Production of ^{99}Mo Using High-Current Alpha Beams

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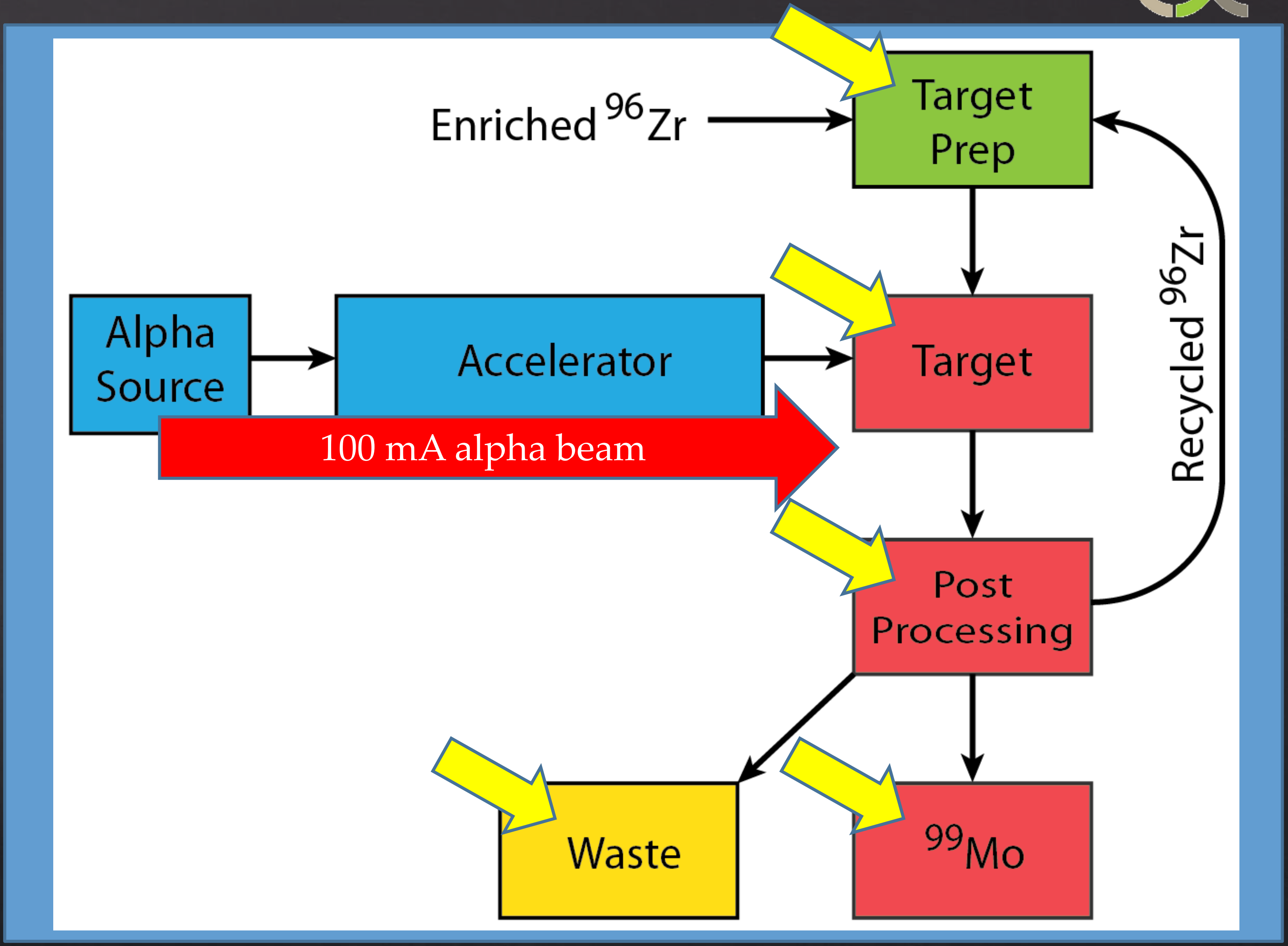
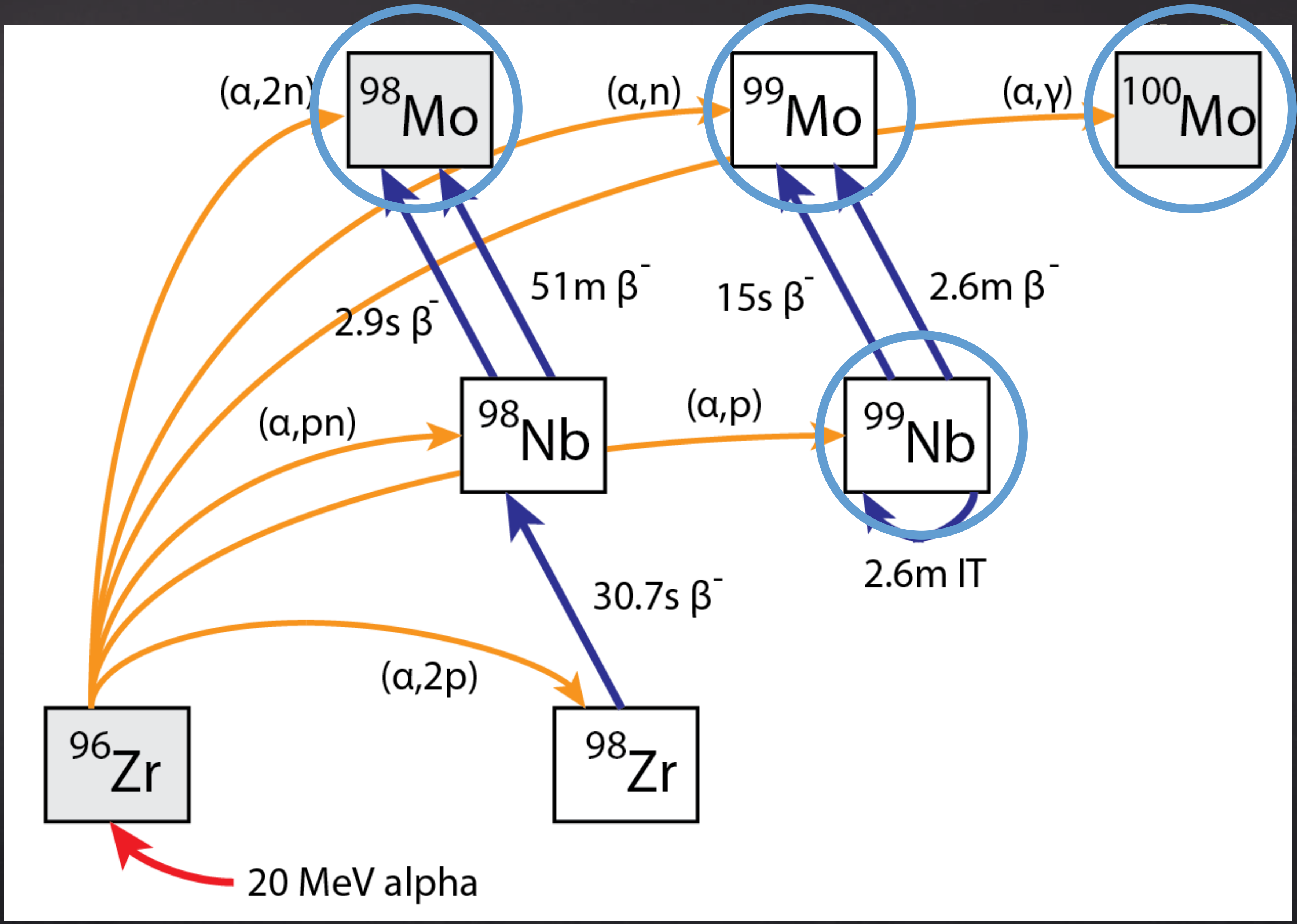
Introduction

- ^{99}Mo from ^{96}Zr by alpha bombardment
- $^{96}Zr(\alpha,n)^{99}Mo$
- High specific activity (> 100 kCi/g)
- >14,000 6-day Ci/year/device
- No uranium involved
- Virtually no nuclear waste generated
- Simplified Chemical processing
- Compatible with current generators

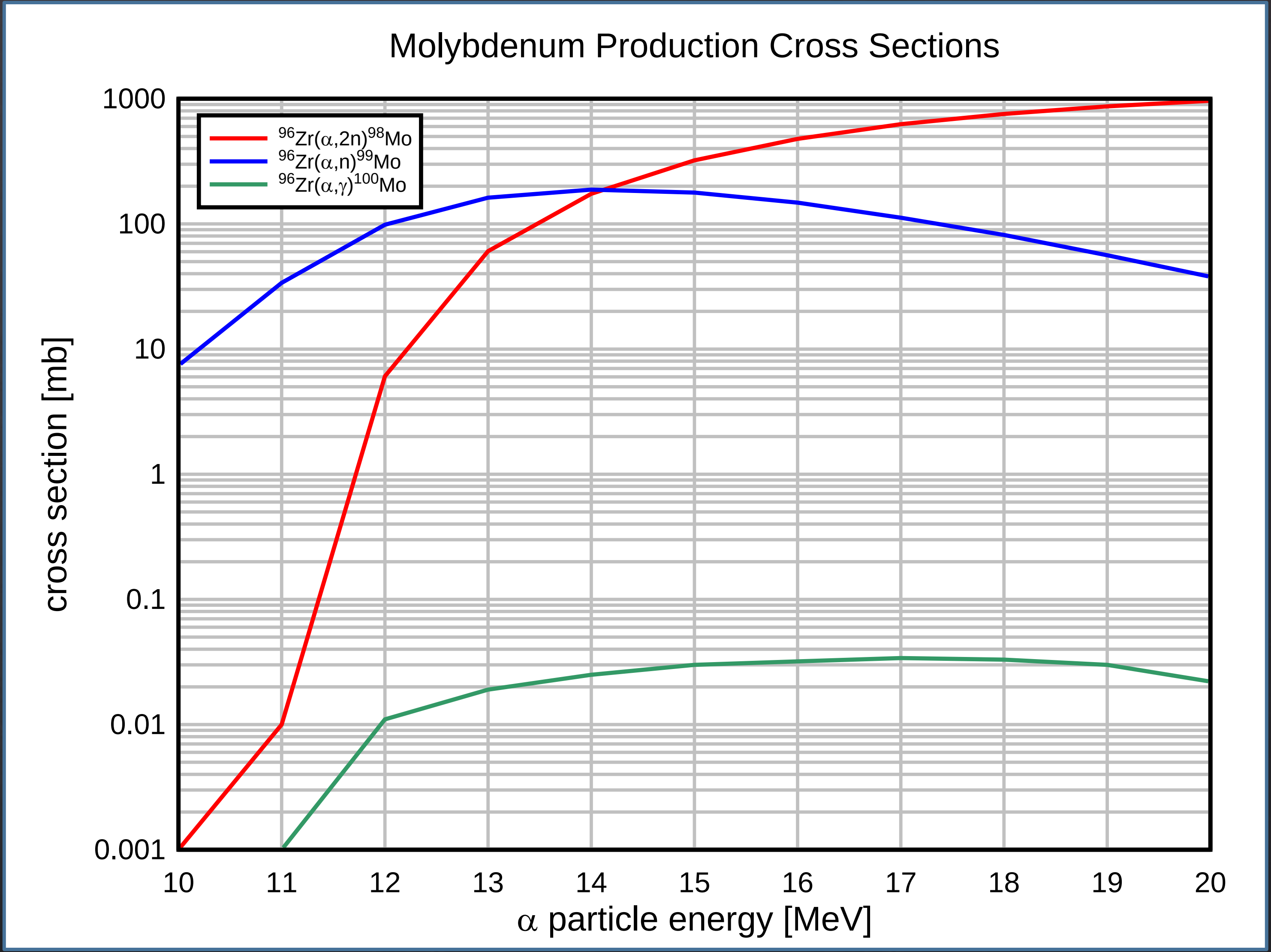
Overview


Enriched ⁹⁶Zr
Target Prep
Alpha Source
Accelerator
Target
100 mA alpha beam
Recycled ⁹⁶Zr
Post Processing
Waste
⁹⁹Mo



(α,2n)
98Mo
(α,n)
99Mo
(α,γ)
100Mo
51m β-
2.9s β-
15s β-
2.6m β-
(α,pn)
98Nb
(α,p)
99Nb
2.6m IT
30.7s β-
(α,2p)
96Zr
98Zr
20 MeV alpha

Molybdenum Production

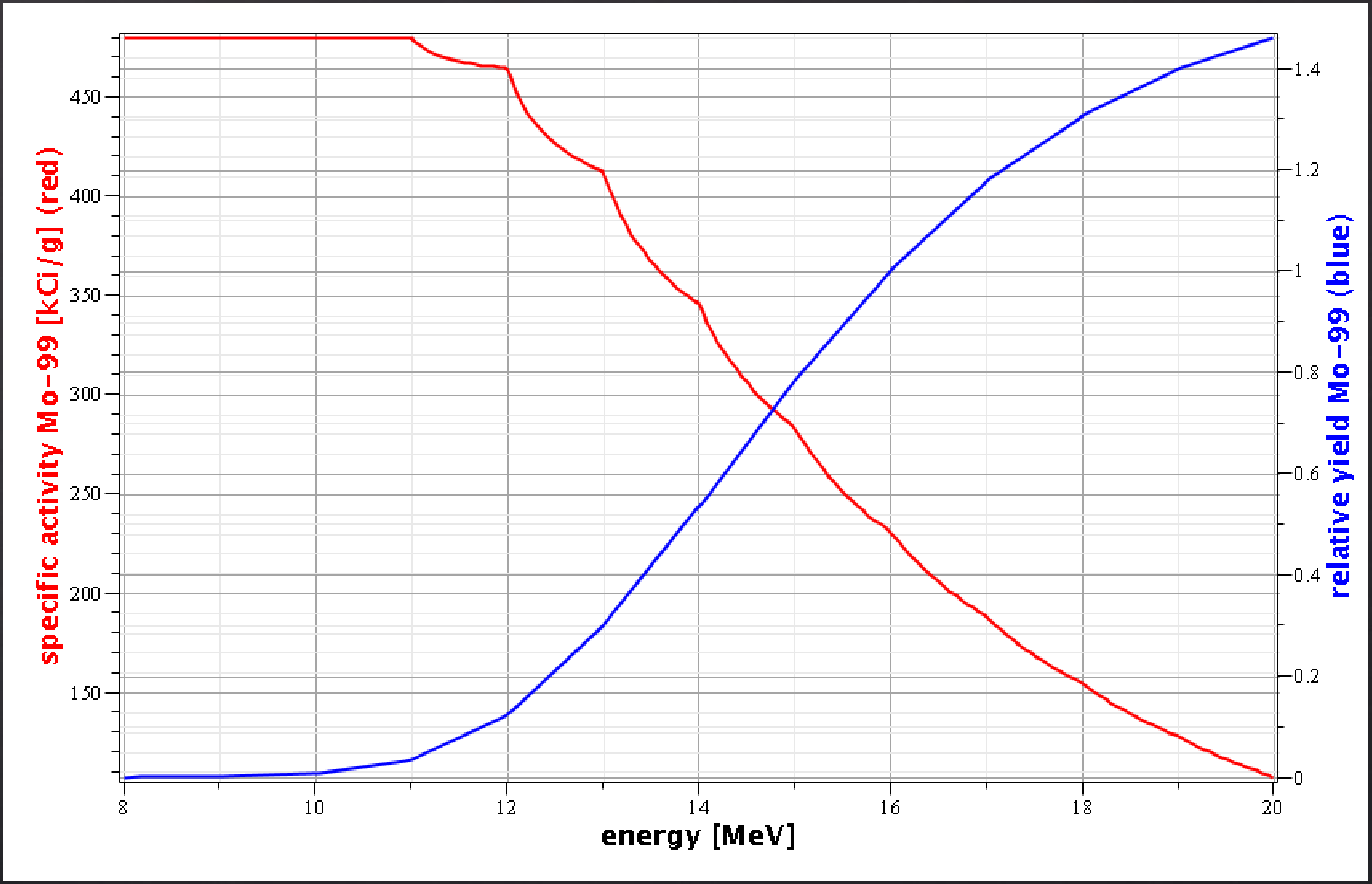


^{99}Mo Yield vs. Specific Activity

Beam Energy	^{99}Mo Yield	^{98}Mo Yield	^{99}Mo Specific Activity
↑	↑	↑↑↑	↓

- At 20 MeV:
  - ^{99}Mo yield is beginning to taper off
  - Specific activity is above 100 kCi/g
    - Pure ^{99}Mo is about 480 kCi/g
  - Other reactions start to occur for higher beam energy

^{99}Mo Yield vs. Specific Activity



^{99}Mo Yield for 100 mA_e Beam

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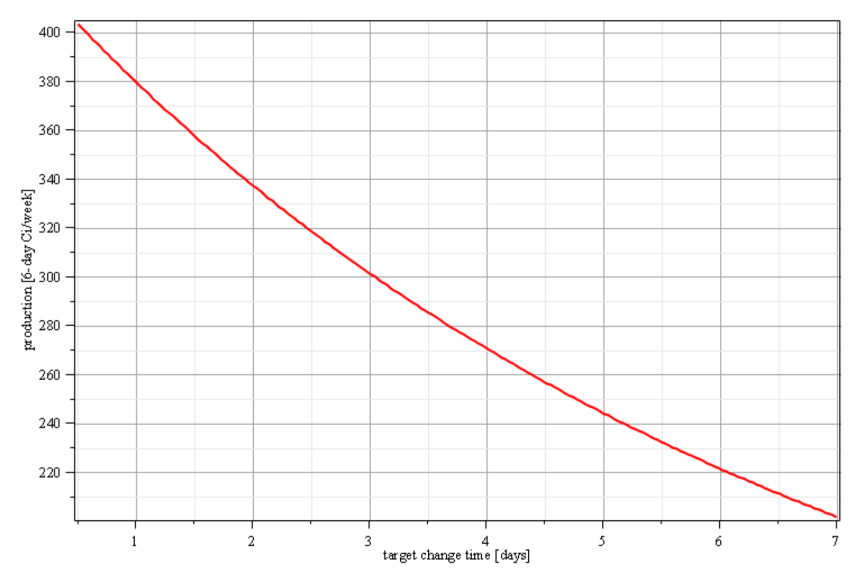

- 54.2 6-day Ci/day
- High flexibility
  - Distributed production over several accelerators
  - Each on a different production cycle
  - Inexpensive chemical processing

^{99}Mo Yield for 100 mA_e Beam

- Weekly yield:
  - 380 6-day Ci/week, 7 batches/week
  - 202 6-day Ci/week, 1 batch/week
  - ~280 6-day Ci/week, 3 batches/week

Duty Cycle	Annual Yield (6-day Ci)
7 batches/week	19,380
3 batches/week	~ 14,280
1 batch/week	10,302

Target Material

- ^{96}Zr is 2.80% of natural zirconium
- Enriched ^{96}Zr is readily available at greater than 99.99%
- 99.99% enriched targets not necessary
- Slightly lower enrichment lowers target cost and allow additional enrichment methods
  - Little change in specific activity
  - Small decrease in yield
  - Still no significant waste material

Number	Target	Reaction	Product	Decay	Product	Decay	Product
1	^{96}Zr	α,γ	^{100}Mo				
2		**α,n**	**^{99}Mo**	**2.75 d**			
3		α,2n	^{98}Mo				
4		**α,p**	**^{99}Nb**	**15 s /2.6 m**	**^{99}Mo**		
5		α,pn	^{98}Nb	2.9 s / 51 m	^{98}Mo		
6		α,2p	^{98}Zr	30.7 s	^{98}Nb	2.9 s / 51 m	^{98}Mo
7	^{94}Zr	α,γ	^{98}Mo				
8		α,n	^{97}Mo				
9		α,2n	^{96}Mo				
10		α,p	^{97}Nb	1.23 h / 53 s	^{97}Mo		
11		α,pn	^{96}Nb	23.4 h	^{96}Mo		
12		α,2p	^{96}Zr				
13	^{92}Zr	α,γ	^{96}Mo				
14		α,n	^{95}Mo				
15		α,2n	^{94}Mo				
16		α,p	^{95}Nb	35 d / 2.61 d	^{95}Mo		
17		α,pn	^{94}Nb	20k y / 6 m	^{94}Mo		
18		α,2p	^{94}Zr				
19	^{91}Zr	α,γ	^{95}Mo				
20		α,n	^{94}Mo				
21		**α,2n**	**^{93}Mo**	**3500 y / 6.9 s**	**^{93}Nb**		
22		α,p	^{94}Nb	20k y / 6 m	^{94}Mo		
23		α,pn	^{93}Nb				
24		α,2p	^{93}Zr	1.6M y	^{93}Nb		
25	^{90}Zr	α,γ	^{94}Mo				
26		**α,n**	**^{93}Mo**	**3500 y / 6.9 s**	**^{93}Nb**		
27		α,2n	^{92}Mo				
28		α,p	^{93}Nb				
29		α,pn	^{92}Nb	700 y / 62 d	^{91}Zr		
30		α,2p	^{92}Zr				

Zirconium Target Purity

- ^{93}Mo – Long-lived radioisotope
  - Suppress by removing ^{90}Zr and ^{91}Zr
- ^{95}Nb, ^{94}Nb, ^{92}Nb – Long-lived radioisotopes
  - Waste disposal issue
  - Suppress by removing ^{90}Zr, ^{91}Zr, and ^{92}Zr
- ^{93}Zr – Very long-lived radioisotope
  - Waste disposal issue
  - Potentially limit recycling of targets
  - Suppress by removing ^{91}Zr

Alpha Particle Source

- Proprietary patented high-current source
- Required high current $^{4}He^{++}$ source
  - High current $^{4}He^{+}$ is easy to make
  - High current $^{4}He^{++}$ is not so easy
- Current source 32 mA_e beam cw or pulsed
- 85% $^{4}He^{++}$ (by current)
- 6 mm beam aperture
- 0.1 (-0.05 +0.15) π·mm·mrad normalize emittance
- X-ray free ECR source
- Operated for 23,000 hours without failure
- Proton, deuterium, tritium, helion, alpha, etc.

Alpha Particle Source

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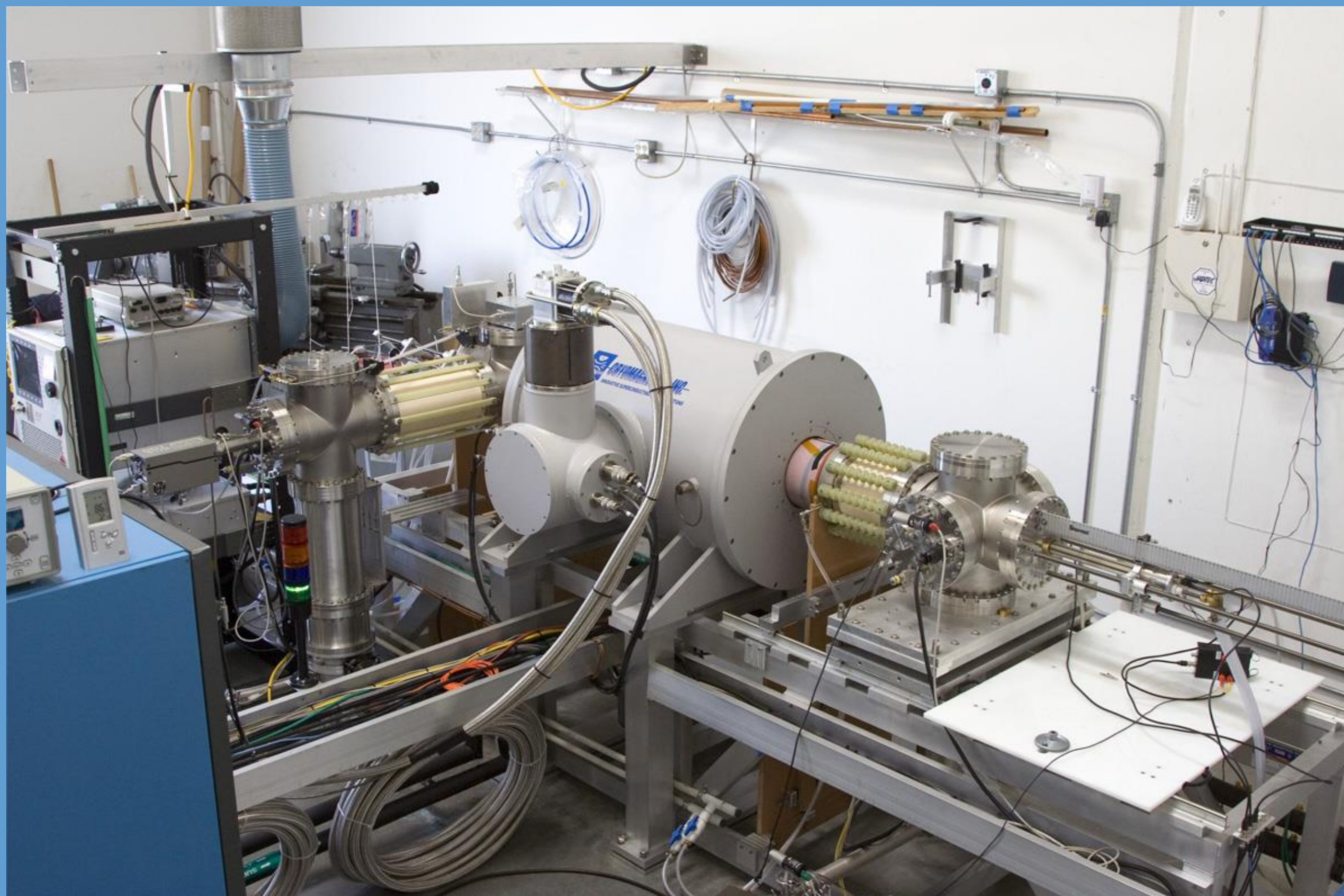

Alpha Source Expansion

- Current source expansion:
  - 96% $^4He^{++}$
  - 50 mA_e
  - Internal or external X-ray shielding

- Future source:
  - 96% $^4He^{++}$
  - 120 mA_e
  - External X-ray shielding

Accelerator

- Required high current $^4He^{++}$ source
  - 160 keV
- Magnetic LEBT
- Room temperature RFQ
  - 8 MeV
- Advanced beam structure – 20 MeV
  - Superconducting cavities
  - H-mode structure with PMQ focusing
  - Hybrid cooling (proprietary technology)
- 8-10 m total length

Targets

- 1 MW power dissipated in target
- Conventional approach:
  - Multiple targets
  - Spread beam over large area
  - Octupole expansion
  - ~1-2 kW/cm^2
- Proprietary high-power target
  - Single target can dissipate 500 kW-1 MW
  - Under development

Cost Analysis

- NEA Full Cost Recovery model
  - https://www.oecd-nea.org/med-radio/guidance/docs/FCR-workbook.xlsx

- 10 systems*

Duty Cycle	Weekly Yield (6-day Ci)	Full Cost Recovery
7 batches/week	3,800	$178
3 batches/week	~ 2,800	~$185
1 batch/week	2,020	$217

** - corresponds to roughly same administrative overhead and other non-editable assumptions in the model. Actual Alpha Source solution is scalable without significant change in FRC/6-day Ci.*

Post-Irradiation Processing

- Relatively simple chemical processing
- Several methods of target processing have already been developed and verified, including effectiveness of the ^{96}Zr recycling
  - Ion-exchange chromatography
  - Fluorination
  - Solubility
- Additional methods are also being developed

Deployment

- Approximately 18 100 mA_e systems could supply the US demand for ^{99}Mo
- Seven 100 mA_e systems could replace the gap created when NRU shuts down in 2016

Conclusions

- High-current alpha beams can be an efficient source for ^{99}Mo
- No significant nuclear waste
- No uranium used
  - Minimal proliferation concerns
- High specific activity
- Distributed, robust production
- Conformable to market demand