The status and future plans of $^{12}C(\alpha,\gamma)^{16}O$ reaction at ERNA

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HELIUM25 – July 21-25/2025

Reaction details

$\sigma(300\ keV) \cong 10^{-17}\mathrm{b}$

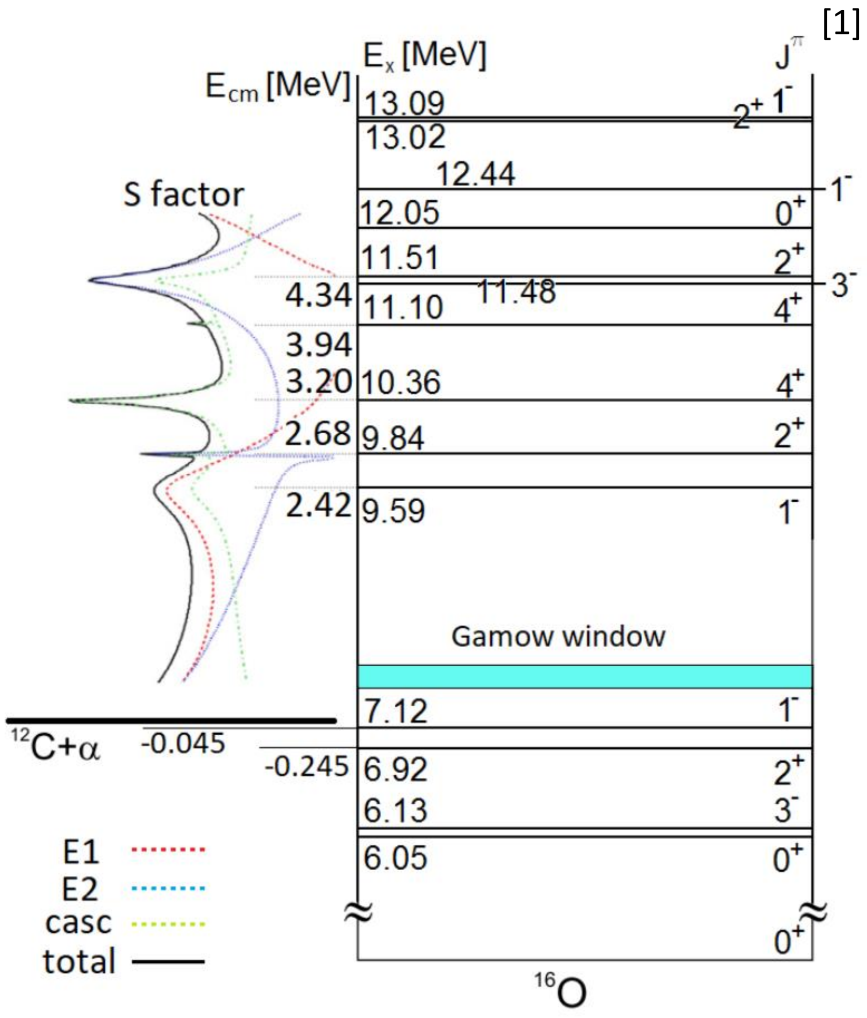
Direct measurement not feasible

Extrapolation through R-Matrix

[1] Schürmann et al. 2012

See talk by J. deBoer yesterday

Reaction details



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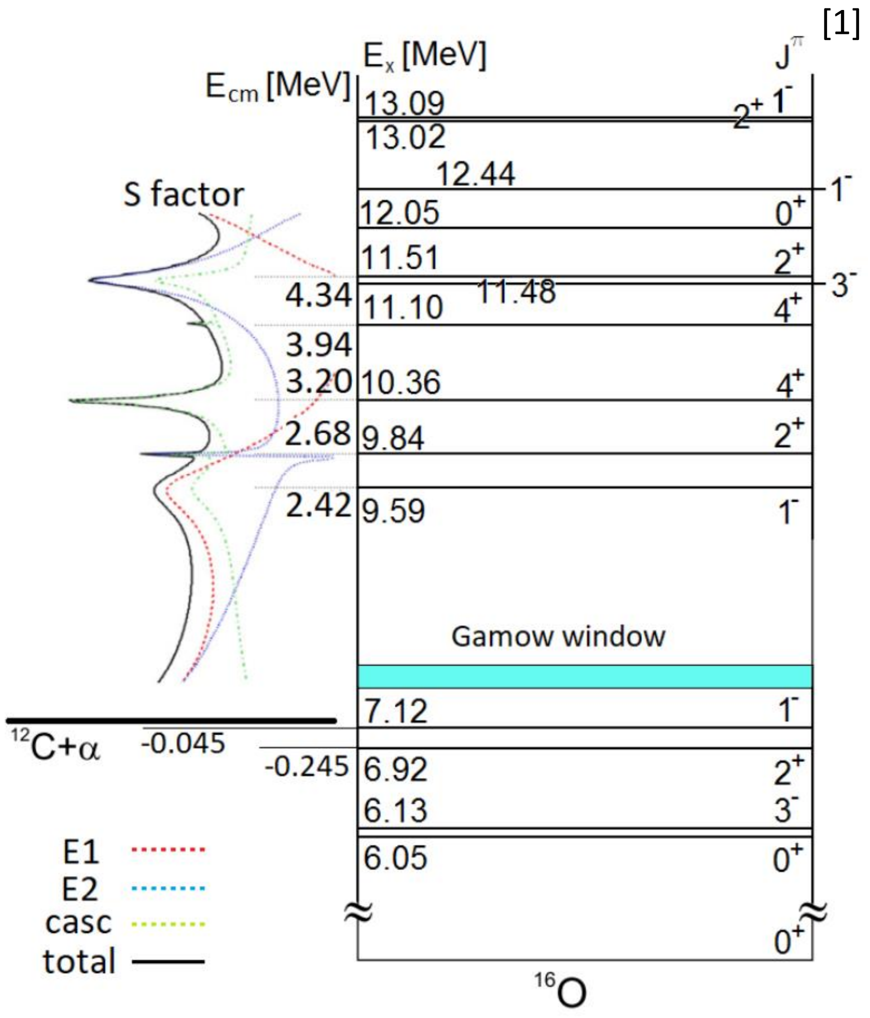

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Direct measurement not feasible

Extrapolation through R-Matrix

- Low energy cross section is dominated by
  - A 1^- and 2^+ subthreshold state, a broad 1^- resonance at 2.4 MeV
  - The ground state transition
  - Contribution of cascade transitions
  - E1 and E2 multipolarities
  - Interference effects are strong

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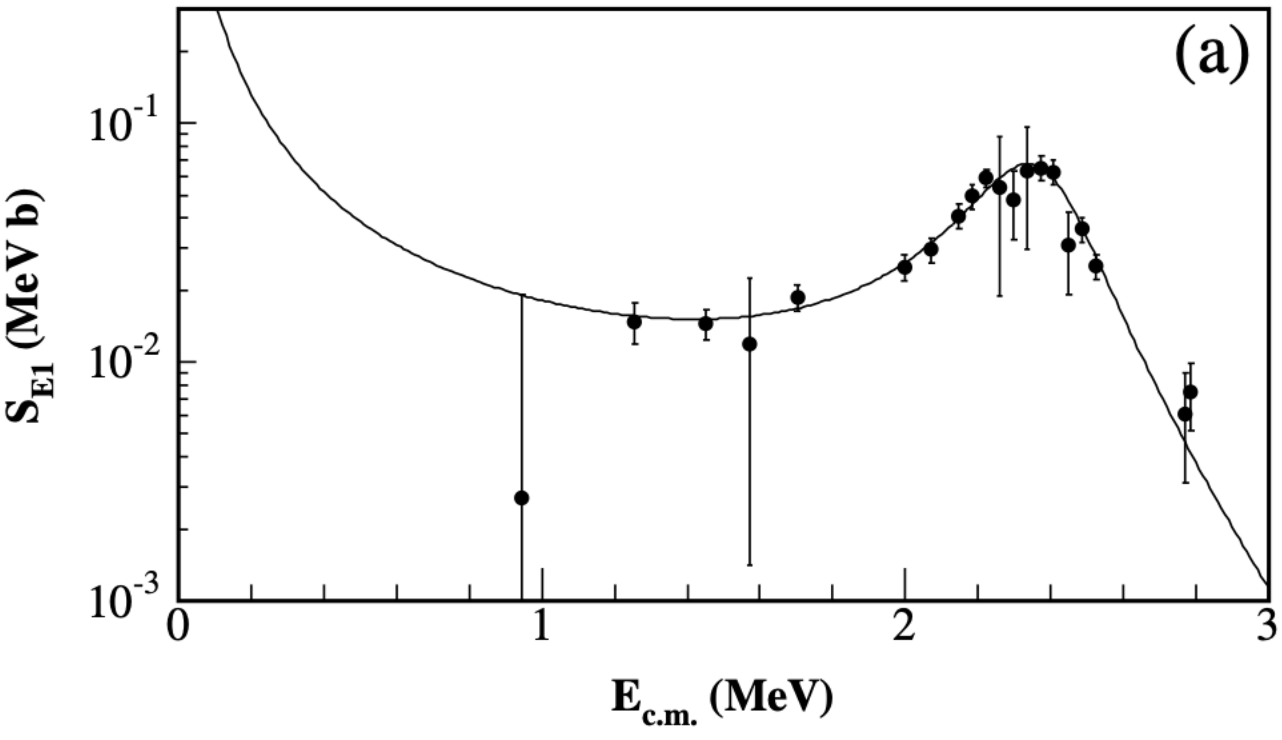
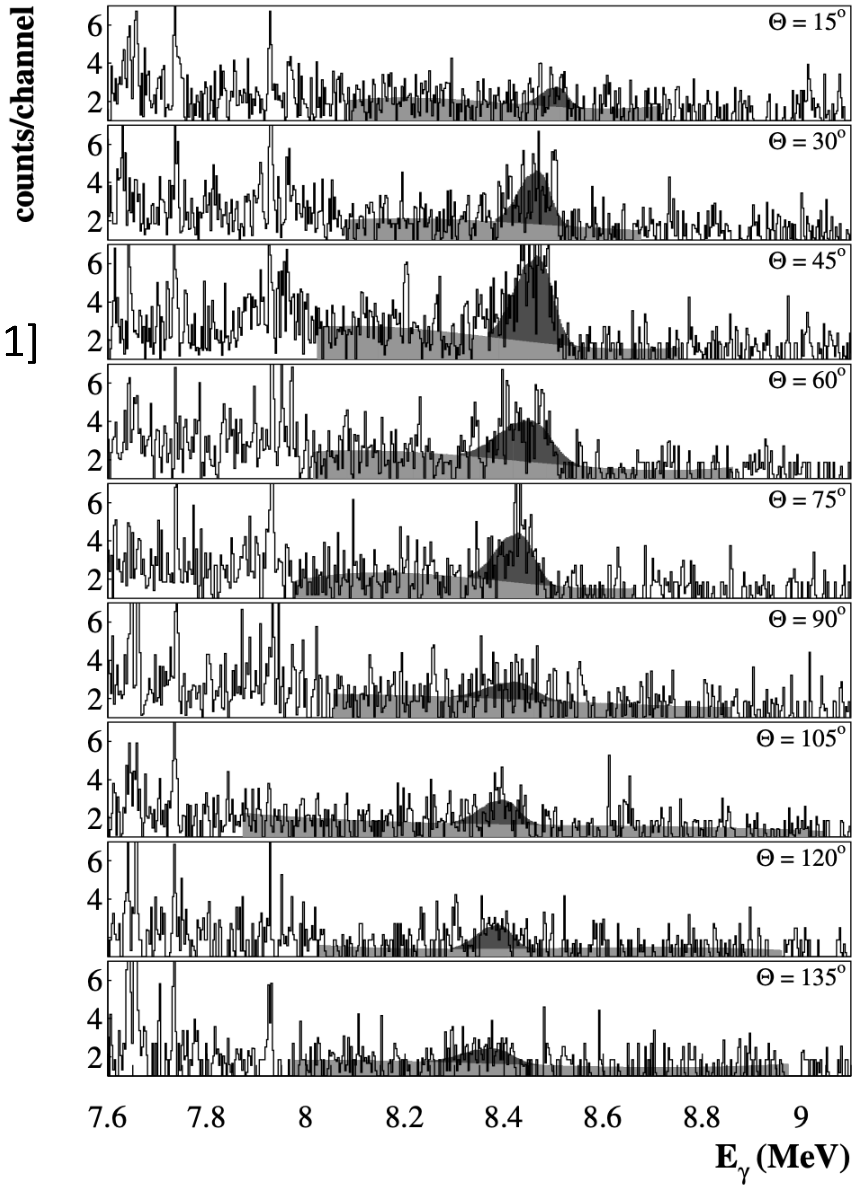
Challenges in Measuring



Implanted 12C, 2-3 10^18 atom/cm^2

[1]



[1] R. Kunz et al., Phys. Rev. Lett., Apr. 2001

Challenges in Measuring

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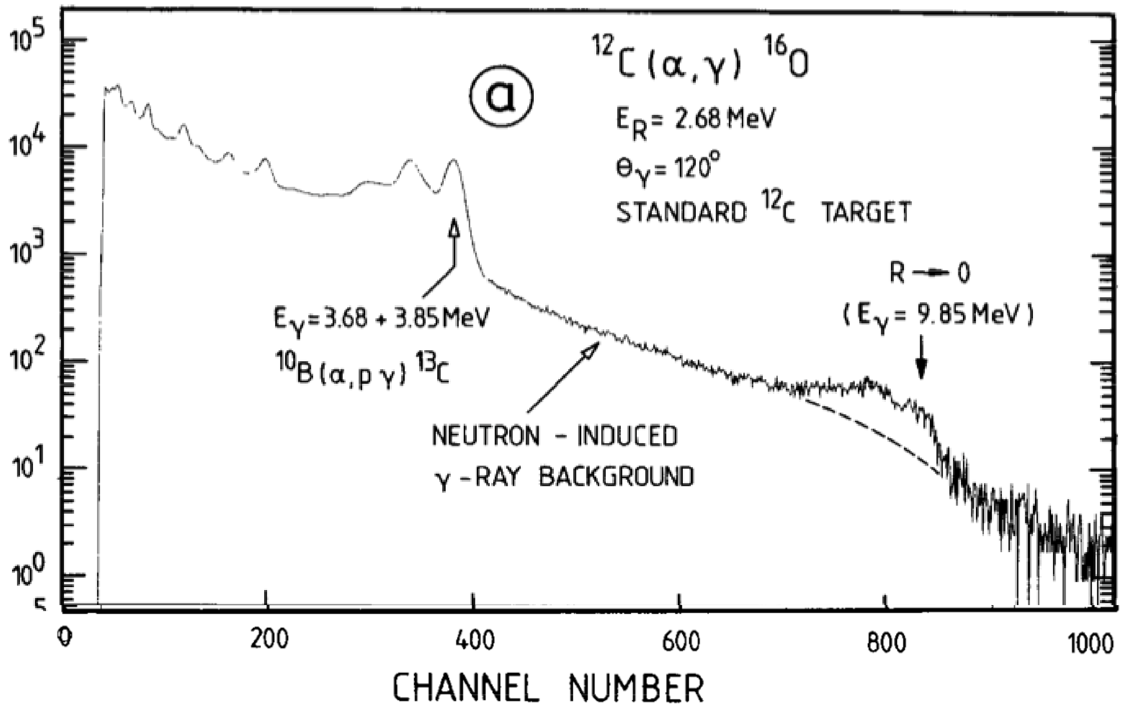
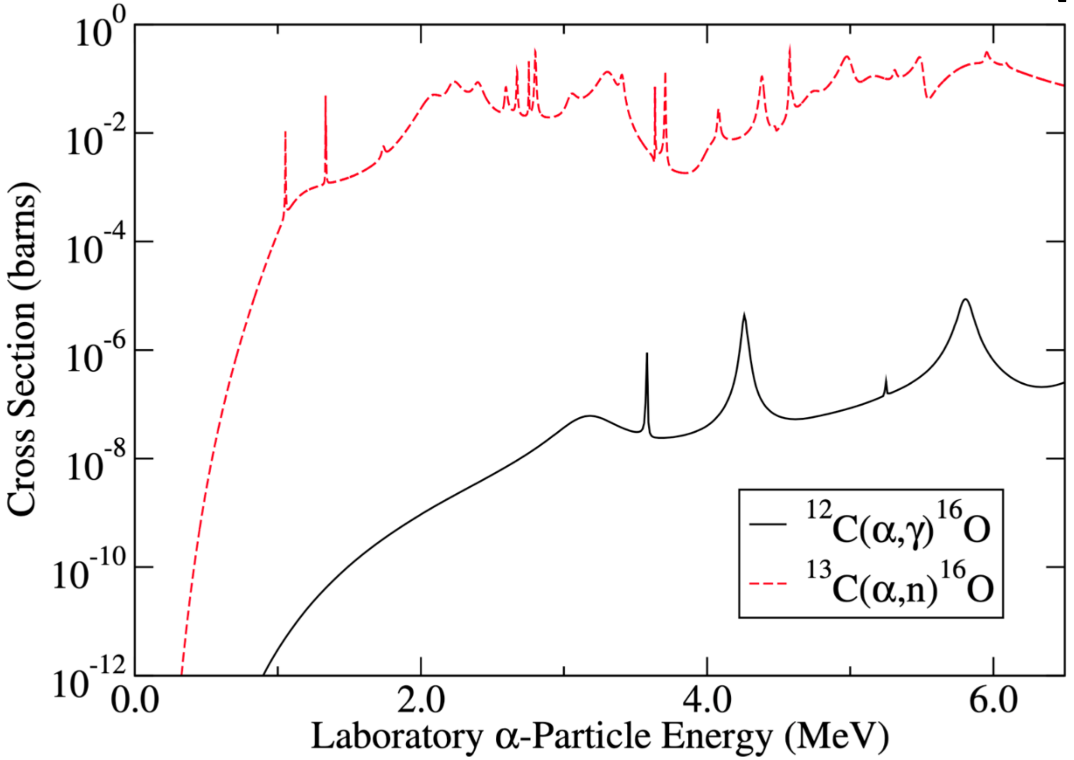
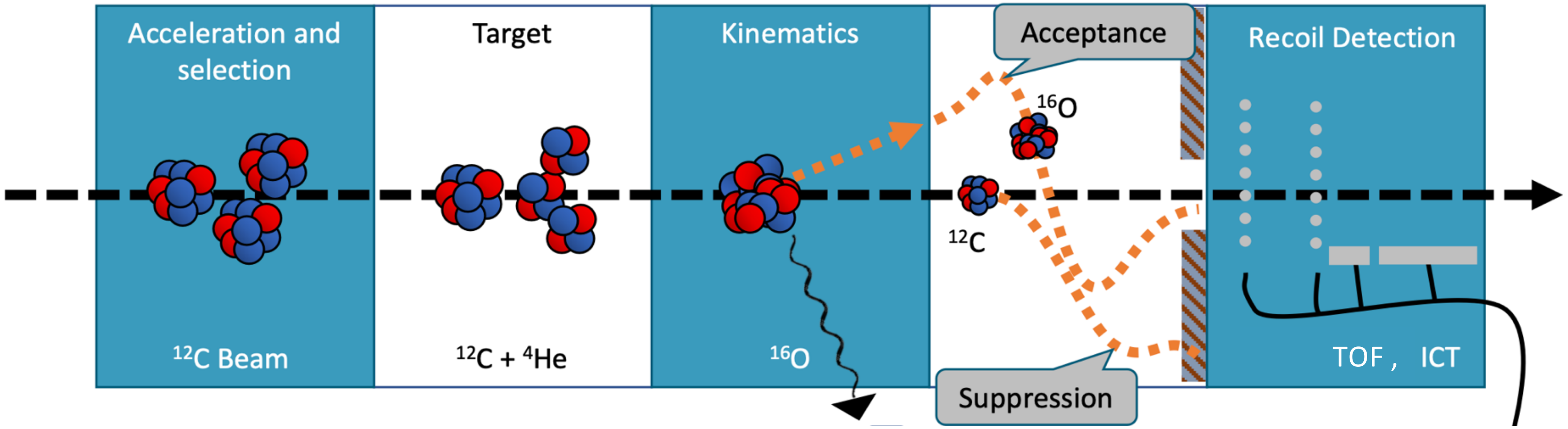


[2]

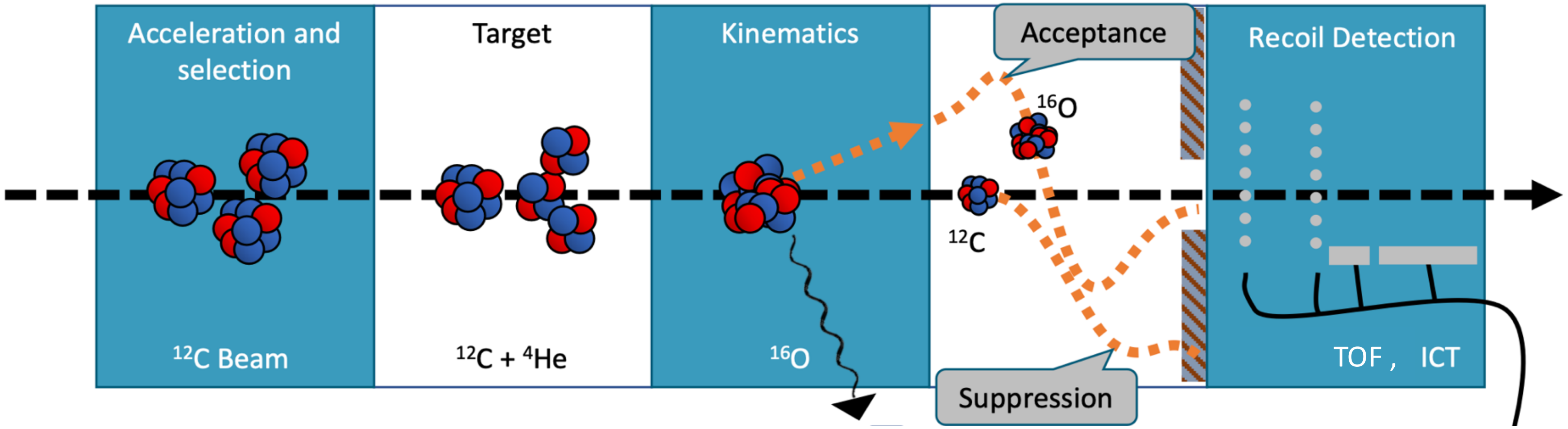


[1] Redder, A et al, Nuclear Physics A 462, n.2 (1987)
[2] deBoer, R. et al, *Reviews of Modern Physics* **89**, (2017).

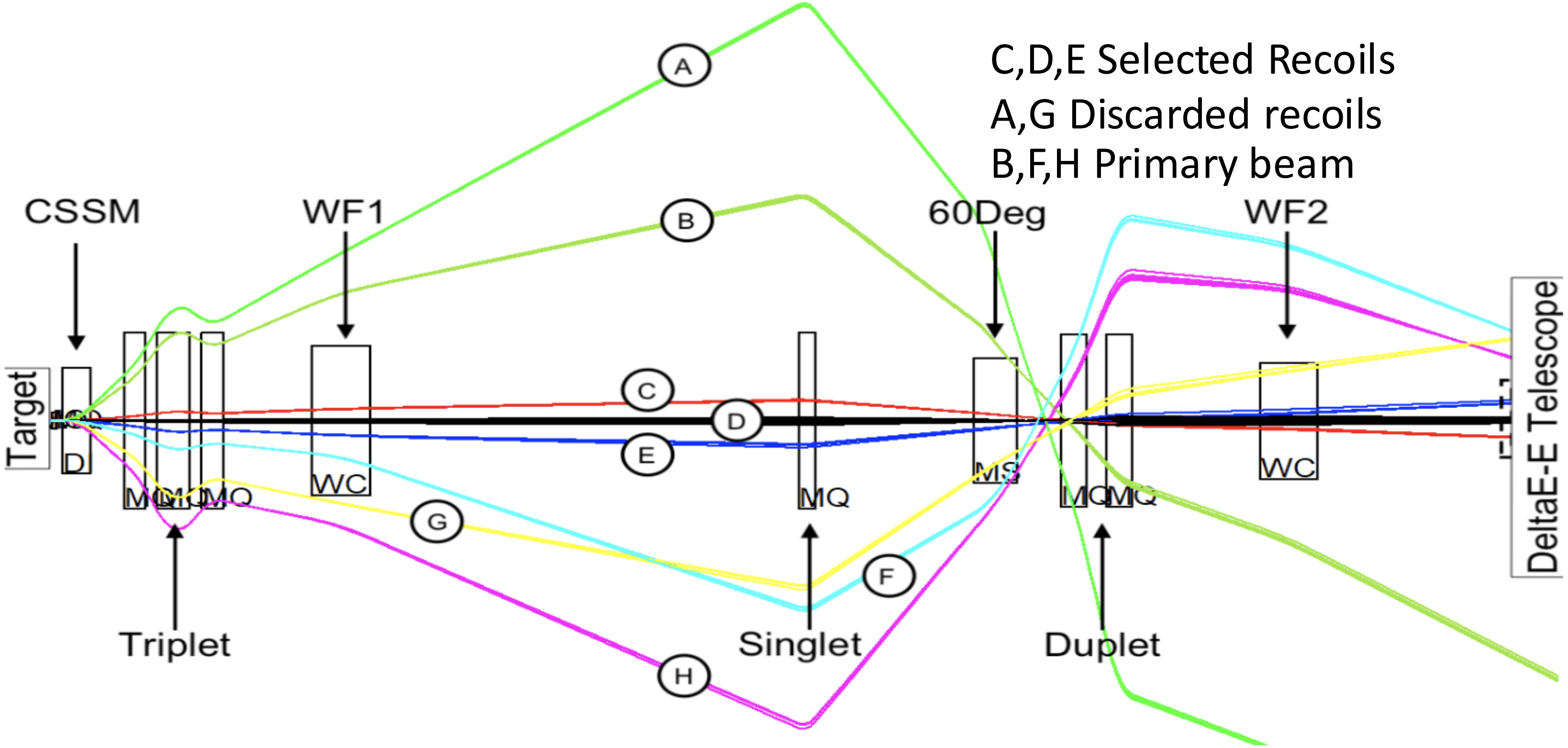
Recoil separator technique



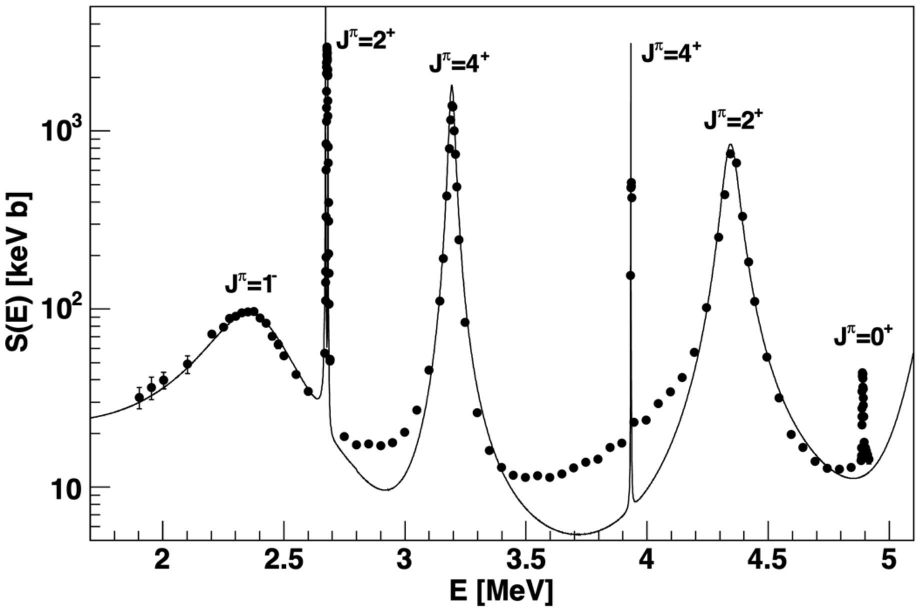
Recoil separator technique



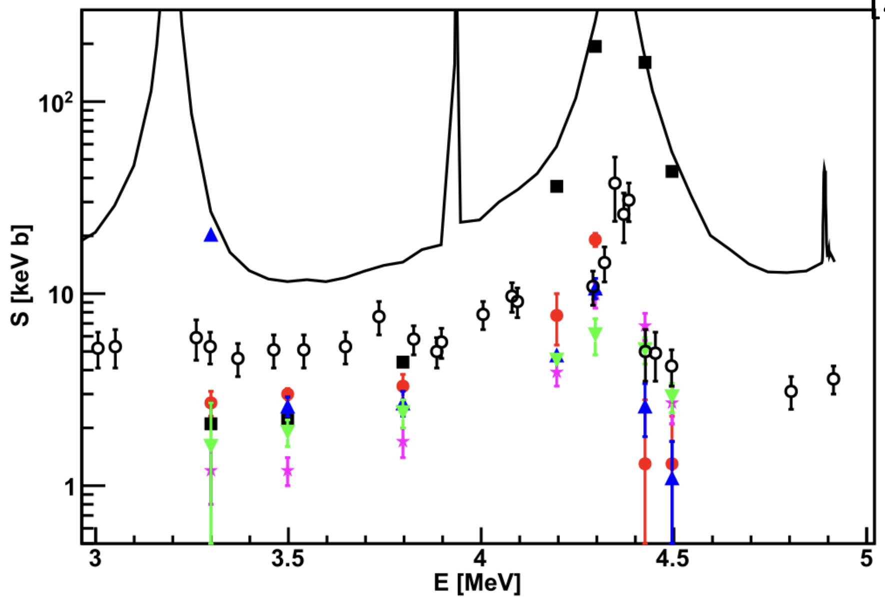
C,D,E Selected Recoils
A,G Discarded recoils
B,F,H Primary beam



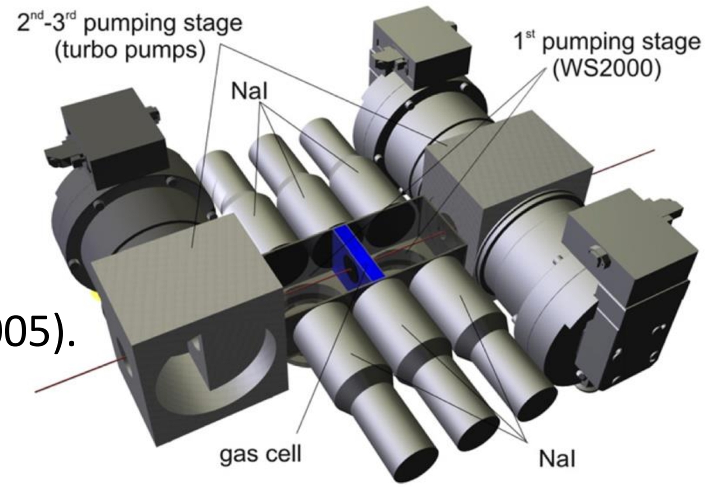
Results by ERNA @ Bochum



Total Cross Section

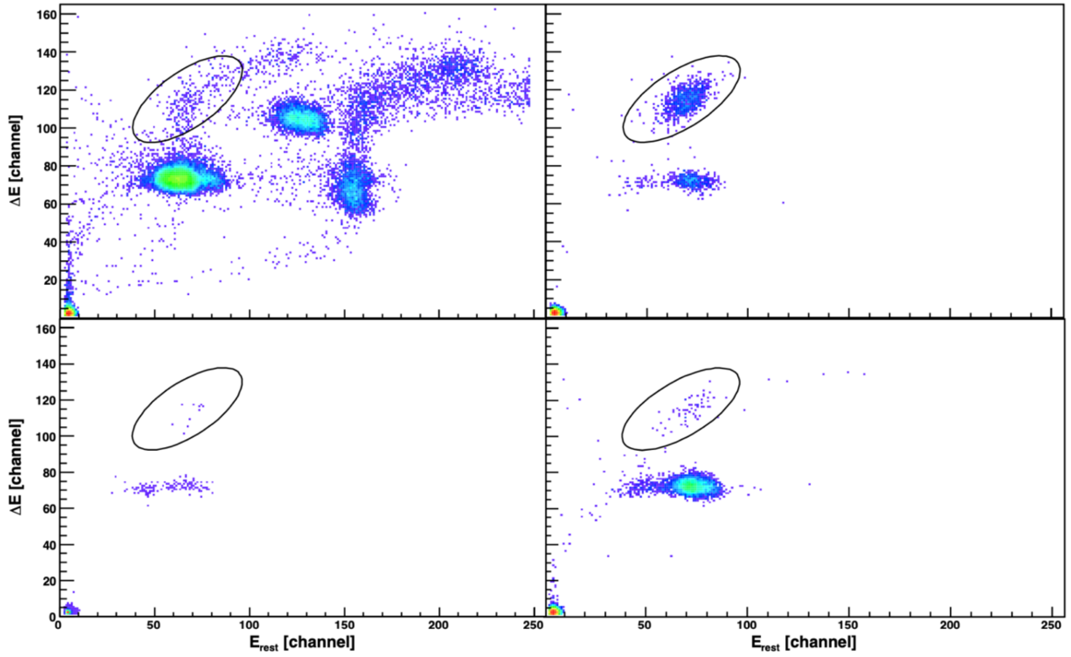


6.05 MeV Cascade Transition



[1] Schürmann, D. *et al*. *The European Physical Journal A* **26**, 301–305 (2005).
[2] Schürmann, D. *et al Physics Letters B* **703**, 557–561 (2011).

Limitations in Bochum



Schürmann, D. - PhD Thesis (2007)

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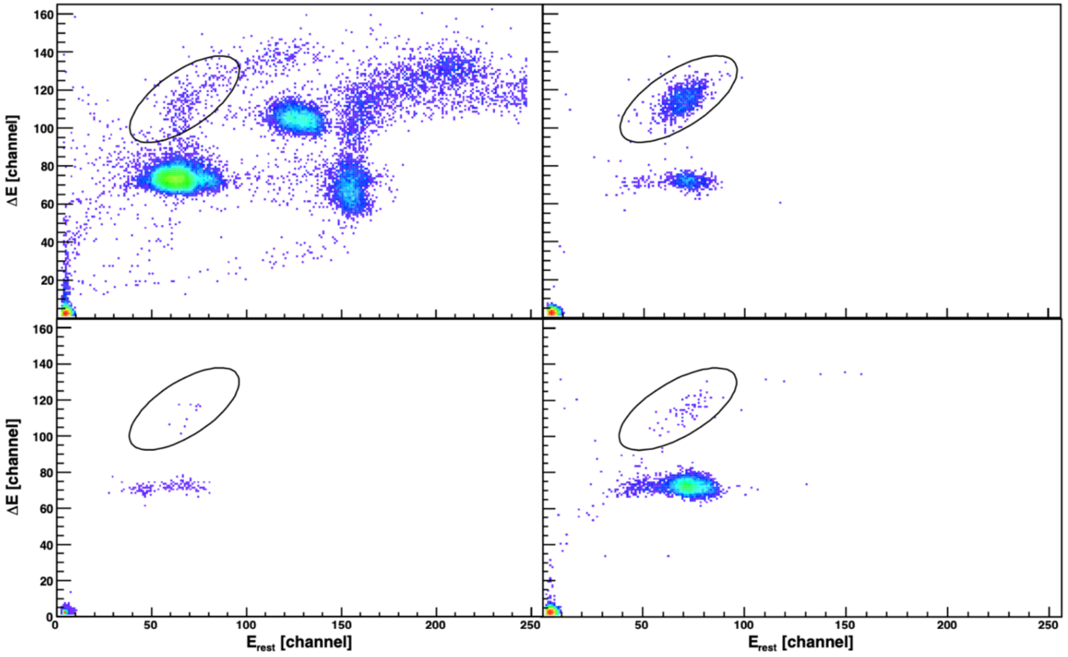

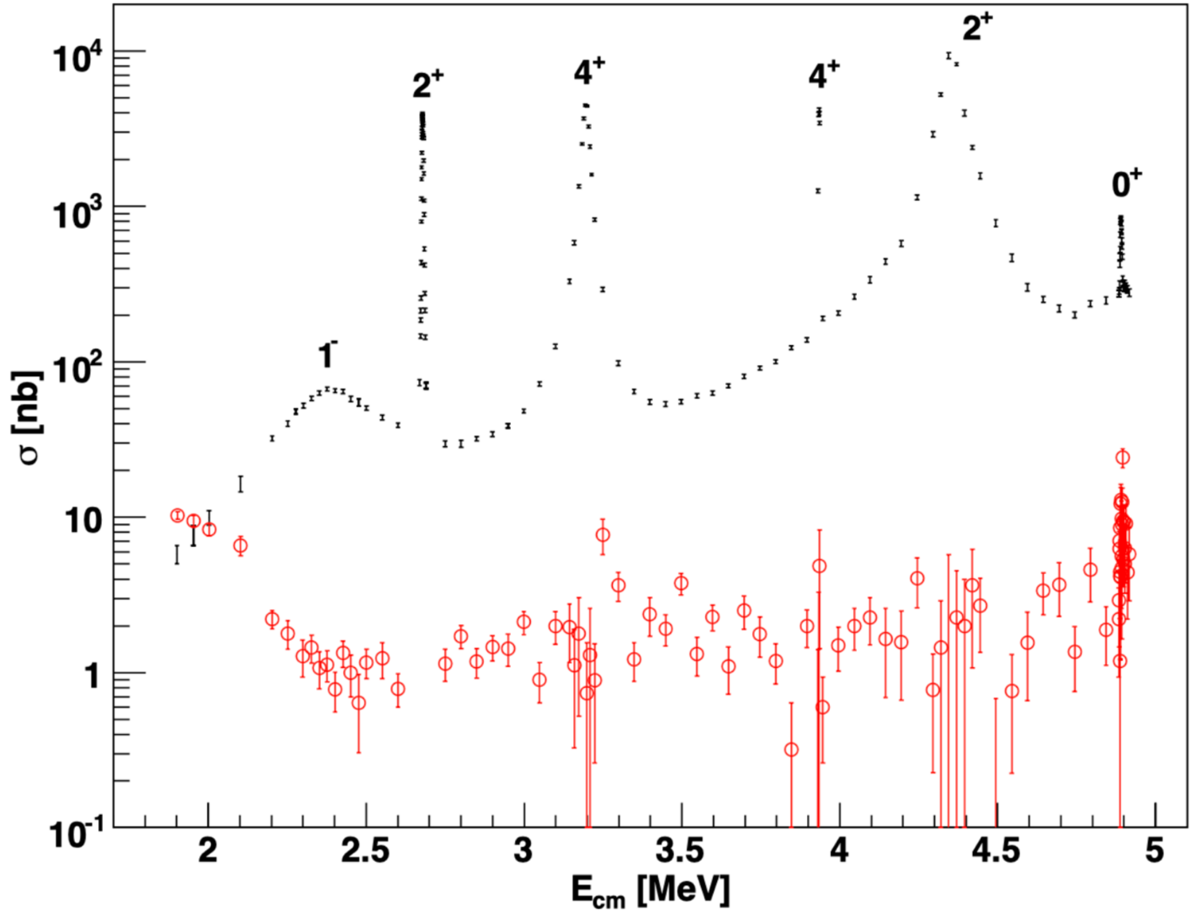

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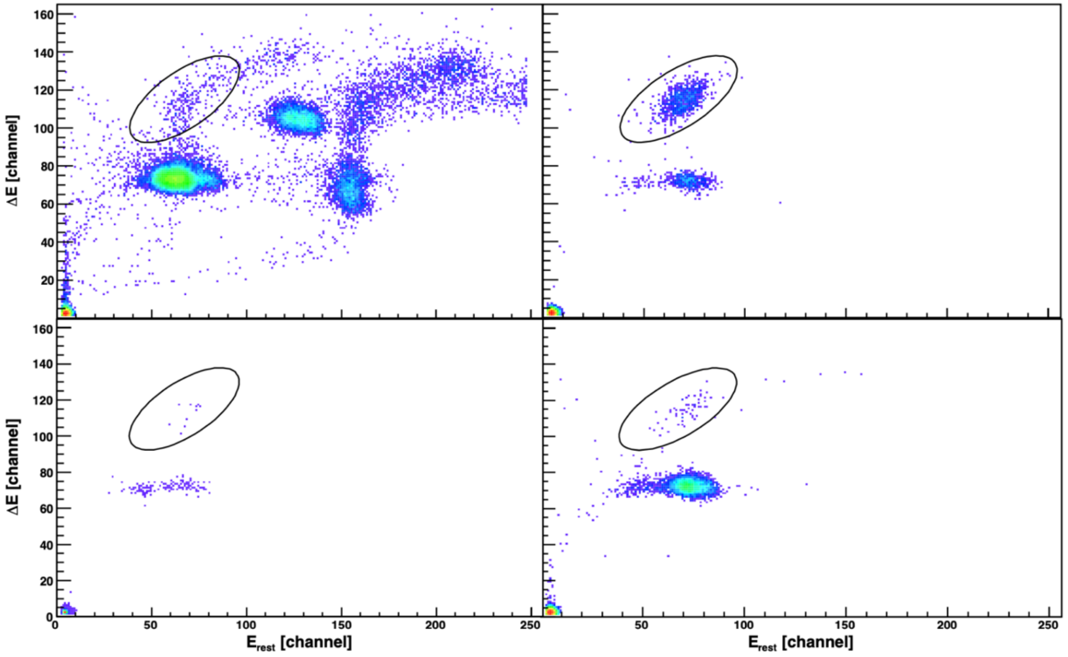

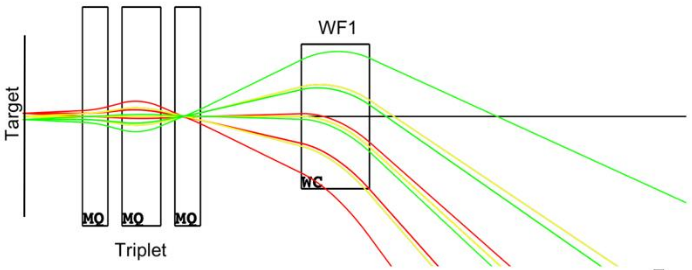

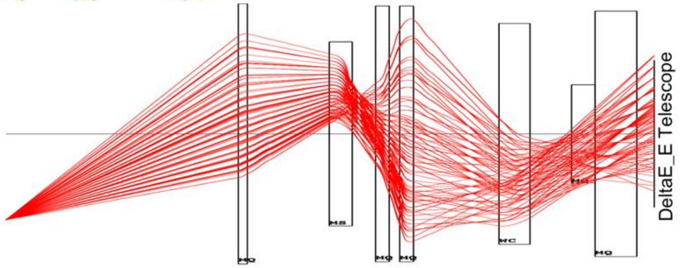

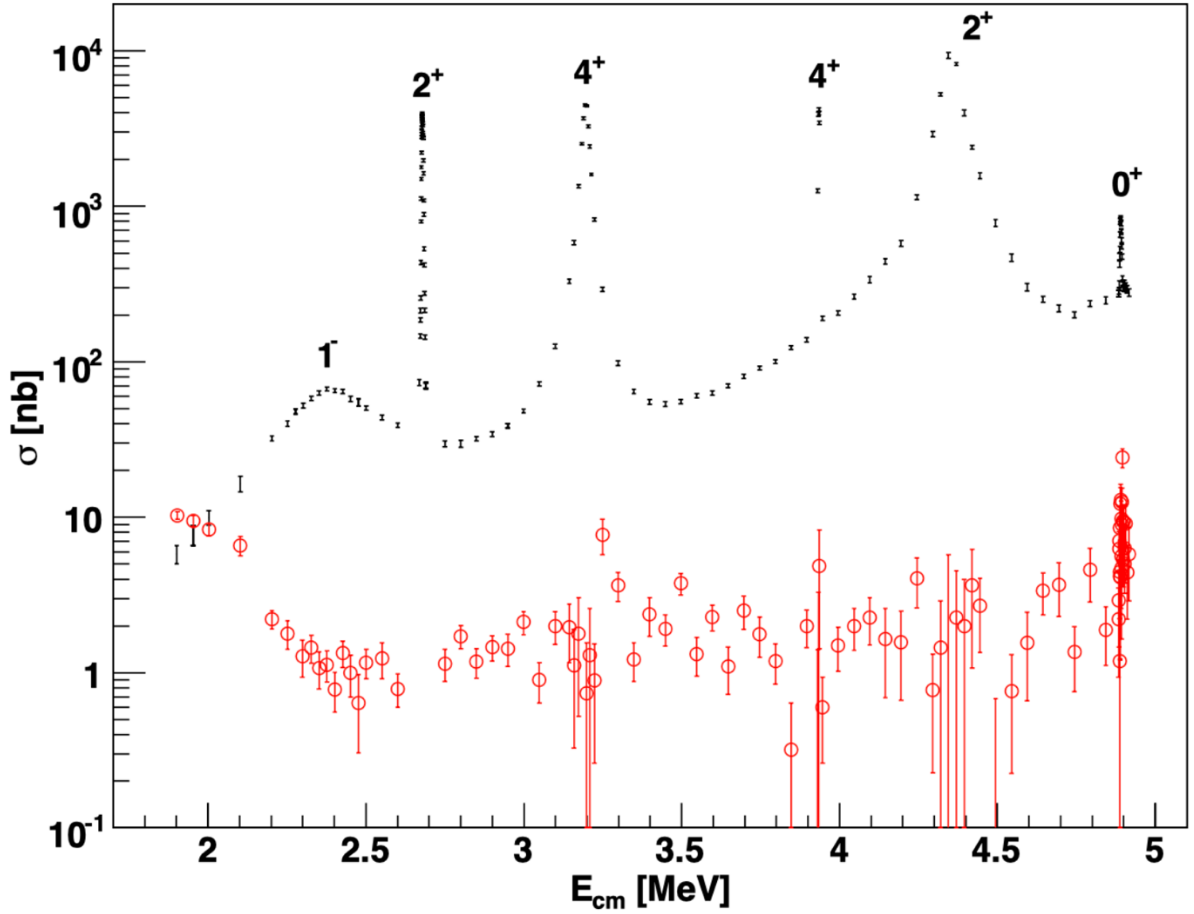

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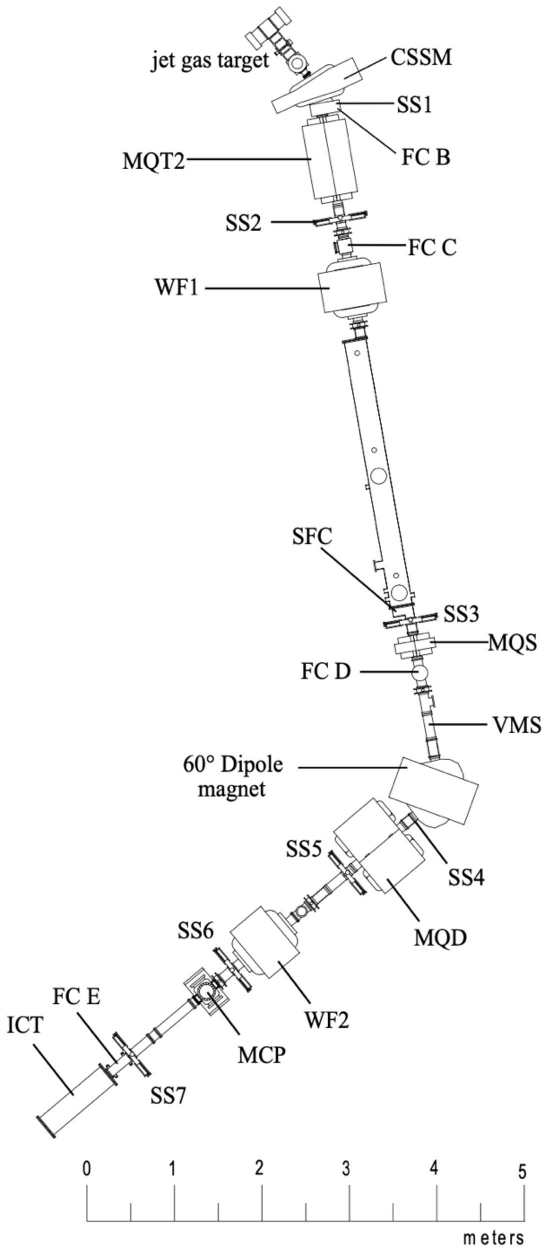
ERNA Recoil Separator (v. 2) @ Caserta

[1]



ERNA Recoil Separator (v. 2) @ Caserta

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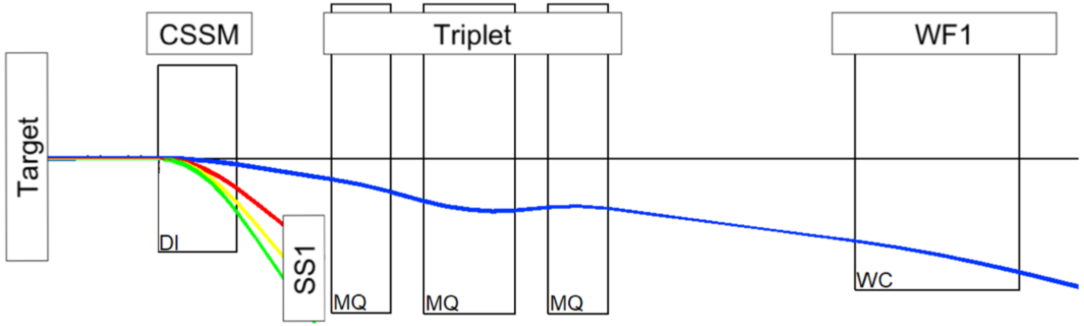
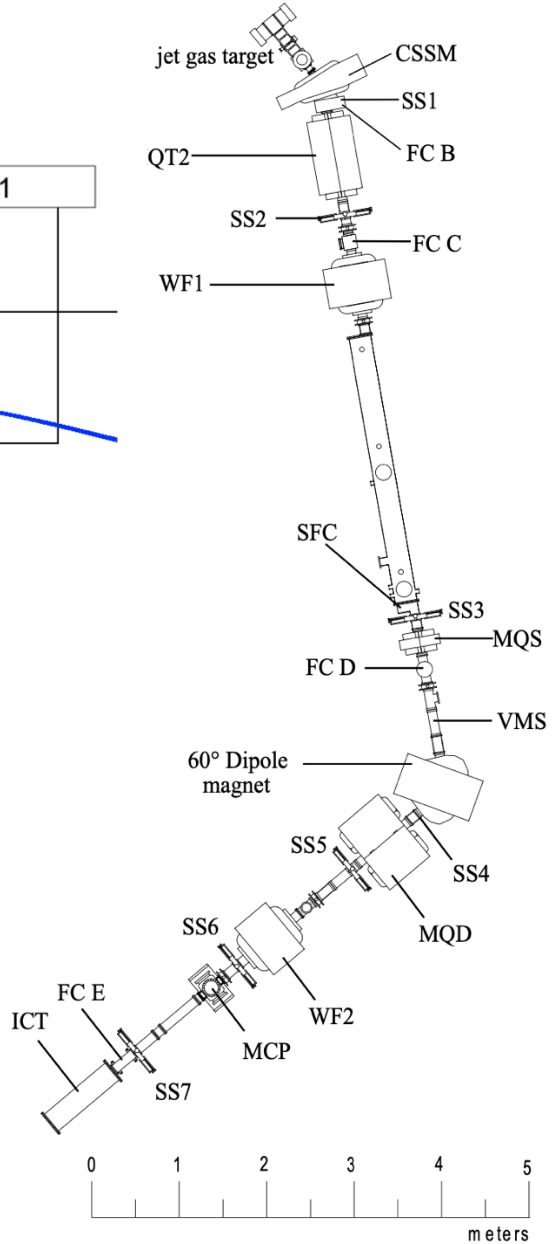
Charge state selection magnet





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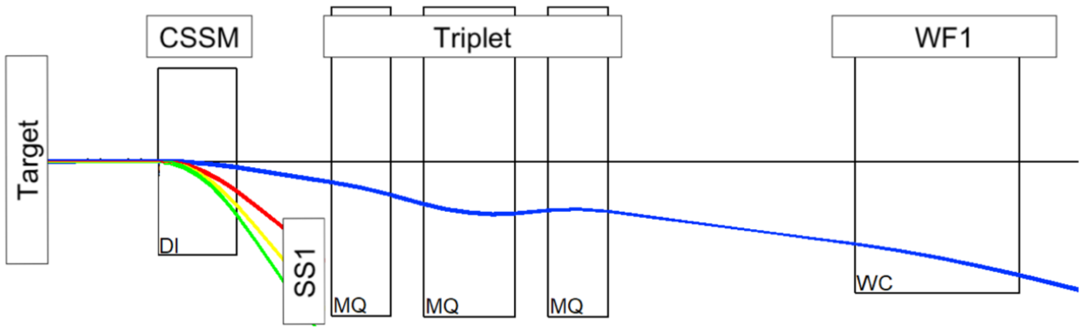
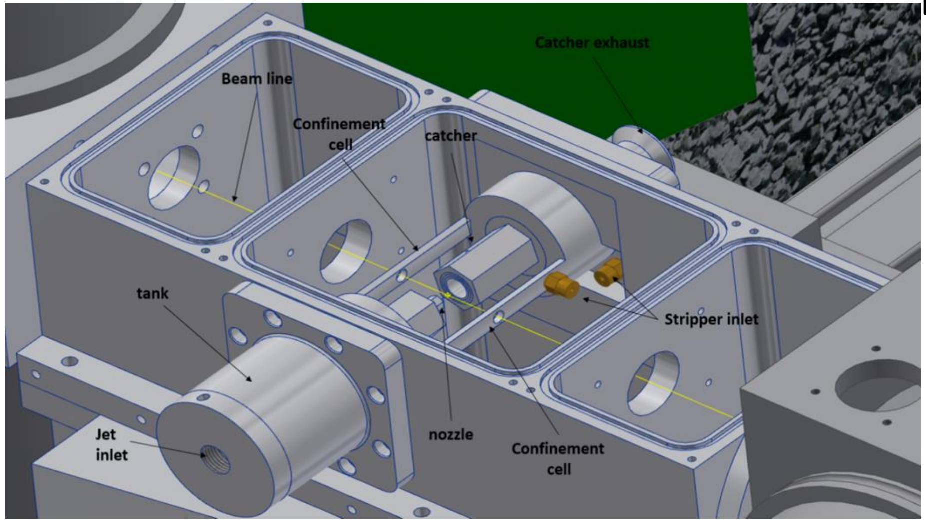


Supersonic He Recirculated Jet Target



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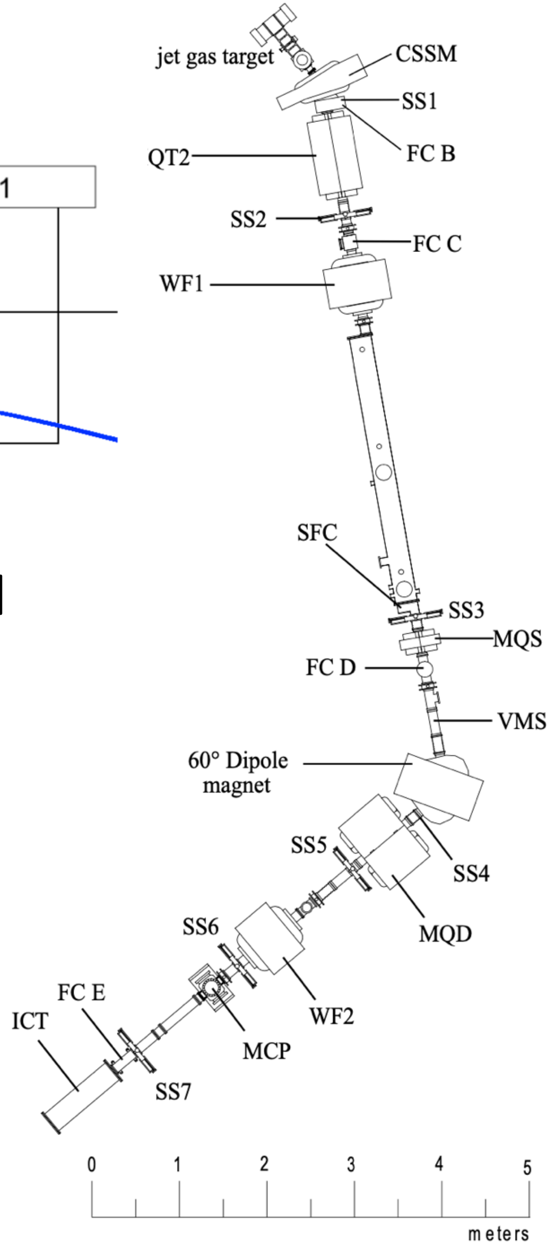

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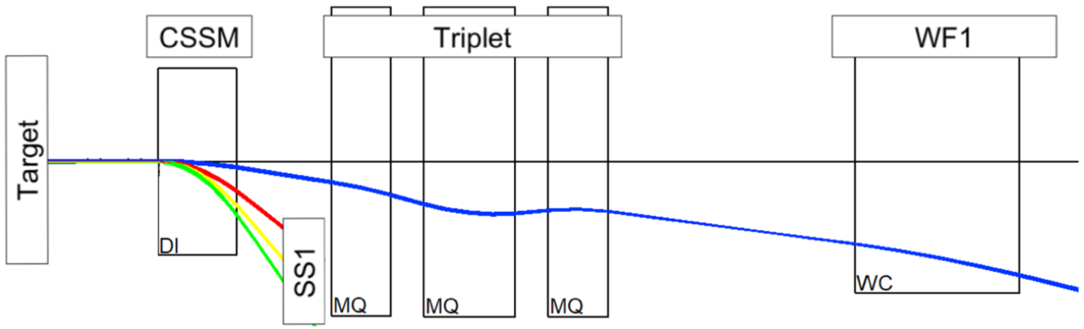

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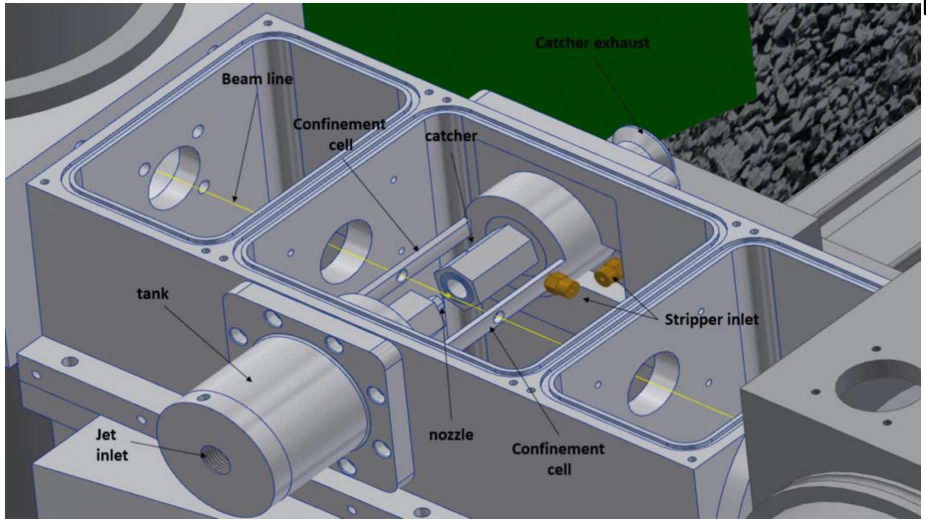
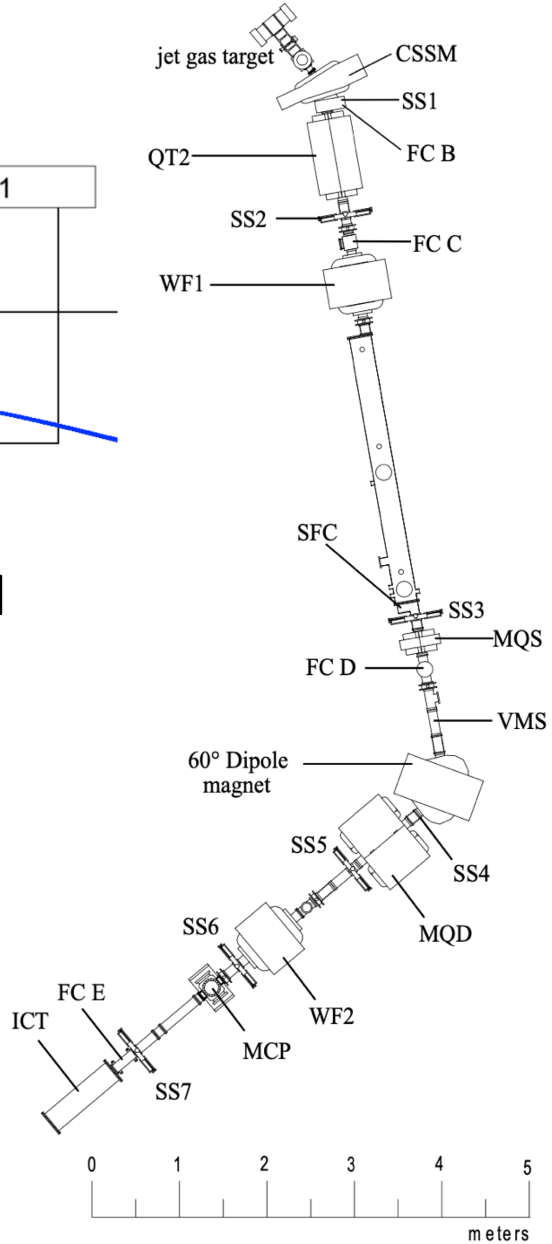
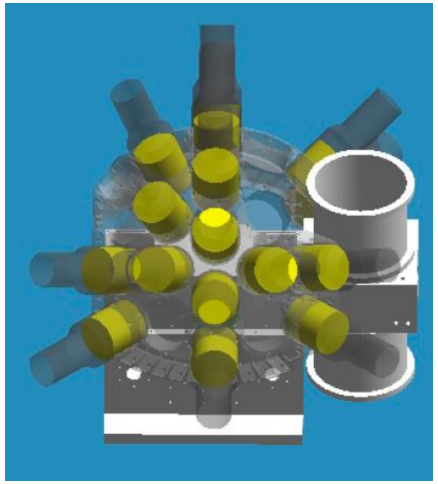




Detectors



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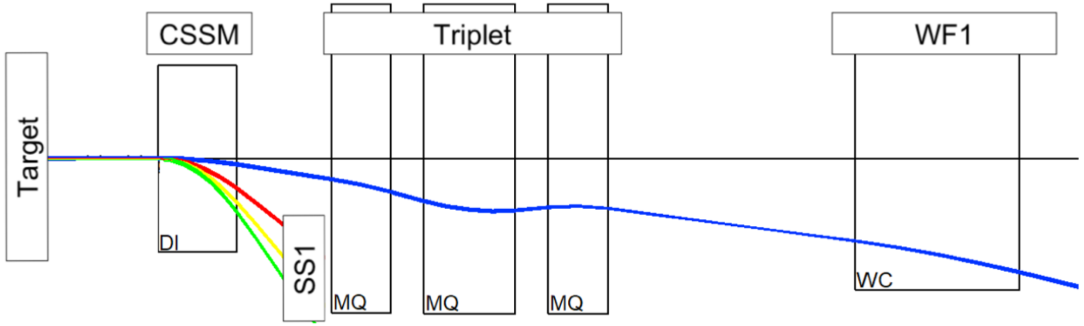

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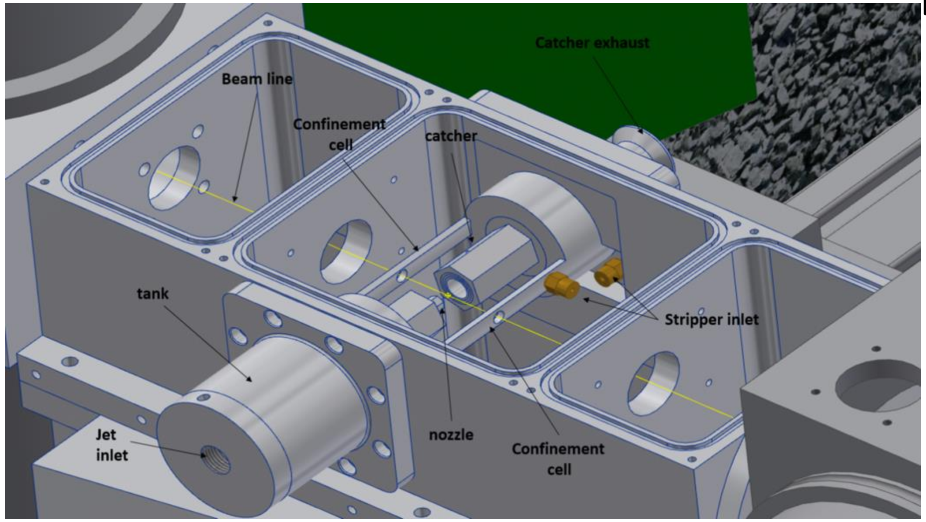

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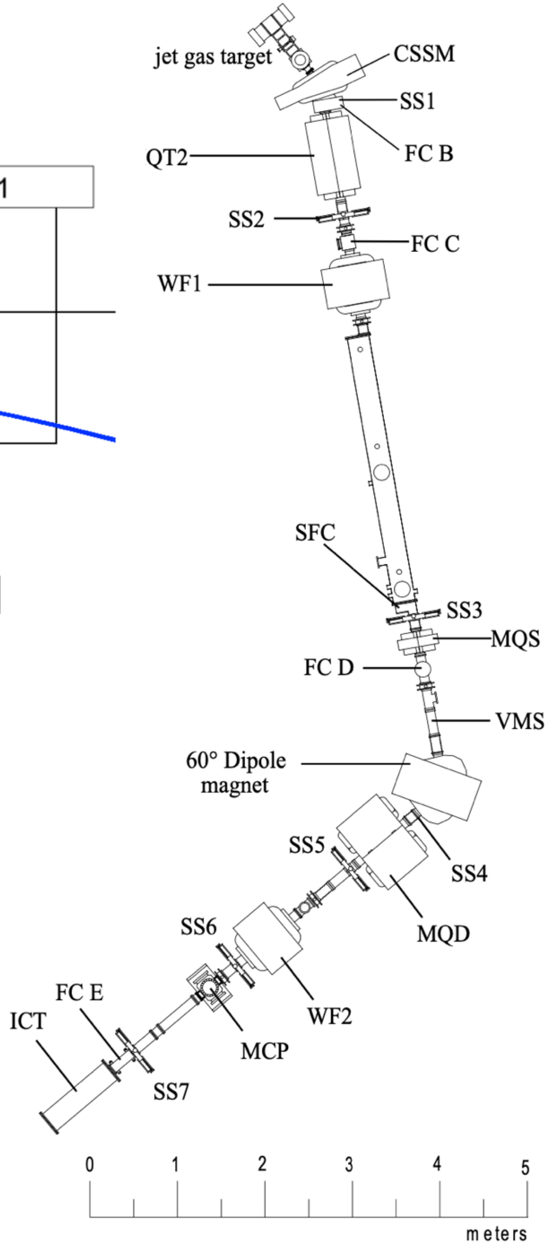

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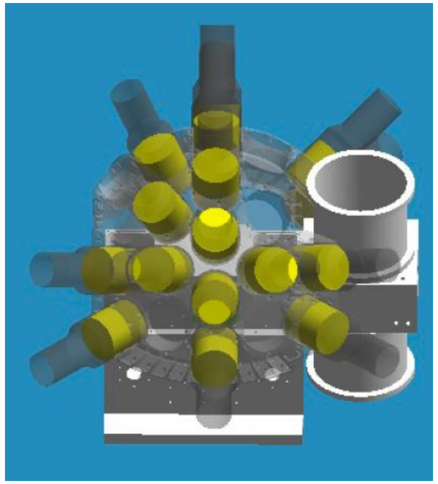

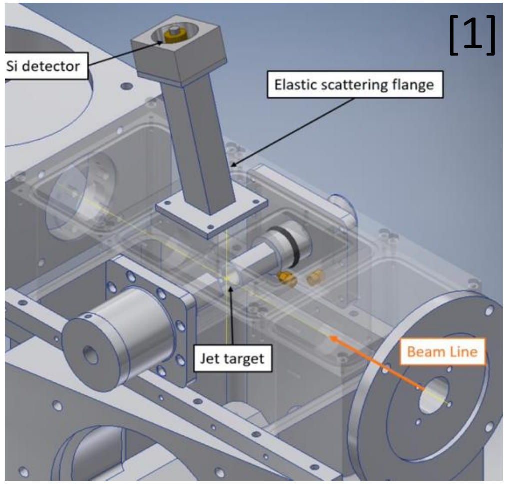

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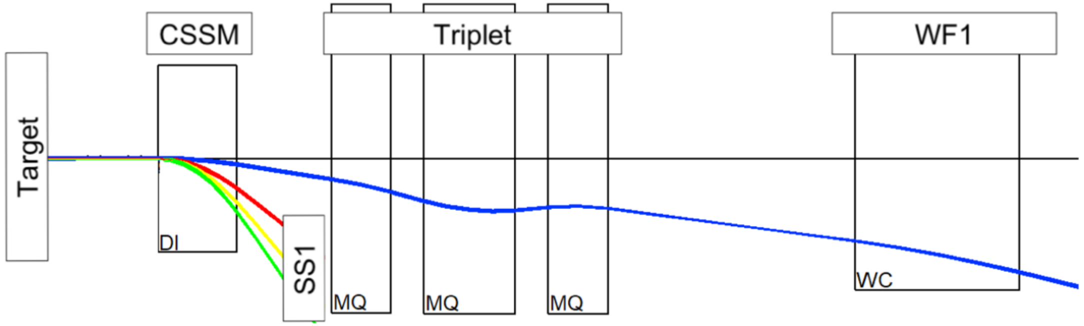

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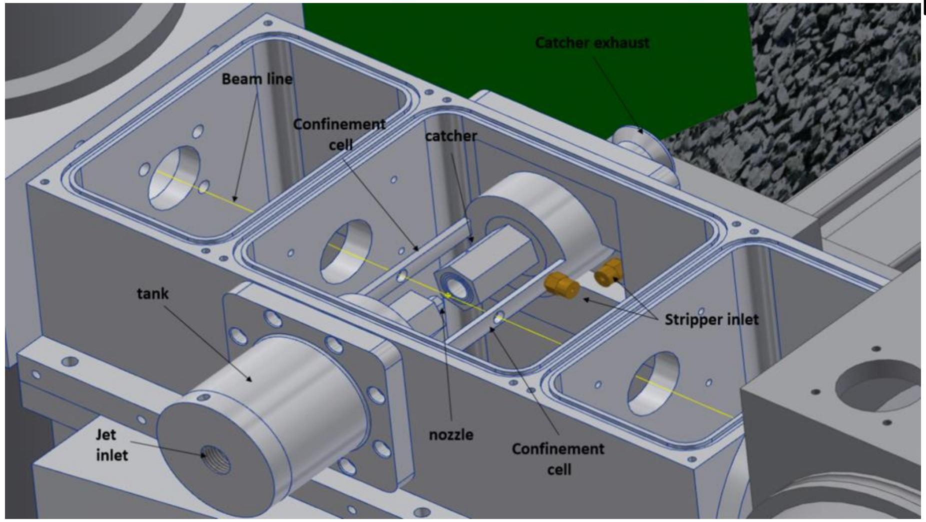

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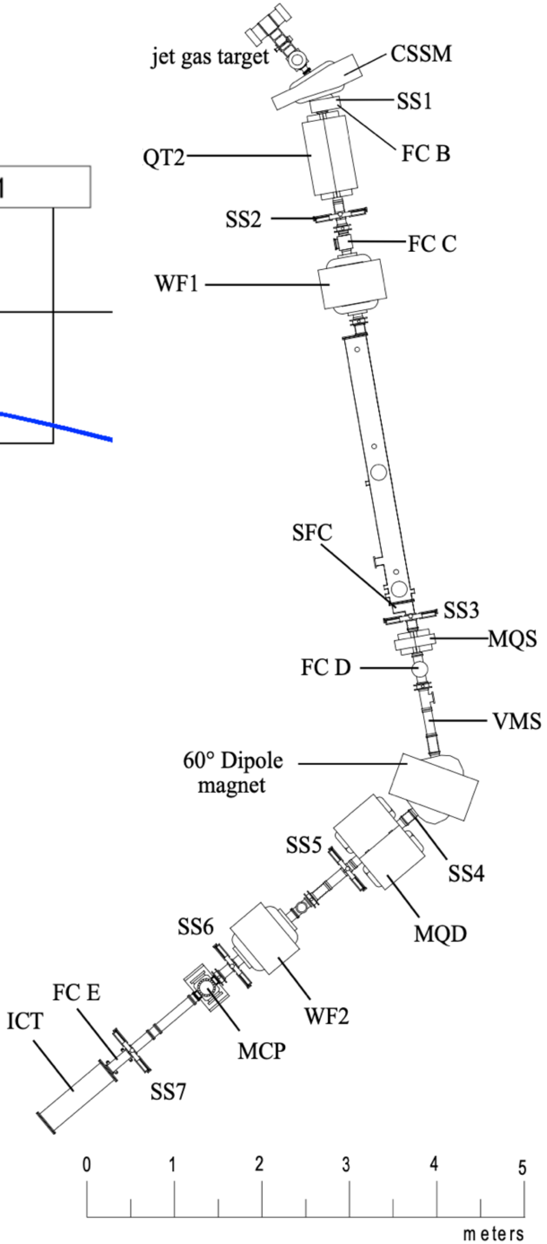

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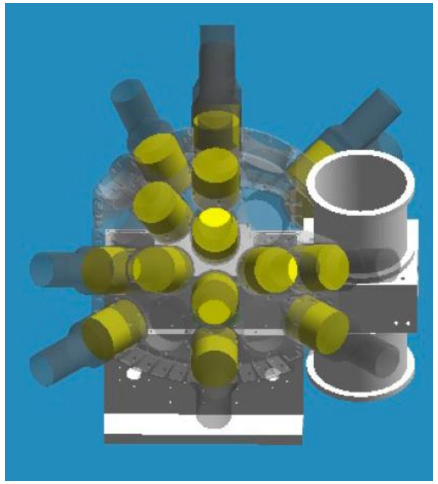
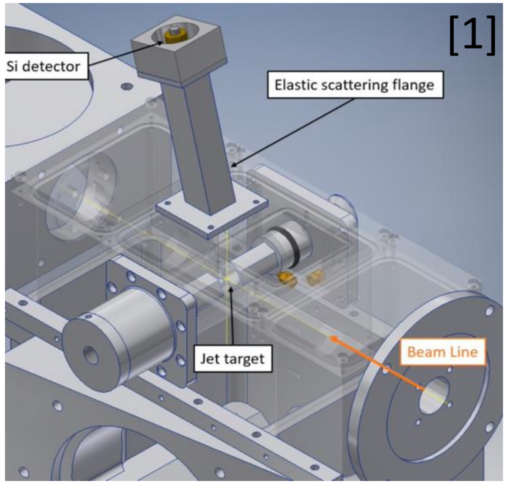
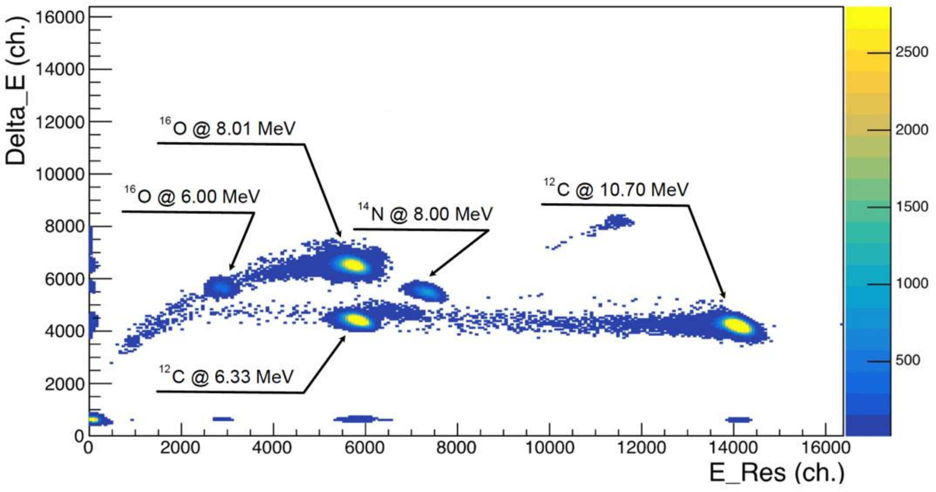
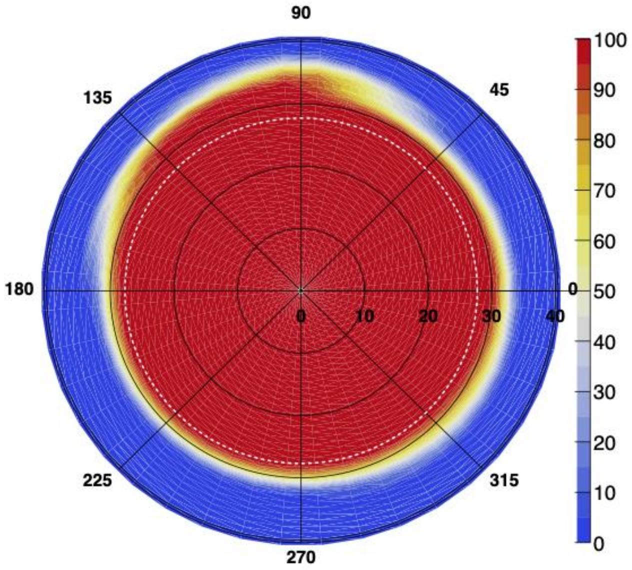


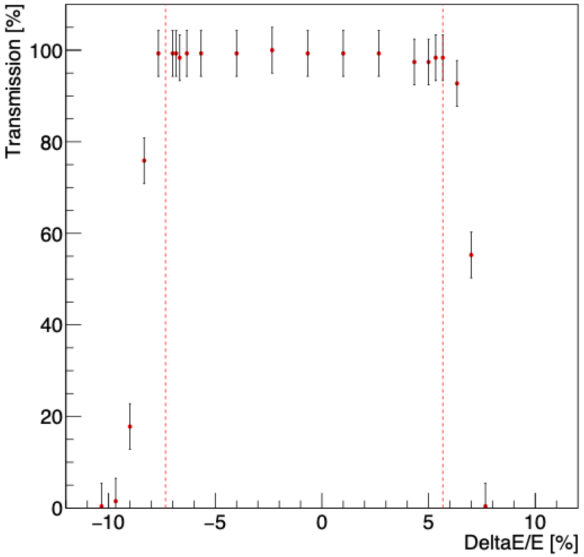




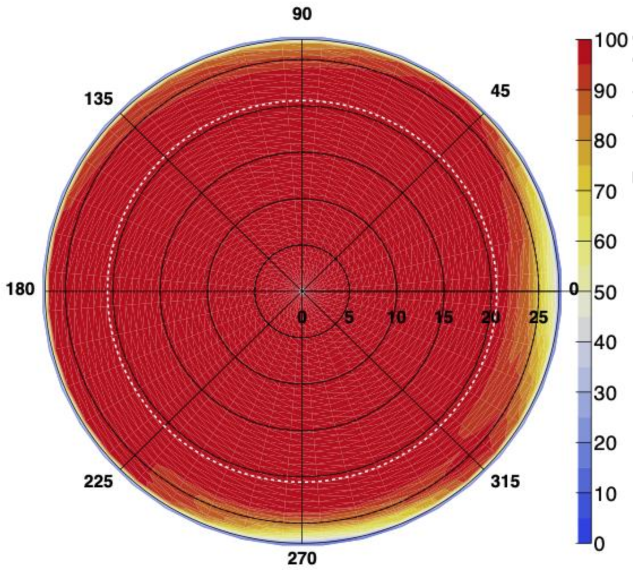
[1] Rapagnani D. – PhD Thesis

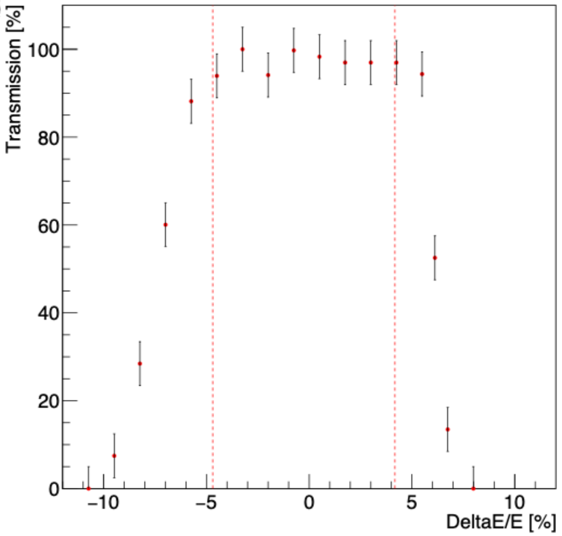
Commissioning - Acceptance





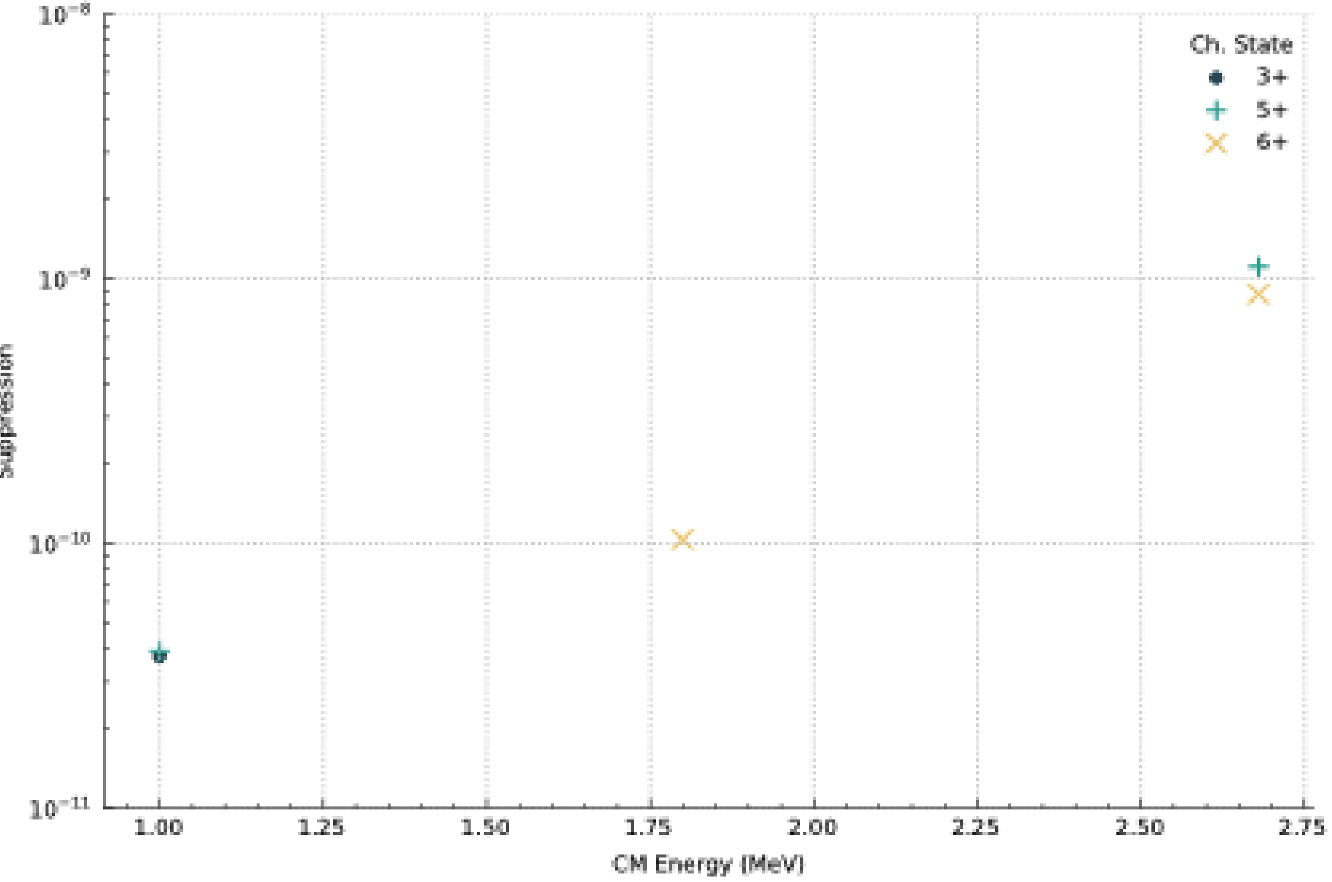
1 MeV



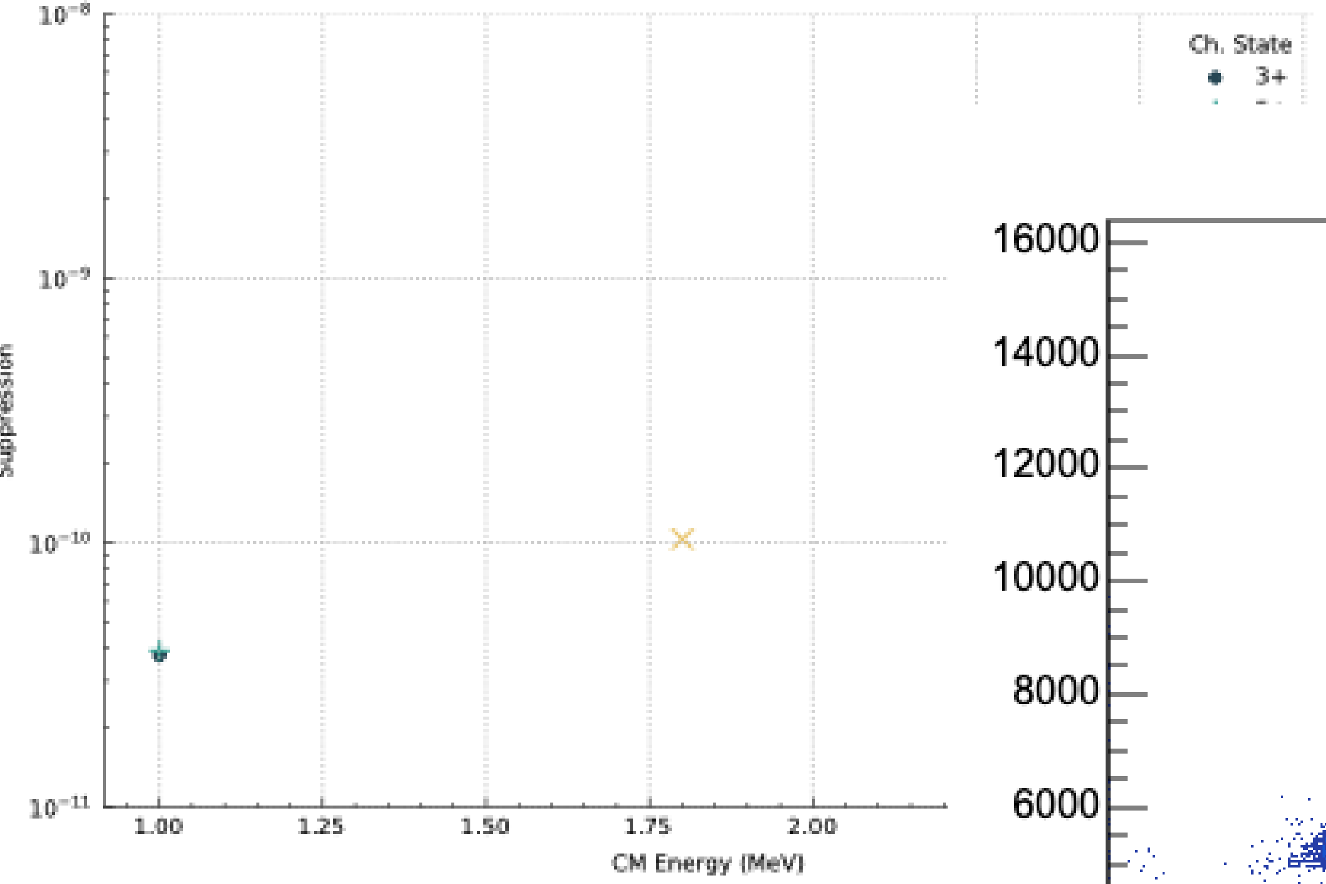


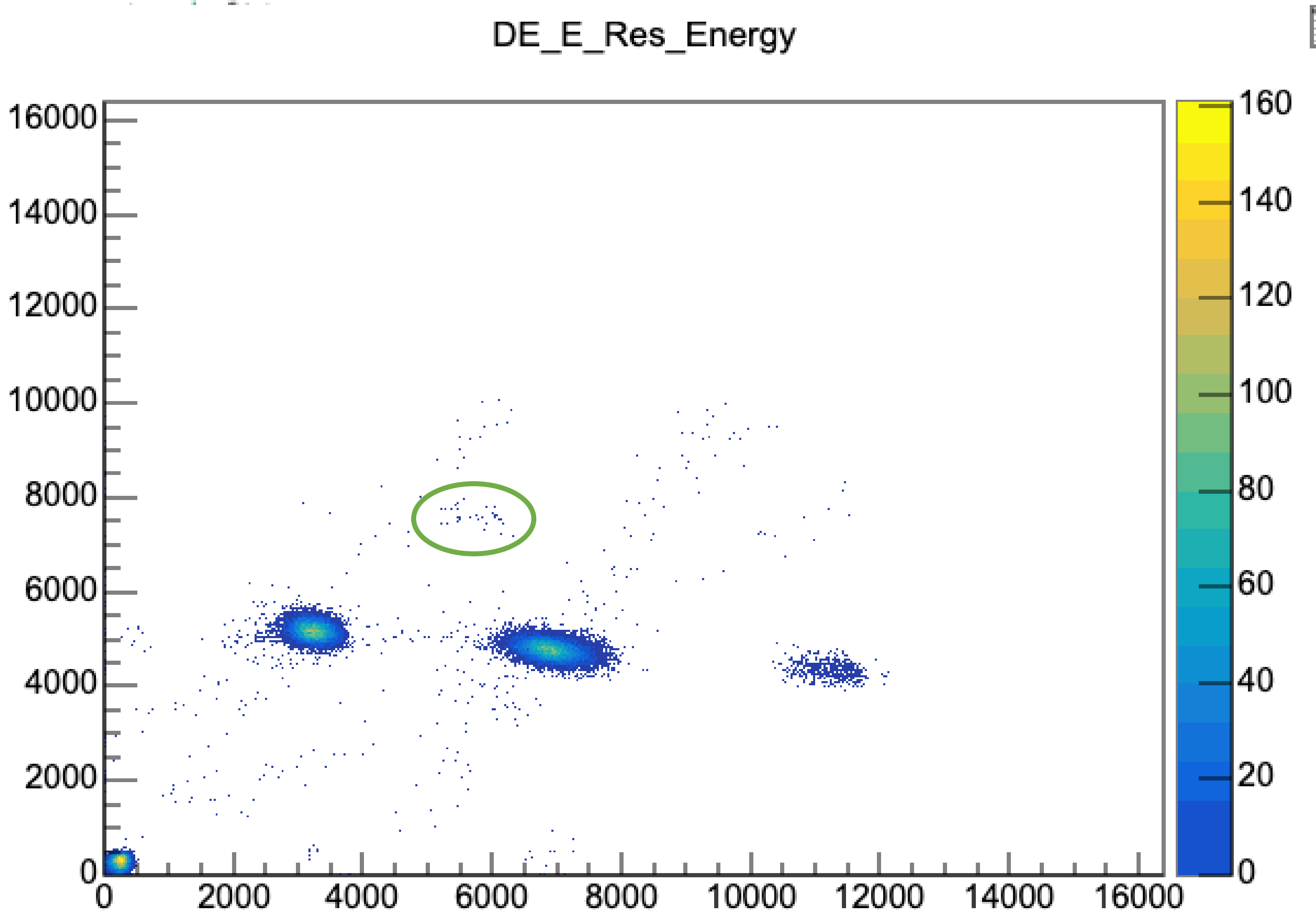
2.68 MeV

Commissioning - Suppression

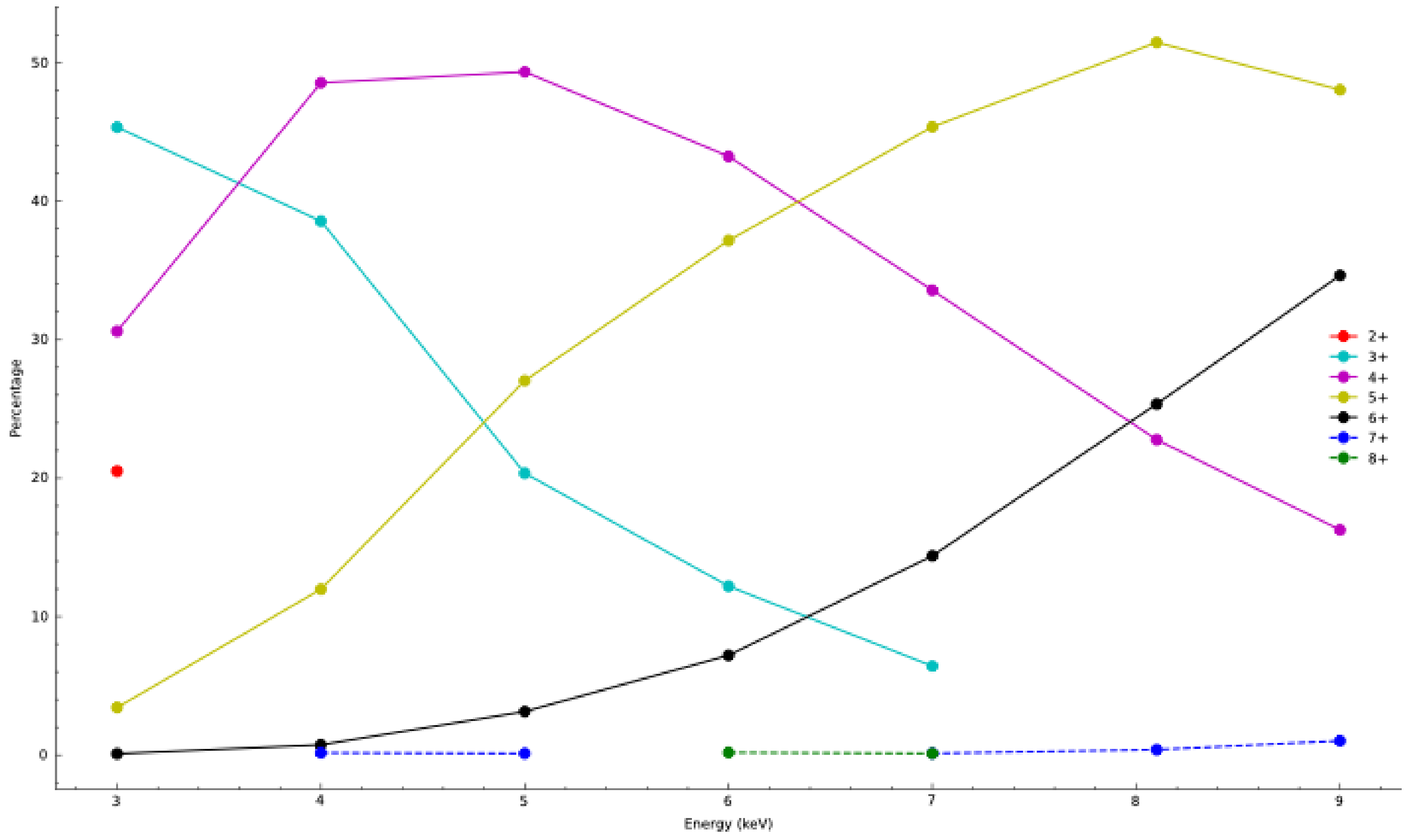


Commissioning - Suppression

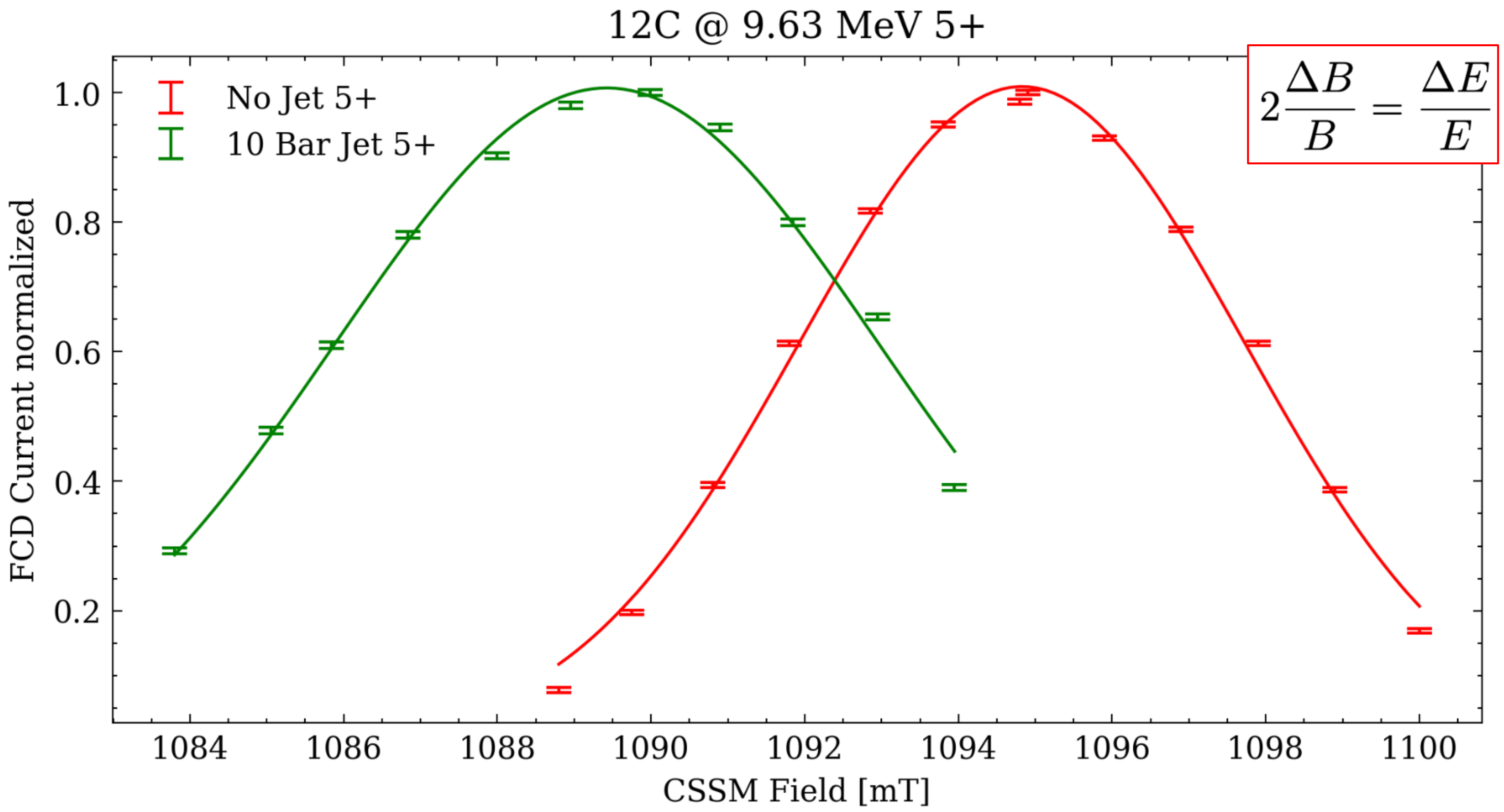




Commissioning – Ch. State Distribution



Commissioning – Jet Target



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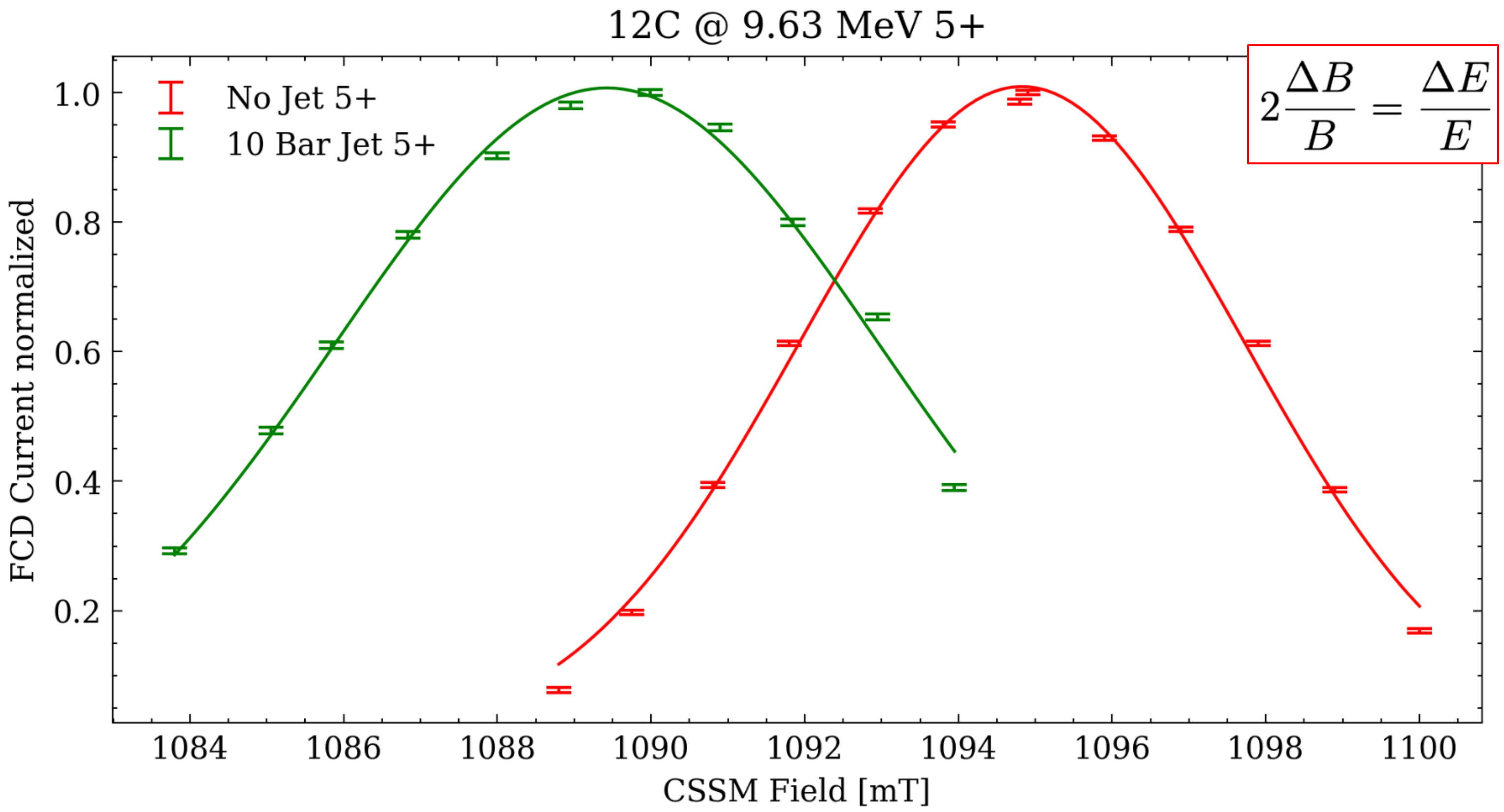
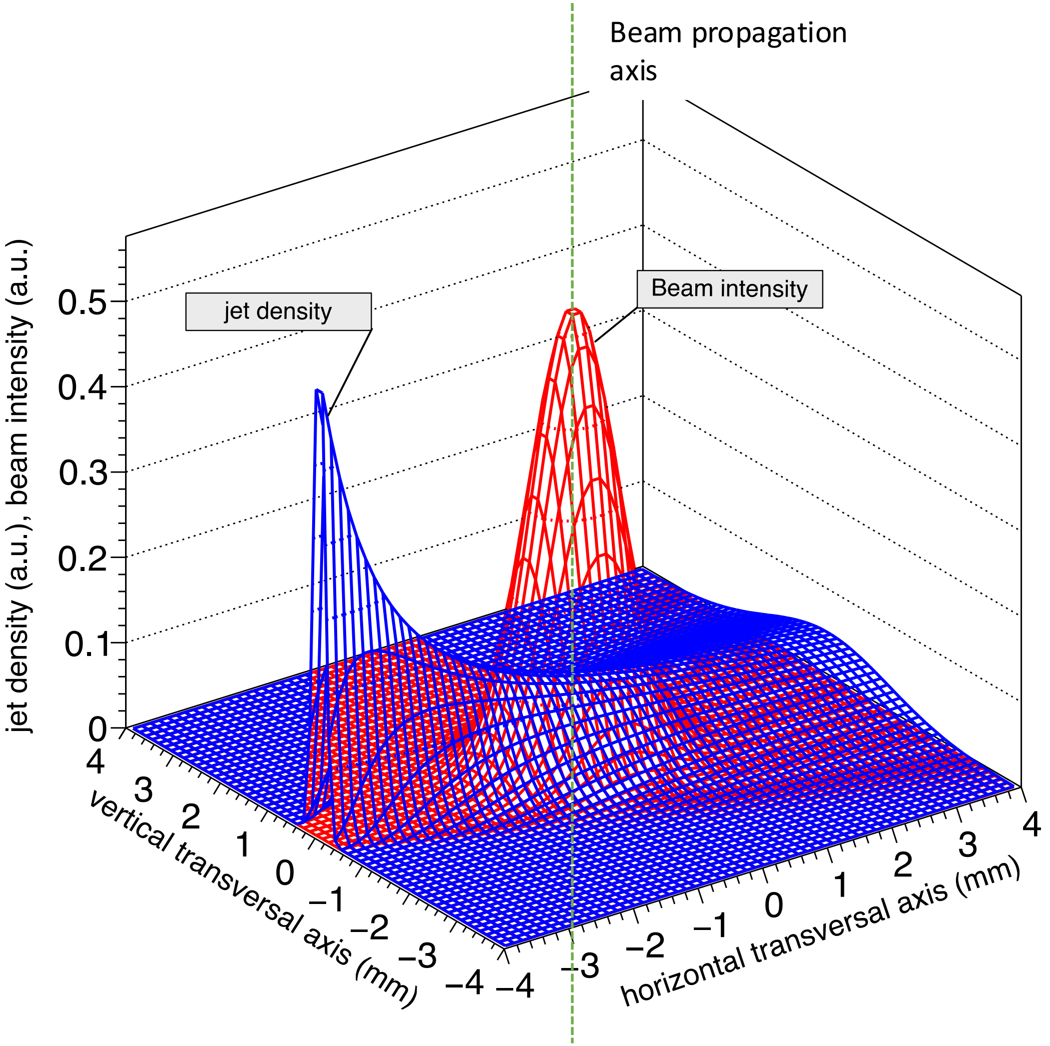


$$2\frac{\Delta B}{B} = \frac{\Delta E}{E}$$

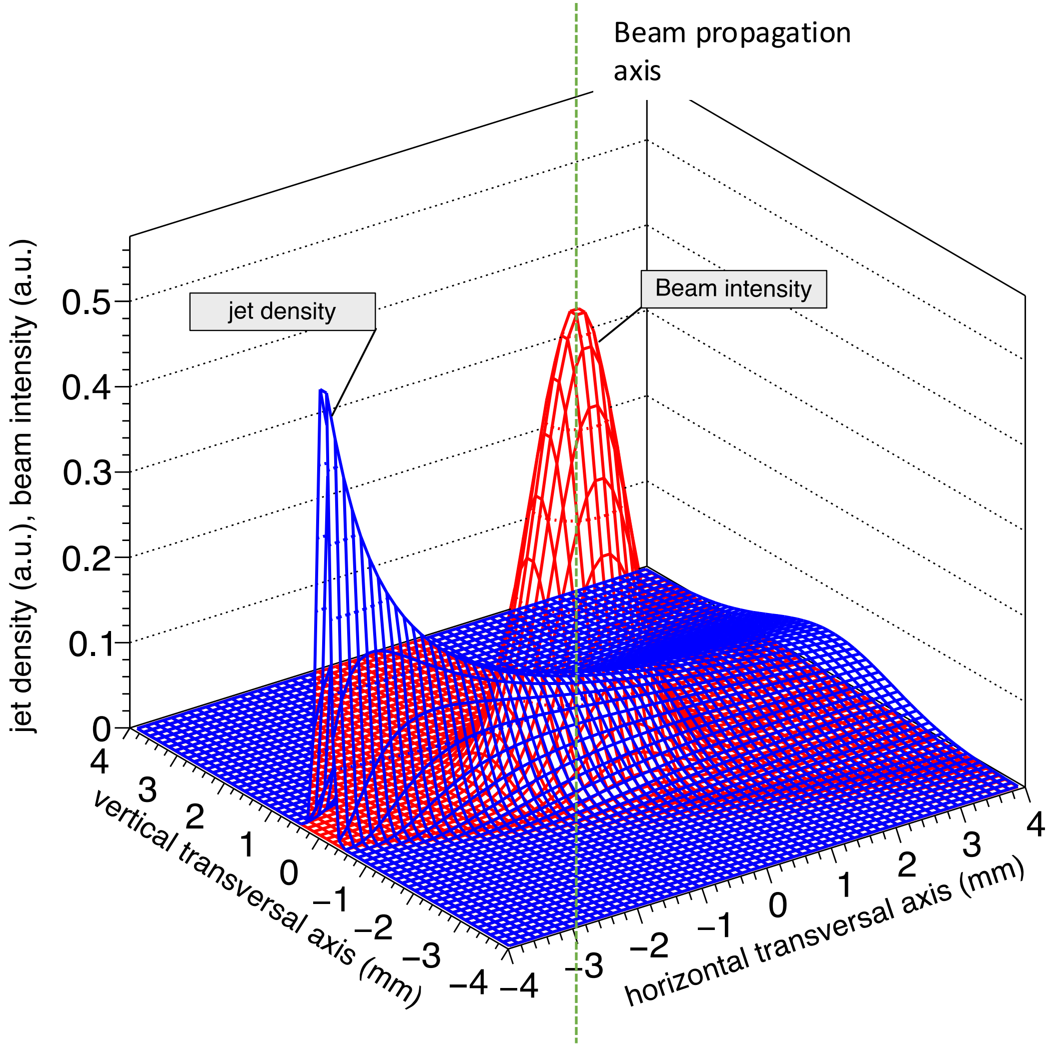
$$\tau_{jet} = (1.73 \pm 0.06) \cdot 10^{18}\ atoms/cm^2$$

Commissioning – Jet Target



Commissioning – Jet Target

$$\overline{\tau_{jet}} = \tau_{jet} \frac{\int_{\Sigma} b\tau \, d\Sigma}{\int_{\Sigma^*} b\tau \, d\Sigma} \frac{\int_{\Sigma^*} b \, d\Sigma}{\int_{\Sigma} b \, d\Sigma}$$



Commissioning – Jet Target

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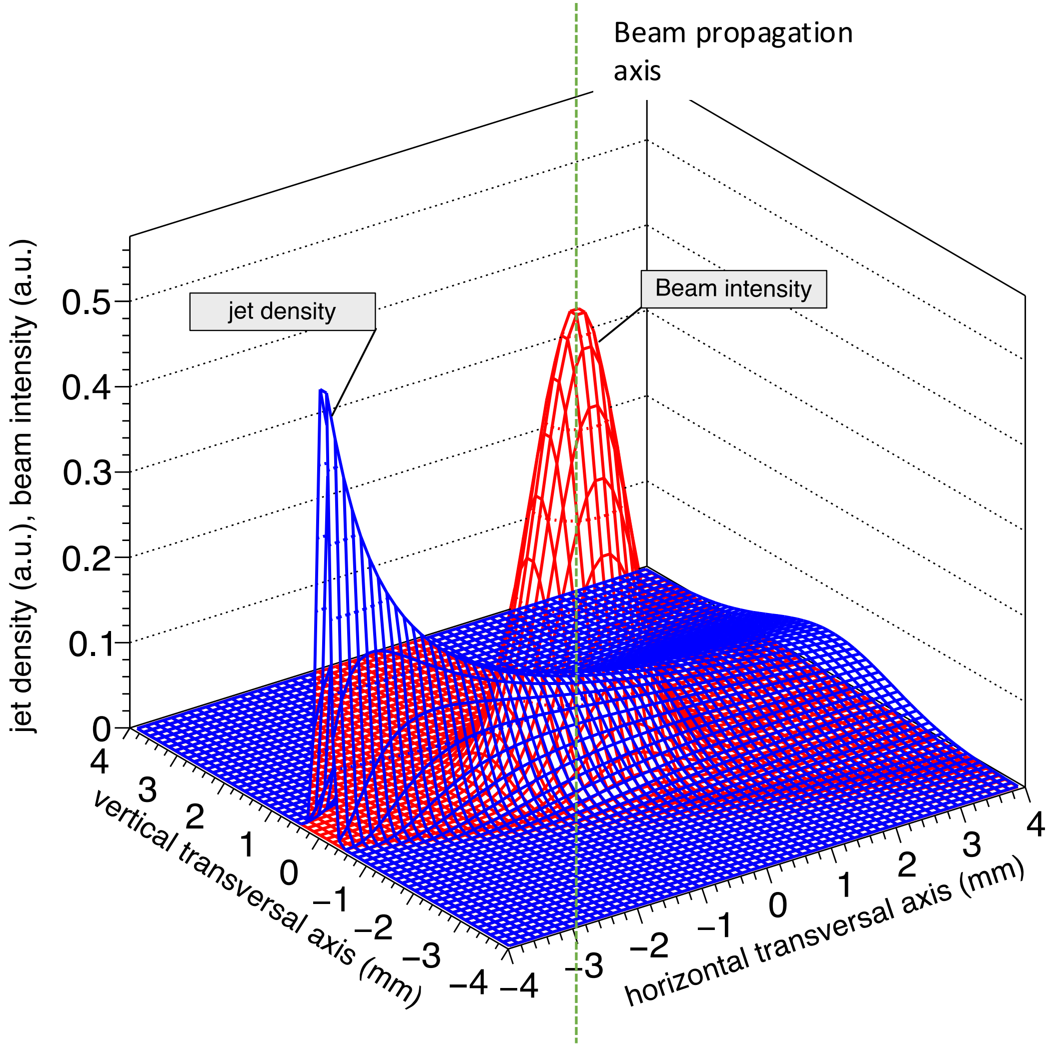
$$\overline{\tau_{jet}} = (1.3 \pm 0.1) \cdot 10^{18} \; atoms/cm^2$$



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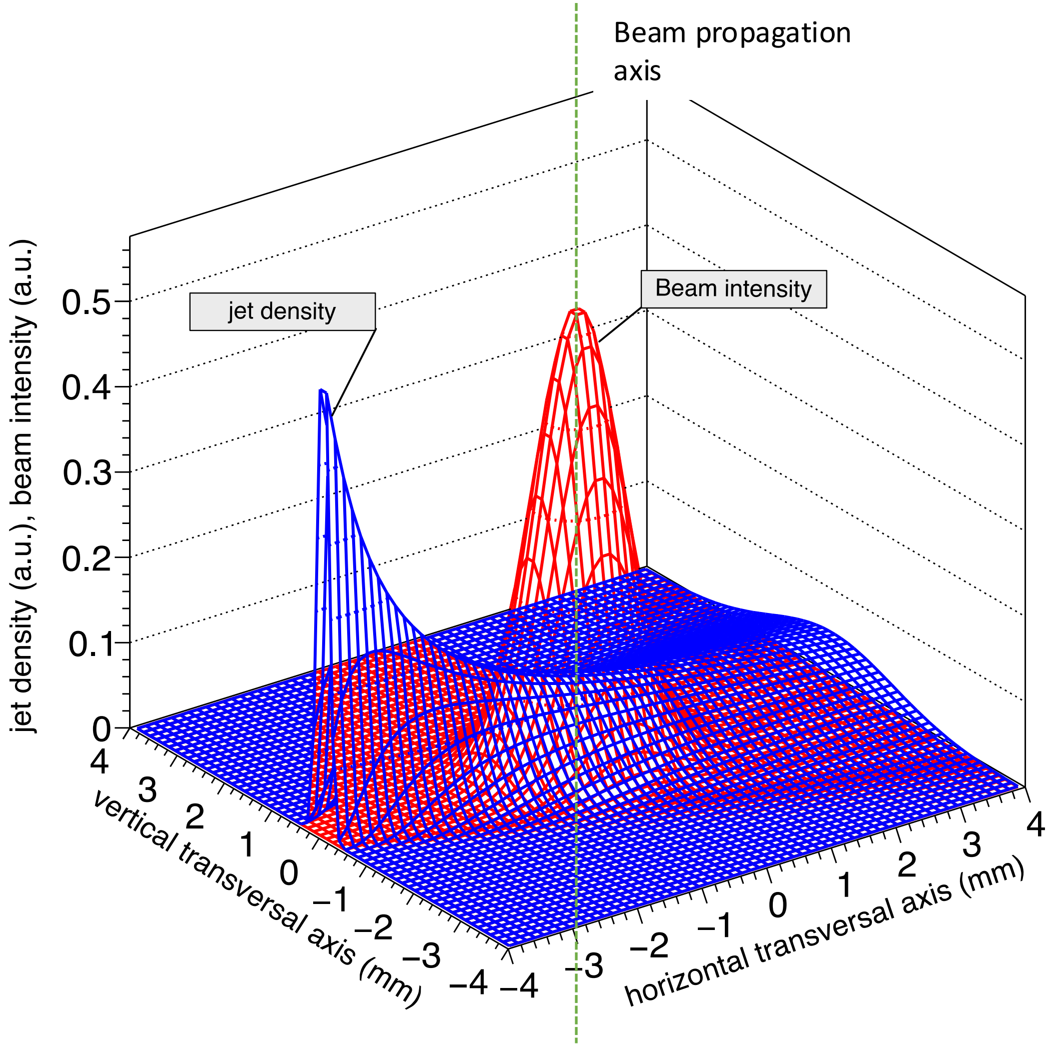
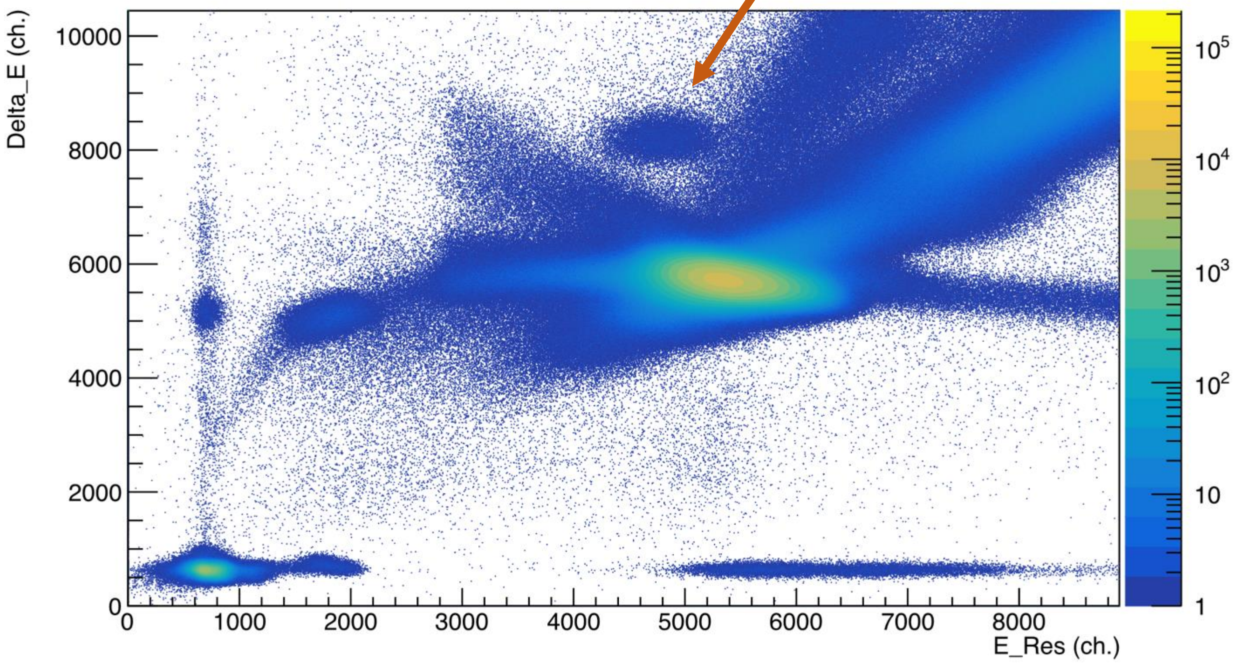


$$Y = \int_{-\infty}^{+\infty} \int_{-\infty}^{+\infty} n_t(x,y) n_p(x,y) \int_{E_0-\Delta E(x,y)}^{E_0} \sigma(E) \phi_q \epsilon T \; dE dx dy$$

Test run

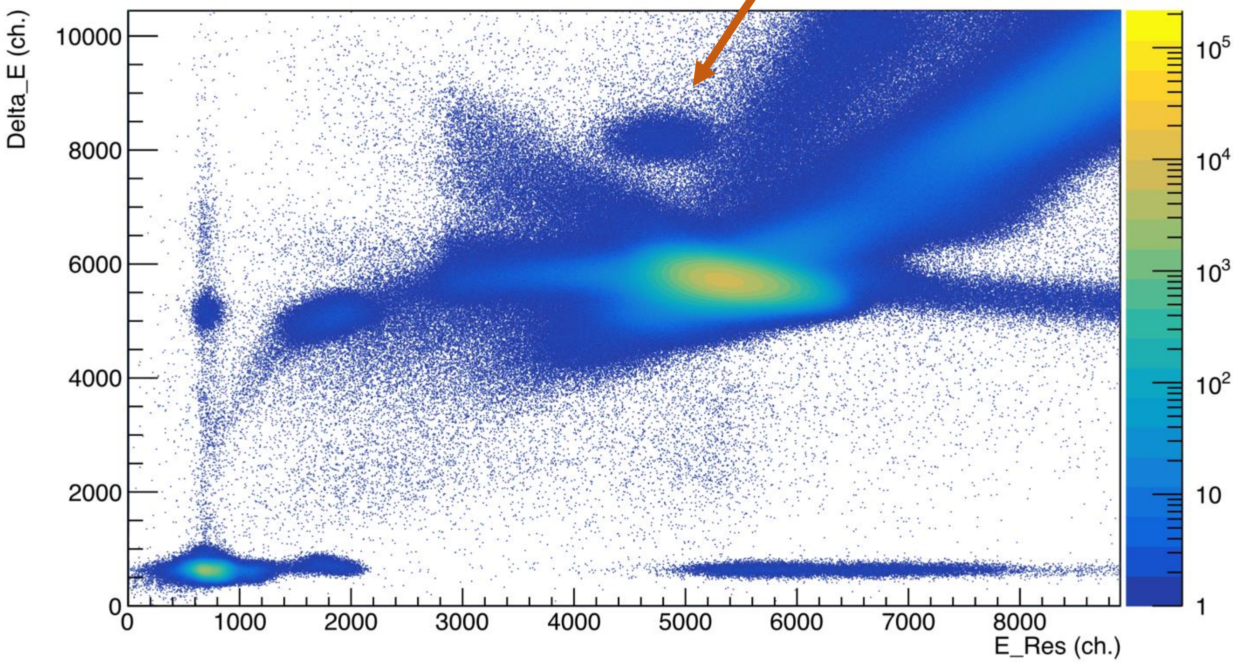
$^{12}C(\alpha,\gamma)^{16}O$

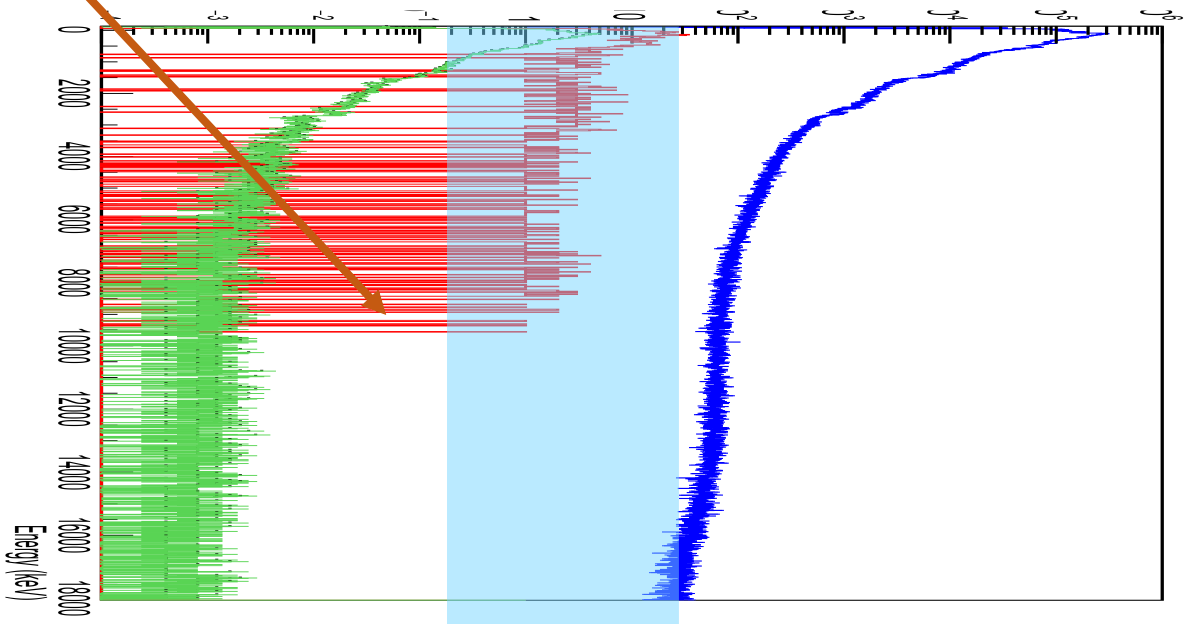


G.S.
Transitions

Test run

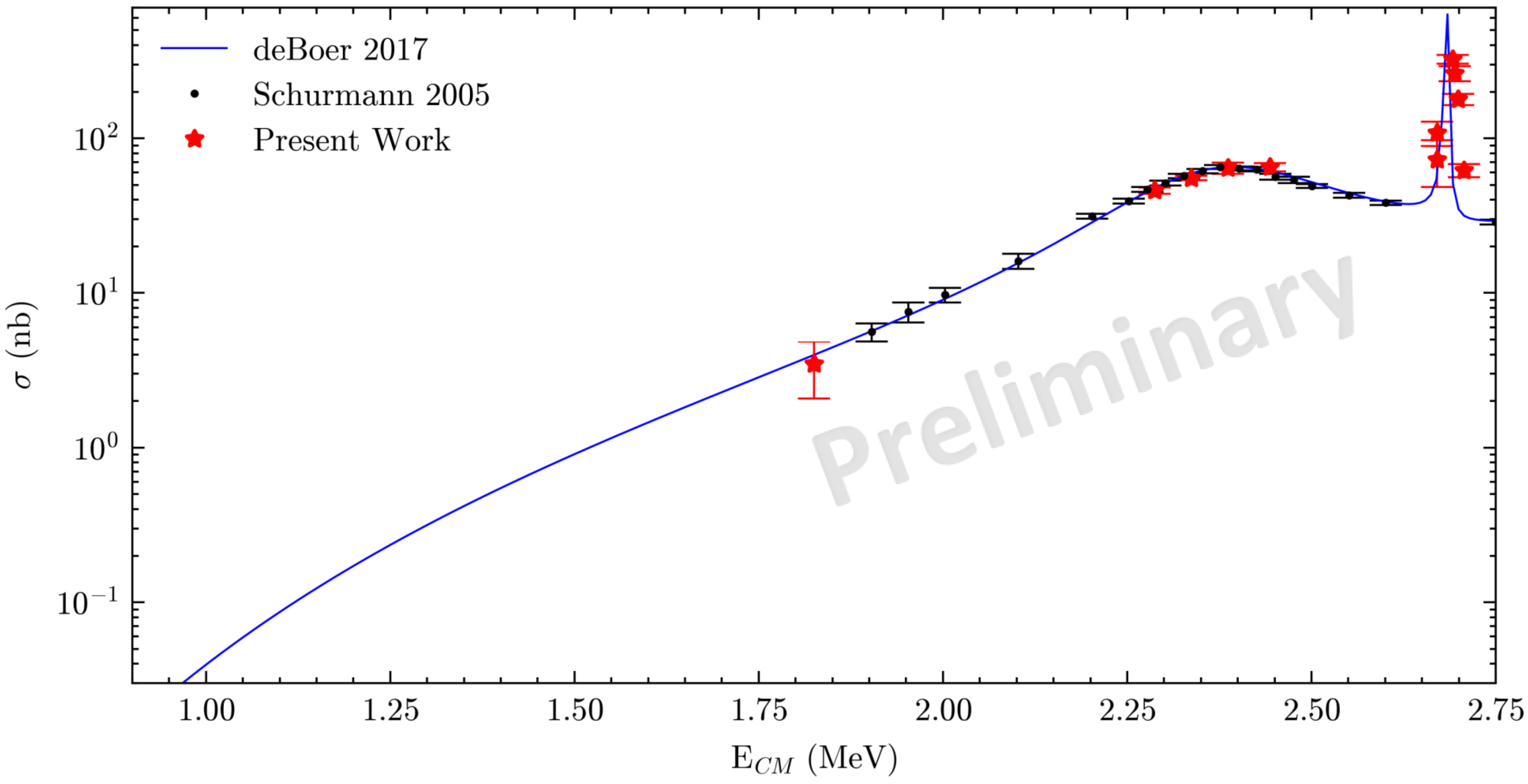
$^{12}C(\alpha,\gamma)^{16}O$





G.S.
Transitions

Expected energy coverage



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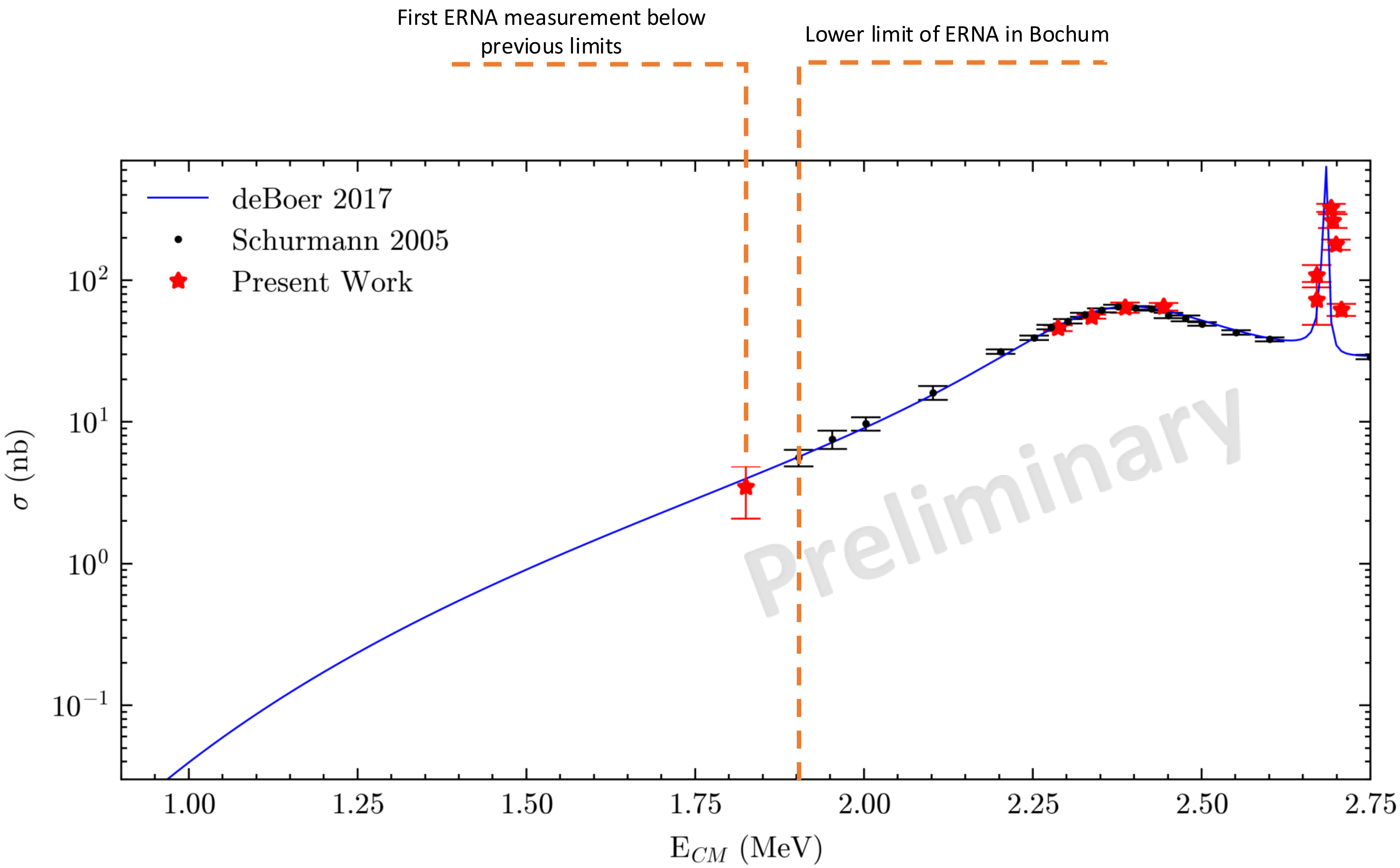
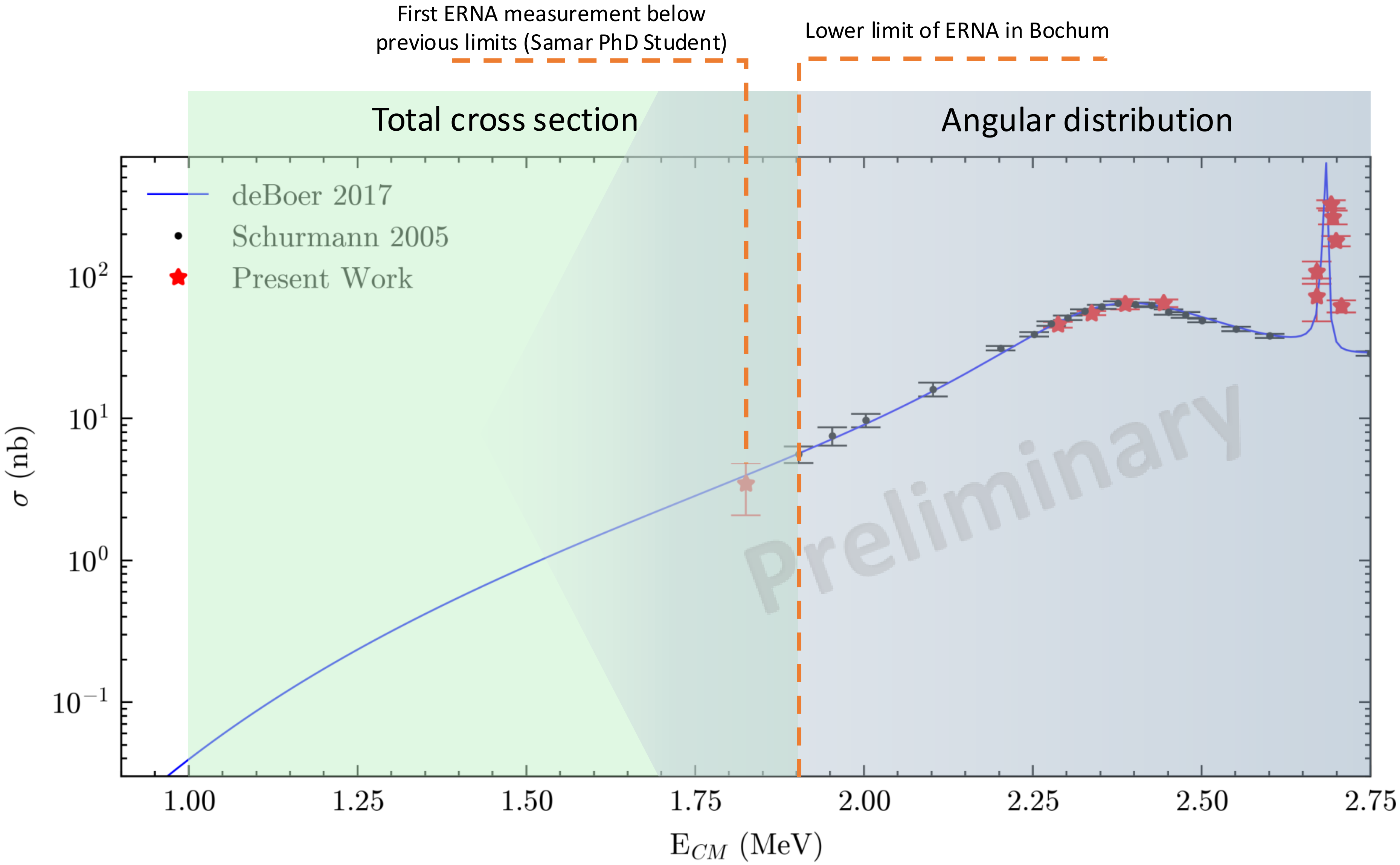
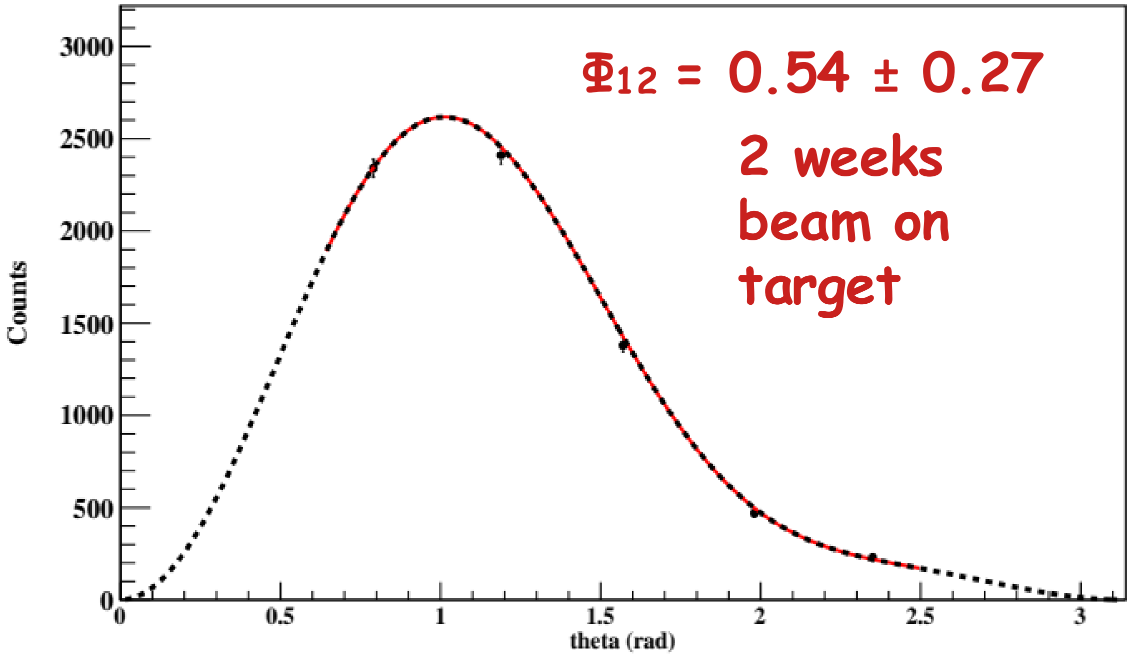


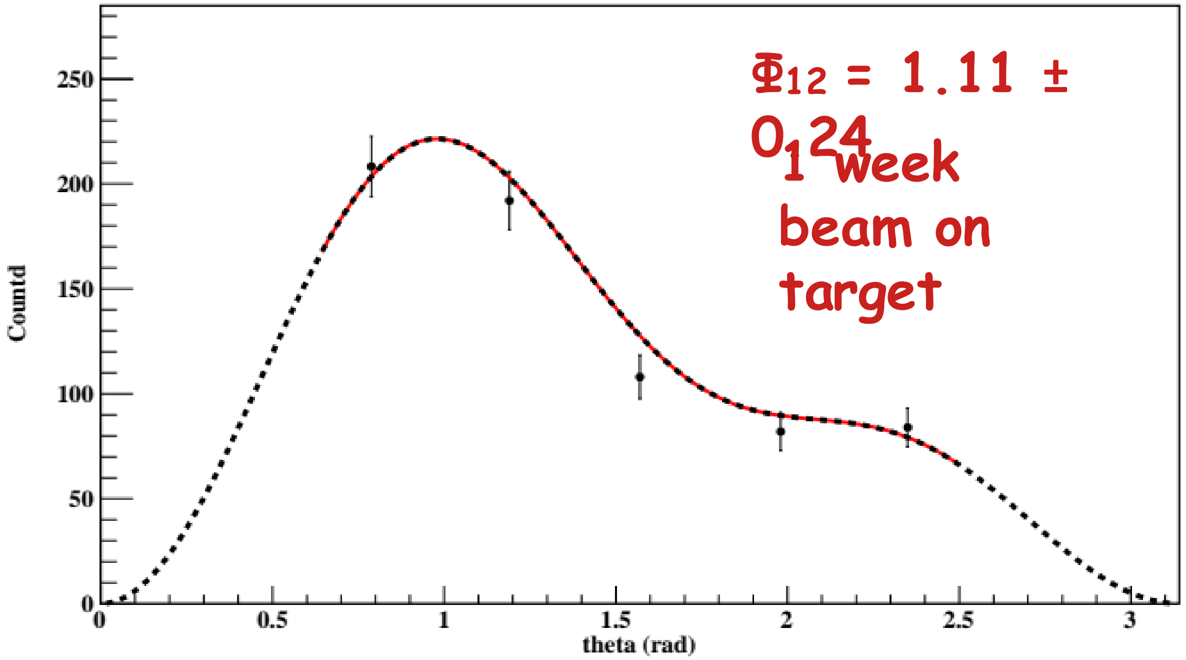
Samar PhD Student

Expected energy coverage



Current campaign focuses

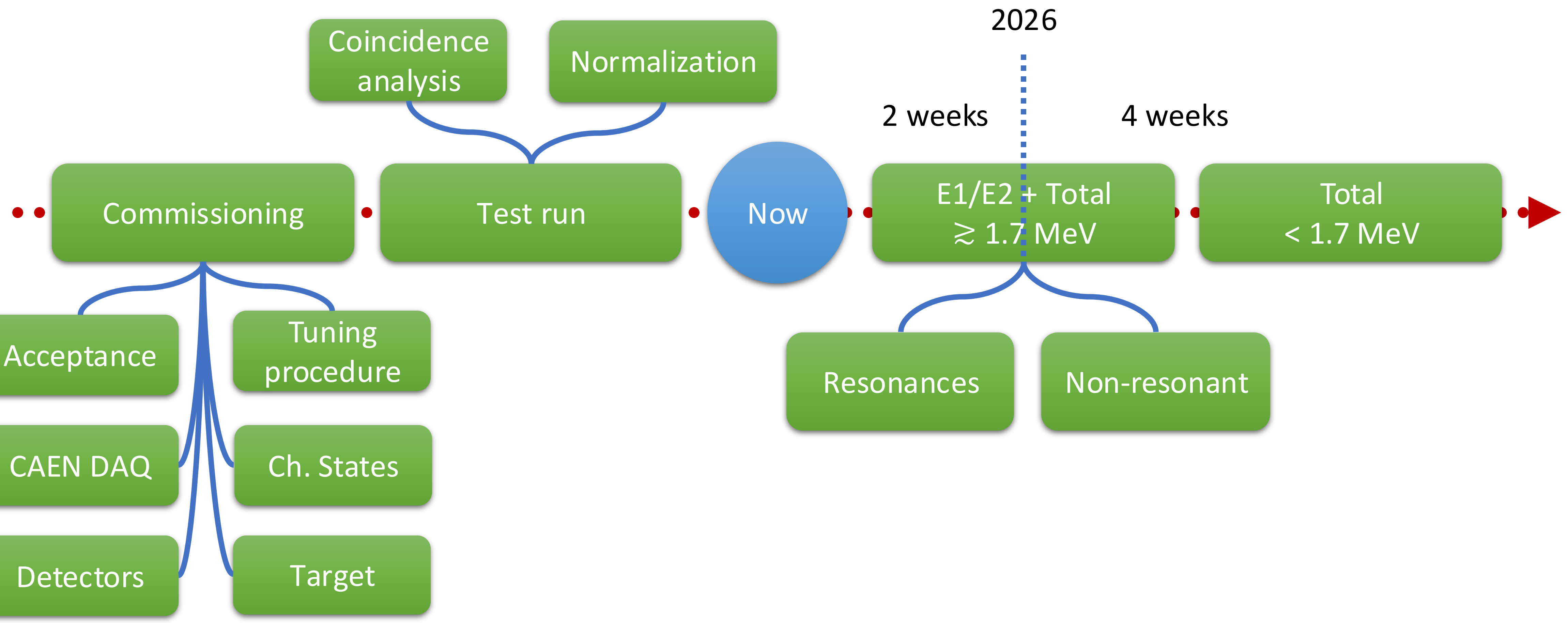




Monte-Carlo Simulated Angular Distibutions at E_{cm} = 2.42 MeV (Left) and E_{cm} = 2.56 MeV (Right)

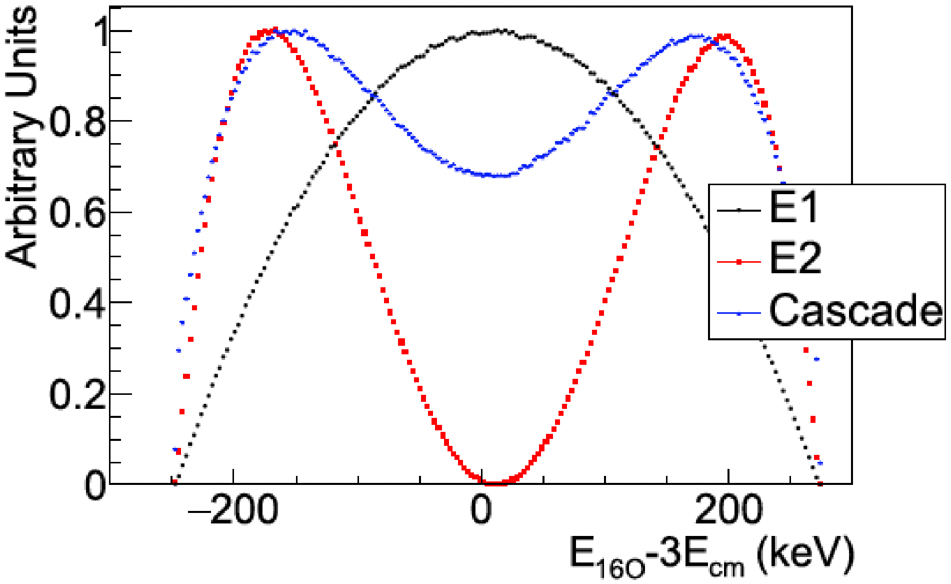
Courtesy of K. Chakraborty

Current status of $^{12}C(\alpha,\gamma)^{16}O$ study with ERNA

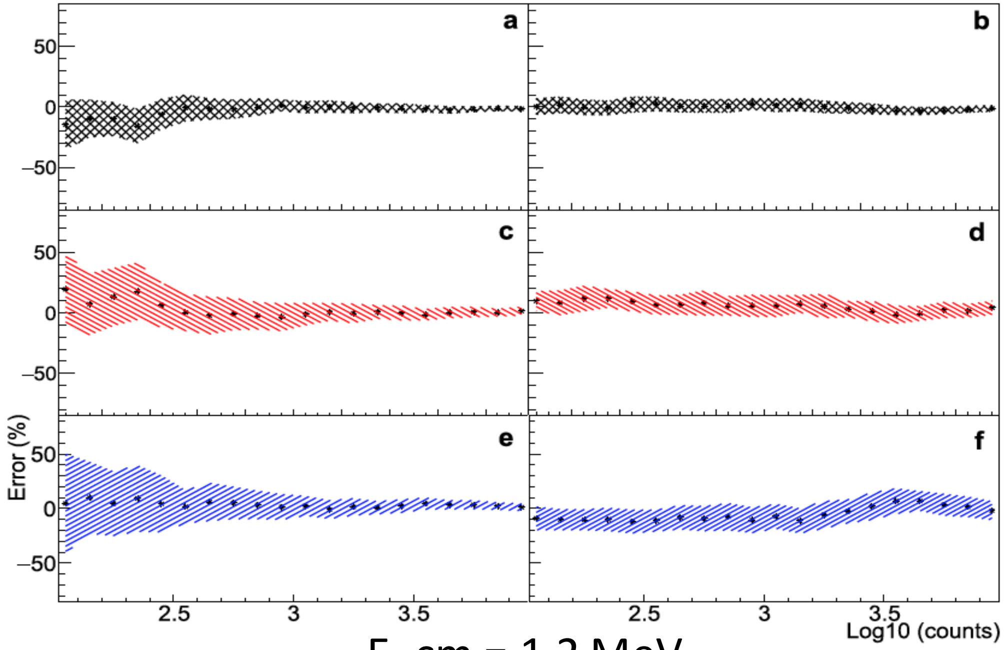


What's next for the $^{12}C(\alpha,\gamma)^{16}O$ ERNA?

E1, E2, Cascade recognition



[1] MC grid search NN method



E_cm = 1.2 MeV

?

[1] Duarte, J. G. *et al*. *Eur. Phys. J. A* **61**, (2025).
[2] Nirkko, M. *et al*. *J. Inst.* **8**, P02001–P02001 (2013).

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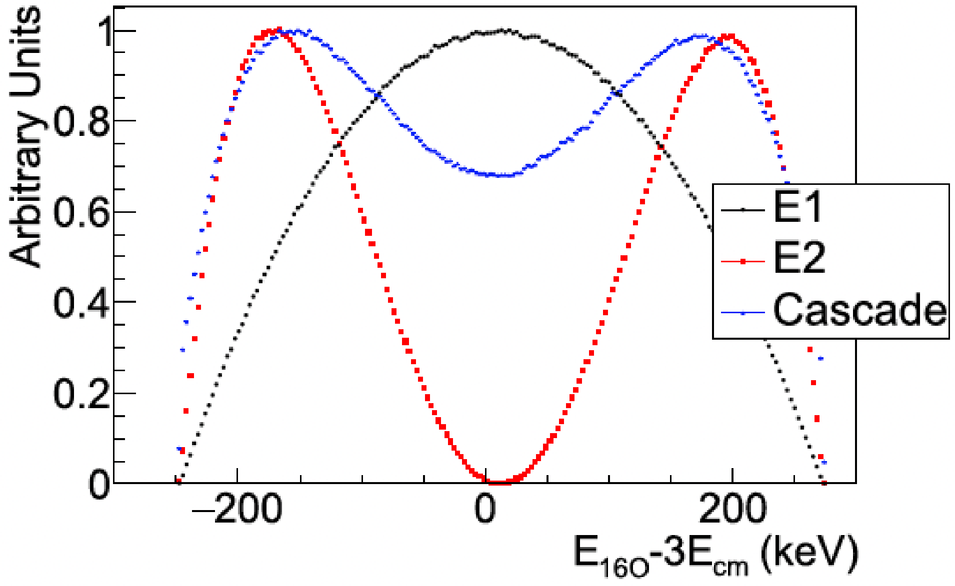
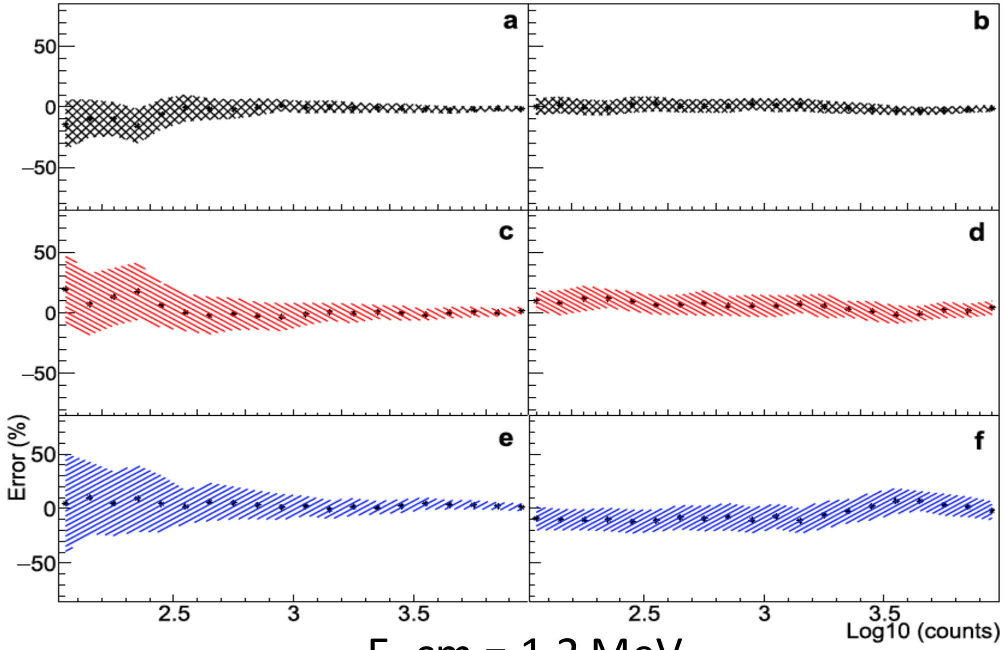


[1]



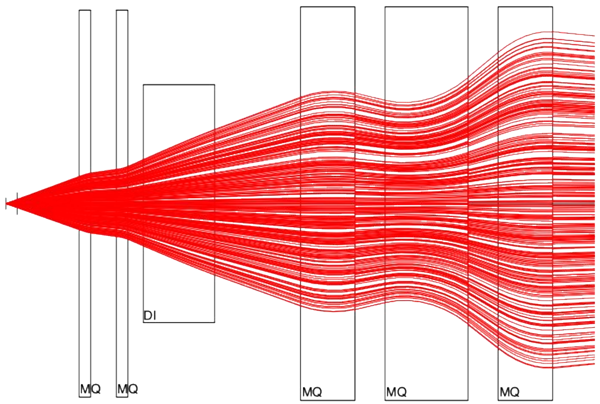
E1

E2

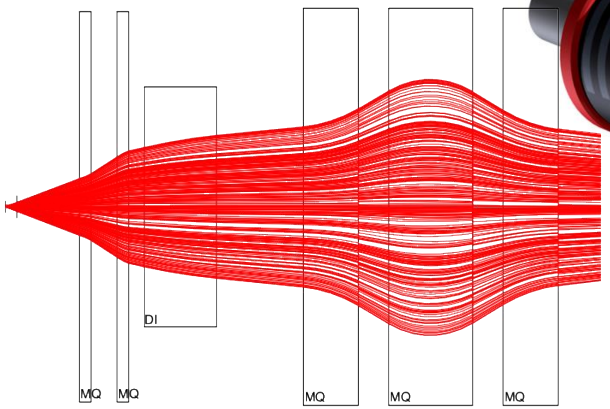
Casc

E_cm = 1.2 MeV

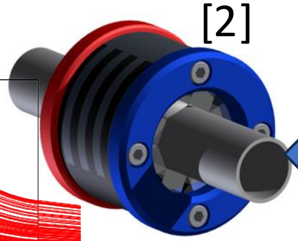
Acceptance improvements



X-axis



Y-axis



[2]

Current capability (MeV_CM) ?

1 E_CM (MeV) 3

[1] Duarte, J. G. *et al*. *Eur. Phys. J. A* **61**, (2025).

[2] Nirkko, M. *et al*. *J. Inst.* **8**, P02001–P02001 (2013).

Conclusion

✓Limitation of the Bochum layout overcome
✓Recoil separator commissioned and characterized (1 MeV < E_CM < 2.7 MeV)
✓Successful test runs on resonances.
✓Common mode error of approx. 7%

❑ Gamma detection exploring E1/E2 ratio
❑ Total cross section at lower energies

ERNA Collaboration

A. Best[1,2], R. Buompane[1,3], K. Chakraborty[1,3], M. De Cesare[1,4], A. Di Leva[1,2], F. Ercolano[1,2], A. Formicola[5], G. Imbriani[1,2], F. Marzaioli[1,3], C. M. Morone[6,7], G. Porzio[1,3],D. Rapagnani[1,2], M. Romoli[1], C. Santonastaso[8], O. Straniero[5,9], R. P. Yadav[5]

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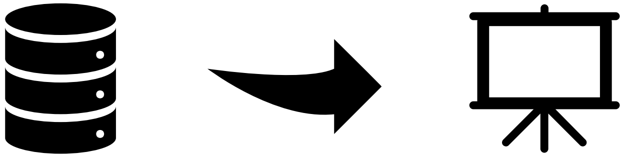
8. RIKEN Nishina Center, Wako, Saitama, Japan
9. INAF, Osservatorio Astronomico d’Abruzzo, Teramo, Italy

ERNA
European Recoil separator for Nuclear Astrophysics

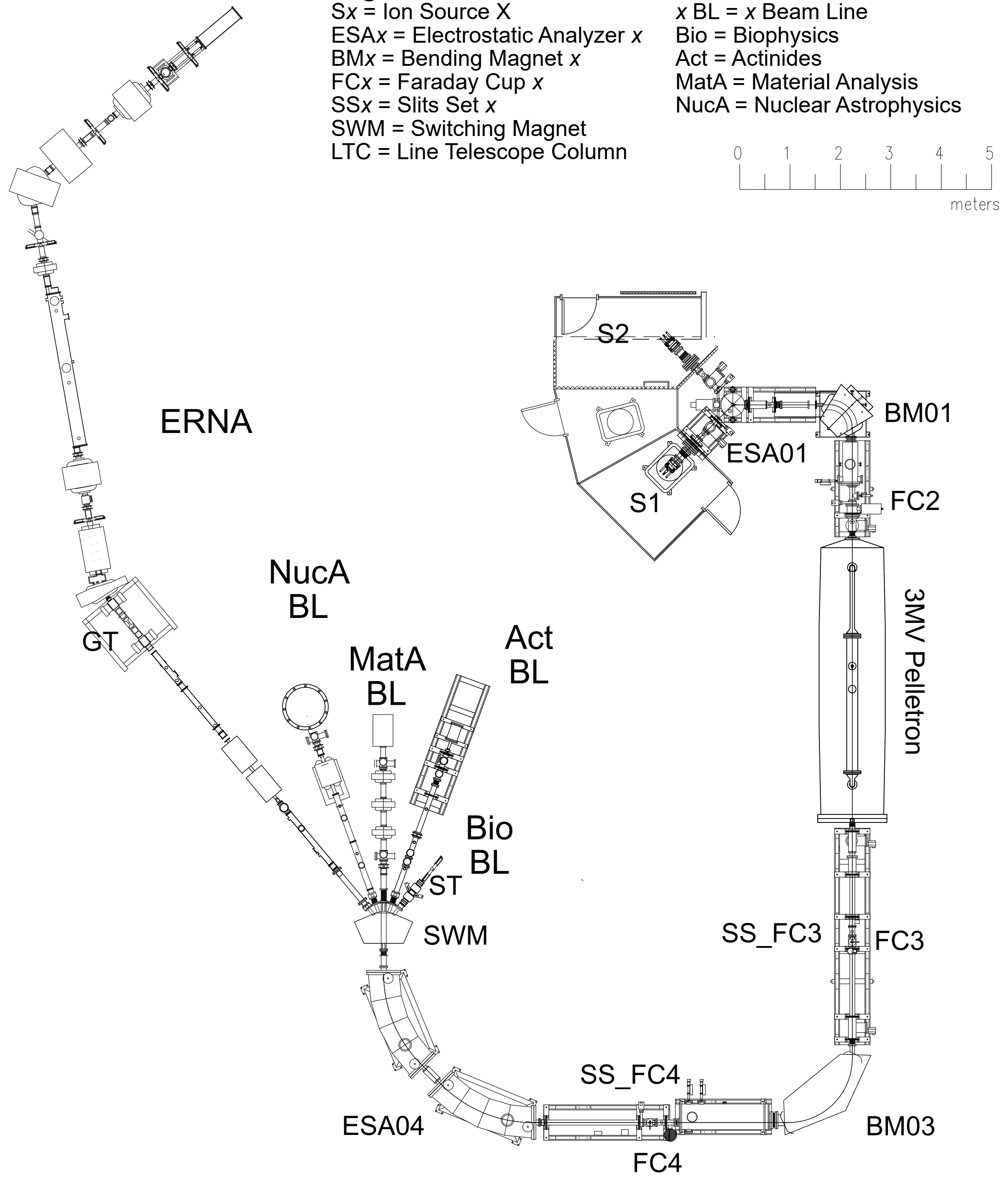
Backup slides

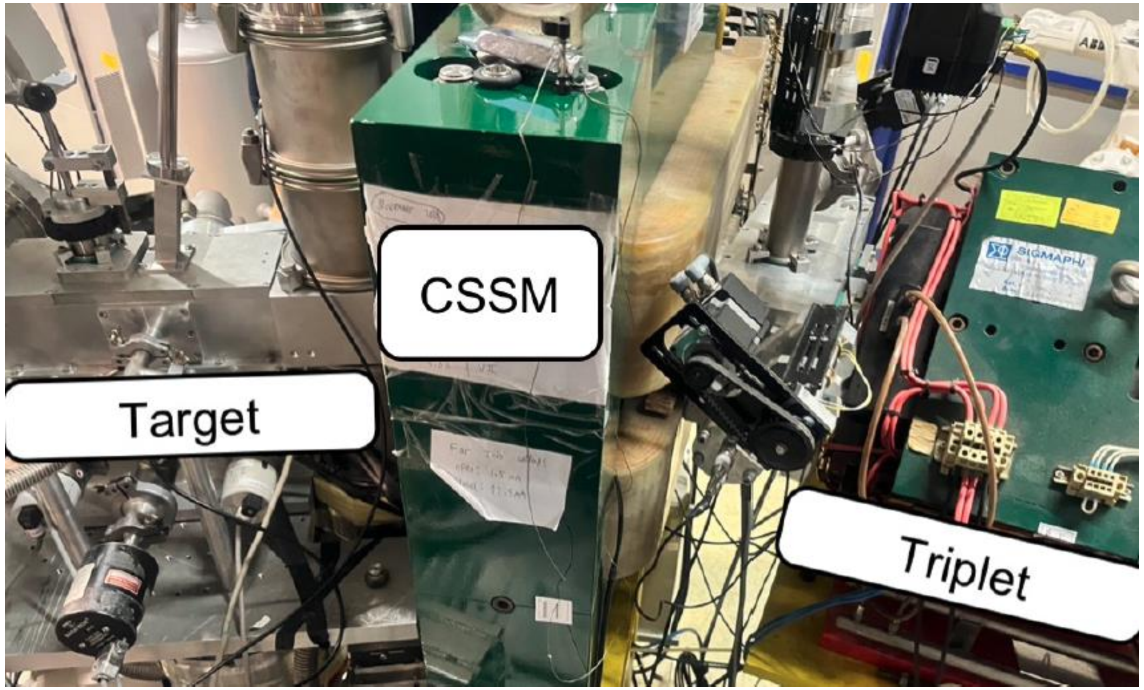


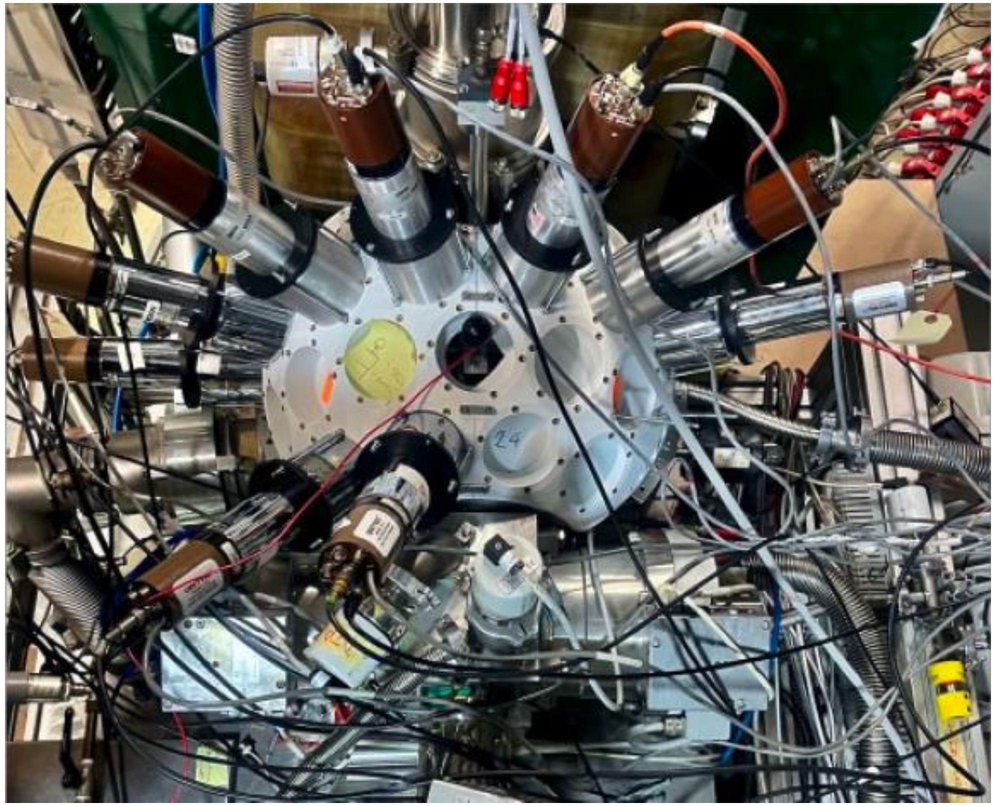
Tandem Accelerator Laboratory

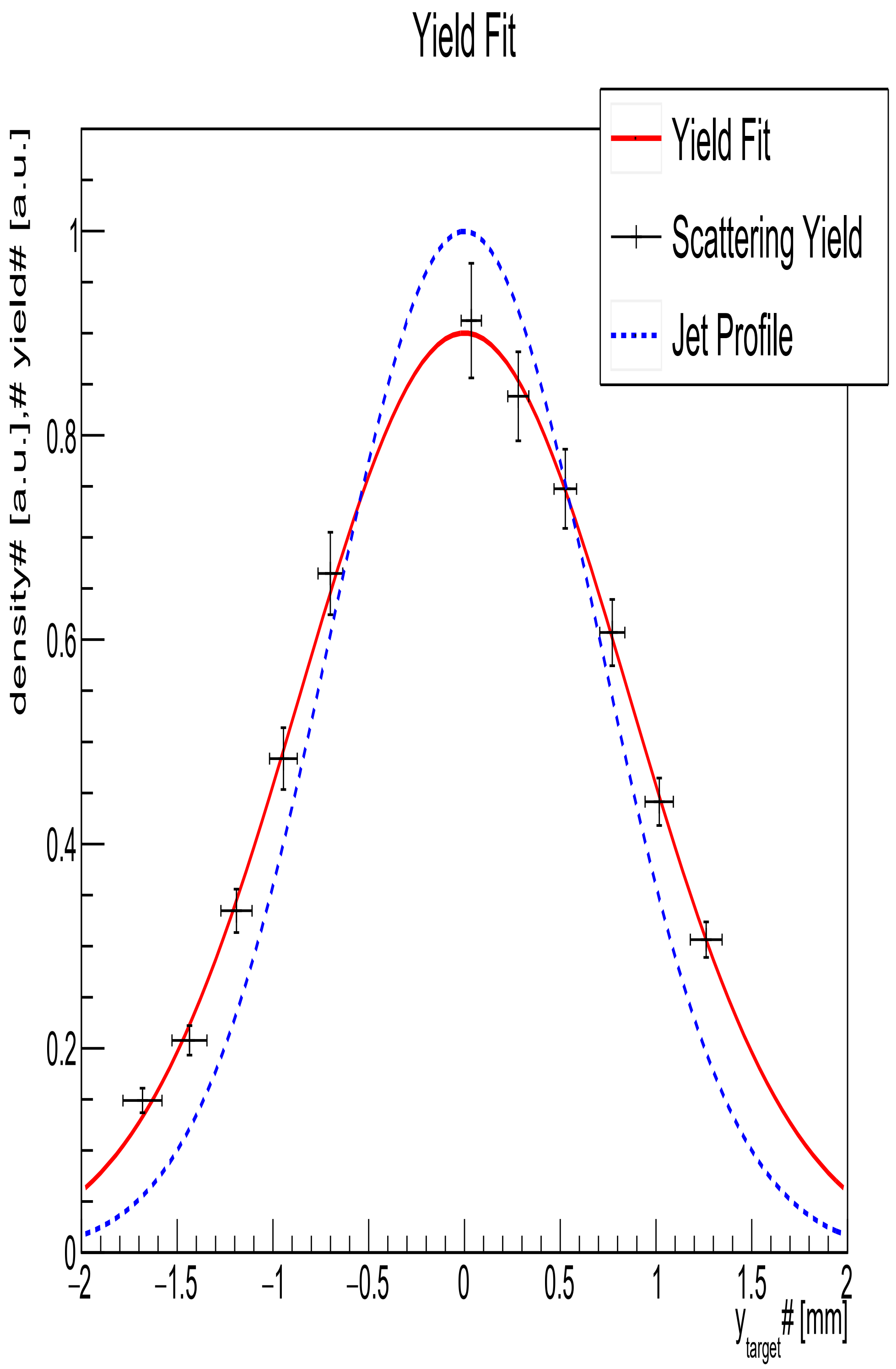
Legend

S*x* = Ion Source X
ESA*x* = Electrostatic Analyzer *x*
BM*x* = Bending Magnet *x*
FC*x* = Faraday Cup *x*
SS*x* = Slits Set *x*
SWM = Switching Magnet
LTC = Line Telescope Column
x BL = *x* Beam Line
Bio = Biophysics
Act = Actinides
MatA = Material Analysis
NucA = Nuclear Astrophysics

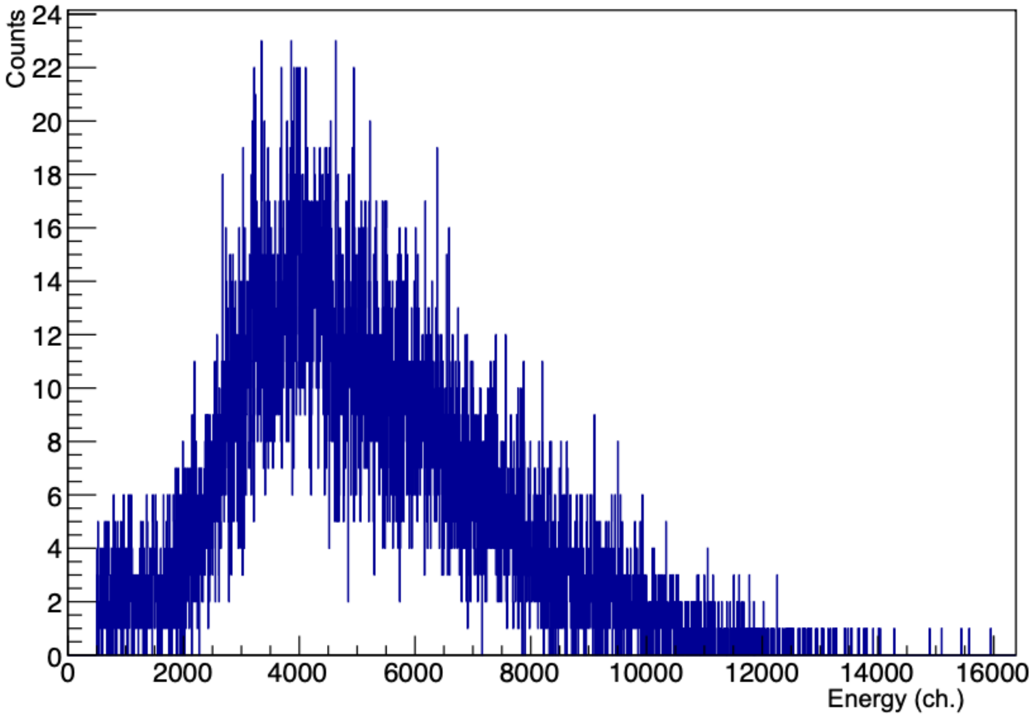



CSSM
Target
Triplet

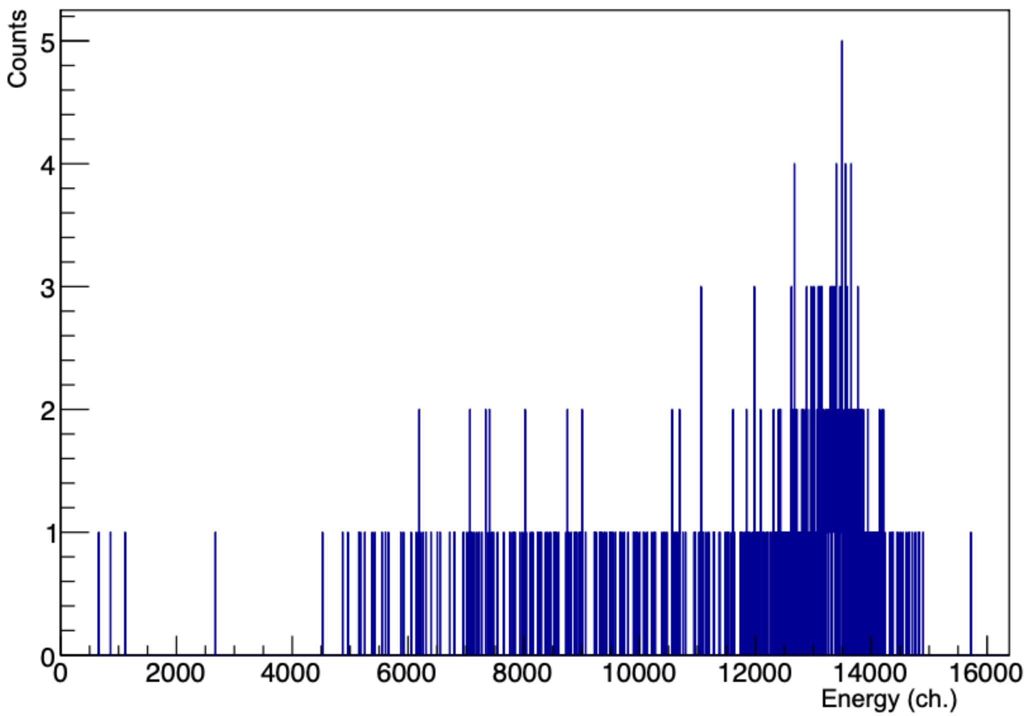




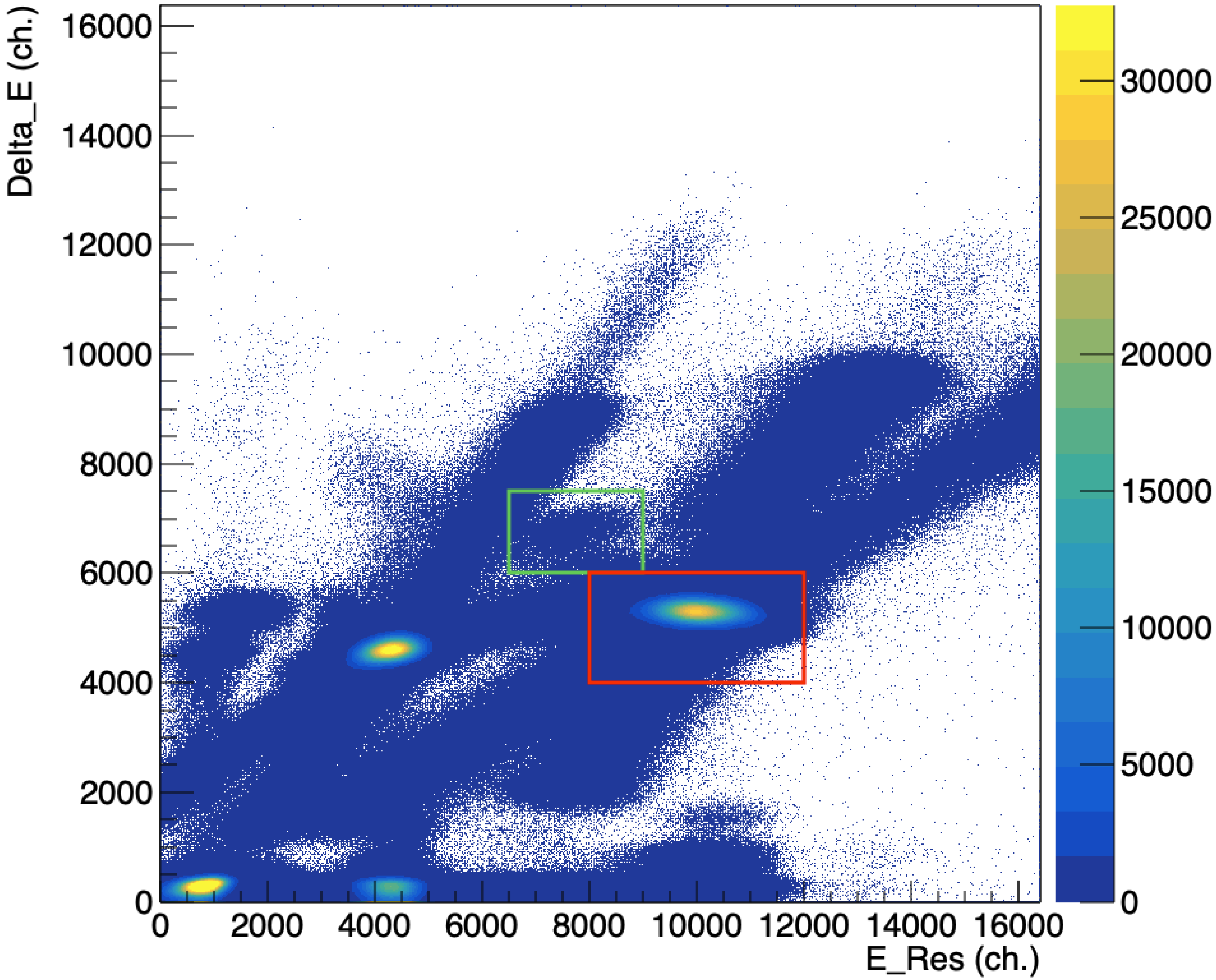
Yield Fit
Yield Fit
Scattering Yield
Jet Profile
density# [a.u.],# yield# [a.u.]
0
0.2
0.4
0.6
0.8
1
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2
y_target # [mm]



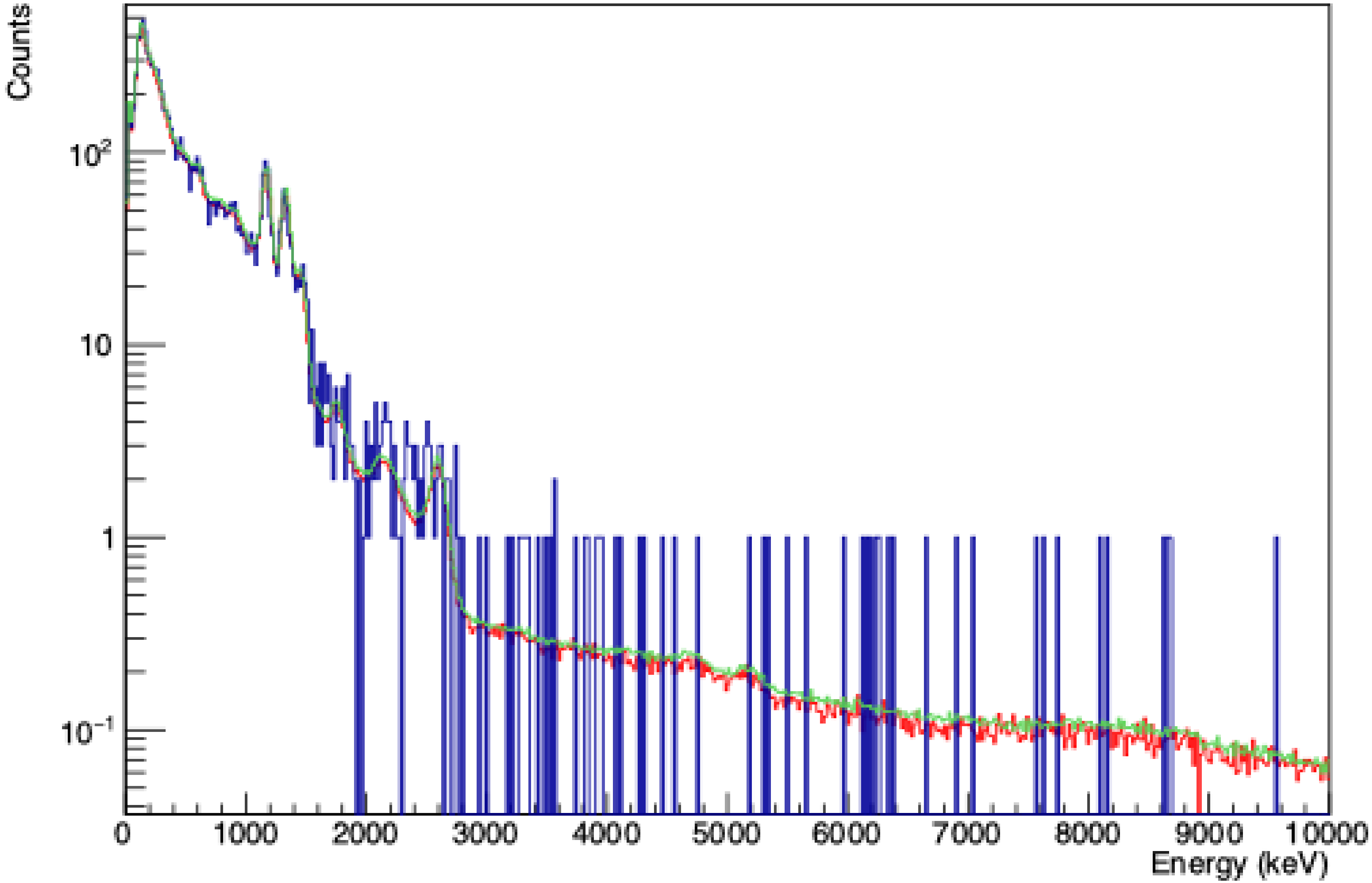
Counts
Energy (ch.)



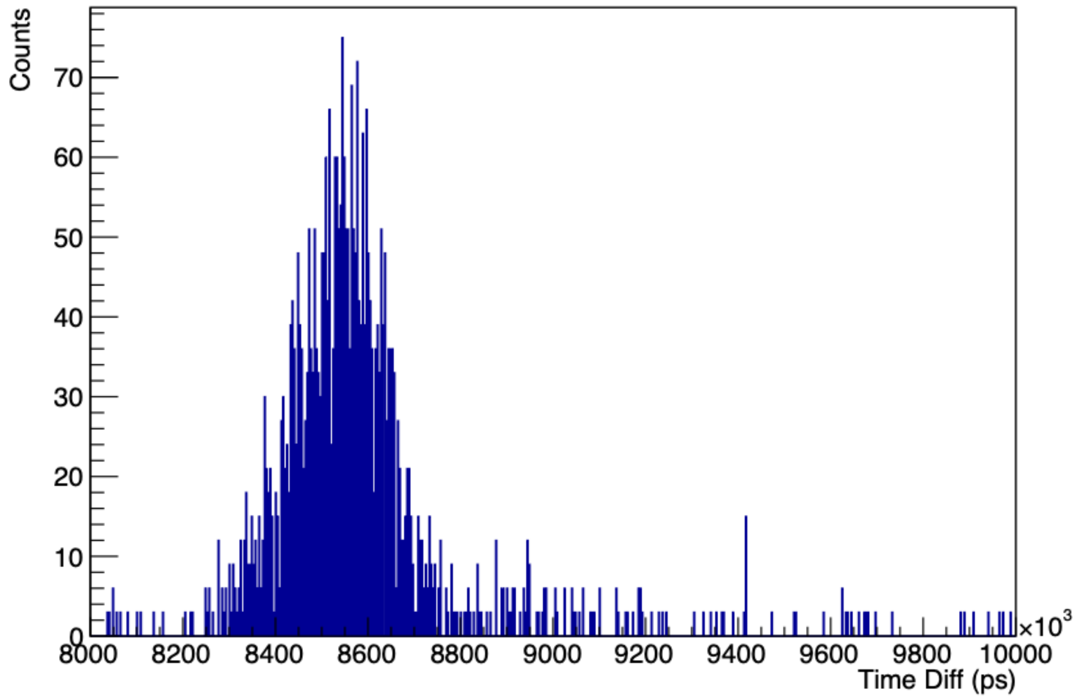
Counts
Energy (ch.)



Delta_E (ch.)
E_Res (ch.)
0
2000
4000
6000
8000
10000
12000
14000
16000
0
5000
10000
15000
20000
25000
30000

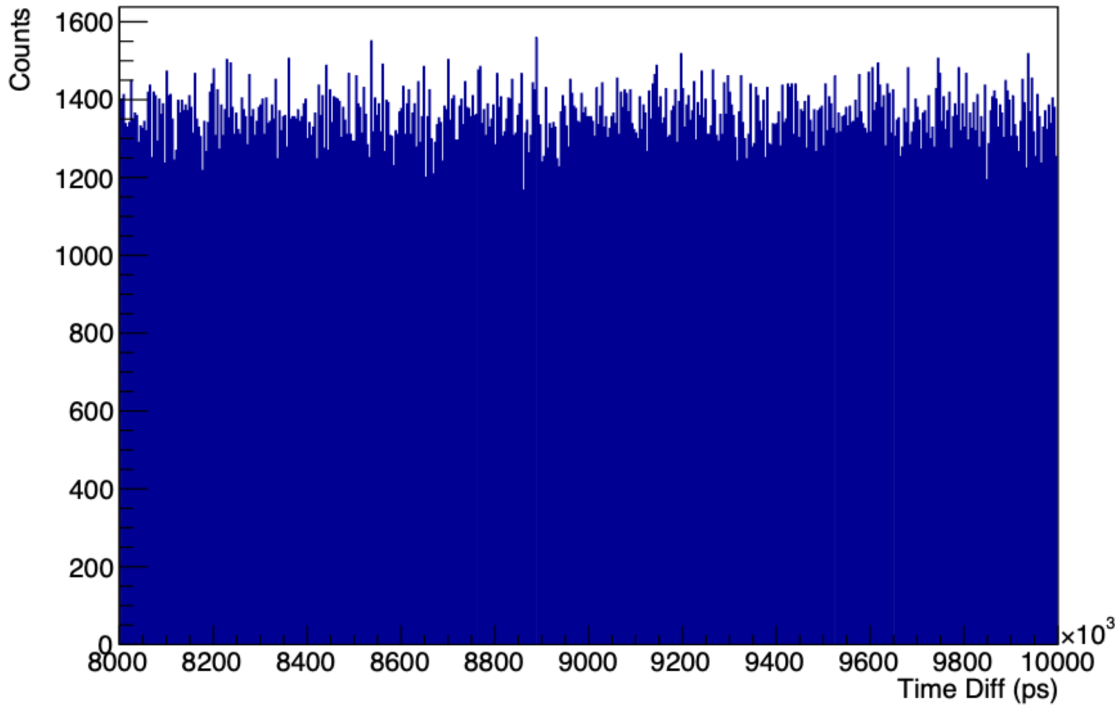


Counts
10^2
10
1
10^{-1}
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Energy (keV)



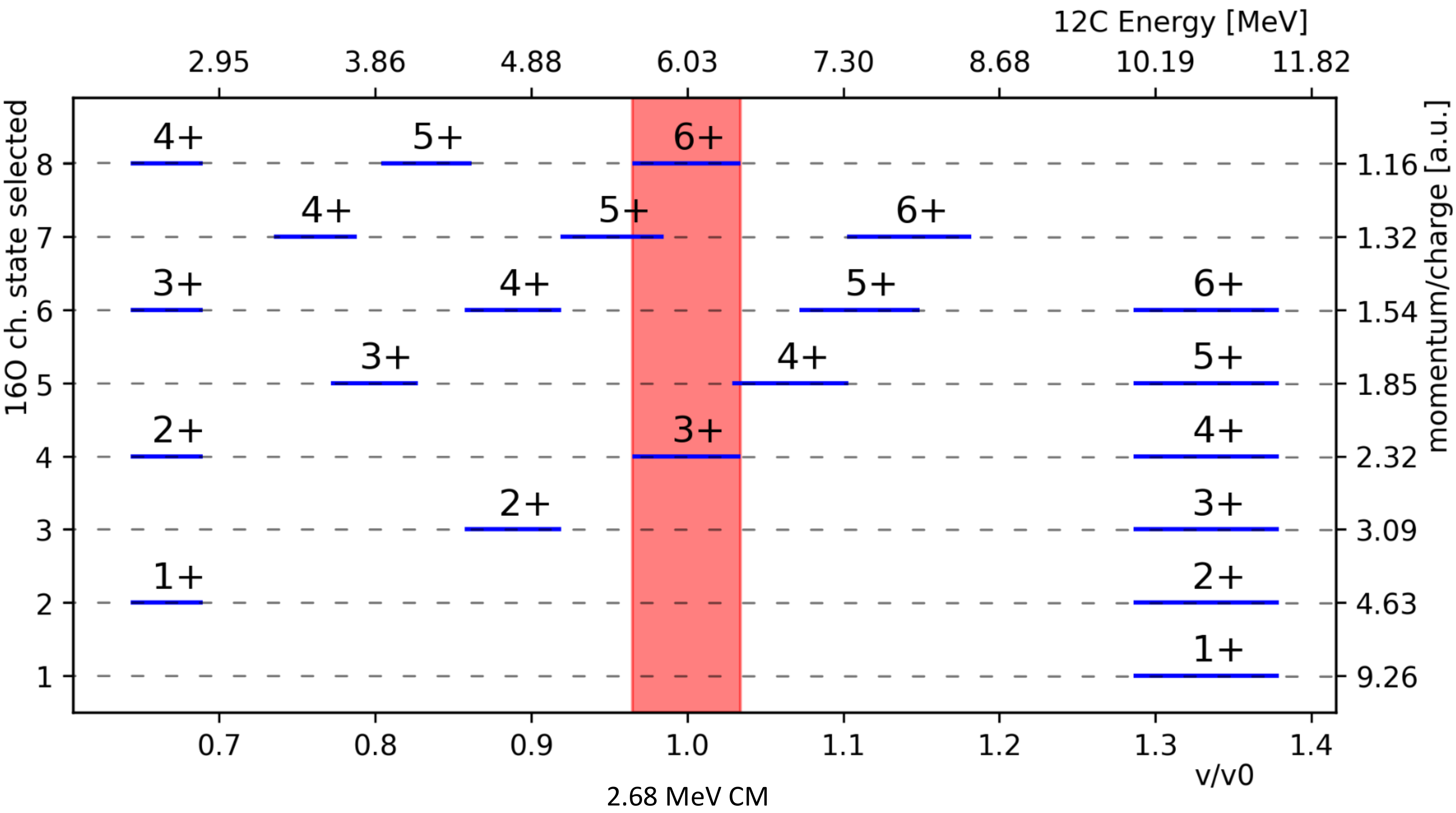
Counts
70
60
50
40
30
20
10
0
8000
8200
8400
8600
8800
9000
9200
9400
9600
9800
10000
×10³
Time Diff (ps)

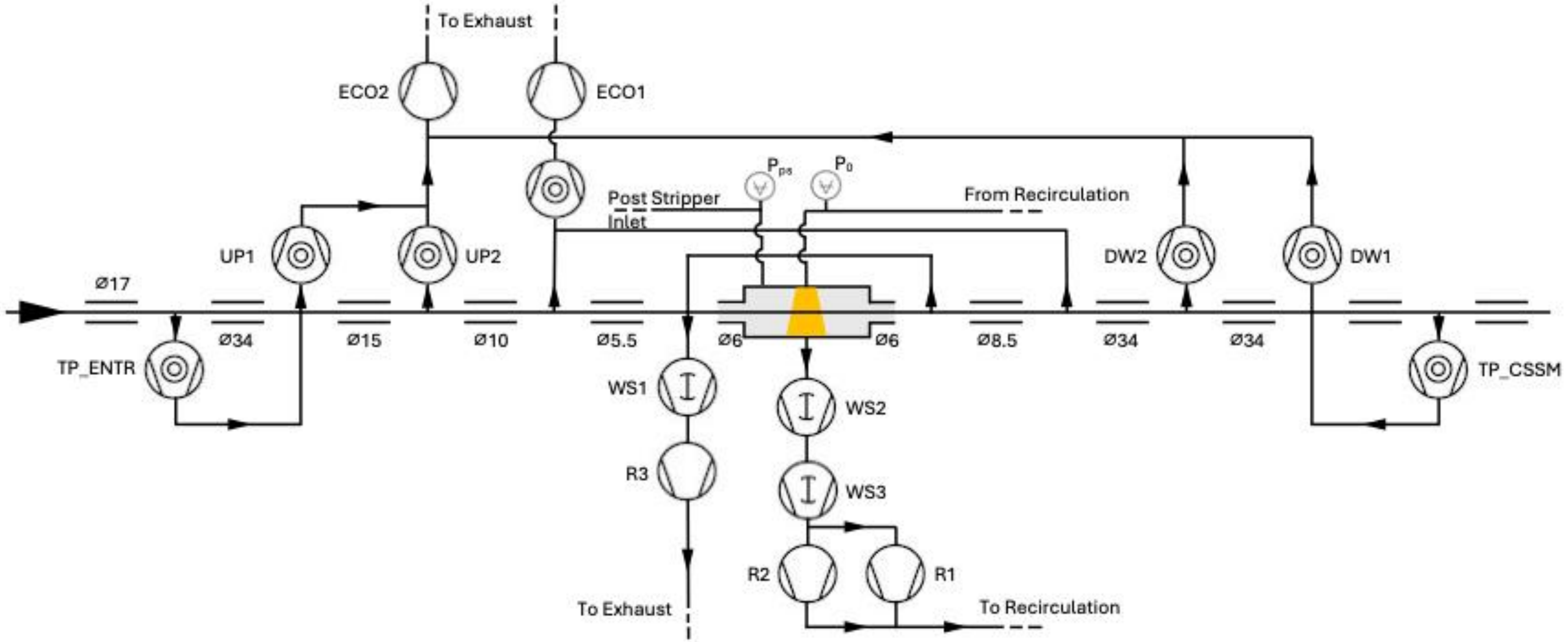
(a)



Counts
1600
1400
1200
1000
800
600
400
200
0
8000
8200
8400
8600
8800
9000
9200
9400
9600
9800
10000
×10³
Time Diff (ps)

(b)


12C Energy [MeV]
2.95
3.86
4.88
6.03
7.30
8.68
10.19
11.82
16O ch. state selected
momentum/charge [a.u.]
1.16
1.32
1.54
1.85
2.32
3.09
4.63
9.26
4+
5+
6+
4+
5+
6+
3+
4+
5+
6+
3+
4+
5+
2+
3+
4+
2+
3+
1+
2+
1+
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
v/v0
2.68 MeV CM



To Exhaust
ECO2
ECO1
Pps
P0
Post Stripper
Inlet
From Recirculation
UP1
UP2
DW2
DW1
Ø17
Ø34
Ø15
Ø10
Ø5.5
Ø6
Ø6
Ø8.5
Ø34
Ø34
TP_ENTR
TP_CSSM
WS1
WS2
WS3
R3
R2
R1
To Exhaust
To Recirculation

Gas Recirculation Stabilization