WEIZMANN INSTITUTE OF SCIENCE

Development of a versatile TPC for neutron-induced reaction studies at the SARAF TOF facility

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Leo Weissman from SNRC

CYGNUS workshop, Sydney, 14/12/2023

SARAF – Soreq Applied Research Accelerator Facility

- Soreq Nuclear Research Center (SNRC) is constructing the Soreq Applied Research Accelerator Facility (SARAF-II), a user facility that will be based on a state-of-the-art light ion accelerator.

- The main SARAF motivation is to replace the current SNRC research reactor with an environment-friendly facility that does not rely on fissile materials.

- Thus, the main focus will be on the production of intense fast-neutron beams; these can be used directly or moderated to thermal and epithermal energies.

- The spectrum of applications will be much broader than that at a typical research reactor:
    - basic neutron-based material, nuclear and particle physics research;
    - high-intensity neutron sources for interdisciplinary scientific research and industrial applications;
    - radiopharmaceutical: to develop and produce radioisotopes for bio-medical applications;
    - non-destructive testing in various areas of nuclear science and engineering.

SARAF-I: Operational 2010-2019

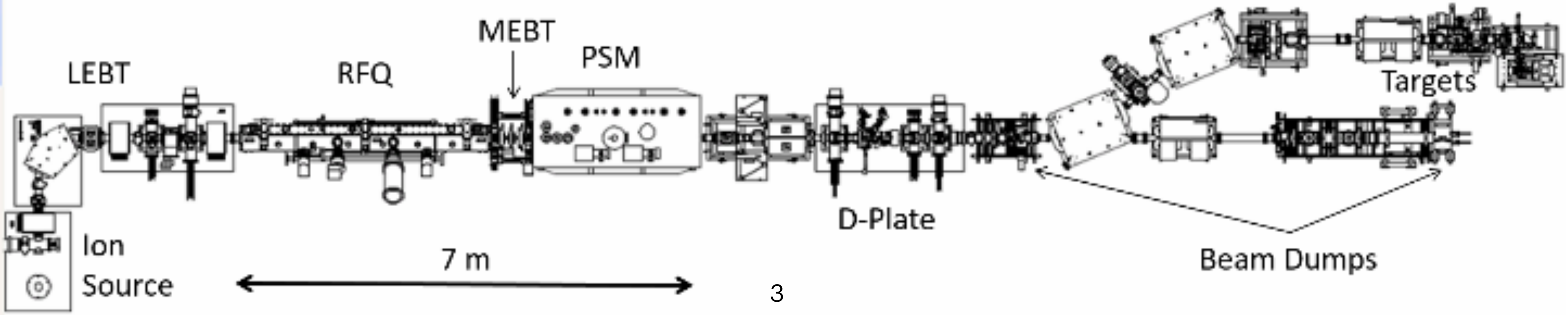
SARAF-I beams

Ion	Energy [MeV]	Current [mA]
p	4	1 (CW)
p	2	2 (CW)
d	5.6	1 (10%)
d	2.6	1.1 (CW)

SARAF I informal user group: 35

Internal users: 12 (34%)
National users: 15 (43%)
International users: 8 (23%)

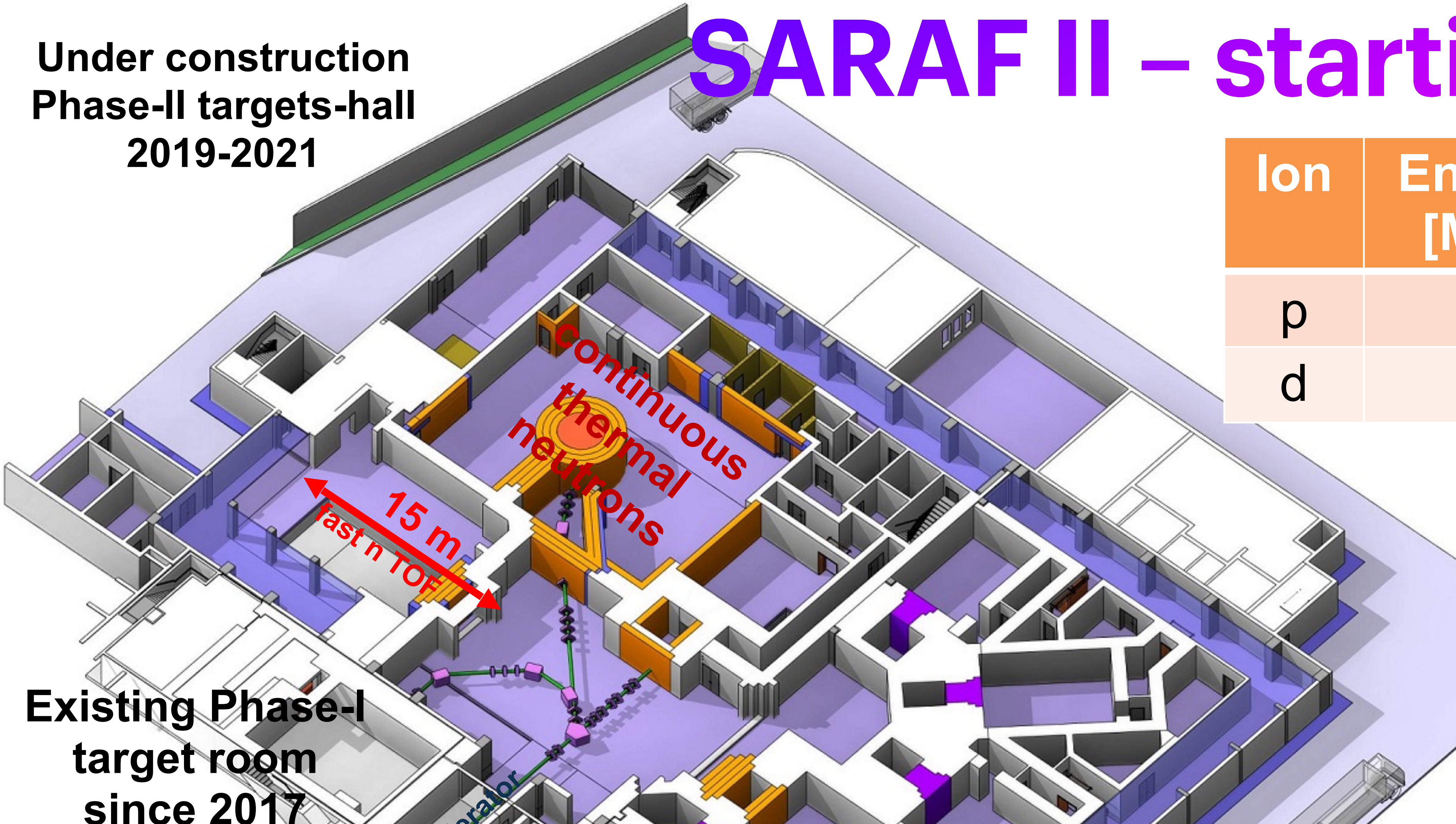
Electron Cyclotron Resonance (ECR) ion source, a Low Energy Beam Transport (LEBT), a 176MHz, 1.5 MeV/u four-rod Radio-Frequency Quadrupole (RFQ), a short Medium Energy Beam Transport (MEBT) and a Prototype Superconducting Module (PSM) , Half Wave Resonators (HWR)



SARAF II – starting 2024

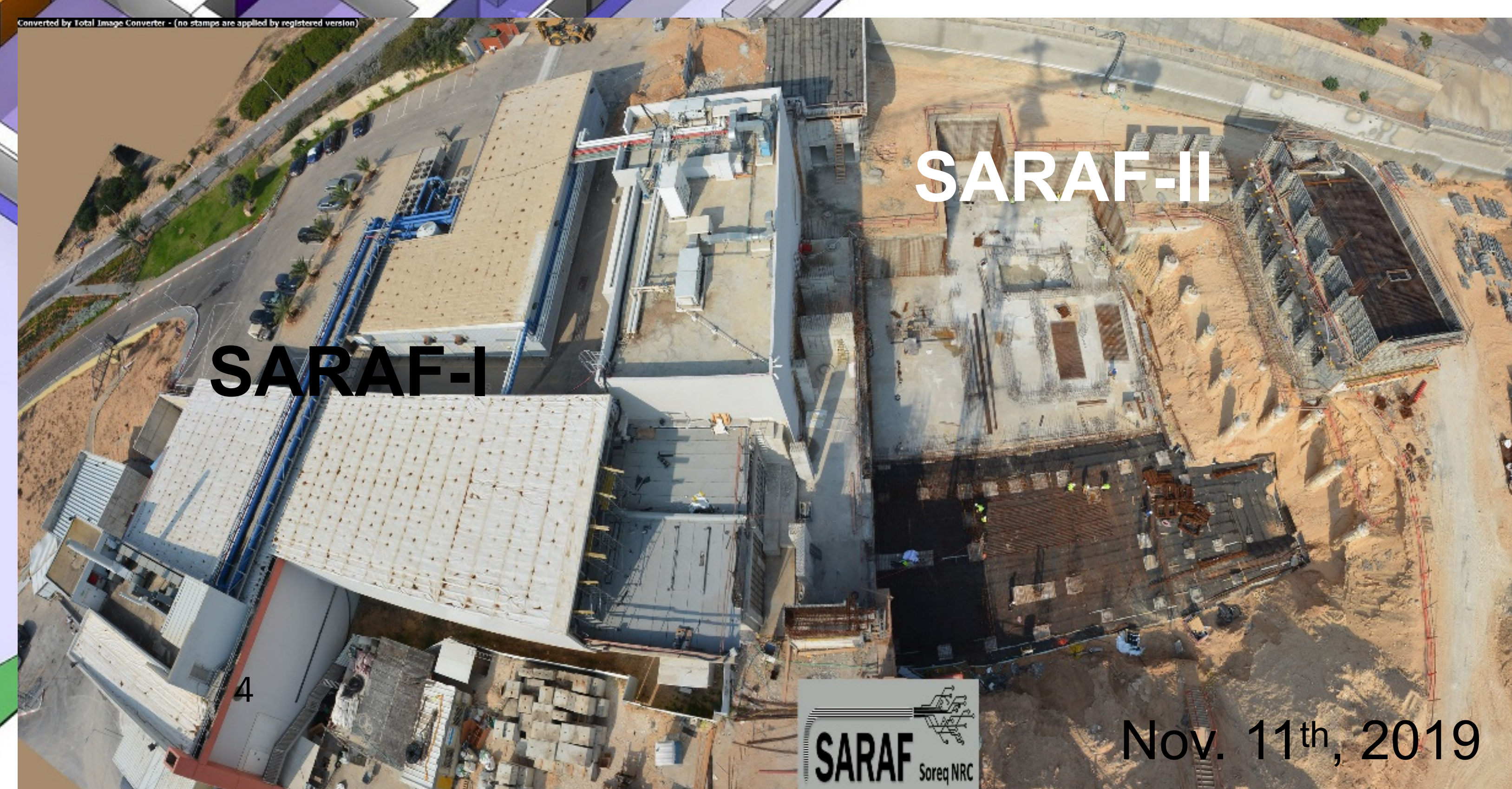
Ion	Energy [MeV]	Current [mA]
p	35	5 (CW)
d	40	5 (CW)

Under construction
Phase-II targets-hall
2019-2021



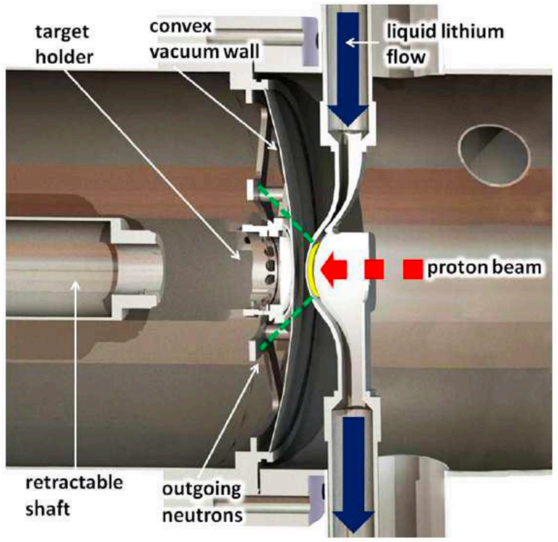
Existing Phase-I
target room
since 2017

Existing
accelerator
since 2006

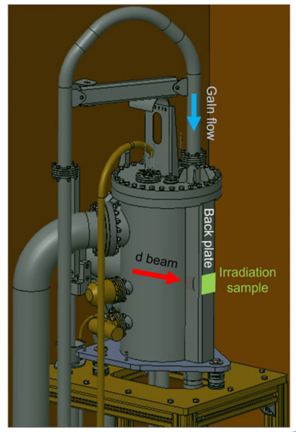


Nov. 11th, 2019

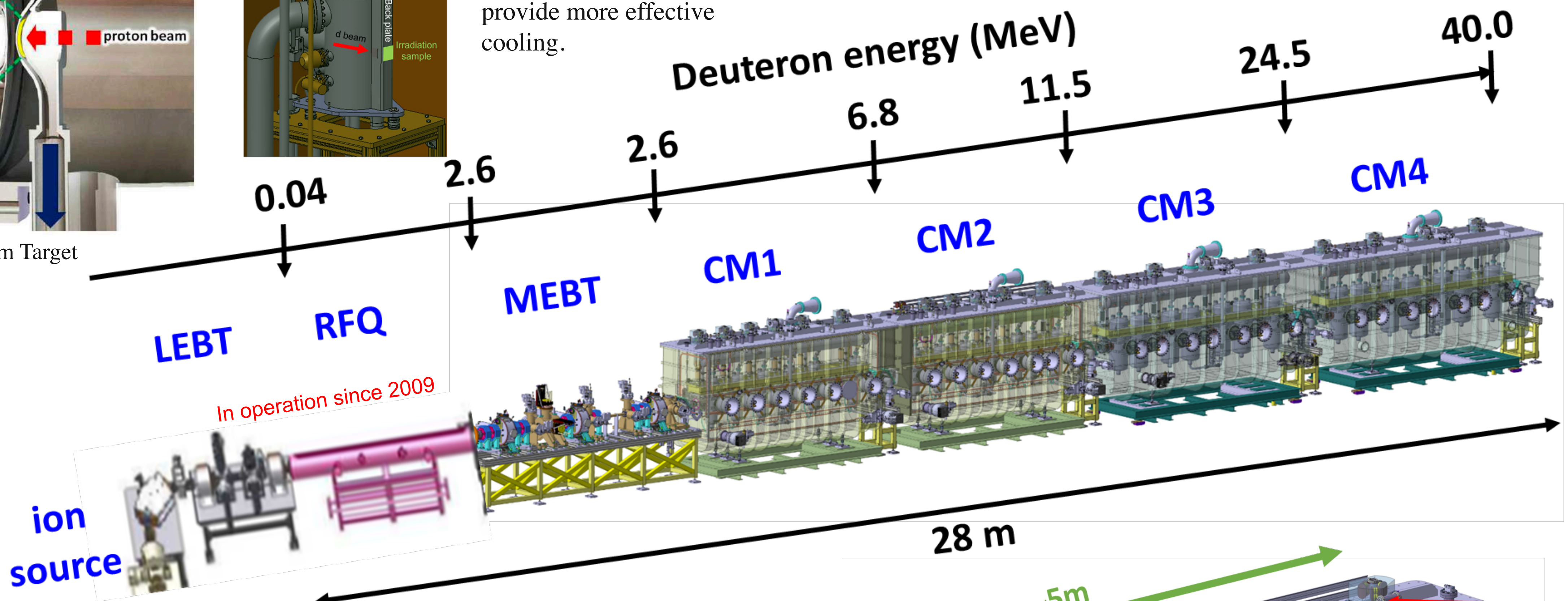
SARAF Phase-II Superconducting RF accelerator

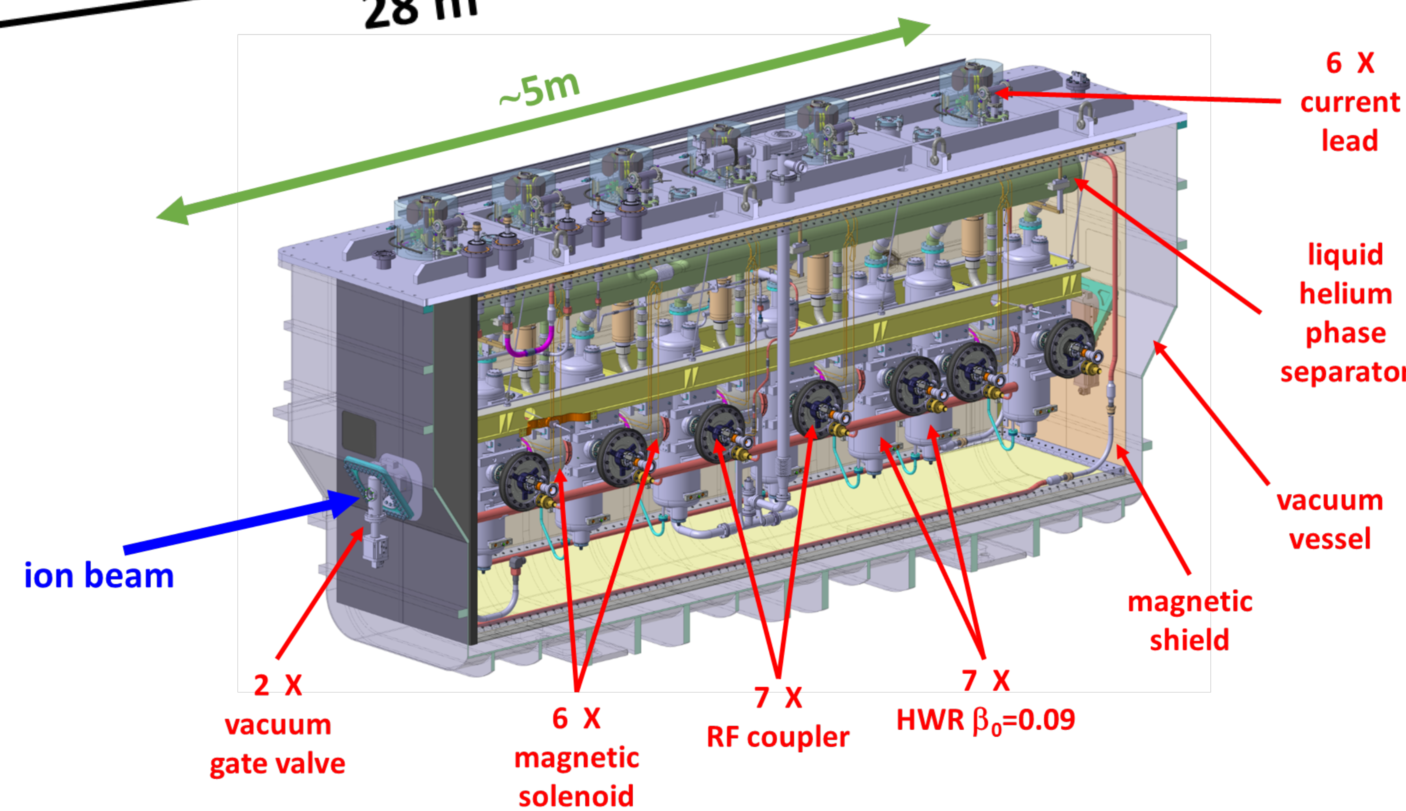


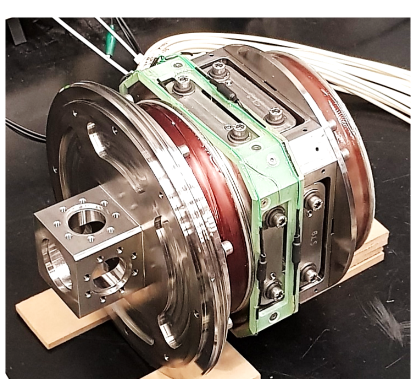
LiLiT -Liquid Jet Lithium Target



Developing GaLn target w/ cooling with liquid metal (e.g., gallium) jet-impingement may provide more effective cooling.







STATUS:

All components are under test and fabrication

HWR ➔

🡐 Solenoid

N. Pichoff *et al.*, IPAC 2018 and IPAC 2019

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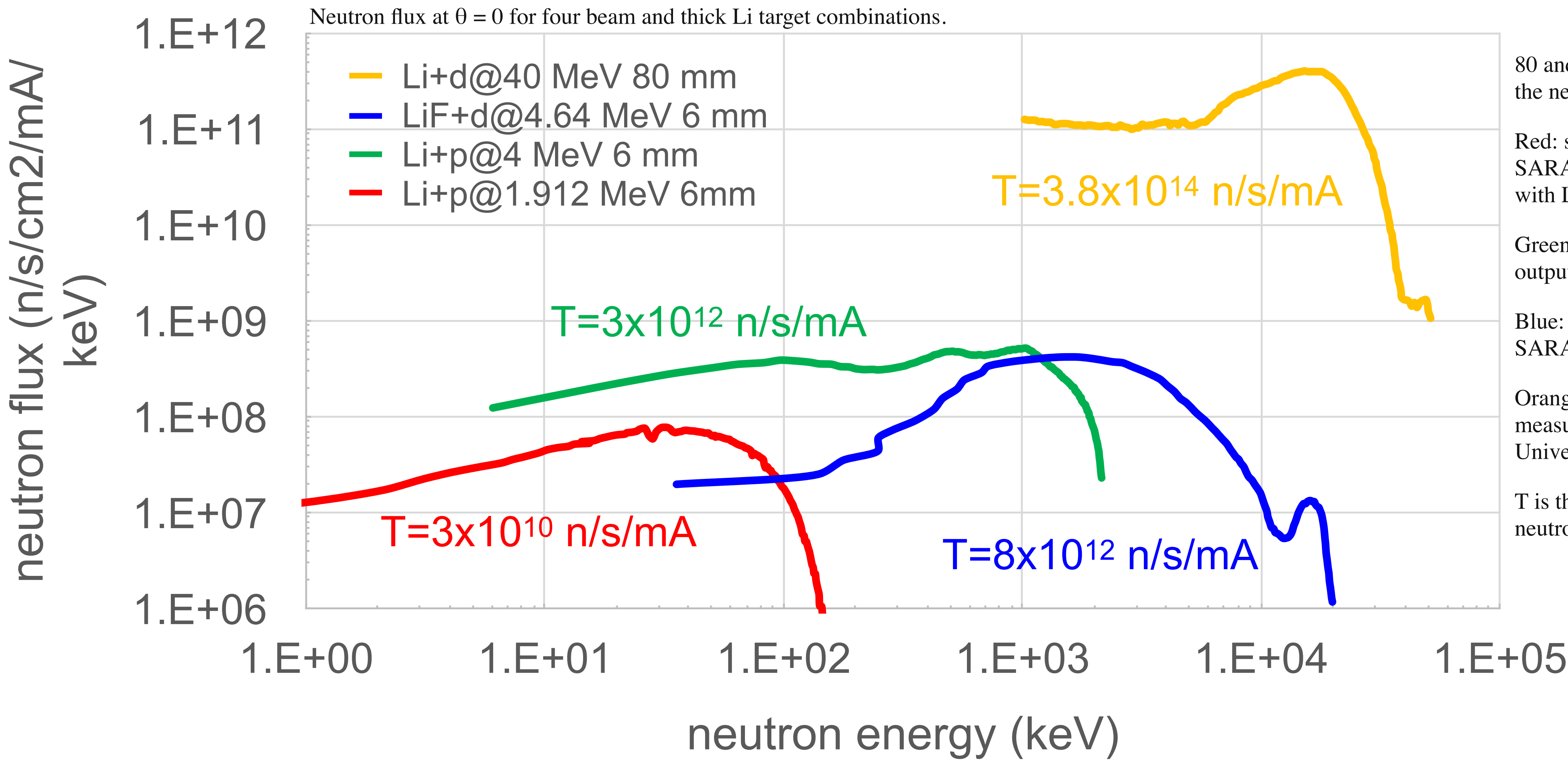
SARAF accelerator and its TOF capabilities

- The main focus will be on the production of intense fast-neutron beams; these can be used directly or moderated to thermal and epithermal energies.

Applications	Conditions	Pulses rate	n/s
Thermal neutron source	5 mA, 40 MeV CW beam on a high-power target	176 MHz	10^{15}
TOF experiment, "white spectrum"	5 mA, 40 MeV pulsed deuteron beam on a thick target	200 kHz	10^{12}
TOF experiment, "monochromatic"	5 mA, 35 MeV pulsed proton beam on a thin target	200 kHz	10^{10}



80 and 6 mm are the distances from the neutron source.

Red: simulated and measured at the SARAF-I s-process measurements with LiLiT.

Green: simulated Sim- SARAF output.

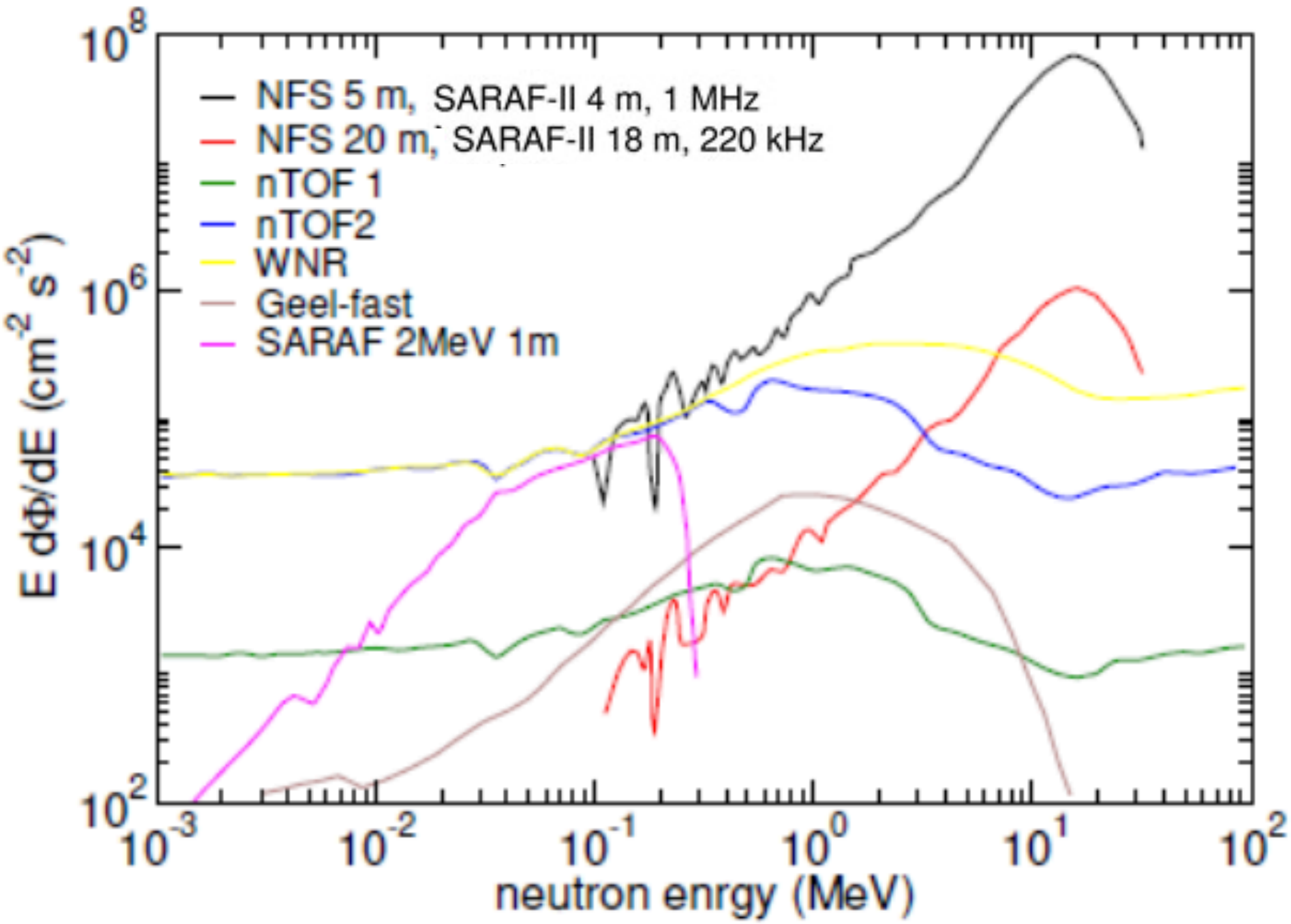
Blue: simulated and measured at SARAF- I with a solid LiF target .

Orange: evaluation based on measurements at Tohoku University.

T is the integral over 4π and neutron energy.

I. Mardor et al., EPJA 54, 91 (2018)

Neutron flux at leading TOF facilities



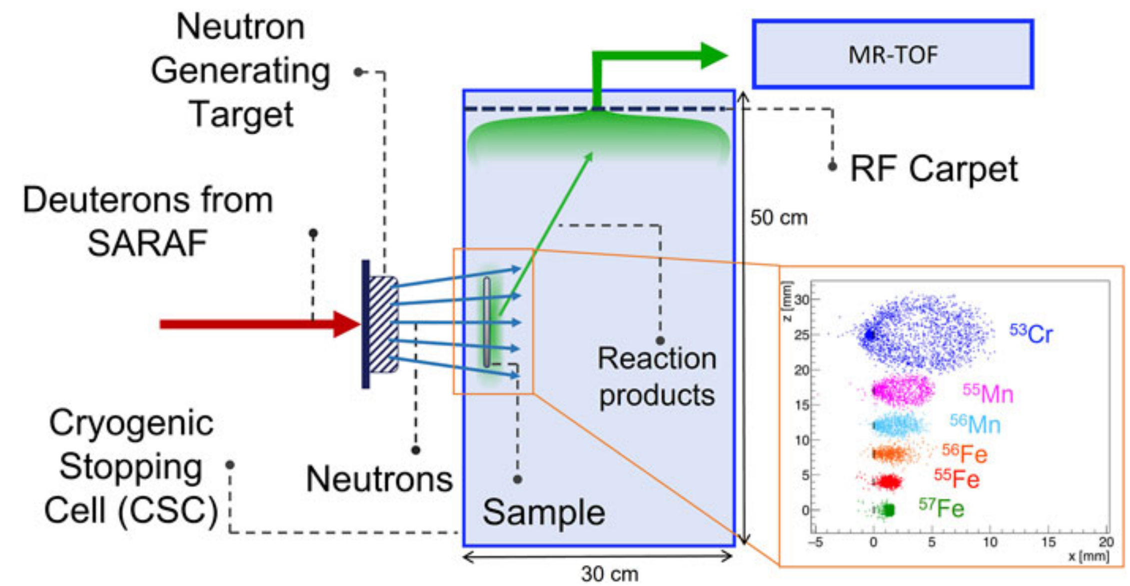
- NFS at SPIRAL(GANIL)
- NTOF (CERN)
- WNR (LANSE)
- GELINA(IRRM)

- The neutron flux at NFS is shown to be superior for neutron energies from 0.1-30 MeV (black curve).
- The NFS facility (GANIL) has characteristics close to SARAF Phase II. The expected neutron fluxes are also similar.
- SARAF with 2 MeV proton beam on Li target will enable TOF with "astrophysical" spectrum (pink curve). The yield is calculated for 5 mA beam, 1 MHz beam at a distance 1 m from the lithium target.

increase the neutrons' yield -> Important astrophysical measurements which could be performed without a strong background from high-energy neutrons – an option available at SARAF only

The Science at SARAF-II

- Searches for Beyond Standard Model Physics (a_{bn} 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 Deuteron and Neutron Induced Cross Sections (up to E_n ~ 50 MeV)
- Material Research (Gen-IV, transmutation, fusion, blistering)
- Neutron Based Therapy (Boron neutron capture therapy)
- Development of New Radiopharmaceuticals (Diagnostics and Therapy)
- Accelerator-based neutron imaging (thermal and high energy)
- Positron Annihilation Spectroscopy
- And maybe also – neutrino physics (well-defined, pulsed, high energy, ν and $\bar{\nu}$)



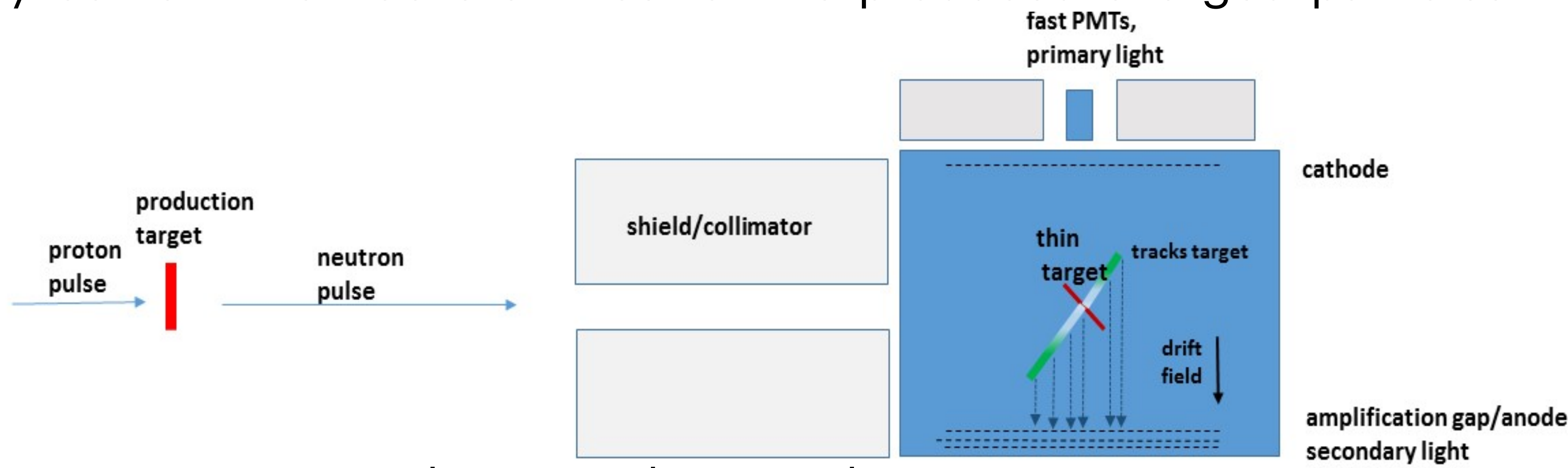
simultaneous measurements of n-induced reactions on given materials

the ranges of 6 possible reaction products from a ^{56}Fe sample

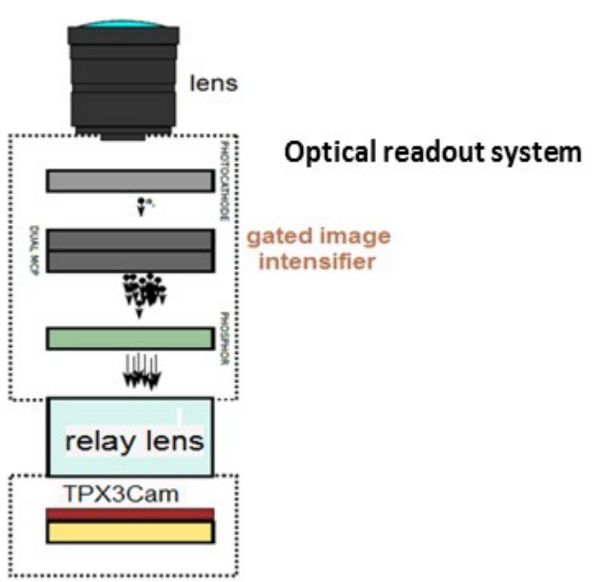
❖ I. Mardor et al.,
"The Soreq Applied Research Accelerator Facility (SARAF) – Overview, Research Programs and Future Plans",
Eur. Phys. Jour. A 54, 98 (2018)

General-purpose O-TPC

- To design and build a general-purpose Optical Time Projection Chamber optimized for the experimental conditions at SARAF-II and capable of taking advantage of the intense and diverse neutron beams.
  - The O-TPC (~ 25x25x25 cm^3) operating in fixed-target or active-target (AT) modes.
  - Capable of operating with a variety of gas mixtures at tunable density – to enhance specific reactions and fully contain the tracks of most of the produced charged particles and nuclides.



- The amplification of the primary ionization electrons deposited along the particle tracks: MPGD technology (cascaded GEM or THGEM). The most suitable multiplier will be selected based on the required position, time and energy resolutions.
- Avalanche-induced electroluminescence (EL) will be recorded by an optical system based on a TimePix3 camera. The primary scintillation signal and the time-tagged 2D camera images will provide 3D track images.



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Proposed studies utilizing O-TPC

Reaction	Energy range, x-section
Neutron-induced fission	Energy: 10 keV-5 MeV, Cross-section ~ 1 barn
^{7}Be(n,α)α reaction: destruction of ^{7}Be during the Big-Bang Nucleosynthesis. "Primordial ^{7}Li problem"	Energy: 10-100 keV, Cross-section: <1 mb
p(n,γ)d reaction: onset of Big-Bang Nucleosynthesis – fundamental interaction .	Energy: 10 keV-1MeV Cross-section: <0.1 mb
^{16}O(n,α)^{13}C reaction: indirect measurement of ^{13}C(α,n)^{16}O – the main source of stellar neutrons	Energy: 4-7 MeV Cross-section: 1-100 mb
^{26}Al(n,p), ^{26}Al(n,α) reactions: destruction of ^{26}Al isotope.	Energy: 10-100 keV Cross-section: ~ 1 b
^{12}C(n,n')3α inelastic scattering populating the Hoyle state.	Energy > 8.5 MeV Cross-section <30 mb

A first demonstration experiment: the measurement of n-induced fission on Thorium

- **Target.** **A** natural **Thorium target with dimensions ⌀=15 mm, 300 ug/cm^2 thick** ThF_4 layer, deposited on a thin carbon substrate (currently available at SARAF)

- **Gas admixture.** It is desirable to avoid light atoms (at least hydrogen or helium) in order to reduce the energy of elastic recoils. **CF_4 gas** was chosen for this evaluation as a compromise (broadly used for TPCs, relatively cheap, and easily available (not environmentally friendly). It has high electron drift velocity (up to 10 cm/μs) and low lateral diffusion properties.

- **Neutrons.** 40 MeV deuteron beam on a thick Be/Li target w/ a repetition rate of 200 kHz. This corresponds to 1.4 x 10^{12} neutrons/s. The average energy of the neutrons is of about 15 MeV, although the high-energy tail extends to 60 MeV. The TPC will be placed 5 m away from the production target in the forward direction and neutron beam collimation of 10 mm, well overlapping Th target. The neutron rate on the target is ~3x10^6 n/s/cm^2 or 11 n per/pulse.

- **Reaction rate.** Taking a neutron-induced fission cross-section on Th as ~ 1 barn - the rate of fission events as ~ **2 fissions/s**.

- **Background rate.** Taking a number of gas molecules @ 200 mbar pressure and assuming the x-section of elastic neutron scattering of the order of 1 barn - the rate is ~**450 events/s**.

The detector simulation

A detailed study employing GEANT4 simulation and custom ATTPCROOTv2 AT-TPC analysis framework (data & simulation) based on FairRoot https://github.com/ATTPC/ATTPCROOTv2

- Modular data analysis framework for Active Target Time Projection Chambers and Solenoidal spectrometers.
- Based on FairRoot package (developed at FAIR).
- Contains a collection of scientific libraries used in nuclear physics:
  ROOT, Geant4, physics generators, management libraries.

Building Geometry

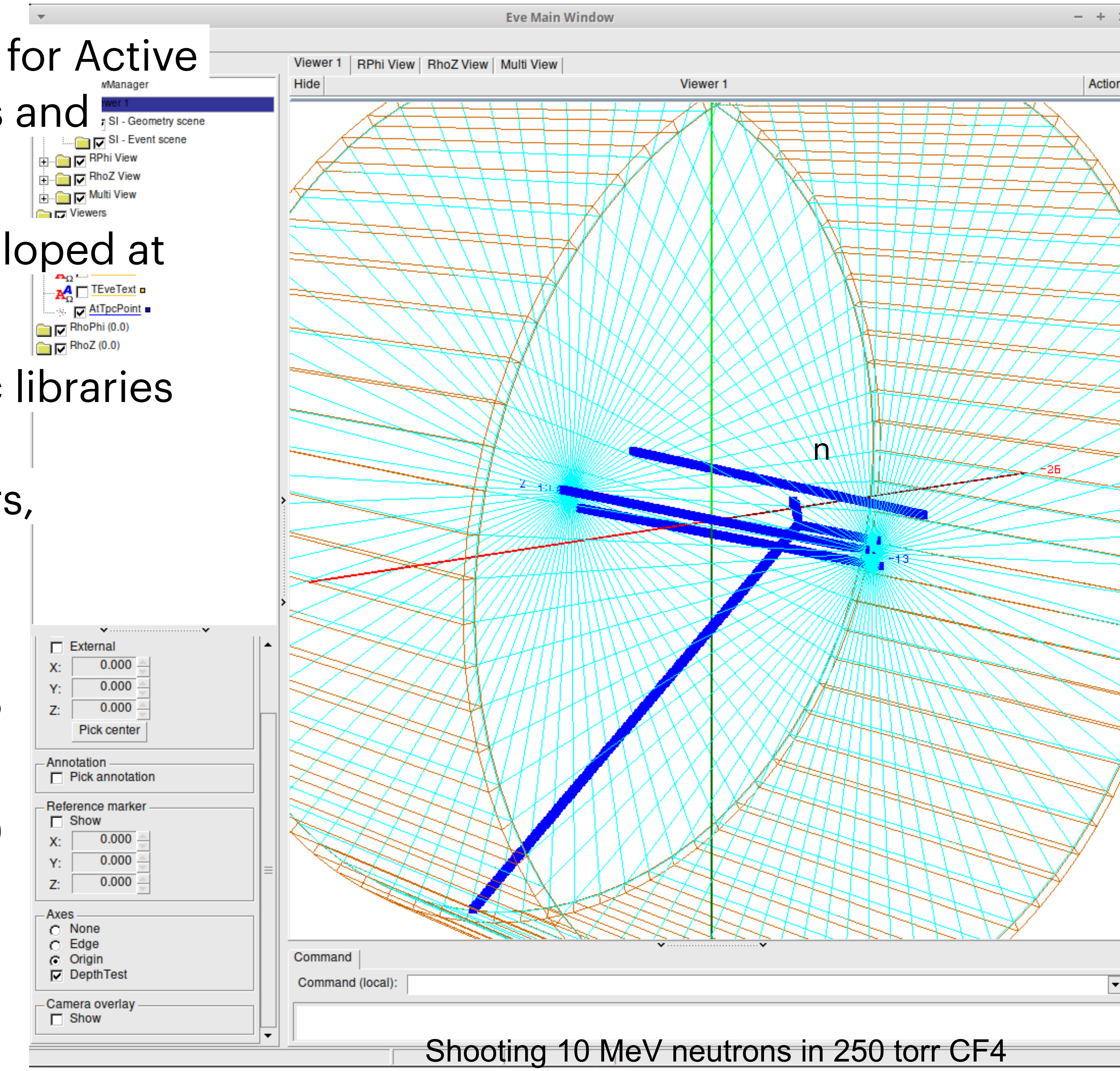
Built detector geometry (R = 25 cm, l =25 cm)

In materials added CF4 gas at 250 torr

Simulating Physics

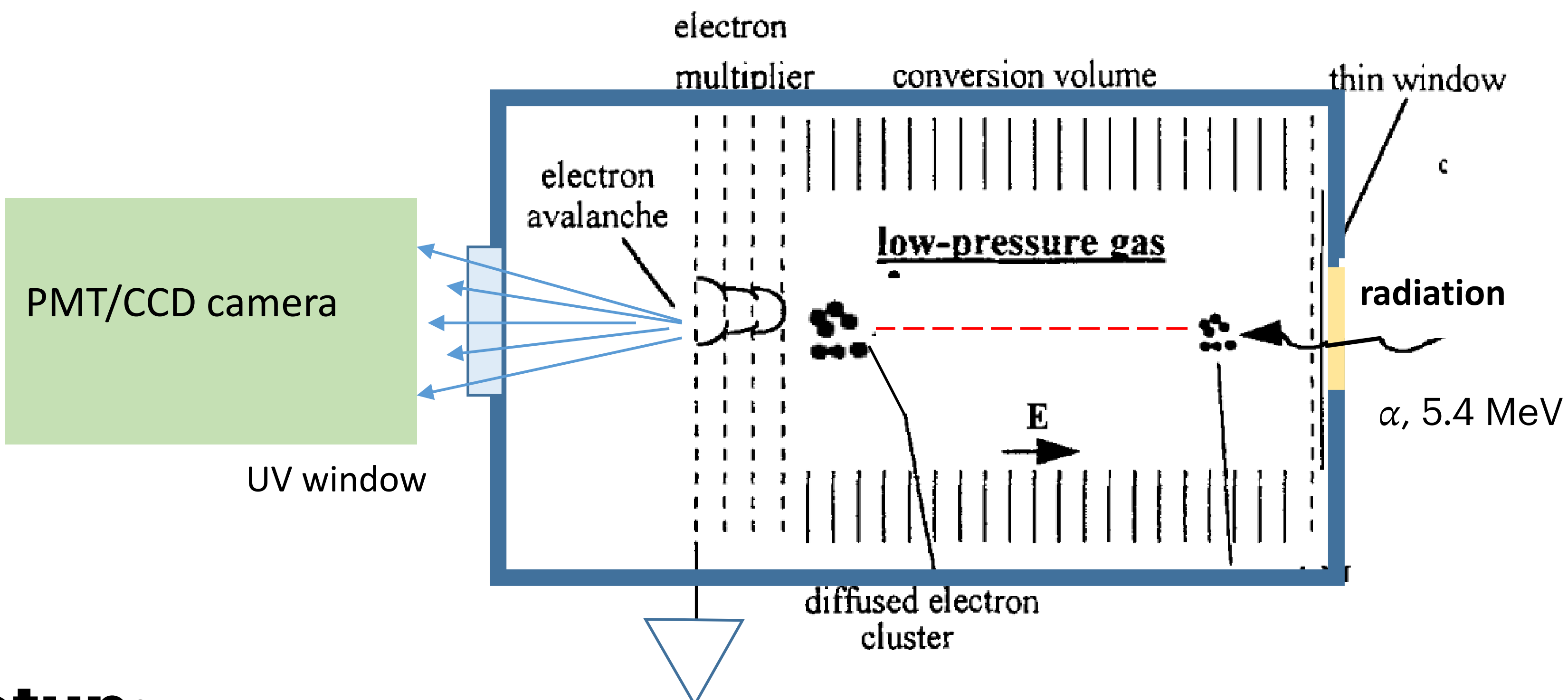
neutron gun is added

Photon physics is implemented



Shooting 10 MeV neutrons in 250 torr CF4

Detector prototyping



Gas/vacuum system:

Two gas channels: CF4 and additional optional gas

Proportional and manual valves.

Pressure gauge (Bevatron)

-> It could be used as a basis for an improved system.

Setup:

Chamber

Collimated alpha and PMT(for triggering)

Drift region with cathode and anode grid size ~ 70 mm

Ring electrodes with voltage division;

E_{drift} ~ 5-10 V/Torr/cm

Multiplication region: two grids ~ 5-7 mm

$E_{multiplications}$ ~ 20-70 V/Torr/cm

Alternative multiplication setups – GEMs, TGEMS

Charge is collected on G2

Light is collected on PMT or similar

Electronics:

Three HV supplies for the electrodes

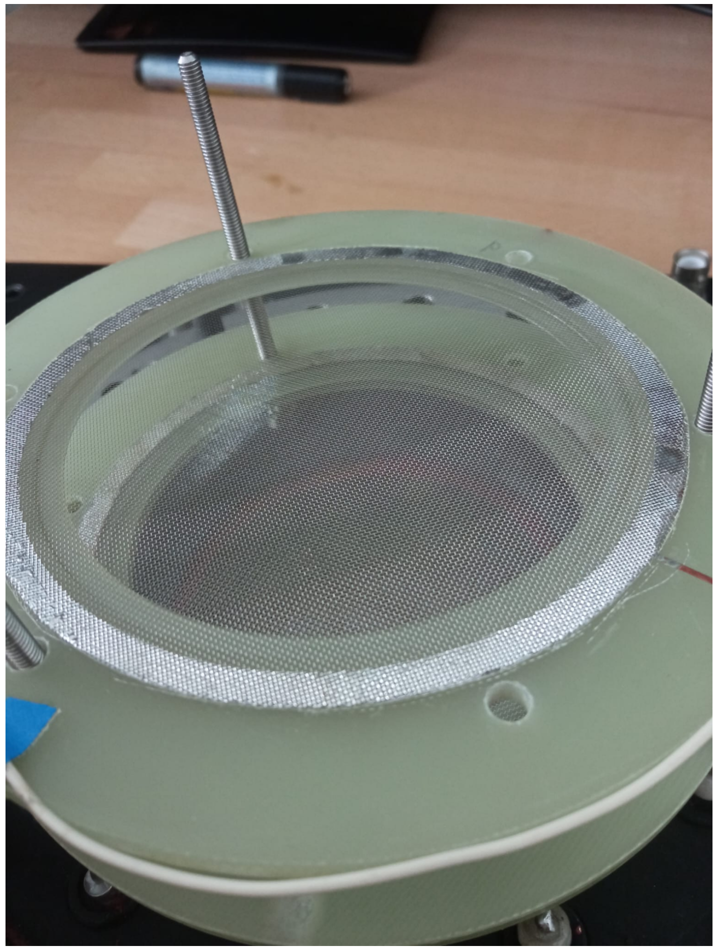
HV PMT supply and spectroscopy amplifier

Preamplifier and spectroscopy amplifier for charge collection

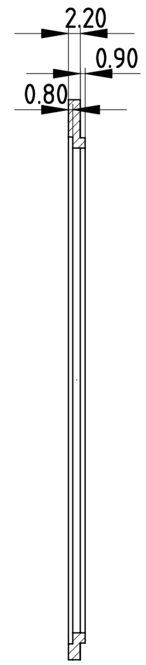
Scope

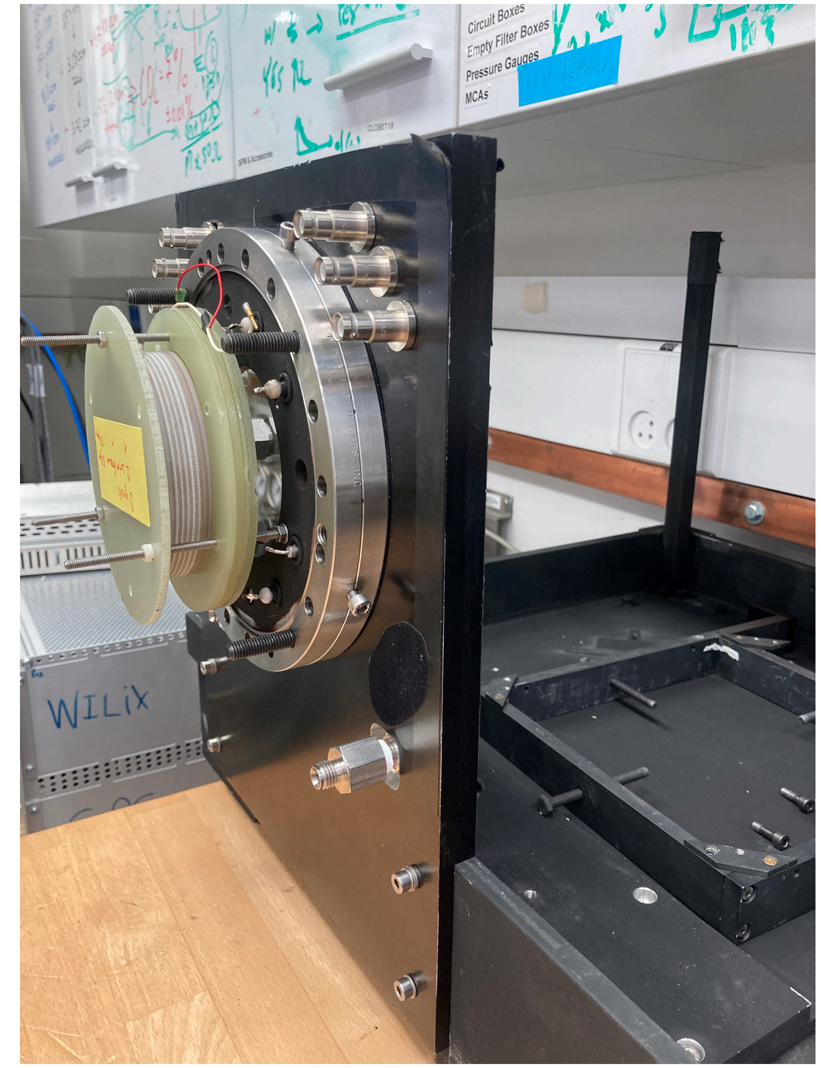
DATA acquisition (three channels)

The detector prototype assembly



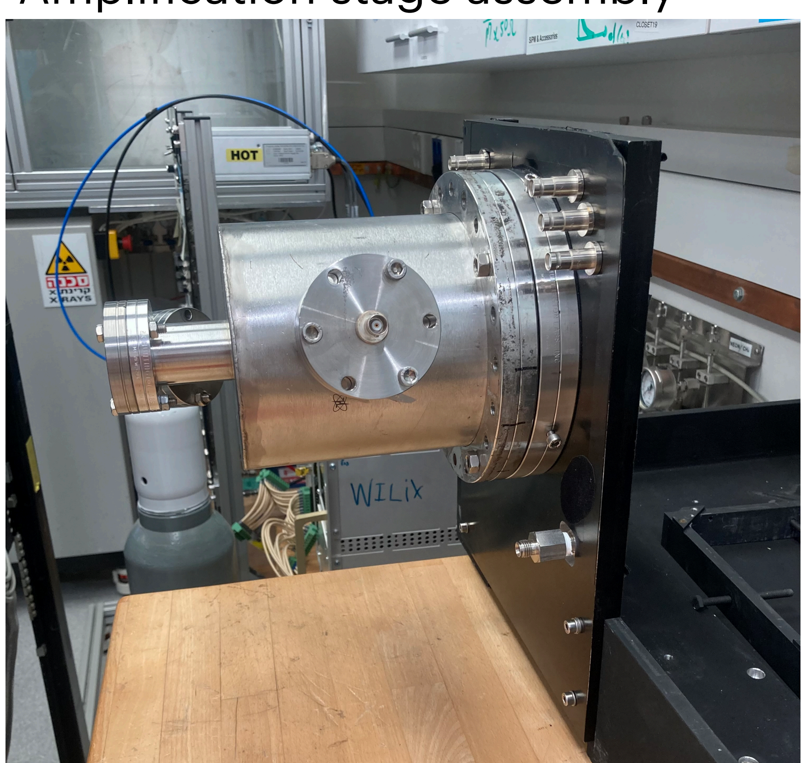
Field cage ring





Field cage assembly

Amplification stage assembly



Gas mixing/
vacuum system

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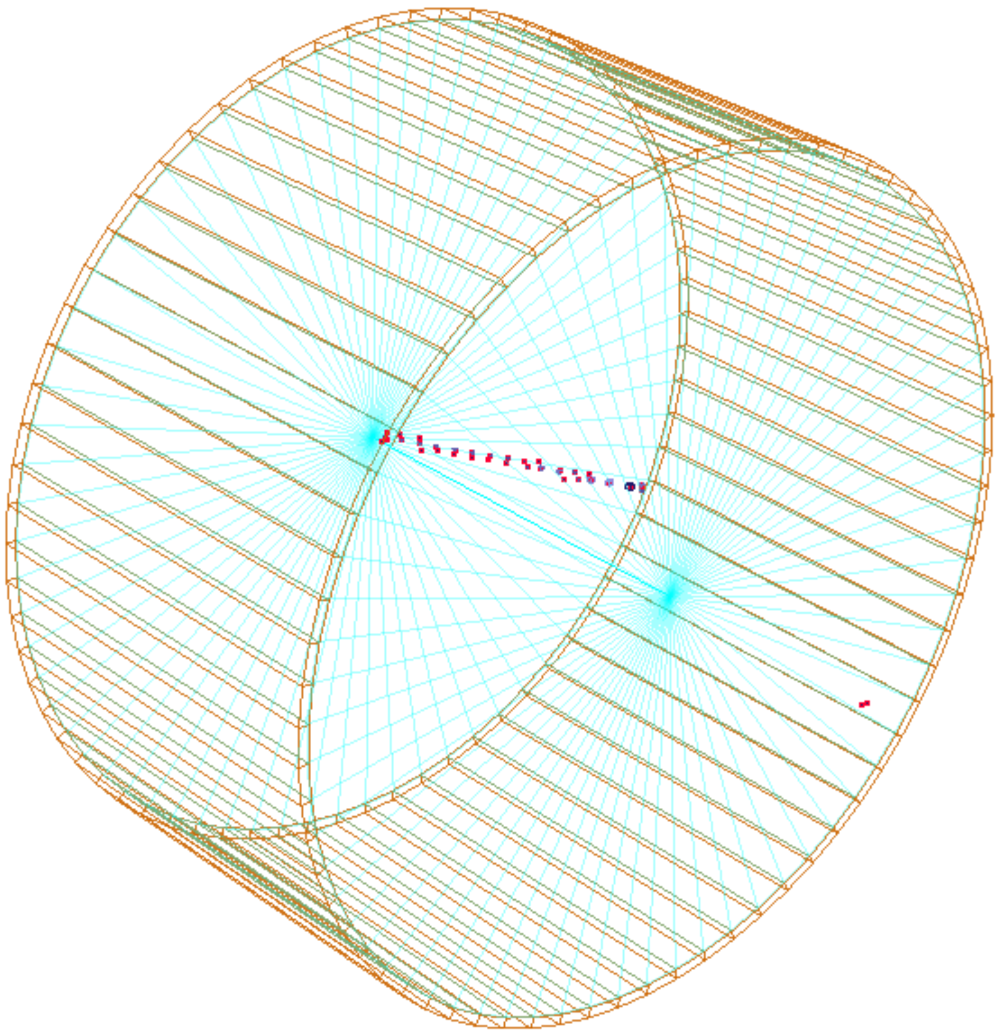
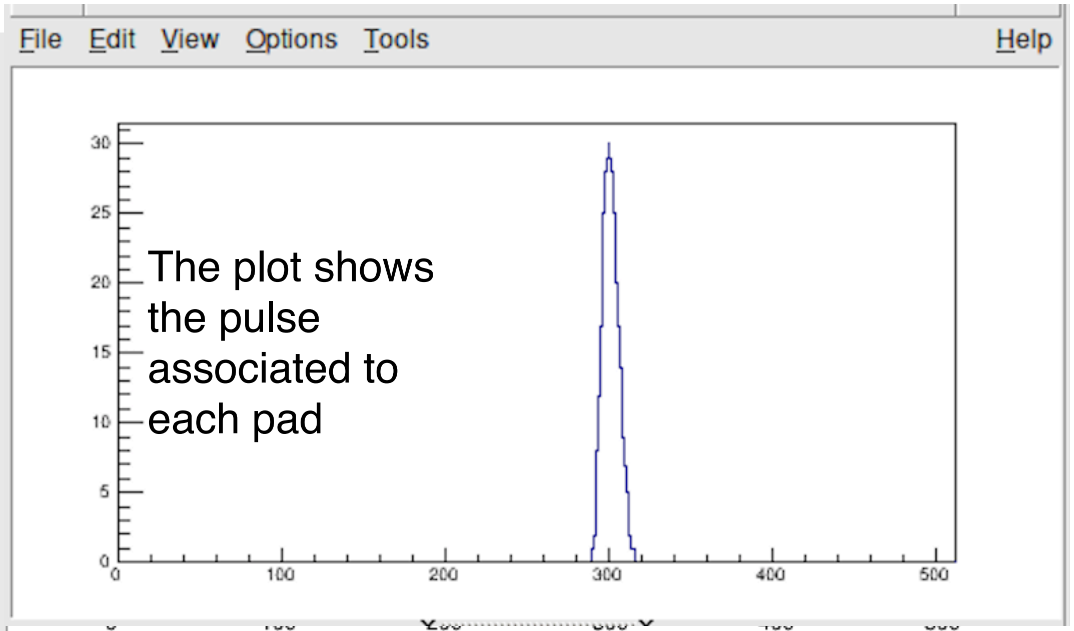
The detector prototype simulation

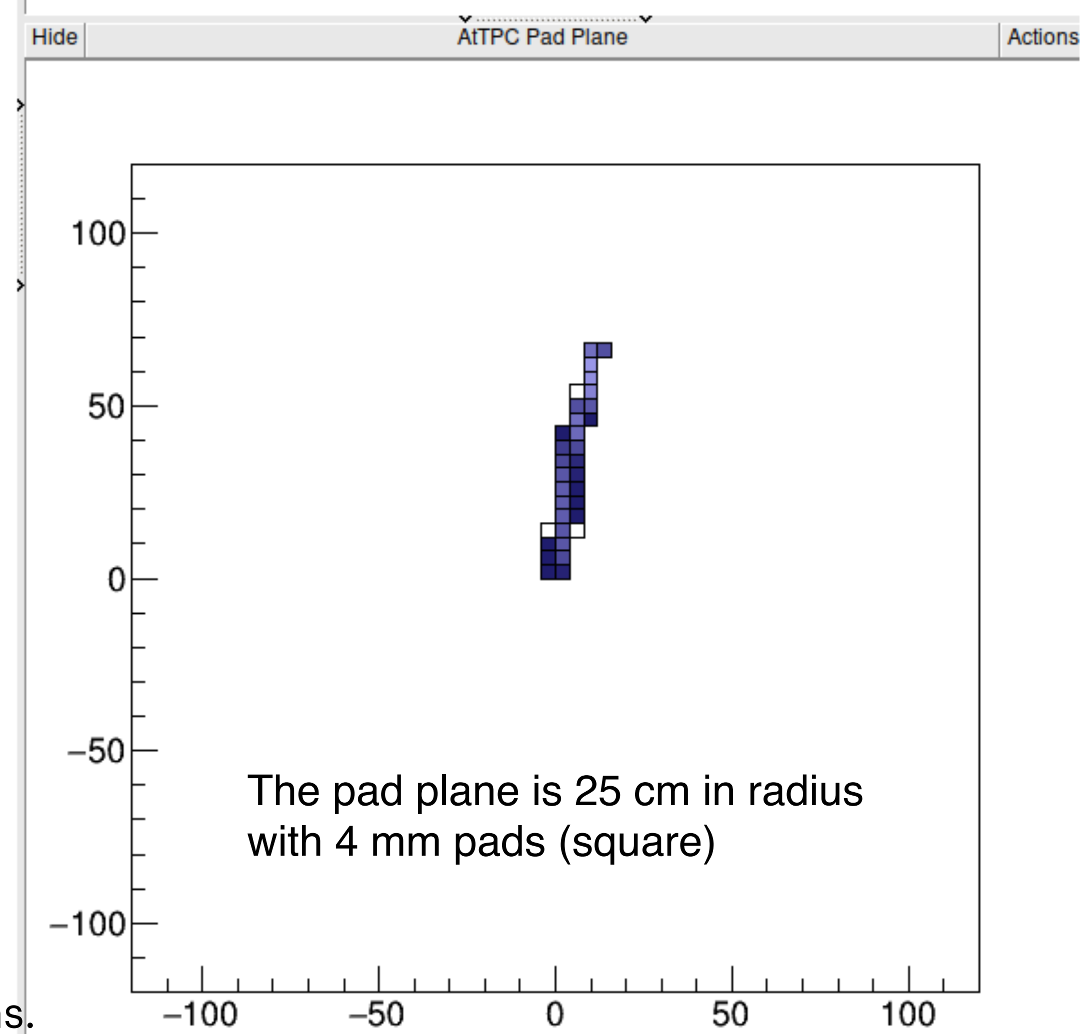
Shooting 4He 5.4 MeV (10000) in 250 torr CF4

α, 5.4 MeV





The plot shows the pulse associated to each pad



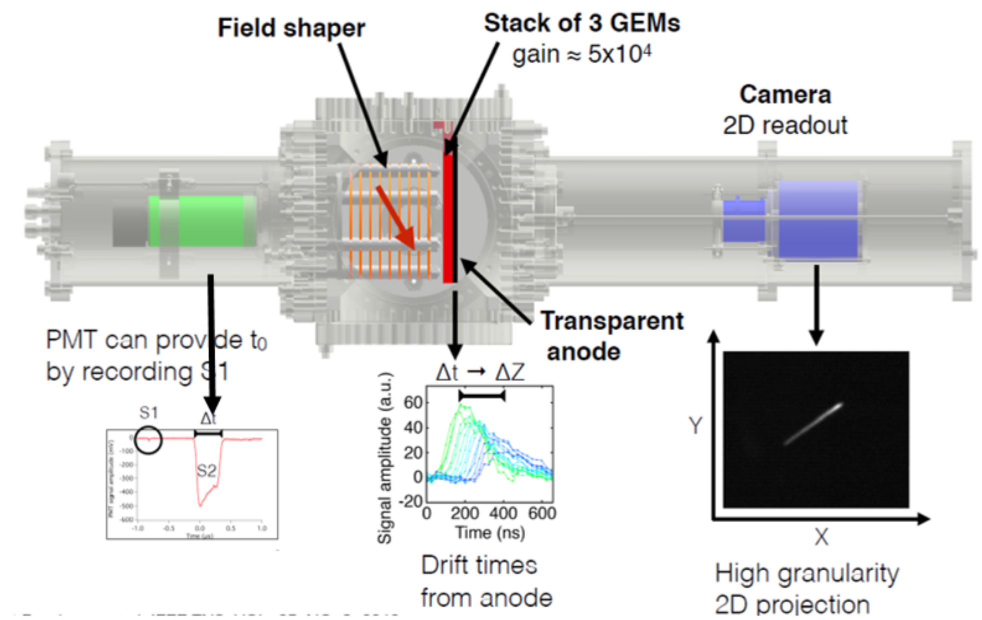
The pad plane is 25 cm in radius with 4 mm pads (square)

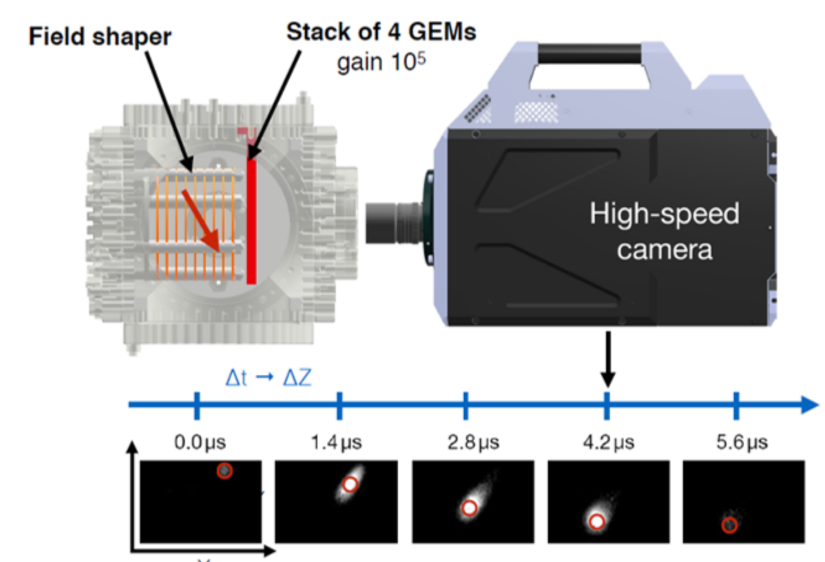
Here is a pad plane that mimics the gas multiplier (THGEM).
Implementation of meshes & GEMs is pending

From that projection in the pad plane, we will generate the optical photons.
Working on optimizing the model in order to model the production of photons along the avalanche.

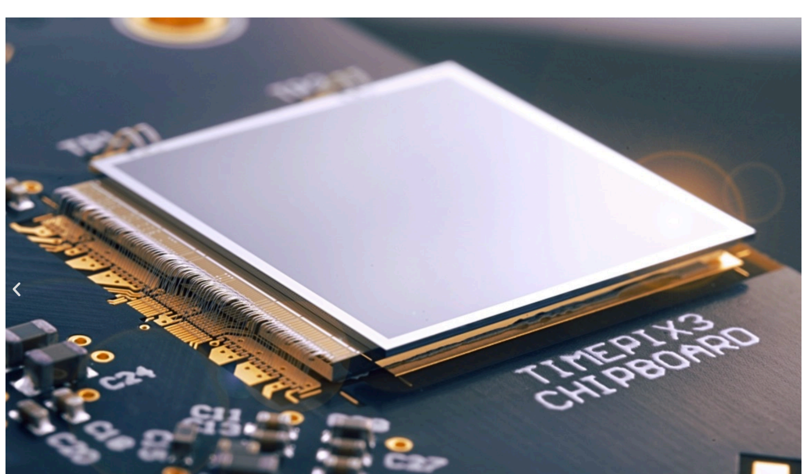
The optical readout system

- Avalanche-induced EL -> recorded by an optical system based on a TimePix3 camera. The primary scintillation signal and the time-tagged 2D camera images will provide 3D track images.
- Cluster structure could be seen in optically read images as well as in PMT wave-forms. Merging these two info can be used to associate timing information w/ 2D images.
- hybrid pixel detector, TPX3Cam consisting of a light-sensitive silicon sensor bump-bonded to a Timepix3, a time-stamping pixelated readout chip. When coupled to an image intensifier, the TPX3Cam allows for single-photon detection.
- The sensor-chip assembly has 256 x 256 pixels of 55 x 55 μm^2 each and a time resolution of 1.6 ns.





Recorded with 10 V/cm drift field corresponding to ≈0.5 cm/μs in Ar/CF_4



Outlook

- SARAF operation in pulsed mode, combined with high instantaneous beam currents (of the order of 5 mA), opens interesting possibilities for neutron time-of-flight experiments.
- SARAF has the potential to become a facility that is competitive with the world-leading TOF laboratories.
- A combination of SARAF neutron beams with TOF capability and a modern detector would allow the measurement of interesting, significant neutron-induced processes involving charged-particle products.
- The detector development lab at Weizmann has vast experience in the field of gaseous radiation detectors and related technologies.
- Current activities include detector prototyping and simulation studies. This will establish the operation conditions and properties of the O-TPC system. We test the auxiliary systems, gas, and DAQ, which are to be exploited for future data taking, analysis, computing, etc.
- The O-TPC system will be investigated first with radioactive sources, such as ^{252}Cf. Subsequently, it will be operated with pulsed neutron beams at SARAF. This should train us in the design and construction capabilities to realize a general-purpose detector for SARAF.

Thank you!