^{7}Be Measurements around a Liquid-Lithium Target High-Intensity Neutron Source

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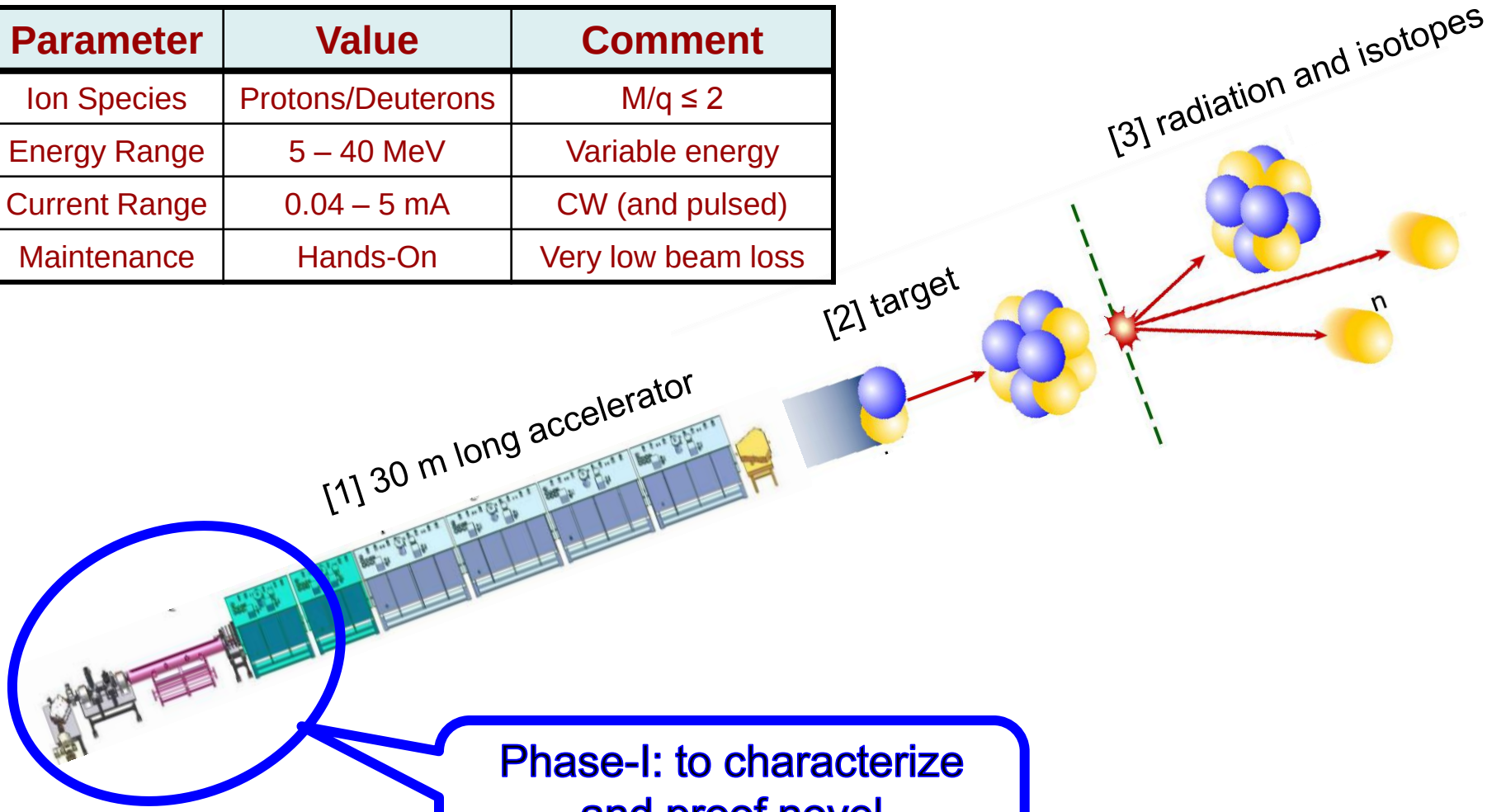
ARIA15
The Third International Workshop Accelerator Radiation Induced Activation
Knoxville, Tennessee, USA, on April 15-17, 2015

Outline

- **S**oreq **A**pplied **R**esearch **A**ccelerator **F**acility (**SARAF**) overview
- **Li**quid **Li**thium **T**arget (LiLiT) for science and applications
- LiLiT proton irradiation at SARAF accelerator
- Calculations of ^{7}Be production and surrounding dose rates
- ^{7}Be measurements around LiLiT after proton irradiation

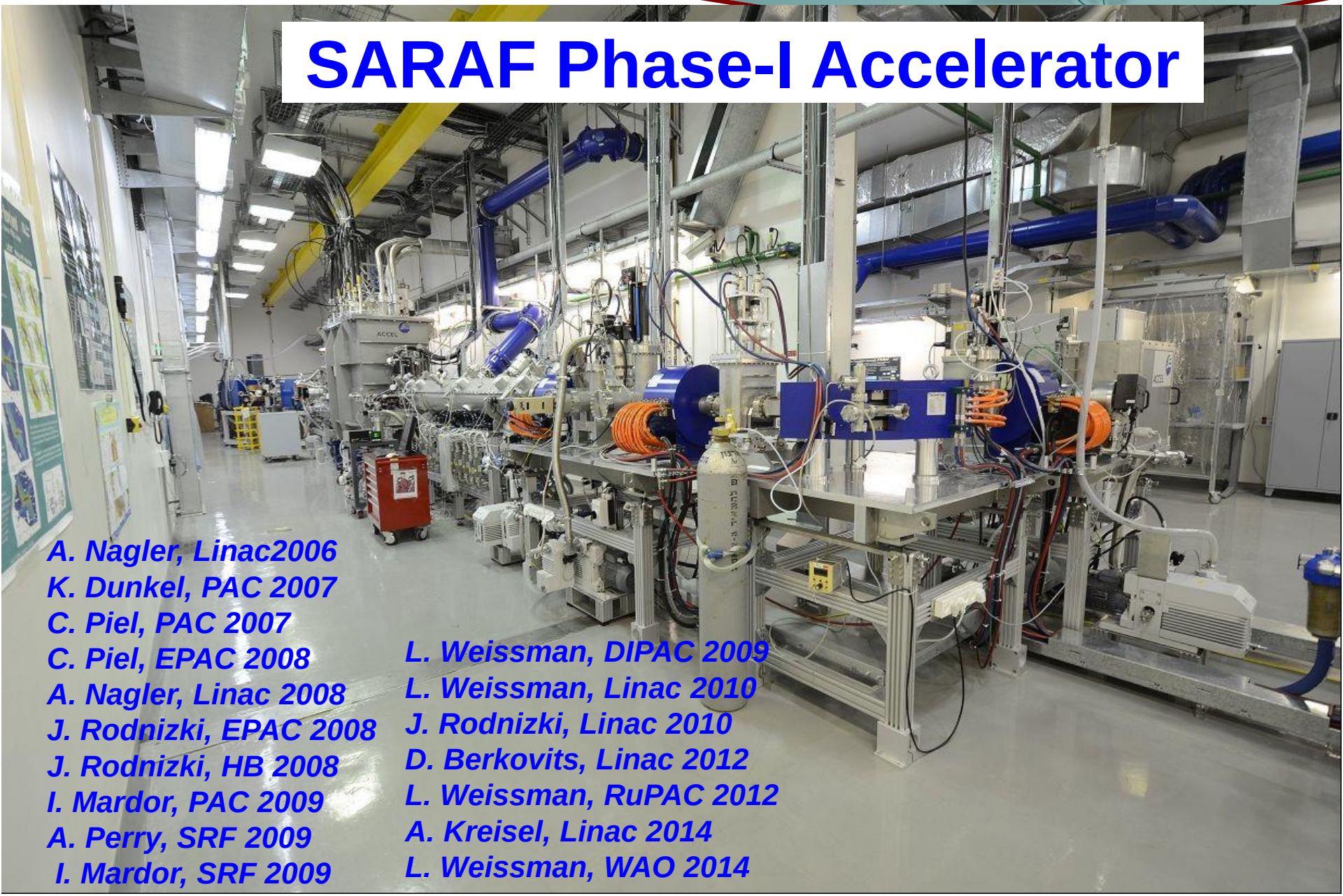
The accelerator that covers the needs

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)
Maintenance	Hands-On	Very low beam loss



Phase-I: to characterize and proof novel acceleration technologies

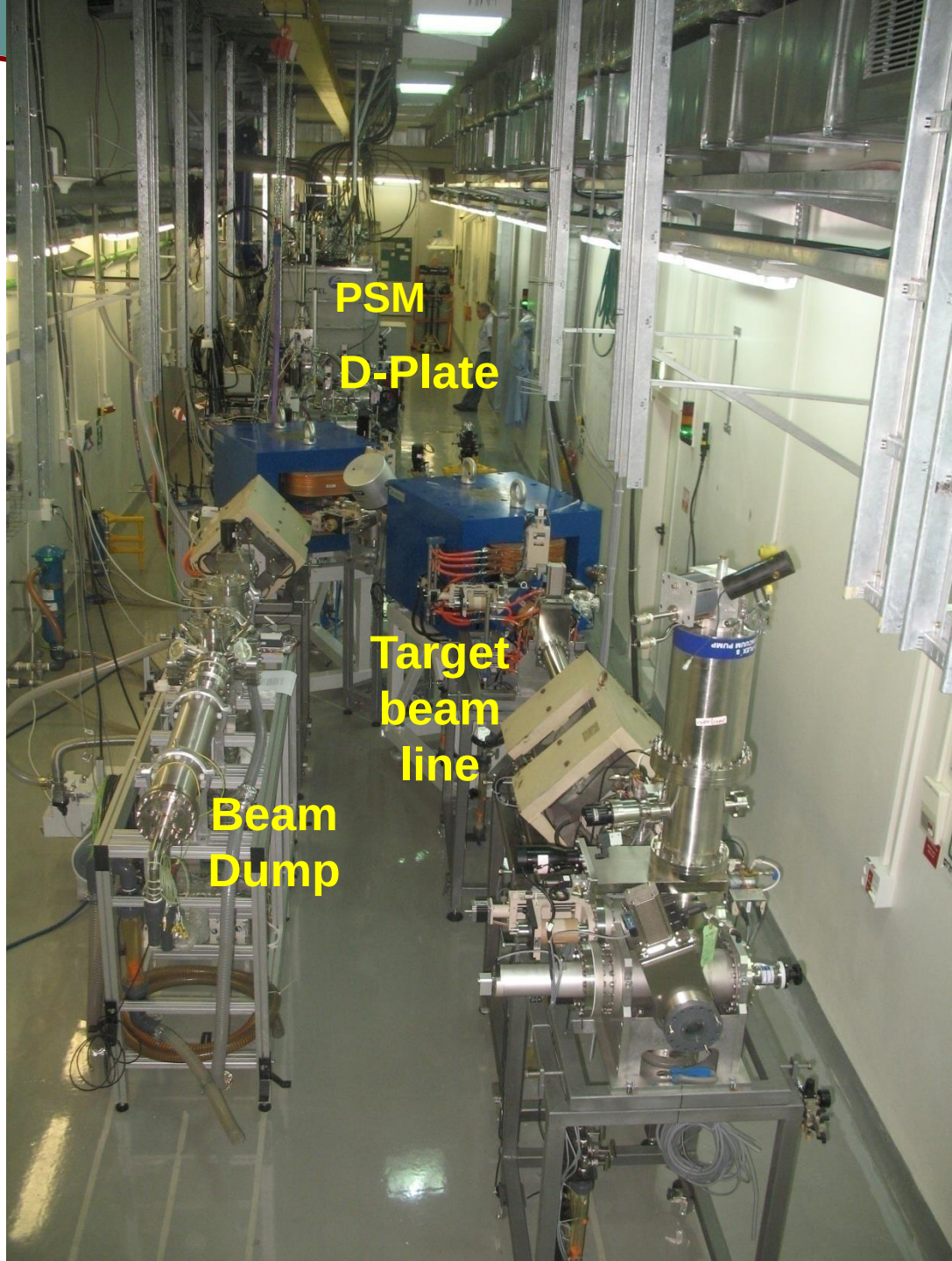
SARAF Phase-I Accelerator



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
D. Berkovits, Linac 2012
L. Weissman, RuPAC 2012
A. Kreisel, Linac 2014
L. Weissman, WAO 2014

SARAF Phase I – downstream

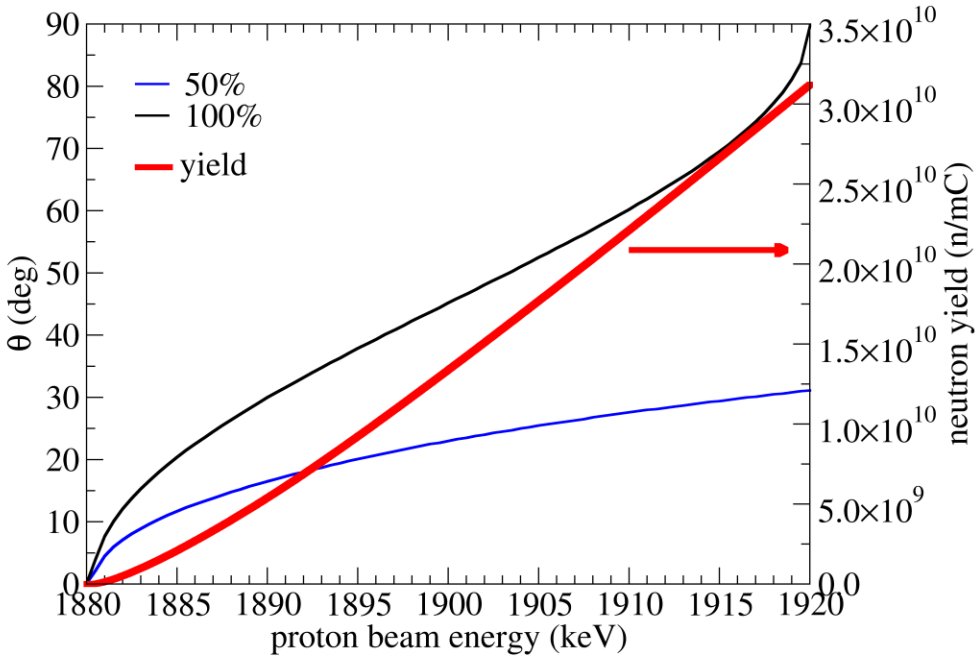
- SARAF Phase-I demonstrates:
  - ☑ 2 mA CW variable energy protons beam (up to 4 MeV)
  - ☑ Acceleration of ions through HWR SC cavities
  - ☑ 50% duty cycle 5 MeV deuterons

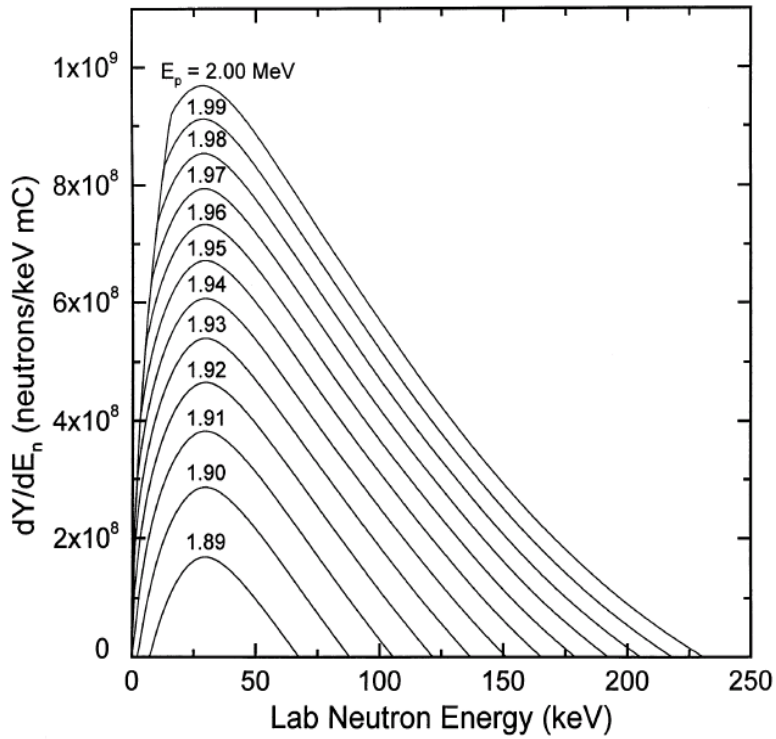


Neutron producing lithium target

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

Angular distribution





C.L. Lee, X.-L. Zhou, Nucl. Instr. and Meth. in Phys. Res. B 152 (1999) 1-11

SARAF Liquid lithium target purpose

- 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

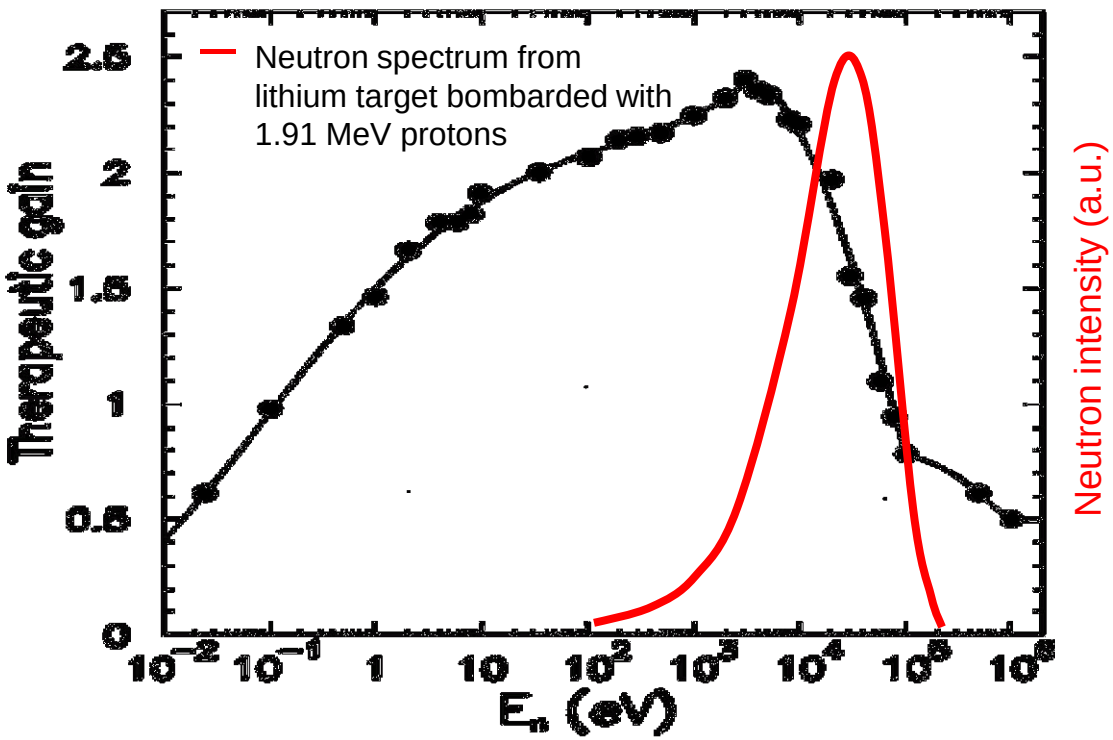
Accelerator based Boron Neutron Capture Therapy

Achieving Optimal neutron Energy for deep-seated tumor therapy:

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 inexpansive**



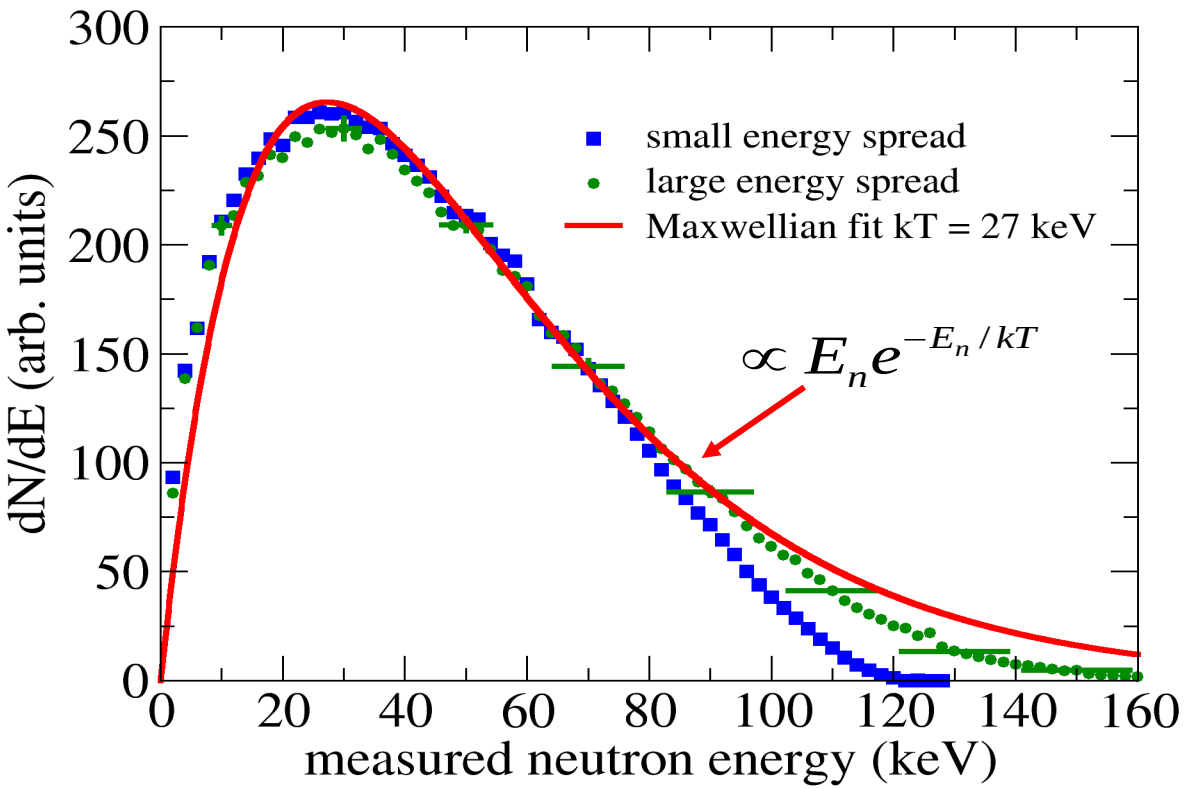
Bisceglie et. al. Phys. Med. Biol. **45** (2000) 49–58.

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

SARAF lithium target >10^{10} s^{-1} mA^{-1}

Nuclear Astrophysics research

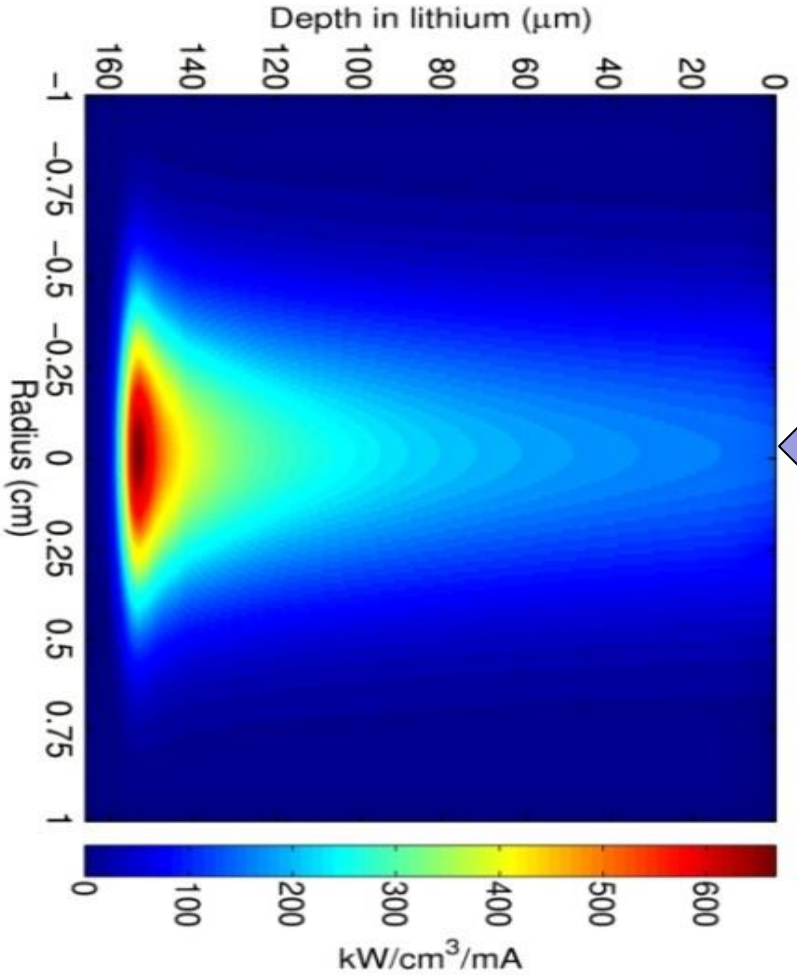
- The (slow) Nucleosynthesis s-process is a sequence of (n,g) reactions at stellar temperatures kT= 10 - 30 keV (He-burning): σ(n,g)
- Experimental integral neutron spectrum near ^{7}Li(p,n) threshold around E_p = 1.912 MeV is stellar-like at T ~25 keV



G. Feinberg et al., PRC 2012

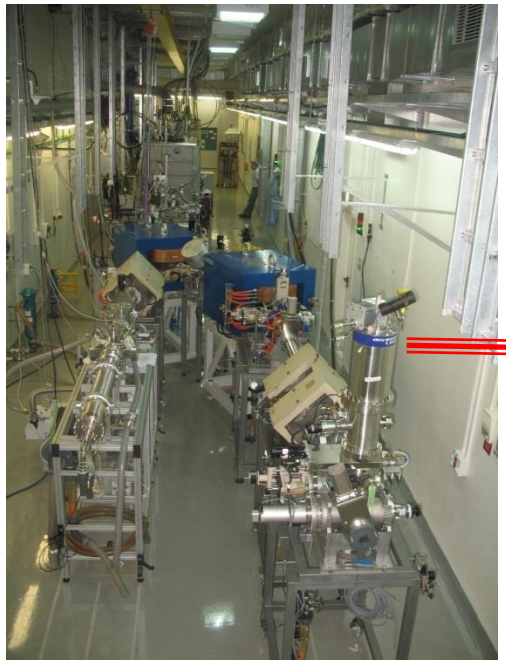
Lithium target challenges:

- Lithium melts at 180˚C and has poor heat capacity.
  - For intense ^{7}Li(p,n) neutron source, deposition of high beam power (>10 kW, ~1 MW/cm^{3}) is needed.
- Blistering of lithium target backing.
- **Radioactive ^{7}Be production through ^{7}Li(p,n)^{7}Be.**

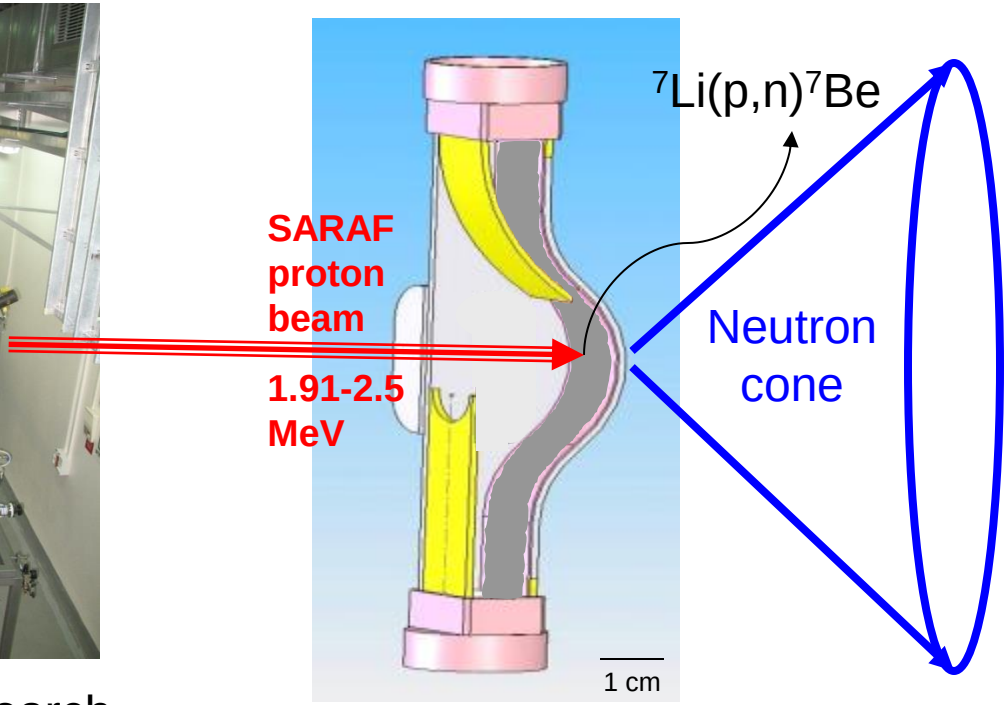


p, 1.91 MeV, σ_r=~2.8 mm

A high intensity epithermal neutron source based on a liquid lithium target

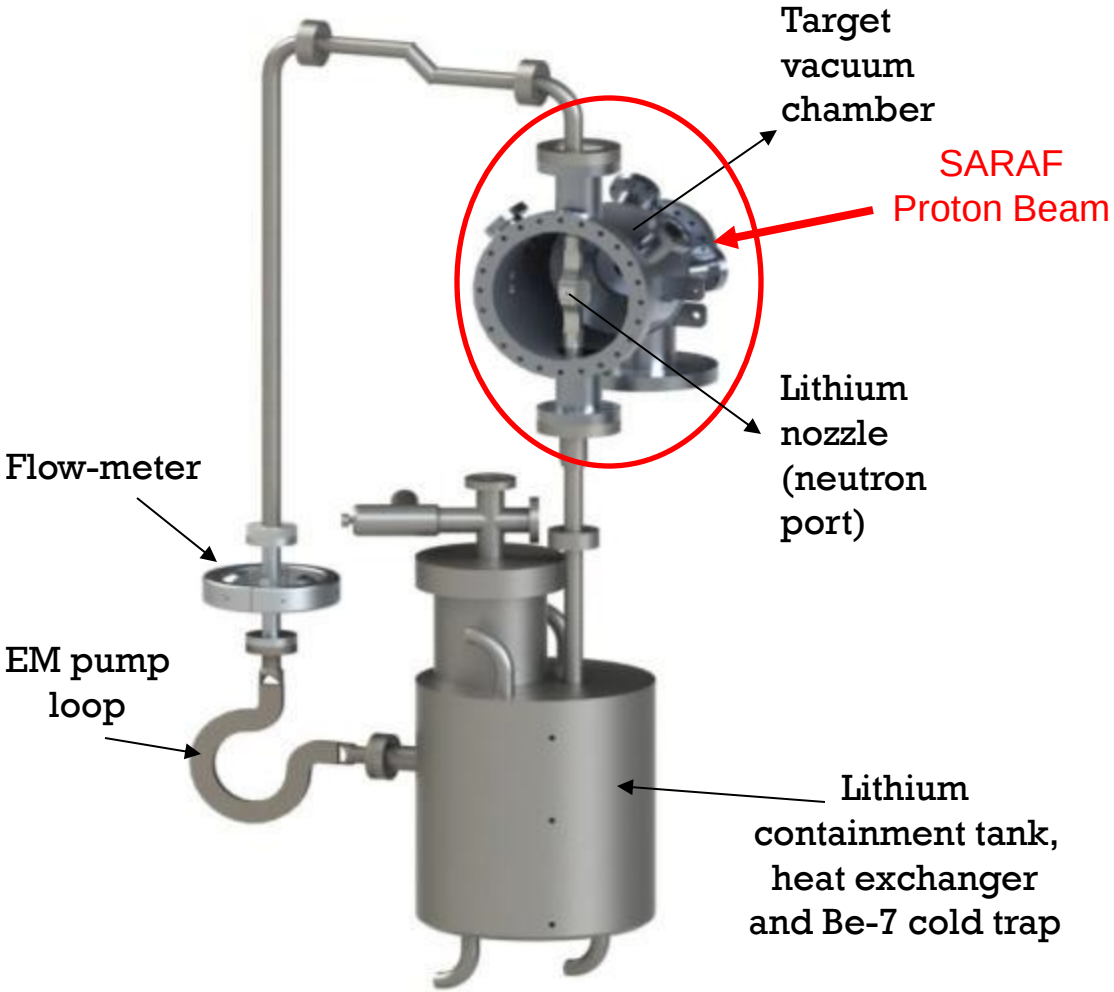


Soreq Applied Research Accelerator Facility (SARAF)



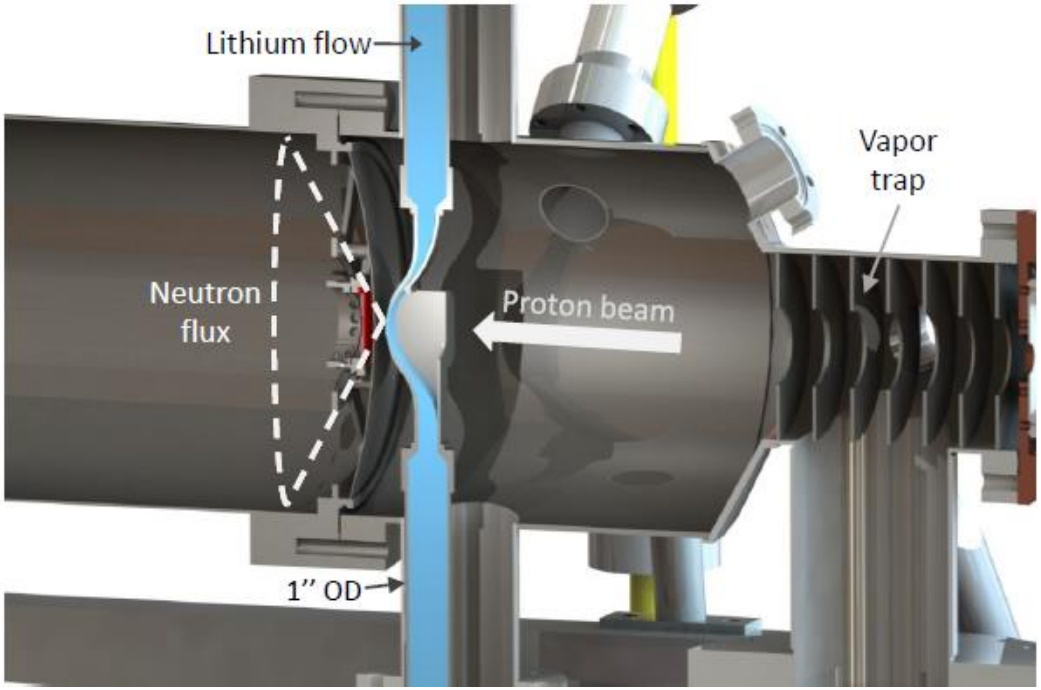
Liquid Lithium Target:
- ✓ High power dissipation
- ✓ No blistering
- • ^{7}Be control ?

LiLiT- Liquid Lithium Target

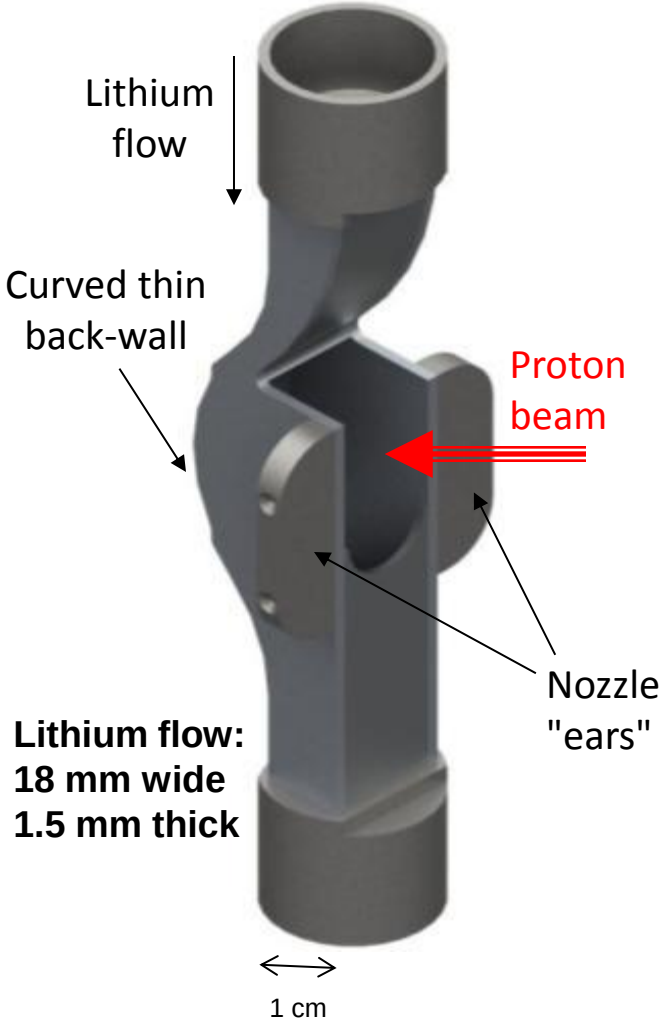


S. Halfon et al., Review of Scientific Instruments 84, 123507 (2013).

Target chamber



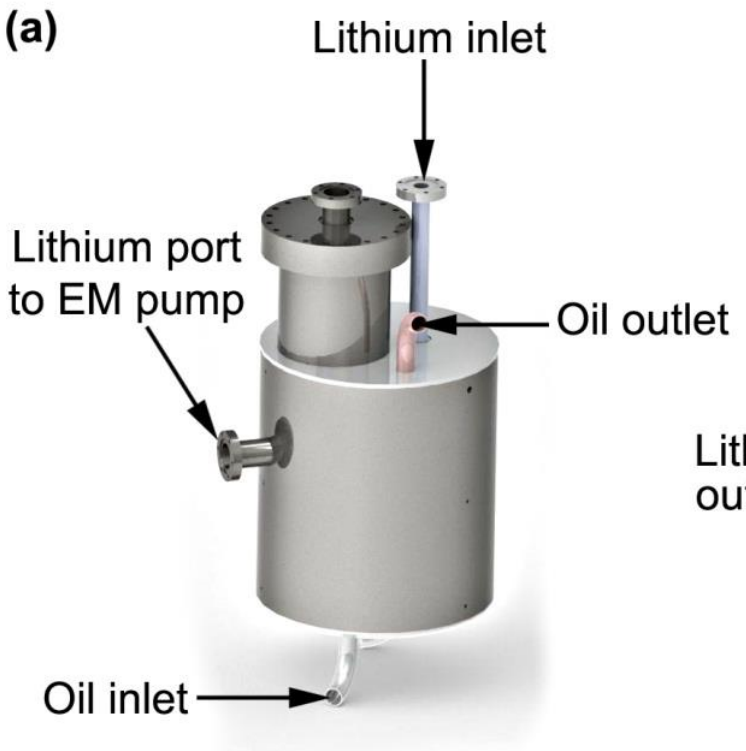
Lithium nozzle

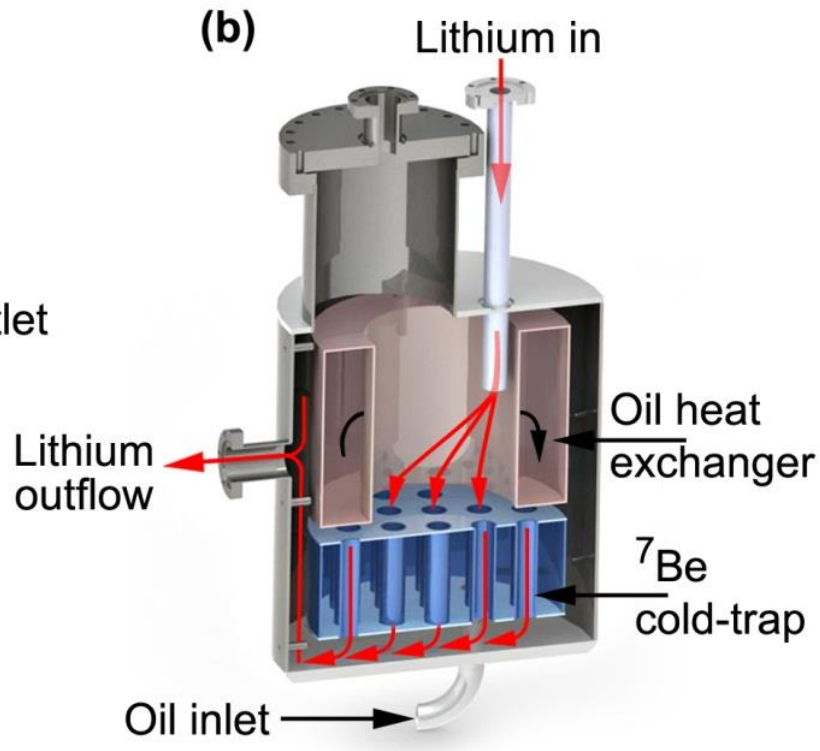


Lithium flow:
18 mm wide
1.5 mm thick

Lithium tank

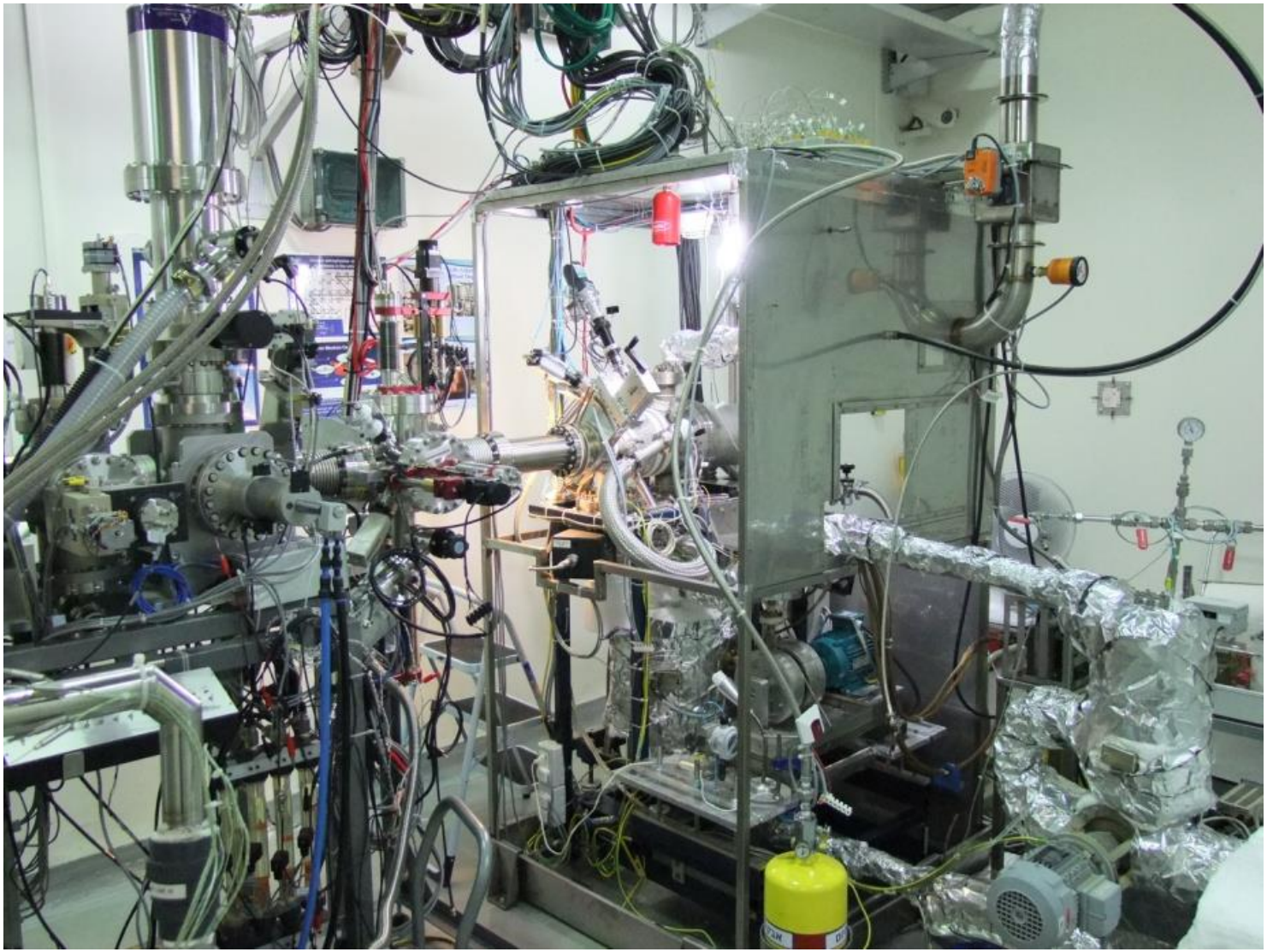
- ~7.5 kg, 15 liters lithium loaded
- Design to remove ~12 kW
- Most of the Be-7 is expected to be accumulate around the coldest part of the loop[1], the cold trap should be cooled to 190°C





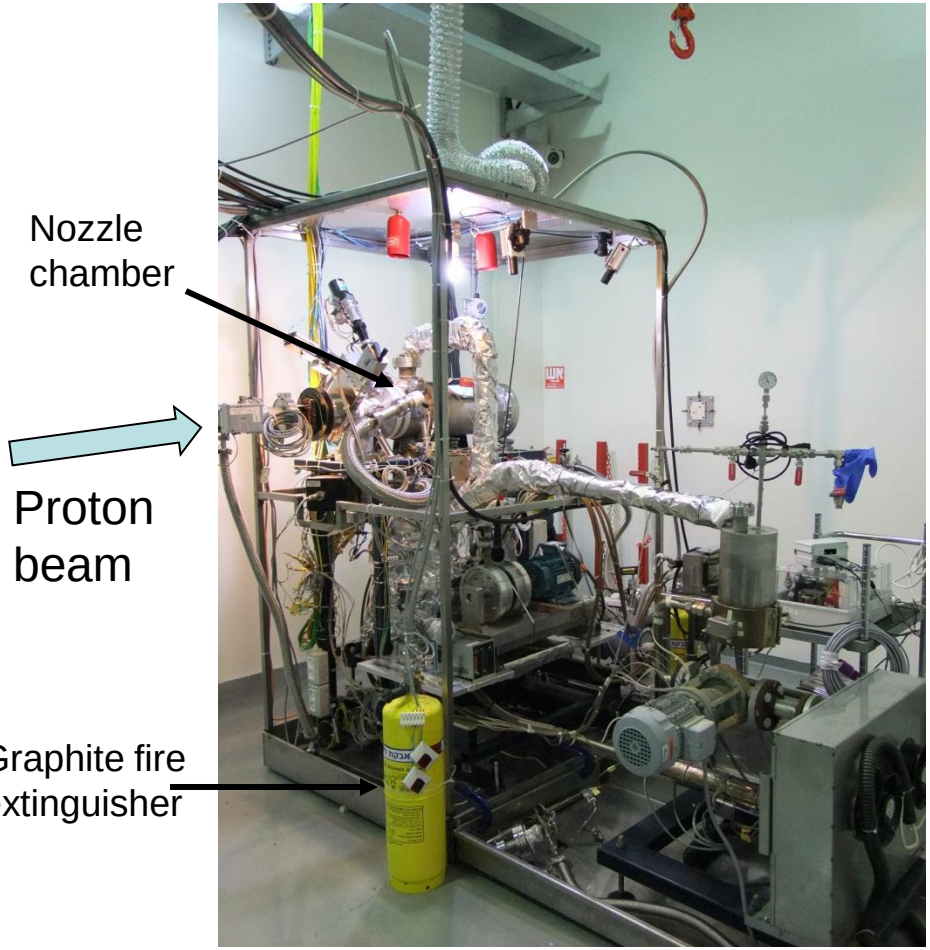
[1] M. da et. al., Fusion Engineering and Design 82 (2007) 2490-2496.

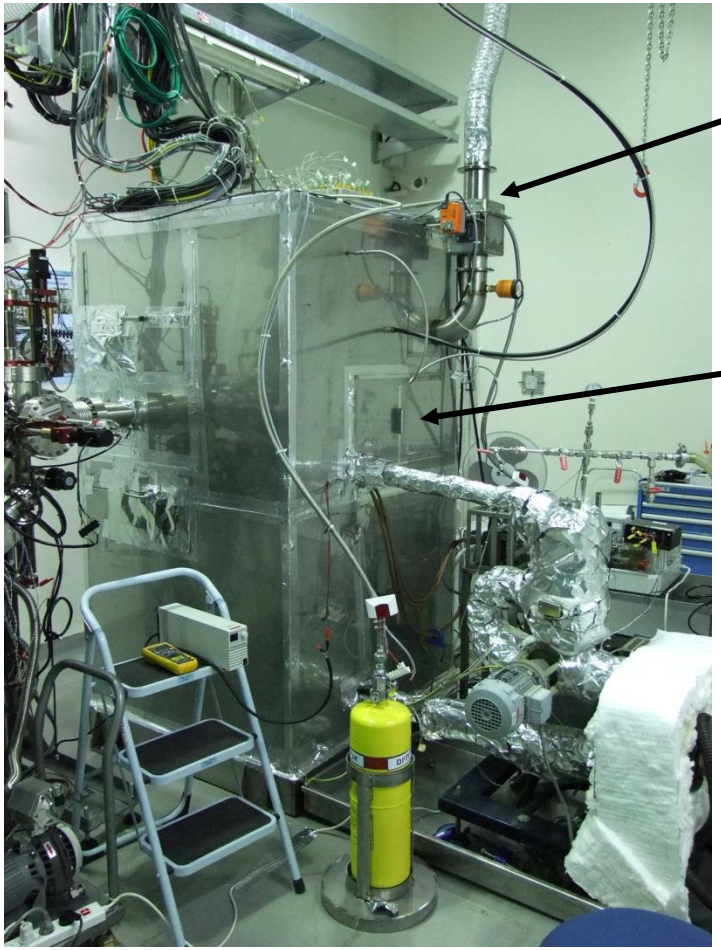
LiLiT at SARAF



Safety Installations in SARAF

- Strict measures to enclose and control lithium that might contain ^{7}Be

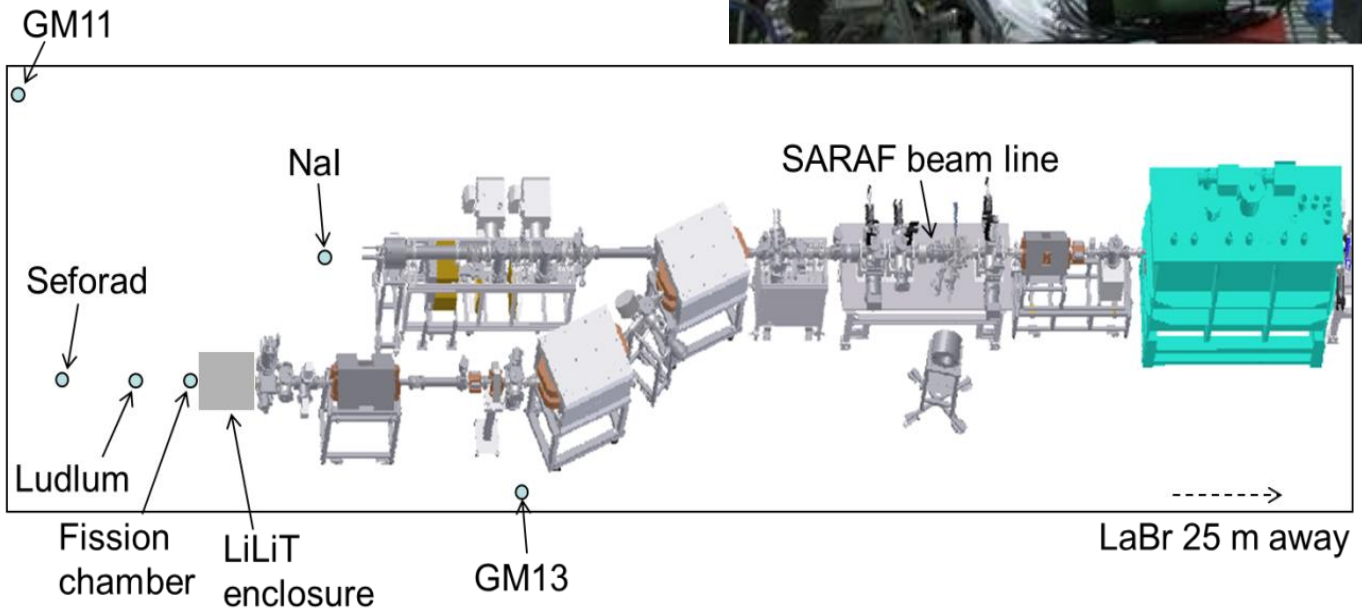




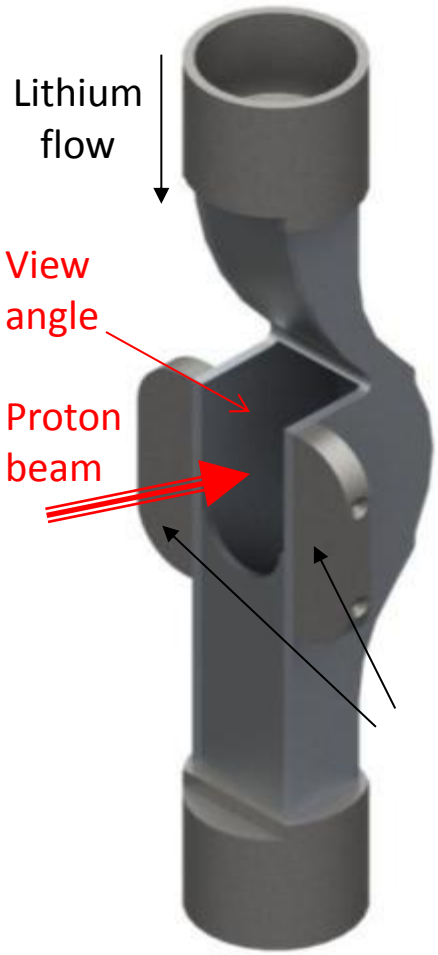
Detectors setup in SARAF beam line for gamma and neutron

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

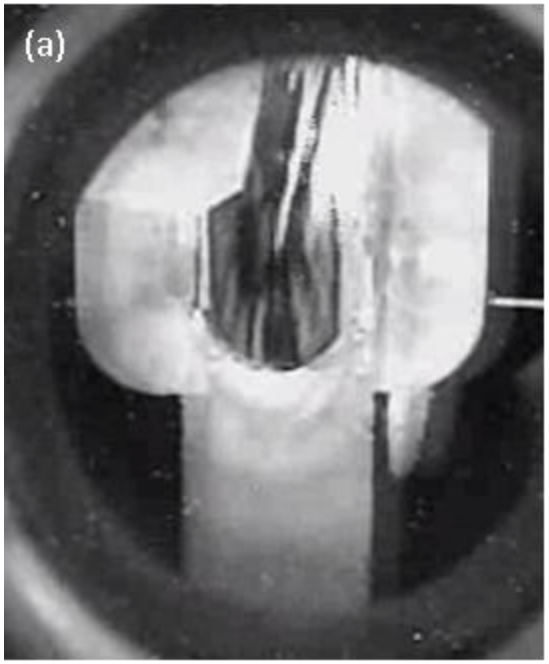
- The measured prompt γ and neutrons rate was calibrated with charge current reading by a high-power Faraday cup.

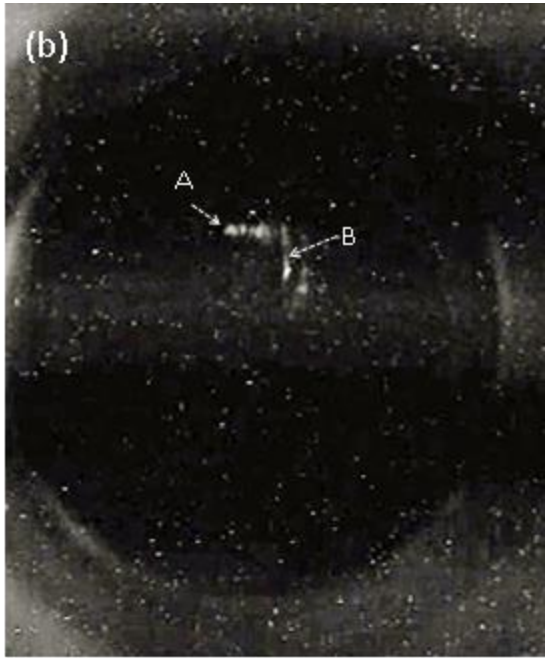


First Liquid Lithium free surface proton irradiation



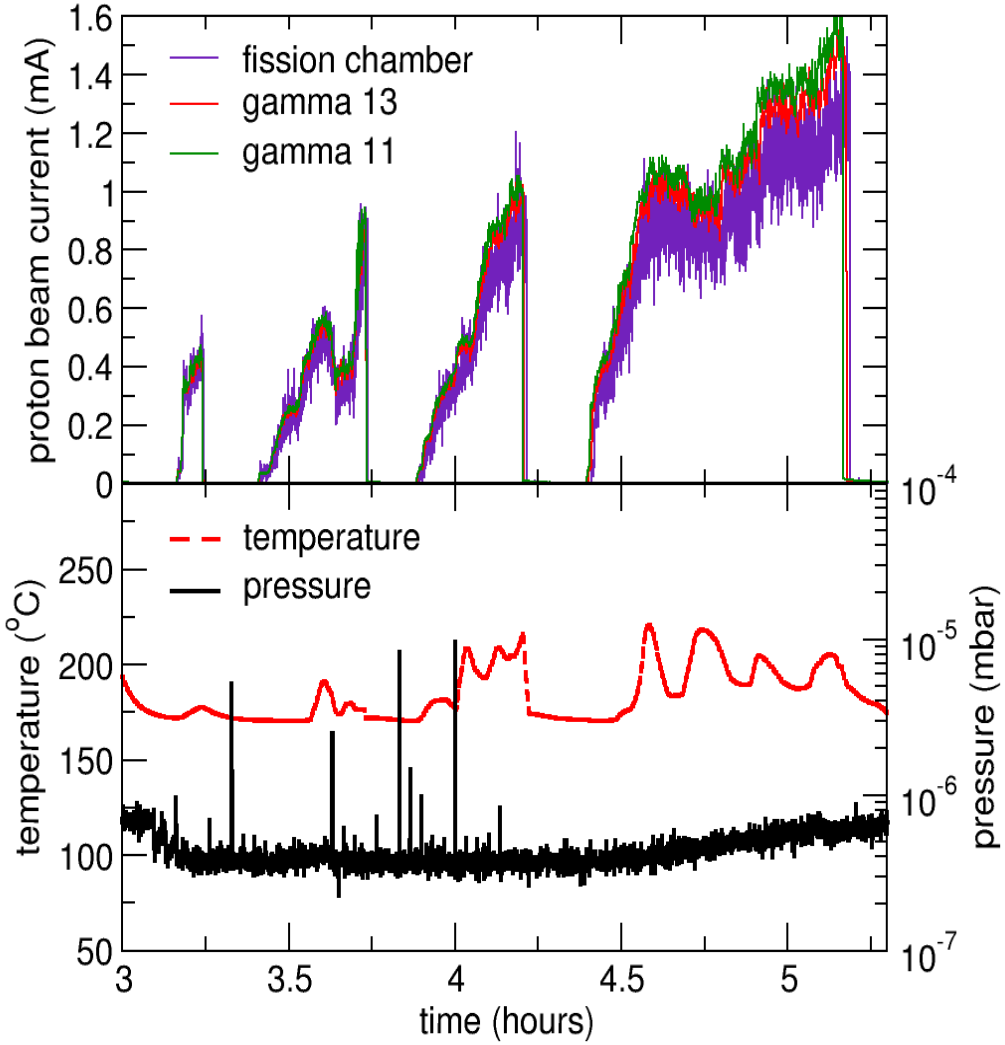
Lithium working velocity: 2.4 m/s

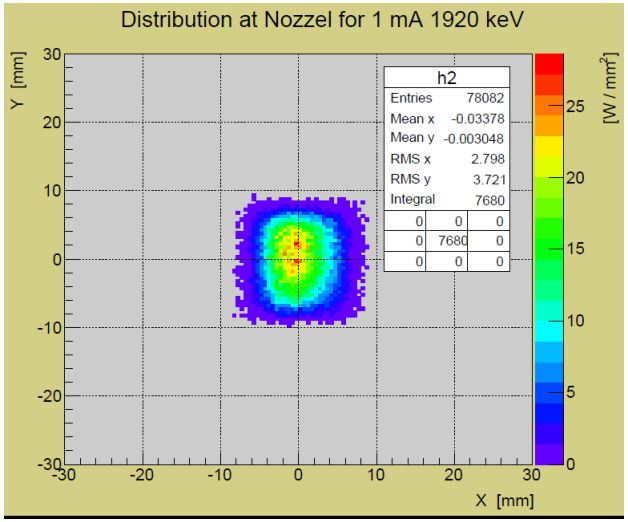




Glow on liquid lithium (A) and nozzle ears (B) during proton beam operation.

Above-threshold experiment E_p=~1.9 MeV





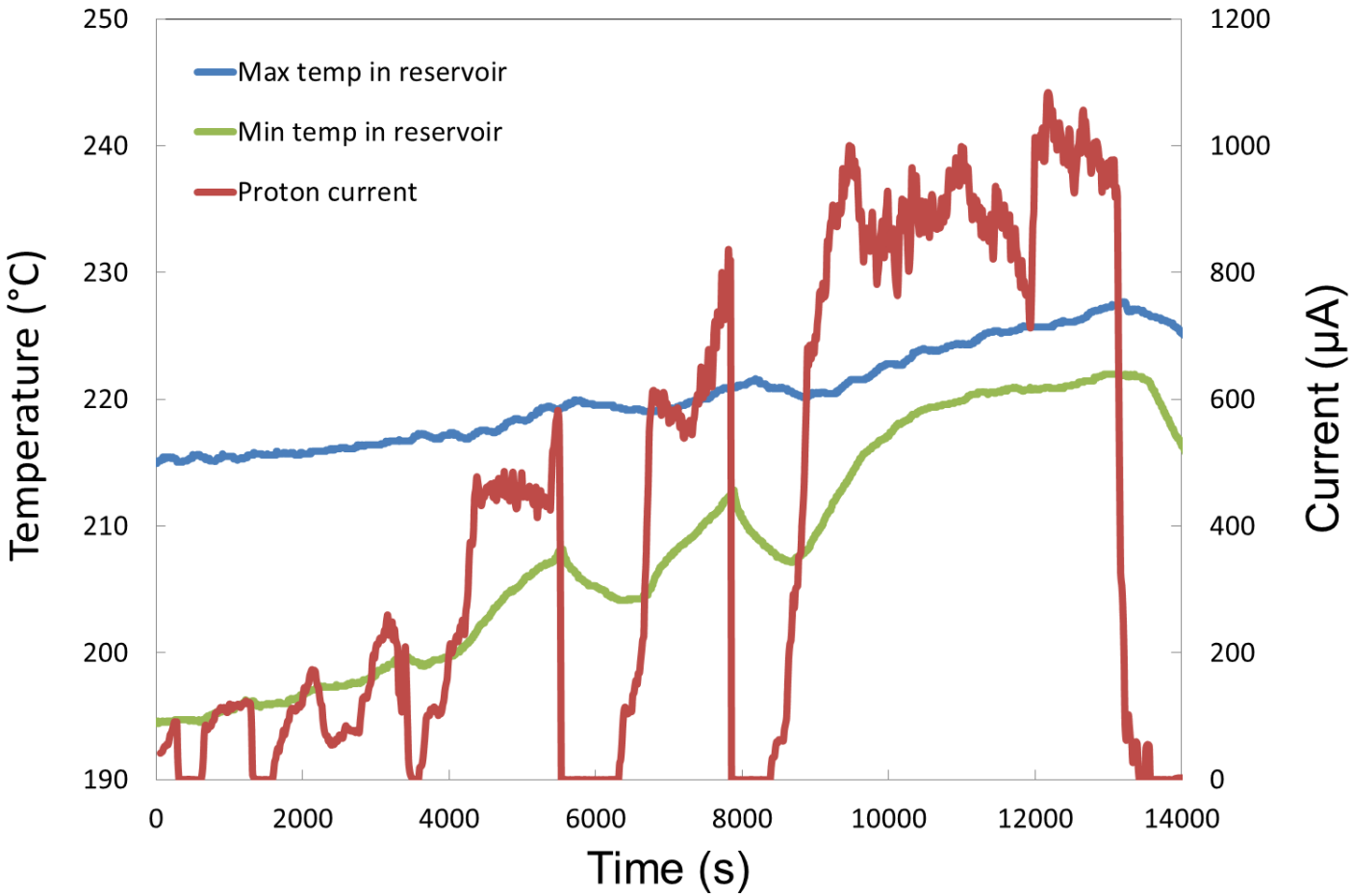
σ_x= 2.8 mm and σ_y=3.8 mm

Peak power densities:
3 kW/cm^2 and
~ 0.6 MW/cm^3

S. Halfon, et al., Review of Scientific Instruments, 85, 056105 (2014).

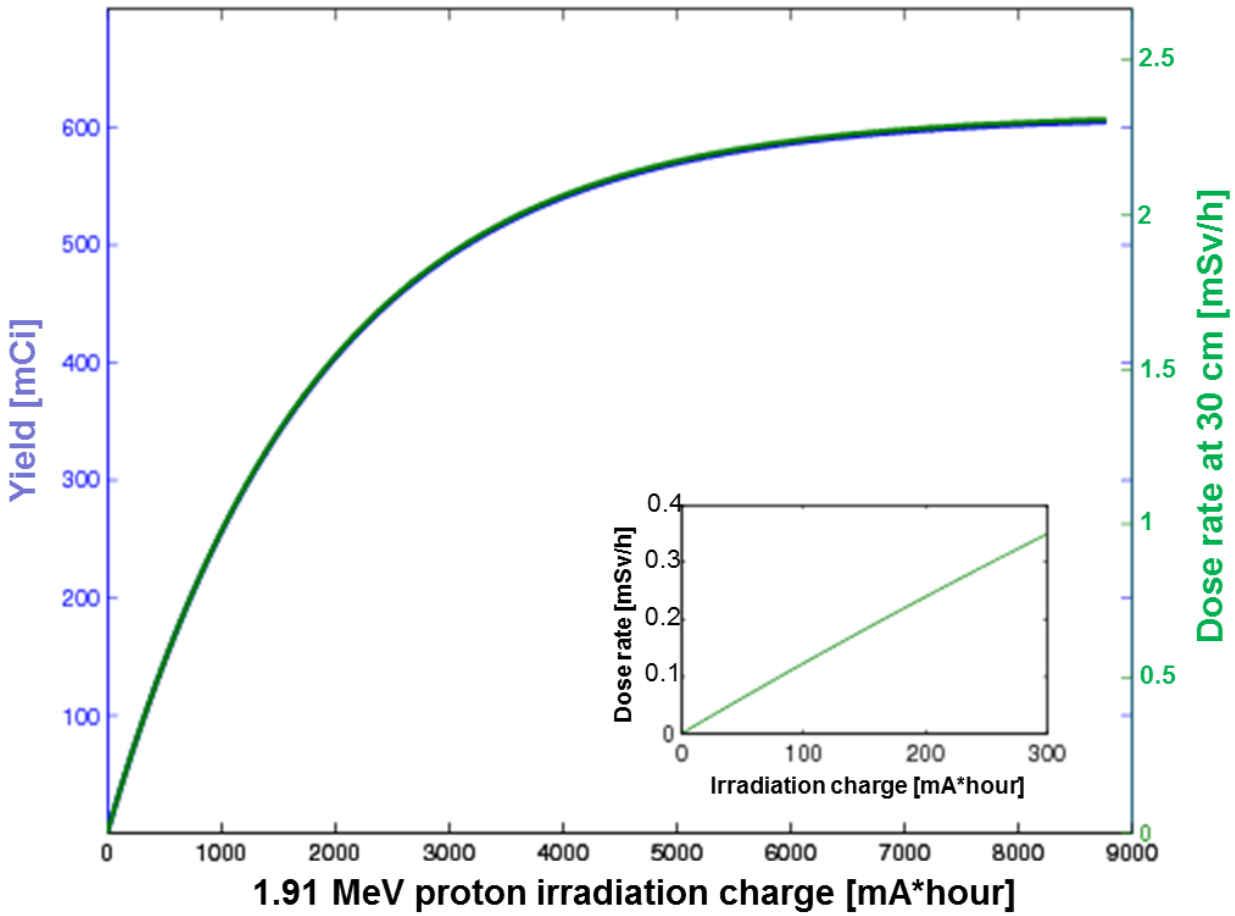
Reservoir temperatures

- Minor changes in the reservoir maximum temperature
- Oil-air heat-exchanger (vents) was not operating, and the cold trap was not sufficiently cooled at this stage to 190°C



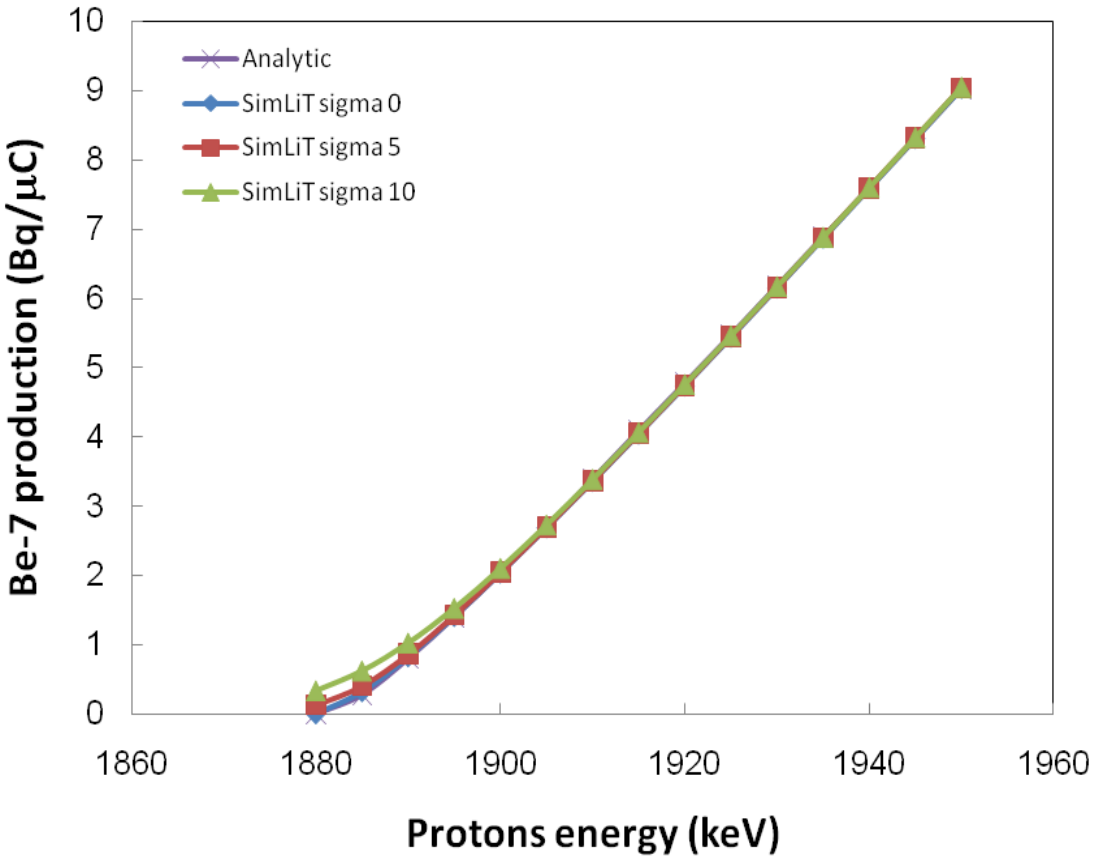
^{7}Be production calculations – point source

- ^{7}Be: half-life of 53 days, 478 keV gamma radiation
- Annual irradiation with 1 mA, 1.91 MeV nominal proton beam energy, will produce saturation dose rate of: 2.25 mSv/h (600 mCi), 30 cm from a point source
- During the initial 300 mA*hours (the relevant range for our usage) the production rate is linear



Proton beam energy distribution

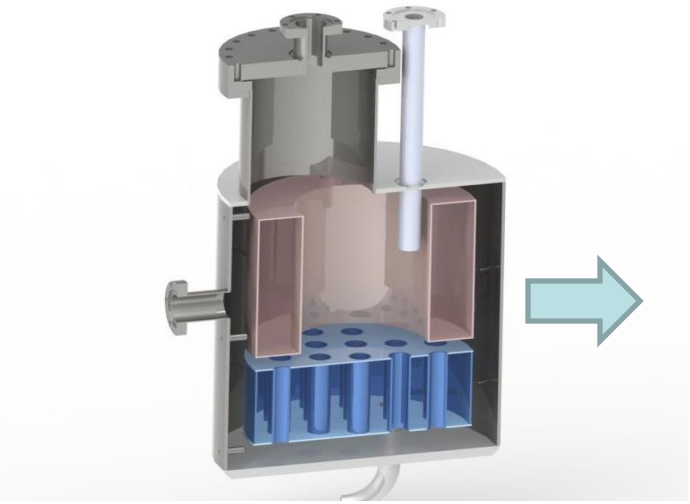
- SARAF proton beam has Gaussian energy distribution ($\sigma \approx 10$ keV)
- Calculations taking into account the realistic energy distribution, using the code SimLiT[1], shows that such energy distribution will not change significantly the ^{7}Be production rate, at energies above 1.9 MeV

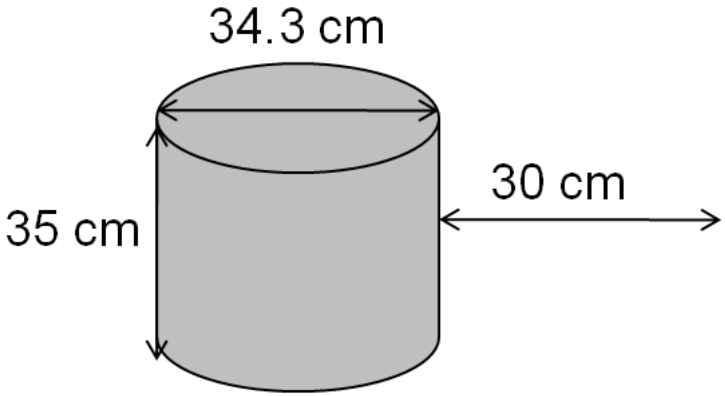


[1]M. Friedman et al. Nucl. Inst. Meth. A 698 117 (2013)

LiLiT realistic ^{7}Be source simulation

- A calculation of the maxumum dose rate due to ^{7}Be activity homogeneously distributed in the LiLiT lithium reservoir, at a distance of 30 cm from the center of the was performed using the Monte-Carlo code MCNP and benchmarked using the deterministic code Microshield .
- The results predict a reduction of 70% in the dose rate compared to a point source assumption, giving expected maximum dose rate of **0.37±0.05 μSv/h/(mA·h) at 1.91 MeV**
- The calculation can be extrapolate to other energies by simply multiplying with by the production rate ratio





^{7}Be activity in LiLiT loop measurements after SARAF proton irradiations

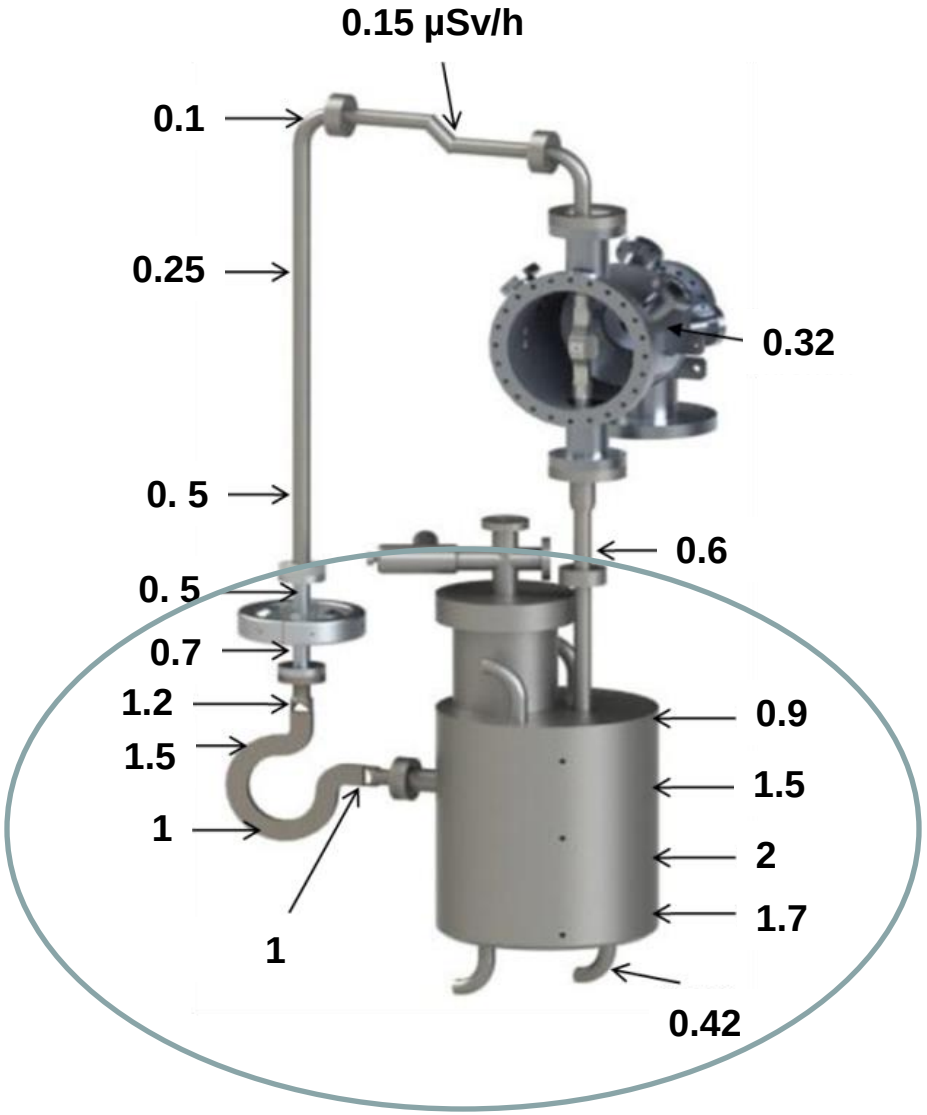
- After few of the proton irradiations at SARAF, ^{7}Be analysis took place:
  - At the first stage the maximum dose rate in front of the lithium reservoir was measured, two examples will be present here:

Date	Energy (keV)	Charge (mA*h)	Expected dose rate [μSv/h]	Measured dose-rate [μSv/h]
Oct. 2015	1910	~0.8	**0.30±0.5**	**0.3**
July 2014	1926	~7.2	**4.61±0.62**	**4.37**

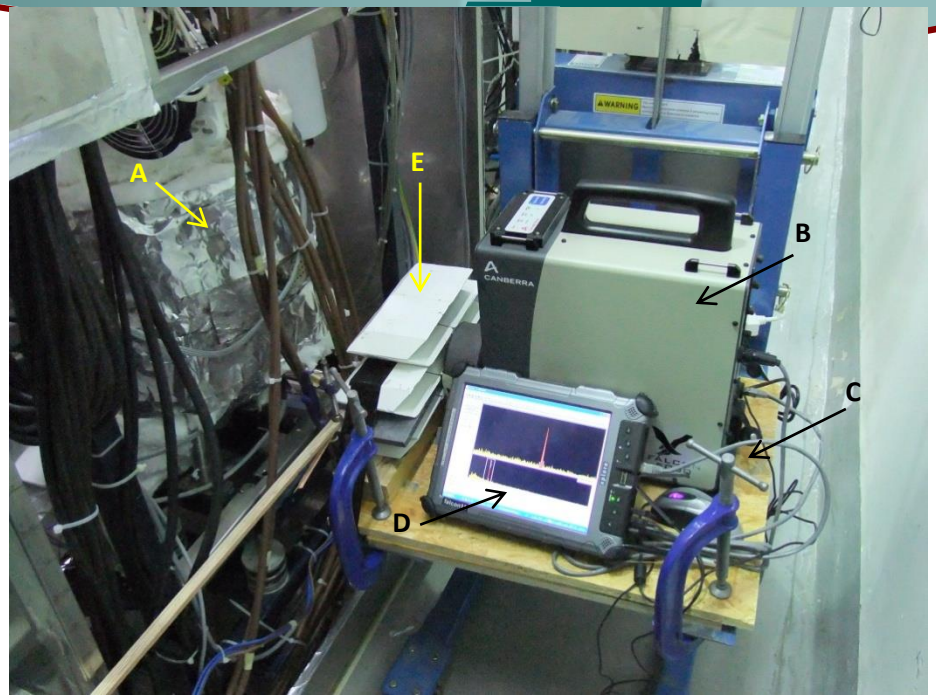
  - The measurements are within the calculation error estimation

^{7}Be distribution measurements

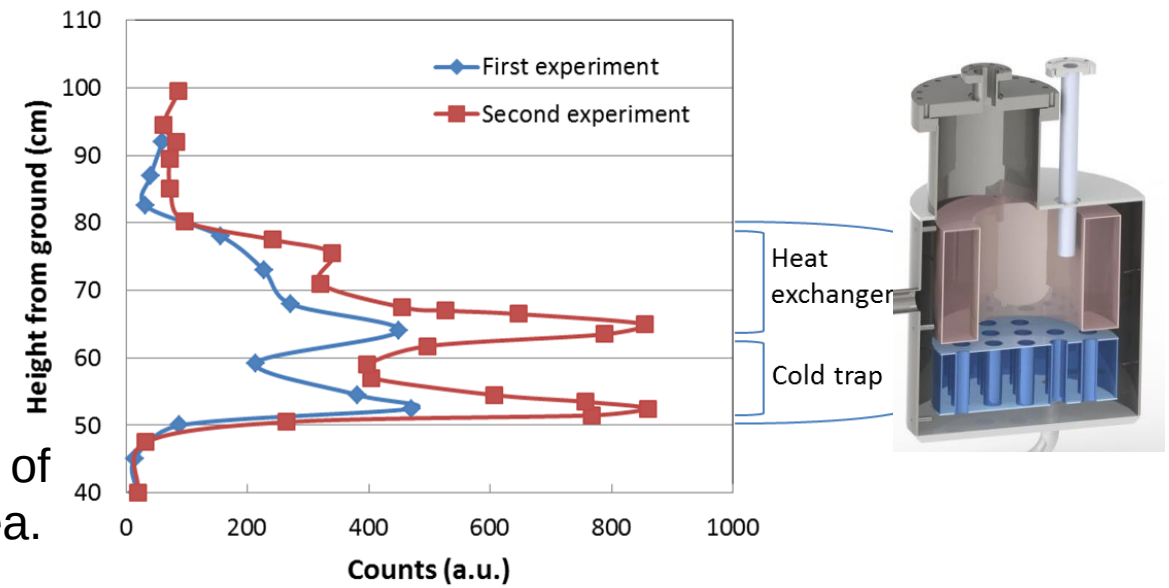
- Portable NaI detector was used to measure the dose-rate distribution around the loop (in contact)
- the activity follows the lithium accumulation areas: highest activity around the reservoir and EMP loop (filled with lithium)



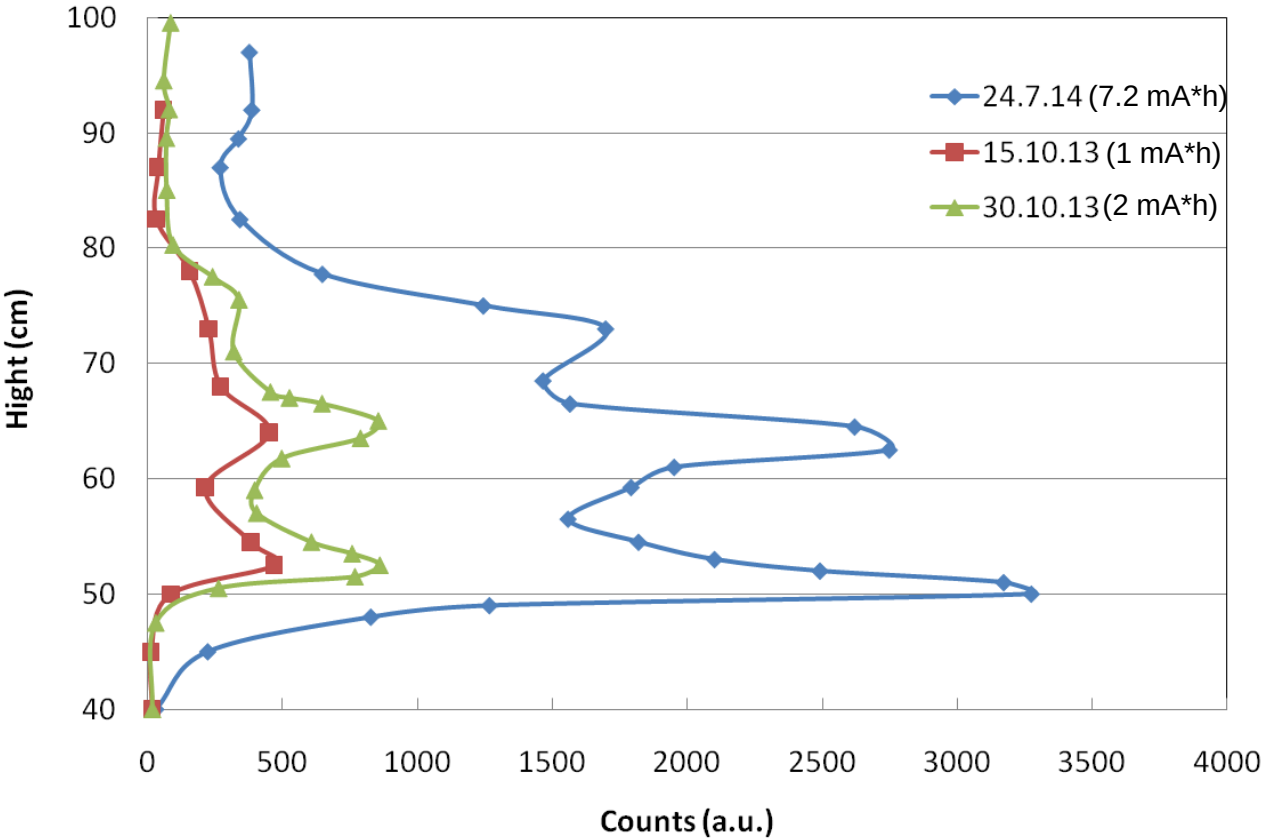
^{7}Be distribution along LiLiT reservoir

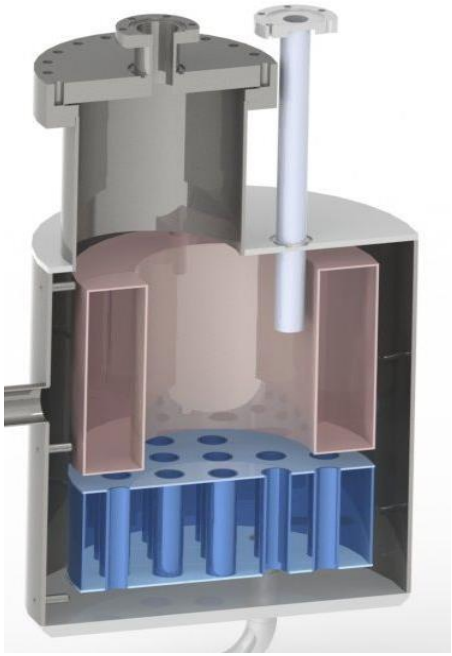


- The reservoir was scanned using HPGe spectrometer measurements, with a lead collimator, leaving only a 55 mm × 10 mm slit in front
- The distribution has peaks in front of the area between the surface and the cold trap and the area between the cold trap and heat exchanger- where higher amounts of lithium are located
- The cold trap was not operating at this stage, hence, no evidence of higher activity at the cold trap area.



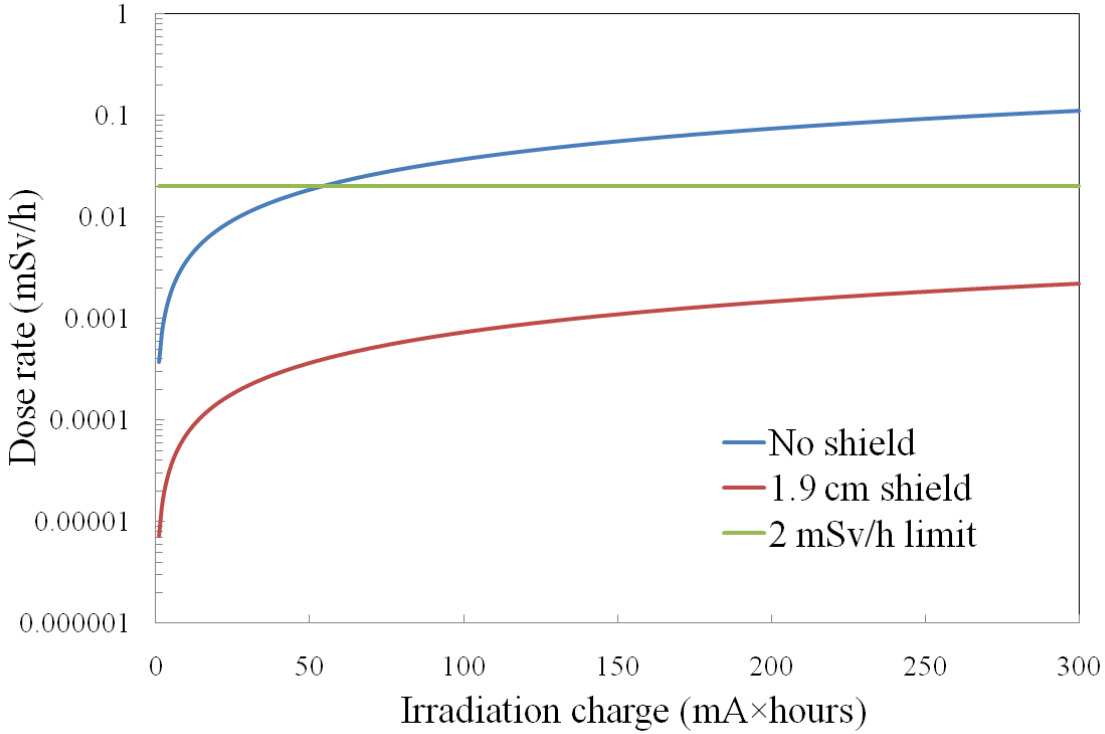
•After longer irradiation time, 7.2 mA*h, highest ^{7}Be activity was measured at the bottom of the reservoir.





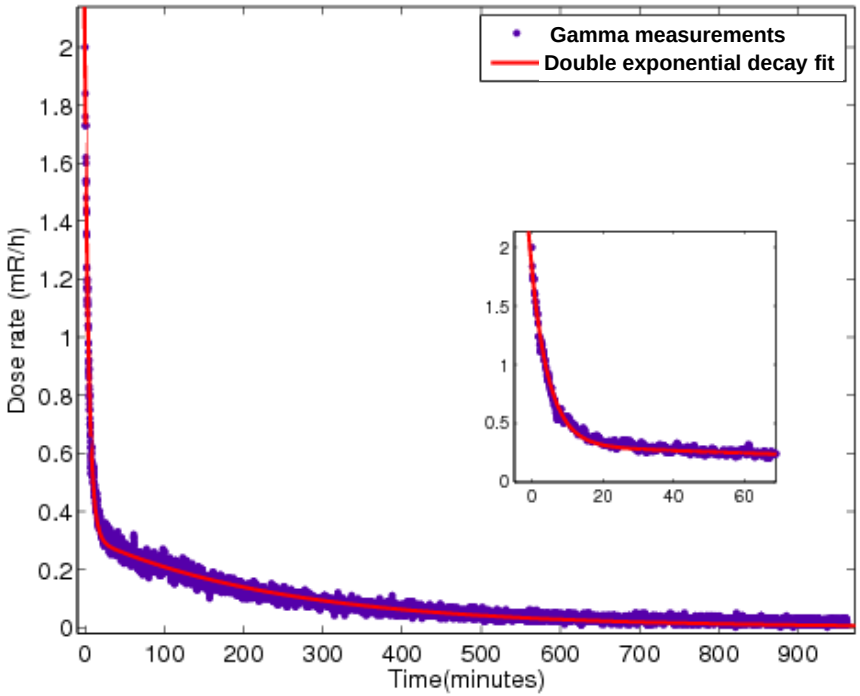
Shielded reservoir

- A 1.9 cm thick lead shield was designed and built for the LiLiT reservoir and will be installed around it when the experimental schedule will impose it
- a shielded reservoir will allow thousands of mA*hours while keeping dose rates in the beam corridor within safety limits



Neutron activation of construction materials

- The LiLiT is constructed of stainless steel 316 (due to its durability with lithium)
- According to the decay scheme measured around the system after proton irradiation, the activation product due to the epithermal neutron flux were identified:



	GM11	Isotope
λ_1	$3.36\times10^{-3}\pm 6.7\times10^{-4}$	^{55}Cr: 0.0033
($t_{1/2}$)	(3.44±0.7 m)	(3.497 m)
λ_2	$6.78\times10^{-5}\pm1.4\times10^{-5}$	^{56}Mn: 7.468×10^{-5}
($t_{1/2}$)	(2.84±0.6 h)	(2.578 h)

- SS 316 contains ~16% Cr and ~2 % Mn
- Production reactions:

  $^{54}Cr(n,\gamma)^{55}Cr$, $^{55}Mn(n,\gamma)^{56}Mn$

First physics measurements at LiLiT

Preliminary (G. Feinberg, PhD. Thesis, Hebrew U, Jerusalem)

$^{94}Zr(n,\gamma)^{95}Zr$ (64 d) : γ spectrometry

LiLiT (30 keV) = **29.1 ± 0.5 mb**

Literature values: **29.04 mb** (ENDF 2011)

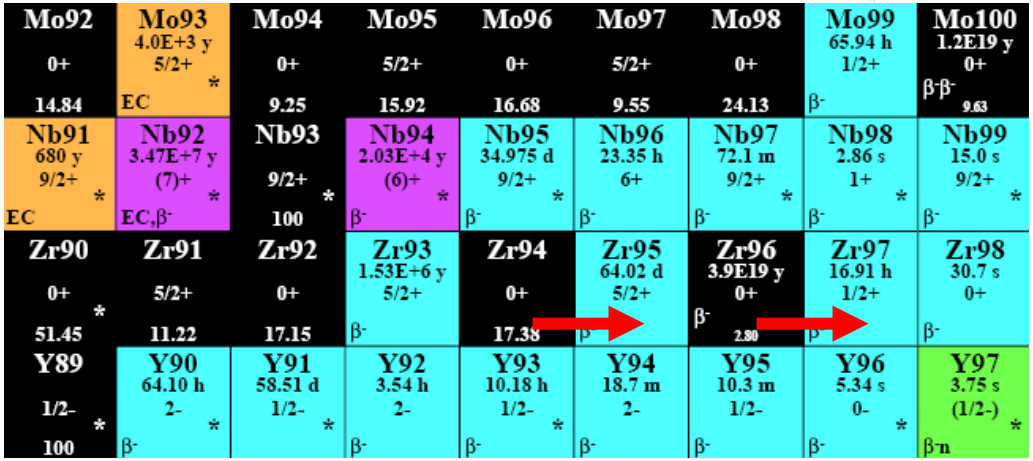
26.1 ± 1 mb (Toukan &Kaeppeler, 1990)

$^{96}Zr(n,\gamma)\,^{97}Zr$ (16.9 h) : γ spectrometry

LiLiT (30 keV) = **13.1 ± 0.9 mb**

Literature values: **10.26 mb** (ENDF 2011)

10.7 ± 0.5 mb (Toukan &Kaeppeler, 1990)



Conclusions

- A liquid lithium target was irradiated safely and stably with high power proton beam and neutron production demonstrated.
- The ^{7}Be dose rate calculation is reliable with precision of ~5 %.
- The activity of ^{7}Be on the bottom of the reservoir became higher than its middle part peak, which might indicate more significant accumulation of ^{7}Be around the reservoir bottom.
- Future plans:
  - Operating the cold trap, and exploring its efficiency in different conditions
  - Mapping the activity distribution during lithium circulation

Thank you for your attention