Intense Pulsed Neutron Generation to Detect Illicit Materials.

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Task:

Develop an intense pulsed neutron generator that is cost effective for implementing in the identification of illicit material and explosives.
Task circa 2006:

Develop a D-D/ D-T pulsed neutron generator based on the principle of the plasma immersion ion implantation (PI³) technique.

$\text{PI}^3\text{NG}$

Produce an intense burst of mono-energetic neutrons for use in neutron detection techniques, such as neutron back-scattering, radiography, as well as time-of-flight activation analysis.
**Mode of operation**

**RF plasma:** 18 MHz  2kW  
**D$_2$ gas pressure:** 1 – 10 mTorr

**Resonant pulse power supply**
Utilizing amorphous toroidal inductor cores for magnetic pulse compression

<table>
<thead>
<tr>
<th></th>
<th>Present</th>
<th>Future</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV</td>
<td>-20 - 40 kV</td>
<td>-100 kV</td>
</tr>
<tr>
<td>Pulse rise time</td>
<td>&lt;800 ns</td>
<td>~100 ns</td>
</tr>
<tr>
<td>Pulse width</td>
<td>up to 40 ms</td>
<td>up to 40 ms</td>
</tr>
<tr>
<td>Pulse rep. rate</td>
<td>up to 400 Hz</td>
<td>10 kHz</td>
</tr>
<tr>
<td>Av. Current</td>
<td>1A  25 mJ/ pulse</td>
<td>&gt;10A 4.5 J / pulse</td>
</tr>
</tbody>
</table>
D-D fusion

\[
\frac{dN}{dt} = n_0 \cdot I_{\text{ion}} \cdot \int \frac{s(E) \cdot dE}{(dE/dx)}
\]

Simplify:

\[
N = 2 \cdot E^{1/2} \cdot n_0 \cdot \sigma(E) \cdot I_{\text{ion}} \cdot \Delta r \cdot t / (45 \cdot e)
\]
\[ n_0 \sim 4 \cdot 10^{22} \text{ cm}^{-3} \]

\[ E \sim 20 \text{ keV} \]

\[ \Delta r \sim 10^{-5} \text{ cm} \]

\[ \sigma \sim 3.5 \cdot 10^{-28} \text{ cm}^2 \]

For 1 A and pulse width \( \sim 10 \mu\text{s} \)

We have 1740 fusions

Or 870 neutrons
Extending to 100 kV, 10 A, pulse width 40 µs at 10 kHz

\[ \Rightarrow 4.5 \times 10^{10} \text{ neutrons per second} \]

Resorting to the D-T reaction would result in at least 2 orders of magnitude increase in yield.

Important factor is the target material.

Pd ideal, but will outgas too rapidly if not kept cool
Task circa 2008:

Implement RFQ accelerator systems for the generation of quasi-monoenergetic neutrons between 4 and 8 MeV through the d(d,n)$^3$He reaction.

Use fast neutron resonance radiography technique to detect explosives.
Resonance features of fast neutron interaction cross-sections.
D-100 facility at P1900

Level-2: RF Transmitter

Level-1: RFQ Linac, Detector, Conveyor

Level-0: Electricals, chillers

Chillers
ADM RFQ linac

Injector electronics & gas supply

Ion Source

D<sup>2</sup>

25 keV

RFQ linac-1

D<sup>+</sup>

RF Amp-1

200 kW RF
425 MHz

RFQ linac-2

RF Amp-2

160 kW RF
425 MHz

HEBT magnetic field

Steered and focused high energy beam

To gas target

4 MeV

4 / 5 MeV

200 kW RF
425 MHz

25 keV

4 MeV

4 / 5 MeV
BEAM ENERGY

AMP 1

AMP 2

RFQ 1

RFQ 2

Relative rf Phase [Deg]

Deuteron Energy [MeV]

RFQ1 & RFQ2 in phase

Varying phase shift

360°

0.6% duty cycle

0.32% duty cycle

3.4 3.6 3.8 4.0 4.2 4.4 4.6 4.8 5.0 5.2

-200 -150 -100 -50 0 50 100 150 200 250

Relative rf Phase [Deg]
Gas target

Accelerator $10^{-6}$ mbar

Vacuum Pumps

Rotating seals with 3 slots

Differentially Pumped Chambers

Deuterium Gas

Gas Cell 3 bar

D$^+$ beam

6.5 x $10^{-4}$ mbar

5.1 x $10^{-3}$ mbar

6.3 mbar
Neutron yield for 3 cm, 3 bar D$_2$ gas target at 100 µA

Neutron flux ($10^4$ n.mm$^{-2}$)

Angle from beam axis (Deg.)

- En=8.2 MeV
- En=7.2 MeV
D-100 RFQ accelerator system

Main RFQ accelerator
- Accelerate ions to 4 MeV

Booster for extra 1 MeV ion acceleration

High Energy Beam Transport to focus and steer ions into gas target

3 cm 3 bar D₂ gas Target

35 keV D⁺ ion source

Spinning disc beam dump

Beam direction
Schematic layout of the D-100 RFQ accelerator facility at Necsa
Extracted proton beam at 180 kW in first cavity

Relative RF phase to booster (Deg.)

Proton energy (MeV)

Booster power (kW)

Energy gain (keV)

At 120°
<table>
<thead>
<tr>
<th>DESIGN</th>
<th>CURRENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 mA, 20% duty cycle</td>
<td>10 mA, 2.5% duty cycle</td>
</tr>
<tr>
<td>3 bar deuterium gas cell</td>
<td>1 bar</td>
</tr>
<tr>
<td>$10^{12}$ n.s$^{-1}$</td>
<td>$10^{10}$ n.s$^{-1}$</td>
</tr>
</tbody>
</table>
Operating specifications for the two accelerator systems.

<table>
<thead>
<tr>
<th>Features</th>
<th>D-100</th>
<th>ADM</th>
</tr>
</thead>
<tbody>
<tr>
<td>operating frequency (MHz)</td>
<td>200</td>
<td>425</td>
</tr>
<tr>
<td>injection energy (keV)</td>
<td>35.0</td>
<td>25.0</td>
</tr>
<tr>
<td>output energy (MeV)</td>
<td>3.7 - 5.1</td>
<td>3.6 - 4.9</td>
</tr>
<tr>
<td>injector output current (pulsed)(mA)</td>
<td>55</td>
<td>12</td>
</tr>
<tr>
<td>booster output current (pulsed)(mA)</td>
<td>50</td>
<td>8</td>
</tr>
<tr>
<td>maximum beam pulse width (ms)</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>repetition rate (Hz)</td>
<td>20-100</td>
<td>20-200</td>
</tr>
<tr>
<td>maximum RF duty factor</td>
<td>20 %</td>
<td>1.2 %</td>
</tr>
<tr>
<td>pulsed RF power requirement (kW)</td>
<td>1000/200</td>
<td>280/160</td>
</tr>
<tr>
<td>linac length (m)</td>
<td>4.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Neutron flux (n.s⁻¹)</td>
<td>$10^{12}$</td>
<td>$10^{10}$</td>
</tr>
</tbody>
</table>
Conventional radiography configuration - ADM

- Neutron beam
- Object or process
- Scintillator screen
- Mirror
- Light tight box
- CCD camera
- Power supply
- Control unit on PC
D-100 detection system

Detectors

Gas Target
Neutron efficiency: 70%
Light conversion: at least 1 photon / neutron
Image intensifier size: 150 mm
Drift scanning: Yes

> 31 km of fibres
289 fibres in 10mm x 10mm block

41 x 41 blocks
Amorphous Si array, pixel size 400 μm
D-100 dose at $10^{12}$
Fast Neutron Radiography for DWIK Detection

![Graph showing linear attenuation vs. neutron energy for Diamond and Kimberlite.](image)

- Neutrons
- Kimberlite run-of-mine
- Diamond Image
The future

- Operation of D-100 and ADM

  Demonstrating
  - intense neutron production
  - explosives detection sensitivity
  - illicit material detection sensitivity

PTB collaboration:
Implementation of short beam pulse system to enable TOF techniques
PROGRAMME THEMES & OUTLINE

The theme of the 9th World Conference for Neutron Radiography: “BIG 5 ON NEUTRON RADIOGRAPHY” is based on the 5 major animals which can be related to the 5 subthemes on neutron radiography which are:

- **LION** - Neutron Sources (New developments / Upgrades)
- **LEOPARD** - Neutron Beams (Fast / Thermal / Cold)
- **RHINO** - Neutron Detectors (New development / Advanced)
- **BUFFALO** - Neutron Methods (Phase Contrast / Dynamic / Micro / etc)
- **ELEPHANT** - Neutron Applications (All sciences / Technology / Engineering)

TECHNICAL PROGRAMME

1st - 2nd October 2010

- School of Radiation Imaging at ThembalABS – North (Johannesburg)

3rd October 2010

- Registration opens at Kwa Maritane
- Welcome Cocktail

4th October 2010

- Conference Opening
- Plenary Conference Sessions
  - Free Lecture and Telescopic view on Southern Skies

5th October 2010

- Plenary Conference Sessions
- Dinner hosted by WCNR in the Kwa Martane Boma

6th October 2010

- Plenary Conference Sessions
Thank You