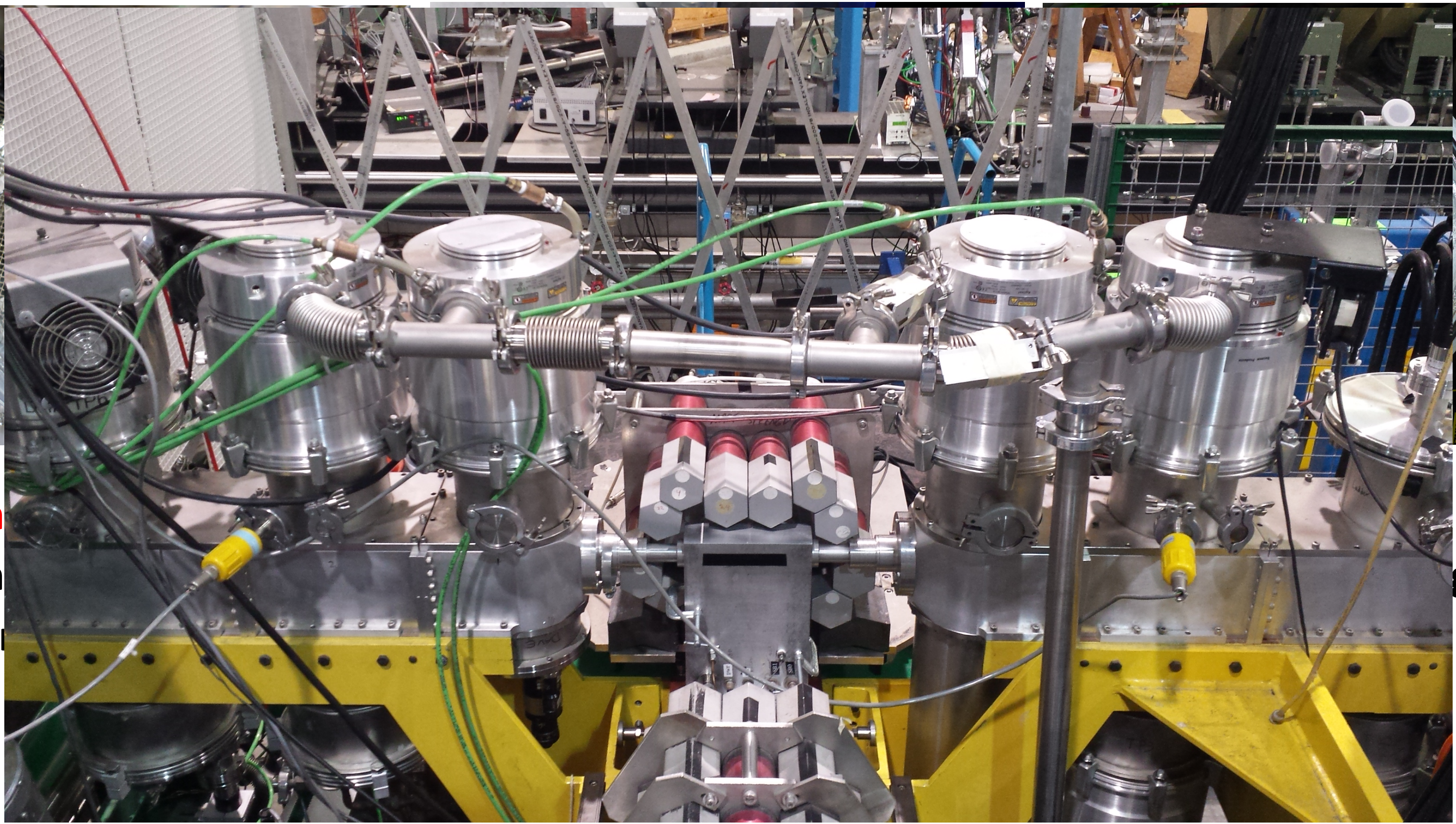
- Pumping Xenon resulted in catastrophic failure of 6 turbo pumps!
- High atomic weight → noble gases generate large quantities of heat when striking the rotor
- Low specific thermal capacity → little heat transfer to stator or housing

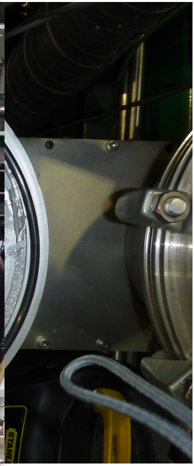
  → High rotor temperatures!

DRAGON gas target – DON'TS!

We learned the hard way…





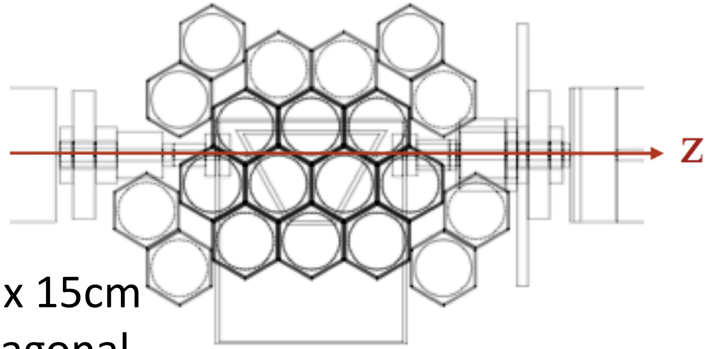


- **Pum**
- **High** **g the rotor**
- **Low**

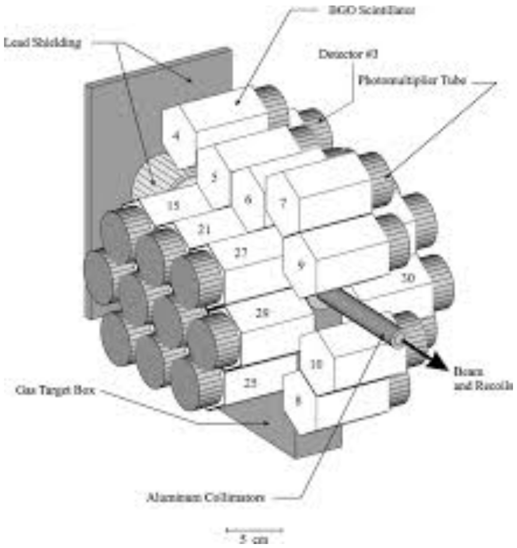
γ-ray detection – BGO array

- **BGO** ($Bi_4Ge_3O_{12}$) array (30 detectors)
- High γ-ray detection efficiency (40 to 80%, depending on multiplicity & energy)
- Combined with TOF → **low random** coincidence rate!
- **Caveat:**
  - Rely on **simulation** for detection efficiency

    → dominates syst. error of the experiment!
  - Limited γ-ray energy resolution (FWHM ~9%)
- **Segmented** BGO array along beam axis → Information about location of reaction
- BGO hit pattern → **resonance energy** (0.5%)



5cm x 15cm hexagonal



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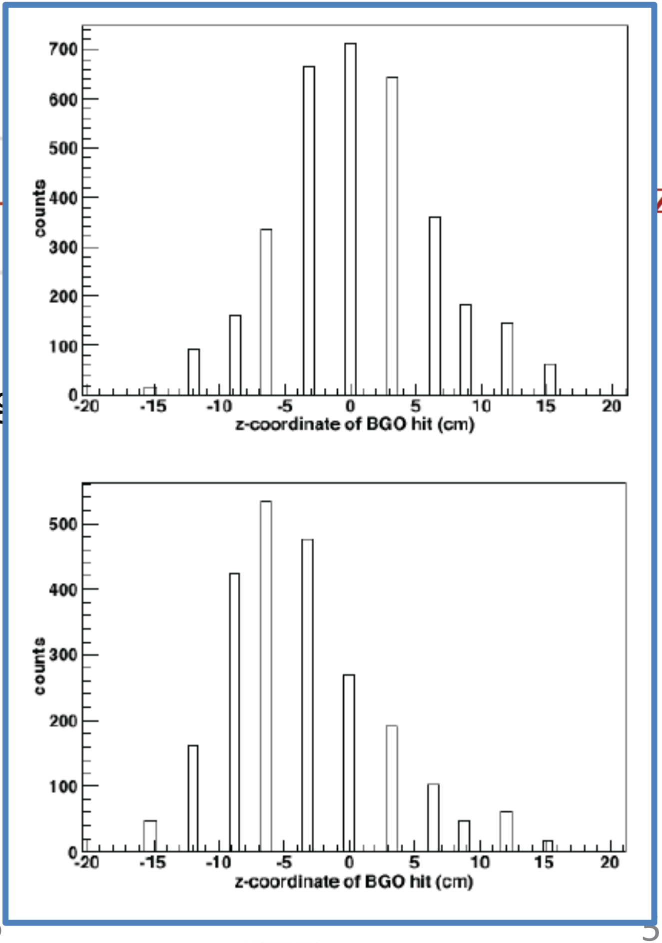
5cm x

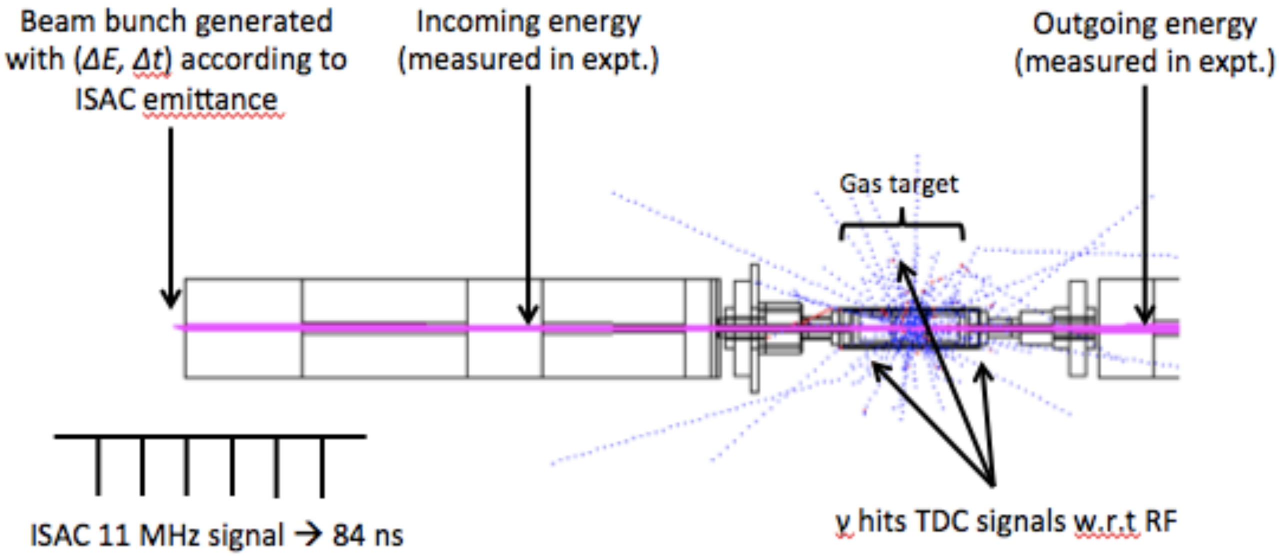
hexag



Upgrade to $LaBr_3$ array – resonant timing technique

- Medium with **better timing properties (sub-ns)** and/or energy resolution
- High-efficiency scintillation material → **$LaBr_3$**
- Timing between **prompt γ-rays & accelerator beam bunch** arrival time → **Reaction position**

Extra sensitive, precise measure of resonance energy!



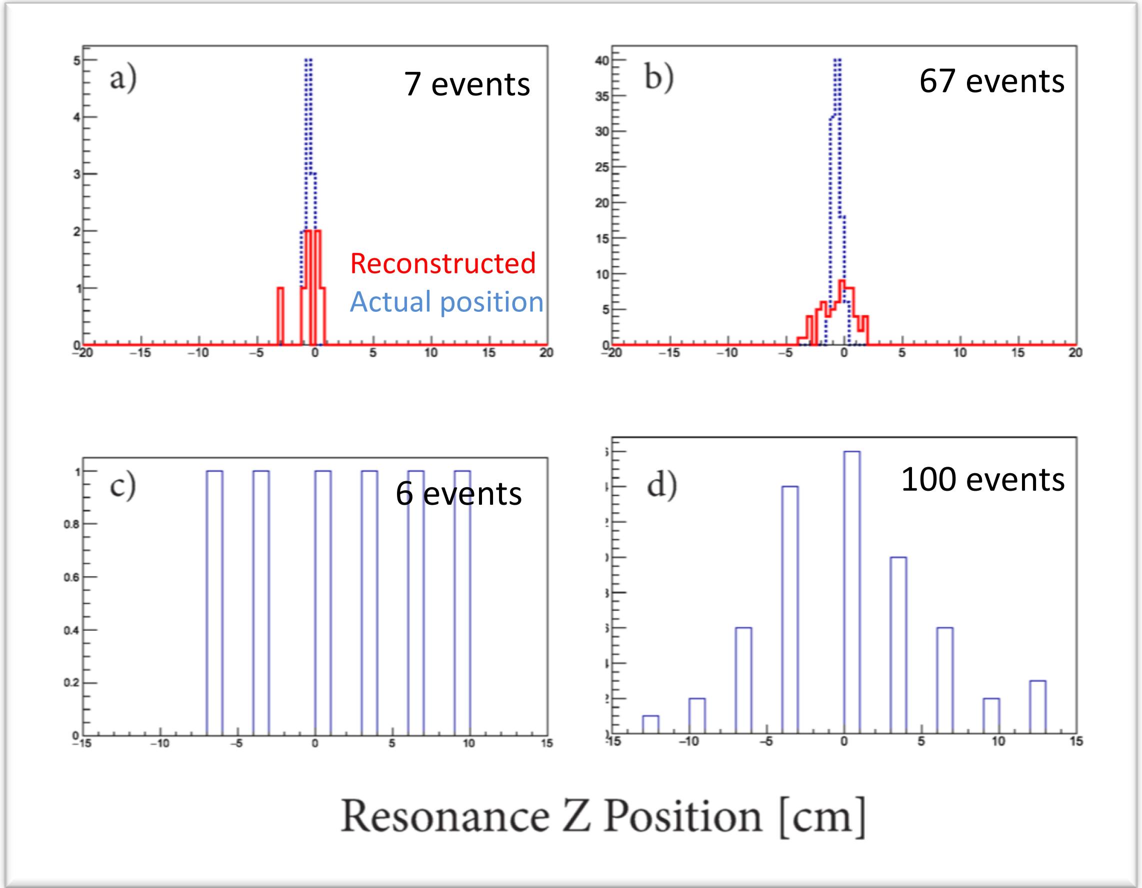
Resonance timing systematics

Timing method outperforms the z-position method!

z_0 within a few events, to ~ ±0.3cm accuracy

Even for larger sample sizes, broadness of distribution in z-position method results in larger centroid uncertainties

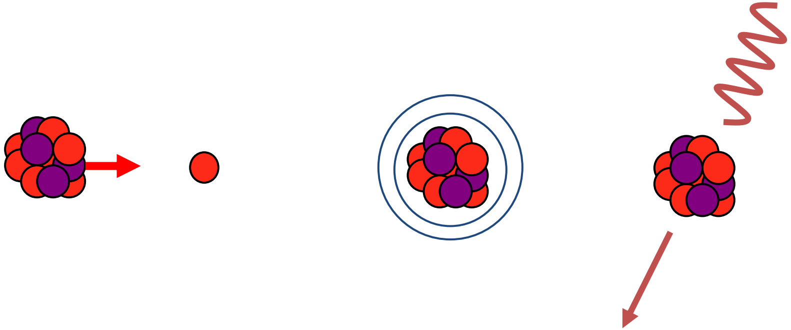
Next:
Proof-of-principle test this summer

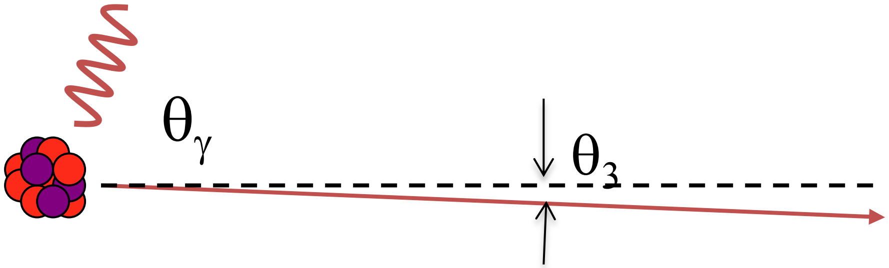


III. Separator specifications

Geometric acceptance

Defines range of reactions that can be measured!





- **Maximum** possible **recoil angle** when E_γ is maximized for $E_\gamma = Q+E_{c.m.}$
- AND emission perpendicular to incident beam direction **($\theta_3=\pi/2$)**
- **Nominal acceptance** (w.r.t zero):

  21 mrad & +/- 4% in E

Non-relativistic limit:

$$\boxed{\tan\theta'_{3,\max} \cong \frac{Q+E_{c.m.}}{\sqrt{2\frac{m_1}{m_2}(m_1+m_2)E_{c.m.}}}}$$

$$\boxed{\frac{d\theta'_3}{dE}=0;\ E_{cm}=Q}$$

Momentum spread:

$$\boxed{\frac{\Delta p'_3}{p'_3}\cong\frac{E_{\gamma,\max}}{p'_1}\cong\theta'_{3,\max}} \xrightarrow[\textit{momenta with}]{\textit{Needs to accept}} \boxed{\Delta p'_3\left(1\pm\frac{\Delta p'_3}{p'_3}\right)}$$

Geometric acceptance

Minimum at $E_{cm} = Q$

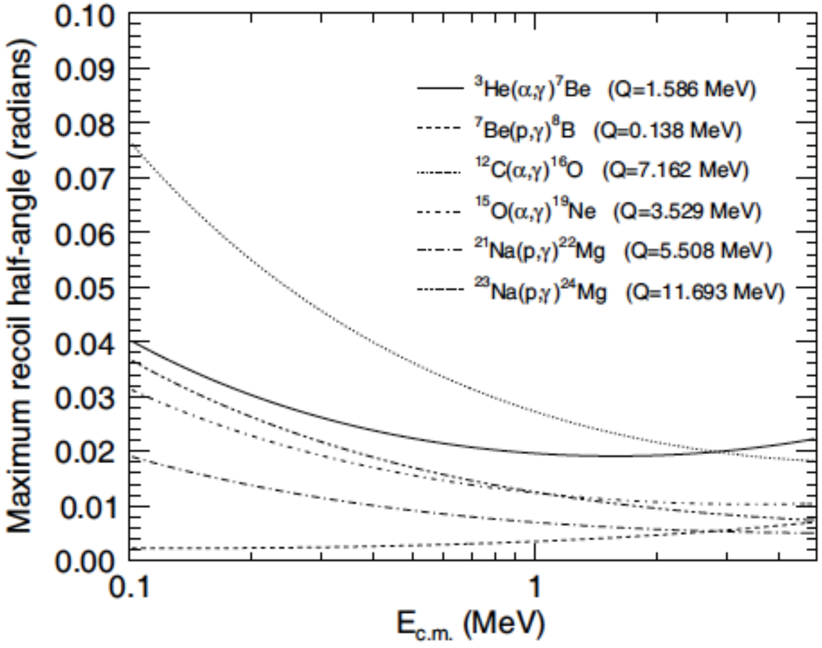
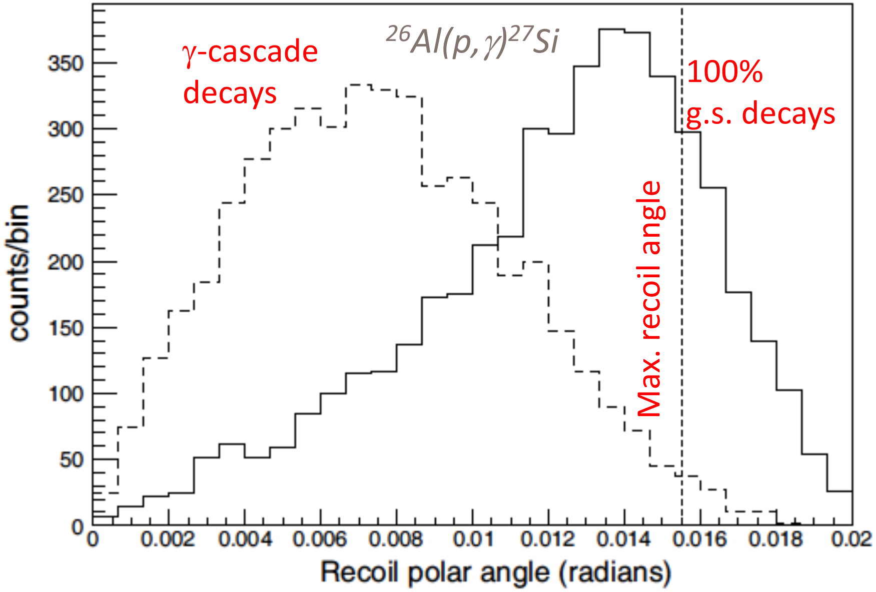


Figure from C. Ruiz et. al., Eur. Phys. A 50, 99 (2014)



γ-cascade decays

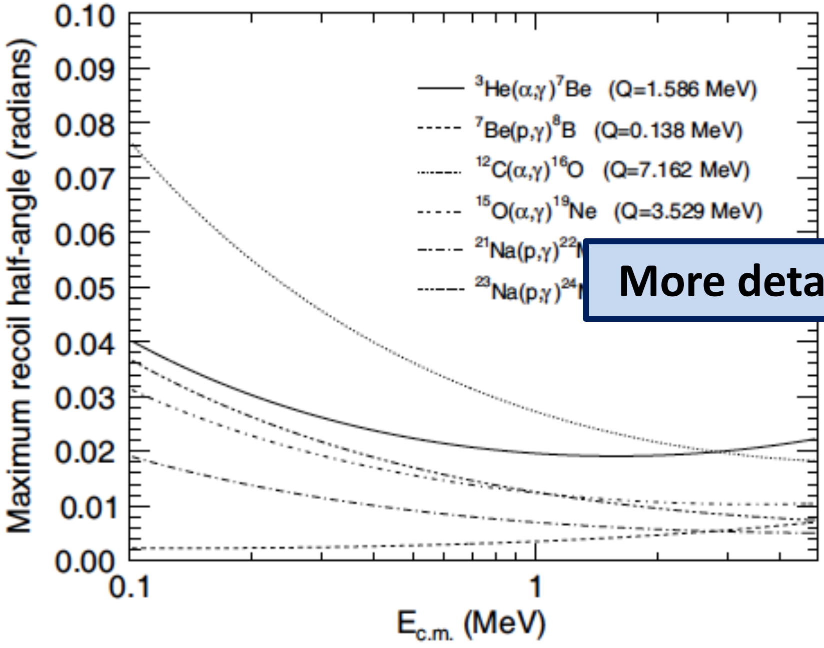
100% g.s. decays

Max. recoil angle

Figure from C. Ruiz et. al., Eur. Phys. A 50, 99 (2014)

Geometric acceptance

Minimum at $E_{cm} = Q$



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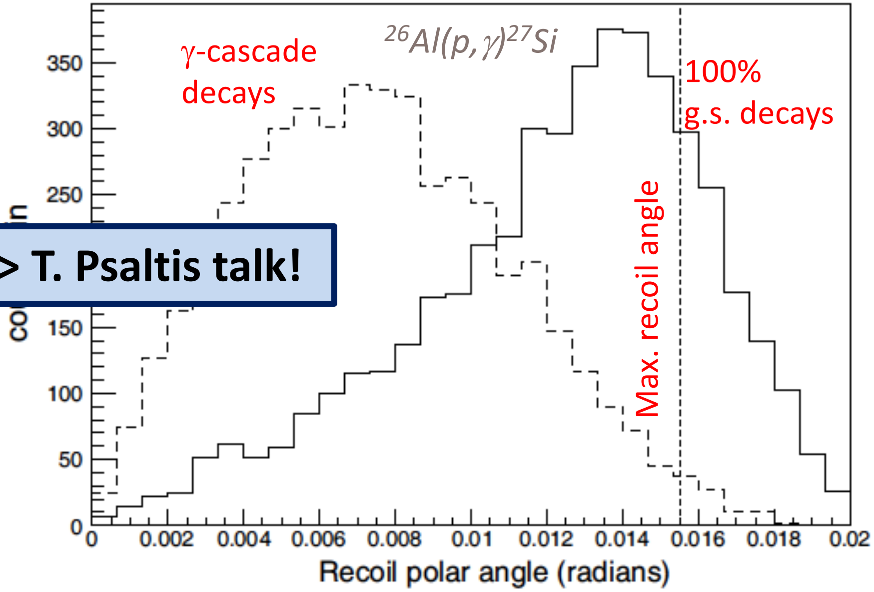
More details -> T. Psaltis talk!



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

γ-cascade decays

100% g.s. decays

Max. recoil angle

Figure from C. Ruiz et. al., Eur. Phys. A 50, 99 (2014)

Rigidity

- DRAGON designed for beam rigidities up to 0.55 Tm
- Limiting factors:
  a) Max. **field strength** at MD1 (0.55 T)
  b) Max. **sustainable voltage** of ED1
- B-field limiting factor for ion energies below 1.34 A MeV
- E-field limiting factor for ion energies corresponding to max. voltage (230 kV)

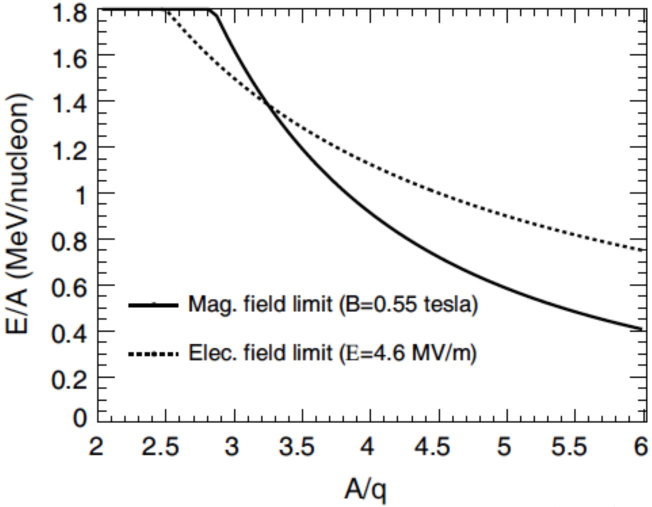


Figure from C. Ruiz et. al., Eur. Phys. A 50, 99 (2014)

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

$$R_E = |\varepsilon|\rho = \frac{pv}{q}$$

- Higher masses → boost charge state
- **Problem:** Difficult to equilibrate in very high charge states

→ Higher fields desired

- **BUT:** Depends on conditioning ability & power supply capability

Separator beam suppression

- **High** intrinsic **beam suppression:** 10^8 to 10^{13} (proton capture)
- Depends on **beam energy & emittance**
- $>10^{14}$ raw suppression demonstrated for $^3He(\alpha,\gamma)^7Be$
- **Coincidence measurement** with prompt γ-rays & PID cuts & TOF

→ **suppression factor** of ~10^{15} for p-capture & ~5×10^{17} for α-capture

*Beam suppression is **NOT** described by a single number, but determined by mass & charge difference, decay mode, energy, detectors, etc…*

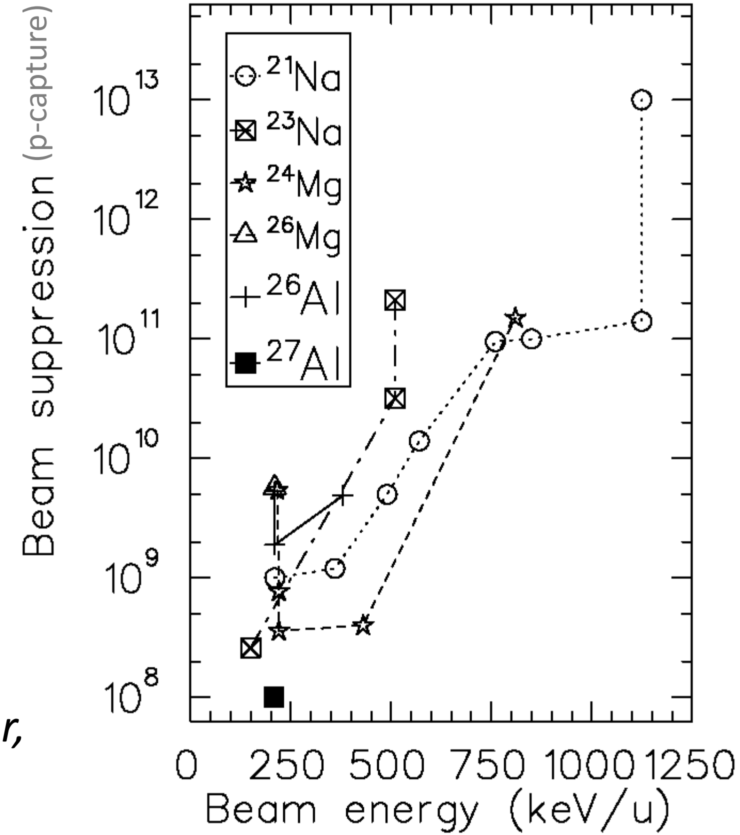
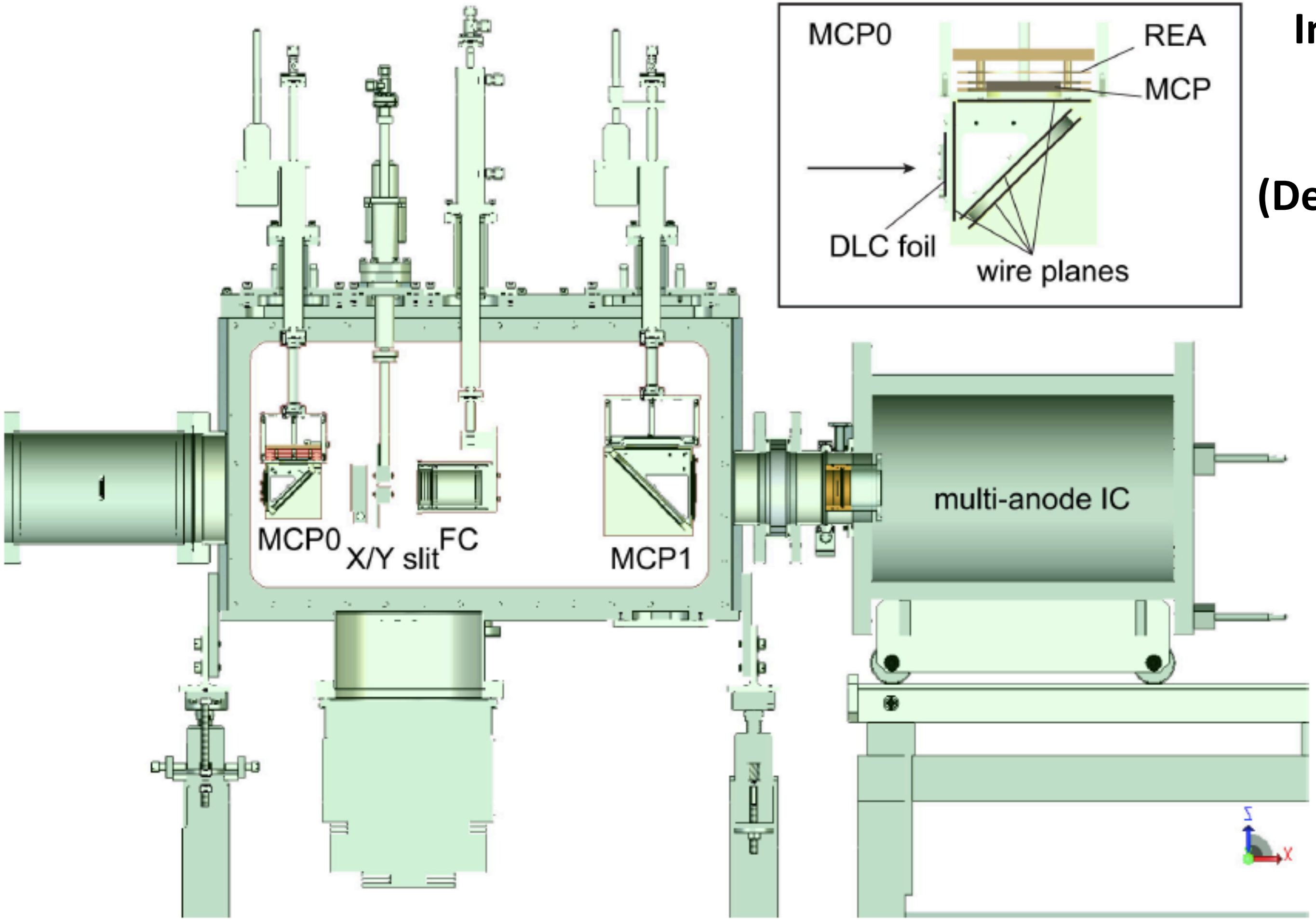


Figure from D. Hutcheon et al. NIMRB 266 (2008)

IV. Particle Detection and Identification

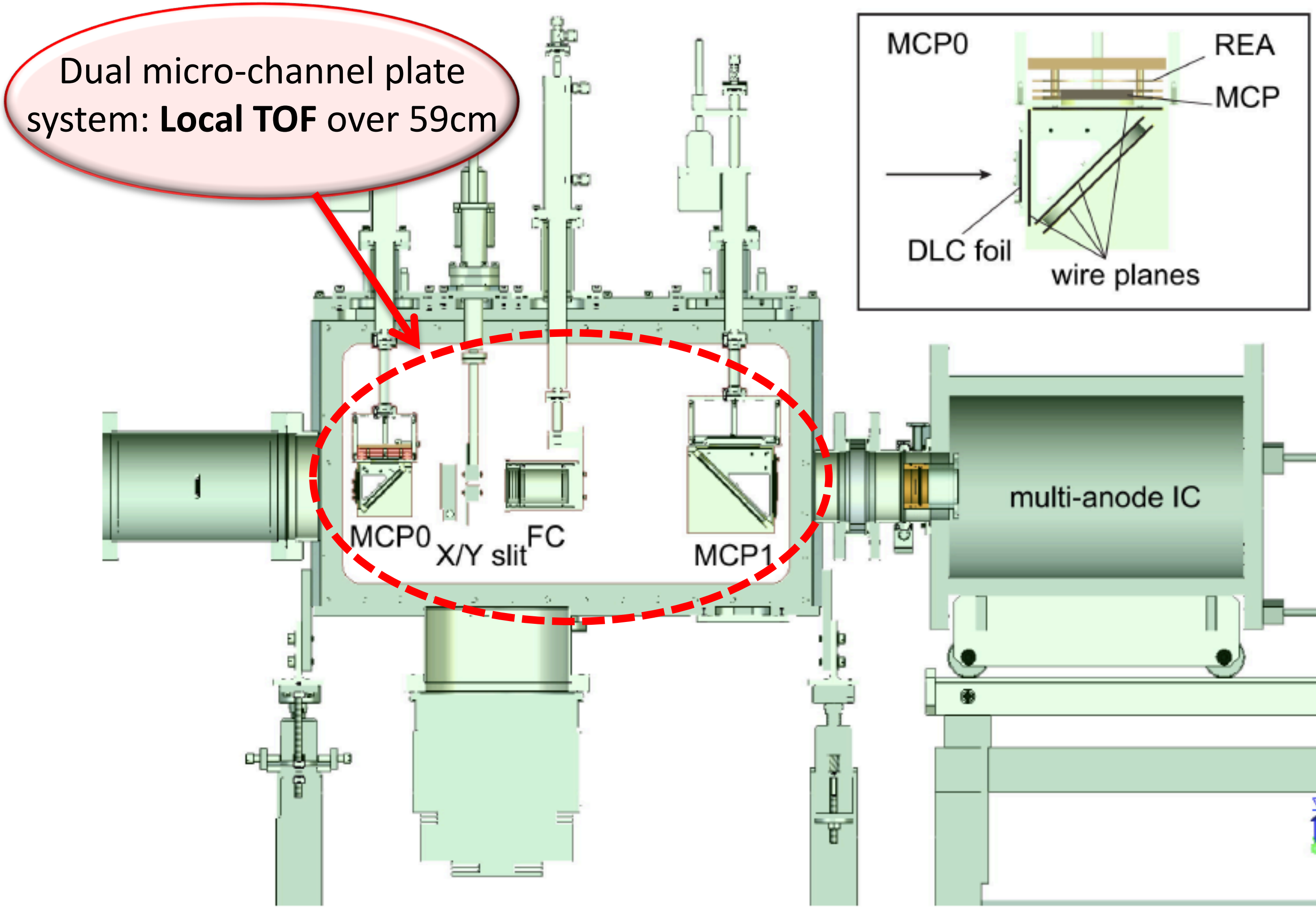
Particle detection – end detectors



Interchangeable end detectors
IC or DSSSD
(Depending on reaction)

- Particle ID
- Local TOF
- ΔE/E, Total E

Particle detection – end detectors



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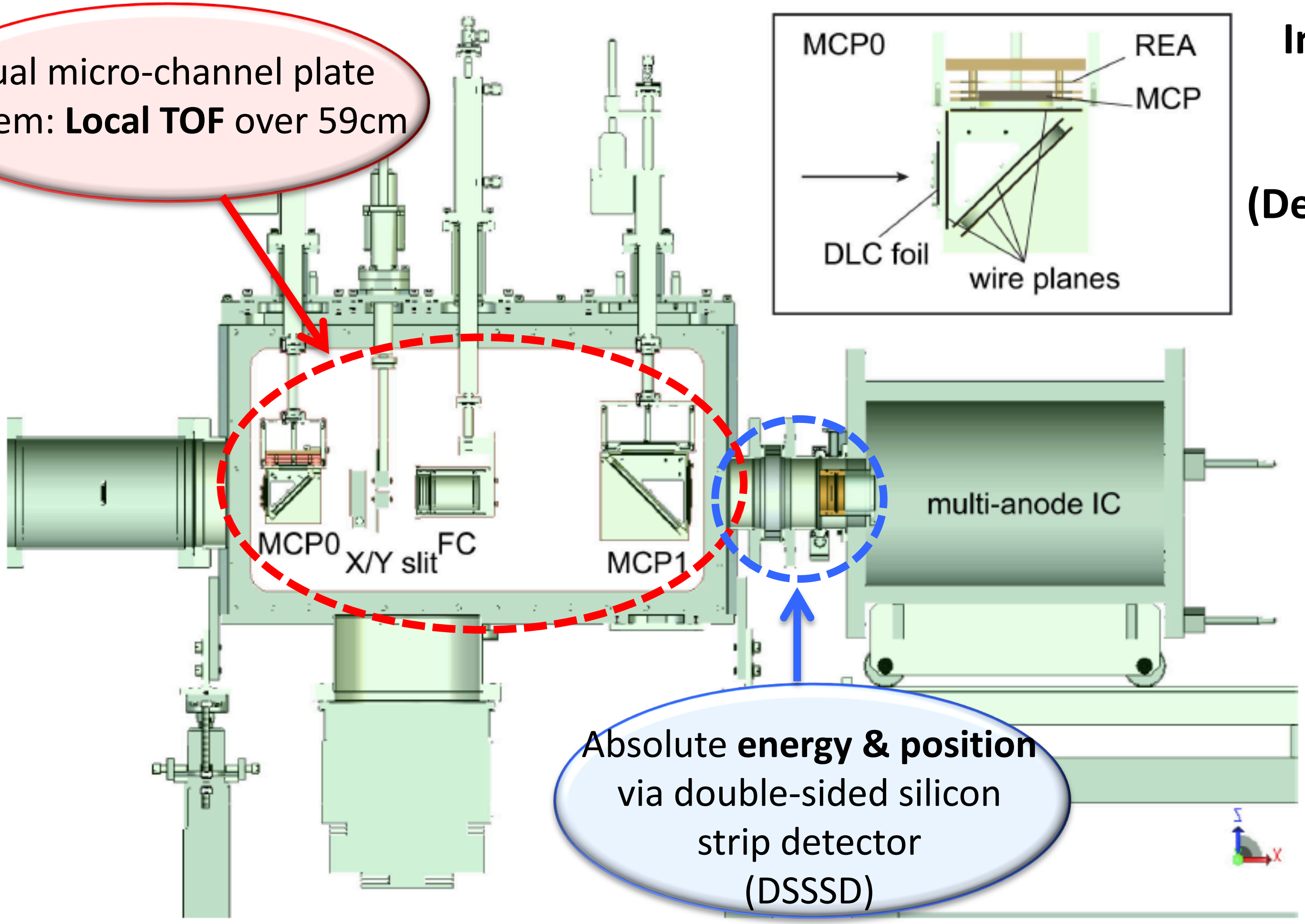

Dual micro-channel plate system: **Local TOF** over 59cm

Absolute **energy & position** via double-sided silicon strip detector (DSSSD)

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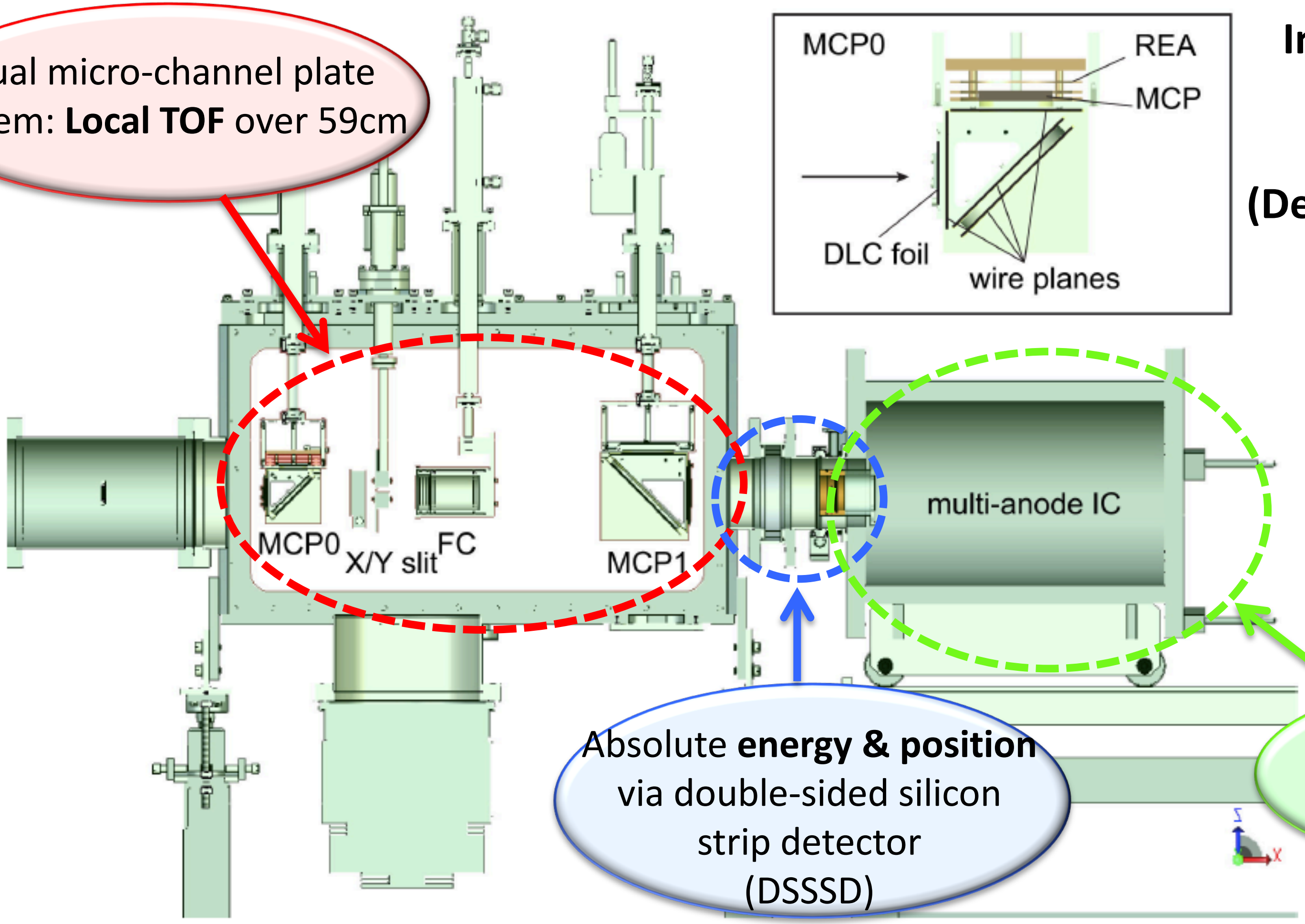
Particle detection – end detectors



Dual micro-channel plate system: **Local TOF** over 59cm

Absolute **energy & position** via double-sided silicon strip detector (DSSSD)

ΔE-E in ionization chamber for **Z-identification**

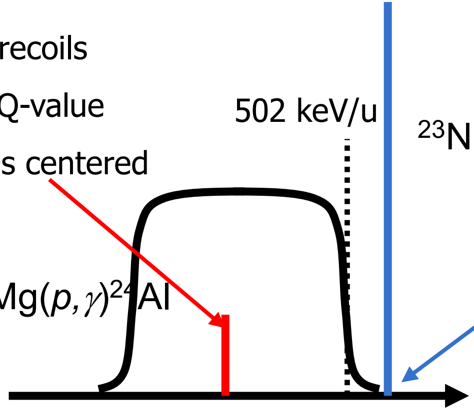
Interchangeable end detectors
IC or DSSSD
(Depending on reaction)

- Particle ID
- Local TOF
- ΔE/E, Total E

Particle detection & identification - Beam composition

- ISOL beams may contain **isobaric contaminants**
- Tradeoff between ΔM/M of mass separator to transmission (beam intensity)
- Stable beams may contain **A/q contaminants** from multi-charge ion source

ΔE-E & BGO distr. allows separation of isobars & isobaric reactions



^{24}Al recoils

low Q-value

BGOs centered

502 keV/u

^{23}Na$(p,\gamma)^{24}$Mg

^{24}Mg recoils

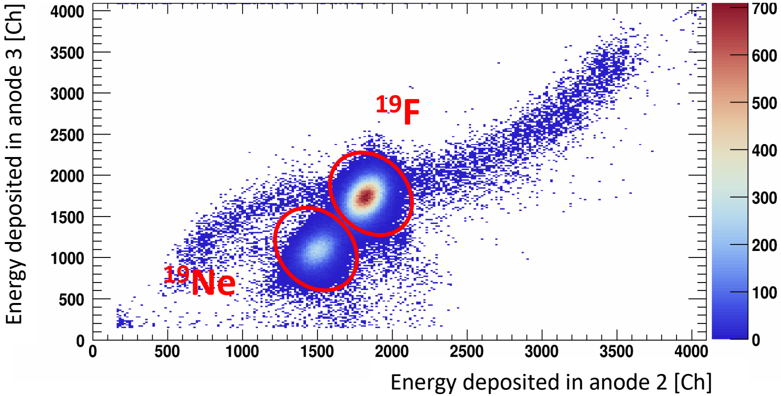
large Q-value

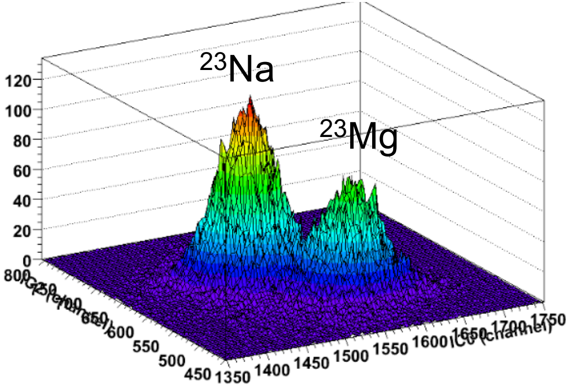
BGOs upstream hit

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

energy

Attenuated beam run





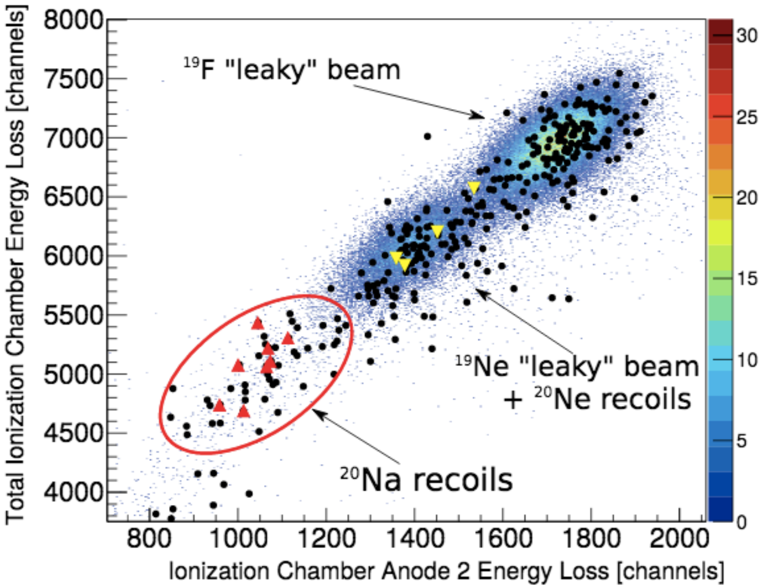
ΔE vs E (ionization chamber)

Particle detection & identification

DRAGON designed to handle contaminants

→ Particle **separation & identification**

→ **ΔE-E excellent separation especially at lower energies**



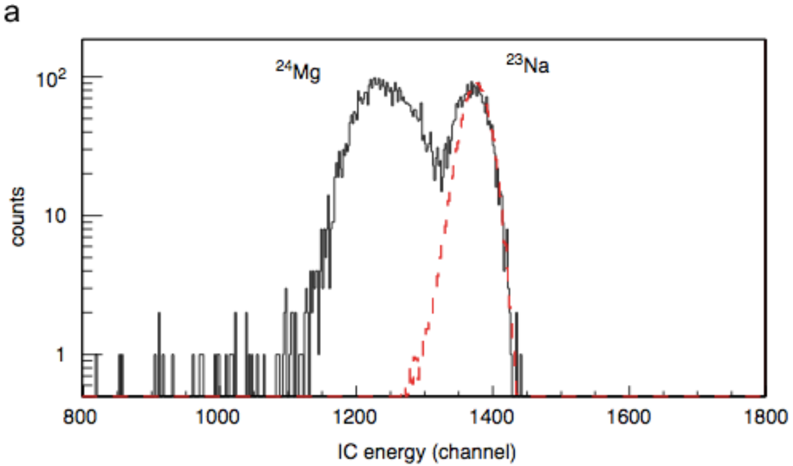


Figure from C. Vockenhuber et. al., NIM Phys. Res. A 603, 372-378 (2009)

Using:

ΔE-E, MCP TOF & Separator TOF, γ-energy, BGO hit pattern

Particle detection & identification - TOF

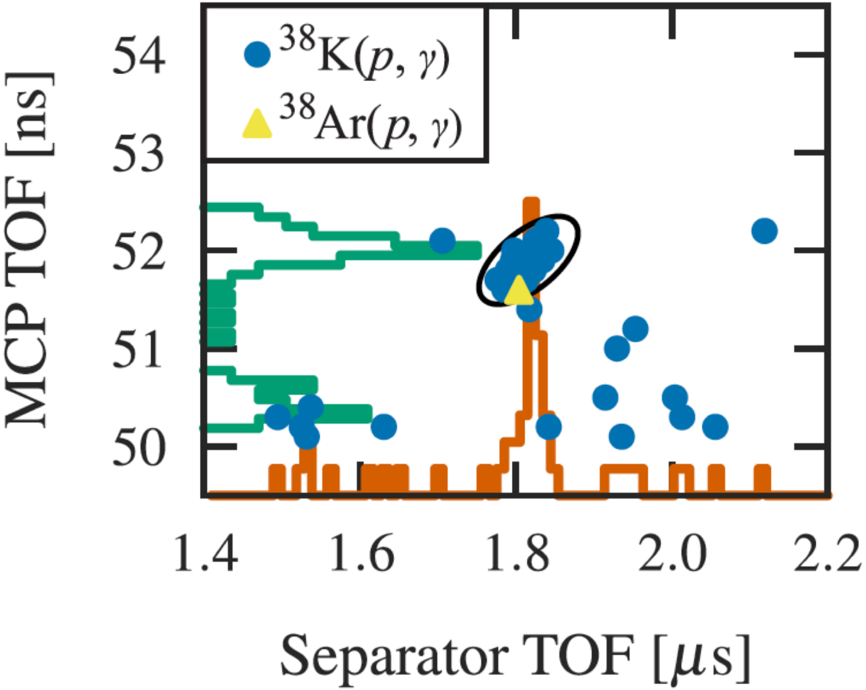


Figure from G. Christian et. al., Phys. Rev. C. 97, 025802 (2018)

^{24}Mg$(p,\gamma)^{25}$Al, E_R=214 keV

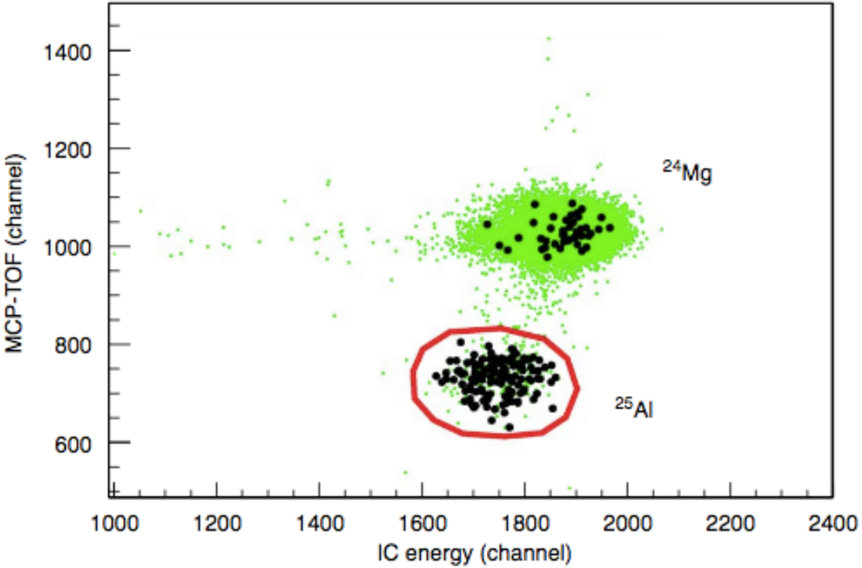
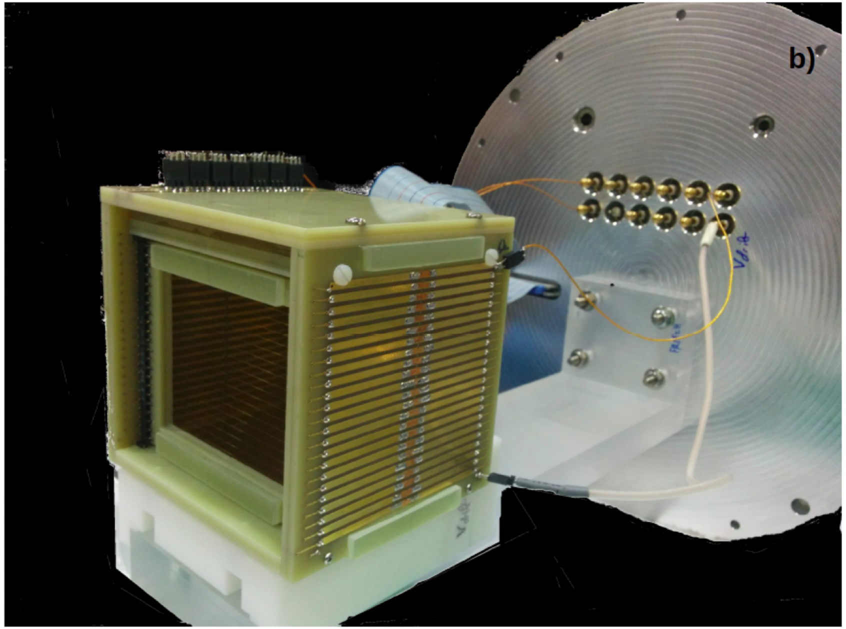
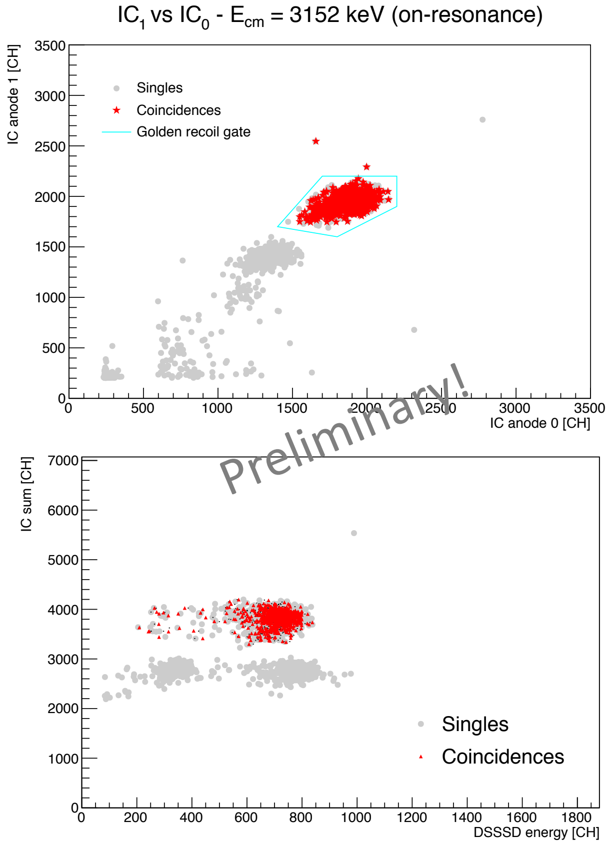


Figure from C. Vockenhuber et. al., NIM Phys. Res. A 603, 372-378 (2009)

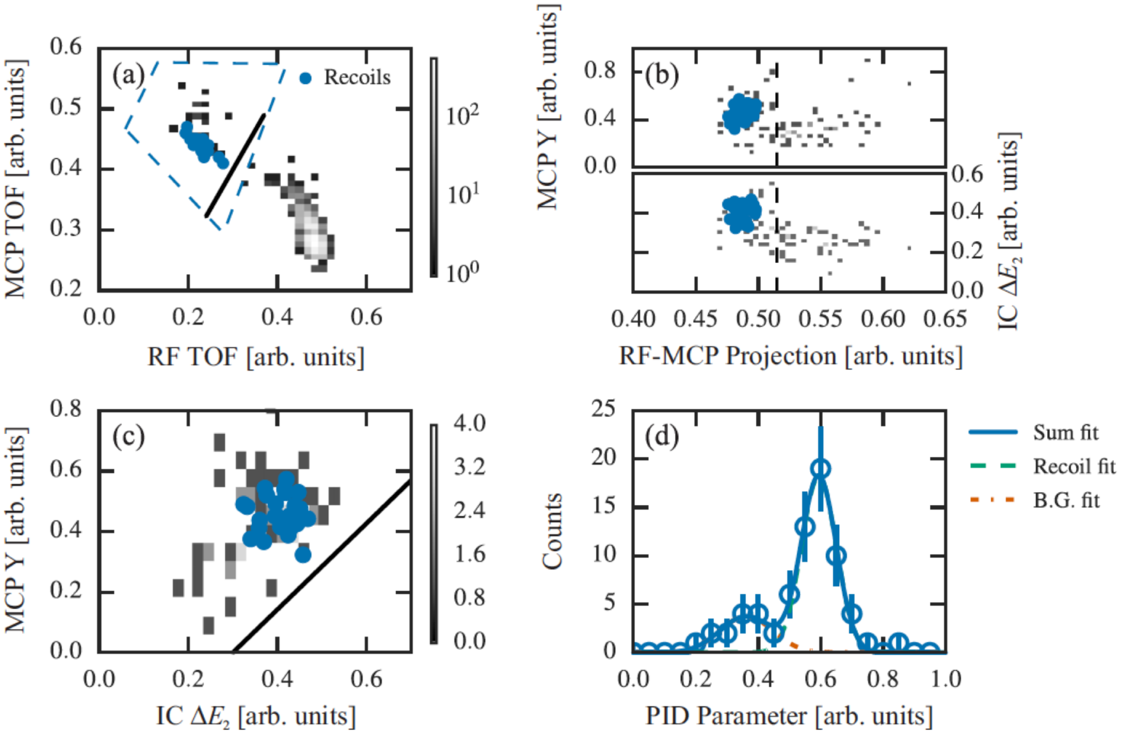
Particle detection – Hybrid detector

Combine properties of IC (ΔE) and DSSSD (operation, position sensitivity & resolution) in hybrid detector





Particle Identification – RF timing



- Time difference between incoming beam bunch (measured from the ISAC I RFQ signal) and the upstream MCP

- Reconstruct separator TOF without prompt γ rays!

→ Allows for singles analysis

Figure from G. Christian et. al., Phys. Rev. C. 97, 025802 (2018)

V. Outlook and Challenges

Successful program at DRAGON

Reaction	Motivation	Intensity (s^{-1})	Purity (beam:cont.)
$^{21}\mathrm{Na}(p,\gamma)^{22}\mathrm{Mg}$	1.275 MeV line emission in ONe novae	5×10^{9}	100%
$^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$	Helium burning in red giants	3×10^{11} to 1×10^{12}	
$^{26g}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	Nova contribution to galactic ^{26}Al	3×10^{9}	30,000:1
$^{12}\mathrm{C}(^{12}\mathrm{C},\gamma)^{24}\mathrm{Mg}$	Nuclear cluster models	3×10^{11}	
$^{40}\mathrm{Ca}(\alpha,\gamma)^{44}\mathrm{Ti}$	Production of ^{44}Ti in SNII	3×10^{11}	10,000:1 – 200:1
$^{23}\mathrm{Mg}(p,\gamma)^{24}\mathrm{Al}$	1.275 MeV line emission in ONe novae	5×10^{7}	1:20 – 1:1,000
$^{17}\mathrm{O}(\alpha,\gamma)^{21}\mathrm{Ne}$	Neutron poison in massive stars	1×10^{12}	
$^{18}\mathrm{F}(p,\gamma)^{19}\mathrm{Ne}$	511 keV line emission in ONe novae	2×10^{6}	100:1
$^{33}\mathrm{S}(p,\gamma)^{34}\mathrm{Cl}$	S isotopic ratios in nova grains	1×10^{10}	
$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$	Stellar helium burning	1×10^{12}	
$^{17}\mathrm{O}(p,\gamma)^{18}\mathrm{F}$	Explosive hydrogen burning in novae	1×10^{12}	
$^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$	Solar neutrino spectrum	5×10^{11}	
$^{58}\mathrm{Ni}(p,\gamma)^{59}\mathrm{Cu}$	High mass tests (p-process, XRB)	6×10^{9}	
$^{26m}\mathrm{Al}(p,\gamma)^{27}\mathrm{Si}$	SNII contribution to galactic ^{26}Al	2×10^{5}	1:10,000
$^{38}\mathrm{K}(p,\gamma)^{39}\mathrm{Ca}$	Ca/K/Ar production in novae	2×10^{7}	1:1
$^{19}\mathrm{Ne}(p,\gamma)^{20}\mathrm{Na}$	^{19}F abundance in nova ejecta	2×10^{7}	1:1 to 4:1
$^{22}\mathrm{Ne}(p,\gamma)^{23}\mathrm{Na}$	NeNa cycle; explosive H burning in classical novae	2×10^{12}	
$^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}$	ν-p process		1:200 to 1:1000

Outlook & Challenges

- $^{12}C(\alpha,\gamma)^{16}O$
  - Suffers from limited acceptance
  - Energy resolution (γ-ray detection)
  - → Upgrade to LaBr3 array

- $^{76}Se(\alpha,\gamma)^{80}Kr$
  - Suffers from high leaky beam rate

  → “Overwhelming” MCPs
  - Reaching rigidity limits (ED voltages)

- $^{15}O(\alpha,\gamma)^{19}Ne$
  - Low intensity
  - Challenging normalization
  - PID expected to be straight forward

- $^{22}Na(p,\gamma)^{23}Mg$
  - Overhead
  - Clean-up
  - Safety

Summary

DRAGON designed to study **nuclear reactions** relevant for nuclear astrophysics in **inverse kinematics**

"Strengths"

- Gas target (variable gas & pressure)
  → enables radioactive beam exp.
- High beam suppression
- Location (access to beams)
- γ-coincidence measurements
- Variable end-detector system
- TOF (local & separator)
- RF Timing
- Beam Diagnostics

PID

"Weaknesses"

- Limited rigidity

→ Limitations for higher masses

- Simulation required for detection efficiency
- Limited γ-energy resolution w BGO array

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The DRAGON facility

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