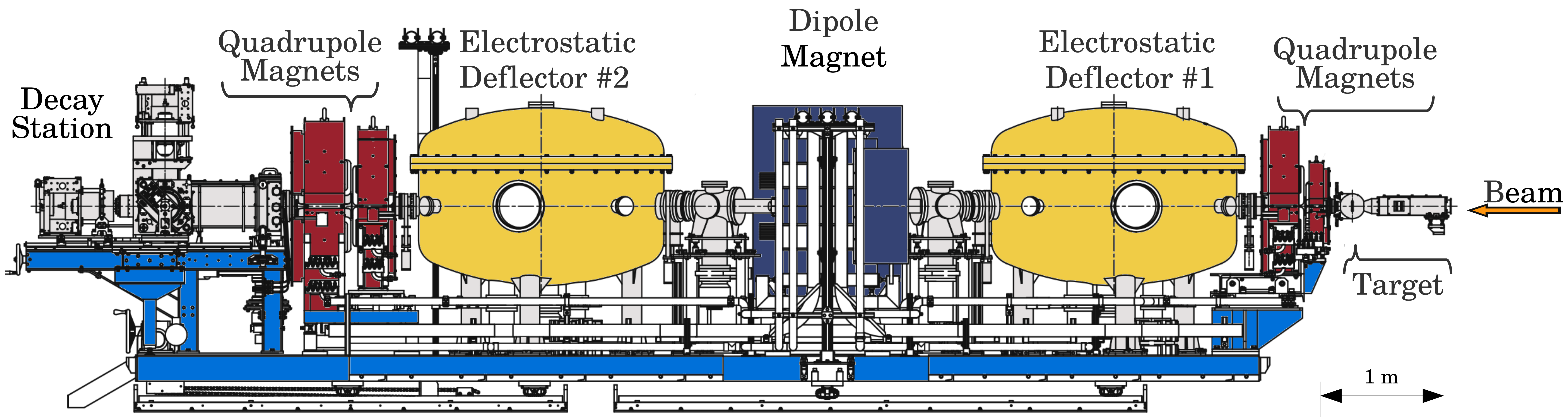
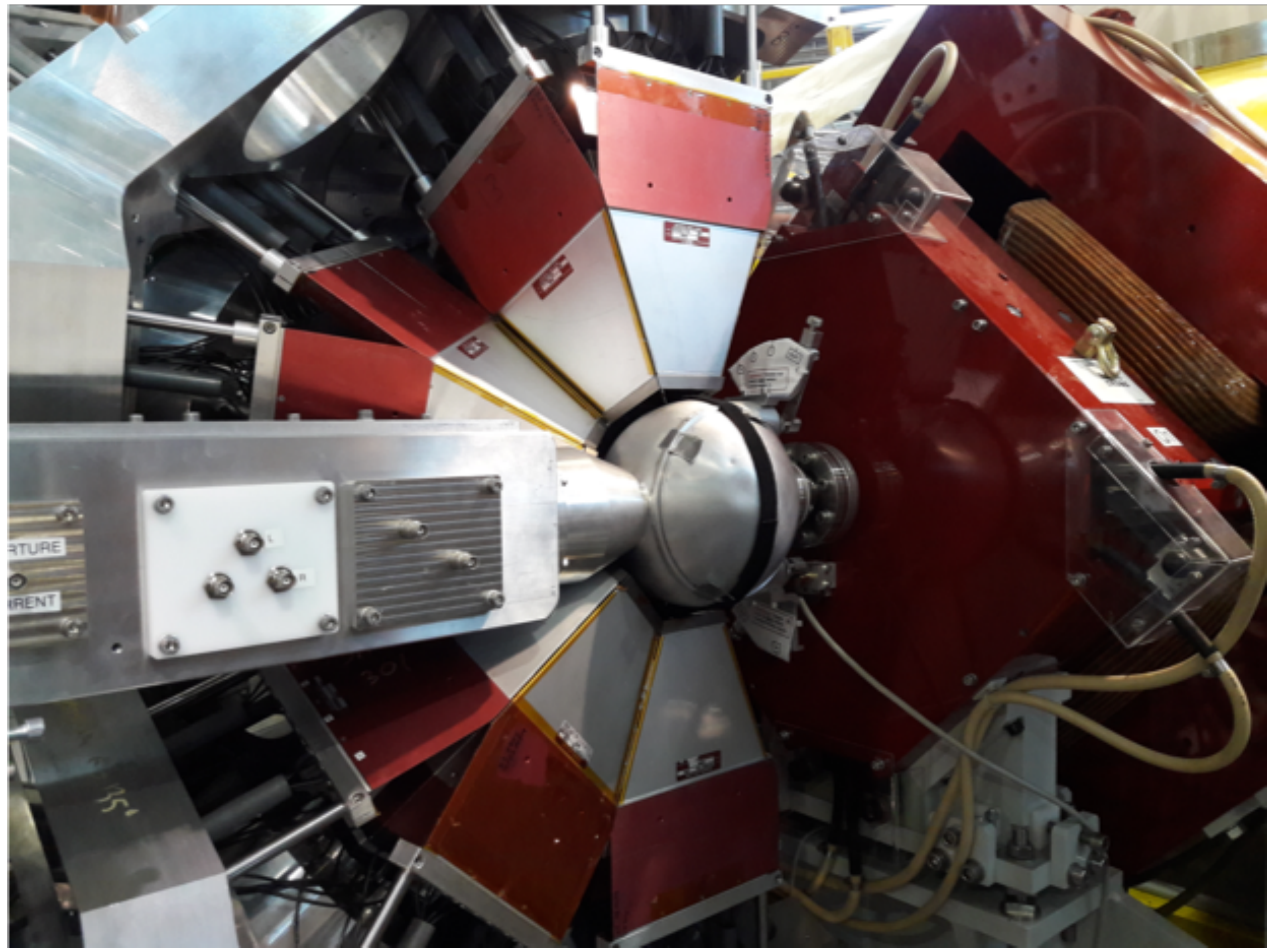
EMMA: The ISAC-II Recoil Spectrometer



- EMMA: recoil mass spectrometer spatially separates heavy products of nuclear reactions from beam & disperses according to mass/charge ratio
- 4 magnetic quadrupole lenses, 1 dipole magnet, 2 electrostatic deflectors, 3 slit systems, target chamber with integral Faraday cup, and modular focal plane detection system w/ PGAC, ionization chamber, and Si detectors

Target Chamber Exterior



- Designed to accommodate 12/16 TIGRESS HPGe γ-ray detectors

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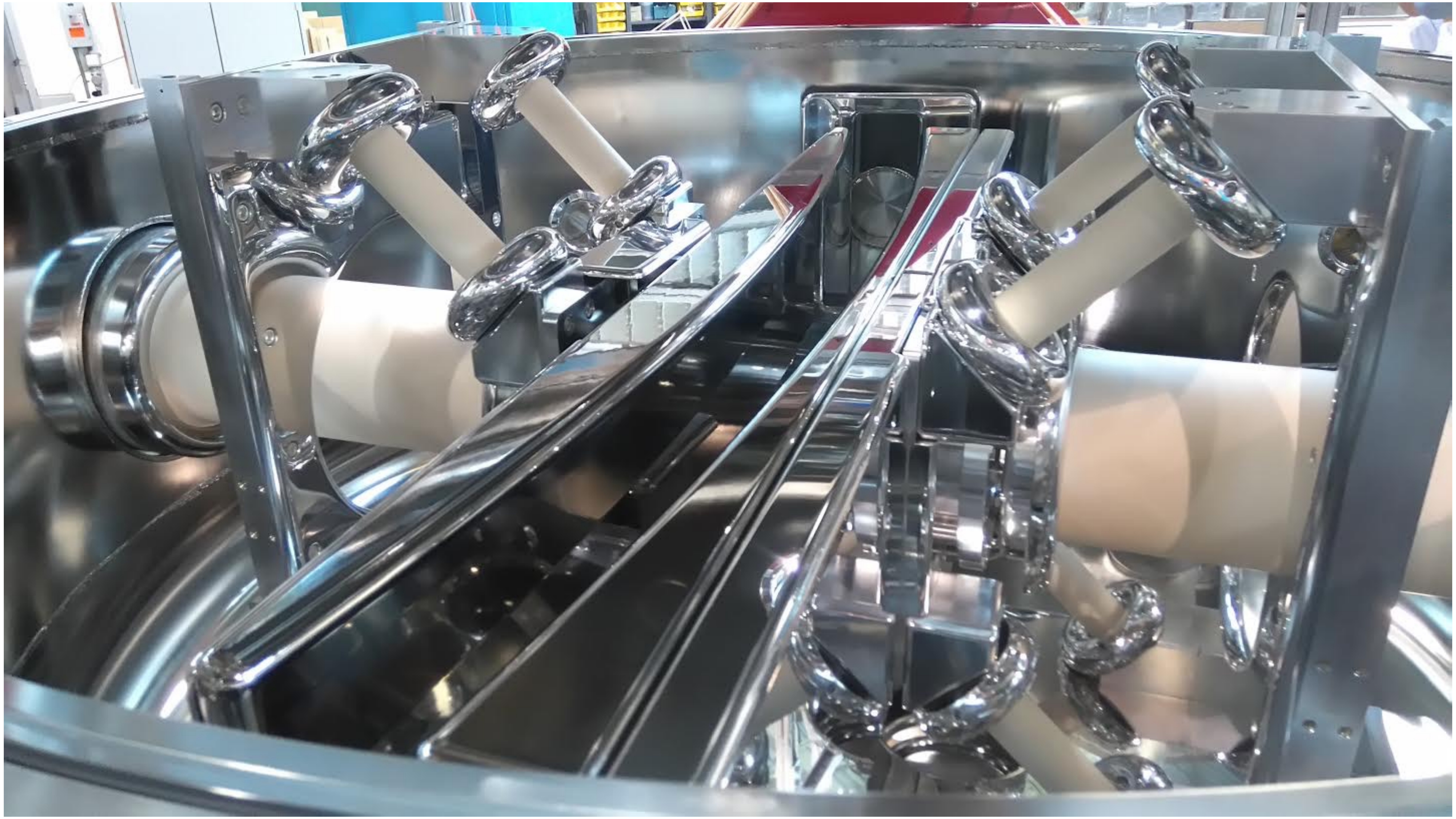
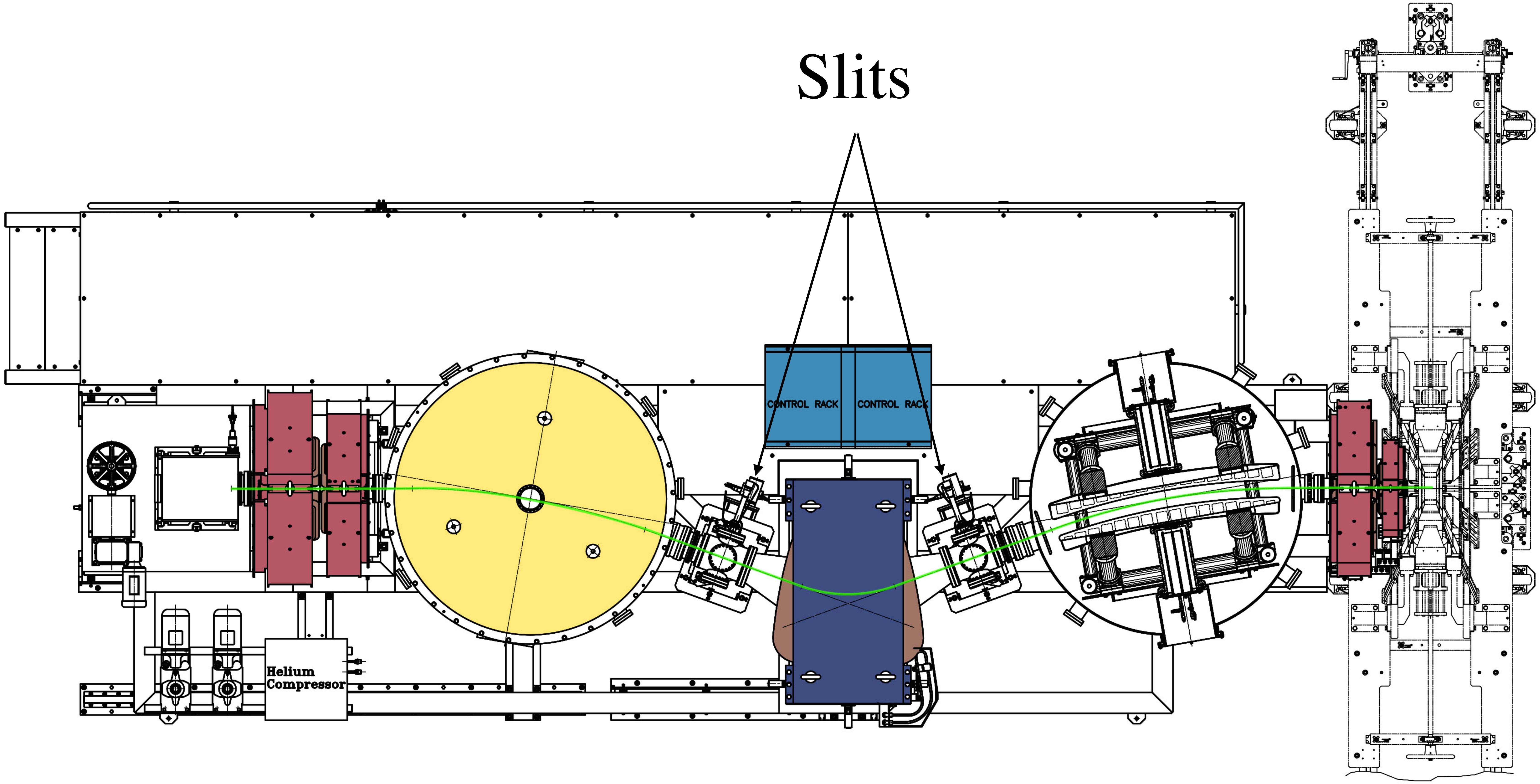
Target Chamber Interior

- Integral Faraday cup with 2 mm entrance aperture coincides spatially with target position
- Rotary target fan with 3 positions
- Mounts for 2 Si surface barrier charged particle detectors downstream at 20° for luminosity measurements
- Mounts for annular, double-sided silicon strip detectors (DSSDs) located 33 mm upstream and downstream of the target

Complete ED2 Electrode Assembly

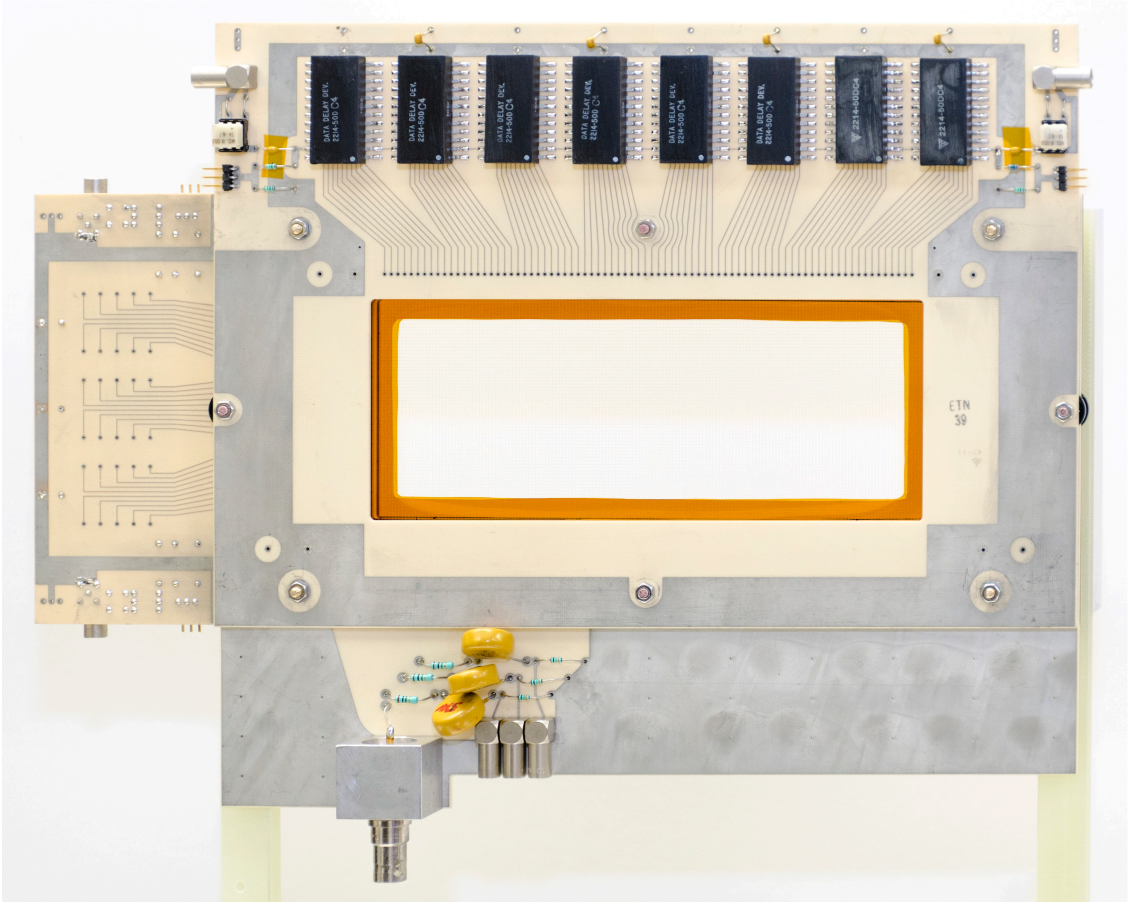


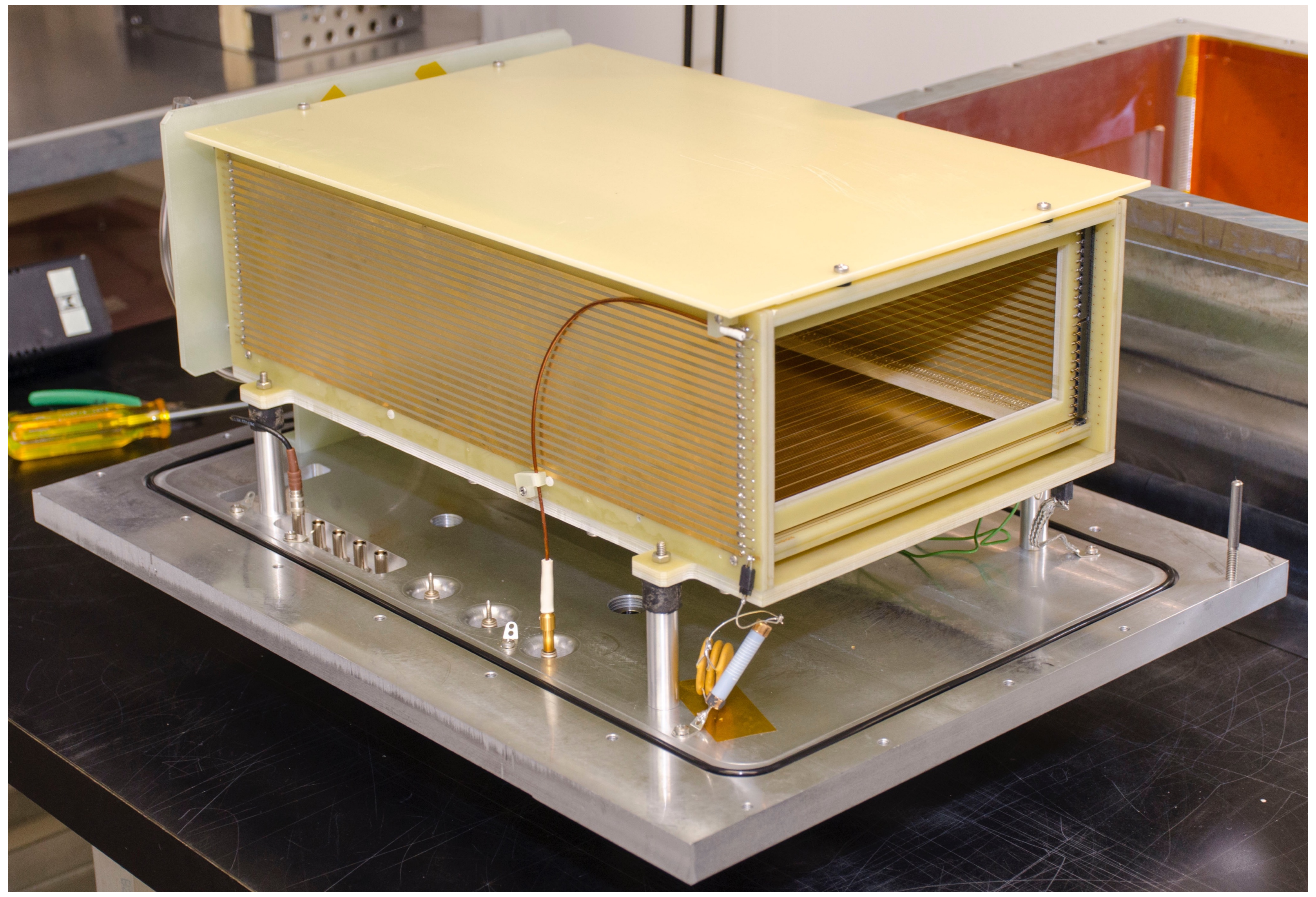
TIGRESS@EMMA



Slits

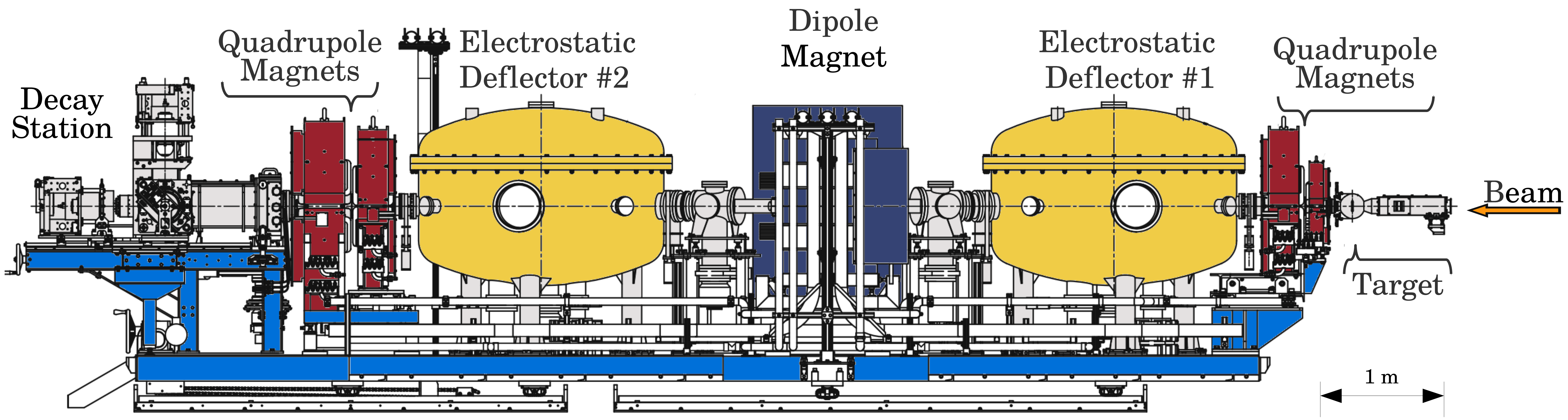
Focal Plane Detectors





- Parallel grid avalanche counter (PGAC) measures position (m/q) + timing
- Segmented, transmission-mount ionization chamber measures energy losses
- Ion-implanted Si detector measures residual energy

Completed Experiments



- Radiative capture: p(^{83}Rb,γ)^{84}Sr reaction cross section at *p* process energies (Lotay and Davids) ✓
- *α* transfer: ^{7}Li(^{17}O,*t*)^{21}Ne to infer ^{17}O(α,γ)^{21}Ne reaction cross section, of interest for the *s* process (Williams, Diget, Laird, and Davids) ✓
- ^{21}Na,Ne(*d*,*p*) and (*d*,*n*) for isospin symmetry tests (Henderson and Adsley) ✓
- ^{94}Sr(α,*n*)^{97}Zr for the weak *r* process (Diget, Laird, and Williams) uses Si-magnetron-sputtered solid He targets✓
- ^{21}Na,Ne on ^{40}Ca to study EM transitions in ^{55}Ni and ^{55}Co with the TIGRESS Integrated Plunger (Asch & Starosta)✓

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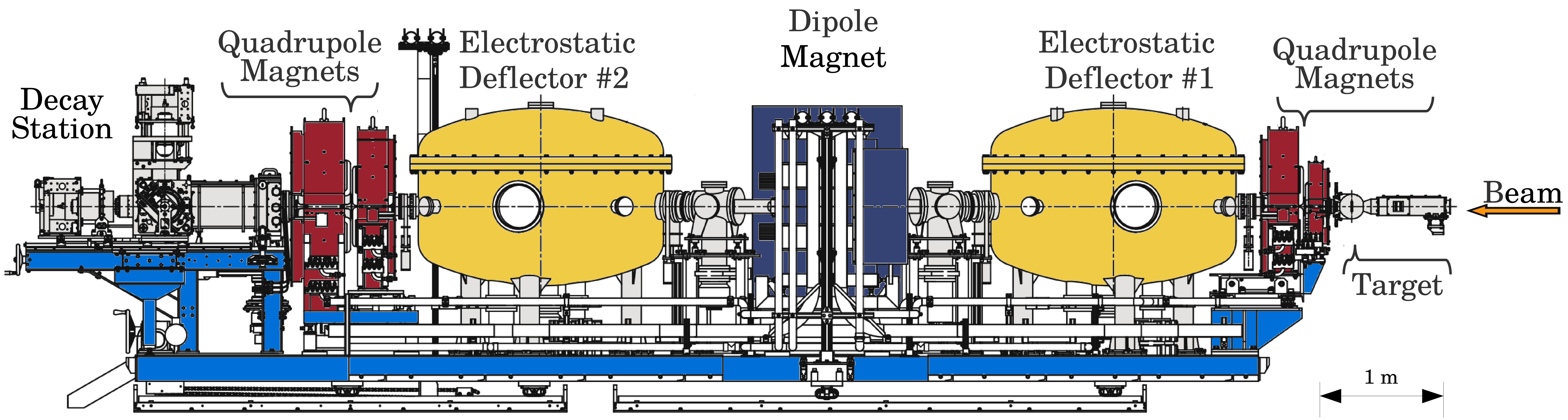
Completed Experiments



- *α* transfer: ^{7}Li(^{22}Ne,*t*)^{26}Mg to infer properties of states in ^{26}Mg relevant to the ^{22}Ne(α,γ)^{26}Mg reaction cross section, which competes with the reaction that serves as the *s* process neutron source ^{22}Ne(α,*n*)^{25}Mg (Adsley, Diget, Laird, and Best) ✓
- ^{93}Sr(α,*n*)^{96}Zr and ^{93}Sr(α,2*n*)^{95}Zr for the *α* or weak *r* process (Diget, Laird, and Williams) used organic glass scintillator neutron detectors ✓

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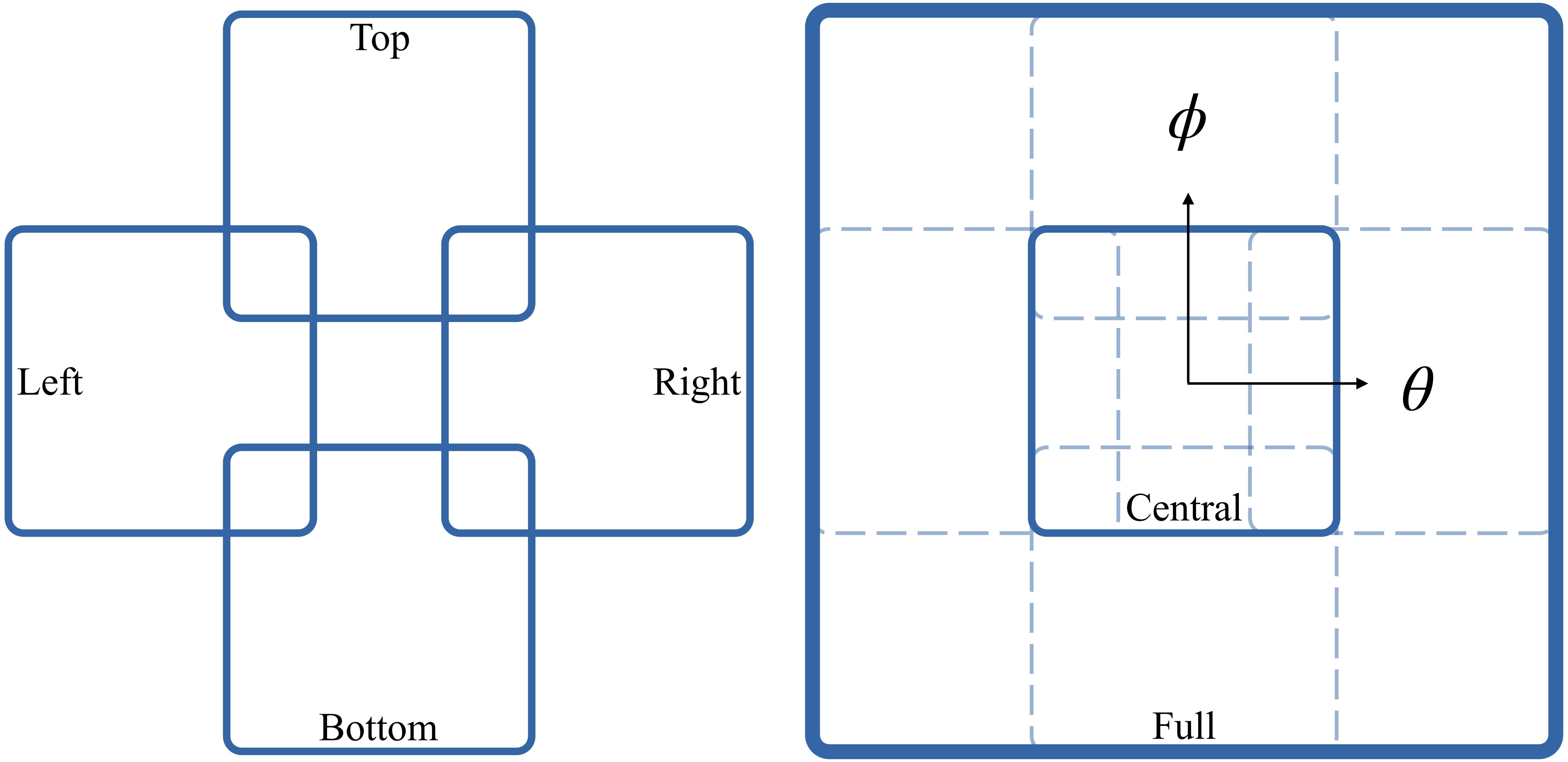
Transmission Efficiency Measurements

- 6/7 completed experiements require absolute cross section determinations; hence the spectrometer’s transmission efficiency must be known
- Trajectories within spectrometer depend only upon their angles and deviations of mass/charge and kinetic energy/charge with respect to central value
- By mistuning spectrometer in kinetic energy/charge, we may infer its transmission efficiency as a function of relative kinetic energy/charge deviation
- Central value is irrelevant, so a mono-energetic α source was used for the measurements

Angular Apertures



Transmission measurements with ^{148}Gd source at the EMMA target position using 6 angular apertures, the largest of which subtended ± 3° by ± 3°; counted α particles reaching the focal plane that triggered the PGAC and stopped in the Si detector

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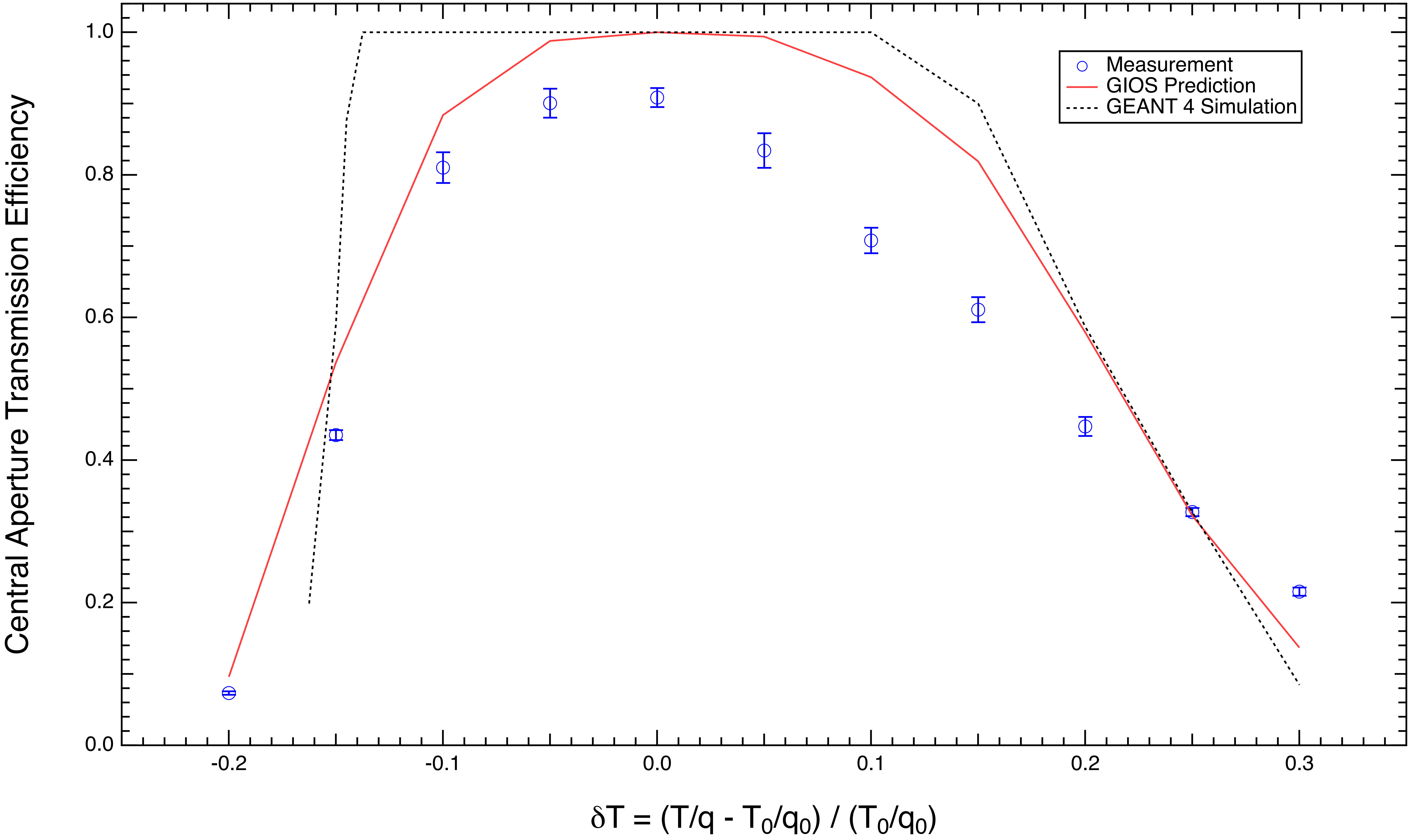
Transmission Efficiency Measurements



Central aperture measurements: ±1.2° by ±1.2°

GIOS: ion optics code used to design EMMA

GEANT 4 simulation of Matt Williams based on as-built components

Empirical Transmission Efficiency Models

- Since ion optics and Monte Carlo codes failed to provide faithful representations of transmission efficiency, tried different approach
- Developed empirical models based on piecewise Gaussian functions to describe measurements with 6 angular apertures at 9 relative kinetic energy/charge deviations δT from -20% to 20%
- Separate models for each relative kinetic energy deviation allow for calculation of transmission efficiency $TE(\theta,\phi)$
- Model parameter determination via χ^2 minimization carried out by Hanyang University PhD students Kihong Pak & Jaeyoung Jeong
- Interpolating between different δT, we have $TE(\theta,\phi,\delta T)$ over the full angular acceptance ±3° by ±3° for all relative kinetic energy deviations relevant to absolute cross section measurements; transmission efficiency beyond 3° estimated via extrapolation of each semi-empirical model

Piecewise Gaussian Models

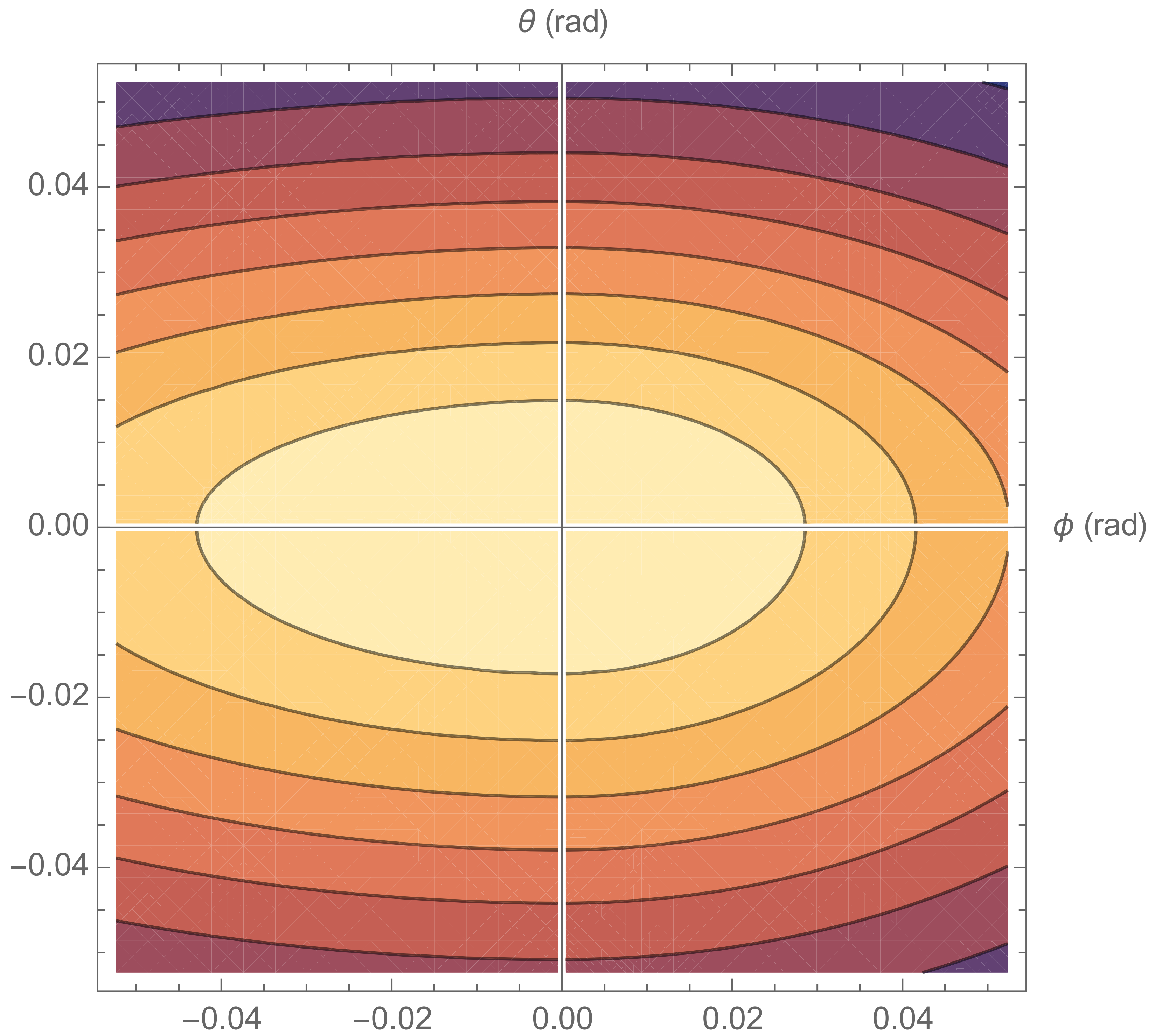
Piecewise Gaussian:

$$\epsilon_{pg}(\theta,\phi) = \begin{cases} \exp\left[-\theta^2/(2\sigma_{\mathrm{R}}^2)\right] \exp -\left[\phi^2/(2\sigma_{\mathrm{T}}^2)\right], & \text{if } \theta \geq 0 \text{ and } \phi \geq 0 \\ \exp\left[-\theta^2/(2\sigma_{\mathrm{R}}^2)\right] \exp -\left[\phi^2/(2\sigma_{\mathrm{B}}^2)\right], & \text{if } \theta \geq 0 \text{ and } \phi < 0 \\ \exp\left[-\theta^2/(2\sigma_{\mathrm{L}}^2)\right] \exp -\left[\phi^2/(2\sigma_{\mathrm{B}}^2)\right], & \text{if } \theta < 0 \text{ and } \phi < 0 \\ \exp\left[-\theta^2/(2\sigma_{\mathrm{L}}^2)\right] \exp -\left[\phi^2/(2\sigma_{\mathrm{T}}^2)\right], & \text{if } \theta < 0 \text{ and } \phi \geq 0. \end{cases}$$

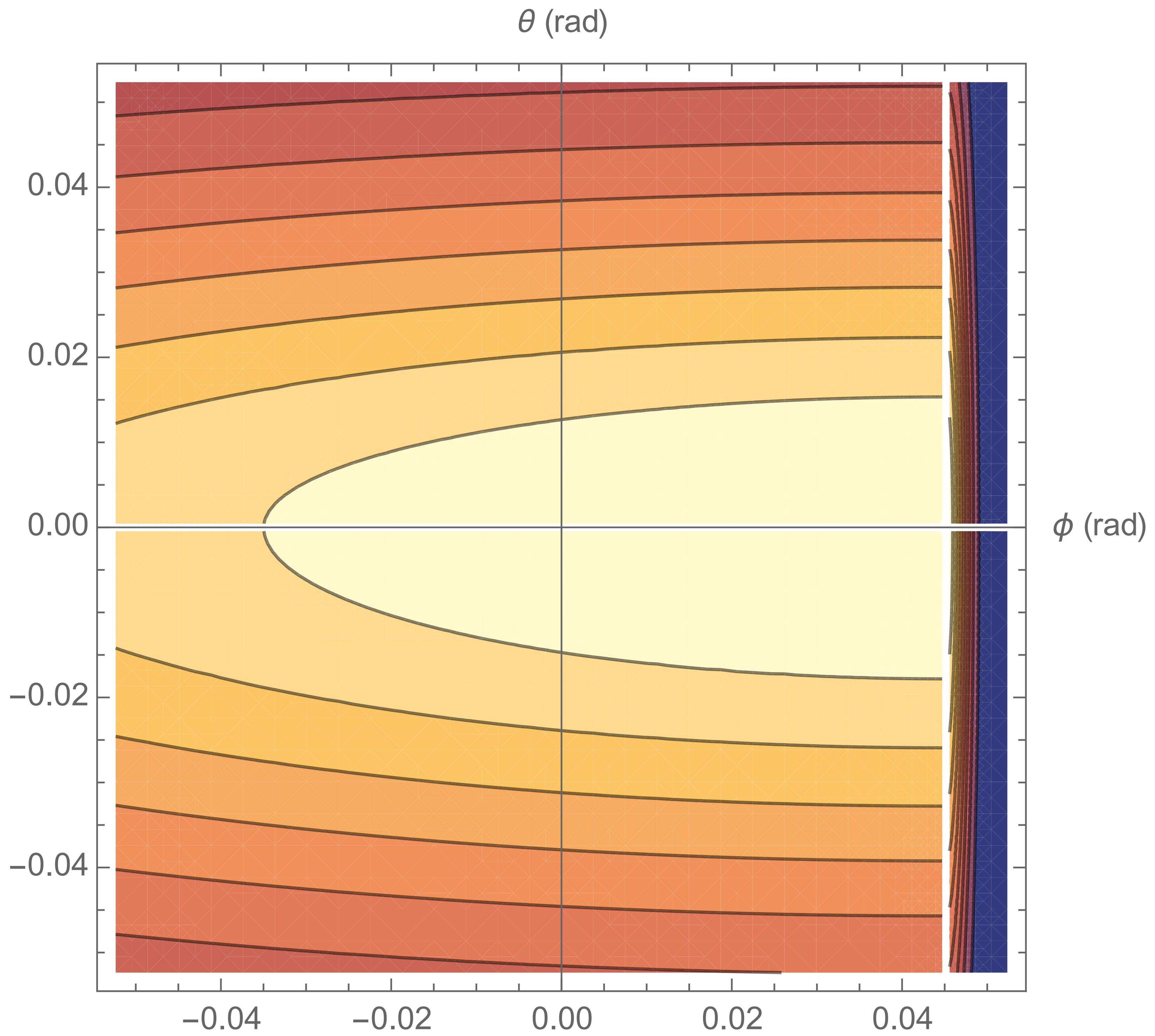
Offset Piecewise Gaussian:

$$\epsilon_{og}(\theta,\phi) = \begin{cases} \exp\left[-(\theta-\theta_0)^2/(2\sigma_{\mathrm{R}}^2)\right] \exp -\left[\phi^2/(2\sigma_{\mathrm{T}}^2)\right], & \text{if } \theta \geq \theta_0 \text{ and } \phi \geq 0 \\ \exp\left[-(\theta-\theta_0)^2/(2\sigma_{\mathrm{R}}^2)\right] \exp -\left[\phi^2/(2\sigma_{\mathrm{B}}^2)\right], & \text{if } \theta \geq \theta_0 \text{ and } \phi < 0 \\ \exp\left[-(\theta-\theta_0)^2/(2(10^\circ)^2)\right] \exp -\left[\phi^2/(2\sigma_{\mathrm{B}}^2)\right], & \text{if } \theta < \theta_0 \text{ and } \phi < 0 \\ \exp\left[-(\theta-\theta_0)^2/(2(10^\circ)^2)\right] \exp -\left[\phi^2/(2\sigma_{\mathrm{T}}^2)\right], & \text{if } \theta < \theta_0 \text{ and } \phi \geq 0. \end{cases}$$

Model Contour Plots



(a) Piecewise Gaussian



(b) Offset Piecewise Gaussian

- Transmission efficiency model contour plots over full angular aperture for the $\delta T = 0$ case
- 4 parameters: $\sigma_L, \sigma_R, \sigma_T, \sigma_B$, or $\theta_0, \sigma_R, \sigma_T, \sigma_B$
- 6 angular aperture measurements
- $\chi^2_\nu = 0.79$ and $\chi^2_\nu = 0.62$ for the 2 models

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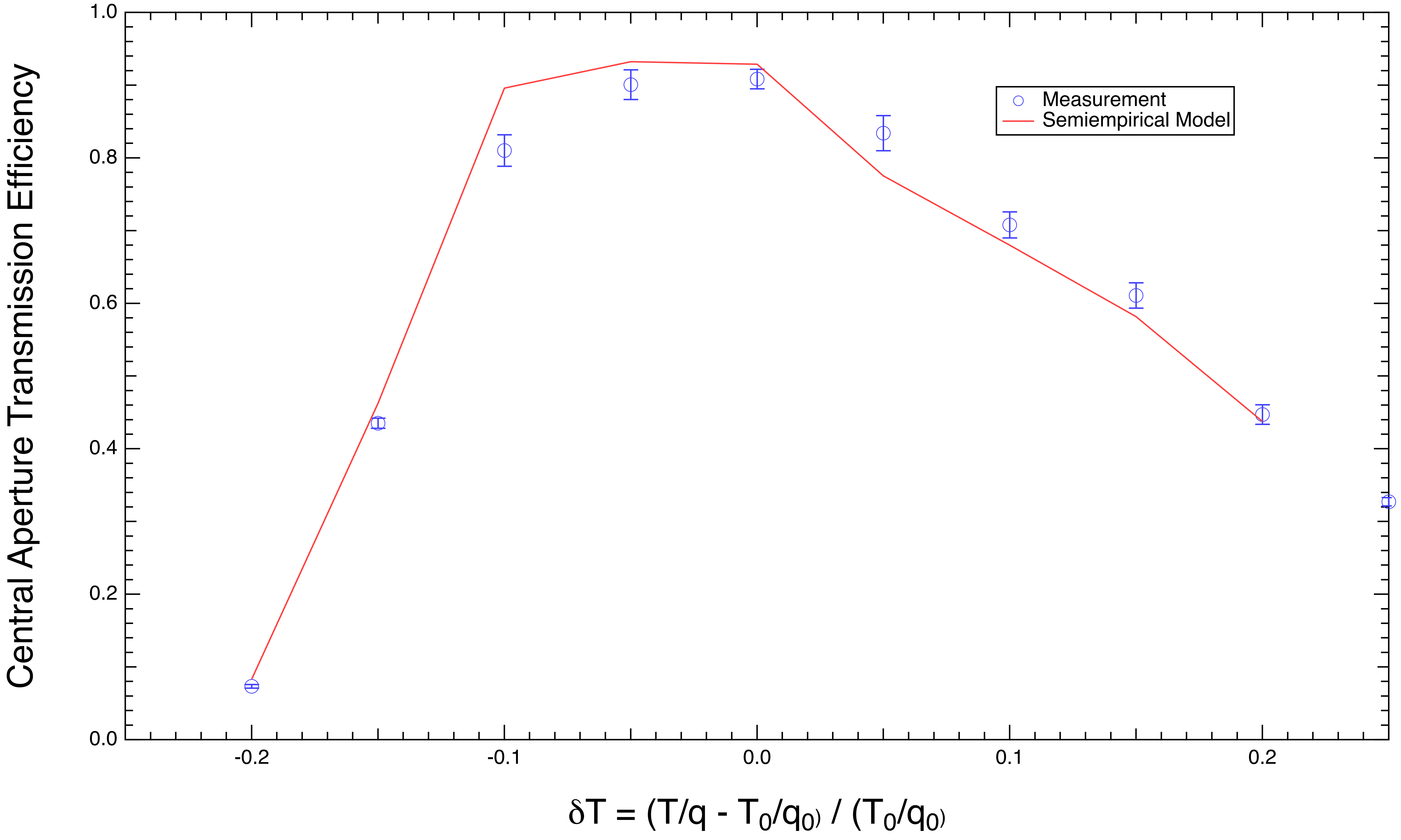
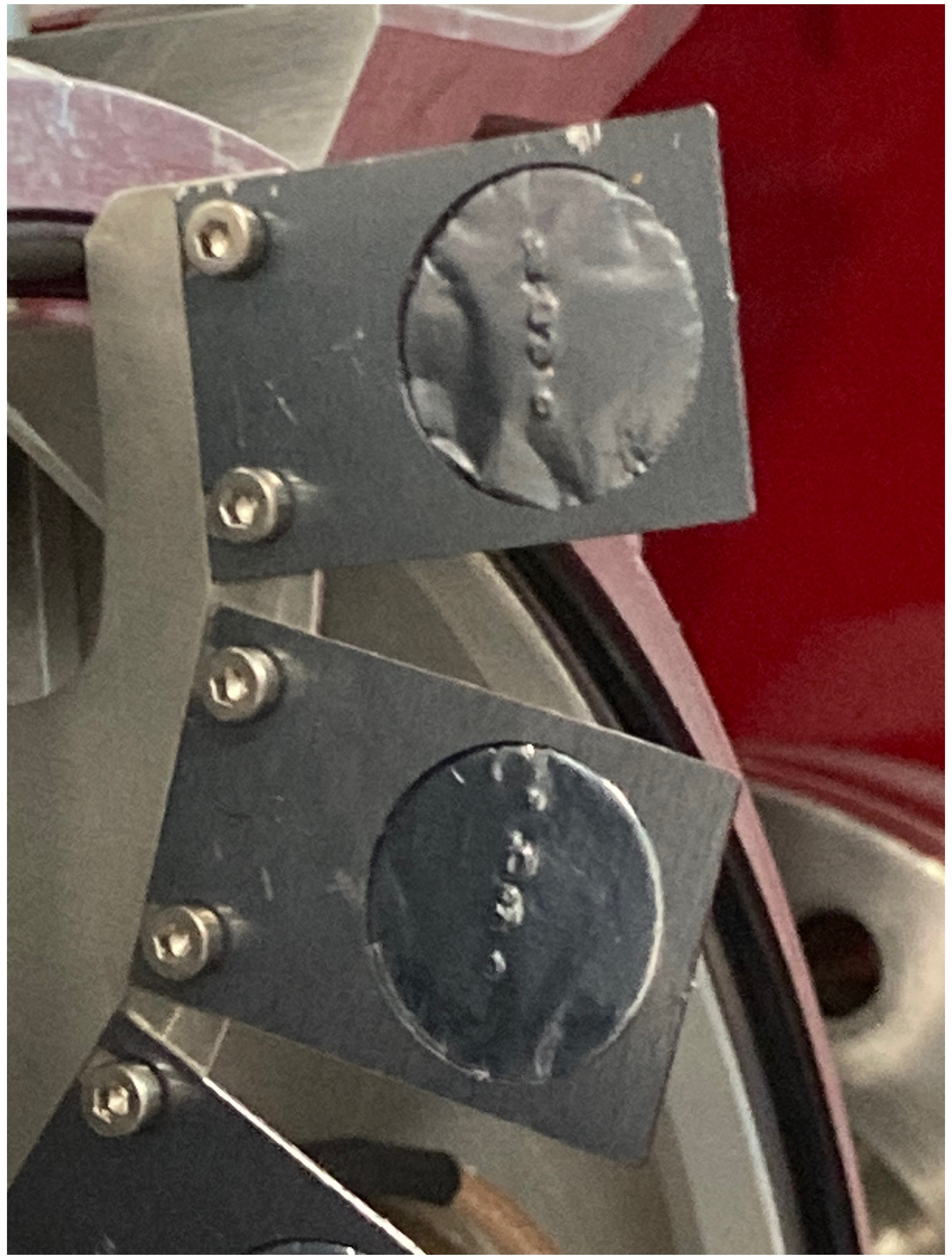
Semi-empirical Model Fidelity: Central Angles

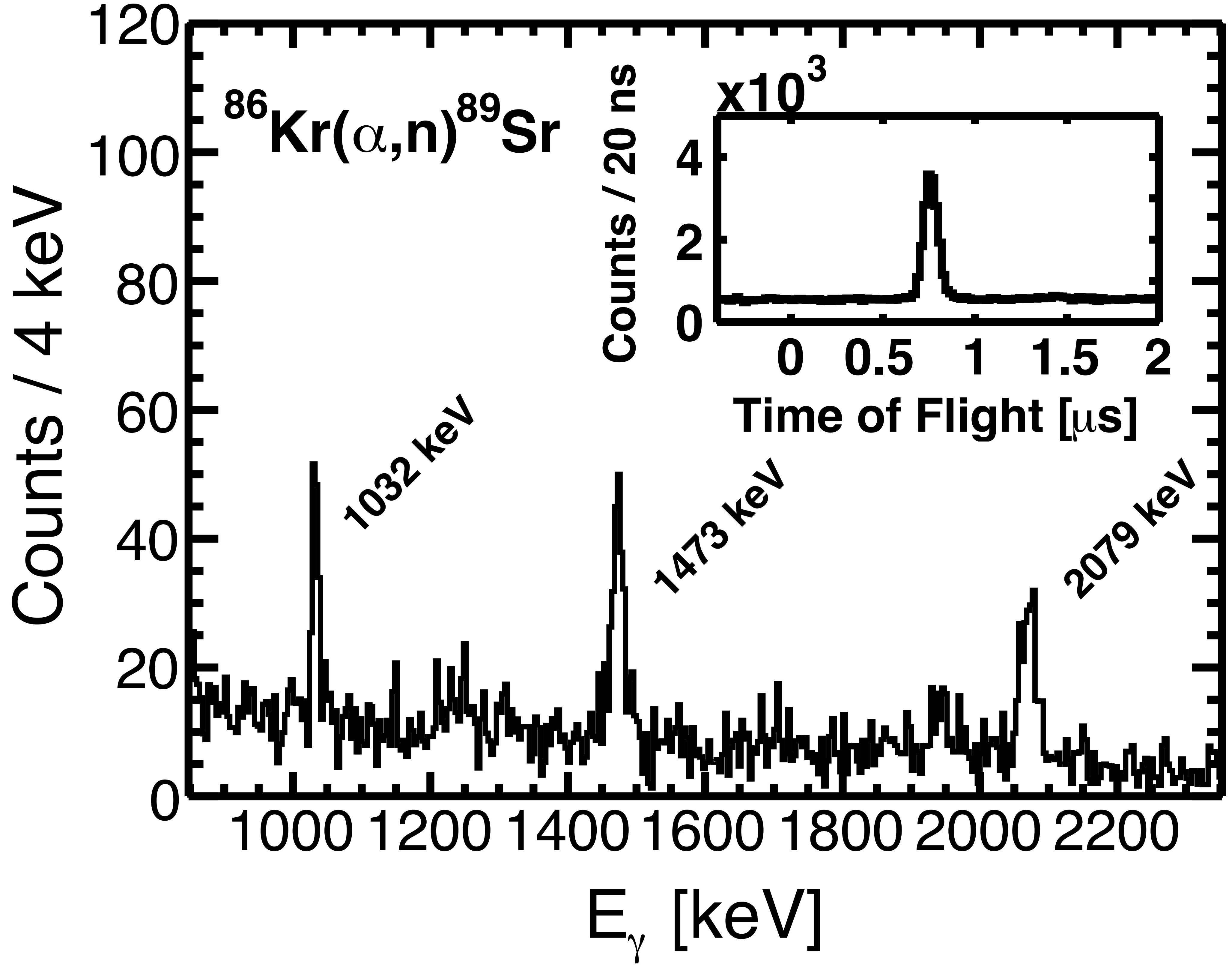


Example: ^{94}Sr(α,*n*)^{97}Zr*

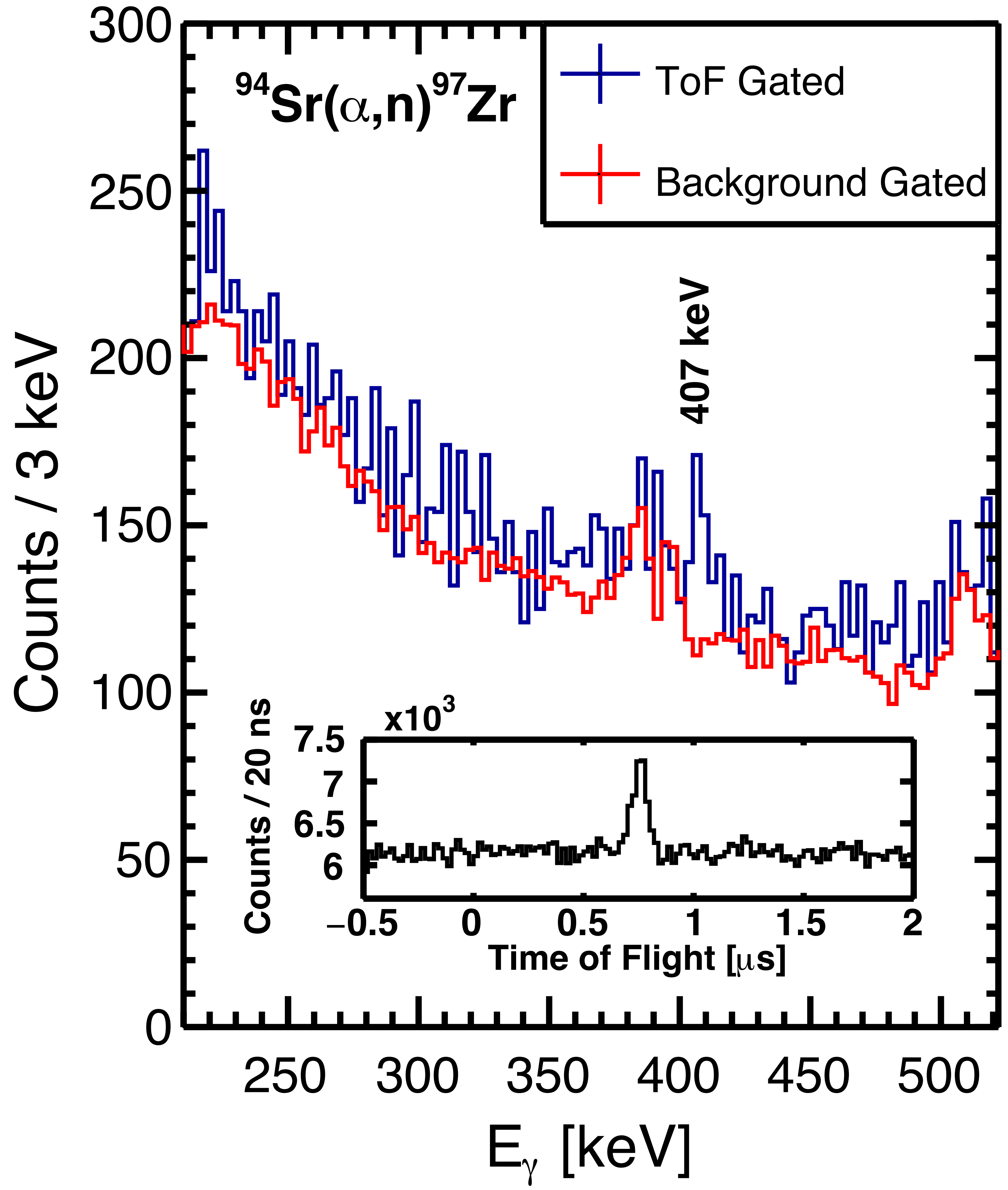
- ^{94}Sr(α,*n*)^{97}Zr: the first cross section measurement of a reaction important in the weak *r* process with an RIB
- Also measured ^{86}Kr(α,*n*)^{89}Sr
- Used magnetron-sputtered thin film amorphous Si:He targets on 8 μm Al backings made in Seville, Spain
- Like previous radiative proton capture measurements, recoil-γ ray coincidences are required for background rejection, and transmission efficiency must be known
- Measured ^{86}Kr(α,*n*)^{89}Sr at 9 and 10.4 MeV and ^{94}Sr(α,*n*)^{97}Zr at 9.9 MeV, within the Gamow windows for the reactions at a temperature of 5 GK

^{86}Kr(α,*n*)^{89}Sr*

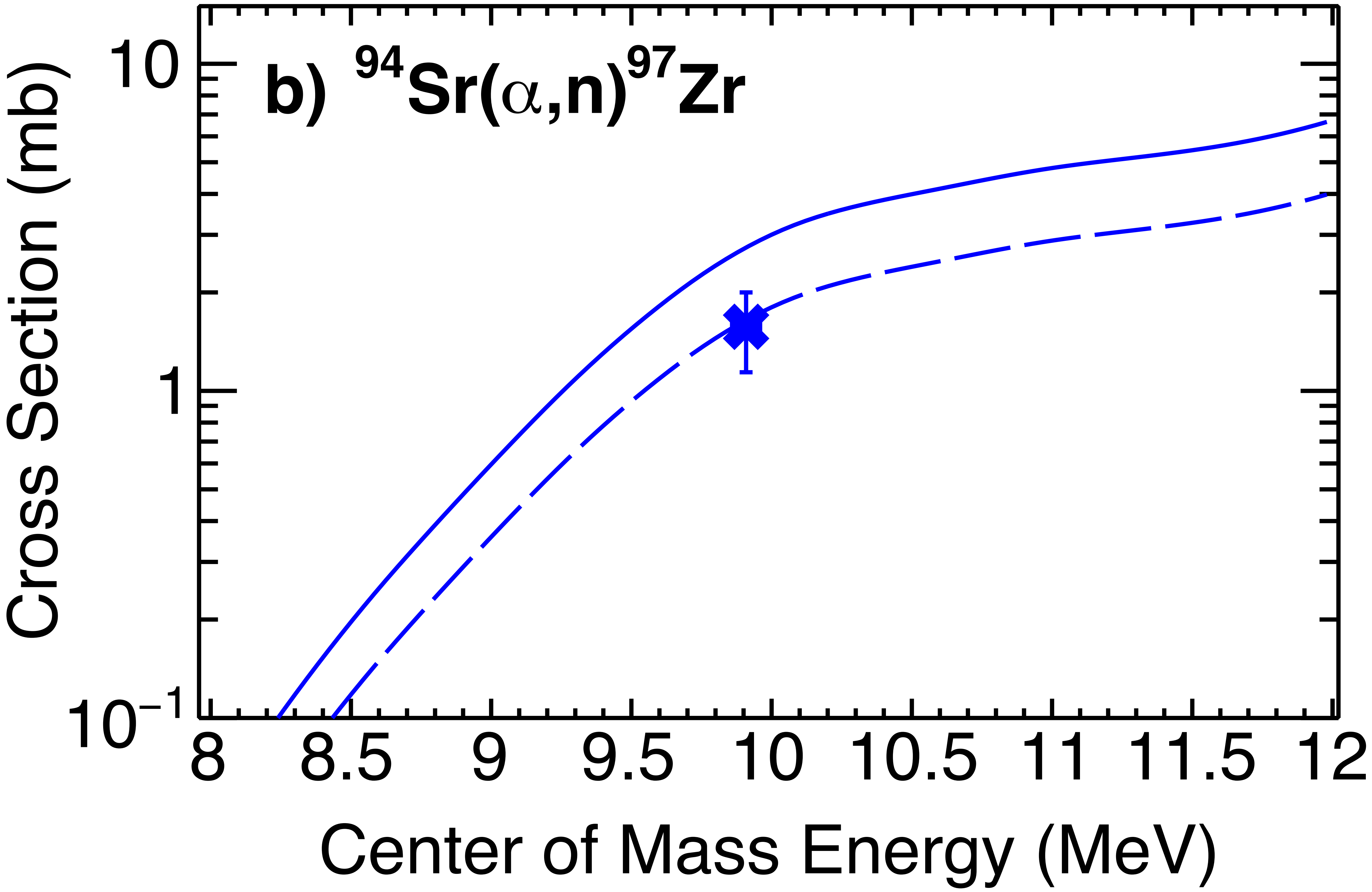



^{86}Kr(α,n)^{89}Sr
Counts / 4 keV
0
20
40
60
80
100
120
1000
1200
1400
1600
1800
2000
2200
E$_\gamma$ [keV]
1032 keV
1473 keV
2079 keV
x10^3
Counts / 20 ns
0
2
4
0
0.5
1
1.5
2
Time of Flight [μs]

$^{94}Sr(\alpha,n)^{97}Zr*$



^{94}Sr(α,n)^{97}Zr



TALYS calculations with scaling factors of 1.0 and 0.6

- Partial cross section is 60% of prediction with TALYS reaction model
- Correlation with Ru abundance implies reduced production

Conclusions

- Integral transmission efficiency measurements of EMMA recoil mass spectrometer carried out over the angular and energy ranges needed for astrophysical reaction cross section measurements
- Ion optical and Monte Carlo simulations of spectrometer failed to reproduce integral measurements
- Mathematical models created to describe angular and energy dependence of differential transmission efficiency
- Monte Carlo simulations of reactions produce distributions of recoil trajectories that enable transmission efficiency determinations for cross section measurements, with relative precision circa 10%, varying with the energy and angular distributions
- 6/7 EMMA experiments completed thus far require reaction cross section determinations
- ^{83}Rb(p, γ) and ^{94}Sr(α, n) reaction cross sections measured in inverse kinematics with TIGRESS γ-ray spectrometer, the 1st *p*-process and weak *r*-process reactions ever measured with radioactive ion beams

Credits & References

- Nicholas Esker, TRIUMF (now at San Jose State University, USA)
- Matt Williams, University of York and TRIUMF (now at University of Surrey, UK)
- Kihong Pak and Jaeyoung Jeong, Hanyang University, Republic of Korea
- Cameron Angus, University of York and TRIUMF (now at Windscale, UK)

- G. Lotay, S. A. Gillespie, M. Williams, T. Rauscher, et al., PRL **127**, 112701 (2021)
- M. Williams, B. Davids, G. Lotay, N. Nishimura, T. Rauscher, S. A. Gillespie, *et al*., PRC **107**, 035803 (2023): ^{83}Rb(p, γ) and ^{84}Kr(p, γ)
- M. Williams, C. Angus, A. M. Laird, B. Davids, C. Aa. Diget, *et al*., PRL **134**, 112701 (2025): ^{94}Sr(α, n) and ^{86}Kr(α, n)