Development of surface-plasma negative ions sources at BINP

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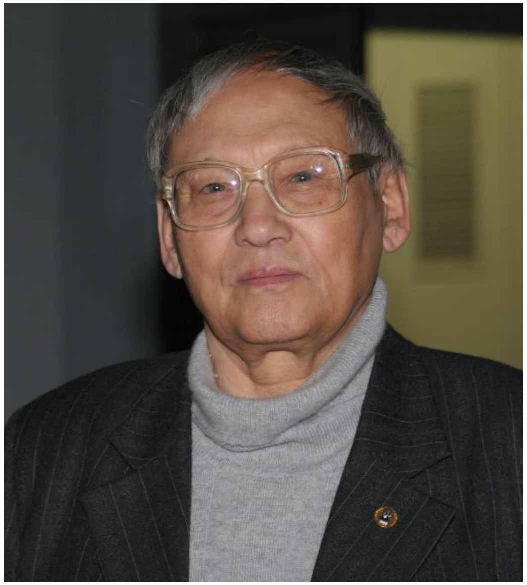
- **Surface-Plasma method and SPS features**
- **Negative Ion Sources, developed at BINP**
- **CW PIG sources for accelerators**
- **High-current RF sources for N-NBI**

Surface-Plasma method of Negative Ion production

Founded and formulated at BINP in 1971-1973.



Key investigators (PNNIB Proceedings 1977,1980) :

BINP (Dimov, Belchenko, Dudnikov)

BNL (Slyuters, Prelec)
LBL (Ehlers, Leung, Graham)
LLL (Hiskes)
FNAL(Schmidt)
LANL (Allison)
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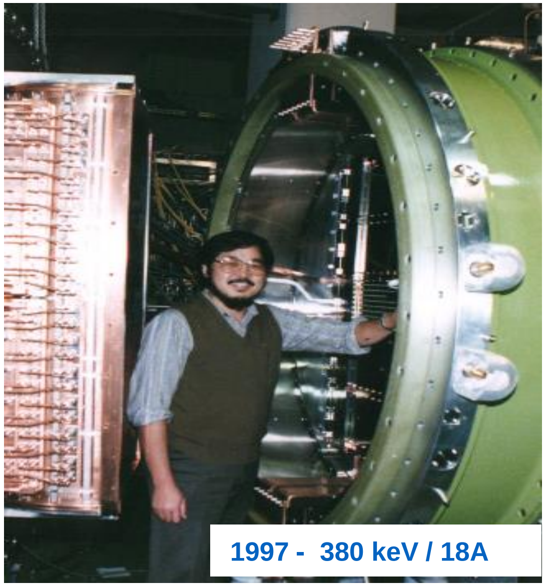
LLL (Hiskes, Karo)
FNAL(Schmidt)
LANL (Allison, Smith, Sherman,York,Stevens)
ORNL (Stirling, Tsai, Whealton)
Stevens Institute of Technology (Seidl, Melnichuk)

FOM (Los, Granneman, Hopman, van Bommel,
van Amersfoort, van Wunnik, Kleyn)
Universitat Bochum (Wiesemann)

KEK (Mori)
JAERI (Okumura, Hanada, Inoue)
NIFS (Kuroda, Kaneko, Oka, Ando, Takeiri)



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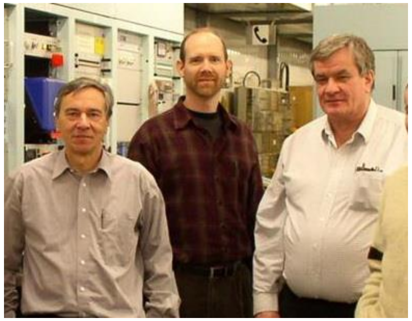


KEK (Mori)
JAERI (Okumura, Hanada, Inoue)
NIFS (Kuroda, Kaneko, Oka, Ando, Takeiri)
ISIS, J-PARK, SNS, IPP, Padova,…
to be continued

Principles of Surface-Plasma Sources

1. Intense bombardment of electrodes by energetic plasma particles

2. Surface conversion of incident H_i^+, H_0 to ions H^- due to kinetic emission

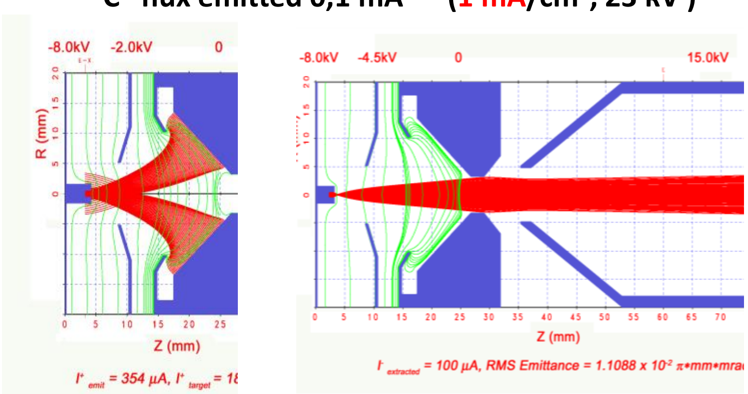
3. Post-acceleration of surface-produced H- ions by near-electrode potential drop

4. Decrease of surface work function to increase the NI kinetic emission

5. Self-organization of plasma structure and surface layer to support NI emission

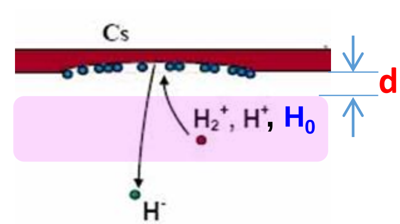
C^- sputter sources (Middleton)

Cs^+ flux to target 0.2 mA (10 mA/cm², 8 кV)
C^- flux emitted 0,1 mA (1 mA/cm², 23 кV)



Surface-Plasma sources (magnetron)

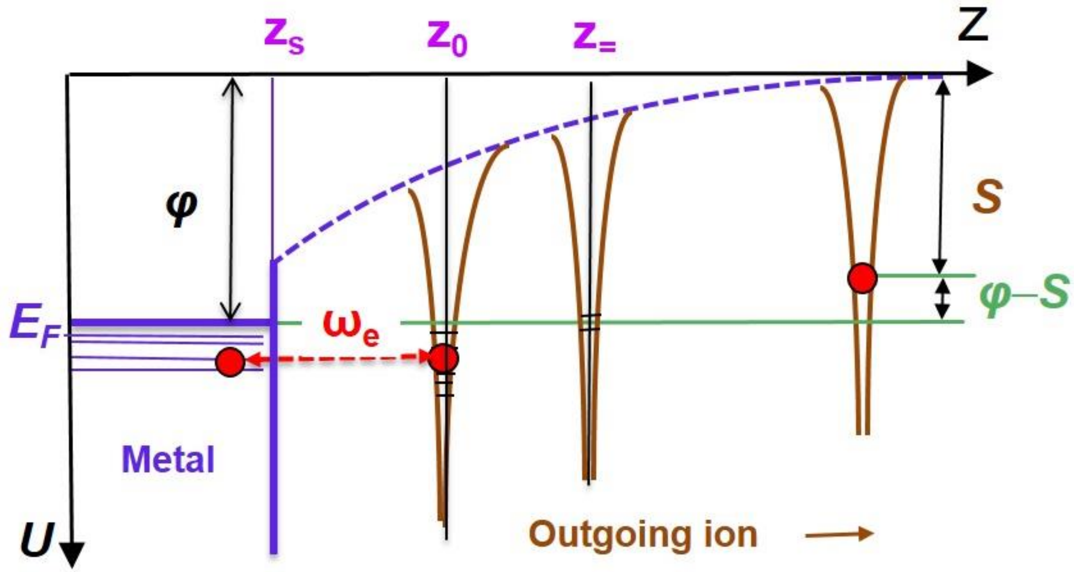
Positive ions flux to cathode 50 A (10 A/cm², 70 V)
H^- ions emission current 0,3 A (3 A/cm², 100 V)



An intense bombardment of electrodes by energetic ions and atoms is provided by plasma through narrow self-adjusted sheath (d ~10^{-2} mm)

Kinetic (nonequilibrium) NI emission

M. Kishinevsky (BINP), J. Hiskes (LLL) , B.Rasser (FOM)



Position of NI Affinity level near metallic surface

Electronic exchange rate ω_e decreases exponentially vs distance z :

$\omega_e = \omega_0 \exp(-z/\lambda)$

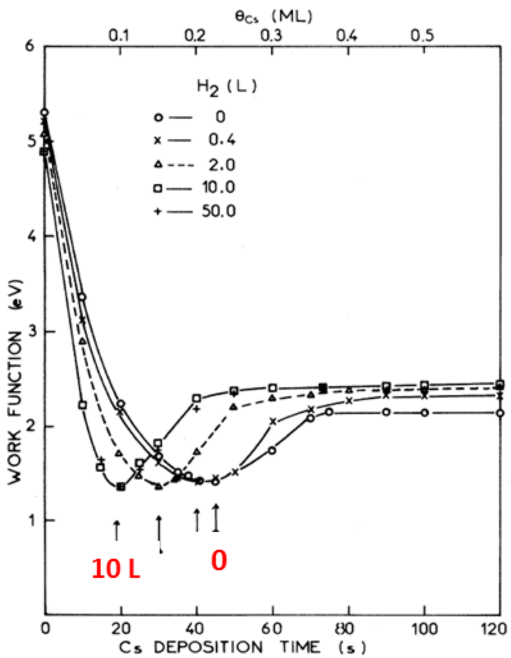
It favors the outgoing NI survival

- Negative ion overcomes the surface barrier φ – S due to initial kinetic energy
- Outgoing atom should pick-up an electron in the close zone $Z_= - Z_S$
- Outgoing Negative ion should be fast in the zone $Z > Z_=$ to keep an extra electron
- Probability to lose electron in the zone $Z > Z_=$ $\quad P_{-0} \sim \int_{z_=}^{\infty} \omega_e dt \cong \omega_= \cdot \frac{\lambda}{v_\perp}$

For H^- ion near W+Cs surface: $\lambda \sim 2a_0$, $\omega_= \sim 7 \cdot 10^{13}\ s^{-1}$, $P_{-0} < 0{,}3$ at $V_\perp > \sqrt{2{,}5eV}$

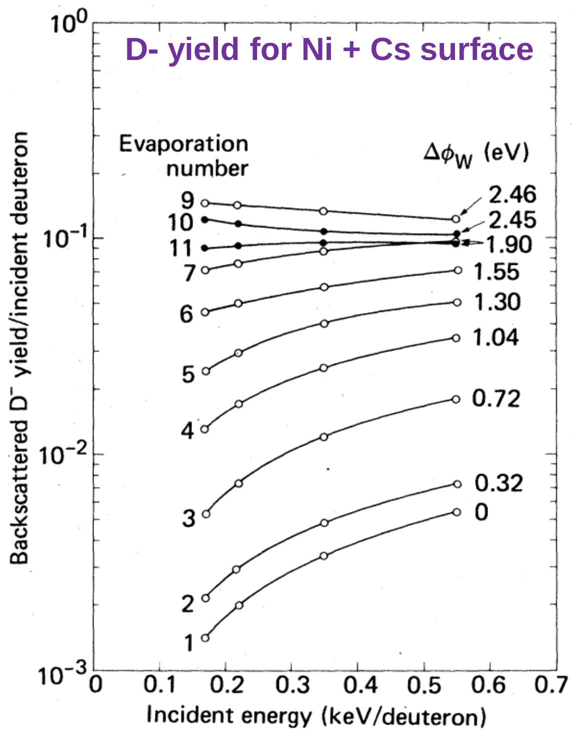
Effect of Cesium on Kinetic NI emission

In principal, there is no need for cesium in Kinetic NI emission



Cs deposition decreases the surface work function

for pure metal and for surface with co-adsorbed Hydrogen



Cs deposition increases NI emission ~10÷100 times

(Schneider et al, 1981)

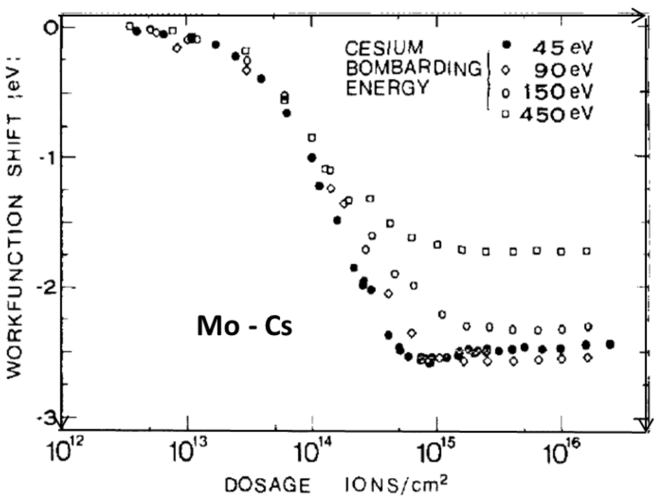
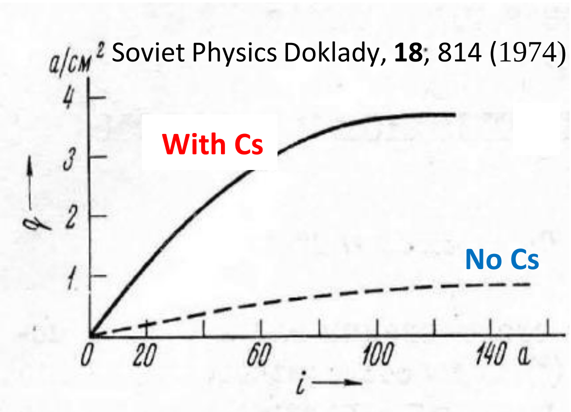


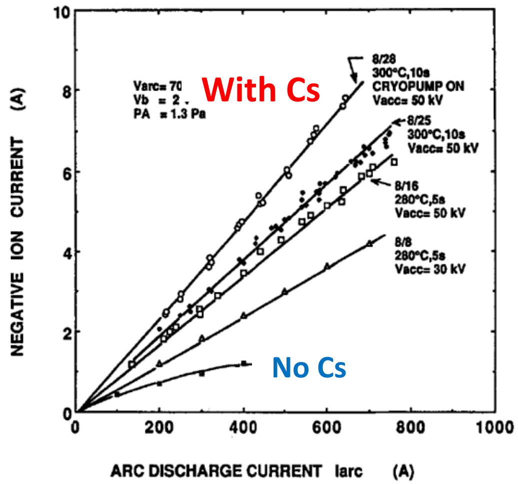
FIG. 1. Work-function shift as a function of the positive cesium ion dosage.

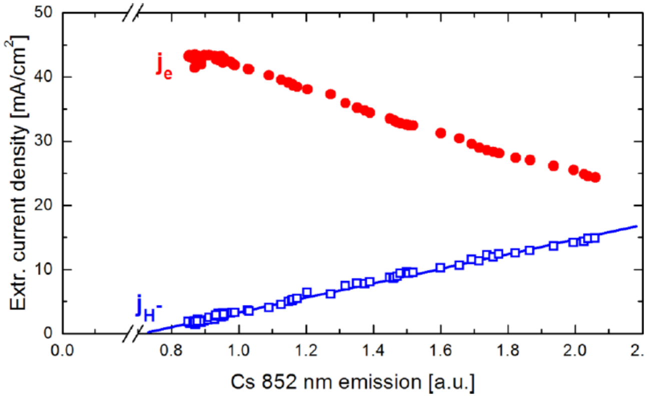
Bombardment by low energy Cs^+ ions (45 eV) **provides the similar decrease of work function. (No solid Cs film produced - Cs implantation?)**

Triple Effect of Cesium in the SPS

1. **Enhancement of H^- production.** Pulsed magnetron – NI emission current density up to 4 A/cm^2
2. **Co-extracted electrons suppression** Ratio e: H^-< 1
3. **Decrease of Operation hydrogen filling pressure (arc and RF SPSs - down to 0,3 Pa)**







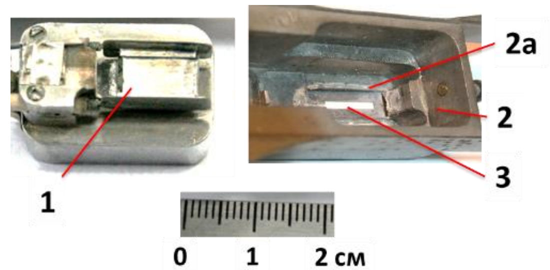
Magnetron SPS (BINP, 1974)

Multi-Ampere SPS (JAERI, 1990)

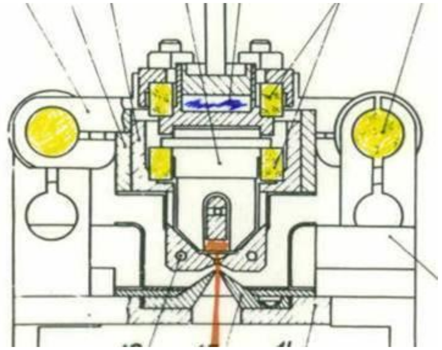
RF source BATMAN (IPP, 2016)

Stable optimal Cs coverage on SPS emitters could be provided
Cesium seed does not prevent the IOS high voltage holding

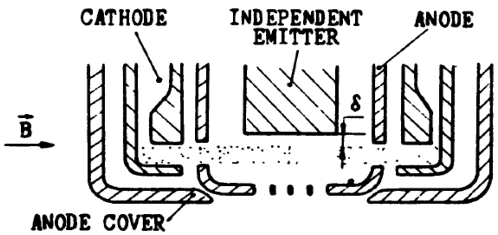
Variety of Experimental H- Ion Sources developed at Budker Institute



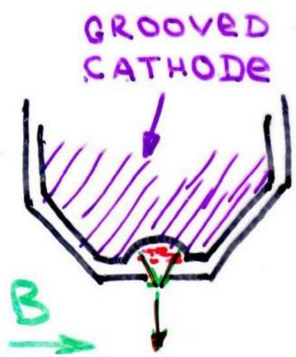
Magnetron (planotron) 1971



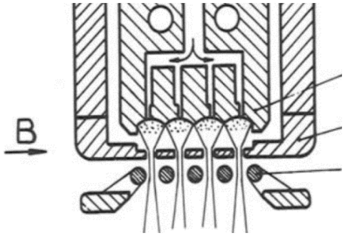
With PIG discharge 1973



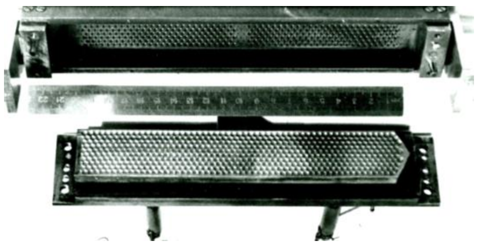
with converter and hollow cathodes PIG 1977



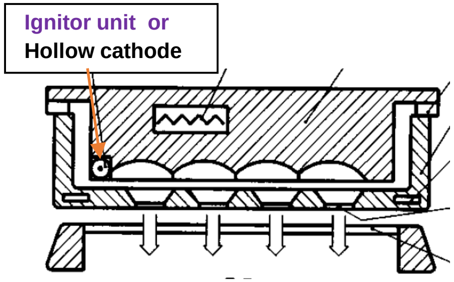
with unclosed ExB drift and geometrical focusing 1978



Multislit Semiplanotron with geometrical focusing 1980



Honeycomb Source with 2D geometrical focusing 1982

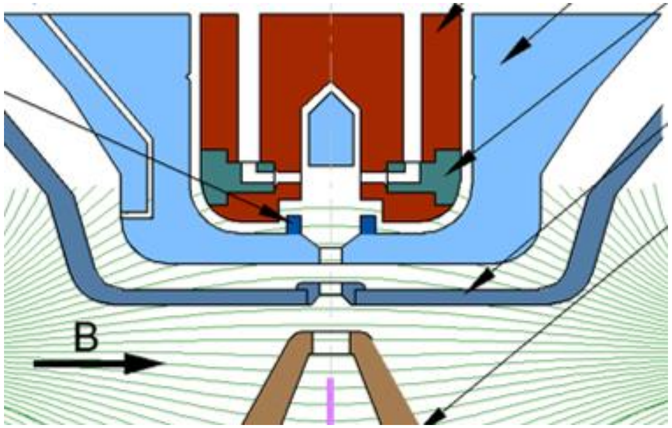


Large Honeycomb Source

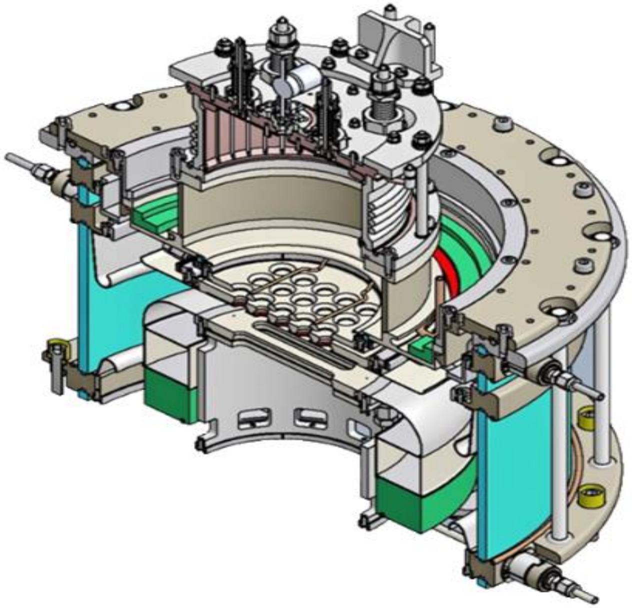
with additional ignitor 1988

with hollow cathodes 1998

Negative Ion Sources developed at Budker Institute in last decade



CW Penning source with hollow cathodes for tandem accelerator
2002 - …

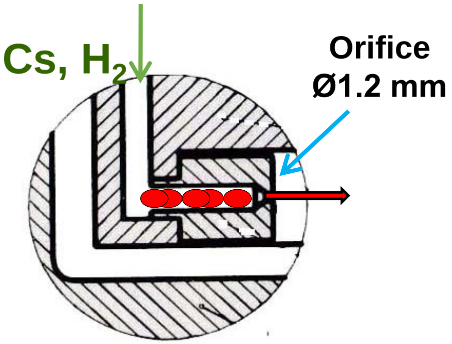


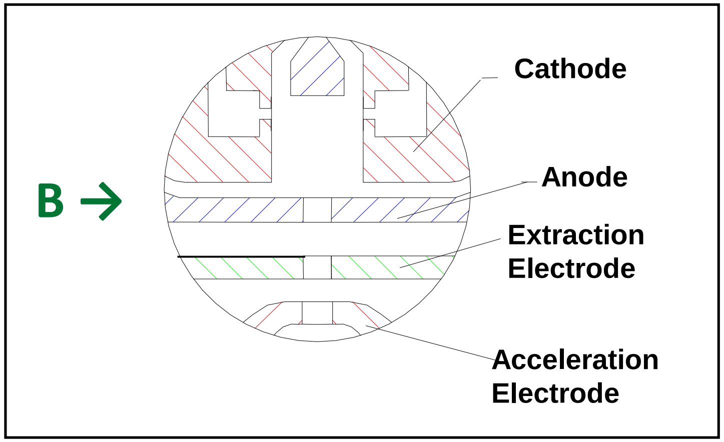
Inductive long-pulsed RF source with directed Cs seed and IOS temperature control
2012 - ….

Development of CW sources for tandem accelerator

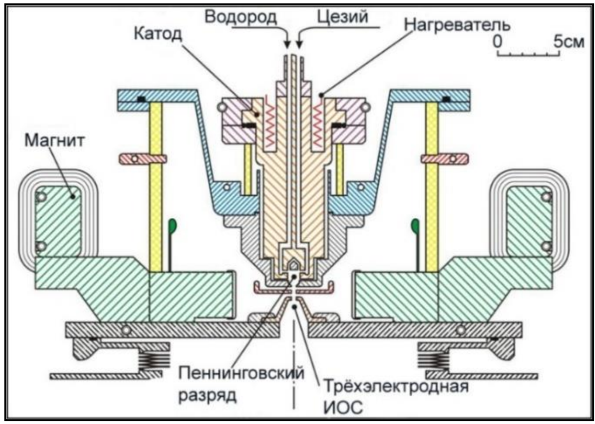
The development of CW Source with Penning geometry and hollow cathodes was started in 1993. The first flange source version was studies since 2002, and it installed to BINP tandem in 2006

Effect of "orificed" hollow cathode





Principal Scheme



First version of CW Source for BINP tandem

Plasma injection from Hollow cathodes supports PIG discharge under low H_2 pressure ~30 mTor

Discharge is localized near emission zone

Long cathode life time (Mo redeposits inside HC)

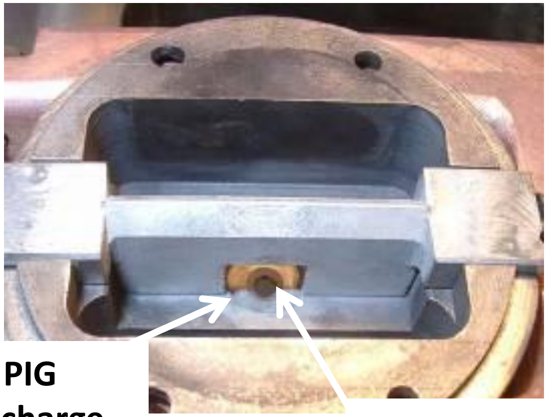
- **Penning discharge**
- **"Orificed" hollow cathode inserts**
- **Dipole magnetic field in discharge and IOS**
- **Triode IOS with circular apertures**
- **H^- ions production on the cesiated anode**
- **CW cesium feed ~ 5 mg/h from cesium pellets to support hollow cathode PIG discharge and to enhance H- yield**

CW Source for tandem and it parts

Source assembly

Cathode

Anode body with
emission aperture

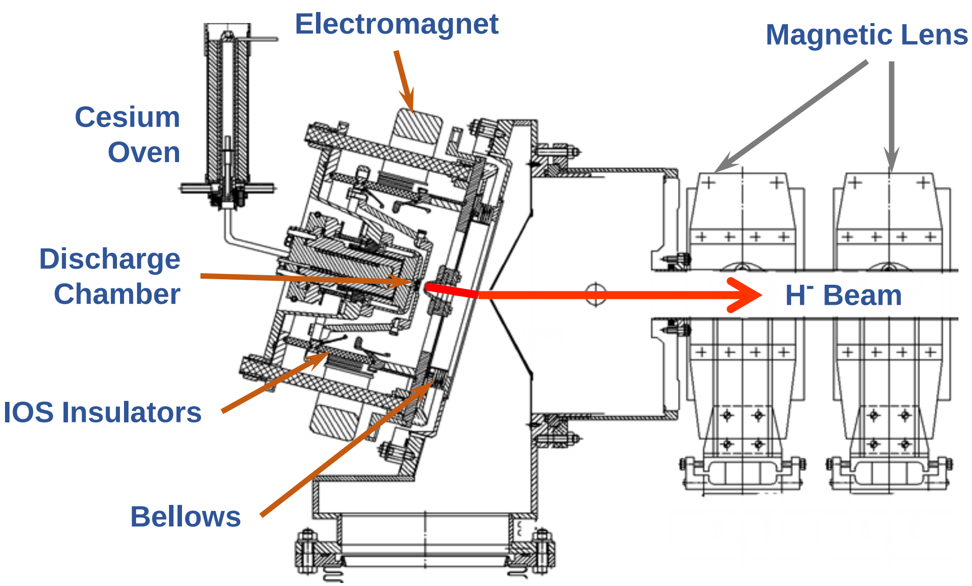


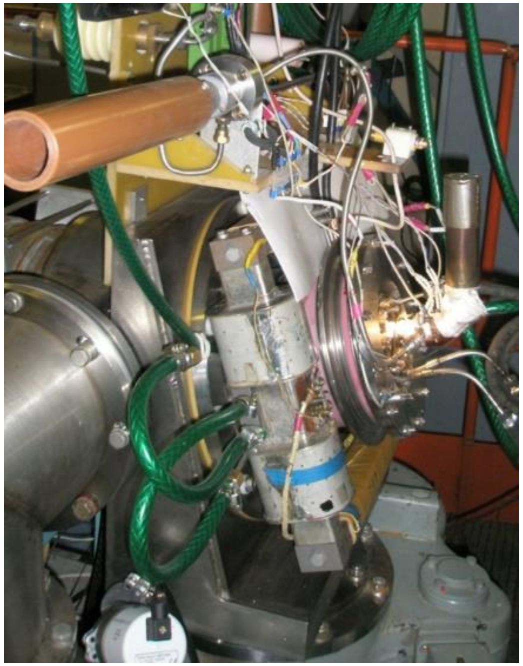
Anode assembly

Extraction Electrode

Acceleration Electrode
and magnetic poles

Source works at BNCT experimental tandem





Installed to the tandem LEBT in 2006 and is operated for more than 10 years

Source view

PIG Discharge	80 V / 10 A
Magnetic field	0.6 kGs
Hydrogen pressure	30 mTor
Cesium feed	< 5 mg/h

H- beam current	1-8 мA
Emission aperture	3 mm
Extraction	1-3 kV/30 mA
Post-acceleration	20 kV/40 mA

Starting time	50 min
Electrode conditioning time	< 10 min
Uninterrupted runs	4 ÷ 6 h/day

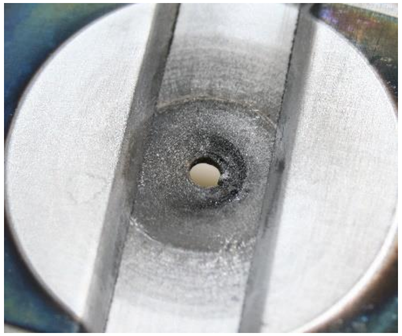
Typical parameters of the source work at BNCT experimental tandem

The CW source Electrodes Erosion and Wear

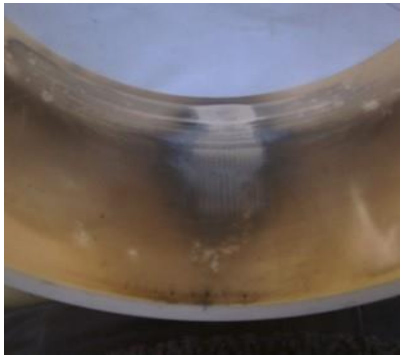
Cathode erosion after 12 month work

Moly film deposition to anode cover after 160 hours run

Accelerated Electrode melting by electrons



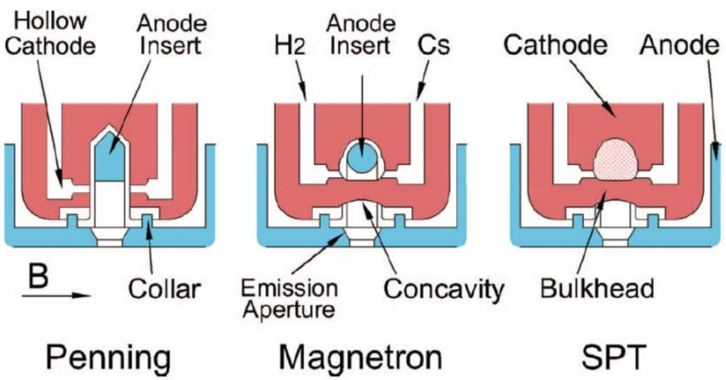
Extracted electrode aperture melting by electrons after 6 month work



IOS ceramics erosion by electrons after 6 month work

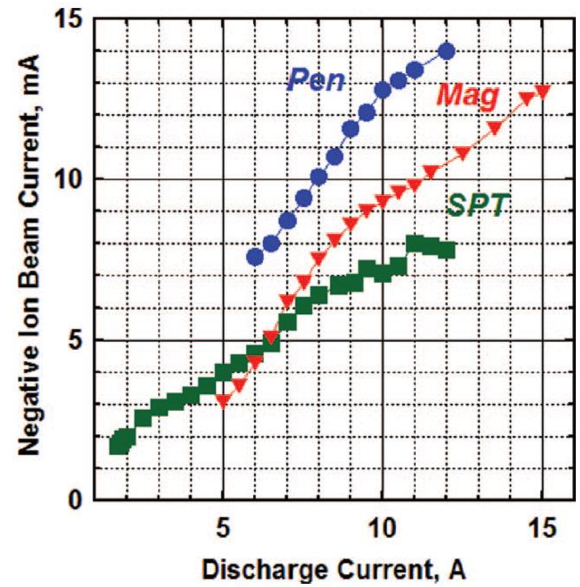
CW Sources with Hollow cathodes Magnetron and Semiplanotron geometry

Magnetron and Semiplanotron CW Sources with hollow cathodes were manufactured to check their capabilities CW negative ion beam production



The basic CW Penning source was modified by introducing the solid central bulkhead between the cathode protrusions

Magnetron source cathode with bulkhead and spherical concavity on the bulkhead plane

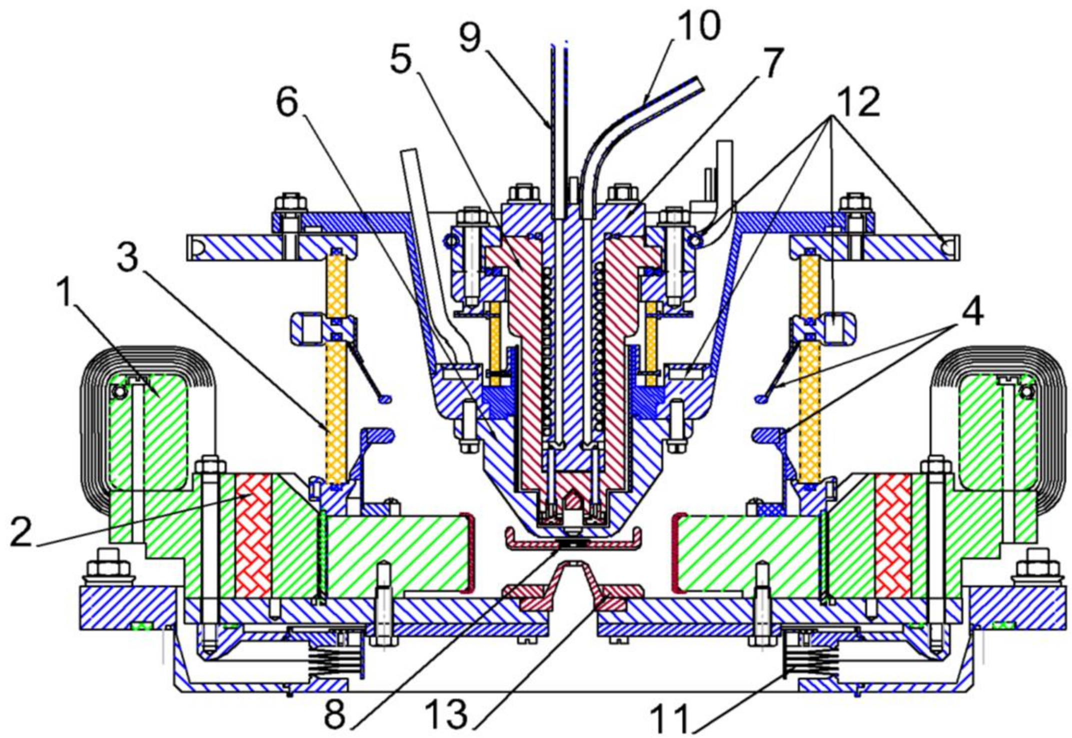


H^- beam current vs discharge current for Penning, magnetron and semiplanotron source.

~ 50% of H– beam, extracted from magnetron is the cathode-produced one (emission aperture Ø1.5 mm)

Lower H– beam production in the CW magnetron and semiplanotron – due to impeded cesium redistribution to the cathode emission area.

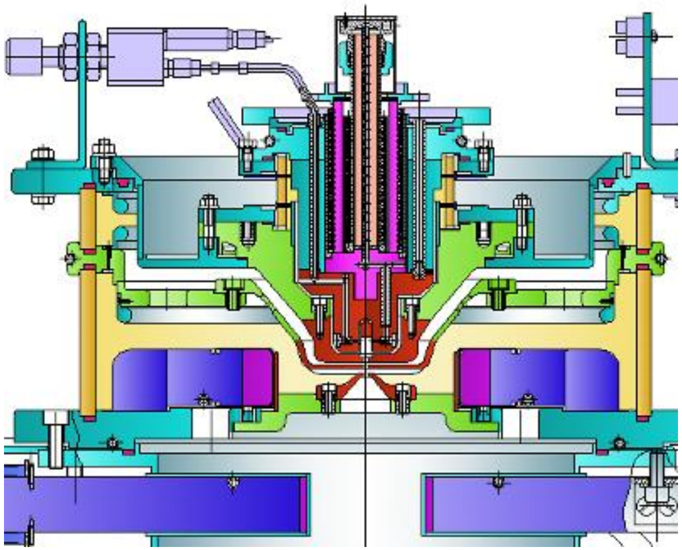
Modification of CW Negative Ion Source for tandem accelerator



Several modifications of Penning source were applied to increase the H- current and reliability, and to decrease the electrodes and ceramics erosion

Reported by A.Sanin in talk WedO6 ***"Operating Experience and Recent Updates of Negative Hydrogen Ion Source at BINP Tandem Accelerator"***

15 mA CW Negative Ion Source

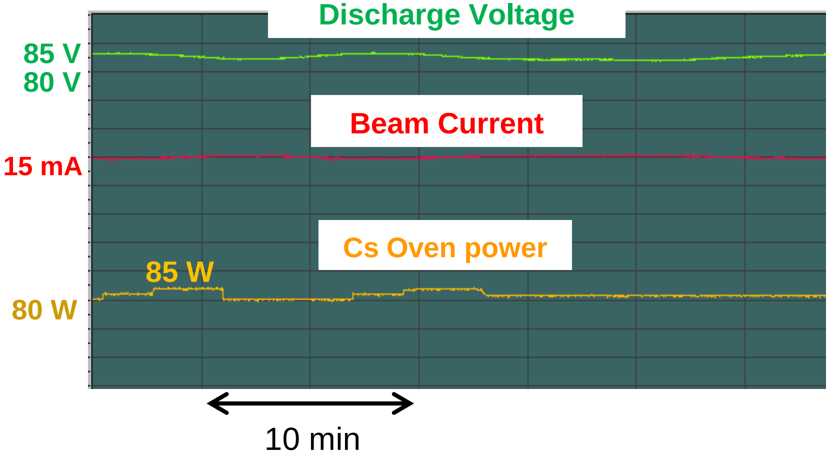


The similar principal scheme

Magnets with yoke are placed inside HV ceramics

Collar around the emission aperture at the anode cover

- Replaceable Insulators
- Replaceable heaters of the cathode and of the Cs oven
- Permanent NdFeB Magnets
- Additional "correlation" magnet system
- Temperature control of electrodes with thermal spacers
- Controlled Air cooling of Cs system coldest point



PIG Discharge Voltage and H- Beam response to Cs seed change

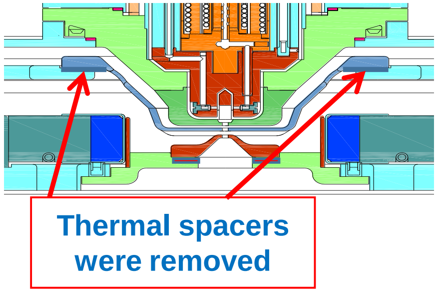
At the stand

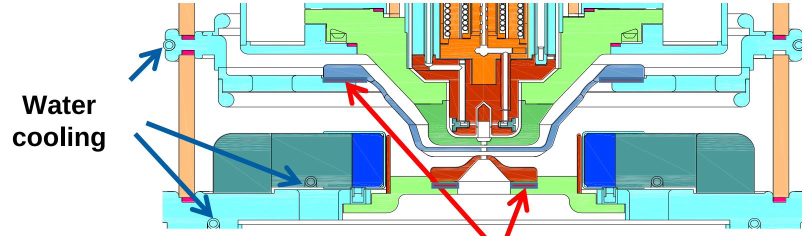
H- beam current	15 мA
Emission current density	150 mA/cm^2
Emission aperture	3.5 mm
Extraction Voltage/current	5-8 kV/30 mA
Acceleration Voltage /current	28 kV/40 mA

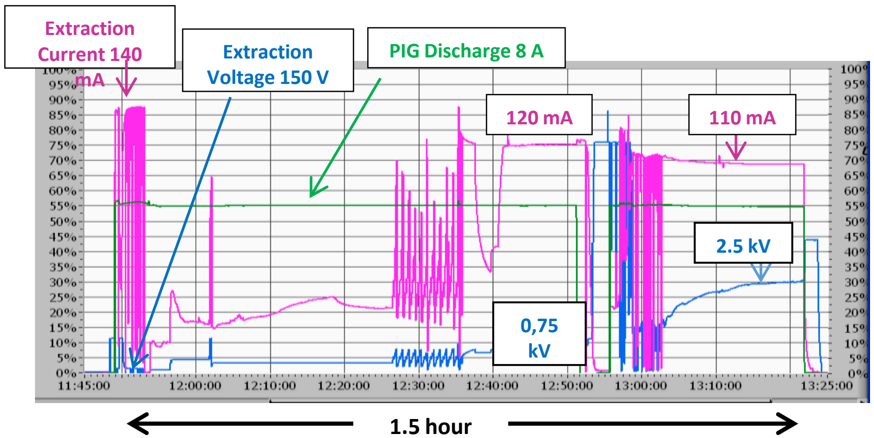
Several >100 hours run were successfully approved

Importance to keep the Extraction Electrode hot

Special Thermal Spacers, installed between flanges and IOS electrodes make the electrode tips hot and improve the source conditioning!

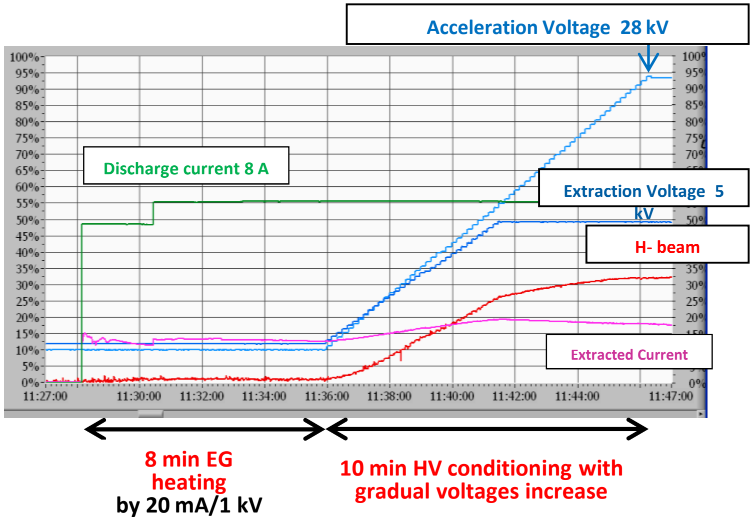






Cold Extraction Electrode

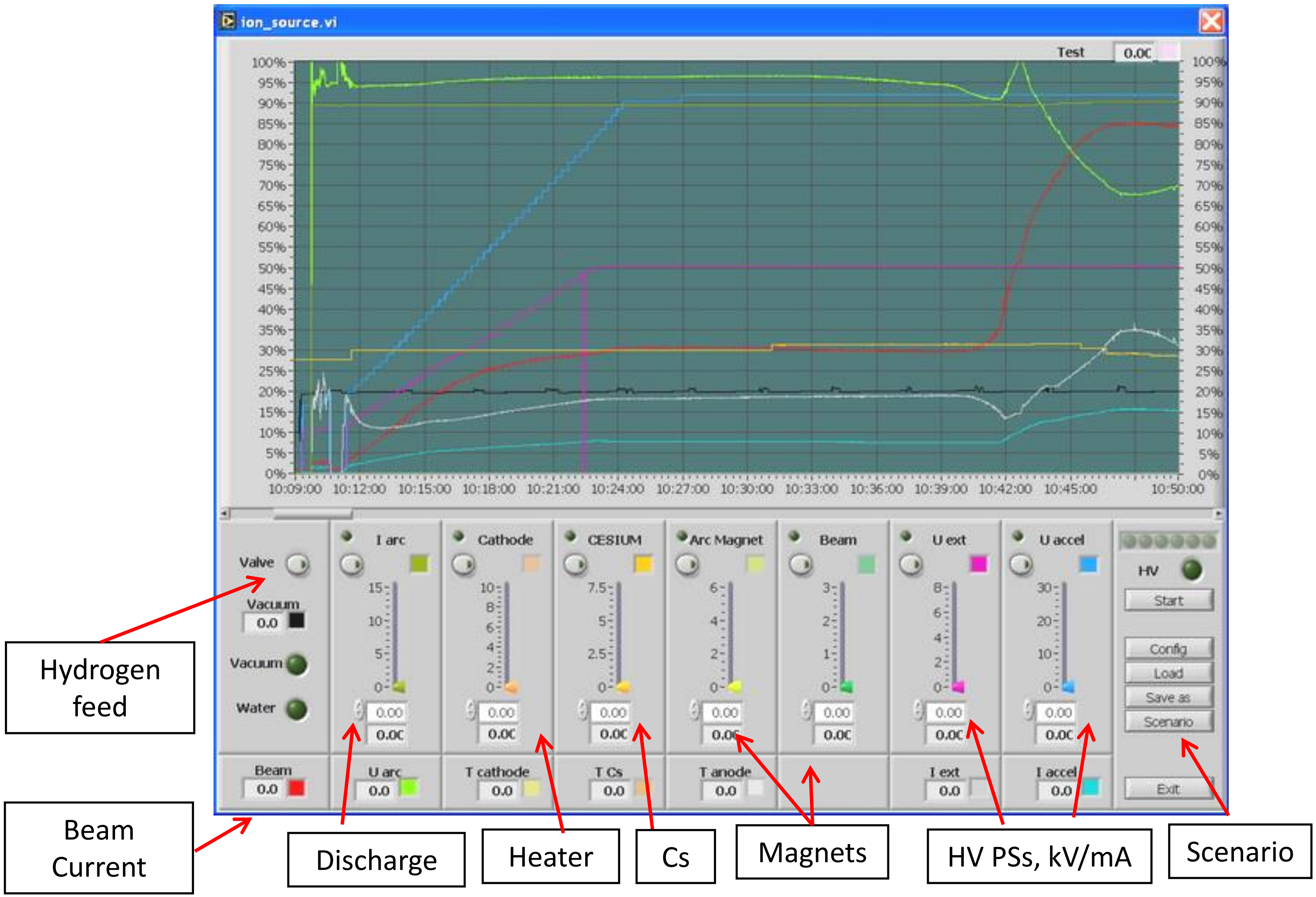
Unlucky attempts to heat and to condition EE. Arcing and dc glow in the extraction gap



Extraction Electode with poor cooling

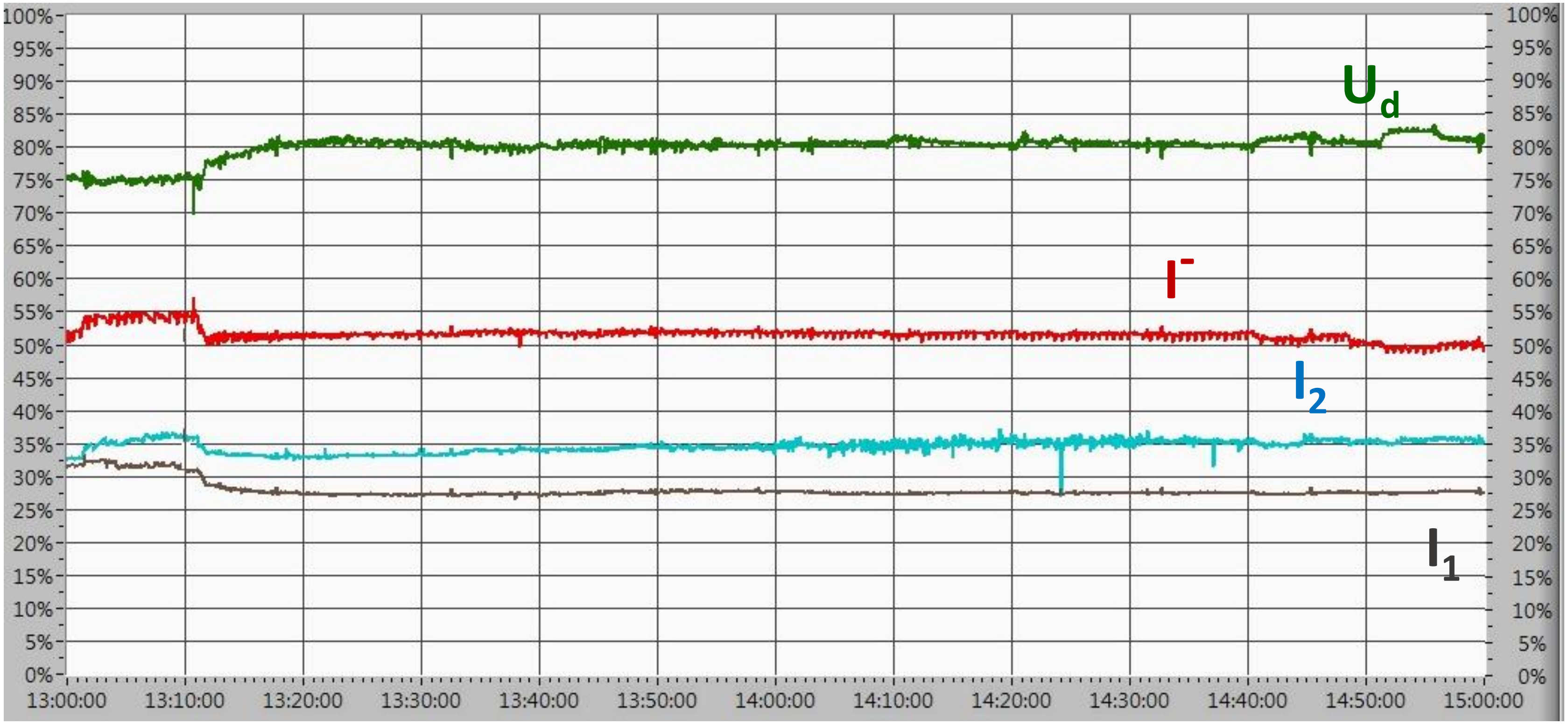
Fast IOS conditioning at the source start

Source Control by Autopilot



15 parameters are monitored

Long Term Runs with 25 mA Beam Production

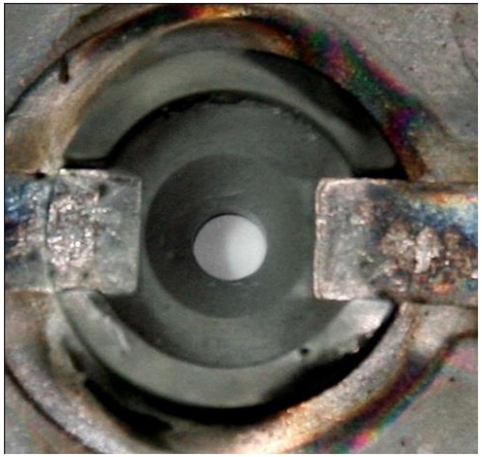


Tracks of 2-hours source run with formation of 25 mA beam.

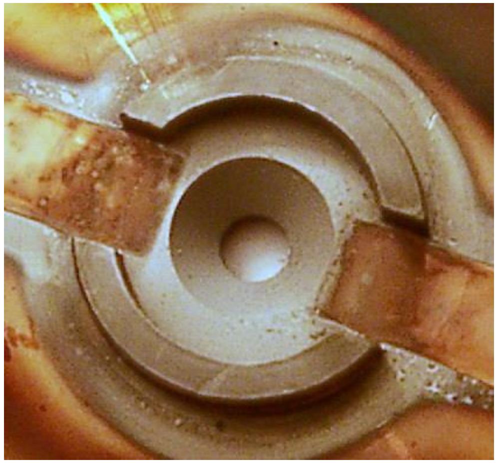
Red - beam current I^-= 25mA (100%=50mA), green - discharge voltage U_d= 80V (100%=100V), brown - extraction electrode current I_1=55mA (100%=200mA); Blue - acceleration electrode current I_2 =70mA (100%=200mA). Horizontal scale is 10 min per division.

Cesium Coverage on the Anode

- **A sizeable deposition of sputtered molybdenum to the emission surface around the emission aperture was revealed in the CW Penning source.**
- **The dynamic Cs coverage on the anode tolerates the overlaying by molybdenum. The thick Cs-Mo film with low work function could be deposited on the anode by co-adsorption of the cesium and molybdenum fluxes.**

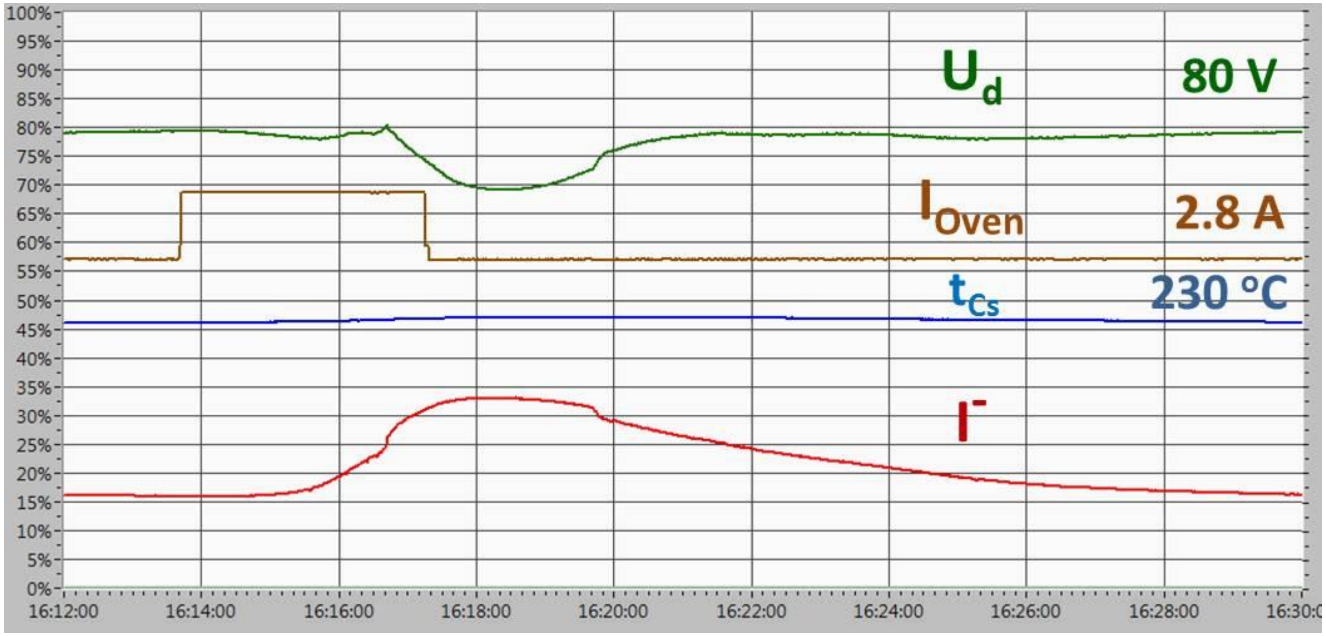


Sputtered molybdenum on the Molybdenum anode cover



Sputtered molybdenum on the Copper anode cover

Source Response to Cesium Seed Change



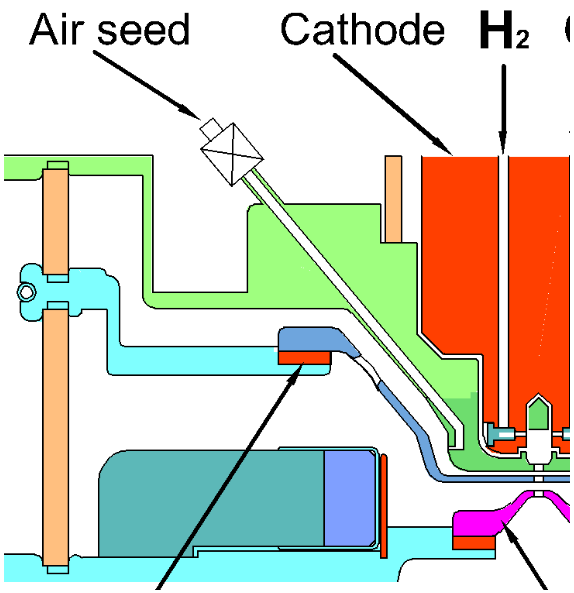
Oven heater current was increased for 3 minutes

I^- - beam current, U_d - discharge voltage, I_{Oven}– oven heating current; t_{Cs} – cesium cold point temperature.

time scale 2 min per division.

- **Beam current and discharge voltage are sensitive to Cs seed change**
- **Gradual 10 min decrease of beam current was recorded after oven power decrease due to anode cesium coverage overlaying by sputtered molybdenum.**

Air Seed to the Extraction Gap



	Before Air deposition	During Air deposition	After Air deposition
Beam Current, mA	14.7	14,0	14.7
Extraction current, mA	34	26	36
Acceleration current, mA	25	22	22
Discharge voltage, V	76	79	78

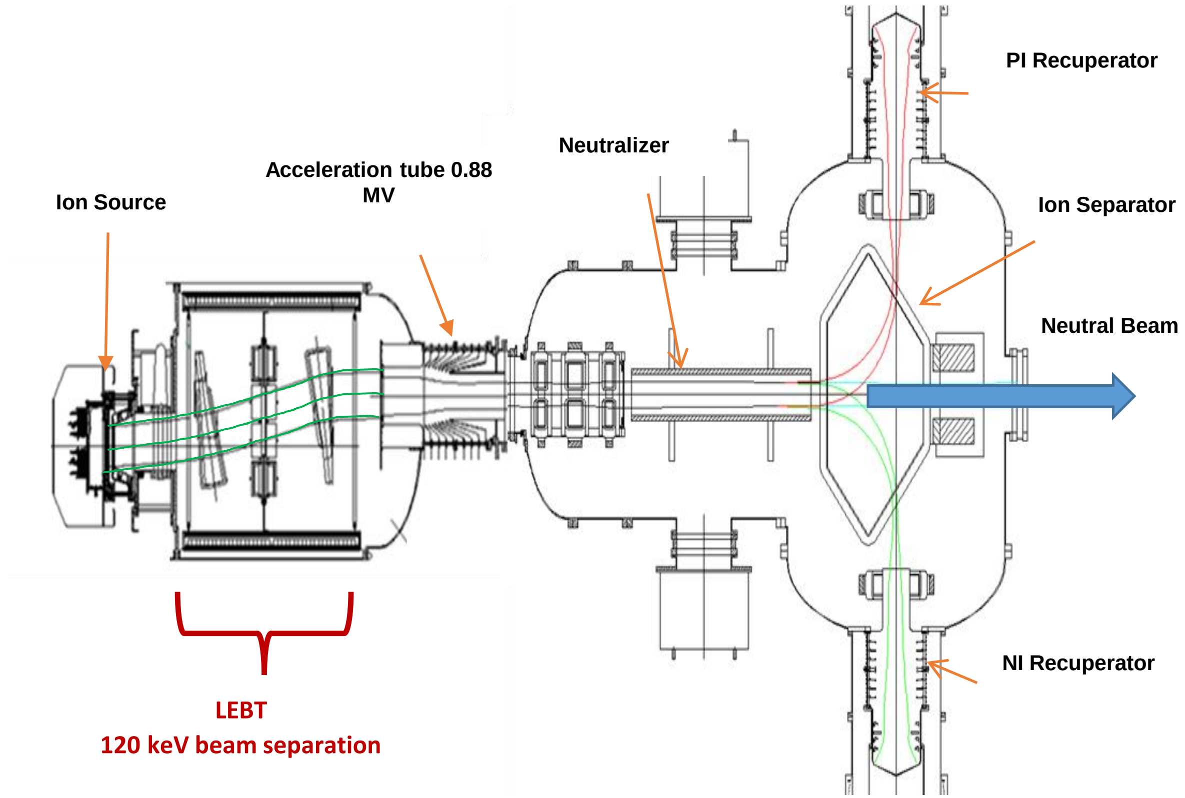
An attempt to passivate cesium coverage on the IOS electrodes by controlled injection of air to the extraction gap was performed.

An air flow up to $5{\cdot}10^{-3}$ L·Tor/s (~5% of H_2 feed) was seeded to the extraction gap

Dynamic Cs coverage on the anode is resistant to residual air leak

BINP work on Negative Ion Based NBI

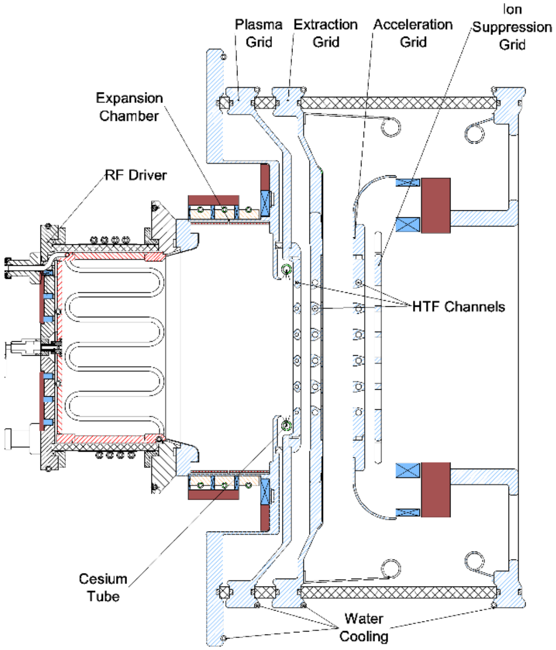
Principal Scheme of BINP 1MeV Negative Ion Based Neutral Beam Injector

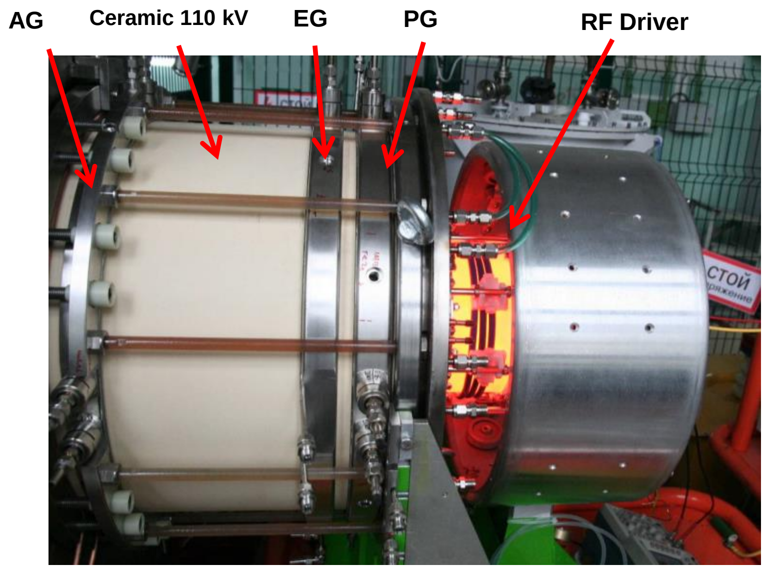


Beam acceleration is produced after purifying from the co-streaming fluxes of primary and secondary particles (gas, fast neutrals, electrons, cesium, light)

Negative ion beam is focused to a single-aperture 0.5-1 MeV accelerating tube. The stresses of the accelerator must be considerably reduced.

Inductive RF source with Surface-Plasma Negative Ions production





What's new

Standard features

Negative Ion production on the cesiated PG surface (Surface-Plasma Source)

Plasma produced by RF driver Electrons are filtered by magnet filter

Positive Bias of plasma grid to suppress electrons extraction

Multiaperture 3-4-grids IOSs

Keeping the driver walls, the extraction and plasma grids hot during cesium operation.

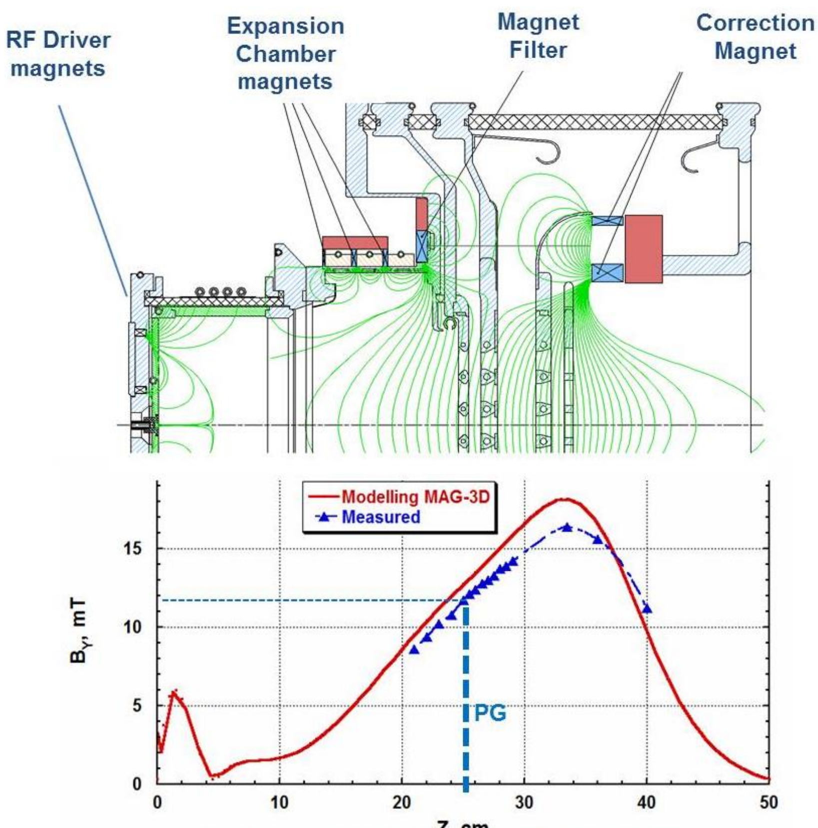
IOS electrodes heating and cooling by circulation of heat transfer fluid (Marlotherm)

Directed distributed cesium deposition to plasma grid via the long distribution tubes, attached to PG

Additional magnets to concave the field in the extraction gap

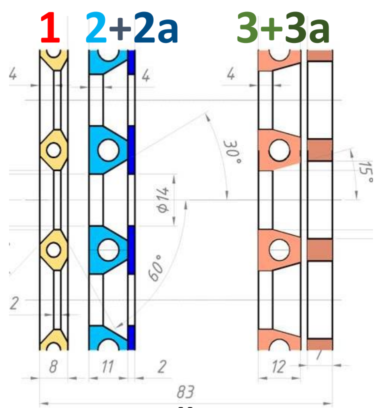
External NIB magnets. No magnets immersed into the hot grids.

Magnet and Ion Optical Systems



Field at PG = 12 mT , Filter strength 90 mT·cm

Magnet positions and magnetic field distribution along the source axis

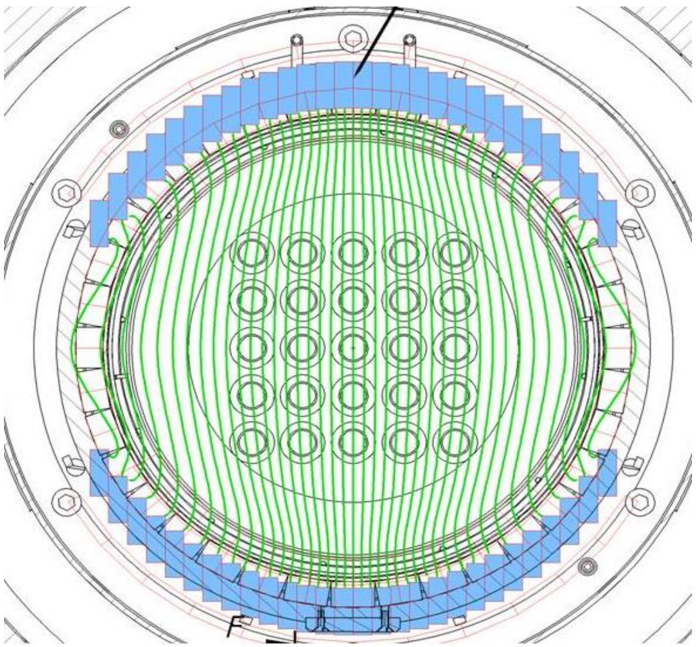


IOS cells geometry

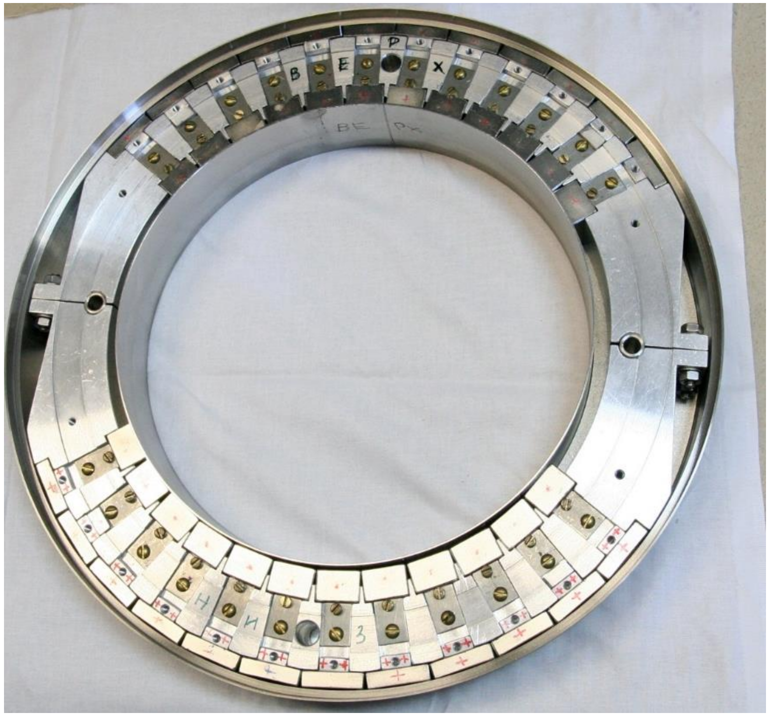
1 - Plasma Grid, 2 - Extraction Grid
2a - Electron Suppression Grid
3 - Acceleration Grid
3a - Positive Ion Suppression Grid

Apertures Diameter , mm	16
Horizontal Pitch, mm	27
Vertical Pitch, mm	27
Aperture Area , cm^2	2
Emission Zone Area, cm	13x13
Extraction gap, mm	6
Acceleration gap, mm	47

Dipole magnetic filter



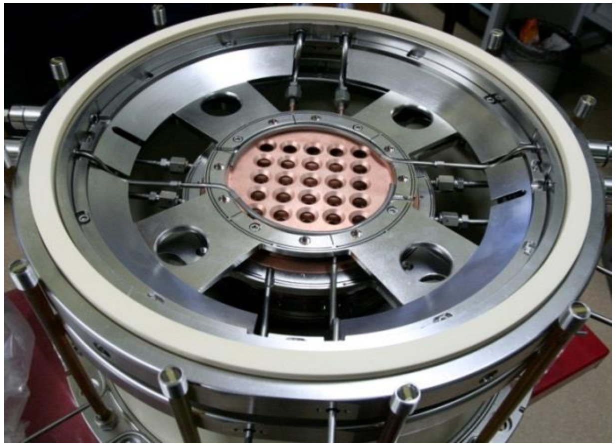
PG magnet filter



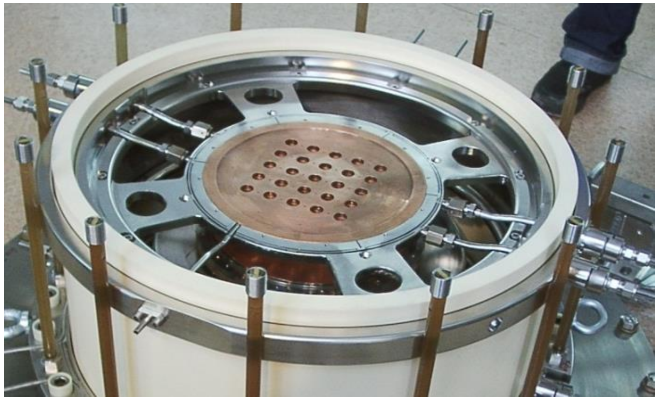
Correlation dipole magnet at AG base

Magnetic field was calculated by 3D code MAGEL3D (M.Tiunov, BINP)

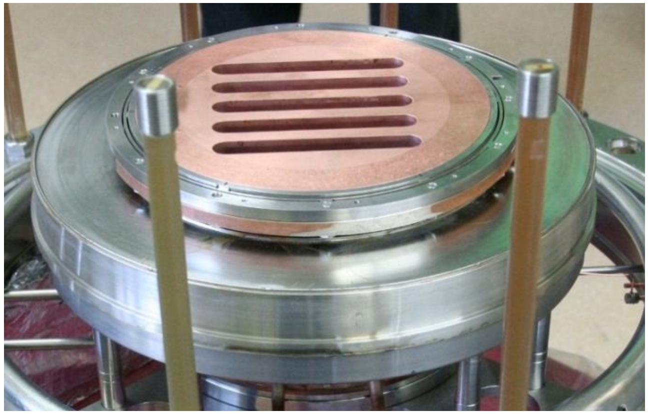
Ion Optical System Grids



Plasma Grid
with 25 emission apertures



Extraction Grid
with 25 apertures



Acceleration Grid with 5 slits

Distributed Cesium Seed

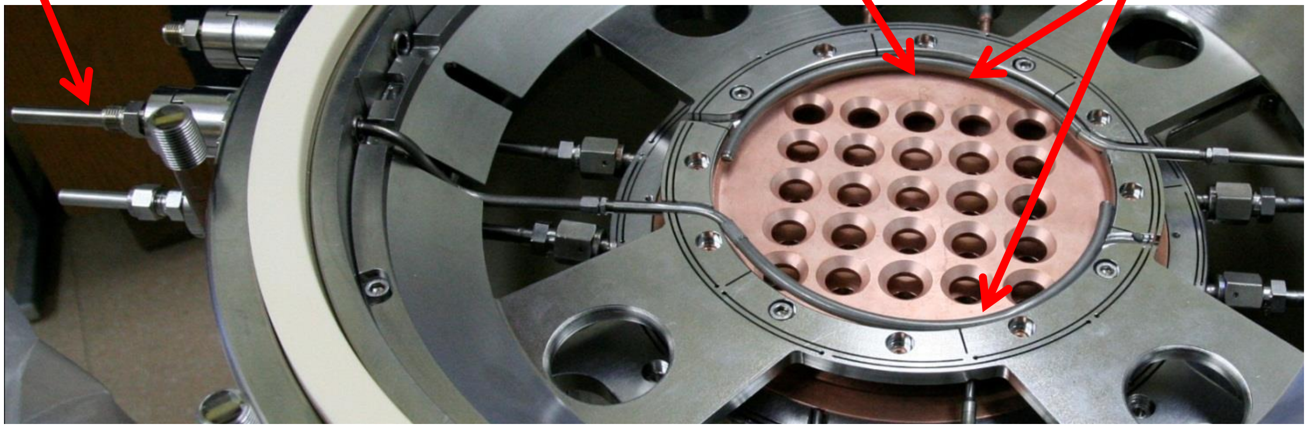
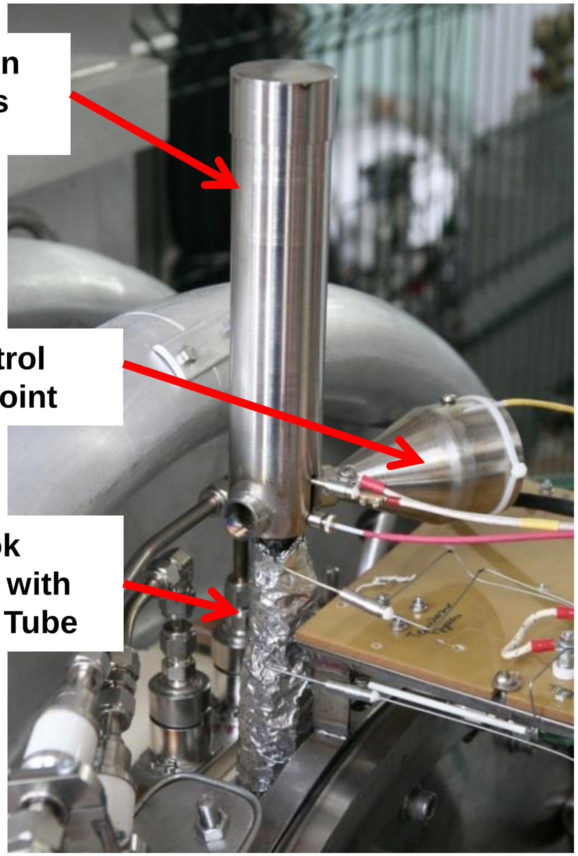


Photo of Plasma Electrode with Cesium Distribution Tubes

- Distribution tubes have ø 0.3 mm openings, drilled with 10 mm pitch. Tubes are heated to ~250 ^{o}C by internal thermocable.
- Two types of Cs systems were developed and studied at separate stand:
  - with metallic cesium and valves
  - with cesium-chromate + titanium pellets
- Cesium redistributes over PG plane by thermal desorption and sputtering too

Cs ovens with cesium-chromate pellets

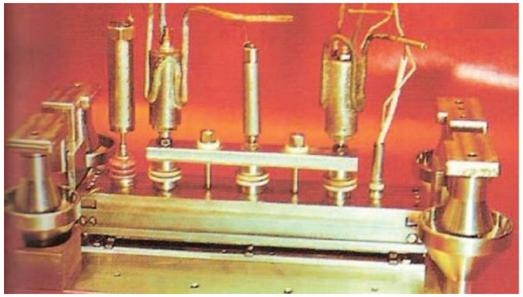


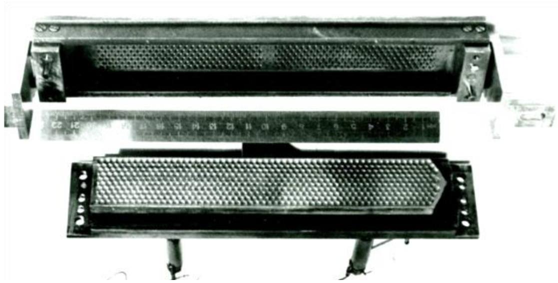
Cs Oven System at the PG flange

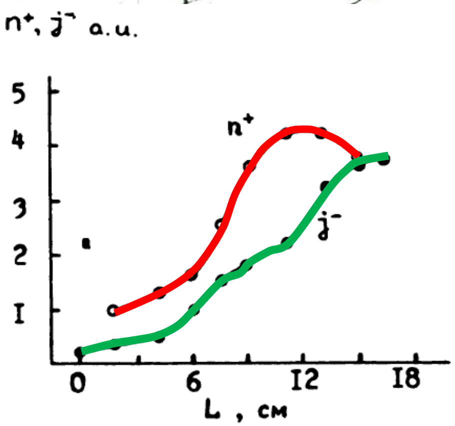
Cs Oven (coat and oven heater detached)
before connection to PG flange

Cesium Redistribution by discharge

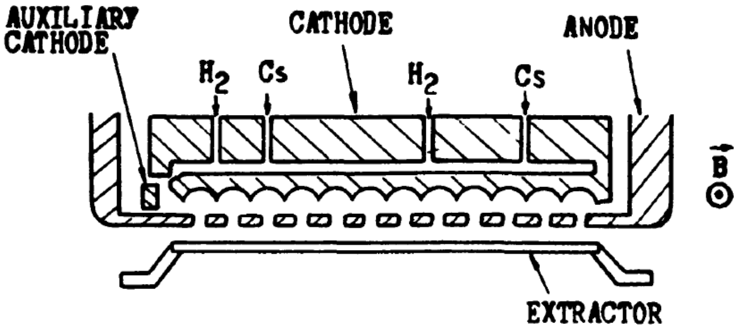
Cathode area 3 x 20 cm^2 BINP, 1982 г.



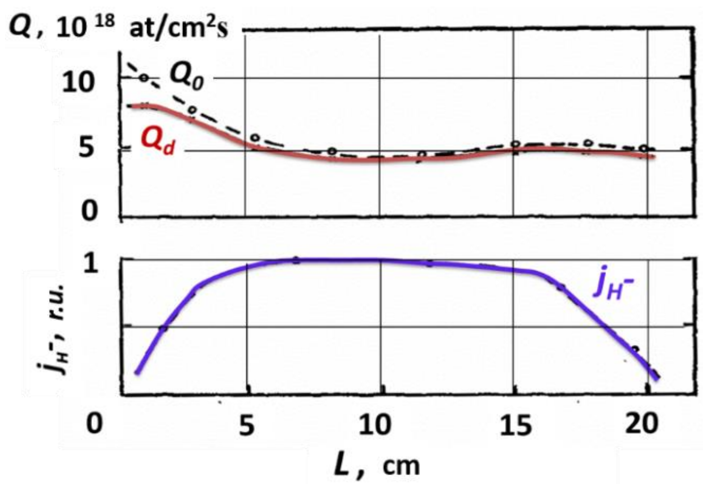




Cs redistribution due to Cs+ ions shift in ExB direction (Self-activation by discharge)



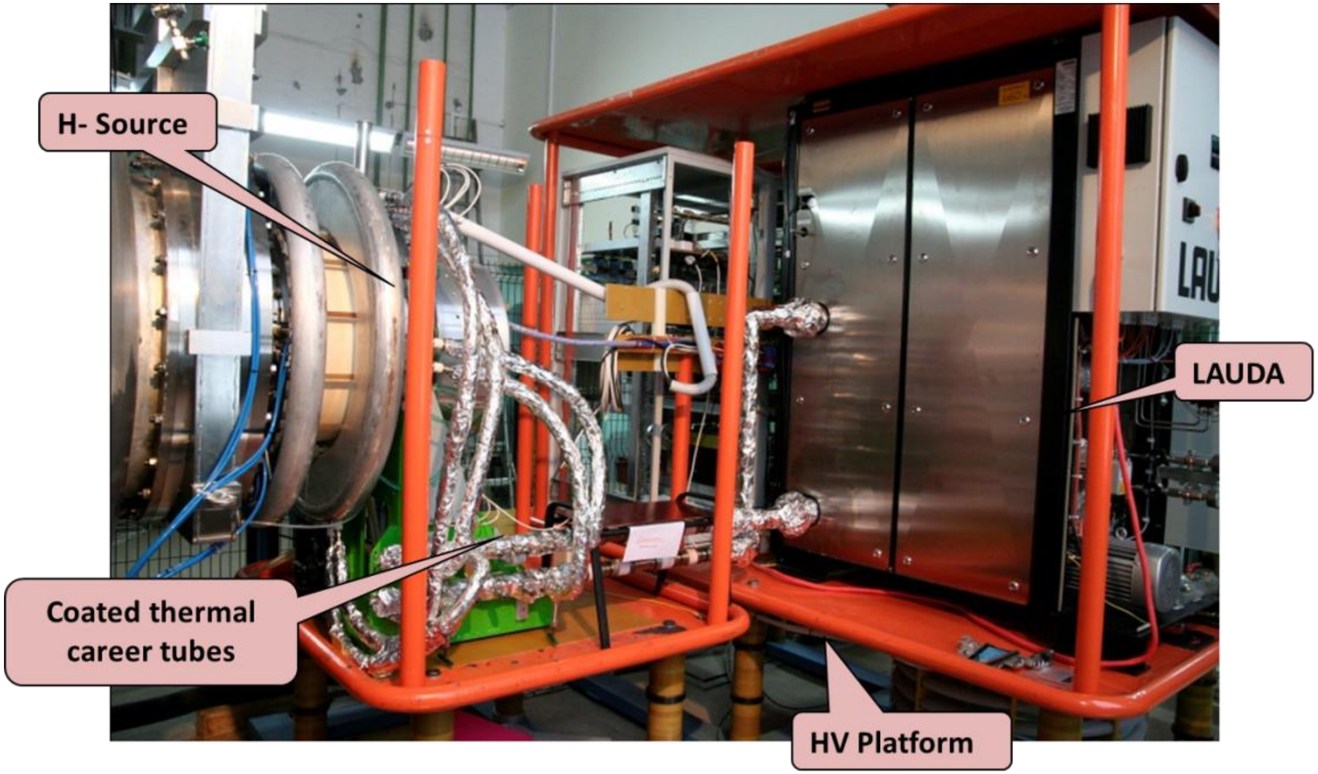
Discharge with auxiliary cathode



Uniform H- beam distribution along 80% of the cathode
after cathode conditioning by the main and auxiliary discharge

The similar Cs redistribution over the PG surface is produced in the RF sources due to Cs$^+$ ions implantation

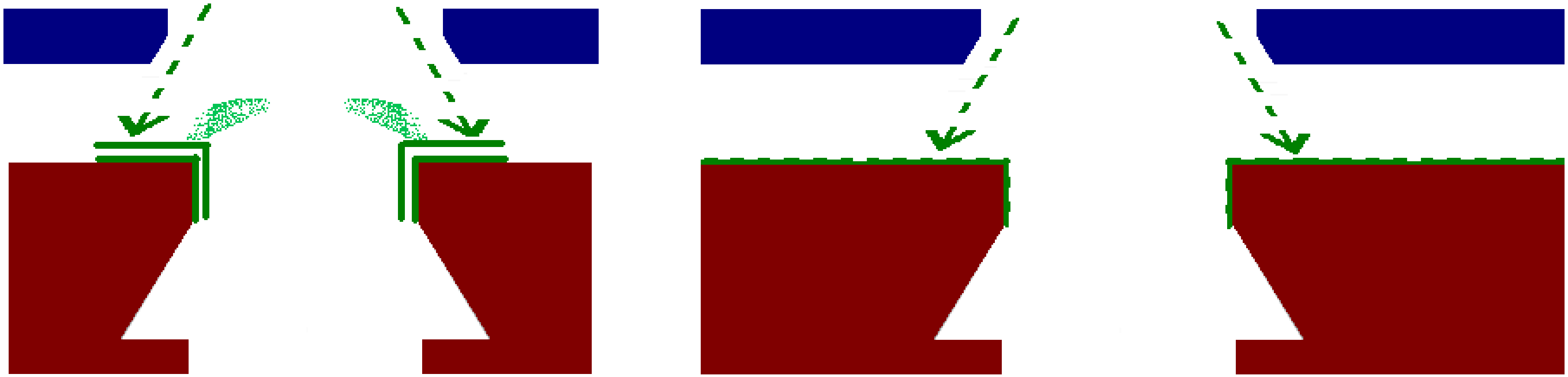
Thermal Stabilization of Electrodes



Thermal Stabilization System LAUDA at 120 kV platform

- **PG heating to 150 - 250°C temperature enhances H- yield**
- **Grids heating is provided by circulation of Heat Transfer Fluid and it is independent of discharge power**

Mechanism of HV holding improvement with Electrodes Heating



Hot electrodes

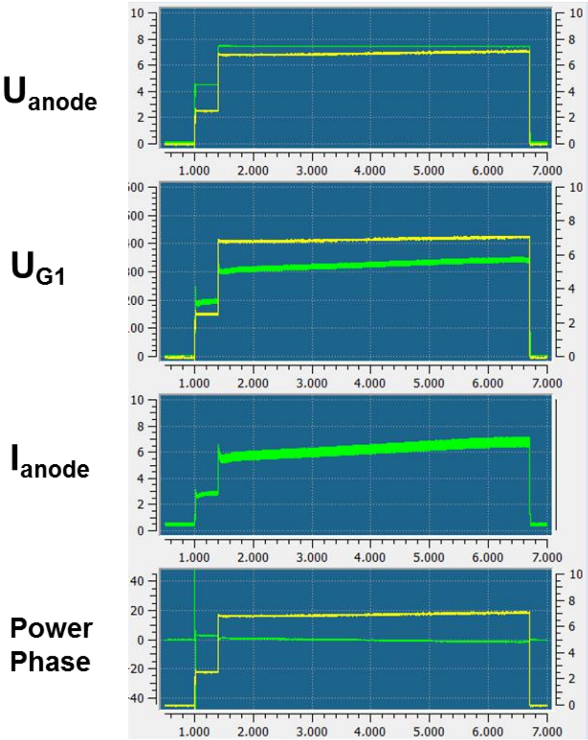
Cold Electrodes

Sputtering of the thick layers of accumulated cesium

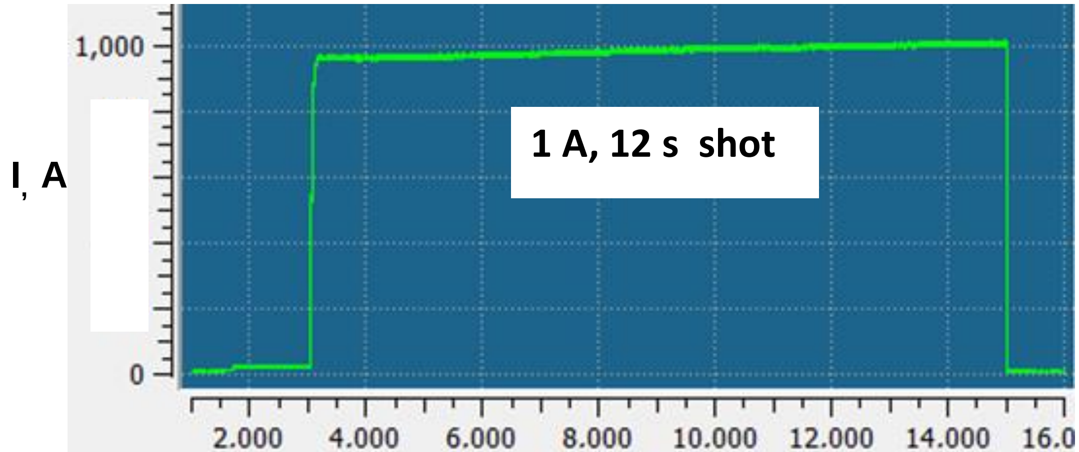
Exponential growth of Cs surface diffusion and thermal desorption with electrode temperature.
Easy Cs removal out of the electrode apertures edges.

No sputtering of the thick layers of accumulated cesium

Source operates stably and reliably



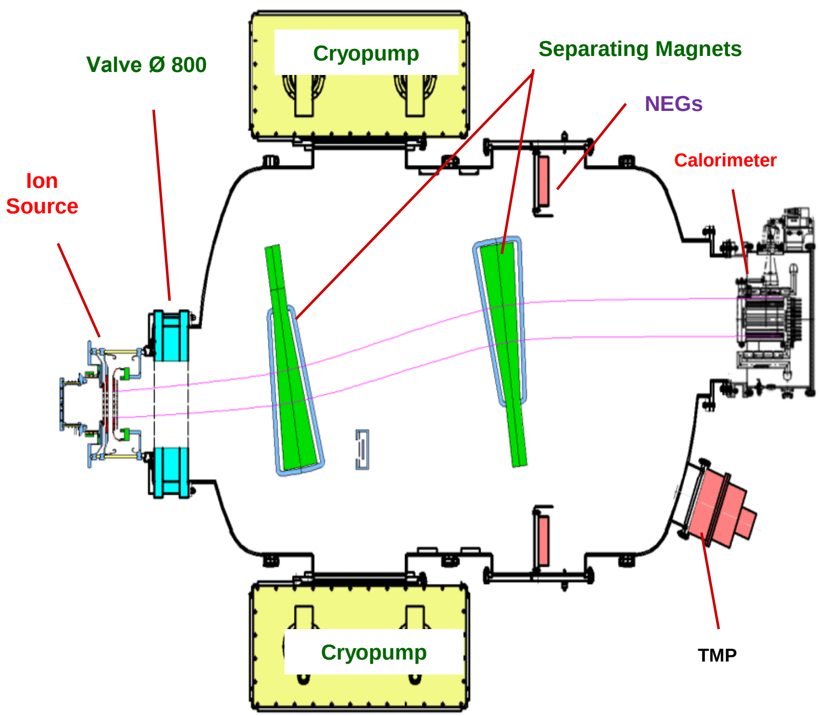
RF Driver - 5 s pulse

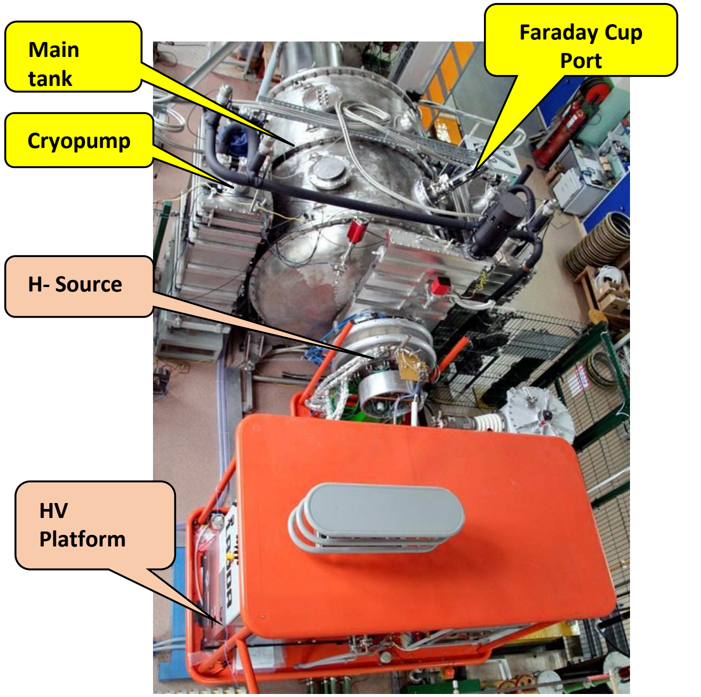


- H- ion beams with current >1A and energy ≥110 keV are regularly produced.
- Power efficiency of H- ion production is 28 kW/A
- H- ion beam was transported through the LEBT to distance 3.5 m

H- beam transport study

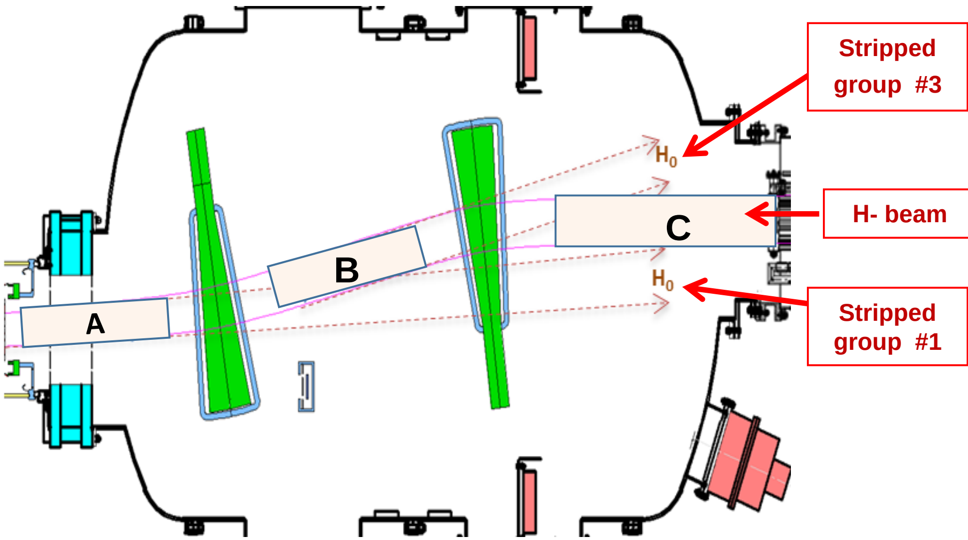
Will be reported in the next talk ThuO9 of O.Sotnikov



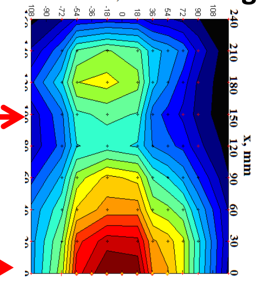


- **Ion Source** is at 120 kV platform and attached to ø 2.1 m x 3.1 m tank
- **Two cryopumps** (four cryocoolers) with hydrogen pumping ~$2 \cdot 10^5$ l/s.
- **Thermo-stabilization system** (70 kW) & auxiliary PSs are at 120 kV (1 MeV) platform.
- **Main PSs** are at basement flour

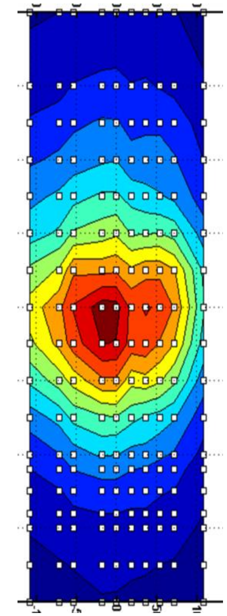
H- beam transport study



Power at calorimeter in two vacuum cases
Beam Magnetic scan



Poor vacuum
Increased H- ions stripping



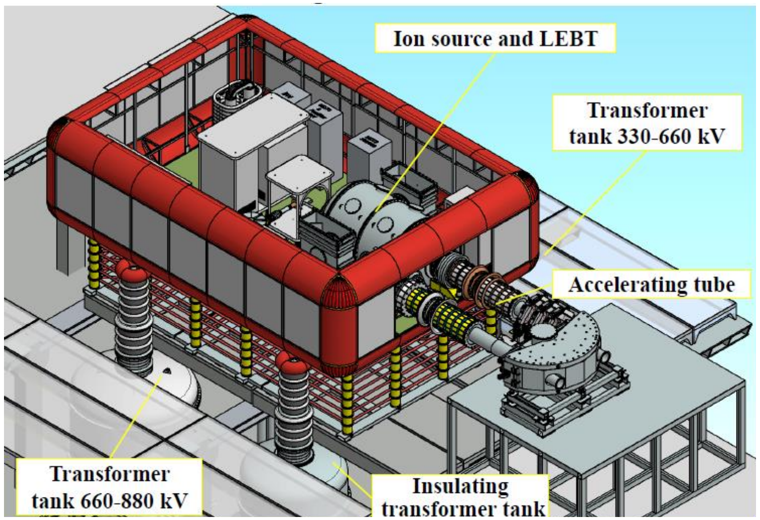
Standard pumping,
Decreased H- ions stripping
No stripped group #3

H- beam is well separated from the parasitic atoms, produced by NI stripping.

~ 80% of the H^- beam with energy 93 keV , outgoing from the source were transported to the calorimeter window 30 x 30 cm

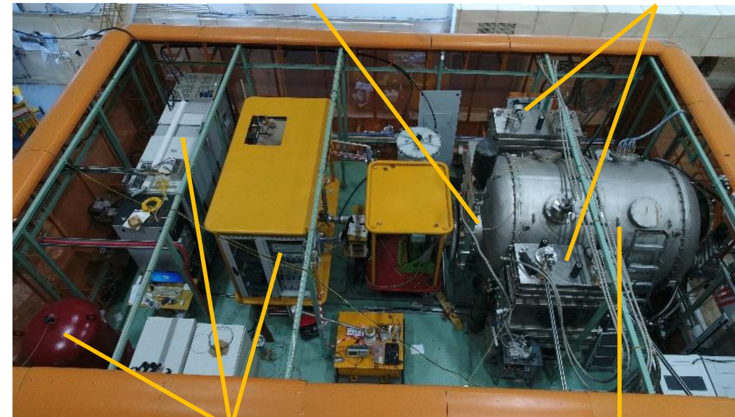
The RF source was moved to the HV platform of the 1 MeV stand.
The transport study will be continued at full beam energy 120 KeV

1 MV, 1.5 A Negative Ion Beam Stand



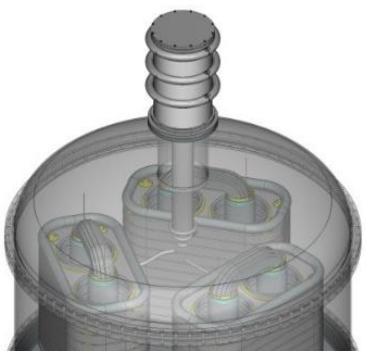
Design

120 keV 1.5 A ion source
Cryopumps

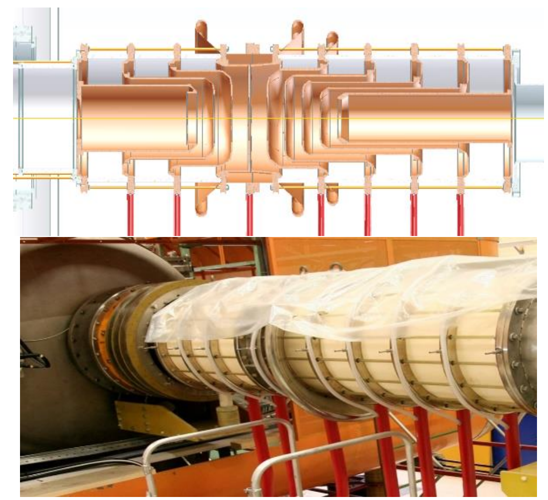


Source power supplies
LEBT tank

0,9 MV platform with NI source and LEBT

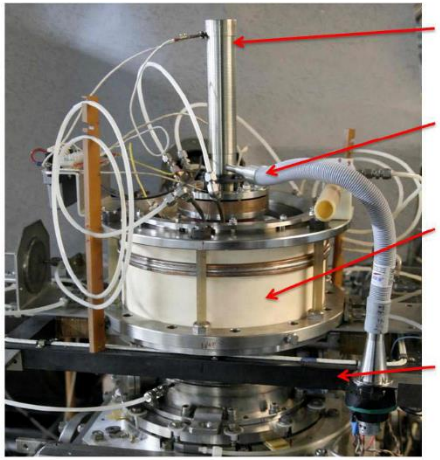


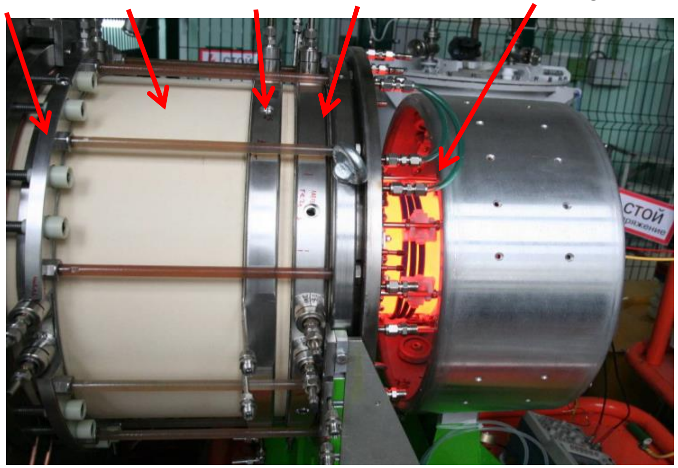
HV rectifier tanks and Bushing

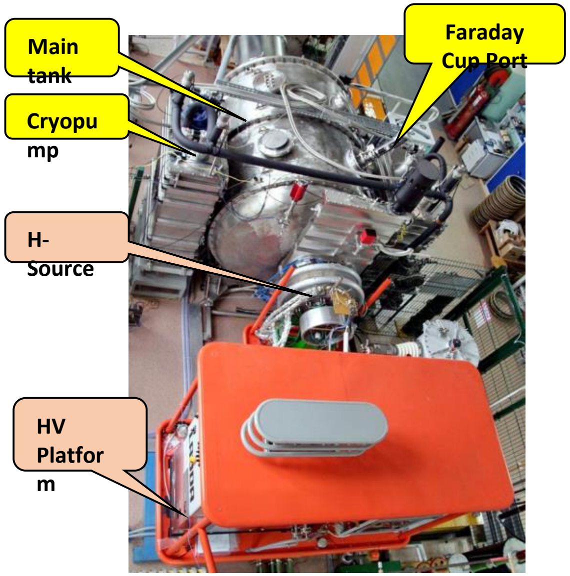


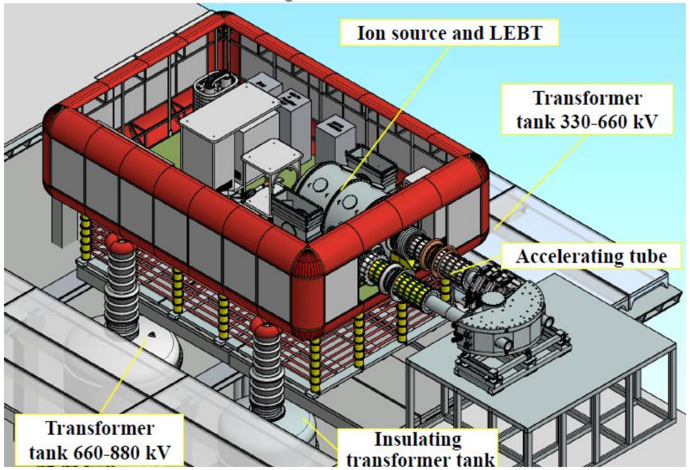
Acceleration tube

You are welcome to visit the BINP NI Facilities









Thank You for attention