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

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Workshop on Accelerator based Neutron Production
ABNP 2014
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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

SOREQ

SARAF Accelerator

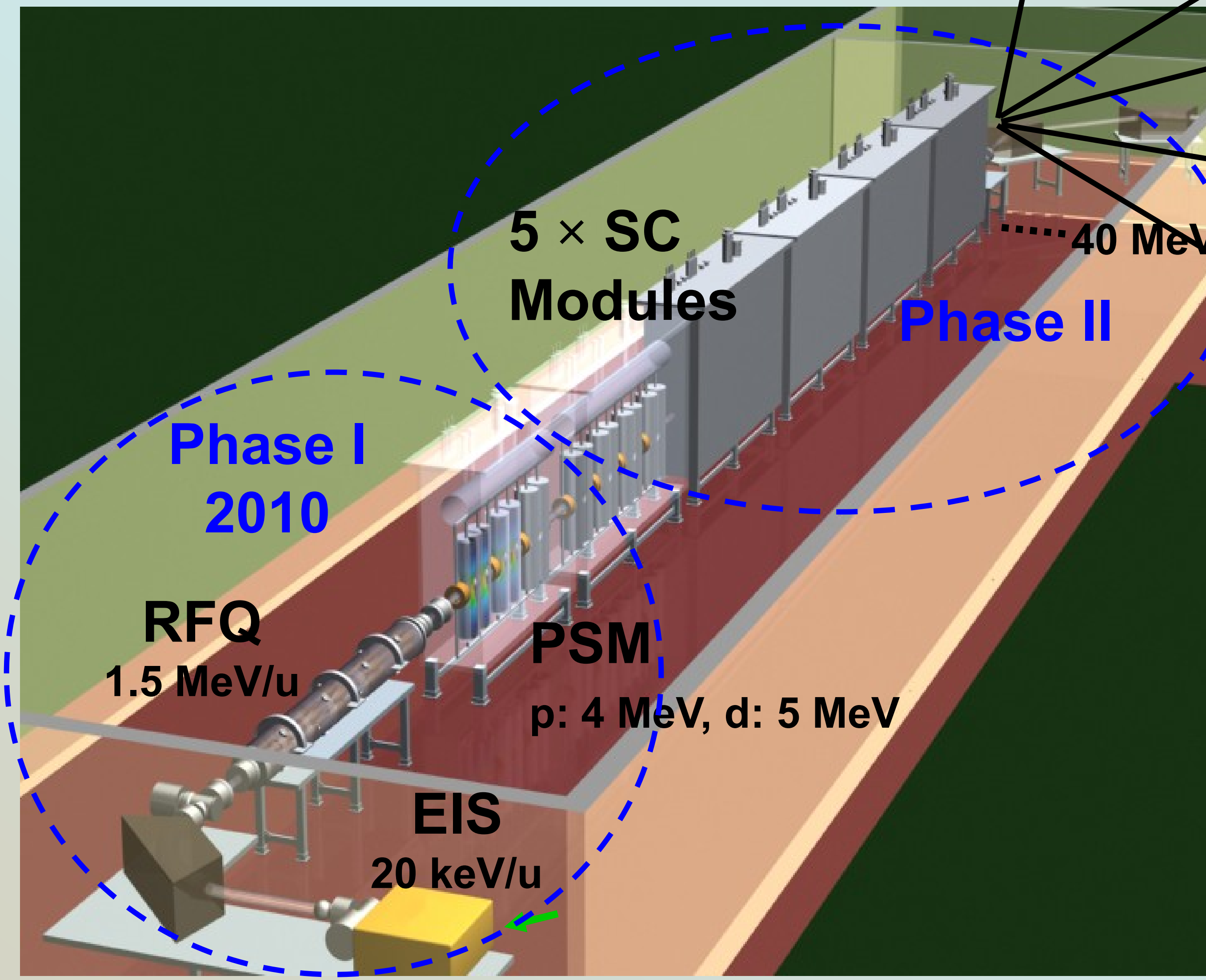
Thermal neutron radiography

Thermal neutron diffraction

Nuclear Astrophysics

Radioactive beams

Radio Pharmaceuticals



Accelerator phase 2 Parameters

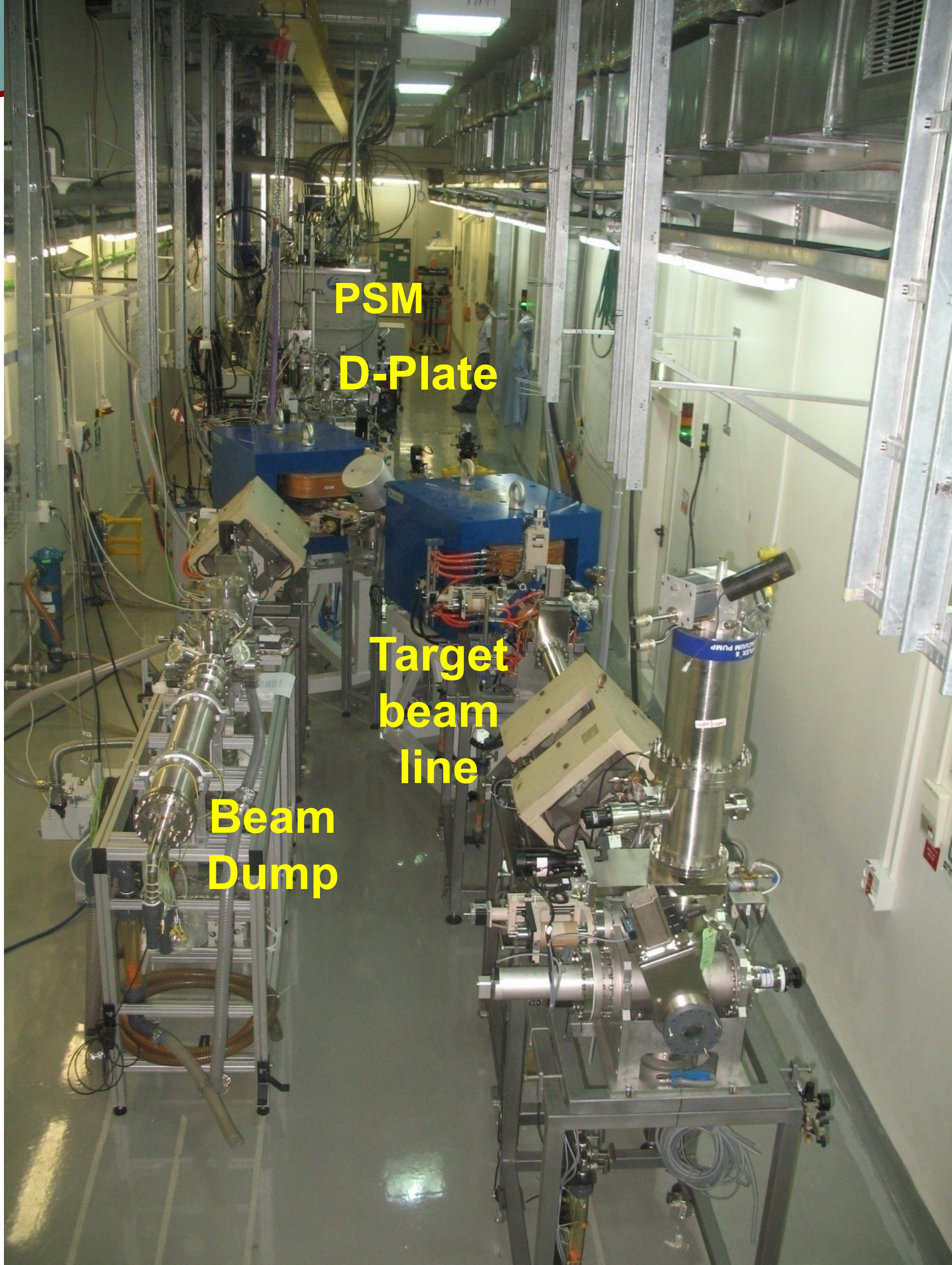
Parameter	Value
Ions	p / d
Energy	5 – 40 MeV
Current	0.04 – 5 mA
Maintenance	Hands-On

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
D. Berkovits, Linac 2012
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

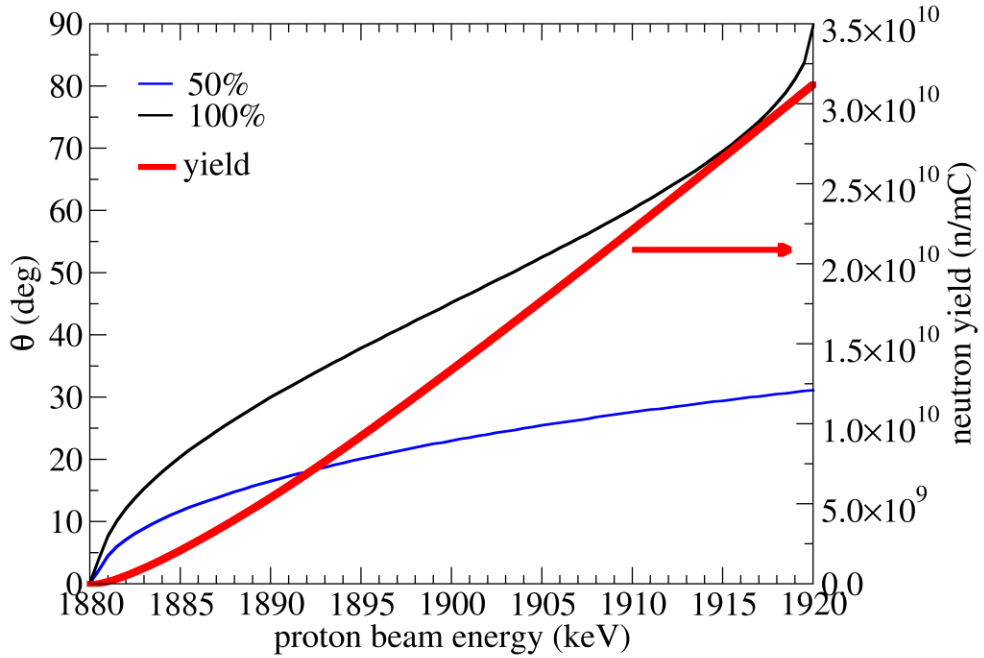
- SARAF phase I: creating unique high intensity neutron flux for advance research on:

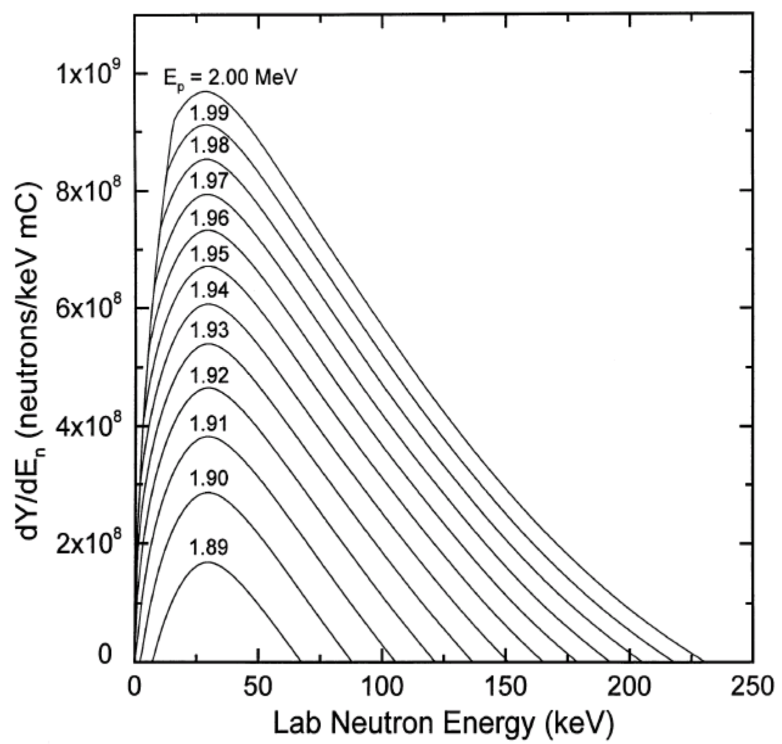
1. Nuclear medicine (BNCT)
2. Stellar and big-bang nuclear astrophysics (nucleosynthesis)
3. Cross section measurements (generation IV reactor and ADS design)
4. Radioactive beams

Neutron producing lithium target

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

Angular distribution





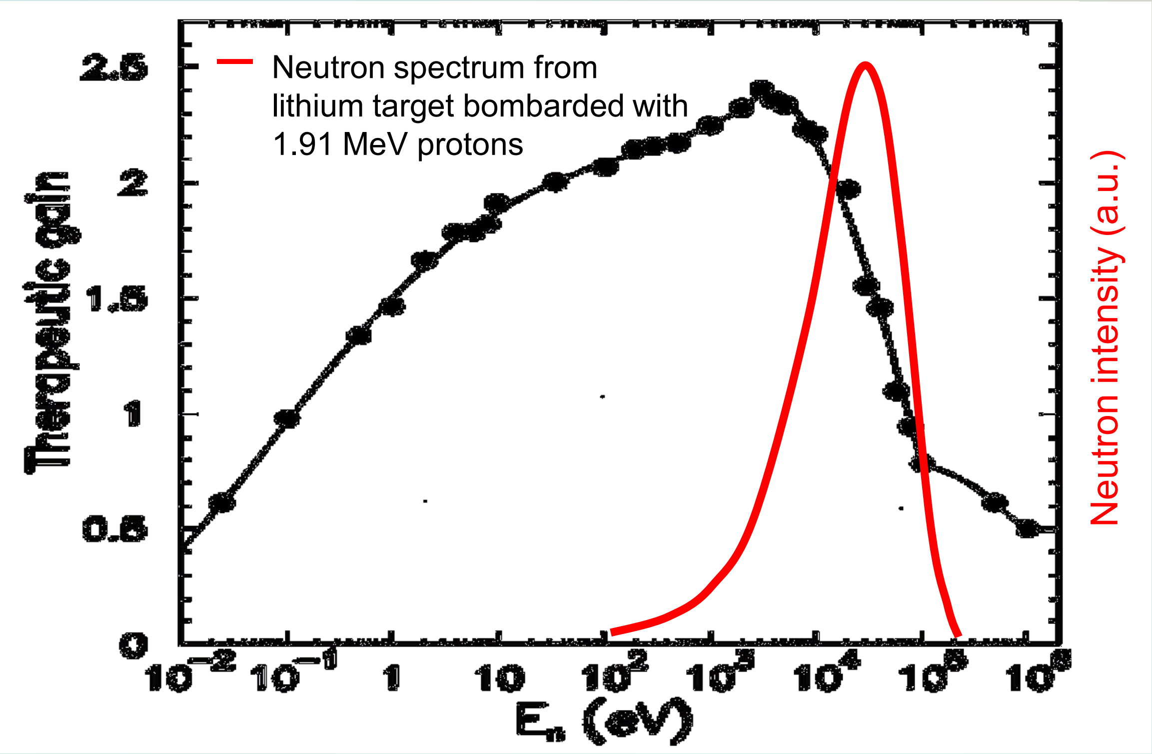
C.L. Lee, X.-L. Zhou, Nucl. Instr. and Meth. in Phys. Res. B 152 (1999) 1-11

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**



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}

LiLiT – High flux keV neutron source

- The research require high neutron flux (>10^9 n/cm^2/s)
  - >4 kW beam power (p, ~2 mA, ~2 MeV)
  - Narrow Gaussian beam (σ=~3 mm, D=~15 mm)

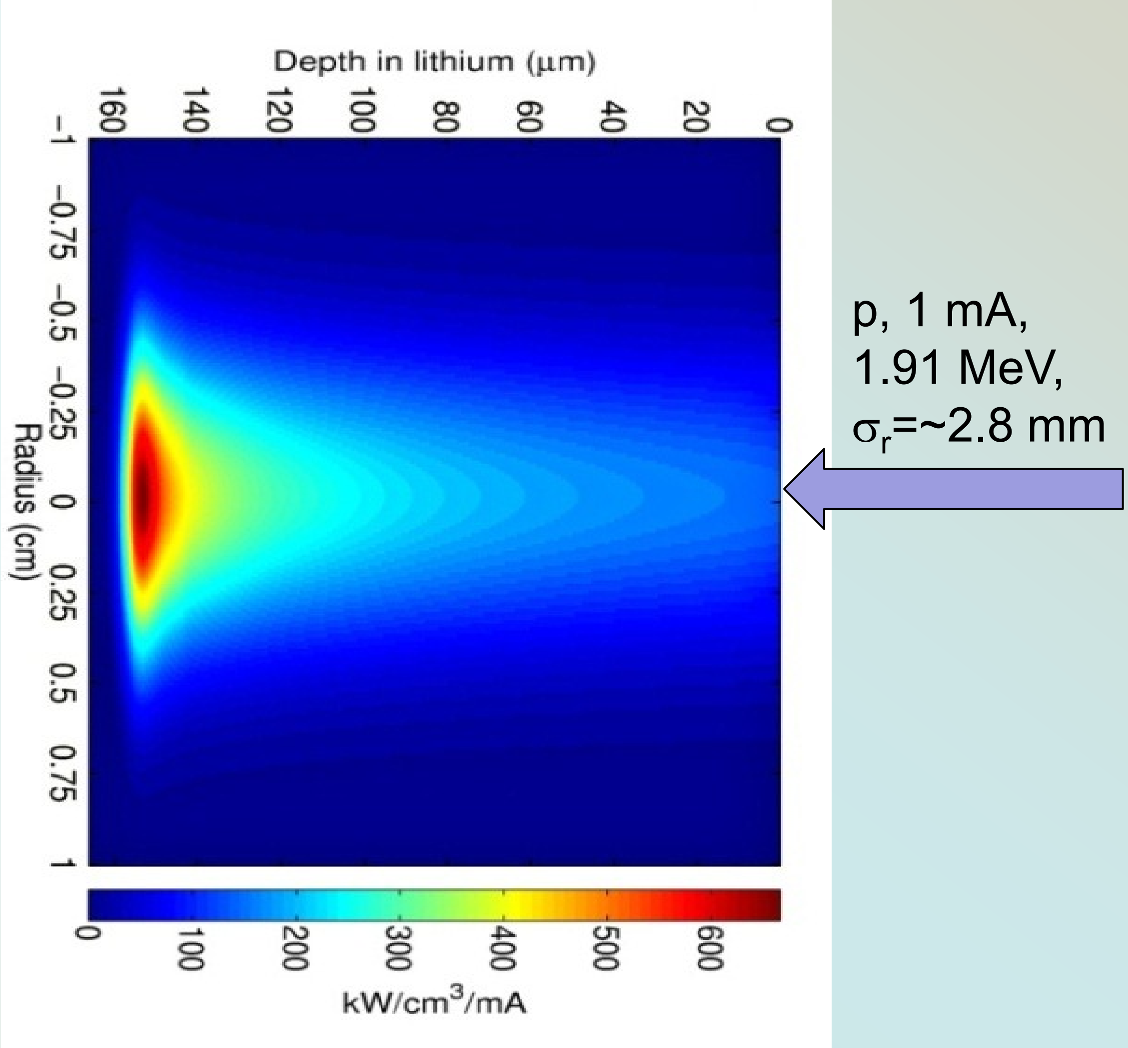
Project	IFMIF *	SPIRAL II *	LiLiT
Reaction specification	d(40 MeV) +Li	d(40 MeV) + C	p(2 MeV) +Li
Projectile range in target (mm)	19.1	4.3	0.2
Maximum beam current (mA)	250	5	2
Beam spot on the target (cm^2)	~100	~10	~1
Beam power (kW)	10000	200	4
Peak power density in the target (MW/cm^3)	0.3	0.15	>1

- The target should dissipate power densities of more then ~1 MW/cm^3

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

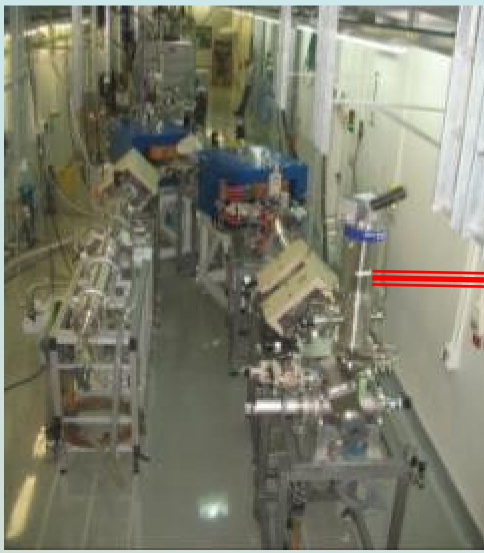
Lithium is attractive, but…

- Lithium melts at 180˚C and have poor heat capacity
  - For $^{7}Li(p,n)$ 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}Be production through $^{7}Li(p,n)\,^{7}Be$

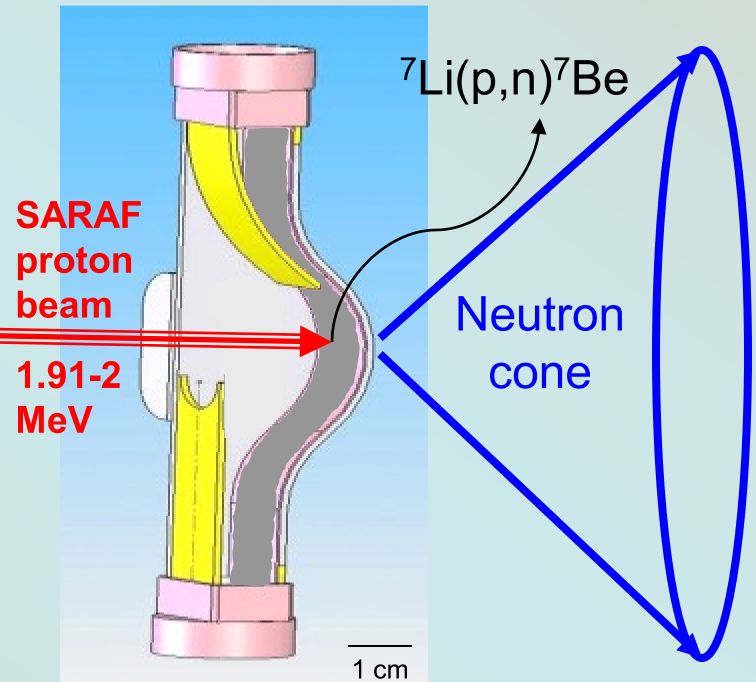


p, 1 mA, 1.91 MeV, σ_r=~2.8 mm

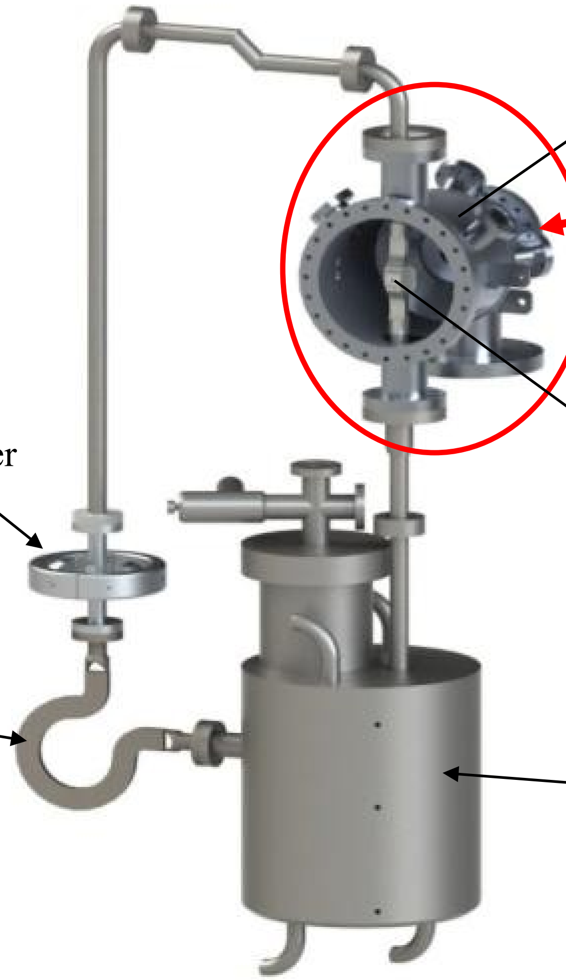
A high intensity epithermal neutron source based on a liquid lithium target



Soreq Applied Research Accelerator Facility (SARAF)

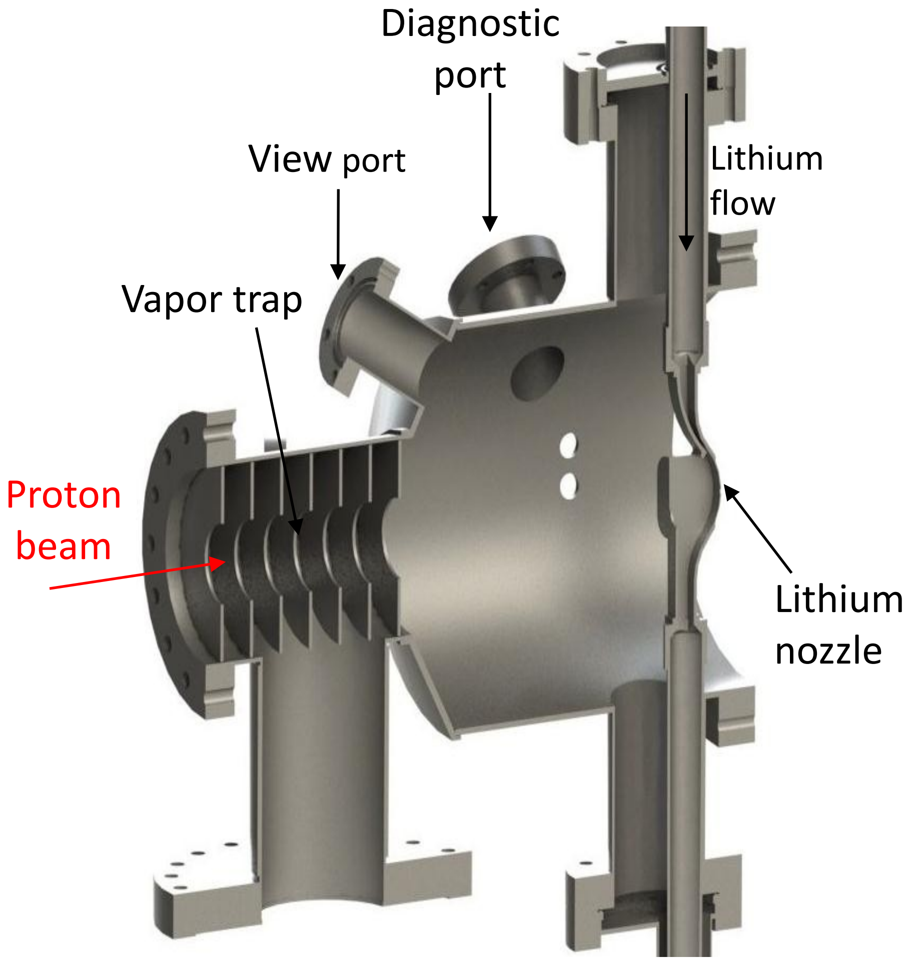


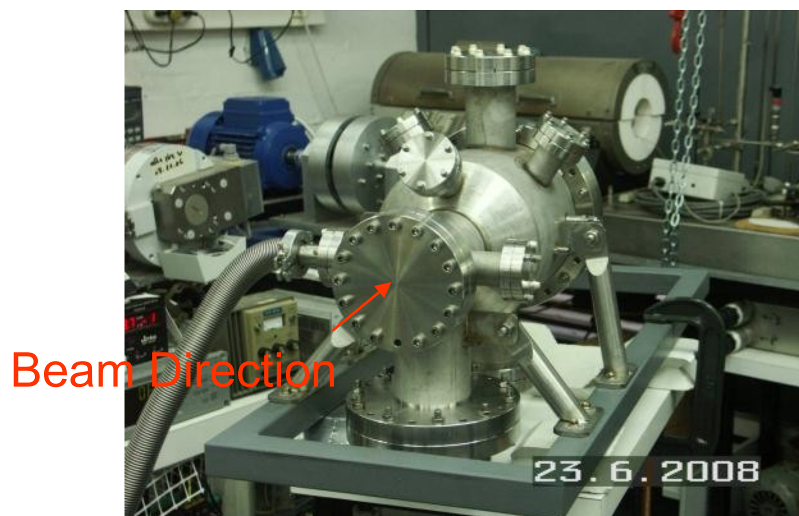
LiLiT- Liquid Lithium Target



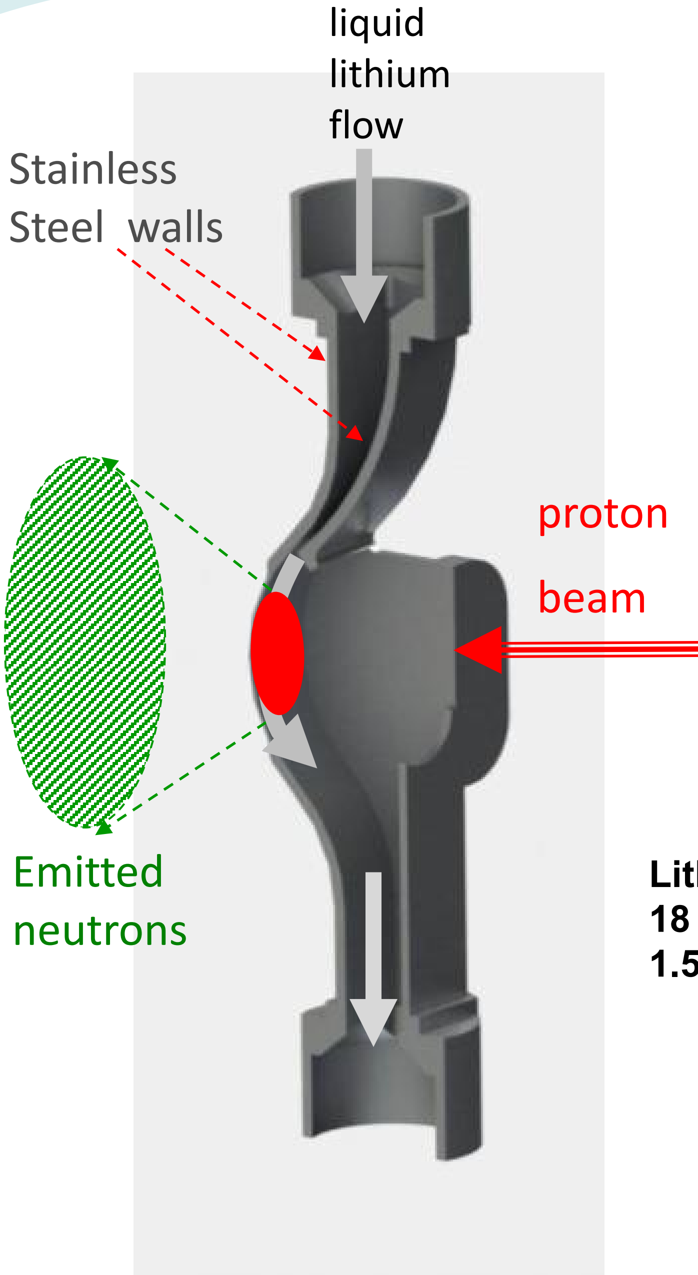
S. Halfon et al., Review of Scientific Instruments 84, 123507 (2013).

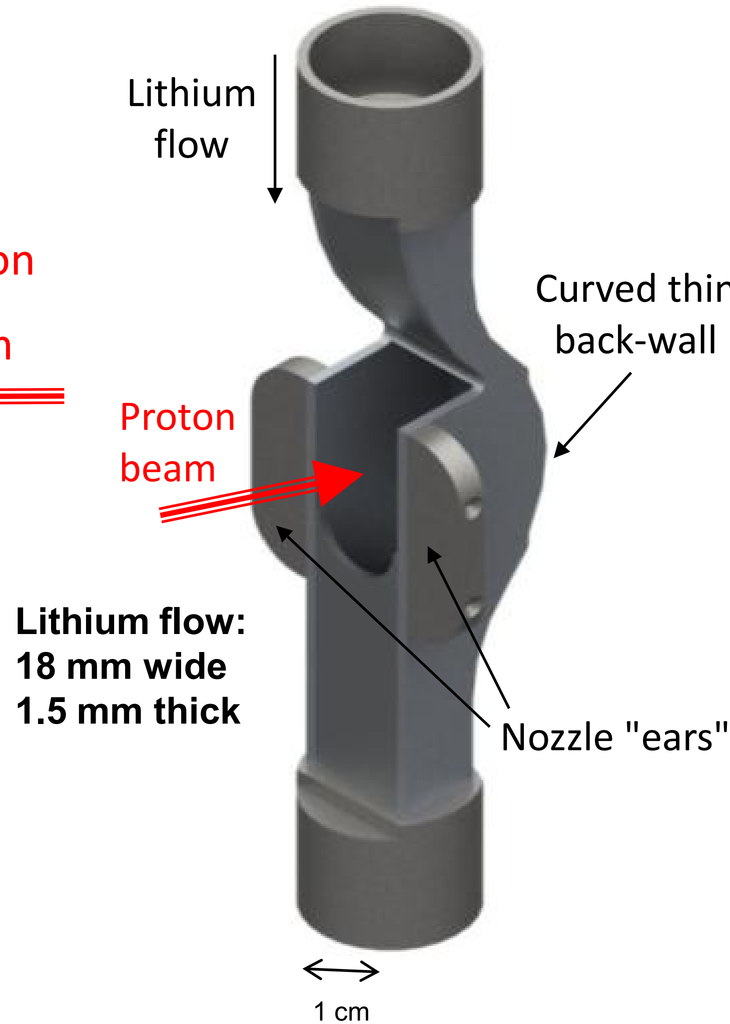
Target vacuum chamber

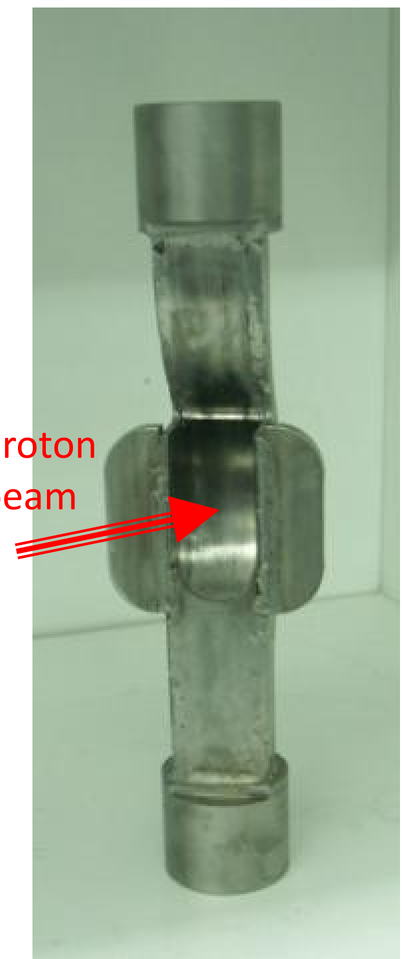




Lithium Nozzle

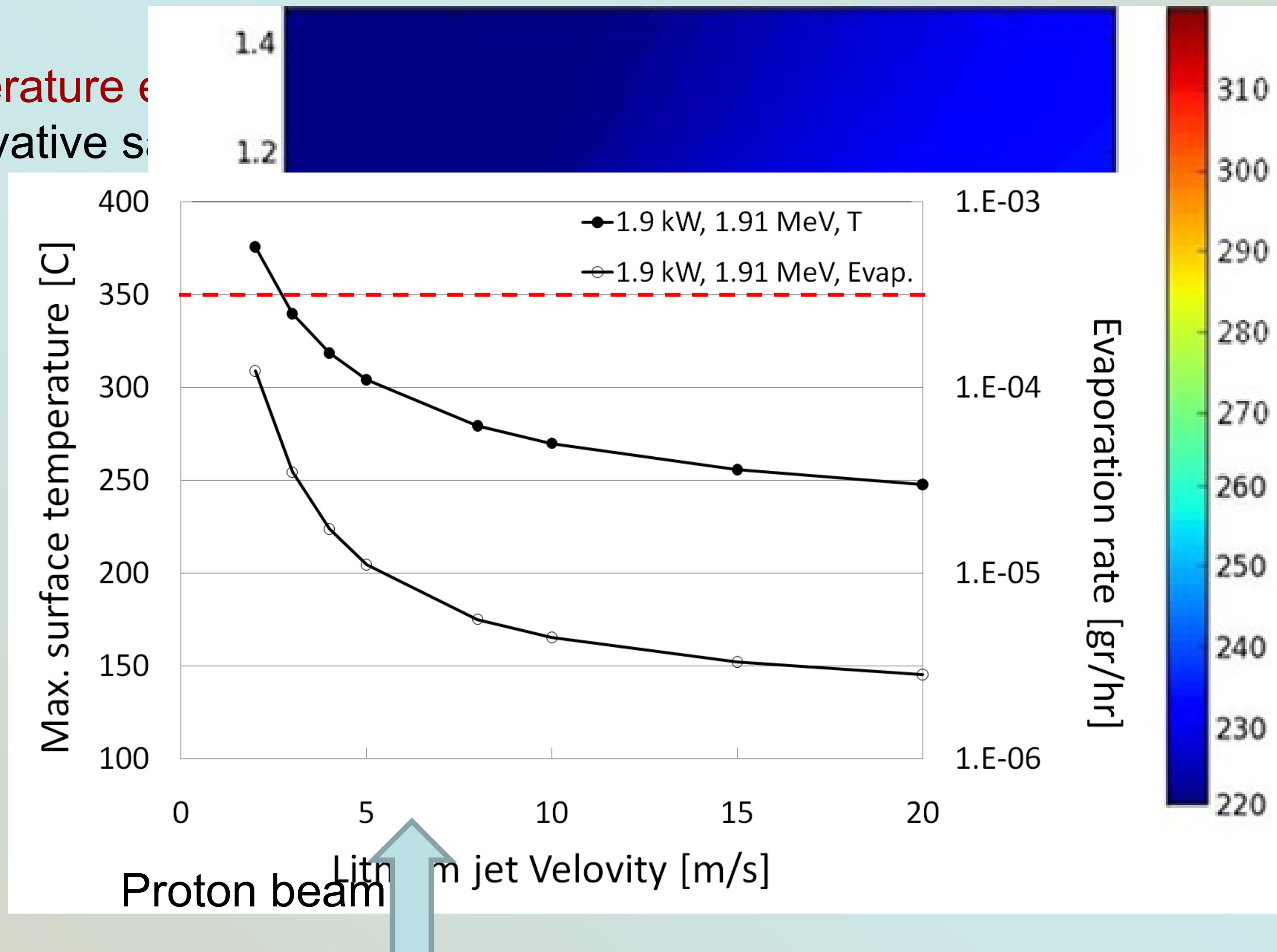






Thermal estimates

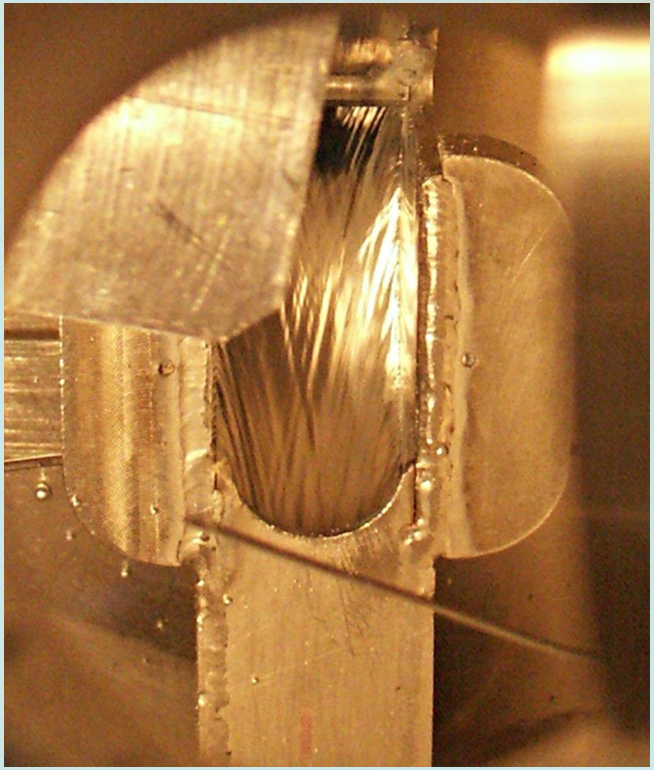
- Gaussian proton beam (σ=2.8 mm, D=14 mm)
- P_{beam}= 4 kW (1.91 MeV, 1 mA)
  - Bulk heating - ΔT=~10°C
- V_{Li}=4 m/s
- Peak temperature e
  - Conservative s)



Preliminary experiments

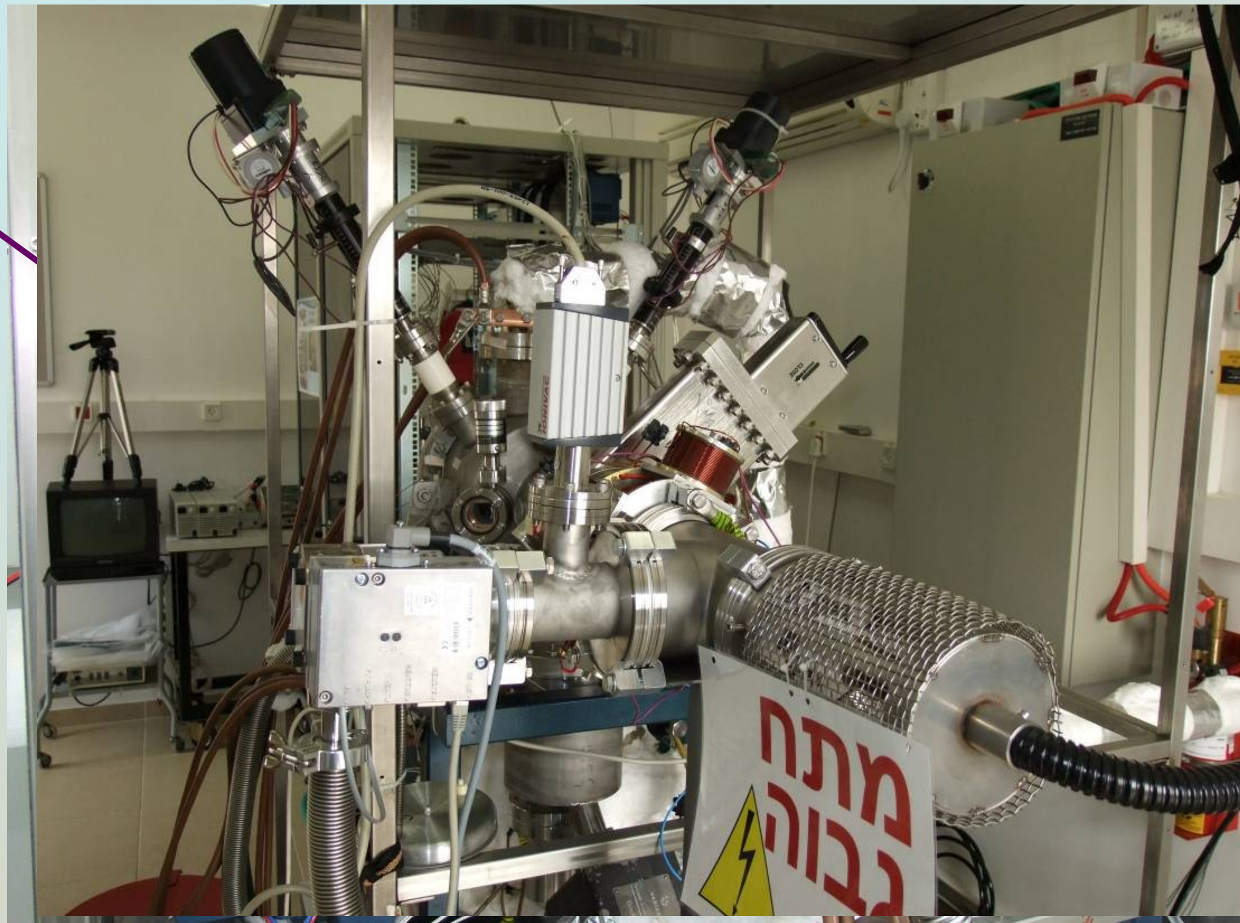
❖ Took place in a fire resistant laboratory:

1. Circulation tests: Stable and full lithium film at velocity up to 7 m/s.
2. Electron gun tests: 1.5 kW (σ_r=~2.8 mm) electron beam irradiations- dissipated power densities of more than 4 kW/cm^2 and volume power density ~2 MW/cm^3 at a lithium flow of ~4 m/s, with:
   - stable temperature
   - beam line vacuum conditions
   - no excessive evaporation.



100 mA, 26 keV (2.6 kW) electron gun at LiLiT

Beam dump



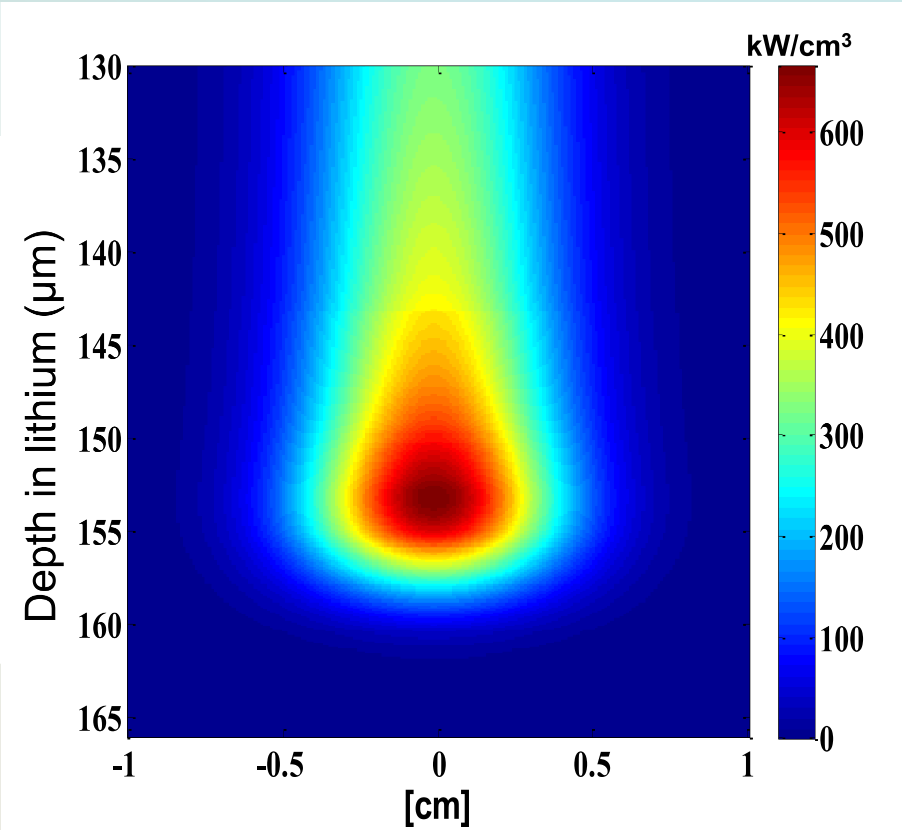
Magnetic lens

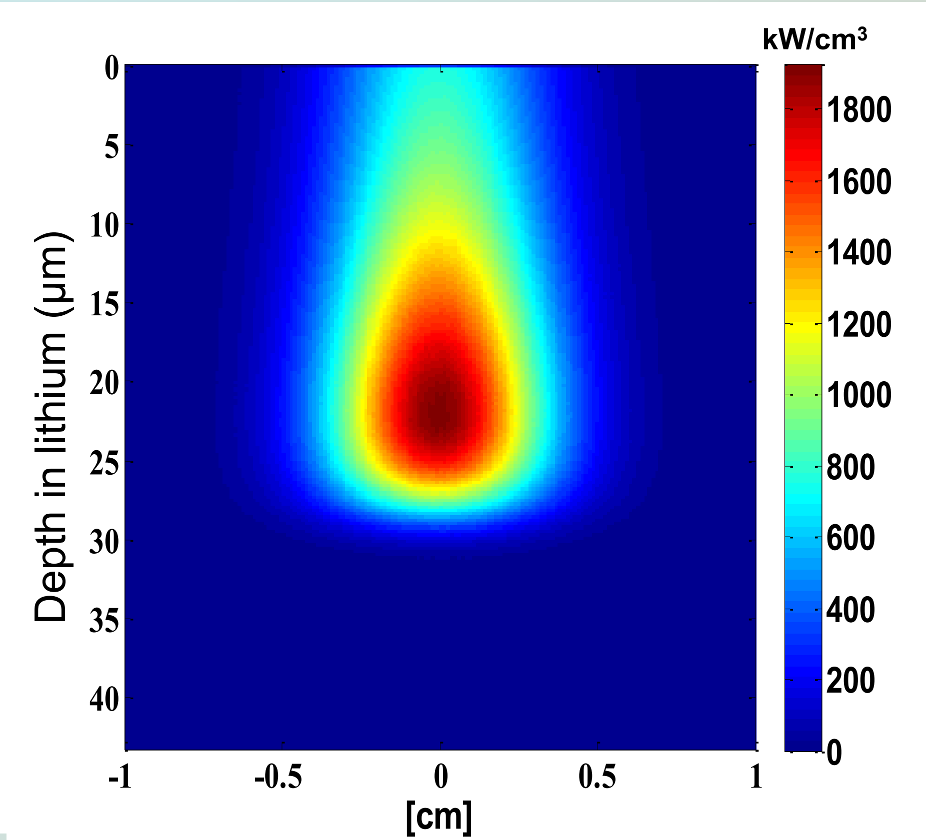
Electron gun thermal deposition tests

- **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 kW), σ=2.8 mm protons in lithium (TRIM)

60 mA, 26 keV (~1.5 kW), σ=2.8 mm electrons in lithium (CASINO)



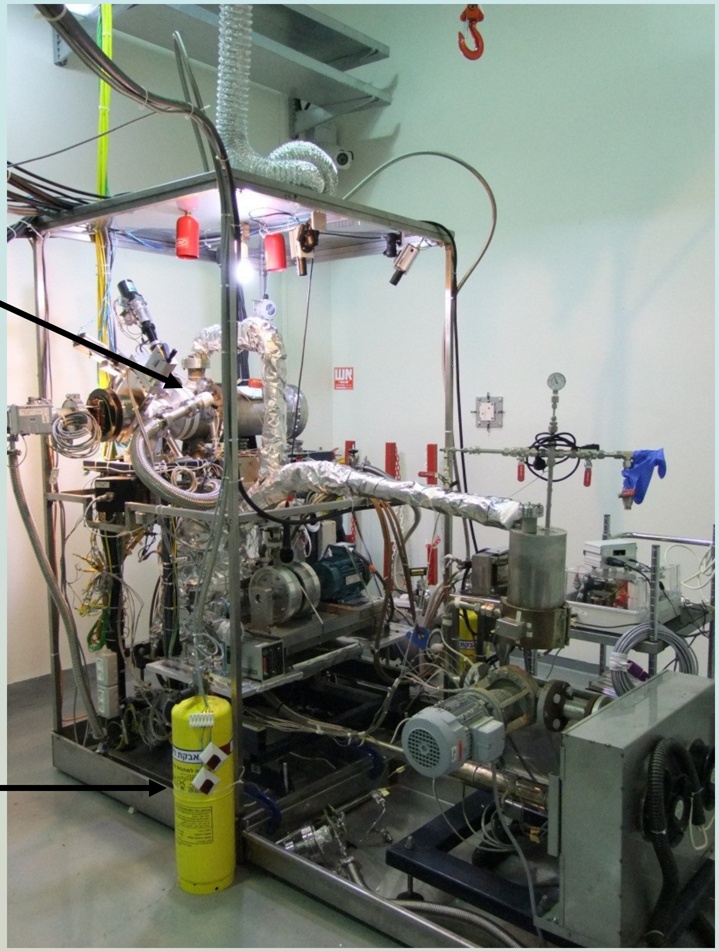


Installation in SARAF accelerator

Nozzle chamber

Proton beam

Graphite fire extinguisher



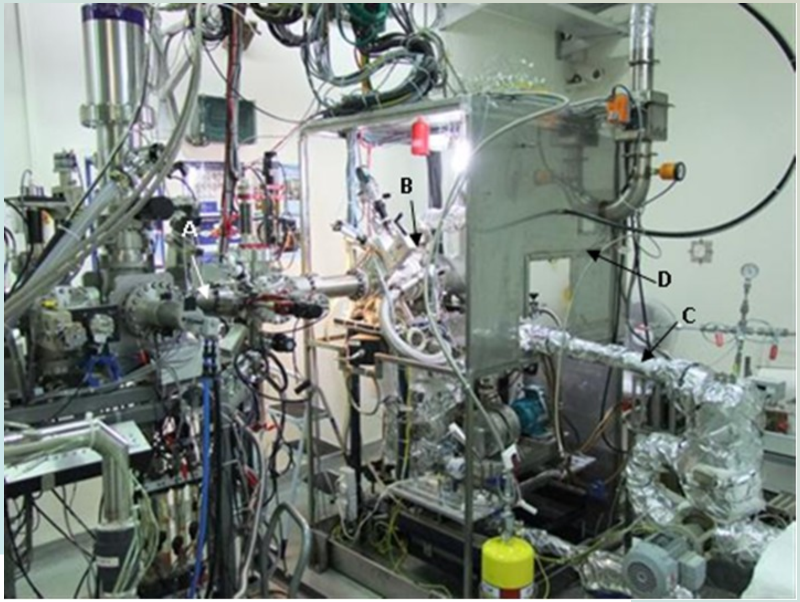
Scrubber port

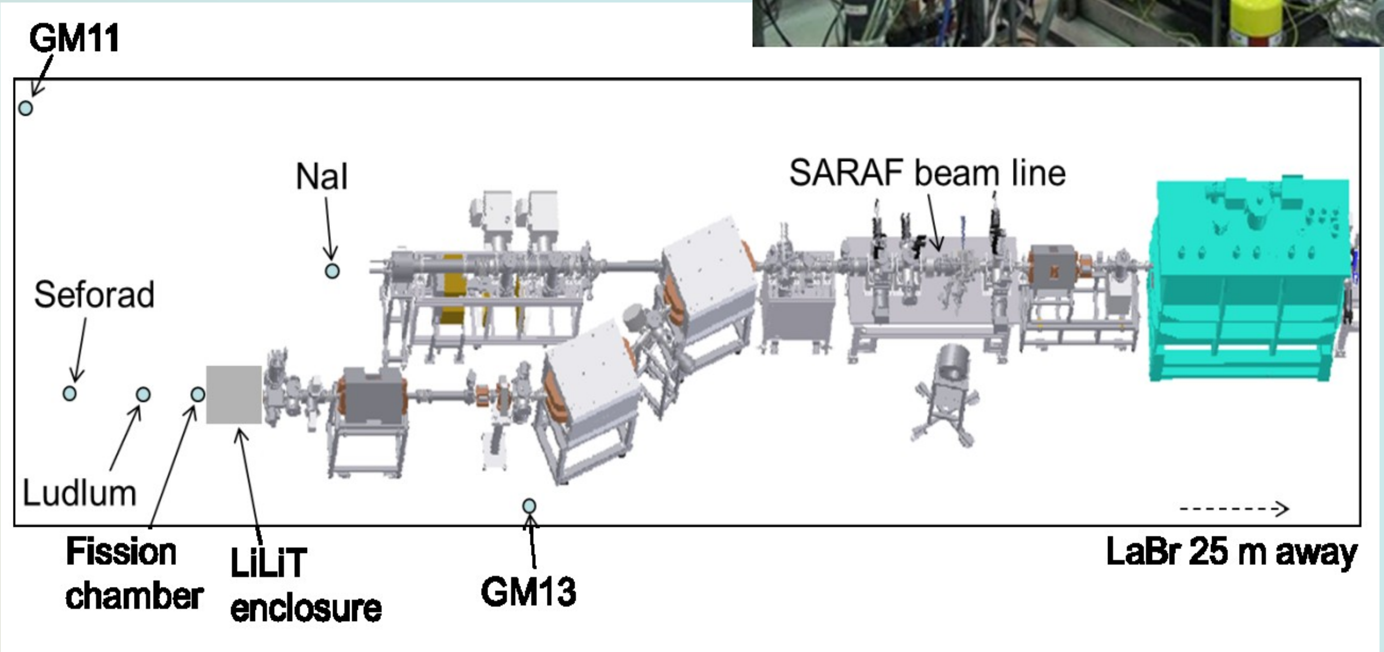
LiLiT enclosure

LiLiT and detectors setup in SARAF beam line

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

- The measured γ exposure rate (in mR/h) was calibrated with charge current reading by a high-power Faraday cup.

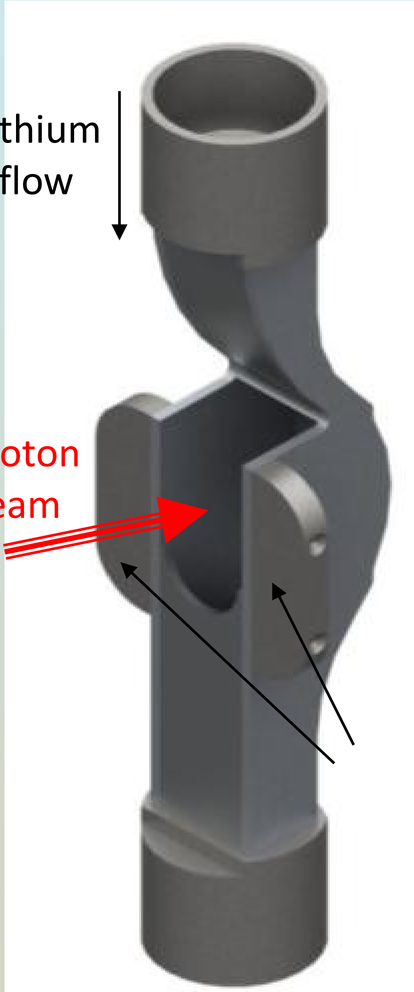


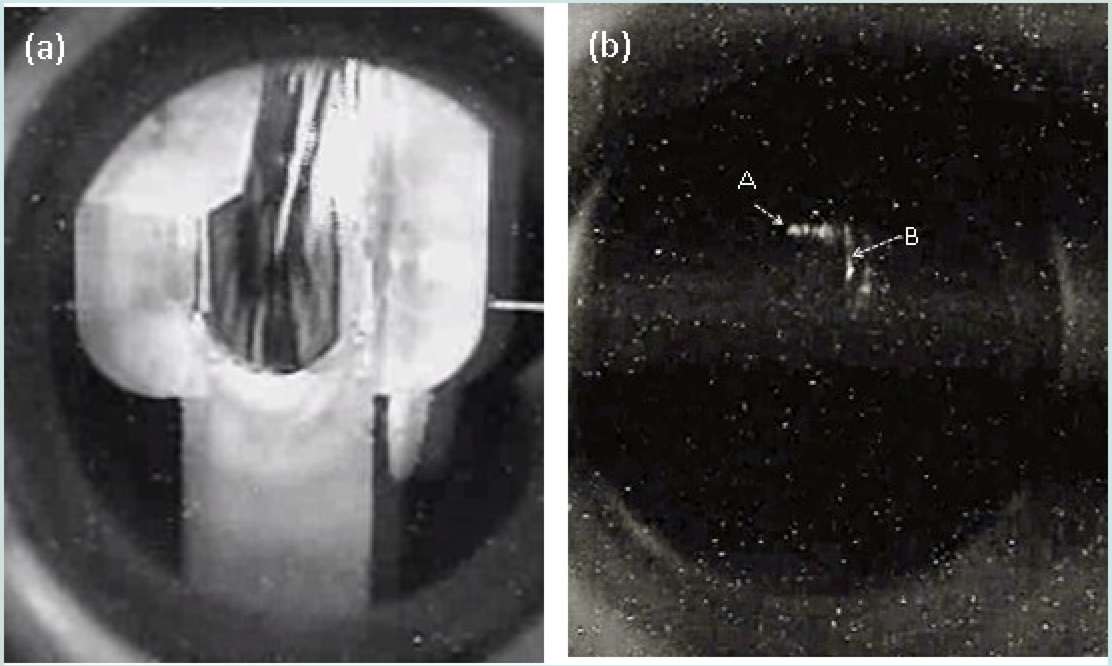


First Liquid Lithium free surface proton irradiation

p, 1.81 MeV, ~1 mA, σ_x=3.9, σ_y=3.4

Lithium working velocity: 2.4 m/s



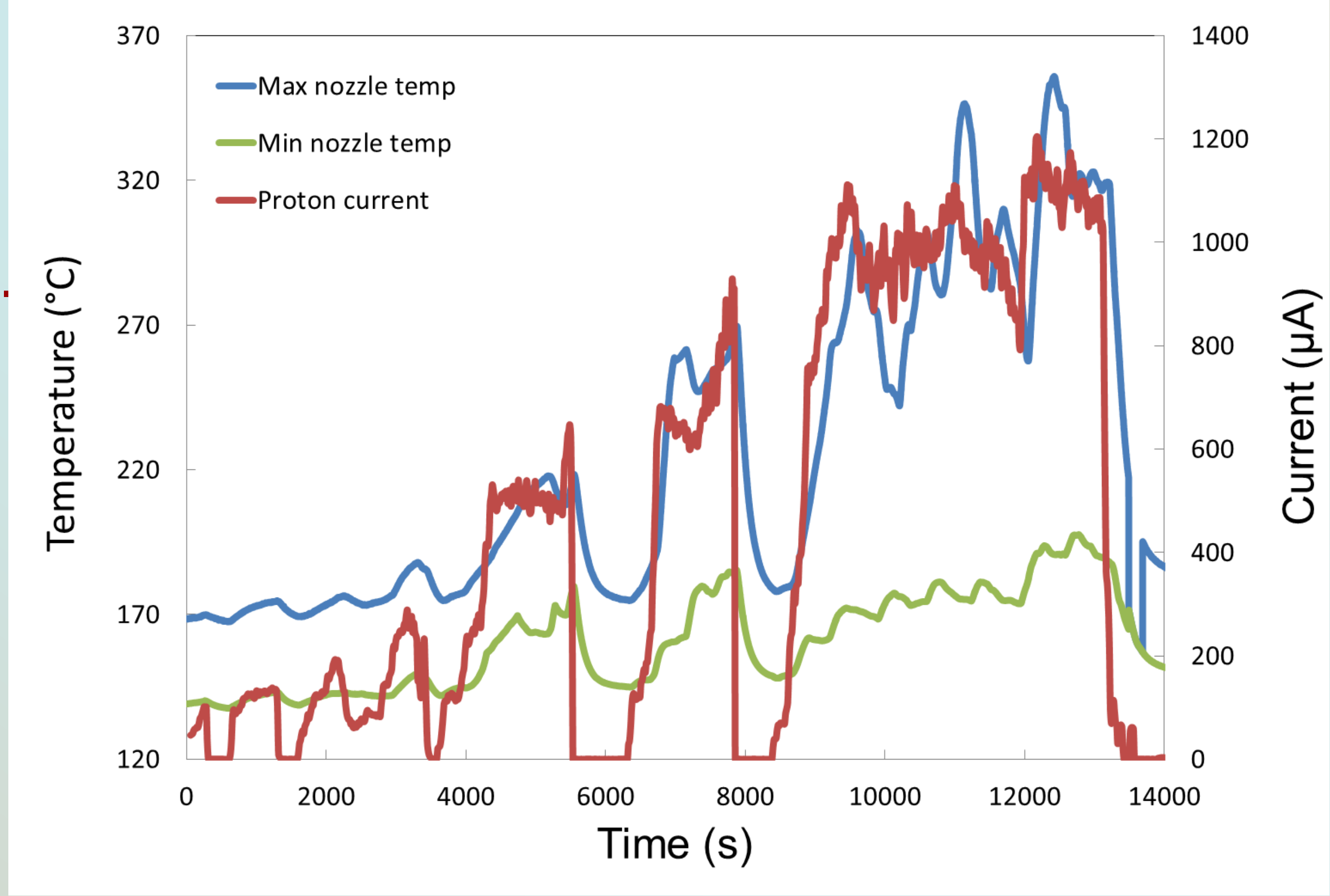


Movie

Under-threshold experiment- current and temperatures

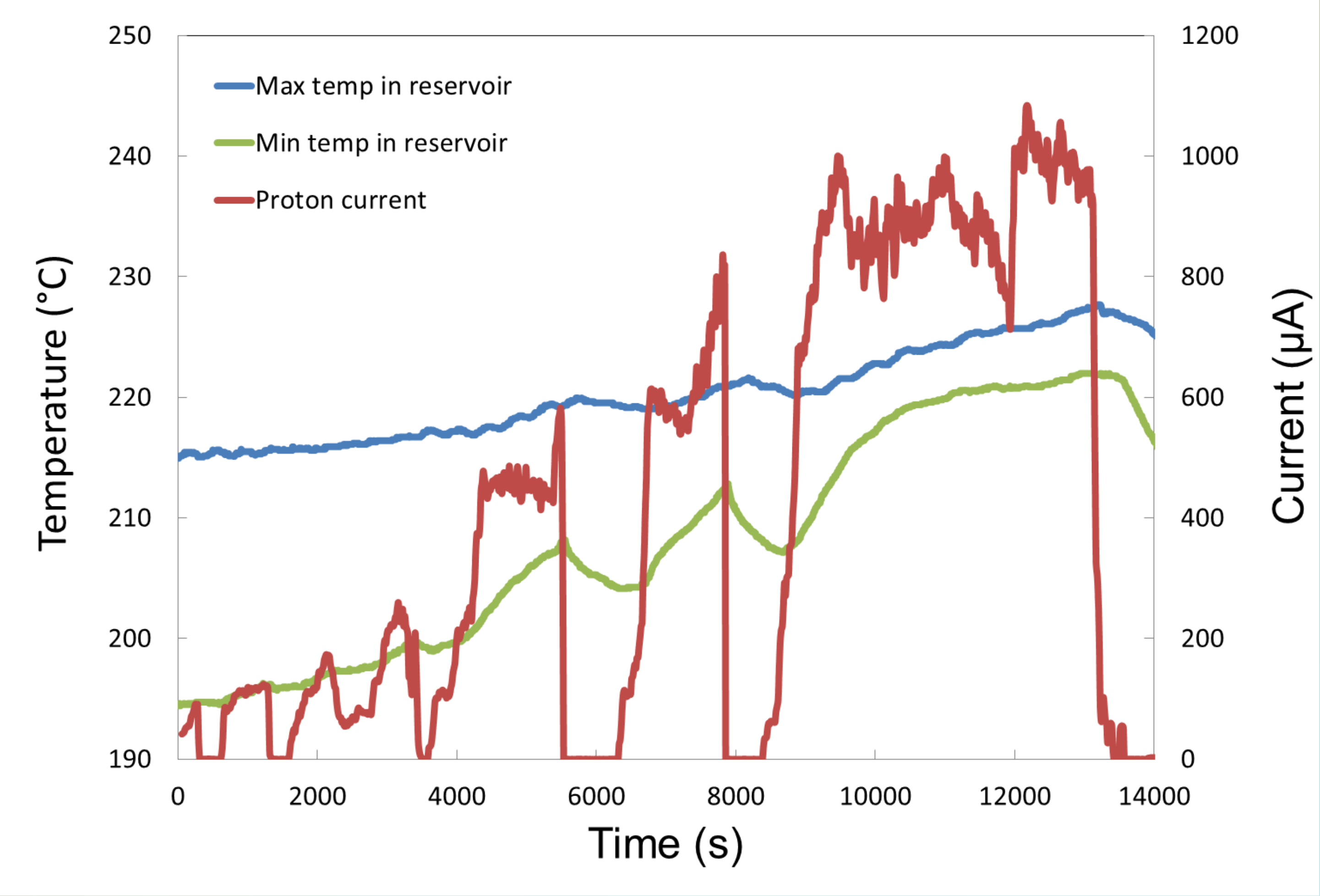
- Stable nozzle temperatures at 1 mA proton current (1.8 kW).
- Peak power densities:

~ 2.3 kW/cm^2 and
~ 0.5 MW/cm^3

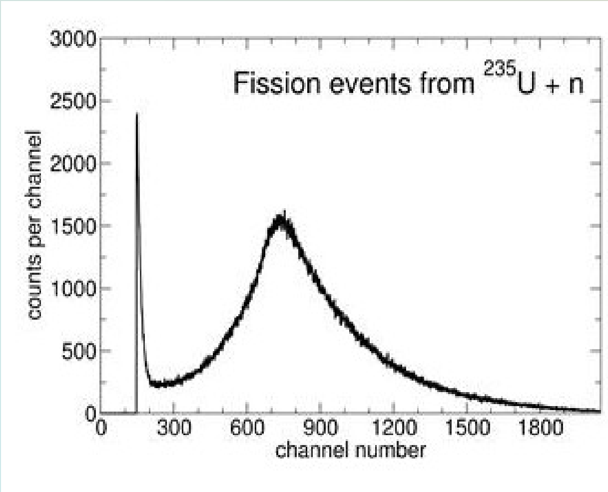


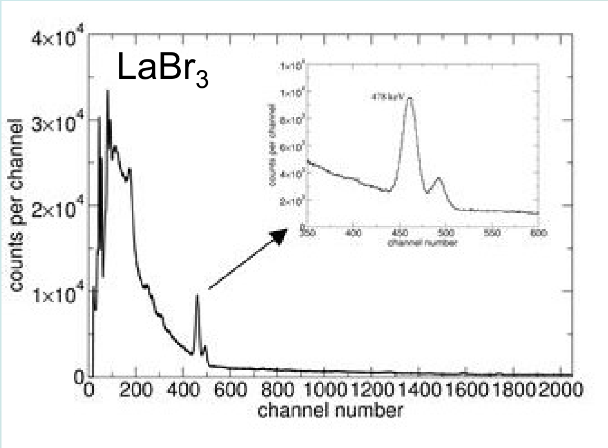
Reservoir temperatures

- Minor changes in the reservoir maximum temperature.
- Oil-air heat-exchanger (vents) was not operating.

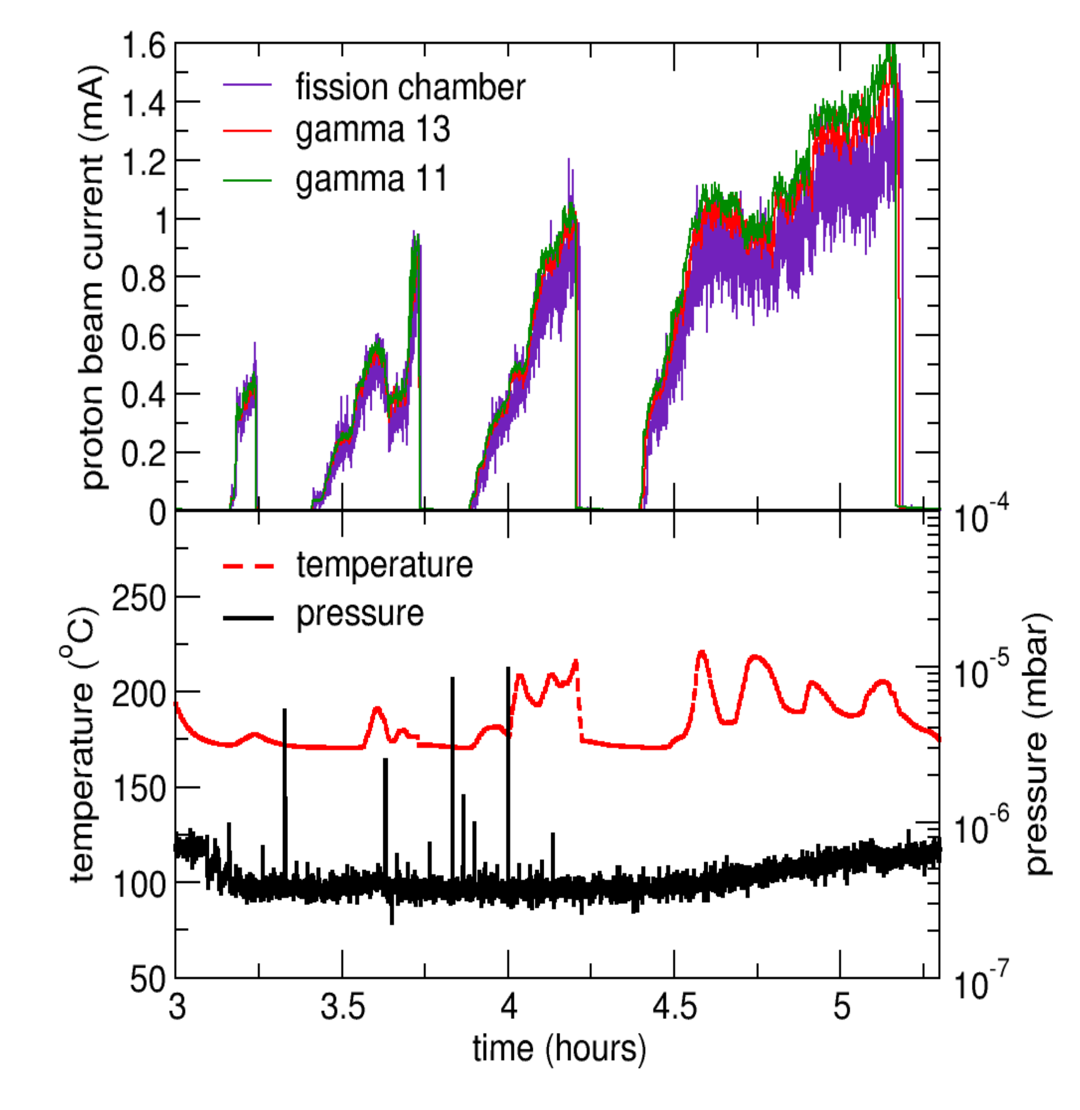


Above threshold experiments- Neutron detectors

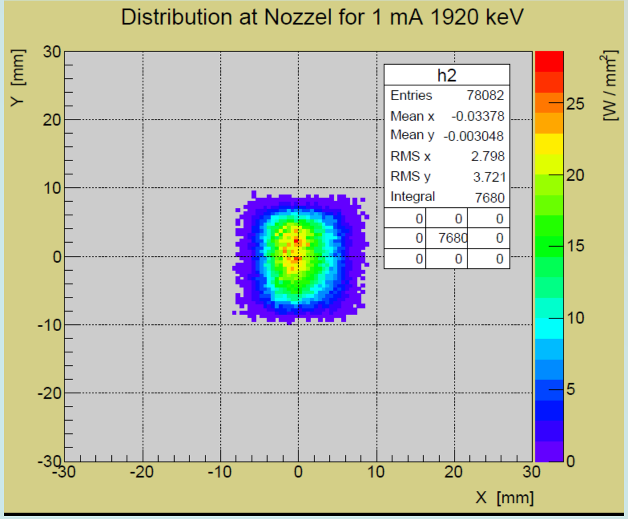




Above-threshold experiment E_p=~1.9 MeV



Total charge = 1.2 mA×h

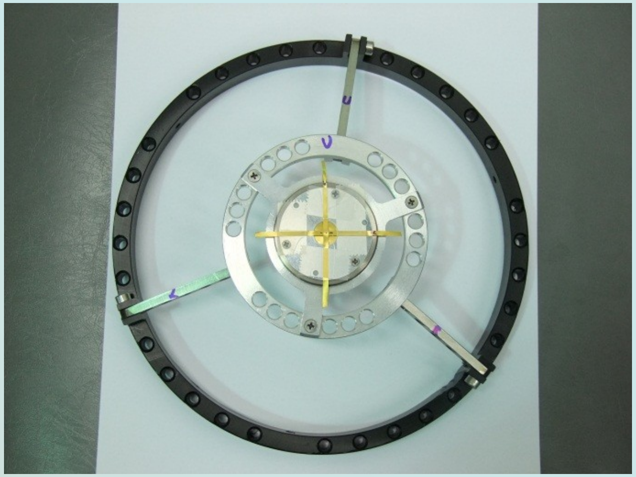


σ_x= 2.8 mm and σ_y=3.8 mm

Peak power densities:
3 kW/cm² and
~ 0.6 MW/cm³

Neutron beam profile

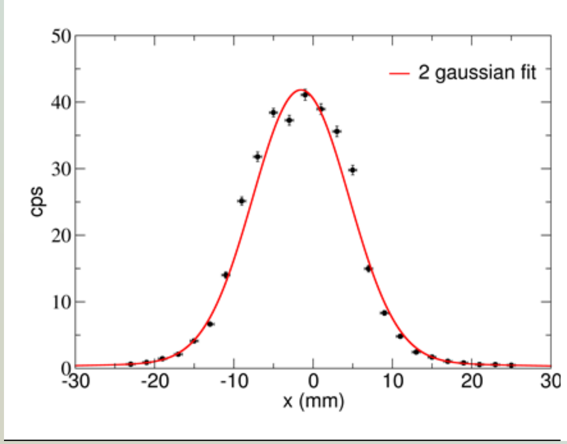
Total neutron rate: ~2×10^{10} n/s/mA



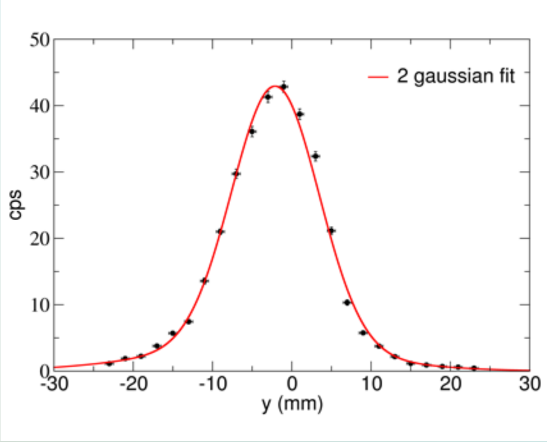
Autoradiography

2 cm

σ = 6 - 6.5 mm

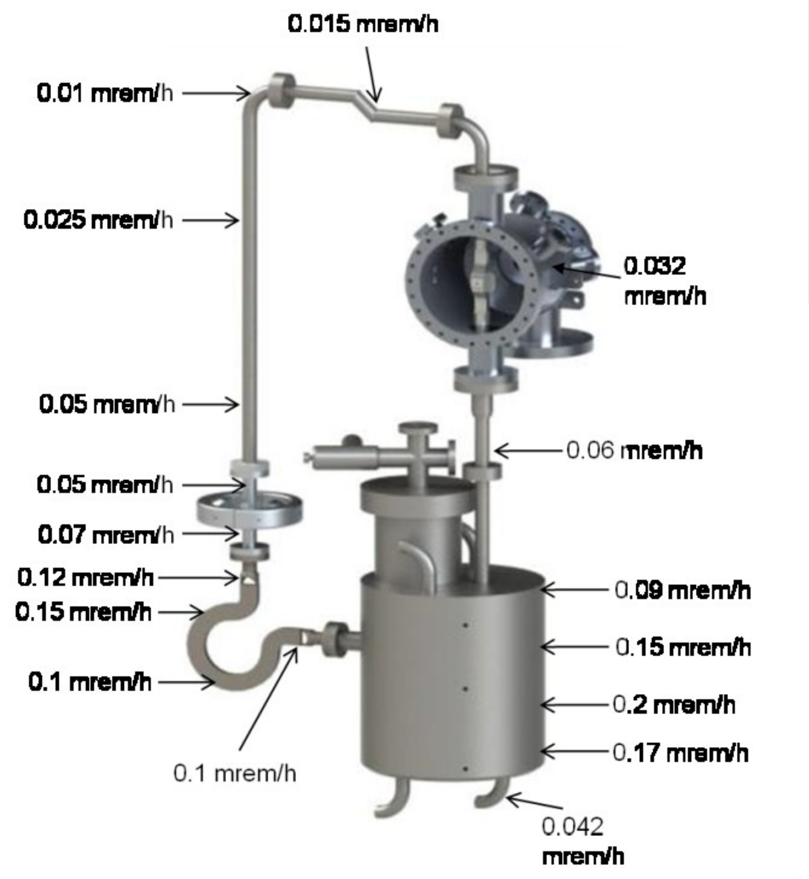


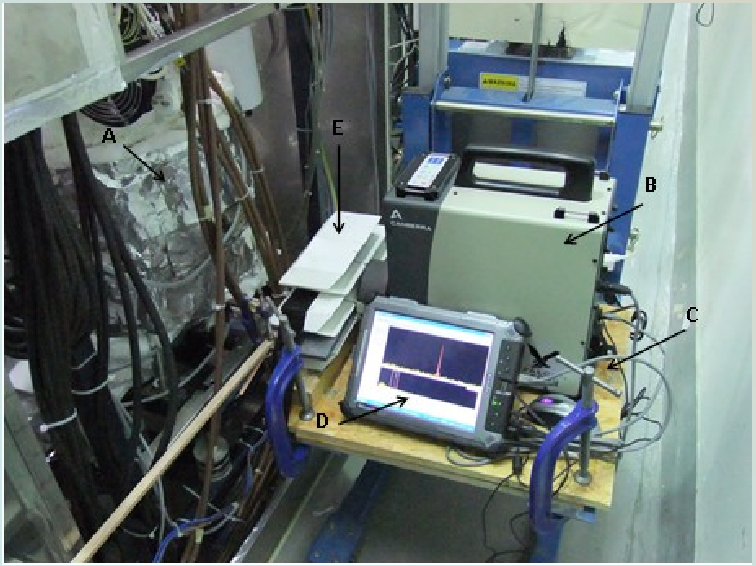
σ_x =6 mm

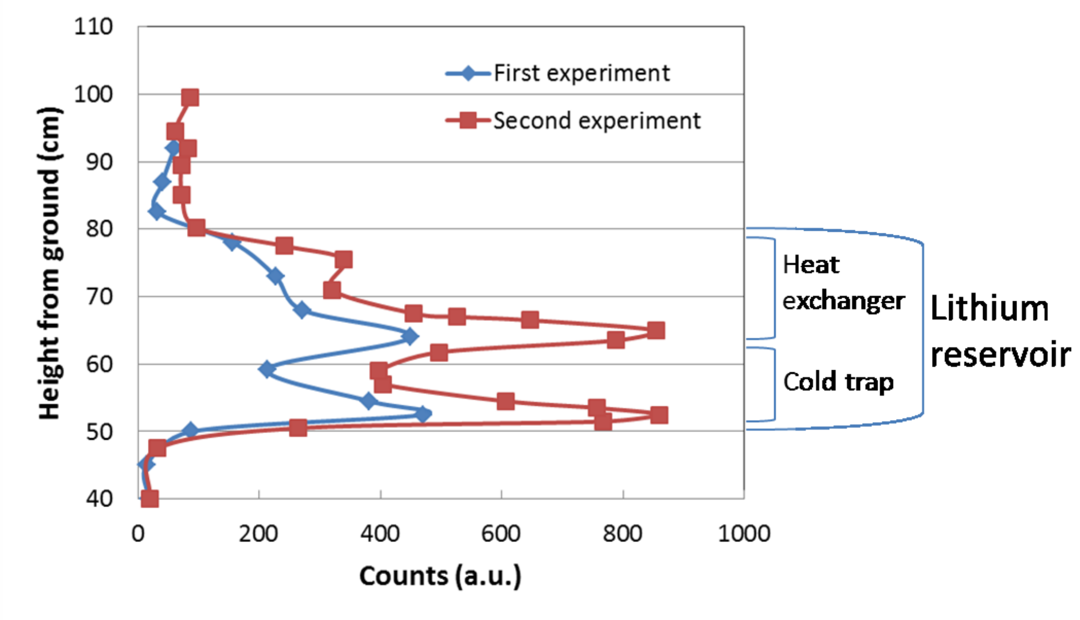


σ_y =5.5 mm

^{7}Be dose rate around LiLiT

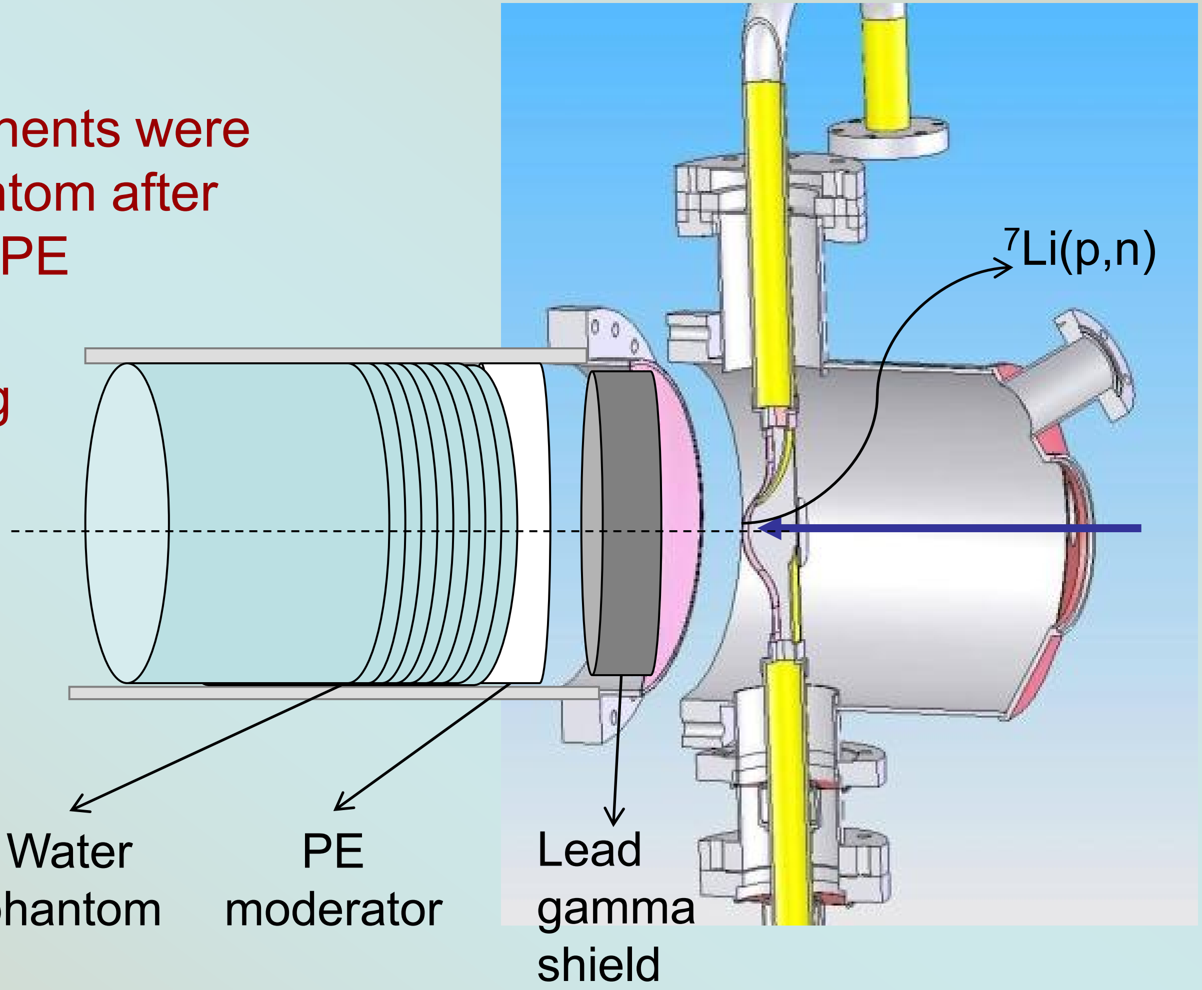






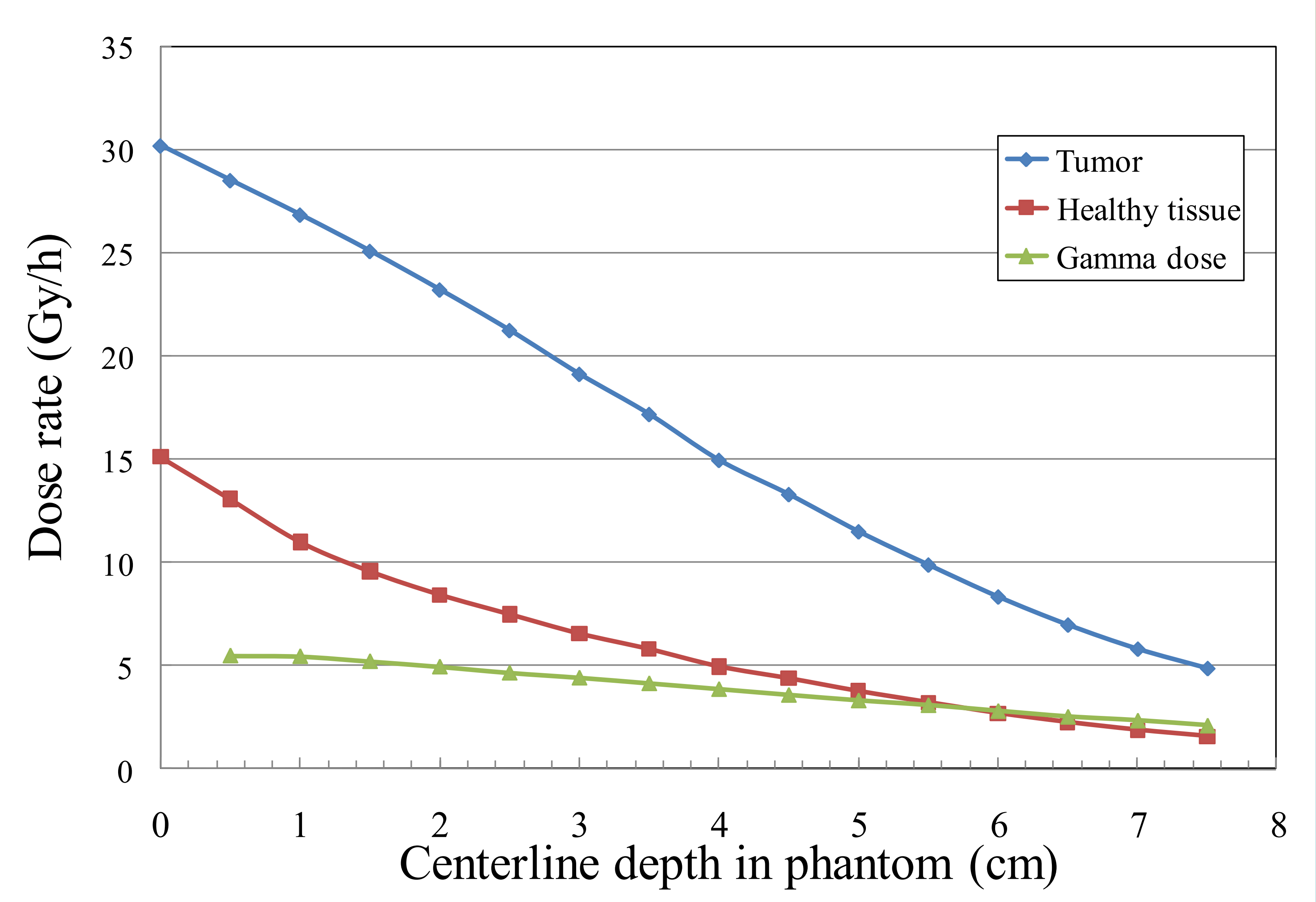
MCNP simulation for BNCT doses - schematic illustration

- 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.

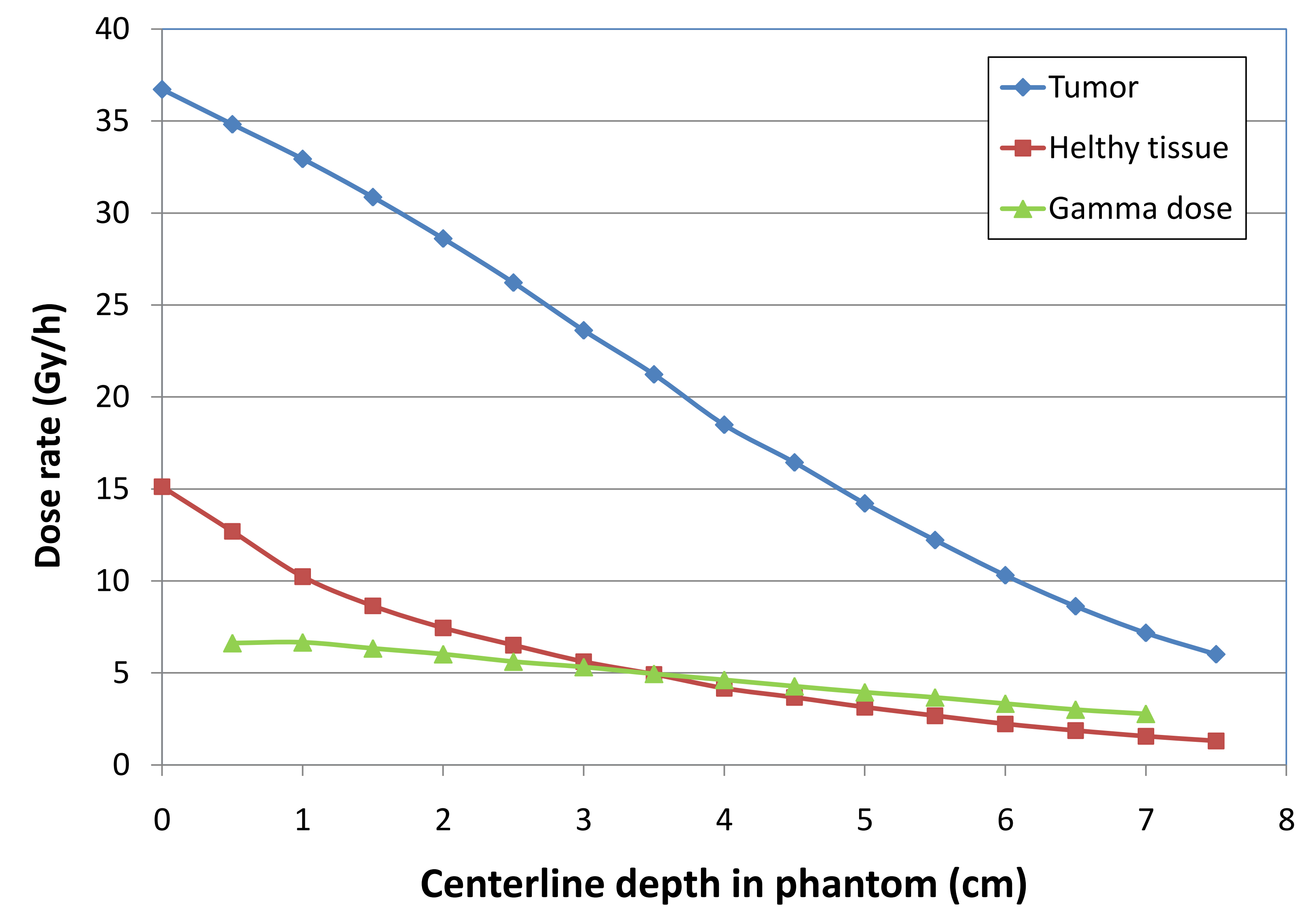


[1] Nakagawa et. al. *J. Neuro-Oncol.* ***62 87–99*** (2003).

BPA maximum allowed charge: 13 mA×h (4 cm deep)



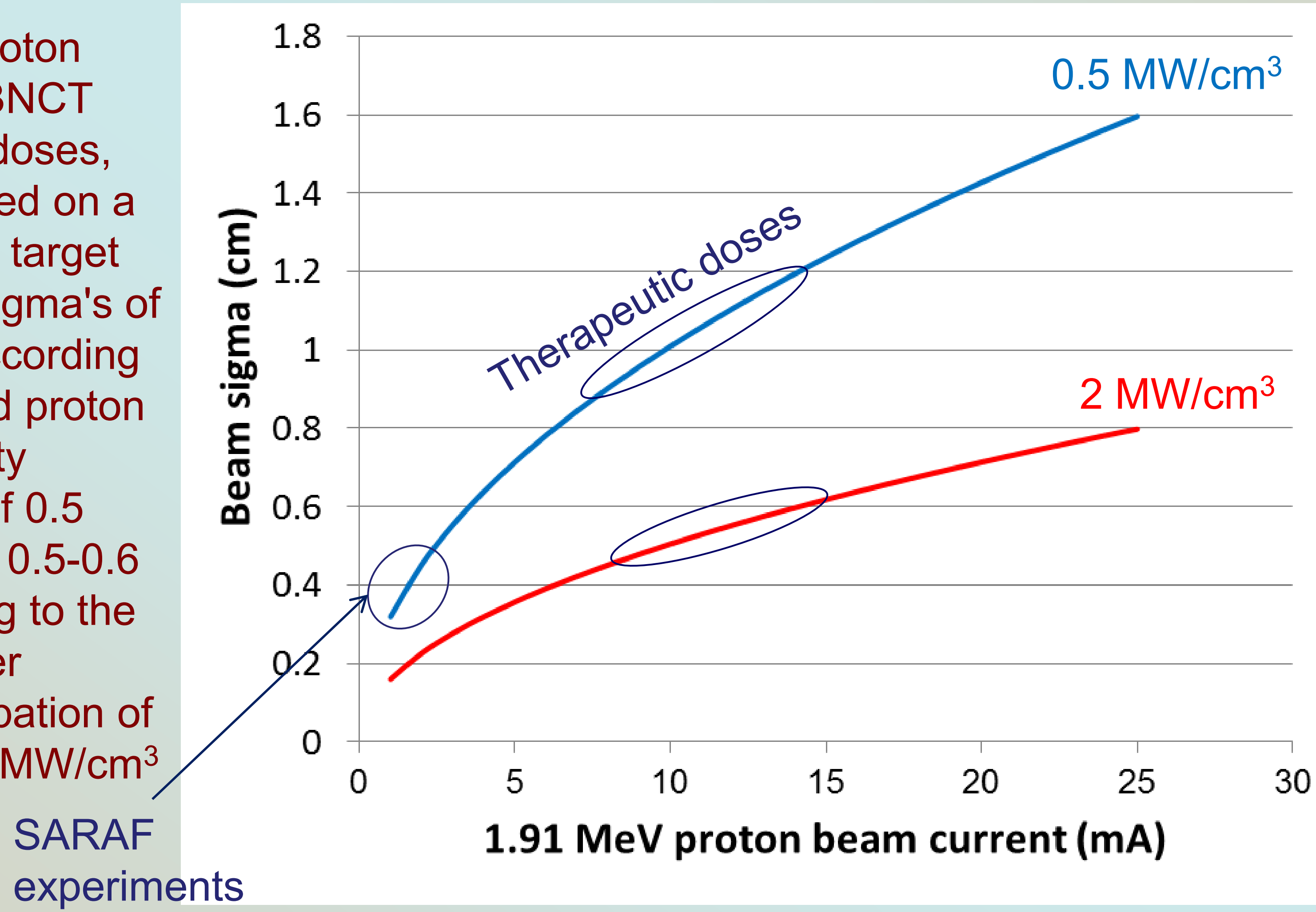
Liposome compound[1]: 15 mA×h (5 cm deep)



[1] P. J. Kueffer et al. PANS 110, 16, 6512–6517 (2013).

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



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.