LiLiT@SARAF

A Liquid-Lithium Target at Soreq Applied Research Accelerator Facility

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Hebrew University

Outline:

1. Background
2. A high-power Liquid-Lithium Target (LiLiT): principle, design and use at SARAF I
3. LiLiT and GaLiT at SARAF II

This talk is humbly dedicated to the memory of Franz Kaeppeler.

PHYSICAL REVIEW C VOLUME 37, NUMBER 2 FEBRUARY 1988

Neutron capture cross section of ^{197}Au: A standard for stellar nucleosynthesis

W. Ratynski* and F. Käppeler
Kernforschungszentrum Karlsruhe, Institut für Kernphysik, D-7500 Karlsruhe, Federal Republic of Germany
(Received 19 October 1987)

^{7}Li(p,n)^{7}Be

^{7}Li (p,n) ^{7}Be

E_{thres}= 1.880 MeV

E_p= 1.912 MeV

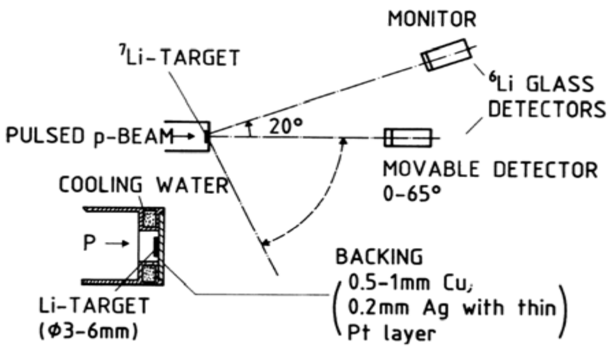


FIG. 1. Experimental setup for determination of the neutron spectrum.

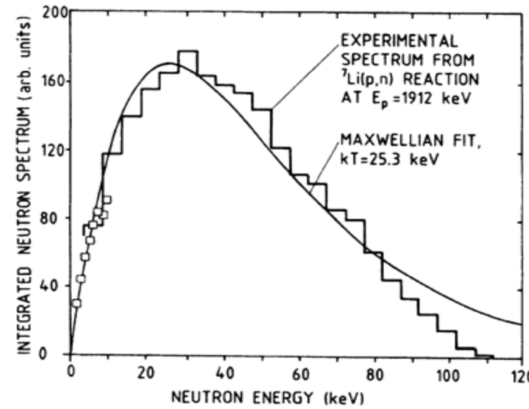
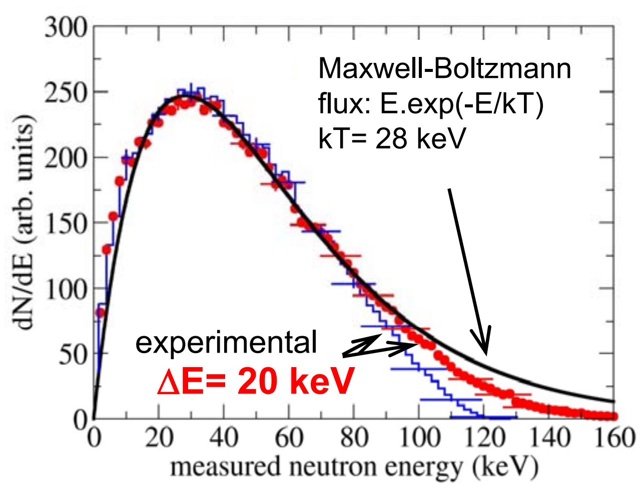


FIG. 3. Total neutron spectrum after integration over all emission angles, for proton energies $E_p = 1912$ keV (top)

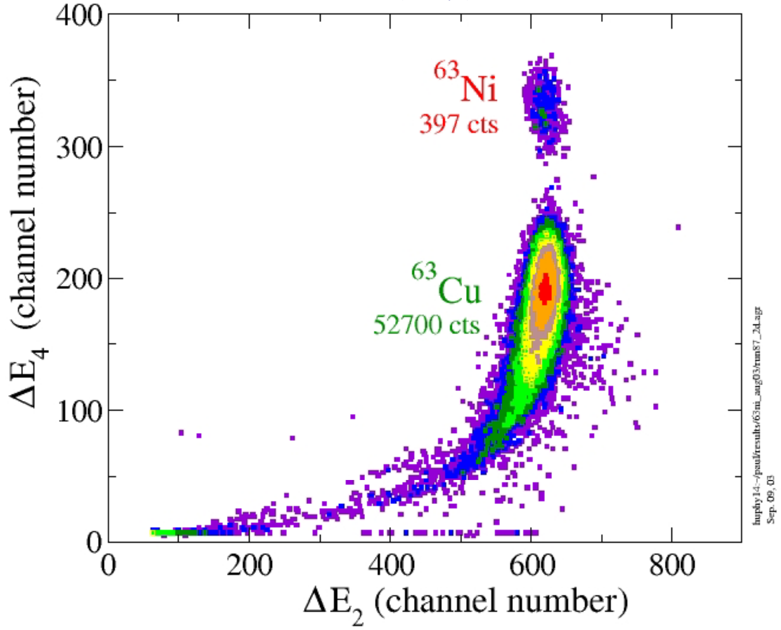
Nuclear astrophysics

The quasi-Maxwellian (kT~ 25 keV) neutron flux enables measurement of stellar s-process cross section by activation
s-process: slow neutron capture producing heavy elements in stars
at thermal energy kT= 5-100 keV



G. Feinberg et al., PRC 2012
See also:
C. Lederer et al., PRC 2012

$^{62}Ni(n,\gamma)^{63}Ni$



1. activation in quasi-Maxwellian neutron flux from $^{7}Li(p,n)^{7}Be$ at Karlsruhe

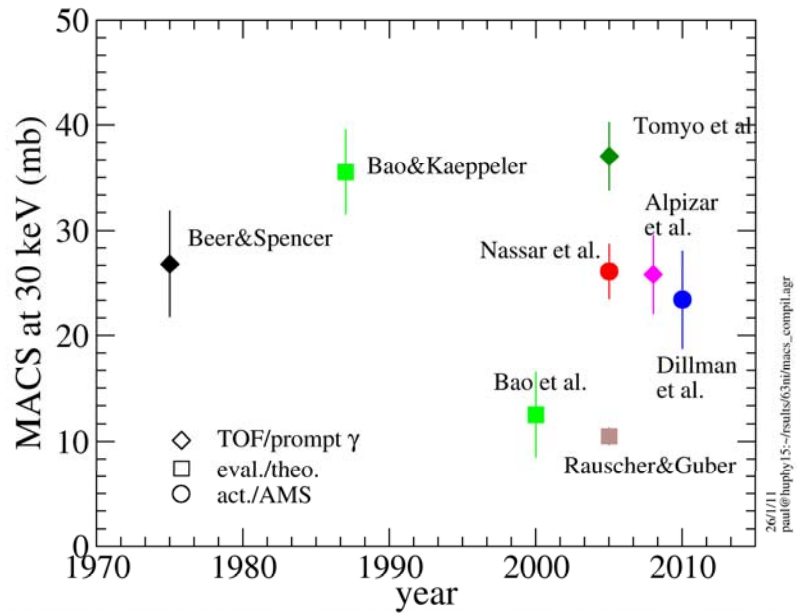
2. Accelerator Mass Spectrometry counting of ^{63}Ni: $^{63}Ni/^{62}Ni = \sigma_{exp} \langle \phi_n t \rangle$

MACS(30 keV)= 26.1 ± 2.6 mb

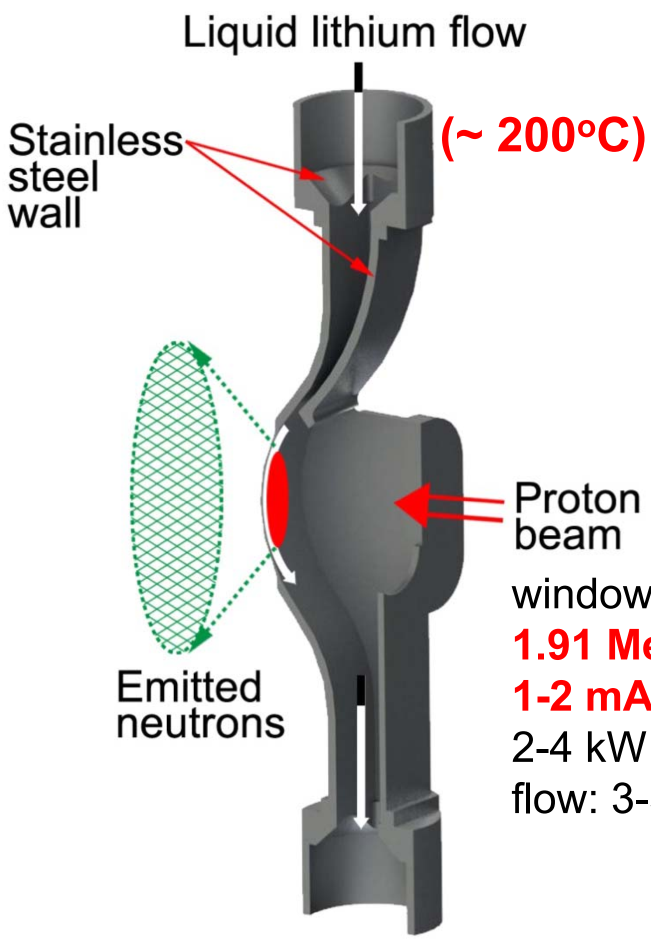
H. Nassar *et al.*, PRL (2005)

In memoriam: Franz Kaeppeler (1942-2021)

$^{62}Ni(n,\gamma)^{63}Ni$

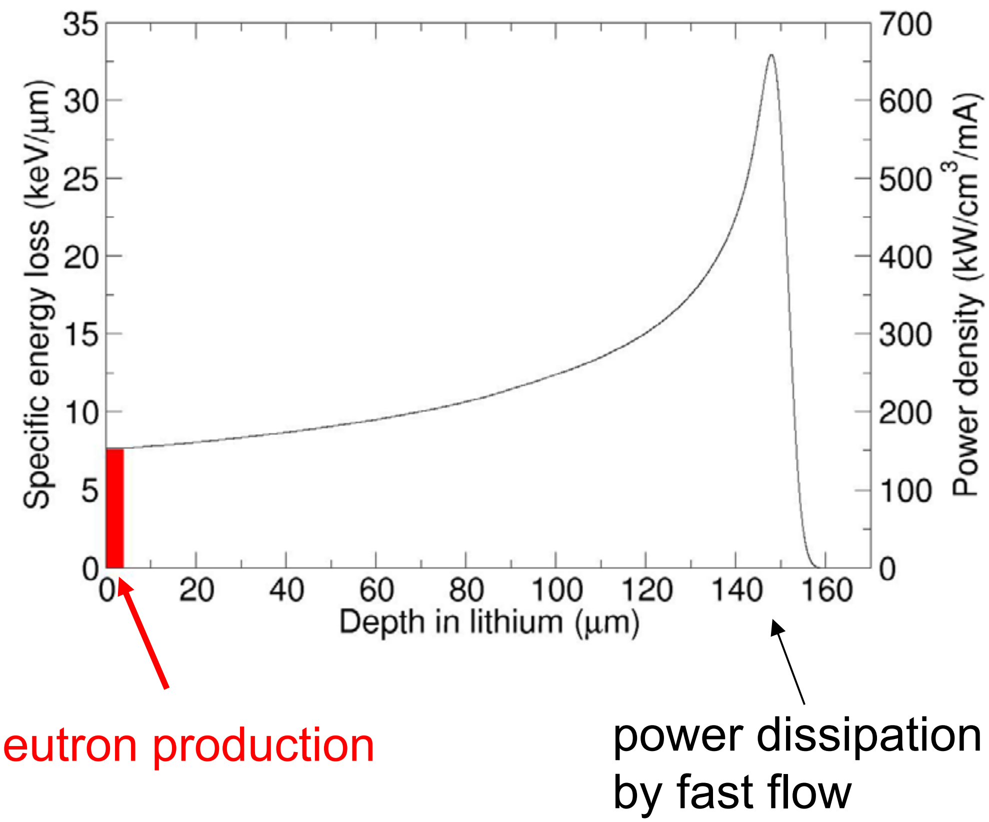


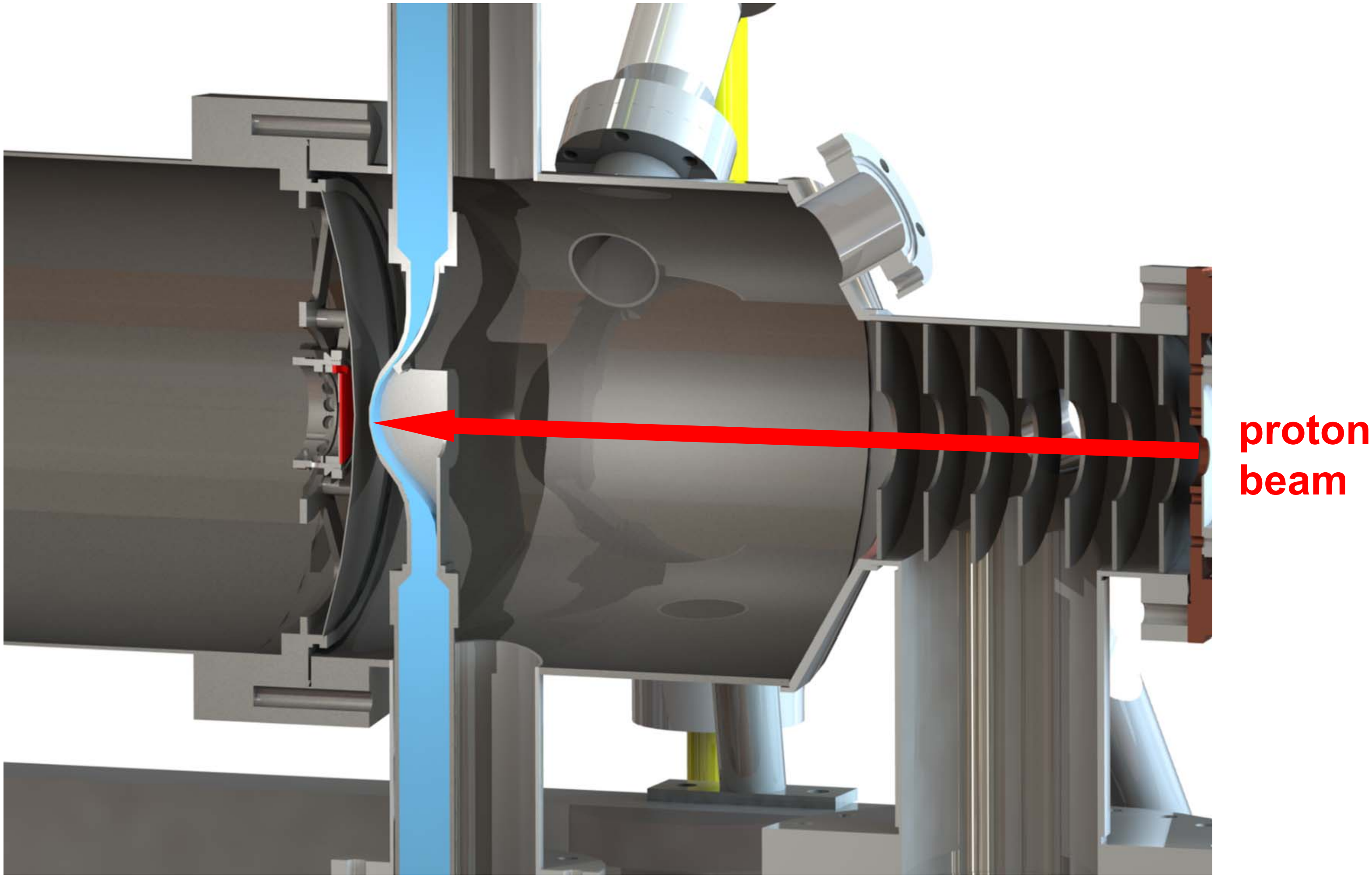
LiLiT (Liquid-Lithium Target) :
neutrons from ^{7}Li(p,n) with a kW-proton beam



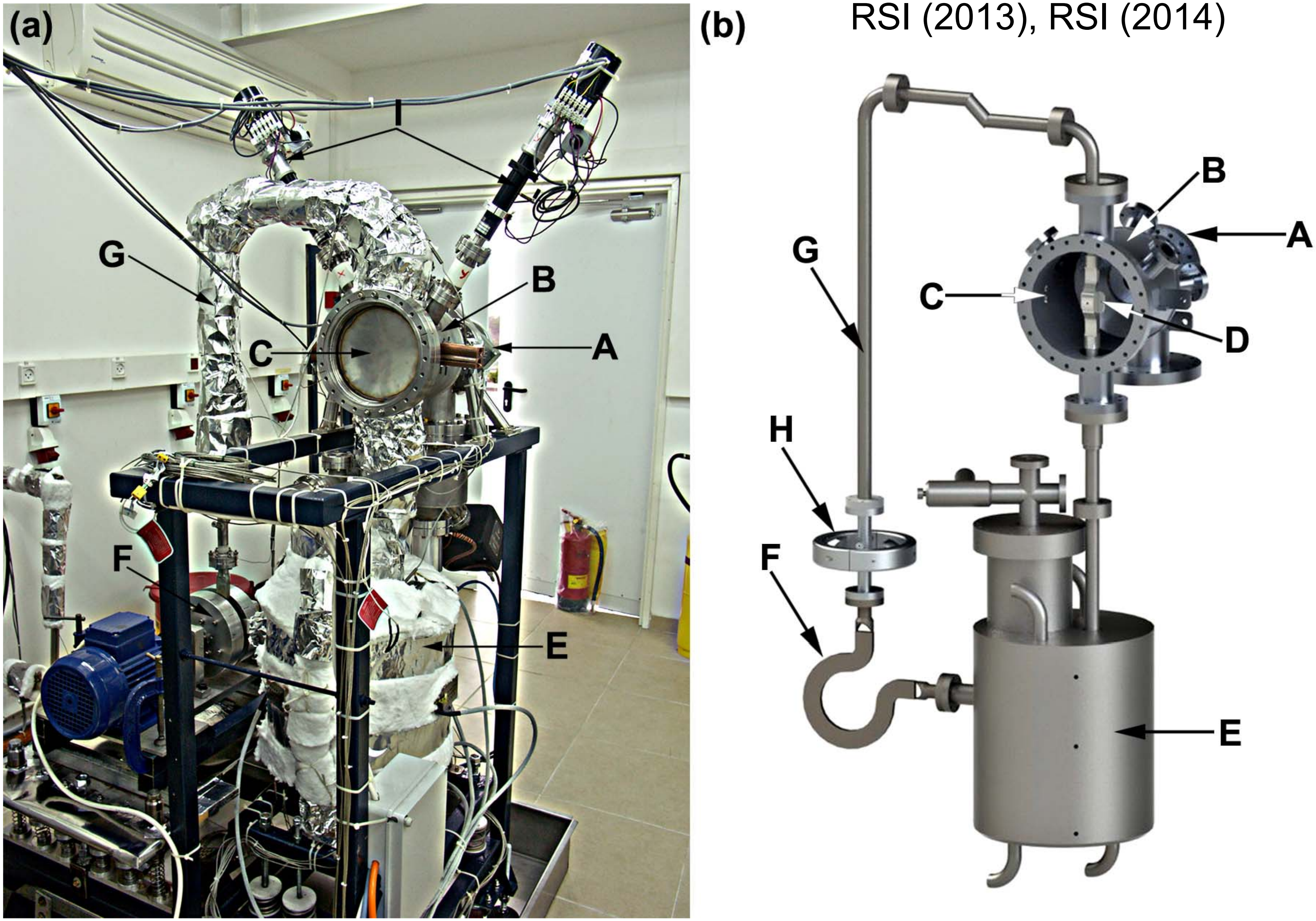
windowless
1.91 MeV,
1-2 mA :
2-4 kW
flow: 3-5 m/s

Higher proton intensity and neutron flux enables activation of small-mass targets
(low-abundance isotopes, radioactive targets

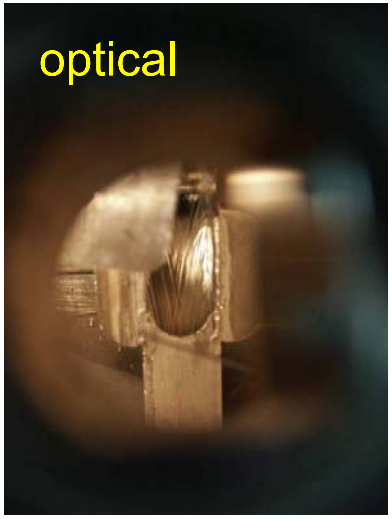



proton
beam

See: S. Halfon et al.,
RSI (2013), RSI (2014)



LiLiT (Liquid-Lithium Target) : neutrons from $^{7}Li(p,n)$ with a kW-proton beam



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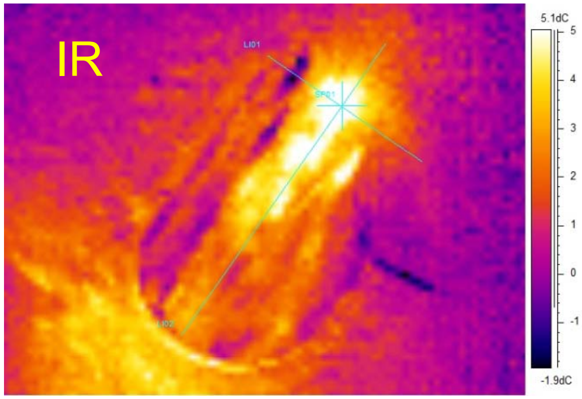
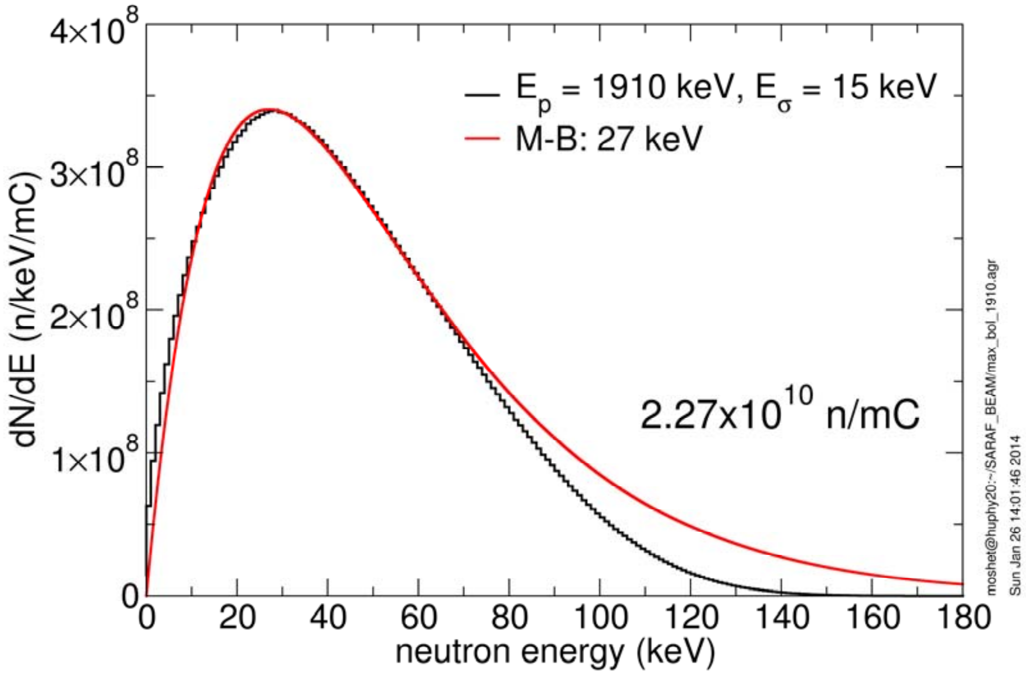
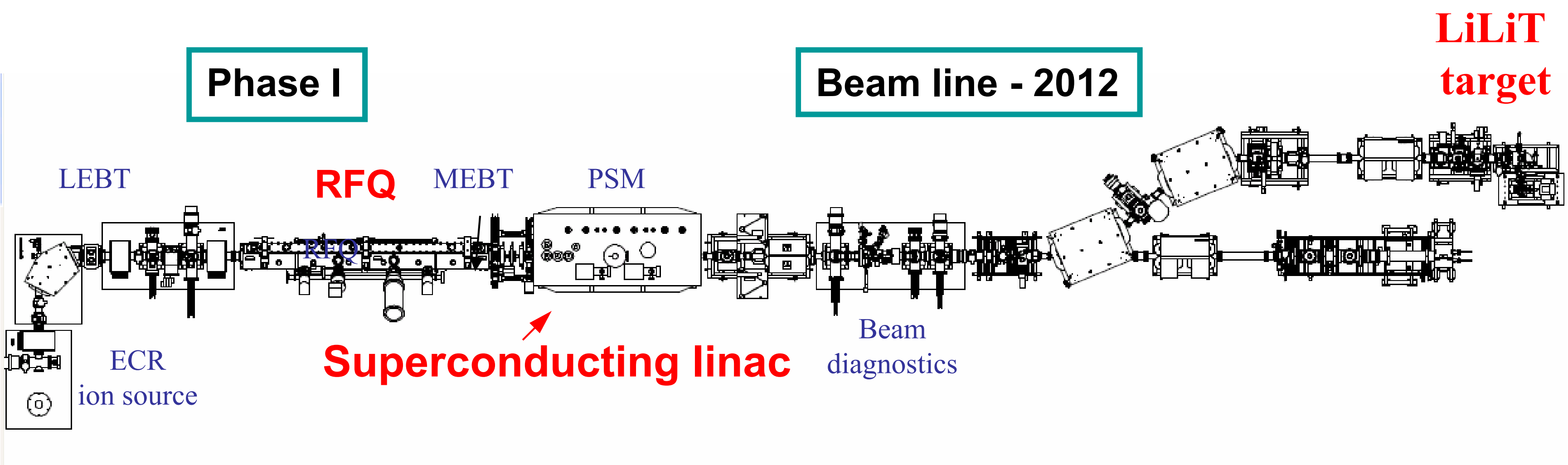




SARAF I, 2013-2018

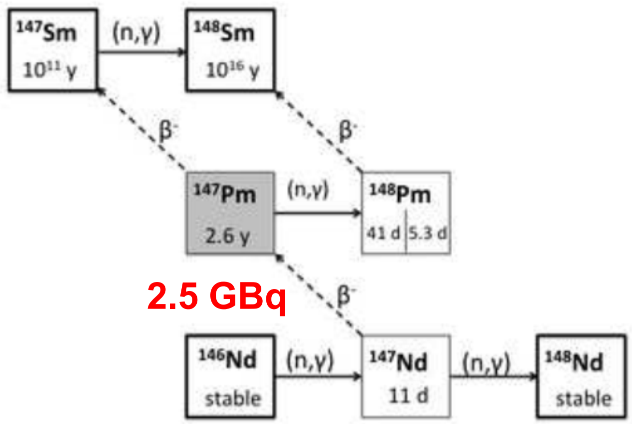


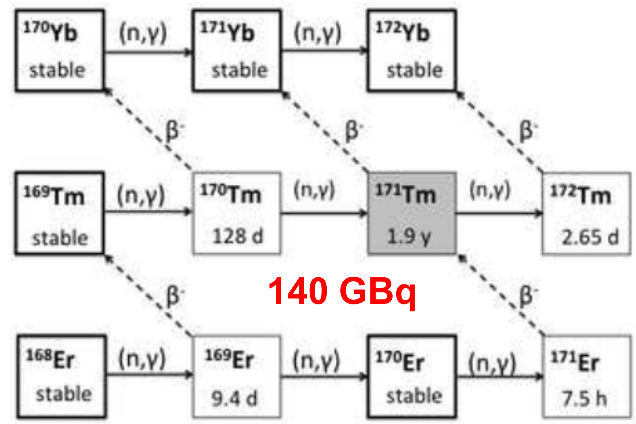
- Linac is operated with a proton (deuteron) beam Continuous Wave (CW), 176 MHz, 1 mA, ~4 MeV or **1.5-2 mA at 2 MeV (3-4 kW)**
- Phase-I commissioned to < 50% duty cycle for deuterons at 4.8 MeV
- Only **CW and slow pulsing** available at present
- Production of accelerator-based neutrons

Experiments at SARAF I-LiLiT: 2014-18; see M.P. et al., EPJ A (2019)

Reaction	Detection	HUJ, SARAF and	Ref./status
^{94,96}Zr(n,γ)	γ spect.	-	Tessler et al., PLB (2015)
^{90}Zr(γ,n)	γ spect.	-	"
^{7}Be(n,α)	CR39	UConn, PSI,ILL,WIS,CERN, TUNL	failed
^{23}Na,^{35,37}Cl(n,γ)	γ spect., AMS	ANU,GUF,HZDR	Pavetich et al., PRC (2019)
^{36,38}Ar(n,γ)	AMS,LLC	ANL, GUF, U Bern	Tessler et al., PRL (2018)
^{53}Mn(n,γ)	γ spect.	PSI	Ulrich et al., subm.
^{69,71}Ga(n,γ)	γ spect.	-	Tessler et al., subm.
^{74,78,80,82}Se (n,γ)	γ spect.	-	in preparation
^{78,80,84,86}Kr(n,γ)	γ, ATTA,LLC	ANL, GUF, U Bern	PRC (2021)
^{80,82,86}Kr(γ,n)	γ, ATTA	ANL, GUF	"
^{92}Zr(n,γ)	AMS	ANU	Pavetich et al., NIMB, in prog.
^{124,126,132,134}Xe(n,γ)	γ spect.	GUF	in progress
^{136,138,140,142}Ce(n,γ)	γ spect.	-	in preparation
^{147}Pm(n,γ)	γ spect.	U Seville, ILL, PSI	Guerrero et al., PLB (2019)
^{171}Tm(n,γ)	γ spect.	U Seville, nTOF, ILL, PSI	Guerrero et al., PRL (2020)
^{208}Pb(n,γ)	β, γ spec.	U Seville	Weissman et al., PRC (2017)
^{209}Bi(n,γ)	α, β, γ spec.	JRC	Shor et al., PRC (2017)

^{147}Pm (2.6 y), ^{171}Tm (1.9 y) *s*- process branching points



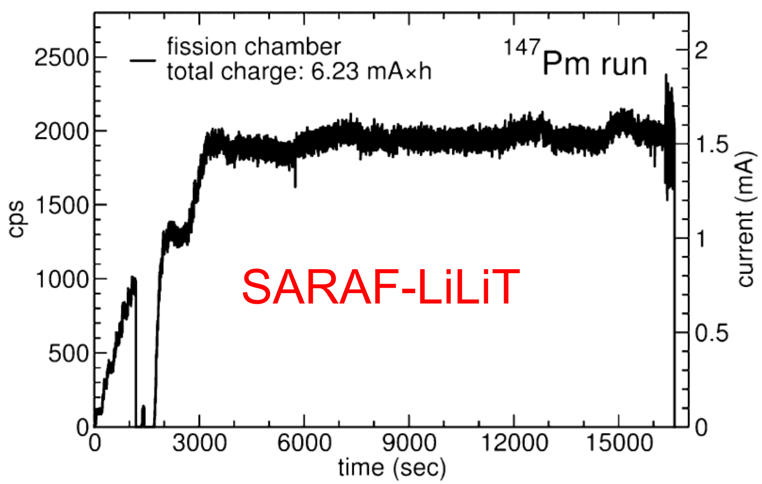


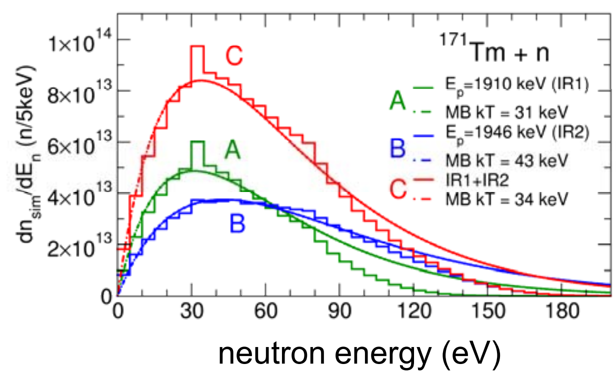
^{146}Nd(n,γ)^{147}Nd(β–)^{147}Pm -> 56 μg target

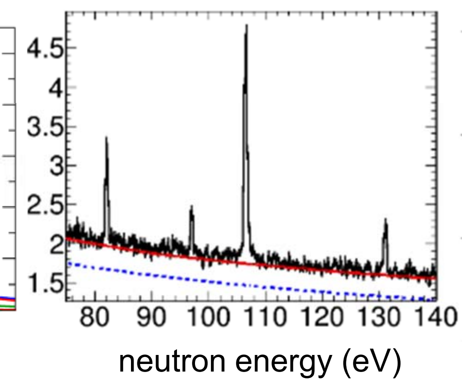
ILL PSI

^{170}Er(n,γ)^{171}Er(β–)^{171}Tm -> 603 μg target

ILL PSI







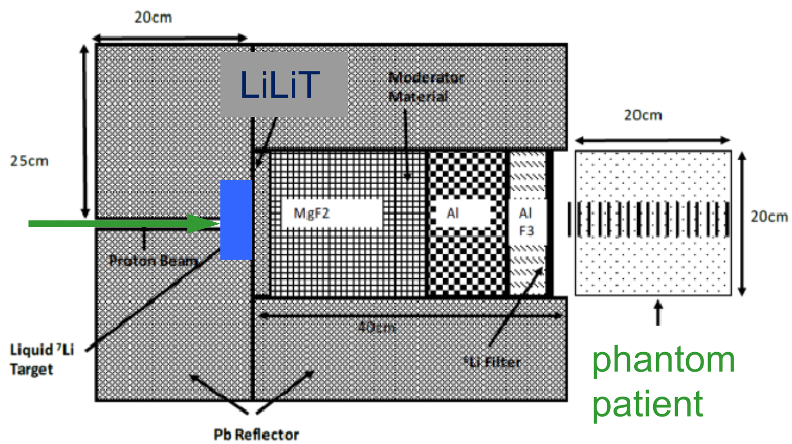
SARAF-LiLiT nTOF

MACS(30 keV)= 826(107) mb
C. Guerrero et al., PLB (2019)

MACS(30 keV)= 384(40) mb
C. Guerrero et al., PRL (2020)

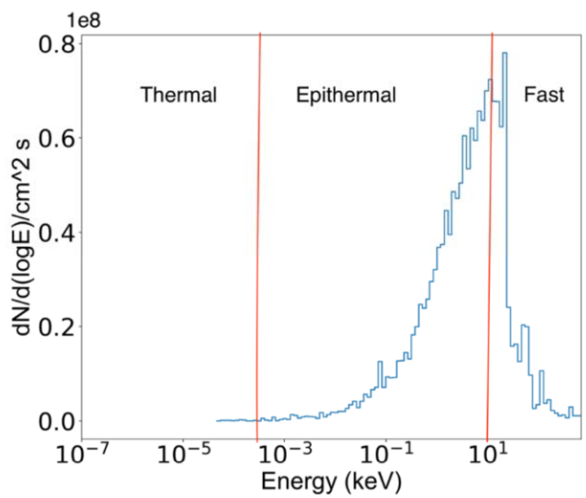
Nuclear medicine: LiLiT neutrons for radiotherapy

3 MeV p beam



BSA design for the SimLit-Geant4 calculation

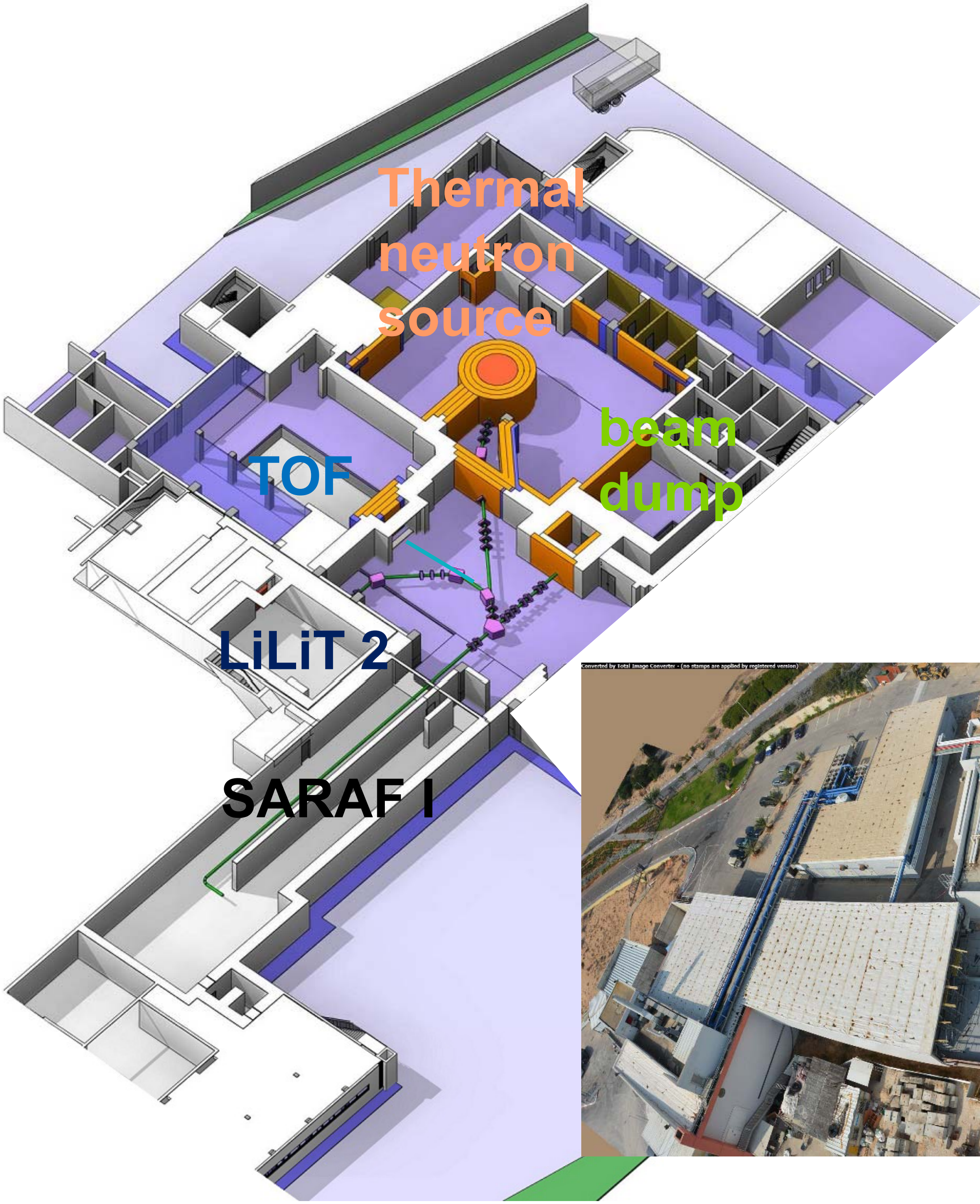
1 MeV n -> keV n



Neutron spectrum at beam port of the optimized BSA

Φ_{epi}= 3×10^7 n/cm^2/s/mA

M.P. et al., UCANS-8, Paris
EPJ WoC (2020)

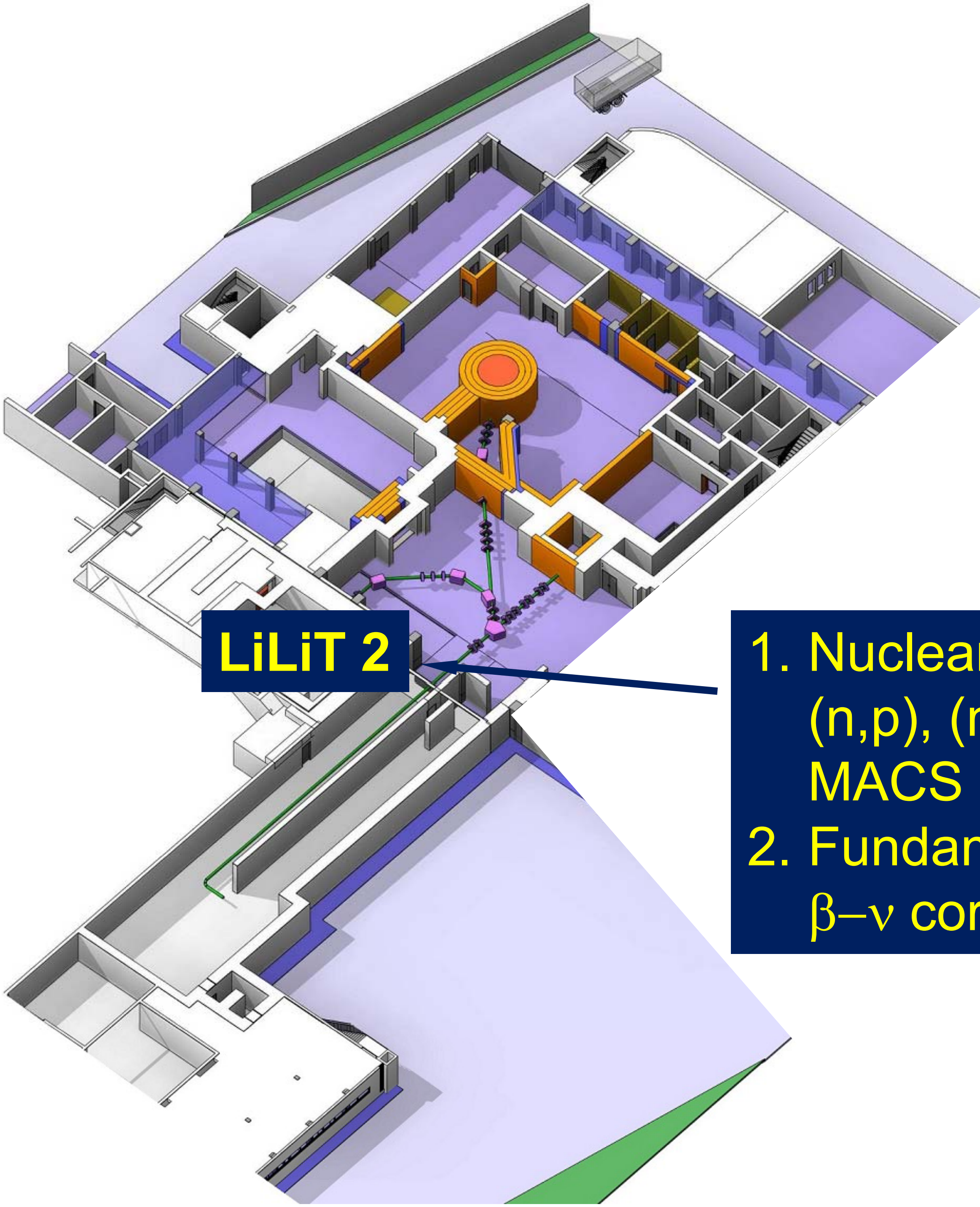


SARAF II
a versatile neutron science laboratory (2024 ->):
basic research
applied science

SARAF II

Parameter	Value	Comment
Ion Species	**Protons / Deuterons**	α, M/q ≤ 2
Energy Range	1.3/2.6 -**35/40 MeV**	p/d, Variable energy
Energy Spread	~60 keV r.m.s.	At 40 MeV
Current Range	10 nA – **5 mA**	**CW (176 MHz)**
Pulsed Mode	**0 –** 200 kHz	Single **1 nsec pulses → variable macro**-pulses
Beam Size	1 mm – few cm	Transverse plane, 2D Gaussian
Emittance	0.2 π·mm·mrad	Transverse
Maintenance	Hands-On	**Very low beam loss**

SARAF-II design
N. Pichoff *et al.*,
IPAC 2019



1. Nuclear astrophysics
   (n,p), (n,α) explosive NS
   MACS
2. Fundamental interactions
   $\beta-\nu$ correlations

(n,p) and *(n,α)* reactions on unstable proton-rich isotopes: ^{26}Al*(n,p)*, ^{56}Ni*(n,p)*,…

M. Friedman, HUJ

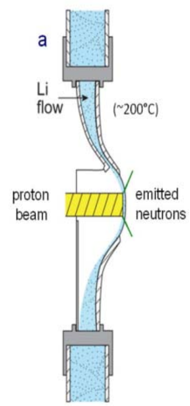
See C. Lederer-Woods et al., PRC (2021, 2021)

Goal: Establish an apparatus for *(n,p)* and *(n,α)* measurements on stable and unstable isotopes at explosive stellar temperatures (~1.5-3.5 GK, ~100-2000 keV).

Protons - SARAF

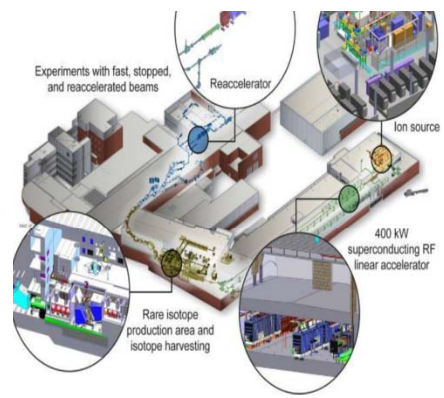
2-5 MeV protons
Beam current > 1 mA.
Operational (currently upgrading)

Neutrons - LiLiT



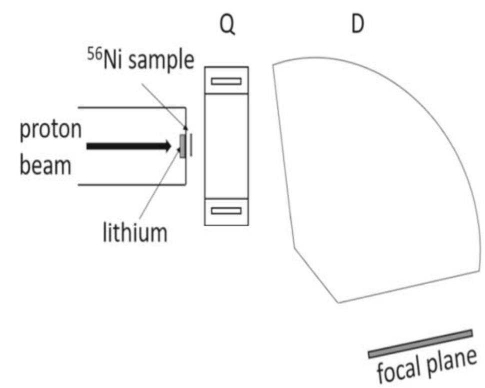
keV neutrons via ^{7}Li(p,n)
Operational
M. Paul *et al.* EPJA **55** (2019)

Targets - FRIB



Isotope Harvesting project
Under construction
E. Abel *et al.* J. Phys. G 46 (2019)

Detection - HUJ



Design stages
efficiency ~0.5%
M. Friedman EPJA **56** (2020)

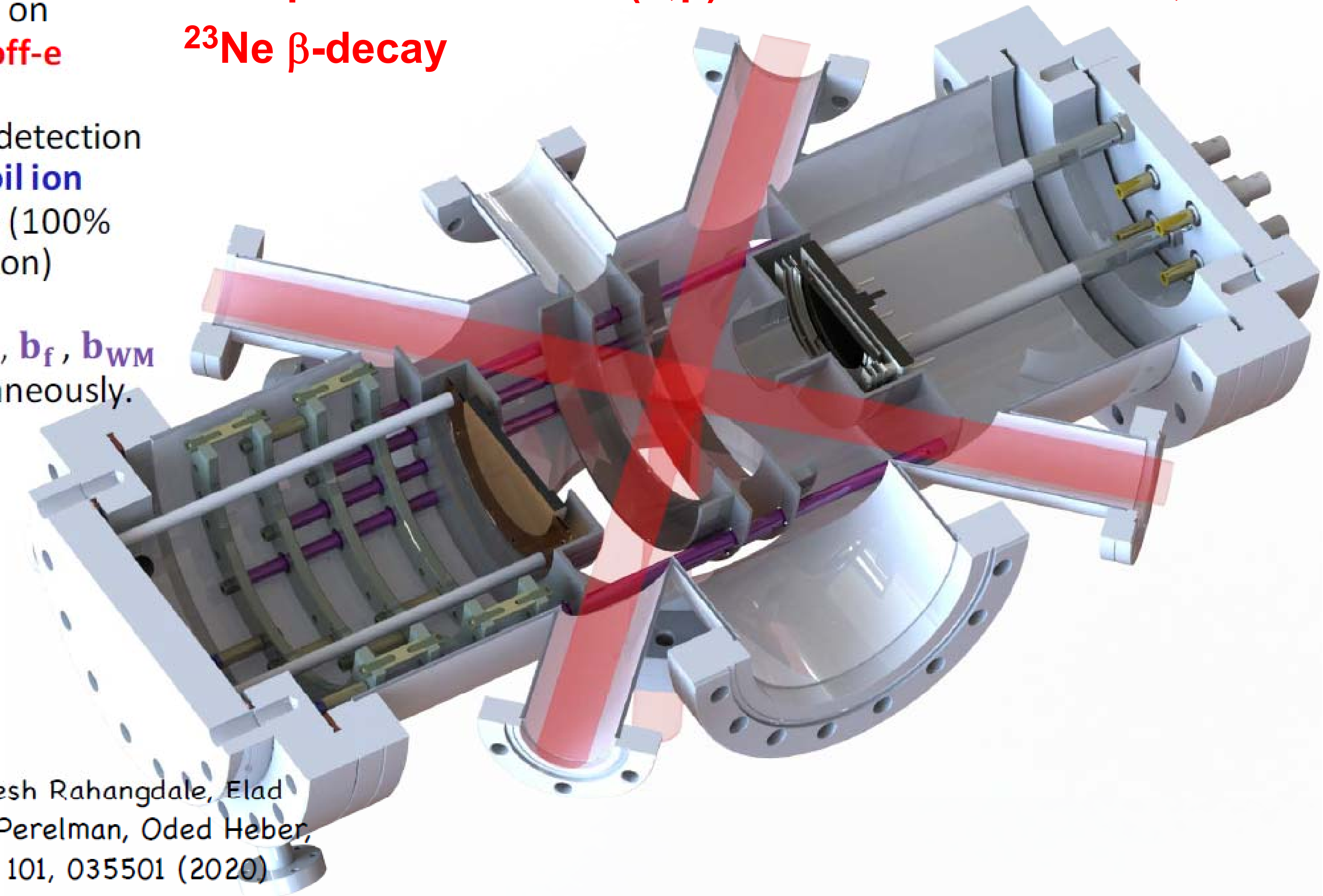
The nuclear microscope: G. Ron et al. (HUJ)

(Magneto-optical-trap High energy Velocity Map Imaging)

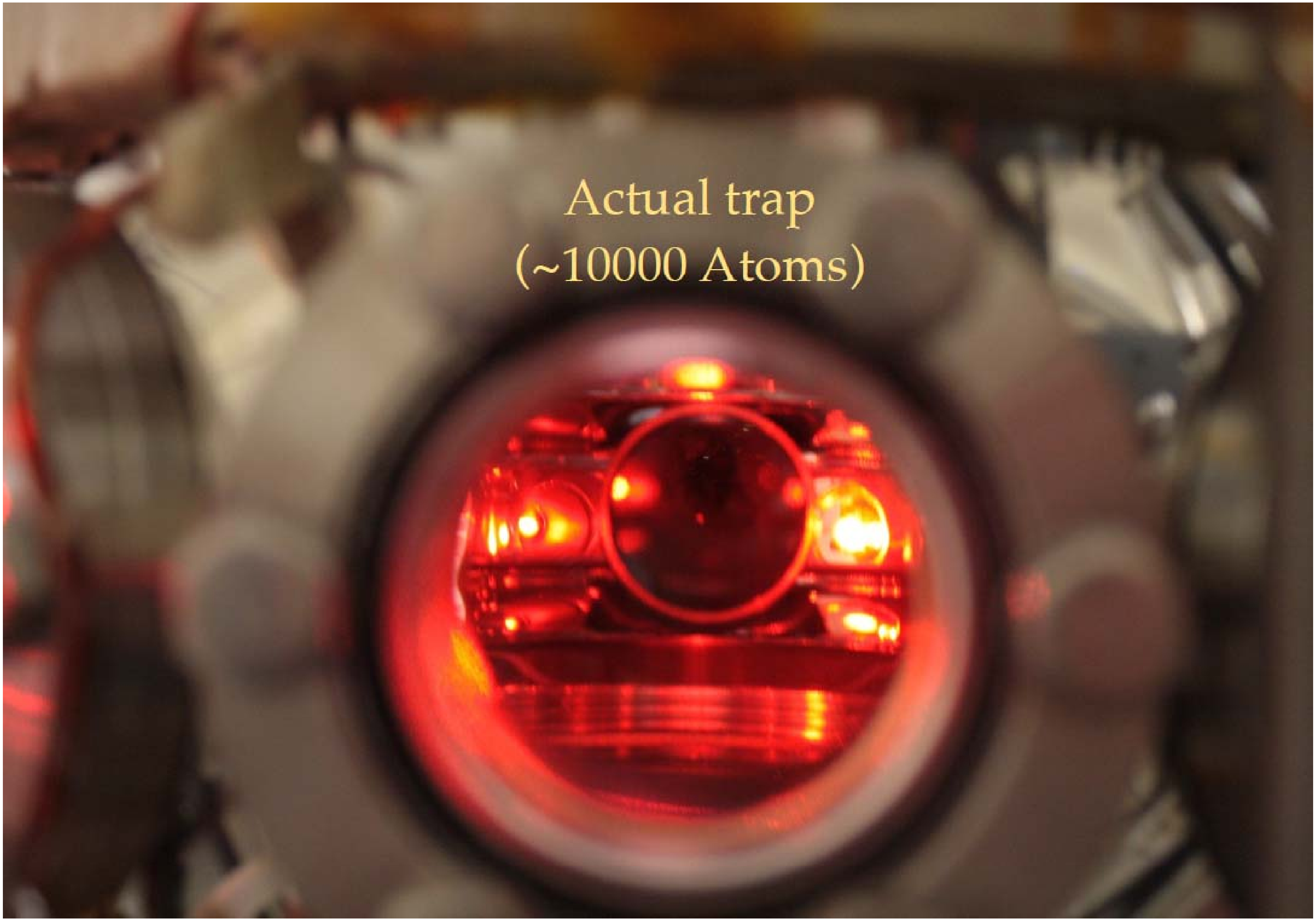
^{23}Ne production: ^{23}Na(n,p)^{23}Ne at SARAF II-LiLiT, ^{7}Li + d

^{23}Ne β-decay

- Trigger on **Shakeoff-e**
- Direct detection of **recoil ion** energy (100% collection)
- Fit $a_{\beta\nu}$, b_f, b_{WM} simultaneously.



Ben Ohayon, Hitesh Rahangdale, Elad Parnes, Gedalia Perelman, Oded Heber, GR, Phys. Rev. C 101, 035501 (2020)

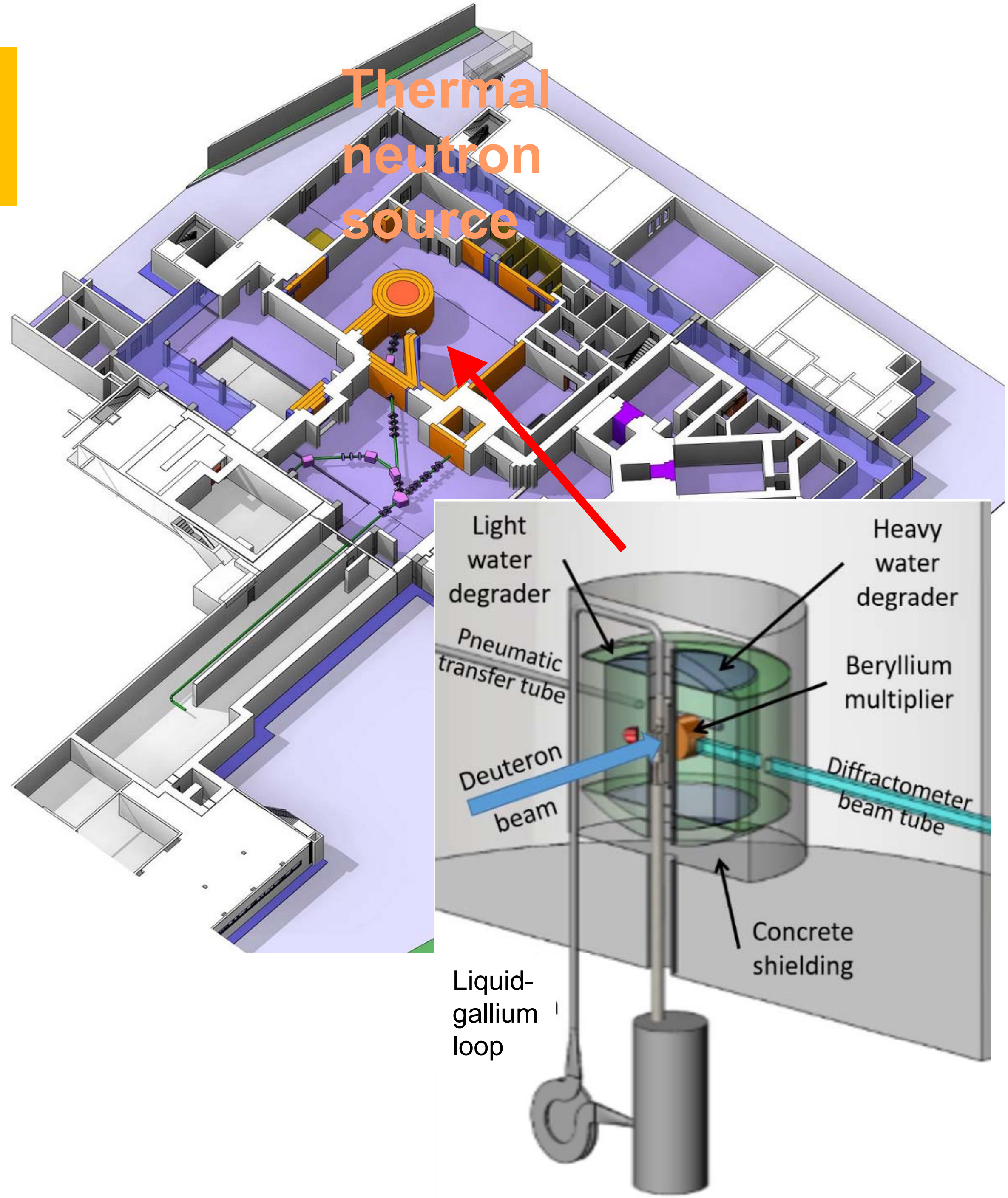

Actual trap
(~10000 Atoms)

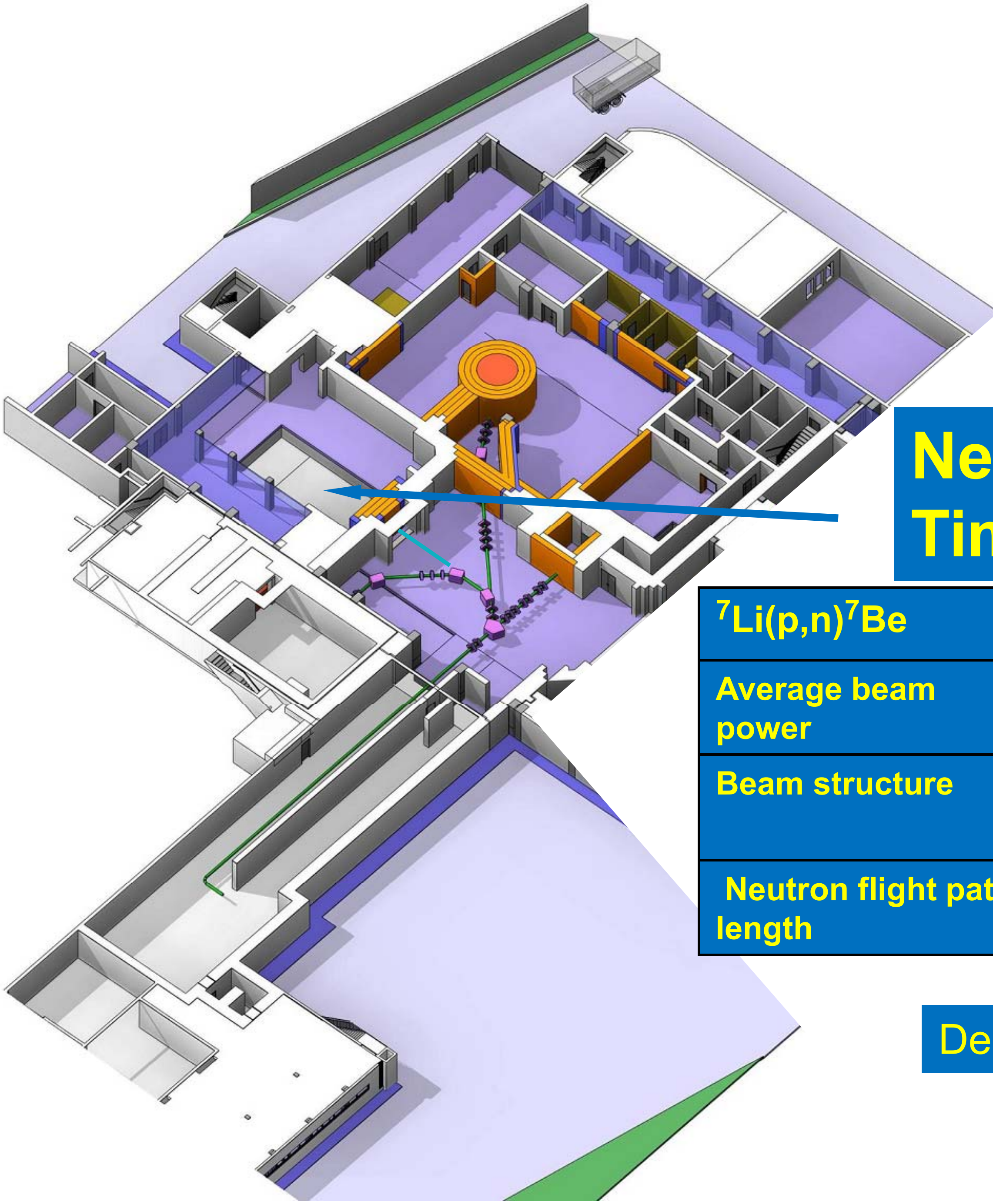
Thermal neutron source

Design: K. Lavie, Y. Eisen, A. Pernik

Soreq NRC

Target	**Liquid gallium-indium jet**
Moderator	Light water
Reflector	Beryllium and polyethylene
Beam power (deuterons)	200 kW CW (5 mA · 40 MeV)
Thermal neutron camera	4×10^5 n/cm^2/sec at L/D=250
Diffractometer	~10^6 n/cm^2/sec at exit port
Rabbit irrad. station	~10^{12} n/cm^2/sec Cd ratio ~ 11.2
Development port	~10^6 n/cm^2/sec at exit port





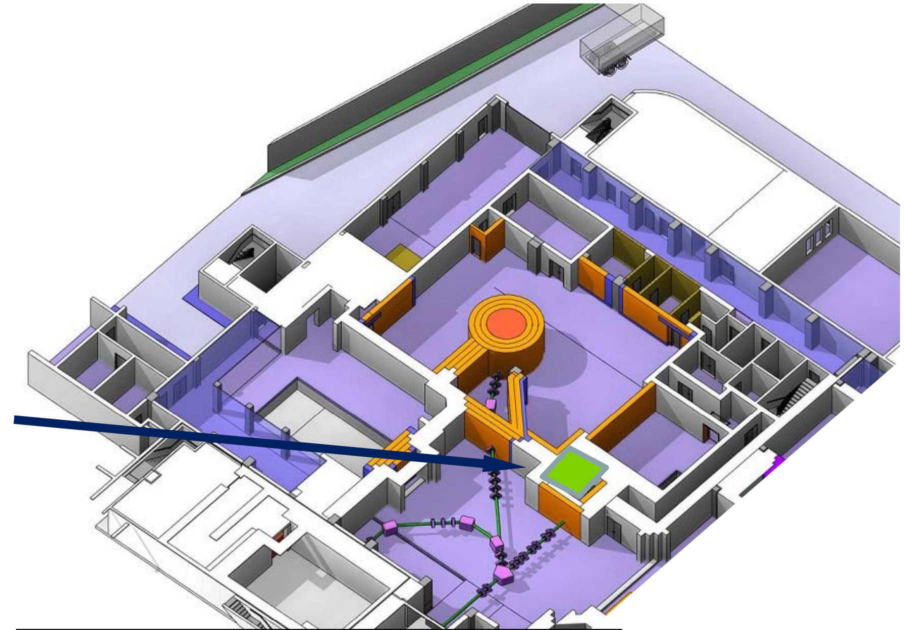
Neutron Time-of-Flight facility

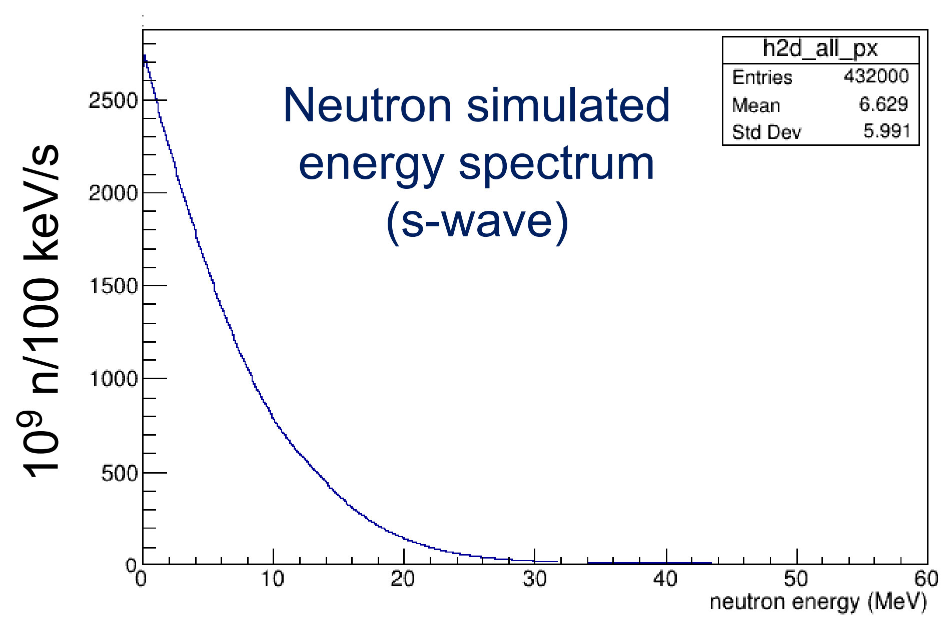
$^{7}Li(p,n)^{7}Be$	**Solid Li or LiF**
Average beam power	Up to 200 W (DC~10^{-3}) (5 mA · 40 MeV)
Beam structure	**Down to 1 nsec bunches at 200 kHz**
Neutron flight path length	**18 m**

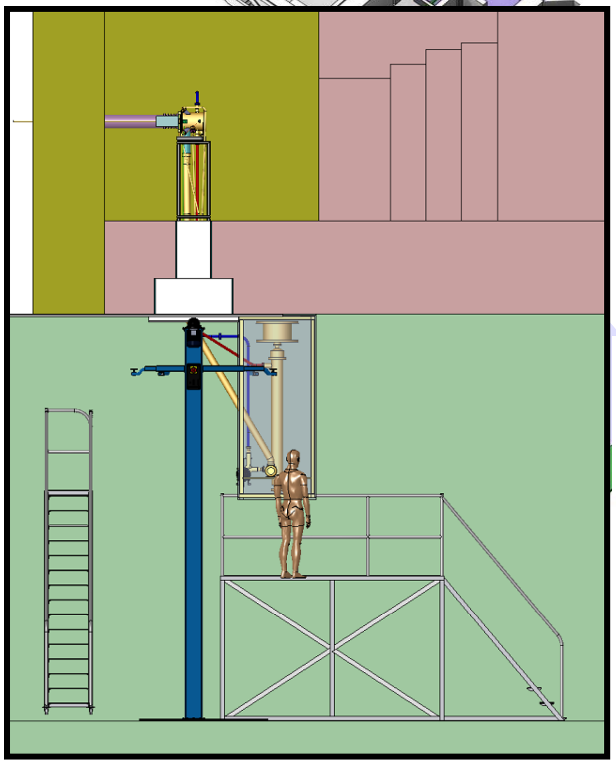
Design: D. Heflinger, T. Hirsh

Beam Dump,
Design: I. Eliahu et al.

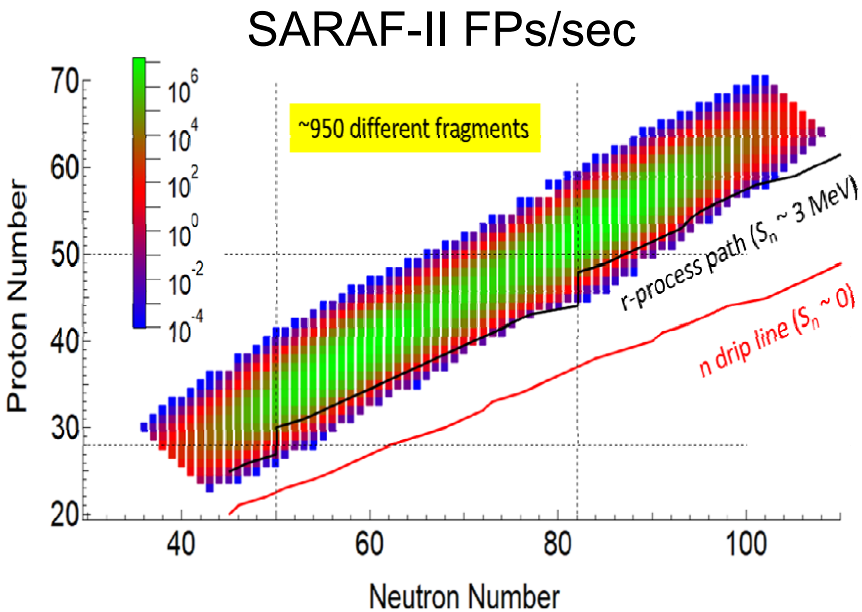
Target	**Liquid gallium-indium jet**
Beam power	**200 kW CW (5 mA · 40 MeV)**
Maximum neutron yield	**10^{15} n/sec**

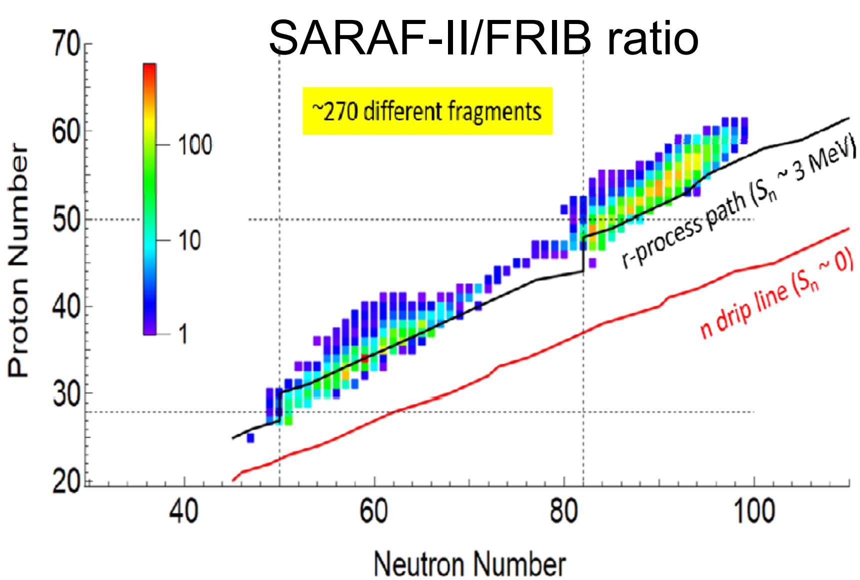


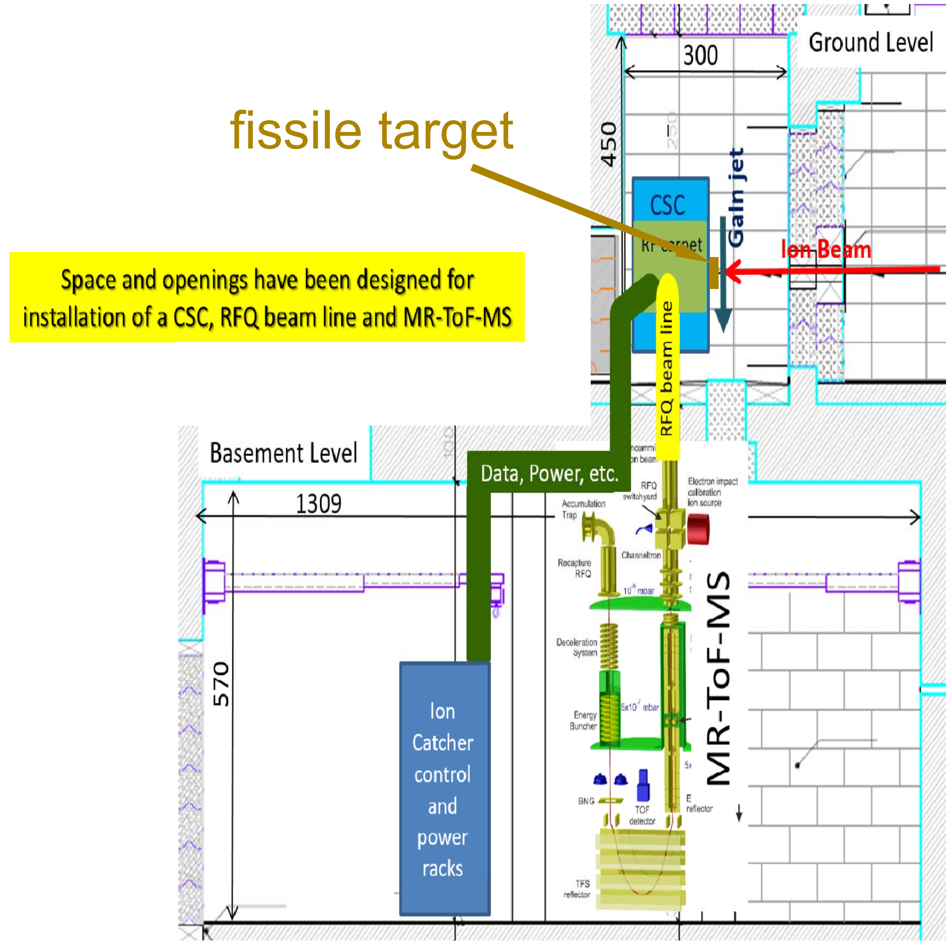




SARAF-II Fission Research Facility: I. Mardor (Soreq NRC, TAU)

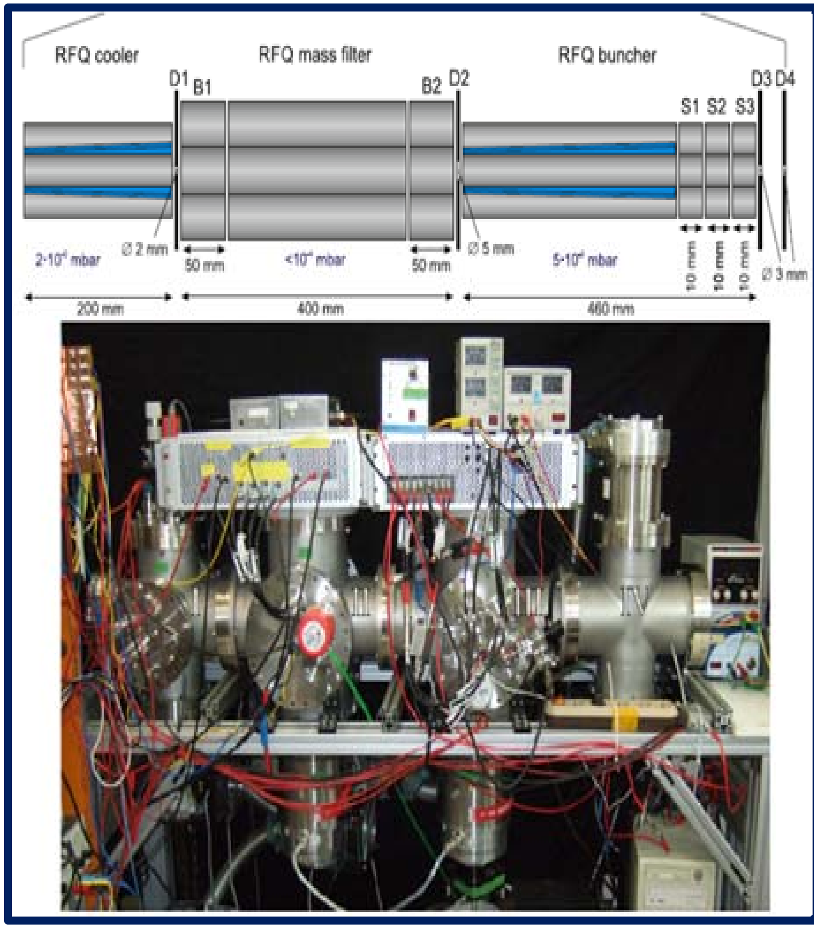


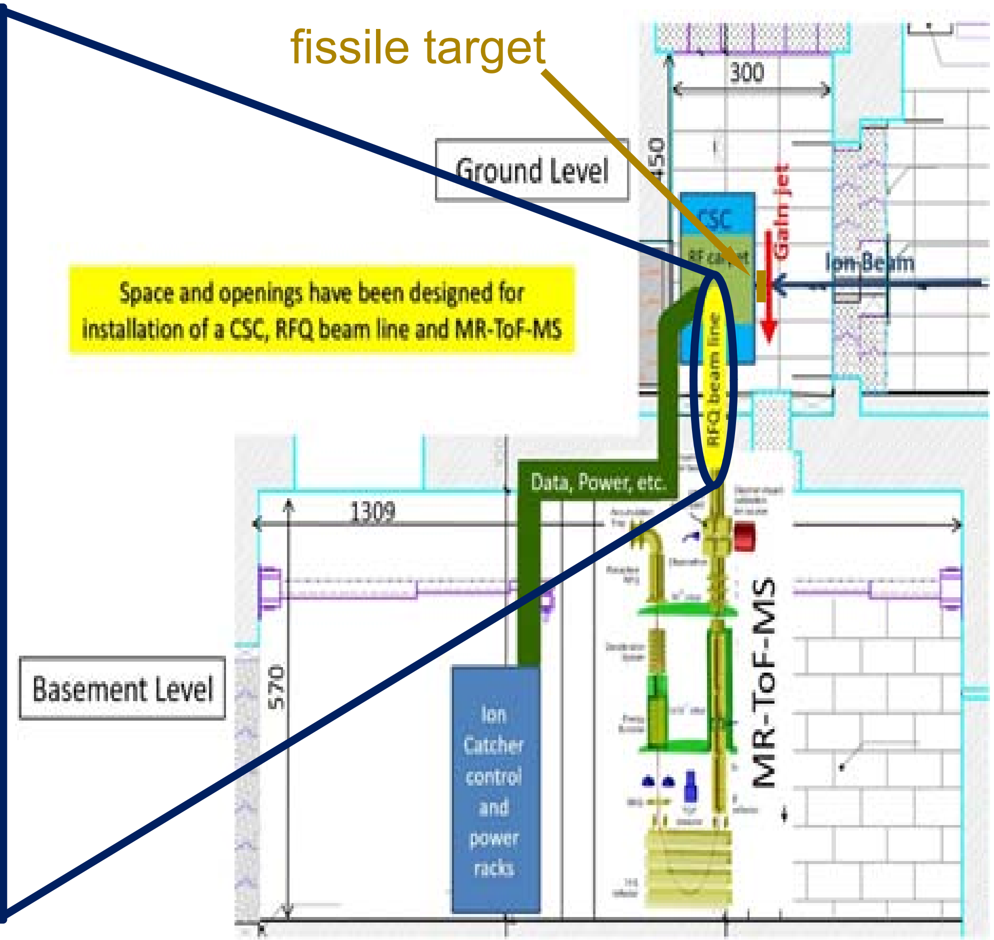




I. Mardor et al., Eur. Phys. Jour. A 54: 91 (2018)

From October 2021: First building block at TAU





- Install 3-RFQ trap system from Justus Liebig University Giessen at Tel Aviv University
- Goals: 1. Increase 3-RFQ trap performance to match SARAF-II requirements
  2. Research its possible application for first measurements of n-capture cross sections on short-lived n-rich nuclei

Thank you for your attention
and
welcome soon to SARAF II

Thanks to many collaborators and institutions:
HUJ: M. Friedman, T. Palchan
SARAF: A. Arenshtam[dec], D. Berkovits, I. Eliahu, G. Feinberg, S. Halfon, A. Kreisel, A. Shor, I. Silverman, M. Tessler
ANL: M. Avila, R. Pardo, E. Rehm, R. Scott, R. Vondrasek
PSI: R. Dressler, D. Schumann
ANU: S. Pavetich, S. Tims, A. Wallner
CERN: T. Storra
GELINA: A. Plompen
GUF: R. Reifarth, M. Weigand
ILL: U. Koester
INAF: S. Cristallo
KIT: F. Kaeppeler[dec]
U. Bern: D. Baggenstos, R. Purtschert
U. Seville: C. Guerrero, J. Lerendegui-Marco
WIS: M. Hass[dec]