Intense Pulsed Neutron Generation to Detect Illicit Materials.
Necsa, Pretoria, South Africa

Original CRP Project title:
Intense pulsed neutron generation based on the principle of the plasma immersion ion implantation technique to detect illicit materials
Objective:

To develop a compact, efficient, fast neutron source using a novel technique based on the principle of plasma immersion ion implantation.

PI$^3$NG

To apply this source for the detection of illicit material through radiographic techniques
**Principle of PI³**

a) Plasma created. No voltage applied to target

b) Negative voltage applied. Rapid repulsion of the electrons, thus forming a sheath

c) Ions move towards the cathode, thus depleting the sheath of charge.
Present System

RF: 18 MHz  2kW

Gas pressure: 1 – 10 mTorr

*Resonant pulse power supply*

Utilizing amorphous toroidal inductor cores

HV: -20 kV  -100 kV

Pulse rise time: <1 µs  ~100 ns

Pulse width: up to 40 µs

Pulse repetition rate: up to 300 Hz  10 kHz

Av. Current: 1A  >10A
Concept is to replenish the target zone with D through the inherent implantation process characteristic of PI³ AT 20kV

“Traditional” PI³ depth profiles for nitrogen into steel typically of the order of 1 – 2 µm,

”Traditional” ion beam implantation depths < 30 nm.

At the same time maintain a median temperature <30C
**D-D fusion**

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

Simplify:

\[
N = 2 \cdot E^{1/2} \cdot n_0 \cdot \sigma(E) \cdot I_{\text{ion}} \cdot \Delta r \cdot \tau / (45 \cdot e)
\]
\[ n_0 \sim 4 \times 10^{22} \text{ cm}^{-3} \]
\[ E \sim 20 \text{ keV} \]
\[ \Delta r \sim 10^{-5} \text{ cm} \]
\[ \sigma \sim 3.5 \times 10^{-28} \text{ cm}^2 \]

For pulse of 1 A and width \( \sim 10 \mu s \)
We have 1740 fusions
Or 870 neutrons

If pulse repetition rate is 1 kHz \( \rightarrow 8.7 \times 10^5 \) per second
Extending to 100 kV, 10 A, pulse width 40 \( \mu \)s at 10 kHz

\[ 4.45 \times 10^{10} \text{ neutrons per second} \]

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, likewise Ti

Ni is a possibility, but diffusion constant and D solubility lower
Advantages

PIII is independent of target shape

Elongated source could be constructed

Broad range of operation, e.g. low and high yield

Possible to select other reactions

Compact
Aspects to address in developing the system included:

Optimization of the pulsed power supply: neutron intensity and timing resolution.

Construction of reliable pulsed power supply:

100 kV, Pulse width $\sim 40 \mu s$, $f \sim >10$ kHz, $I \sim 10$ A
DWIK

Diamond Within Kimberlite
Utilize resonance features of fast neutron interaction cross-sections.
DWIK Detection Process

Neutrons

Kimberlite run-of-mine

$E_n$ high

Image 1

$E_n$ low

Image 2

Diamond Image

$E_n = 7 \text{ & } 8 \text{ MeV}$
Radiofrequency Quadrupole (RFQ) linac

Injector electronics & gas supply

D²

200 kW RF 425 MHz

D⁺

25 keV

0 keV

RF Amp-1

RFQ linac-1

4 MeV

160 kW RF 425 MHz

RFQ linac-2

4 / 5 MeV

HEBT magnetic field

Steered and focused high energy beam

To gas target
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ion species</td>
<td>D⁺</td>
</tr>
<tr>
<td>RF operating frequency</td>
<td>425 MHz</td>
</tr>
<tr>
<td>injection energy</td>
<td>25.0 keV</td>
</tr>
<tr>
<td>output energy</td>
<td>3.6 - 4.9 MeV</td>
</tr>
<tr>
<td>injector output current (pulsed)</td>
<td>12 mA</td>
</tr>
<tr>
<td>RFQ2 output current (pulsed)</td>
<td>6-8 mA</td>
</tr>
<tr>
<td>maximum beam pulse width</td>
<td>100 µs</td>
</tr>
<tr>
<td>repetition rate</td>
<td>20-200 Hz</td>
</tr>
<tr>
<td>maximum RF duty factor</td>
<td>1.2 %</td>
</tr>
<tr>
<td>pulsed RF power requirement (RFQ1/RFQ2)</td>
<td>280/160 kW</td>
</tr>
<tr>
<td>linac length</td>
<td>4.4 m</td>
</tr>
</tbody>
</table>
Accelerator facility

Real building at DebTech

DWIK Demonstration Facility - artist's impression

Radiation shield

Acceleration of deuteron ions

Neutron production
Gas target development

- D(d,n)$^3$He (3 bar)
- 7 MeV ± 500 keV (0 deg)
- $\sim 10^{10}$ n s$^{-1}$ (4π) (80 μA)
- beam purity < 10% n+γ
A complete turnkey RFQ dual linear accelerator (LINAC) system:

Delivering:

a) 100 Hz pulsed D beam, up to 80µA at 0.8% duty cycle.
b) Beam energy variable between 3.2 and 5 MeV with peak performance at 4 and 5 MeV (and H⁺, at half the energy).
A complete turnkey RFQ dual linear accelerator (LINAC) system:

Delivering:

a) 100 Hz pulsed D beam, up to 80µA at 0.8% duty cycle.
b) Beam energy variable between 3.2 and 5 MeV with peak performance at 4 and 5 MeV (and H+, at half the energy).
c) Gas target at 3 bar. Water-cooled 5mm W beam dump.
d) Up to $10^{10}$ neutrons/second, in a 30° forward cone.
e) Cooled CCD imaging detector system.
f) Control system for the RF power amplifiers (160 and 280 kW)
But want more throughput!

Up the beam current from 80µA to 50 mA

Up the duty cycle from 0.8% to 20%
<table>
<thead>
<tr>
<th><strong>New RFQ specifications</strong></th>
<th><strong>OLD</strong></th>
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<tbody>
<tr>
<td>ion species</td>
<td>D⁺</td>
</tr>
<tr>
<td>operating frequency</td>
<td>200 MHz</td>
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<tr>
<td>injection energy</td>
<td>35.0 keV</td>
</tr>
<tr>
<td>output energy</td>
<td>3.7 - 5.1 MeV</td>
</tr>
<tr>
<td>injector output current</td>
<td>55 mA</td>
</tr>
<tr>
<td>(pulsed)</td>
<td></td>
</tr>
<tr>
<td>booster output current</td>
<td>50 mA</td>
</tr>
<tr>
<td>(pulsed)</td>
<td></td>
</tr>
<tr>
<td>maximum beam pulse width</td>
<td>2 ms</td>
</tr>
<tr>
<td>repetition rate</td>
<td>20-100 Hz</td>
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<tr>
<td>maximum RF duty factor</td>
<td>20 %</td>
</tr>
<tr>
<td>pulsed RF power requirement</td>
<td>1000/200 kW</td>
</tr>
<tr>
<td>(RFQ/booster)</td>
<td></td>
</tr>
<tr>
<td>linac length</td>
<td>4.5 m</td>
</tr>
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Gas Target – Present target gas to ion beam

Ion Source
- Create 35 keV D$^+$ ions

Radio Frequency Quadrupole Linear Accelerator (RFQ LINAC) (Main accelerator)
- Accelerate ions to 4 MeV

Booster
- Additional 1 MeV ion acceleration

HEBT (High Energy Beam Transport)
- Focus and steer ions into Gas Target

Beam dump
- Dissipates ion beam

Gas Target
- Present target gas to ion beam
Schematic layout of the RFQ accelerator facility at Necsa
DWIK 100 Neutron Source: RF Transmitter System

- Trombone
- RF Power
- Coaxial Switch
- Dummy Load
- Transformer
- Power Supply
- Control Unit
- To RFQ Cavity

Main (RFQ) Amplifier
Booster Amplifier
RFQ Cavity
DWIK at NECSA

Level-2: RF Transmitter

Level-1: RFQ Linac, Detector, Sicon Conveyor

Level-0: Chillers, Electricals
Ion injector, 30 mA at 35 keV

1 MeV Spiral booster

Main RFQ cavity
4 MeV

electrodes

stems
Imaging Detector

Designed:
- DebTech, South Africa

Manufactured:
- Scintillator: Bicron, USA
- Image intensifiers, Photek, UK

Neutron efficiency: 70%
Light conversion: at least 1 photon / neutron
Image intensifier size: 150 mm
Drift scanning: Yes
<table>
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<th>DESIGN</th>
<th>CURRENT</th>
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<tr>
<td>50 mA, 20% duty cycle</td>
<td>10 mA and the duty cycle of 2.5%</td>
</tr>
<tr>
<td>3 bar deuterium gas cell</td>
<td>up to 1 bar</td>
</tr>
<tr>
<td>$10^{12} \text{ n.s}^{-1}$ at 7.2 MeV or 8.2 MeV</td>
<td>$10^{10}$ neutrons per second</td>
</tr>
</tbody>
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Radiation shielding that is adequate for a 2.5% duty cycle

Fully implemented multiple-computer control system (more than 20 computers and consoles) built on a Siemens PLC hardware and software platform
End of 2006 DebTech terminates DWIK project

There has been an investment of over $40m.

Present facility at Necsa would cost >$8m to replace.

A Necsa – iThembaLABS collaboration effort
Opportunities for R&D are vast and intended to be open to all

e.g.

Radio-isotopes: e.g. $^{195}$Pt  $^{117}$Sn

Scanning: contaminants, contraband, illicit material, PGMs

Fast neutron radiography/tomography: geosciences, cultural heritage

Accelerator science & technology
Some activities already investigated
at Necsa and iThembaLABS
FAST NEUTRON GENERATION
Gas target with plasma window

- A. Hershcovitch (BNL) - electron welding
- plasma T 10000-20000K, \( K_n << 1 \), ideal gas

\[
p = \rho \cdot R \cdot T \quad \text{low density (~40)}
\]
\[
\eta = a \cdot T^x \quad \text{high viscosity}
\]
\[
F = q \cdot V \cdot B \quad \text{Lorentz force focusing}
\]
Fig. 1. Schematic of the plasma window and a single cathode needle.
plasma window

target with plasma window at NECSA
Requests to use this facility are welcome

THANK YOU!