Recent Achievements in Studies of Negative Beam Formation and Acceleration in the Tandem Accelerator at Budker Institute

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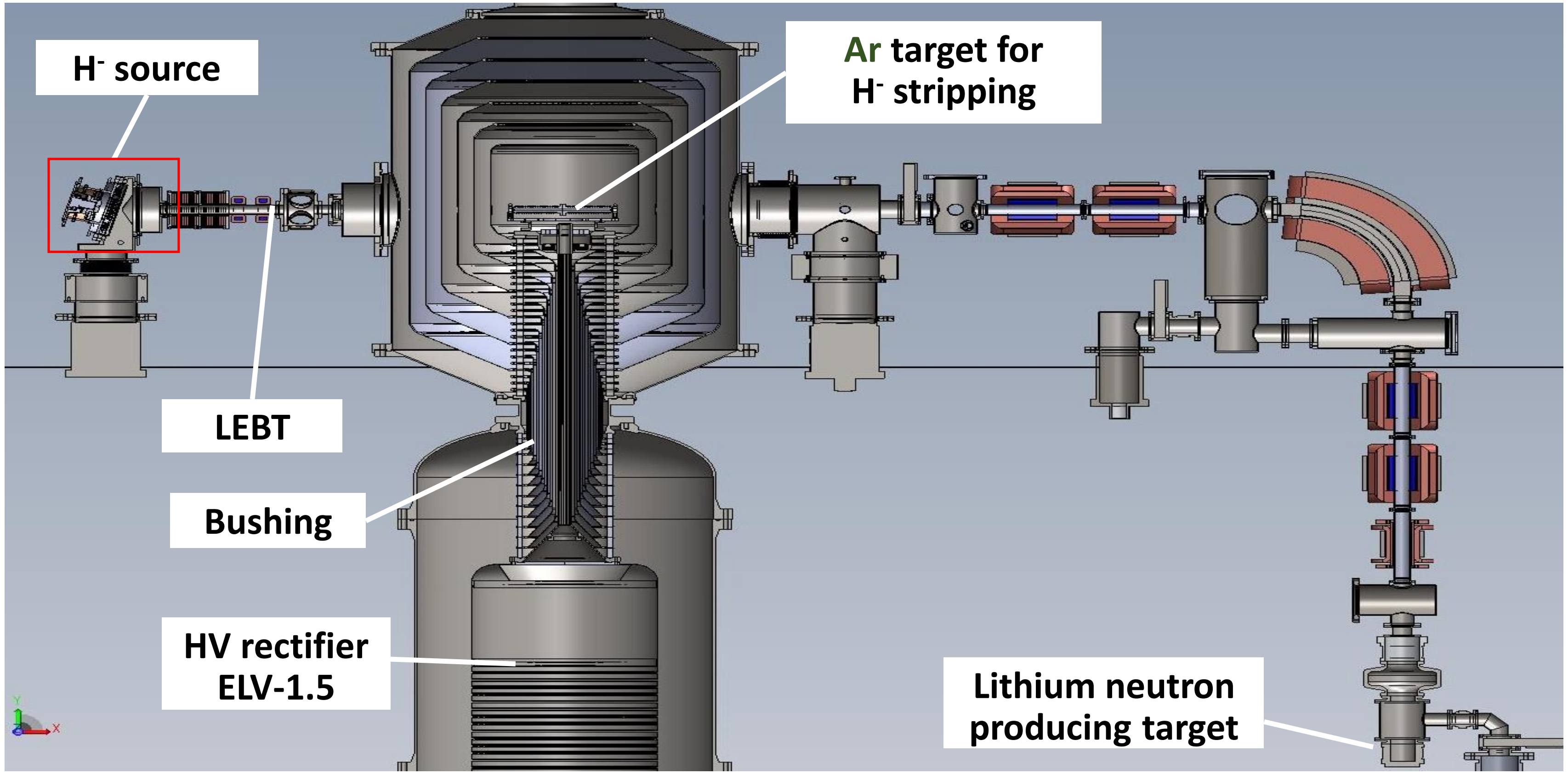
- Tandem Accelerator with Vacuum Isolation :
  - Description
  - Status
- Negative ion injection scheme:
  - Negative Ion source
  - LEBT with beam position control
- New injectors for tandem
  - 15 mA injector
  - Injector with negative ion beam pre-acceleration to 130 KeV

BINP Accelerator-Based Neutron Source for BNCT *

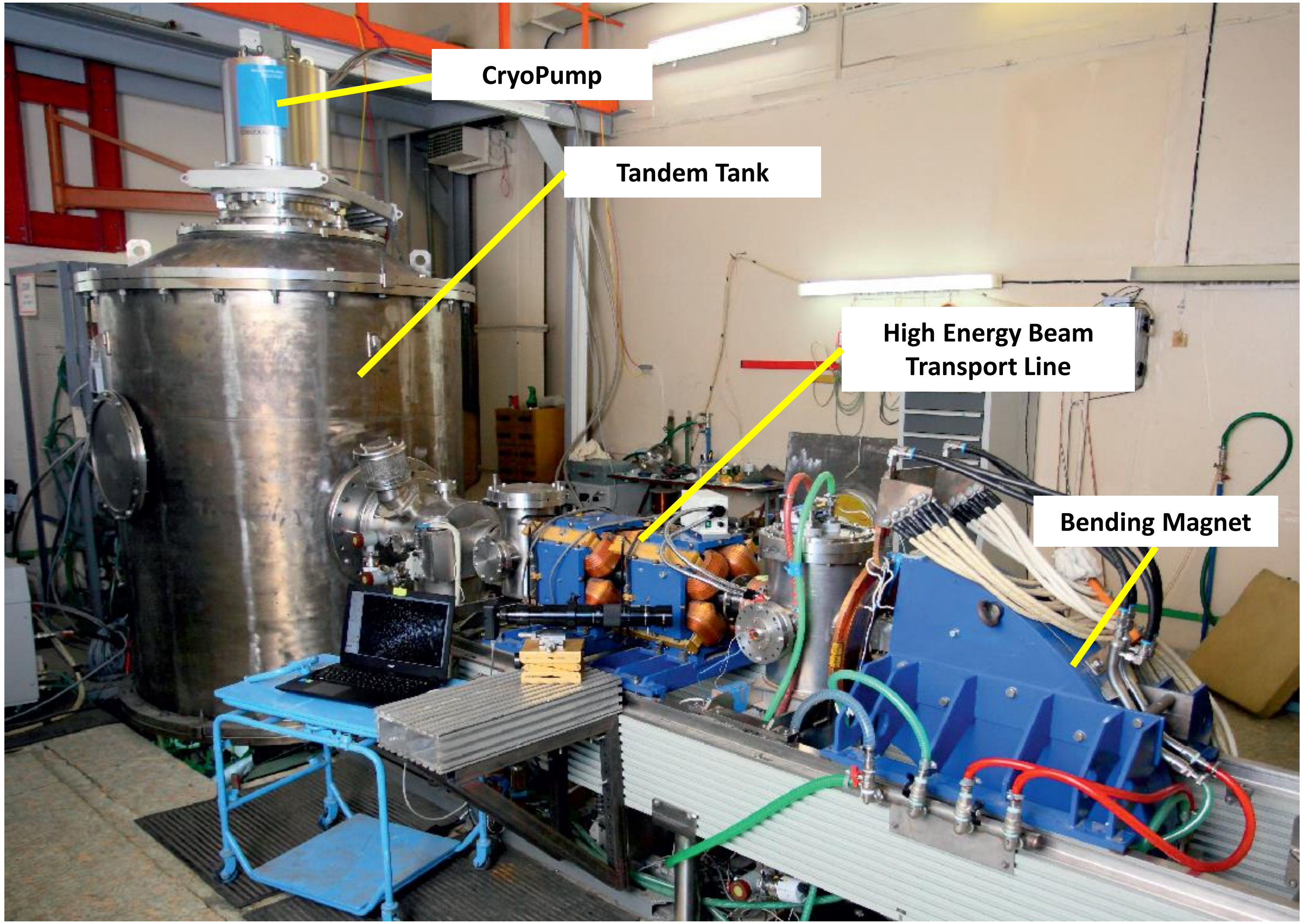
*B. Bayanov, V. Belov, E. Bender, M. Bokhovko,G. Dimov, V. Kononov, O. Kononov, N. Kuksanov, V. Palchikov, V. Pivovarov, R. Salimov, G. Silvestrov, A. Skrinsky, and S. Taskaev, *Nucl. Instrum. Meth. Phys. Res. A.* **413**, 397 (**1998**)



Tandem VITA is designed for use in the accelerator-based neutron source for BNCT (1998)

Experimental accelerator-based neutron source is in operation at BINP since 2006.

BINP Accelerator-Based Neutron Source in the Hall

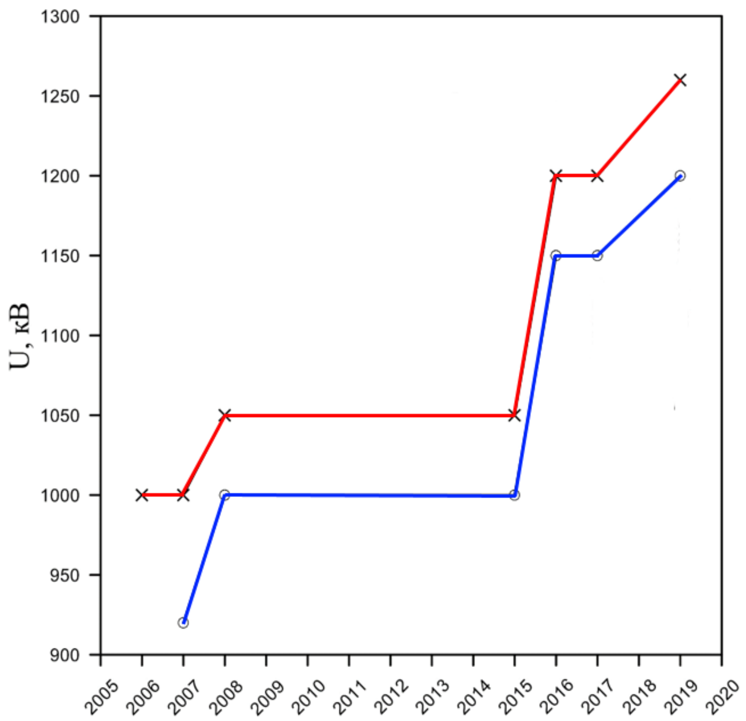


BINP Accelerator-Based Neutron Source for BNCT

The maximal tandem voltage:

× - maximal voltage with breakdowns

o - voltage without breakdowns for more than 1 hour

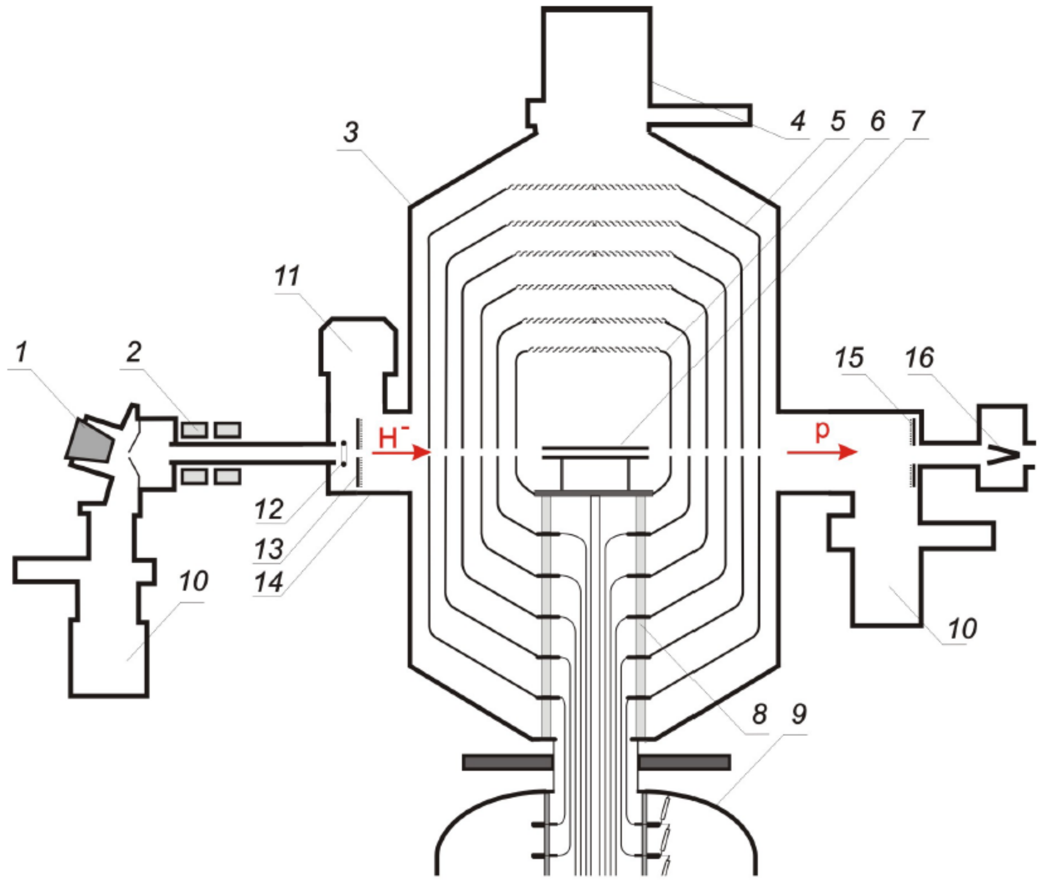


Progress in tandem voltage

Date	Proton beam, мА	Improvements
05.2014	1,6	Minimize the power of high energy x-ray radiation from the tandem during acceleration. Overheated input aperture was eliminated.
12.2015	5	Suppression of secondary charged particles: Cooled aperture at the tandem entrance; Improved pumping of the LEBT and tandem entry box; Negatively biased electrodes near the tank walls; Negatively biased ring installed in front of the input aperture
12.2017	6	Beam positioning with the help of wire scanner
01.2018	7	*In situ* beam positioning with the help of CCD cameras
12.2018	9	Negative ion source was boosted to higher (>10 mA) output current

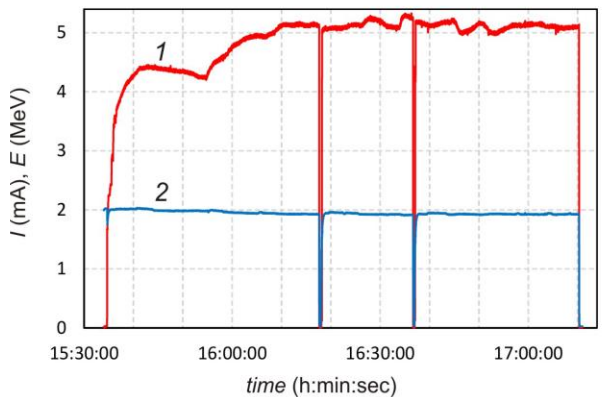
Progress in 2 MeV proton beam production

Suppression of Parasitic Currents in the Accelerator



Tandem Modernization
11 - cryogenic pump; 12 - biased ring;
13 - cooled diaphragm with a grid; 15 – exit grid

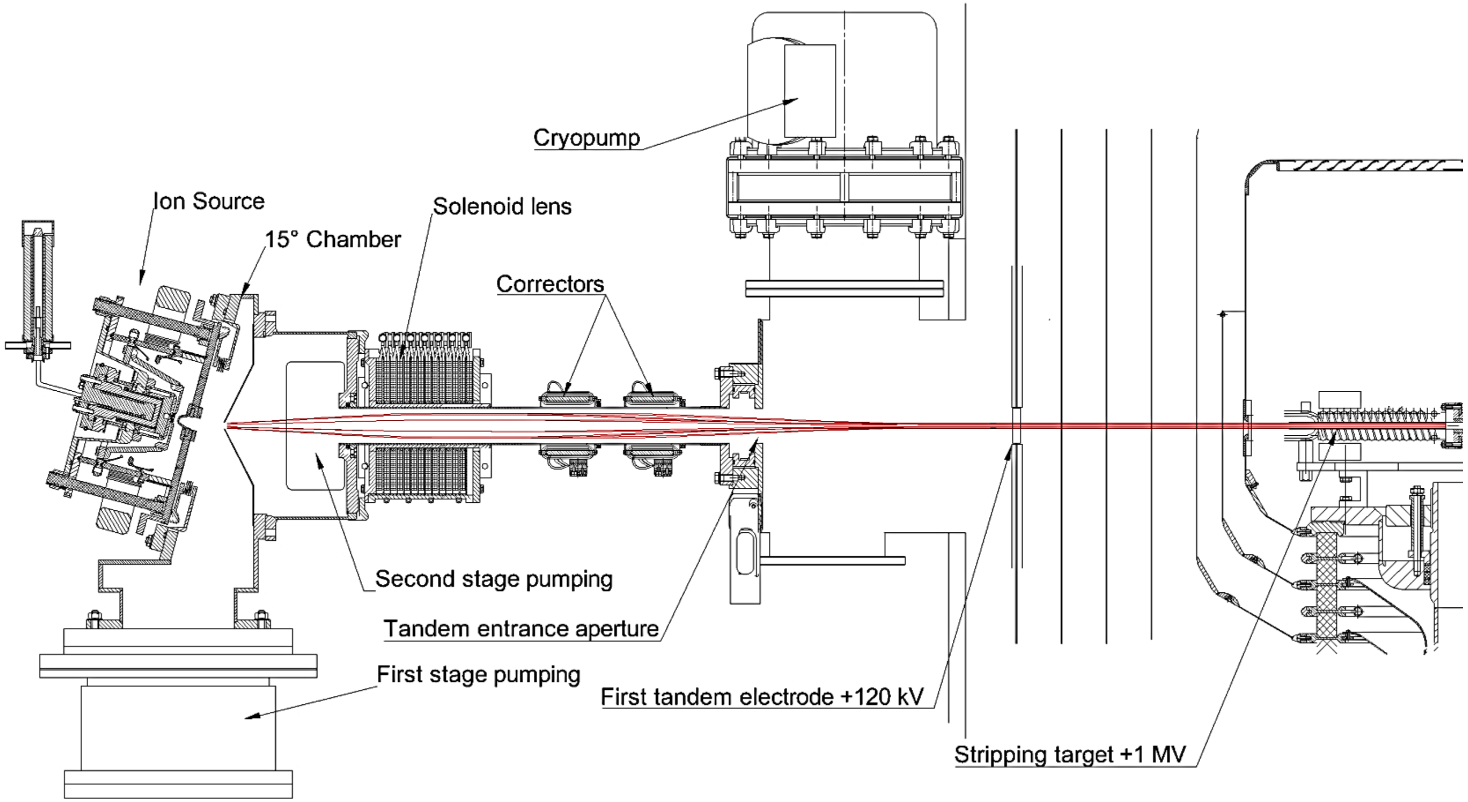
- **An additional cryogenic pump (11) was installed.**
- **The negatively biased ring (12) is installed to suppress the electrons accompanying the negative hydrogen ion beam.**
- **The water cooled diaphragm (13) was mounted, which limits the gas and ultraviolet radiation flow into the accelerator and prevents the secondary electron emission.**
- **The back surface of the diaphragm from the accelerator side is covered by a negatively biased tantalum wire grid to suppress secondary electrons.**
- **The similar grid (15) was mounted within the exit unit of the accelerator.**



Proton current and energy evolution during 1.5 hour run

The suppression of parasitic currents in the accelerator improved the stability of accelerator operation with respect to full voltage breakdown and allowed the proton beam current to be significantly increased from **1.6 to 5 mA**.

Scheme of Negative Ion Injection to Tandem

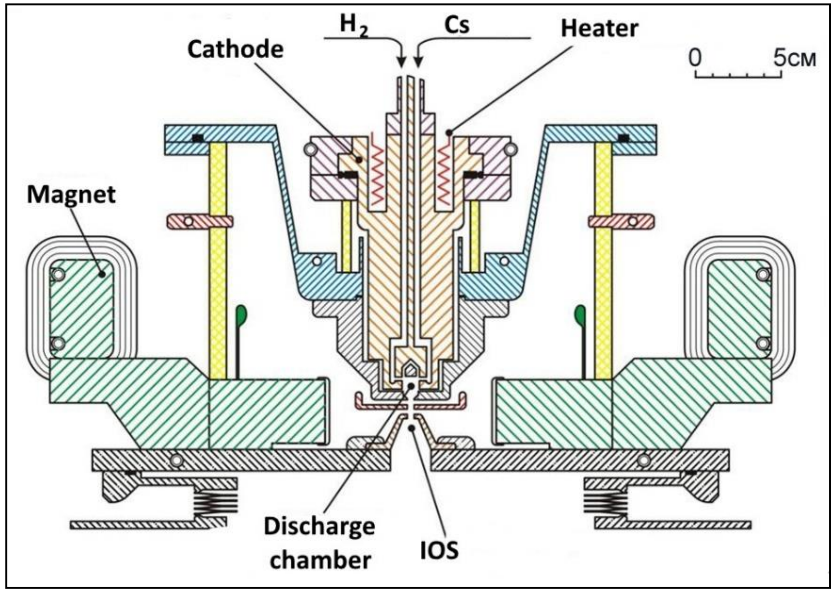


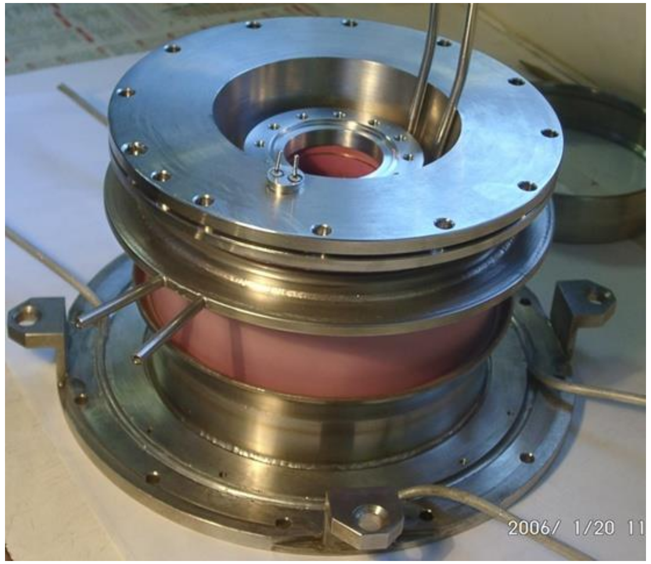
- 10 mA DC Penning SPS with differential pumping and 15^0 beam turn before entering LEBT
- LEBT with solenoidal magnetic lens and correctors for the beam steering
- Additional cryopump at the tandem entrance
- An increased 1^{st} acceleration gap of tandem

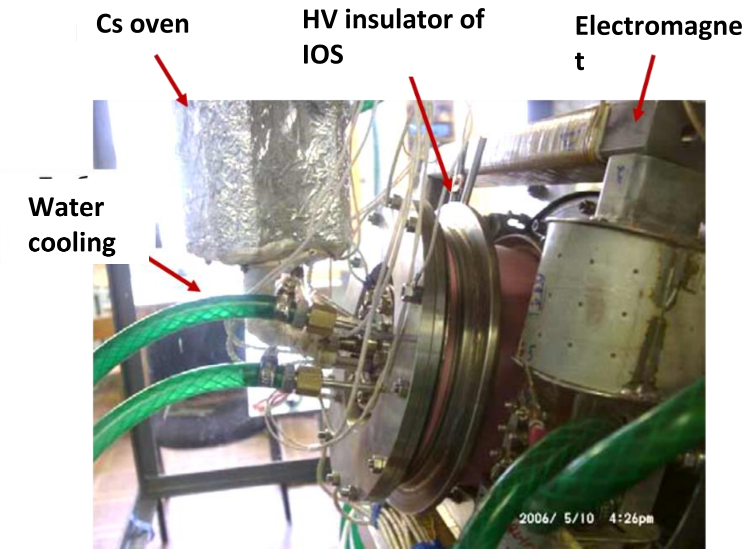
Calculated H- ions trajectories are shown in red (Comsol)

DC Penning Negative Ion Source with Hollow Cathodes

First version of DC Penning SPS (2006)



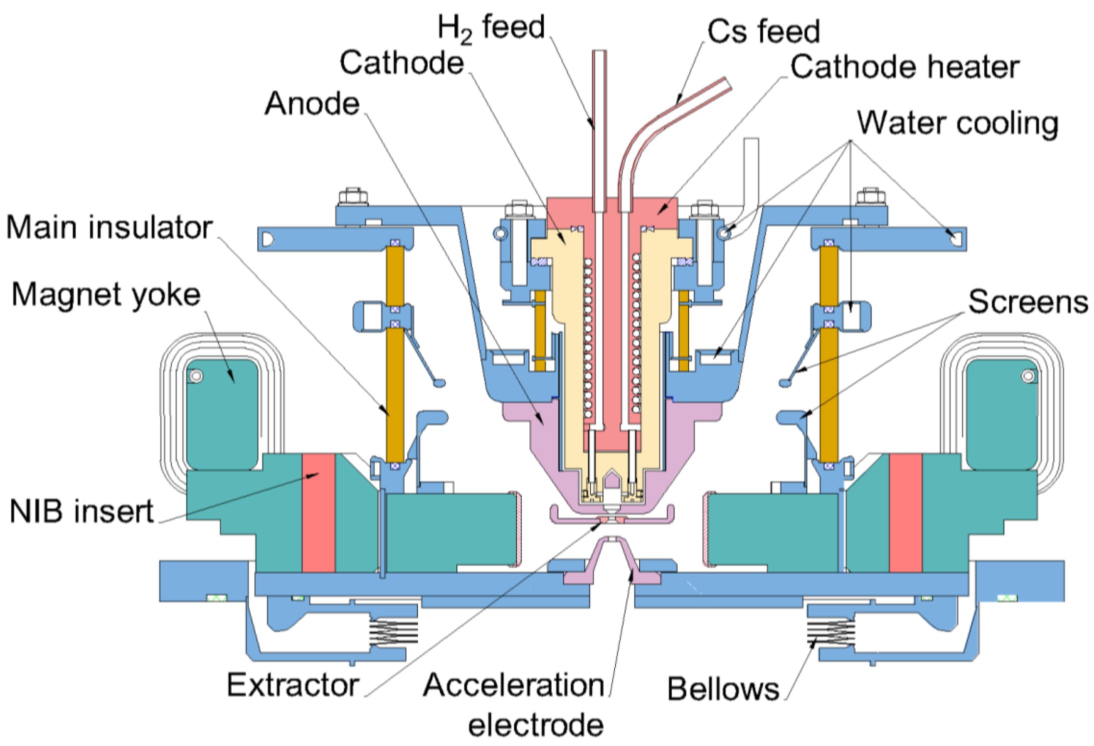




- DC Penning discharge with orificed hollow cathode inserts
- Dipole magnetic field in discharge and IOS
- Triode IOS with circular apertures
- H^- ions production on the cesiated anode
- Cesium feed ~ 5 mg/h

Beam parameters	
H^- beam current	Up to 10 mA
Beam energy	18 ÷ 25 keV
Beam regular divergence	80 mrad
Normalized 1 RMS XX' emittance	0.18 π·mm·mrad

DC Penning Negative Ion Source Upgrade (2015)



Year	Days	Hours
2006-2014	358	1693
2015	53	265
2016	70	341
2017	121	658
2018	92	516
2019	77	431
2020*	49	377
Total	820	4281

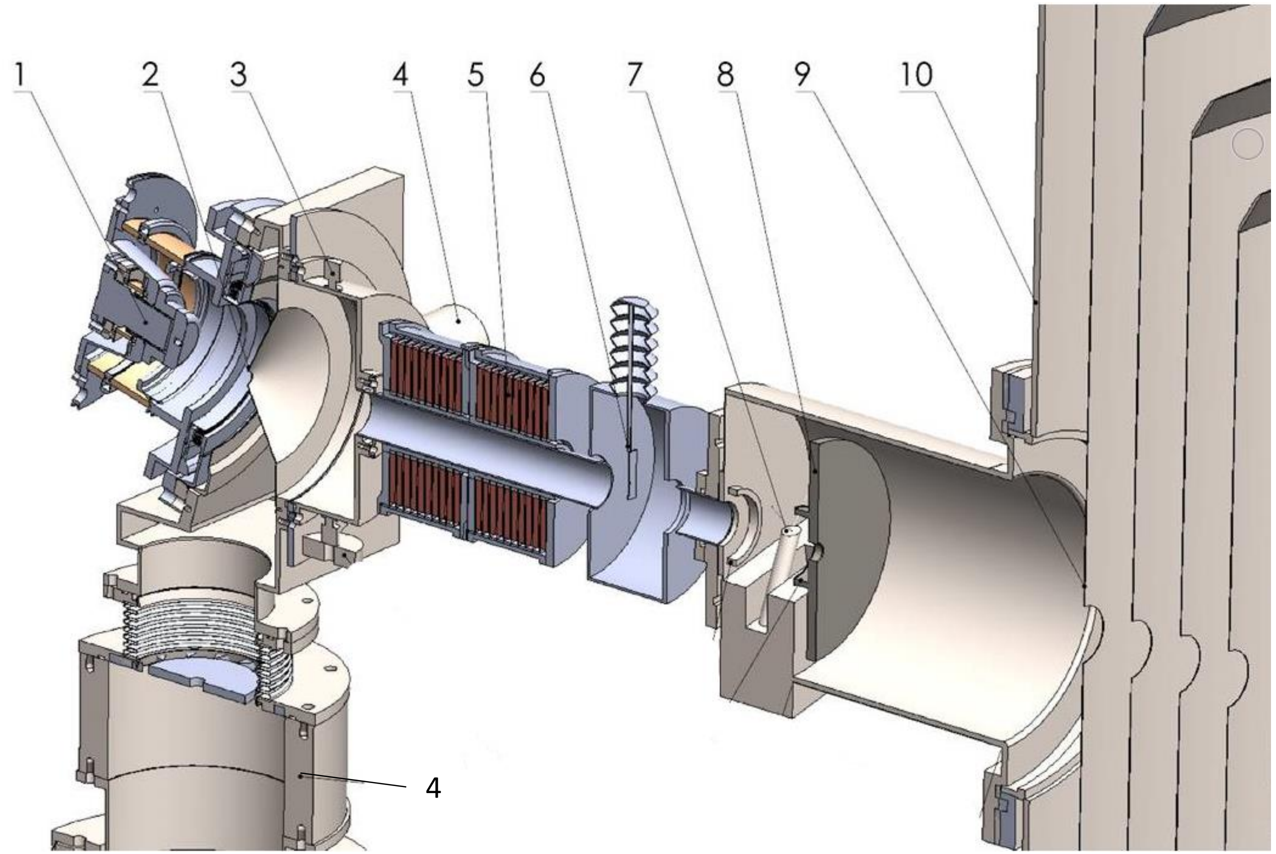
* in operation

Source Operation Statistics at the Tandem

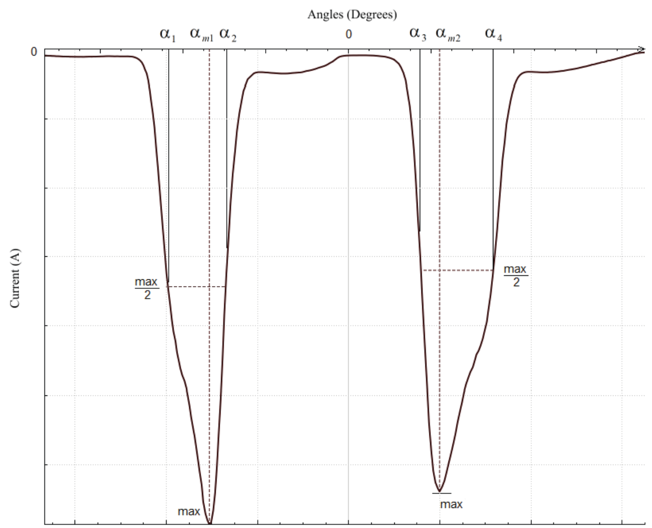
- **NdFeB magnet insert for field increase up to 0.1 T**
- **Upgraded acceleration voltage power supply**
- **Detachable cathode heater**
- **Replaceable high voltage insulators**
- **Replaceable extraction electrode insert**

- **Both source modifications have operated for 1693 + 2588 = 4281 hours with average daily run ~ 5 hours.**
- **Source start time ~ 50 minutes**

Beam Position Control in the LEBT



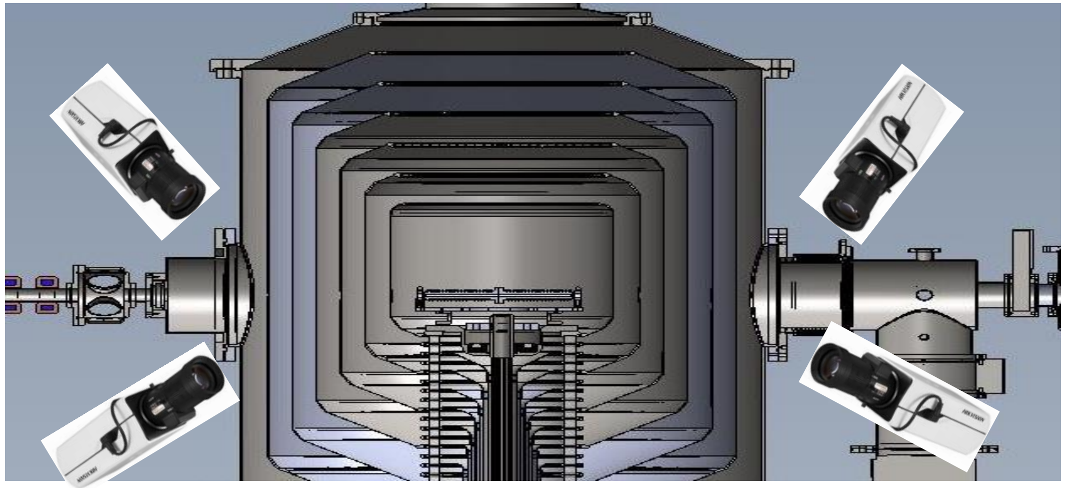
1 - ion source, 2 - diaphragm, 3 - vacuum gauge, 4 - ion source vacuum pumps,
5 - magnetic lenses, 6 - box with movable diaphragm for beam scan,
7 - wire scanner, 8 - tandem entrance diaphragm,
9 - first tandem electrode at 120 kV, 10 - vacuum tank of tandem.
Magnetic correctors are not shown, they were replaced by the box 6



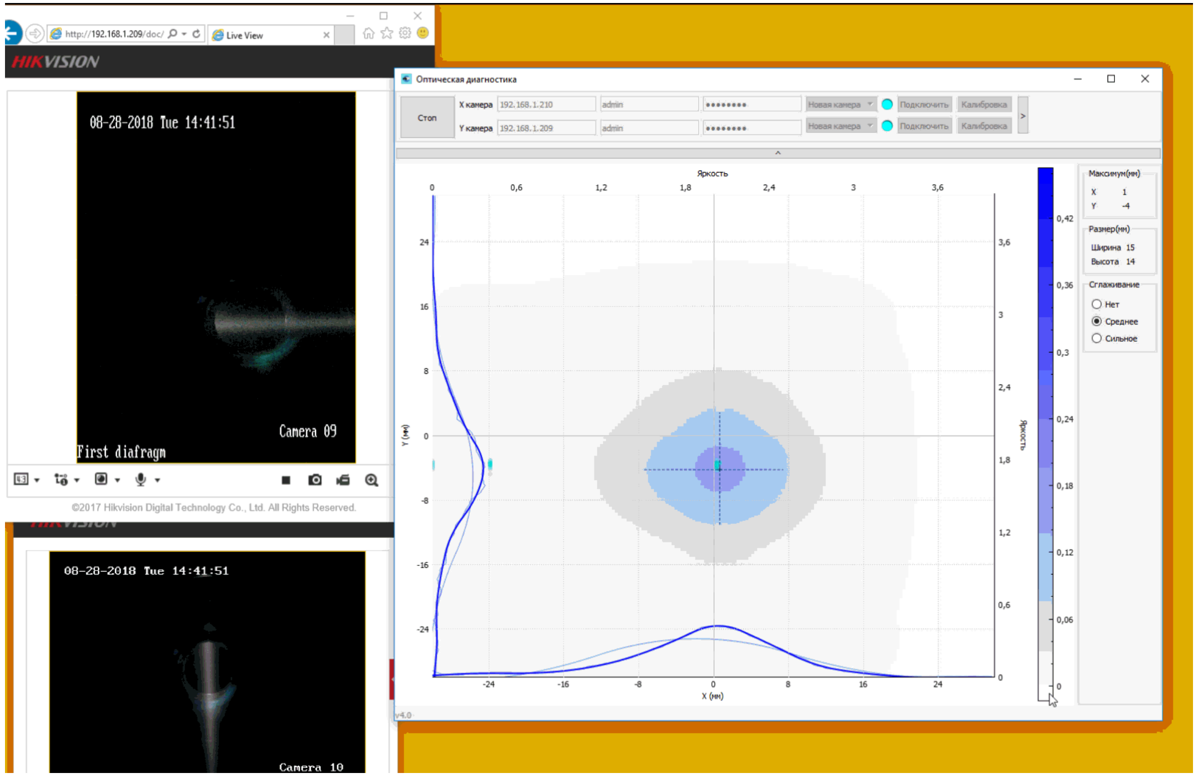
Wire scanner (D-Pace) used to monitor negative ion beam position

T. Bykov, et al. AIP Conference Proceedings 2052, 050013 (2018)

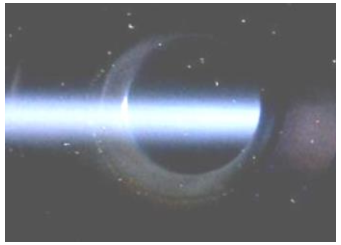
Beam Position Control with CCD Cameras



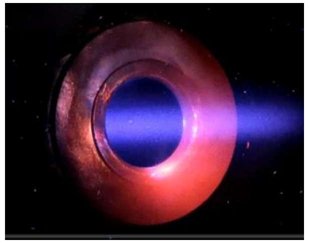
4 CCD cameras observing the entrance and exit apertures are used to record beam position



Interface for online reconstruction of beam profile



Beam view at entrance tandem aperture

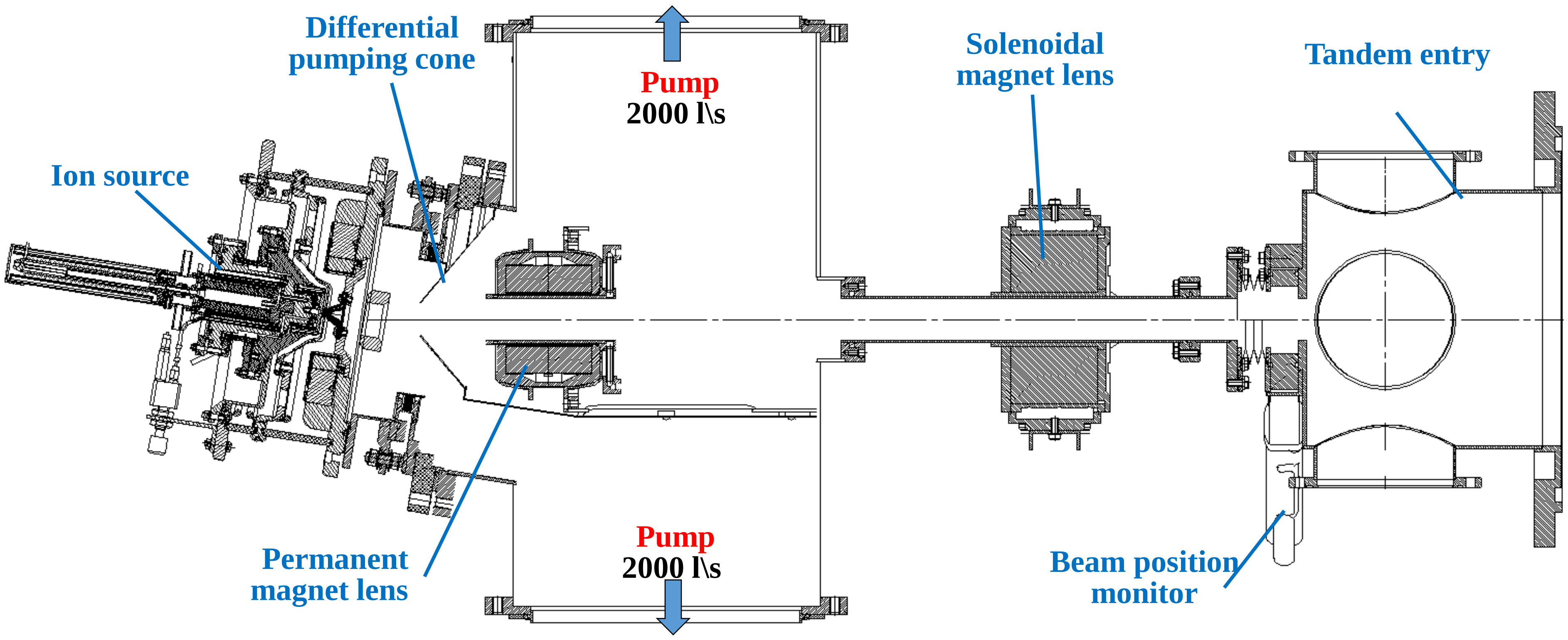


Beam view at exit tandem aperture

Injection Scheme Upgrades

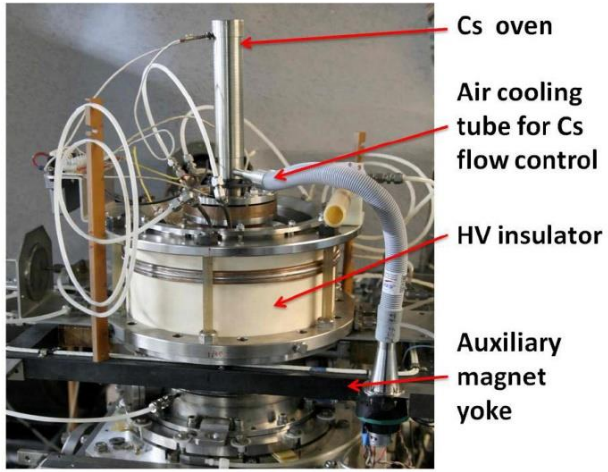
- Negative ion source upgrade to output current of 15 mA
- Reduction of H- beam stripping losses inside the ion source chamber and LEBT
  - LEBT with an increased tube diameter and magnetic lens aperture
  - Improved differential pumping of the ion source
- An increased beam deflection to suppress the secondary particles flux to the LEBT
- Negative ion beam acceleration to energy 130 keV before injection into the tandem

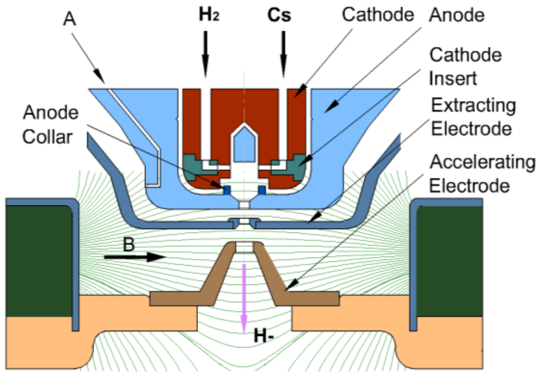
New Injector under Development for VITA (2020)



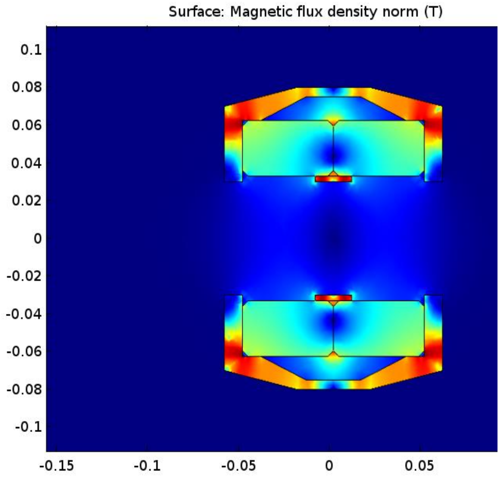
- Next version of BC Penning SPS with 15 mA H- beam yield
- An additional large aperture magnetic lens at the LEBT entrance
- Improved differential pumping system with high speed turbomolecular pumps

15 мA Ion Source and Magnetic Lens

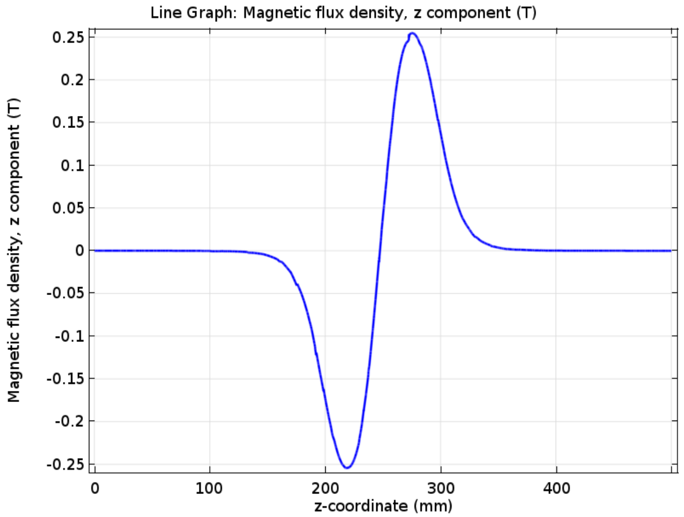




H- beam current	15 мA
Emission current density	150 mA/cm^2
Emission aperture	3.5 mm
Normalized 1 RMS emittance	0.18·mm·mrad



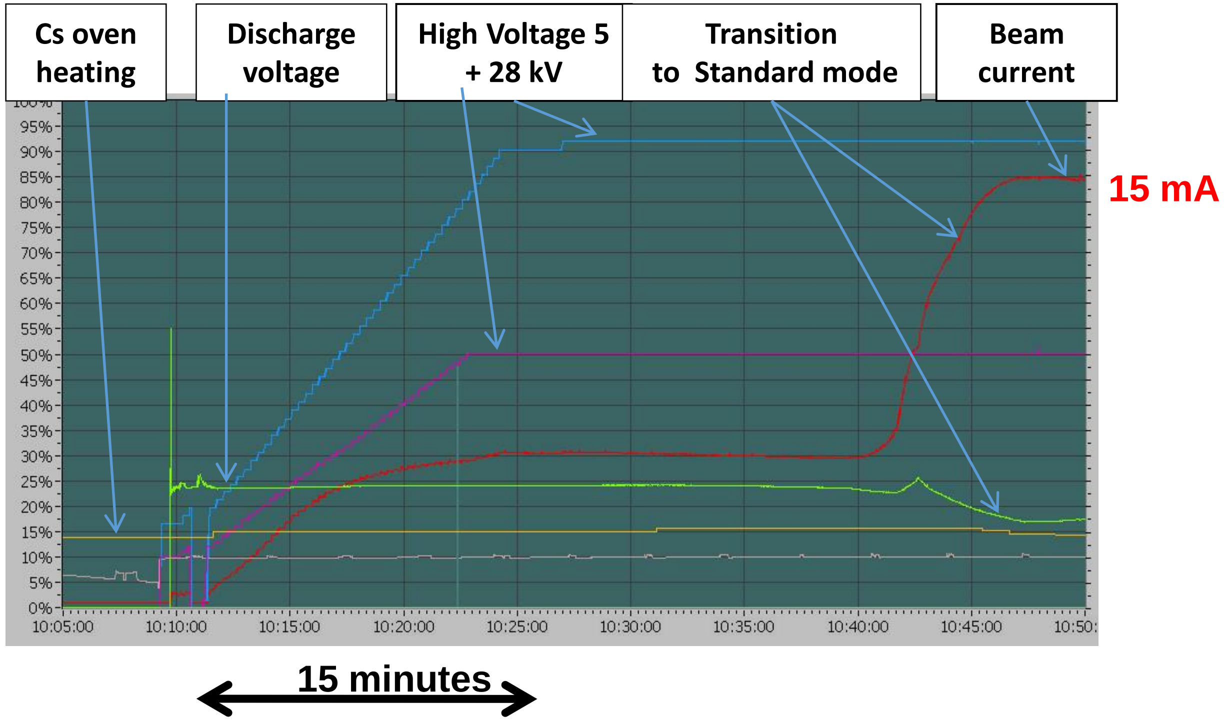
Magnetic field distribution in the lens



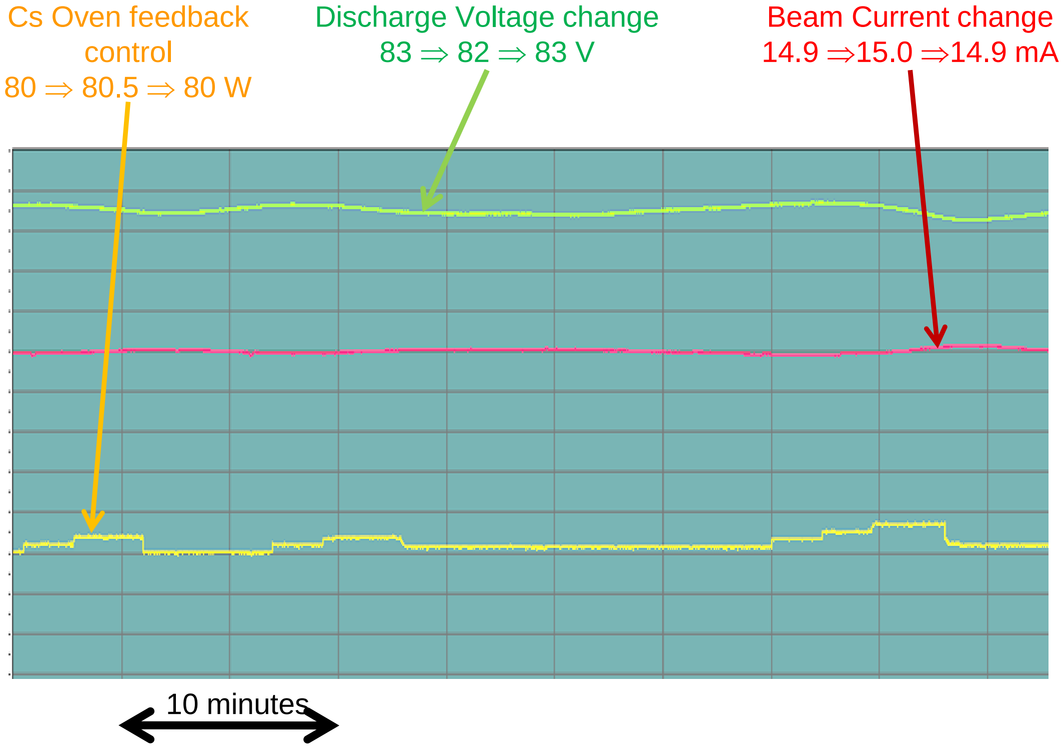
Magnetic field along lens axis

- Large aperture lens made using permanent NdFeB magnets
- Aperture diameter is 55 mm (fits existing tandem transport channel)
- Maximal magnetic field is 2.5 kG
- Short focal length is 250 mm

Unattended Control of Source Operation

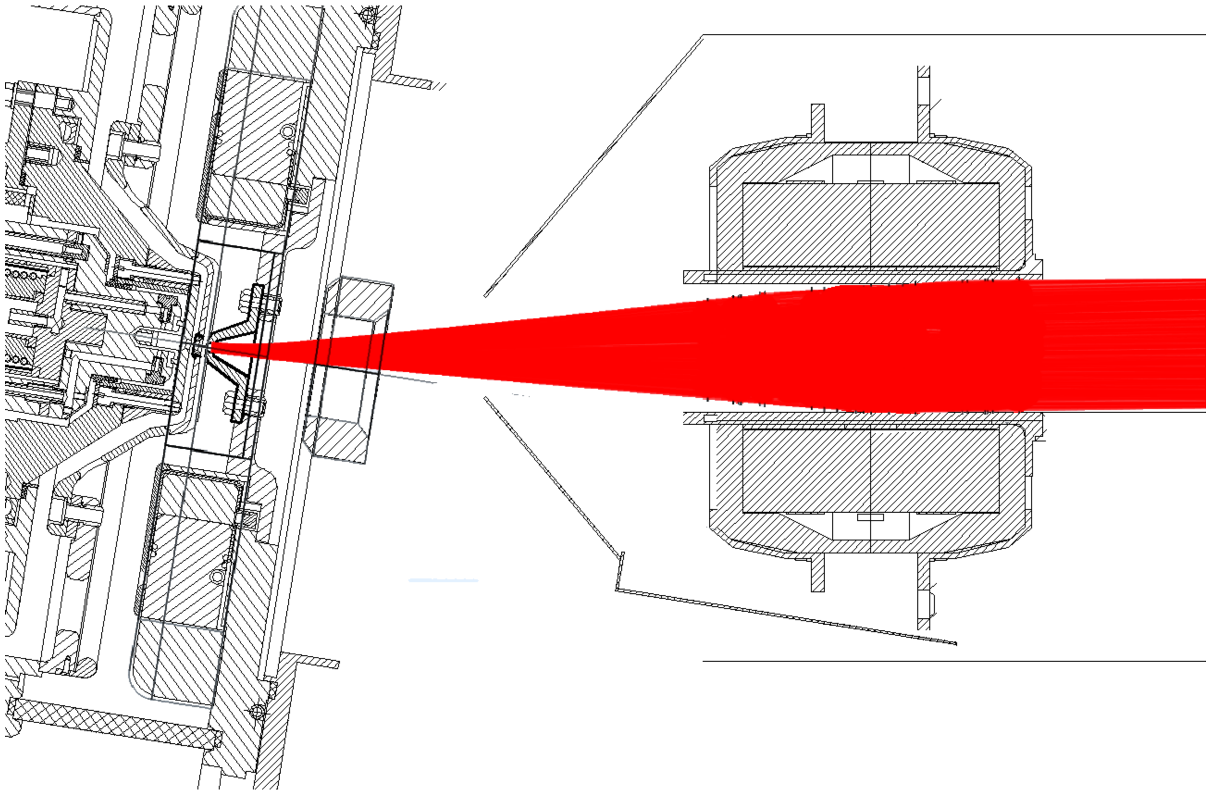


Source start by computer



Cs seed control by PC during the run

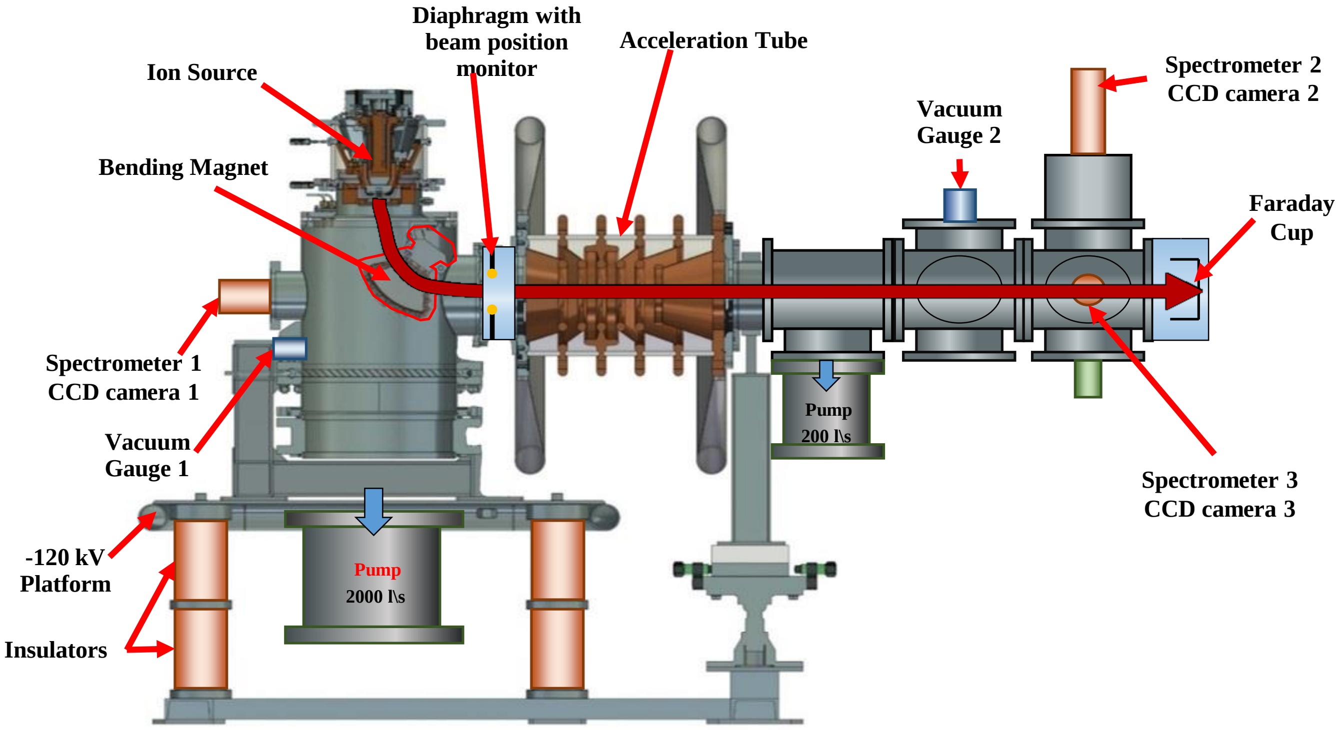
Numerical Simulations of the Beam Transport to LEBT

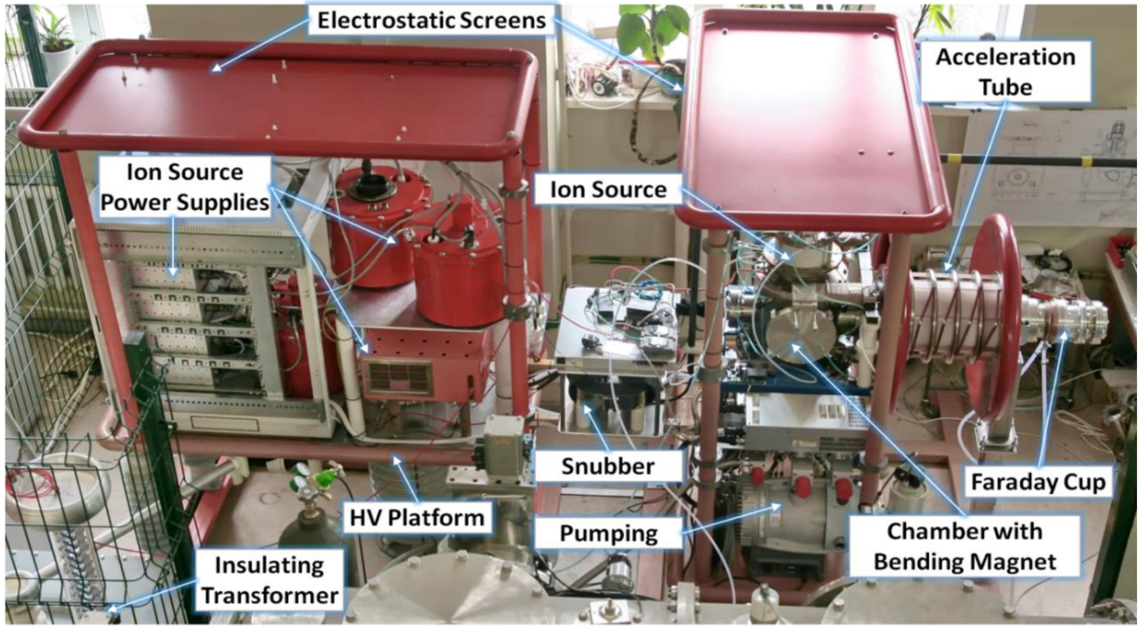


Calculated negative ion beam trajectories

100 % H- beam transmission to the LEBT entrance

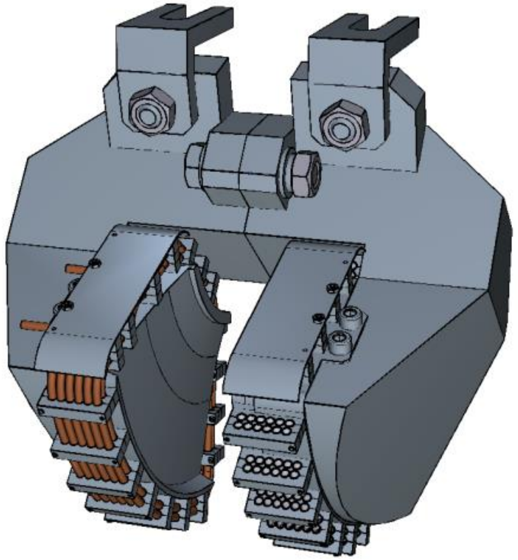
Injector with Beam Pre-acceleration to 130 keV





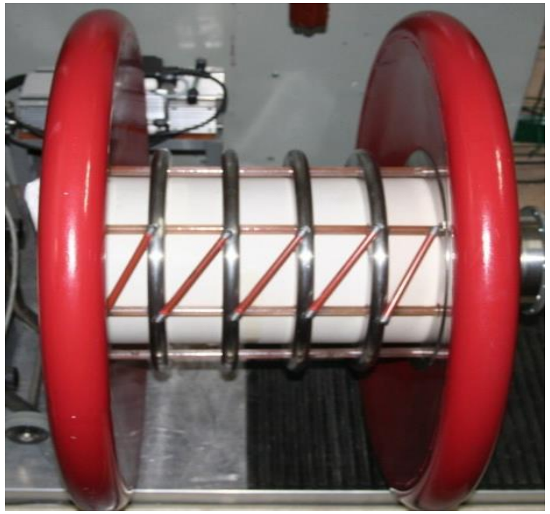
- Penning SPS with DC output H- current up to 15 mA
- Bending chamber with beam 90^0 turn for separation of secondary particles
- Preliminary beam acceleration to 130 keV for improving the beam transport through tandem
- Beam diagnostics using Faraday cup and beam position monitor
- Optical diagnostics for beam profile and position in the transport chamber

Elements of 130 keV Injector



Bending magnet

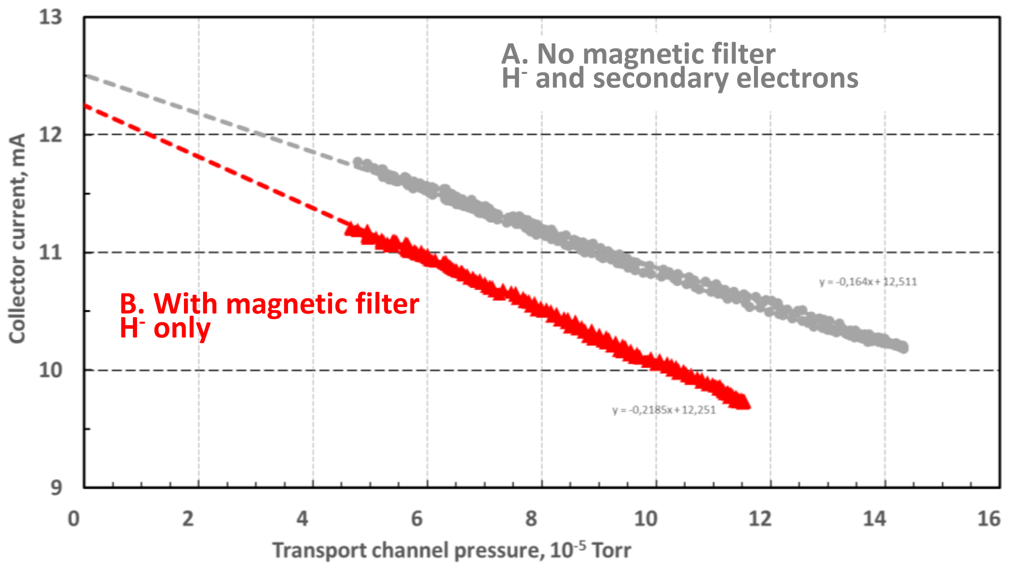
- Made of permanent NdFeB magnets
- Turns and focuses the beam in both transverse directions
- The magnet gap is 50 mm



Acceleration tube

- Consists of five sections
- Electrodes with ambient air cooling
- The aperture is 120 mm

H- Beam Acceleration and Electrons Filtering



The transmitted current vs the pressure in the transport channel with and without magnetic filter.

- **95% beam transmission was achieved during acceleration and transport.**
- **0.4 mA income of accelerated secondary electrons was recorded. They could be produced due to H- stripping and secondary emission from the electrodes.**
- **Reliable operation of the ion source and pre-accelerator with output ions energy of 133 keV and current of 14.5 mA was achieved.**

SUMMARY

- **Study and modification of the Tandem VITA of the Accelerator-Based Neutron Source have resulted in increase of the accelerated proton beam current up to 9 mA at energy 2 MeV.**

- **Two new injectors with the negative ion beam current of 15 mA are prepared for installation to tandem.**

Thank You for Attention