Research Programs and Plans at the Soreq Applied Research Accelerator Facility - SARAF

Israel Mardor, on behalf of the SARAF team
Soreq NRC, Yavne, Israel

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Adelaide, Australia, September 11th-16th, 2016

September 16th, 2016
Outline

- The SARAF linear accelerator
- The Liquid Lithium Target (LiLiT)
- Research programs at SARAF Phase I
- Research potential and plans for SARAF Phase II
# SARAF Accelerator Complex

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ion Species</td>
<td>Protons/Deuterons</td>
<td>M/q ≤ 2</td>
</tr>
<tr>
<td>Energy Range</td>
<td>5 – 40 MeV</td>
<td>Variable energy</td>
</tr>
<tr>
<td>Current Range</td>
<td>0.04 – 5 mA</td>
<td>CW (and pulsed)</td>
</tr>
<tr>
<td>Operation</td>
<td>6000 hours/year</td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>Maintenance</td>
<td>Hands-On</td>
<td>Very low beam loss</td>
</tr>
</tbody>
</table>

**Phase I - 2010**

- LEPT
- RFQ
- PSM
- MEPT

- EIS
- Energy: 20 keV/u
- L (m): 5

**Phase II - 2022**

- 5 × SC Modules
- Energy: p: 4 MeV
- d: 5.2 MeV
- L (m): 9
- Phase II - 2022

**Applications**

- Thermal n radiography
- n Diffraction
- Beam Dump
- Nuclear Astrophysics
- Nuclear Physics
- Nuclear Medicine and Therapy
SARAF
Phase II
2023
SARAF Phase I

A. Perry, SRF 2009  J. Rodnizki, Linac 2010  L. Weissman, WAO 2014
The Liquid Lithium Target - LiLiT

- Proton energy: \(~ 2 \text{ MeV}\)
- Maximum current: 3.5 mA
- Achieved power: \(~ 3 \text{ kW}\)
- Achieved power density:
  \[2.5 \text{ kW/cm}^2, 0.5 \text{ MW/cm}^3\]
- \(T_{\text{operation}} \approx 220^0\text{C}\)
- \(T_{\text{max}} \approx 350^0\text{C}\)
- Operating at SARAF since 10/2013

- Wall assisted lithium jet
- Jet size: 18 mm \(\times\) 1.5 mm
- Lithium operating velocity: 7 m/s (max design: 20 m/s)

S. Halfon et al., Review of Scientific Instruments 84 (2013) 123507
S. Halfon et al., Review of Scientific Instruments 85 (2014) 056105
Present SARAF Phase I Performance

Selected world leading achievements:

- Maximal total CW power: **5.7 kW (3.6 MeV, 1.6 mA)**
- Numerous irradiations of the Liquid Lithium Target (LiLiT) with **1.9 MeV, 1.2 mA CW** protons (~2.5 kW/cm², 0.5 MW/cm³ at beam center), generating 3-5×10¹⁰ n/sec, peaked at ~27 keV
- Generation of high energy neutrons via d-Li
- **3.6 MeV** protons at **0.3 mA CW** were kept on a **30 μm SS316** foil, cooled by liquid NaK, for **tens of hours**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Protons</th>
<th>Deuterons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (MeV)</td>
<td>4.0</td>
<td>5.6</td>
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<tr>
<td>Current (mA)</td>
<td>2.0</td>
<td>0.4</td>
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<td>Duty Cycle (%)</td>
<td>100 (CW)</td>
<td>10</td>
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</table>
## Research Programs at SARAF Phase I

<table>
<thead>
<tr>
<th>Subject</th>
<th>P.I.</th>
<th>Institute</th>
<th># of students</th>
</tr>
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<tbody>
<tr>
<td>Inter stellar nucleosynthesis</td>
<td>M. Paul</td>
<td>Hebrew University</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>A. Shor</td>
<td>Soreq NRC</td>
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<tr>
<td></td>
<td>M. Hass</td>
<td>Weizmann Institute</td>
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<tr>
<td></td>
<td>G. Ron</td>
<td>Hebrew University</td>
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<td></td>
<td>S. Vaintraub</td>
<td>Soreq NRC</td>
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<tr>
<td>Neutrons destruction of $^7$Be to Solve the Primordial $^7$Li Problem</td>
<td>M. Gai</td>
<td>U. Conn and Yale</td>
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<tr>
<td></td>
<td>D. Schumann</td>
<td>PSI</td>
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<tr>
<td></td>
<td>T. Stora</td>
<td>ISOLDE-CERN</td>
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<td></td>
<td>L. Weissman</td>
<td>Soreq NRC</td>
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<td></td>
<td>M. Paul</td>
<td>Hebrew University</td>
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<td></td>
<td>M. Hass</td>
<td>Weizmann Institute</td>
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<tr>
<td>Accelerator based BNCT</td>
<td>M. Paul</td>
<td>Hebrew University</td>
<td>1</td>
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<td></td>
<td>M. Srebnik</td>
<td>Hadasa HUJI</td>
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<td></td>
<td>D. Steinberg</td>
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<td>Generation IV reactors neutron cross section</td>
<td>A. Plompen</td>
<td>IRMM-JRC</td>
<td>1</td>
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<tr>
<td></td>
<td>F.-J. Hambsch</td>
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<td></td>
<td>A. Shor</td>
<td>Soreq NRC</td>
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<td>Deuterons cross section measurements</td>
<td>A. Kreisel</td>
<td>Soreq NRC</td>
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<tr>
<td></td>
<td>L. Weissman</td>
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<tr>
<td></td>
<td>J. Mrazek</td>
<td>NPI-Rez</td>
<td></td>
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</table>
Scientific Experiments at SARAF Phase I

Neutron spectra via 4.6 MeV d on a thick solid Li target, T. Y. Hirsh, PhD Dissertation (2012)

$^{63}$Cu(d,p)$^{64}$Cu cross-section measured at SARAF, L. Weissman et al., NIM B342, 7 (2015)

$\gamma$ (left) and n (right) spectra via 1.9 MeV protons on LiLiT

Comparison of MACS (30 keV) from the literature (black dots) and the work at LiLiT@SARAF (red squares) for $^{94}$Zr (top) and $^{96}$Zr (bottom)
From Phase I (present) to Phase II (next decade)

**Phase I**

*present* – in beam corridor
- μA – 2 mA, 2-4 MeV proton CW beams, 3-5 MeV deuteron pulsed beams
- $10^{10}$ n/s at 30 keV (forward, MACS)

**Phase I**

2017 – in Phase I target room
- μA – 2 mA, 2-4 MeV proton, 3-5 MeV deuteron CW beams
- $10^{12}$ n/s, peaked at 30 keV - 2 MeV (4π)
- $10^{12}$ n/s up to 20 MeV (with deuteron beams)

**Phase II**

2023 – in Phase II target hall
- μA – 5 mA, 5-40 MeV proton and deuteron CW beams
- $10^{15}$ n/s peaked at ~15 - 20 MeV, up to 50 MeV

*These specifications will make SARAF Phase II one of the world's most potent deuteron, proton and fast neutron sources*
Development of new radiopharmaceuticals

- Reachable only via irradiation by high power proton, deuteron and neutron beams
- Production of neutron-rich isotopes via (d, p) (equivalent to (n, γ))
- Typically, for A >~ 100 (d, 2n) cross sections are significantly larger than for (p, n)
- NSAC Isotopes Subcommittee recommended “~40 MeV, variable energy, multi-particle accelerators” for future isotope development and production in the US

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*A. Aprahamian & D. Geesaman, A Strategic Plan for the Isotope Development and Production for Research and Application Program, 2009*
Specialty and Competitiveness of SARAF Phase II (1)

Two-Stage Irradiation

40 MeV d-Li vs. 1400 MeV p-W, 0 deg forward spectra, 8 cm downstream the primary target

T. Stora et al., EPL 98, 32001 (2012)
Search for physics beyond the Standard Model

- ‘High Precision Frontier’ – direct & focus the ‘High Energy Frontier’
- Generate ultra-pure samples of exotic nuclei & measure in traps - EIBT ($^6$He) and MOT ($^{18,19,23}$Ne)
  - $^9$Be($n$, $\alpha$)$^6$He ($E_n > 0.8$ MeV)
  - $^{19}$F($p$, 2$n$)$^{18}$Ne ($E_p > 13$ MeV)
  - $^{19}$F($p$, n)$^{19}$Ne ($E_p > 4$ MeV)
  - $^{23}$Na($n$, p)$^{23}$Ne ($E_n > 3.7$ MeV)

The HUJI Magneto-Optic Trap (MOT) based Ne setup

The WIS Electrostatic Ion Beam Trap (EIBT) based He setup

N. Severijns et al., Rev. Mod. Phys. 78, 991 (2006)
S. Vaintraub et al. J. of Physics 267 (2011)
Exploration of light exotic nuclei

- Measure nuclear properties away from the valley of stability, extension of stable nuclei models
- Especially light exotic isotopes, where ab-initio calculations provide quantitative predictions
- It is advantageous to study a chain of isotopes, and compare to current and new nuclear models.
## Specialty and Competitiveness of SARAF Phase II (2)

<table>
<thead>
<tr>
<th>Project</th>
<th>IFMIF *</th>
<th>SPIRAL II *</th>
<th>SARAF II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction specification</td>
<td>d(40MeV) +Li</td>
<td>d(40MeV) + C</td>
<td>d(40MeV) +Li</td>
</tr>
<tr>
<td>Projectile range in target [mm]</td>
<td>19.1</td>
<td>4.3</td>
<td>19.1</td>
</tr>
<tr>
<td>Maximum beam current [mA]</td>
<td>2 x 125</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Beam spot on the target [cm²]</td>
<td>~100</td>
<td>~10</td>
<td>~1</td>
</tr>
<tr>
<td>Beam density on the target [mA/cm²]</td>
<td>2.5</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td>Neutron production over 4π [n/deuteron]</td>
<td>~0.07</td>
<td>~0.03</td>
<td>~0.07</td>
</tr>
<tr>
<td>Neutron source intensity [n/s]</td>
<td>~10^{17}</td>
<td>~10^{15}</td>
<td>~10^{15}</td>
</tr>
<tr>
<td>Maximal neutron flux on the back-plate [n/ (sec · cm²)] (0-60 MeV neutrons)</td>
<td>~10^{15}</td>
<td>~10^{14}</td>
<td>~5·10^{14}</td>
</tr>
<tr>
<td>&lt;E_n&gt; on the back-plate [MeV]</td>
<td>~10</td>
<td>~12</td>
<td>~10</td>
</tr>
</tbody>
</table>

Neutron based material research and cross sections

- ADS, waste transmutation, Generation IV fission reactors, fusion reactors
- An intermediate step towards IFMIF, for irradiation of miniature material samples

High Energy Neutron induced cross sections

- Very limited data above 14 MeV, at discrete points, inconsistent with models
- Necessary for background calculations for searches of ‘dark matter’ and other exotic particles


A. H. Couture PhD Dissertation (2011)
Neutron based therapy

- Accelerator based Boron Neutron Capture Therapy (BNCT)
- More efficient and practical than reactor based BNCT
- Enables the most suitable spectrum for therapy (peaked at 3 - 5 keV)
- For ~1 hour therapy, require a flux of $\sim 10^9 \text{n s}^{-1} \text{cm}^{-2}$

Accelerator based neutron imaging

- Thermal neutron imaging with medium energy deuteron accelerators
- Fast neutron imaging for contrast over broad densities and atomic numbers

14 MeV n MTF phantom image. DT Generator $5 \times 10^3 \text{n/cm}^2/\text{sec.}$
I. Sabo-Napadensky et al., JINST 7, C06005 (2012)
Nuclear Astrophysics – S-process and BBN

- High precision Stellar and Big Bang Nucleosynthesis cross sections
- Study long existing puzzles such as the Primordial $^7\text{Li}$ Problem, overabundant $^{107}\text{Pd}$, $^{26}\text{Al}$, etc.
- Maxwellian-Averaged Cross Sections (MACS) for kT at tens to hundreds of keV (up to the GK range)
- High neutron rate and variable proton and deuteron energy will enable measurements at various kT on rare and/or radioactive targets
- For more details on s-process nucleo-synthesis and chemical evolution at SARAF, see M. Tessler, M. Paul et. al., this conference (talk 287)

B. M. Oginni et al., PRC 83 025802 (2011)
Exploration of neutron-rich exotic isotopes

- Nuclear astrophysics – r-process
- Extension of nuclear models towards neutron-rich isotopes
- Generate a world competitive n-rich exotic isotopes source by high-energy (~7-8 MeV) neutron induced fission of $^{238}$U
- A thin $^{238}$U target is planned within a gas-extraction system
- Fission fragments will be separated, manipulated, identified and studies via dedicated instrumentation

L. Weissman & M. Paul, N-Rich RI Production at SARAF Phase II, October 2013, internal report

SARAF II Capabilities compared to FRIB

FRIB - Reaccelerated
SARAF II – Recaptured
Higher rates than FRIB

SARAF II – 2-Stage method
Higher rates than FRIB

B. Sherrill, Facility for Rare Isotope Beams, HRIBF Workshop (2009)
Summary and Outlook

- Soreq NRC is constructing SARAF as basic and applied research users facility in Yavne, Israel
- SARAF Phase I is completed and operational
- Groundbreaking results in high current SC ion acceleration and high power irradiation targets
- Phase I research programs are ongoing, to be expanded with the construction of a Phase I target room at mid 2017
- SARAF II is mostly funded, to be completed at the first half of the next decade
- SARAF II will be a world competitive p, d & n source, with leading rates in the light exotic and fission fragment regions
- We look forward to letters of intent and proposals for research programs at SARAF for Phase I and Phase II