An Inexpensive Compact Neutron Generator for Gamma Calibration and other Applications

DOE STTR GRANT: DE-FG02-07ER86294: “Gamma Calibration Source”
STTR with LBNL

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Adelphi Makes Neutron Generators
(thanks to DOE STTR’s with LBNL and DNDO SBIR)

- DD reaction at high neutron yields
- Actively vacuum pumped (uses lecture bottle of Deuterium)
  - Serviceable and long lived
- Sealed versions (DD and DT)
  - Field portable and rugged

<table>
<thead>
<tr>
<th>Model Number</th>
<th>Fusion Reaction</th>
<th>Yield (n/sec)</th>
<th>Status</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>DD-108</td>
<td>DD (2.5 MeV)</td>
<td>$\sim 10^8$</td>
<td>4 fabricated</td>
<td>$98K</td>
</tr>
<tr>
<td>DD-109</td>
<td>DD</td>
<td>$2 \times 10^9$</td>
<td>2 sold</td>
<td>$158K</td>
</tr>
<tr>
<td>DD-110</td>
<td>DD</td>
<td>$8 \times 10^9$</td>
<td>1 sold</td>
<td>$316K</td>
</tr>
<tr>
<td>DT-111</td>
<td>DT</td>
<td>$10^{11}$ (expected)</td>
<td>1 sold KSU (2-3 months)</td>
<td>$280K</td>
</tr>
</tbody>
</table>
Plasma Ion Sources

- Plasma ion sources fabricated by Adelphi & LBNL
  - 13.45 MHz RF Plasma Ion sources
    - Helical and Spiral Antenna coupling
  - Electron Cyclotron Resonance (ECR) Plasma Ion Sources
    - Segmented Magnet: Large diameter, high current
    - Annular Permanent Magnets: small diameter
- Atomic Species (D+) good in all cases (>90%).
- Long Lived (unlike Penning Diode)
Axial Generator DD-108

- D-D neutron yield of $10^8$ n/sec
- 1-5 mA of beam current & 100 kV of acceleration voltage
Model DD-109 Generator with RF Plasma Ion Source

Measured Yield $10^8$ n/s
Model DD-109 Neutron Generator using ECR Source

Operating at 10 mA, 120 kV, $1.5 \times 10^9$ n/s
Gamma Calibrator

- **Need:**
  - No long-lived gamma-ray calibration sources with energies above 3.5 MeV

- **Idea:**
  - Produce high energy gamma lines using PGNAA and inexpensive neutron generator
  - Use inexpensive components from consumer electronics
Neutron Generator for Gamma Calibration

ORIGINAL DESIGN: Gamma Calibrator

- Neutron Generator enclosed in HDPE moderator with PVC gamma converter.
- Uses inexpensive “microwave oven” magnetron
- All supporting components inside.

Design size: 12” x 18” x 22”
Compact ECR Source

- Meas. Atomic Species ($D^+$): 92%
- Measured ion current: 1-2 mA
- Uses inexpensive magnetron & COTS annular permanent magnets
Neutron Generator for Gamma Calibration

Neutron Generator using Compact ECR Ion Source

Prototype using DD-108 accelerator section: measure yield $7 \times 10^7$ n/s
Low Power Operation

- We want low Power operation = Field portable
- Measured: Magnetron Ave power: 117 W (2 ms, 167 pps, 33% duty factor)
Neutron Generator for Gamma Calibration

Calibration Lines from PVC (Chlorine)

<table>
<thead>
<tr>
<th>Energy [MeV]</th>
<th>Expected cts per second</th>
<th>Measured counts per second</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.864</td>
<td>0.33</td>
<td>0.60</td>
</tr>
<tr>
<td>3.062</td>
<td>0.19</td>
<td>0.26</td>
</tr>
<tr>
<td>4.980</td>
<td>0.11</td>
<td>not observed</td>
</tr>
<tr>
<td>5.715</td>
<td>0.14</td>
<td>1.09</td>
</tr>
<tr>
<td>6.111</td>
<td>0.45</td>
<td>1.13</td>
</tr>
<tr>
<td>6.620</td>
<td>0.25</td>
<td>0.44</td>
</tr>
<tr>
<td>6.628</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7.414</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>7.790</td>
<td>0.12</td>
<td>0.15</td>
</tr>
<tr>
<td>8.579</td>
<td>0.034</td>
<td>0.031</td>
</tr>
</tbody>
</table>

Adelphi Technology, Inc.
Neutron Generator for Gamma Calibration

PGNAA Calibration Lines from Ni and Pb

Ni: 8998 keV
Gaussian Fit

Pb: 7368 keV
Background subtraction
Status of Gamma Calibrator

Completed:
- First compact ECR plasma ion source using inexpensive “microwave oven” magnetron & permanent magnets working.
- Prototype ECR-driven neutron generator working.
- PGNAA calibration spectra measured using DD generators.

Next:
- Fabricate compact acceleration section integrated with moderator & gamma transducer.
- Demonstrate gamma calibration
- Determine safety of device.
OTHER APPLICATIONS

- **Materials Analysis using PGNAA and NAA**
- Small Laboratory Materials Analyzer
  - What if you didn’t need a reactor?
- Mining and coal analyzer
  - Replace $^{252}$Cf
Laboratory Neutron Source

Model DD-110

- Easily and inexpensively moderated and shielded
- Easily serviced and long lived
- Do PGNAA and NAA with HPGe detector

Model DD-109

24”
Prototype Mining On-Site Analyzer (Heliocentric at Adelphi)

- Trace-Element Prompt Gamma Neutron Activation Analysis (PGNAA):
  - Deep penetration radiation performs bulk analysis
  - Deconvolve γ-ray spectrum to obtain elemental composition
- Applications in mining, oil sands and environmental clean up.
- Pure elements were used to calibrate
- Detection limits for 1000 sec measurements

![Nickel Calibration Curve Using PGNAA](image)

\[ y = 0.00927x - 0.01488 \]

\[ R^2 = 0.99348 \]
Prototype Performance – Test Samples

- Customers provide samples for measurement
- Samples previously measured by alternate methods
- PGNAA measurements were compared to customer measurements to assess the instrument’s accuracy

Customer samples have a variety of physical properties
Graphs are generated for each element to assess the instrument's accuracy.
### Other Elements – Summary (Heliocentric)

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

This R&D permits the following application:

- Replace $^{252}\text{Cf}$ with compact ECR-driven DD neutron generator
- Generator to fit existing coal analyzer
- Identification of previously undetected pollutants
  - Pulsing of generator should improve sensitivity by 10 X.
- Long lifetime and field serviceable
- Target Customers: Scantech Limited and Sabia Inc
Neutron Generator for Gamma Calibration

Summary

Gamma Calibrator

- Prototype Compact Neutron Generator Fabricated
  - Compact ECR source using inexpensive components
  - More than meets required neutron yield
- Demonstrated use as calibration source
- Need to produce Beta Prototype gamma source (6 months)

Materials Analysis

- Demonstrated use for PGNAA and DGAA for materials analysis
  - Mining (Heliocentric) and coal analysis applications
- Fast and Thermal Neutron Laboratory Source Available NOW
Fast Neutron Radiograph of California’s Finest, using DD-109