Current status of the liquid lithium target development

LiLiT Team
presented by S. Halfon

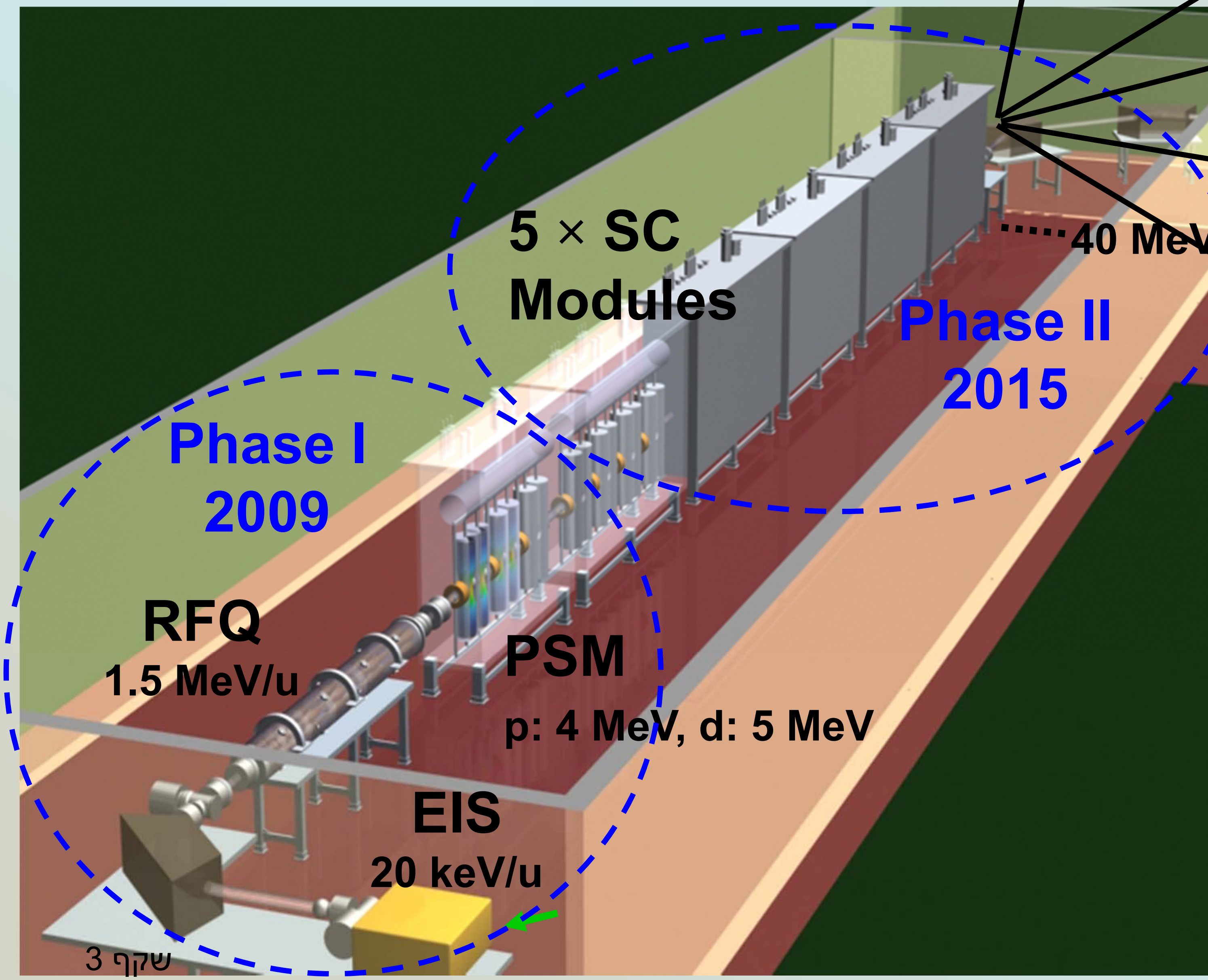
4th High-Power Targetry Workshop

May 3, 2011

Outline

- Soreq Applied Research Accelerator Facility (SARAF) overview
- Liquid Lithium Target
  - research application and requirements (BNCT, astrophysics)
  - design features
  - lithium circulation and e-gun experiments

SARAF Accelerator



Thermal neutron radiography

Thermal neutron diffraction

Nuclear Astrophysics

Radioactive beams

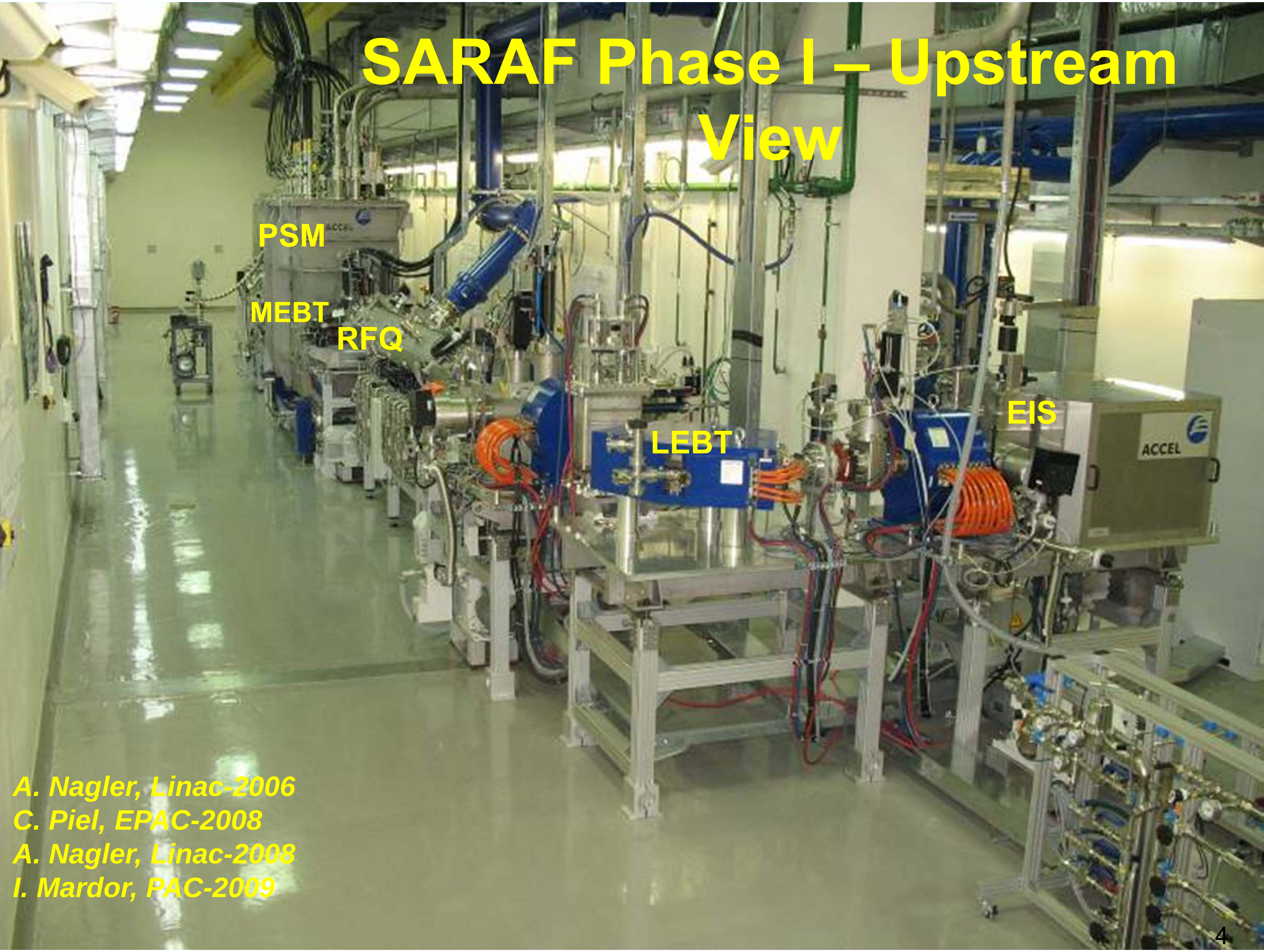
Radio Pharmaceuticals

Accelerator Parameters

Parameter	Value
Ions	p / d
Energy	5 – 40 MeV
Current	0.04 – 2 mA
Maintenance	Hands-On

- Current upgradeable to 4 mA

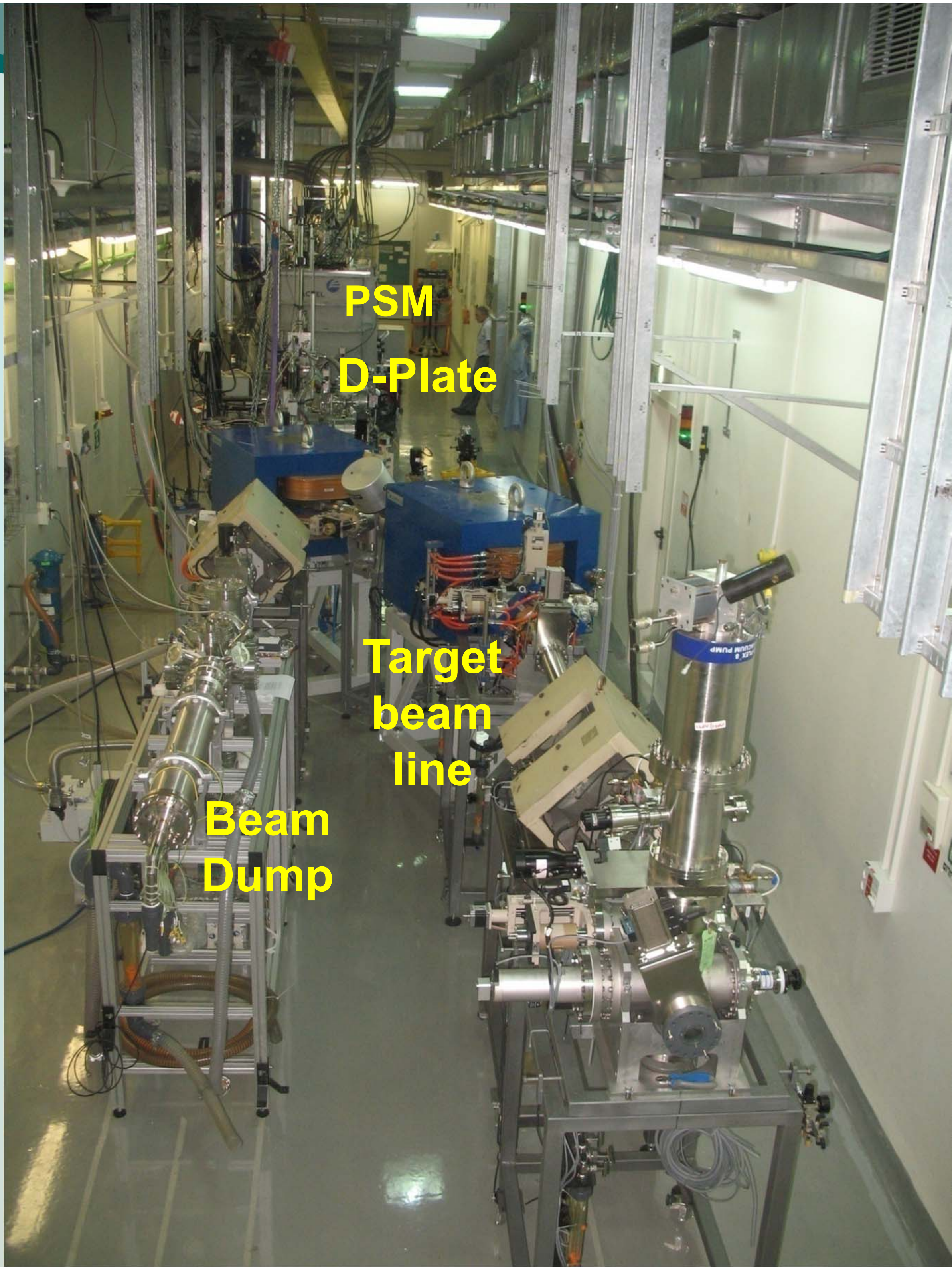
SARAF Phase I – Upstream View



A. Nagler, Linac-2006
C. Piel, EPAC-2008
A. Nagler, Linac-2008
I. Mardor, PAC-2009

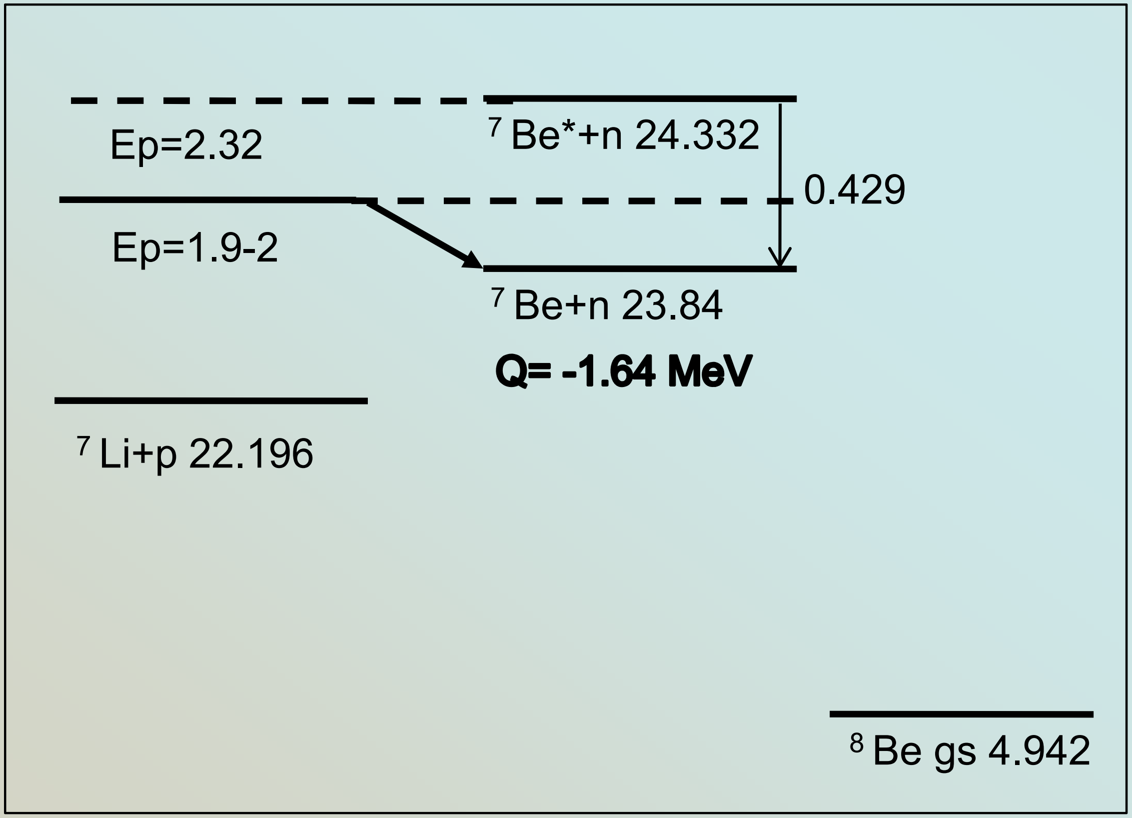
SARAF Phase I – downstream

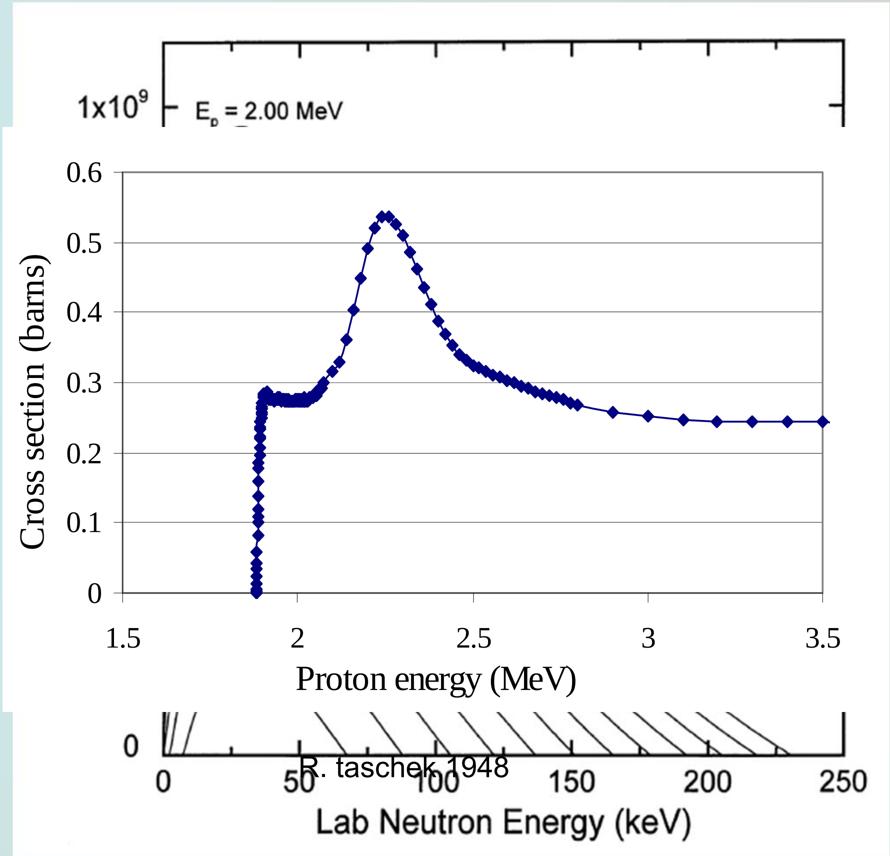
- Commissioning of Phase-I is approaching finalization
- The current challenges include conditioning the RFQ to enable acceleration of CW deuterons
- 1 mA CW proton beam have been accelerated through the entire Phase-I up energy of 3.7 MeV
- Low duty cycle 2.5 mA deuteron beam have been accelerated to energy of 4.3 MeV



Neutron producing lithium target - ^{7}Li(p,n)^{7}Be

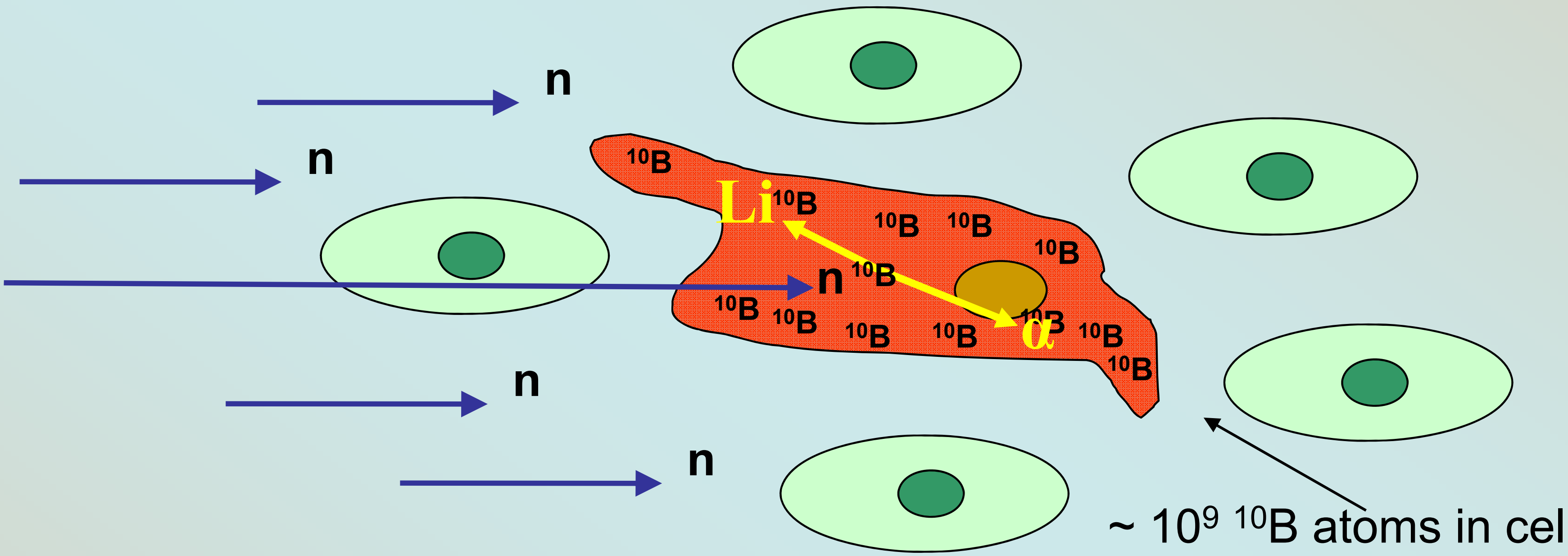
- $E_{thr}(p)$= 1.881 MeV ,Q = -1.644 MeV.
- Produces keV-energy forward-collimated neutrons near threshold.





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

Boron Neutron Capture Therapy



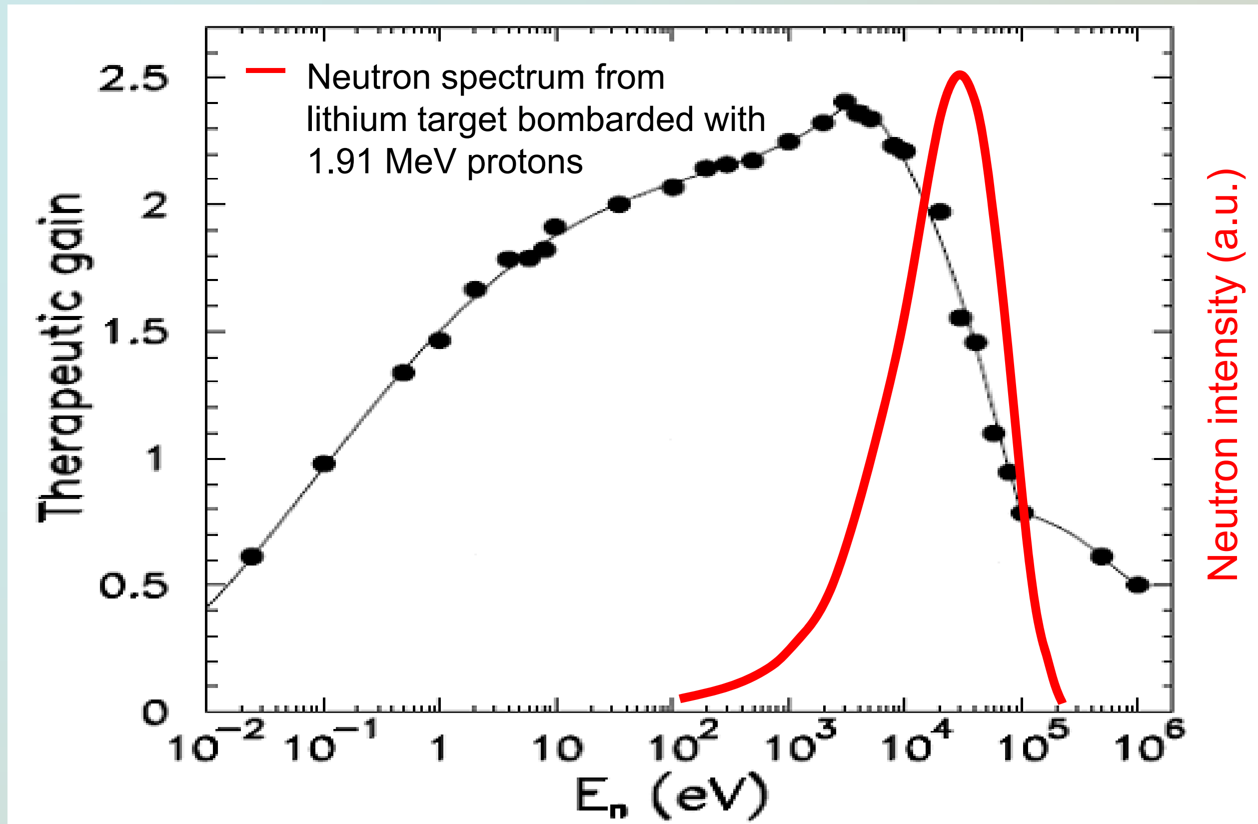
1. Selectively deliver ^{10}B to the tumor cells
2. Irradiate the target region with neutrons
3. The short range of the $^{10}B(n,a)^7Li$ reaction product, 5-8 mm in tissue, restrict the dose to the boron loaded area

The neutron energy effect on therapy

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**

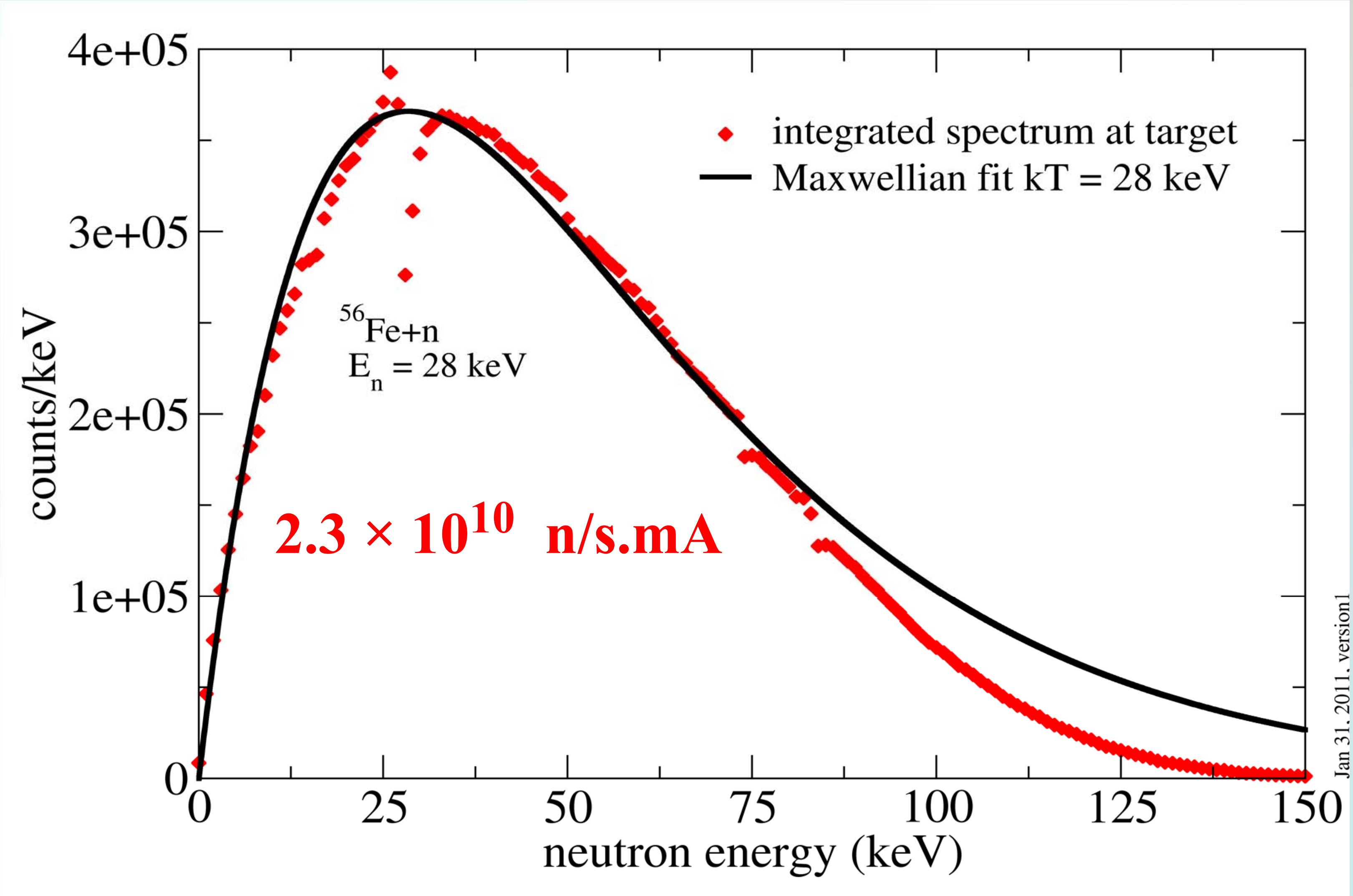


Bisceglie et. al. Phys. Med. Biol. **45** (2000) 49–58.

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}

Astrophysical research: at Ep=1.91 MeV a neutron spectrum of maxwellian with kT= ~ 28 keV is produced- *typical stellar neutron energy in s-proces*



LiLiT full-geometry simulation (GEANT4)

LiLiT – High flux keV neutron source

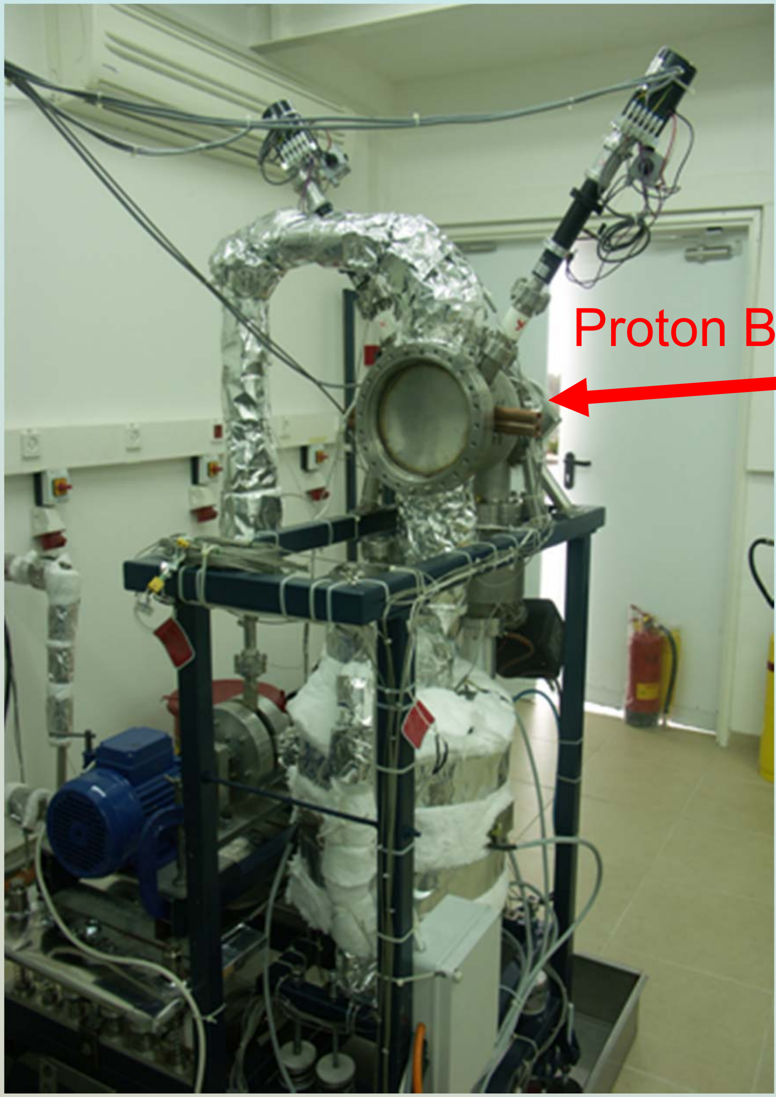
- Both researches require high neutron flux (~10^9 n/cm^2/s) hence high power Lithium Target
- 4 – 10 kW beam power (p, 2-4 mA, 1.9-2.5 MeV)
- Gaussian beam (σ=2 mm, D=12 mm)

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)	2 x 125	5	2
Beam spot on the target (cm^2)	~100	~10	~1
Beam density on the target (mA/cm^2)	2.5	0.5	>2 (peak)

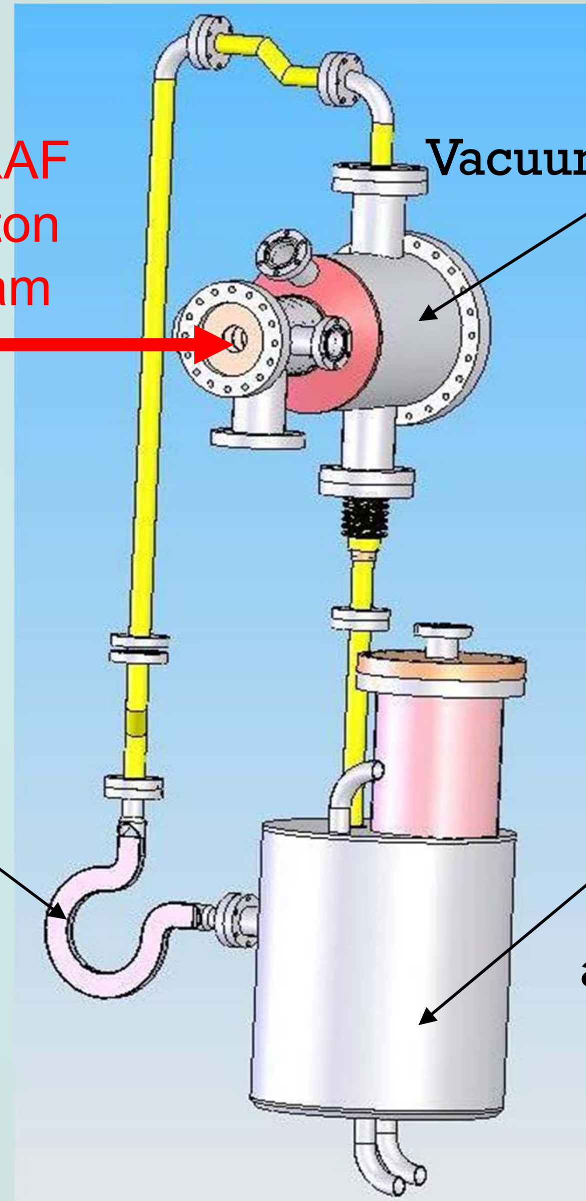
- The target should dissipate power densities of more then ~1 MW/cm^3

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

Liquid lithium loop

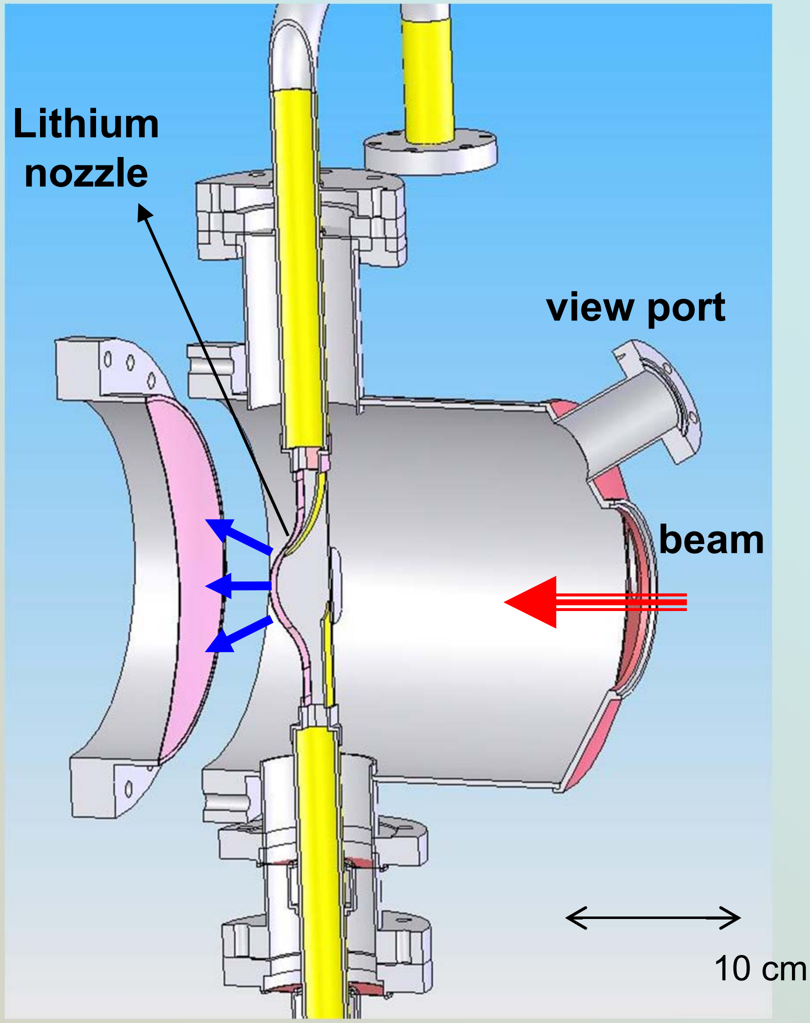


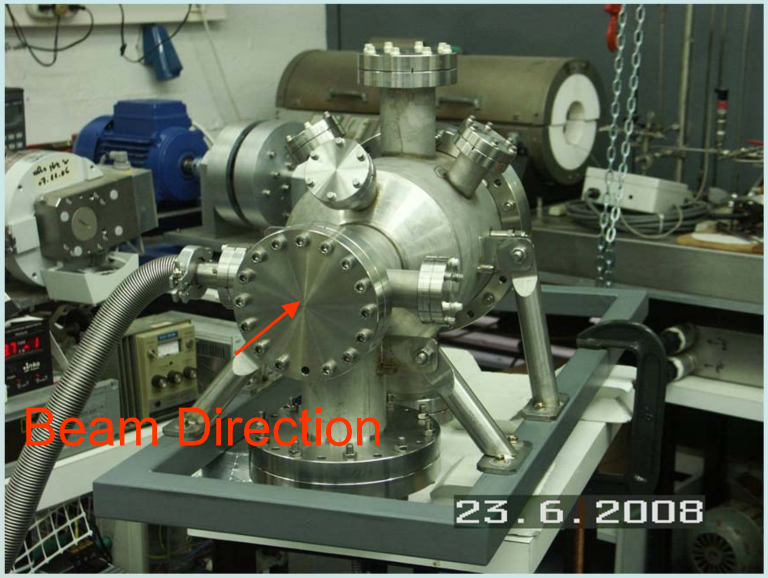
Neutron port



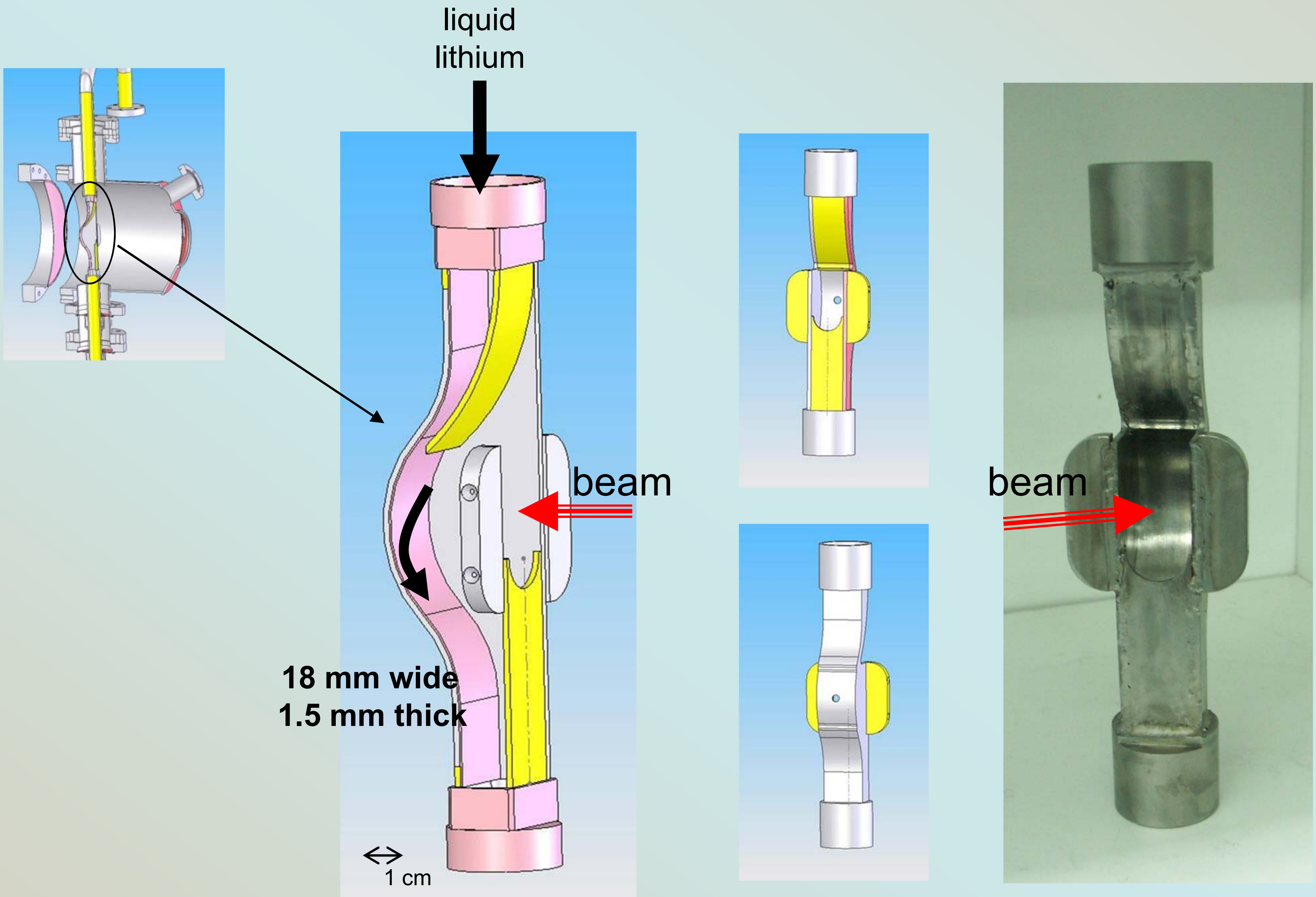
Accelerator port

Target chamber

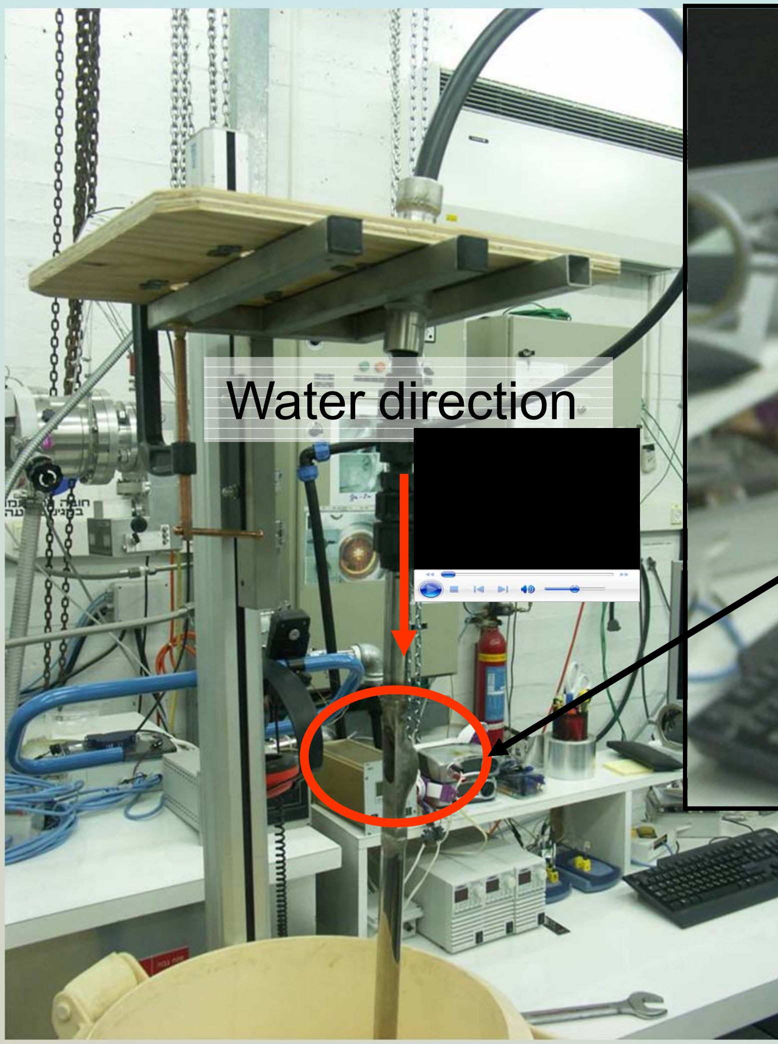


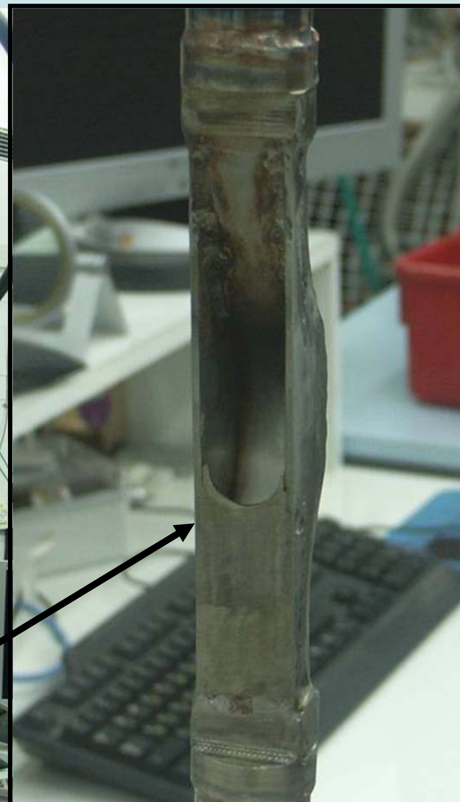


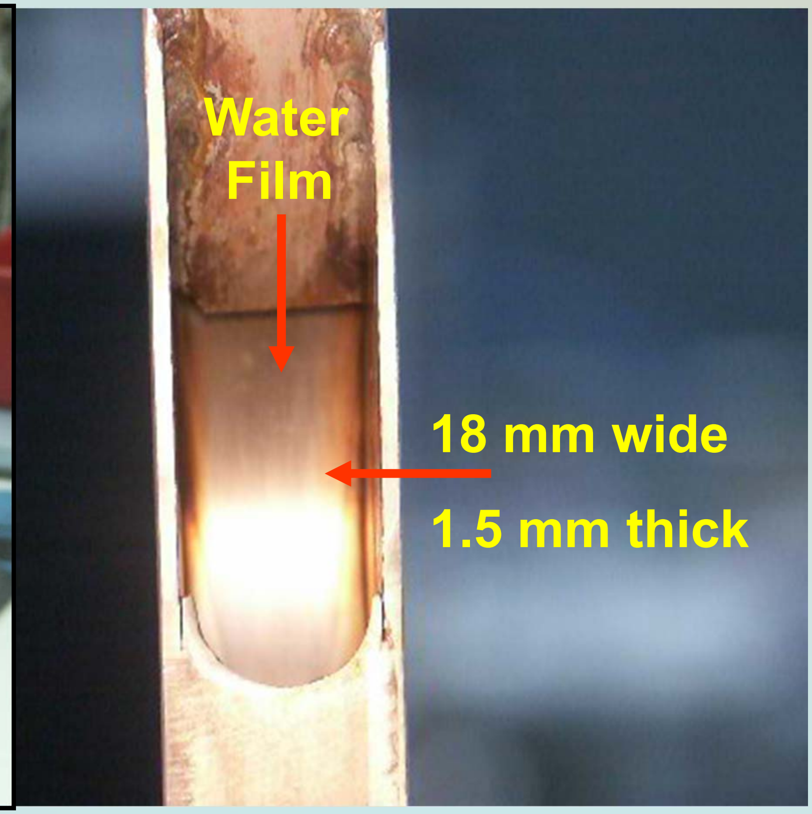
Lithium Nozzle



Concave jet - Water test

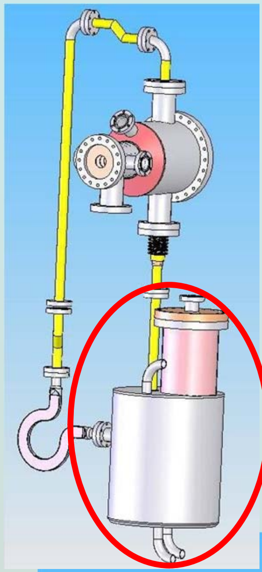






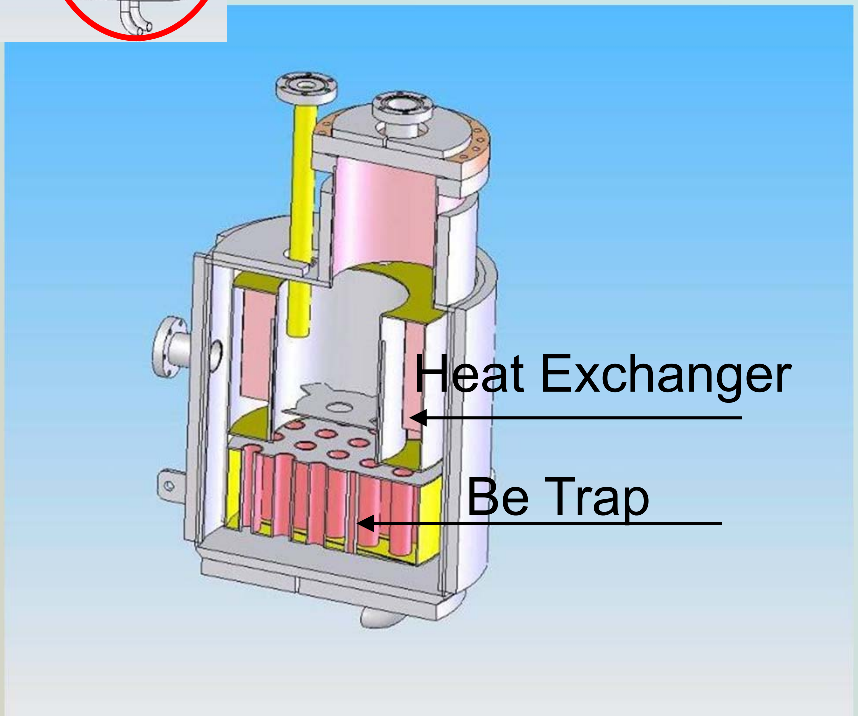
- Meas. flow rate: 48 l/min
- extracted velocity: 26 m/s

Lithium tank



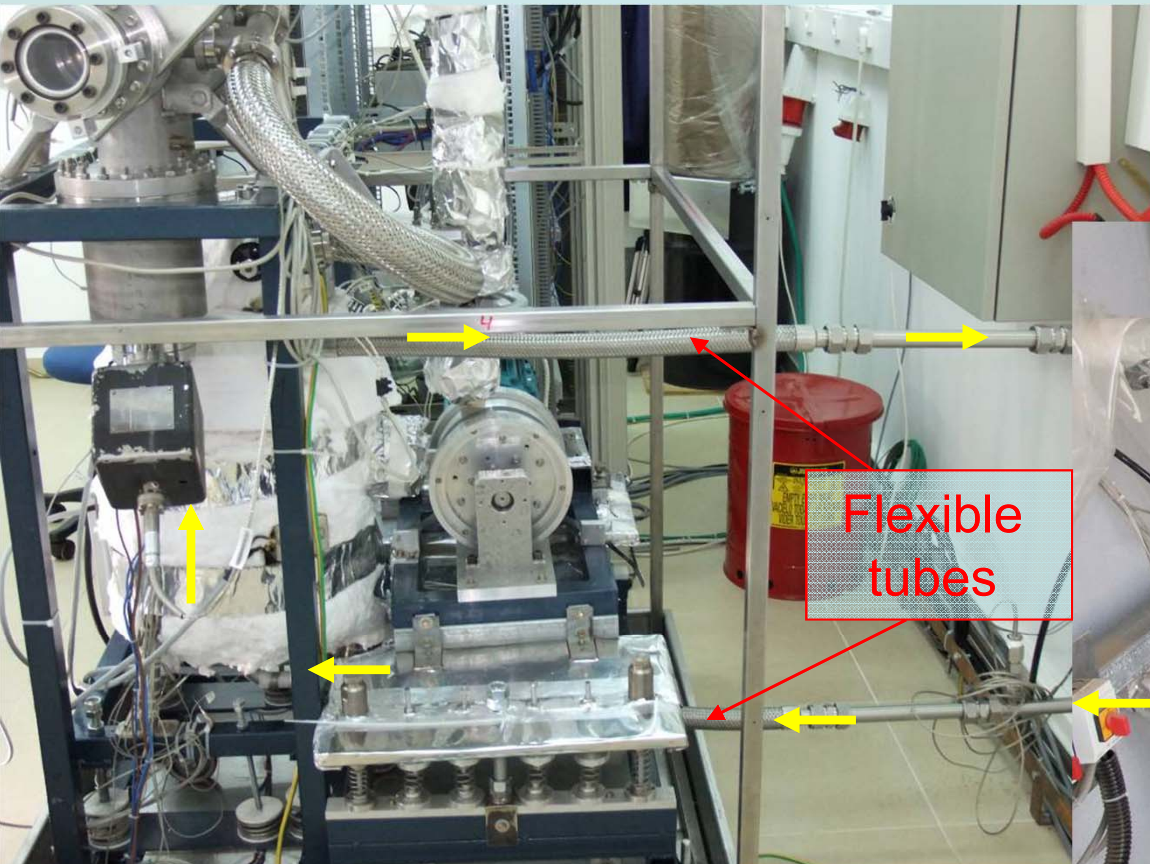
Design to remove ~12 kW

Cross Section

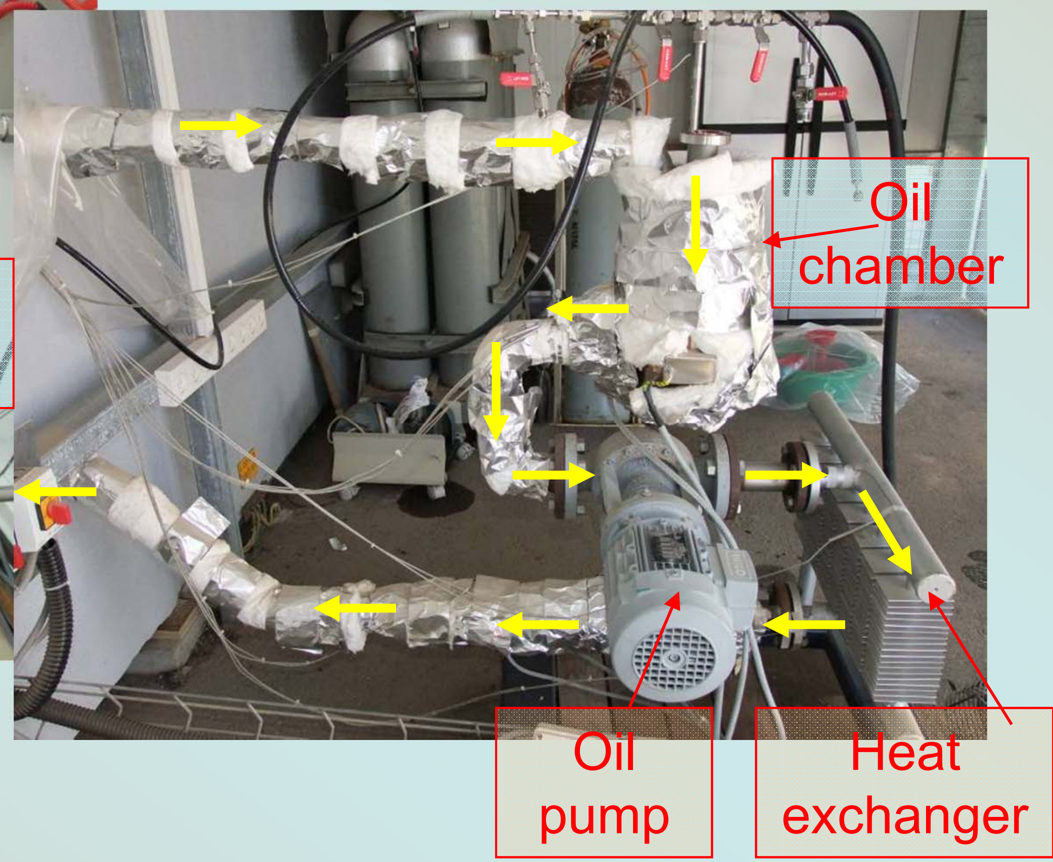


Oil cycle

Inside the lab

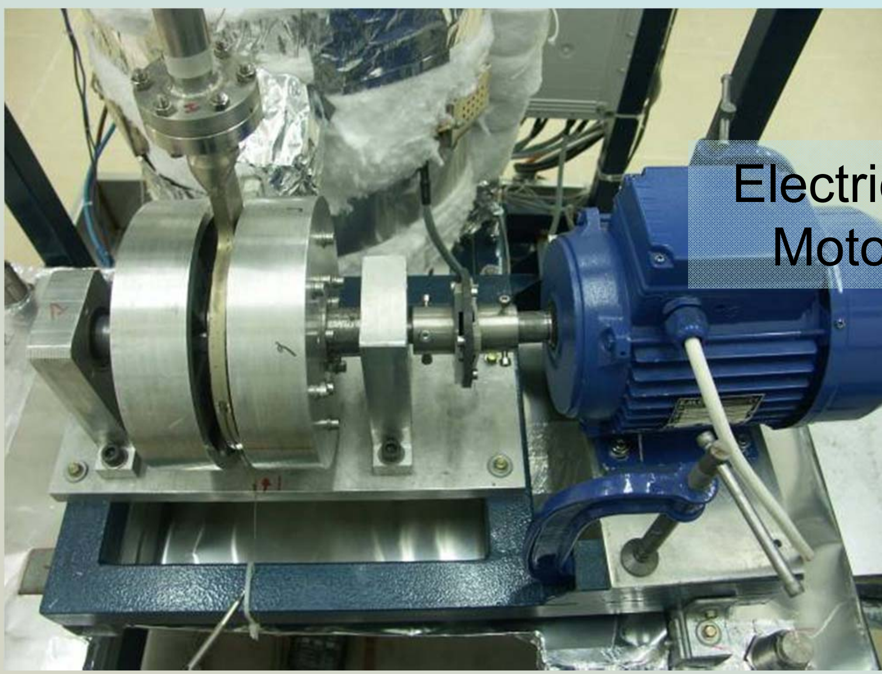


Outside the lab



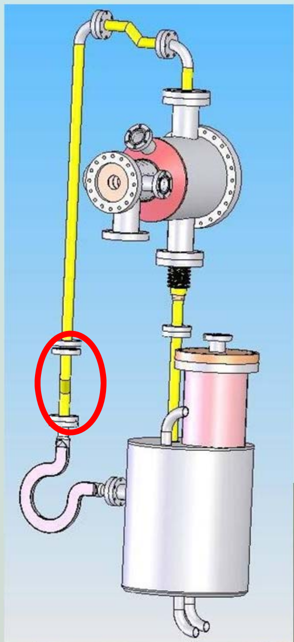
Electro-magnetic pump

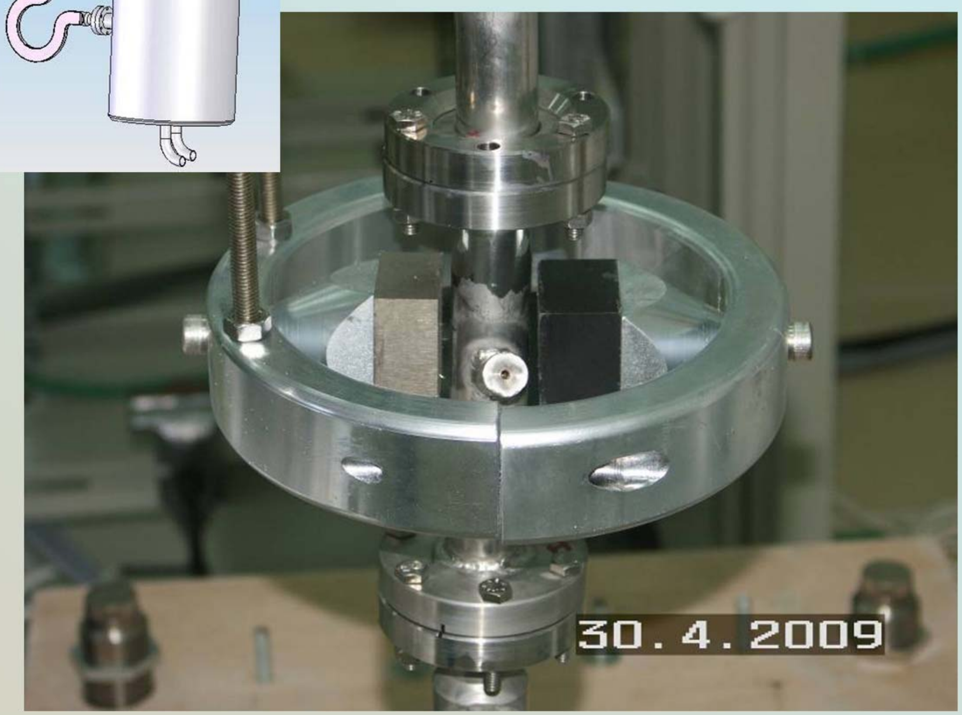
Permanent
SmCo
Magnets



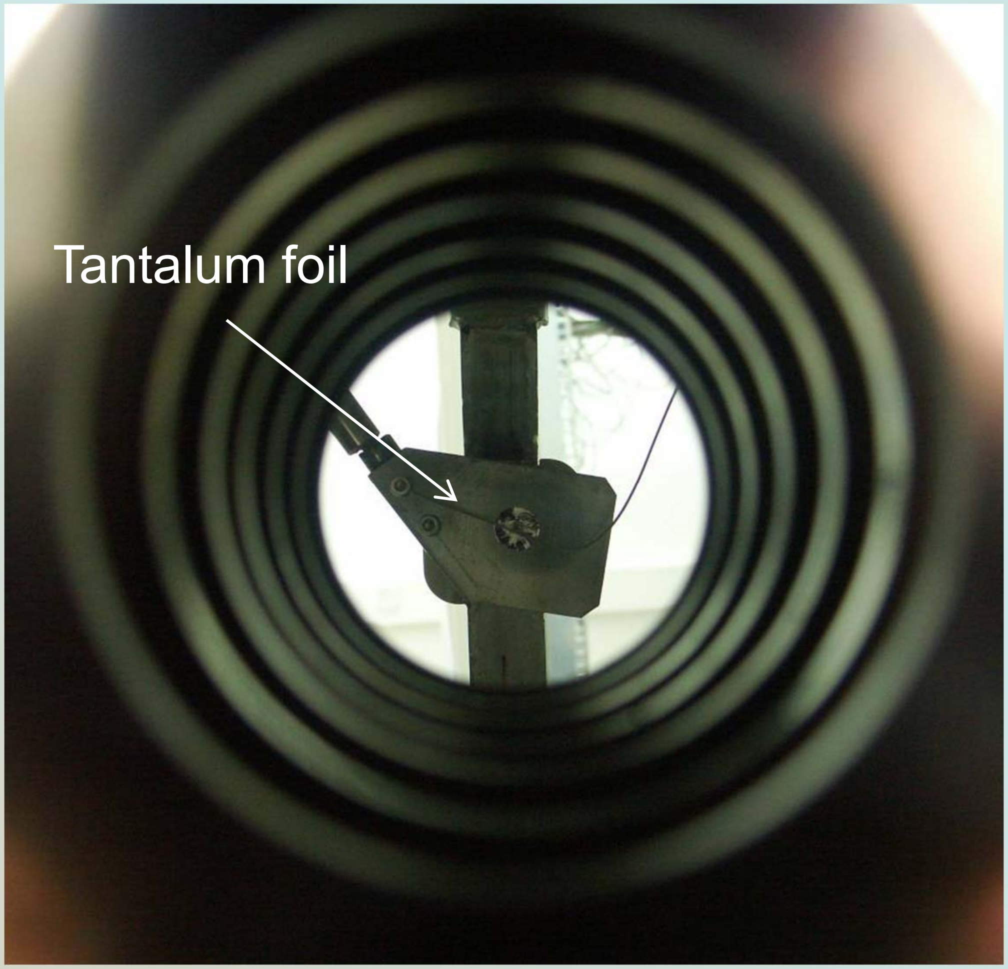
Electrical
Motor

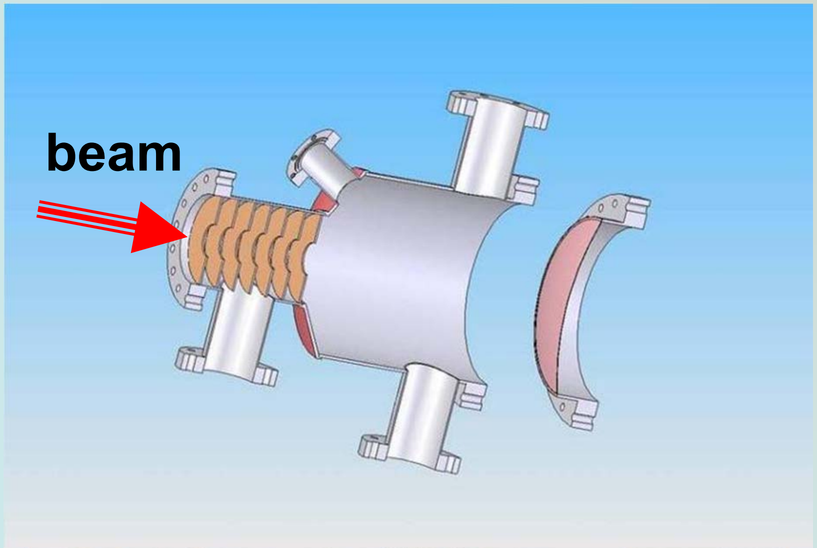
DC electro-magnetic flow meter





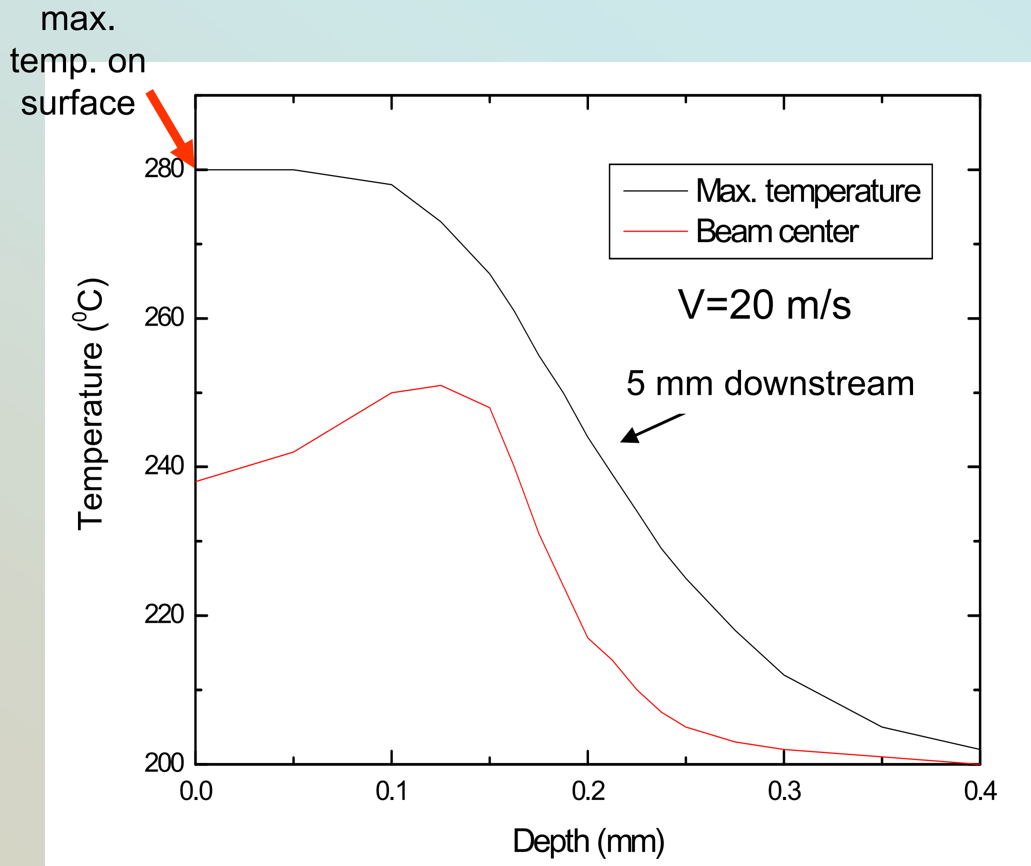
Lithium vapor trap

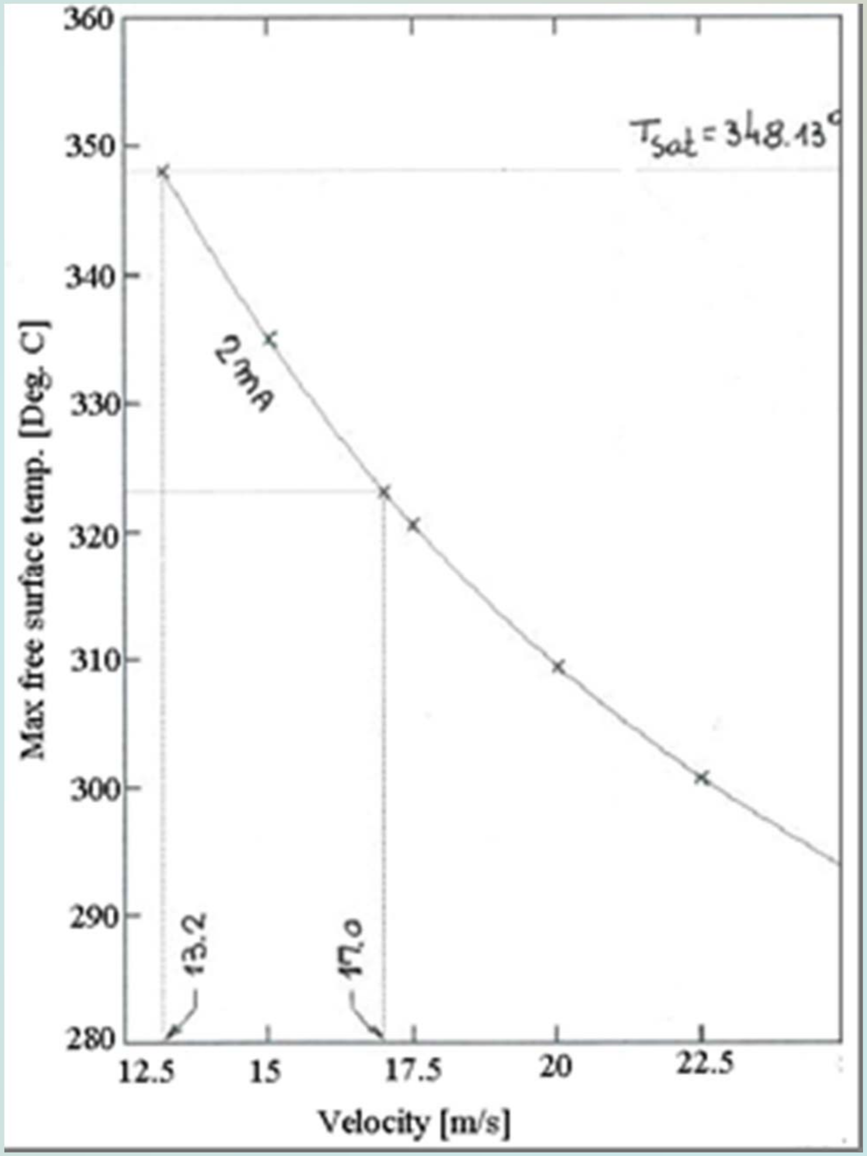




Thermal evaluations

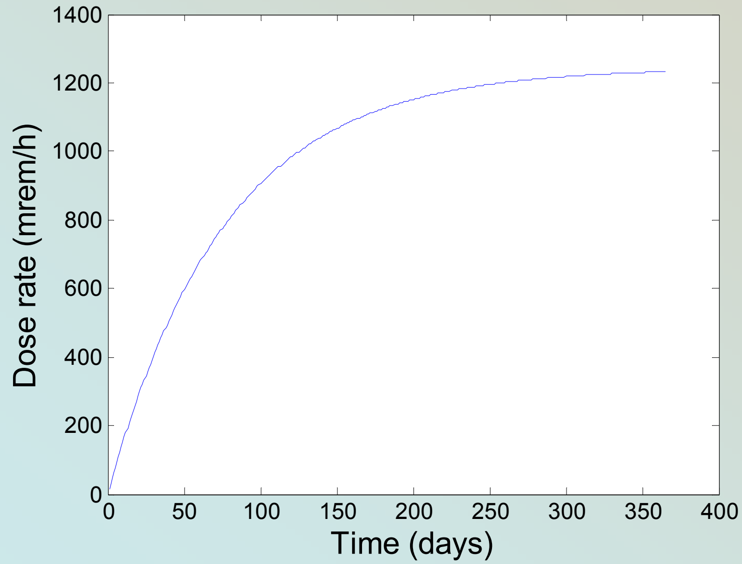
- Peak temperature elevation at the beam bombarding area
  - Conservative saturation point: 350°C (lithium boiling point at 10^{-5} Torr)





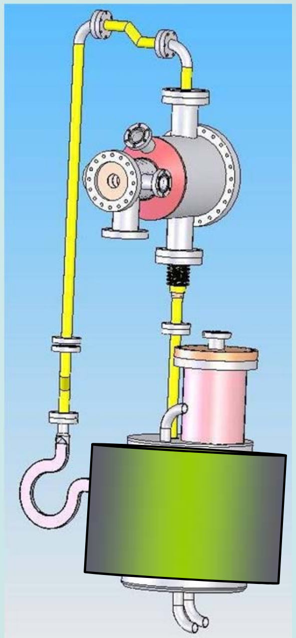
Be-7 production

- ^{7}Be: half-life of 53 days, 478 keV gamma radiation.
- Annual irradiation with 4 mA, 2 MeV proton beam, 8 hours a day, will produce the following dose rate, 30 cm from the system.



Solutions:

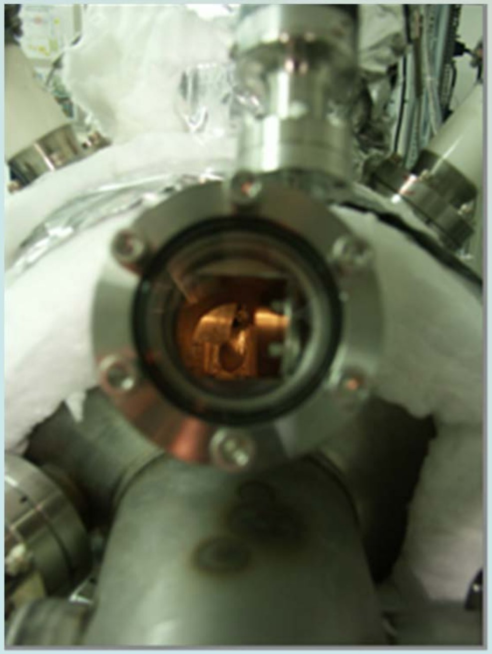
1. Most of the Be-7 will be accumulating at the cold trap and heat exchanger area[1]. The temperature in the loop and in the cold trap will be set according thermodynamic analysis of ^{7}Be in molten lithium.
2. The area will be shielded (~ 1.5-3 cm of Pb).
3. The irradiation periods were calculated in advance in order to control the radiation levels.

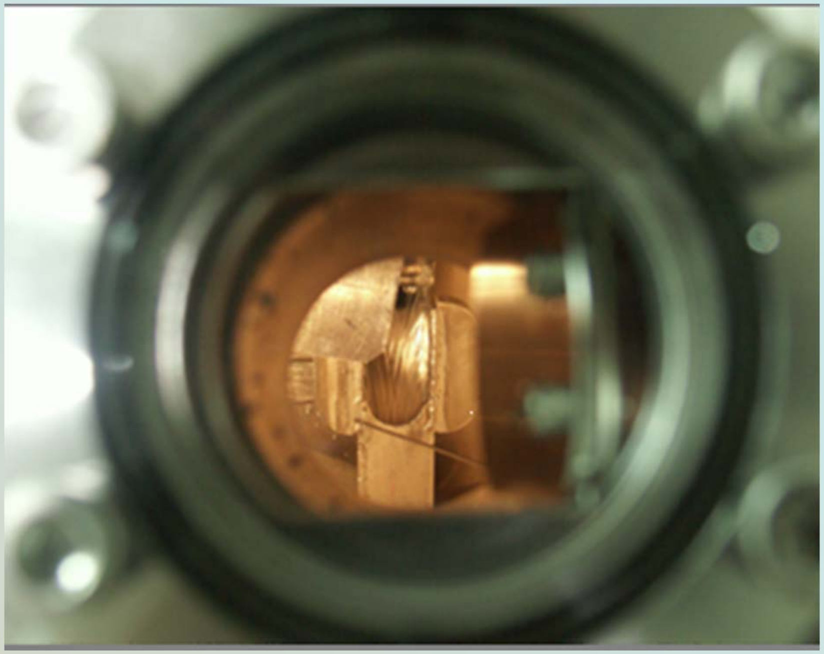


[1] M. Ida et. al., Fusion Engineering and Design 82 (2007) 2490-2496.

Lithium circulation test

- Lithium heated up to 200°C.
- Pressure: 8×10^{-6} Torr
- Velocity: up to 5 m/s
- Stable and full lithium film



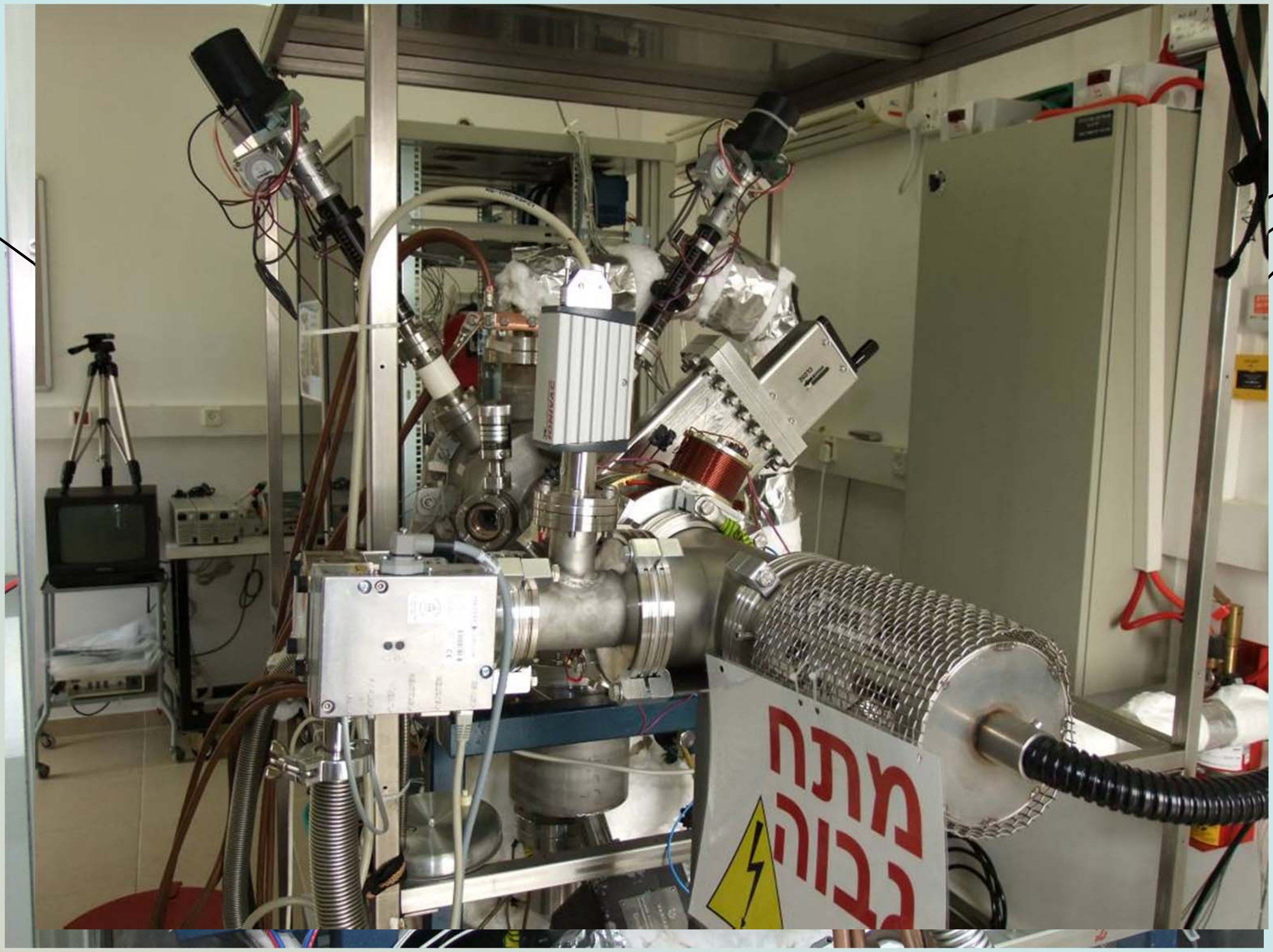


Lithium insertion and circulation movie

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

Beam dump

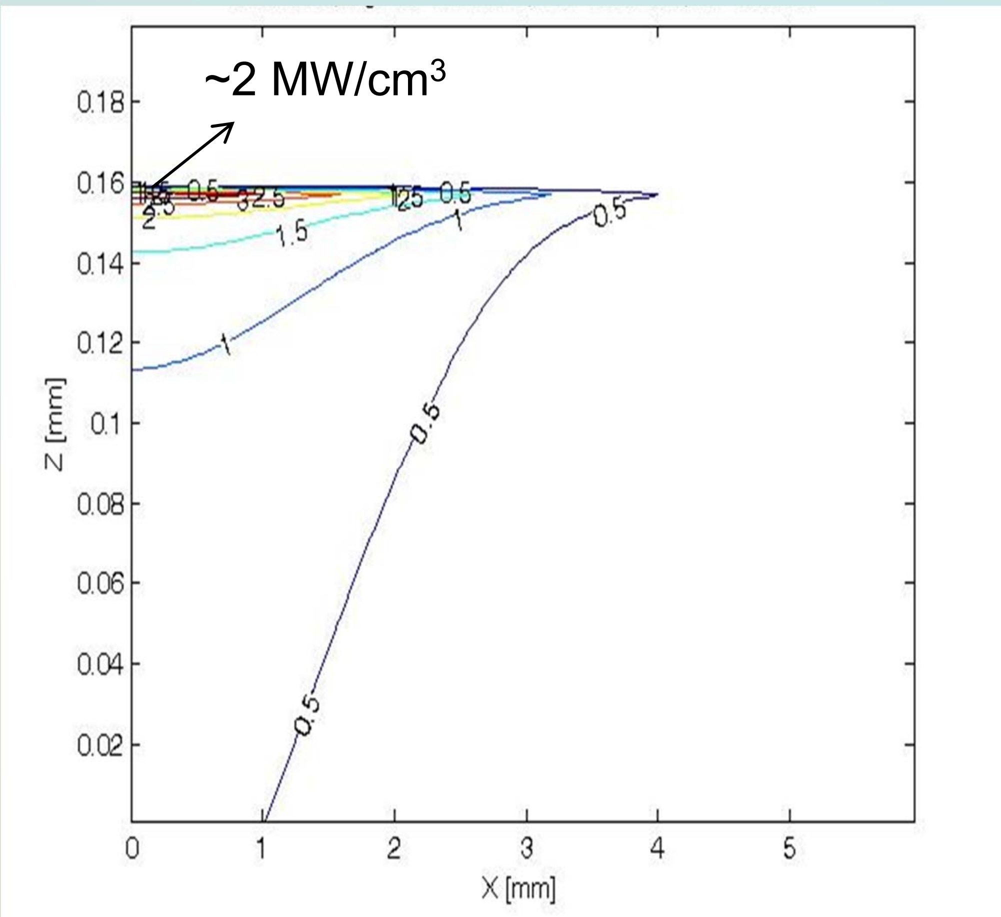
Magnetic lens



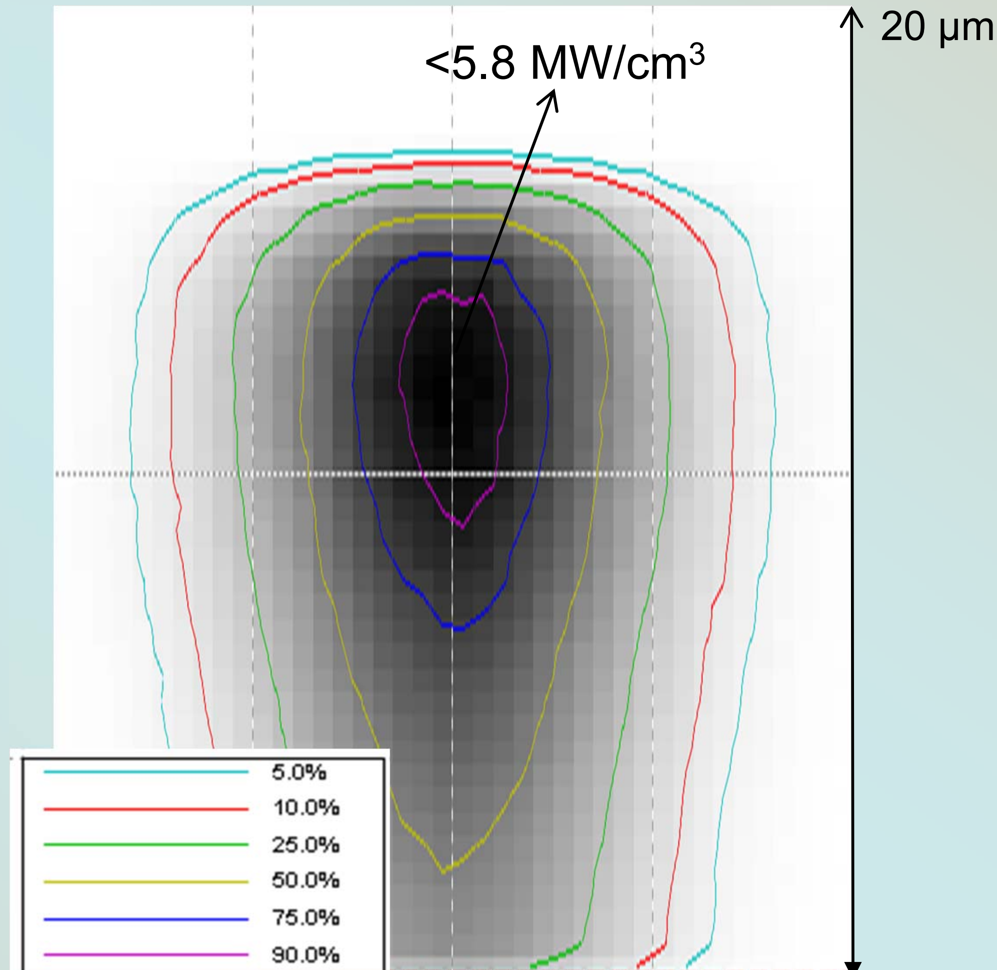
Electron gun off line tests

- E-gun simulation: High intensity – 20 keV, ~1 A
  electron gun will simulate thermal deposition of SARAF proton beam.
- E-gun power density: 5.8 MW/cm^3 at 1 A

energy deposition of 2 MeV, 2mA protons in lithium

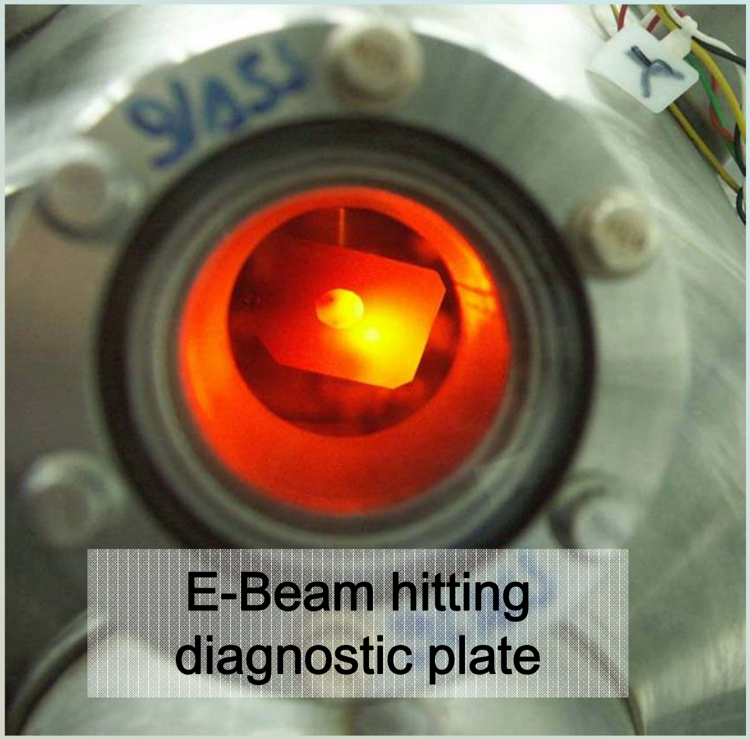


energy deposition of 20 keV electrons in lithium

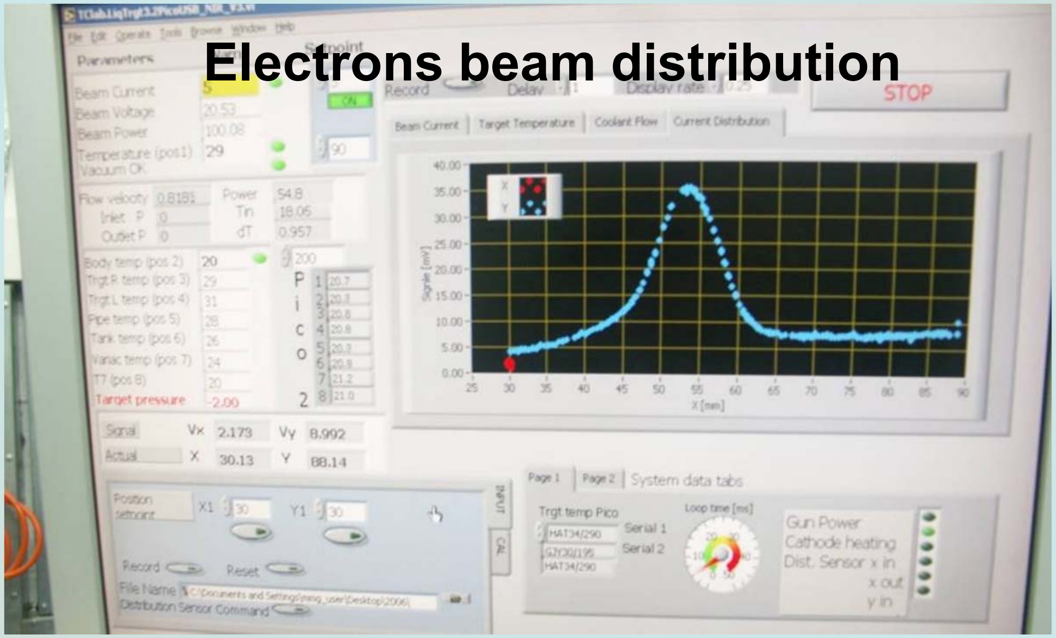


E-gun experiment

- E-beam focusing, using magnetic lens, on diagnostic plate
- Measurement of e-beam distribution (up to 10 mA)
- Applying higher beam power on the lithium flow



E-Beam hitting diagnostic plate



Electrons beam distribution

e-gun experiment results

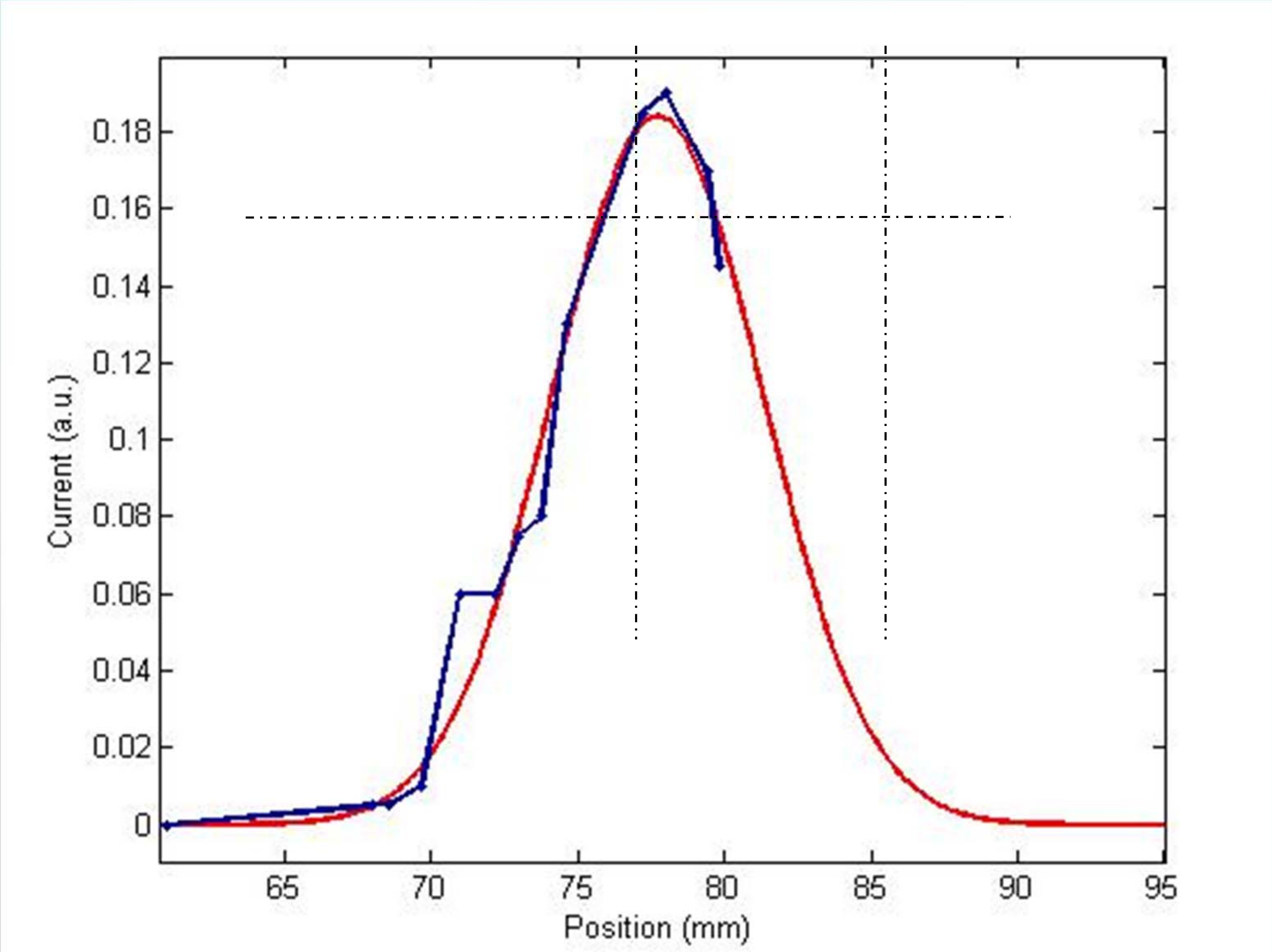
- Electron Beam shape measurement
- Velocity measurement - ~3 m/s (~30 % of EM pump capability)
- Stable lithium flow at irradiation up to 2 kW (at 3 m/s)
- Excessive evaporation when ~2.2 kW beam was applied (at 3 m/s)

E- beam profile:

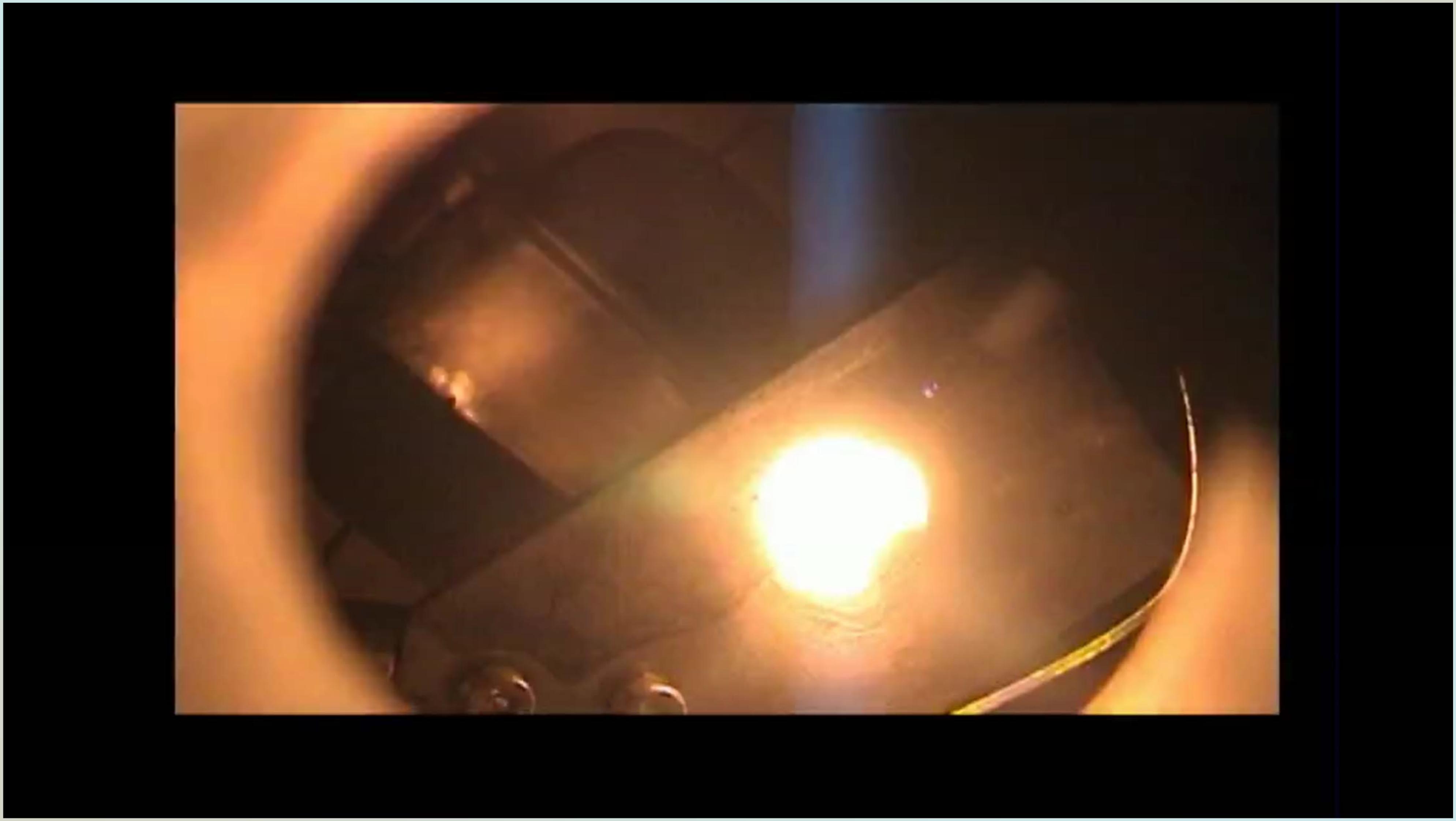
Blue: measurement of 10 mA beam

Red: Gaussian with FWHM= 8.3 mm and σ=3.5 mm

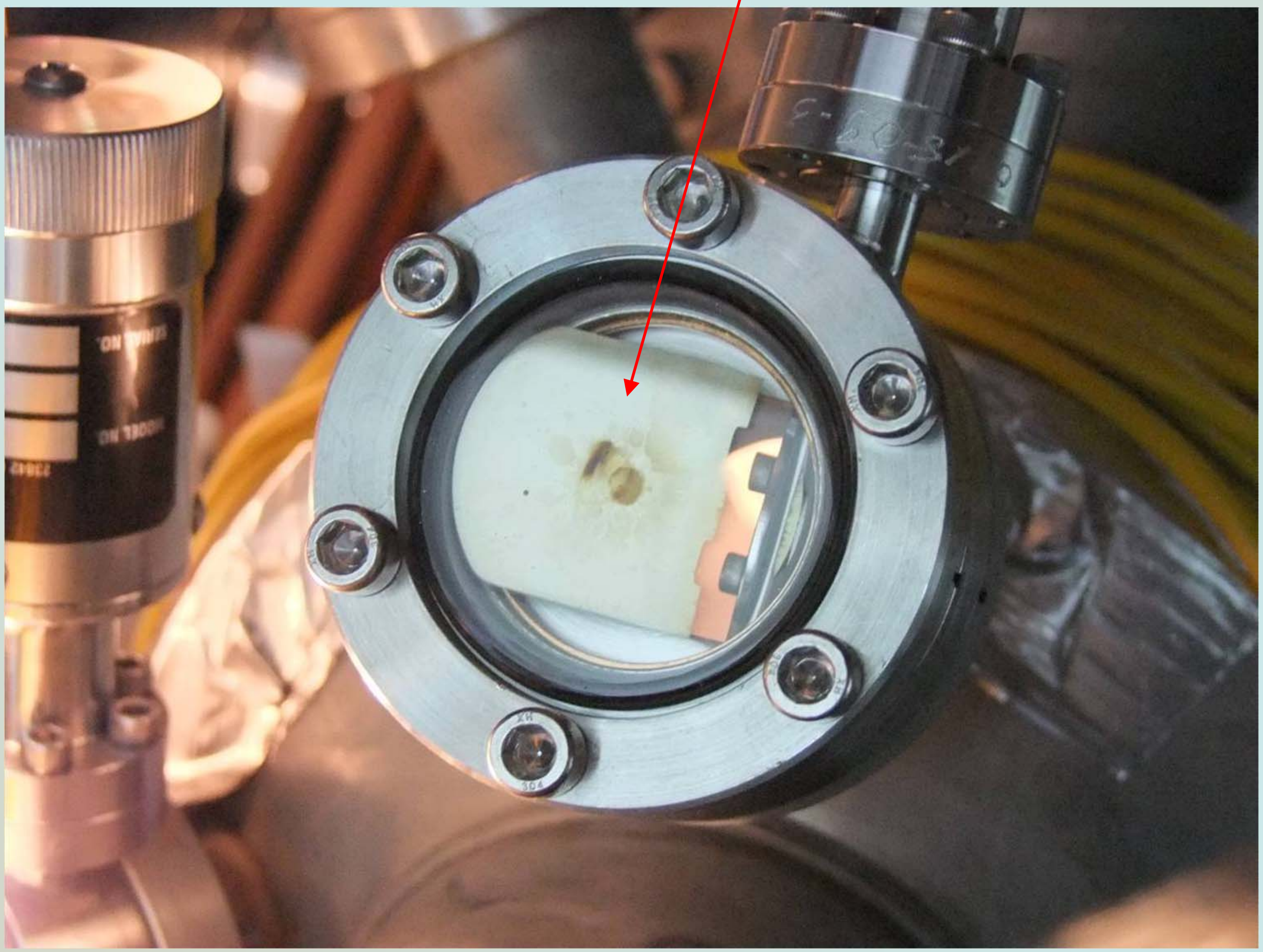
The maximal electron beam power density was 2.85 kW/cm2 (0.83 MW/cm^3)



e-gun on lithium

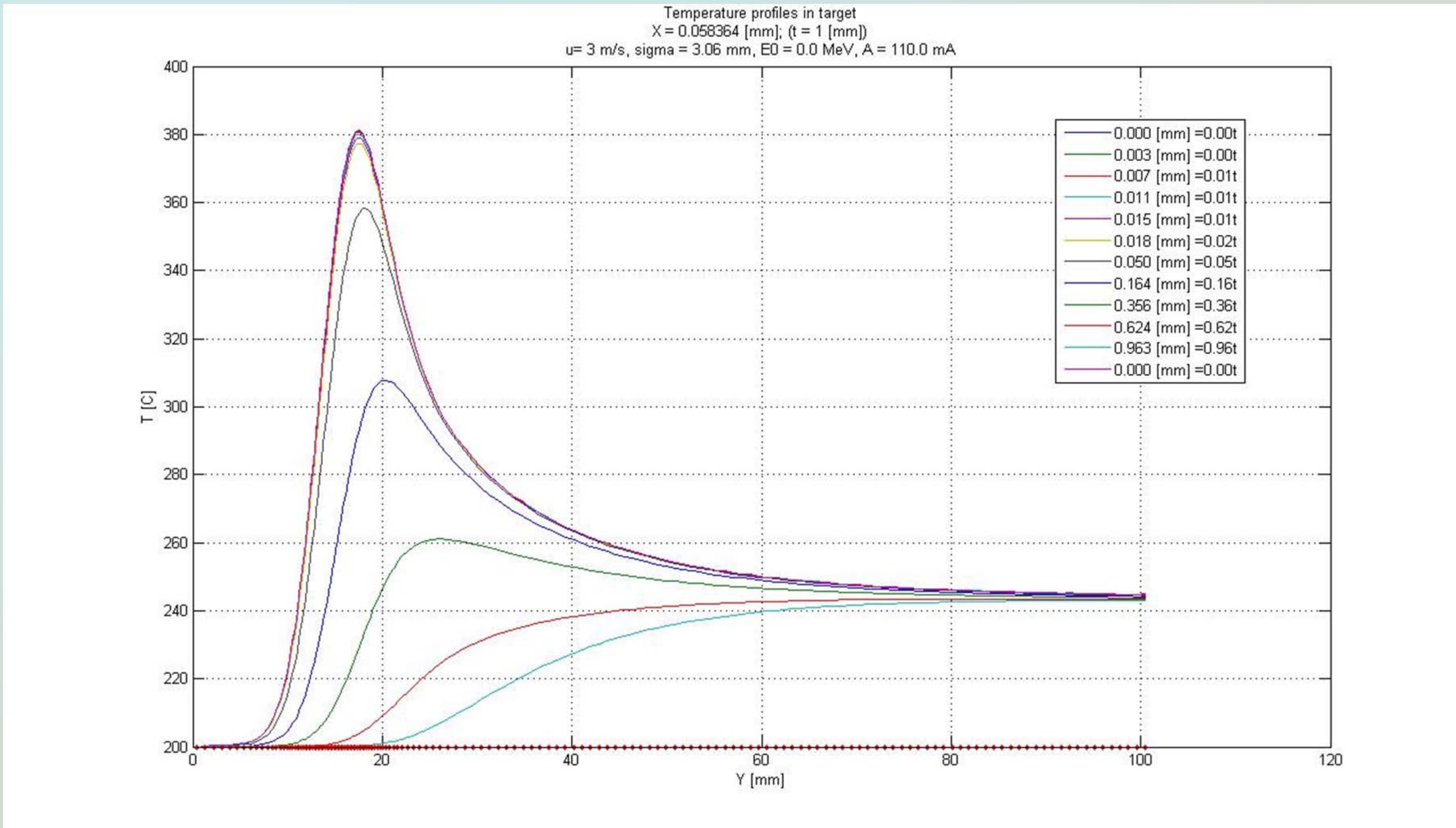


Lithium vapors on viewport window



Temperature calculation for 2.2 kW electron irradiation

Calculated Max temperature=
380˚C
Expected saturation temperature:
350˚C



Flow

Our future plans

- E-gun irradiation at higher flow velocity
- Transportation and connection to SARAF accelerator beam line
- Proton beam heat removal experiments
- Be-7 dynamics in the system
- Neutron measurements

The LiLiT Team:

M. Paul, A. Arenshtam, D. Berkovits, M. Bisyakoev, I. Eliyahu, G. Feinberg, N. Hazenshprung, D. Kijel, A. Nagler, I. Silverman

Thanks to J. Nolen, C. Reed & Y. Momozaki
for the help with design and training

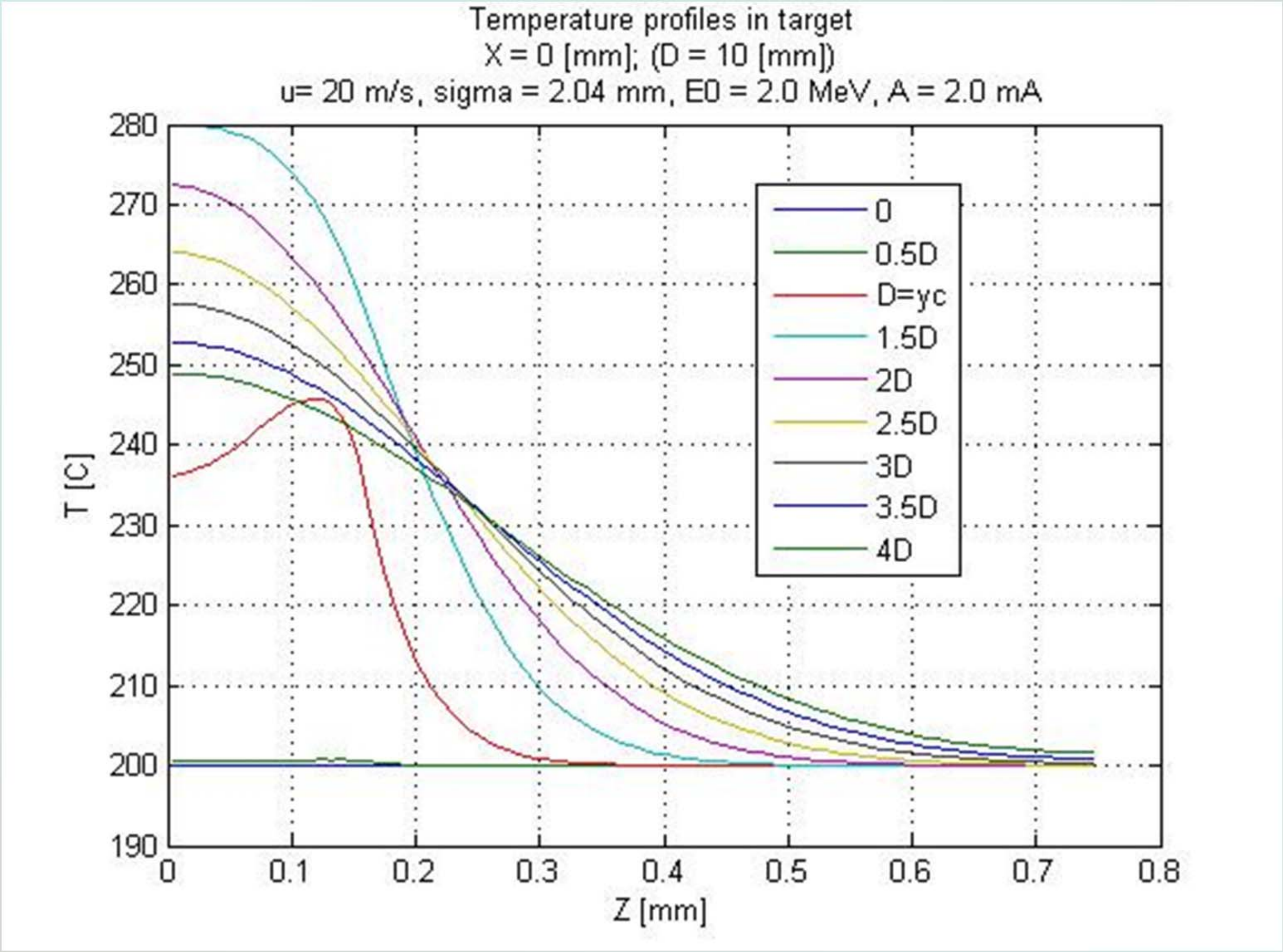
Thank you

As built system

Fire-proof dry room for 20 keV e-gun experiments

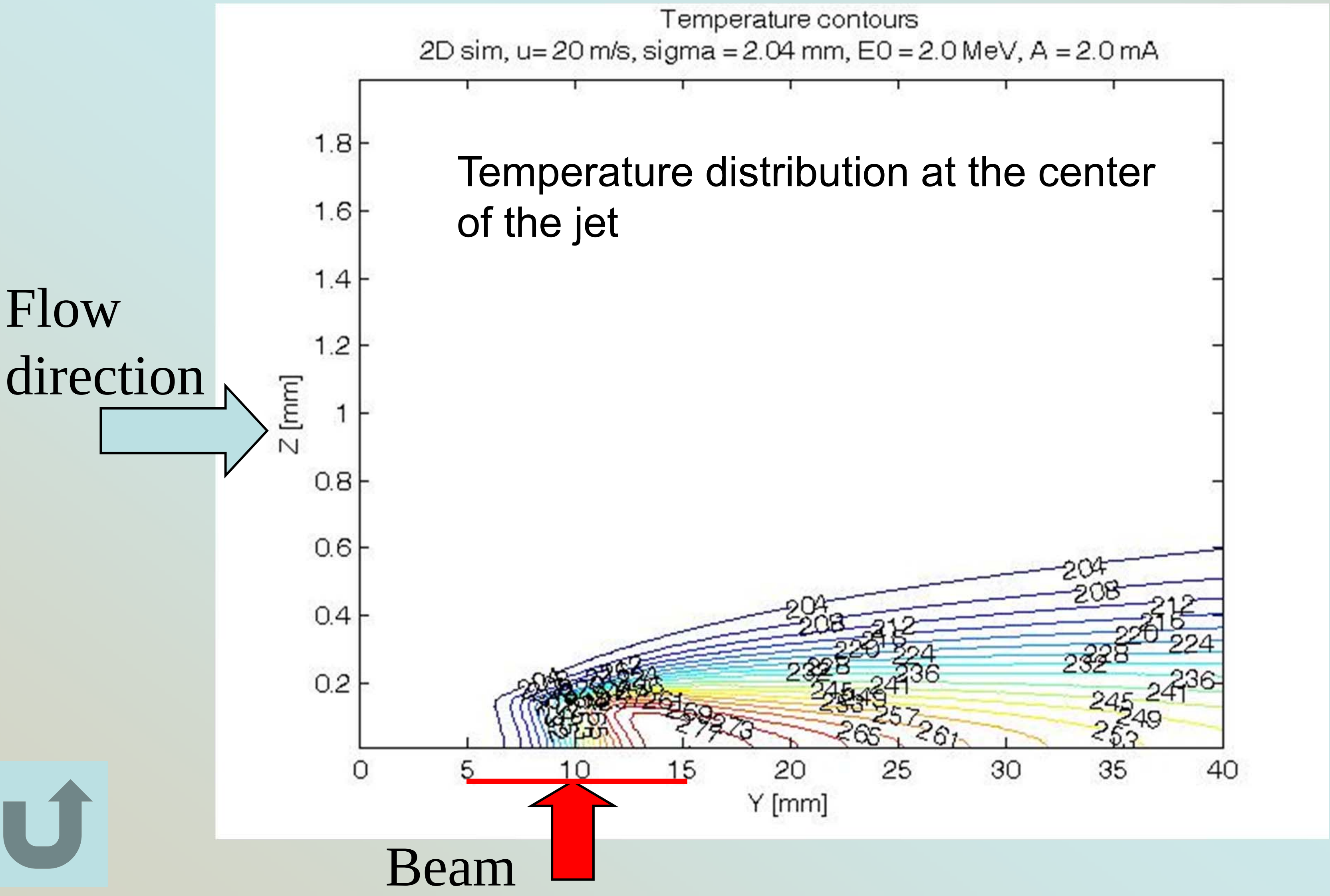
LiLit @ 4kW heating power

Beam



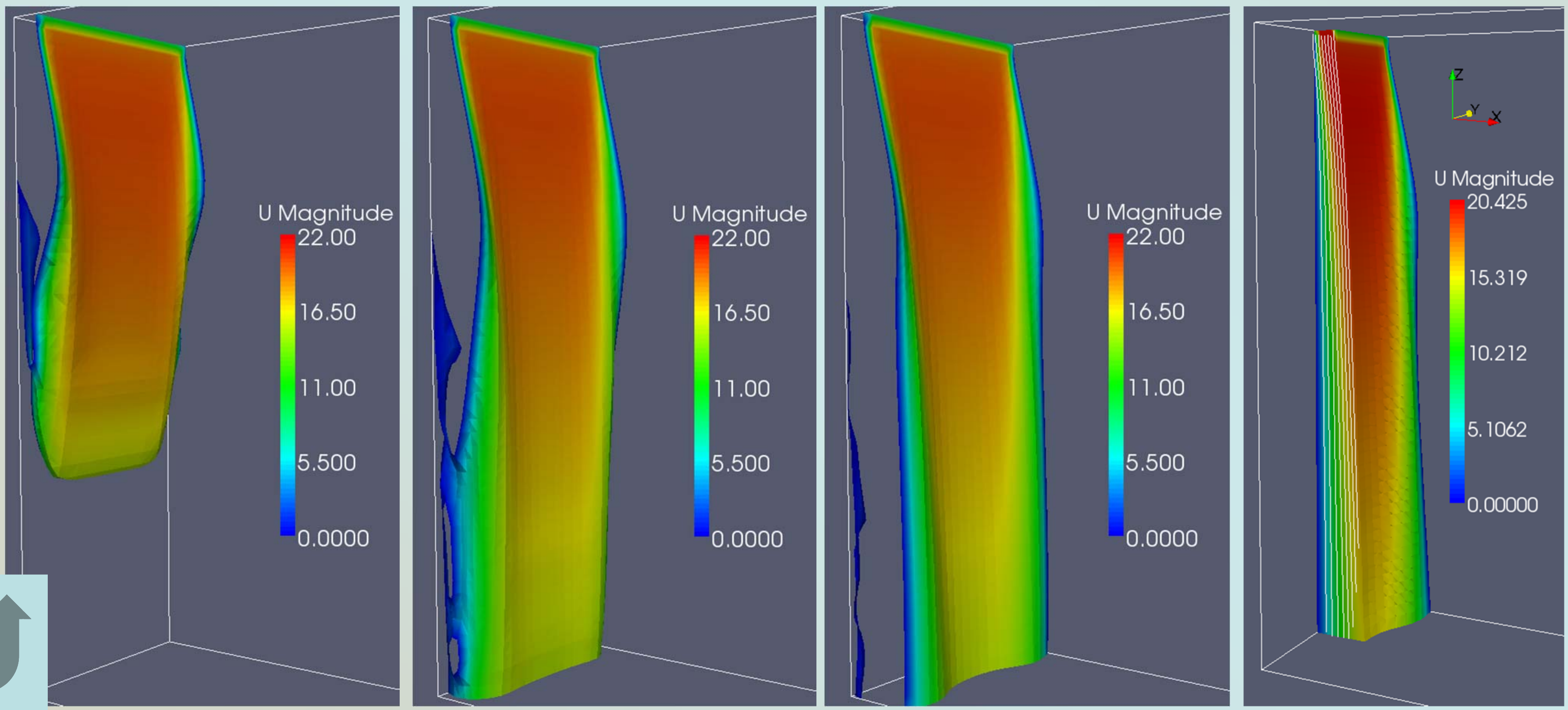
Depth wise temperature distribution

LiLit @ 4kW heating power



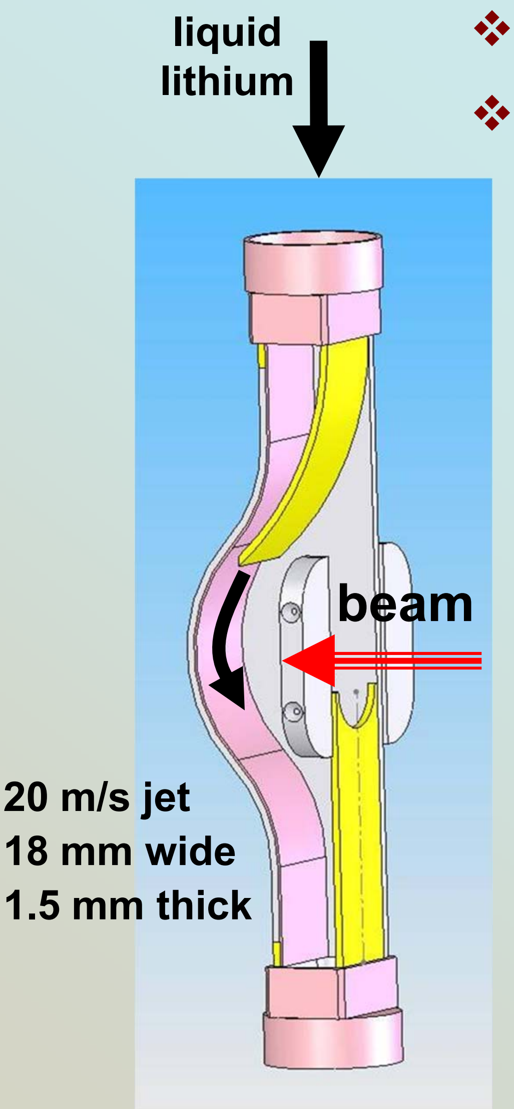
CFD simulations

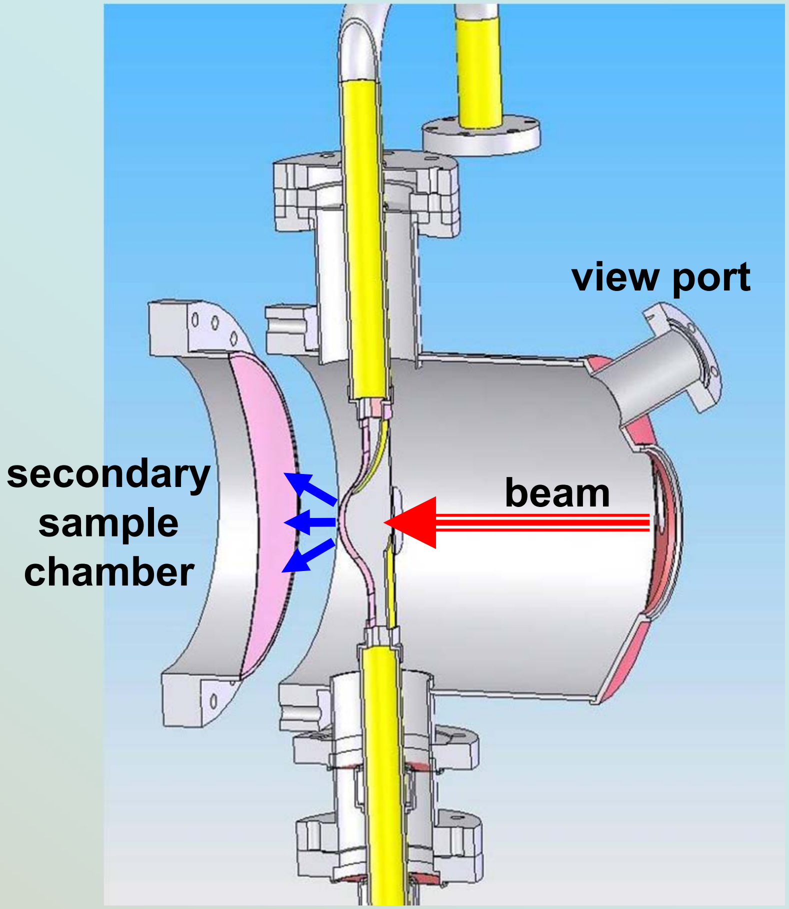
- 3D flow simulations are done with OpenFoam (open source CFD code)
- Currently only strait wall jet flow is simulated
- Planed improvements include concave flow and power deposition

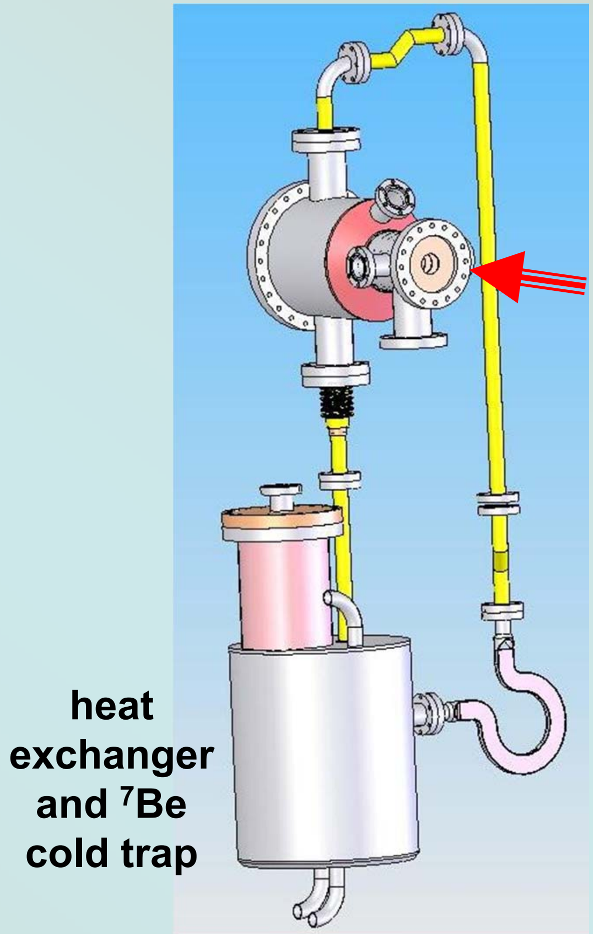


LiLiT jet chamber

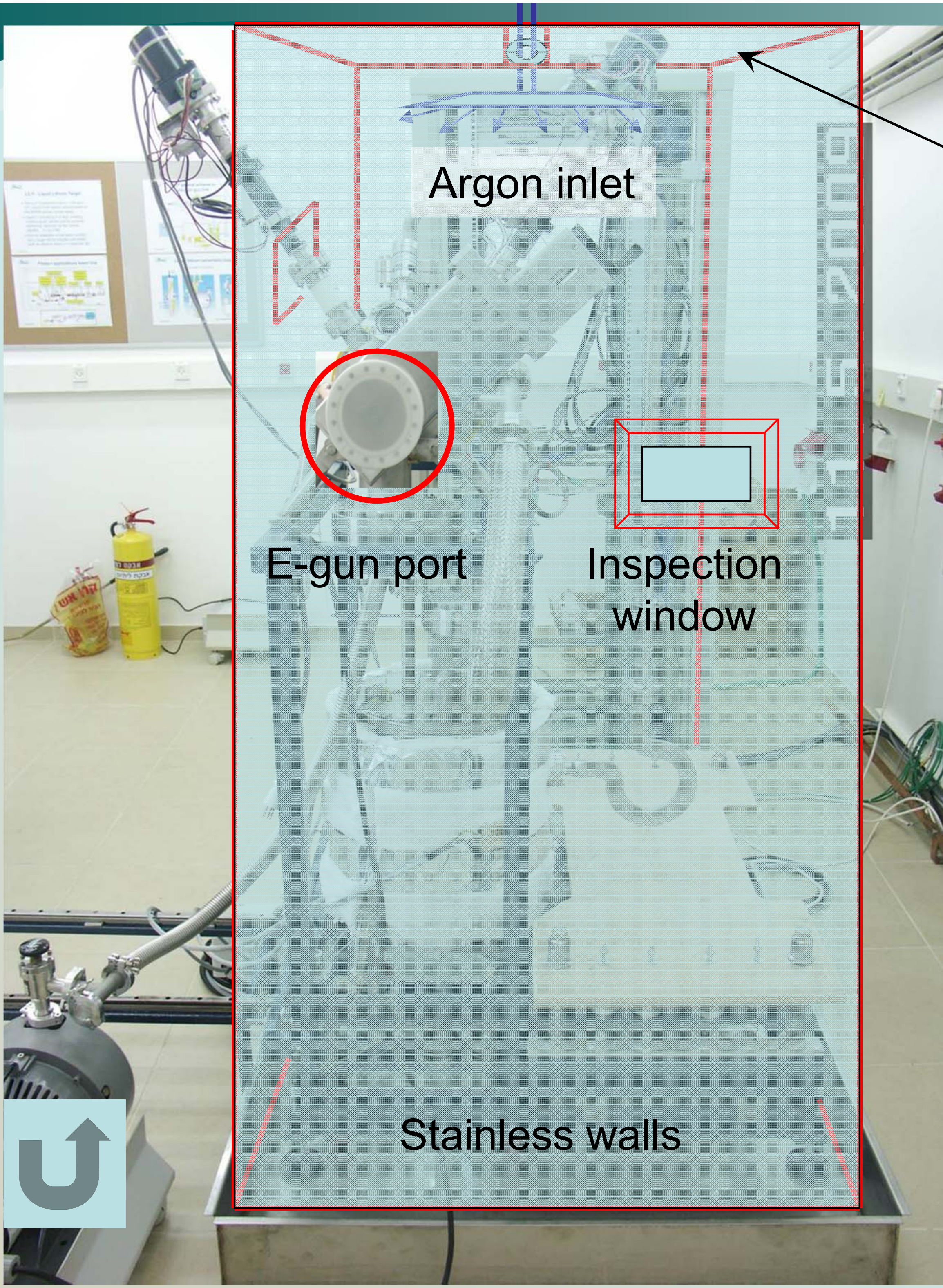
- built for 2 MeV 3.5 mA protons
- Gaussian beam spot size with σ=2 mm





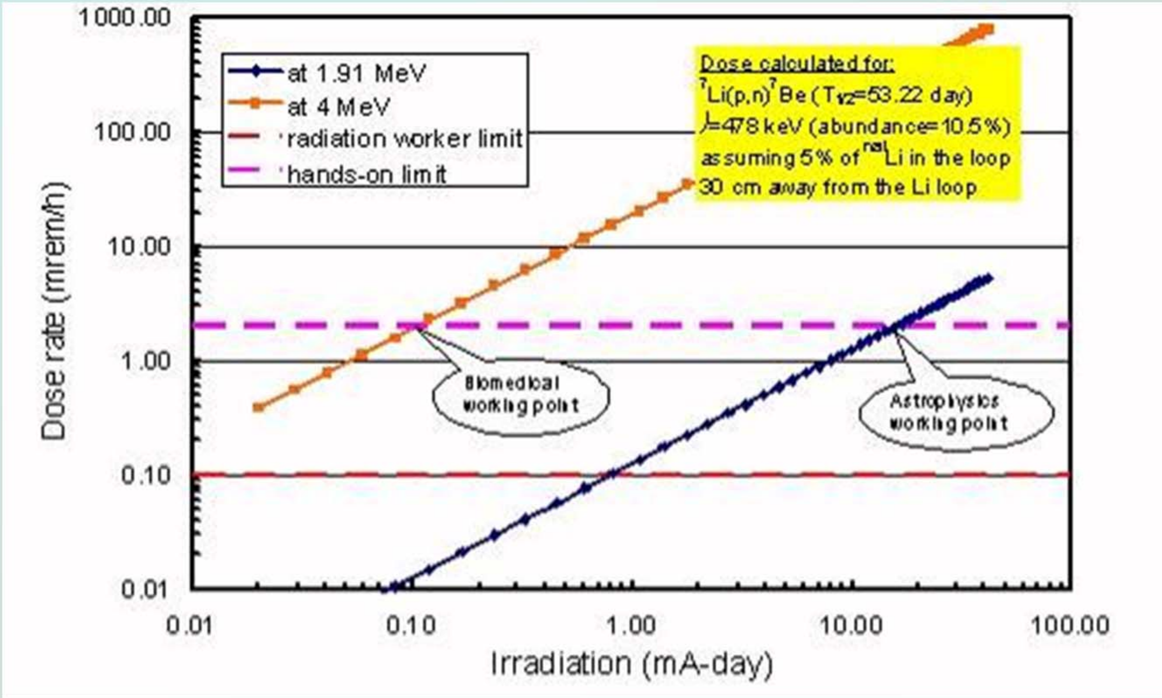


Stainless steel fire protection enclosure



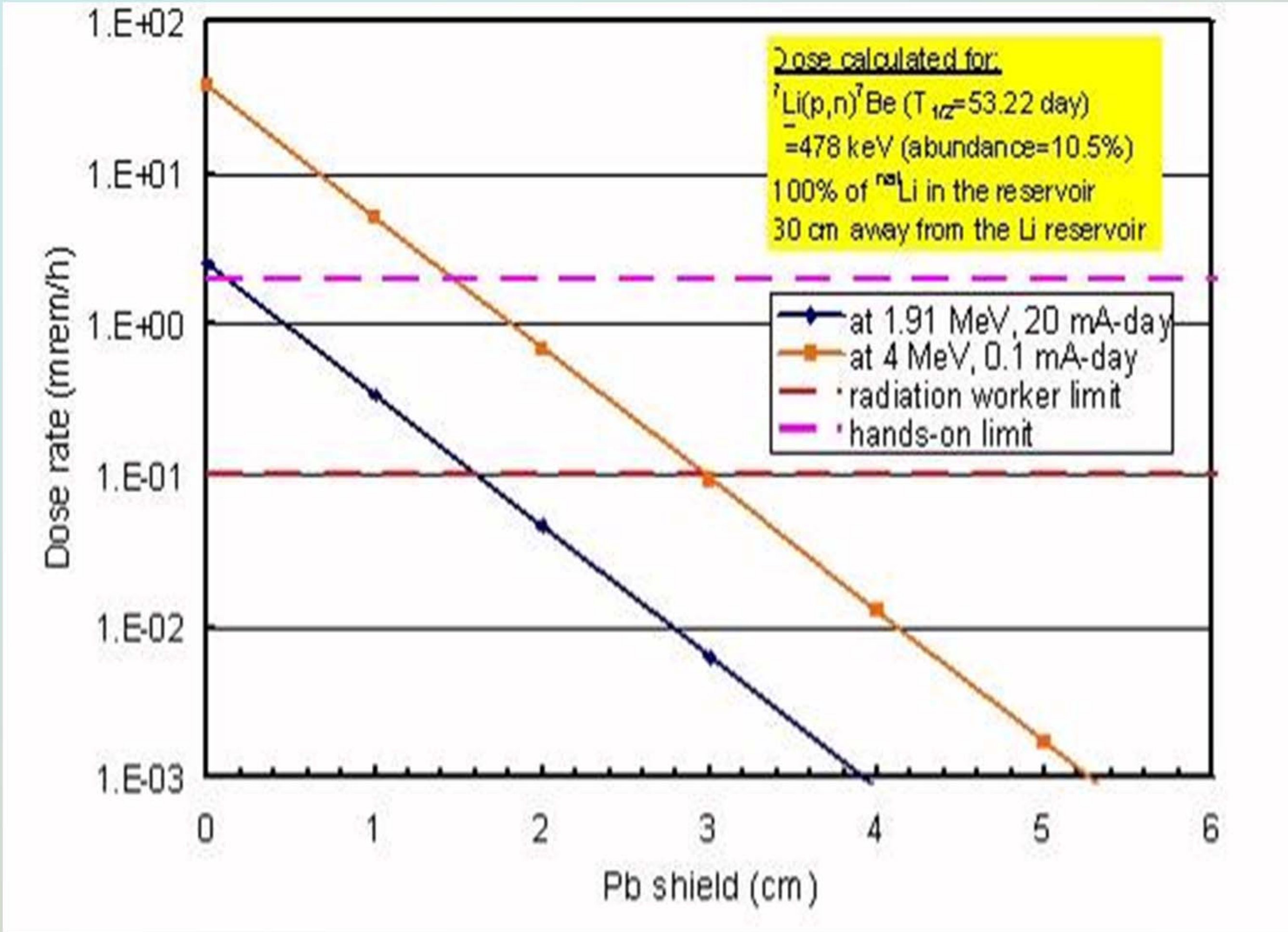
Explosion roof, held on hinges

Radiation from ^{7}Be



The LiLiT loop dose rate as function of integral irradiation duration and intensity. Based on the assumption that 5% of the Li is left in the loop

Radiation shielding



Li reservoir dose rate 30 cm behind a lead shield as function of the lead thickness

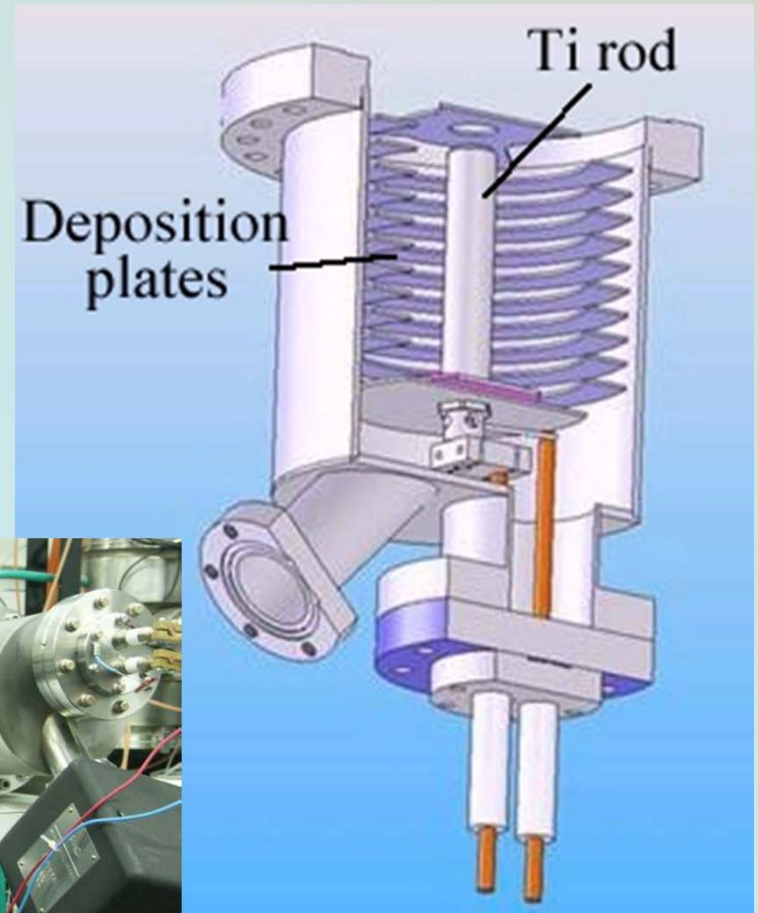
Electro-magnetic pump parameters

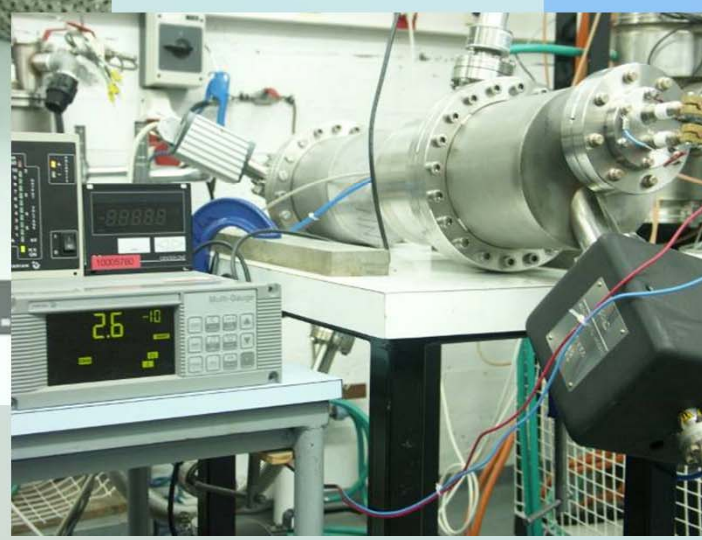
- Sm2Co17 permanent magnets: 12 units, 40x40x20 mm

- Operating temperature: up to 300 C
- Electrical Motor: Three Phase, 1.5 kW, 2800 rpm
- Variable Speed Motion Control: Three Phase, 1.5 kW
- Pump Dimensions: L= 700, D=350, H=320

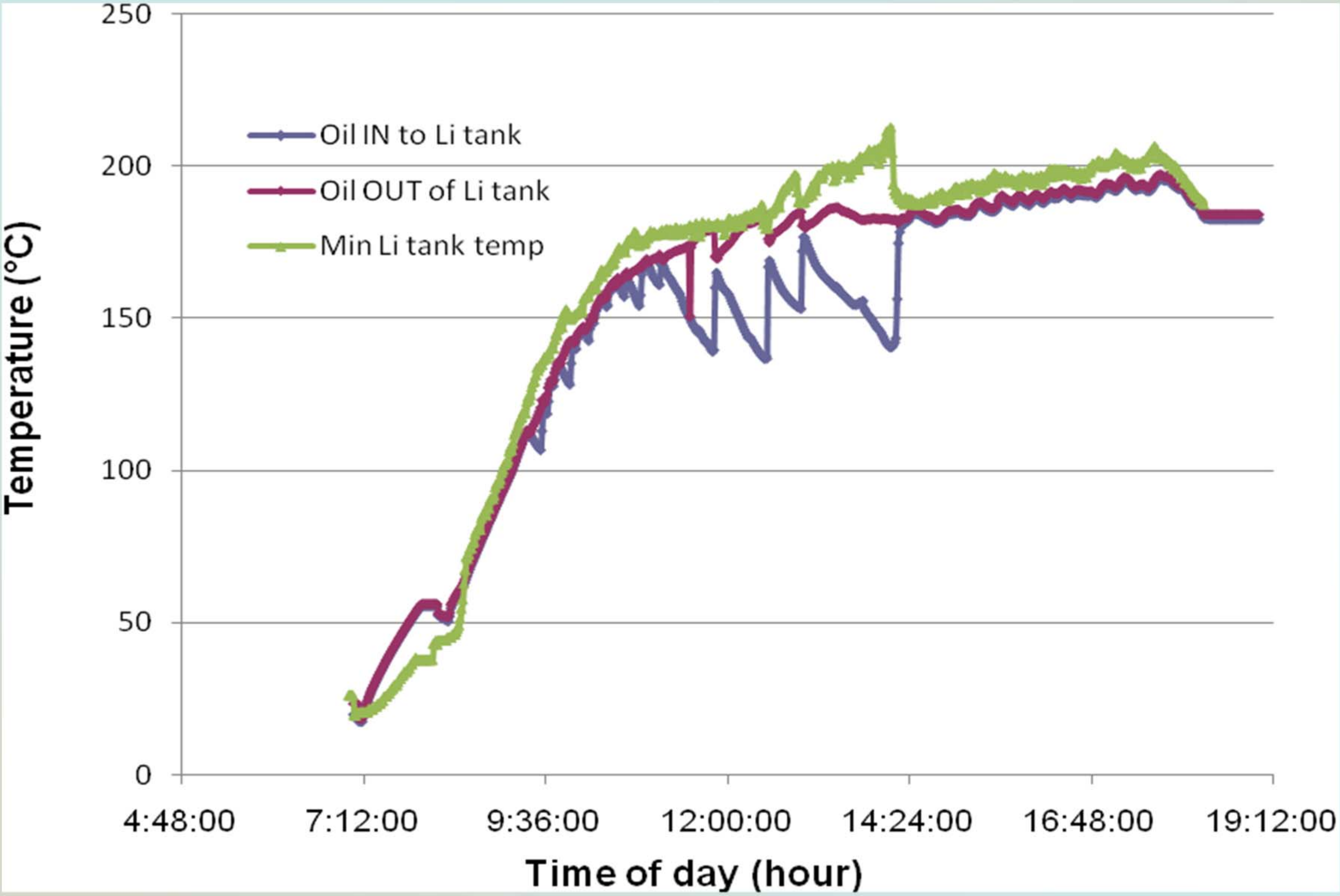
- Loop sizes: OD 173.5 mm, width 20 mm, thickness 6 mm
- Magnetic Field at center: 3.2 kG
- Momentum Test: 115 N.m
- Calculated pressure: 8 At

Titanium adsorption vacuum pump





Oil temperature

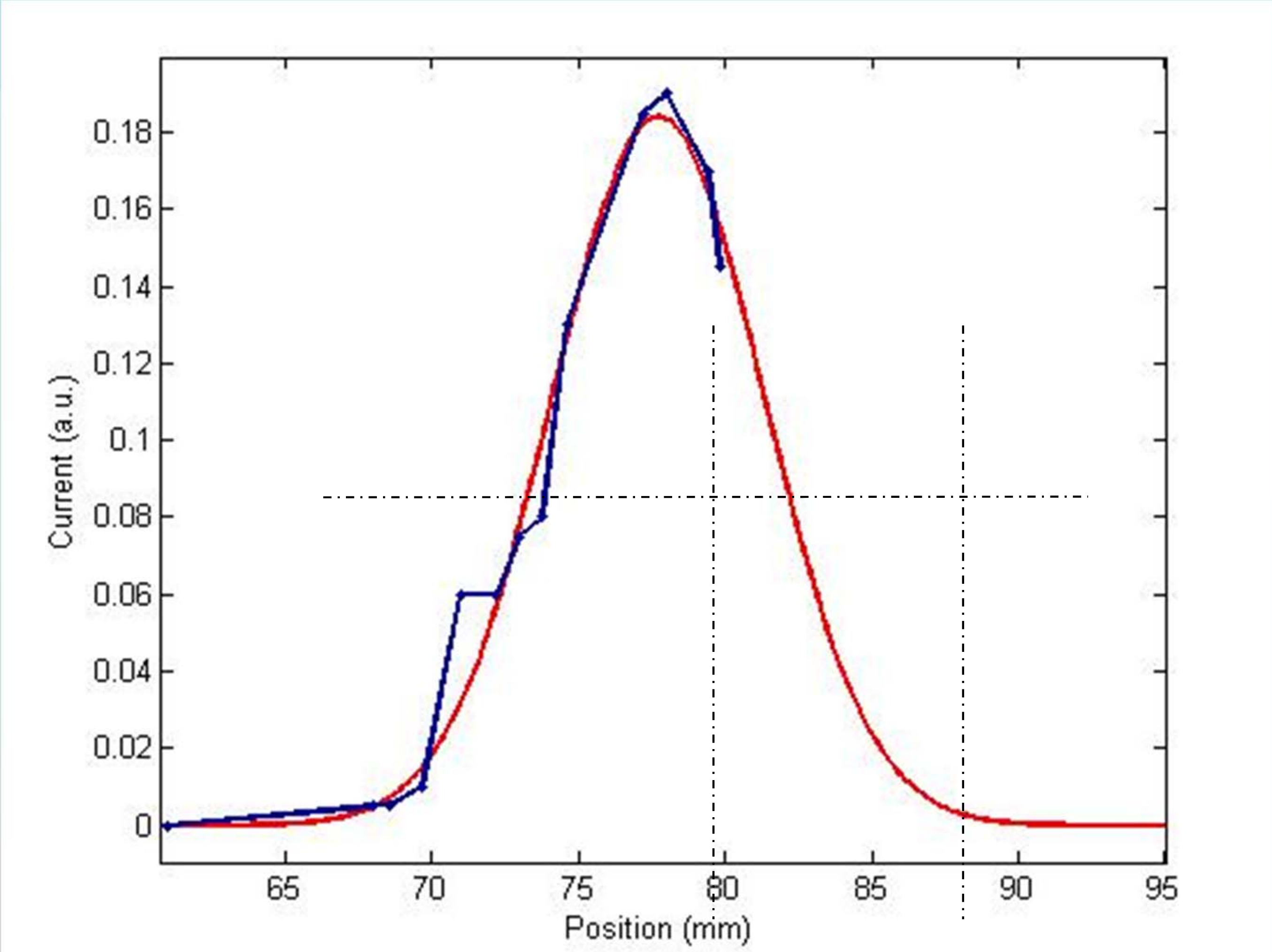


מהירויות של המשאבה EMP

מס' הרצה	יחידות EMP 1-10 SPEED (%)	מהירות m/s	הספק מקסימאלי (זרם mA) - kW	טמפרטורה / הספק
1- 4	2 (20%)		1 (50)	
5	2 (20%)	2.35	1.4 (70)	* 1.2kW/615°C
6	2.5 (25%)	2.75	1.6 (80)	* 1.2kW/614°C
7	3 (30%)	3.14	2.2 (110)	* 1.2kW/571°C

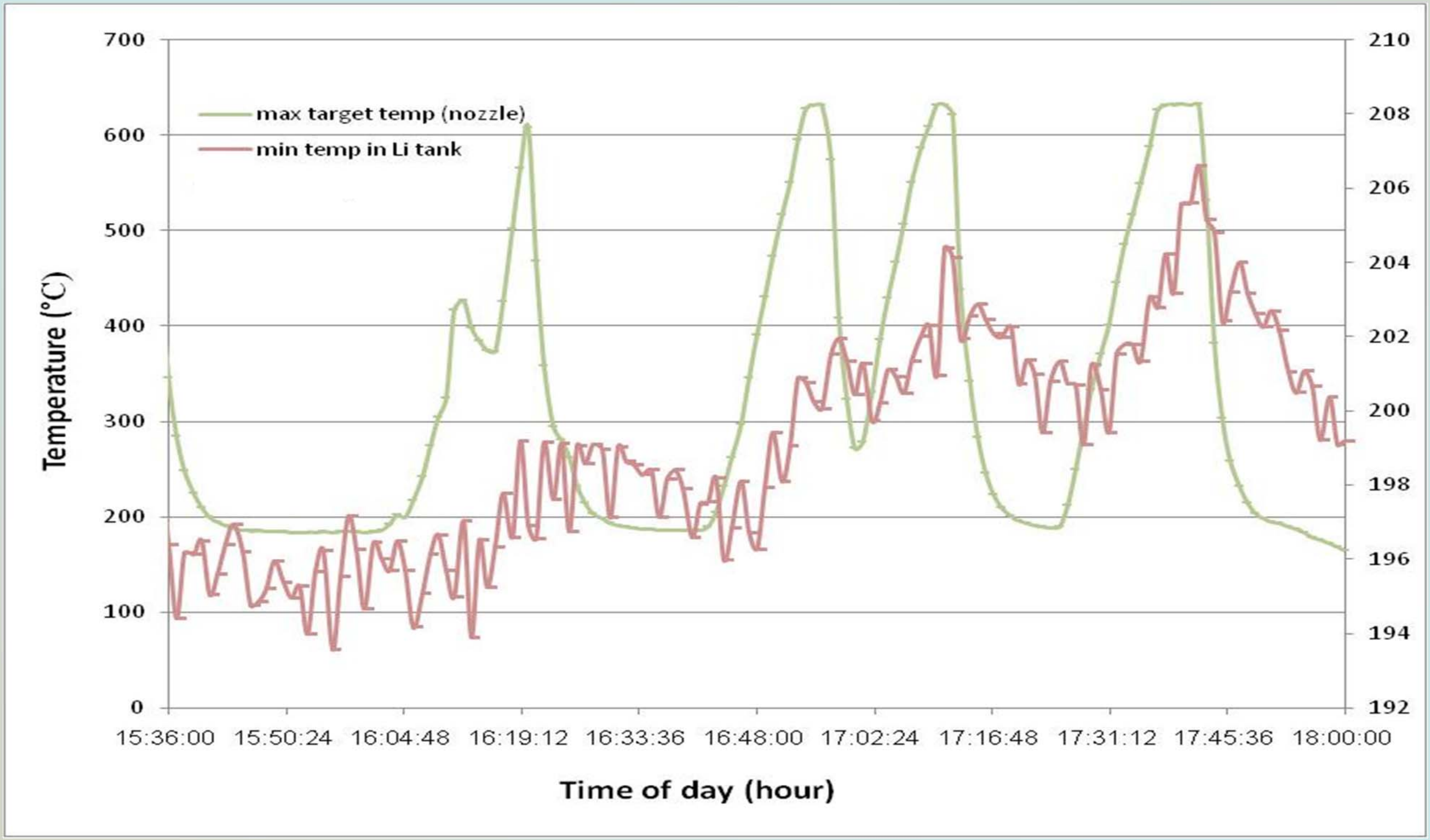
* הפרשי טמפרטורות ביחס למהירות זרימה הם על פי רישום ידני

צפיפות ההספק המקסימאלית בנסויי הינה 2.85 kW/cm2 והצפיפות ההספק הנפחית

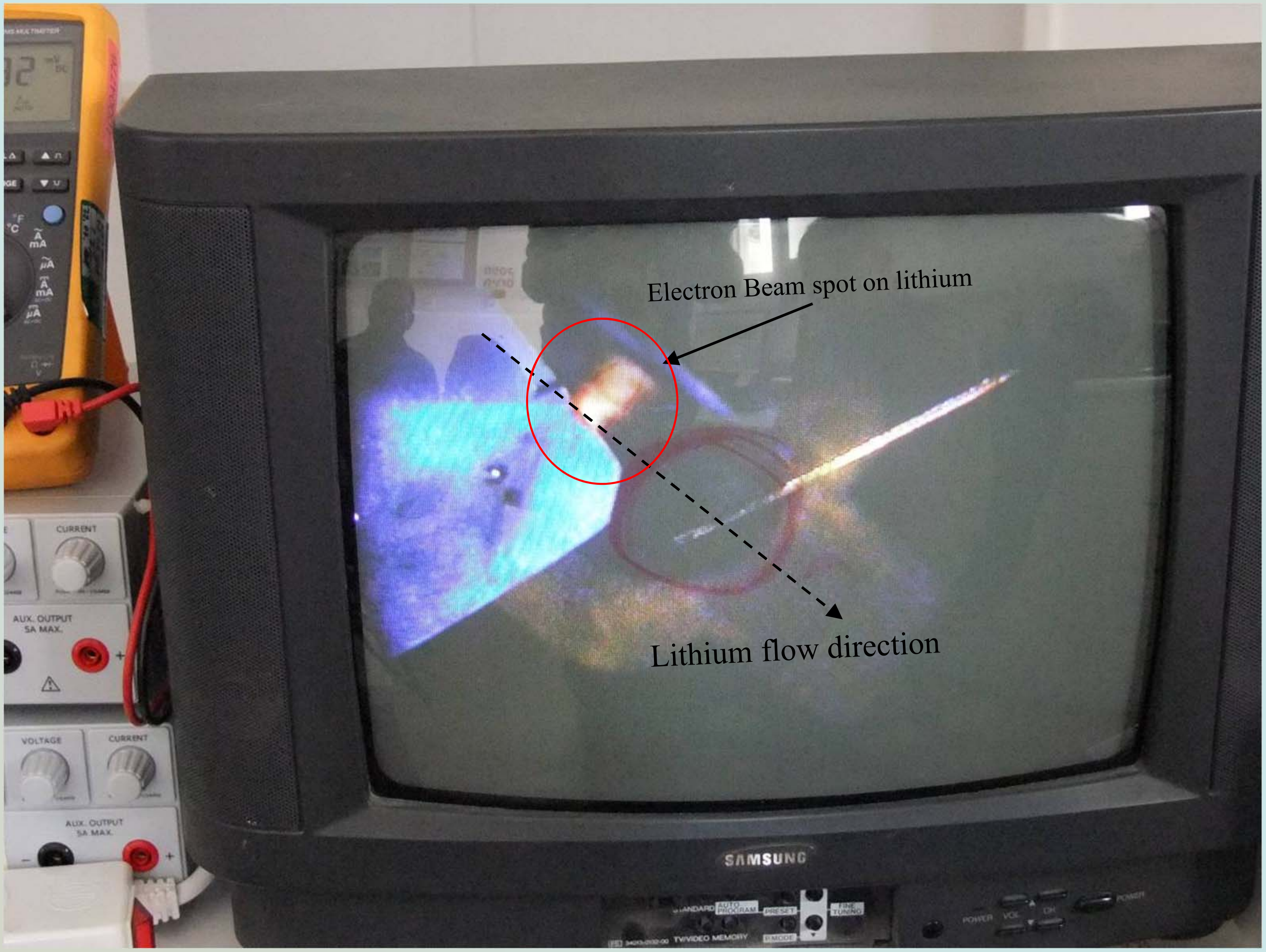


פרופיל קרן האלקטרונים בזרם של כ-10 mA (כחול) והתאמתם לגאוסיין (אדום) אשר מרכזו ב- 78 mm.
בעל רוחב מחצית גובה של 8.3 mm וסיגמא של 3.5 mm

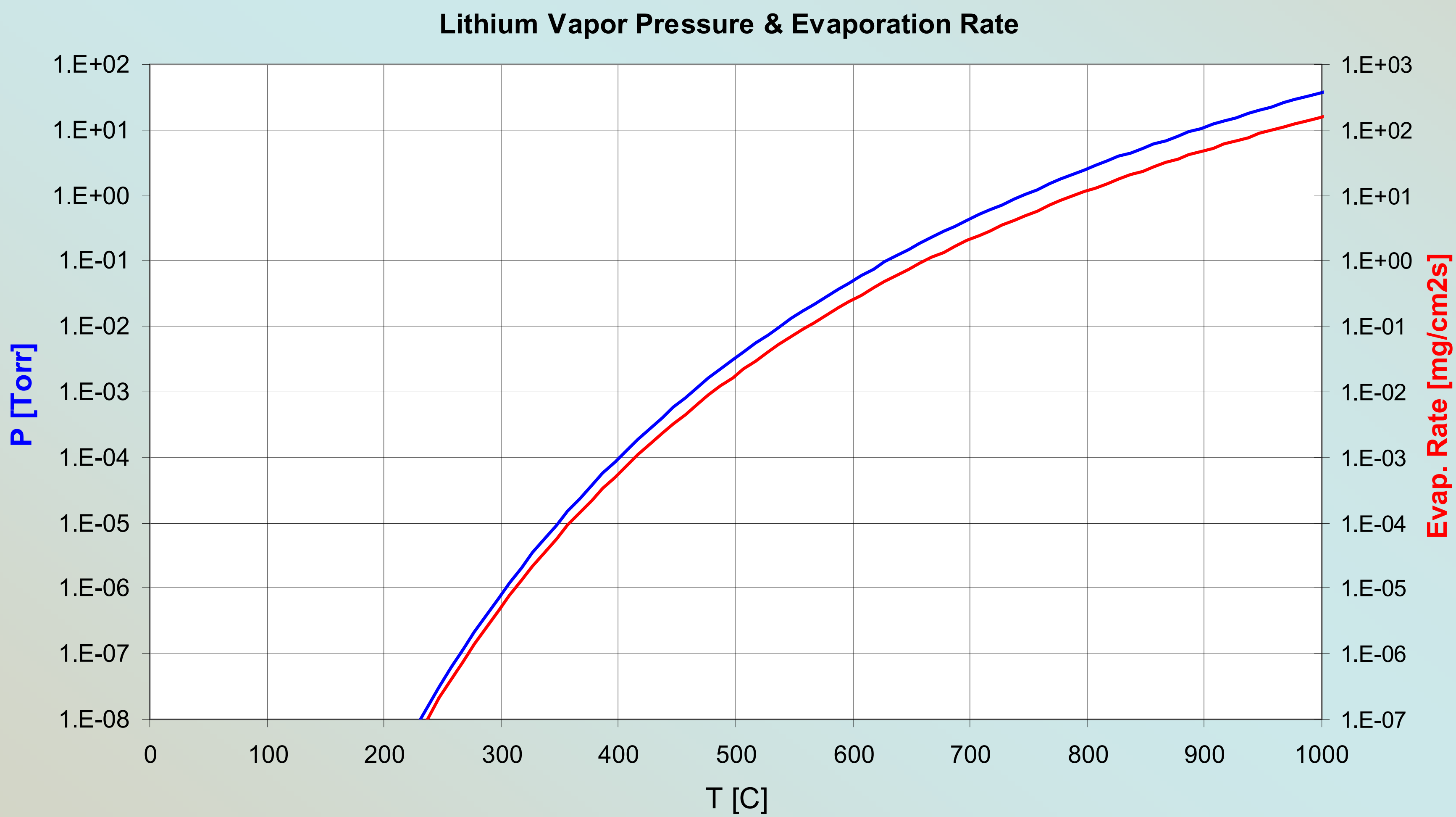
טמפרטורת הליתיום המינימאלית שנמדדה במיכל
במקביל לטמפרטורת אוזני הנחיר
במהלך ארבעת ההקרנות האחרונות בתותח האלקטרונים

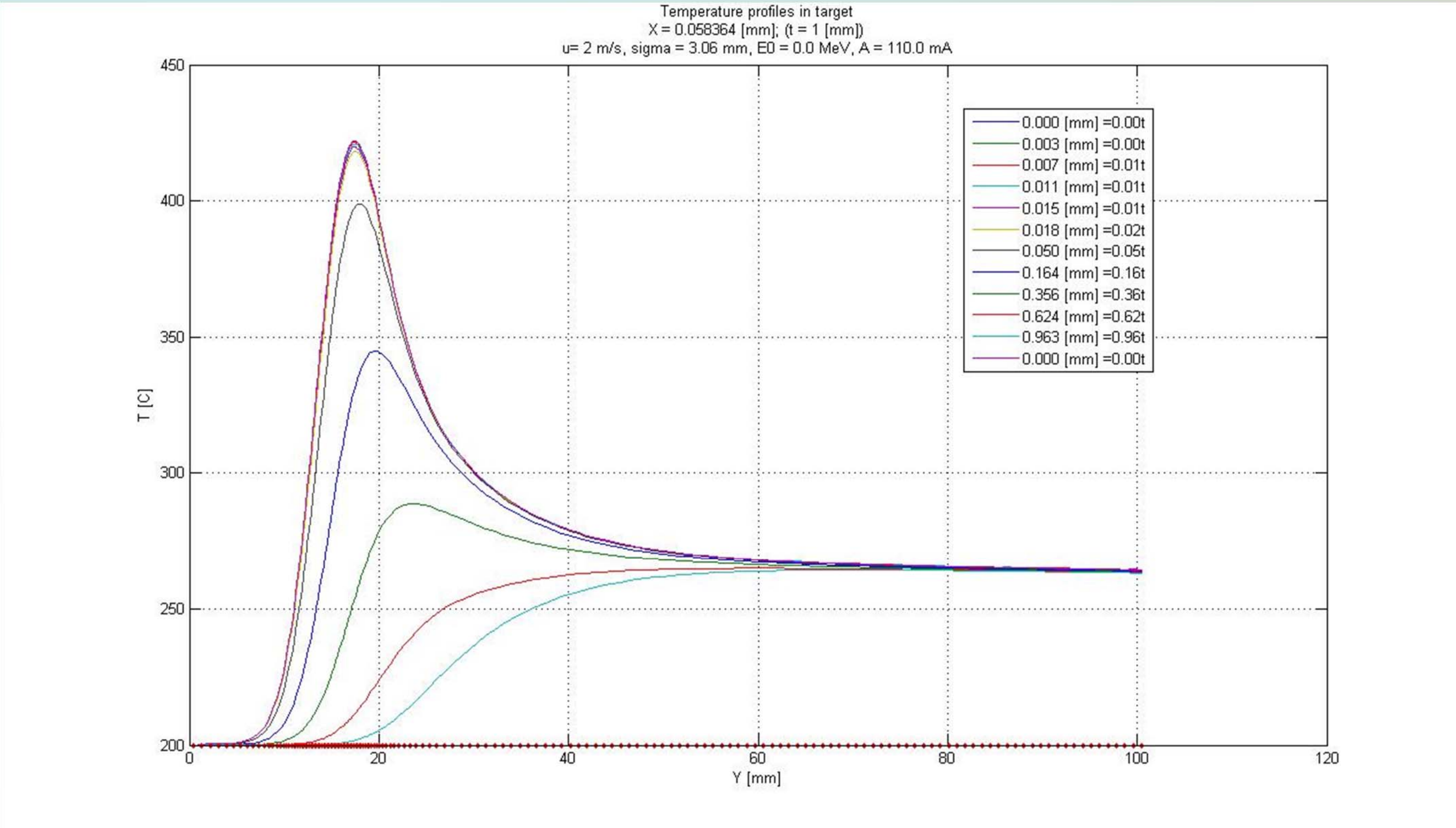


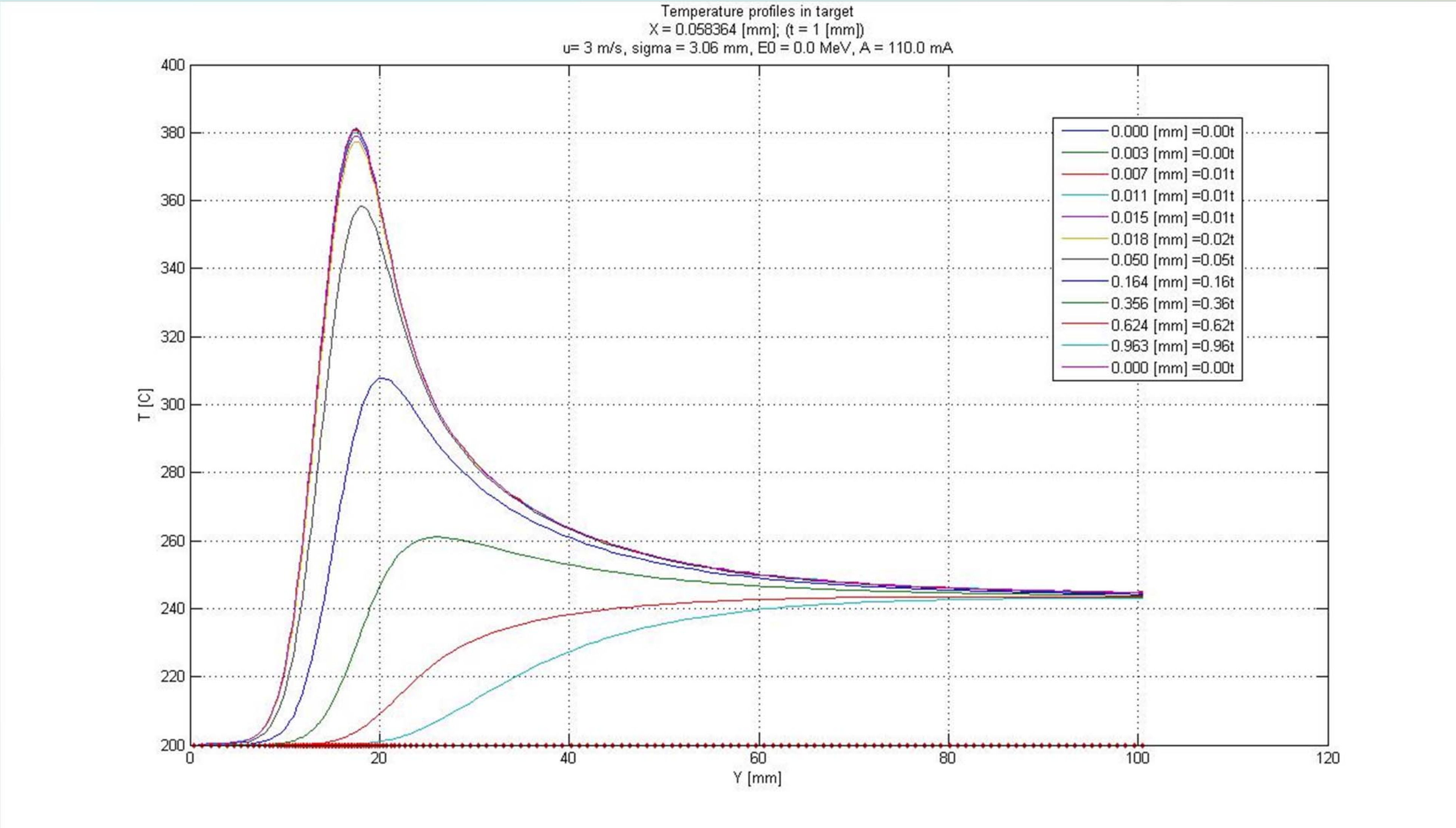
צילום הליתיום מסוחרר בנחיר
בעת הקרנה בתותח אלקטרונים



Lithium Vapor Pressure & Evaporation Rate




Temperature profiles in target
X = 0.058364 [mm]; (t = 1 [mm])
u= 2 m/s, sigma = 3.06 mm, E0 = 0.0 MeV, A = 110.0 mA
T [C]
Y [mm]
0.000 [mm] =0.00t
0.003 [mm] =0.00t
0.007 [mm] =0.01t
0.011 [mm] =0.01t
0.015 [mm] =0.01t
0.018 [mm] =0.02t
0.050 [mm] =0.05t
0.164 [mm] =0.16t
0.356 [mm] =0.36t
0.624 [mm] =0.62t
0.963 [mm] =0.96t
0.000 [mm] =0.00t


Temperature profiles in target
X = 0.058364 [mm]; (t = 1 [mm])
u= 3 m/s, sigma = 3.06 mm, E0 = 0.0 MeV, A = 110.0 mA
T [C]
Y [mm]
0.000 [mm] =0.00t
0.003 [mm] =0.00t
0.007 [mm] =0.01t
0.011 [mm] =0.01t
0.015 [mm] =0.01t
0.018 [mm] =0.02t
0.050 [mm] =0.05t
0.164 [mm] =0.16t
0.356 [mm] =0.36t
0.624 [mm] =0.62t
0.963 [mm] =0.96t
0.000 [mm] =0.00t

SARAF – Sores Applied Research Accelerator Facility

- To enlarge the experimental nuclear science infrastructure and promote the research in Israel
- To develop and produce radioisotopes primarily for bio-medical applications
- To modernize the source of neutrons at Soreq and extend neutron based research and applications