Research possibilities with an Ion Catcher System at SARAF

Israel Mardor[1,2], Timo Dickel[3,4]
[1]Soreq NRC, Yavne, Israel
[2]Tel Aviv University, Tel Aviv, Israel
[3]Justus-Liebig-Universität Gießen, Gießen, Germany
[4]GSI, Darmstadt, Germany

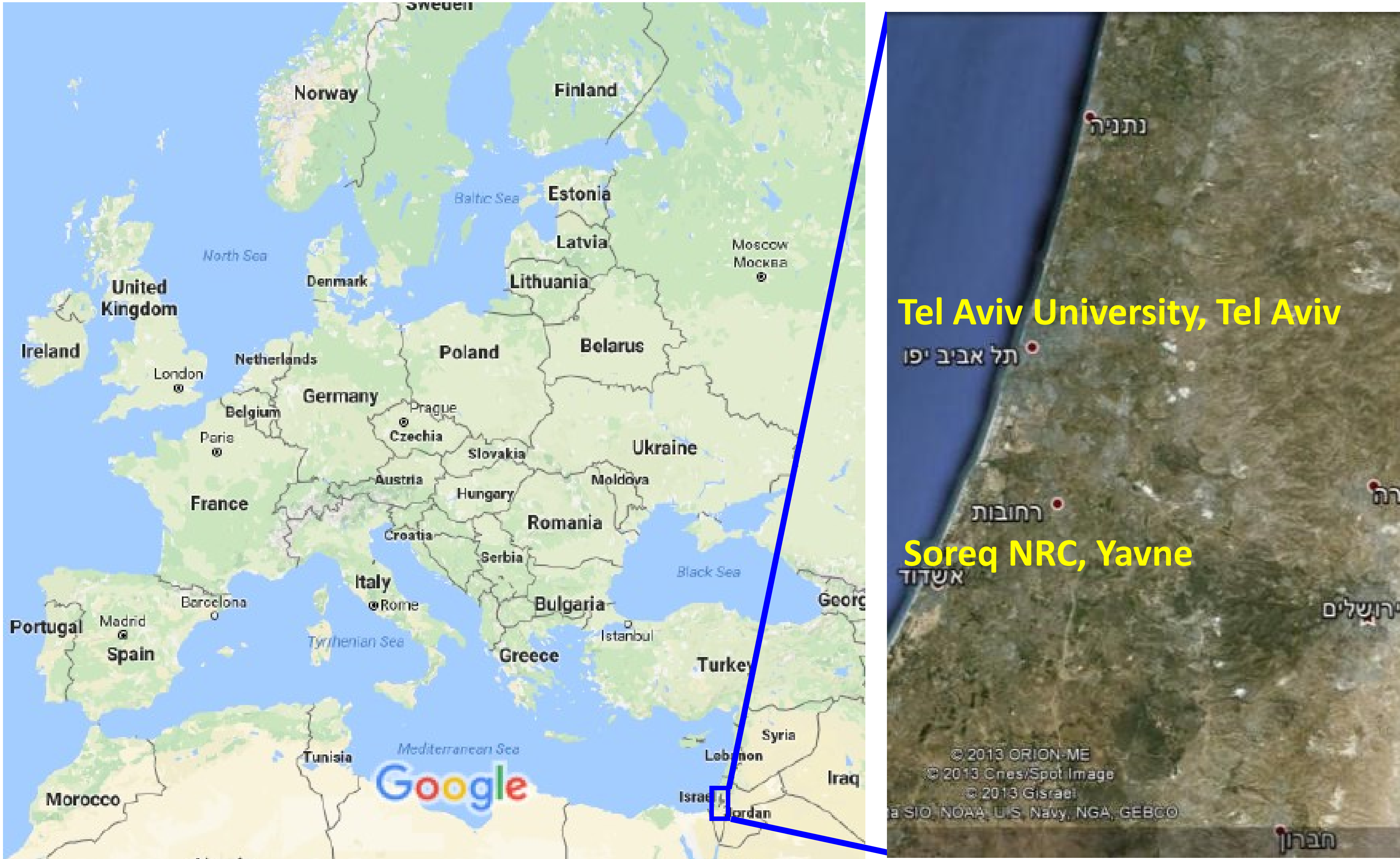
NUSTAR Annual Meeting, GSI, Darmstadt, March 1st 2018

Outline

- Overview of SARAF and LiLiT
- SARAF + LiLiT + Ion Catcher:
  - High rate n-rich isotope generation via neutron induced fission

Our geographical location

Frankfurt – Tel Aviv: ~3,000 km, ~4.5 hours flight

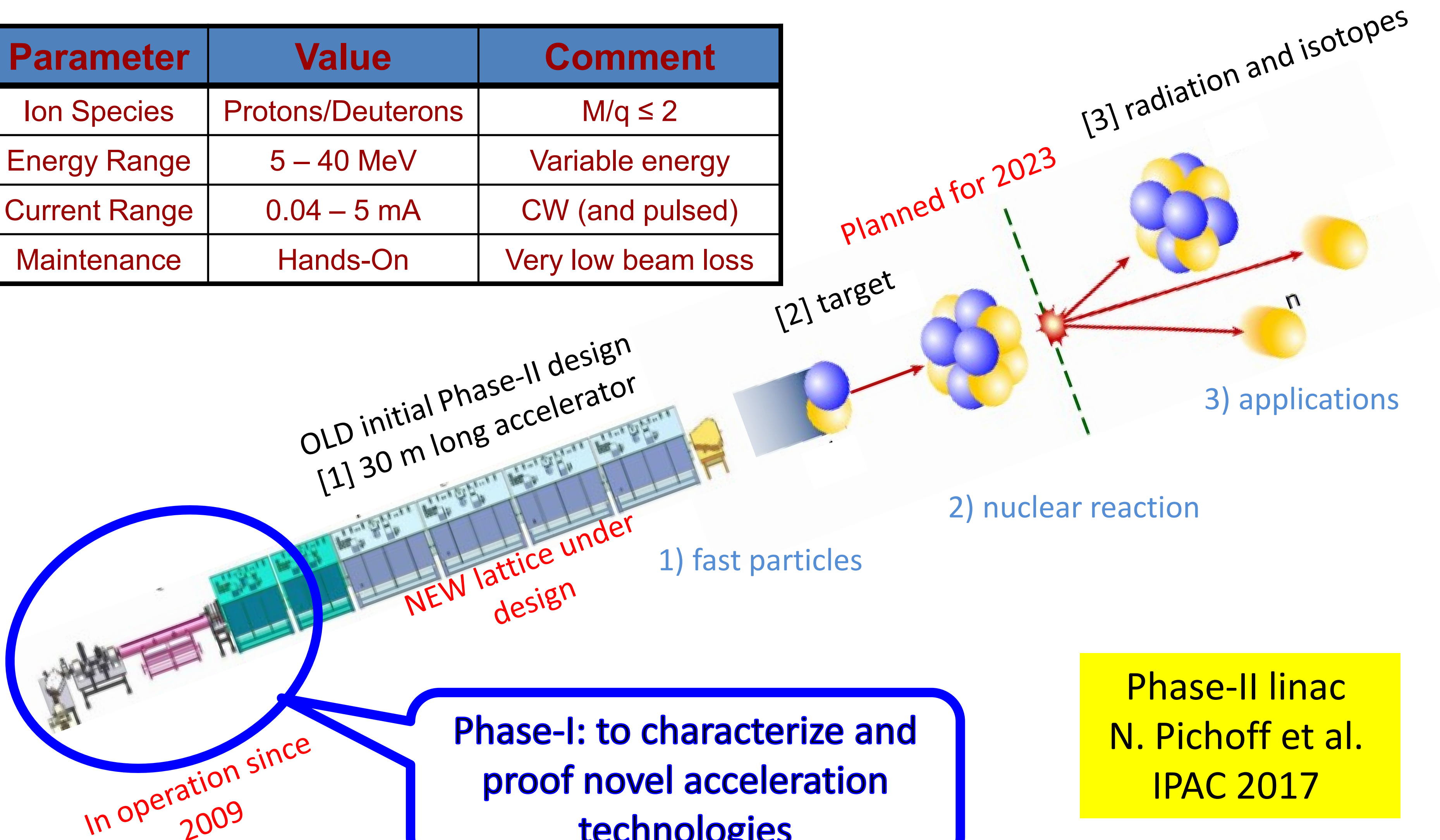


SARAF – Soreq Applied Research Accelerator Facility

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

SARAF concept and top level requirements

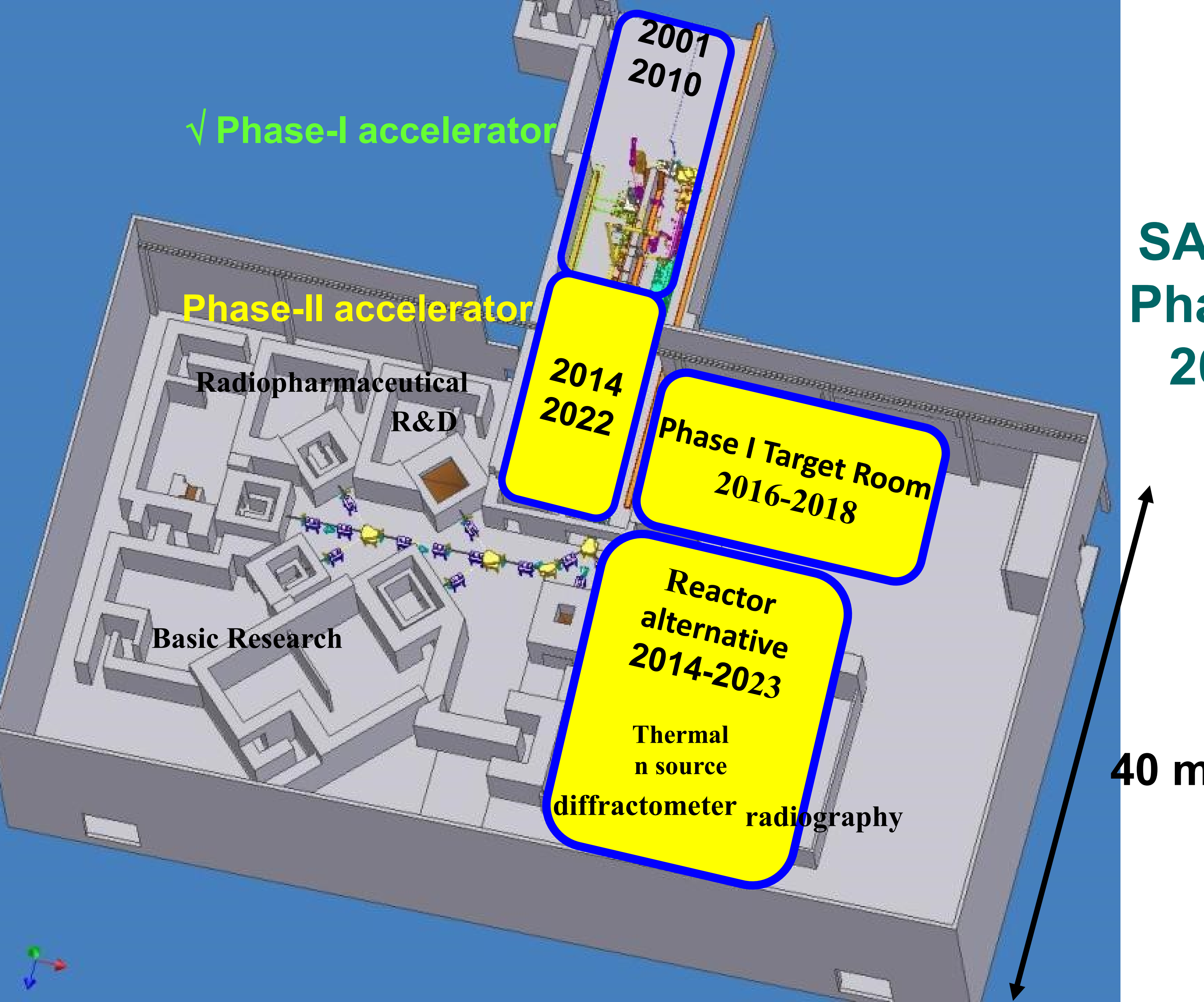
Parameter	Value	Comment
Ion Species	Protons/Deuterons	M/q ≤ 2
Energy Range	5 – 40 MeV	Variable energy
Current Range	0.04 – 5 mA	CW (and pulsed)
Maintenance	Hands-On	Very low beam loss



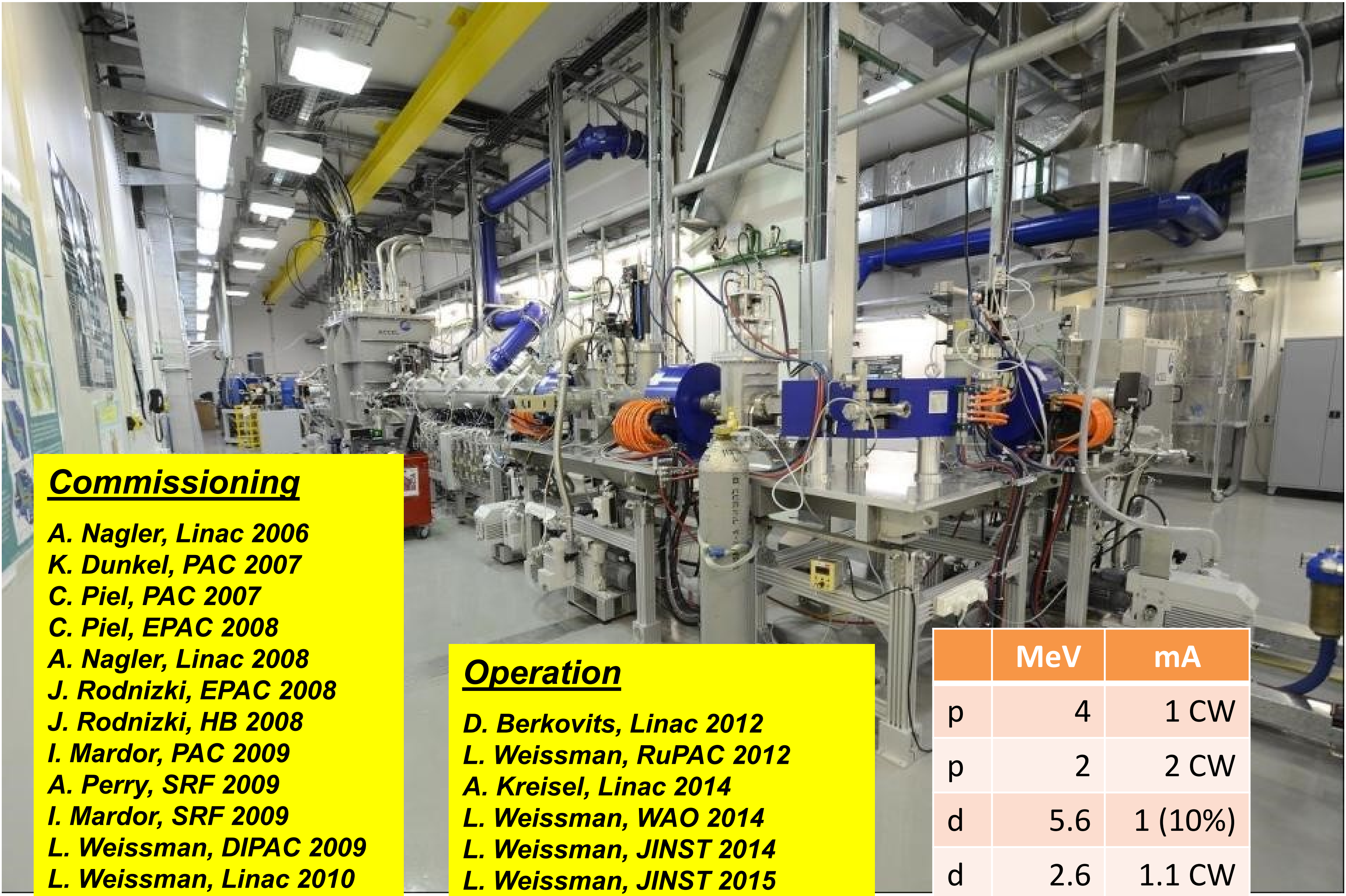
Phase-I: to characterize and proof novel acceleration technologies

Phase-II linac
N. Pichoff et al.
IPAC 2017

SARAF Phase II 2023



SARAF-I on site collaboration with Research Instruments (formerly Accel Instruments)



Commissioning

A. Nagler, Linac 2006
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

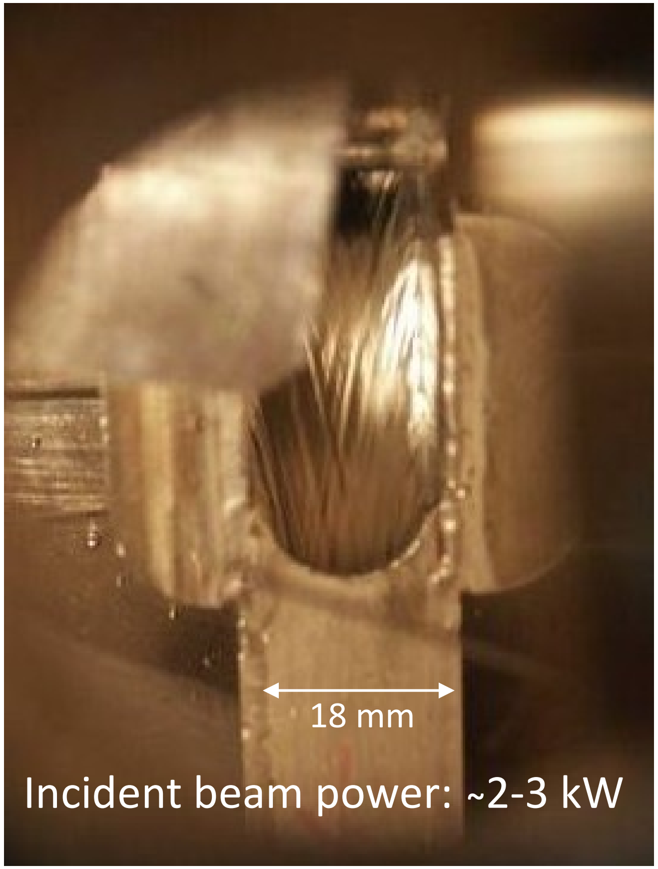
Operation

D. Berkovits, Linac 2012
L. Weissman, RuPAC 2012
A. Kreisel, Linac 2014
L. Weissman, WAO 2014
L. Weissman, JINST 2014
L. Weissman, JINST 2015

	MeV	mA
p	4	1 CW
p	2	2 CW
d	5.6	1 (10%)
d	2.6	1.1 CW

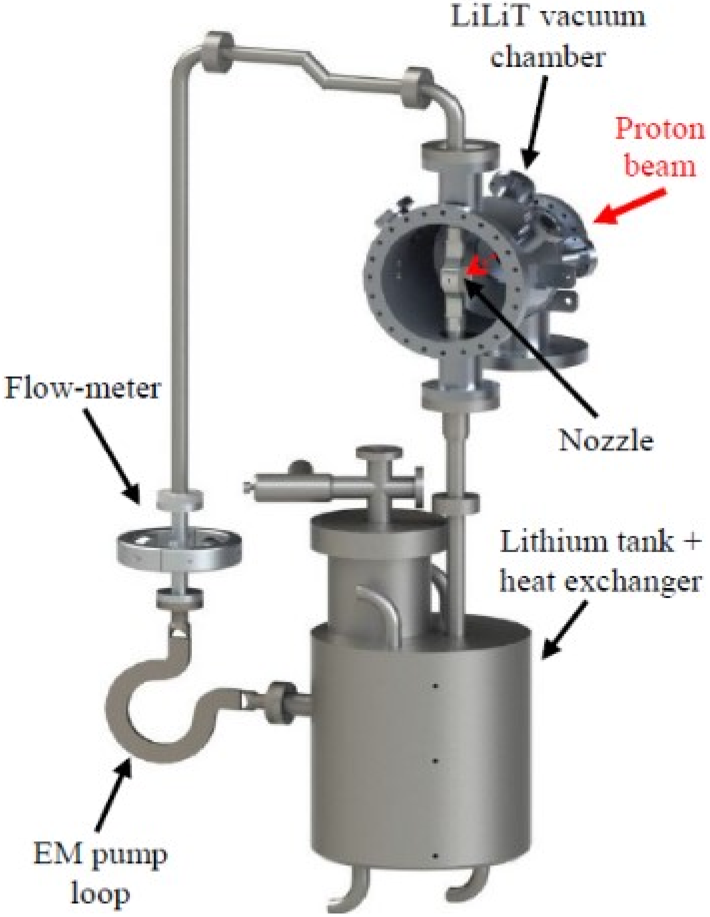
… see therein several contributions regarding components design, upgrades and developments

Liquid Lithium Target (LiLiT) overview



peak power areal density: ~ 2.5 kW/cm^2
peak power volume density protons: ~ 0.5 MW/cm^3
peak power volume density electrons: ~ 2 MW/cm^3

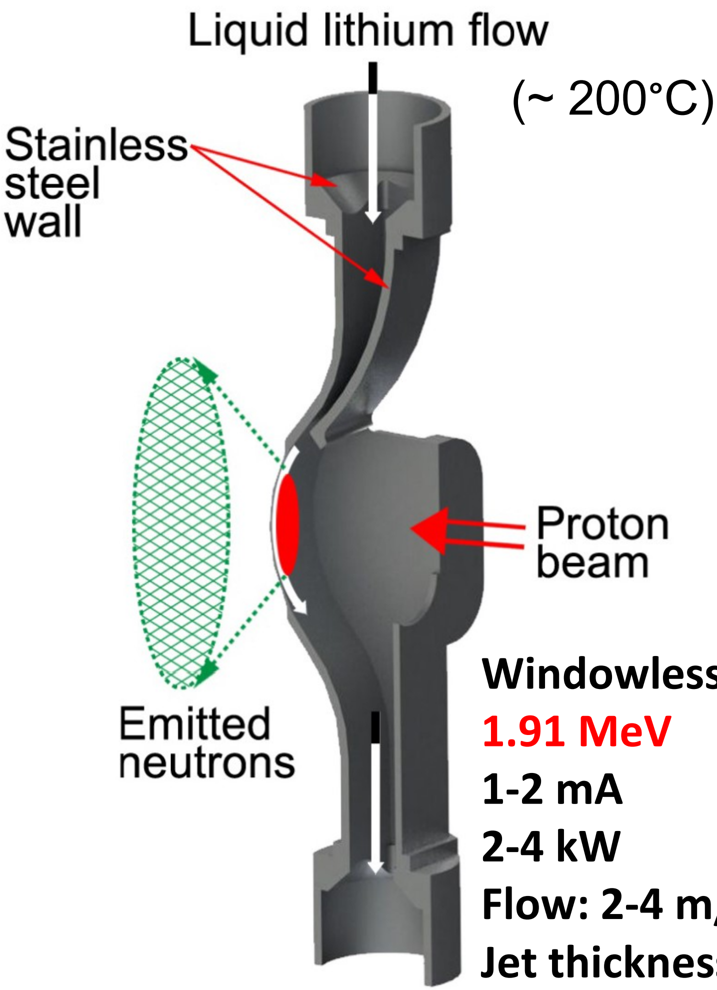
I_p = 1-2 mA, 1.91 MeV
$I_n < 3 - 5 \times 10^{10}$ n/s



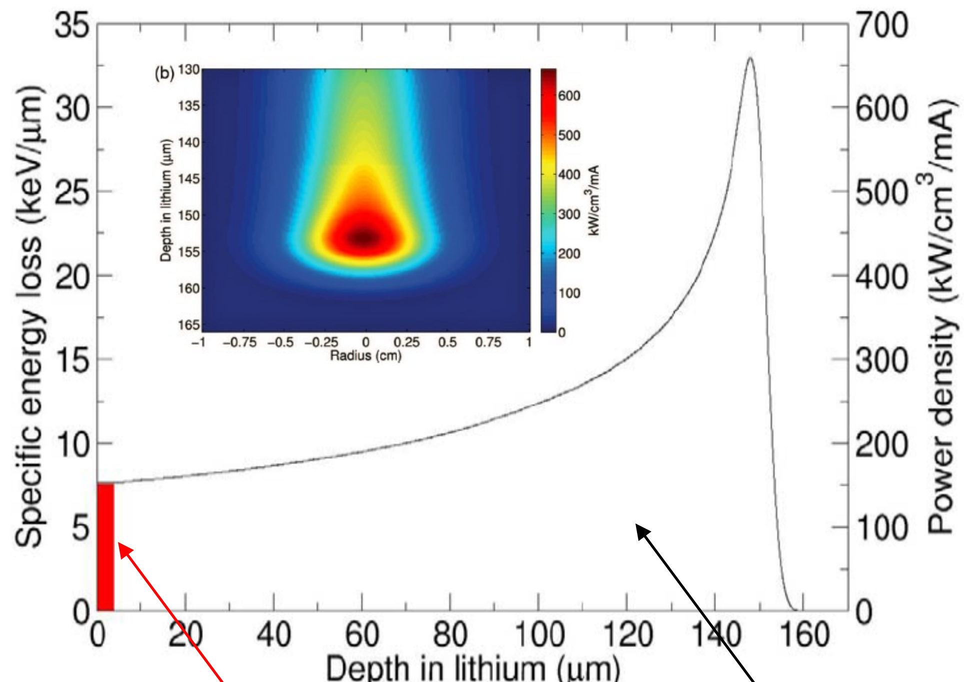
S. Halfon et al., RSI 84, 123507 (2013)
S. Halfon et al., RSI 85, 056105 (2014)
S. Halfon et al., ARI 106, 57 (2015)

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

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



Windowless
1.91 MeV
1-2 mA
2-4 kW
Flow: 2-4 m/s
Jet thickness: 1.5 mm

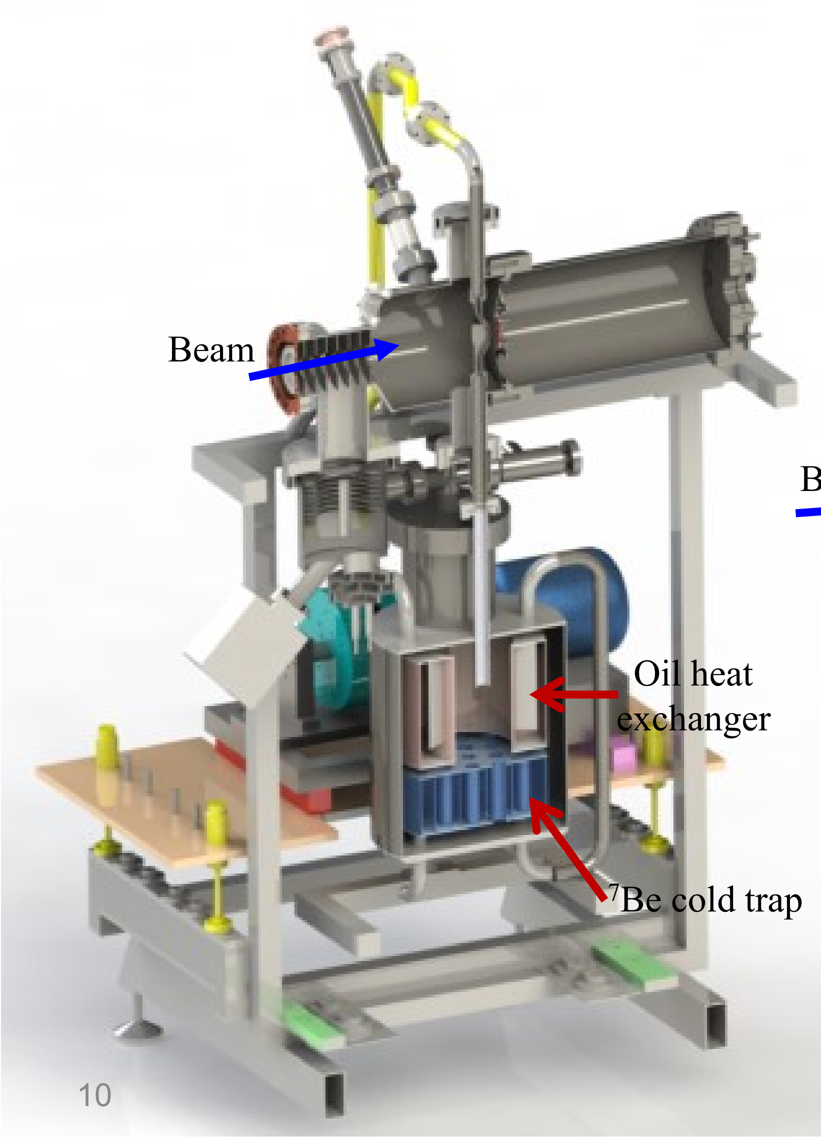


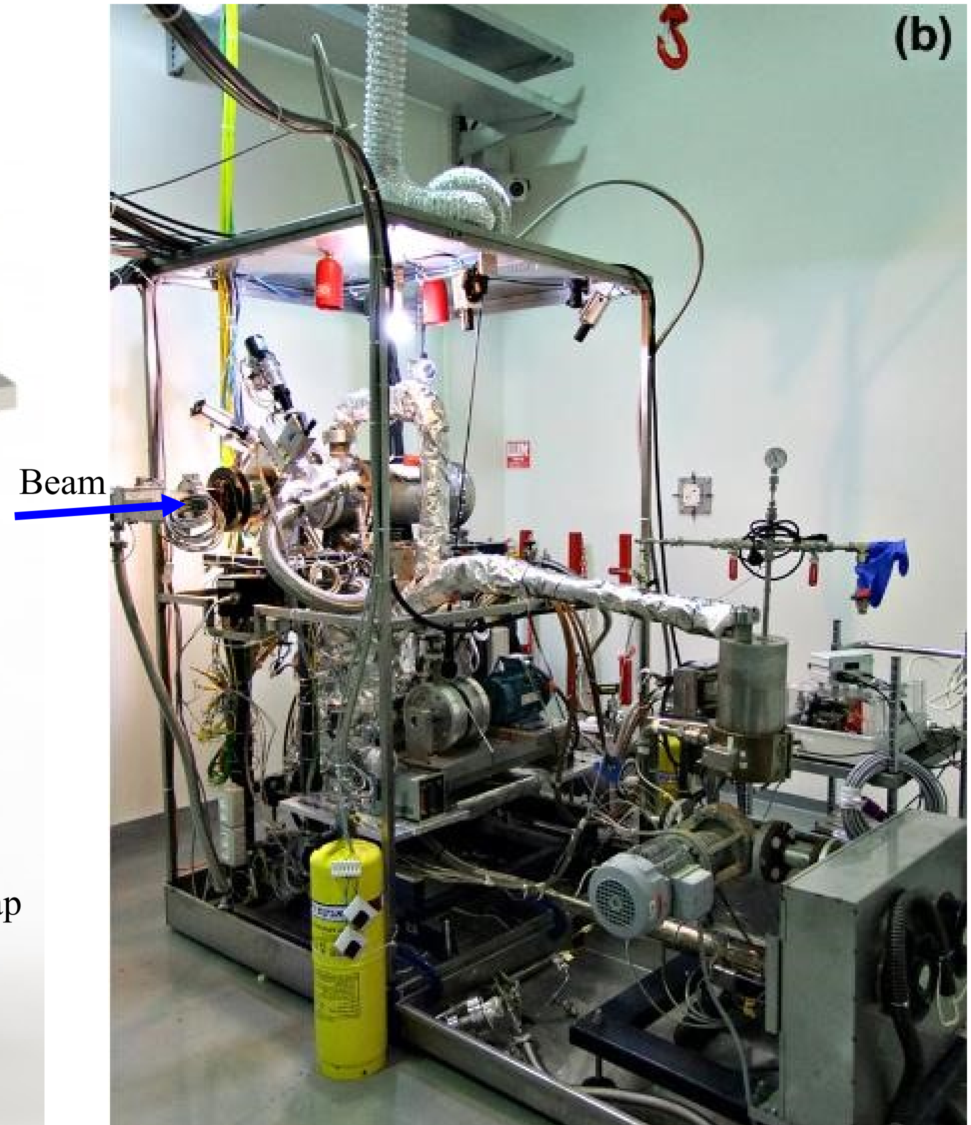
neutron production
$E_p = E_{p\_thresh}$ = 1.880 MeV

power dissipation by fast flow

Li flow: both neutron producing target and power dump

LiLiT at SARAF beam corridor (1/3)





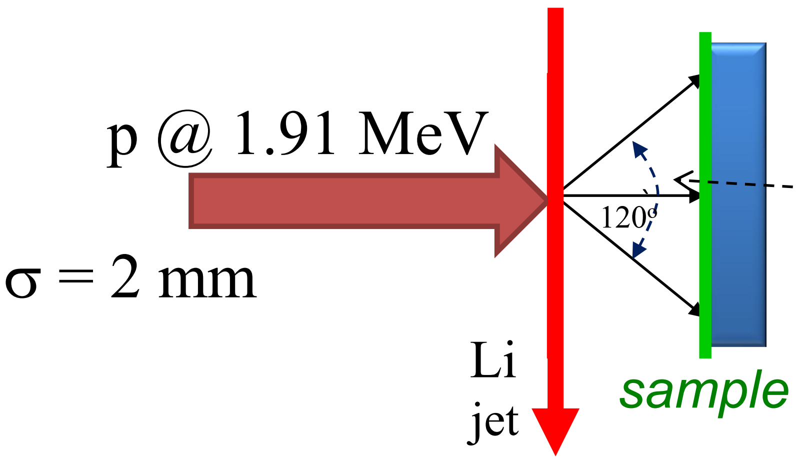
LiLiT at SARAF beam corridor (2/3)

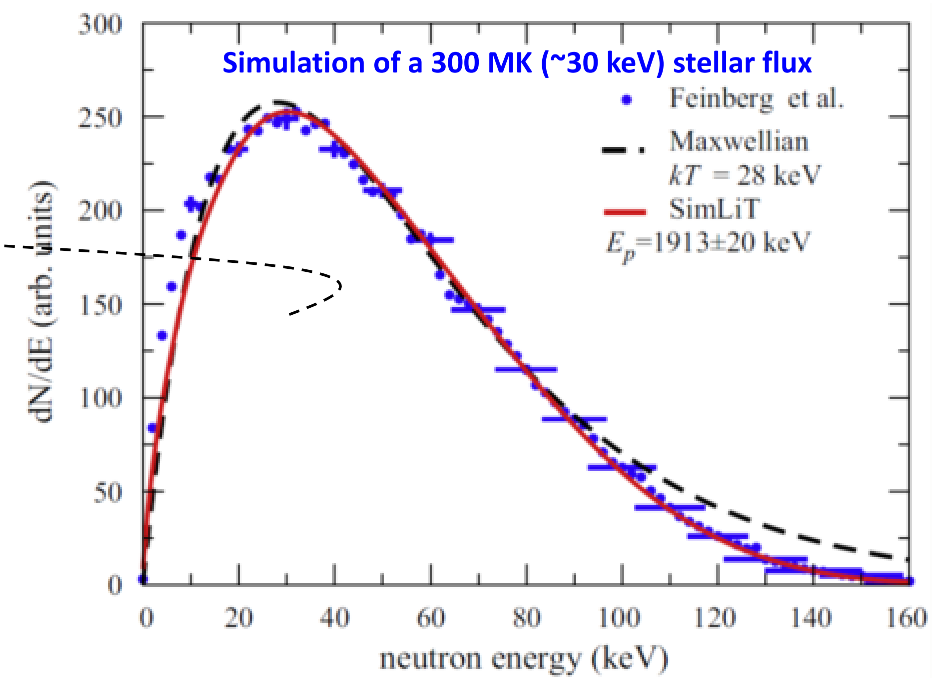
Beam

The original motivation for LiLiT - mimicking s-process nucleosynthesis

$^{7}Li\,(p,n)\,^{7}Be$, $E_p = 1.91$ MeV
($Q = -1.644$ MeV, $E_{th} = 1.880$ MeV)

W. Ratynski and F. Kaeppeler, Karlsruhe
PRC (1988), I~50 μA
Maxwellian Averaged Cross Sections (MACS)



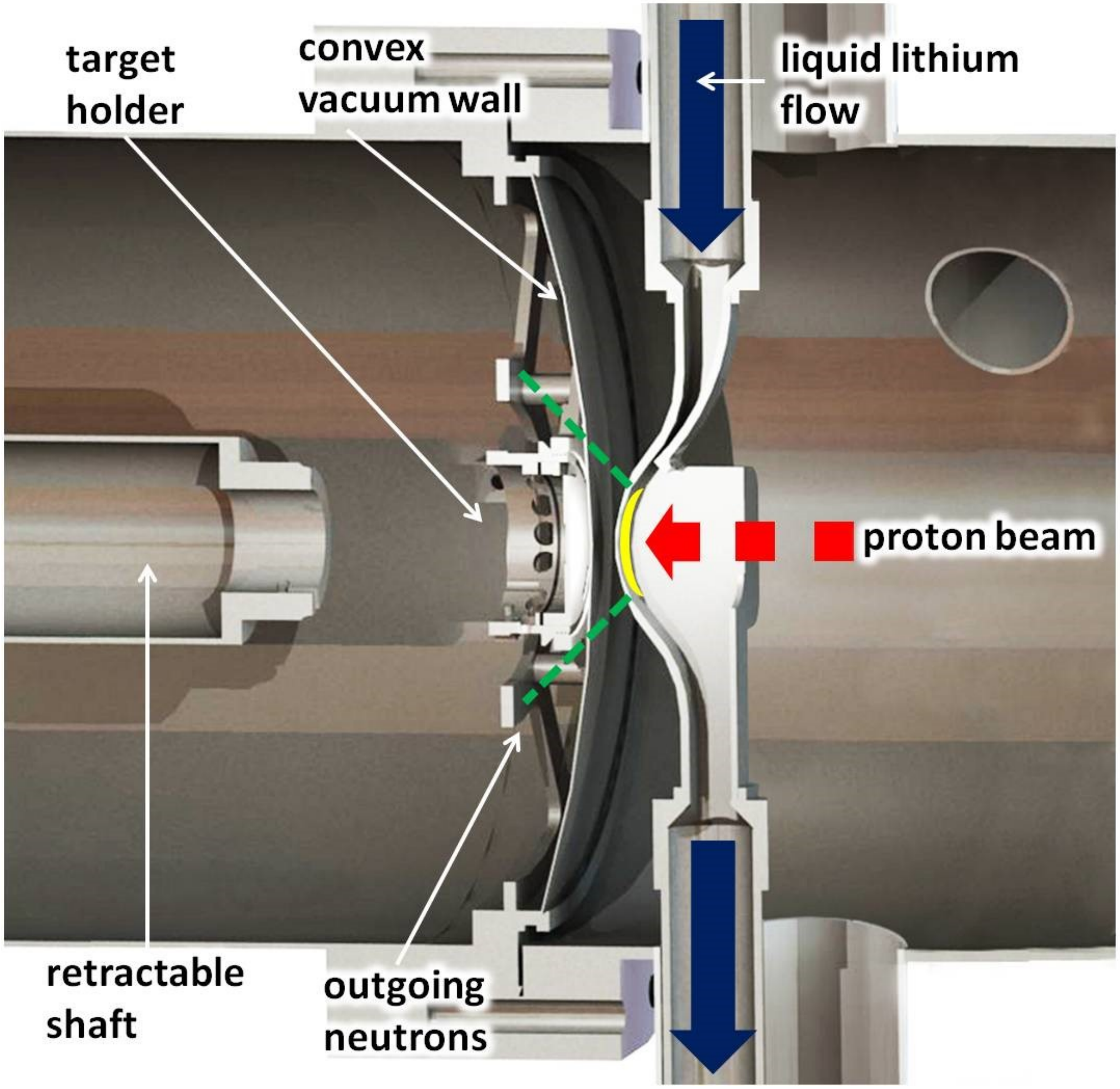


solid target: $I_p < 100\ \mu A$
$I_n < 1 \times 10^9$ n/s

Liquid target: $I_p \sim 2$ mA
$I_n \sim 5 \times 10^{10}$ n/s

G. Feinberg *et. al.*, Nucl. Phys. A 2009, Nucl. Phys. A 2012, Phys. Rev. C 2012
M. Friedman *et. al.*, NIM A 2013
M. Paul *et al.*, NIC *PoS* 2014
M. Tessler *et al.*, Physics Lett. B 2015

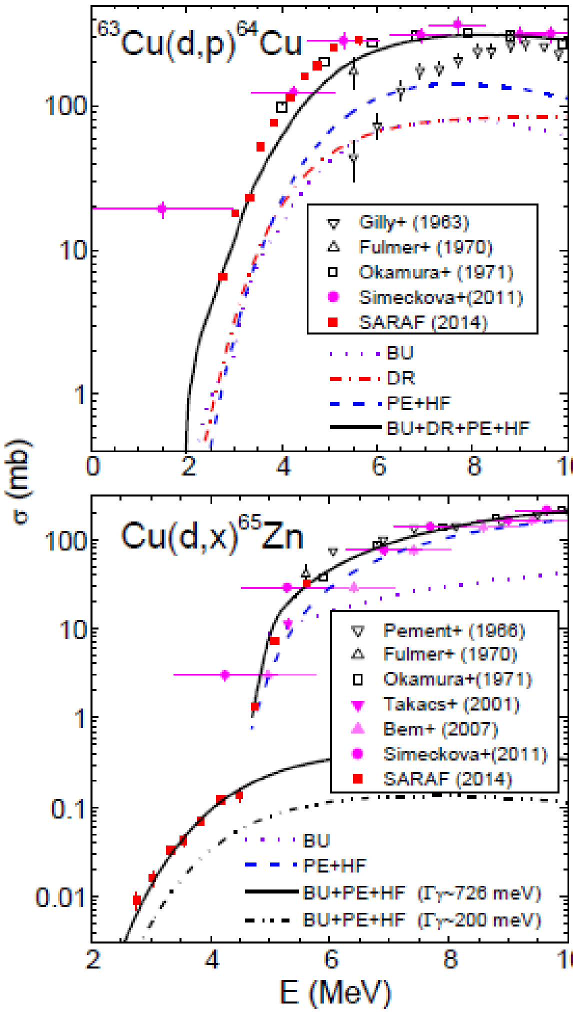
LiLiT Experimental setup



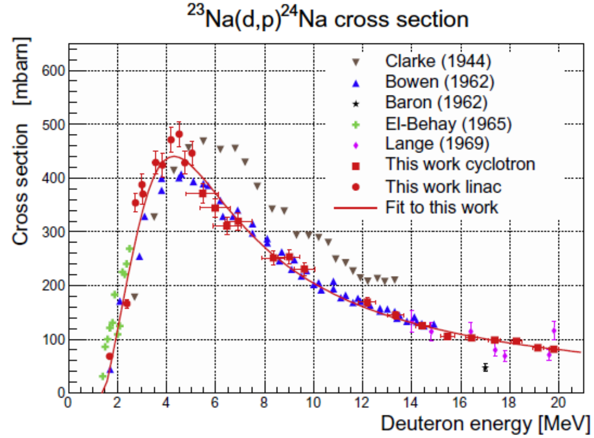
SARAF-LiLiT nucleosynthesis research program

	Target	Detection technique	Collaboration HU-SARAF-	status
Benchmark and higher precision	^{nat}Zr(n,γ)	γ spec	-	M. Tessler et al., PLB 751 (2015) 418
	^{nat}Ce(n,γ)	γ spec	-	Under analysis
	^{23}Na^{35,37}Cl(n,γ)	γ spec + AMS	Goethe U Frankfurt – Dresden-Rossendorf-ANU	S. Pavetich et al., NIC 2016
	^{92}Zr(n,γ)	AMS	ANU-ANL	Under analysis
	^{208}Pb(n,γ)^{209}Pb	γ spec	U. Seville	L. Weissman et al., PRC 96 015802 (2017)
	^{209}Bi(n,γ)^{210g}Bi	α + β + γ spec	JRC IRMM Geel	A. Shor et al., PRC 96 055805 (2017)
Noble gases	^{nat}Kr(n,γ)	γ + β spec + MOT atom trap	ANL - Goethe U - U. Bern	Under analysis
	^{36,38,40}Ar(n,γ)	AMS + γ spec	ANL - Goethe U	M. Tessler et al., submitted to PRL
Radioactive targets	^{7}Be(n,α)	CR-39	U Conn - PSI - CERN	M. Gai et al., Preliminary results
	^{171}Tm(n,γ)	γ spec	U. Seville-PSI-CERN	C. Guerrero et al., submitted to PRL
	^{147}Pm(n,γ)	γ spec	U. Seville-PSI-CERN	C. Guerrero, ND2016

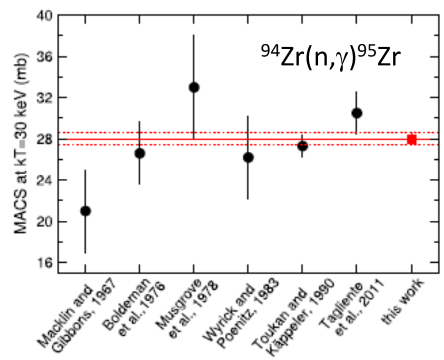
SARAF-I selected published measurements

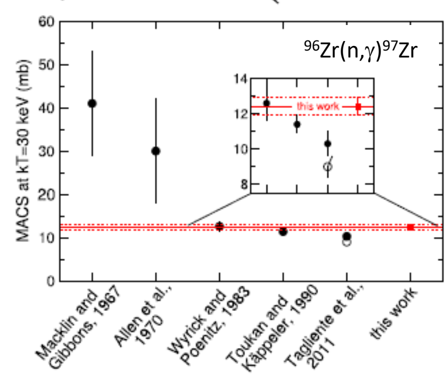


Plots: I. Mardor et al., arXiv 1801.06493v2 (2018)
Data: L. Weismann et al., NIMB 342 7 (2015)

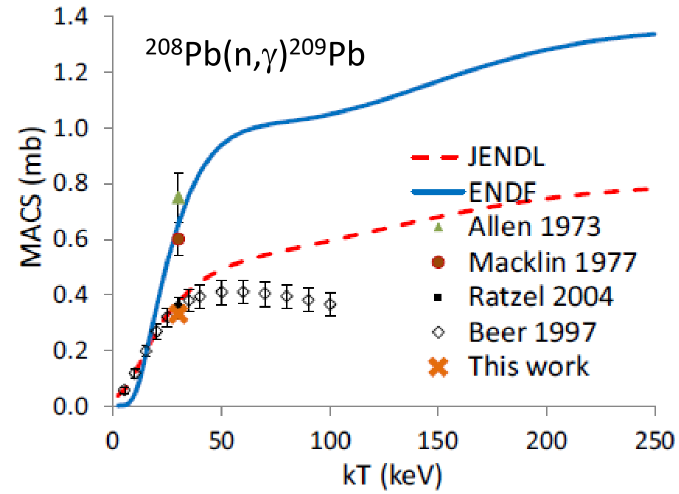


T. Hirsh et al., NIMB 362 29 (2015)

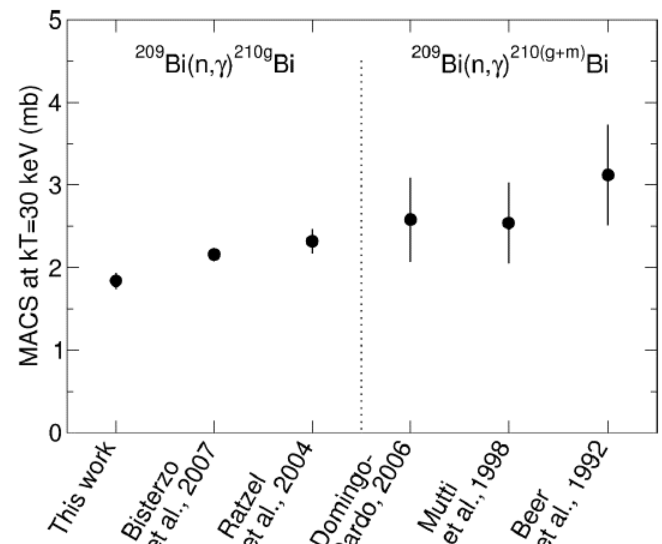




M. Tessler et al., PLB 751 418 (2015)



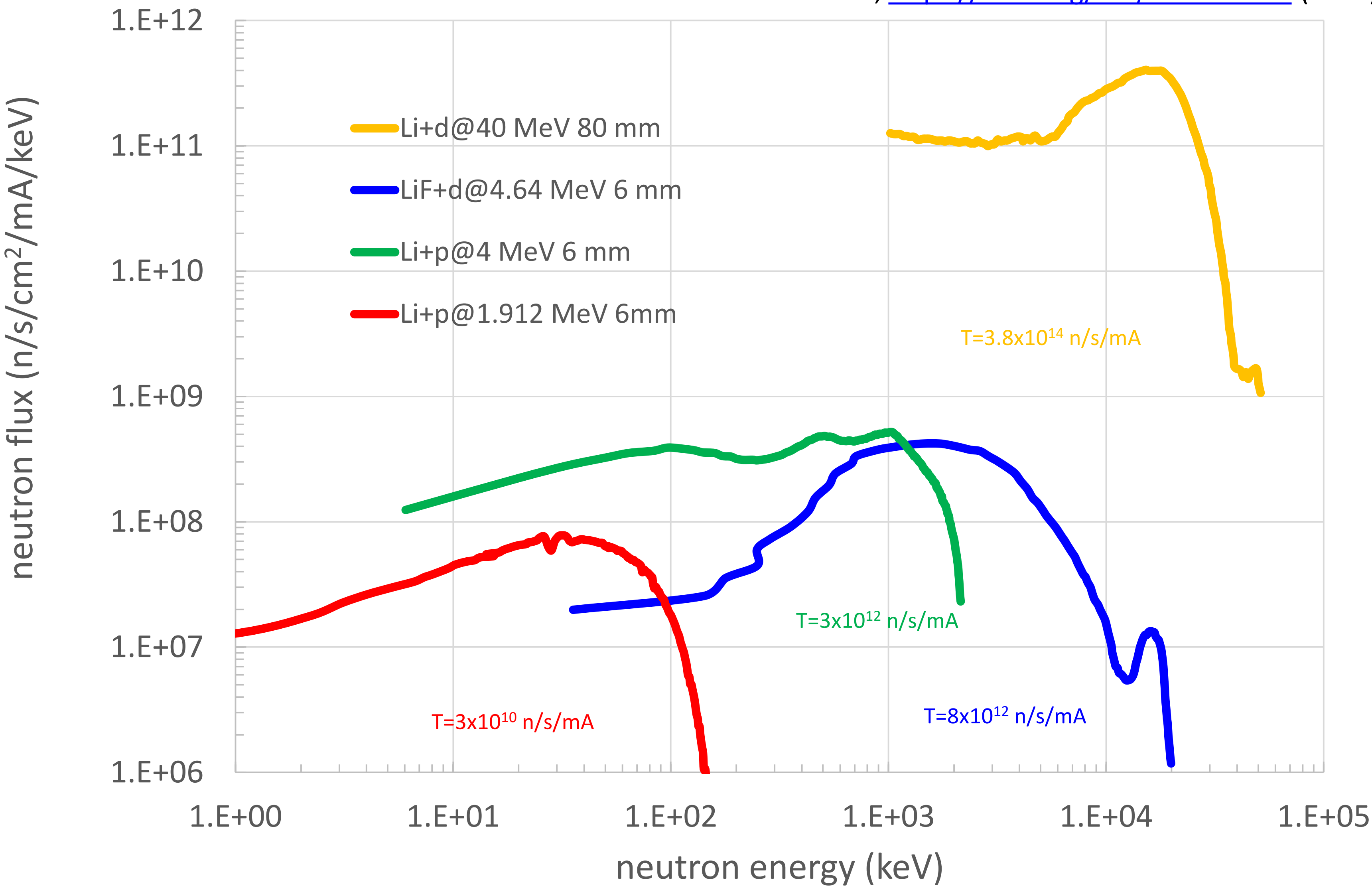
L. Weismann et al., PRC 96 015802 (2017)



A. Shor et al., PRC 96 015802 (2017)

Neutron θ=0° flux at SARAF I and II

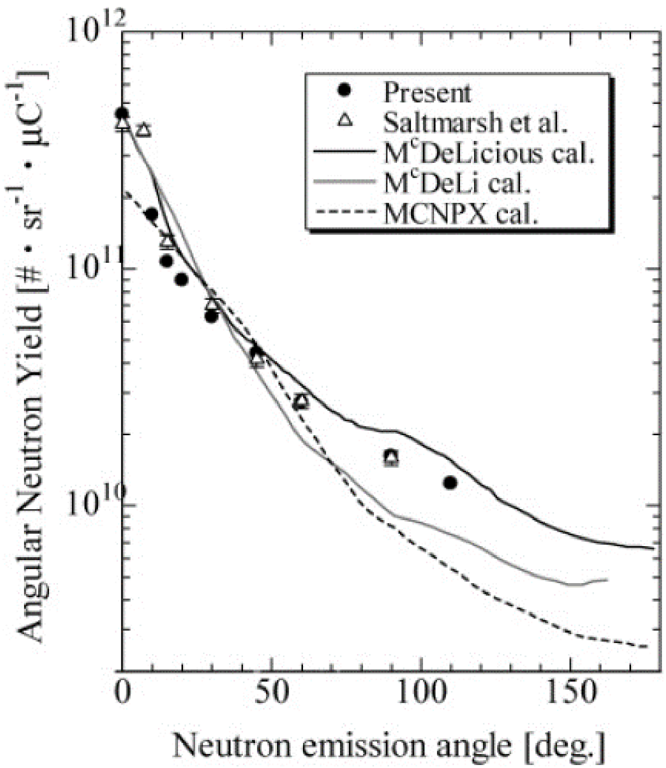
I. Mardor et al., https://arxiv.org/abs/1801.06493 (2018)

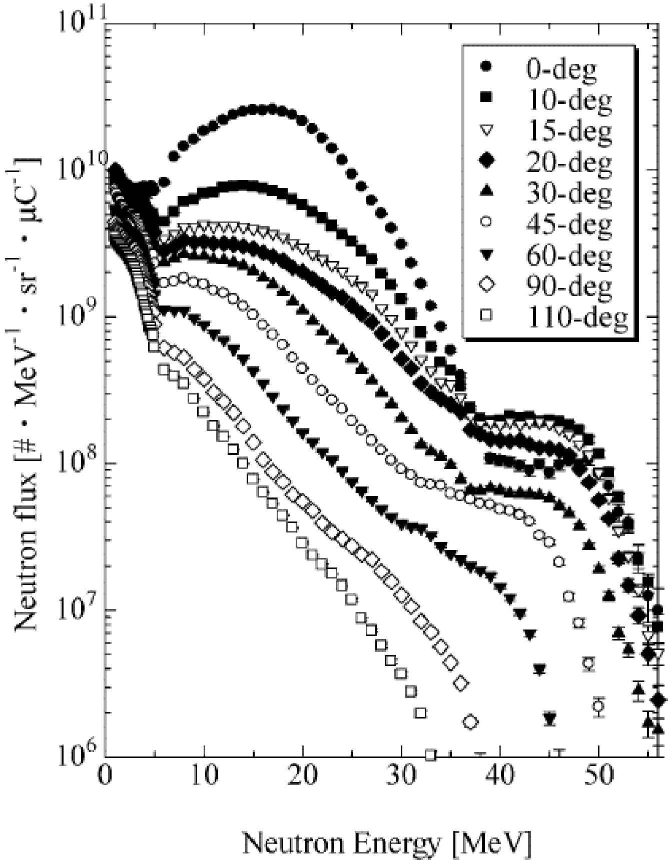


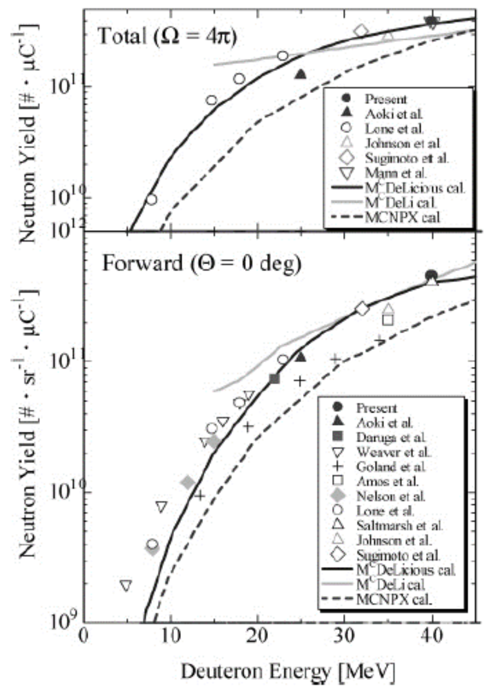
M. Tessler PLB 2015 A. Kreisel SNRC 2013

T. Hirsh 2012 (in I. Mardor & D. Berkovits, NPN 2015) T. Hirsh 2012 (in D. Berkovits, LINAC 2012)

SARAF II neutron source: Li(d,xn) at E_d = 40 MeV



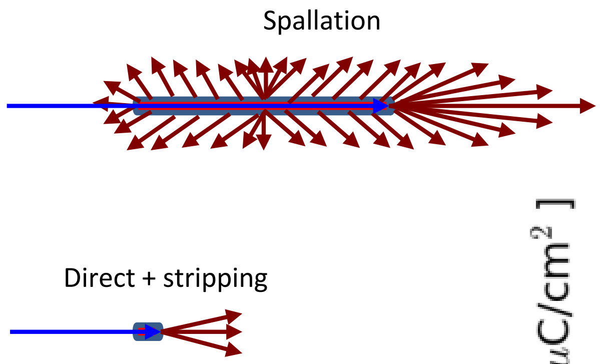


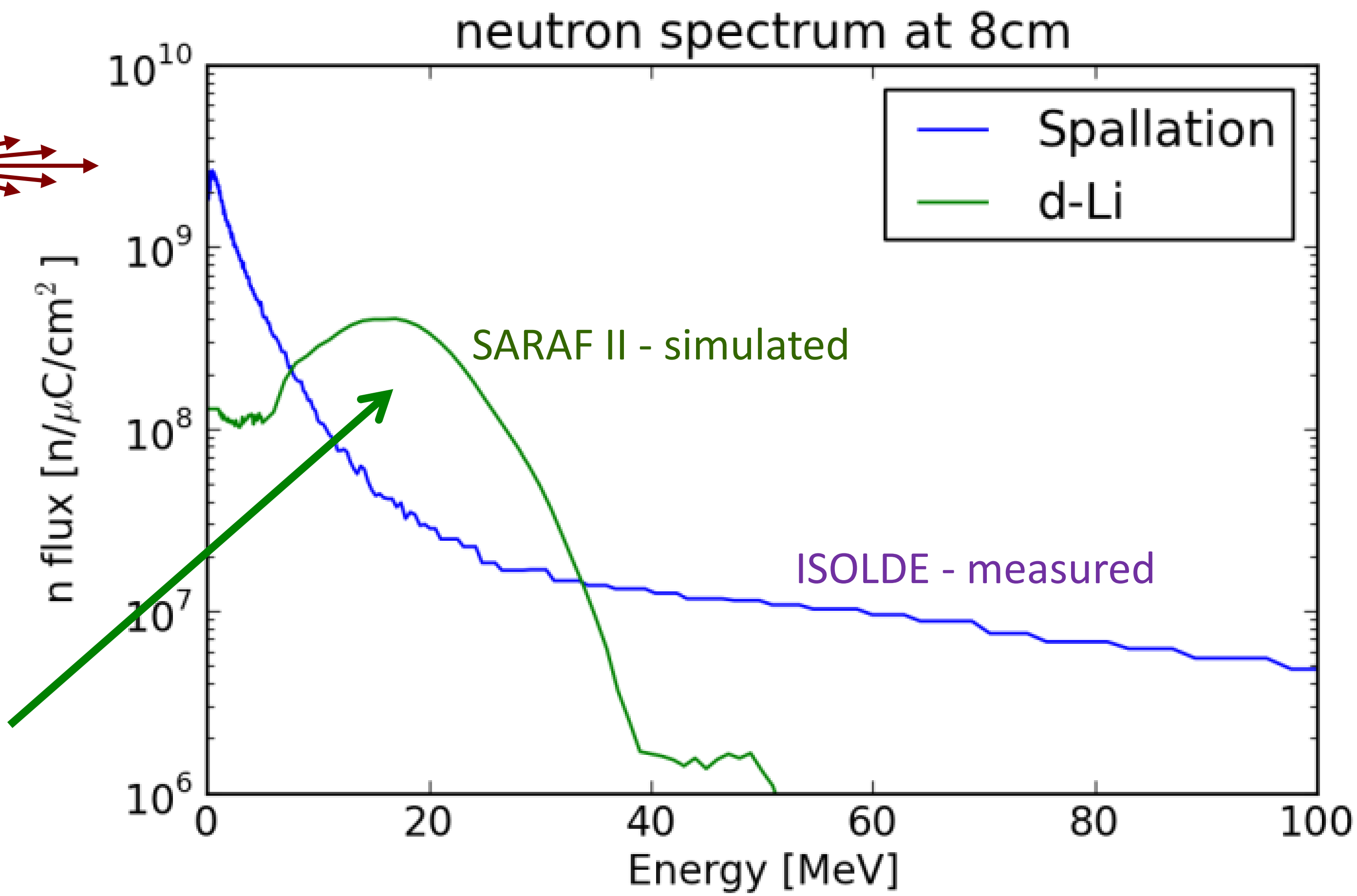


M. Hagiwara et al., Fus. Sci. Tech. 48,3, 2005.

Spallation vs. stripping neutron spectra

40 MeV d-Li vs. 1400 MeV p-W, 0° spectra, 8 cm downstream the primary target





Area optimal for
(n,α) (n,p) (n,2n)
(n,f)

T. Stora et al., EPL, 98, 32001 (2012)

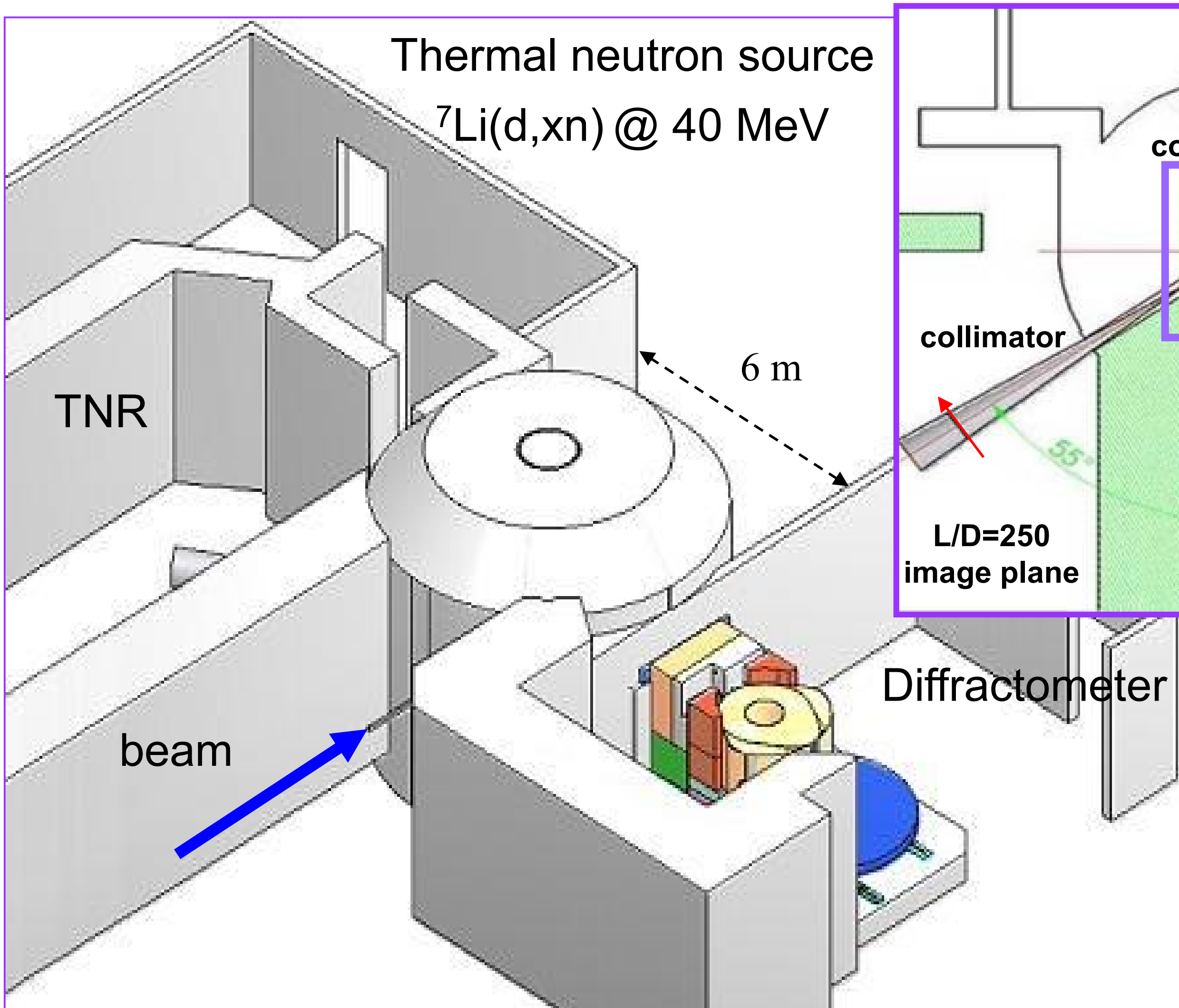
T. Hirsh, WIS PhD Thesis 2012
D. Berkovits *et al.* LINAC 2012
I. Mardor *et al.,* NPN 2015, PoS 2017

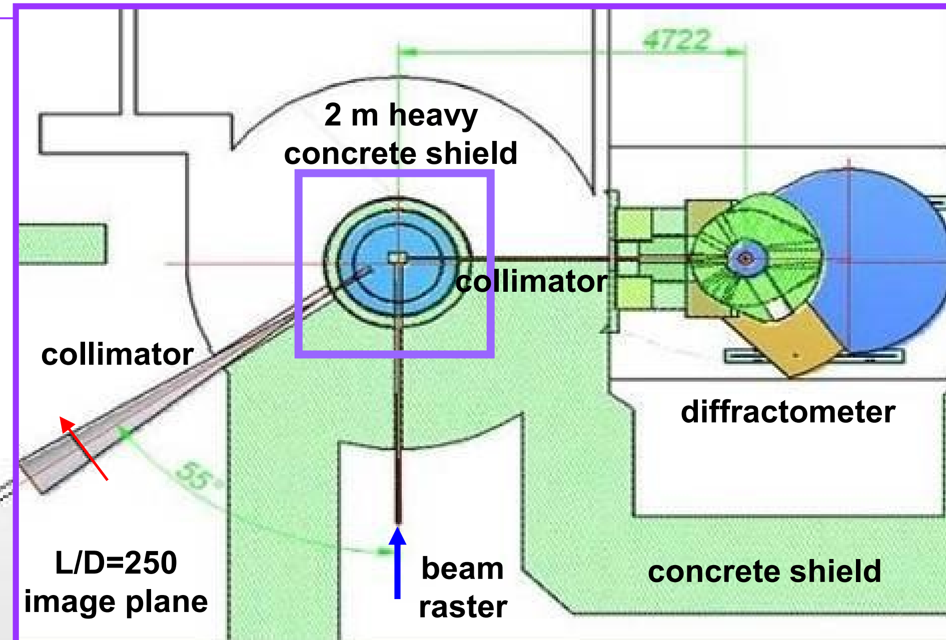
The Science at SARAF (Phases I, II)

- **Searches for Beyond Standard Model Physics ($a_{\beta\nu}$ of ^{6}He, ^{23}Ne, etc.)**
- **Nuclear Astrophysics (s-process cross sections, r-process input)** ←
- **Exploration of Exotic Nuclei (low z and fission products)**
- **High Energy Neutron Induced Cross Sections (up to E_n ~ 50 MeV)**
- **Neutron Based Material Research (Gen-IV, transmutation, fusion)**
- **Neutron Based Therapy (Boron neutron capture therapy)**
- **Development of New Radiopharmaceuticals (Diagnostics and Therapy)**
- **Accelerator based neutron imaging (thermal and high energy)** ←
- **And maybe also – neutrino physics (well-defined, pulsed, high energy, n and anti-n)**

- I. Mardor & D. Berkovits, *The Soreq Applied Research Accelerator Facility (SARAF)*, Nuclear Physics News, 25:1, 16-22 (2015)
- I. Mardor et al., *Research Programs and Plans at the Soreq Applied Research Accelerator Facility - SARAF*, PoS (INPC2016) 109 (2017)
- I. Mardor et al., "The Soreq Applied Research Accelerator Facility (SARAF) – Overview, Research Programs and Future Plans", https://arxiv.org/abs/1801.06493 (2018)

SARAF Phase II Thermal neutron source conceptual system design



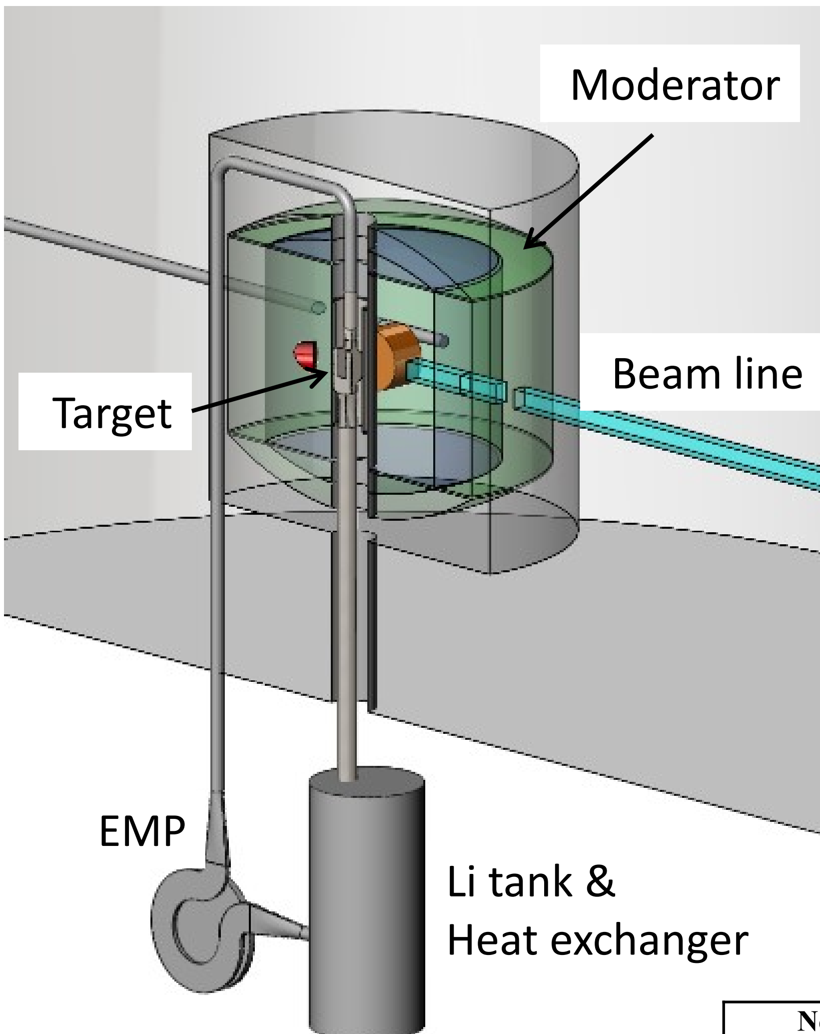


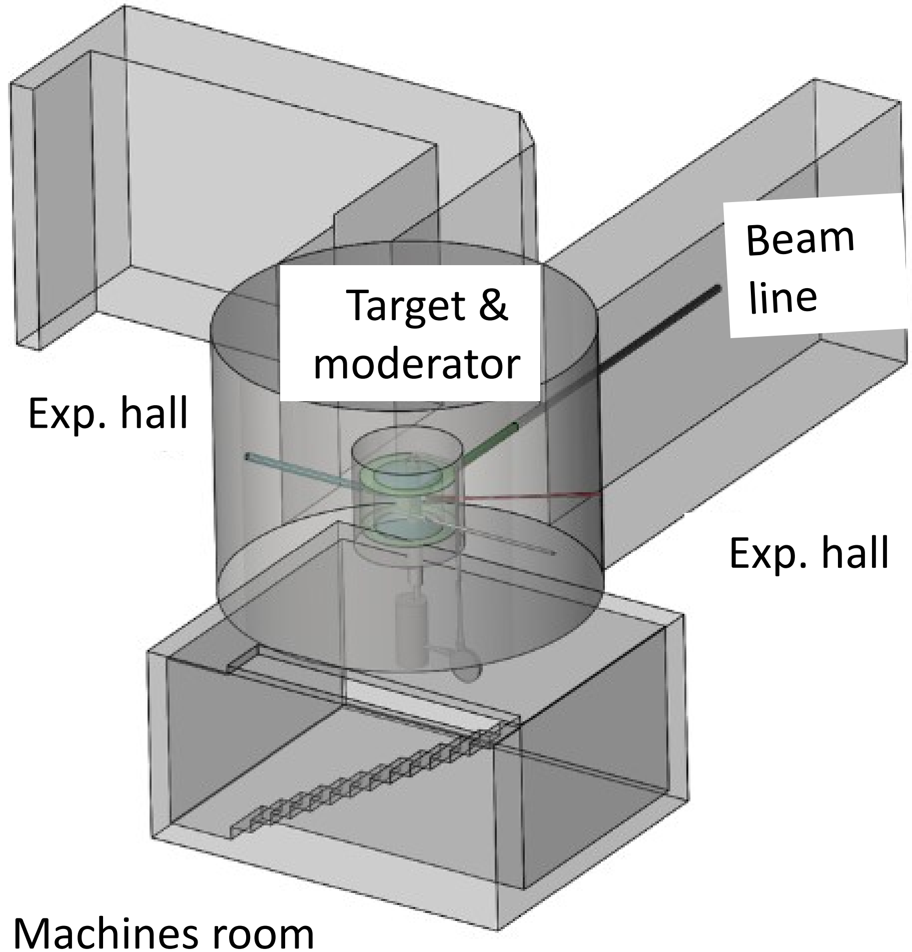
- Soreq 5MW reactor – **~10^{17} n/sec**
- SARAF Phase II - **~10^{15} n/sec**

But:

- Because of **small** source of **fast** neutrons at SARAF Phase II,
- Thermal n flux **in the image plane** for both cases is similar;
- **~10^6 n/sec/cm^2 (~4-5 m)**

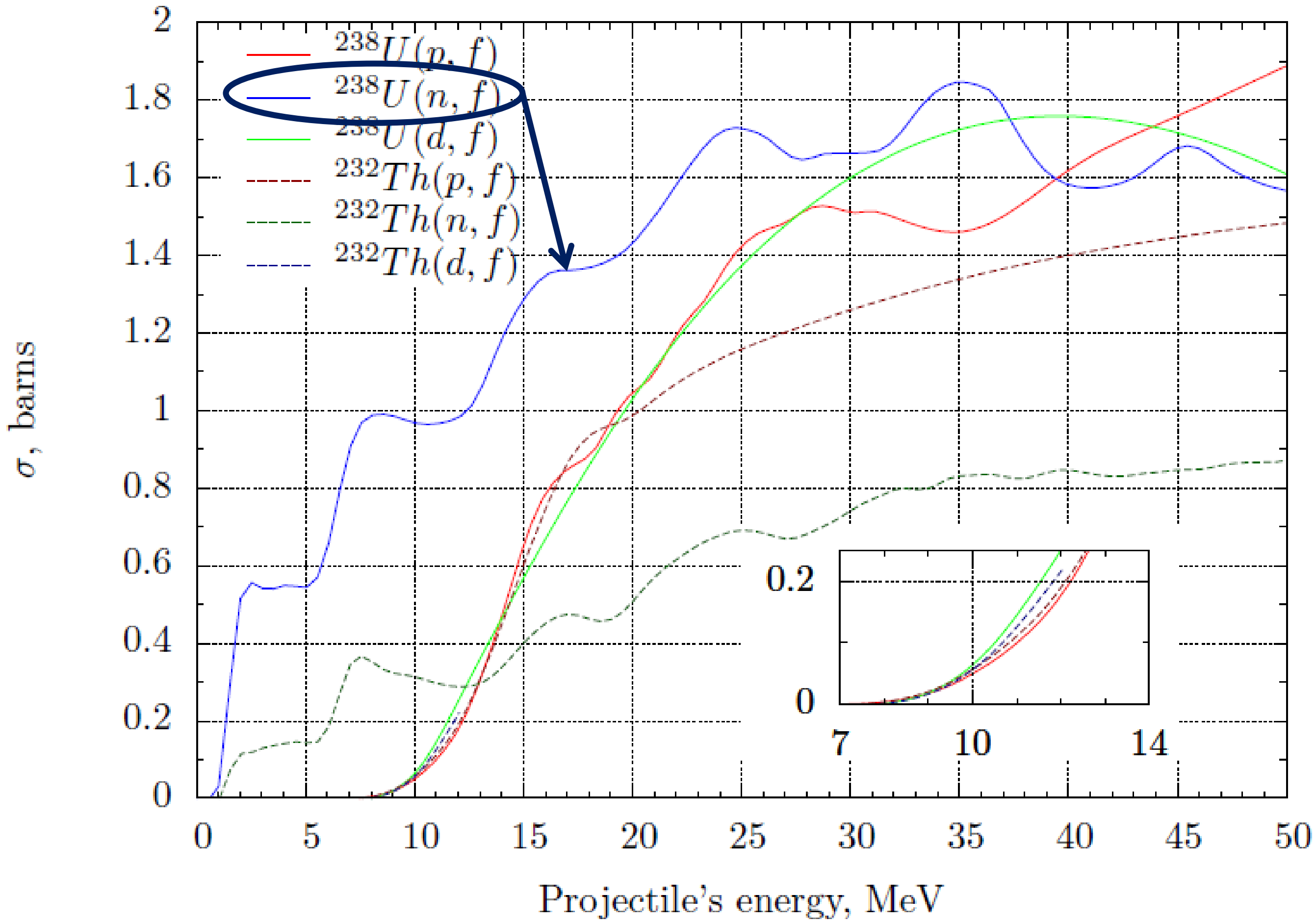
SARAF II Li jet target system layout





Neutron producing target	Moderator	Reflector	multiplier	Shield
Liquid lithium jet- 2.5 cm thick	Heavy water tank, 1.2 m dia.	Surrounding light water/ PE, 20 cm thick	Be 25 cm dia, 15 cm thick.	2-2.5 cm concrete

Fission fragments research potential at SARAF



- n induced fission cross section at ~10 MeV is similar to p, d at ~20 MeV and higher
- Advantage of neutron irradiation is the production of n-richer fission fragments
- E_n ~ 10 MeV is optimal in terms of n-rich fission fragments versus prompt neutrons

Dmitry Gorelov, PhD thesis, U. Jyvaskyla, December 2015; D. Gorelov et al., NIM B376, 46 (2016)

JYFL irradiation target for n-induced fission

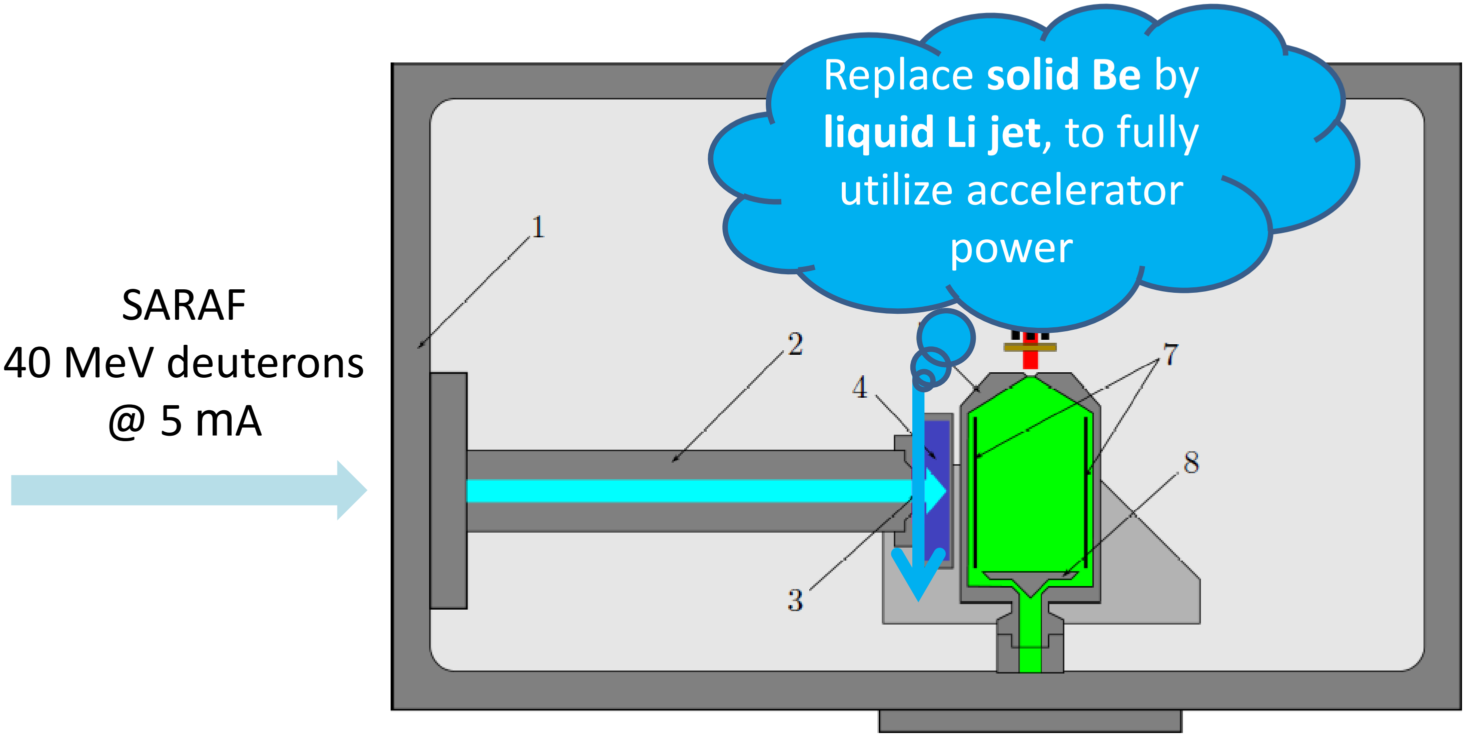


Figure 2.14: The idea of the project. 1 — target chamber; 2 — beam line; 3 — beryllium (Be) target; 4 — cooling water; 5 — fission ion guide; 6 — sextupole ion guide (SPIG); 7 — fissile targets; 8 — gas diffuser.

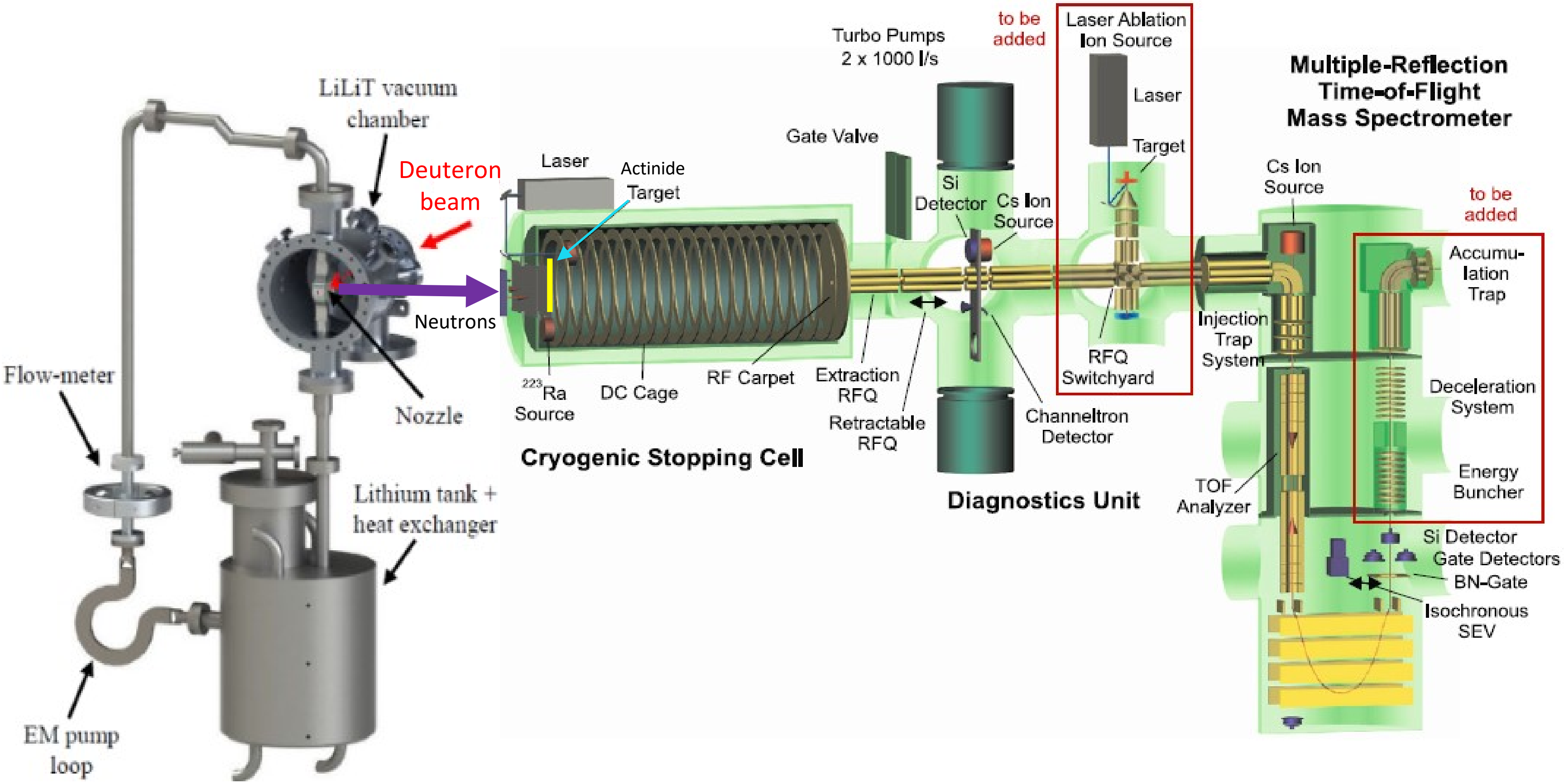
For SARAF high power beam, we most probably require a stopping cell a la FRS CSC:

- Faster extraction times, enabling reach to more exotic isotopes
- Higher overall stopping efficiency

Dmitry Gorelov, PhD thesis, U. Jyvaskyla, December 2015; D. Gorelov et al., NIM B376, 46 (2016)

SARAF-II n-rich facility layout

The combination of SARAF high power accelerator, LiLiT and FRS Ion Catcher
may bring SARAF to be competitive with world planned facilities of n-rich exotic isotopes

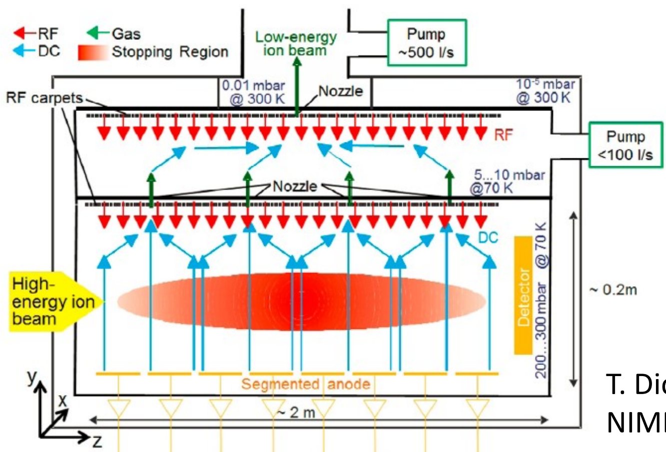


S. Halfon et al., RSI 84, 123507 (2013)

W. R. Plass et al., NIM B 317 457 (2013)

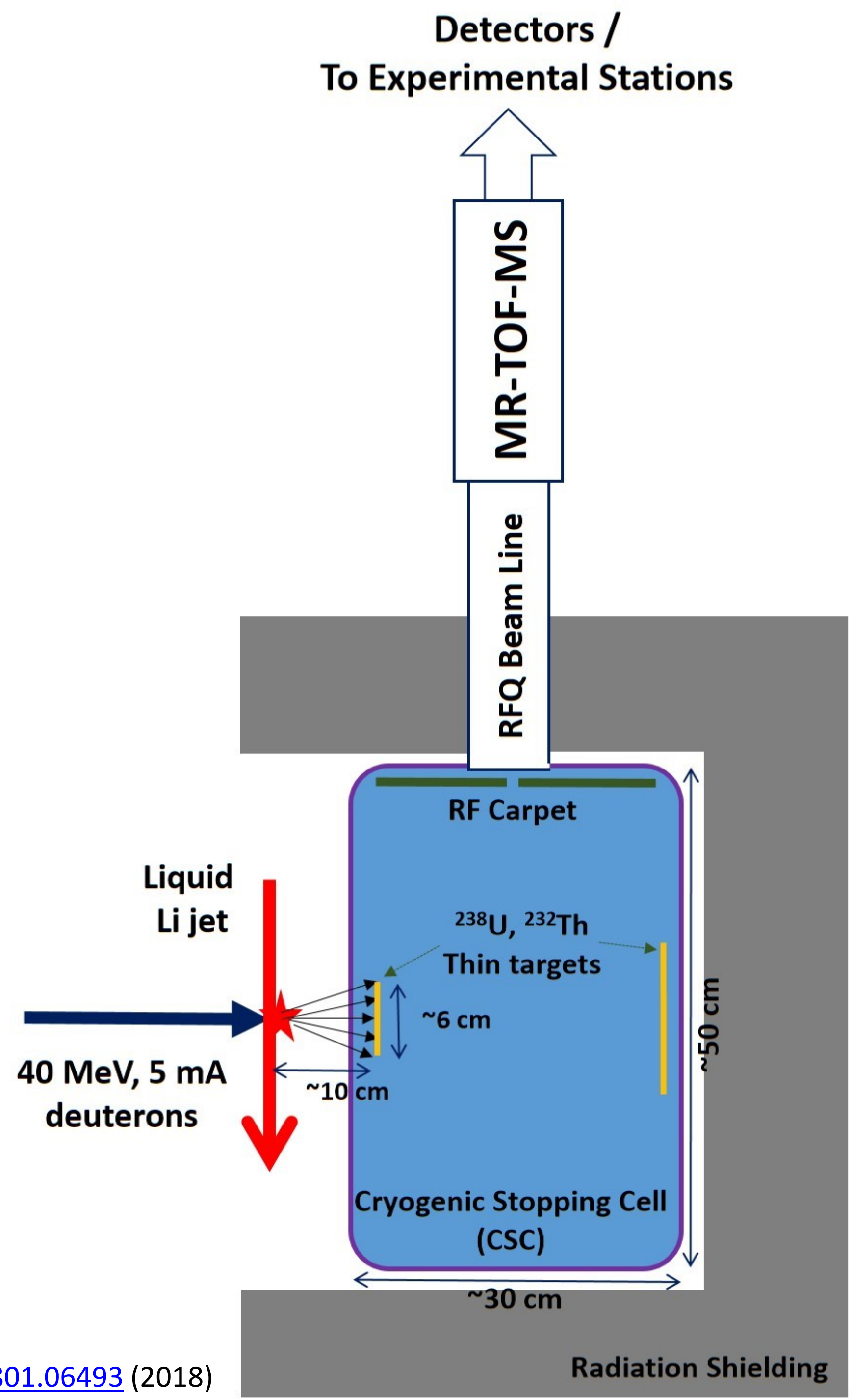
Conceptual layout for the SARAF Ion Catcher

- Avoid neutron irradiation of instrumentation
- Use next generation CSC design for FAIR:



T. Dickel et al., NIMB 376 216 (2016)

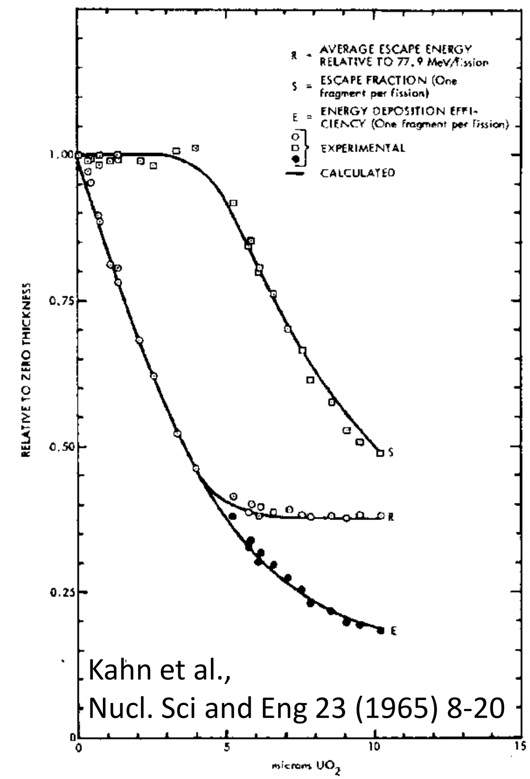
- He buffer gas density: ~0.2 mg/cm^3
- Fission product (FP) range in CSC: ~10 cm
- Almost full stopping of FPs in CSC
- CSC Extraction efficiency: 60%
- RFQ Transmission: 90%
- MR-TOF-MS efficiency: 50%
- Detector efficiency / Transfer transmission to experiments: 80%
- In following estimations: 1 thin target



I. Mardor et al., https://arxiv.org/abs/1801.06493 (2018)

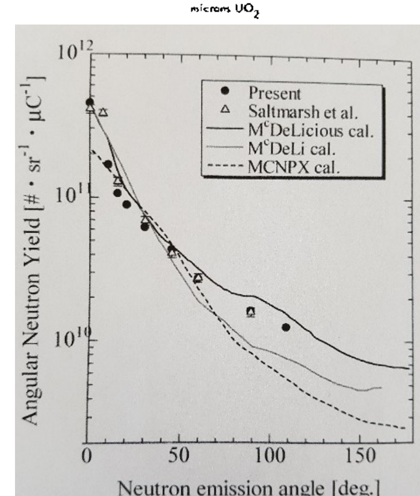
Expected fission fragment rate at SARAF

Inputs		
U target area	1.0E+01	cm^2
Distance from source	5.0E+00	cm
Solid angle	4.0E-01	sr
Corresponding opening angle	2.1E+01	deg
Accelerator current	5.0E+03	µA
Neutron yield on target	2.8E+14	n/sec
Foil thickness	1.0E+01	microns
Number of foils	1.0E+00	
Uranium density	1.9E+01	g/cm^3
Number of U atoms	4.8E+20	at
Total Uranium mass	1.9E-01	g
Foil thickness	1.9E+01	mg/cm^2
Fission cross-section	1.2E+00	barn
Fissions rate	**1.6E+11**	**fiss/sec**



Kahn et al.,
Nucl. Sci and Eng 23 (1965) 8-20

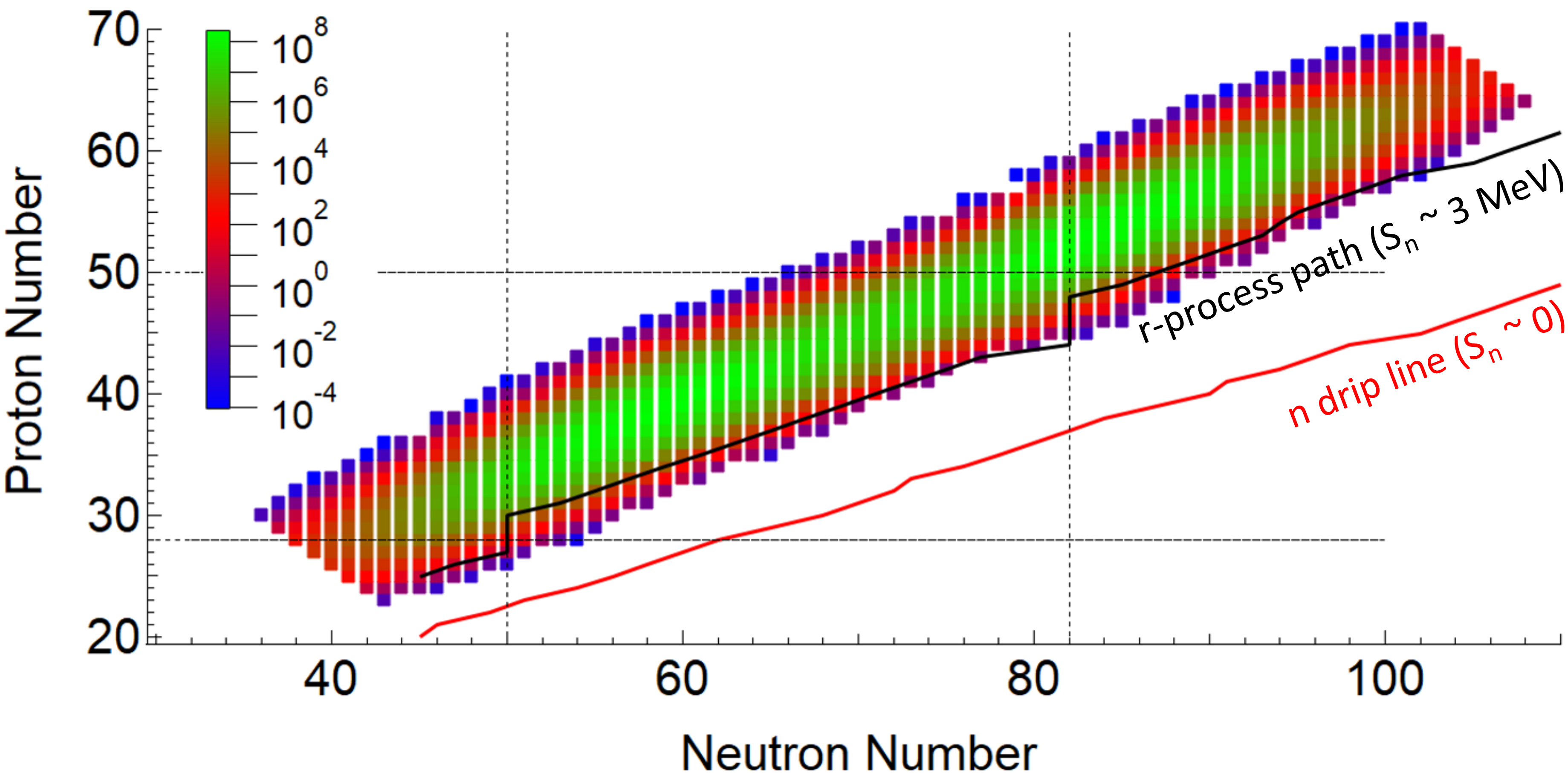
- 1.6×10^{11} Fissions inside the U target
- Setup may be improved by increasing solid angle, optimizing actinide target angle w.r.t. beam, and adding more actinide targets
- Nevertheless, next slides use above estimate



M. Hagiwara *et al. Fus. Sci. Tech.*, 48 (2005) 1320

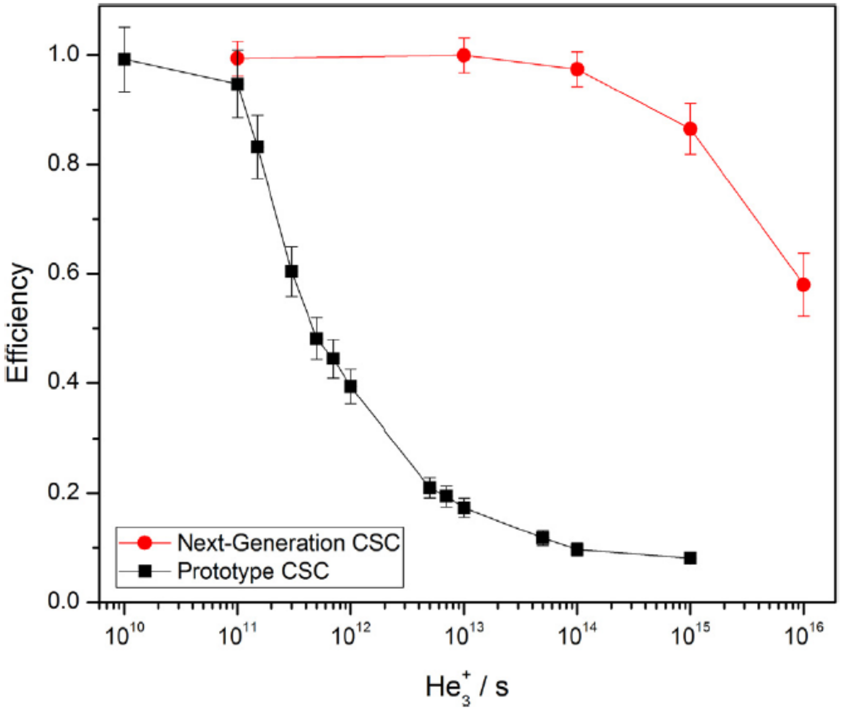
I. Mardor et al., https://arxiv.org/abs/1801.06493 (2018)

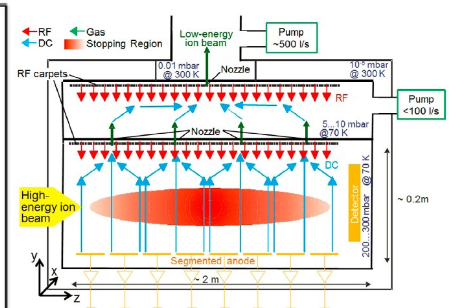
SARAF II n-rich isotope production rates

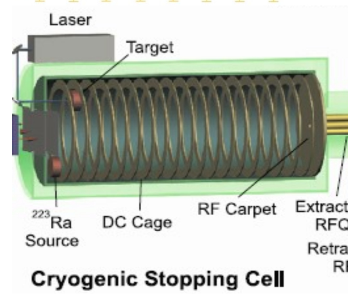


- SARAF-II isobarically separated isotopes in the experimental station, after MR-TOF-MS (isotopes/sec)
- Based on ^{238}U and ^{232}Th targets (higher yield option per fission product)
- Use E_n=14 MeV (n, fiss) cross sections (1.2 barn for ^{238}U, 0.4 barn for ^{232}Th)
- Fission yields from JENDL FPY-2011 http://wwwndc.jaea.go.jp/cgi-bin/FPYfig?iso=nU238&eng=e2
- FY's used are weighted averages of the values at E_n=14 MeV (60%) and E_n=0.5 MeV (40%)

Handling of SARAF-II high rates at an ion catcher







- ~40 eV → 1 He-e⁻ pair
- ~100 MeV / FP → ~2×10^6 He-e⁻ pairs / FP
- ~10^{10} FP/sec in buffer gas → ~2×10^{16} He-e⁻ pairs/sec
- ~60% extraction efficiency for LEB design
- Dedicated design for SARAF CSC could yield higher efficiency (also for higher rates)

Do not need/want to measure all FPs at once:

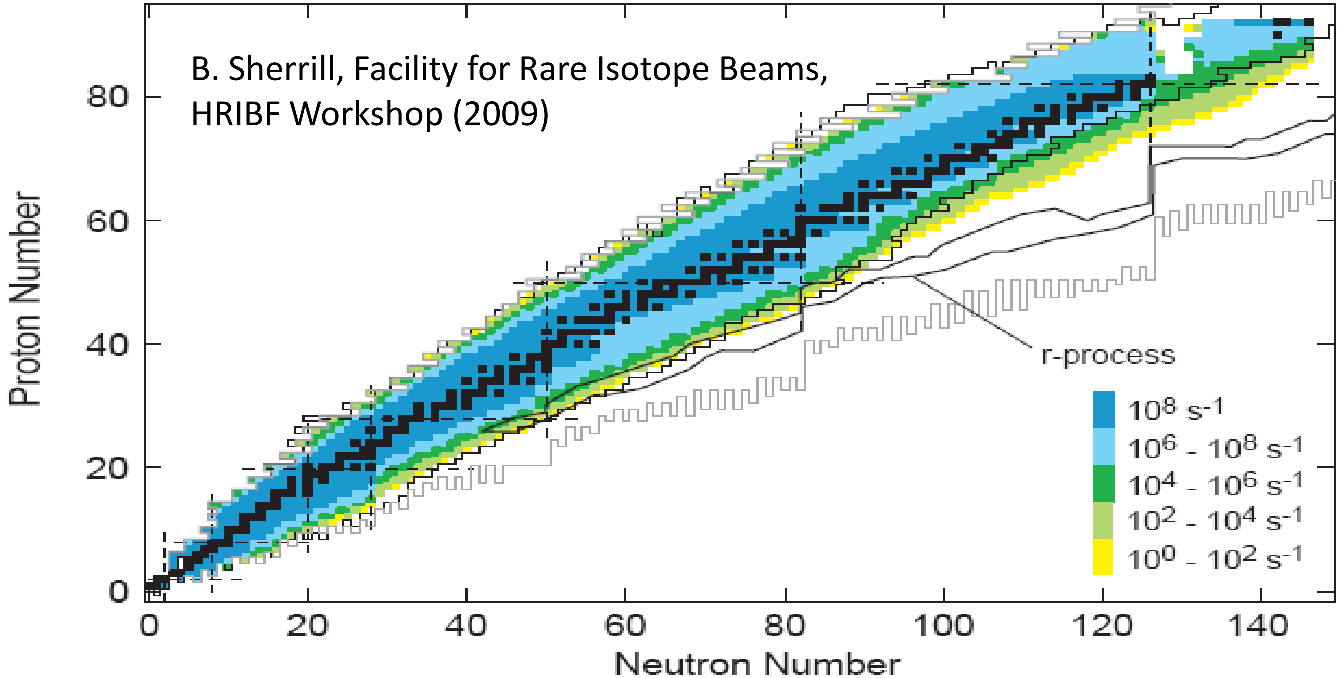
- Degraders around actinide targets will suppress heavier FPs
- Lower buffer gas pressure will suppress lighter FPs (will hit CSC walls)

Coarse mass filtering prior to high-resolving MR-TOF-MS mass measurements / filtering:

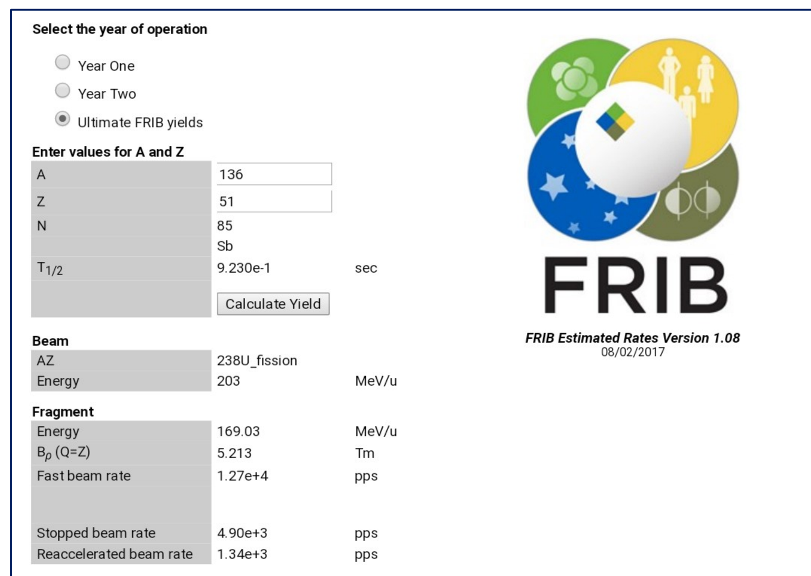
- RFQ beam line – M/ΔM ~ 250 (~1u), 90% transmission, (~10^9 FP/sec)
- MR-TOF-MS itself – M/ΔM ~ up to 70,000 (re-trapping schemes) (~10^7 FP/sec)

Detailed design and simulations needed to ensure full utilization of SARAF’s output

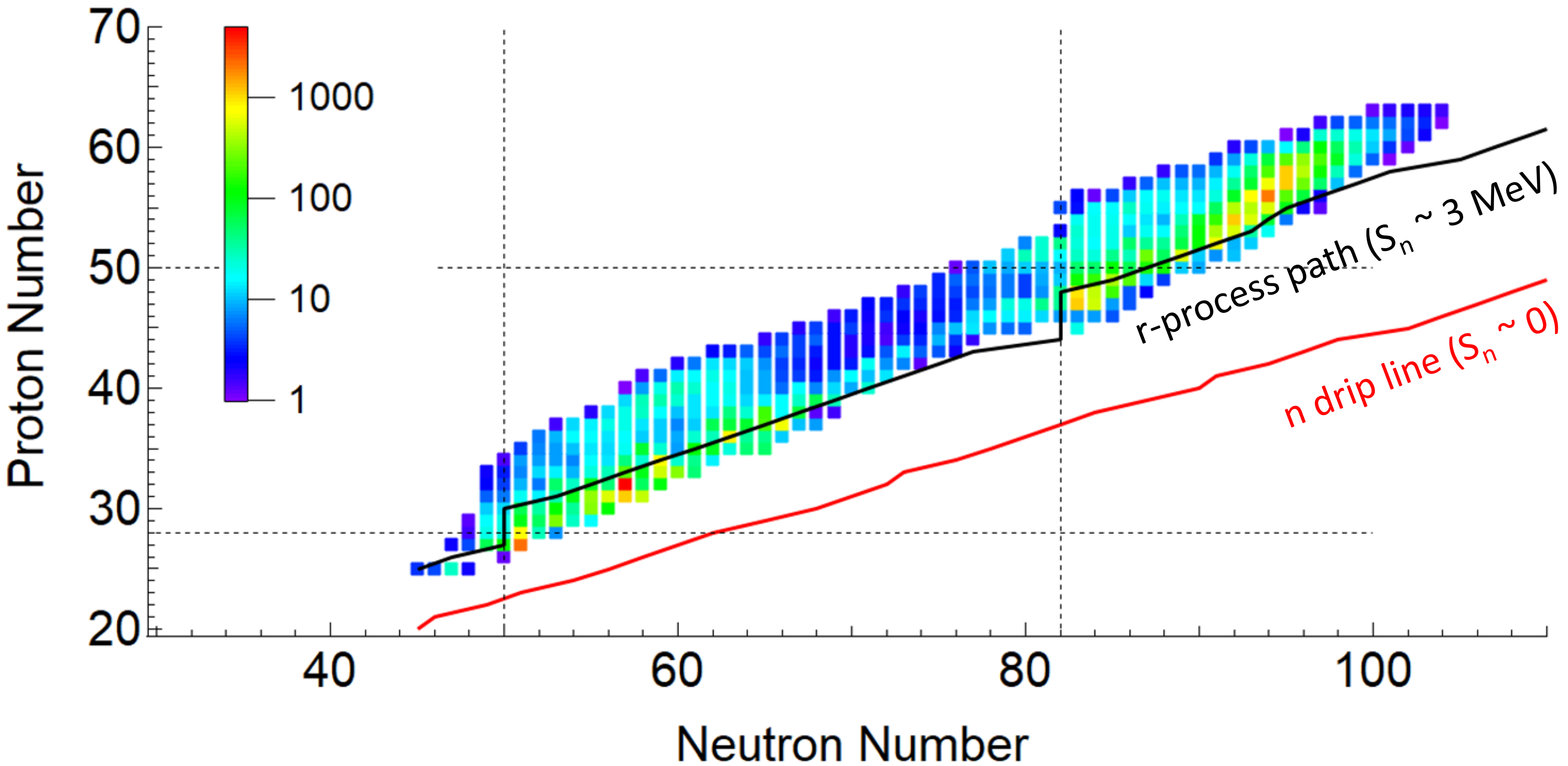
Perspective – FRIB expected rates



- For all SARAF-II expected FPs, extracted FRIB rates from their online calculator:
- 'Stopped beam' rates
- 'Ultimate FRIB yields'
- 'FRIB Estimated Rates Version 1.08', August 2017
- Fission products cross sections from LISE++ 3EER Model
- https://groups.nscl.msu.edu/frib/rates/fribrates.html
- Plotted FPs for which R(SARAF-II) > R(FRIB)



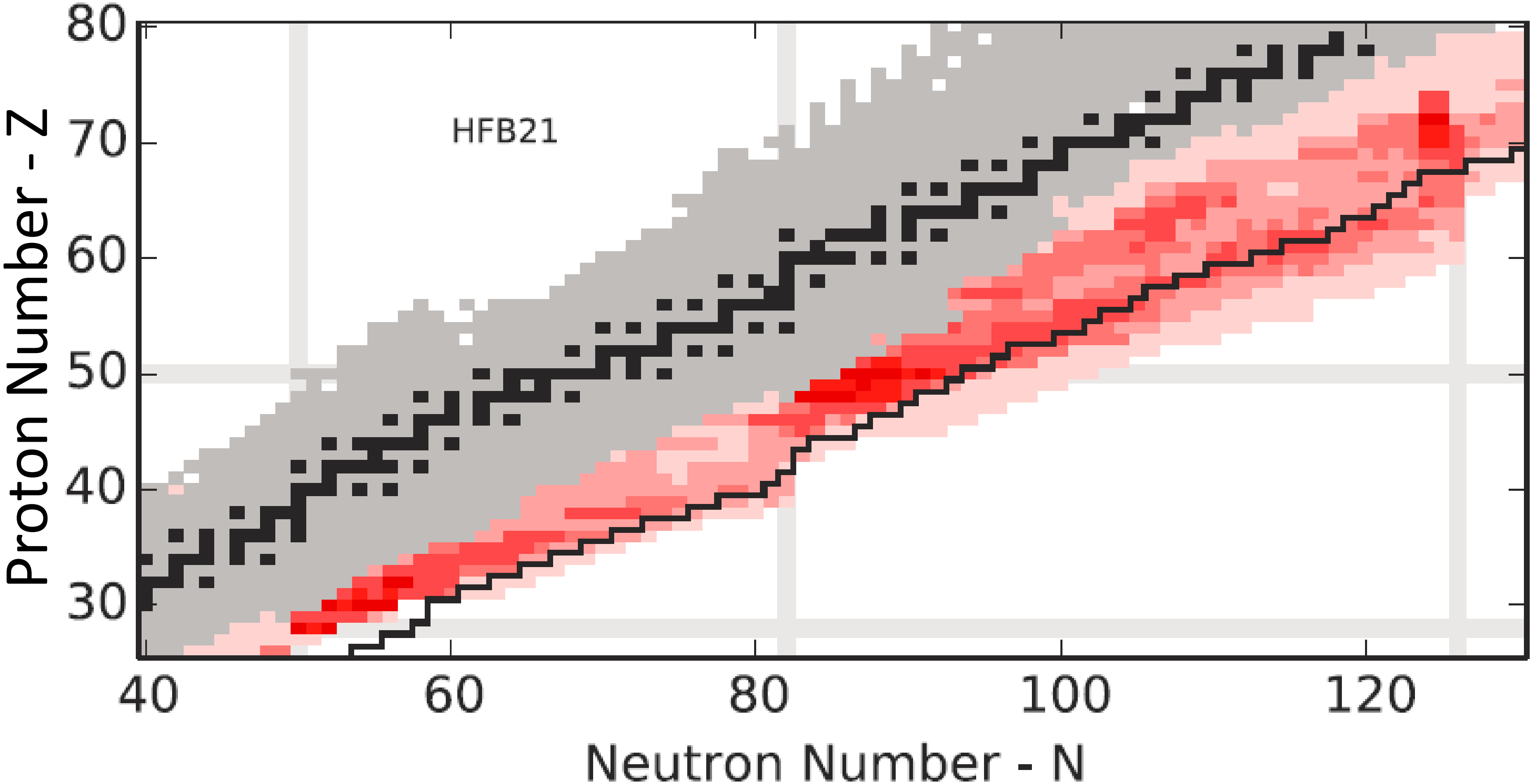
SARAF II / FRIB rates ratio



- FPs for which R(SARAF-II) > R(FRIB)
- FRIB rates are 'stopped beam'
- FRIB rates taken from 'FRIB Estimated Rates Version 1.08', August 2017 ('Ultimate FRIB yields')
  Fission products cross sections from LISE++ 3EER Model
  https://groups.nscl.msu.edu/frib/rates/fribrates.html

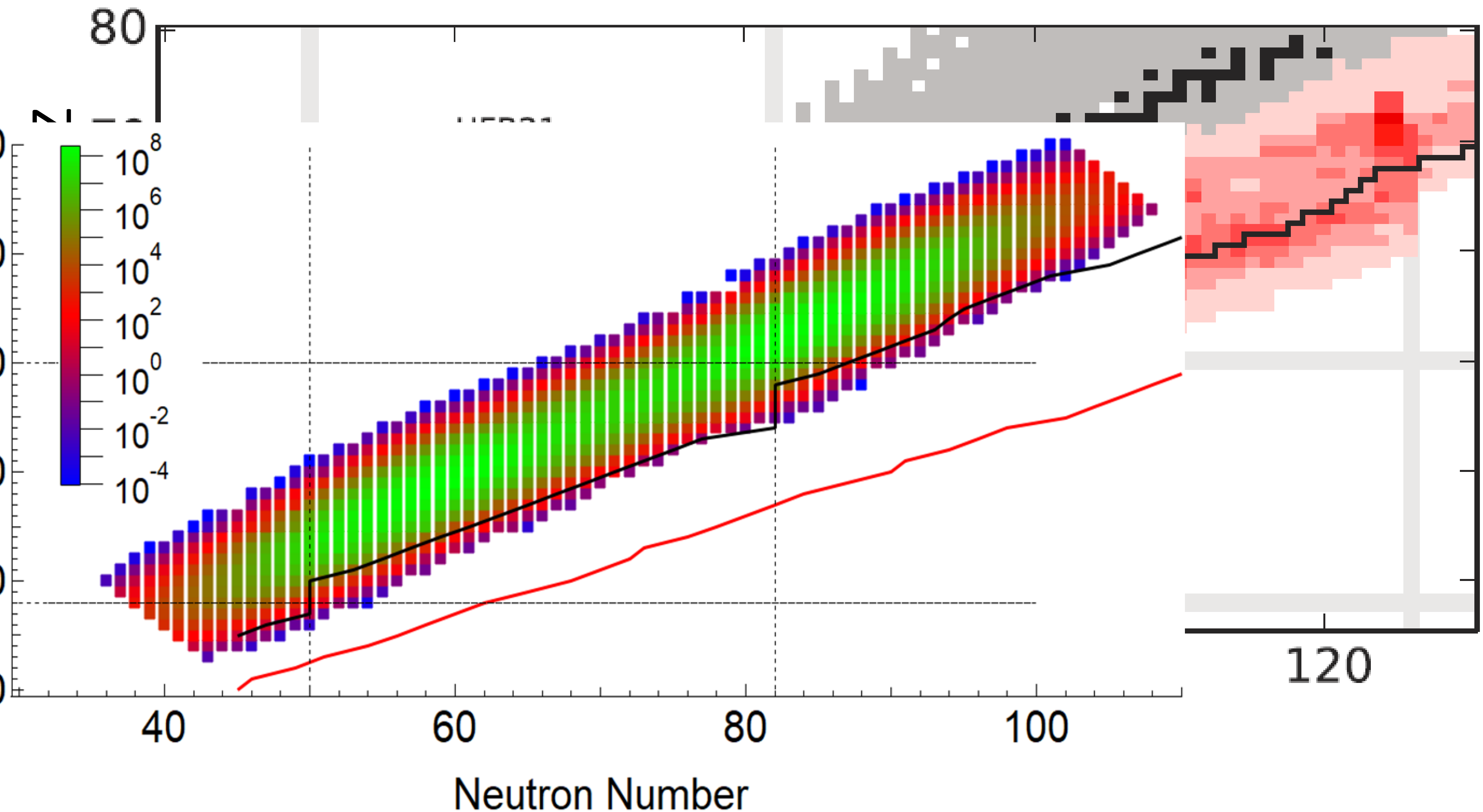
Impact of nuclear properties on the r-process

A. Aprahamian et al., Sensitivity studies for the main r process: nuclear masses, AIP Advances 4, 041101 (2014)



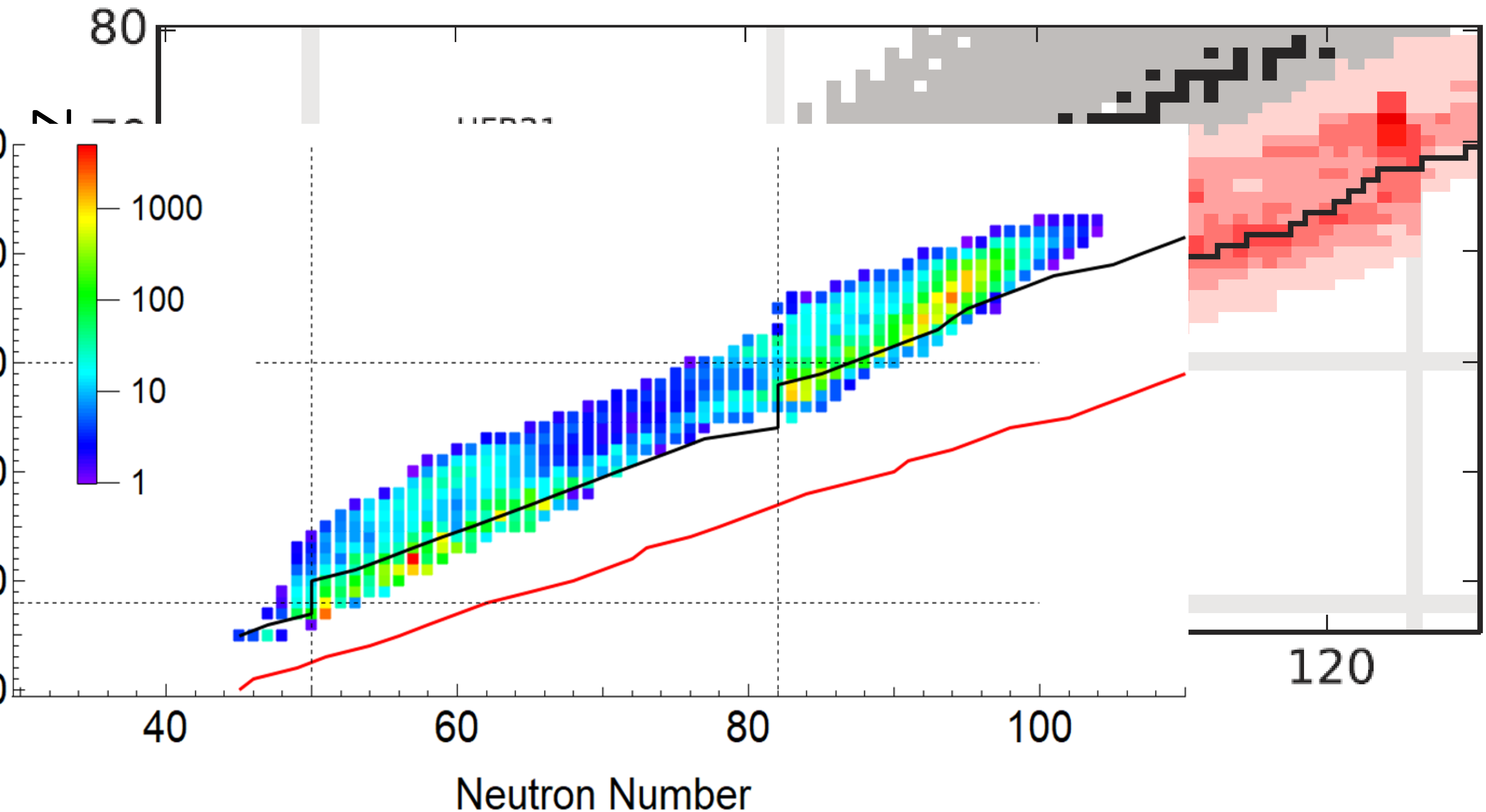
Impact of nuclear properties on the r-process

A. Aprahamian et al., Sensitivity studies for the main r process: nuclear masses, AIP Advances 4, 041101 (2014)

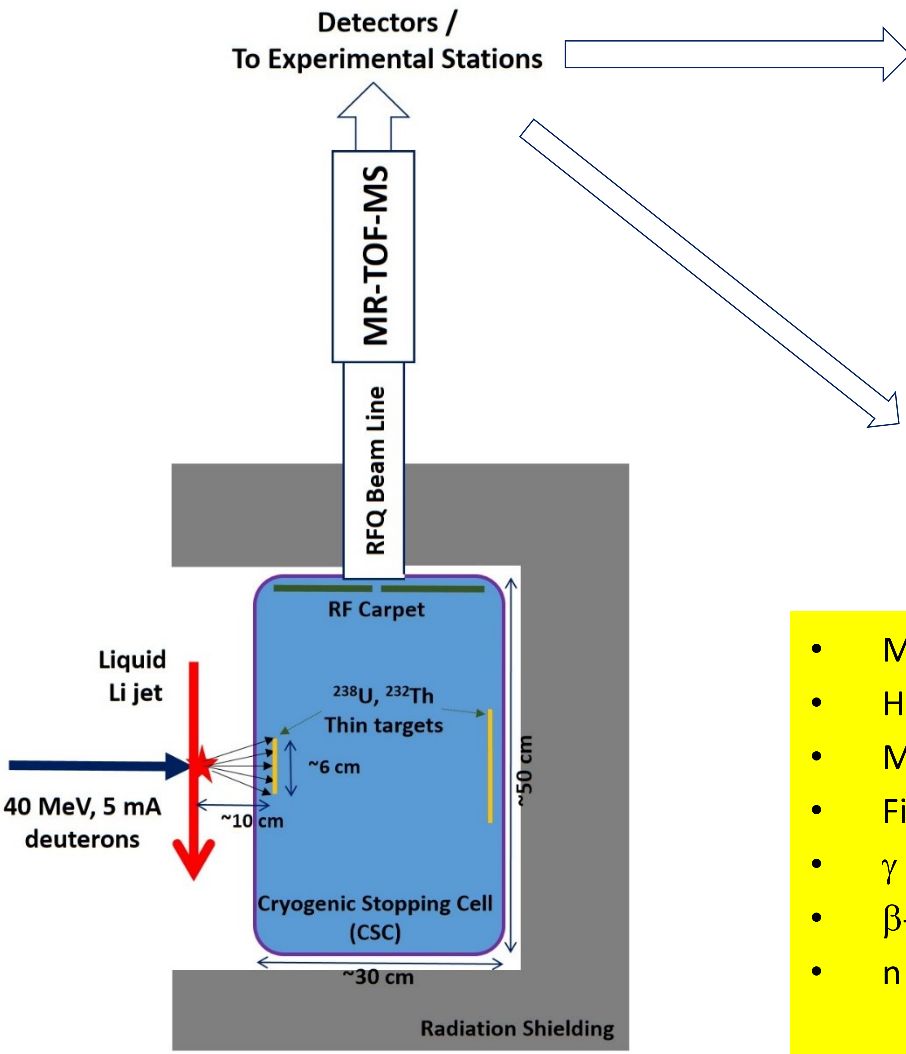


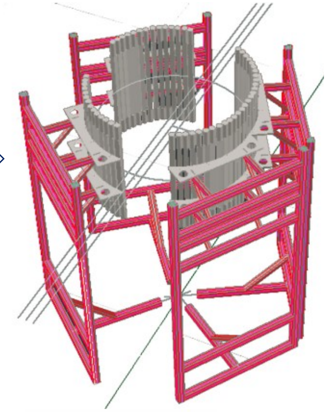
Impact of nuclear properties on the r-process

A. Aprahamian et al., Sensitivity studies for the main r process: nuclear masses, AIP Advances 4, 041101 (2014)



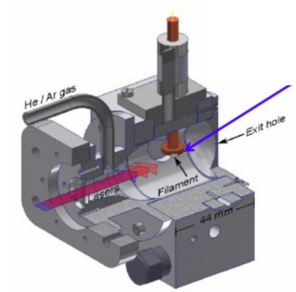
Nuclear properties of n-rich isotopes at SARAF-II





Array of n, β and γ detectors
such as
VANDLE
Versatile Array of Neutron
Detectors at Low Energy

W. A. Peters et al., NIM A 836, 122-133 (2016)



Laser spectroscopy
such as in
IGISOL @ JYFL

A. R. Dicker et al., Hyp. Int. 227 139–145 (2014)

- Masses, Q-values, n-separation energies
- Half lives
- Mass and isotope fission fragment distributions
- Fission fragment isomer ratios
- γ excitation levels
- β-delayed neutron emission probabilities (P_n)
- n spectra and energy levels
  - Constraints on σ(n,γ) from γ and/or neutron spectra
- Spin, dipole and quadrupole moments
- Mean-square charge radii

I. Mardor et al., https://arxiv.org/abs/1801.06493 (2018)

Summary and Outlook

- Soreq NRC is constructing SARAF as a user facility for the international scientific community. SARAF Phase I is completed and operational. Research programs are ongoing, to be expanded at the new Phase I target room during 2018
- SARAF II is mostly funded. To be completed at the first half of the next decade
- The high neutron luminosity of SARAF + LiLiT and an Ion Catcher a la FRS, may constitute a world competitive facility for n-rich exotic isotopes research
- There is an opportunity to disseminate FRS-IC technology to another facility and physics field. Specifically, gain expertise in intra-CSC irradiation targets
- In preparation for the above, for technical studies of the FRS Ion Catcher, and also for basic and applied nuclear science, it may be useful to measure fission yield distributions and isomer yield ratios with a ^{252}Cf source
- Irradiating actinide targets in the CSC with an external d-t neutron generator may also be of interest
- SARAF is open to new collaborators and contributions. We look forward to research proposals and letters of intent

I. Mardor et al., "The Soreq Applied Research Accelerator Facility (SARAF) – Overview, Research Programs and Future Plans", Submitted to European Physics Journal A as an invited review, https://arxiv.org/abs/1801.06493 (2018)

Acknowledgements

- This initiative is inspired by and based on:
  Leo Weissman & Michael Paul, *Neutron-Rich Radioactive-Ion Production at SARAF Phase II*, October 2013, internal report

- Thanks for fruitful discussions with:
  Michael Paul (HUJI), Eli Piasetzky (TAU), Ishay Pomerantz (TAU), Leo Weissman (Soreq NRC), Stephane Goriely (ULB), Gabriel Martinez-Pinedo (TUD), Wolfgang R. Plaß and the FRS Ion Catcher Collaboration, Iain Moore and the JYFL IGISOL Group