

## ***Long-Lifetime High-Yield Neutron Generators using the DD reaction and application of PGNAA***

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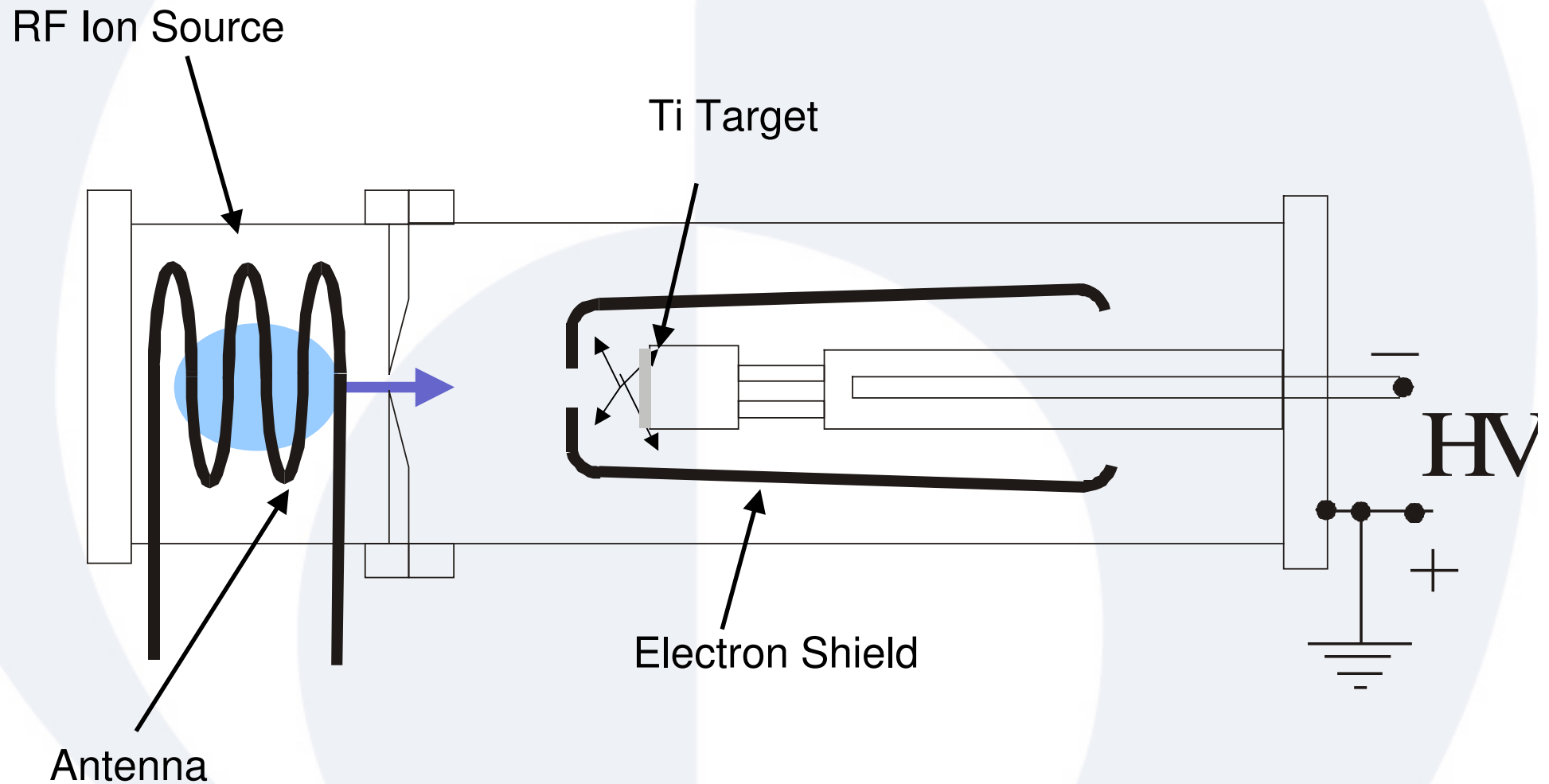
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## *Outline*

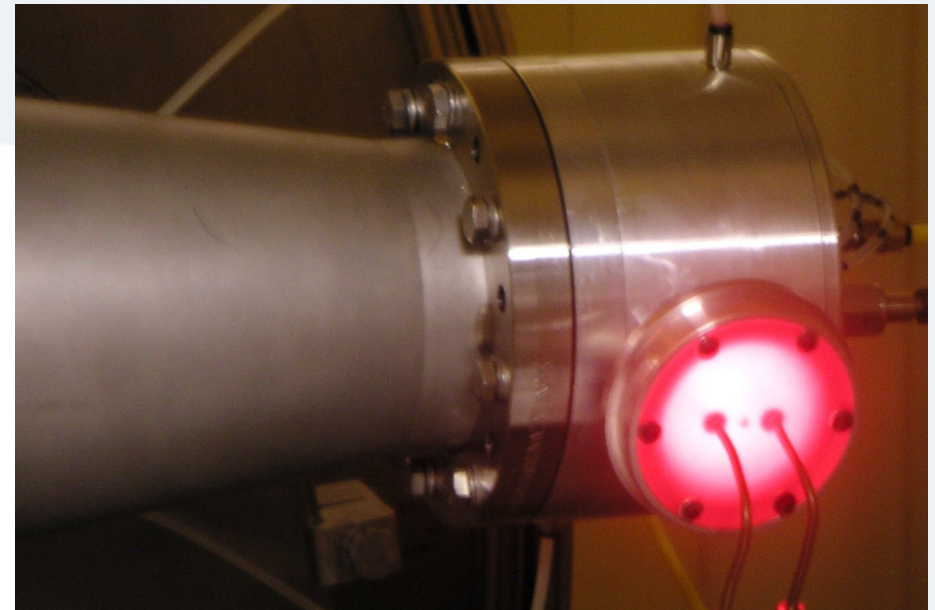
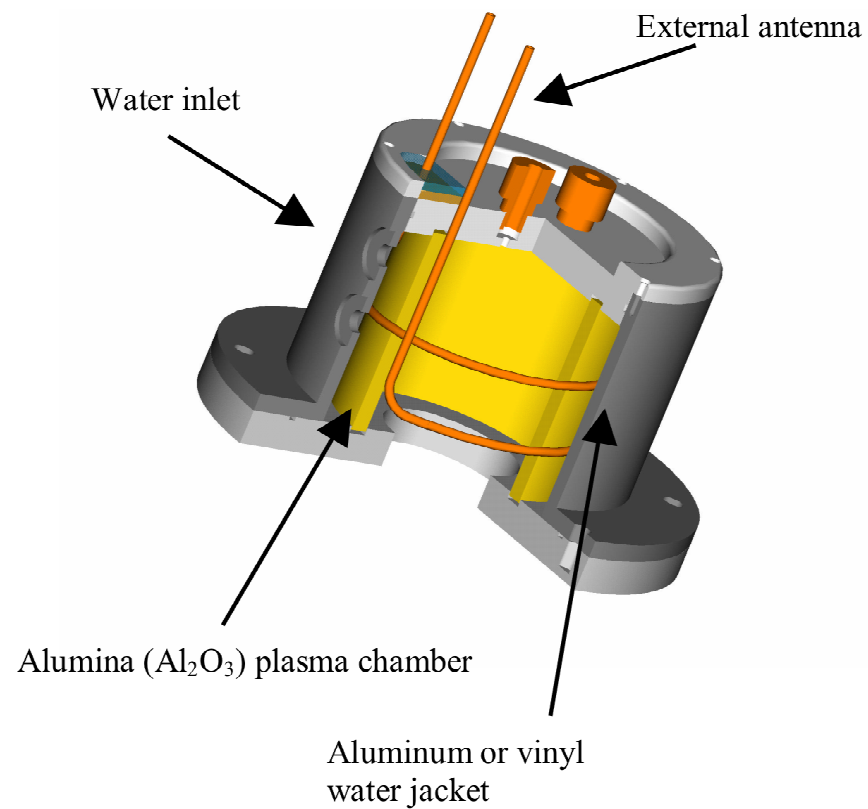
- Plasma Neutron Generators
- RF Plasma Source
- Neutron Yield
  - Current Designs
  - Efficiency
- Research Applications
- Mining Instrument Application
  - Industry Need
- Prototype Test Results
- Conclusion

## ***Axial Generator: Function***

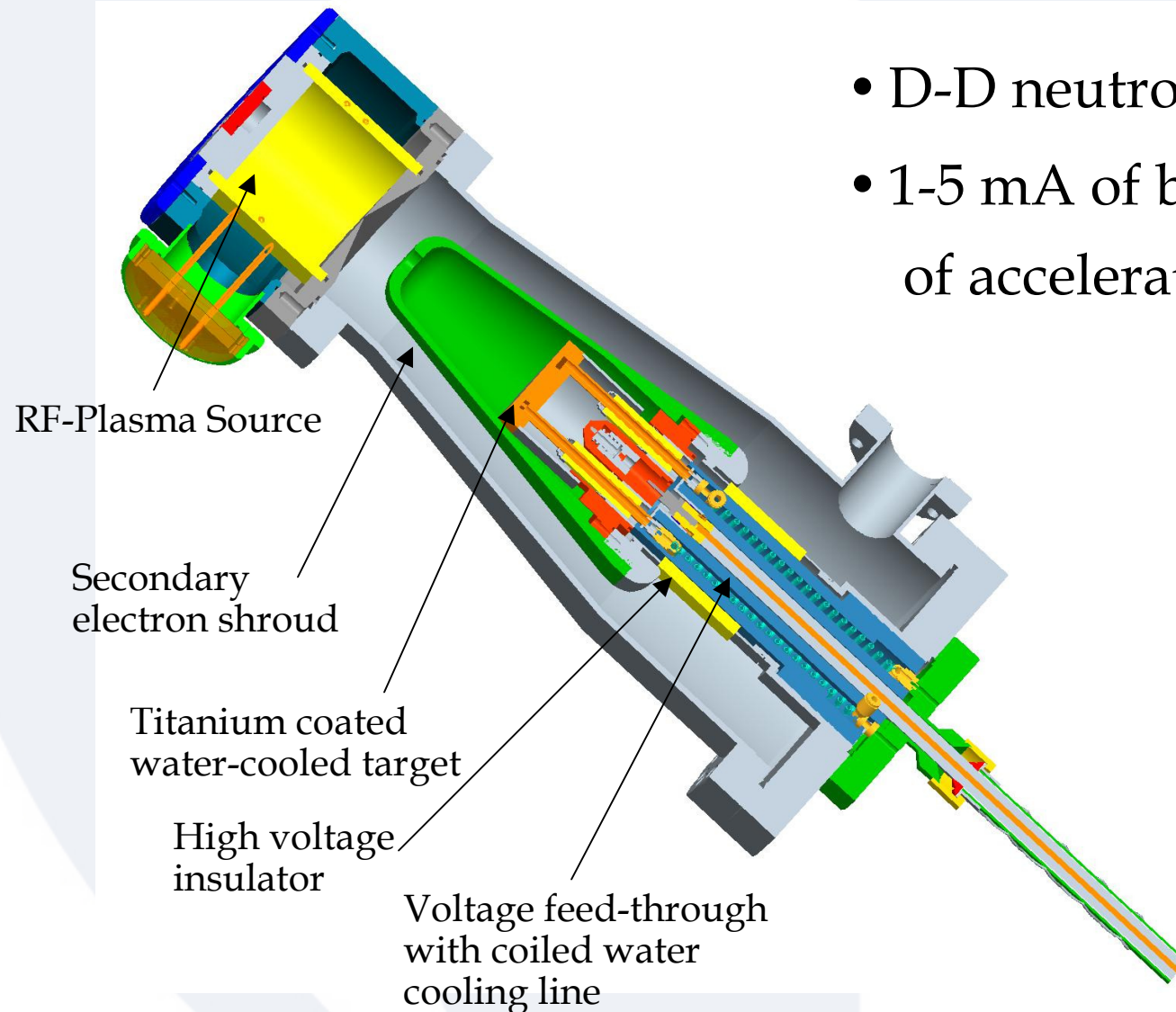


## *RF Plasma Source: Coil Antenna*

- Mechanically and thermally stable and rugged



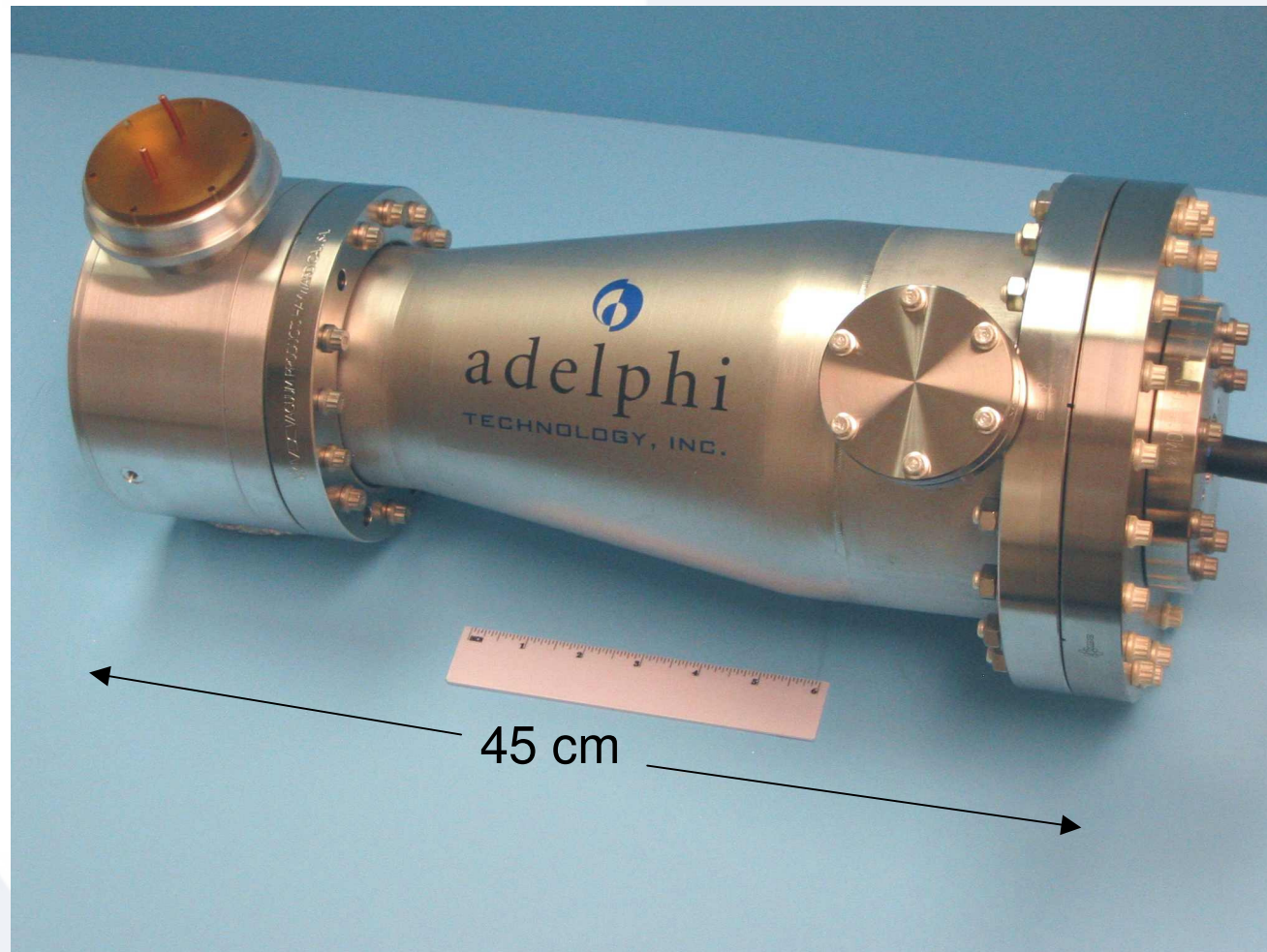
## ***Axial Generator DD-108***



- D-D neutron yield of  $10^8$  n/sec
- 1-5 mA of beam current & 80 kV of acceleration voltage

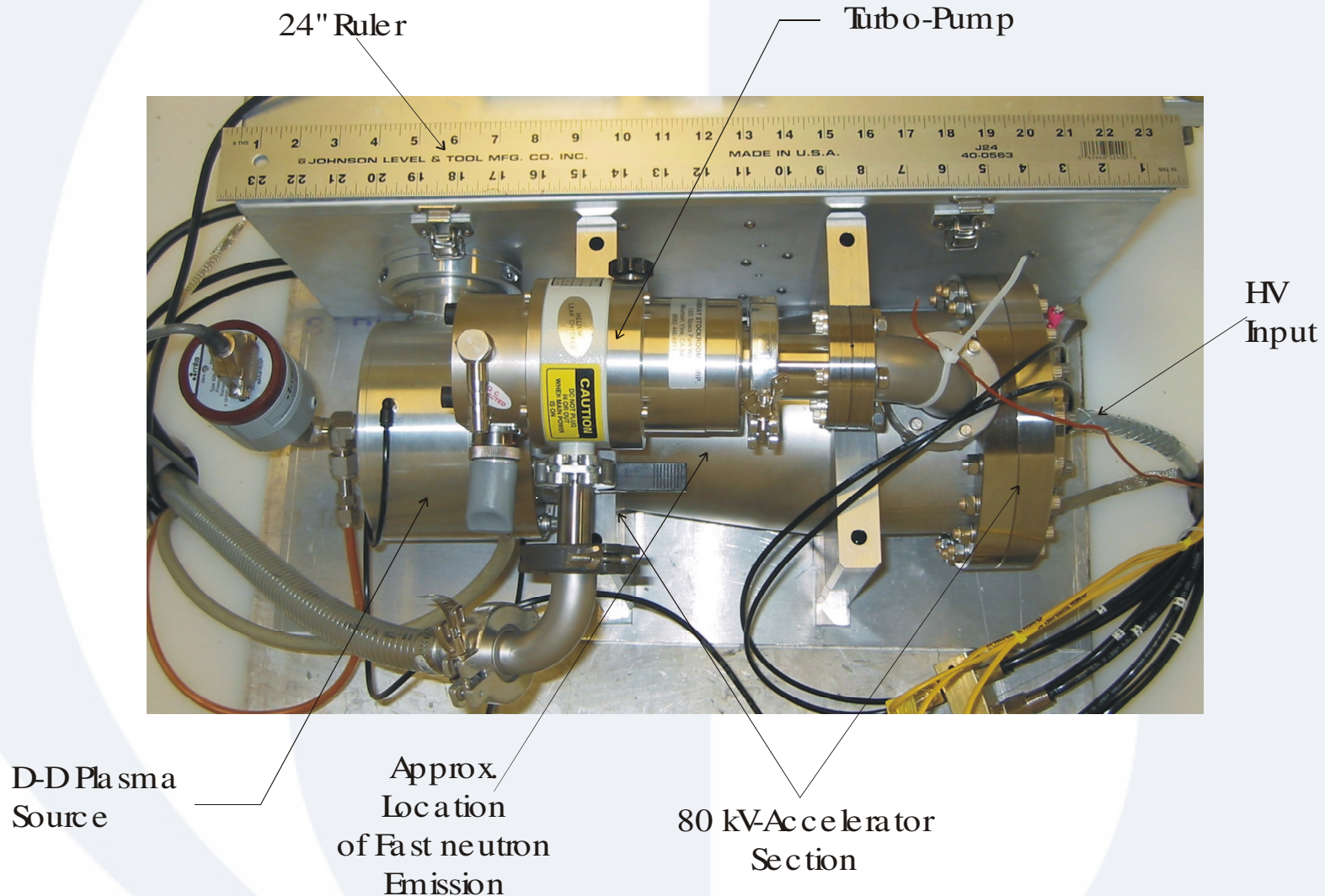
## ***Axial Generator DD-108***

- DD-108: Output measured at  $10^8$  n/s



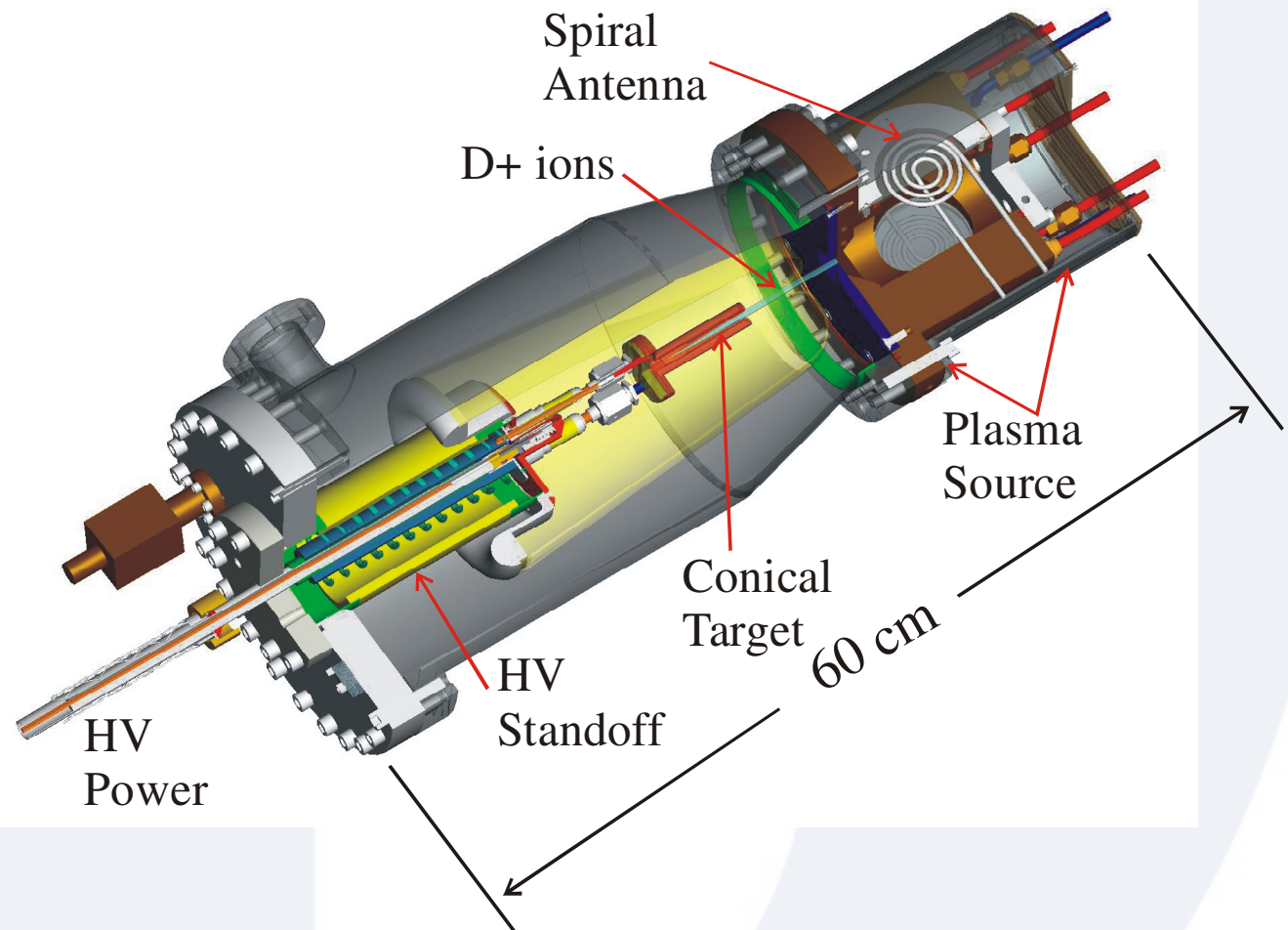
## Axial Generator DD-108: Installed

- Ancillary equipment: RF matching, pumps, meters, D2 supply, cooling



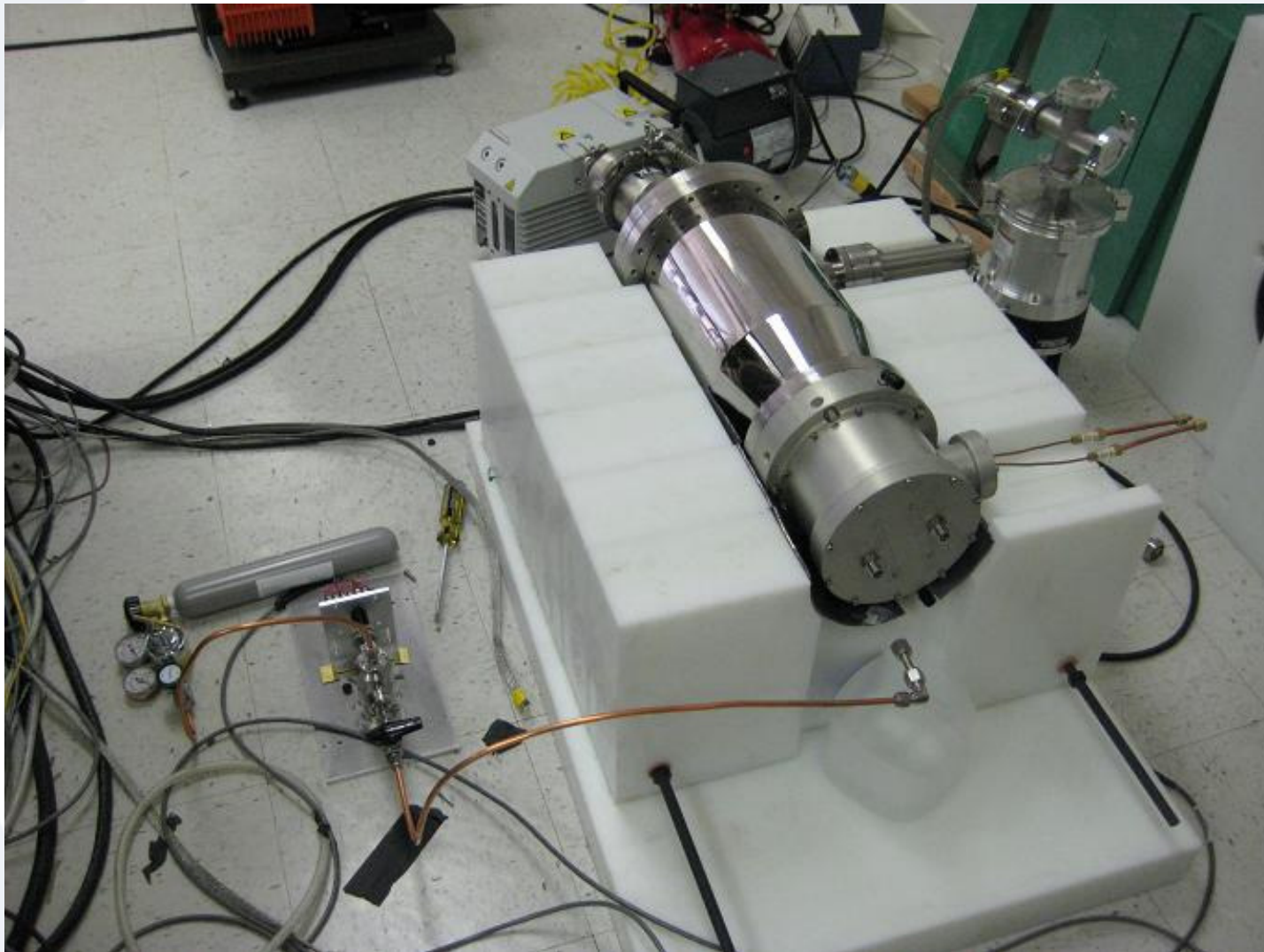
## ***Axial Generator – DD-109***

- Small apparent spot size
  - high brightness fast neutron source
- Yield  $10^9$  n/sec



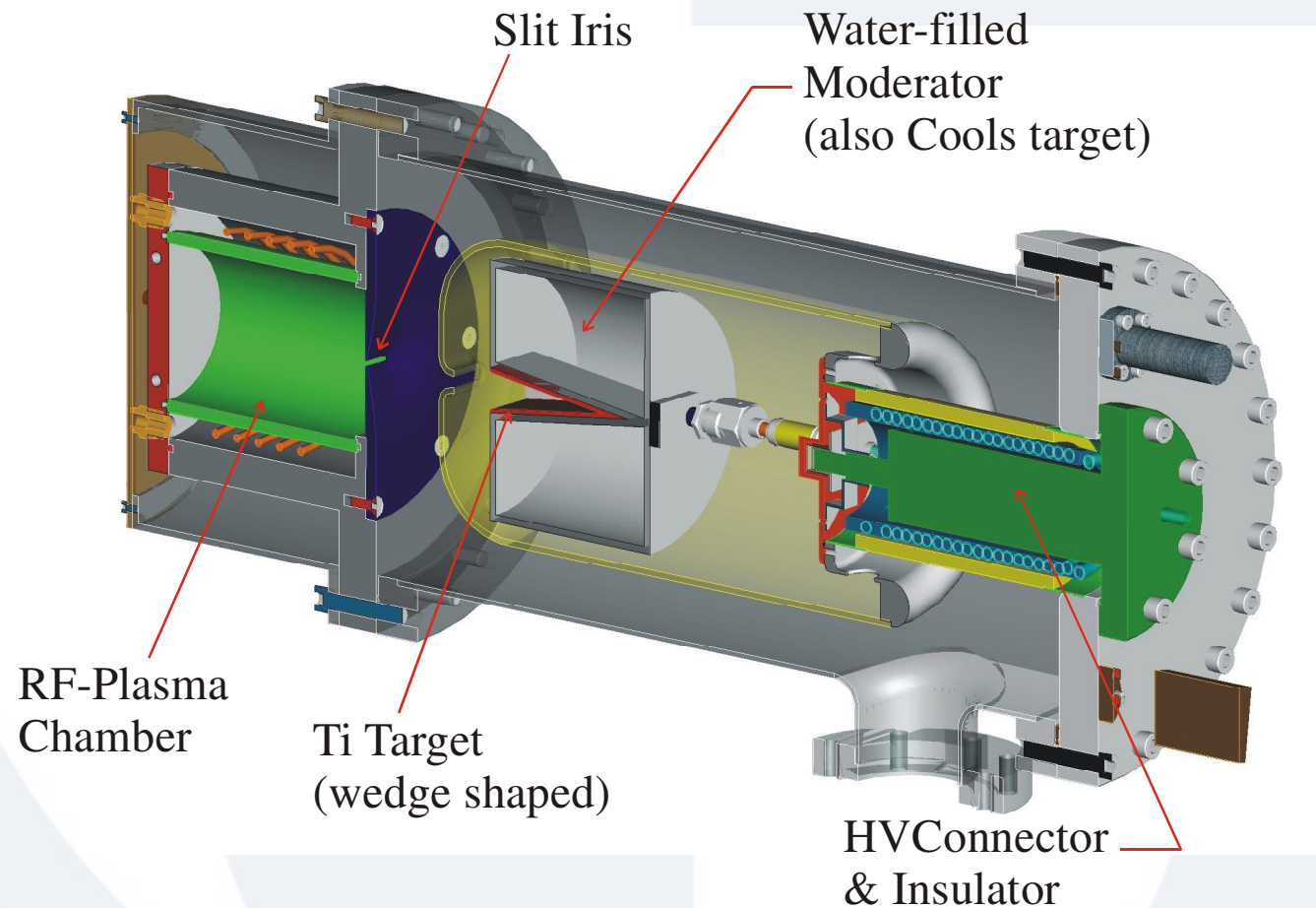


## ***DD-109 Neutron Generator***



## ***Axial Generator DD-110***

- Cooling and moderator function integrated



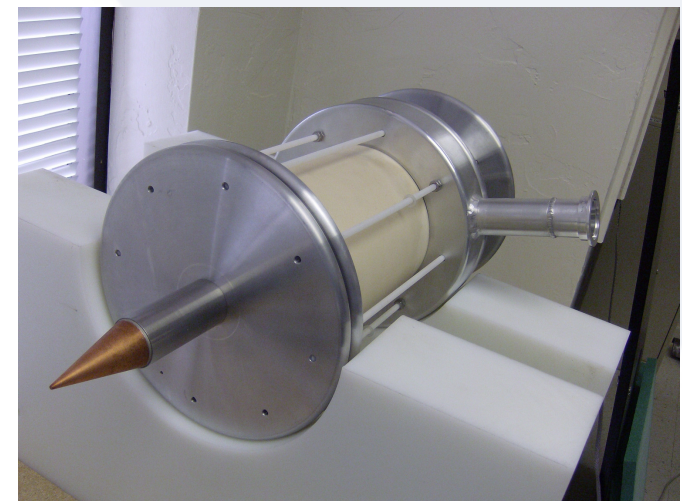
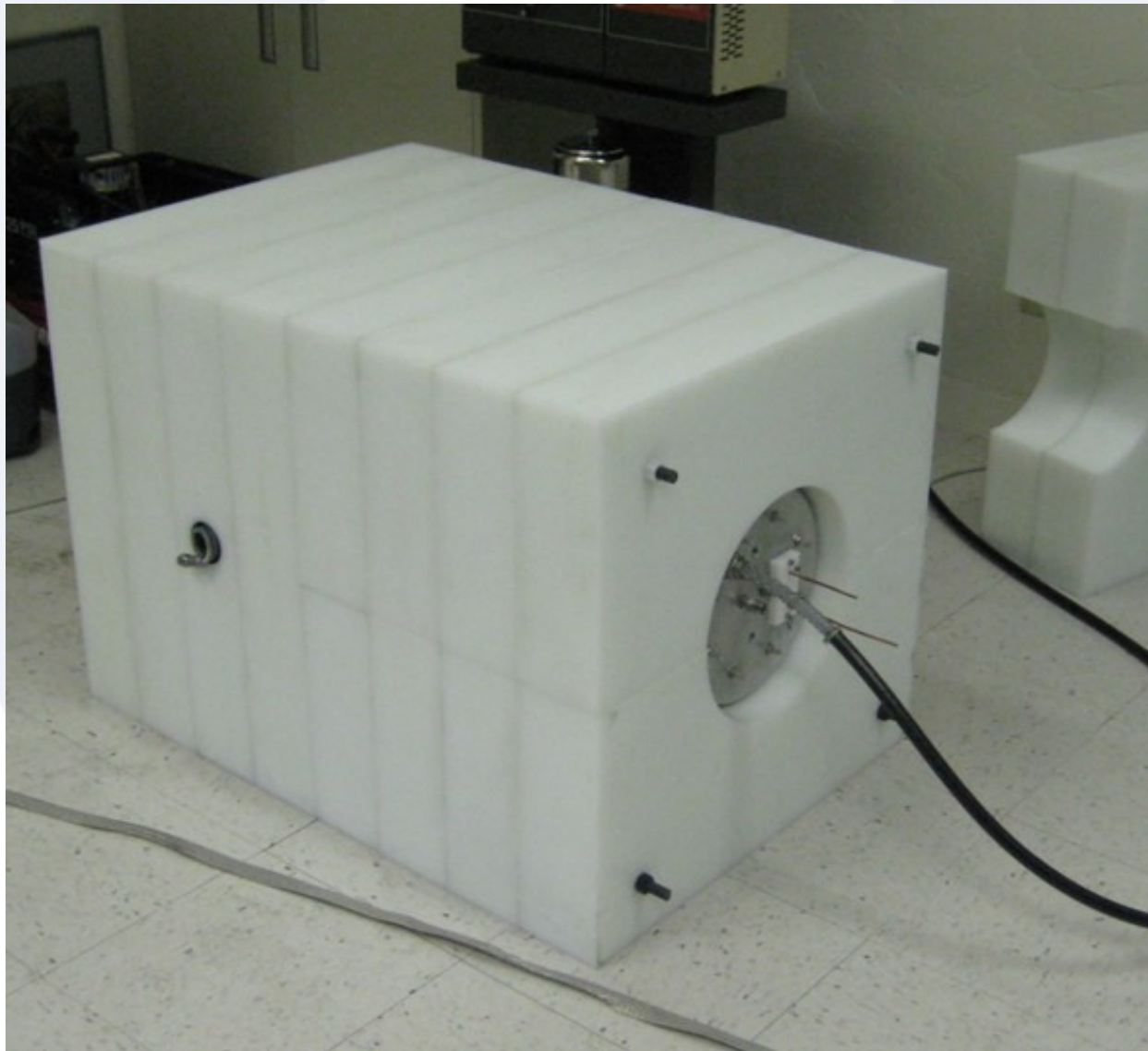
## ***DD-110 Neutron Generator***



## ***Integrated Thermal Neutron Sources***

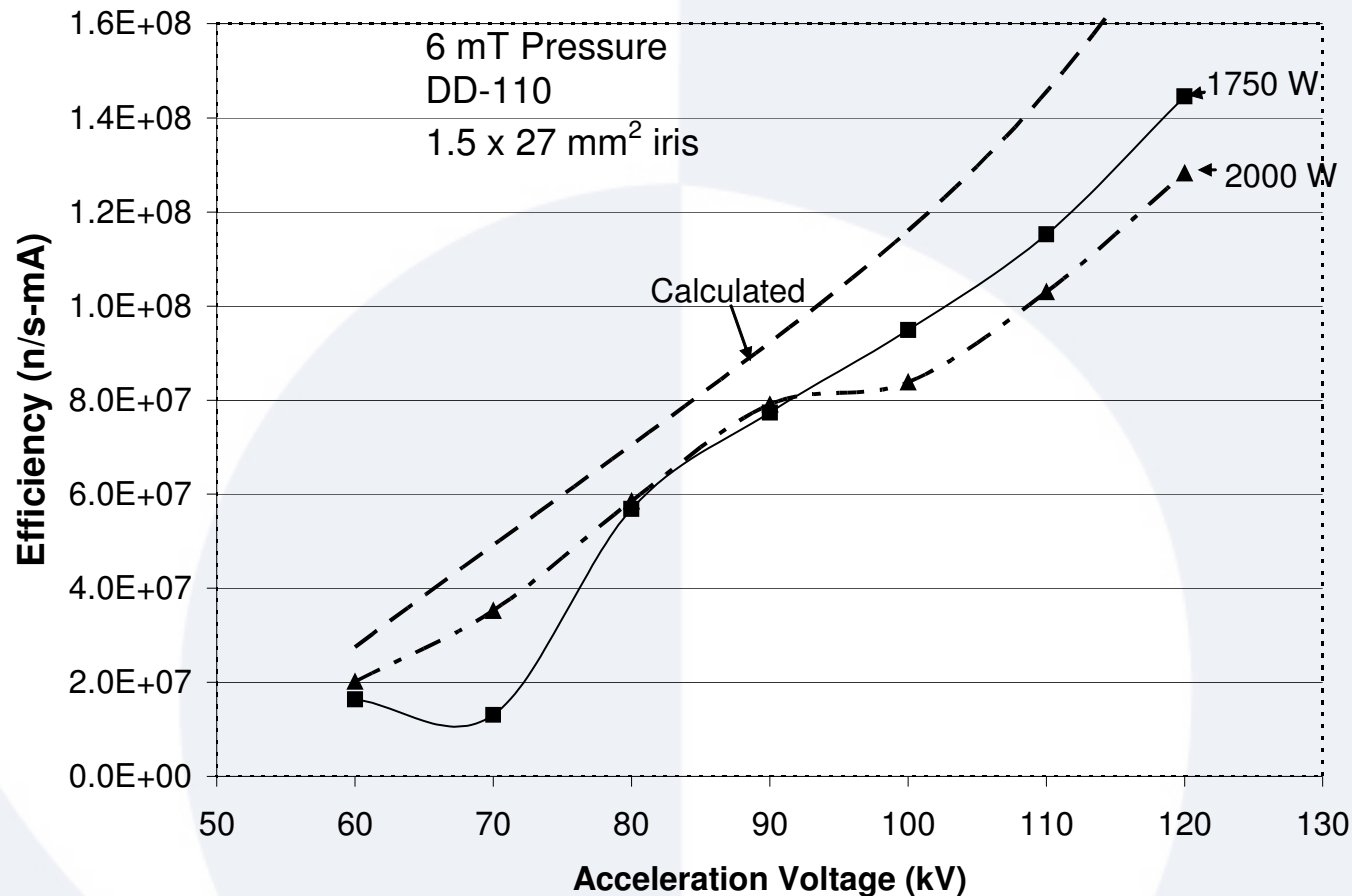
- We want maximum thermal neutron flux for PGAA and NAA
- F. A. Sanchez Analysis 2006 (Sect. 7, IAEA report)
  - Minimized distance to moderator
  - Minimizes moderator material used
- Adelphi Solution
  - Use axial fast neutron source
  - Integrate fast neutron source to moderator
    - Use moderator as part of generator structure

# ***“Thermal” Generator DD-108T***



## Neutron Yield Efficiency

- The efficiency of neutron production per mA of beam current as a function of accelerator voltage for two RF plasma powers.



## *Research Applications*

- Neutron Radiography
- SNM Detection
  - Delayed Neutron Response
    - Timed Neutron (Differential Die-Away Technique)
    - Neutron Spectroscopy
  - Delayed Gamma Ray Response
    - Timed Gammas
    - Gamma Spectroscopy
- Explosive Detection
  - Associated Particle and other 2-D Imaging
  - Gamma Ray Compton Camera
  - Fast Neutron Transmission Spectroscopy
  - Fast Neutron Scattering



## ***Industrial Research - Spectroscopy***

- Trace-Element Prompt Gamma Neutron Activation Analysis (PGNAA):
  - Deep penetration radiation performs bulk analysis
    - no sample prep. required
  - Elements capture neutrons and re-emit unique  $\gamma$ -ray signature
  - Deconvolution of  $\gamma$ -ray spectrum to obtain elemental composition
  - Neutrons emitted by an electric neutron generator
    - Safe
    - On-off switchable (non radioactive);
- Platform technology:
  - Can measure the content of any sample in any state
- Applications in clean mining (tailings), oil sands and Clean Tech (clean soil).





# Long-Life, High-Yield D-D Neutron Generator

## Periodic Table of Elements for PGAA

<b>1 H</b> $1^1_1\text{H}$ 1.00784 2223-3 0.03350-0.31260 82.02 b		<b>2 He</b> $3^4_{2}\text{He}$ 4.002602 - 0.00070 1.94 b	
<b>3 Li</b> $6^7_3\text{Li}$ (7.59%) $7^7_3\text{Li}$ (92.41%) 6.941 2032-193 0.0381-0.70.50 1.37 b		<b>4 Be</b> $9^9_4\text{Be}$ 9.0122 6310-1600 0.00550-0.99990 7.63 b	
<b>11 Na</b> $23^{23}_{11}\text{Na}$ (100%) 22.98977 47-50 0.590-0.5300 3.29 b		<b>12 Mg</b> $24^{24}_{12}\text{Mg}$ (78.9%) $25^{24}_{12}\text{Mg}$ (10.0%) $26^{24}_{12}\text{Mg}$ (11.1%) 24.305 585-600 0.0320-0.600 3.71 b	
<b>19 K</b> $39^{39}_{19}\text{K}$ (93.26%) $41^{39}_{19}\text{K}$ (6.73%) 39.0983 40.078 77-40 1.36-2.060 1.95 b		<b>20 Ca</b> $40^{40}_{20}\text{Ca}$ (96.94%) $42^{40}_{20}\text{Ca}$ (4.94%) $44^{40}_{20}\text{Ca}$ (0.12%) 40.078 1943-110 0.3520-0.4310 2.62 b	
<b>23 V</b> $51^{51}_{23}\text{V}$ (100%) 50.9415 1424-11 4.81/4.960 5.10 b		<b>24 Cr</b> $52^{52}_{24}\text{Cr}$ (73.73%) $53^{52}_{24}\text{Cr}$ (2.62%) $54^{52}_{24}\text{Cr}$ (2.08%) $56^{52}_{24}\text{Cr}$ (19.57%) 51.9961 51.9961 635-40 1.39-3.050 2.49 b	
<b>26 Fe</b> $56^{56}_{26}\text{Fe}$ (91.75%) $57^{56}_{26}\text{Fe}$ (2.12%) $58^{56}_{26}\text{Fe}$ (0.28%) $60^{56}_{26}\text{Fe}$ (0.05%) 55.845 55.845 7631-90 0.653-2.560 11.62 b		<b>27 Co</b> $59^{59}_{27}\text{Co}$ (100%) 58.9332 230-8 7.1937.180 5.6 b	
<b>28 Ni</b> $58^{58}_{28}\text{Ni}$ (68.077%) $60^{58}_{28}\text{Ni}$ (26.223%) $62^{58}_{28}\text{Ni}$ (5.7%) 58.6934 58.6934 6990-40 1.49/4.390 0.993-3.900 9.02 b		<b>29 Cu</b> $63^{63}_{29}\text{Cu}$ (69.15%) $65^{63}_{29}\text{Cu}$ (30.85%) 63.546 63.546 276-70 0.2951-3.00 4.10 b	
<b>30 Zn</b> $64^{64}_{30}\text{Zn}$ (48.6%) $66^{64}_{30}\text{Zn}$ (27.7%) $67^{64}_{30}\text{Zn}$ (4.1%) $68^{64}_{30}\text{Zn}$ (18.6%) 65.39 65.39 1077-190 1.65-2.750 6.93 b		<b>31 Ga</b> $69^{69}_{31}\text{Ga}$ (100%) 69.723 69.723 634-40 1.55-2.750 6.93 b	
<b>32 Ge</b> $70^{70}_{32}\text{Ge}$ (24.2%) $72^{70}_{32}\text{Ge}$ (75.8%) 72.64 72.64 594-70 1.12-30 8.60 b		<b>33 As</b> $75^{75}_{33}\text{As}$ (100%) 74.9216 74.9216 59-40 2.0-4.50 5.50 b	
<b>34 Se</b> $76^{76}_{34}\text{Se}$ (62.6%) $77^{76}_{34}\text{Se}$ (33.4%) $78^{76}_{34}\text{Se}$ (3.9%) 76.247 76.247 614-40 2.14/12.00 9.30 b		<b>35 Br</b> $79^{79}_{35}\text{Br}$ (50.69%) $81^{79}_{35}\text{Br}$ (49.31%) 79.904 79.904 245-100 0.950-3.900 5.90 b	
<b>37 Rb</b> $85^{85}_{37}\text{Rb}$ (72.1%) $87^{85}_{37}\text{Rb}$ (27.9%) 85.4678 85.4678 567-900 0.091-0.360 6.9 b		<b>38 Sr</b> $86^{86}_{38}\text{Sr}$ (70.48%) $87^{86}_{38}\text{Sr}$ (27.83%) $88^{86}_{38}\text{Sr}$ (1.69%) 87.62 87.62 638-90 1.02/1.30 6.25 b	
<b>39 Y</b> $89^{89}_{39}\text{Y}$ (100%) 88.90585 88.90585 6060-120 0.76/1.260 7.70 b		<b>40 Zr</b> $90^{90}_{40}\text{Zr}$ (51.45%) $91^{90}_{40}\text{Zr}$ (48.55%) 91.224 91.224 934-700 0.1250-1.850 6.46 b	
<b>41 Nb</b> $93^{93}_{41}\text{Nb}$ (100%) 92.90638 92.90638 778-50 2.02-2.480 5.71 b		<b>42 Mo</b> $96^{96}_{42}\text{Mo}$ (95.94%) $98^{96}_{42}\text{Mo}$ (3.75%) $100^{96}_{42}\text{Mo}$ (0.31%) 95.94 95.94 181-5 1.92-2.480 5.71 b	
<b>43 Tc</b> $98^{98}_{43}\text{Tc}$ (100%) 98.90625 98.90625 181-5 1.92-2.480 5.71 b		<b>44 Ru</b> $101^{101}_{44}\text{Ru}$ (100%) 101.07 101.07 540-70 1.53-2.750 6.6 b	
<b>45 Rh</b> $103^{103}_{45}\text{Rh}$ (100%) 102.9055 102.9055 192-21 22.6/1450 4.6 b		<b>46 Pd</b> $106^{106}_{46}\text{Pd}$ (100%) 105.9264 105.9264 181-5 4.0-6.90 4.49 b	
<b>47 Ag</b> $107^{107}_{47}\text{Ag}$ (100%) 107.8682 107.8682 199-09 6.17/10.30 11.71 b		<b>48 Cd</b> $112^{112}_{48}\text{Cd}$ (24.03%) $114^{112}_{48}\text{Cd}$ (52.72%) $116^{112}_{48}\text{Cd}$ (12.76%) $118^{112}_{48}\text{Cd}$ (8.49%) 112.411 112.411 558-06 1.960-2.520 6.5 b	
<b>49 In</b> $113^{113}_{49}\text{In}$ (4.29%) $115^{113}_{49}\text{In}$ (95.71%) 114.818 114.818 273-3 1.31-2720 2.62 b		<b>50 Sn</b> $116^{116}_{50}\text{Sn}$ (24.22%) $117^{116}_{50}\text{Sn}$ (75.78%) 118.710 118.710 1294-900 0.134-0.540 4.992 b	
<b>51 Sb</b> $121^{121}_{51}\text{Sb}$ (63.6%) $123^{121}_{51}\text{Sb}$ (36.4%) 121.757 121.757 564-50 2.7-5.130 9.90 b		<b>52 Te</b> $127^{127}_{52}\text{Te}$ (5.4%) $128^{127}_{52}\text{Te}$ (18.6%) $129^{127}_{52}\text{Te}$ (30.9%) $130^{127}_{52}\text{Te}$ (54.9%) 127.6 127.6 603-50 2.5/4.70 4.32 b	
<b>53 I</b> $127^{127}_{53}\text{I}$ (100%) 126.90447 126.90447 126-90 1.42-6.20 9.81 b		<b>54 Xe</b> $129^{129}_{54}\text{Xe}$ (26.4%) $131^{129}_{54}\text{Xe}$ (73.6%) 131.29 131.29 868-20 6.7/240 -	
<b>55 Cs</b> $133^{133}_{55}\text{Cs}$ (100%) 132.90545 132.90545 17-60 2.47/30.30 2.90 b		<b>56 Ba</b> $135^{135}_{56}\text{Ba}$ (6.73%) $137^{135}_{56}\text{Ba}$ (73.21%) $138^{135}_{56}\text{Ba}$ (19.96%) $140^{135}_{56}\text{Ba}$ (0.10%) 137.327 137.327 627-500 0.209-1.10 3.99 b	
<b>57 La</b> $139^{139}_{57}\text{La}$ (100%) 138.90471 138.90471 270-70 2.6-20.60 6.01 b		<b>72 Hf</b> $178^{178}_{72}\text{Hf}$ (100%) 178.49 178.49 212-06 29.3/1190 10.2 b	
<b>73 Ta</b> $182^{182}_{73}\text{Ta}$ (100%) 180.94788 180.94788 146-190 3.28/18.40 4.60 b		<b>74 W</b> $184^{184}_{74}\text{W}$ (100%) 183.84 183.84 208-40 8.91-5 b 11.5 b	
<b>75 Re</b> $186^{186}_{75}\text{Re}$ (100%) 185.08557 185.08557 187-90 2.09/16.0 14.7 b		<b>76 Os</b> $190^{190}_{76}\text{Os}$ (100%) 189.224 189.224 187-90 10.9/425 14 b	
<b>77 Ir</b> $193^{193}_{77}\text{Ir}$ (100%) 192.222 192.222 352-18 10.9/425 14 b		<b>78 Pt</b> $195^{195}_{78}\text{Pt}$ (100%) 194.98686 194.98686 358-30 94.94-650 7.75 b	
<b>79 Au</b> $197^{197}_{79}\text{Au}$ (100%) 196.96655 196.96655 412-2.1 200.69 268-09 251/3840 26.6 b		<b>80 Hg</b> $200^{200}_{80}\text{Hg}$ (23.47%) $201^{200}_{80}\text{Hg}$ (22.82%) $202^{200}_{80}\text{Hg}$ (29.87%) $203^{200}_{80}\text{Hg}$ (6.84%) $204^{200}_{80}\text{Hg}$ (6.99%) 200.59 200.59 348-600 0.4-3.440 9.89 b	
<b>81 Tl</b> $205^{205}_{81}\text{Tl}$ (70.6%) $207^{205}_{81}\text{Tl}$ (29.4%) 204.3863 204.3863 348-600 0.4-3.440 9.89 b		<b>82 Pb</b> $206^{206}_{82}\text{Pb}$ (24.1%) $207^{206}_{82}\text{Pb}$ (22.3%) $208^{206}_{82}\text{Pb}$ (53.6%) 207.2 207.2 738-1900 0.1970-1540 9.156 b	
<b>83 Bi</b> $209^{209}_{83}\text{Bi}$ (100%) 208.98038 208.98038 417.1-1200 0.01719-0.0330 9.156 b		<b>84 (Po)</b> (209) - - - -	
<b>85 (At)</b> (210) - - - -		<b>86 (Rn)</b> (222) - - - -	
<b>87 (Fr)</b> (223) - - - -		<b>88 (Ra)</b> (226) 12.8 b 13 b	
<b>57 La</b> $138^{138}_{57}\text{La}$ (0.055%) $139^{138}_{57}\text{La}$ (99.945%) 138.9055 138.9055 1596-200 5.84/0.600 9.66 b		<b>58 Ce</b> $136^{136}_{58}\text{Ce}$ (0.185%) $138^{136}_{58}\text{Ce}$ (72.04%) $140^{136}_{58}\text{Ce}$ (27.775%) 140.115 140.115 662-600 0.24-0.630 2.94 b	
<b>59 Pr</b> $141^{141}_{59}\text{Pr}$ (100%) 140.90765 140.90765 177-100 1.05/11.50 2.65 b		<b>60 Nd</b> $142^{142}_{60}\text{Nd}$ (27.2%) $143^{142}_{60}\text{Nd}$ (12.5%) $144^{142}_{60}\text{Nd}$ (80.3%) 140.90765 140.90765 144.24 696-4 93.3500 16.60	
<b>61 (Pm)</b> $147^{147}_{61}\text{Pm}$ (100%) (146.9145) (146.9145) (144.9127) (144.9127) 168.4 b 21.2 b		<b>62 Sm</b> $150^{150}_{62}\text{Sm}$ (100%) 150.36 150.36 334-03 4790/56220 39 b	
<b>63 Eu</b> $151^{151}_{63}\text{Eu}$ (47.8%) $153^{151}_{63}\text{Eu}$ (52.2%) 151.965 151.965 90-0.1 1430/45800 9.2 b		<b>64 Gd</b> $157^{157}_{64}\text{Gd}$ (24.8%) $158^{157}_{64}\text{Gd}$ (75.2%) 157.25 157.25 162-0.22 7210/487700 160 b	
<b>65 Tb</b> $159^{159}_{65}\text{Tb}$ (100%) 158.92534 158.92534 178-23.40 1.78-23.40 6.84 b		<b>66 Dy</b> $163^{163}_{66}\text{Dy}$ (24.89%) $164^{163}_{66}\text{Dy}$ (75.11%) 162.5 162.5 164-1.1 146/9940 90.2 b	
<b>67 Ho</b> $165^{165}_{67}\text{Ho}$ (100%) 164.93032 164.93032 167-11 164-20 56/1570 9.7 b		<b>68 Er</b> $162^{162}_{68}\text{Er}$ (26.75%) $164^{162}_{68}\text{Er}$ (68.48%) $166^{162}_{68}\text{Er}$ (4.77%) 167.26 167.26 204-20 8.72/1000 6.99 b	
<b>69 Tm</b> $169^{169}_{69}\text{Tm}$ (100%) 168.93421 168.93421 169-19 2.94 b		<b>70 Yb</b> $174^{174}_{70}\text{Yb}$ (32.7%) $176^{174}_{70}\text{Yb}$ (67.3%) 174.876 174.876 173-04 515-19 2.94 b	
<b>71 Lu</b> $175^{175}_{71}\text{Lu}$ (100%) 174.876 174.876 150-13 45.2/76.60 7.2 b		<b>89 (Ac)</b> (227) (227) 232.03770 13.26 b	
<b>90 Th</b> $232^{232}_{90}\text{Th}$ (100%) 232.03770 232.03770 4060-1300 1.39/7.570 9.91 b		<b>91 (Pa)</b> $231^{231}_{91}\text{Pa}$ (100%) 231.036 231.036 10.5 b	
<b>92 U</b> $238^{238}_{92}\text{U}$ (99.2742%) $235^{238}_{92}\text{U}$ (0.7258%) 238.02891 238.02891 4060-1300 1.39/7.570 9.91 b		<b>93 (Np)</b> $237^{237}_{93}\text{Np}$ (100%) (237) (237) 175.9 b 14.5 b	
<b>94 (Pu)</b> $239^{239}_{94}\text{Pu}$ (100%) (239) (239) 175.9 b 7.7 b		<b>95 (Am)</b> $241^{241}_{95}\text{Am}$ (100%) (241) (241) 175.9 b 7.7 b	
<b>96 (Cm)</b> $247^{247}_{96}\text{Cm}$ (100%) (247) (247) 175.9 b 7.7 b		<b>97 (Bk)</b> $247^{247}_{97}\text{Bk}$ (100%) (247) (247) 175.9 b 7.7 b	
<b>98 (Cf)</b> $251^{251}_{98}\text{Cf}$ (100%) (251) (251) 175.9 b 7.7 b		<b>99 (Es)</b> $252^{252}_{99}\text{Es}$ (100%) (252) (252) 175.9 b 7.7 b	
<b>100 (Fm)</b> $257^{257}_{100}\text{Fm}$ (100%) (257) (257) 175.9 b 7.7 b		<b>101 (Md)</b> $258^{258}_{101}\text{Md}$ (100%) (258) (258) 175.9 b 7.7 b	
<b>102 (No)</b> $259^{259}_{102}\text{No}$ (100%) (259) (259) 175.9 b 7.7 b		<b>103 (Lr)</b> $260^{260}_{103}\text{Lr}$ (100%) (260) (260) 175.9 b 7.7 b	

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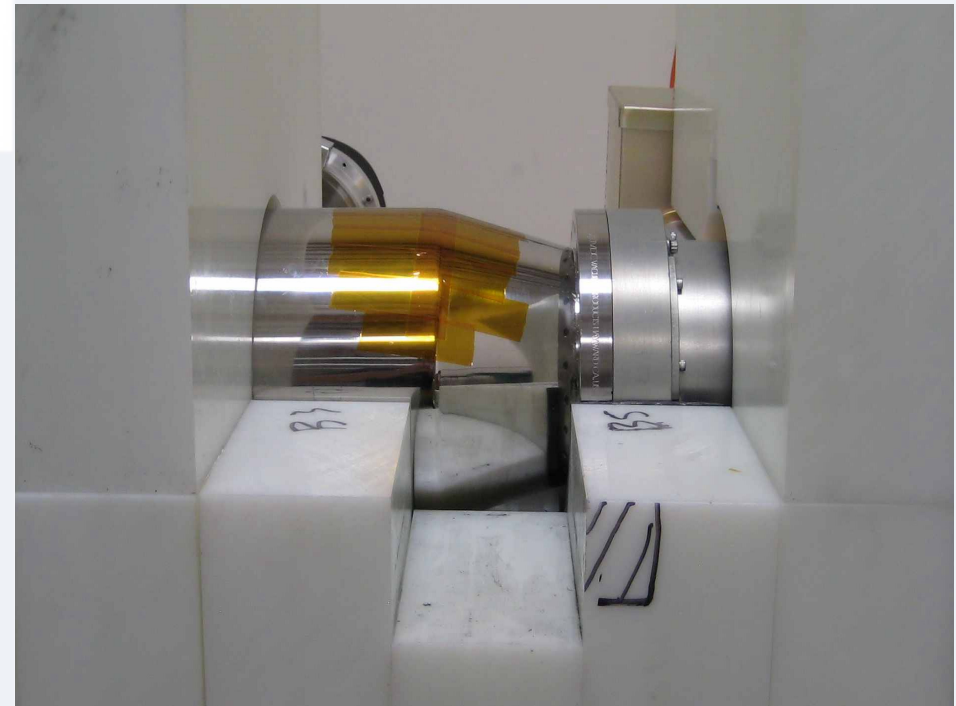
## ***Base Metal Mining Proposed Solution***

- Real-time results while mining enables
  - On-the-spot ore/waste determination
    - Huge penalty of processing waste instead of ore
      - up to ~\$3M loss per day (hauling, dilution, etc.)
      - Better smelter returns
    - Particularly relevant for deep underground or large open pit mines
  - Additional benefits
    - In-situ assessment of deleterious elements and environmental contaminants
    - Immediate mill to mine reconciliation/billing
- Optimization of advanced drilling campaigns
  - Optimize resource discovery with finite drill time
    - Very useful for delineation drilling
    - Particularly relevant in the case of “deposits open at depth”
    - Saves on drill commissioning/decommissioning costs (~\$100K+)



## ***D-D Neutron Generator & Moderator***

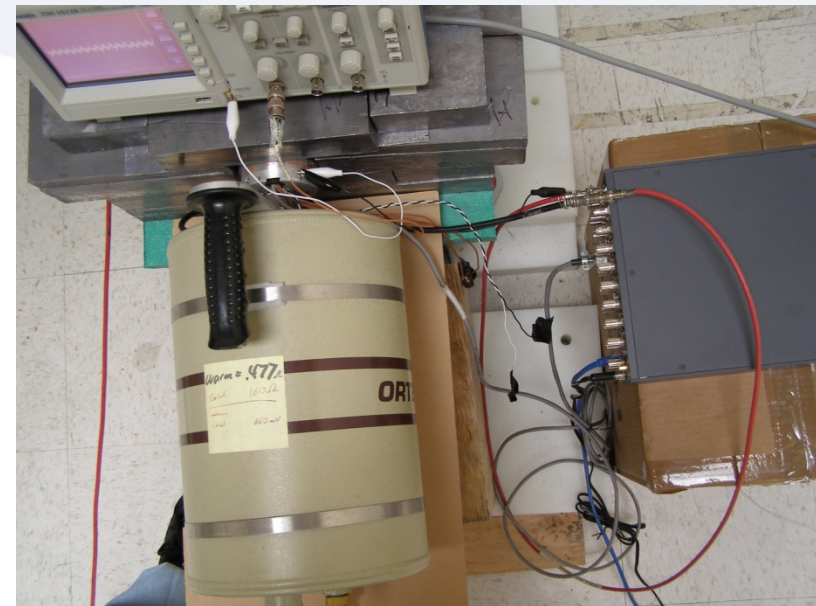
- Yields  $10^9$  n/s isotropic at 2.45 MeV (mono-energetic)
- Approximately  $10^5$  n·cm<sup>-2</sup>·s<sup>-1</sup> in the sample
- Provides the ability to throttle, stop or pulse neutron production on command
- Neutron moderator designed to minimize background noise



Neutron Generator encased in moderator

## ***Detector and Electronics***

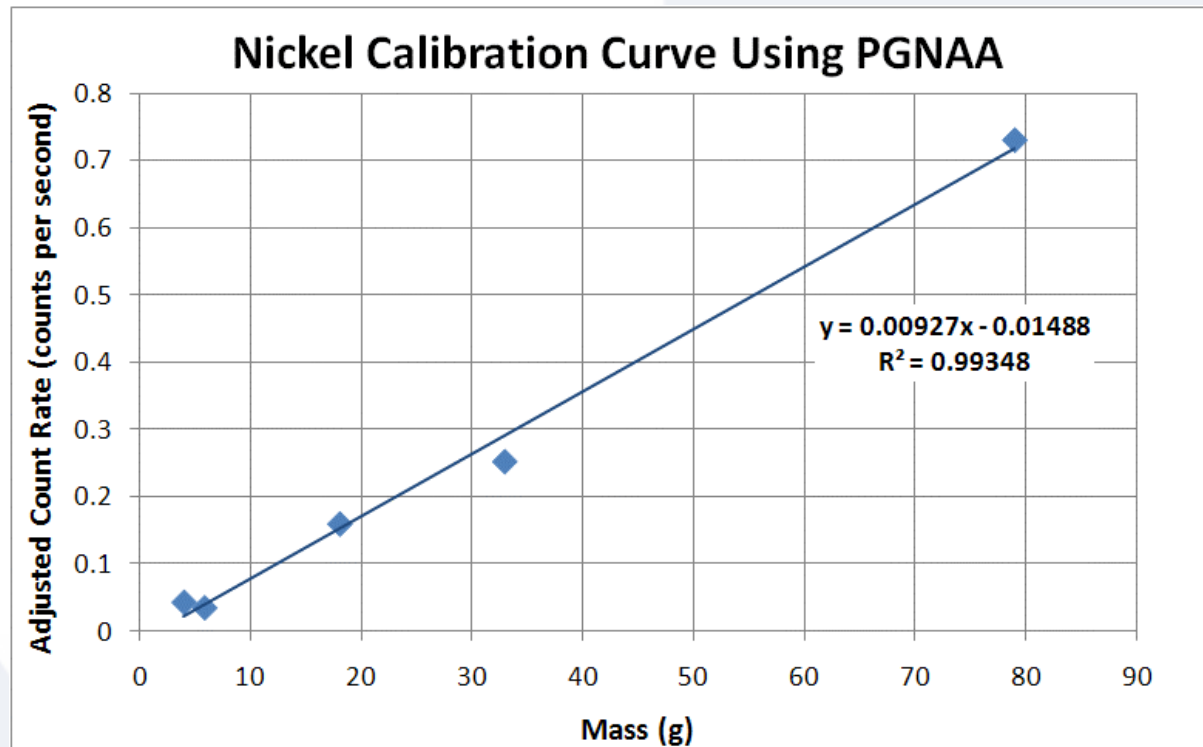
- Detector is coaxial HPGe (~100 cm<sup>3</sup> volume)
- Digital Multi-Channel Analyzer (MCA) for signal processing
- Post-Processing
  - Algorithms interpret the test spectrum into an elemental composition



Detector and electronics

## Prototype Performance – Calibration

- Pure elements are used to calibrate the instrument
- Detection limits for 1000 second measurements are established using the calibration measurements



## ***Prototype Performance – Test Samples***

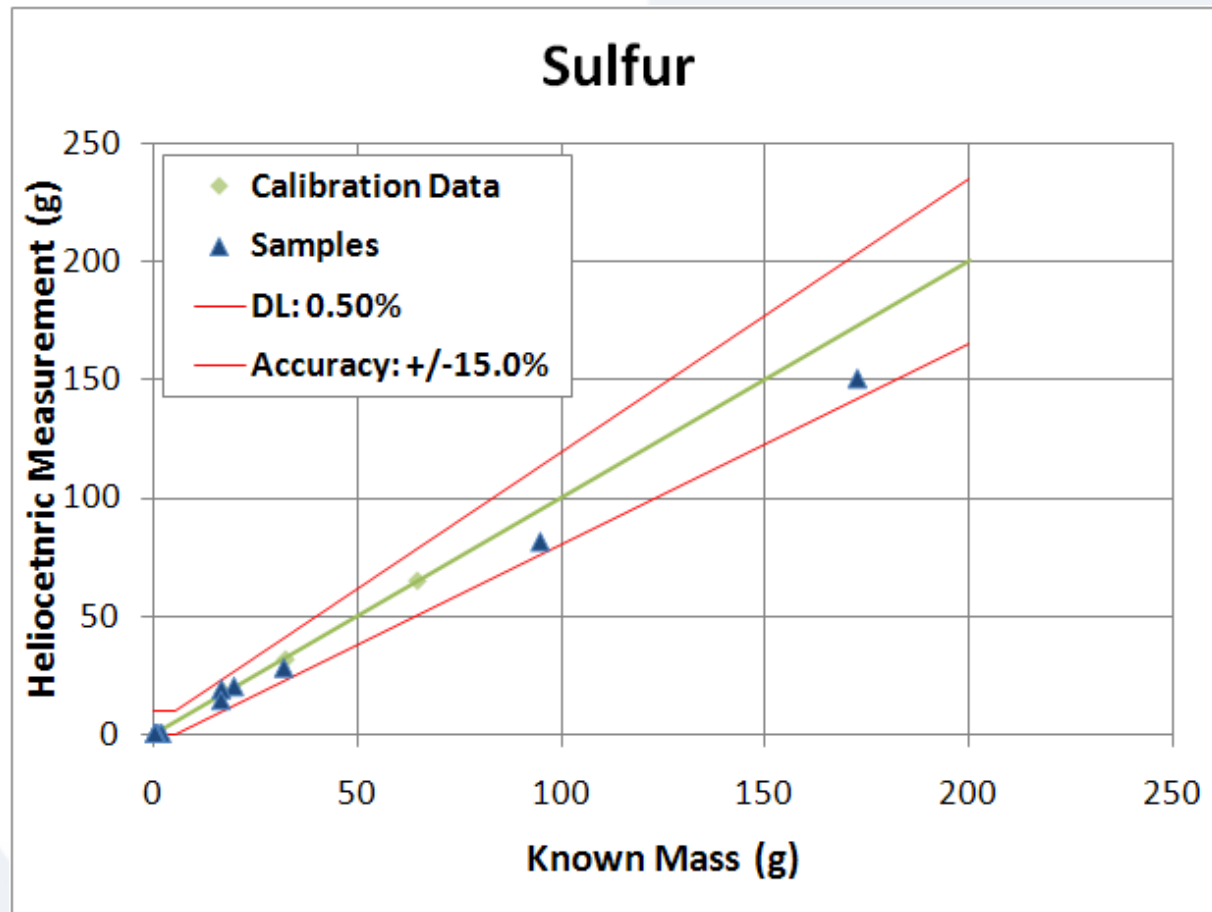
- Customers provide samples for measurement
- Samples previously measured by alternate methods
- PGNA measurements are compared customer measurements to assess the instrument's accuracy



Customer samples have a variety of physical properties

# Prototype Performance – Accuracy

- Graphs are generated for each element to assess the instrument's accuracy



## Results – Summary

Element		Detection Limit: prototype	Detection Limit: target for final instrument
Aluminum	Al	<b>0.2% (DGNA)</b>	0.02 % (DGNA)
Cobalt	Co	<b>0.5%</b>	0.05 %
Copper	Cu	<b>0.6%</b>	0.1 %
Chromium	Cr	<b>0.9%</b>	0.1%
Iron	Fe	<b>1.5%</b>	0.1%
Nickel	Ni	<b>0.5%</b>	0.05 %
Sulfur	S	<b>0.5%</b>	0.1 %
Zinc	Zn	<b>3%</b>	0.2 %
Integration time	t	<b>1,000 s</b>	300 s
Absolute accuracy	+/-	<b>15%</b>	5%



## Conclusions

- The Prototype Elemental Analyzer has achieved its target performance level
  - +/- 15% measurement accuracy
  - Detection limits of 0.5% to 1.5% for 1 kg samples
- Performance is consistent for a range of customer samples with varying physical properties
- Prototype performance scaling for the final instrument is on schedule.

