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

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

26th International Nuclear Physics Conference
Adelaide, Australia, September 11th-16th, 2016

September 16th, 2016

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Outline

- The SARAF linear accelerator
- The **Li**quid **Li**thium **T**arget (**LiLiT**)
- Research programs at SARAF Phase I
- Research potential and plans for SARAF Phase II

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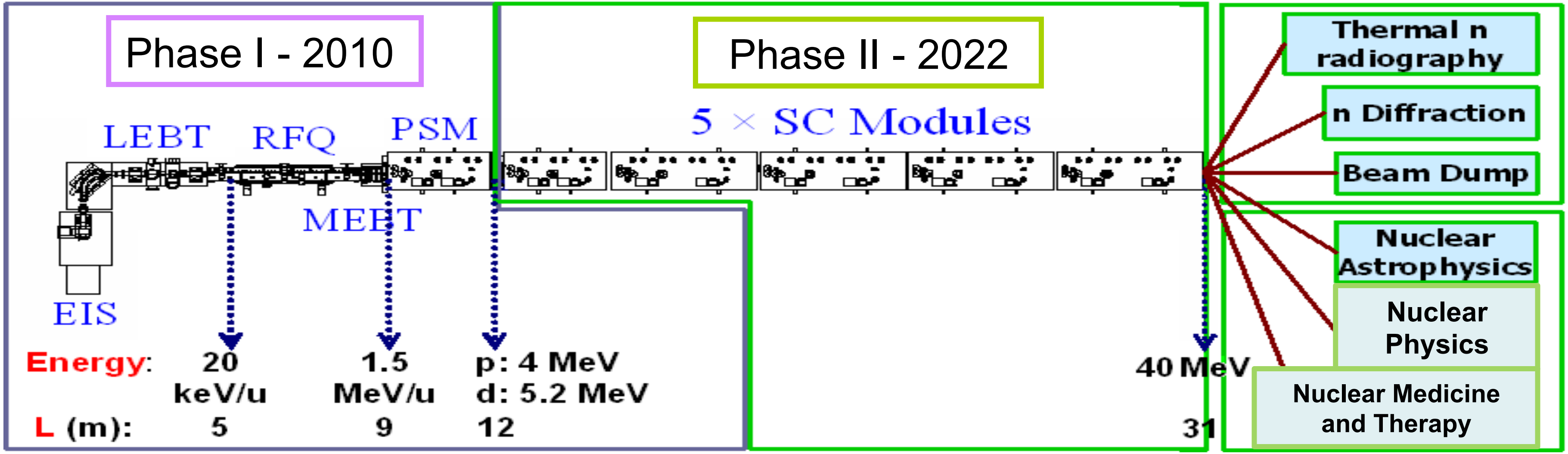
SARAF Accelerator Complex

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



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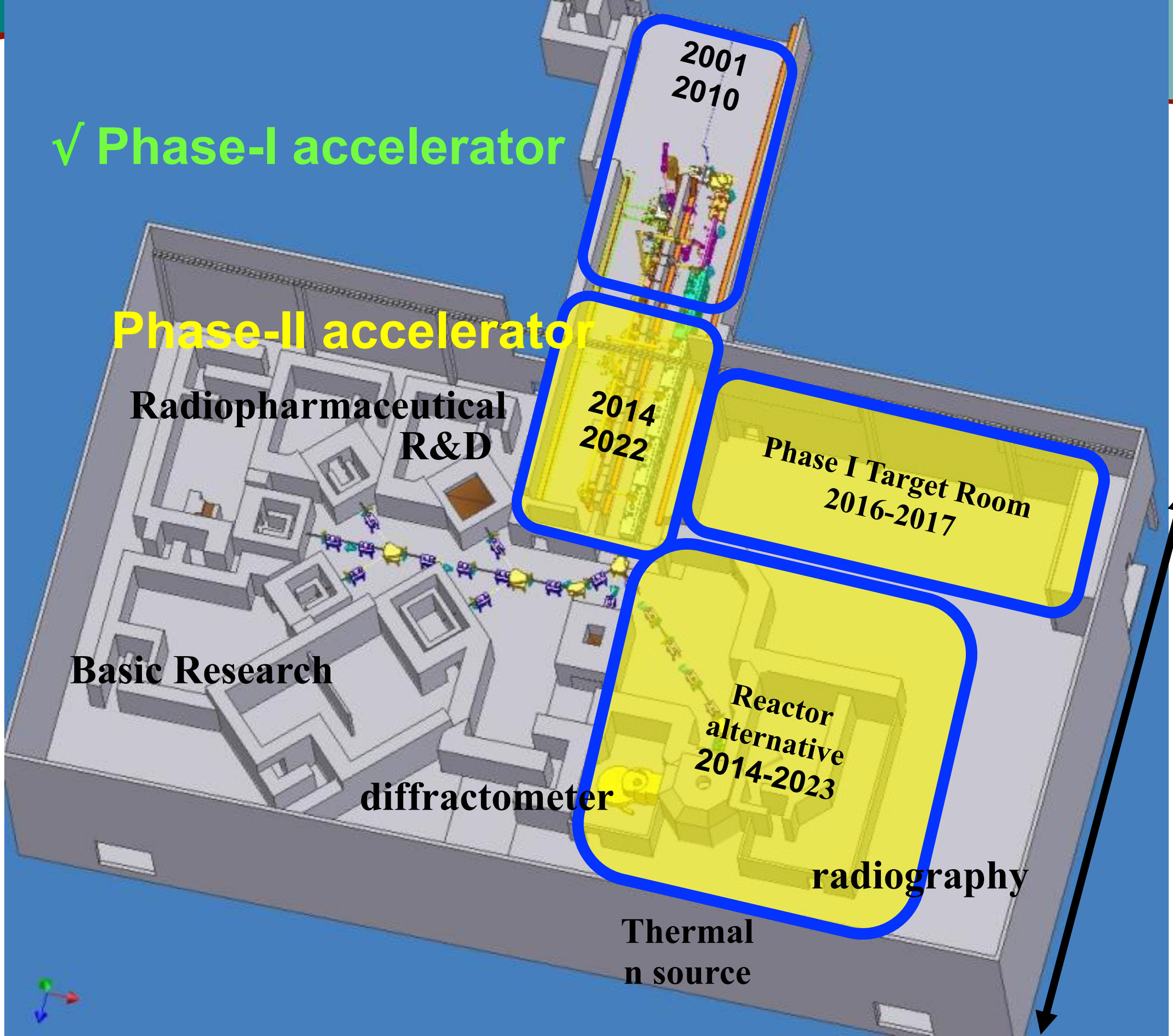
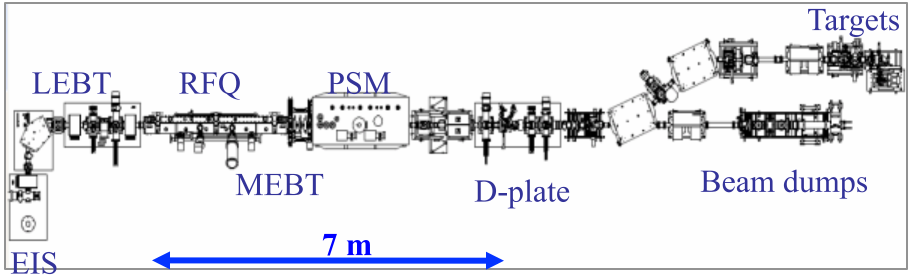
SARAF Phase II 2023

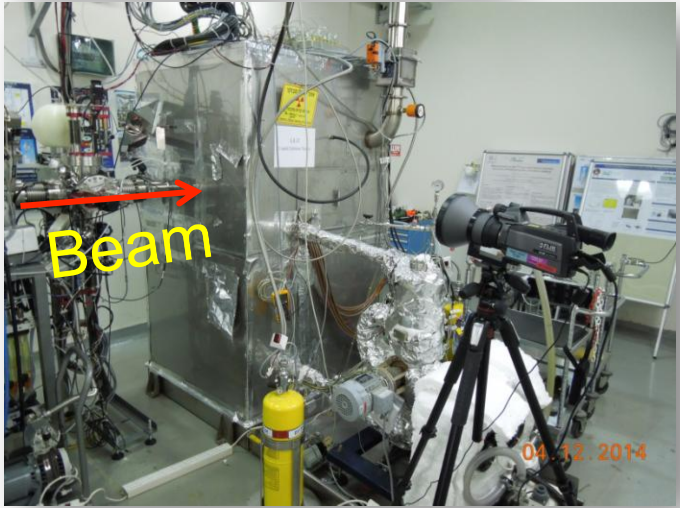


40 m

SARAF Phase I



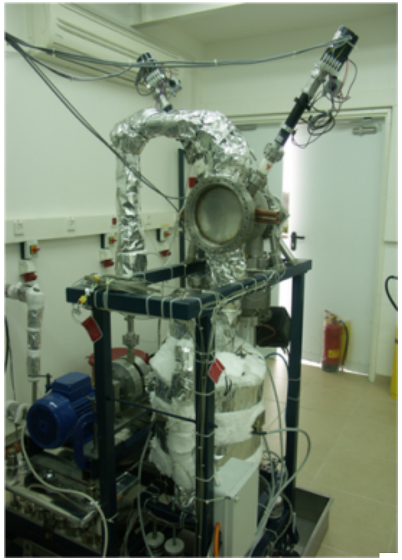
A. Nagler, Linac 2006
A. Nagler, Linac 2008
J. Rodnizki, EPAC 2008
A. Perry, SRF 2009
I. Mardor, SRF 2009
L. Weissman, DIPAC 2009
L. Weissman, Linac 2010
J. Rodnizki, Linac 2010
D. Berkovits, Linac 2012
L. Weissman, RuPAC 2012
A. Kreisel, Linac 2014
L. Weissman, WAO 2014

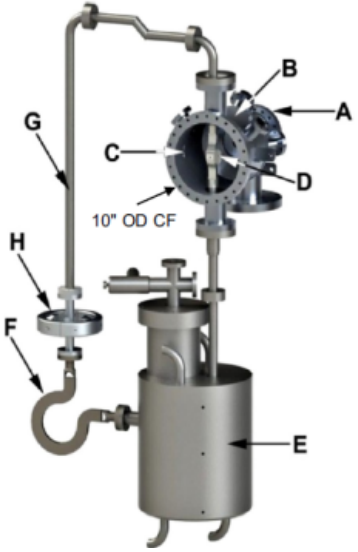


The Liquid Lithium Target - LiLiT

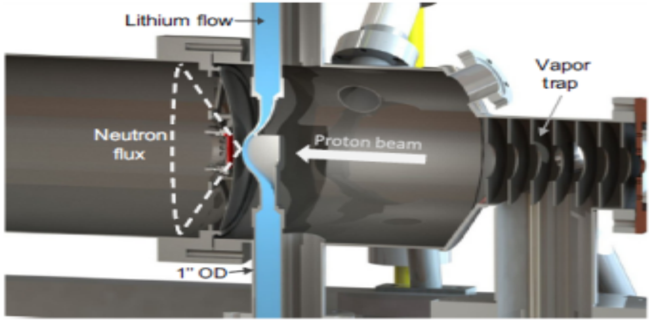
- Proton energy: **~ 2 MeV**
- Maximum current: **3.5 mA**
- Achieved power: **~ 3 kW**
- Achieved power density:

  2.5 kW/cm^2, 0.5 MW/cm^3
- $T_{operation}$ ≈ **220^{0}C**
- T_{max} ≈ **350^{0}C**
- Operating at SARAF since **10/2013**





- Wall assisted lithium jet
- Jet size: **18 mm × 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

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Present SARAF Phase I Performance

Parameter	Protons	Deuterons
Energy (MeV)	4.0	5.6
Current (mA)	2.0	0.4
Duty Cycle (%)	100 (CW)	10

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/cm^2**, **0.5 MW/cm^3** at beam center), generating **3-5×10^{10} 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**

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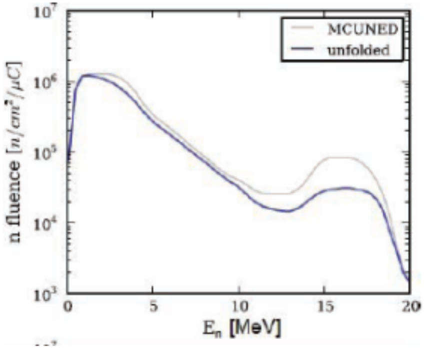
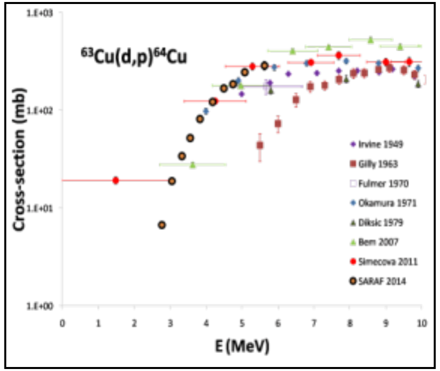
Research Programs at SARAF Phase I

Subject	P.I.	Institute	# of students
Inter stellar nucleosynthesis	M. Paul	Hebrew University	3
	A. Shor	Soreq NRC	
β decay study of exotic nuclei in traps for beyond SM physics	M. Hass	Weizmann Institute	4
	G. Ron	Hebrew University	
	S. Vaintraub	Soreq NRC	
Neutrons destruction of ^{7}Be to Solve the Primordial ^{7}Li Problem	M. Gai	U. Conn and Yale	3
	D. Schumann	PSI	
	T. Stora	ISOLDE-CERN	
	L. Weissman	Soreq NRC	
	M. Paul	Hebrew University	
	M. Hass	Weizmann Institute	
Accelerator based BNCT	M. Paul	Hebrew University	1
	M. Srebnik D. Steinberg	Hadasa HUJI	
Generation IV reactors neutron cross section	A. Plompen F.-J. Hambsch	IRMM-JRC	1
	A. Shor	Soreq NRC	
Deuterons cross section measurements	A. Kreisel L. Weissman	Soreq NRC	
	J. Mrazek	NPI-Rez	

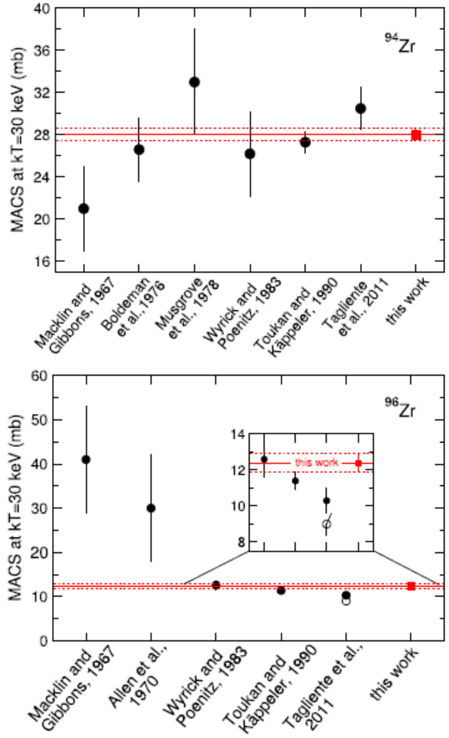
Scientific Experiments at SARAF Phase I



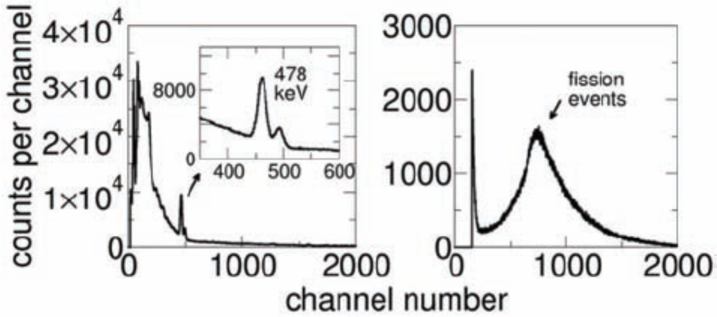
Neutron spectra via 4.6 MeV d on a thick solid Li target, **T. Y. Hirsh, PhD Dissertation (2012)**



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



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)
M. Tessler et al., Phys. Lett. B751 (2015) 418-422



γ (left) and n (right) spectra via 1.9 MeV protons on LiLiT
S. Halfon et al., Rev. Sci. Inst. 85, 056105 (2014)

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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

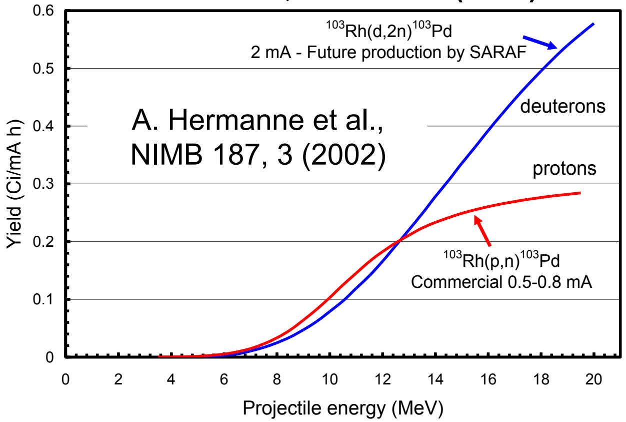
These specifications will make SARAF Phase II one of the world's most potent deuteron, proton and fast neutron sources

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*

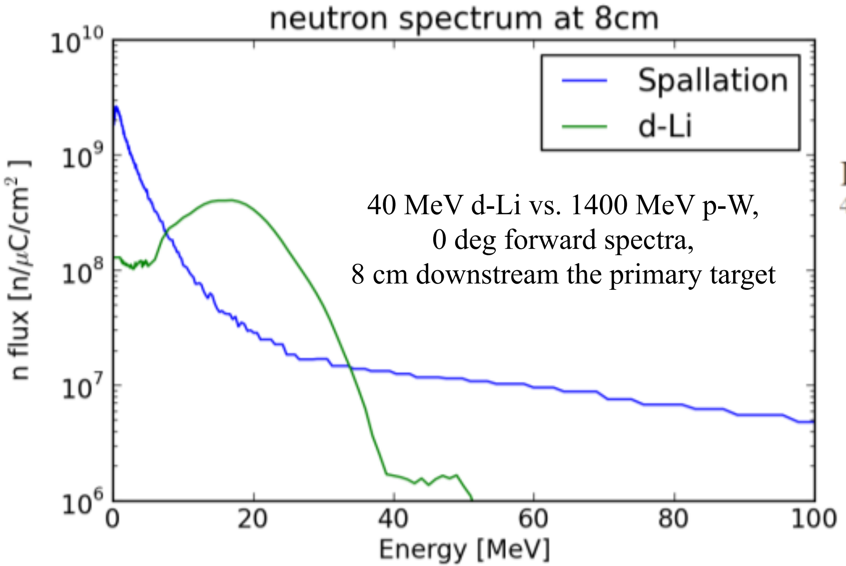
Target/ Product	Protons energy range (MeV)	Protons TTY MBq/mAh	Deuterons energy range (MeV)	Deuterons TTY MBq/mAh
^{64}Ni/^{64}Cu	19 → 8	650	21 → 8	900
^{61}Ni/^{61}Cu	20 → 8	1890	20 → 8 [^{60}**Ni(d,n)**]	720
^{103}Rh/^{103}Pd	20 → 8	12	20 → 8	22
^{186}W/^{186}Re	30 → 8	11	20 → 10	19
^{111}Cd/^{111}In	30 → 8	95	20 → 8 (**^{nat}Cd**)	20
^{114}Cd/^{114m}In	30 → 8	2,2	20 → 9	3,6
^{nat}Er/^{170}Tm	30 → 9	0,065	20 → 9	0,055
^{169}Tm/^{169}Yb	30 → 9	2,2	20 → 9	3,74
^{192}Os/^{192}Ir	20 → 9	0,18	20 → 9	0,88
^{100}Mo/^{99}Mo	40 → 8	14,3	40 → 20	16,2
^{176}Yb/^{177}Lu	NA	NA	20 → 8	1,02

A. Hermanne, Nucl. Data (2007)

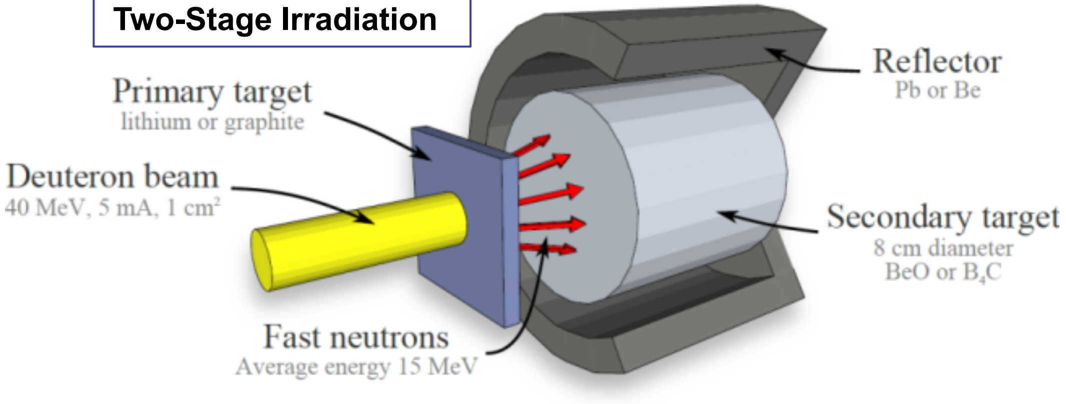


*A. Aprahamian & D. Geesaman, A Strategic Plan for the Isotope Development and Production for Research and Application Program, 2009

Specialty and Competitiveness of SARAF Phase II (1)



Two-Stage Irradiation

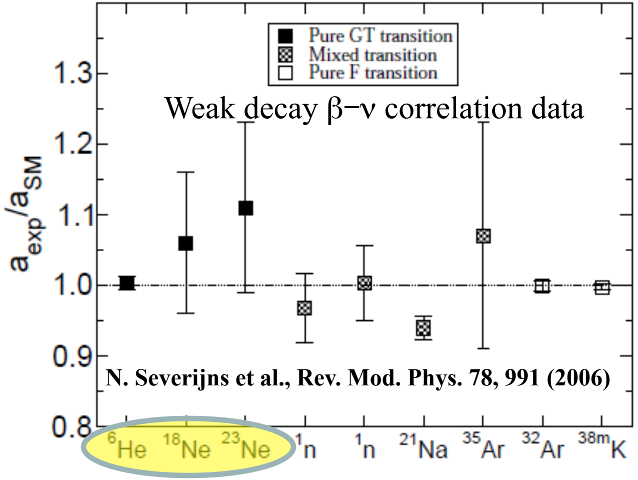


Material	Reaction	half life [msec]	Yield $\left[\frac{10^{12}\ atoms}{mA\ sec}\right]$
BeO	$^{9}Be(n,\alpha)^{6}He$	*807*	2.53
	$^{9}Be(n,p)^{9}Li$	*178*	0.033
	$^{16}O(n,p)^{16}N$	*7130*	0.9
B_4C	$^{11}B(n,\alpha)^{8}Li$	*838*	0.87
	$^{11}B(n,p)^{11}Be$	*13810*	0.14
	$^{12}C(n,p)^{12}B$	*20*	0.24
	$^{13}C(n,p)^{13}B$	*17*	$6.63 \cdot 10^{-4}$

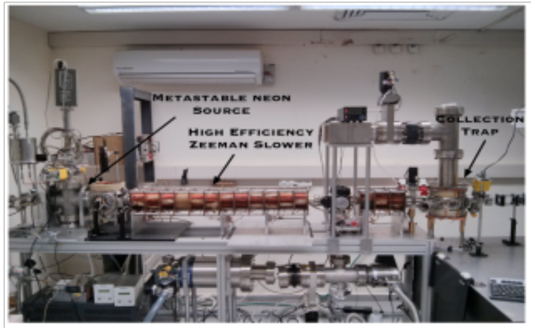
M. Hass *et al.,* J. Phys. G. 35 (2008)
T. Hirsh *et al.,* J. Phys. NPA 337 (2012)
T. Stora *et al.,* EPL 98, 32001 (2012)

Search for physics beyond the Standard Model

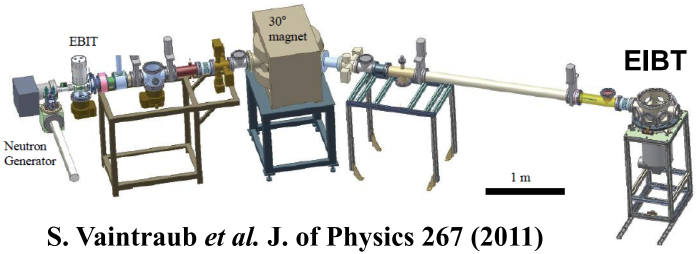
- ‘High Precision Frontier’ – direct & focus the ‘High Energy Frontier’
- Generate ultra-pure samples of exotic nuclei & measure in traps - EIBT (^{6}He) and MOT (^{18,19,23}Ne)
  - ^{9}Be(n, α)^{6}**He** (E_n > 0.8 MeV)
  - ^{19}F(p, 2n)^{18}**Ne** (E_p > 13 MeV)
  - ^{19}F(p, n)^{19}**Ne** (E_p > 4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

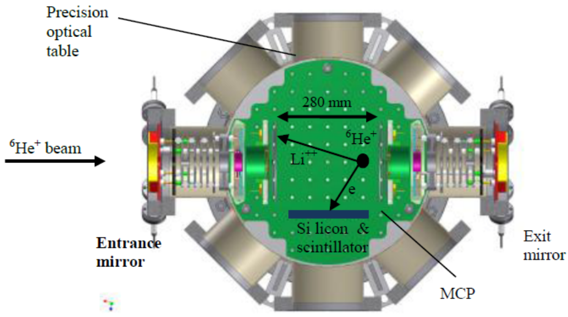


The HUJI Magneto-Optic Trap (MOT) based Ne setup



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

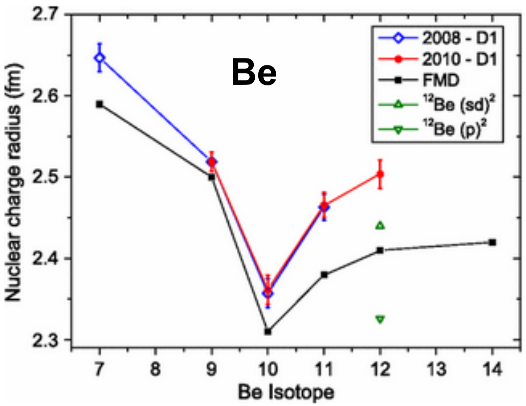




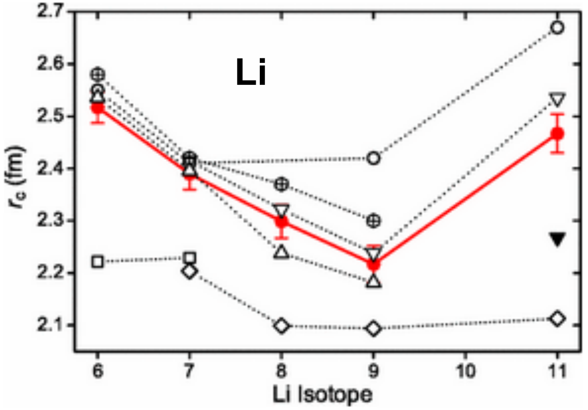
S. Vaintraub *et al.* J. of Physics 267 (2011)
O. Aviv *et al.* J. of Physics 337 (2012)

Exploration of light exotic nuclei

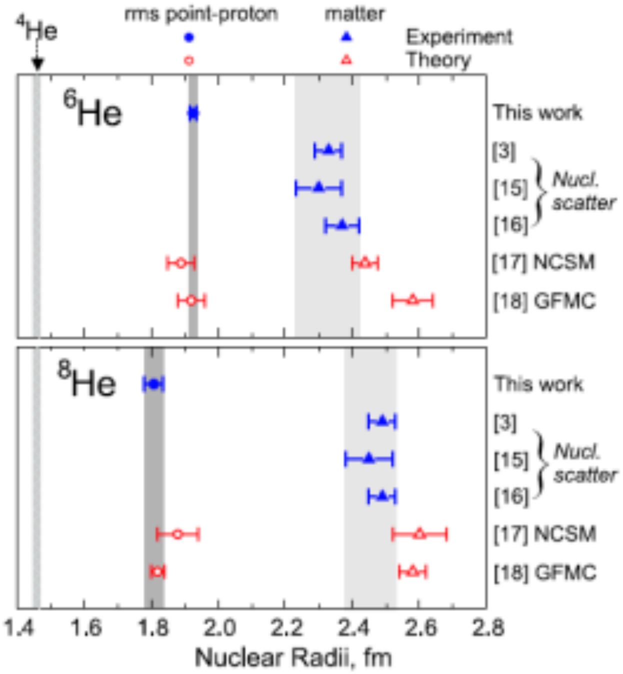
- Measure nuclear properties away from the valley of stability, extension of stable nuclei models
- Especially light exotic isotopes, where ab-initio calculations provide quantitative predictions
- It is advantageous to study a chain of isotopes, and compare to current and new nuclear models.



A. Krieger et al., PRL 108, 142501 (2012)



R. Sánchez et al., PRL 96, 033002 (2006)



P. Mueller et al., PRL 99, 252501 (2007)

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Specialty and Competitiveness of SARAF Phase II (2)

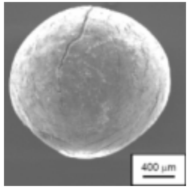
Project	IFMIF *	SPIRAL II *	SARAF II
Reaction specification	d(40MeV) +Li	d(40MeV) + C	d(40MeV) +Li
Projectile range in target [mm]	19.1	4.3	19.1
Maximum beam current [mA]	2 x 125	5	5
Beam spot on the target [cm^2]	~100	~10	~1
Beam density on the target [mA/cm^2]	2.5	0.5	5
Neutron production over 4π [n/deuteron]	~0.07	~0.03	~0.07
Neutron source intensity [n/s]	$\sim10^{17}$	$\sim10^{15}$	$\sim10^{15}$
Maximal neutron flux on the back-plate [n/(sec · cm^2)] (0-60 MeV neutrons)	$\sim10^{15}$	$\sim10^{14}$	$\sim5\cdot10^{14}$
<En> on the back-plate [MeV]	~10	~12	~10

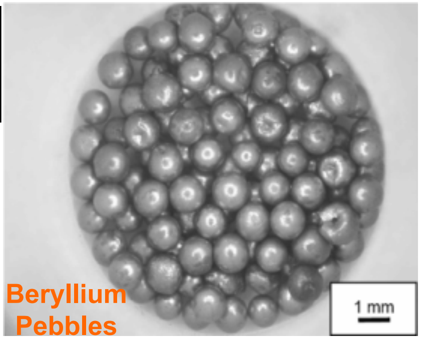
D.Ridikas et.al. “Neutrons For Science (NFS) at SPIRAL-2 (Part I: material irradiations), Internal Report DSM/DAPNIA/SPhN, CEA Saclay (Dec 2003)

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

Beryllium Pebbles
Neutron Multiplier Blankets

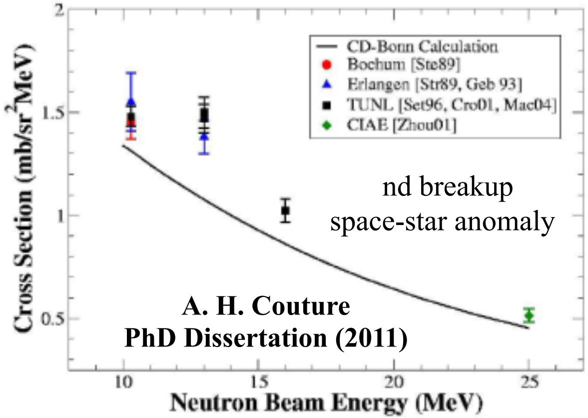




E. Rabaglino, FZKA 6939, Karlsruhe (2004)

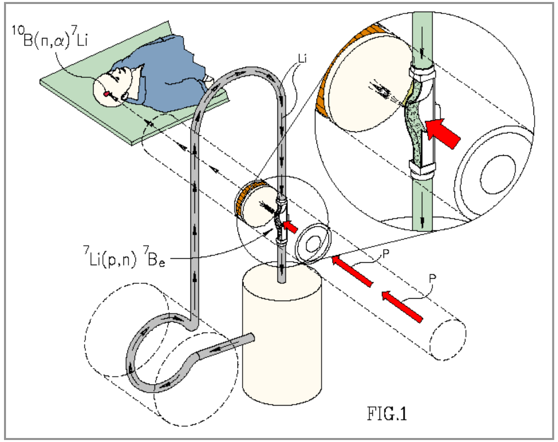
High Energy Neutron induced cross sections

- 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



Neutron based therapy

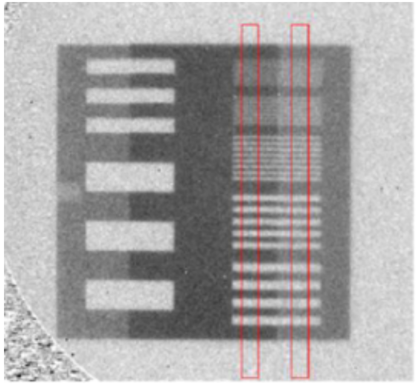
- Accelerator based Boron Neutron Capture Therapy (BNCT)
- More efficient and practical than reactor based BNCT
- Enables the most suitable spectrum for therapy (peaked at 3 - 5 keV)
- For ~1 hour therapy, require a flux of ~10^9 n·s^{-1}·cm^{-2}



Paul et al. US patent WO/2009/007976

Accelerator based neutron imaging

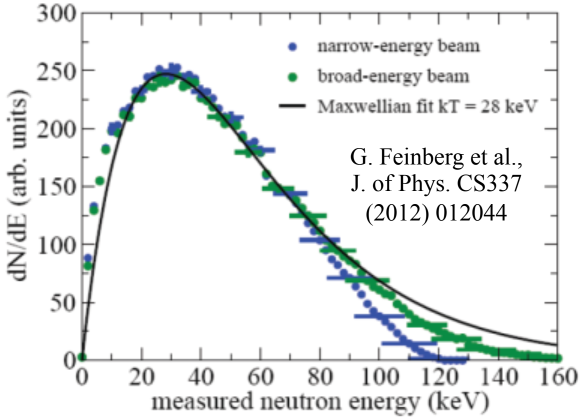
- Thermal neutron imaging with medium energy deuteron accelerators
- Fast neutron imaging for contrast over broad densities and atomic numbers

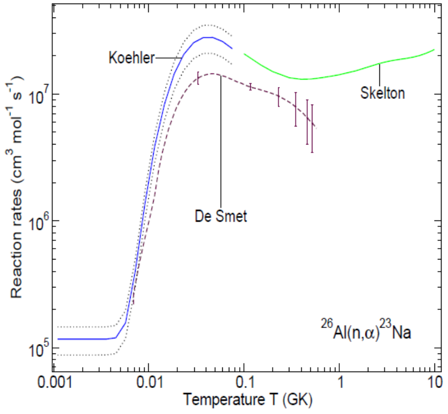


14 MeV n MTF phantom image. DT Generator 5×10^3 n/cm^2/sec.
I. Sabo-Napadensky et al., JINST 7, C06005 (2012)

Nuclear Astrophysics – S-process and BBN

- High precision Stellar and Big Bang Nucleosynthesis cross sections
- Study long existing puzzles such as the Primordial ^{7}Li Problem, overabundant ^{107}Pd, ^{26}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)

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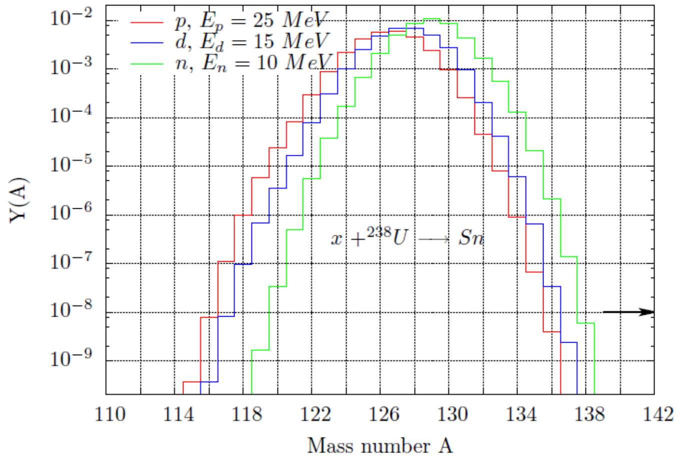
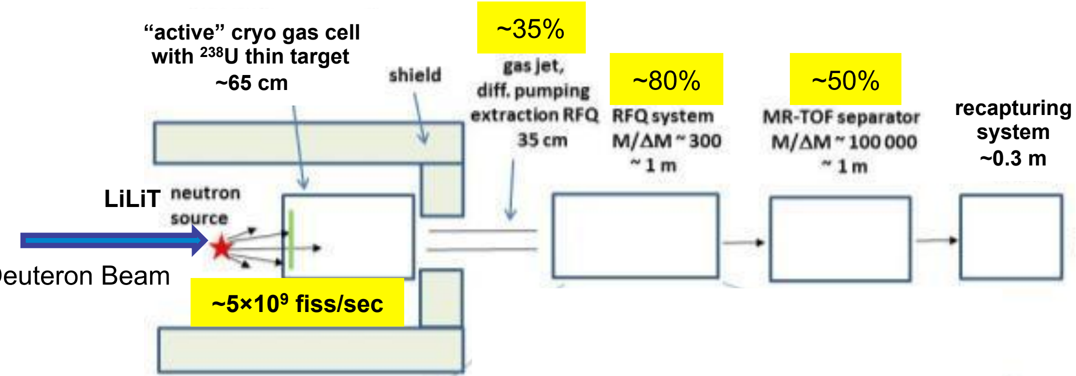
Exploration of neutron-rich exotic isotopes

- 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



Dmitry Gorelov, PhD thesis, U. Jyvaskyla, December 2015



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

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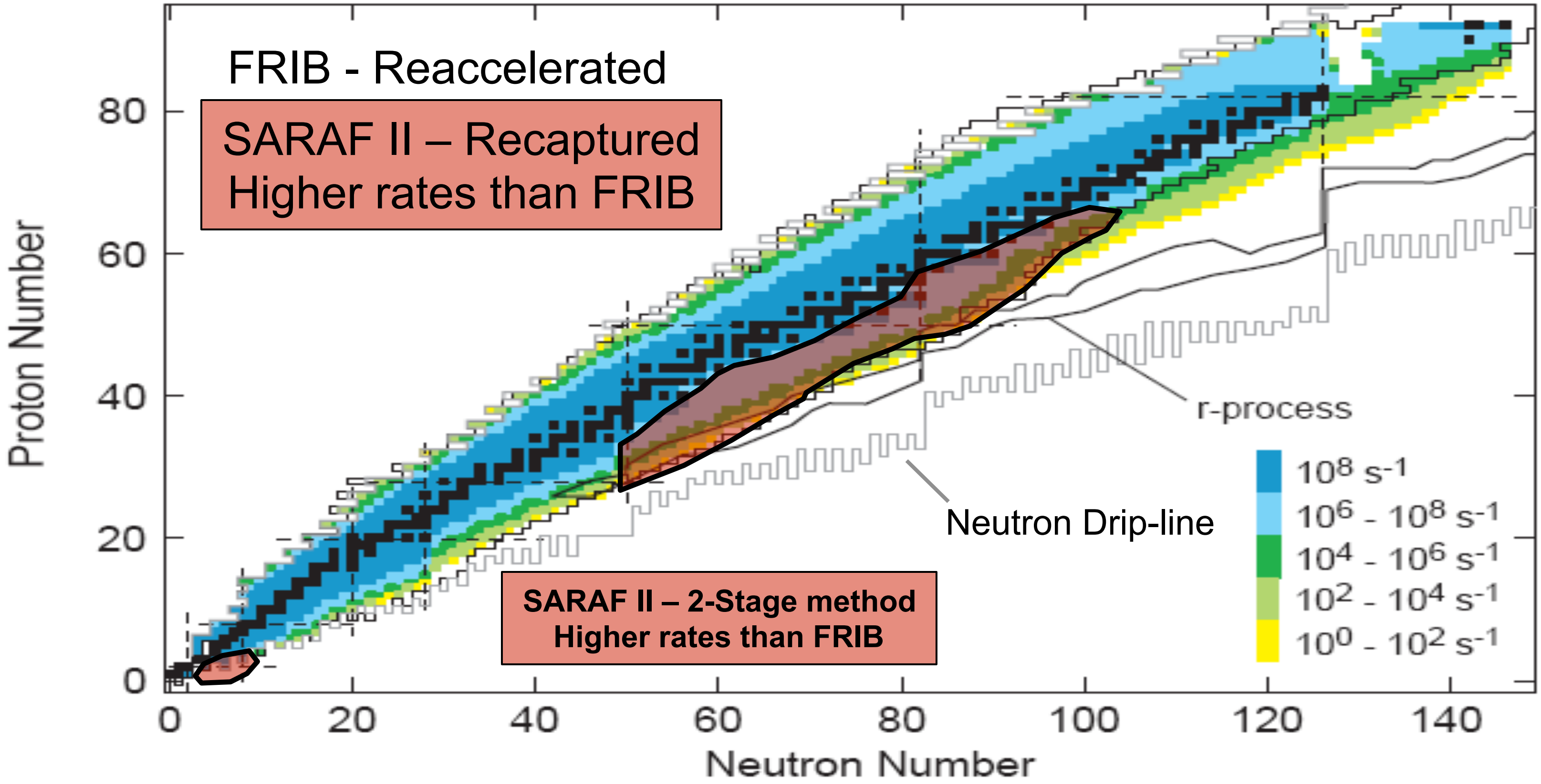
SARAF II Capabilities compared to FRIB



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