Advances in the development of a Vacuum Insulated Tandem Accelerator and its applications

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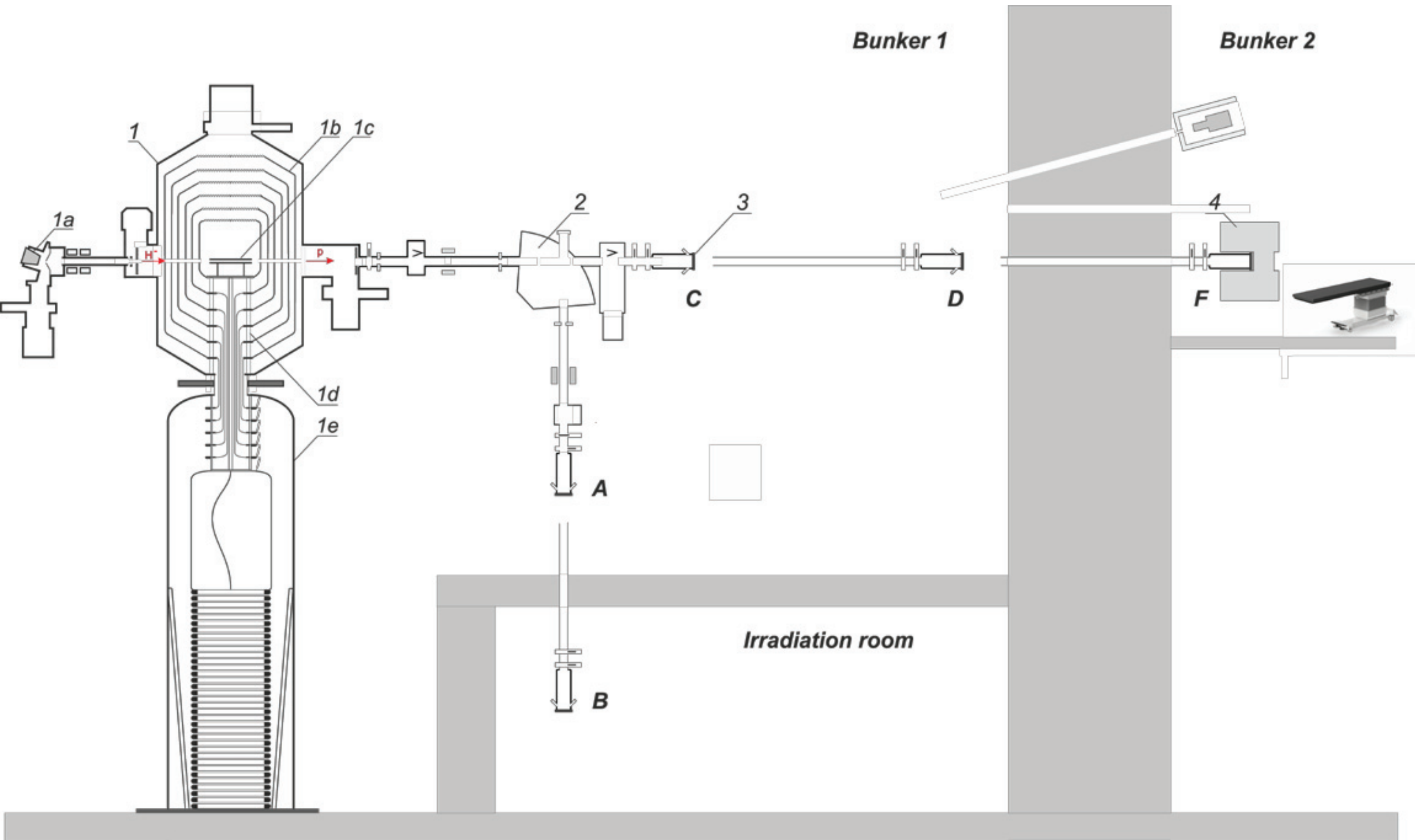
XXVII RuPAC
Alushta 2021

Achievements – significant
Applications – numerous

Facility is a state-of-the-art device comprised

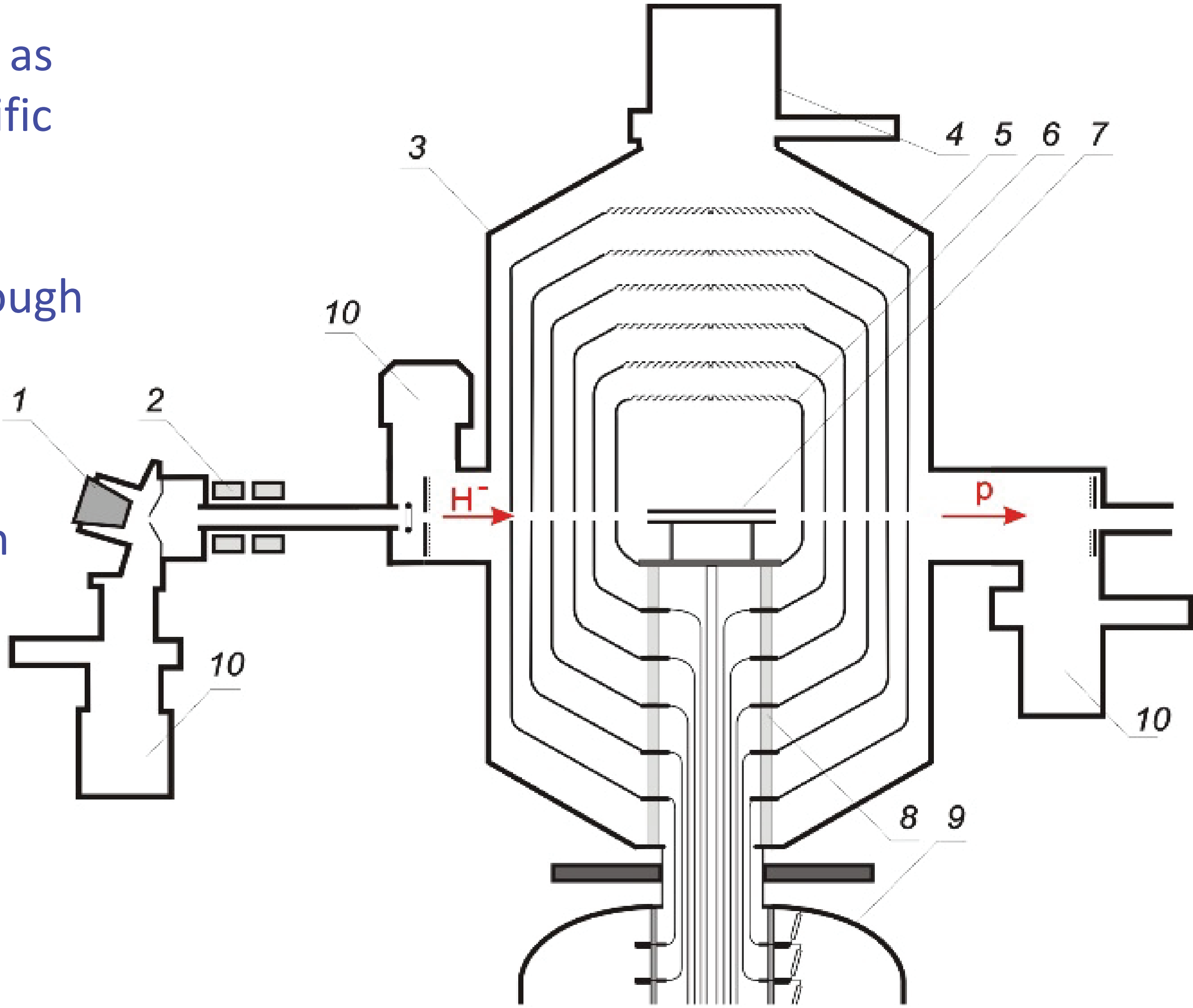
- the Vacuum Insulation Tandem Accelerator (VITA)
- a solid lithium target
- a Beam Shaping Assembly



The original design tandem accelerator, which was named as **Vacuum-Insulated Tandem Accelerator (VITA)**, has a specific design that does not involve accelerating tubes, unlike conventional tandem accelerators. Instead of those, the nested intermediate electrodes (*5*) fixed at single feedthrough insulator (*8*) is used, as shown in Figure.

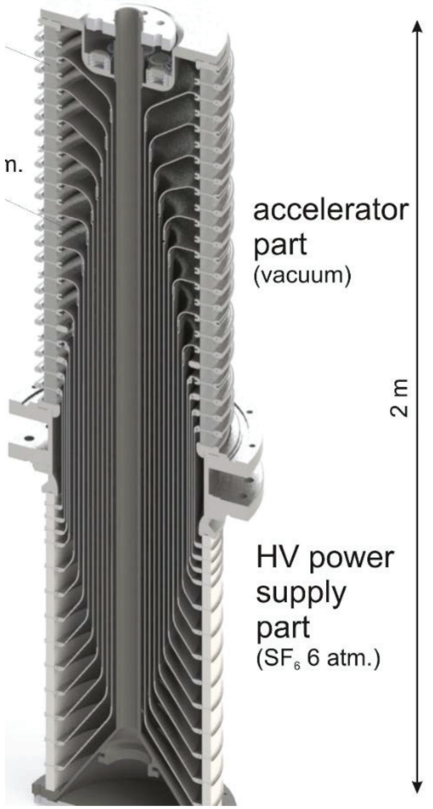
The advantage of such an arrangement is moving ceramic parts of the feedthrough insulator far enough from the ion beam, thus increasing the high-voltage strength of the accelerating gaps given high ion beam current.

A consequence of this design was also a fast rate of ion acceleration—up to 25 keV/cm.



VITA: 1 – H^- source, 2 – magnetic lenses,
3 – accelerator, 4 – cryogenic pump,
5 – intermediate electrodes, 6 – high-voltage electrode,
7 –gas stripper, 8 – insulator, 9 – high-voltage power supply,
10 – turbomolecular pumps.

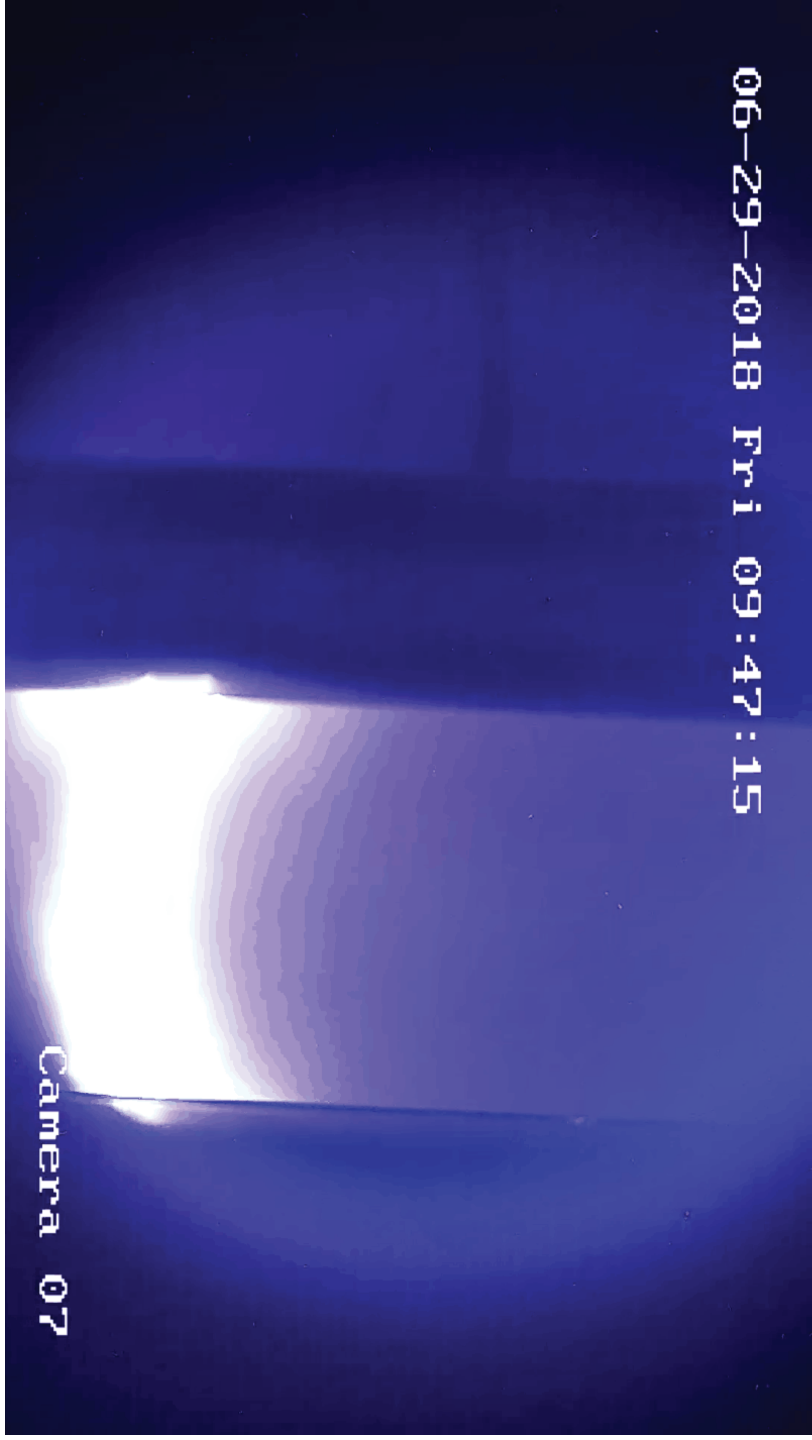
Advance # 1: elimination of high-voltage breakdowns



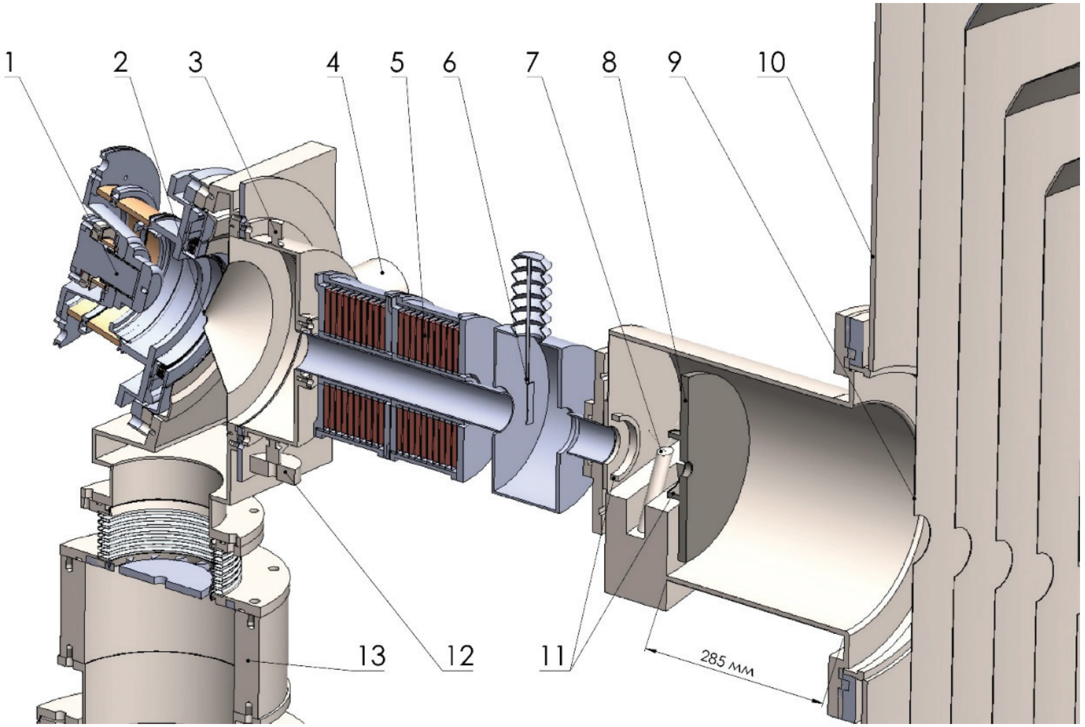
For the compactness of the accelerator, the average electric field strength on the insulator was chosen to be 14 kV/cm, which is 1.5 times higher than the recommended one.

This led to breakdowns along the surface of smooth ceramic insulators with a height of 73 mm, from which the feedthrough insulator was assembled.
Such breakdowns occurred approximately once every 10–20 min; they did not lead to a decrease in the electric strength of the accelerator, but required 15 s to restore the parameters of the ion beam.

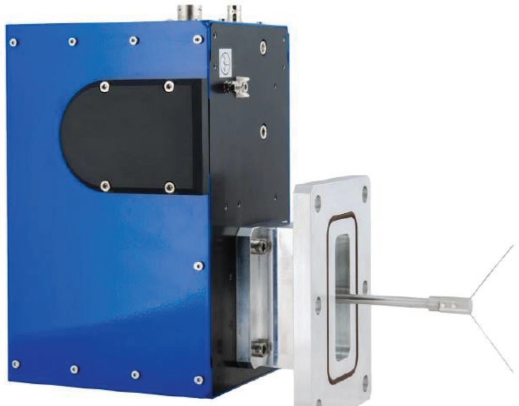
To eliminate breakdowns along the vacuum surface of insulators, smooth ceramic insulators were replaced with corrugated insulators.

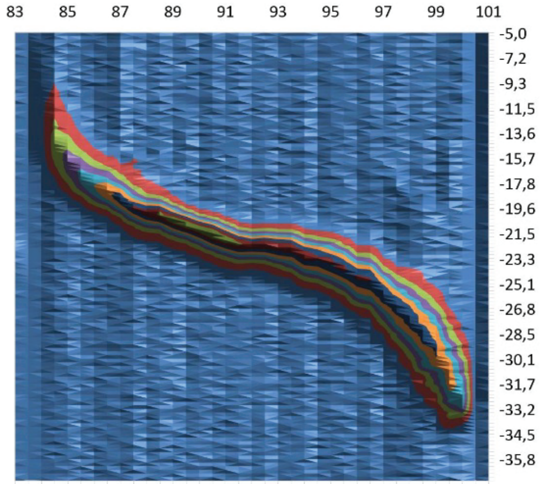


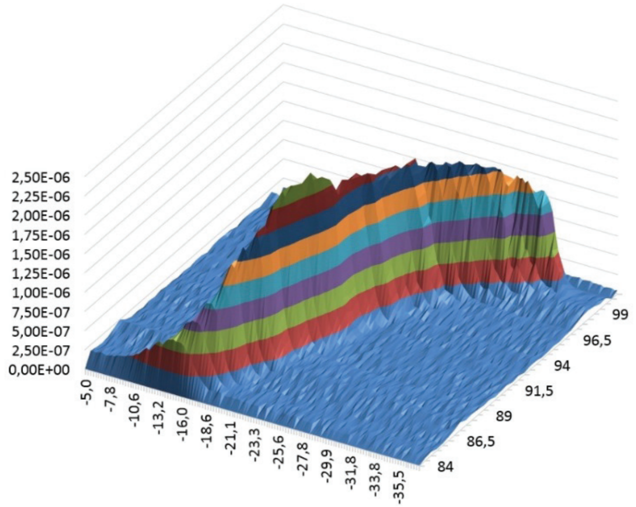
Advance # 2: wire scanner OWS-30 (D-Pace, Canada) is used to control the position and size of the ion beam at the entrance to the accelerat



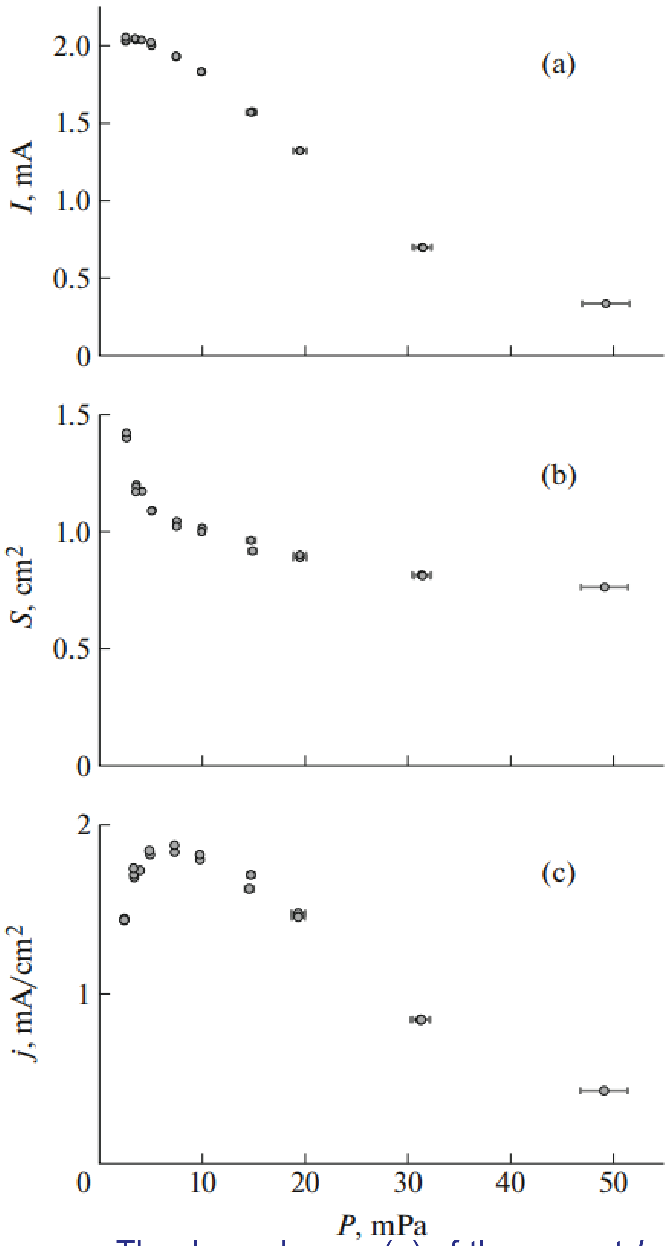
(1) source of negative hydrogen ions,
(2) cone diaphragm,
(3) vacuum lamp,
(4) turbomolecular pumps,
(5) magnetic lenses,
(6) movable diaphragm,
(7) OWS-30 wire scanner,
(8) cooled diaphragm,
(9) first electrode of the accelerator,
(10) vacuum tank of the accelerator,
(11) metal rings,
(12) leak valve.







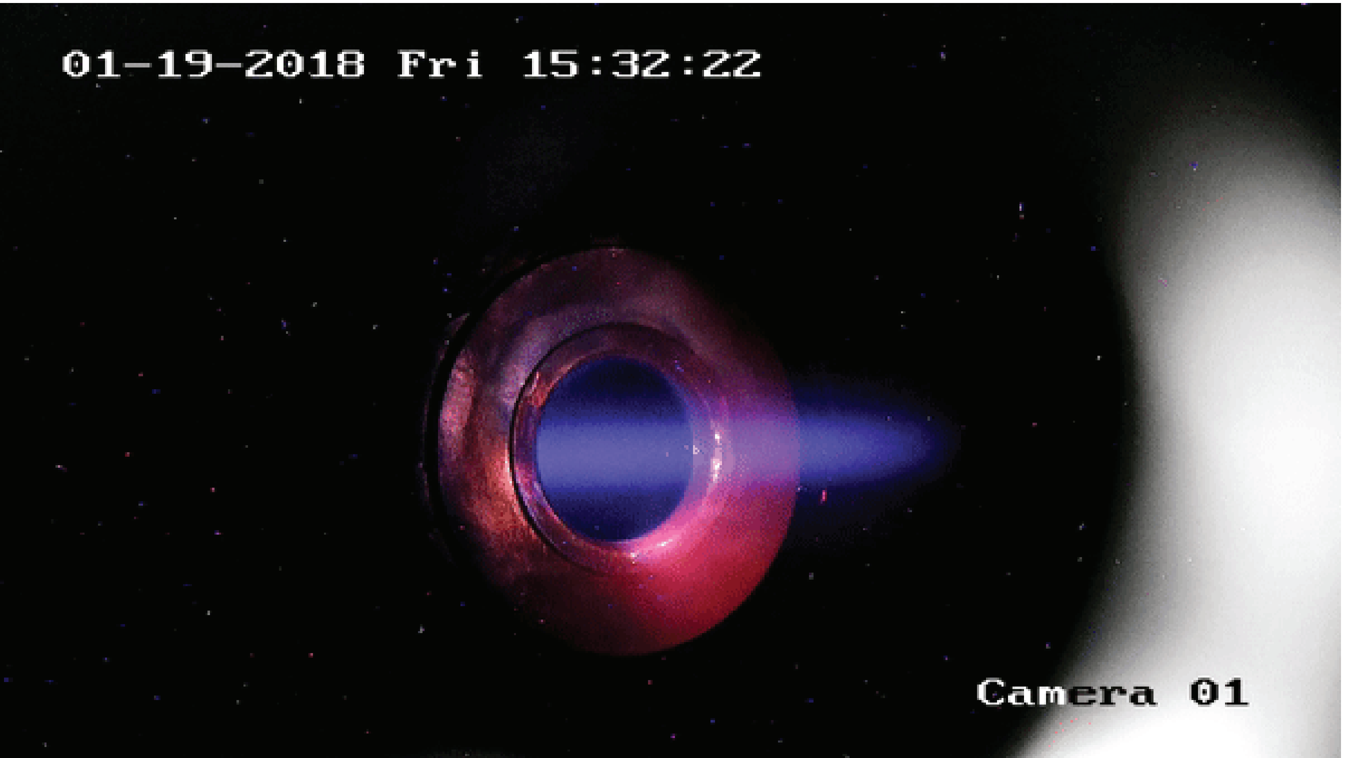
The phase portrait of the ion beam

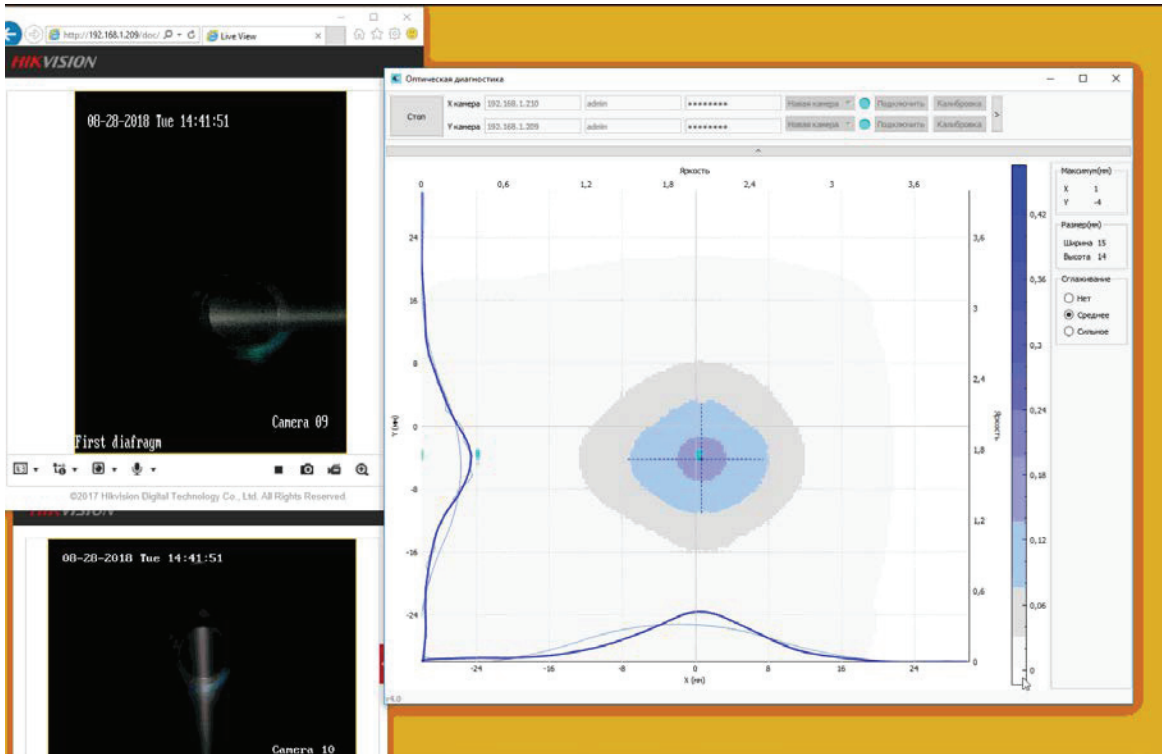


The dependences (a) of the current I, (b) the cross sectional area S, (c) the current density j of the ion beam on the residual gas pressure P

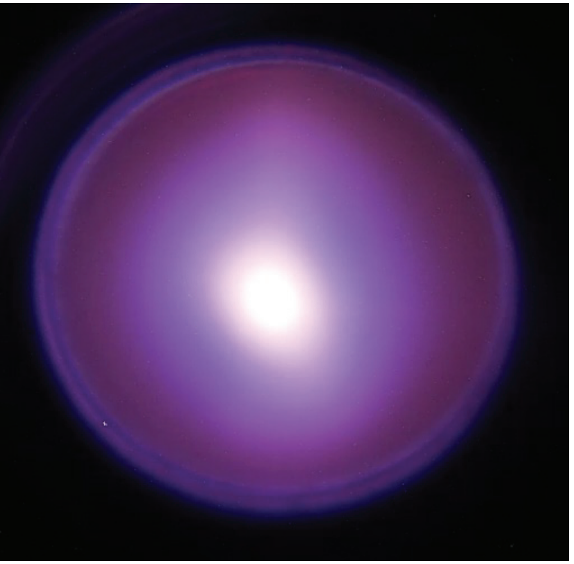
Advance # 3: The position and size of the ion beam in the accelerator are controlled by two pairs of video cameras overseeing the input and output diaphragms of the external accelerating electrode

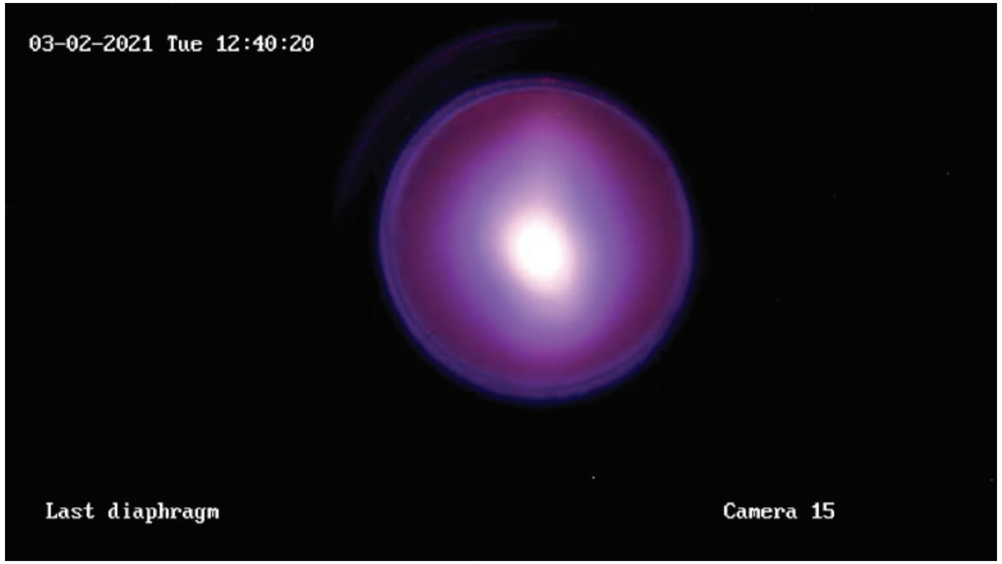
The presence of a gas stripper in a tandem accelerator is often considered a disadvantage. We managed to neutralize the disadvantages and turn the use of a gas stripper into an advantage. The additional gas flow makes it possible to visualize the beam for diagnostics of its position and size and improves the high-voltage strength of the accelerating gaps.

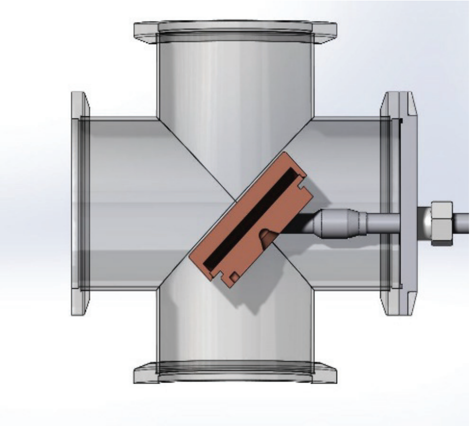


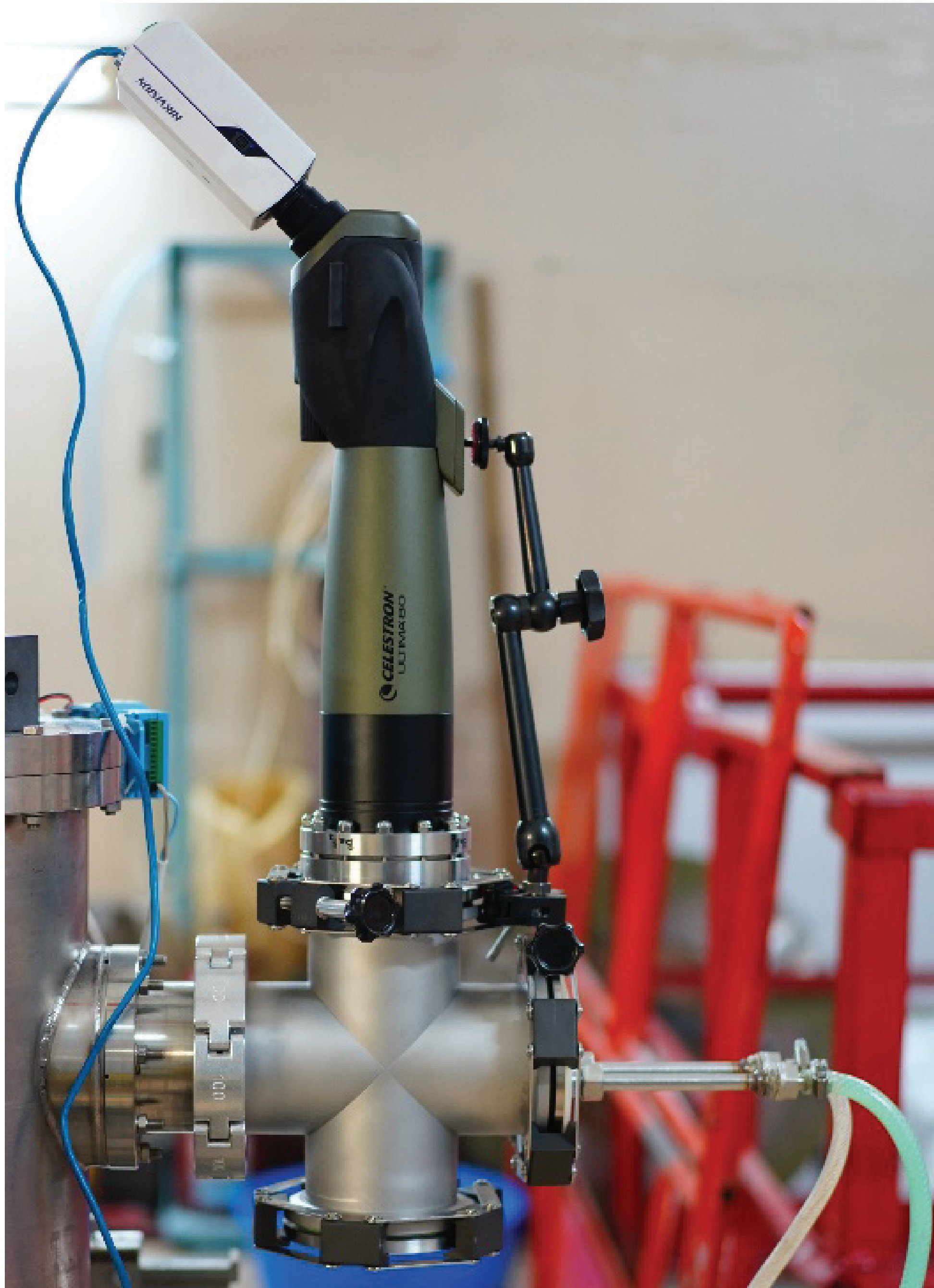


Advance # 4: The position and size of the ion beam inside the gas stripper is monitored with Celestron Ultima 80-45 telescope looking axially through a cooled mirror.





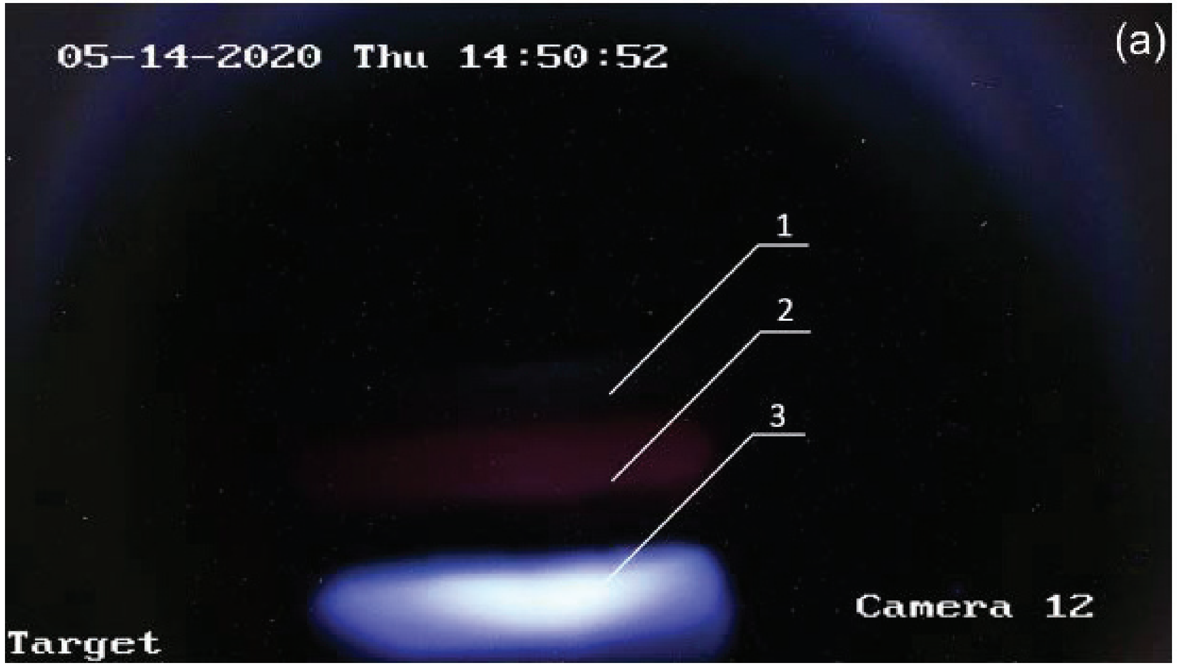




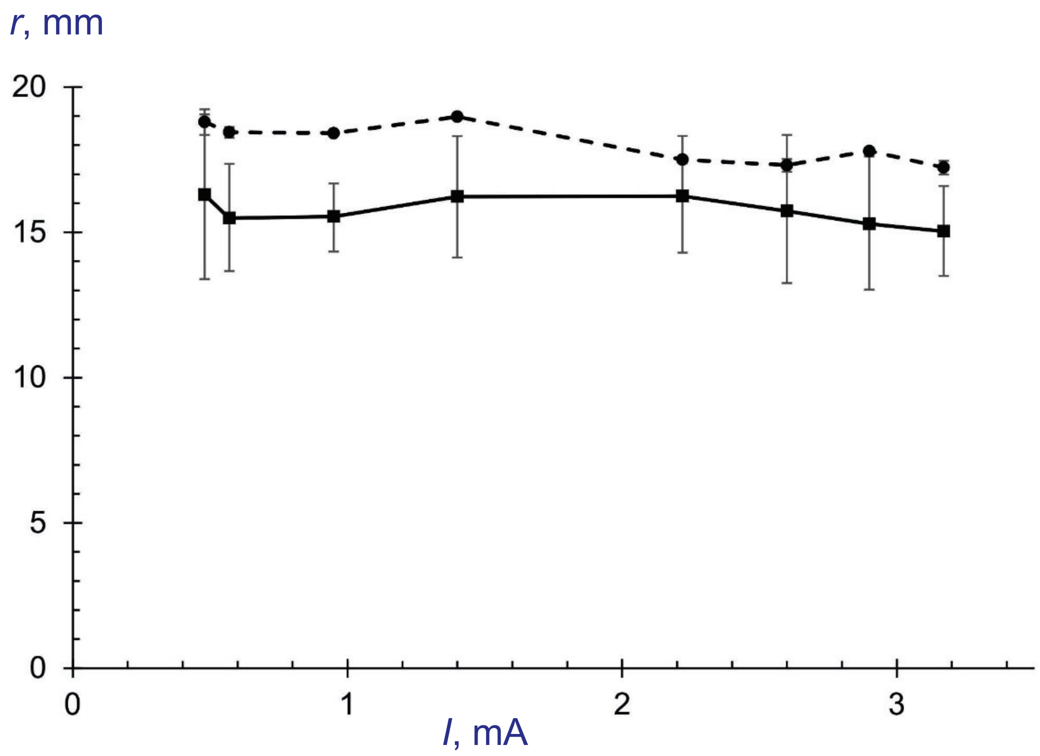
Advance # 5: The magnitude of the argon ion beam current was measured by mass spectroscopy using a bending magnet and a cooled diaphragm; it is 2000 times smaller than the proton beam current.

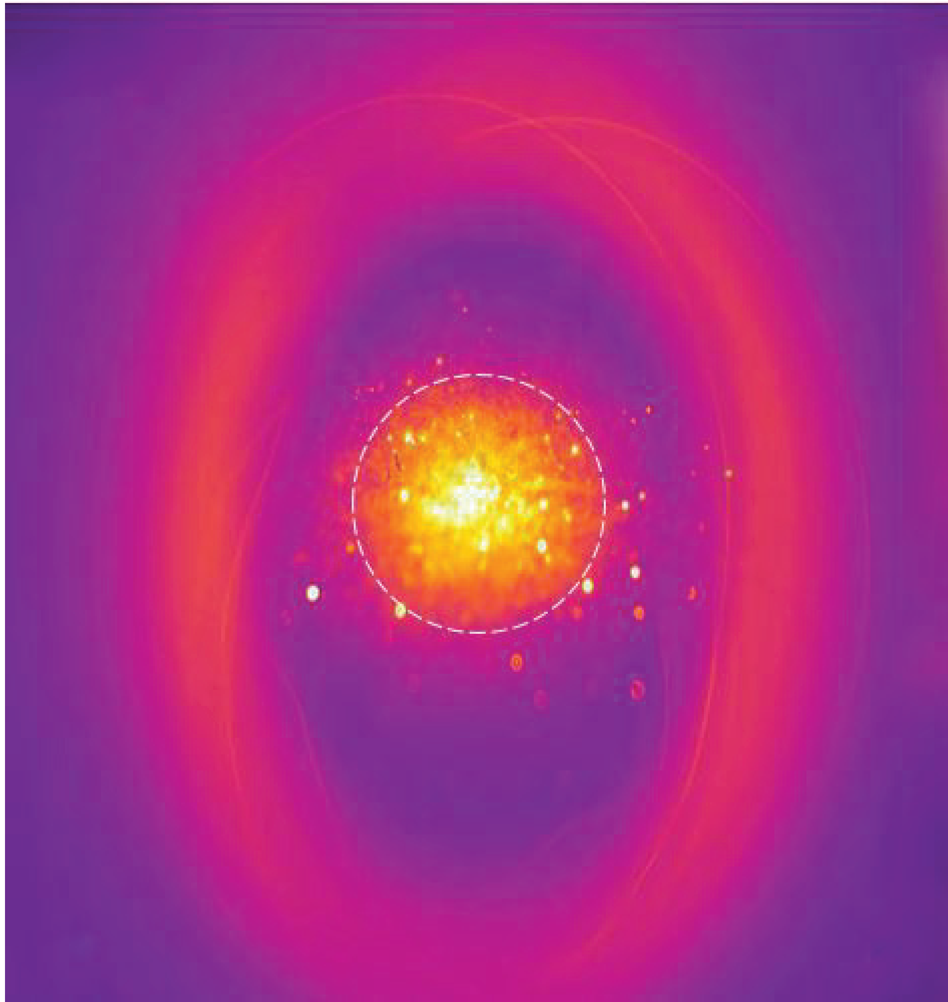
The reliability of the measurement is provided by visualization of an argon ion beam on the surface of a lithium target, as confirmed by an experiment with increased gas injection and an estimate of the possible contribution of the proton beam.

Such a small value of the current of the argon ion beam poses no danger either as an additional heating of the lithium target or as an additional load of a high-voltage power supply and therefore does not require the previously proposed suppression means.



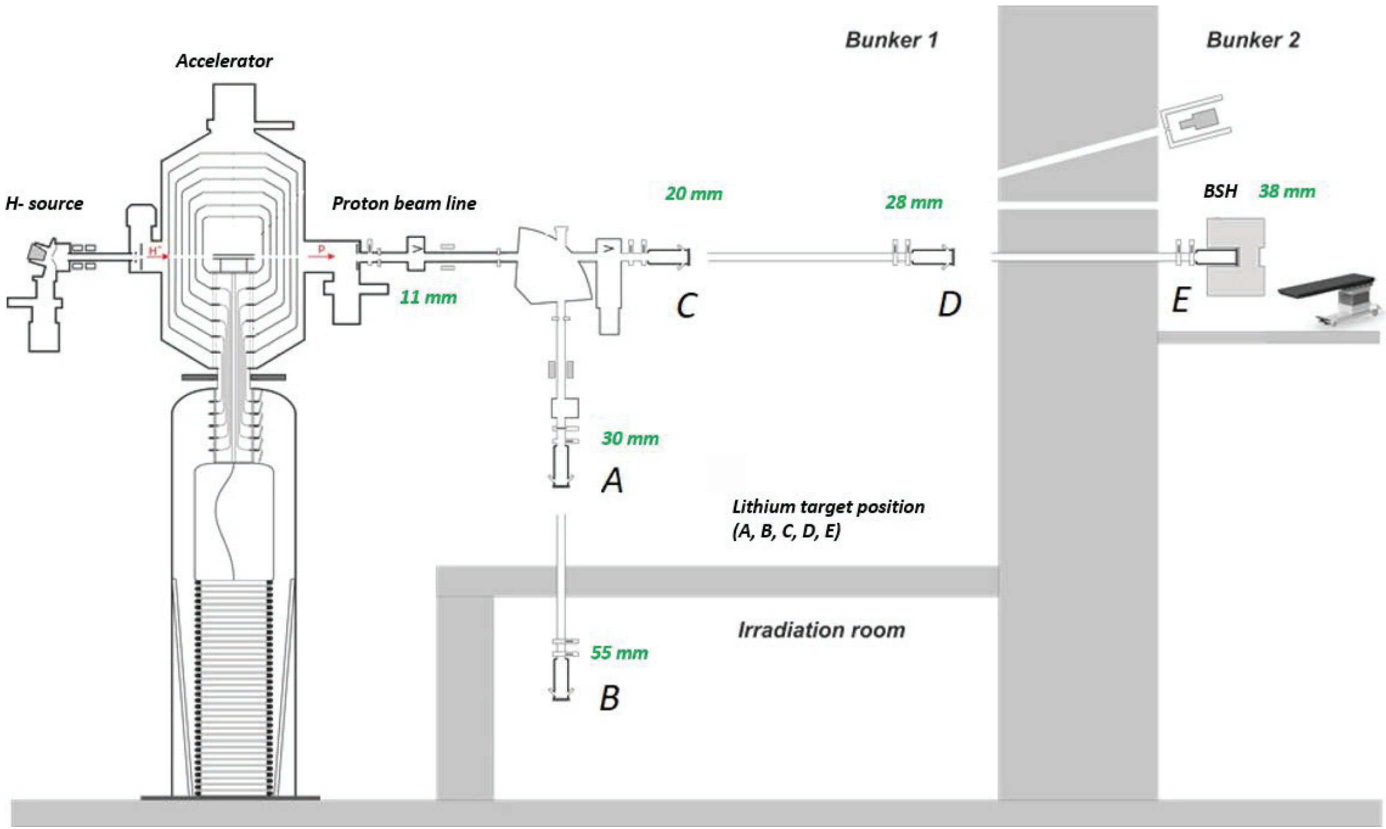
Advance # 6: No appreciable influence of the spatial charge on the proton beam transport.

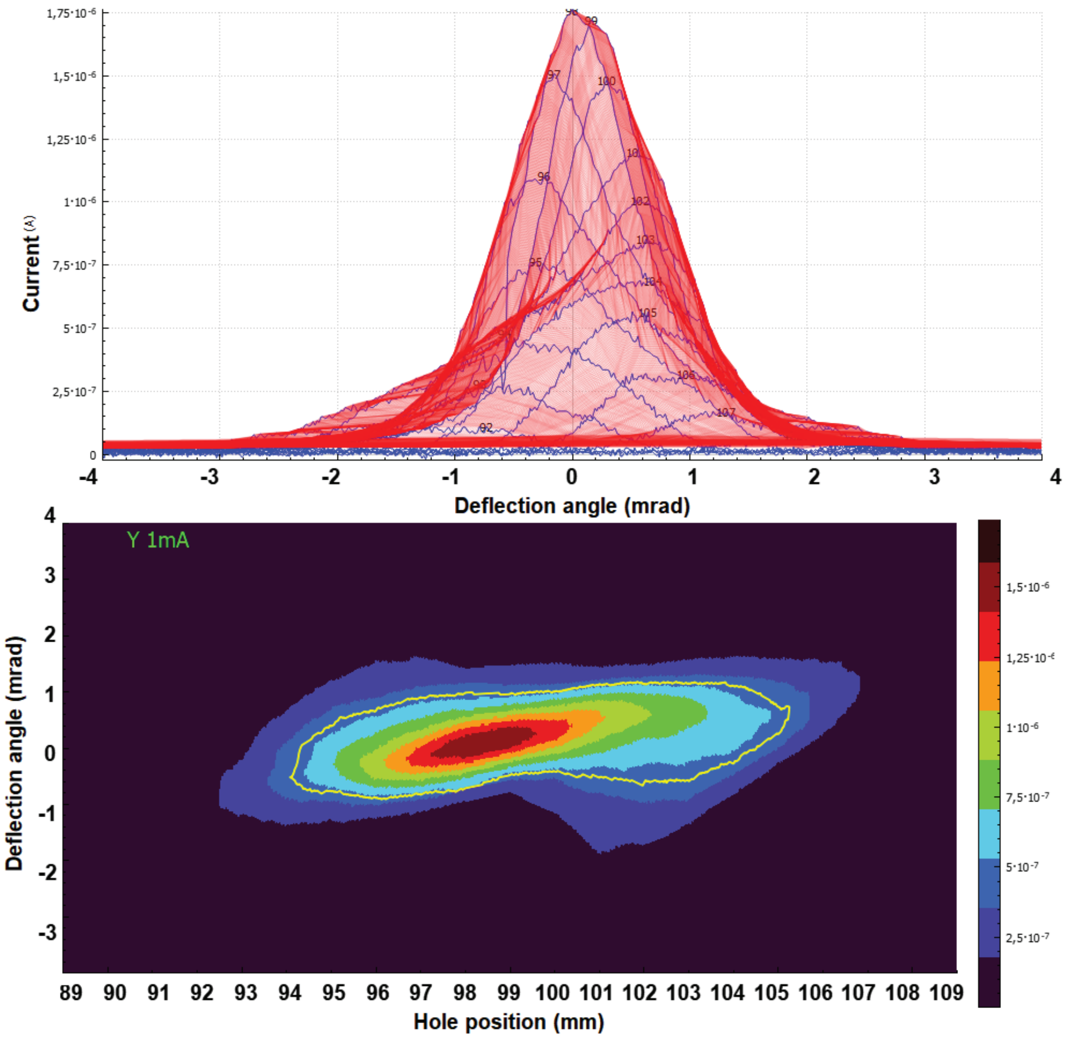




Advance # 7: 9 methods for measuring the proton beam profile implemented. Phase portrait of a beam of protons and neutrals measured.

The proton beam has a characteristic size of 11 mm,
a divergence of 1.5 mrad,
and a normalized emittance of 0.23 mm mrad.





RESULT:

High power DC proton/deuteron beam (20 kW):
Monochromaticity and stability: 0.1%
Energy: ranges from 0.6 MeV to 2.3 MeV
Current: ranges from 1 pA to 10 mA (10 orders!)

High flux neutron beam (2 10^{12} s^{-1}):
- thermal (D_2O or Plexiglas moderator)
- epithermal (MgF_2 moderator)
- exclusively epithermal (no fast and thermal)
- over-epithermal
- monoenergetic (kinematic collimation)
- fast

Bright source of photons:
- 478 keV - $^{7}Li(p,p'\gamma)^{7}Li$
- 511 keV – $^{19}F(p,\alpha e^{+}e^{-})^{16}O$

- **α-particles** in $^{7}Li(p,\alpha)\alpha$ and $^{11}B(p,\alpha)\alpha\alpha$
- **positrons** in $^{19}F(p,\alpha e^{+}e^{-})^{16}O$

Application # 1: Boron Neutron Capture Therapy

Neutron source VITA meets the requirements of BNCT to the greatest extent

The neutron source VITA commercialized by TAE (CA, USA):

1st source is installed in new BNCT Center at Xiamen Humanity Hospital in Xiamen, P.R. China in 2020. It is planned to start treatment in early 2022;

2nd source will be made for National Oncological Hadron Therapy Center (CNAO) in Pavia, Italy;

3rd source will be made for National Medical Research Center of Oncology in Moscow, Russia;

- *I hope the list will go on*

tae LIFE SCIENCES

NEUBORON

CNAO
Centro Nazionale di Adroterapia Oncologica

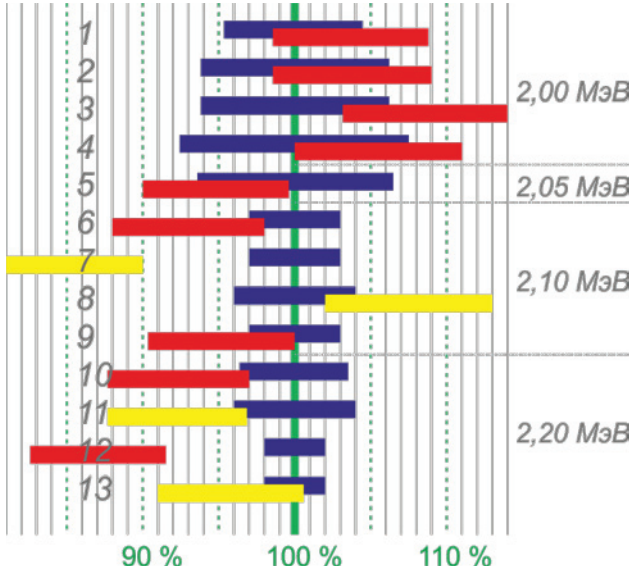
НМИЦ
ОНКОЛОГИИ
им. Н. Н. Блохина

Visit
of the Prime Minister
of the Russian Federation
M. Mishustin to BINP
March 05, 2021

Application # 1: Boron Neutron Capture Therapy

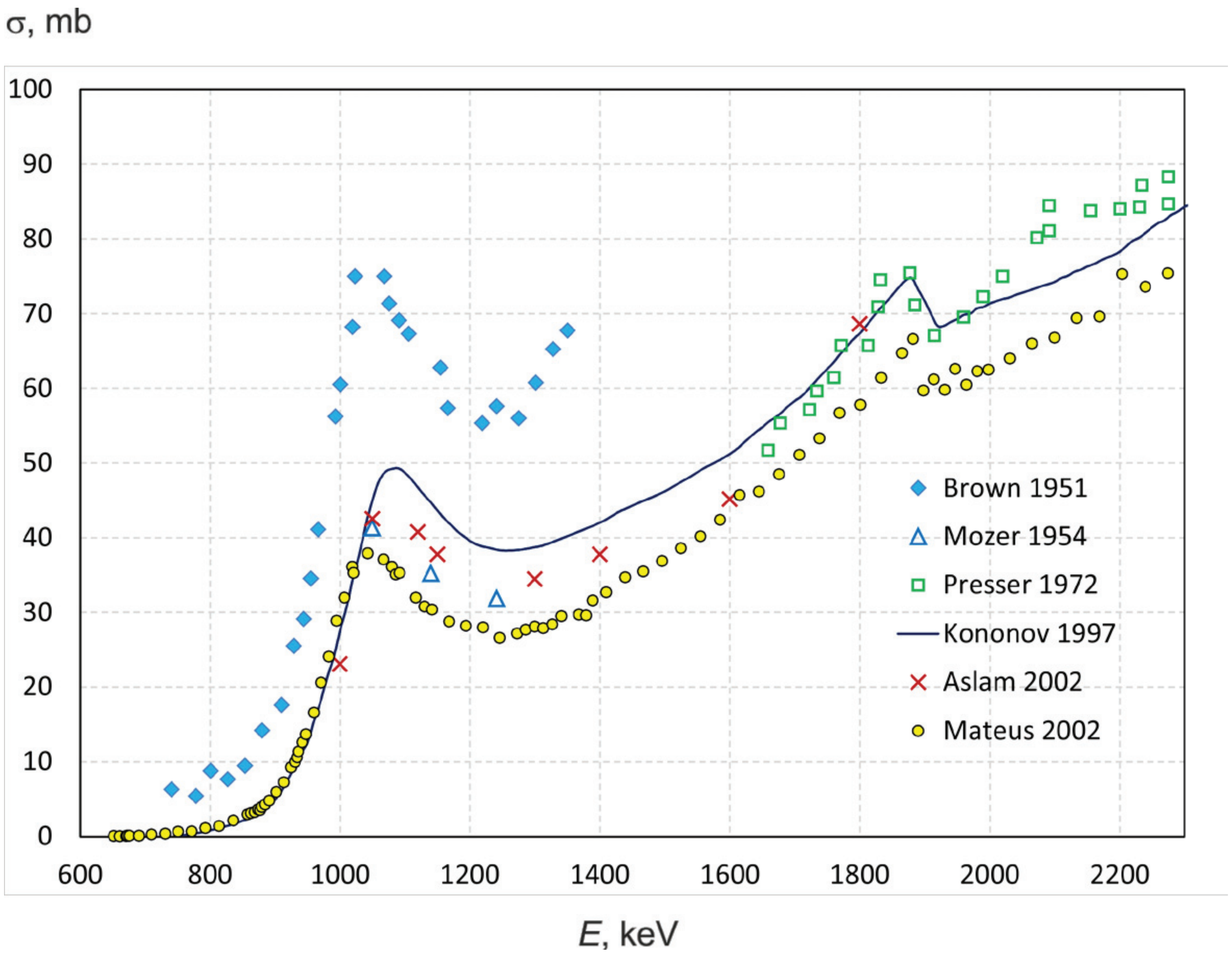
Our new results:

- A small-sized detector for measuring boron dose and gamma-ray dose is developed and used [JINST 16 (2021) P01024];
- New method for measuring the sum of the fast neutron dose and the nitrogen dose is proposed and implemented [Radiation Research 196 (2021) 192-196];
- New method for *in situ* measuring the lithium layer thickness is proposed and implemented [JINST 15 (2020) P10006];
- The neutron yield of the $^7Li(p,n)^7Be$ reaction in lithium target was measured [Biology 10 (2021) 824];
- A number of new boron delivery drugs have been tested [Intern. J. Molecular Sciences 22 (2021) 7326; Intern. J. Radiation Oncology, Biology, Physics; Pharmaceutics 13 (2021) 1490; Chemical Phys. Letters; …]
- Our patent on new boron delivery drug, jointly with colleagues from Moscow, [RU2729458, WO 2020/246913] is recognized as the best Russian invention of the 21st century.



Application # 2: Fundamental knowledge

$^7Li(p,p'\gamma)^7Li$ reaction cross-section



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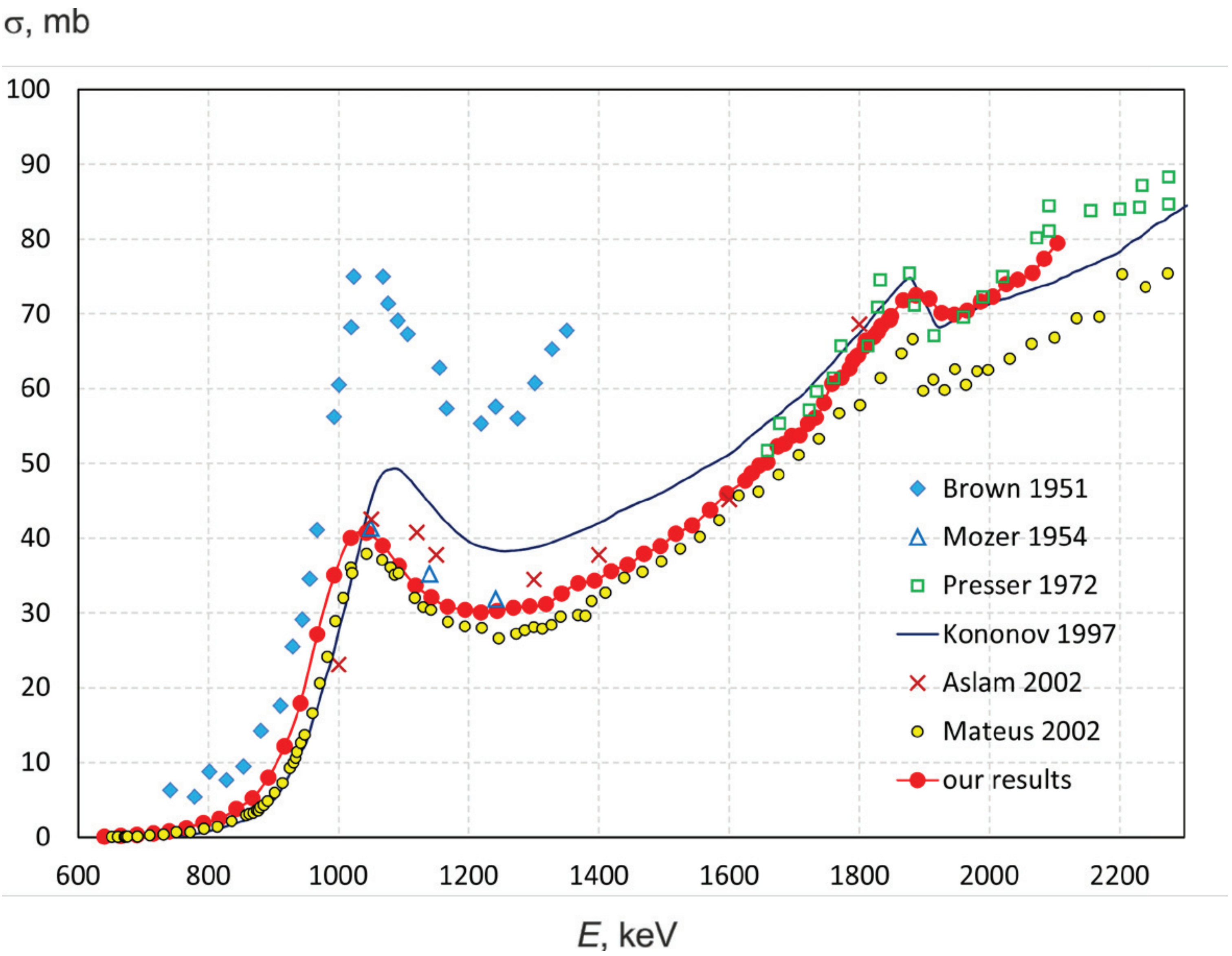
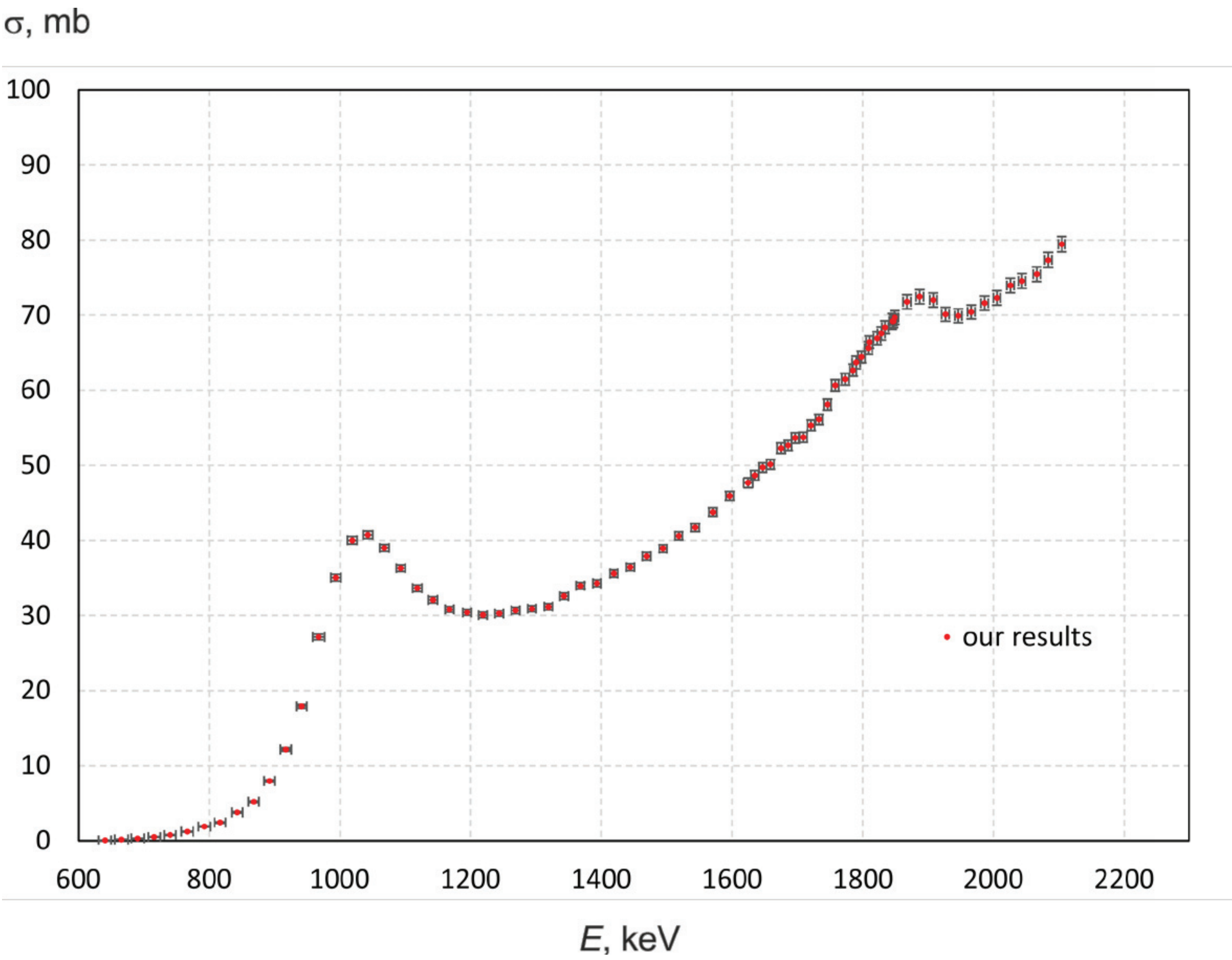


[Nucl. Instrum. Methods Phys. Res., Sect. B, vol. 502, pp. 85-94, June 2021]

Application # 2: Fundamental knowledge

$^{7}Li(p,p'\gamma)^{7}Li$ reaction cross-section



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Application # 2: Fundamental knowledge

^{7}Li(p,p‘γ)^{7}Li reaction cross-section

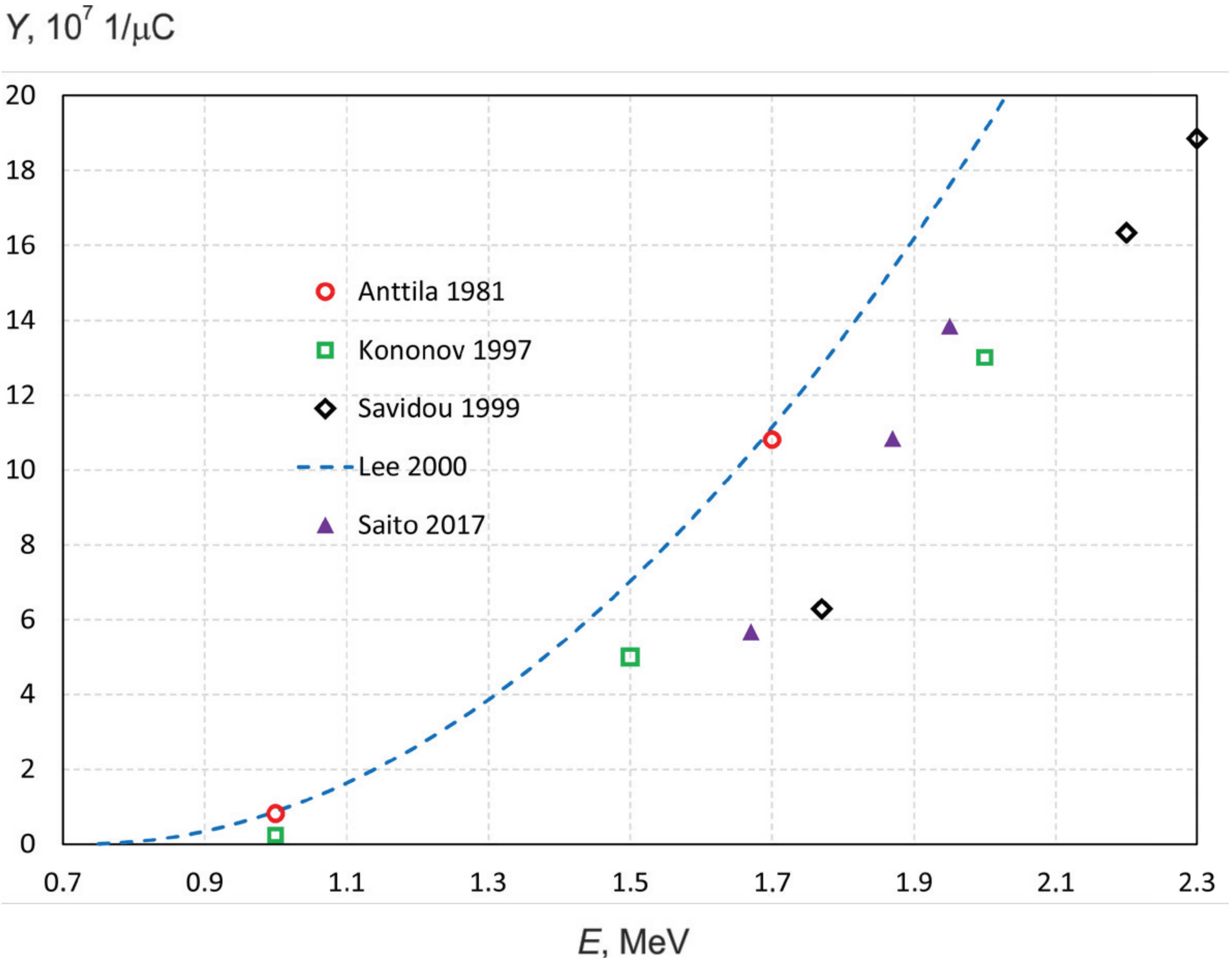
Table 2
^{7}Li(p,p’γ)^{7}Li reaction cross section.

E, keV	Δ*E*, keV	σ, mb	Δσ, mb
640.1	9.7	0.065	0.013
665.3	10.0	0.176	0.026
690.5	9.5	0.36	0.04
715.8	9.3	0.50	0.04
740.0	9.1	0.78	0.04
766.2	9.0	1.23	0.05
792.4	8.8	1.91	0.06
816.5	8.5	2.45	0.07
842.7	8.4	3.78	0.09
867.9	8.4	5.22	0.11
892.0	8.1	7.97	0.14
917.2	8.1	12.16	0.23
941.3	8.0	17.91	0.27
967.4	9.1	27.15	0.38
993.6	7.5	35.05	0.49
1018.7	7.4	40.03	0.50
1042.8	7.3	40.75	0.48
1067.9	7.1	39.01	0.47
1093.0	7.0	36.32	0.44

[Nucl. Instrum. Methods Phys. Res., Sect. B, vol. 502, pp. 85-94, June 2021]

Application # 2: Fundamental knowledge

478 keV photon yield from a thick lithium target



Application # 2: Fundamental knowledge

478 keV photon yield
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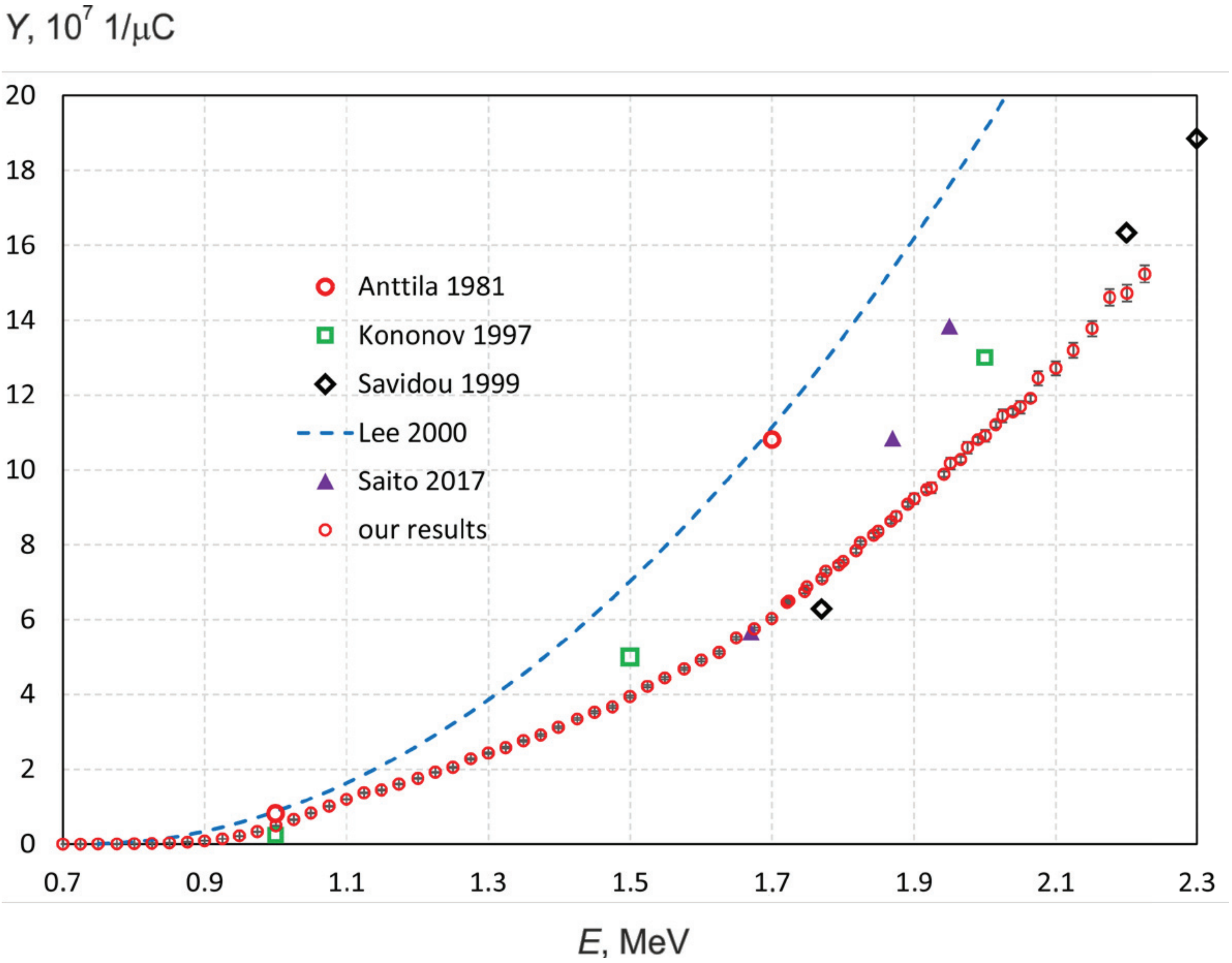

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Application # 2: Fundamental knowledge

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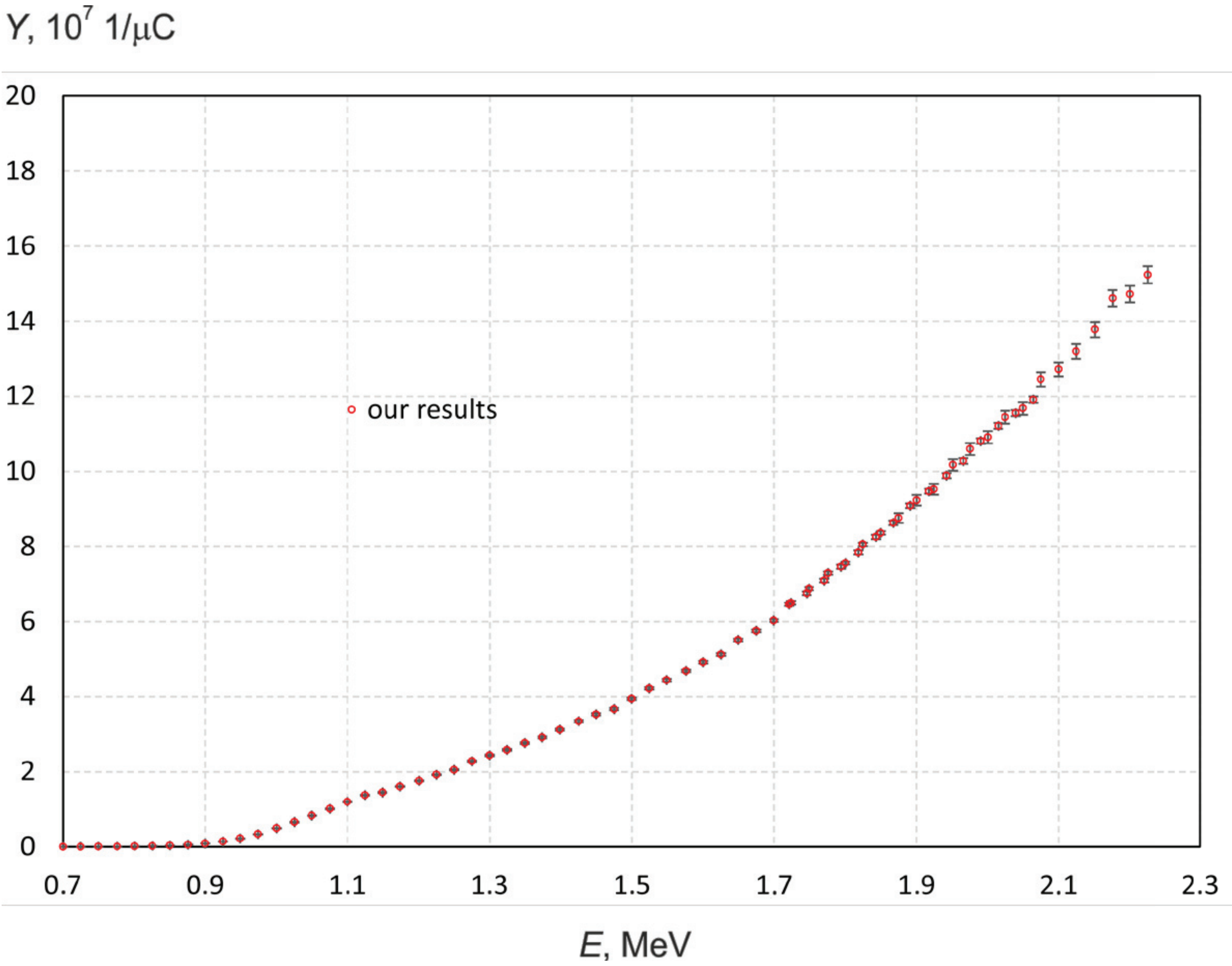


[Nucl. Instrum. Methods Phys. Res., Sect. B, vol. 502, pp. 85-94, June 2021]

Application # 2: Fundamental knowledge

478 keV photon yield from a thick lithium target

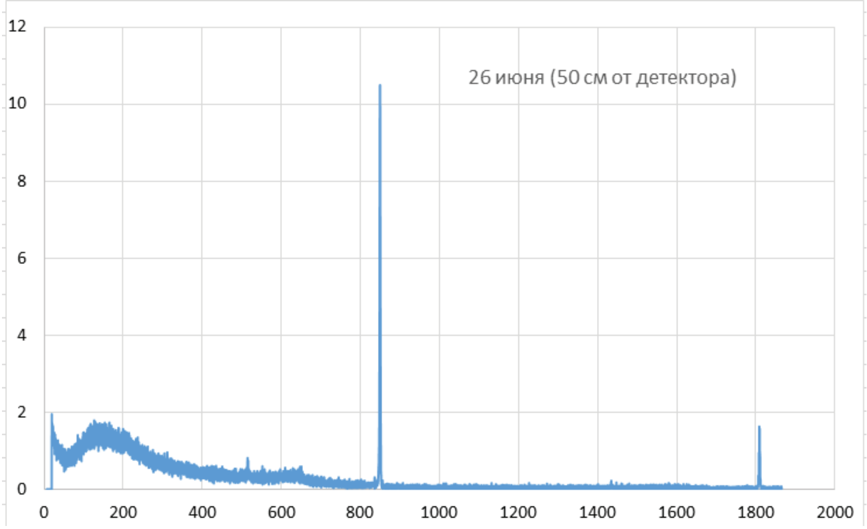
Table 1
478 keV photon yield from a thick natural lithium target.

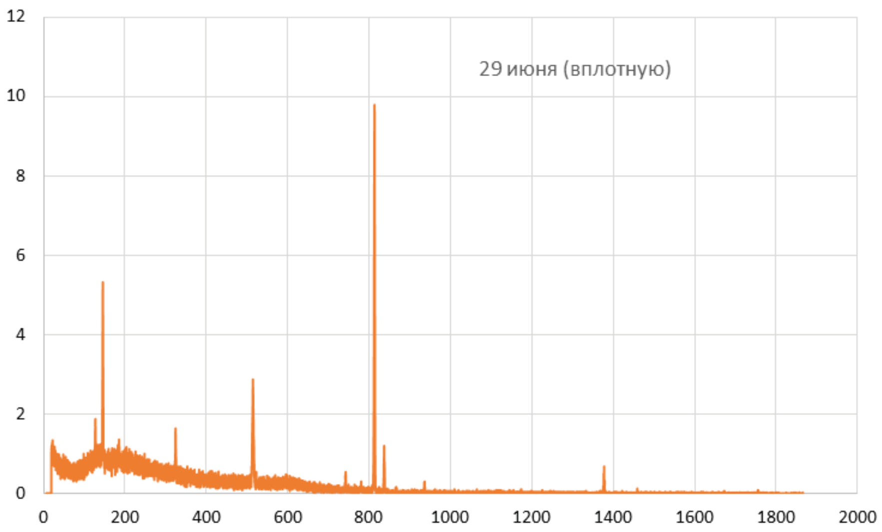
E, keV	Δ*E*, keV	*Y*, 10^7 μC^{-1}	Δ*Y*, 10^7 μC^{-1}
650.2	1.2	0.00058	0.00008
675.5	0.9	0.0010	0.0001
700.1	1.0	0.0020	0.0002
724.9	0.9	0.0037	0.0002
749.5	1.0	0.0059	0.0002
776.2	1.1	0.0102	0.0002
800.6	1.1	0.0158	0.0003
825.5	1.1	0.0255	0.0003
850.2	1.2	0.0386	0.0005
875.4	1.2	0.0593	0.0006
900.1	1.1	0.0919	0.0007
924.6	1.2	0.143	0.0009
949.3	1.4	0.224	0.001
974.0	1.1	0.340	0.001
1000.6	1.4	0.496	0.002
1025.3	1.4	0.661	0.011
1050.0	1.6	0.834	0.008
1075.3	1.4	1.01	0.01
1099.9	1.8	1.20	0.01

[Nucl. Instrum. Methods Phys. Res., Sect. B, vol. 502, pp. 85-94, June 2021]

Application # 3: ITER

Boron carbide ceramics and steel 316L(N)-ITER Grade for ITER (Cadarache, France) were tested by thermal and fast neutrons

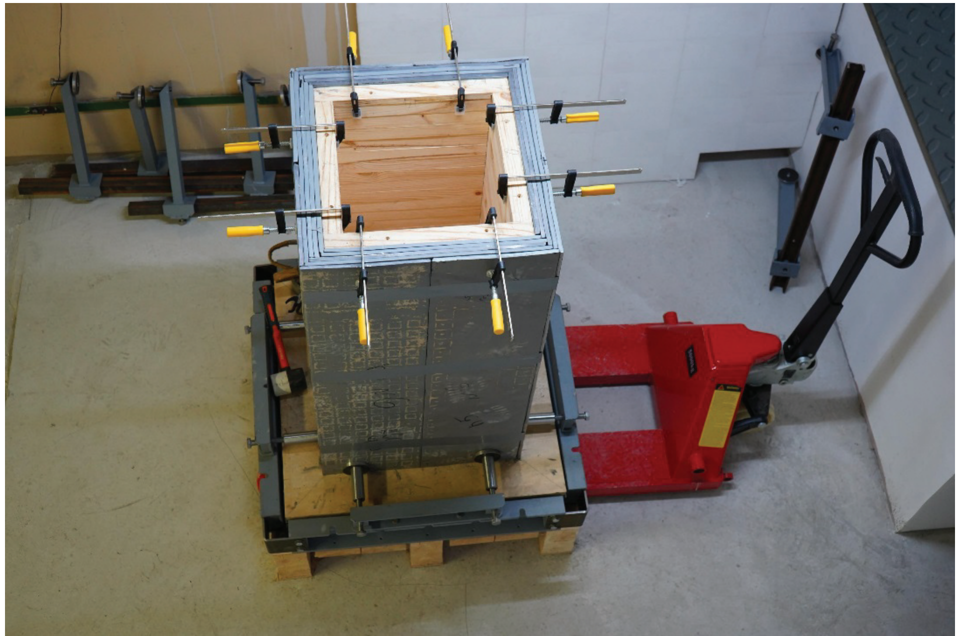




[Fusion Eng. Des., vol. 168, 112426, March 2021; Nuclear Fusion (2021)]

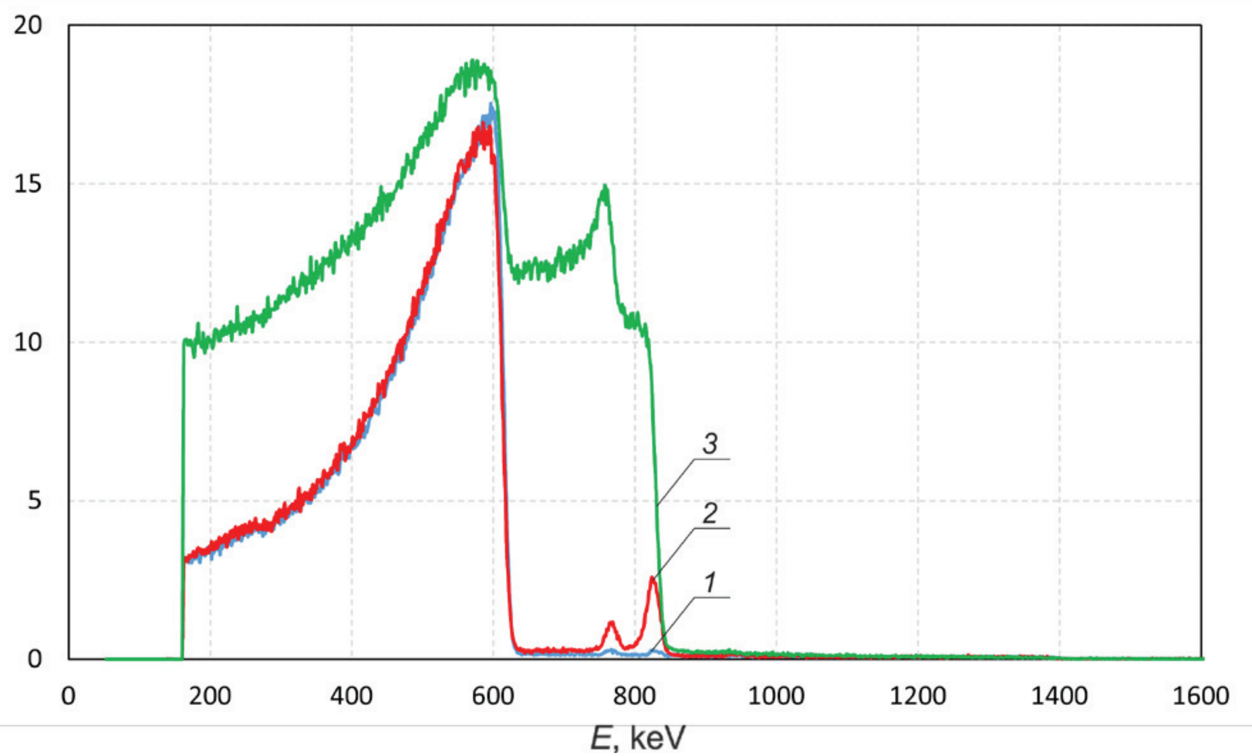
Application # 4: CERN

The neutron source is planned to be used for radiation tests of fibers of the laser calorimeter calibration system of the Compact Muon Solenoid electromagnetic detector developed for the High-Luminosity Large Hadron Collider in CERN

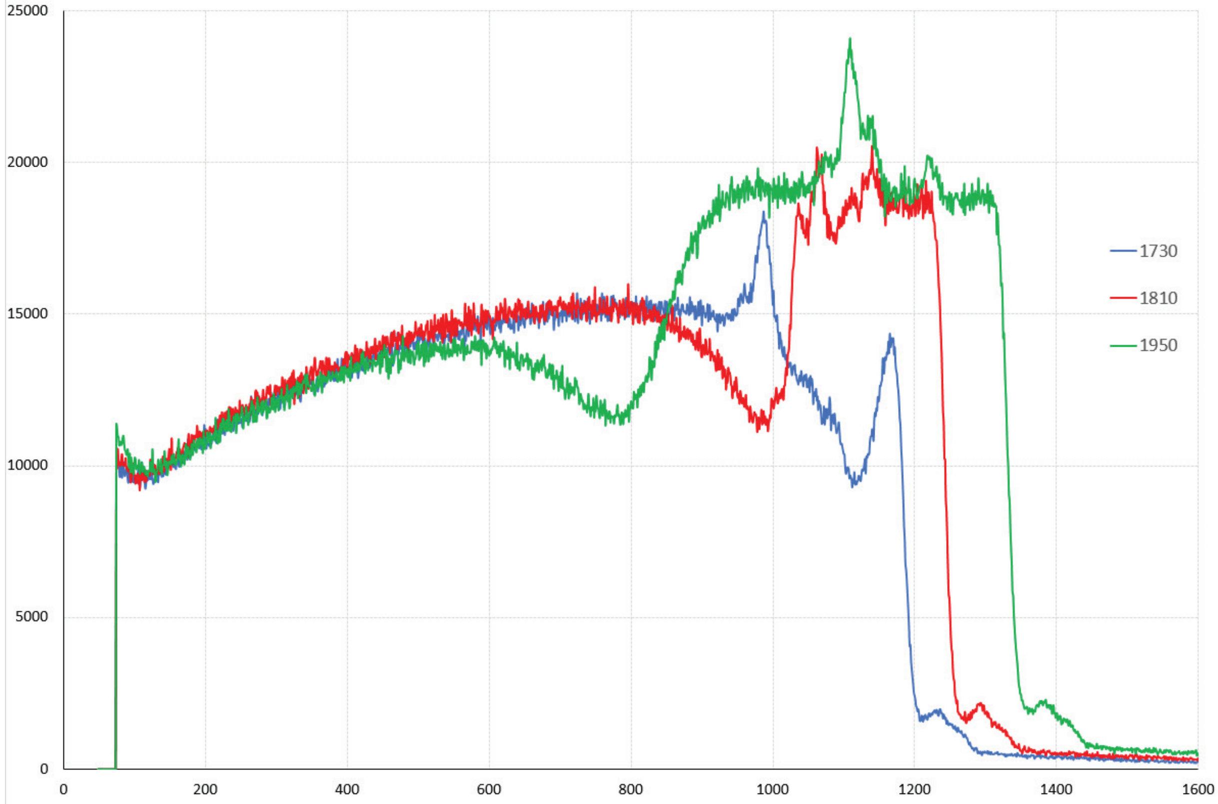


Application # 5: Proton microscope

elemental analysis of the surface of materials by backscattered protons



Signals of the alpha-spectrometer upon irradiation with 1 MeV protons of the freshly deposited lithium layer of the target (1) and the lithium layer after deliberate admission of atmospheric air into the target unit for 10 min (2) and for 1 h (3)



We determine that on the surface of the freshly deposited lithium layer there are lithium oxide of 2.4 ×10^{16} atoms/cm^2 density (~ 6 nm of lithium oxide of crystal density) and carbon over it of 6×10^{15} atoms/cm^2 density (~ 0.5 nm of carbon of crystal density)

150 nm boron carbonitride film on 0.5 mm silicon substrate

Our plans:

- to make a unique proton micro- nanoscope;
- to test new boron delivery drugs for many researchers groups;
- to study the radiation resistance of optical fibers developed for the High-Luminosity Large Hadron Collider in CERN jointly with Saclay Nuclear Research Center (France);
- to study the activation of materials developed for ITER (France) jointly with Russian ITER team;
- to study the energy and angular characteristics of the $^{11}B(p,\alpha)\alpha\alpha$ reaction products jointly with BINP detectors laboratory;
- to characterize the epithermal neutron field jointly with the Laboratory of Subatomic Physics and Cosmology CNRS-IN2P3, Grenoble-Alpes University (France) and the Laboratory of Micro-Irradiation, Metrology, and Neutron Dosimetry, IRSN (Cadarache, France);
- to develop boron imaging technique jointly with the University of Pavia (Italy), and the Due2lab s.r.l. (Parma, Italy);
- to produce ultracold neutrons and focus them jointly with National Laboratory of Frascati (Italy);
- to realize new ideas in VITA, lithium target, and BSA for an even better neutron source for BNCT clinics;
- …

CONCLUSION

Neutron source based on VITA and lithium target is in operation now

This source produces:

- DC proton/deuteron beam (0.6 MeV – 2.3 MeV; 1 pA – 10 mA)
- Neutrons – thermal, epithermal, over-epithermal, monoenergetic, fast
- Photons – 478 keV, 511 keV
- α-particles – $^{7}Li(p,\alpha)\alpha$, $^{11}B(p,\alpha)\alpha\alpha$
- Positrons – $^{19}F(p, \alpha e^{-}e^{+})^{16}O$

We are open for joint research

This work was supported by the Russian Science Foundation (grant number 19-72-30005)

Российский научный фонд

Thank you for your attention!