

Using beams of reclaimed ^{44}Ti to explore the mechanism of core collapse in supernovae

Jennifer Fallis

For the TRIUMF- ^{44}Ti Collaboration



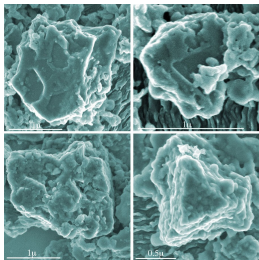
Road map

- ^{44}Ti production in supernovae & importance of $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$
- Creating beams of ^{44}Ti at TRIUMF
- Planned and other possible measurements:
 - $^{44}\text{Ti}(\alpha, p)$ @ TUDA
 - $^{44}\text{Ti}(\alpha, \gamma)$ @ DRAGON
 - $^{44}\text{Ti}(p, \gamma)$ @ DRAGON
 - ... and EMMA?
- TRIUMF implantation station

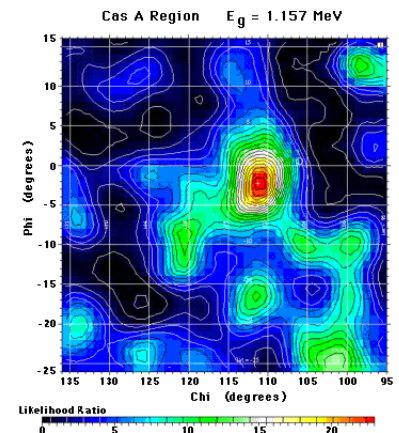


Supernova observables

- Supernovae explosions are incredibly complex and most observables are very general, resulting from the overall features of the explosion.
 - Light curves - include all energy given off as photons.
 - Spectroscopy provides elemental abundances, but only measures the total number of all isotopes of any given element.
 - **Observations of individual isotopes are particularly useful for comparing models to observations**



- presolar grains
- γ -ray telescope observations



- Accurate models, however, need precise reaction rates to be sufficiently constrained.



^{44}Ti production

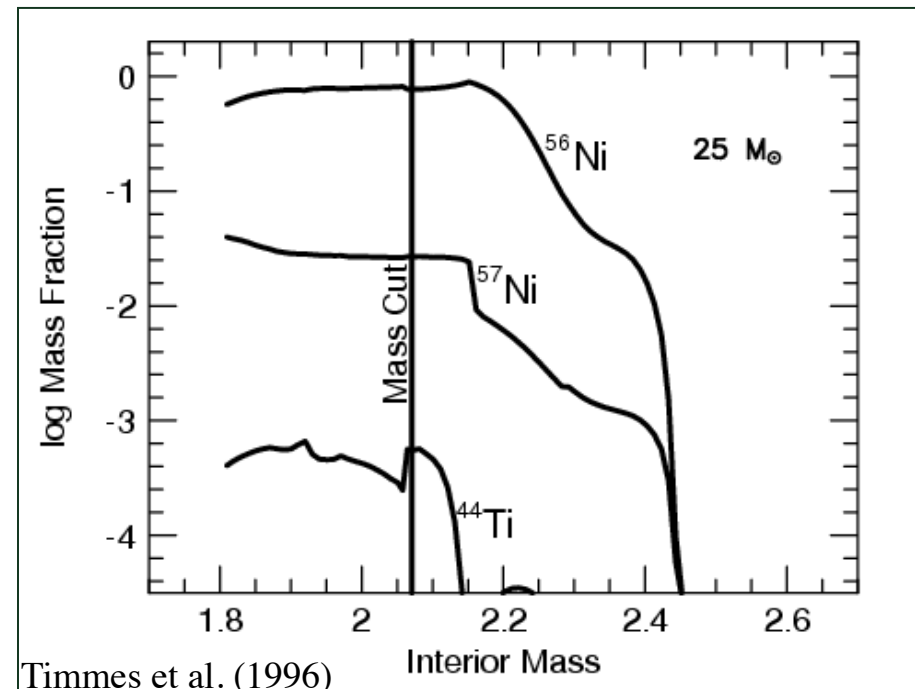
In neutrino driven explosions:

And α -rich freeze out

Magkotsios et al. ApJ suppl, 191 (2010)

^{44}Ti is synthesized in the α -rich freeze out that occurs in the shock-heated Si layer that lies just above the detonating core and so the amount ejected sensitively depends on location of the 'mass cut'

- Material that 'falls back' is not available for detection
- ^{44}Ti yield a sensitive diagnostic of the explosion mechanism
- Thus, VERY useful for models to make comparisons against



Most important reactions determined from sensitivity studies

Magkotsios <i>et al.</i> (2010):	The <i>et al.</i> (1998)
$^{44}\text{Ti}(\alpha, p)^{47}\text{V}$	$^{44}\text{Ti}(\alpha, p)^{47}\text{V}$
$^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$	$^{45}\text{V}(p, \gamma)^{46}\text{Cr}$
$^{45}\text{V}(p, \gamma)^{46}\text{Cr}$	$^{40}\text{Ca}(\alpha, \gamma)^{44}\text{Ti}$
$^{40}\text{Ca}(\alpha, p)^{43}\text{Sc}$	$^{57}\text{Co}(p, n)^{57}\text{Ni}$
$^{17}\text{F}(\alpha, p)^{20}\text{Ne}$	$^{36}\text{Ar}(\alpha, p)^{39}\text{K}$
$^{21}\text{Na}(\alpha, p)^{24}\text{Mg}$	$^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$
$^{41}\text{Sc}(p, \gamma)^{44}\text{Ti}$	$^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$
$^{44}\text{Ti}(p, \gamma)^{45}\text{V}$	$^{57}\text{Ni}(p, \gamma)^{58}\text{Cu}$
$^{57}\text{Ni}(p, \gamma)^{58}\text{Cu}$	$^{58}\text{Cu}(p, \gamma)^{59}\text{Zn}$
$^{43}\text{Sc}(p, \gamma)^{44}\text{Ti}$	$^{36}\text{Ar}(\alpha, \gamma)^{40}\text{Ca}$
	$^{44}\text{Ti}(p, \gamma)^{45}\text{V}$
	$^{57}\text{Co}(p, \gamma)^{58}\text{Ni}$
	$^{57}\text{Ni}(n, \gamma)^{58}\text{Cu}$
	$^{54}\text{Fe}(\alpha, n)^{57}\text{Ni}$

Measured at TRIUMF with DRAGON

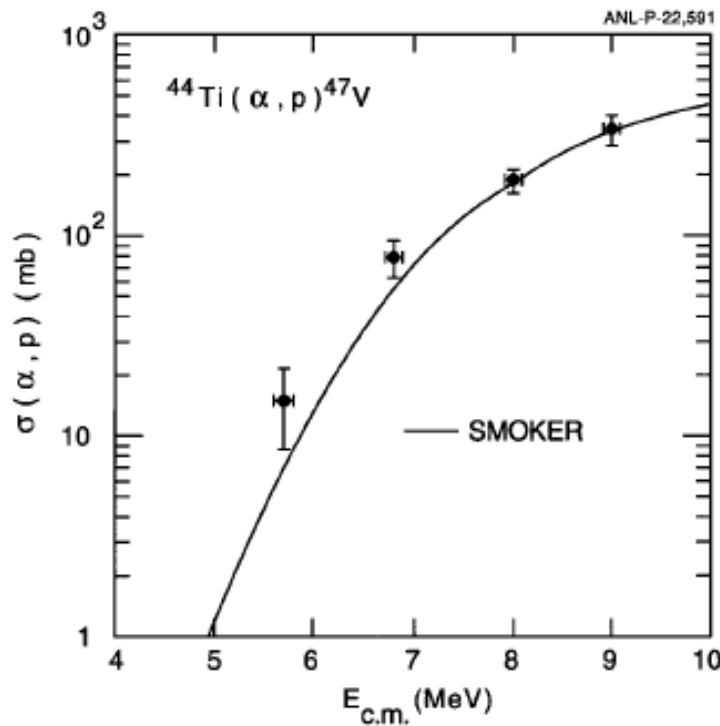
Letter of intent submitted, but this is a challenging beam to produce



Experimental data for $^{44}\text{Ti}(\alpha, p)$

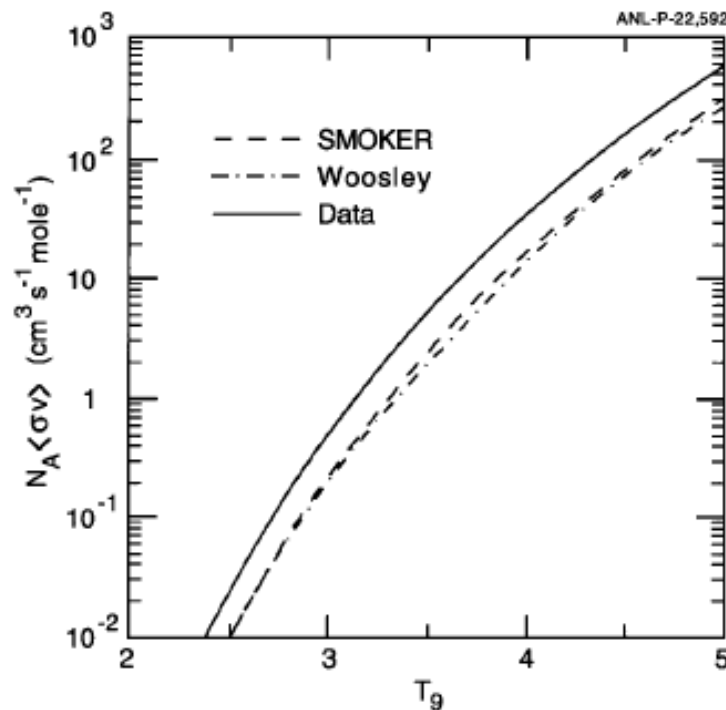
Only measurements are by Sonzogni et al. [*PRL* 84 (2000)] :

- 4 data points
- Energies higher than those required to study the reaction at astrophysically relevant temperatures



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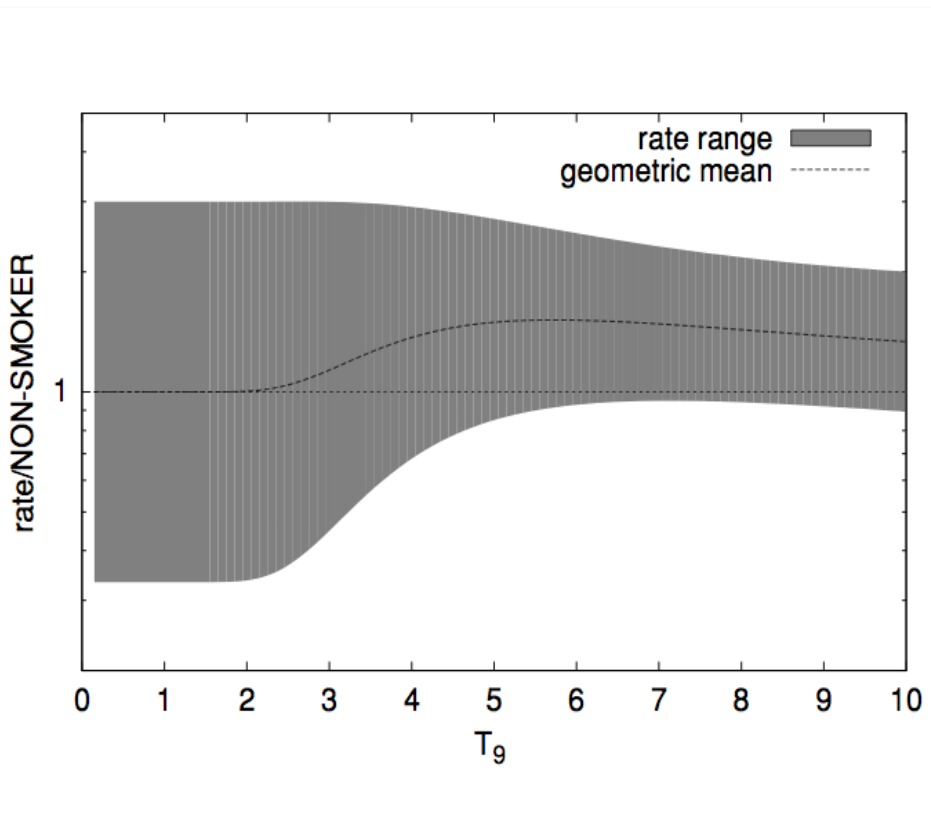


- 4 data points
- Energies higher than those required to study the reaction at astrophysically relevant temperatures
- Found a rate 2x higher than the SMOKER rates.



Experimental data for $^{44}\text{Ti}(\alpha, p)$

Only measurements are by Sonzogni et al. [*PRL* 84 (2000)] :



- 4 data points
- Energies higher than those required to study the reaction at astrophysically relevant temperatures
- Found a rate 2x higher than the SMOKER rates.
- Hoffman *et al.*, [*ApJ* 715 (2010)] recalculated a rate from this data & find a rate consistent with NON-SMOKER within uncertainties

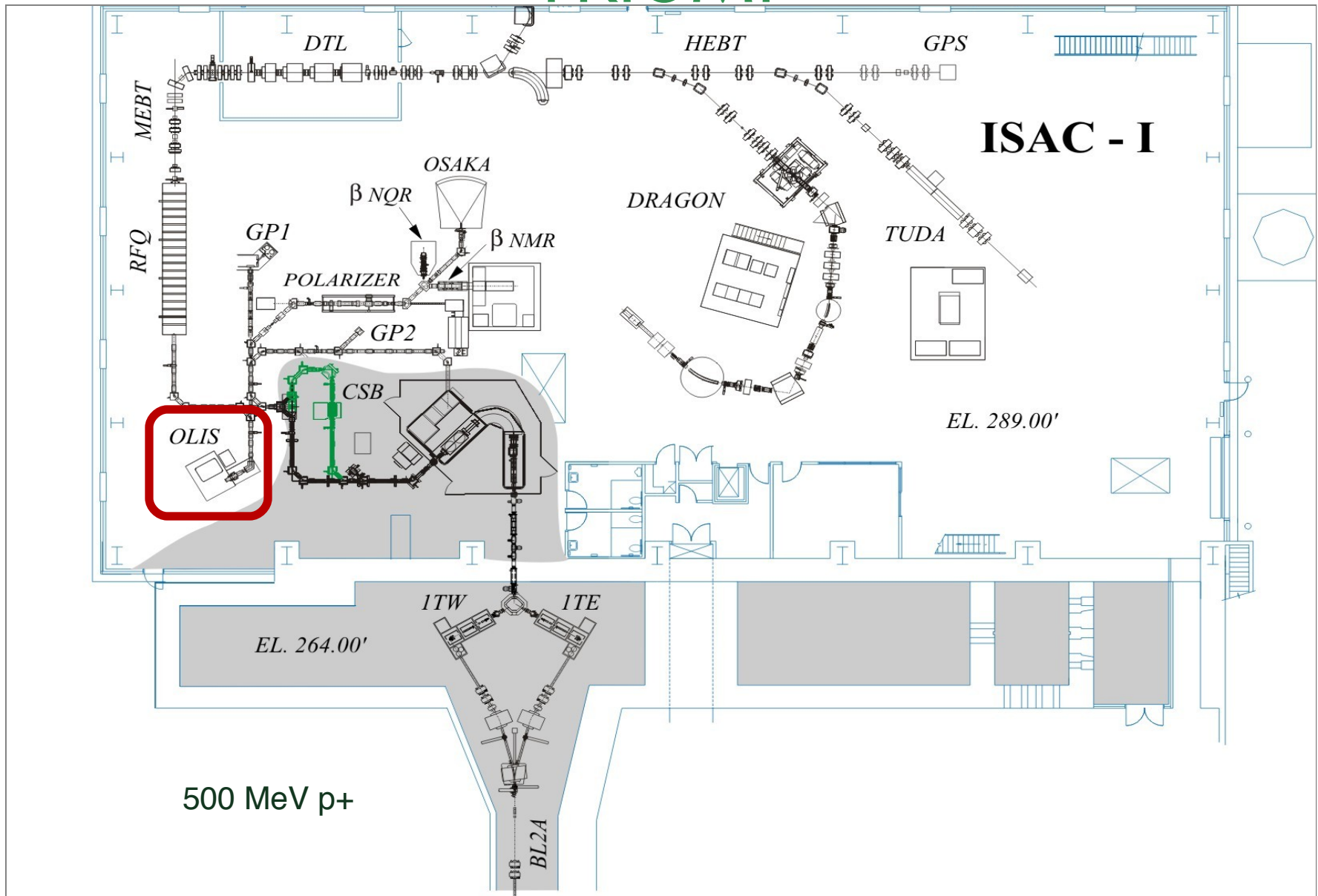


How to measure $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$:

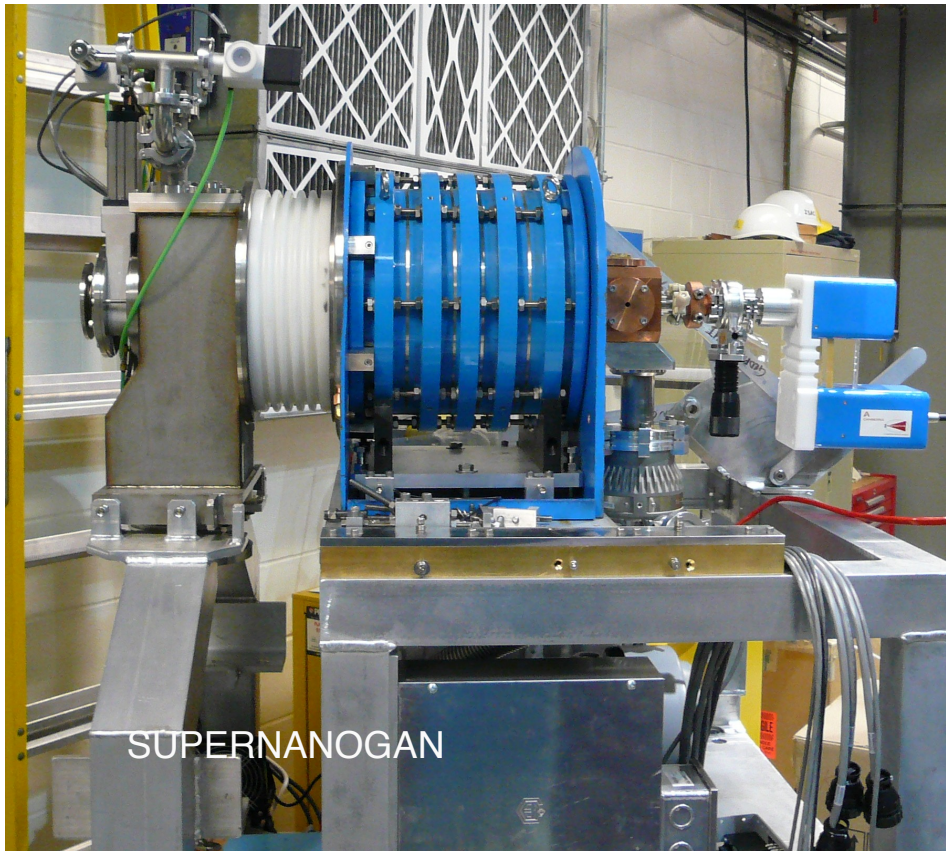
- ^{44}Ti targets? \Leftarrow Tariq's talk this morning
- ^{44}Ti beams?
 - difficult to produce and extract**
 - On-line production using the ISOL technique followed by immediate acceleration
 - Also low production rates**
 - On-line production using fragmentation.
- Off-line production using an enriched source of ^{44}Ti , available through the ERAWAST program in the TRIUMF off-line ion source



TRIUMF



The plan for ^{44}Ti beams off-line: Supernanogan



- ISAC-I accelerator limited to $A/q \leq 6$.
- Use of a stripping foil can provide beams of ions up to $A=30$
- For beams above $A=30$ high charge states are needed from the source.
- Supernanogan ECR source can provide these high charge states
- Beam up to $A=150$ from the off-line source can now be accelerated.



^{44}Ti (α, p) Requirements

- Previous $^{44}\text{Ti}(\alpha, p)$ experiment: **10^5 pps**
- A TUDA measurement 1 MeV lower in energy requires **$\sim 10^{12}$ total ions on target**
- With $\sim 10^{16}$ atoms available we would require:
0.01% combined source and accelerator efficiency
- **More ^{44}Ti and better efficiencies would allow for measurements at even lower energies.**



The plan for ^{44}Ti beams off-line: Supernanogan



Source efficiencies depend on the method of acquiring material:

- Gas leak *1 - 10% efficiency*
- Sputter source
0.01 - 0.1% efficiency
- Oven ... *depends on the properties of the material*
0.1% - 1% ?



The plan for ^{44}Ti beams off-line

- ^{44}Ti can be provided in the form of TiF_4
 - TiF_4 sublimates at 284°C
 - Lessons from recent ^{33}S beam:
 - Melting point 115°C / Boiling point 445°C
 - Didn't even have to turn on oven to get a good vapour pressure
 - There is a possibility of getting up to 1% efficiency out of source when using TiF_4 .
- ... But this needs testing...



Efficiency tests - Done

Ti wire sputter test:

- Wire produced $\sim 2.7 - 3.6 \times 10^8$ pps $^{48}\text{Ti}^{7+}$ at the source cup
- Ran for 5 days
- ^{48}Ti is 74% of natural abundance
- No measured difference in Ti wire weight after the test (0.1mg scale)

\therefore Minimum sputter efficiency was 0.017%

Good enough... but not great



Efficiency tests - planned

- The Problems:
 - putting a small enough sample in the Supernanogan to use it up in the time available for beam development
 - Knowing how much material was in the sample
- The Solution:



Efficiency tests - planned

- The Problems:
 - putting a small enough sample in the Supernanogan to use it up in the time available for beam development
 - Knowing how much material was in the sample
- The *Solution*: using a small amount of a low concentration solution of TiF_4 in water.
 - An oven for TiF_4 tests has been ordered
 - TiF_4 needs to be acquired
 - Hope to run in winter shutdown (late Dec. - early Apr.)



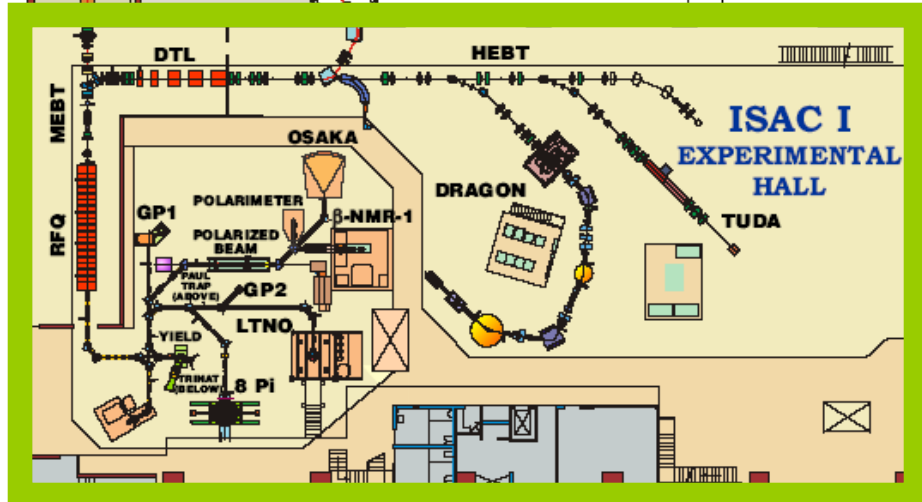


- ^{44}Ti is radioactive, $t_{1/2} = \sim 60 \text{ y}$
- No other radioactive isotope ever used in OLIS
- + ^{14}C experiment also has “stage 1” approval (join forces)
- + ^{44}Ti beam was produced from an ECR source at Argonne National Lab.

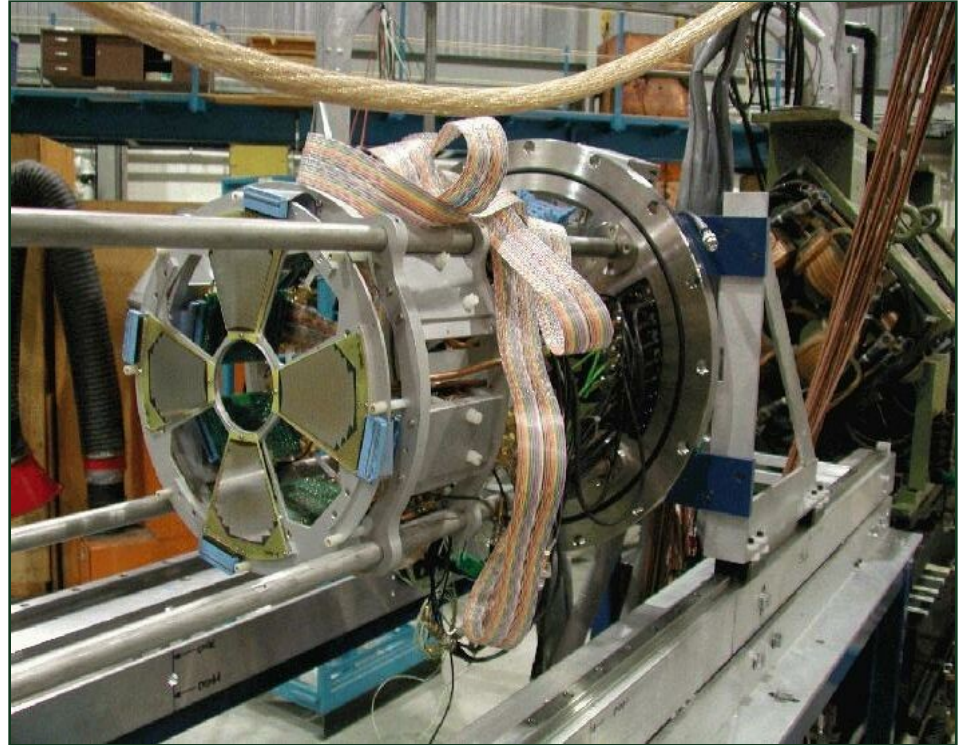
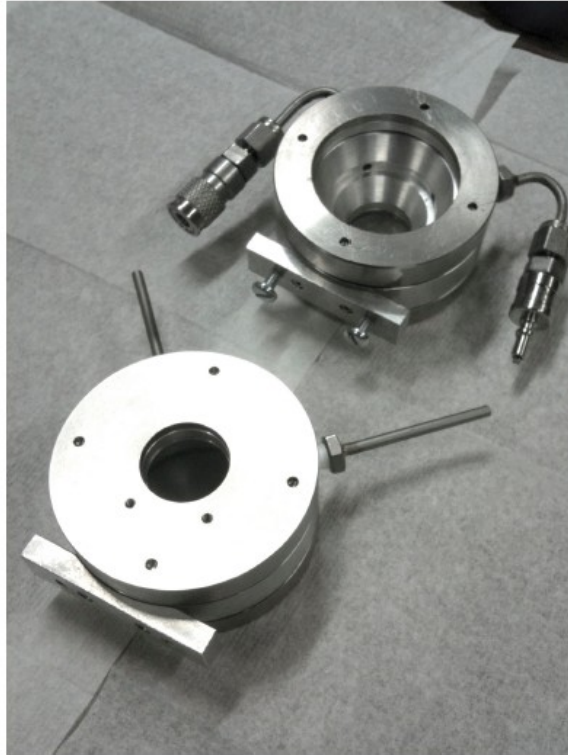




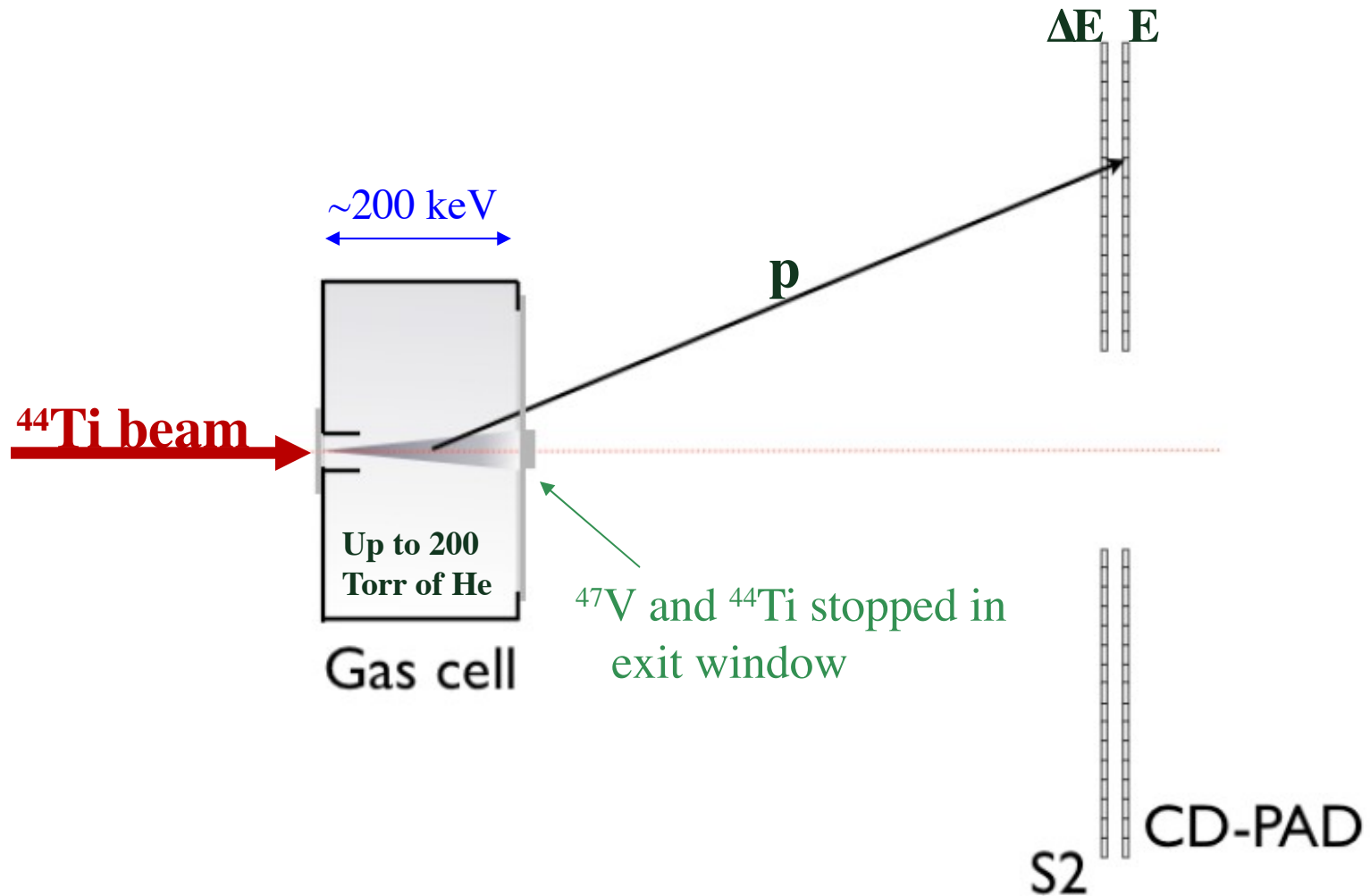
ISAC I: 150 keV/u - 1.9 MeV/u



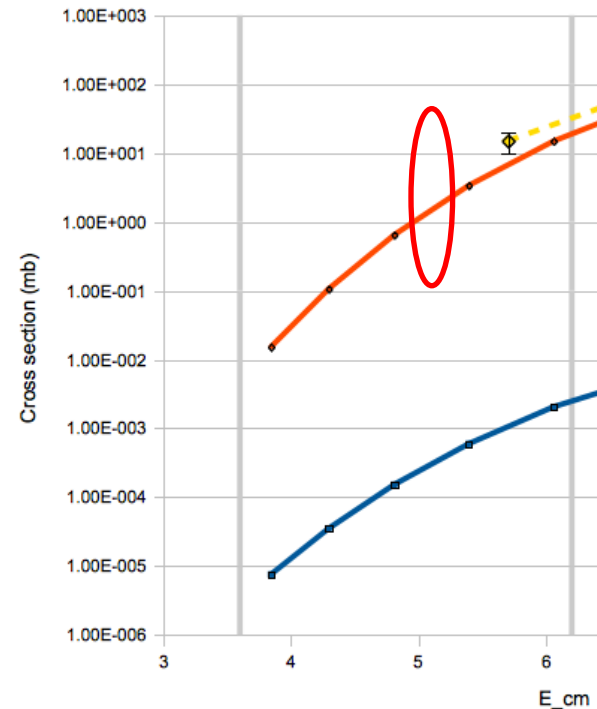
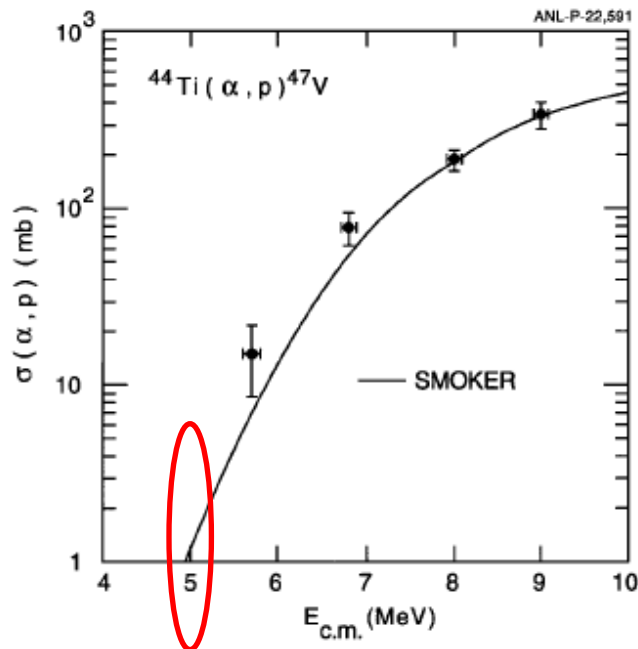
The experiments: $^{44}\text{Ti}(\alpha, p)$ at TUDA



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$E_{C.M.}$ (MeV)	Cross-section (mb)	Events/day	# 12 hour shifts
5	4	195	2
4	1	65	4
3	0.5	14	10

↑ With 10^6 pps beams



So, we have a ^{44}Ti beam
what else can we do with it...

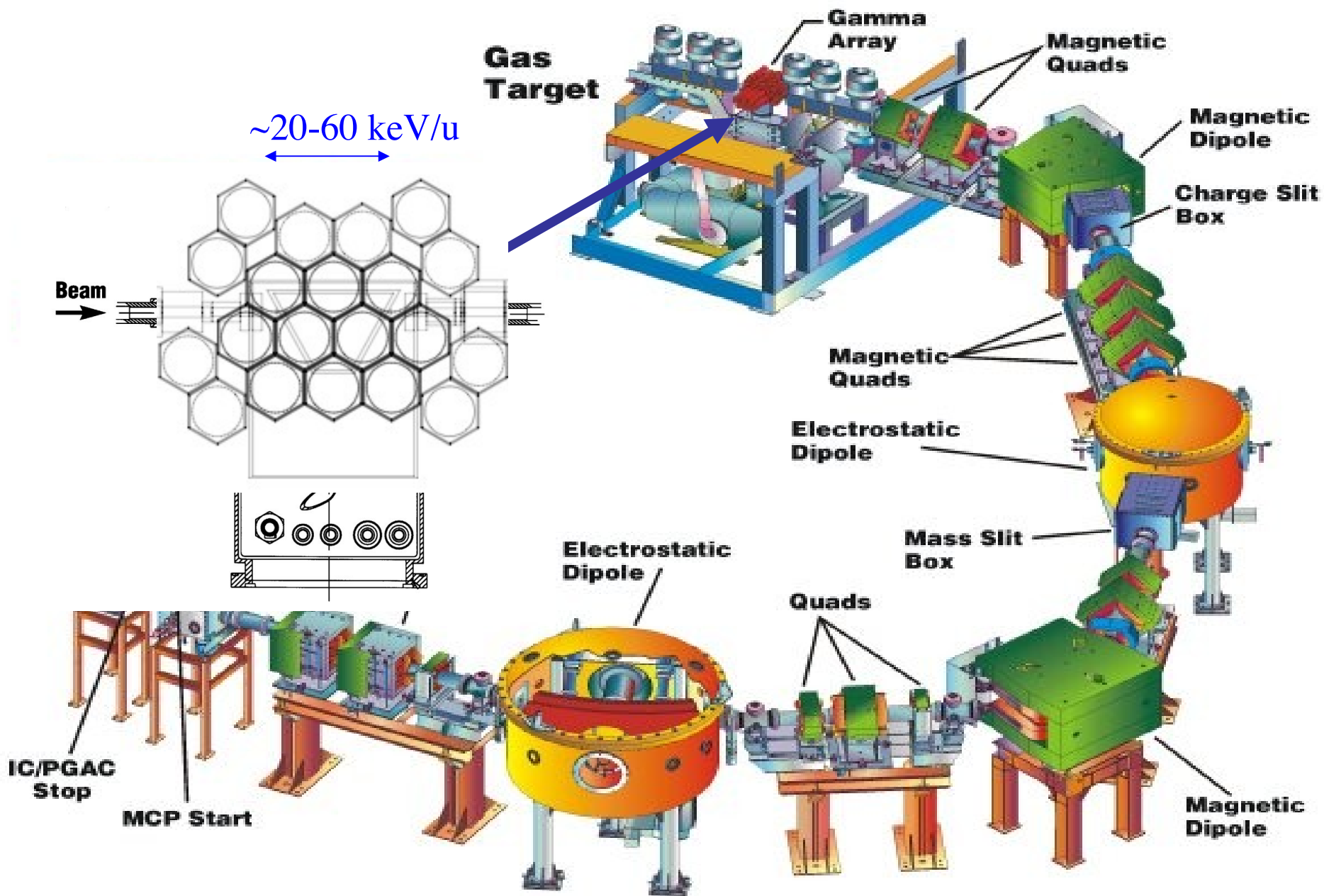


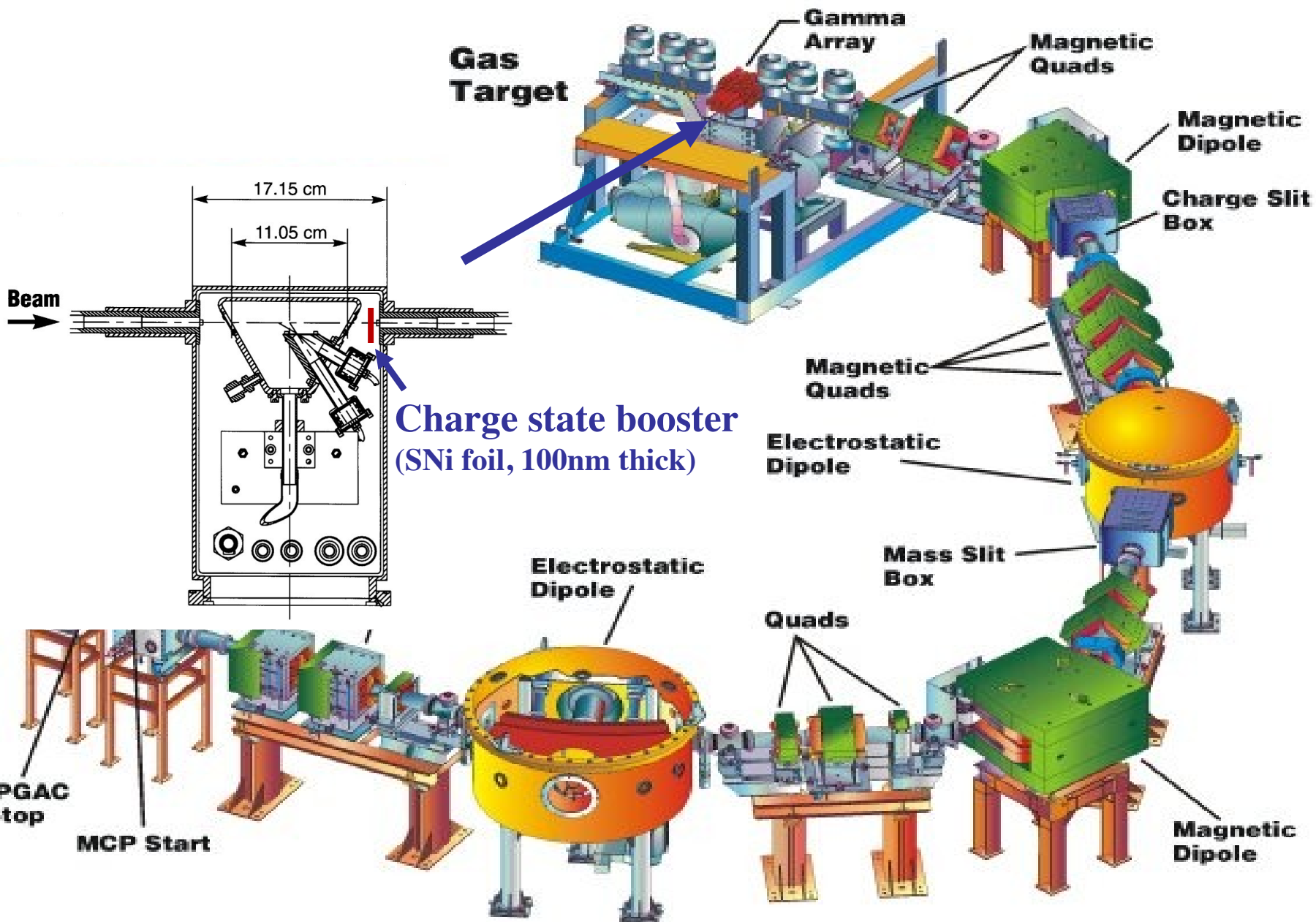
^{44}Ti production destruction

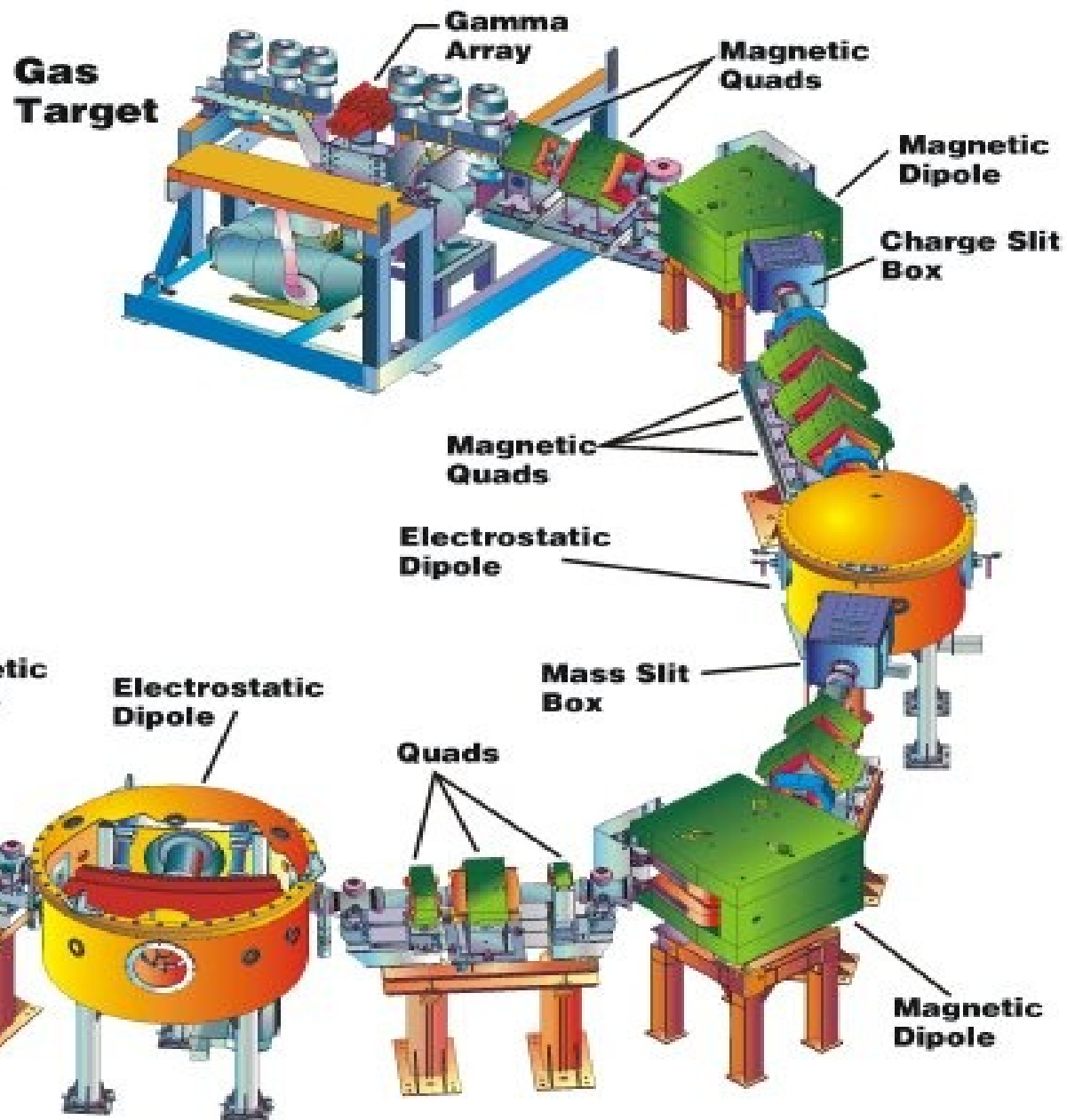
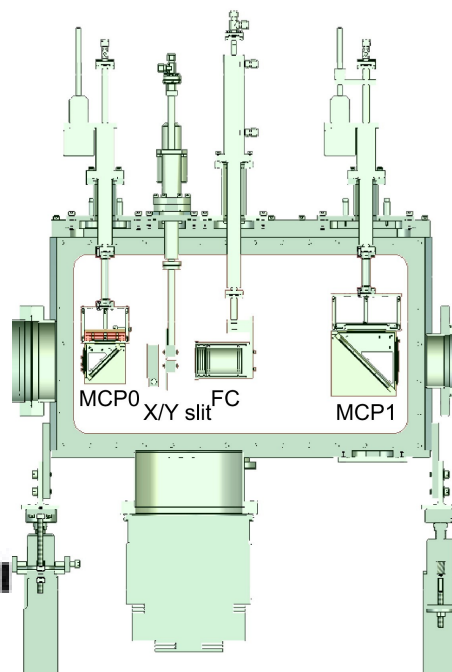
Radiative
capture

	Magkotsios <i>et al.</i> (2010):	The et al. (1998):
$^{44}\text{Ti}(\alpha, \text{p})^{47}\text{V}$	✓	✓
$^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$	-	✓
$^{44}\text{Ti}(\text{p}, \gamma)^{45}\text{V}$	✓	✓
Rates used	NON-SMOKER	SMOKER



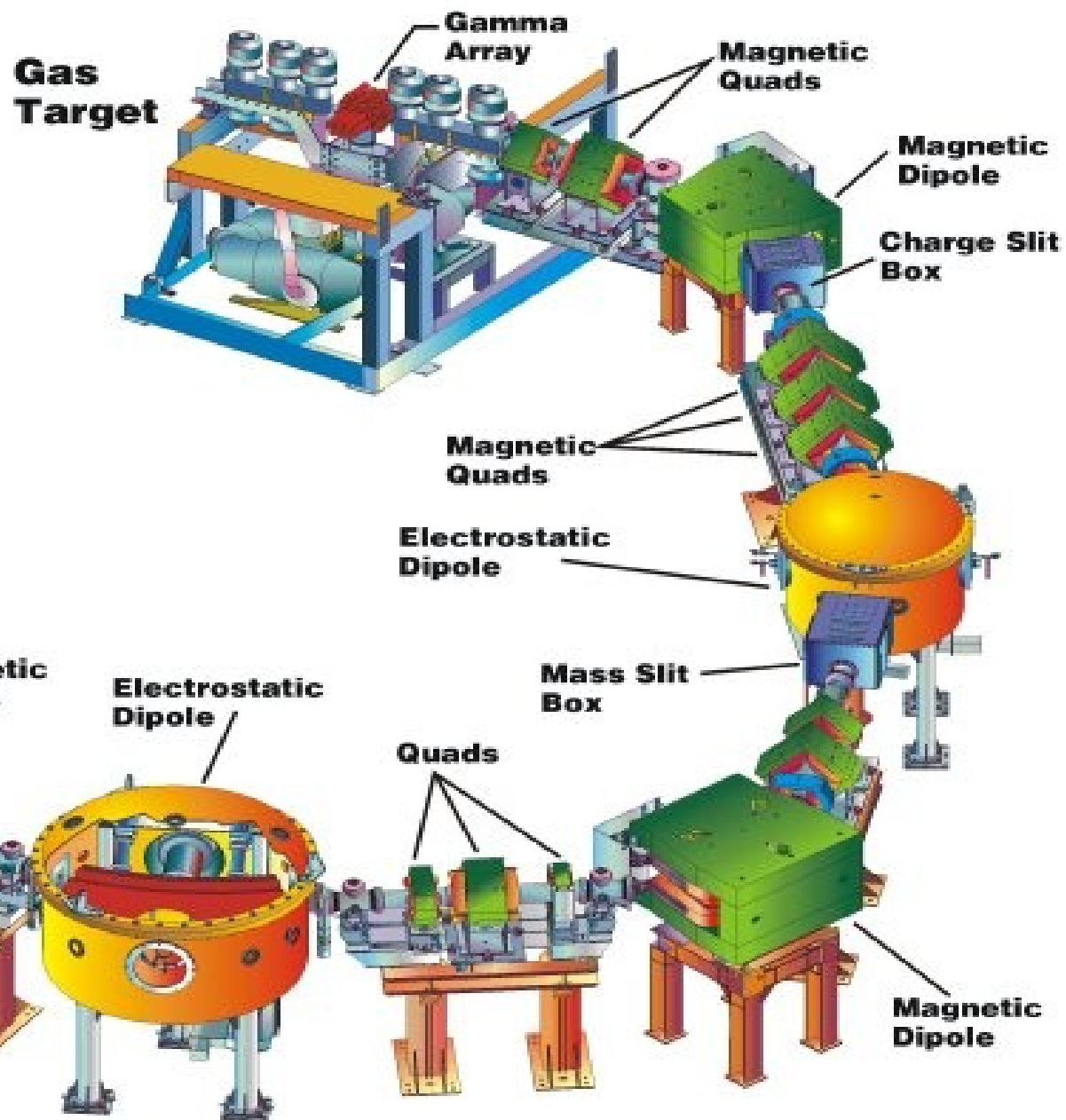






Raw suppression for
p-capture $10^8 - 10^{10}$

Up to 10^{15} with γ +H.I.
coincidence

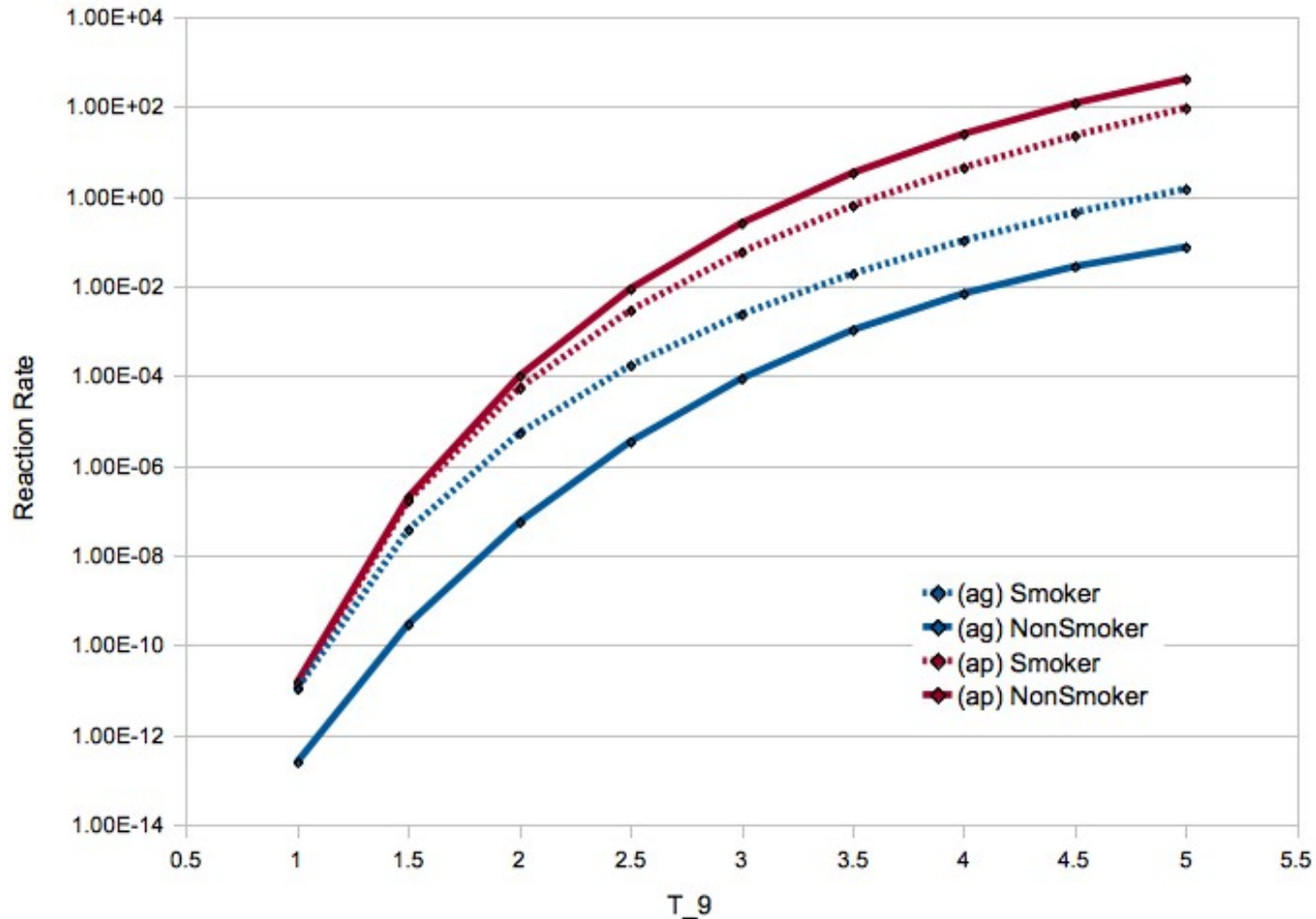


Current experimental data for $^{44}\text{Ti}(\alpha, \gamma)$

(Yes, that's really all there is...)



Changes between SMOKER and NON-SMOKER codes: result of suppression of (α,γ) reactions on self conjugate nuclei due to isospin selection rules



^{44}Ti (α, γ) Requirements

- for 10^8 pps
 - 6.2 MeV: ~ 0.6 counts/hr at the end detector.
- for 10^9 pps
 - 6.2 MeV: ~ 6 counts/hr
 - 4.9 MeV (middle of Gamow window) : ~ 0.4 counts/hr
- For 10^{10} pps
 - 3.6 MeV: ~ 0.14 counts/hr



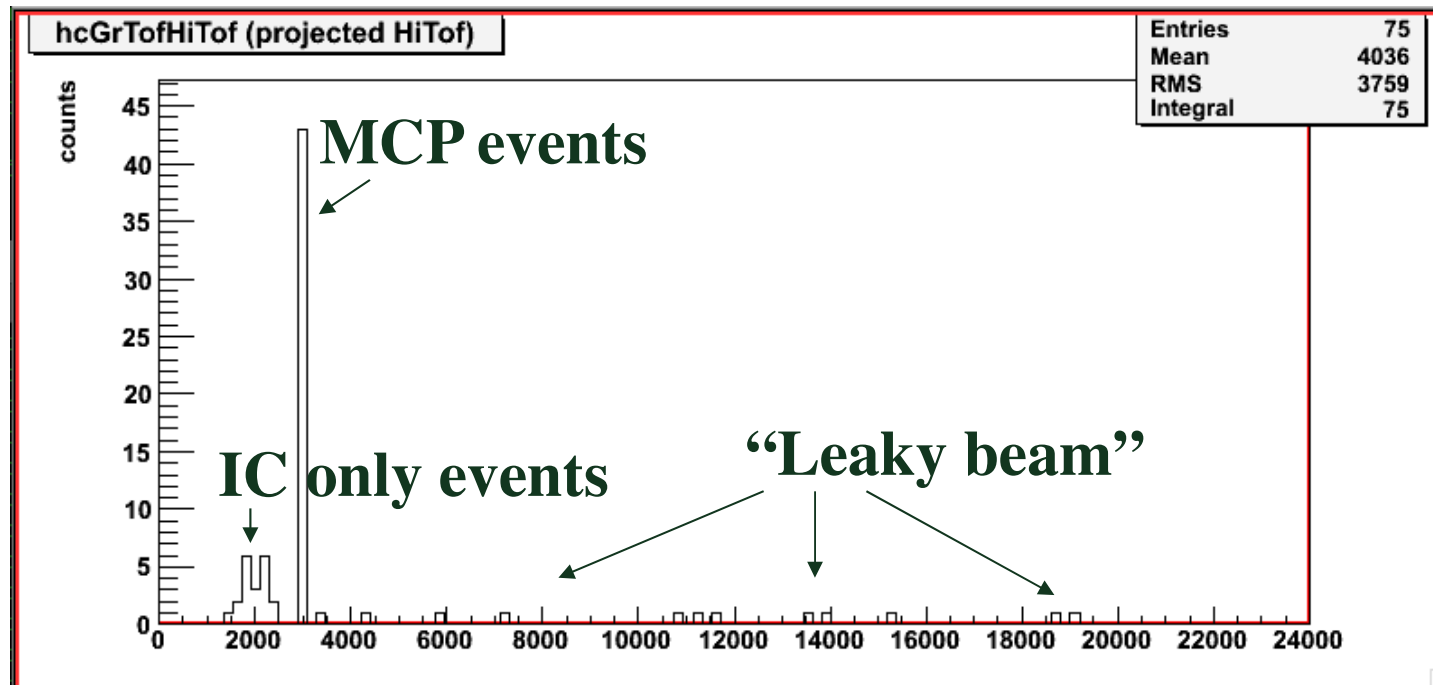
Current experimental data for $^{44}\text{Ti}(p,\gamma)$

(... nothing here either ...)

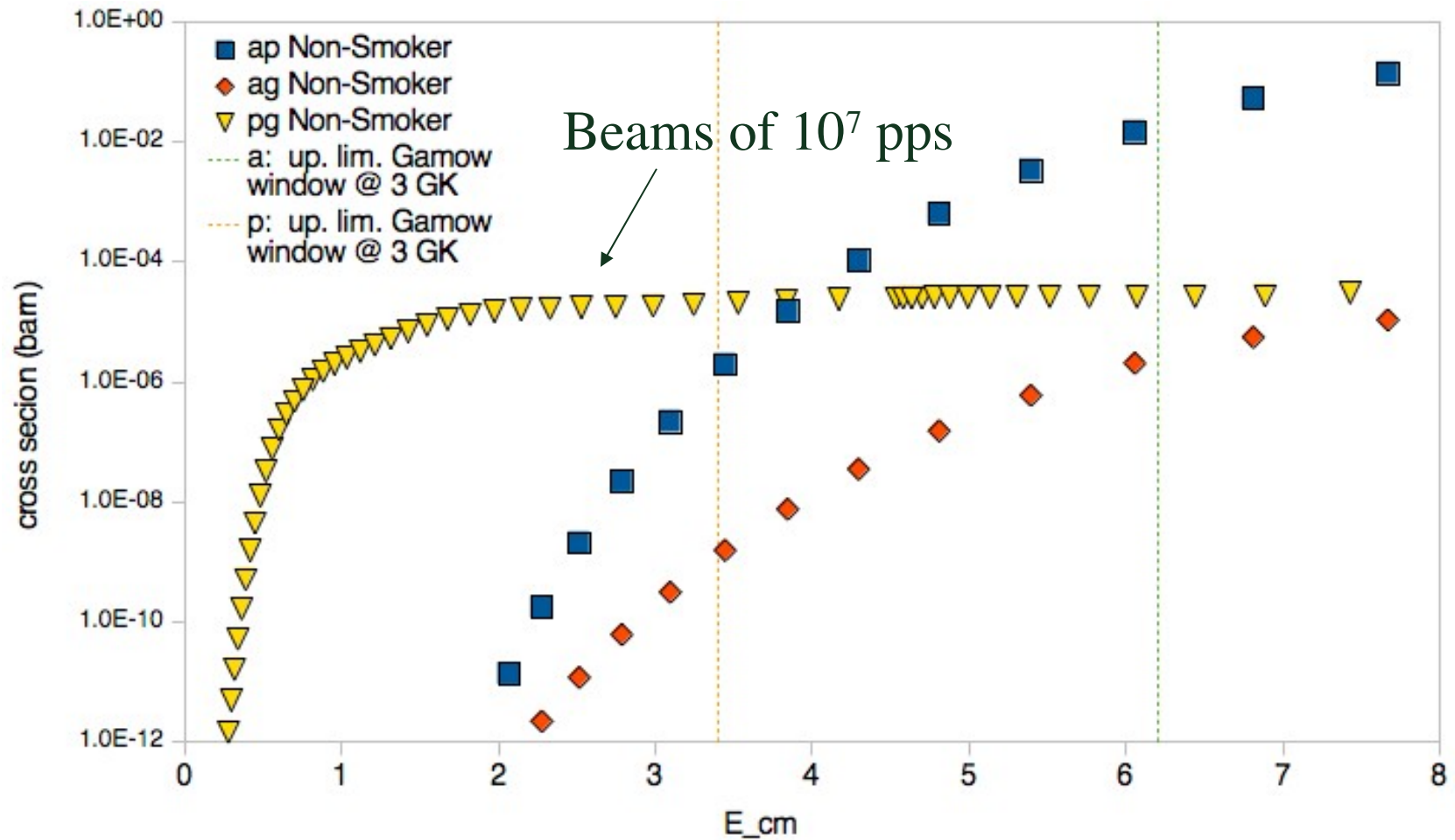


(p, γ) separation?

- Ran a test with $^{58}\text{Ni}(p,\gamma)^{59}\text{Cu}$ in April at 1.4 MeV/u:
 - Avg. beam suppression in 'singles' mode $\sim 1.2\text{E}8$
 - Avg. beam suppression in 'coincidence' mode $\sim 3.0\text{E}10$



NON-SMOKER cross sections for $^{44}\text{Ti}(p,\gamma)$



ISAC-I beam energies: 150 keV/u - 1.9 MeV/u

$^{44}\text{Ti}(\alpha, \gamma)$: (for upper limit of Gamow window at 3 GK)

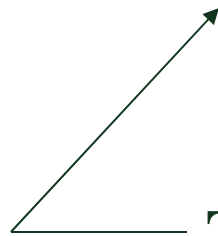
$$E_{\text{res}} = 6.2 \text{ MeV}$$

$$E_{\text{beam}} = 1.69 \text{ MeV/u}$$

$^{44}\text{Ti}(p, \gamma)$: (for the middle of the Gamow window at 3 GK)

$$E_{\text{res}} = 1.87 \text{ MeV}$$

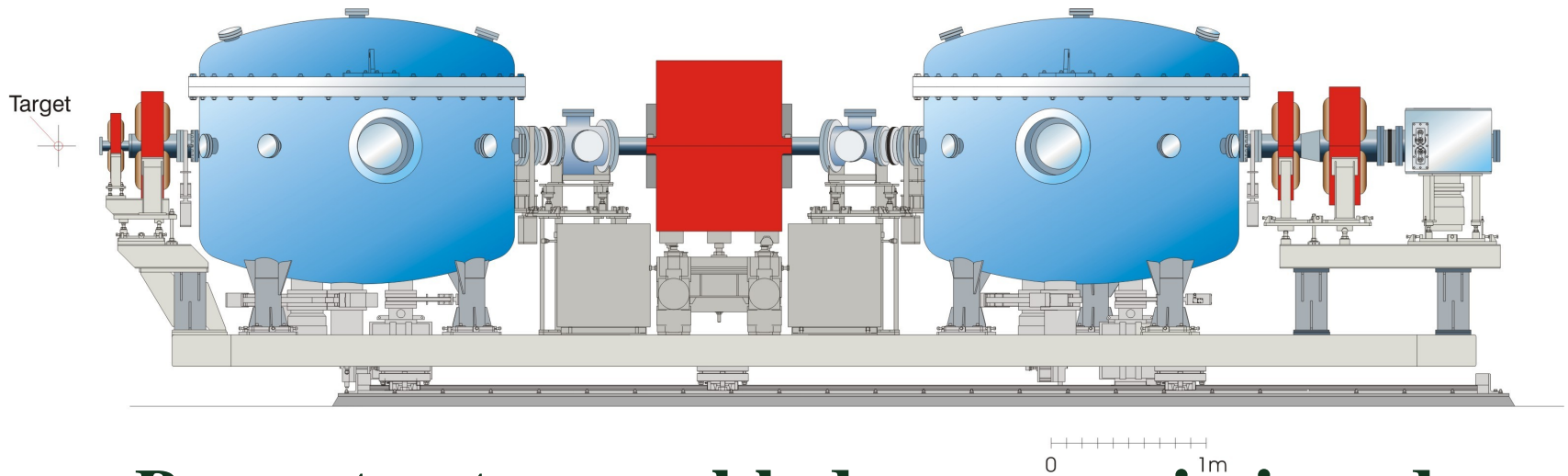
$$E_{\text{beam}} = 1.9 \text{ MeV/u}$$



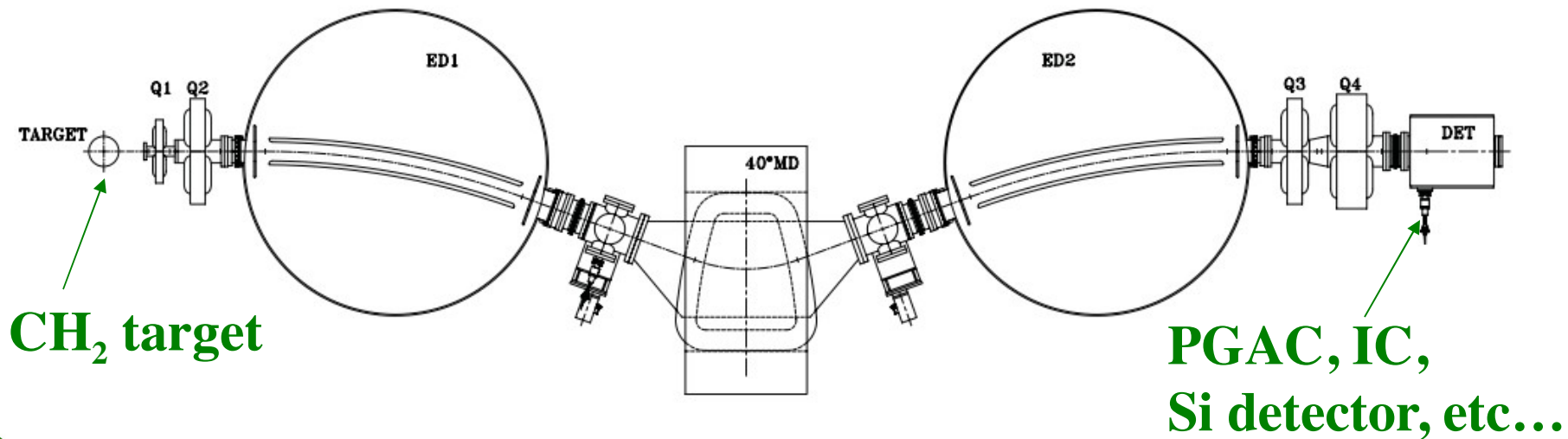
This is the upper limit of E_{beam} to DRAGON. To measure radiative capture rates for higher temperatures...



EMMA (ElectroMagnetic Mass Analyser)



But not yet assembled or commissioned



Summary of The Plan

- Test the efficiency of TiF_4 from Supernanogan
- Acquire safety approval Feasible on a ~1 yr time scale
- Run $^{44}\text{Ti}(\alpha, p)^{47}\text{V}$ at TUDA ← Possibly 2013 if all goes very well
- Measure $^{44}\text{Ti}(p, \gamma)^{45}\text{V}$ at DRAGON ← Not too much of a stretch
- Guided by TUDA results, confirm or deny the NON-SMOKER rate for $^{44}\text{Ti}(\alpha, \gamma)^{48}\text{Cr}$ at DRAGON



Collaborators

TRIUMF:	<i>J. Fallis, C. Ruiz, D. Hutcheon</i>
U. Edinburgh:	<i>A. St.J. Murphy, G. Lotay, P. J. Woods, M. Aliotta, T. Davinson, D. Mountford, G. Lotay, A. Shotter</i>
U. York:	<i>B. R. Fulton, A. M. Laird, M. Taggart, S. Fox, C. A. Diget, M. Bently, J. Brown, P. Adsley</i>
SFU:	<i>J. M. D'Auria</i>
UNBC:	<i>A. Hussein</i>
CSM:	<i>U. Greife, U. Hager</i>
McMaster:	<i>A. A. Chen, J. Chen, D. Irvine, K. Setoodehnia</i>
TU-Munich:	<i>S. Bishop, A. Parikh, C. Vockenhuber</i>
ANL:	<i>J. Clark, C. Deibel</i>



Now on to the target implantation station at
TRIUMF....



Direct measurement of $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$

- TRIUMF-CENPA (U. Wash) proposal
- High-quality, high-density ^{22}Na target fabricated at ISAC
- Chamber designed at TRIUMF, built at CENPA
- (p,γ) run at CENPA

PHYSICAL REVIEW C 83, 034611 (2011)

Absolute determination of the $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ reaction rate in novae

A. L. Sallaska,^{1,*} C. Wrede,¹ A. García,¹ D. W. Storm,¹ T. A. D. Brown,^{1,†} C. Ruiz,² K. A. Snover,¹ D. F. Ottewell,² L. Buchmann,² C. Vockenhuber,^{2,‡} D. A. Hutcheon,² J. A. Caggiano,^{2,§} and J. José³

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(Received 20 September 2010; revised manuscript received 18 December 2010; published 23 March 2011)

Direct Measurements of $^{22}\text{Na}(p,\gamma)^{23}\text{Mg}$ Resonances and Consequences for ^{22}Na Production in Classical Novae

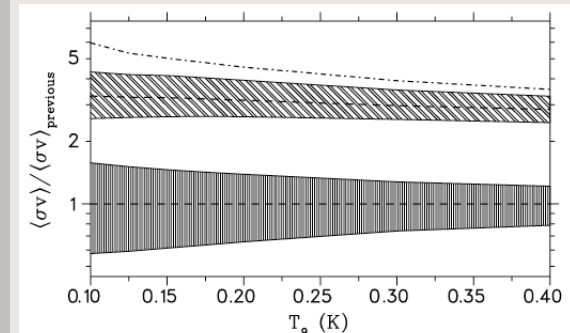
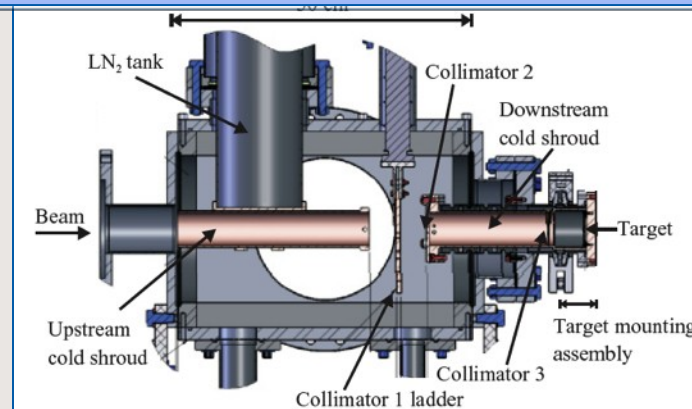
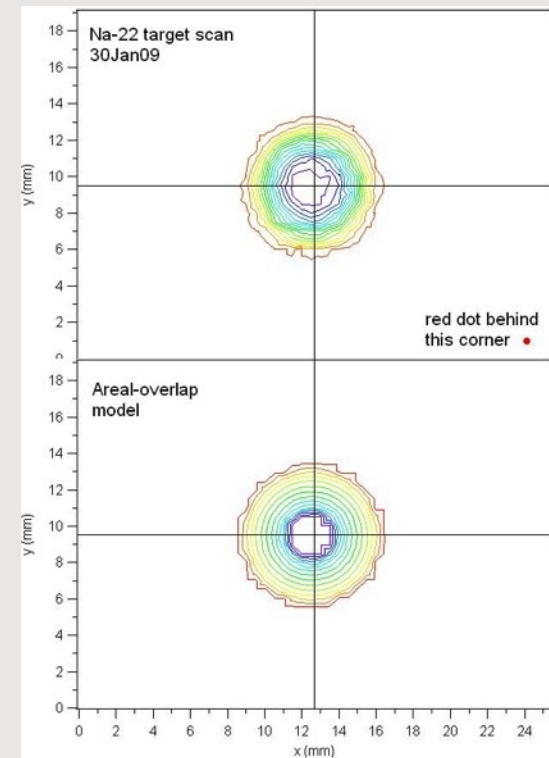
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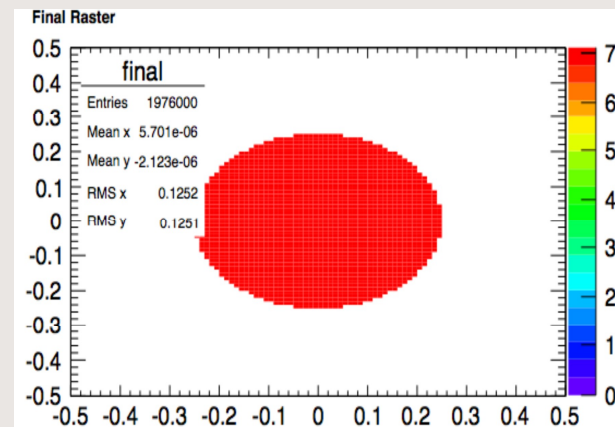
(Received 12 July 2010; published 8 October 2010)

Stronger resonance strengths measured: reaction rate much higher:
reduction in net ^{22}Na \rightarrow **changes detectability distance of novae by factor 2!**

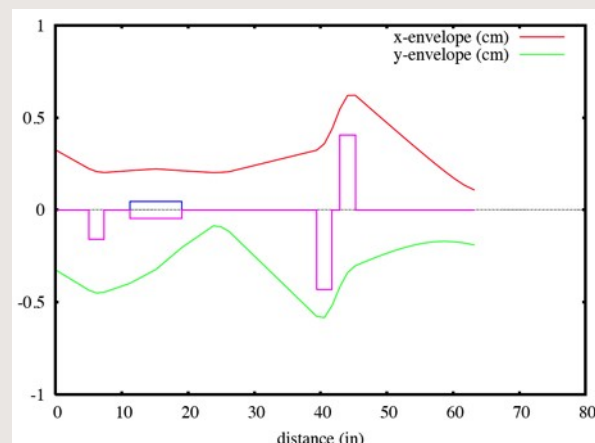


Why Implant?

- ^{26}Al experiment - S1200 $^{26}\text{Al}(n,p)^{26}\text{Mg}$, $^{26}\text{Al}(n,\alpha)^{23}\text{Na}$, core-collapse supernovae TRIUMF-LANL
 - Require high-quality $1 \times 10^{16} \text{ cm}^{-2}$ target, implanted at shallow depth so recoils from (n,p) and (n, α) reactions can be observed
 - Need high-intensity low-velocity ^{26}Al beam
- Future RIBs
 - Many medium-to-long-lived isotopes for implantation for similar neutron-induced experiments, for astrophysical s-process studies – & possibly recovered ^{44}Ti in ISAC ion source
- Custom α -sources
- Target uniformity
 - ^{26}Al targets being used also for charged-particle experiments - important to have uniformity \Rightarrow beam raster
- Safe handling
 - Targets can be fragile, need to be vented and handled with care (and with min. exposure)

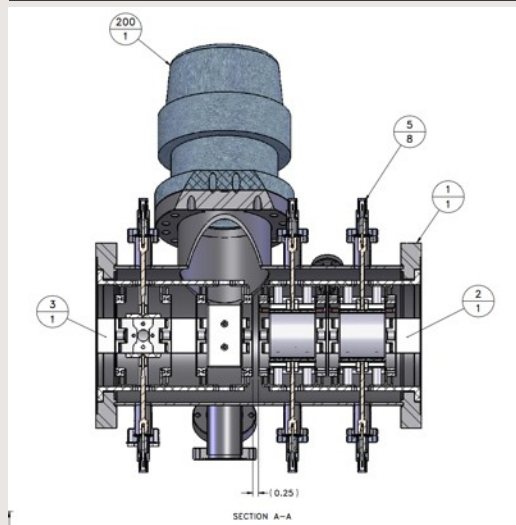
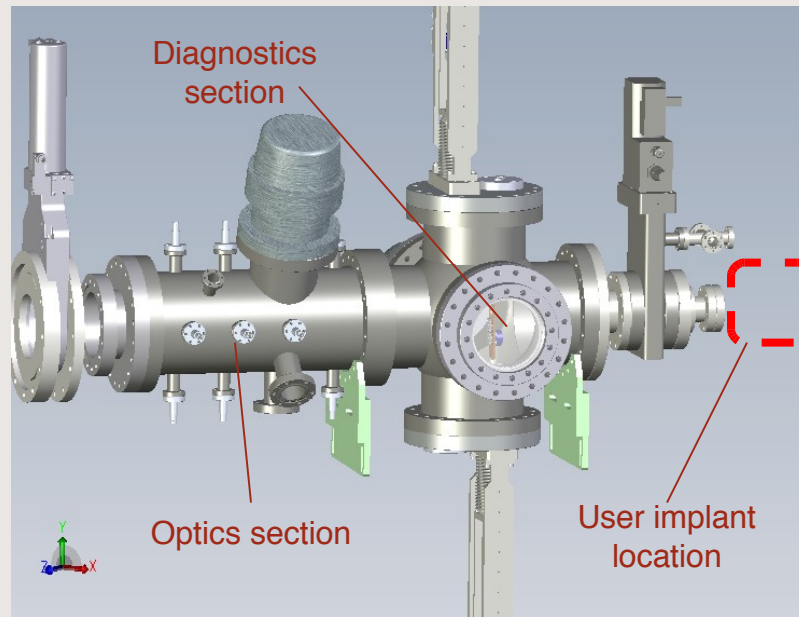
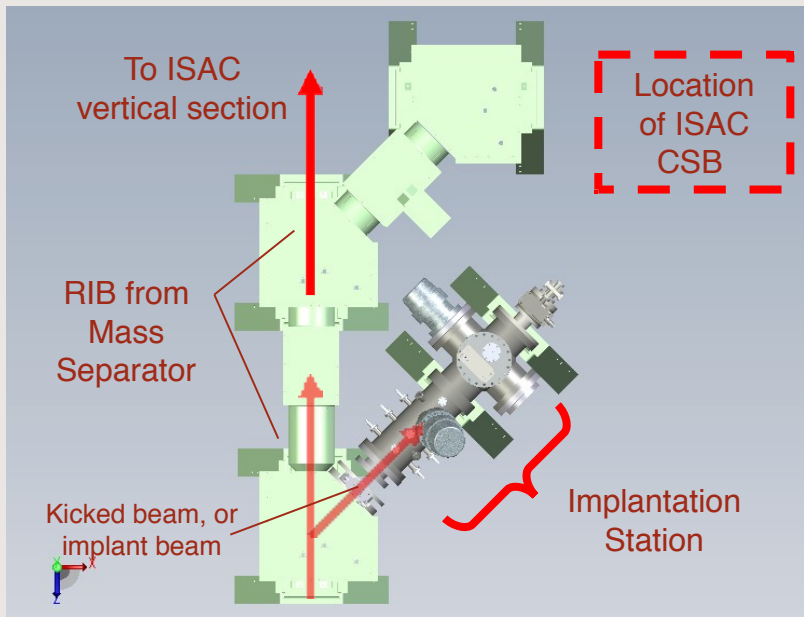


Simulations determined optimum raster efficiency and uniformity achieved for 2mm FWHM beam at typical target diameters



29 kV ISAC beam optics for implant location

Finished Design – ISAC Implantation Station



- Dedicated HV and dry vacuum with UHV specs
- Slow pump/vent for thin foils
- 1×10^{-8} Torr operating pressure
- Commissioned May 2011 with ^{26}Al test target, 2×10^{15} at/cm²
- Treated as a User Facility – each use is an experiment requiring proposal to TRIUMF EEC
- Highly customized target holders can be used
- Now available for public usage

IIS (cont)

