High-Power Proton Irradiation and Neutron Production with a Free Surface Liquid-Lithium Target


Workshop on Accelerator based Neutron Production
ABNP 2014
14-15 April 2014, INFN Laboratori Nazionali di Legnaro
Outline

• Soreq Applied Research Accelerator Facility (SARAF) overview

• Liquid Lithium Target (LiLiT)
  – research application and requirements (BNCT, nuclear astrophysics)
  – design features
  – lithium circulation and e-gun experiments

• LiLiT proton irradiation at SARAF accelerator

• Feasibility of Accelerator-based BNCT
SARAF Accelerator

Phase I
2010

RFQ
1.5 MeV/u

PSM
p: 4 MeV, d: 5 MeV

EIS
20 keV/u

Phase II
5 × SC Modules

40 MeV

Thermal neutron radiography

Thermal neutron diffraction

Nuclear Astrophysics

Radioactive beams

Radio Pharmaceuticals

Accelerator phase 2 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions</td>
<td>p / d</td>
</tr>
<tr>
<td>Energy</td>
<td>5 – 40 MeV</td>
</tr>
<tr>
<td>Current</td>
<td>0.04 – 5 mA</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Hands-On</td>
</tr>
</tbody>
</table>
SARAF phase-I linac – upstream view

A. Nagler, Linac 2006
K. Dunkel, PAC 2007
C. Piel, PAC 2007
C. Piel, EPAC 2008
A. Nagler, Linac 2008
J. Rodnizki, EPAC 2008
J. Rodnizki, HB 2008
I. Mardor, PAC 2009
I. Mardor, SRF 2009
L. Weissman, DIPAC 2009
L. Weissman, Linac 2010
J. Rodnizki, Linac 2010
D. Berkovits, Linac 2012
A. Perry, SRF 2009
L. Weissman, RuPAC 2012
SARAF Phase I – downstream

- SARAF Phase-I demonstrate:
  - 2 mA CW variable energy protons beam
  - Acceleration of ions through HWR SC cavities
  - 50% duty cycle 4.8 MeV deuterons
Liquid lithium target purpose

- SARAF phase I: creating unique high intensity neutron flux for advance research on:
  1. Nuclear medicine (BNCT)
  2. Stellar and big-bang nuclear astrophysics (nucleosynthesis)
  3. Cross section measurements (generation IV reactor and ADS design)
  4. Radioactive beams
Neutron producing lithium target

- $^7\text{Li}(p,n)^7\text{Be}$:
  - $E_{\text{thr}}(p) = 1.880$ MeV, $Q = -1.644$ MeV.
  - Produces keV-energy forward-collimated neutrons near threshold.

Neutron spectrum for BNCT

Optimal Energy for deep-seated tumor: 0.5 eV – 10 keV

Accelerator based BNCT with lithium target:
1. Produce most suitable neutrons for therapy
2. Small- in hospital
3. Good public acceptability
4. Relatively cheap

Neutron flux: Optimal \( \approx 10^9 \text{ s}^{-1} \text{ cm}^{-2} \) on beam port ** (for ~1 hour therapy)

SARAF lithium target \( >10^{10} \text{ s}^{-1} \text{ mA}^{-1} \)

LiLiT – High flux keV neutron source

• The research require high neutron flux ($>$10$^9$ n/cm$^2$/s)
  – $>$4 kW beam power (p, $\sim$2 mA, $\sim$2 MeV)
  – Narrow Gaussian beam ($\sigma=\sim$3 mm, D=$\sim$15 mm)

<table>
<thead>
<tr>
<th>Project</th>
<th>IFMIF *</th>
<th>SPIRAL II *</th>
<th>LiLiT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction specification</td>
<td>d(40 MeV) +Li</td>
<td>d(40 MeV) + C</td>
<td>p(2 MeV) +Li</td>
</tr>
<tr>
<td>Projectile range in target (mm)</td>
<td>19.1</td>
<td>4.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Maximum beam current (mA)</td>
<td>250</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Beam spot on the target (cm$^2$)</td>
<td>$\sim$100</td>
<td>$\sim$10</td>
<td>$\sim$1</td>
</tr>
<tr>
<td>Beam power (kW)</td>
<td>10000</td>
<td>200</td>
<td>4</td>
</tr>
<tr>
<td>Peak power density in the target (MW/cm$^3$)</td>
<td>0.3</td>
<td>0.15</td>
<td>$&gt;$1</td>
</tr>
</tbody>
</table>

• The target should dissipate power densities of more then $\sim$1 MW/cm$^3$

Lithium is attractive, but...

- Lithium melts at 180°C and have poor heat capacity
  - For $^7\text{Li}(p,n)$ neutron source intense enough for BNCT, deposition of high beam power (>10 kW, >0.5 MW/cm$^3$) is needed. Beam power will cause melting and distraction of lithium target.

- Radioactive $^7\text{Be}$ production through $^7\text{Li}(p,n)^7\text{Be}$

\[ p, 1 \text{ mA}, 1.91 \text{ MeV}, \sigma_r \approx 2.8 \text{ mm} \]
A high intensity epithermal neutron source based on a liquid lithium target

Soreq Applied Research Accelerator Facility (SARAF)
LiLiT- Liquid Lithium Target

Target vacuum chamber

- Beam Direction

- Lithium nozzle

- Lithium flow

- View port

- Diagnostic port

- Vapor trap

- Proton beam
Lithium Nozzle

Stainless Steel walls

Lithium flow

Proton beam

Lithium flow: 18 mm wide 1.5 mm thick

Curved thin back-wall

Proton beam

Nozzle "ears"

Emitted neutrons

1 cm
Thermal estimates

- Gaussian proton beam ($\sigma=2.8$ mm, $D=14$ mm)
- $P_{\text{beam}} = 4$ kW (1.91 MeV, 1 mA)
  - Bulk heating - $\Delta T=\sim 10^\circ C$
- $V_{Li}=4$ m/s
- Peak temperature elevation at the beam bombarding area:
  - Conservative saturation point: $350^\circ C$ (lithium boiling point at 10$^{-5}$ mbar)

![Graph showing thermal estimates]
Preliminary experiments

- Took place in a fire resistant laboratory:
  1. **Circulation tests:** Stable and full lithium film at velocity up to 7 m/s.
  2. **Electron gun tests:** 1.5 kW ($\sigma_r=\sim2.8$ mm) electron beam irradiations- dissipated power densities of more than 4 kW/cm$^2$ and volume power density $\sim2$ MW/cm$^3$ at a lithium flow of $\sim4$ m/s, with:
     - stable temperature
     - beam line vacuum conditions
     - no excessive evaporation.
100 mA, 26 keV (2.6 kW) electron gun at LiLiT
**Electron gun thermal deposition tests**

- E-gun tests: High intensity – 26 keV, ~60 mA
electron gun emulate the power deposition peak of SARAF 1.91 MeV proton beam- up to 3 mA.

1 mA, 1.91 MeV, (2=2V),protons in lithium (TRIM)

60 mA, 26 keV (~1.5 kW), \( \sigma = 2.8 \) mm electrons in lithium (CASINO)
Installation in SARAF accelerator

Nozzle chamber

Proton beam

Graphite fire extinguisher

Scrubber port

LiLiT enclosure
LiLiT and detectors setup in SARAF beam line

A. Gamma detectors - $^7\text{Li}(p,p')$ 478-keV prompt $\gamma$ emission.
B. Neutron detectors.

- The measured $\gamma$ exposure rate (in mR/h) was calibrated with charge current reading by a high-power Faraday cup.
First Liquid Lithium free surface proton irradiation

$p, 1.81 \text{ MeV}, \sim 1 \text{ mA}, \sigma_x = 3.9, \sigma_y = 3.4$

Lithium working velocity: 2.4 m/s

Movie
Under-threshold experiment-current and temperatures

- Stable nozzle temperatures at 1 mA proton current (1.8 kW).
- Peak power densities:
  - ~2.3 kW/cm² and
  - ~0.5 MW/cm³
Reservoir temperatures

- Minor changes in the reservoir maximum temperature.
- Oil-air heat-exchanger (vents) was not operating.
Above threshold experiments - Neutron detectors

Fission events from $^{235}\text{U} + \text{n}$

LaBr$_3$
Above-threshold experiment

$E_p = \sim 1.9 \text{ MeV}$

Total charge = $1.2 \text{ mA}\times\text{h}$

- Peak power densities:
  - $3 \text{ kW/cm}^2$
  - $\sim 0.6 \text{ MW/cm}^3$

$\sigma_x = 2.8 \text{ mm}$ and $\sigma_y = 3.8 \text{ mm}$
Neutron beam profile

Total neutron rate: $\sim 2 \times 10^{10}$ n/s/mA

$\sigma_x = 6$ mm  \hspace{1cm} $\sigma_y = 5.5$ mm

Autoradiography

$\sigma = 6 - 6.5$ mm
$^7$Be dose rate around LiLiT

![Diagram showing dose rates around a facility with labels for different dose rates at various heights from ground.](image)

- **First experiment**
- **Second experiment**

<table>
<thead>
<tr>
<th>Height from ground (cm)</th>
<th>Counts (a.u.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
</tr>
<tr>
<td>80</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td></td>
</tr>
<tr>
<td>50</td>
<td></td>
</tr>
<tr>
<td>40</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>200</td>
<td>800</td>
</tr>
<tr>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>600</td>
<td>400</td>
</tr>
<tr>
<td>800</td>
<td>200</td>
</tr>
<tr>
<td>1000</td>
<td>0</td>
</tr>
</tbody>
</table>

**Legend:**
- Heat exchanger
- Cold trap
- Lithium reservoir
MCNP simulation for BNCT doses - schematic illustration

- The BNCT dose components were calculated in water phantom after lead gamma shield and PE moderator.
- Dose analysis according to clinical trials protocols [1].
- $^{10}$B compounds: BPA.

BPA maximum allowed charge: 13 mA×h (4 cm deep)
Liposome compound\textsuperscript{[1]}: 15 mA×h (5 cm deep)

Conclusions: Therapeutic beams characterization

- 10-15 mA proton beams, for BNCT therapeutic doses, can be applied on a liquid lithium target with beam sigma's of 1-1.2 cm (according to the proved proton power density dissipation of 0.5 MW/cm$^3$), or 0.5-0.6 cm according to the proved power density desipation of electrons- 2 MW/cm$^3$.

SARAF experiments
Conclusions

- Accelerator-based BNCT is feasible with a liquid lithium target and 2 MeV, 10-15 mA proton accelerator.
- Such design will have the following advantages:
  - **Small**: low energy accelerator (medium size RFQ).
  - **Low activation**: proton energy < 2MeV, neutron energy < 200 keV.
  - **Low cost**: >5 M$
Thank you for your attention.