Operational Experience, Recent Experimental Achievements and Future Goals of the Soreq Applied Research Accelerator Facility SARAF

Dan Berkovits

November 9th 2012

@ ESS
Outline

- Introduction
  - The need
  - The accelerator requirements
- Phase-I components and operation
- Plans for Phase-II
- Examples of some Phase-I and II studies
SARAF – Soreq Applied Research Accelerator Facility

- To enlarge the experimental nuclear science infrastructure and promote research in Israel

- To develop and produce radioisotopes for bio-medical applications

- To modernize the source of neutrons at Soreq and extend neutron based research and applications
### 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 - 2009
- LEBT
- RFQ
- PSM
- EIS

**Energy:**
- 20 keV/u
- 1.5 MeV/u
- 4 MeV
- 5.2 MeV

**L (m):**
- 5
- 9
- 12

#### Phase II - 2019
- 5 x SC Modules
- 40 MeV

**Applications:**
- Thermal n radiography
- n Diffraction
- Beam Dump
- Nuclear Astrophysics
- Radioactive beams
- Radio Pharmaceuticals
Neutron production with low energy deuterons

\[ ^9\text{Be}(d, xn) \]
\[ E_d=40 \text{ MeV} \]

2x10^{15} fast n/s (per 40 MeV 5 mA d)

K. Lavie et al. INS 2004
Neutron yield from d and p beams

- In the range of tens of MeV projectiles, neutron yield from deuterons is higher than that of protons by a factor of 3-5

Production of radiopharmaceutical isotopes

- Today, most radiopharmaceutical isotopes are produced by protons
- Deuterons
  - Production of neutron-rich isotopes via the \( \text{(d,p)} \) reaction (equivalent to the \( \text{(n,\gamma)} \) reaction)
  - Typically, the \( \text{(d,2n)} \) cross section is significantly larger than the \( \text{(p,n)} \) reaction, for \( A > \sim 100 \)

<table>
<thead>
<tr>
<th>Target/Product</th>
<th>Protons</th>
<th>Deuterons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>energy range (MeV)</td>
<td>TTY MBq/mAh</td>
</tr>
<tr>
<td>(^{103}\text{Rh} / {^{103}\text{Pd}})</td>
<td>20 → 8</td>
<td>12</td>
</tr>
<tr>
<td>(^{186}\text{W} / {^{186}\text{Re}})</td>
<td>30 → 8</td>
<td>11</td>
</tr>
<tr>
<td>(^{111}\text{Cd} / {^{111}\text{In}})</td>
<td>30 → 8</td>
<td>95</td>
</tr>
<tr>
<td>(^{114}\text{Cd} / {^{114}\text{In}})</td>
<td>30 → 8</td>
<td>2.2</td>
</tr>
<tr>
<td>(^{\text{nat}}\text{Er} / {^{170}\text{Tm}})</td>
<td>30 → 9</td>
<td>0.065</td>
</tr>
<tr>
<td>(^{169}\text{Tm} / {^{169}\text{Yb}})</td>
<td>30 → 9</td>
<td>2.2</td>
</tr>
<tr>
<td>(^{192}\text{Os} / {^{192}\text{Ir}})</td>
<td>20 → 9</td>
<td>0.18</td>
</tr>
<tr>
<td>(^{100}\text{Mo} / {^{99}\text{Mo}})</td>
<td>40 → 8</td>
<td>14.3</td>
</tr>
<tr>
<td>(^{176}\text{Yb} / {^{177}\text{Lu}})</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

Hermanne Nucl. Data (2007)

I. Silverman et al. NIM B (2007)
Accelerator requirements

- **Low energy** – moderate accelerator cost
- **Deuterons** – be efficient in neutron production
  - enable neutron-rich isotope production
- **Protons** – common isotopes production
- **High intensity** – a n flux similar to the IRR1 TNR image plane
- **Variable energy** – be specific in isotopes production
- **CW** – avoid thermal stress in targets
- **Pulsed** – enable beam tuning with space charge (using slow pulses)
- **Low beam loss** – enable hands-on maintenance

→ superconducting RF linear accelerator
SARAF Accelerator (2003 design view)

Phase-I working

PSM – Prototype Superconducting Module
176 MHz HWR

M. Pekeler, SRF 2003 (HWR)
K. Dunkel, EPAC 2004 (linac)
M. Peiniger, LINAC 2004
A. Shor, LINAC 2004 (beam dynamics)
P. Fischer, PAC 2005 (RFQ)
M. Pekeler, PAC 2005 (LLRF)
M. Pekeler, SRF 2005 (HWR)
C. Piel, PAC 2005 (ECR)
C. Piel, PAC 2005 (HPA)

M. Pekeler, HPSL 2005 (beam dynamics)
M. Pekeler, HPSL 2005 (PSM)
P. Fischer, EPAC 2006 (RFQ)
M. Pekeler, LINAC 2006 (PSM)
C. Piel, EPAC 2006 (linac)
J. Rodnizki, LINAC 2006 (beam dynamics)
I. Mardor, LINAC 2006 (halo monitor)
I. Mardor, LINAC 2006 (FOP)
J. Rodnizki, HB 2006 (beam dynamics)

B. Bazak et al., linac 2010
SARAF Phase-I 176 MHz linac

4-rod, 250 kW, 4 m, 1.5 MeV/u

P. Fischer et al., EPAC06

M. Pekeler, LINAC 2006
HWR – Basic parameters

- $f = 176$ MHz & bandwidth $\sim 130$ Hz
- height $\sim 85$ cm high
- Optimized for
  - $\beta=0.09$ @ first 12 cavities (2 modules)
  - $\beta=0.15$ @ 32 cavities (4 modules)
- Bulk Nb single wall 3 mm (in SS vessel)
- $E_{\text{peak, max}} = 25$ MV/m & $E_{\text{peak}}/E_{\text{acc}} \sim 2.9$
- $Q_0 \sim 10^9$ @ 4.45 K
- Designed cryogenic Load $< 10$ W (@$E_{\text{max}}$)
- Measured response to pressure $= 57$ Hz/mbar
SARAF Phase II simulations with error analysis

Simulations shown in next slide:
• 4 mA deuterons at RFQ entrance.
• Last macro-particle=1 nA

<table>
<thead>
<tr>
<th>Component</th>
<th>Error Description</th>
<th>Static</th>
<th>Dyn.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quadrupole Magnets</td>
<td>Misalignment x,y,z [mm]</td>
<td>± 0.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rotation $\theta$ [mrad]</td>
<td>± 3</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>Magnetic field [%]</td>
<td>± 2</td>
<td>± 0.5</td>
</tr>
<tr>
<td>Solenoids</td>
<td>Misalignment x,y,z [mm]</td>
<td>± 0.2</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>Magnetic field [%]</td>
<td>± 2</td>
<td>± 0.5</td>
</tr>
<tr>
<td>HWR</td>
<td>Misalignment x,y,z [mm]</td>
<td>± 0.4</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>Rotation $\theta$ [mrad]</td>
<td>± 6</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>Field strength [%]</td>
<td>± 2</td>
<td>± 0.5</td>
</tr>
<tr>
<td></td>
<td>Phase [degree]</td>
<td>± 1</td>
<td>± 0.25</td>
</tr>
</tbody>
</table>

B. Bazak et al., Submitted for Publication
J. Rodnizki et al., HB2008

Errors are double than in: J. Rodnizki et al. LINAC 2006, M. Pekeler HPSL 2005
Errors are double than the fabrication and operation tolerances.
Deuteron beam envelope radius at SARAF SC Linac

Solenoids 19

Tail emphasis simulations

200 realizations

Standard: $\varepsilon_x = 0.2$ mm mrad

70 realizations

3.4 mA deuterons

32k/193k particles in core/tail

Last macro-particle = 1 nA

B. Bazak et al., Submitted for Publication

J. Rodnizki et al., HB2008

General Particle Tracer 2.80 2006,
Pulsar Physics S.B. van der Geer,
M.J. de Loos http://www.pulsar.nl/
**Beam loss criterion**

Halfon et al., 2009

---

* Beam loss criterion which will yield the specified dose rate along SARAF SC linac


2. R. A. Hardekopf, "Beam loss and activation at LANSCE and SNS", The 7th ICFA mini-workshop on high intensity high brightness hadron beams, Lake Como, Wisconsin, September 1999.


SARAF phase-I linac – upstream view

A. Nagler, Linac2006
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
A. Perry, SRF 2009

I. Mardor, SRF 2009
L. Weissman, DIPAC 2009
L. Weissman, Linac 2010
J. Rodnizki, Linac 2010
L. Weissman, RuPAC 2012
Beam lines downstream the linac

E. Reinfeld et al. ICALEPCS 2011
L. Weissman et al. RuPAC 2012
SARAF Phase-I linac status

Difficulties and challenges at high energy are caused by instabilities and space charge effects at the low energy front end.

A journey of a thousand miles begins with a single step (Laozi 604 bc - 531 bc)

- SARAF Phase-I is the first to demonstrate:
  - 1 mA CW variable energy protons beam
  - Acceleration of ions through HWR SC cavities
  - Acceleration of ions through a separated vacuum SC module
Linac is operated routinely with CW 1mA protons at ~4 MeV
Phase I commissioned to 50% duty cycle 4.8 MeV deuterons
The accelerator is used most of the time to:
  - Study high intensity beam tuning
  - Interface with high intensity targets
  - Develop of high intensity targets
Projectile in target power density

Energy loss rate (eV/A) vs. Target depth (μm)

- 3.9 MeV p in Fe
- 26 MeV d in Mo
- 600 MeV p in Pb

1 m
Production target
Heat removal and radiation damage tests

3.7 MeV 0.1 mA protons, 2.5 W/mm²

3.9 MeV 0.2 mA protons
15 W/mm²
2 mm thick SS
water cooled target

➔ The most important parameter for accelerator beam tuning are:
• meeting the designed beam heat flux in units of W/mm²
• Intensity ramping without moving beam center neither changing the beam shape

I. Silverman et al.
PATENT
The accelerator vacuum protection worked well during the tests.
Experience with the Tungsten Beam dump

The beam dump 50 micron Tungsten sheet fused to a water cooled cooper plate. Up to 10 MeV, no activation and low neutron radiation is expected.
Beam optics study

- LINAC and beam line tune is done with a pulsed beam
- Different beam diagnostics instruments require different pulsed beam parameters (duty cycle and beam intensity)
  During CW beam tuning intensity is ramped by a factor of \(~100\).
Beam intensity control using LEBT aperture

- A quartz viewer upstream of the target, enables efficient studies of the front end parameters’ influence on the beam profile near the target.
- In the example below, the effect of opening the LEBT aperture is shown:

  - LEBT aperture is used to vary the beam intensity within an order magnitude.
  - The measurements show that to first order, the beam position on target is independent on the aperture opening.
Beam intensity control by LEBT solenoids

Varying the 1st LEBT solenoid enables increase of the beam intensity by another order of magnitude. The measurements show that the beam position on target is independent on the solenoid current.

On the other hand, the measurements show some shifts of the beam position and shape with change of: the 3rd solenoid current, by using the LEBT steerers and the LEBT dipole.
Insight into RFQ beam loss

RFQ measured beam transmission 75-85% for 1 mA
60-65% for 4 mA

In accordance to simulations by B. Bazak
2008
Some technical issues
We are studying techniques to improve coupler cooling
Couplers heating during 3.9 MeV p beam operation

- HWR1: 230 kV, beam on 0-0.1 mA, beam off
- HWR2: 460 kV, beam on 0.1-0.2 mA
- HWR3: 460 kV
- HWR4: 720 kV
- HWR5: 830 kV

Vacuum pressure:
- Beam on
- Beam off
- RF on
- RF off

12 h duration.
Deterioration of piezo range

Piezo range (Hz) vs Months

- HWR6
- HWR5
- HWR4
- HWR3
- HWR2
- HWR1

Cavity BW

A. Perry et al., SRF 2009

Beam axis
176 MHz RF power amplifiers development

- Six 4 kW RF amplifiers are in routine operation
Basic 5.5 kW RF power amplifier

5.5 kW conceptual block diagram

Inside view of the 5.5 kW drawer

5.5 kW drawer power test

- RF frequency – [174 -178] MHz
- RF power - 5.5 kW CW (1dB)
- Power Gain – 24 dB (22 W @ 5.5 kW)
- Current consumption – 220 A (50VDC)
- Water cooling requirements – 25 l/min
- Size – 19”, 7U, 550 mm deep
- RF in connector – N-type
- RF output connector 7/8” EIA
- DC in 10 mm brass bolts
- Controls: FRD, RFL, Temp & Fault for each module
10 kW RF system

Conceptual electrical diagram

10 kW RF Power test

- Two RF 5.5 kW amplifier drawers are combined
- Can operate into infinite VSWR
- High Gain (only 35 W RF drive)
- 2 Power Supplies – 50 VDC, 220 A each
- Water cooling – 50 l/min
- Two 10 kW systems in one 48 U 25” RACK

Kaizer et al. LINAC12
SARAF Phase-II linac plans

- Demonstrate high intensity targets durability (2012)

- Demonstrate RFQ CW operation for deuterons
  - Keep existing RFQ
  - or
  - Build another RFQ

- Sign a contract with vendor(s) to design and build the linac up to 40 MeV

- Operation by 2019
ANL conceptual design (2012)

- The ion source and LEBT are in the original position
- New (RFQ) MEBT and superconducting linac
- 176 MHz $\beta=0.09$ and $\beta=0.16$ Half Wave Resonators
- Total superconducting linac = 19.47 m
- 7 low-$\beta$ HWR operating at 1 MV and 21 high-$\beta$ HWR operating at 2 MV
  - Beam dynamics study at [B. Mustapha et al. IPAC 2012, J. Rodnizki et al. LINAC12]
- Total (static and dynamic) power dissipation ~ 350 W @4K

P. Ostroumov et al. LINAC12
Work with AES

Design based on experience gained for the development of cavities for ATLAS
[Z. Conway et al. LINAC12]
[M. Kelly et al. LINAC12]
and for PXIE
[Z. Conway et al. LINAC12]
[P. Ostroumov IPAC 2012]

- \( \frac{df}{dP} \) is less than 2 Hz/mbar (and 3.5 Hz/mbar for the high \( \beta \))
- A “flat” area helps to reduce \( \frac{df}{dP} \)
- Slow Tuner @ 2000 lb \( \Delta f \approx 90 \) kHz
• Total heat loss to 4.2K = 1.59 W
• Transition to 79 mm (3-1/8 inch) coaxial line outside of the cryomodule
The superconducting modules

- 7 SC HWR + 7 SC solenoids
- Length 4.8 m
- Width 1.9 m
- Height 1.65 m

Z. Conway et al. LINAC12

Each SC solenoid unit includes X-Y steerers and a cold BPM

- 7 SC HWR + 4 SC solenoids
- Length 4.6 m
- Width 1.9 m
- Height 1.65 m
Interfaces with the existing building
Research and applications

Examples

- Nuclear astrophysics at phase-I
- Nuclear medicine at phase-I
- Radioactive beams for basic physics I+II
- Neutron radiography at phase-II
Liquid Lithium Target - LiLiT

- The basis for most of the R&D at SARAF
- Liquid target enables utilization of the SARAF high power beam

At SARAF Phase I:
\[ ^7\text{Li}(p,n)^7\text{Be} \quad E_{th} = 1.880 \text{ MeV} \]

At SARAF Phase II:
An upgrade of LiLiT will be used with a deuteron beam to produce faster neutrons and higher flux

D. Kijel, A. Arnshtam et al. 2008
LiLiT - Lithium installed and heated
Lithium jet circulating

Measured velocity 7 m/s
Maximum $e$ power density
2.0 MW/cm$^3$ @ 4 m/s

Simulation of stellar neutron spectrum for the study of nucleo-synthesis

Measurement of S process cross sections

<table>
<thead>
<tr>
<th>Mo</th>
<th>92</th>
<th>93</th>
<th>94</th>
<th>95</th>
<th>96</th>
<th>97</th>
<th>98</th>
<th>99</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb</td>
<td>p</td>
<td>p</td>
<td>s.r</td>
<td>s.r</td>
<td>s.r</td>
<td>s.r</td>
<td>s.r</td>
<td>s.r</td>
<td>s.r</td>
</tr>
<tr>
<td>Zr</td>
<td>90</td>
<td>91</td>
<td>92</td>
<td>93</td>
<td>94</td>
<td>95</td>
<td>96</td>
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<td>Y</td>
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<tr>
<td>Sr</td>
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<td>89</td>
<td>90</td>
<td>90</td>
<td>91</td>
<td>92</td>
<td>93</td>
<td>94</td>
<td>95</td>
</tr>
</tbody>
</table>

Principal shown at Karlsruhe at low current

- SARAF + LiLiT will enable study of rare processes with up to 3 mA (factor of 50 w.r.t Karlsruhe)
- N-capture of $^{90}$Sr is one of first reactions to be studied
- RF beam produces a broad spectrum, more similar to Maxwellian

$^7\text{Li}(p,n)^7\text{Be} \quad E_p = 1.912 \text{ MeV}$

W. Ratynski and F. Kaeppeler, PR C (1988), Karlsruhe, $\sim 50 \mu\text{A}$

G. Feinberg et al., PRC 2012
Boron Neutron Capture Therapy (BNCT)

1. Selectively deliver $^{10}$B to the tumor cells

2. Irradiate the target region with neutrons

3. The short range of the $^{10}$B($n,\alpha$)$^{7}$Li reaction product, 5-8 $\mu$m in tissue, restrict the dose to the boron loaded area

M. Paul (HUJI)

Accelerator-based BNCT

1. Produces the most suitable neutron spectrum for therapy
2. Accelerator free of residual activity
3. Small – can be installed in hospital
4. Good public acceptability
5. Relatively low cost

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

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

- Neutrons spectrum from lithium target bombarded with 1.91 MeV proton
  O.E. Kononov et. al., Atomic energy, 94 (2003) 6

S. Halfon et al. ICNCT 2008
S. Halfon et. al., Appl Radiat Isot. 2009
S. Halfon et al. INS26 2012
I. Silverman et al. CARRI 2012
S. Halfon et al. ICNCT 2012
Two-stage irradiation

Yield calculated for a 40 MeV, 1 mA deuteron beam and for a ~ 800 cm$^3$ cylindrical porous secondary target.

For $^6$He, see ISOLDE Experiment, Stora et al., EPL, 98, 32001 (2012)
Spallation vs. stripping neutron spectra

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

T. Stora et al. EPL (2012)
Spellation vs. stripping neutron spectra

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

\[ R = 5\, \text{cm} \quad L = 5\, \text{cm} \]
$^6\text{He}$ β-decay in electrostatic trap

\[
dW \propto \xi \left( 1 + a \frac{p_e}{E_e} \cos \theta \right)
\]

\[
dW_{SM} (^6\text{He}) \propto \left( 1 - \frac{1}{3} \frac{p_e}{E_e} \cos \theta \right)
\]

New physics beyond the Standard Model’s V-A structure

S. Vaintraub et al. J. of Physics 267 (2011)
LiFTiT@SARAF-I

Lithium Fluoride Thick Target


- 5 MeV deuterons
- $5 \cdot 10^{12}$ n/sec/mA
- Isotropic
- Fast neutrons up to 20 MeV

Measured raw neutron spectrum

Primary target based on D. Petrich et al., NIM A 596 (2008) 269-275

MCUNED simulation by J. Sanz et al., NIM A 614 (2010) 323-330
B₄C target for $^{11}\text{B}(n,\alpha)^{8}\text{Li}$ $T_{1/2}=838\text{ ms}$

- High porosity (65%)
- 1-5 micrometer grains
- Melting point 2300 °C
- 90% B content
**8Li RIB system at SARAF phase I**

- Production of $^8$Li by using fast neutrons from LiFTiT
- Calculated yields ($^8$Li/sec/mA):
  - $4 \cdot 10^9$ - SARAF-I, 5 MeV deuterons
  - $6 \cdot 10^6$ - $10^{10}$ n/s neutron generator
Thermal neutron source

Thermal Neutron Radiography (TNR)
Neutron production with low energy deuterons

\[ ^9\text{Be}(d,xn) \]
\[ E_d = 40 \text{ MeV} \]

8x10^{14} fast n/s
(per 40 MeV 2 mA d)

K. Lavie et al. INS 2004
Thermal neutron source $^9$Be(d,xn)

- 2 m heavy concrete shield
- L/D=250 image plane
- beam raster
- 10 mm thick 100 cm$^2$ Be water cooled target
- 15 cm thick Be amplifier
- 20 cm H$_2$O reflector
- 30 mm x 50 mm collimator
- 10 mm thick 100 cm$^2$ Be target
- 40 MeV x 2 mA d beam
- water cooling
- thermal Pb+Fe water cooled shield
- $\Phi=120$ cm D$_2$O moderator
- $F=120$ cm $D_2O$ moderator
- beam
- concrete shield

Comparison of neutrons flux density

<table>
<thead>
<tr>
<th>Project</th>
<th>IFMIF *</th>
<th>SPIRAL II *</th>
<th>SARAF</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 4\pi (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;En&gt; on the back-plate (MeV)</td>
<td>~10</td>
<td>~12</td>
<td>~10</td>
</tr>
</tbody>
</table>

Summary

- SARAF requires a new kind of an accelerator
  - Light ions, high-intensity, CW, variable-energy
- SARAF phase-I is in routine operation with 1 mA CW protons, gaining valuable experience for CW machines
- Targets for high-intensity low-energy beams are under development and testing
- A conceptual design for Phase-II was completed
- Phase-I is used for basic and applied research
- Phase-II research and applications are under preliminary design
This work was carried out by:

L. Weissman  A. Arenshtam  Y. Ben-Aliz  D. Berkovits
Y. Buzaglo  O. Dudovich  Y. Eisen  I. Eliyahu
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