

A high-intensity source of stellar-energy neutrons for rare-nuclide activation

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for
SARAF-LiLiT collaboration

ERAWAST II Workshop, Paul Scherrer Institute, Aug 30 - Sep 2, 2011

B²FH
 Burbidge et al.
 RMP 29, 547 (1957)

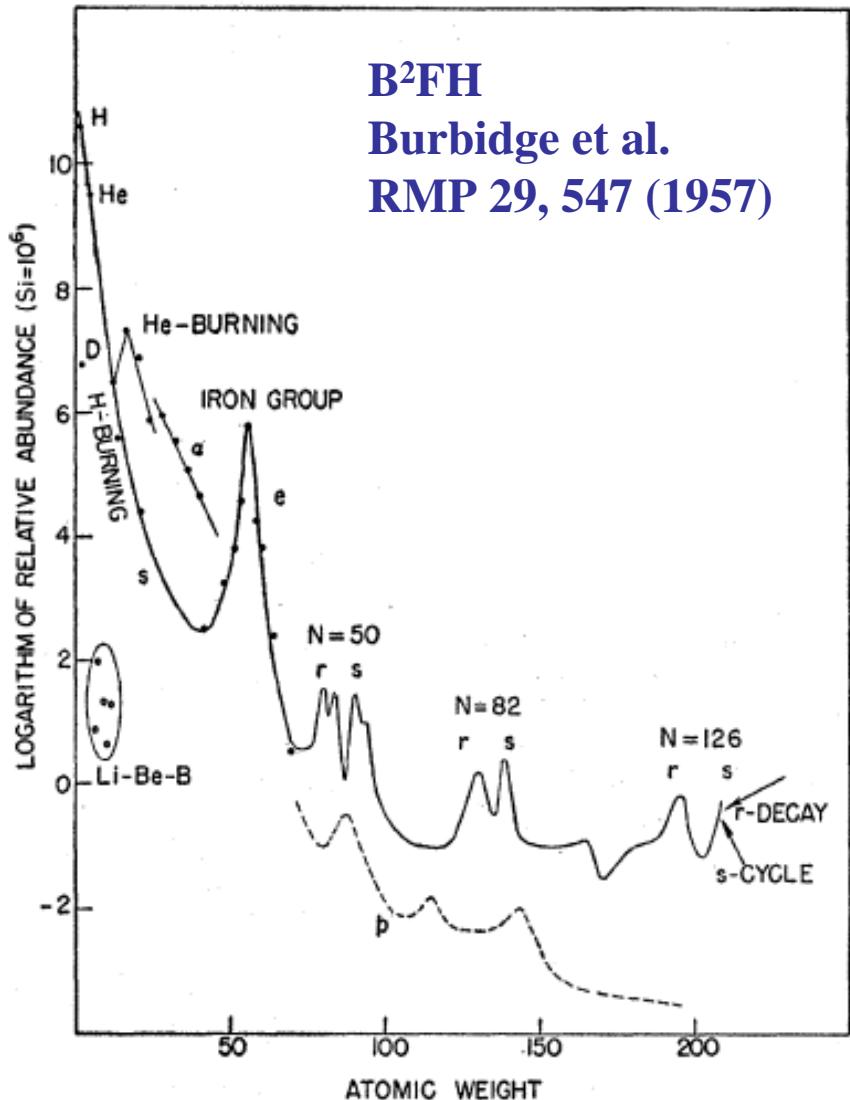
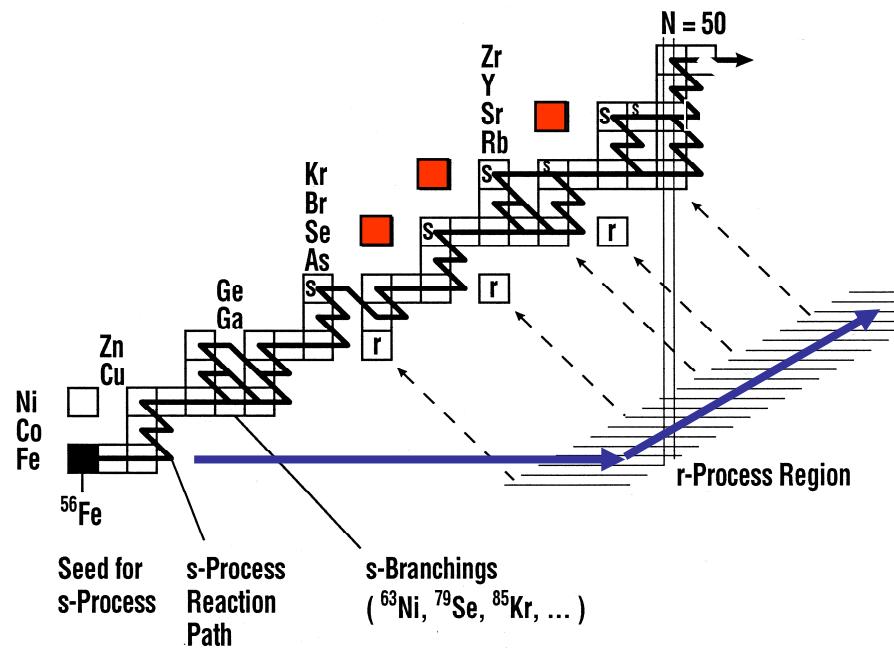


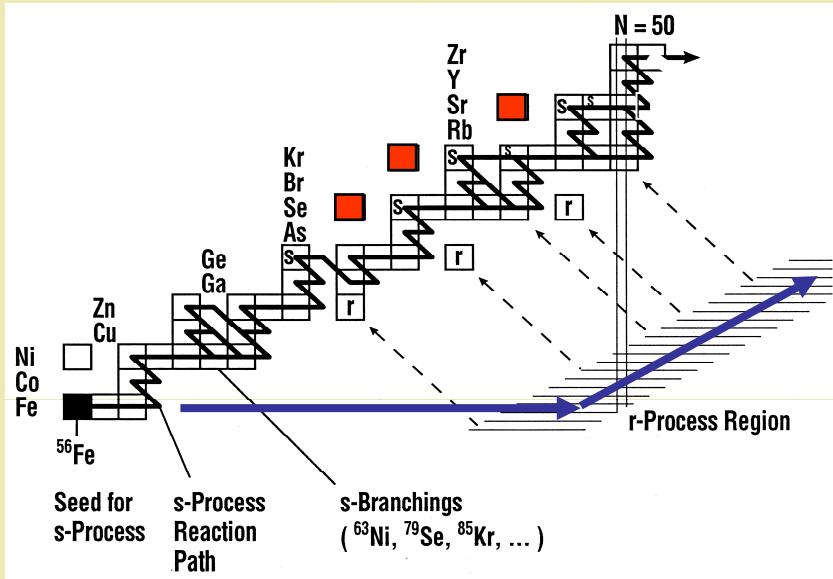
FIG. I,1. Schematic curve of atomic abundances as a function of atomic weight based on the data of Suess and Urey (Su56). Suess and Urey have employed relative isotopic abundances to determine the slope and general trend of the curve.



s-process regimes and sites

	<i>"weak" component</i>	<i>main component</i>
Temperature	$60 < A < 90$ $2.2\text{-}3.5 \times 10^8 \text{ K}$ 25-30 keV	$90 < A < 209$ $0.9 \times 10^8 \text{ K}$ 10 keV
Neutron density	$10^6\text{-}10^7 \text{ cm}^{-3}$	$10^8\text{-}10^{10} \text{ cm}^{-3}$
Neutron source	$^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$	$^{13}\text{C}(\alpha, n)^{16}\text{O}$, $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$
Stellar site	core helium burning in massive stars	thermal pulses asymptotic giant- branch (AGB) stars

Nuclear astrophysics need good quality data on (n, γ) cross sections on stable and unstable nuclei. The relevant quantity is the Maxwellian-averaged cross section (MACS) defined as:



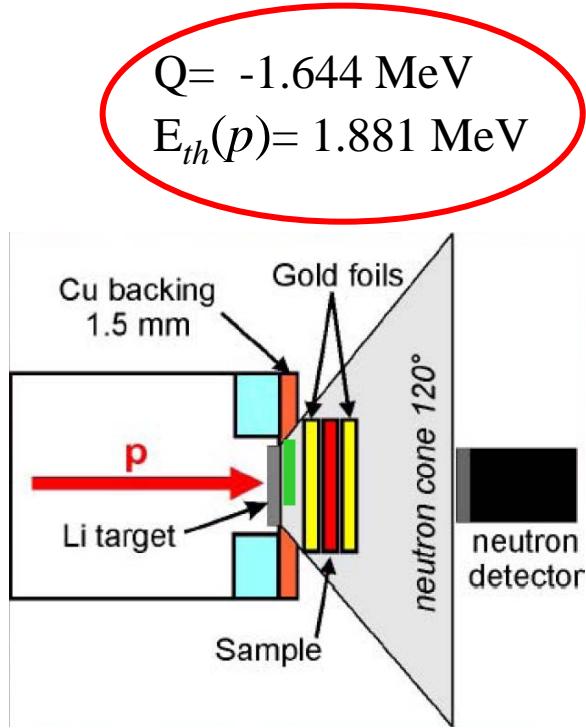
$$\frac{\langle \sigma v \rangle}{v_T} = \frac{1}{v_T} \frac{\int \sigma(E_n) (dn / dE_n) v dE_n}{\int (dn / dE_n) dE_n}$$

$$\frac{dn}{dE_n}(MB) \propto \sqrt{E_n} \exp(-\frac{E_n}{kT})$$

$$\frac{\langle \sigma v \rangle}{v_T} = \frac{2}{\sqrt{\pi}} \frac{\int \sigma(E_n) E_n \exp(-E_n / kT) dE_n}{\int E_n \exp(-E_n / kT) dE_n}$$

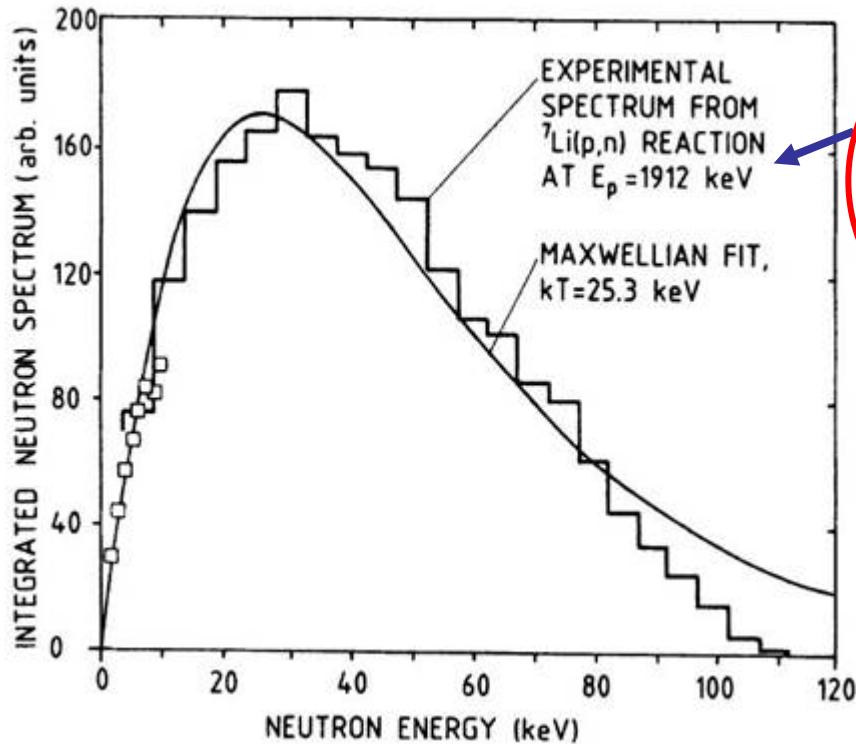
- traditional neutron time-of-flight measurements of $\sigma = \sigma(E_n)$ at nuclear reactors
more recently at spallation neutron sources :
CERN (n -TOF), Los Alamos (LANSCE, DANCE, Geel (GELINA))
- activation measurements using the $^7\text{Li}(p,n)^7\text{Be}$ reaction

$^7\text{Li}(p,n)^7\text{Be}$ as neutron source



- for $E_p=1912 \text{ keV} \rightarrow$ quasi-maxwellian energy distribution with $kT=25 \text{ keV}$
- neutron emission: forward peaked with 120° opening angle

Thick target integral spectrum:

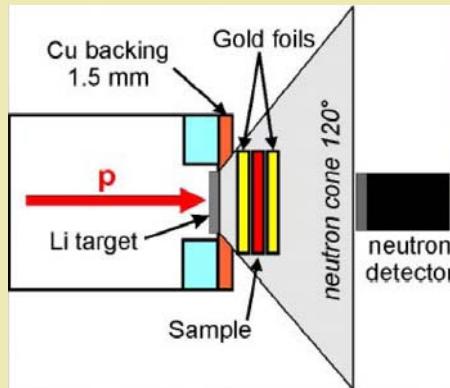


Ratynski and Käppeler, Phys. Rev. C 37 (1988)

$$dn / dE_n \approx E_n \exp(-E_n / kT)$$

$$\sigma_{\text{exp}} = \frac{\int \sigma(E_n) (dn / dE_n) dE_n}{\int (dn / dE_n) dE_n} \xrightarrow{\text{red arrow}} \frac{\langle \sigma v \rangle}{v_T} \approx \frac{2}{\sqrt{\pi}} \sigma_{\text{exp}}$$

${}^7\text{Li}(p,n)$
neutron source



$$I_p < 50\text{-}100 \mu\text{A}, E_p = 1.912 \text{ MeV}, N_n \sim 0.5\text{-}1 \times 10^9 n/\text{s}$$

Proton beam (and neutron intensity) limited by target cooling

In particular for radioactive targets (usually ng's), higher fluxes are needed:

conventional Li target \uparrow mg \rightarrow ng \uparrow high-power Li target
 \uparrow $\mu\text{A} \rightarrow \text{mA}$ \uparrow
 \uparrow W \rightarrow kW

A high-intensity neutron source based on ${}^7\text{Li}(p,n)$ requires two components:

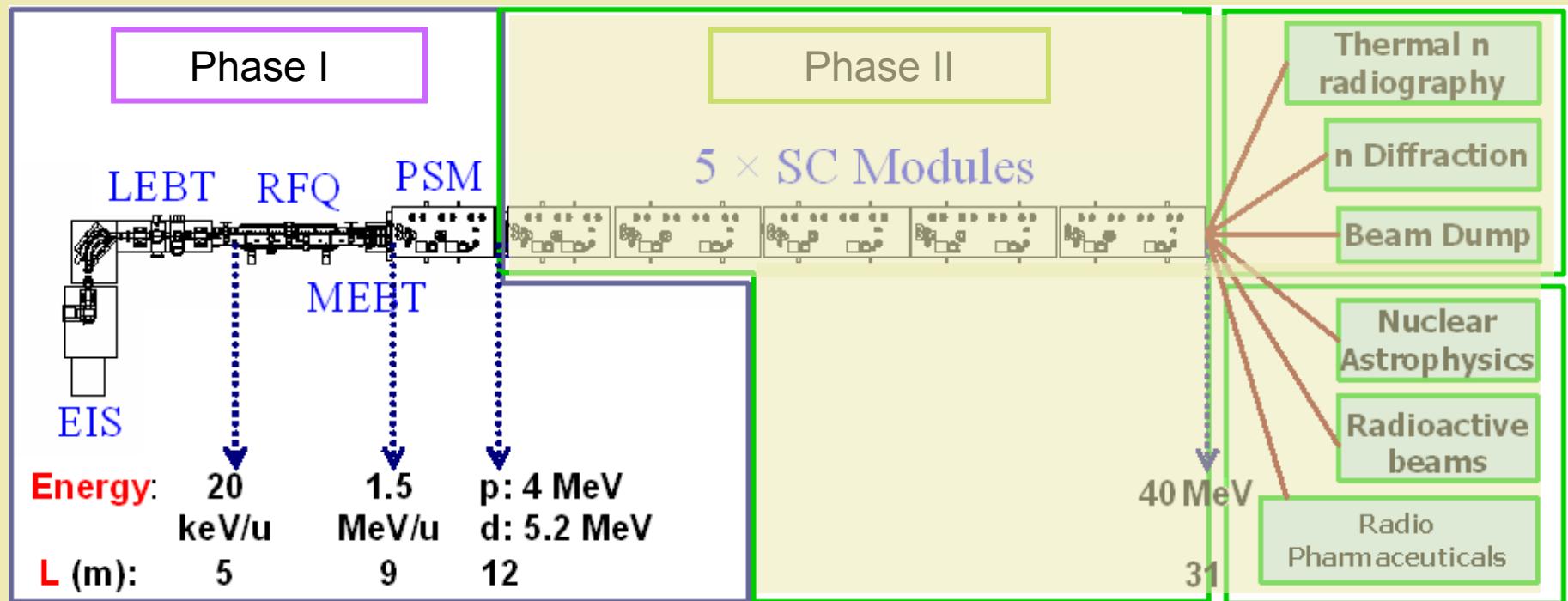
- high-intensity proton beam -> RF accelerators (RFQ, linac)
- high-power Li target

The present project:

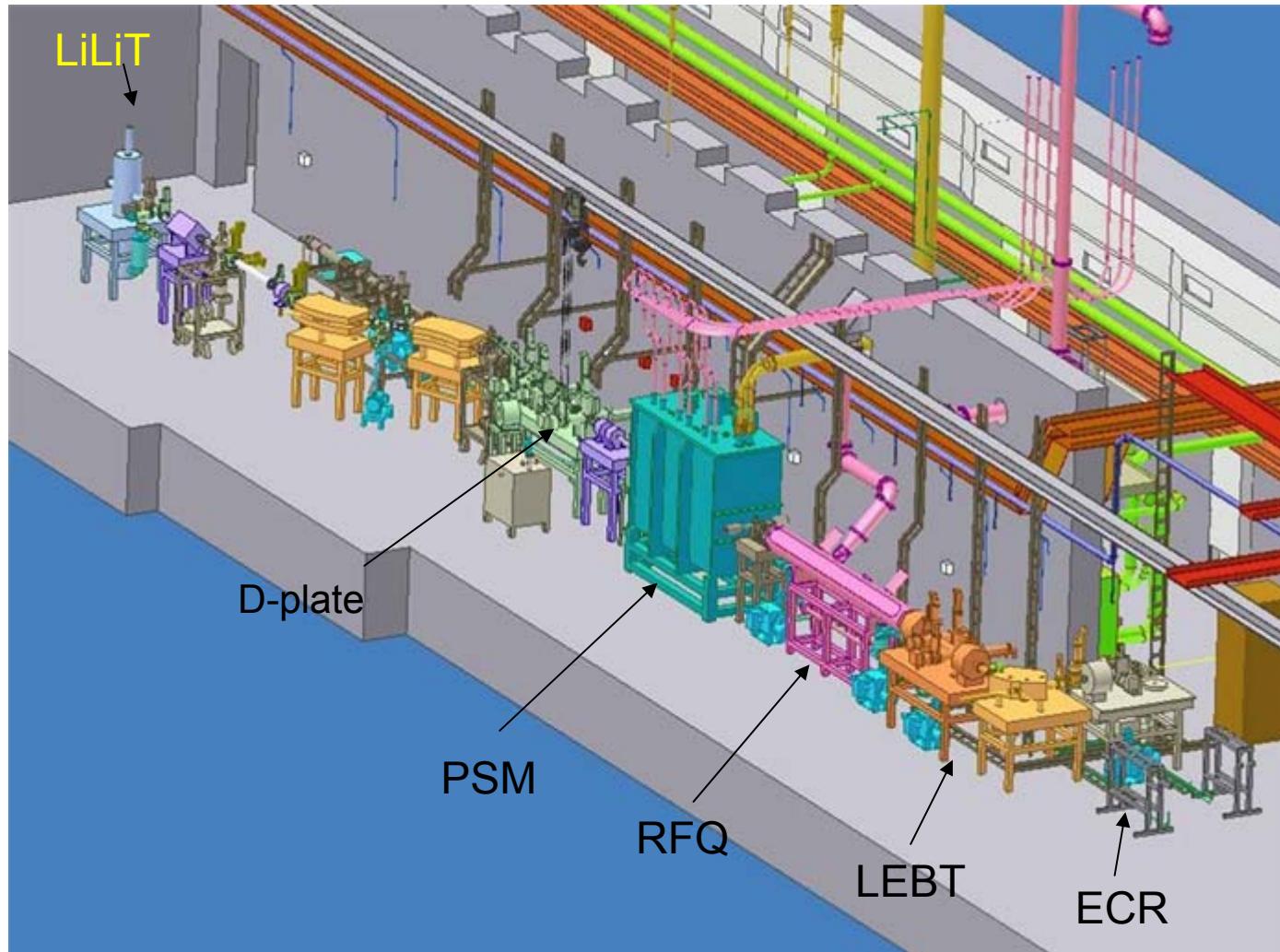
- SARAf light-ion accelerator facility
- design and construction of a **Liquid-Lithium Target (LiLiT)**
- The LiLiT target is a forced-flow windowless liquid-lithium jet designed to act as ;
- neutron production target
- power beam dump ($\sim 5\text{-}7 \text{ kW}$)

SARAF Layout: a high-intensity light-ion superconducting linac

Parameter	Value	Comment
Ion Species	$p, d, {}^{3,4}\text{He}^{++}$	$m/q \leq 2$
Energy Range	5 – 40 MeV	
Current Range	0.04 – 2 mA	Upgradable to 4 mA
Maintenance	Hands-On	Very low beam loss



Phase I setup for experiments



SARAF phase I linac – view downstream

PSM

MEBT

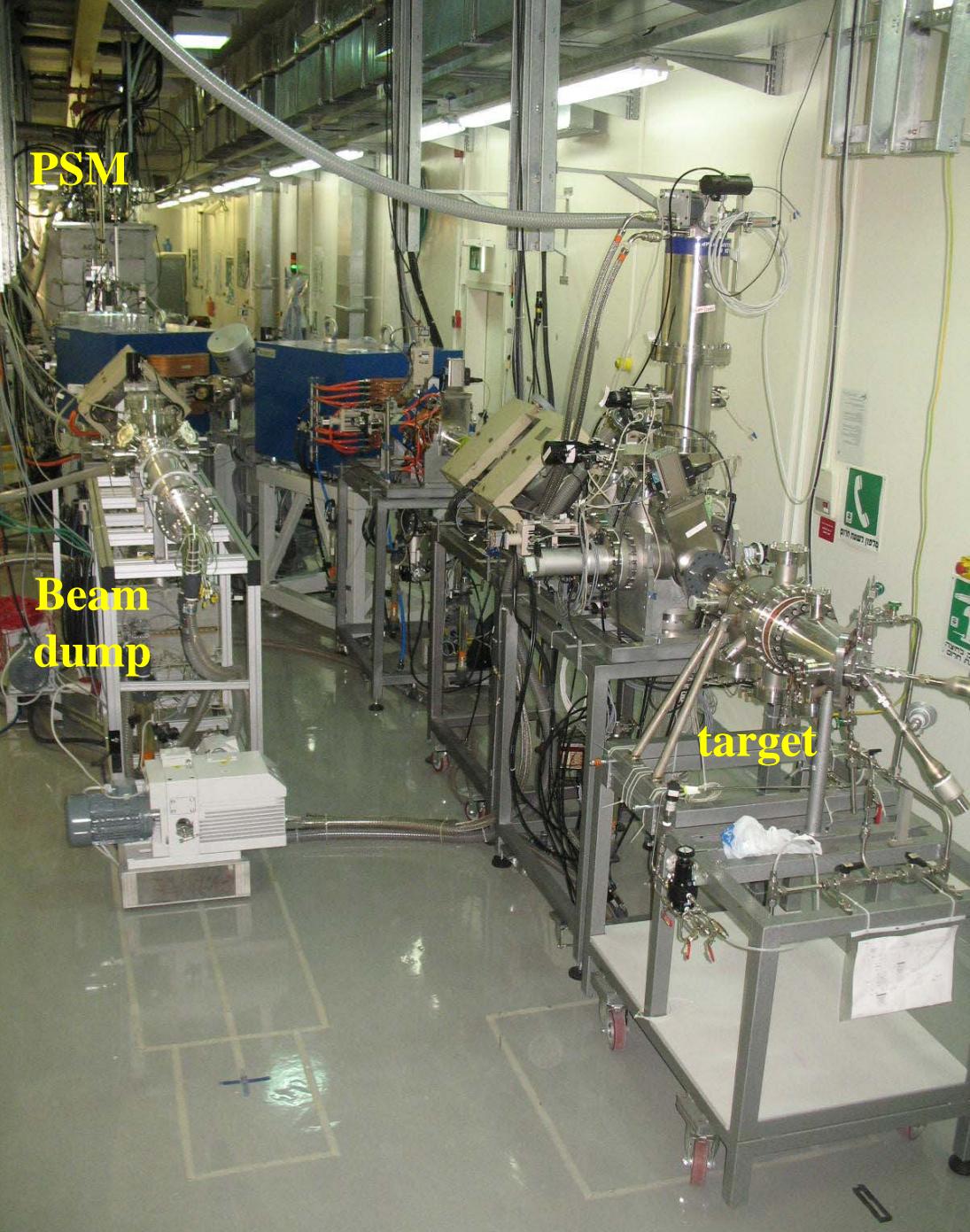
RFQ

LEBT

EIS

L. Weissman, LINAC10
I. Mardor et al., SRF09
I. Mardor et el., PAC09





“Beam lines”

SARAF phase I
proton beam
operational:
 $50\mu\text{A} - 2 \text{ mA}$, $1.5 - 3 \text{ MeV}$

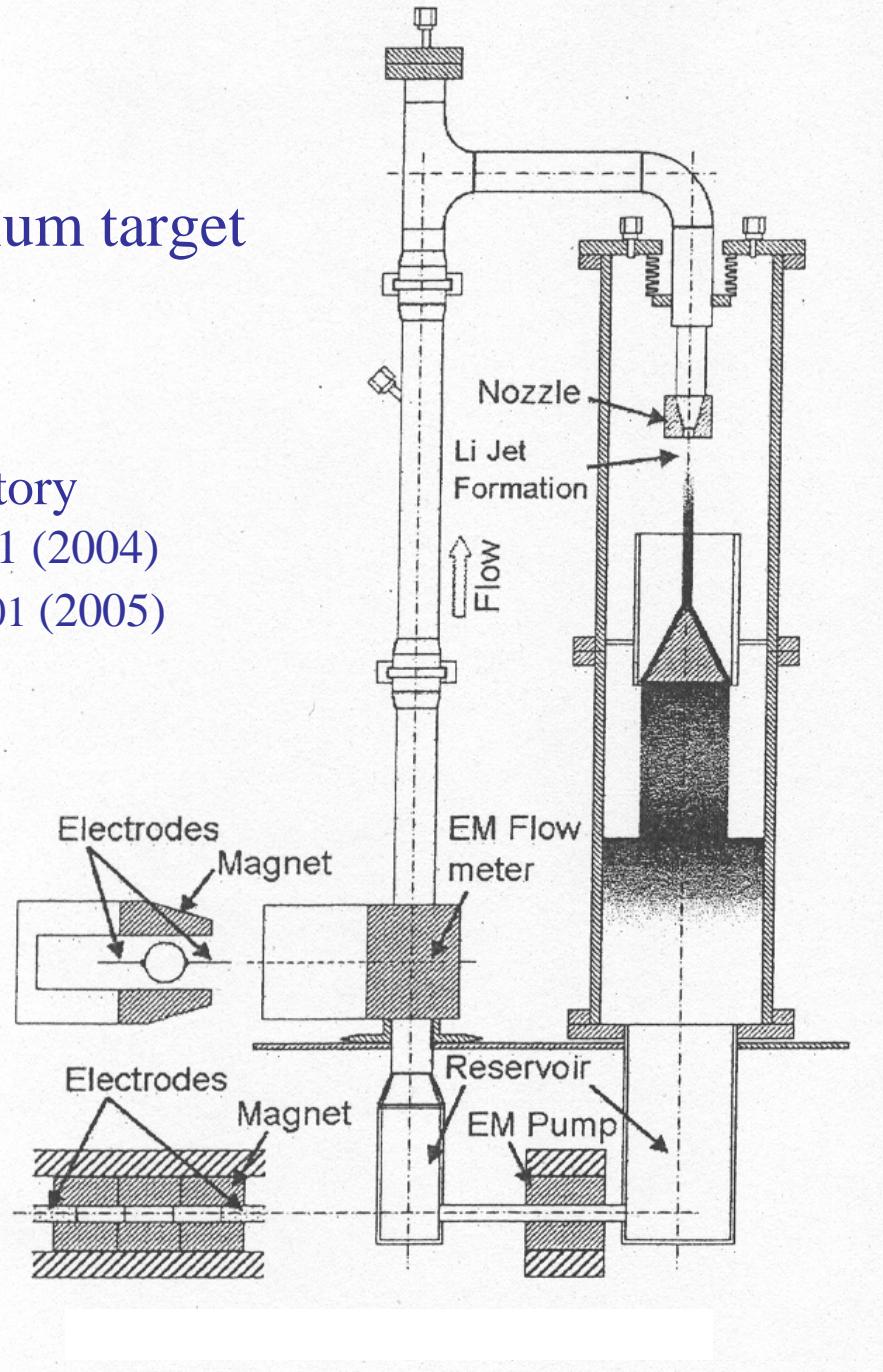
Towards a liquid-lithium target

Liquid-Li loop

Argonne National Laboratory

C. Reed *et al.*, NP A 746, 161 (2004)

J. Nolen *et al.*, RSI 76, 073501 (2005)

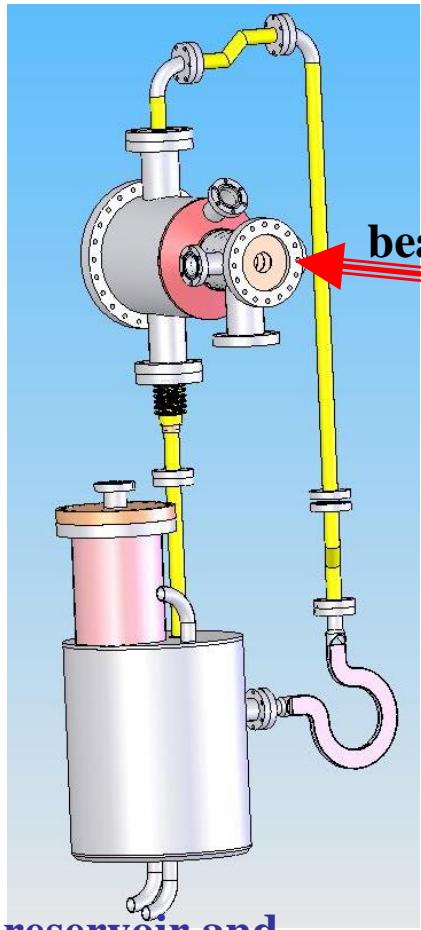


Physical properties of lithium

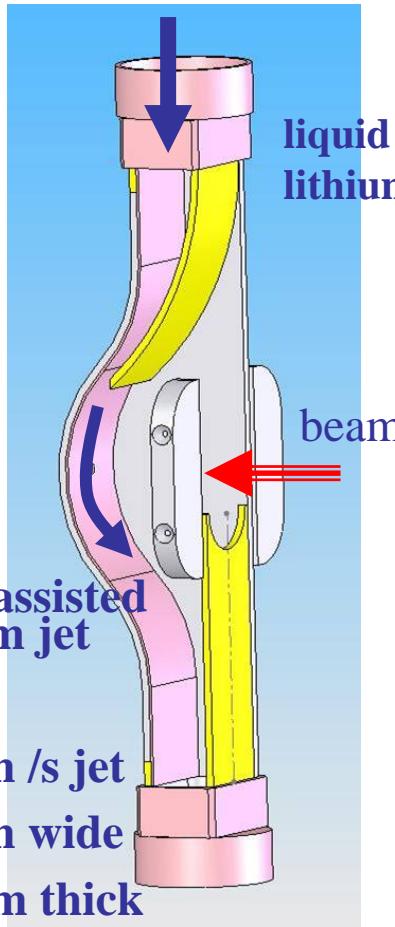
	lithium	
melting temp. :	<u>181 °C</u>	
	T = 220 °C (liquid)	Water(20°C)
density:	$\rho = 0.510 \text{ g/cm}^3$	1.0
specific heat:	$C_p = 4350 \text{ J/kg K}$	4183
thermal conductivity:	$K_{th} = 43.9 \text{ W/m K}$	0.6
thermal diffusivity:	$\kappa = K_{th}/\rho \quad C_p = 2.84 \times 10^{-5} \text{ m}^2/\text{s}$	1.5×10^{-7}
surface tension :	0.326 N/m	0.075
dynamic viscosity :	$\eta = 5.40 \times 10^{-4} \text{ Pa.s}$	8.9×10^{-4}
kinematic viscosity :	$\nu = \eta/\rho = 1.06 \times 10^{-6} \text{ m}^2/\text{s}$	8.9×10^{-7}
electrical resistivity :	$\rho = 2.5 \times 10^{-7} \Omega \text{ m}$	2.5×10^5
Prandtl number:	$\nu/\kappa = 0.037$	6.0
vapor pressure:	<u>$5 \times 10^{-9} \text{ Torr}$</u>	
proton range	$(E_p = 1.91 \text{ MeV}) = 9.2 \text{ mg/cm}^2 = 180 \mu\text{m}$	

LiLiT: Liquid Lithium target

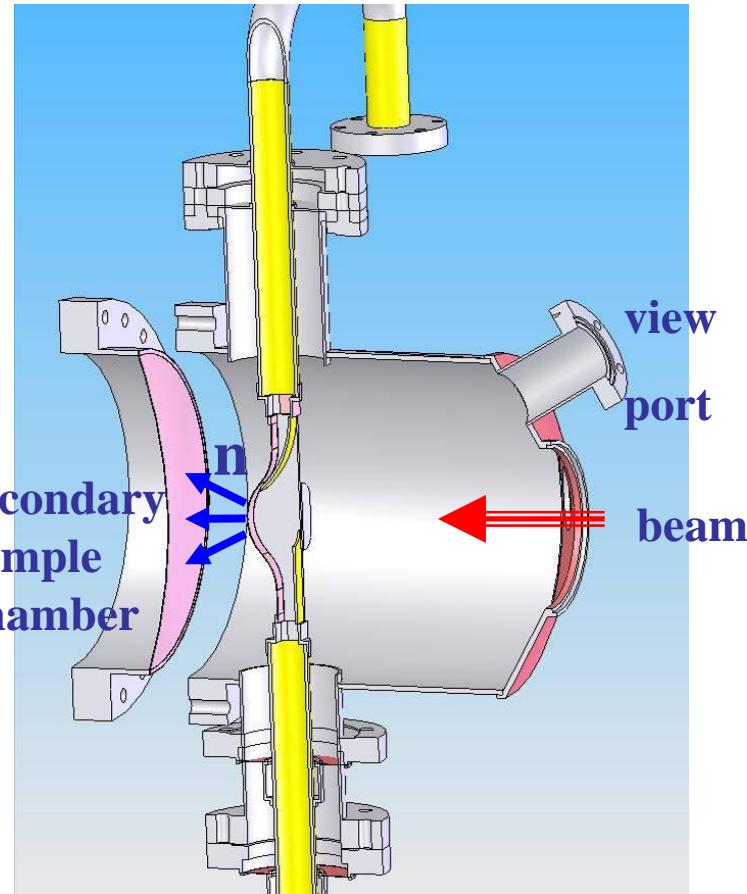
- designed for 2 MeV 3.5 mA protons
- Gaussian beam with $\sigma \sim 2$ mm



Li reservoir and
heat exchanger



Wall-assisted
lithium jet
4-20 m/s jet
18 mm wide
1.5 mm thick

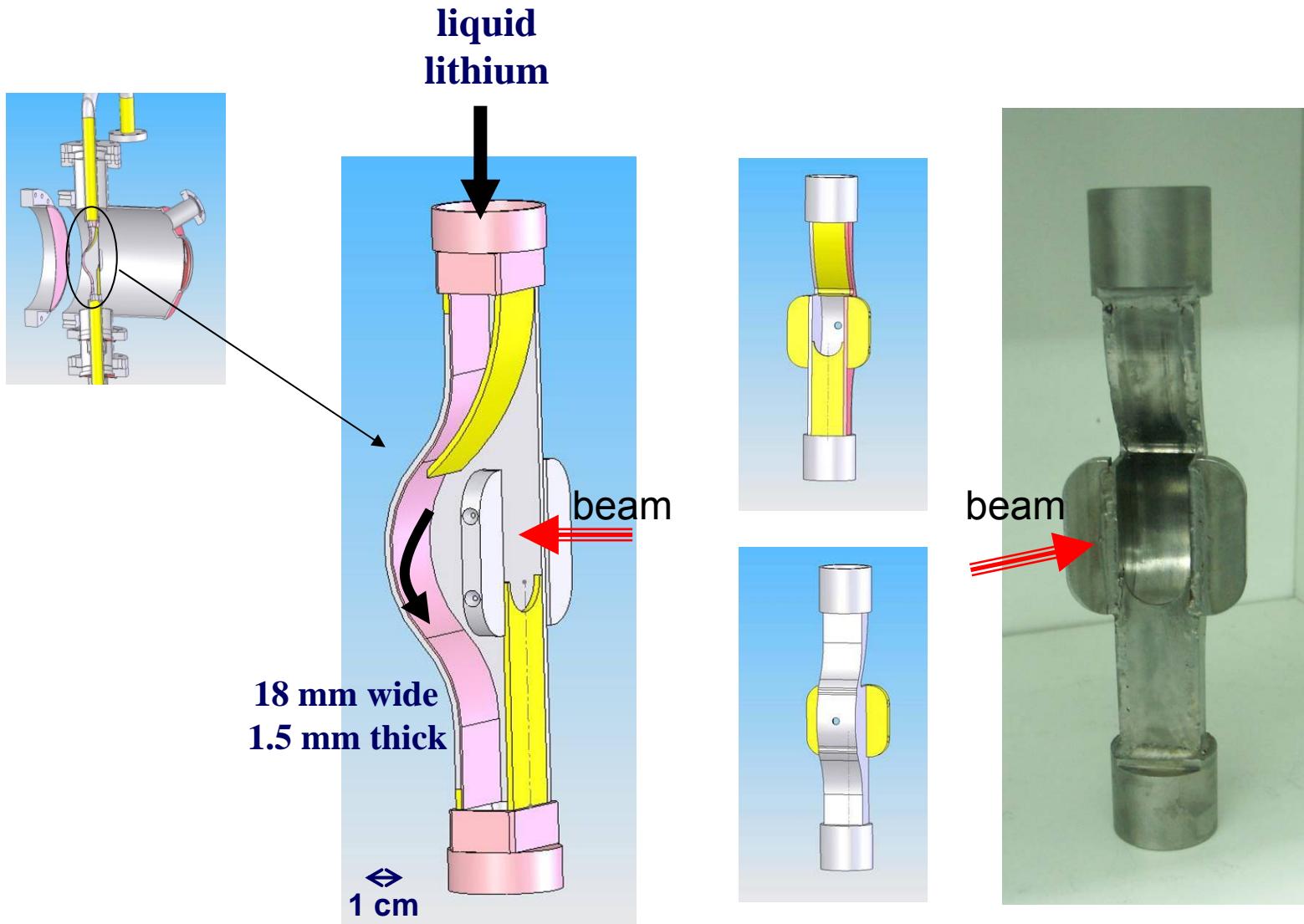


view
port
beam

secondary
sample
chamber

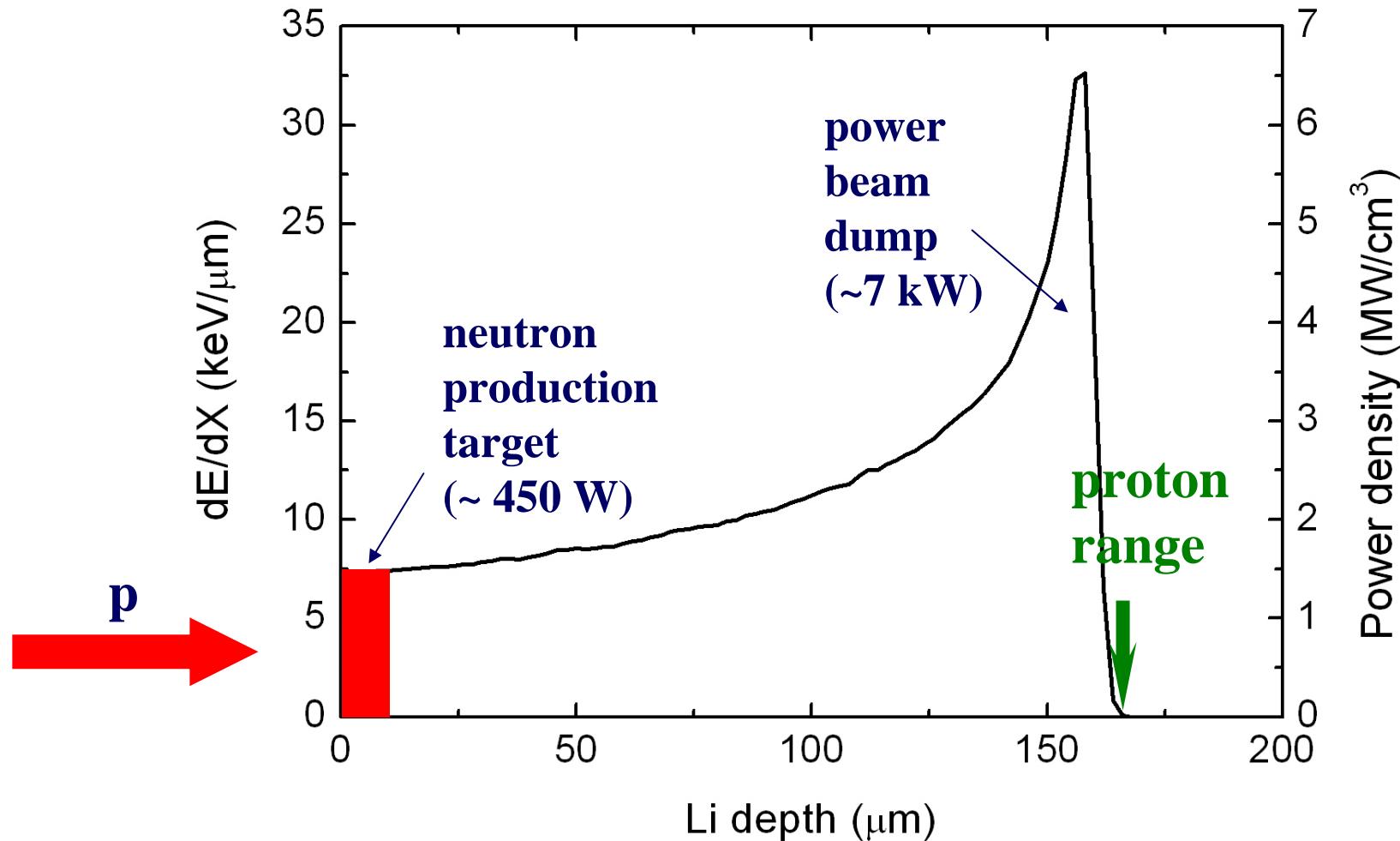
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Lithium Nozzle

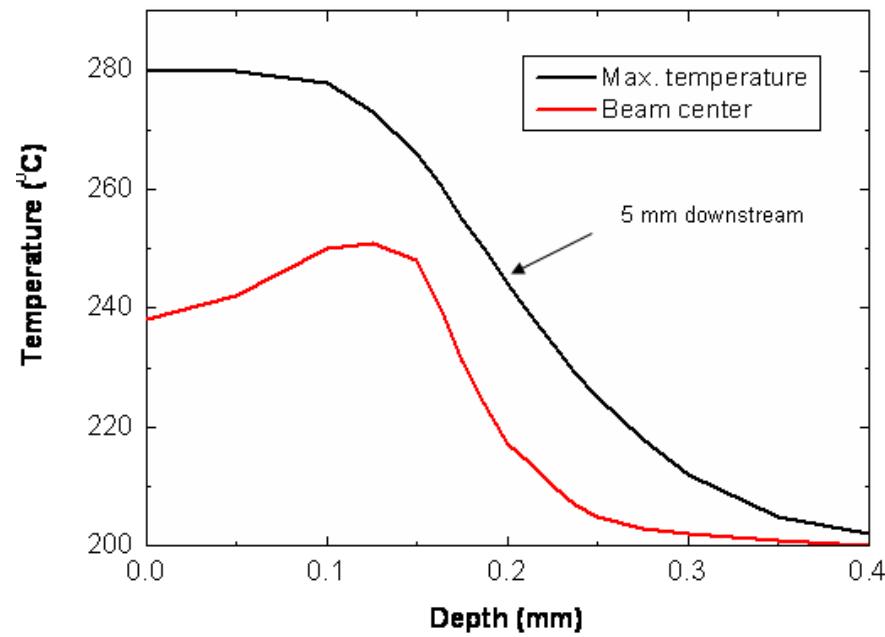
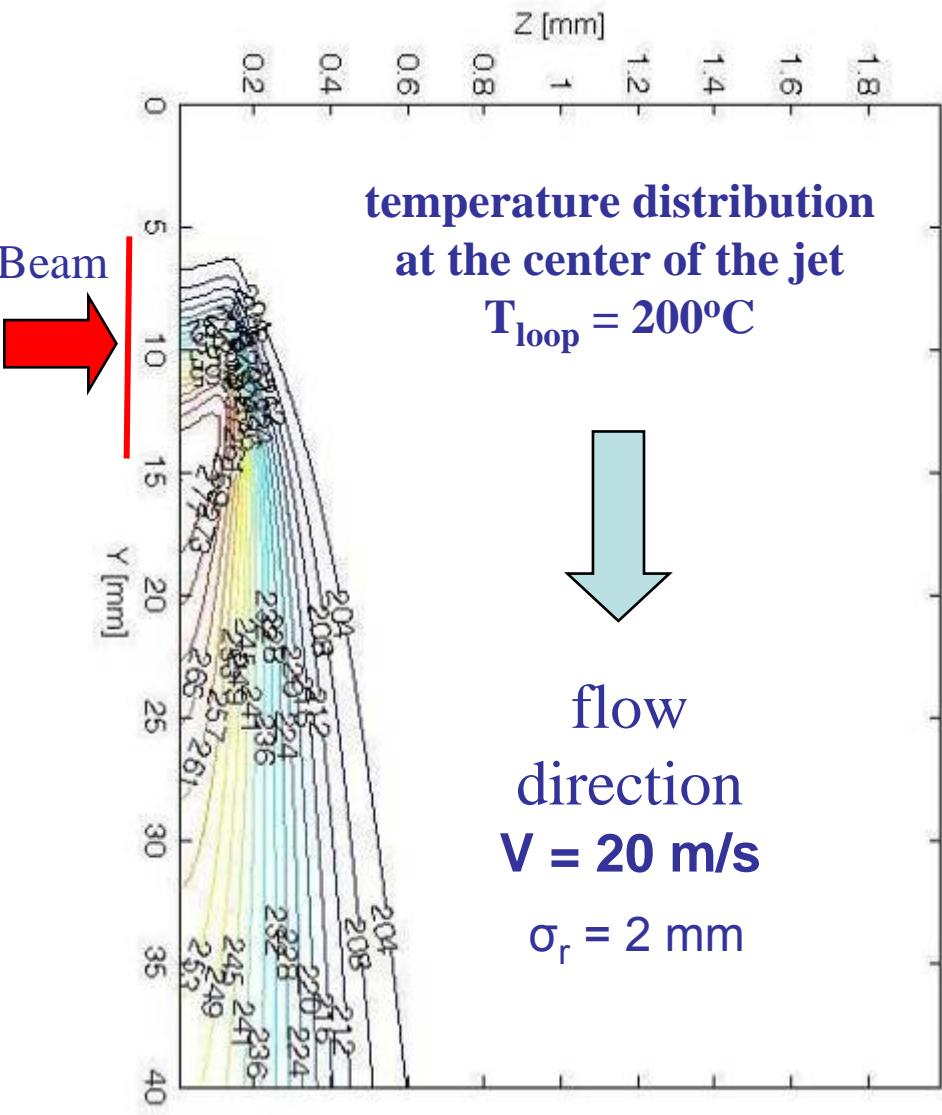


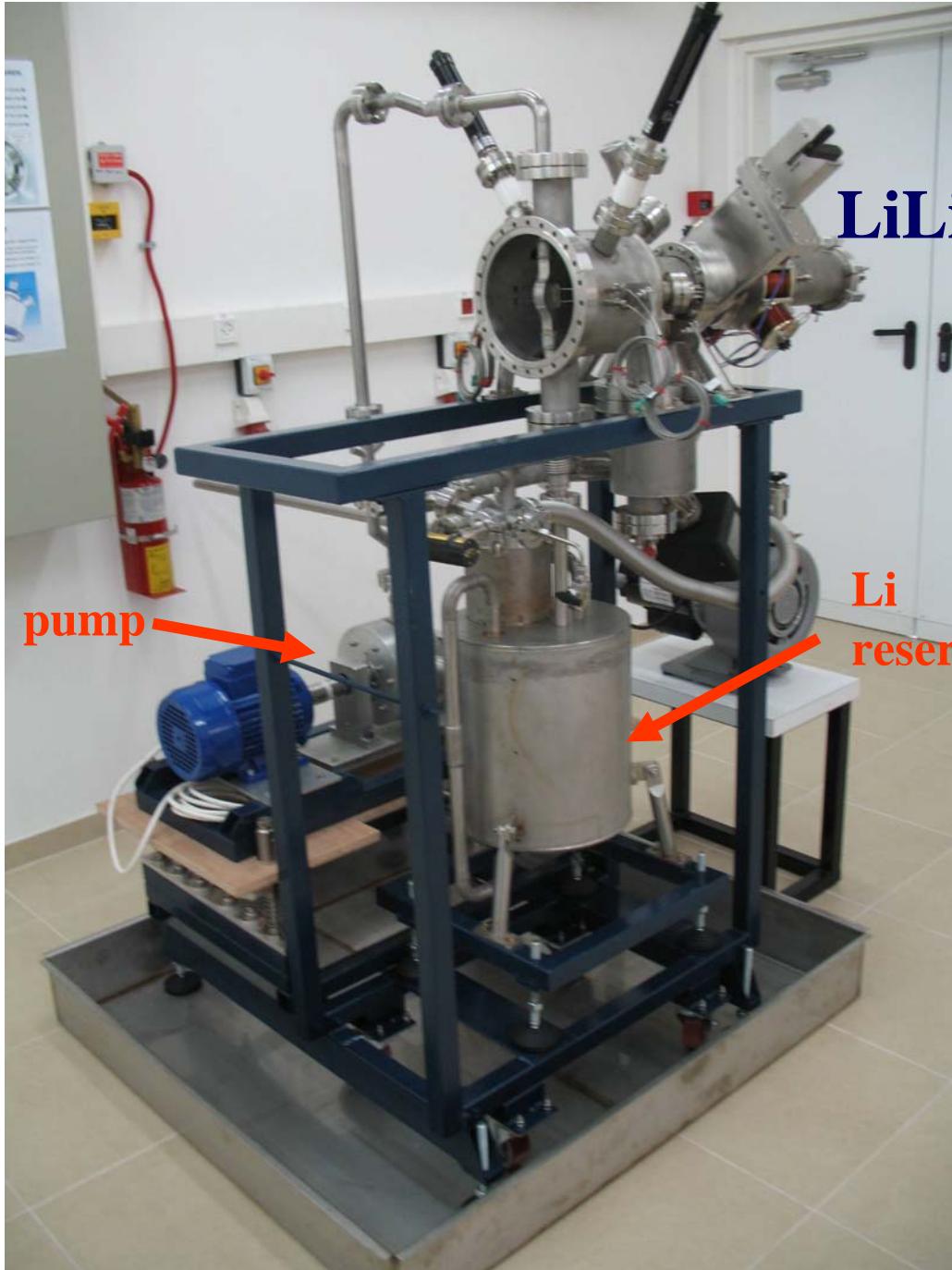
Neutron production target and beam power dump

$I_p = 4 \text{ mA}$
 $E_n = 1.91 \text{ MeV}$
 $\Delta S = 0.2 \text{ cm}^2$



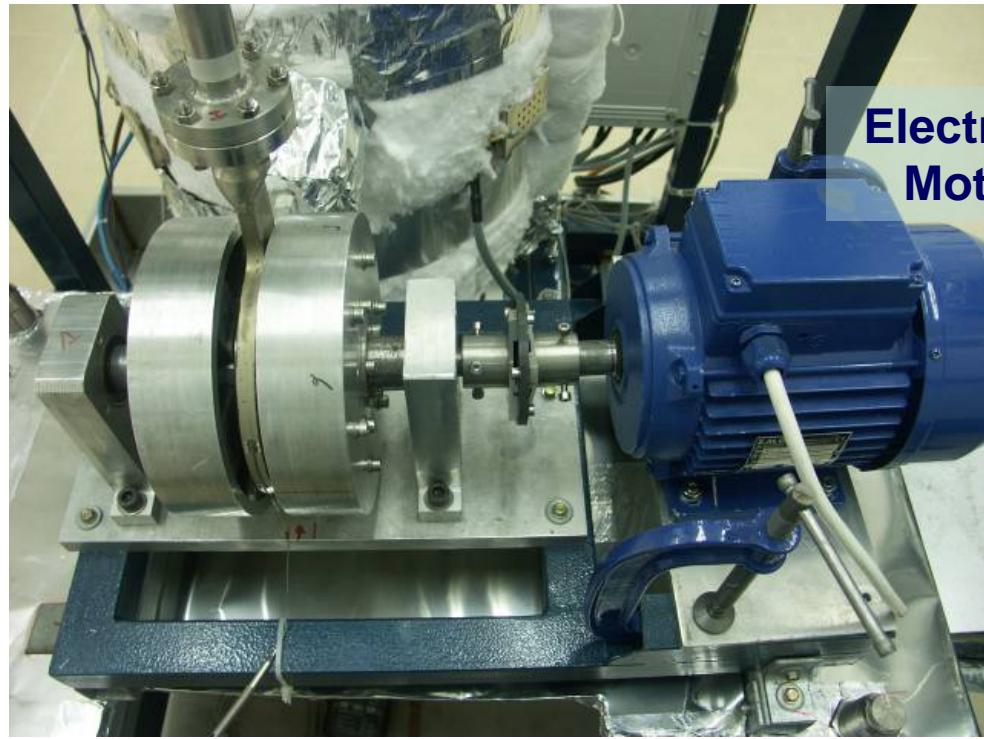
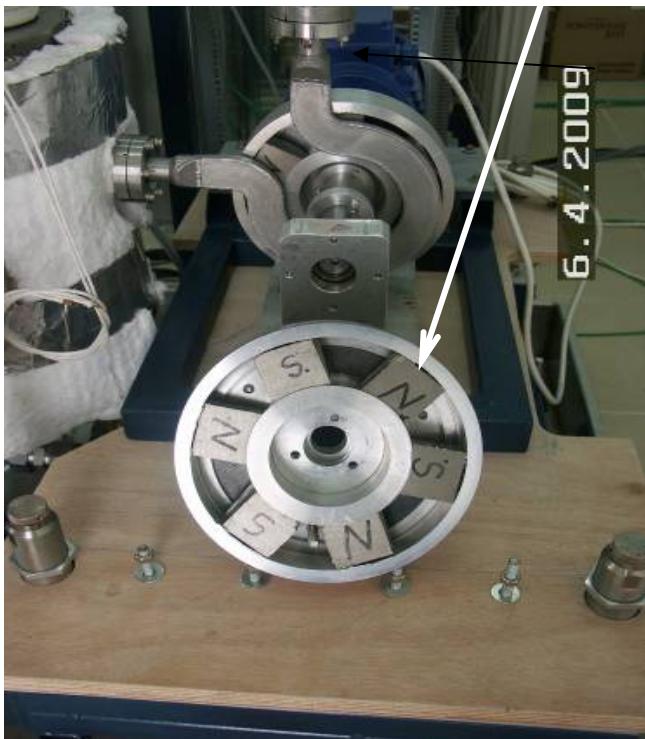
LiLiT @ 4kW beam power expected thermal behavior





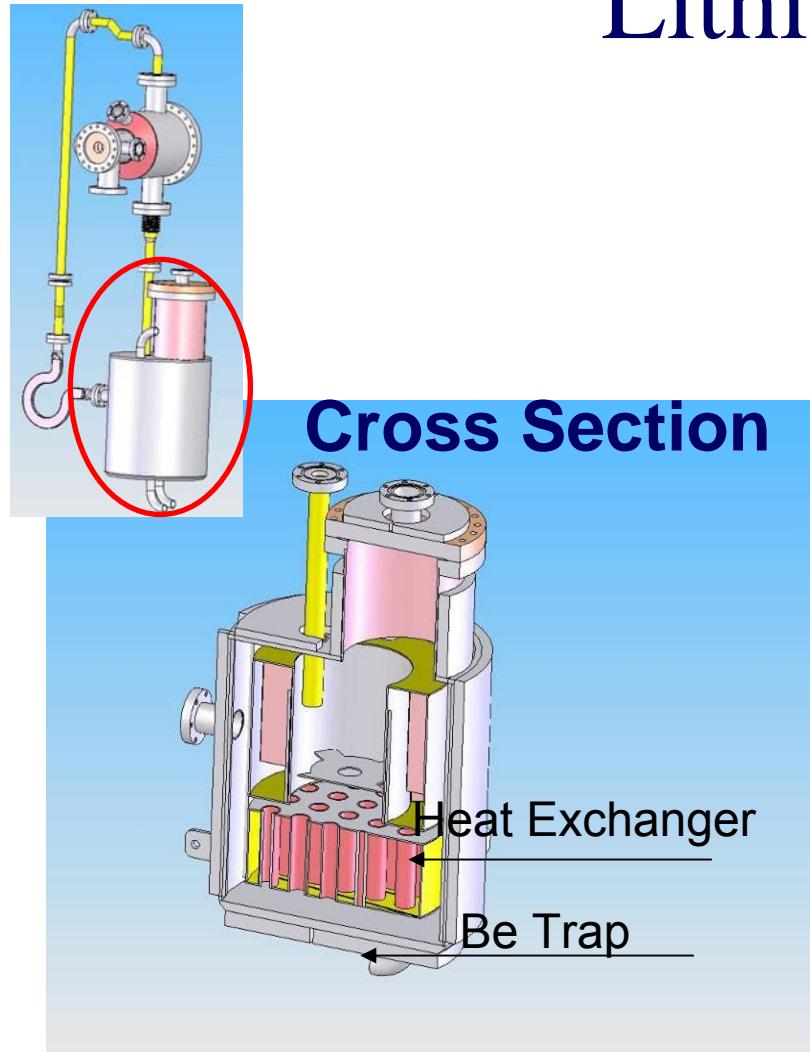
Electro-magnetic pump

Permanent
SmCo
Magnets



Electrical
Motor

Lithium tank

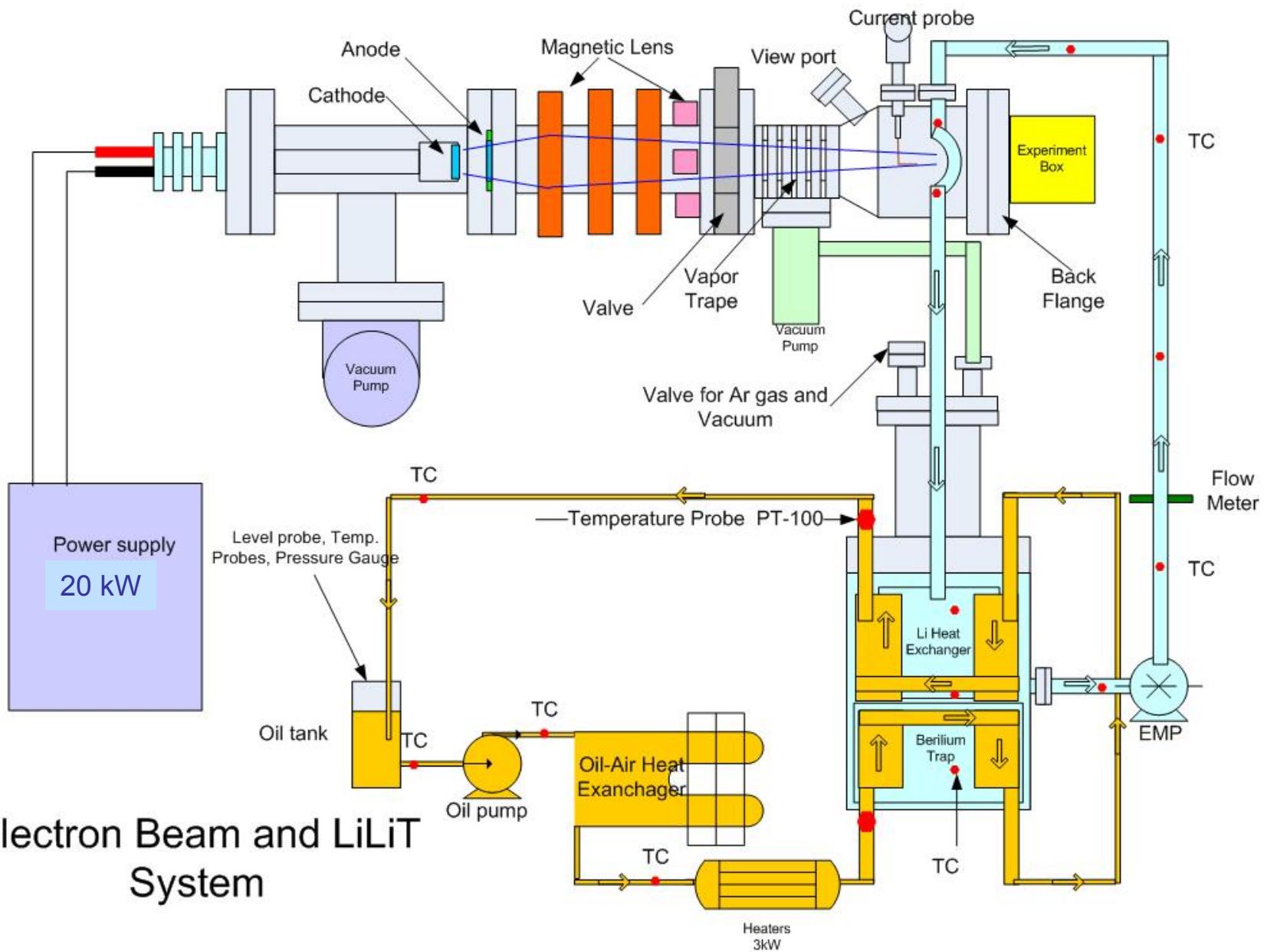


Design to remove ~12 kW





LiLiT general scheme in electron gun beam line



Commissioning steps :

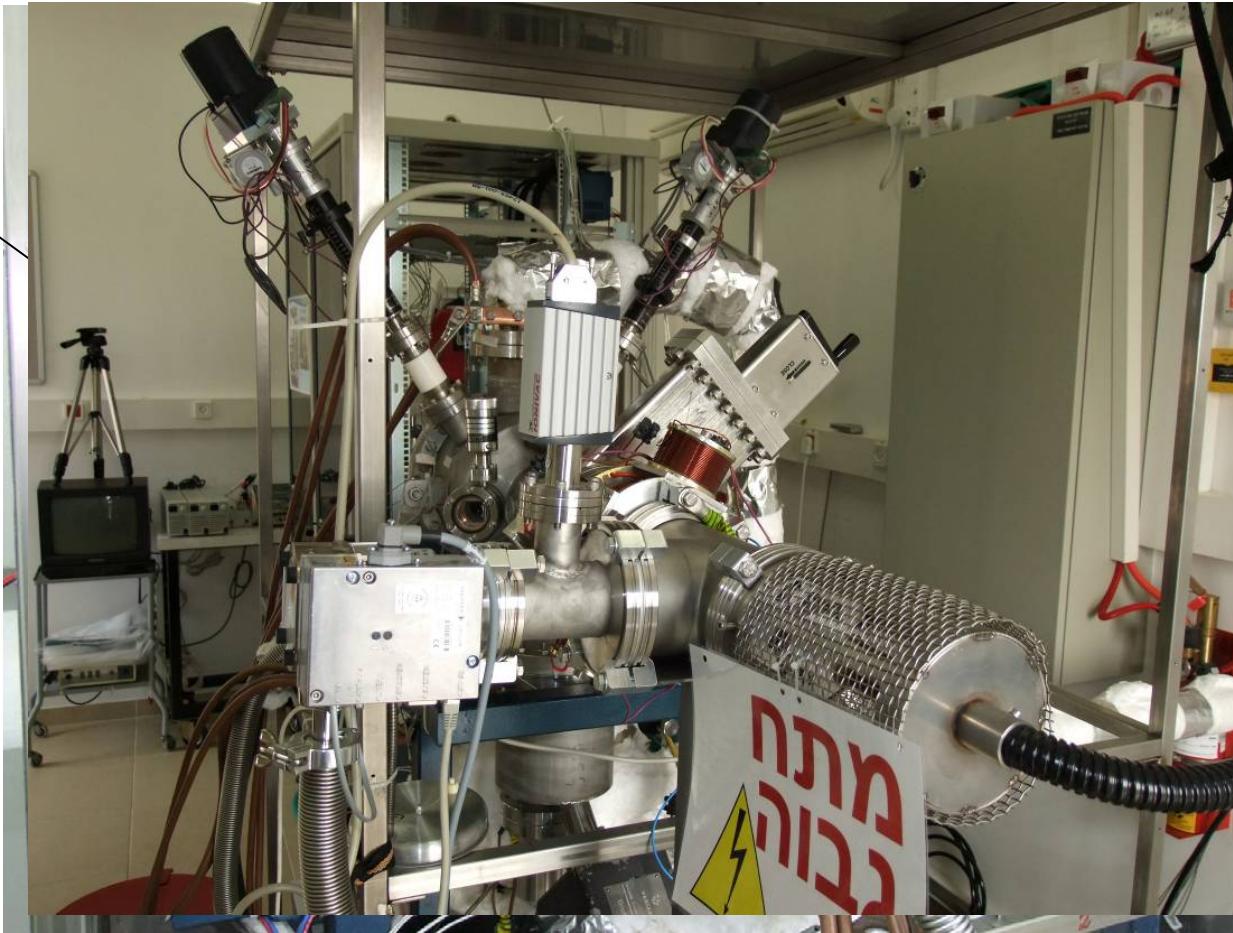
- Li circulation tests
 - thermal tests with a 20 kW electron gun (20 kV, 1 A)
-
- online installation and proton beam tests



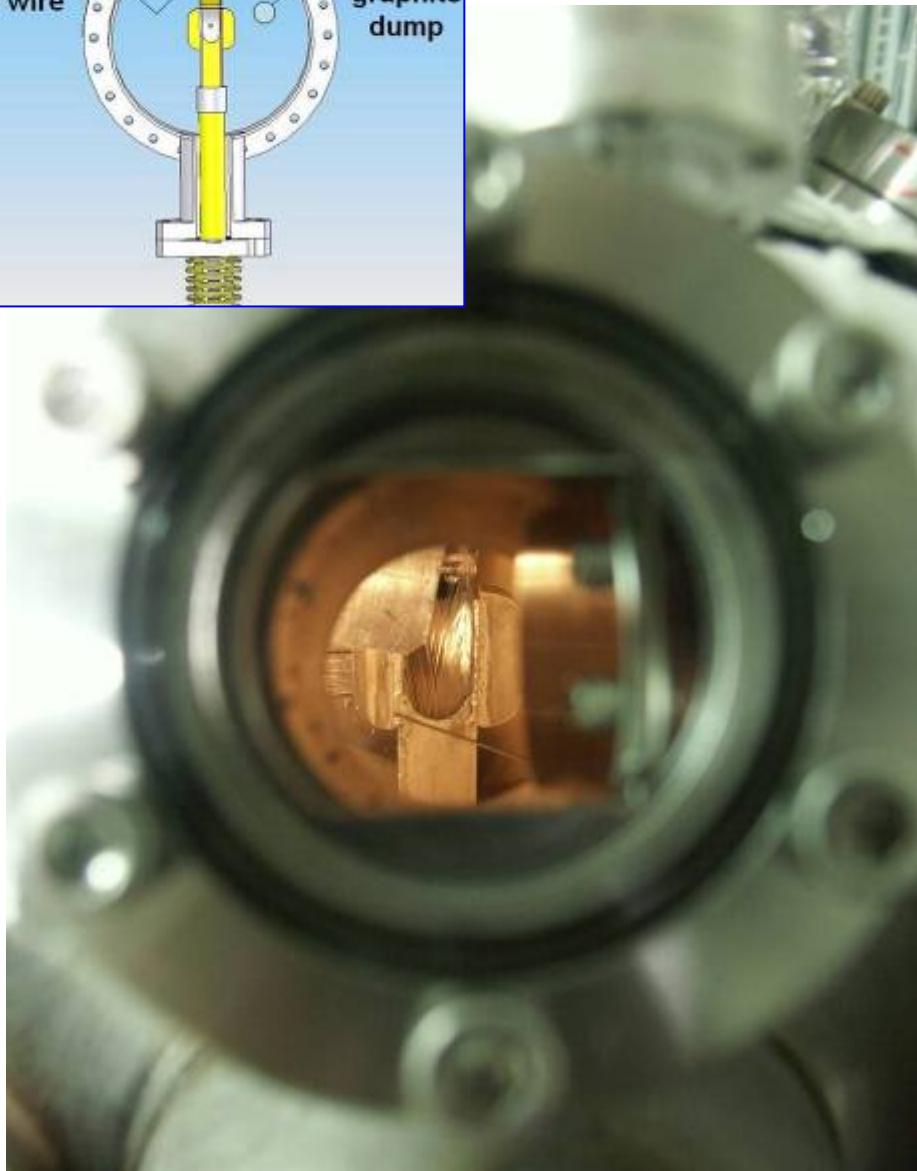
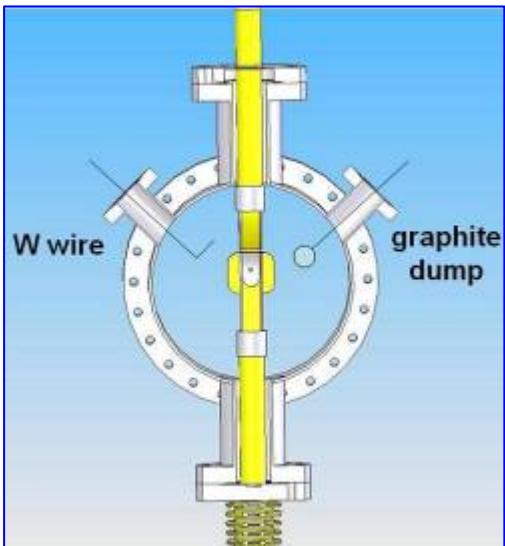
1A, 20 keV (20 kW) electron gun at LiLiT

Beam dump

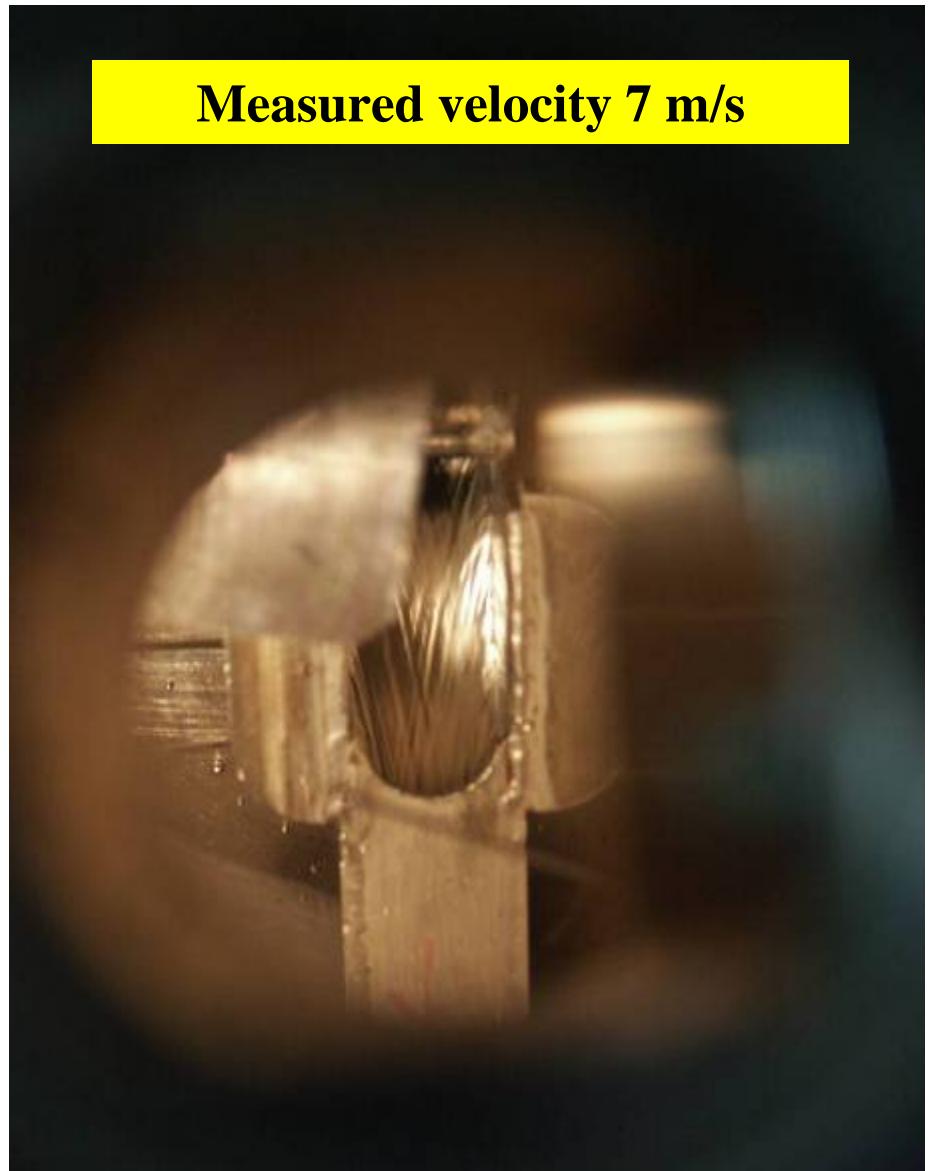
Magnetic lens



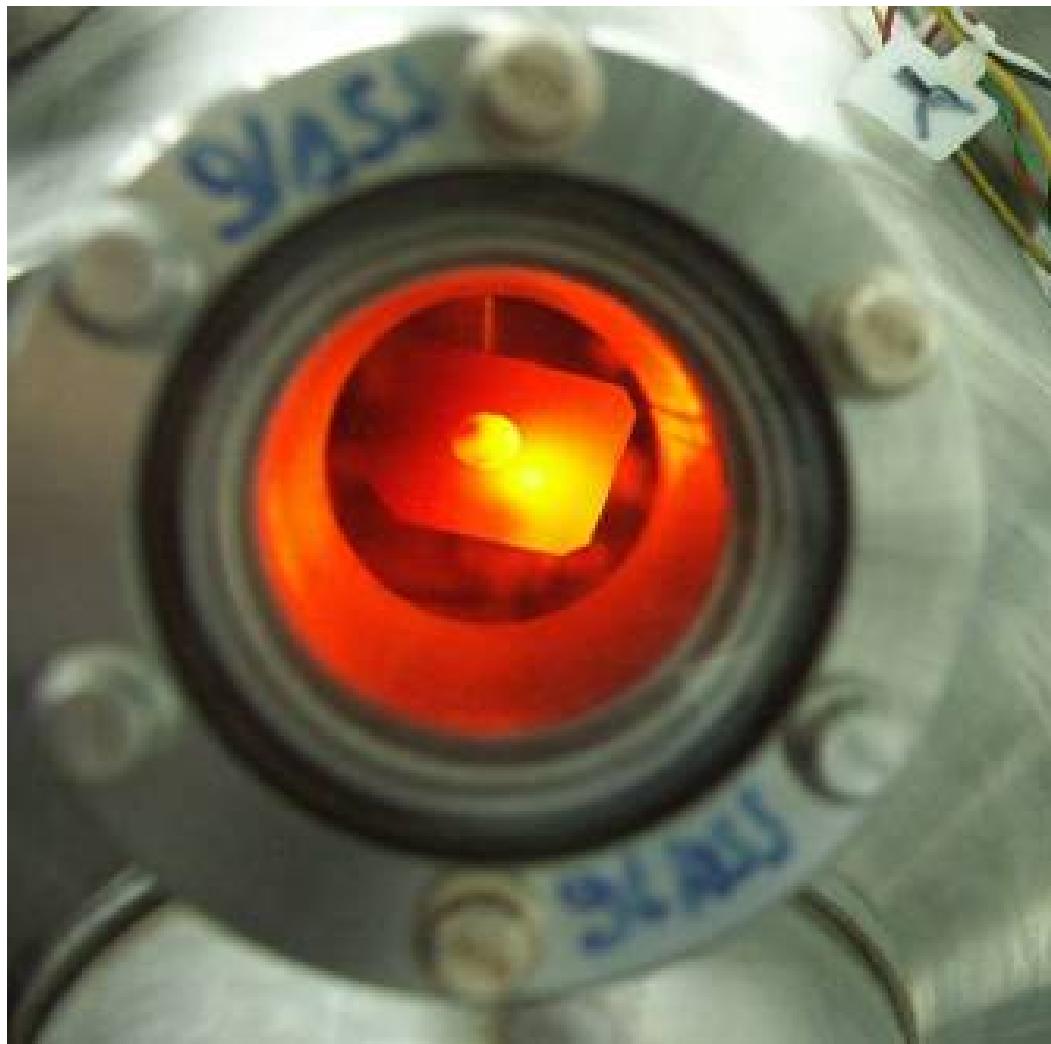
Lithium circulation



Measured velocity 7 m/s

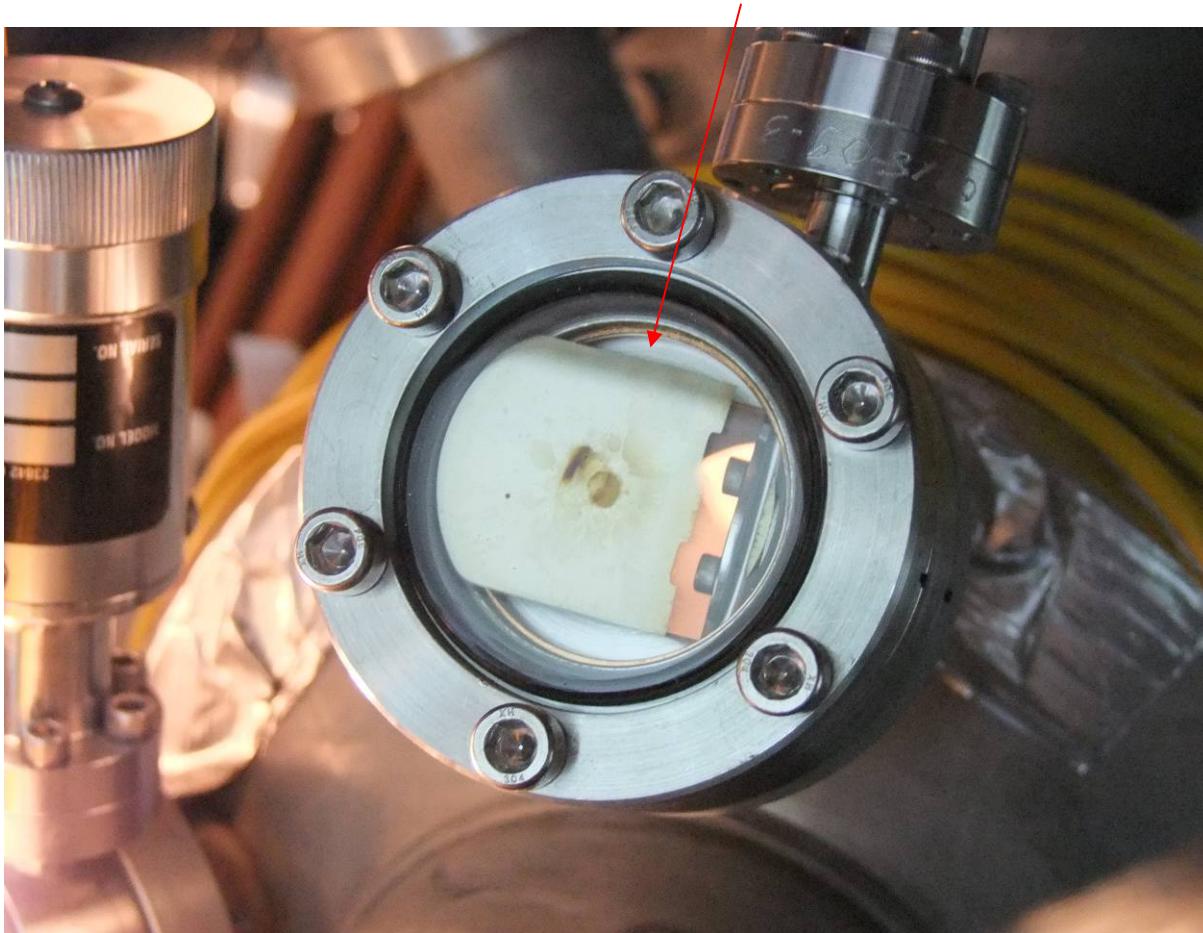


e-gun thermal tests
e-gun on Li flow : 2 kW movie



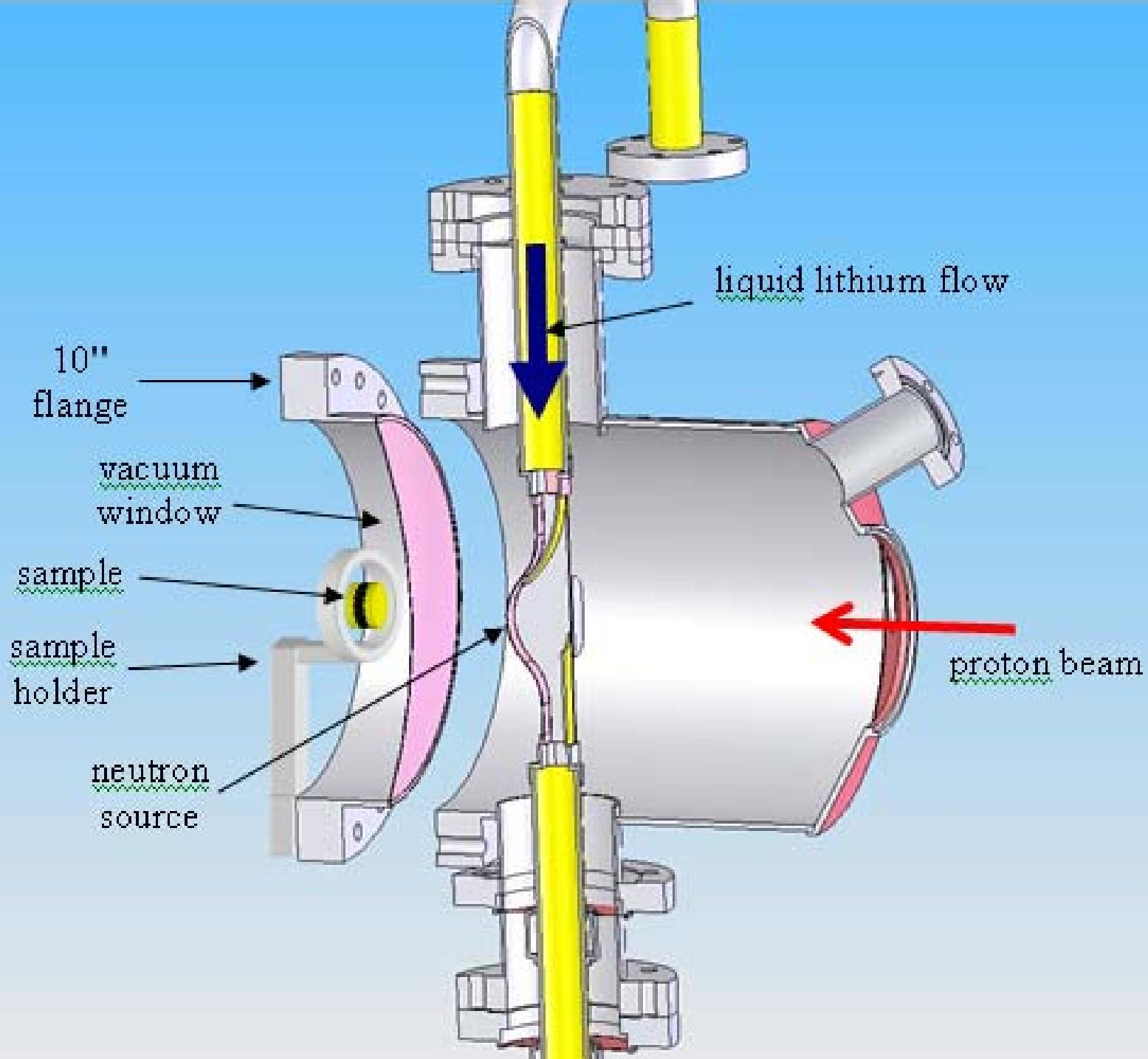
e-beam hitting
diagnostic plate

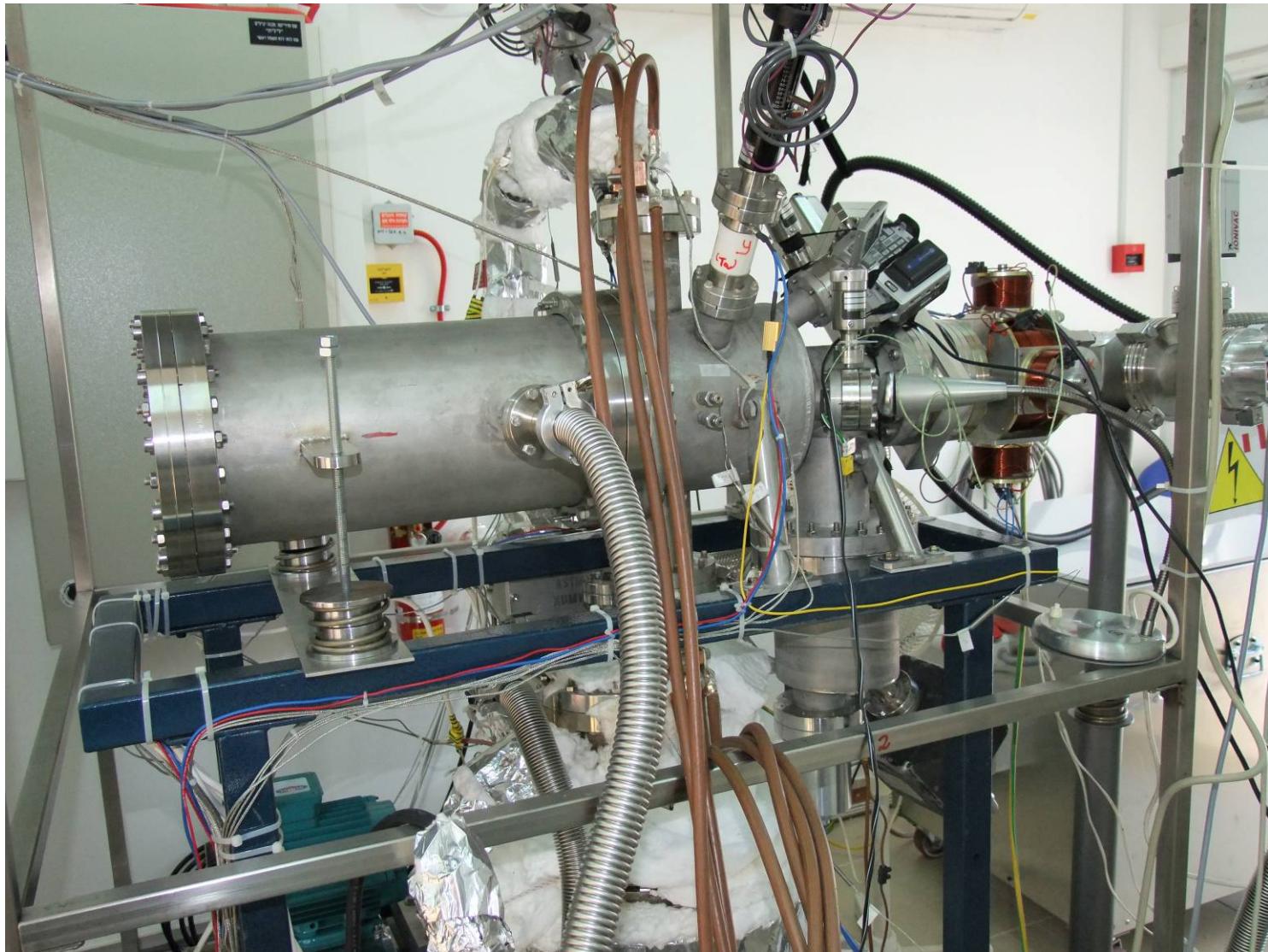
2.2 kW at $v \sim 3\text{m/s}$:
lithium vapors on viewport window



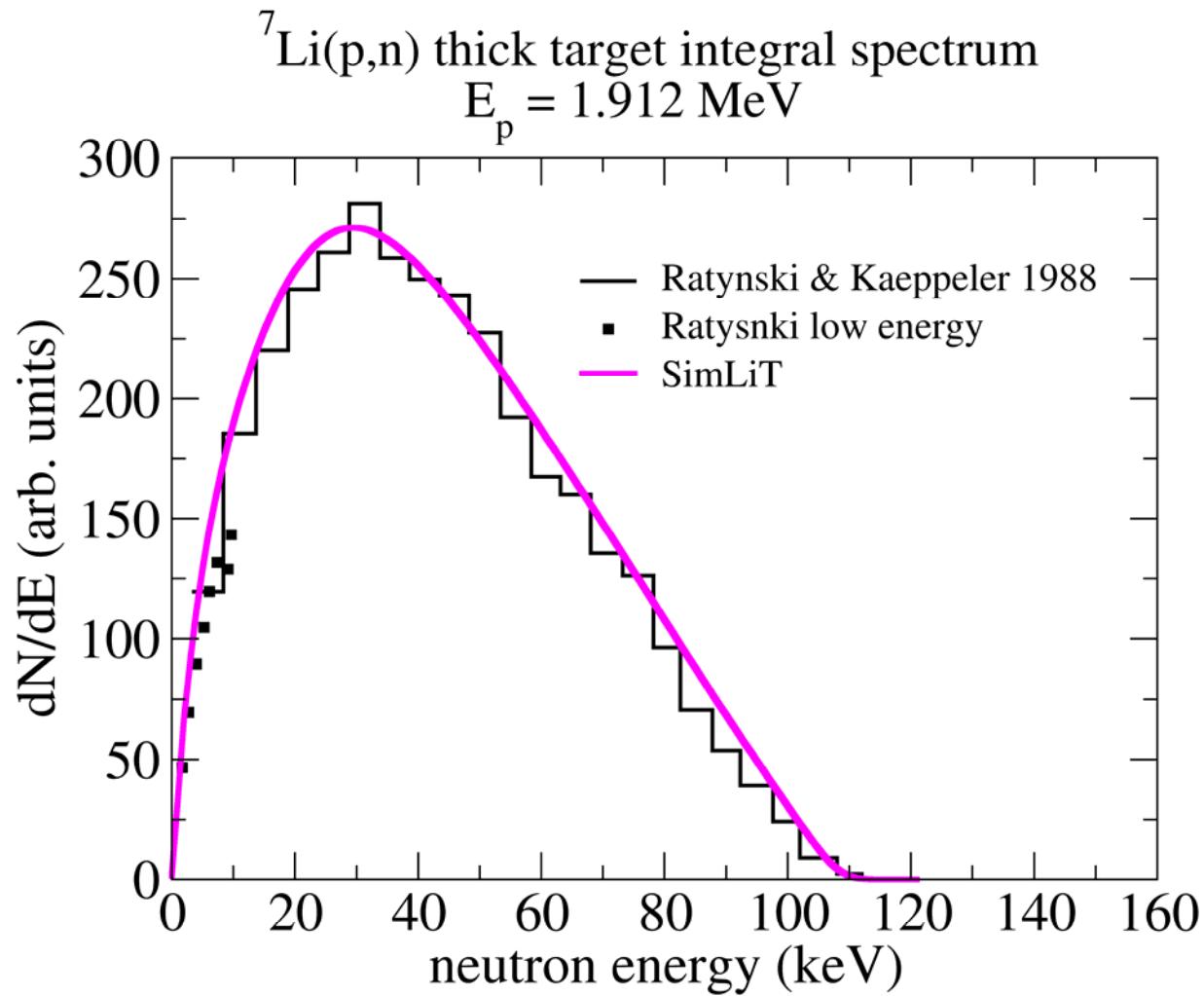
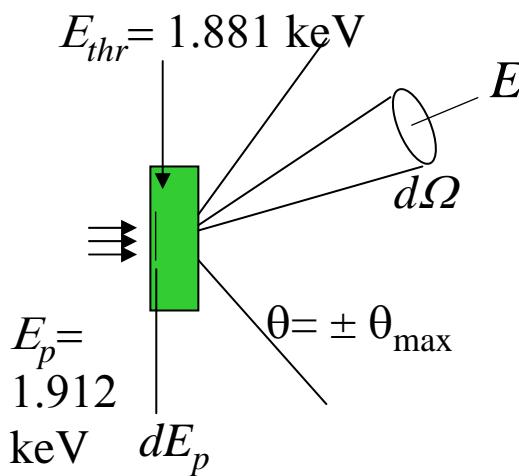
e-gun experiment results

- Electron Beam shape measurement
- Velocity measurement - ~ 3 m/s ($\sim 30\%$ of EM pump capability)
- Stable lithium flow at irradiation up to 2 kW (at 3 m/s)
- Excessive evaporation when ~ 2.2 kW beam was applied





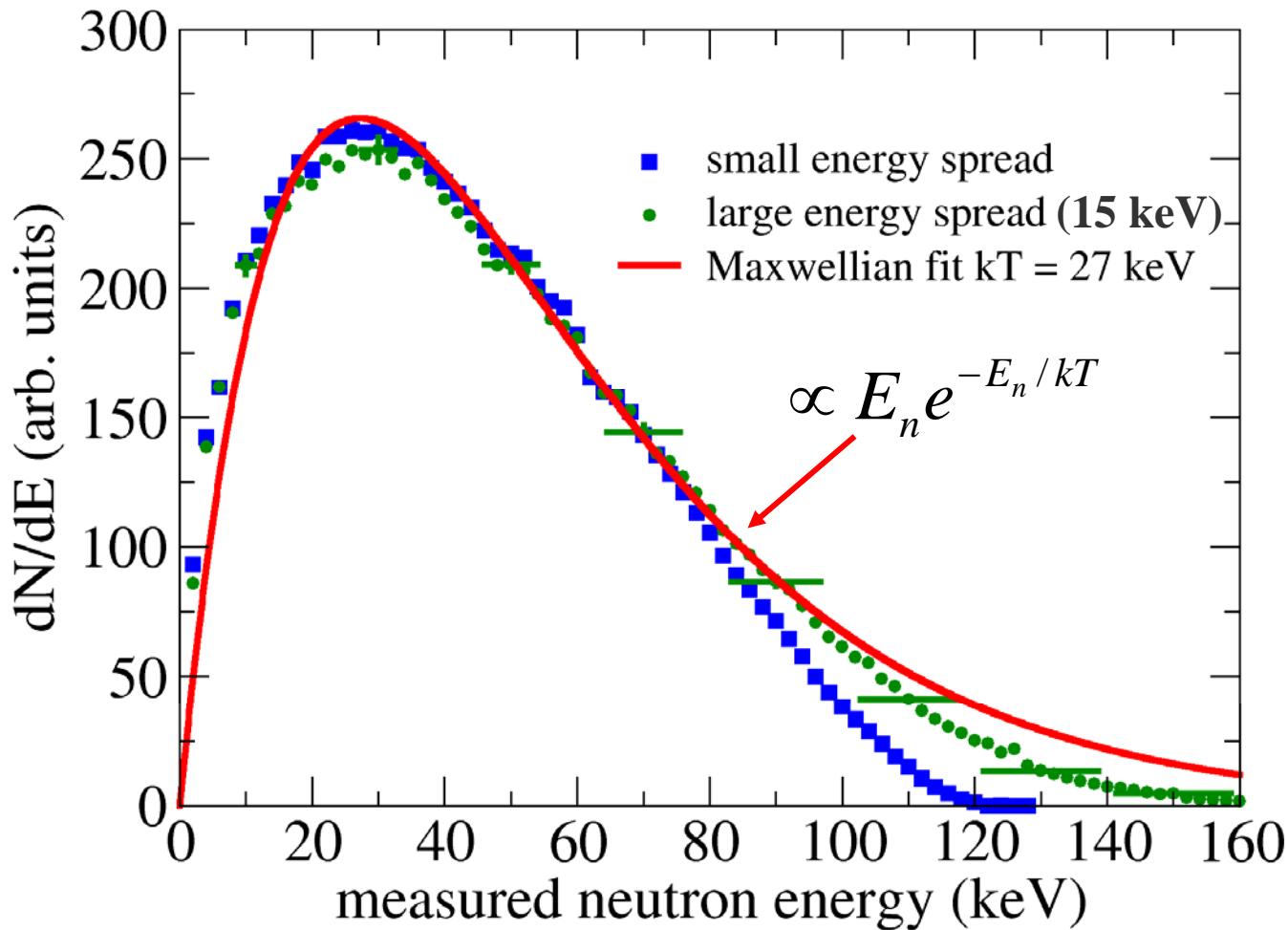
SimLiT: a simulation tool to calculate the neutron spectrum and intensity



SimLiT: $dn / dE_n = n_p \int dE_p \left(\frac{dE_p}{dx} \right)^{-1} \int d\Omega \frac{d\sigma(p,n)}{d\Omega} f_{kin}(\Omega, E_n)$

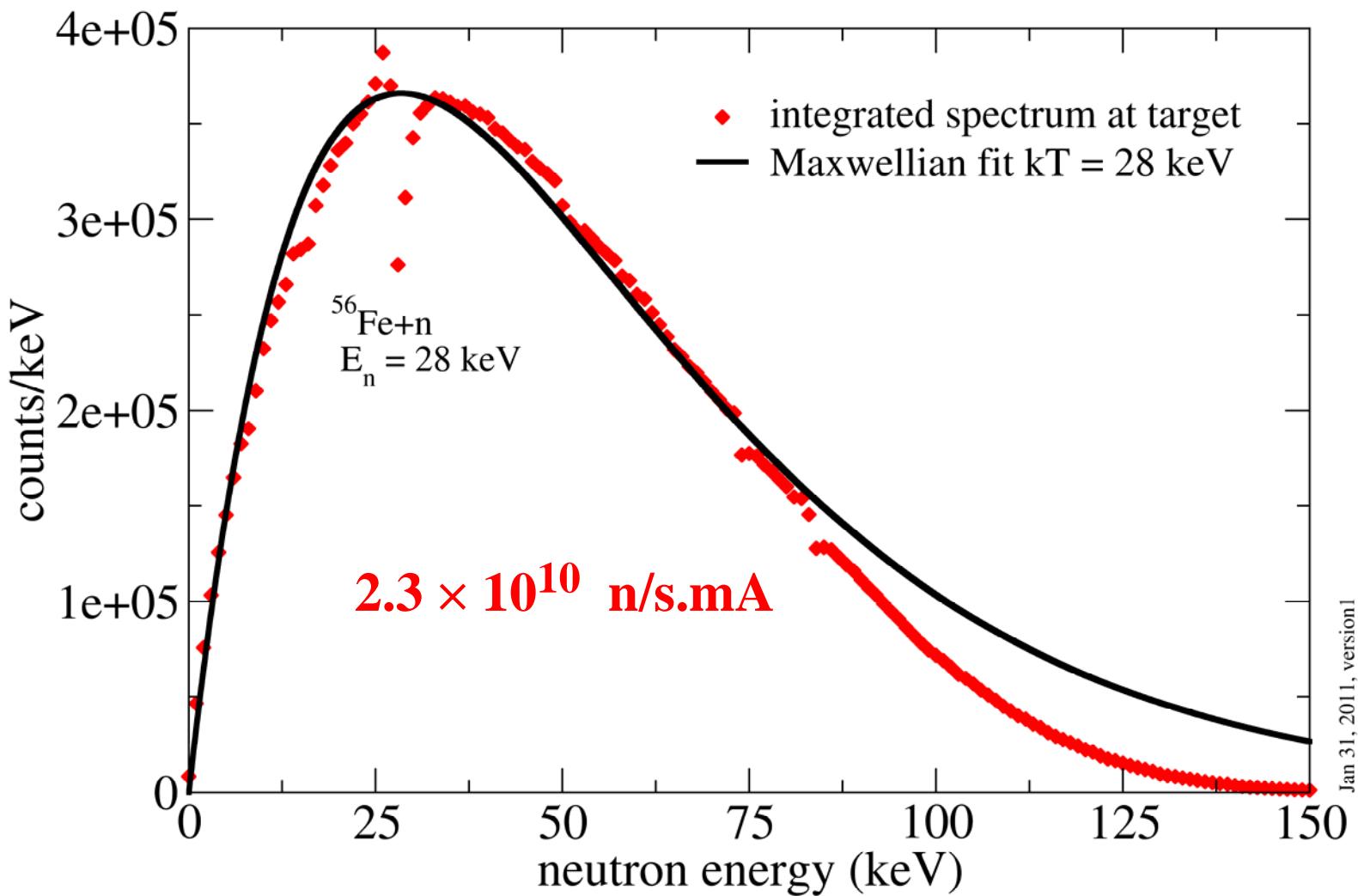
.

Experimental integral near-threshold ${}^7\text{Li}(p,n)$
spectra: $E_p = 1.912 \text{ MeV}$



January 22, 2011, version 1
mfriedman@huphy20:~/Documents/paper_GeeI/fig4_exp_int.agr

LiLiT simulation (full geometry)



Collaboration

Hebrew U, Jerusalem: *Dan Cohen, Moshe Friedman, Eytan Tsuk, Joshua Granot, M.P.*

Soreq NRC, Yavne: *Gitai Feinberg, Shlomi Halfon, Alex Arenshtam, Dan Berkovits, Michael Bisyakoev, Yossi Eisen, Ilan Eliyahu, Nir Hazensprung, Tsviki Hirsch, Dany Kijel, Ami Nagler, Asher Shor, Ido Silverman*

Summary

1. LiLiT high-power target was built and tested off-line with an electron gun (beam power 2 kW at flow velocity of 3 ms⁻¹)
2. Installation and on-line tests at SARAf expected early 2012
3. Au activation measurements and real target measurements following