Negative Ion and Neutral Beams Injectors at the Budker Institute of Nuclear Physics

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and the beams development group

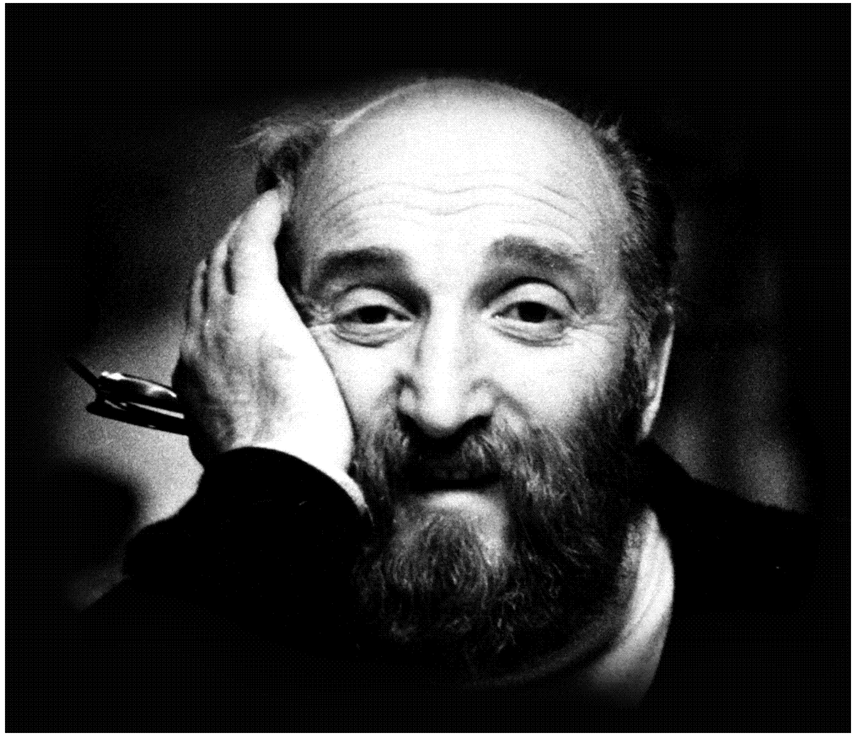
The 6th International symposium NIBS'18 (Negative Ions, Beams and Sources)

Outline

- Introduction
- Ion source development for charge-exchange injection into storage rings

  Historical achievements in the experiments
- Further development of the basic ion source design
- Neutral beams for plasma diagnostics in fusion devices
- Neutral beams based on positive ions for plasma heating
- High energy neutral beams based on negative ions and effective neutralizers
- Conclusions

How it was started 60 years ago.

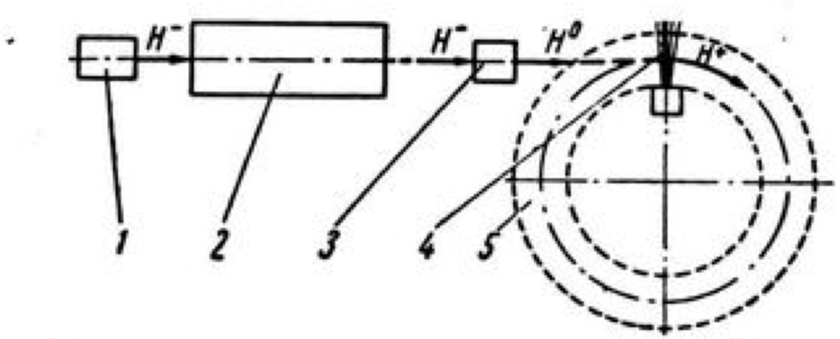


Academician G.I Budker

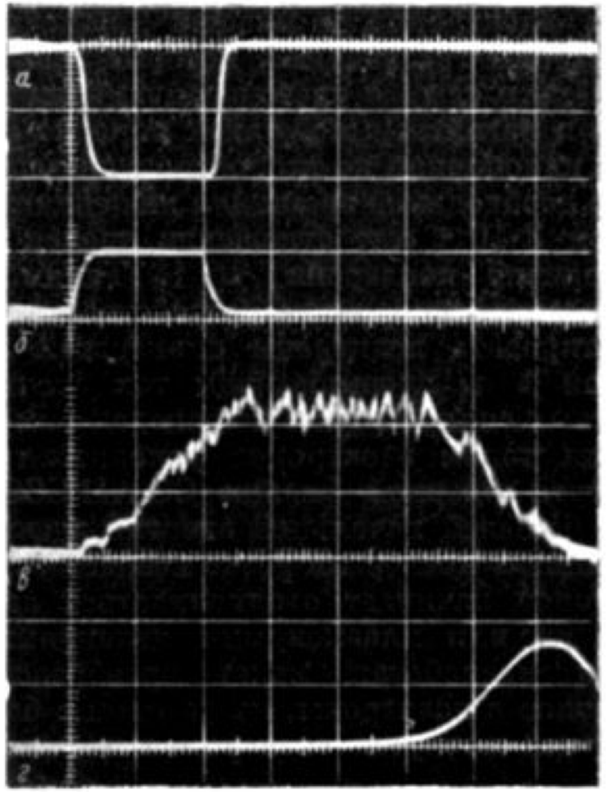
Prof. G.I Dimov

How it was started....

Charge-exchange injection of protons into storage rings
G.I.Budker, G.I.Dimov et al, 1965



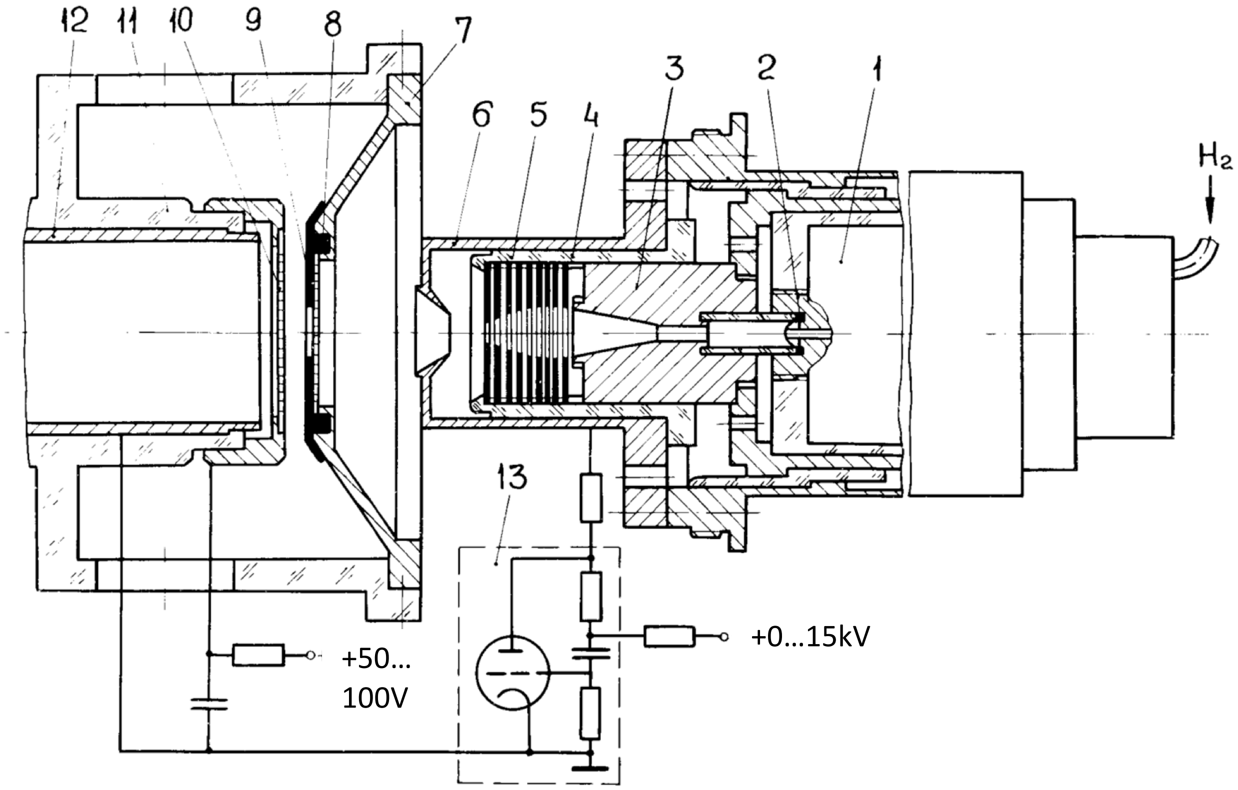
1-RF negative ion source, 2-accelerator, 3-neutralizer,
4-internal gas target, 5-storage ring



Oscilloscope traces of proton accumulation

Later on…

Arc-discharge plasma source – initial version (1968)

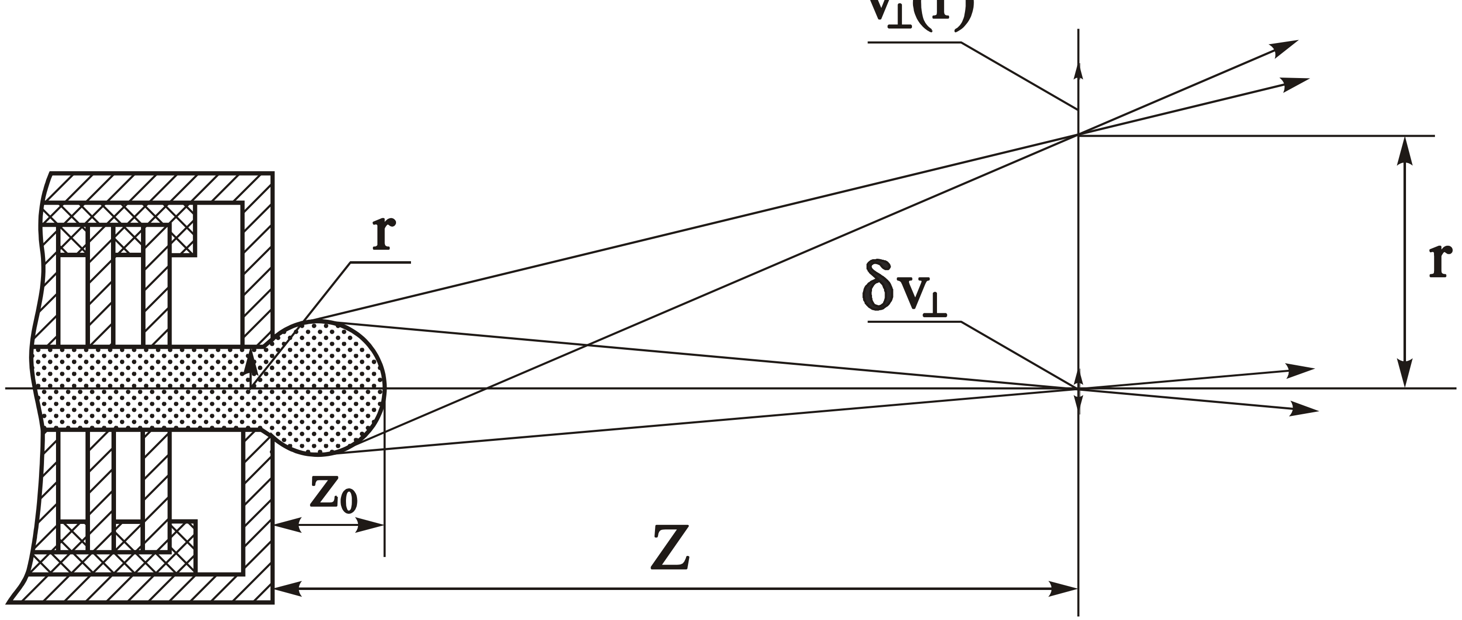


1-pulse gas valve
2-discharge trigger
3-cathode body
4-electrically floating washer stuck
5-insulator
6-anode
7-10-IOS electrodes
11-insulator
12-neutralizer
13-breakdown protection network

Characteristics:
ion flux ~ 50-100A
pulse 100-200µs

Plasma emitter with low transverse ion temperature

Plasma ions in the diverging plasma jet are collisionless.

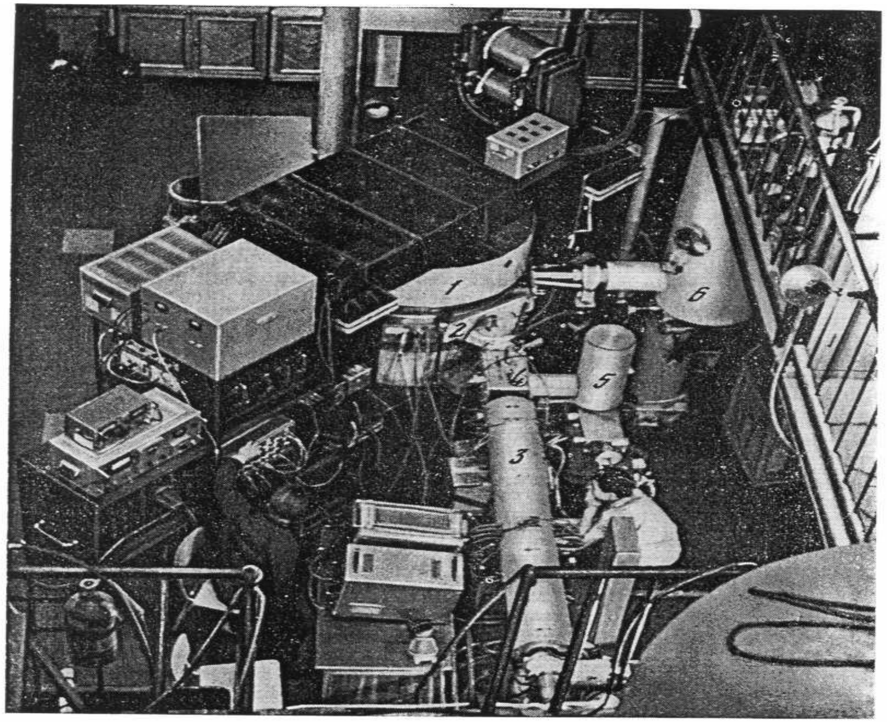


r ~ 0.3 cm n_0 ~ 10^{14} cm^{-3} T_{i0} ~ 3÷5 eV

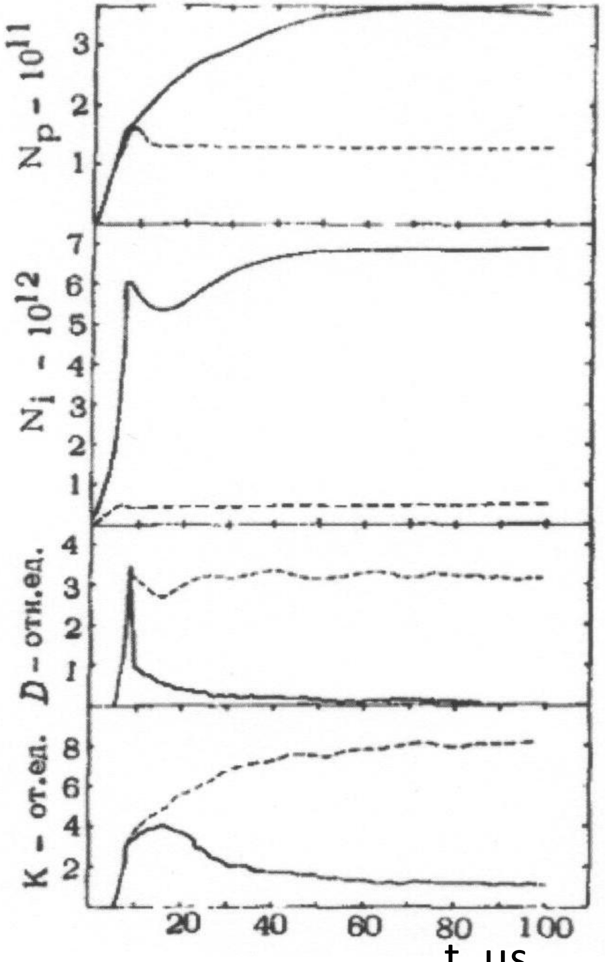
z_0 ~ 1 cm $T_i \approx T_{i0}\, z_0^2/Z^2$

Experimentally measured $T_i \approx 0.2$ eV

Experiments on charge-exchange injection



View of the experimental storage ring.



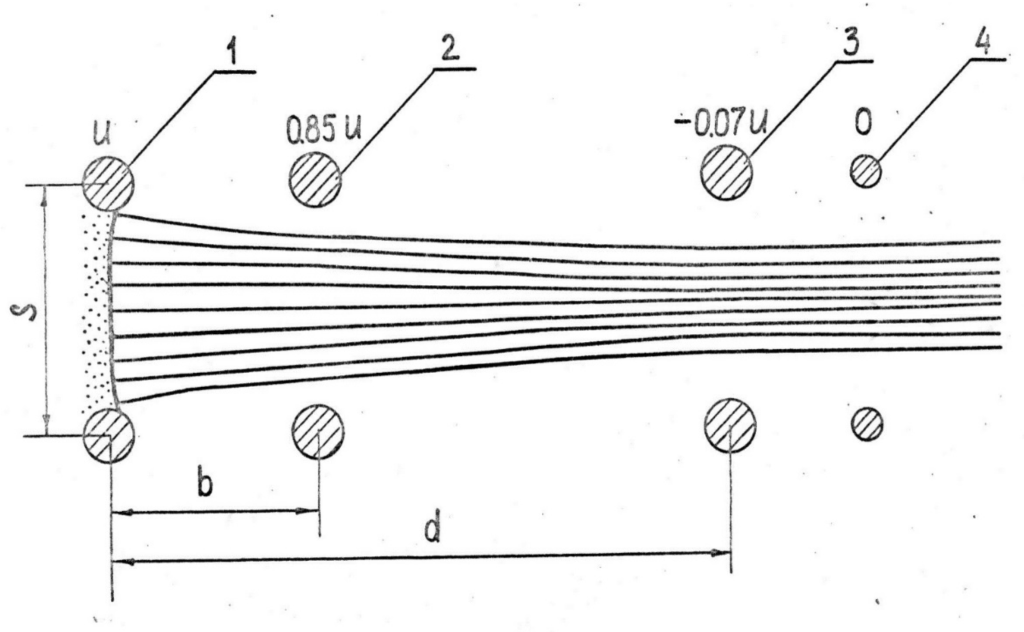
Number of accumulated protons

Number of secondary ions

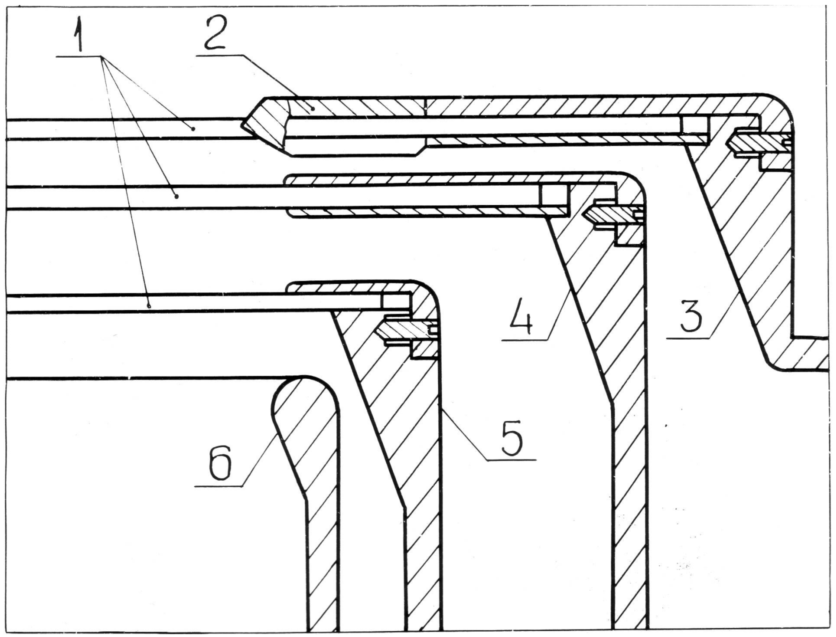
Amplitude of dipole oscillations

Amplitude of quadruple oscillations

Initial IOS design



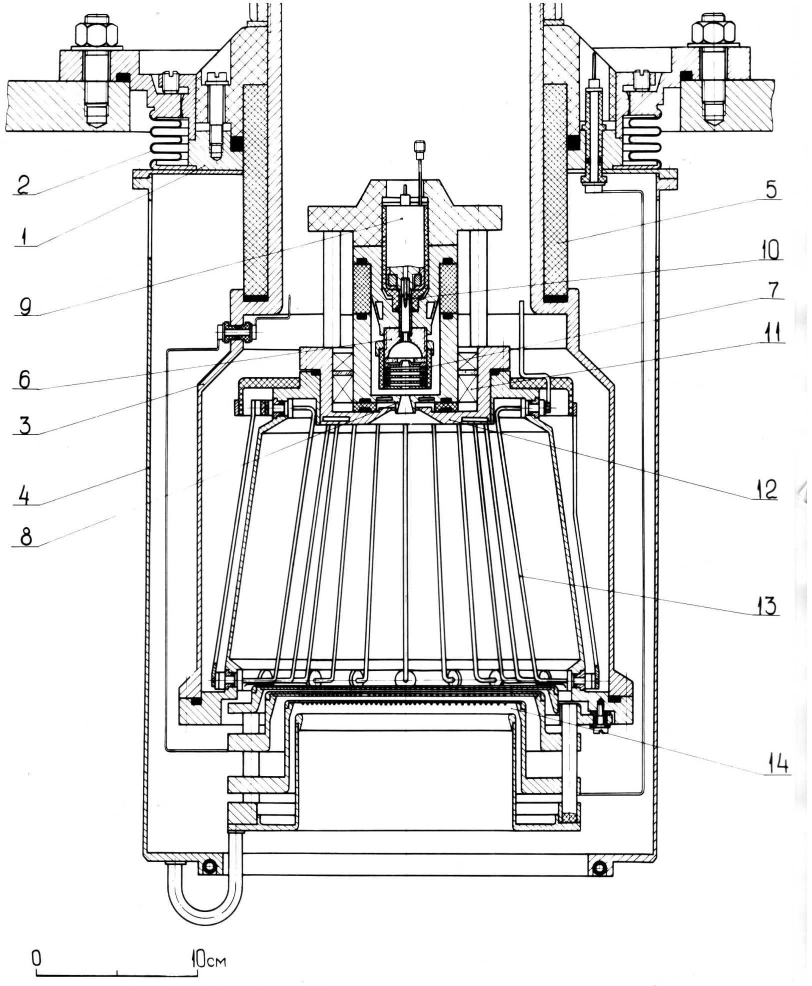
Four electrode IOS: 1-plasma grid, 2-extracting grid, 3-accelerating grid, 4-grounded grid



INAK IOS uses the wires strained with a spring-loaded mandrel :1- Mo wires, 2-Pierce electrode, 3-6 IOS electrodes

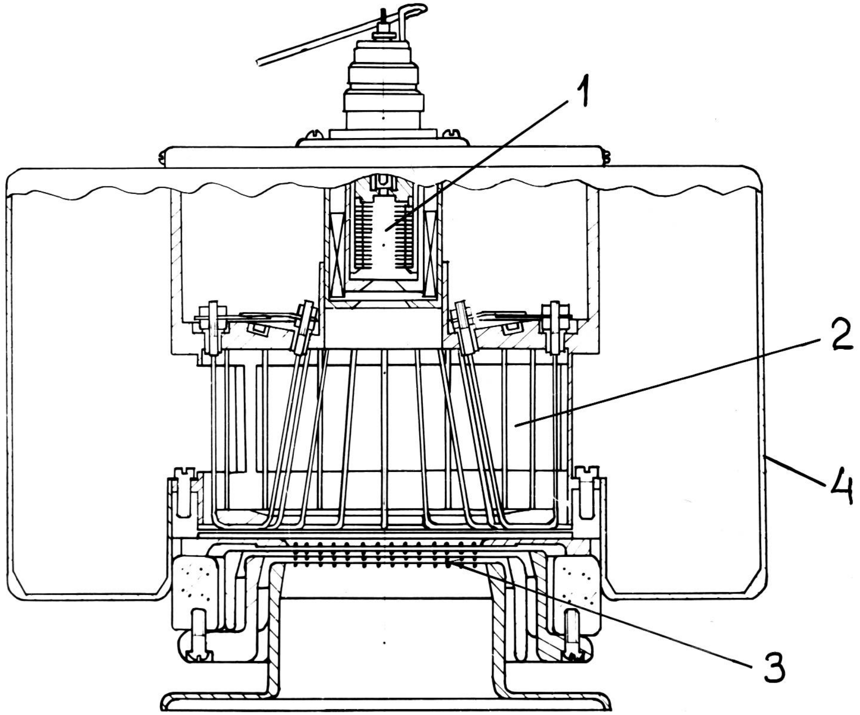
First generation of ion sources for plasma heating

Quasi-stationary beam (INAK)



4-casing
5-mail isolator
6-10--arc-discharge plasma source
11-magnetic coil
13-toroidal solenoid
12-magnet shield
14-IOS electrodes

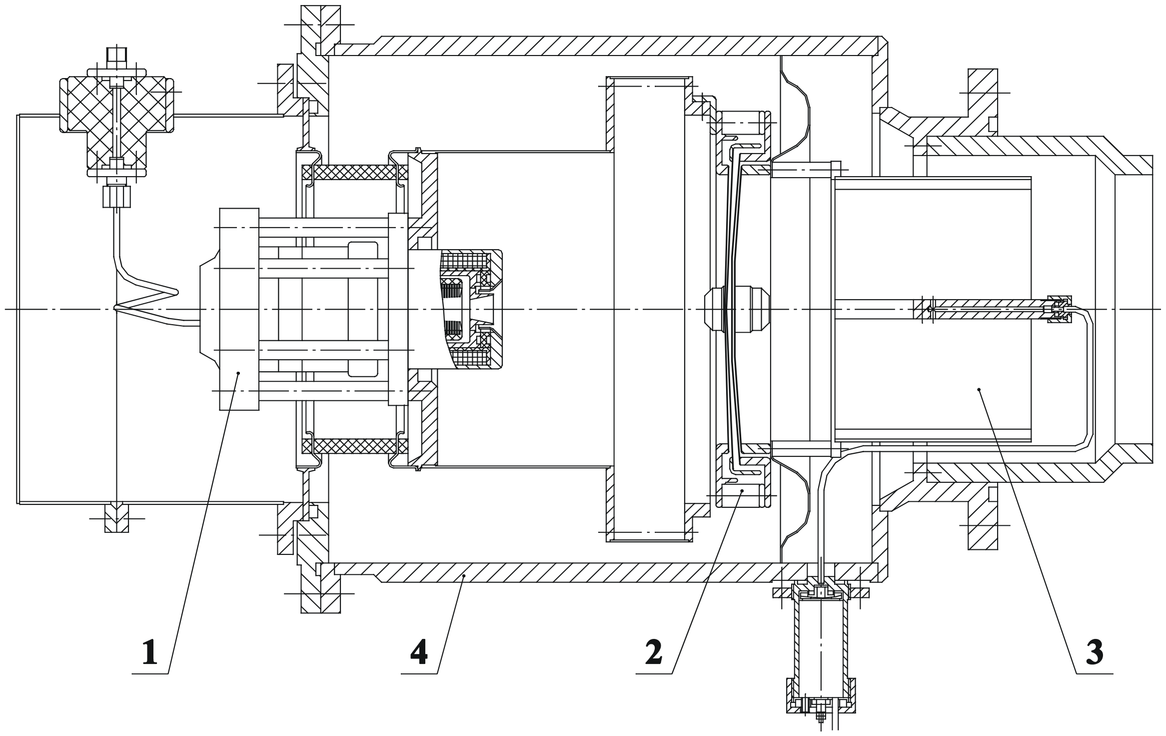
Pulse beam (START)



1-arc-discharge plasma source
2-toroidal solenoid
3-IOS electrodes
4-casing

First generation of ion sources for plasma heating -continued

IF-6 ion source

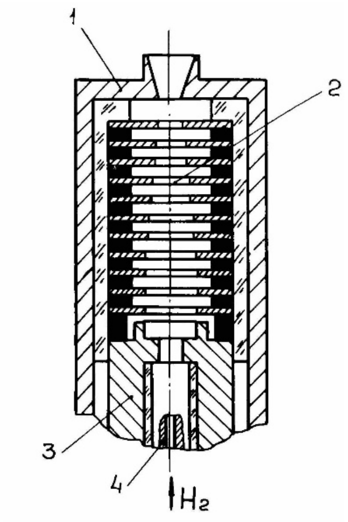


1- plasma source
2-concaved IOS (drilled)
3-neutralizer tube
4-casing

Characteristics:
Energy -6-14keV
Pulse- upto 0.1c
Proton beam current-12-36A
Beam divergence - 1.7 - 2.5·10^{-2}
Focal length – 65-250cm

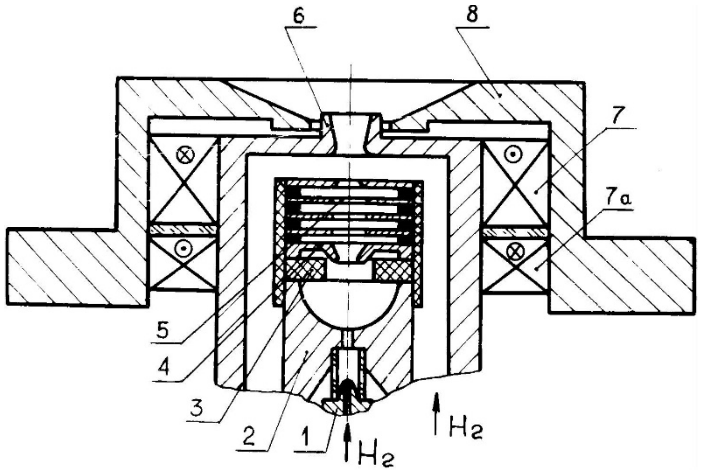
Arc-discharge plasma source-evolution

1960s



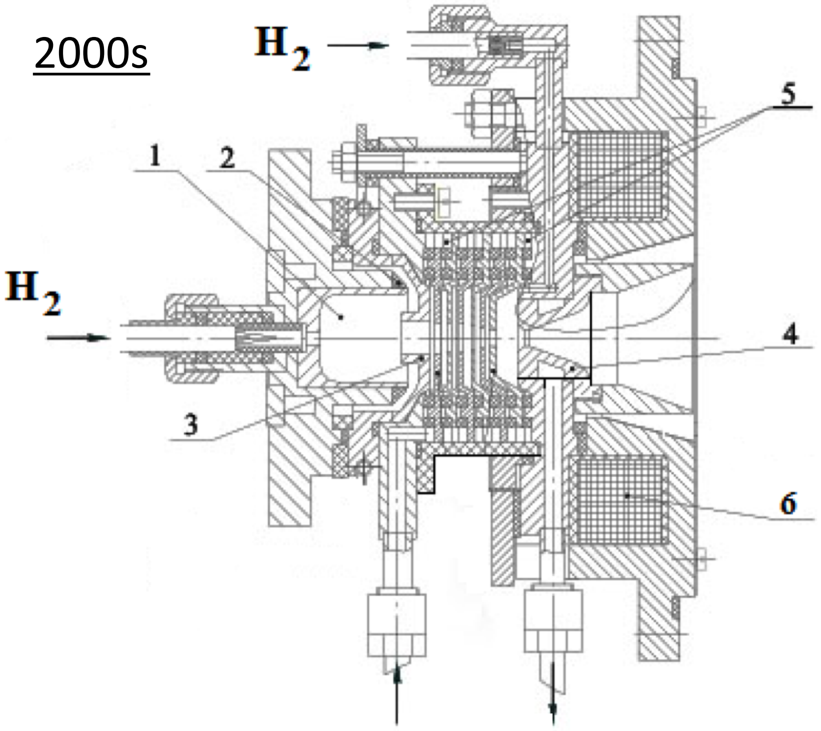
1-anode, 2-arc channel, 3-cathode, 4-trigger electrode

Late 1970s



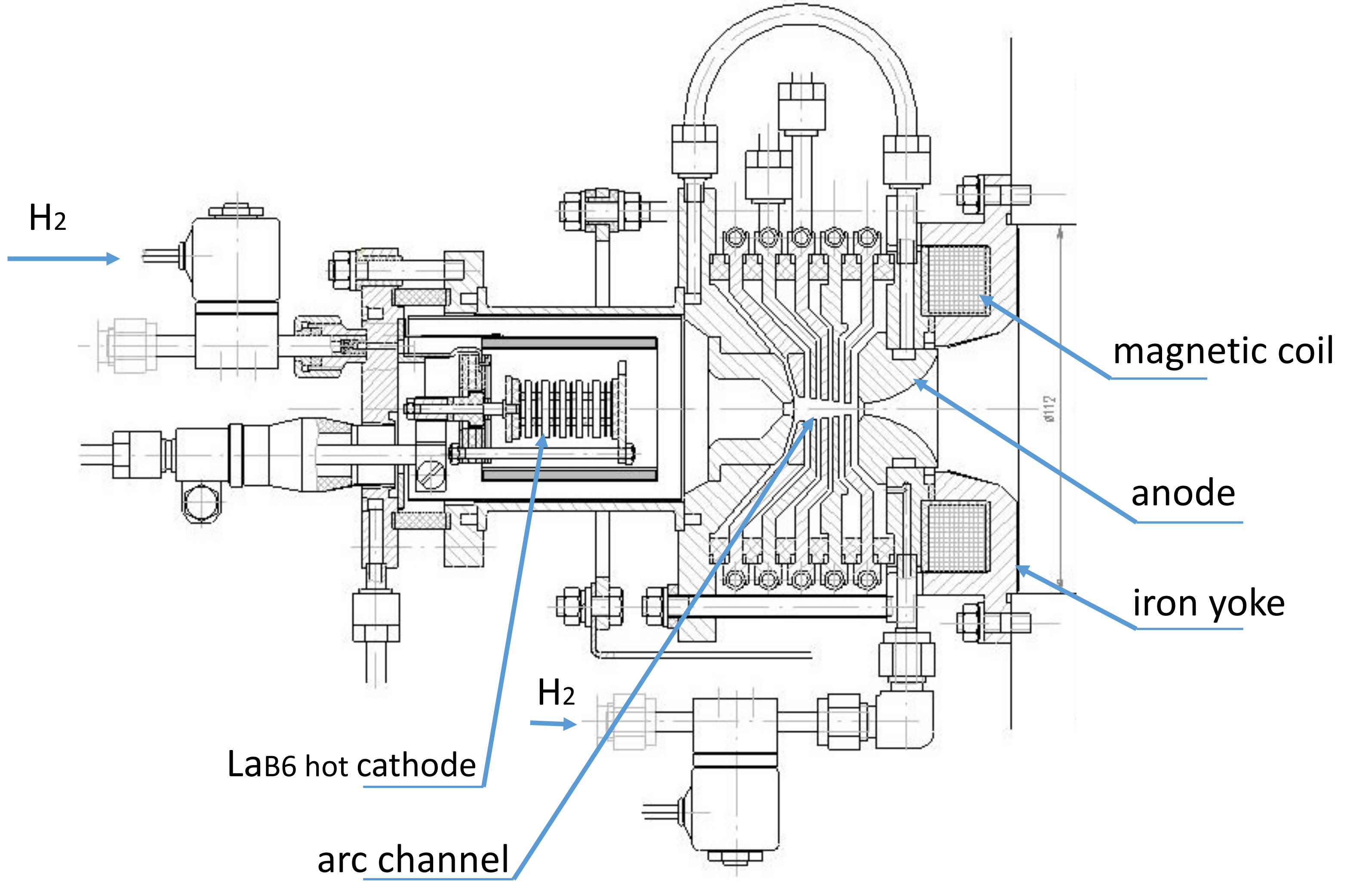
1-trigger, 2-cathode, 3-ceramic insert, 4-floating washer, 5-arc channel, 6-anode, coils, 8-iron yoke

2000s



1-cathode, 2-cathode nozzle, 3-floating washer, 4-anode, 5-arc channel, 6-magnetic coil

Arc-discharge plasma source with LaB_6 hot cathode and augmented cooling of the electrodes – current version



Characteristics:

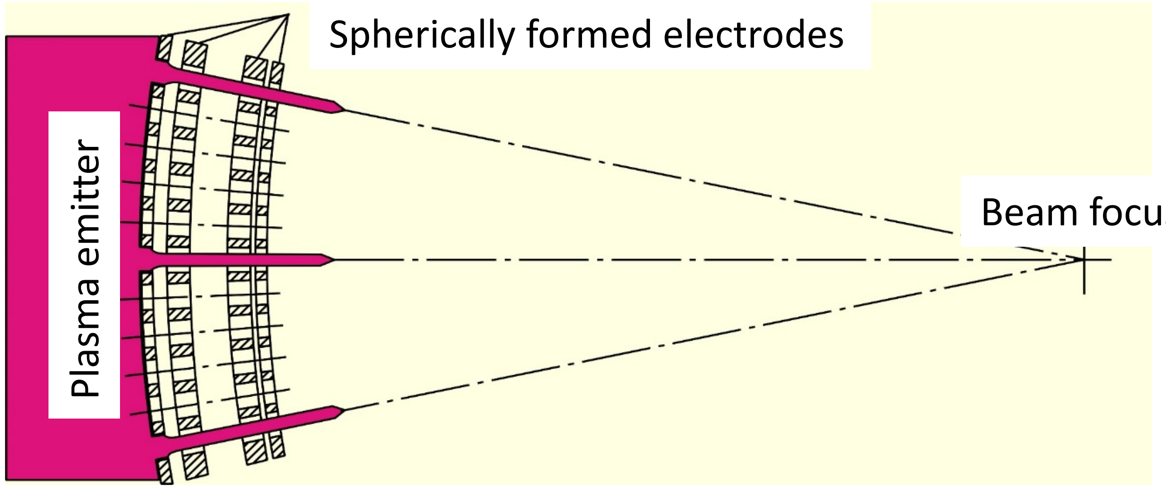
arc current -100-400A
ion output ~ 10-50A
pulse duration – 10s

Arc-discharge plasma source with cold/hot cathode: ballistic beam focusing in ion optical system

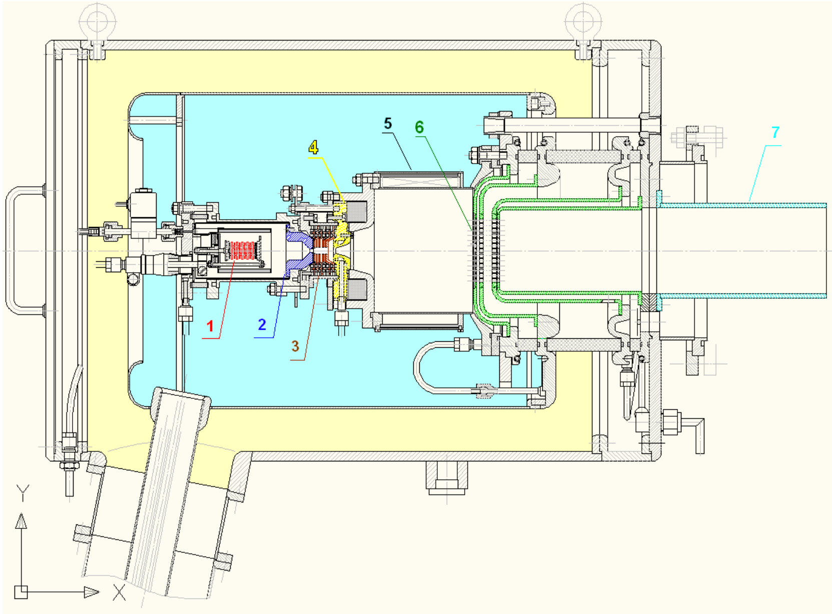
Flux density in diverging plasma jet $J(r,z)=I/\pi^2 z^2(1+r^2/z^2)^2$

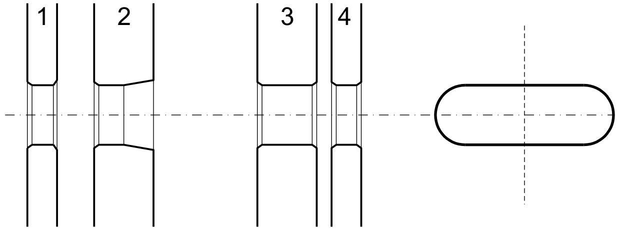
IOS electrode gaps $d(r)=d_0(1+r^2/z^2)$

Current density profile at focal plane $j(r,F)=\frac{I_b e^{-r^2/(\delta\alpha F)^2}}{\pi^2 F^2 \delta\alpha^2}$



Diagnostic beam RUDI (KFA Juelich)



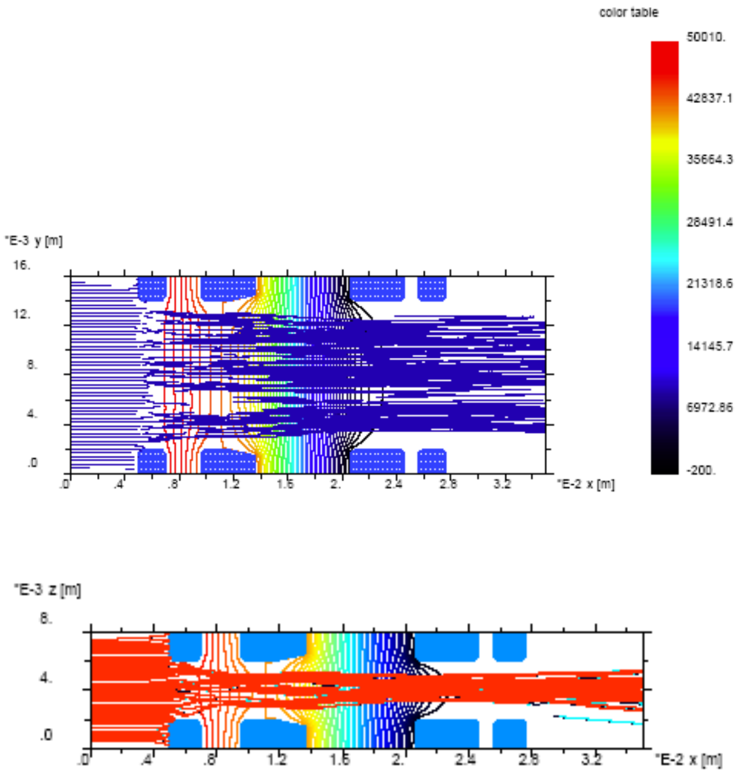


RUDI beamlet – slotted four grid IOS

1-4 arc-discharge plasma generator with hot cathode
5- expander chamber with permanent magnets,
6 – IOS electrodes

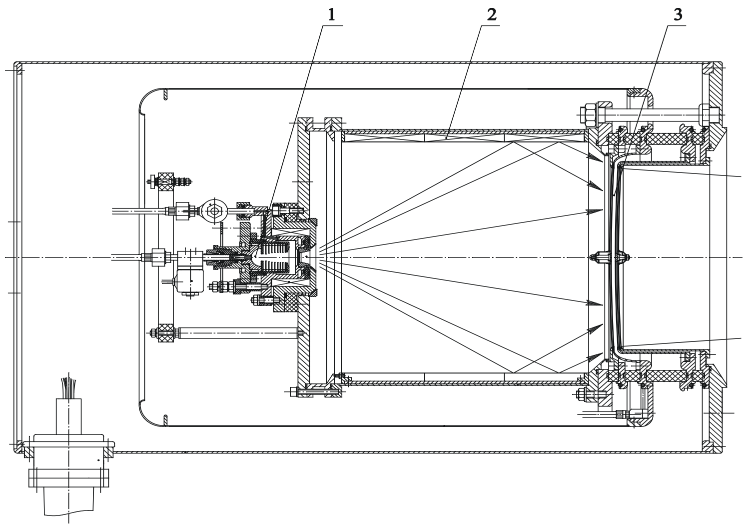
Characteristics:
Beam energy – 50keV
Ion beam current – upto 3A
Pulse duration- 10s with modulation

<u>IOS grids cooling is inertial.</u>



Beam formation in the elementary cell of IOS

Ion source for plasma heating (GDT, MST)

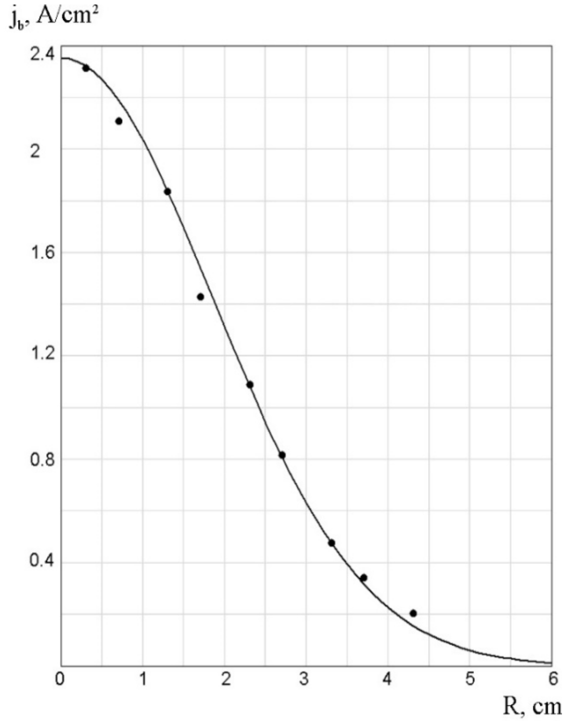


1- plasma source
2-permanent magnets
3-concaved IOS (photo etching)

IOS grids fixed on central insert as in IF-6 ion source.

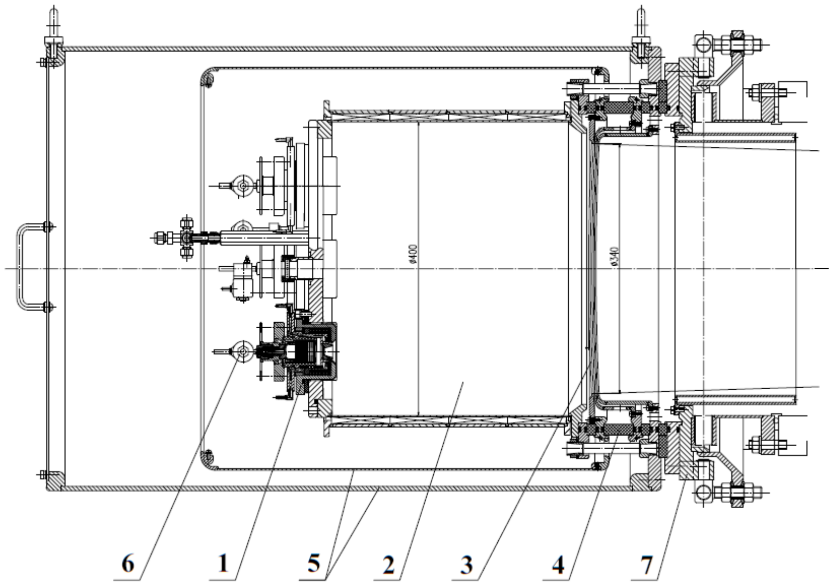
Characteristics:

Energy	5keV
Pulse	5mc
Proton beam current	50A
Beam divergence	$2\cdot10^{-2}$
Focal length	120cm



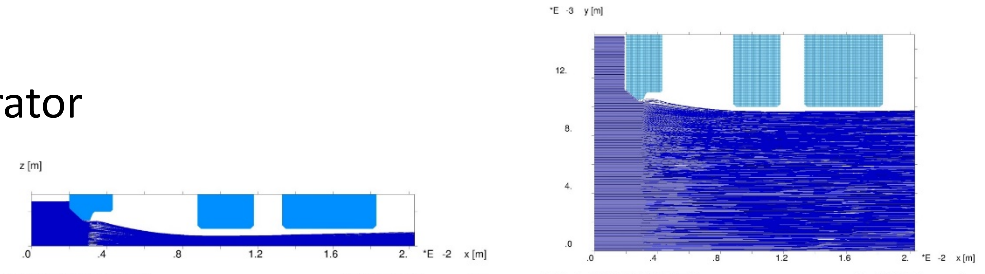
Neutral current density In focal plane 120cm downstream from the source

Latest development –low energy heating beam

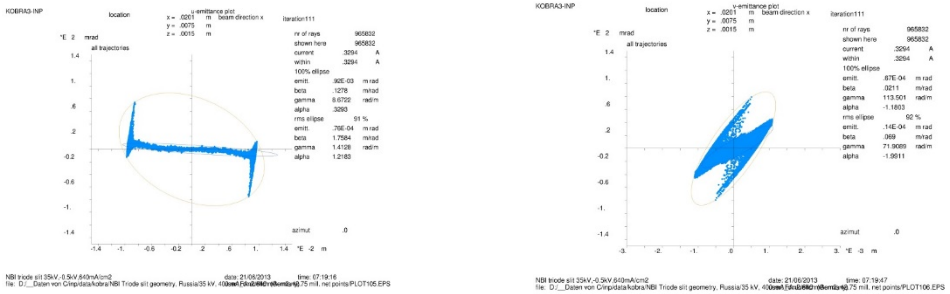


1- arc-discharge plasma generator
2- expander chamber
3- concaved grids (milled)
4 – insulator
5 – shields
6 – gas valve
7- aiming gimbal

Characteristics:
Beam energy – 15keV
Ion beam current – upto 175A
Pulse duration- 30ms



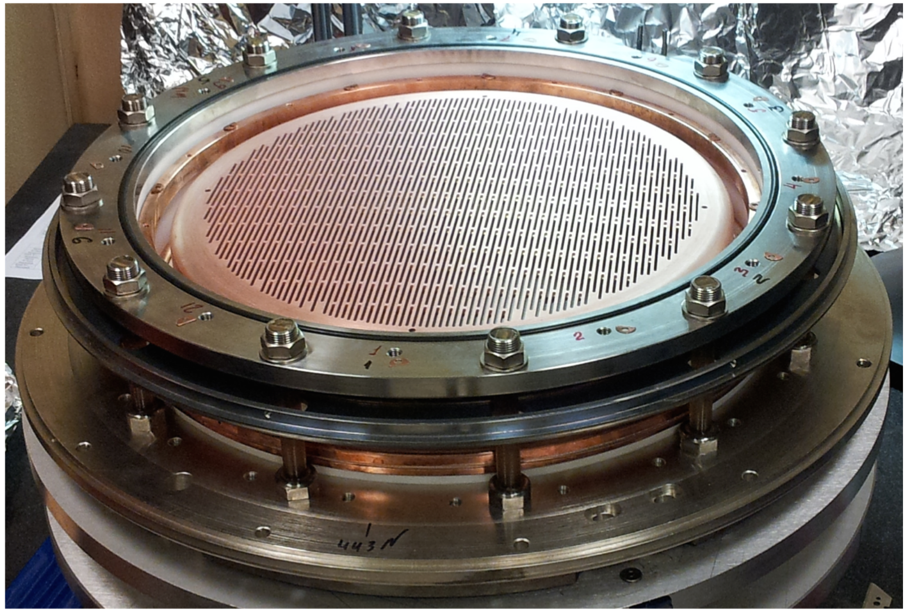
Beam formation in elementary cell of IOS:
Across the slit, along the slit

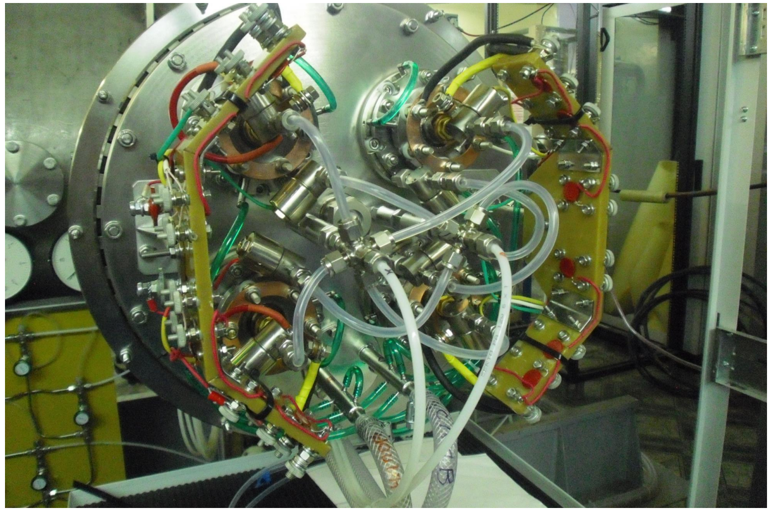


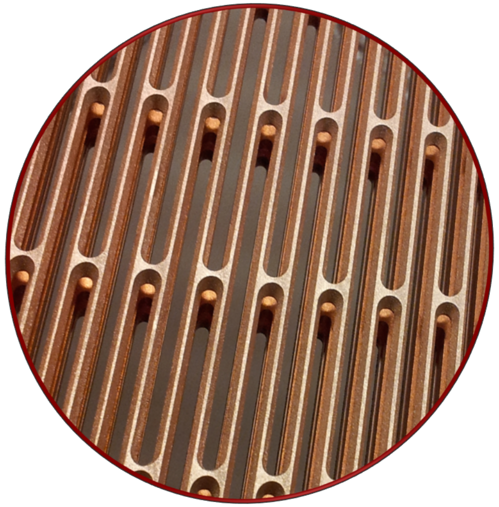
Emittans diagram: across the slit, along the slit

Distinctive features of 1.7MW, 15keV, 30ms beam

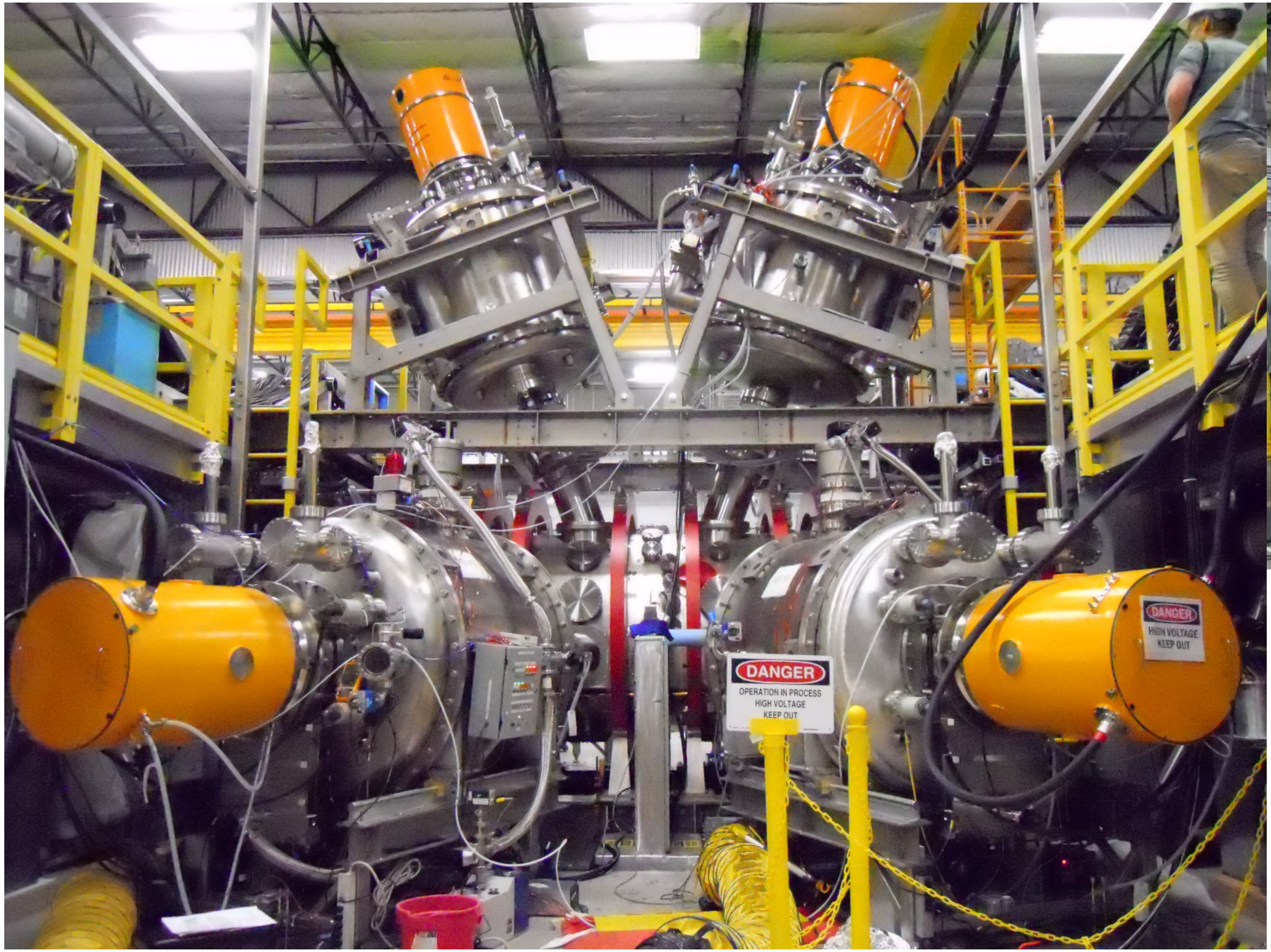
- Slotted grids
- Initial beam size - Ø 340 мм
- Ballistic focusing by concaved grids
- Different angular divergences along x and y
- Plasma emitter is produced with four arc-discharge plasma generators
- 48-poles magnet is used in plasma box to provide the plasma emitter with diameter of Ø40cm



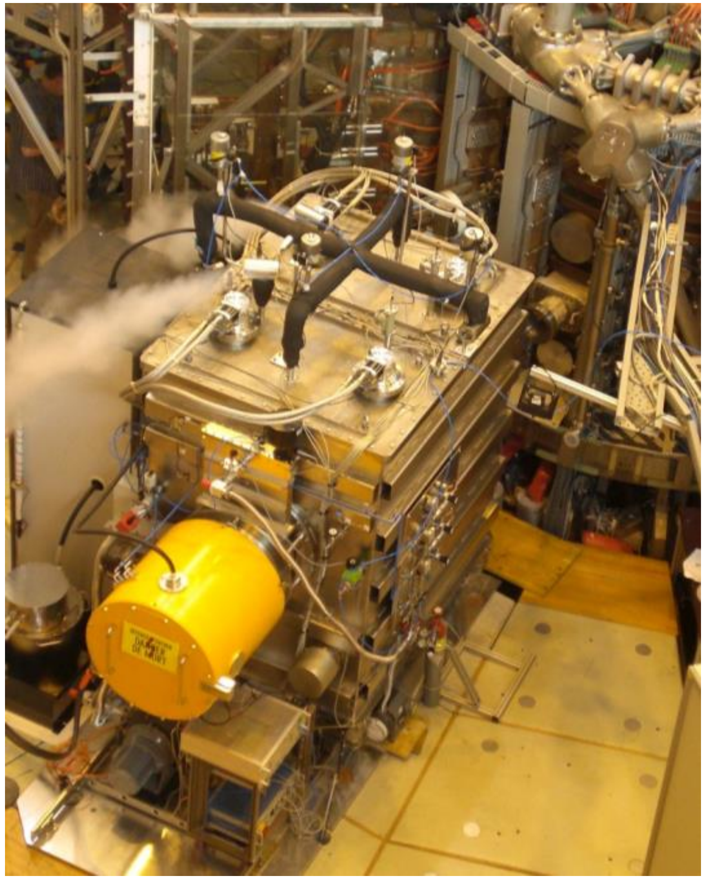


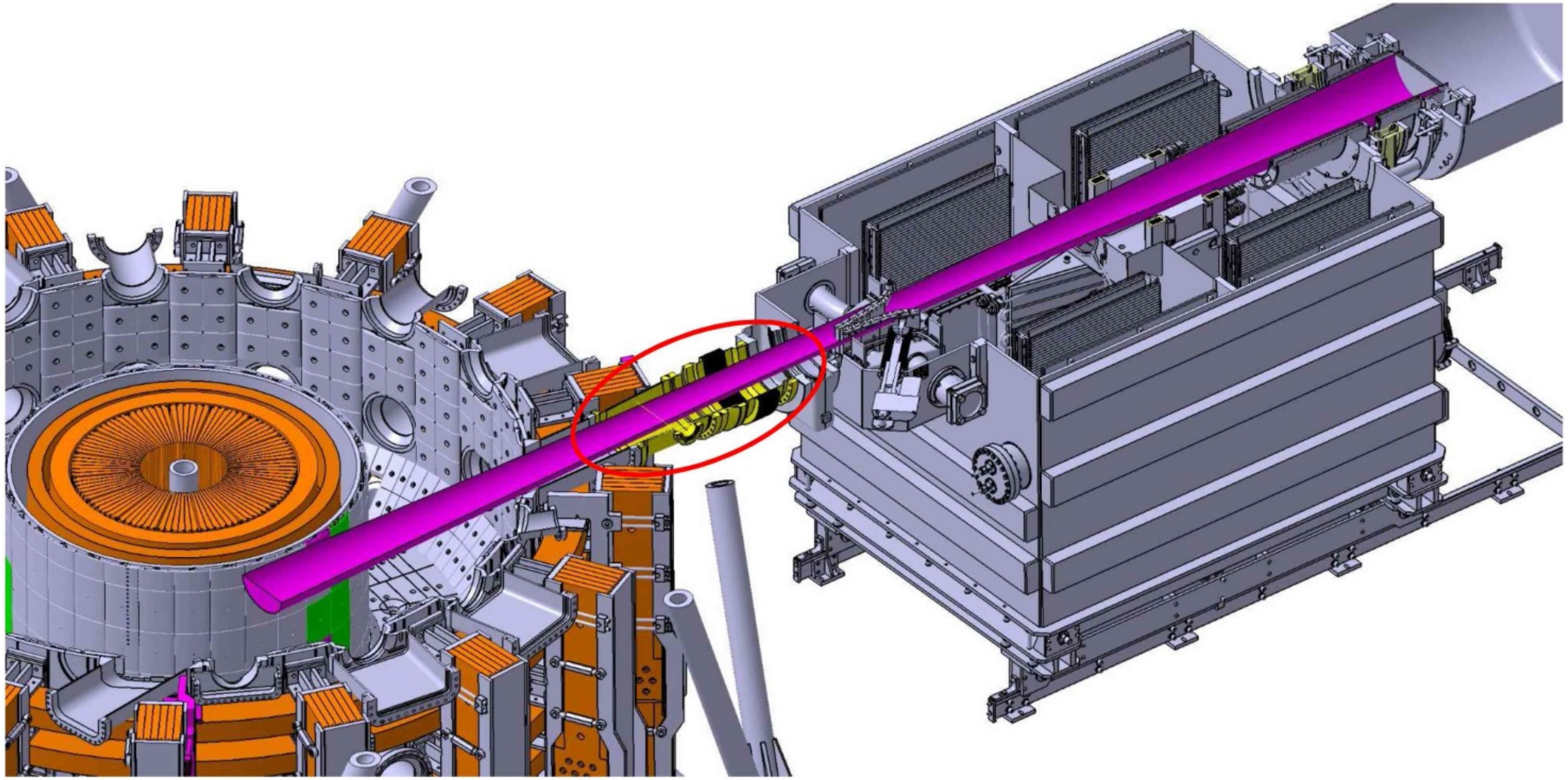


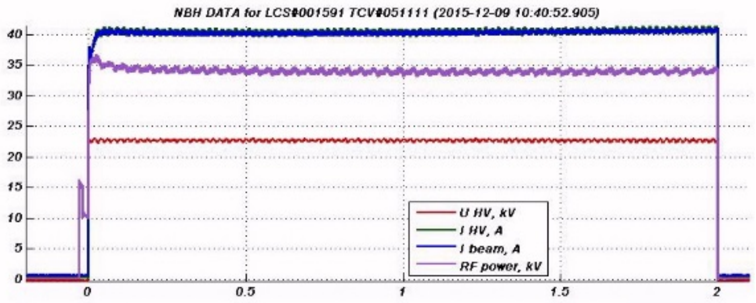
View of the neutral beams at C-2U



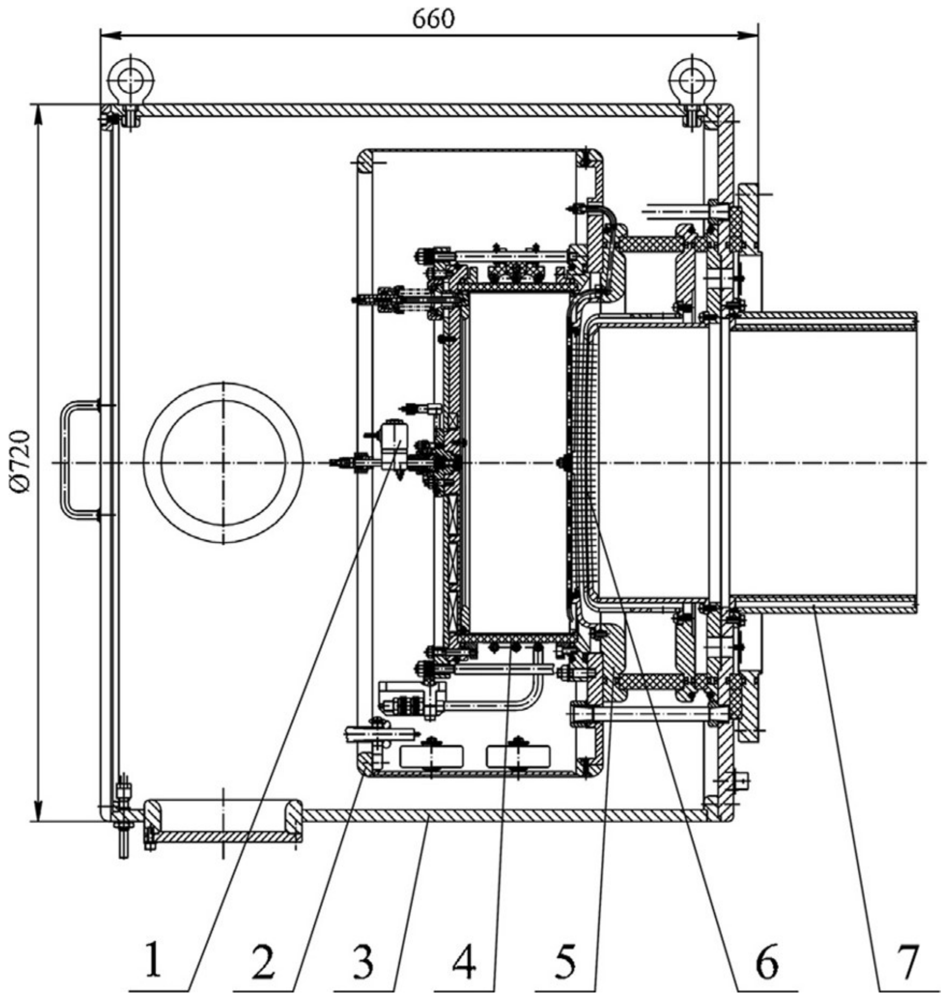
1 MBT, 2s neutral beam of TCV tokamak (GLOBUS-M3)





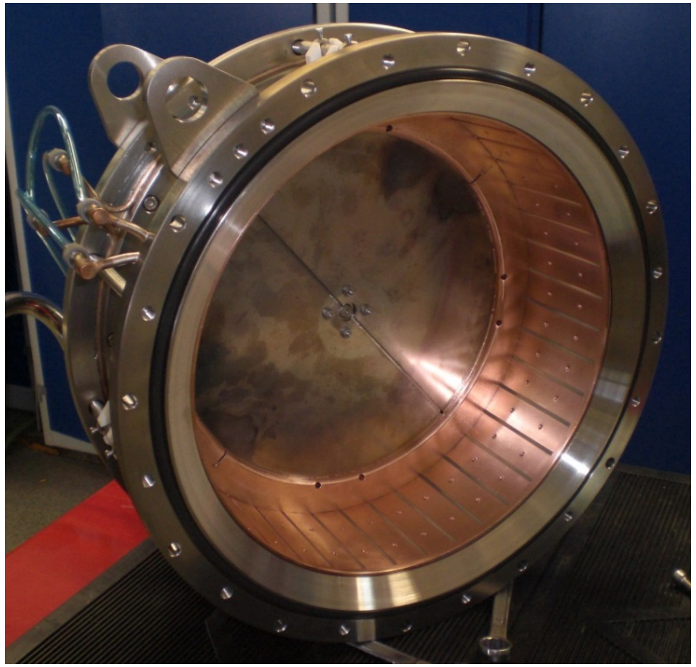


RF ion source of TCV tokamak

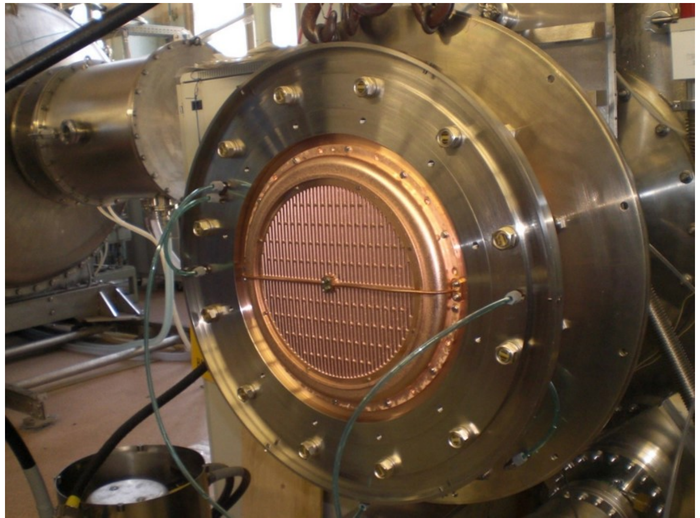


1 – gas valve, 2 – internal magnetic shield,
3 – external shield, 4 – RF plasma box,
5 – insulator unit, 6 – IOS grids, 7 – neutralizer

RF plasma box

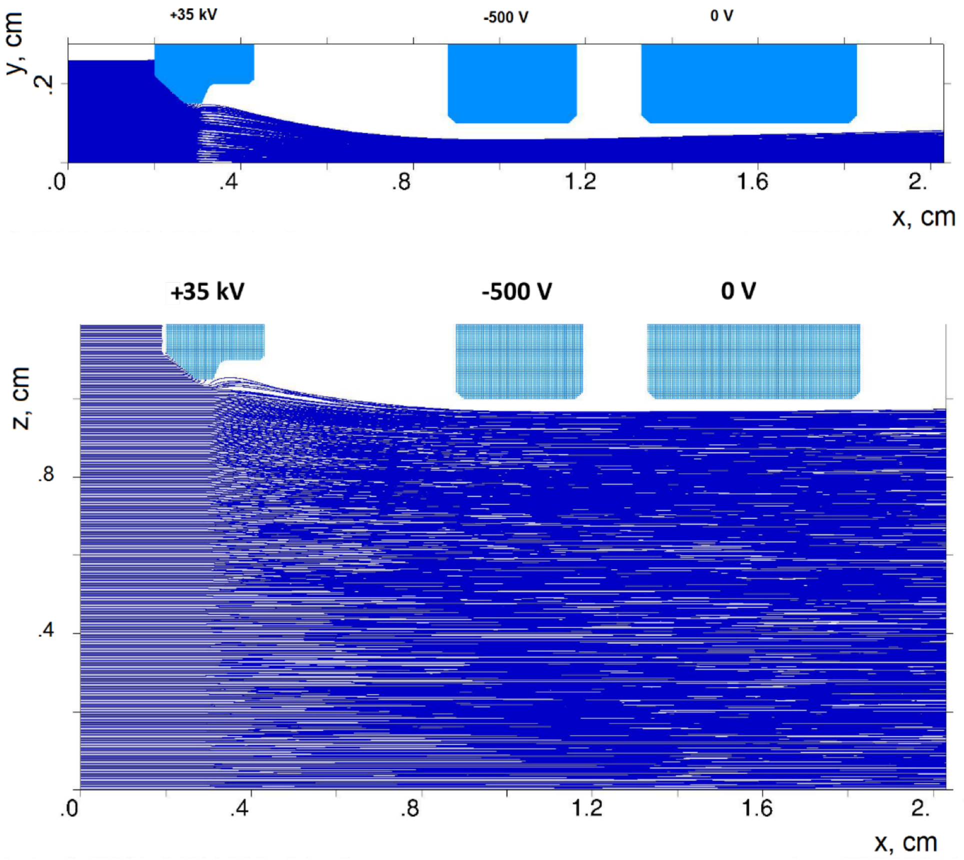


Slotted IOS with distributed heat removal from plasma grid

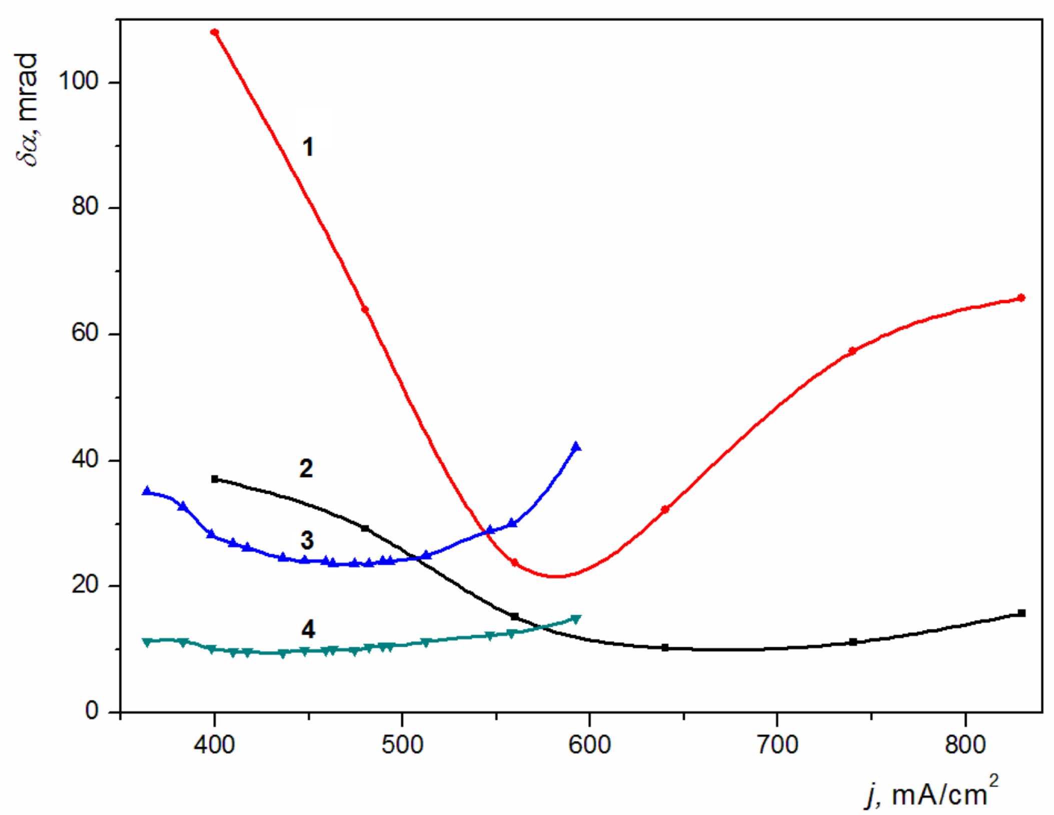


IOS optimization for TCV ion source

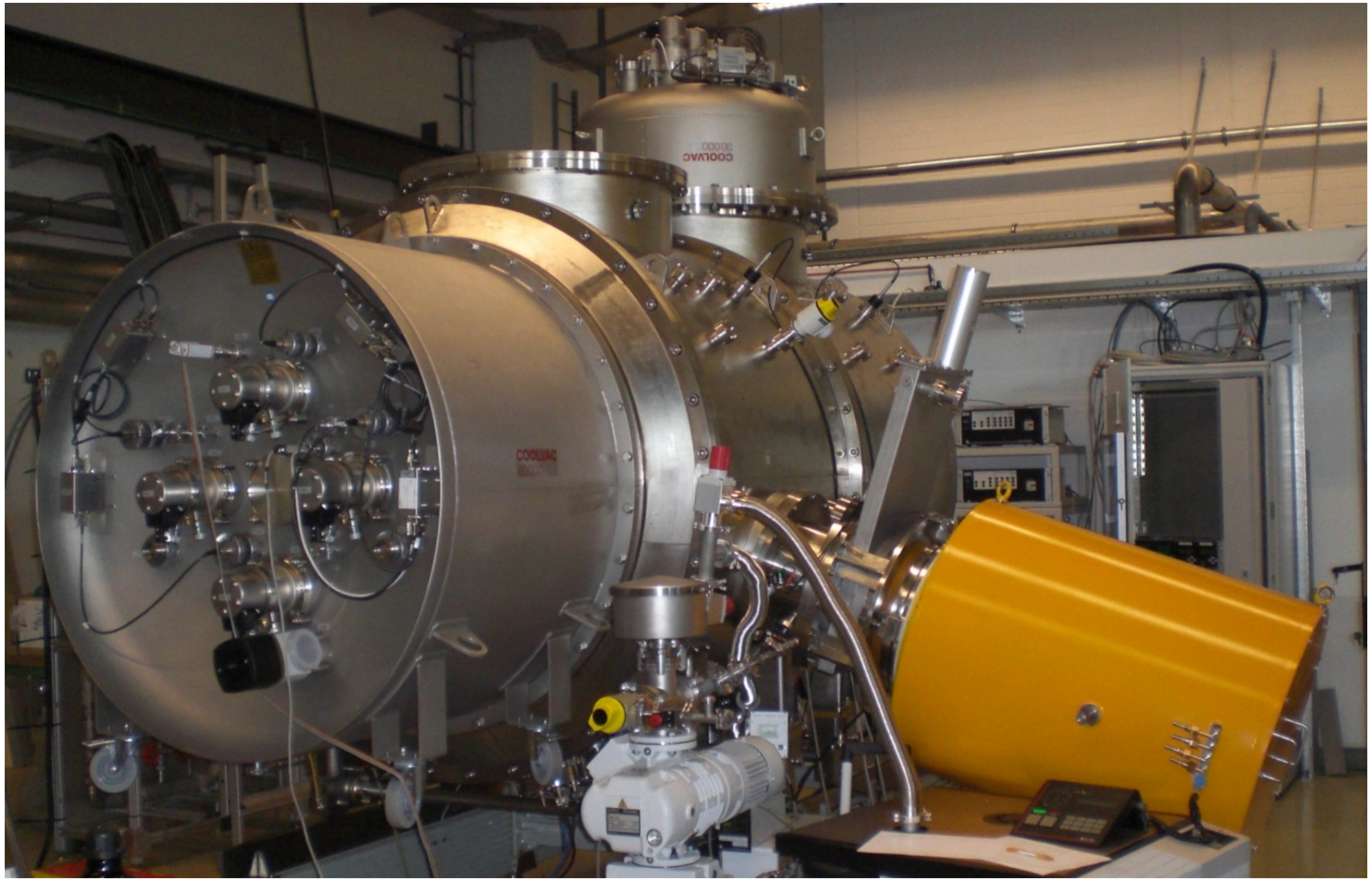
The results of simulation of the beam formation with KOBRA-INP code

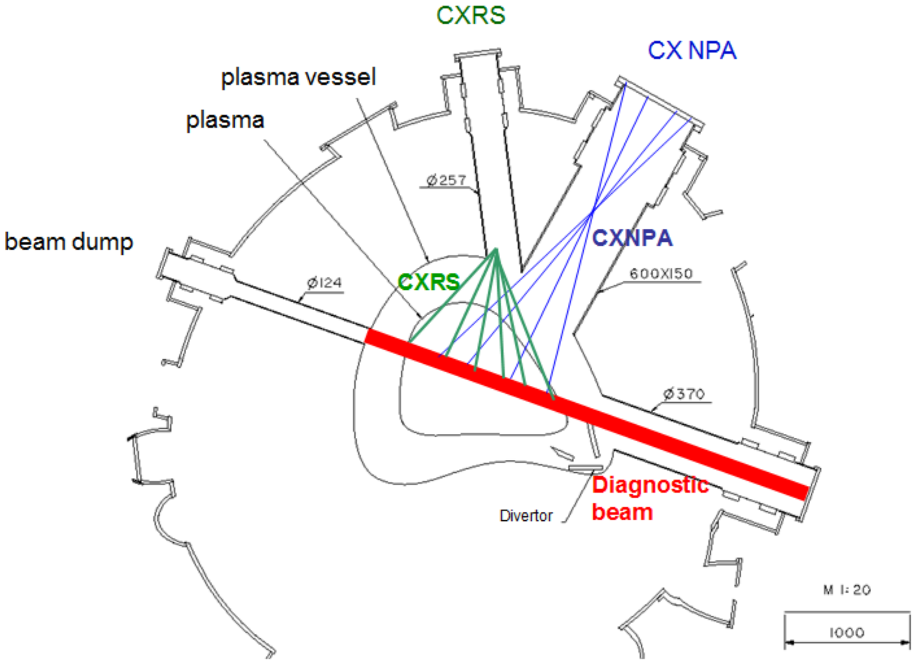


Comparison of simulated and measured angular divergence as a function of ion current



Diagnostic beam of W-7X stellarator

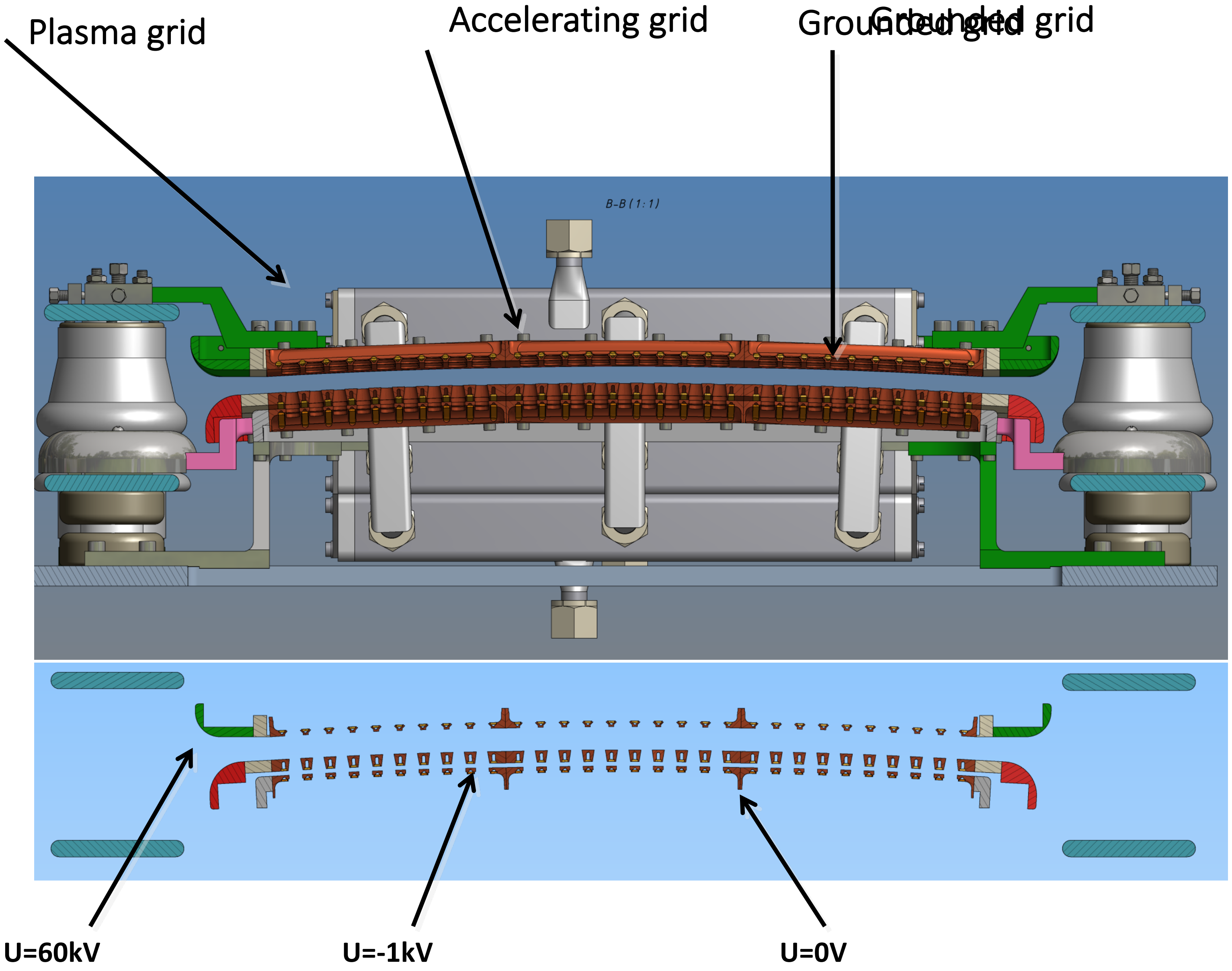




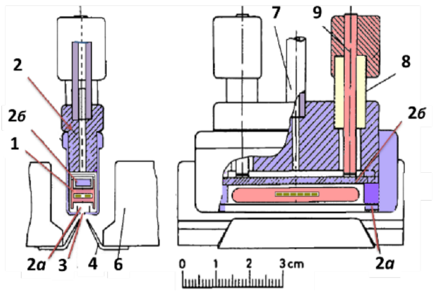
Beam energy:	60 keV
Eq. Neutral beam	
current/ion current:	2.4/8 A
Pulse duration:	2.5A
with modulation	10 s

Development of high power long pulse ion sources(>100 s): multi-slotted IOS with active water cooling

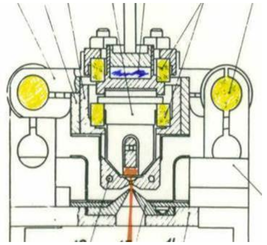
- Steady-state power supply of RF plasma emitter with power of 50kW
- High voltage modulator 40kV, 50A, 100s



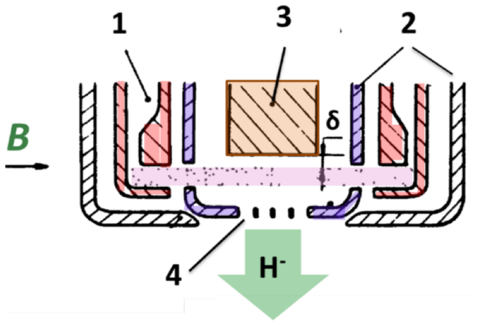
Surface-plasma Negative Hydrogen Ion Sources previously developed at BINP



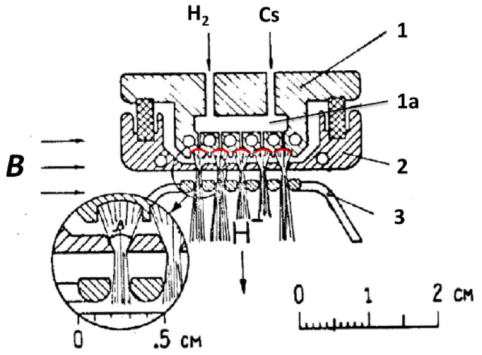
Magnetron (planotron) 1973



With Penning discharge geometry 1975

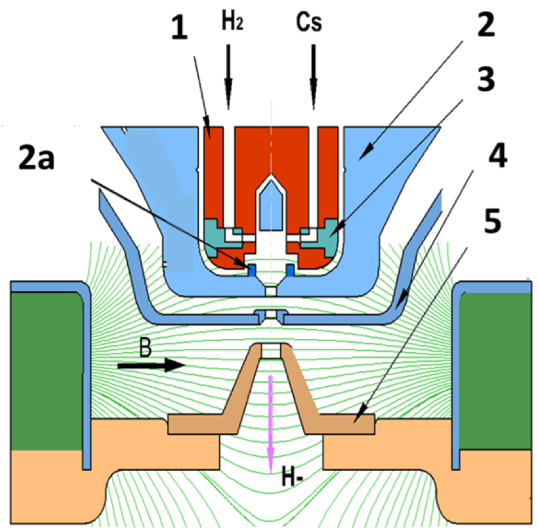


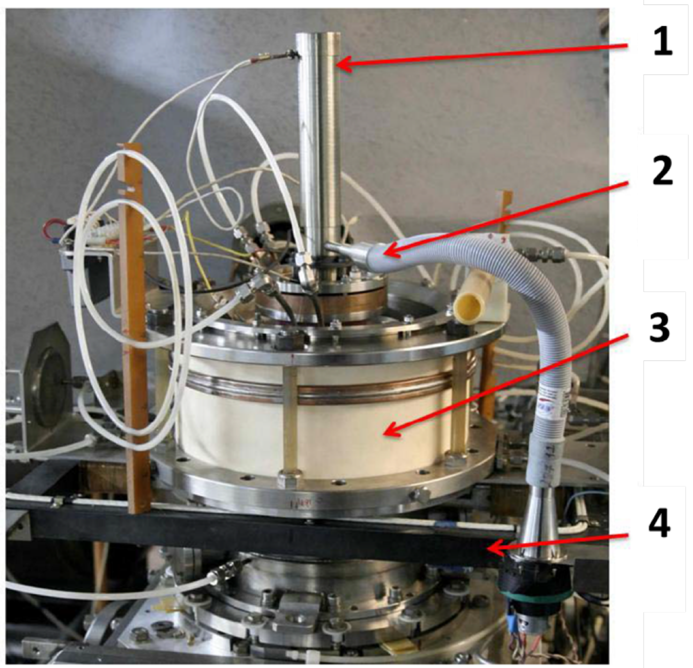
with converter and hollow cathodes
PIG discharge 1977



Ion source with non-closed electron ExB
drift and ballistic focusing 1978

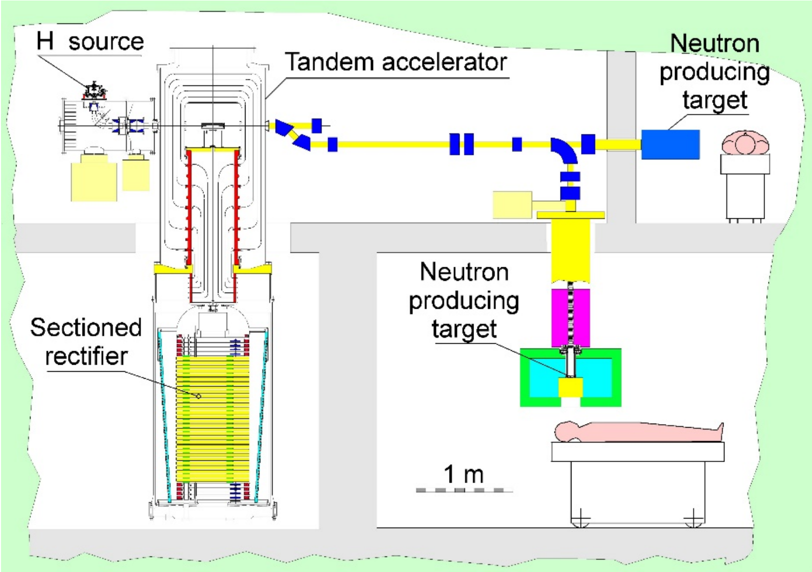
Modern Surface-plasma Negative Hydrogen Ion Sources

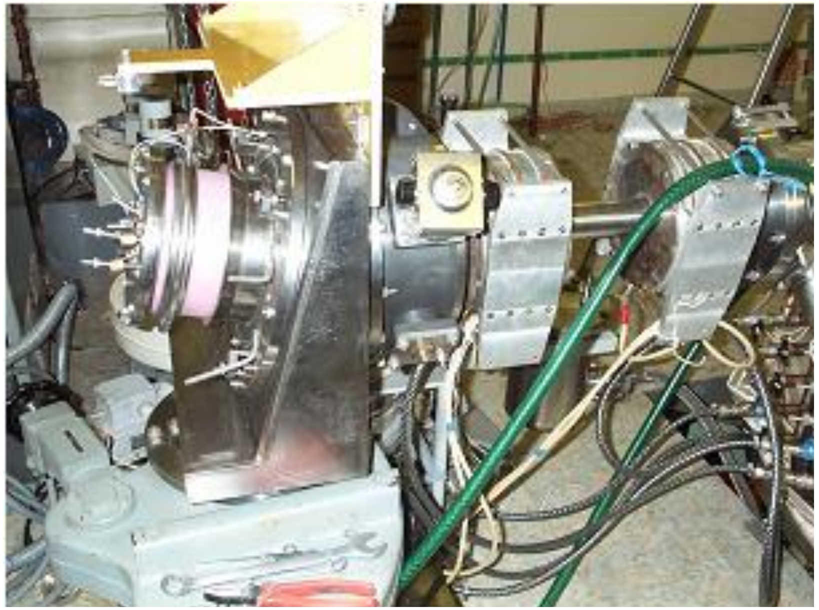


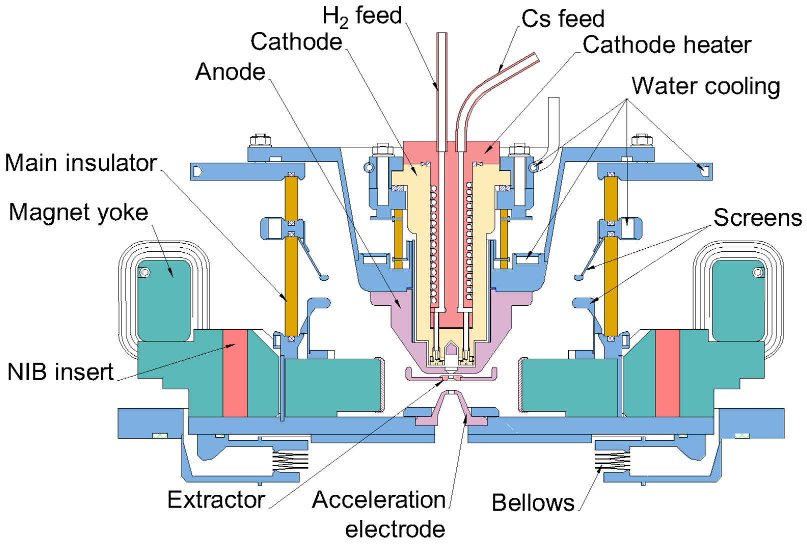


15 (25) mA CW SPS with Penning geometry and hollow cathodes for BNCT 2006

Accelerator-based neutron source for BNCT

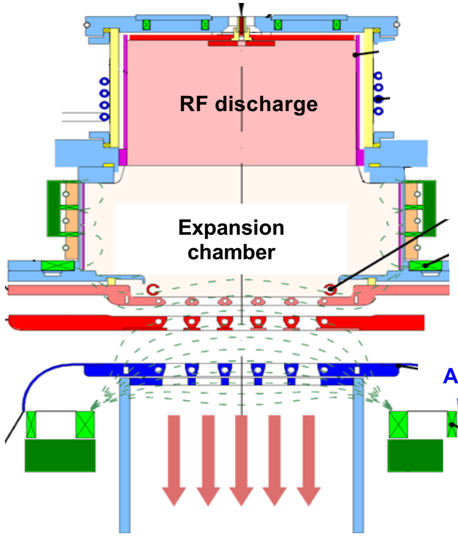


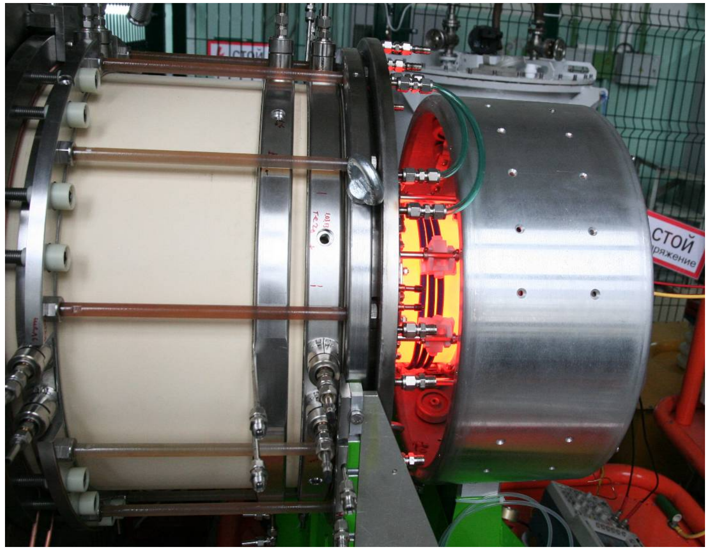




The main parameters of the ion source	
H^- beam current	**upto 15 mA**
Beam energy	**25 keV**
Beam regular divergence (at 90% of intensity)	**80 mrad**
Normalized RMS XX' emittance	**0.18 π·mm·mrad**
Normalized RMS YY' emittance	**0.15 π·mm·mrad**

Modern Surface-plasma Negative Hydrogen Ion Sources cntd



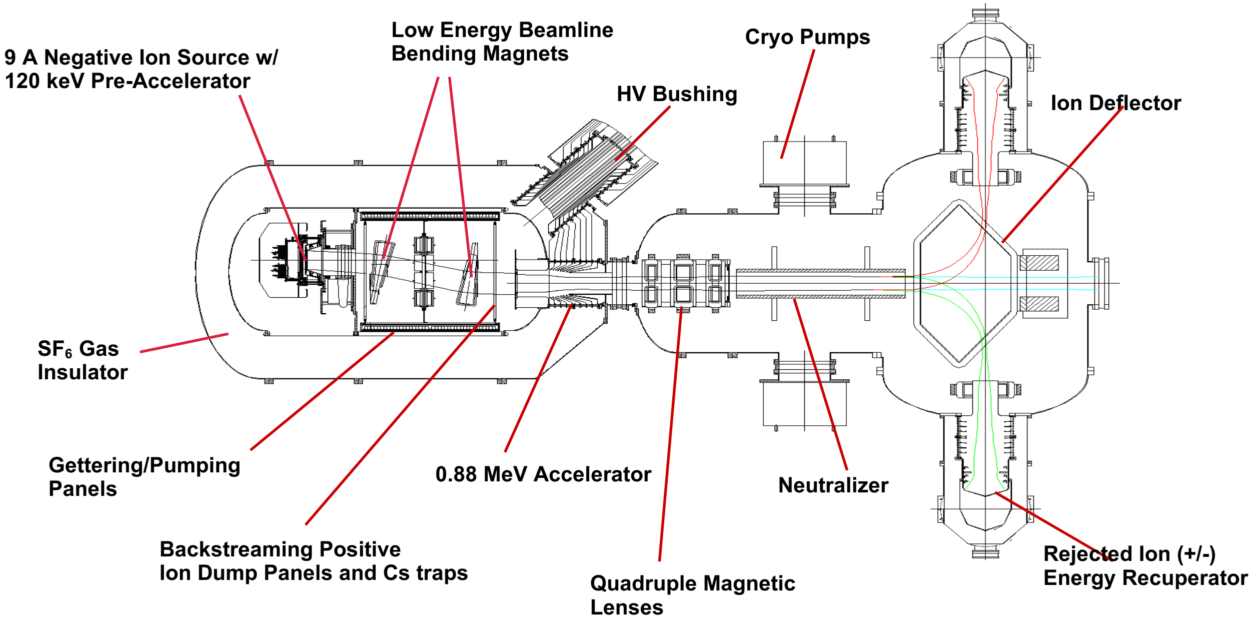


Inductive RF source with Surface-Plasma production of Negative Ions

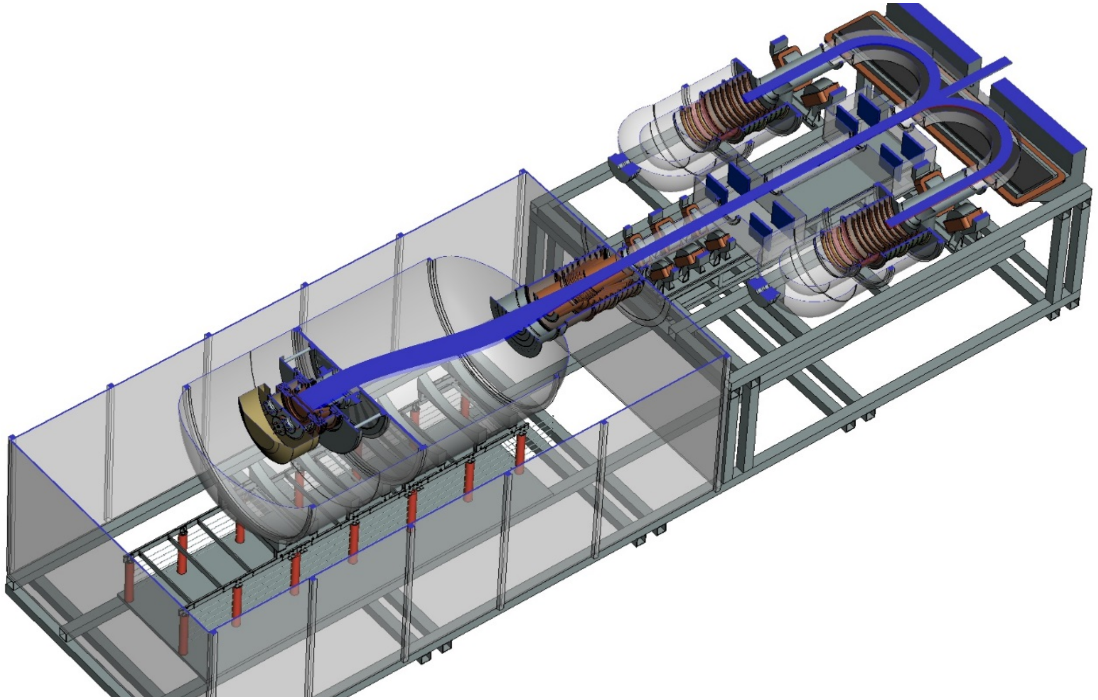
- **Active temperature control of IOS grids (heating/cooling by hot fluid)**
- **Cesium seed to PG periphery**
- **Convex magnetic field in the IOS gaps**

10MW, 1MeV neutral beam injector based on negative ions

Schematic diagram of the high energy neutral beam injector with separation of the beam formation and acceleration

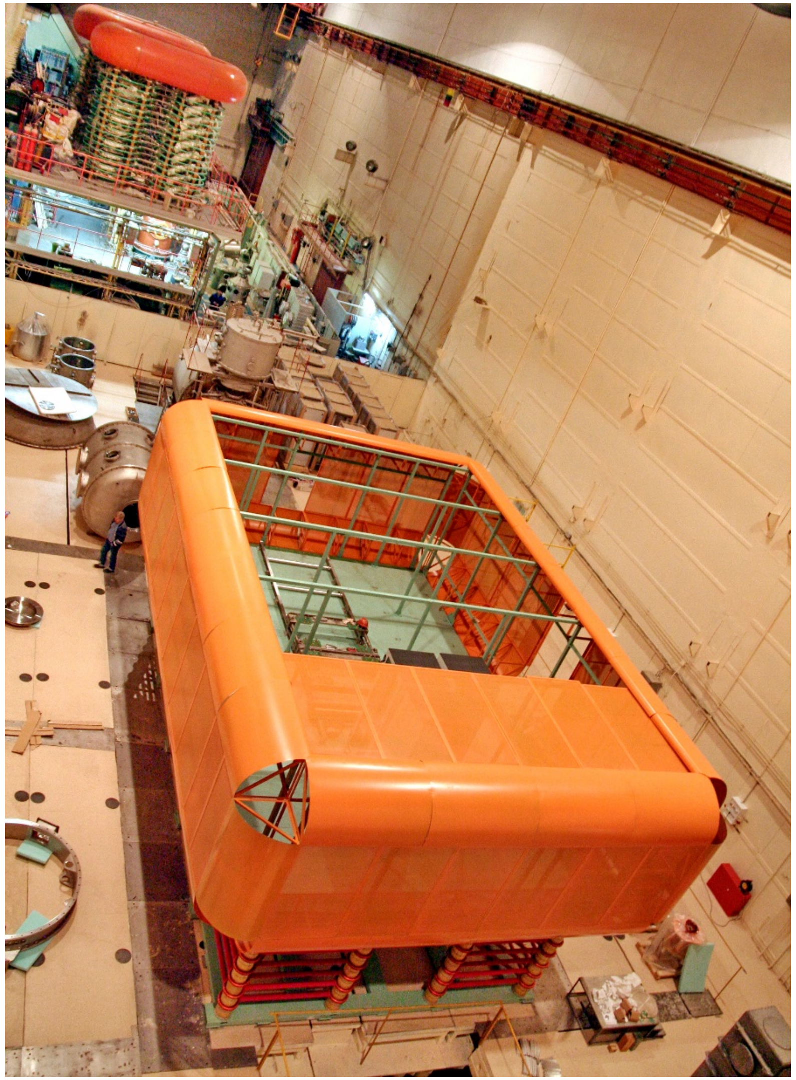


General view of the neutral beam



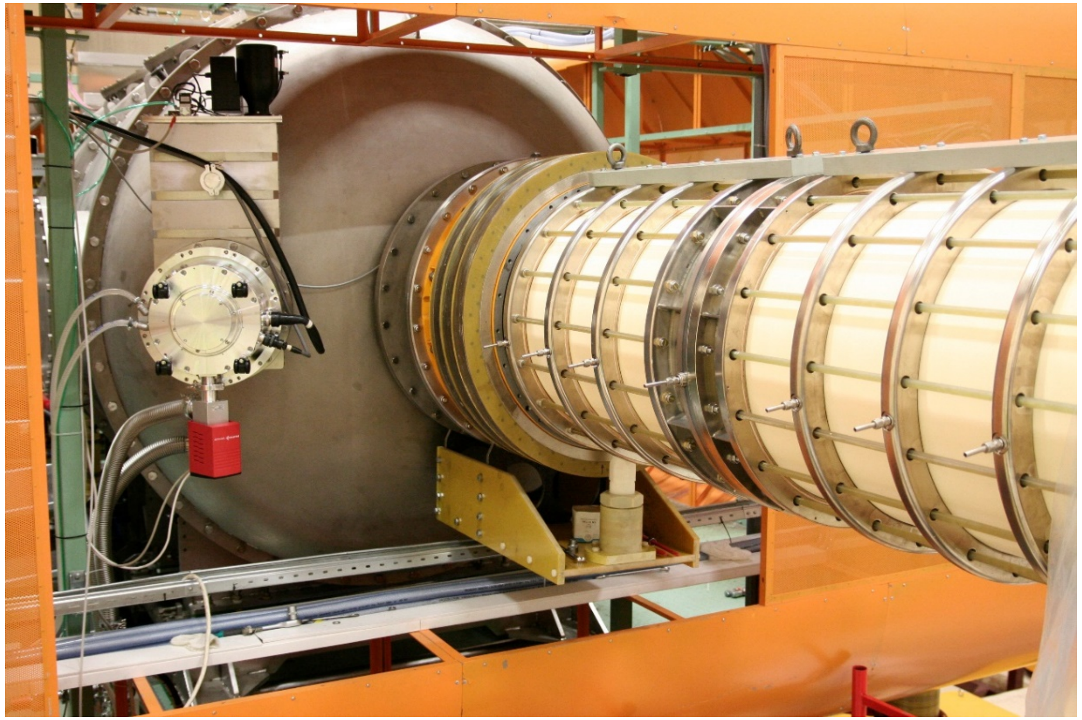
1 MV, 3MW test stand for negative ion beam studies

View of high voltage platform

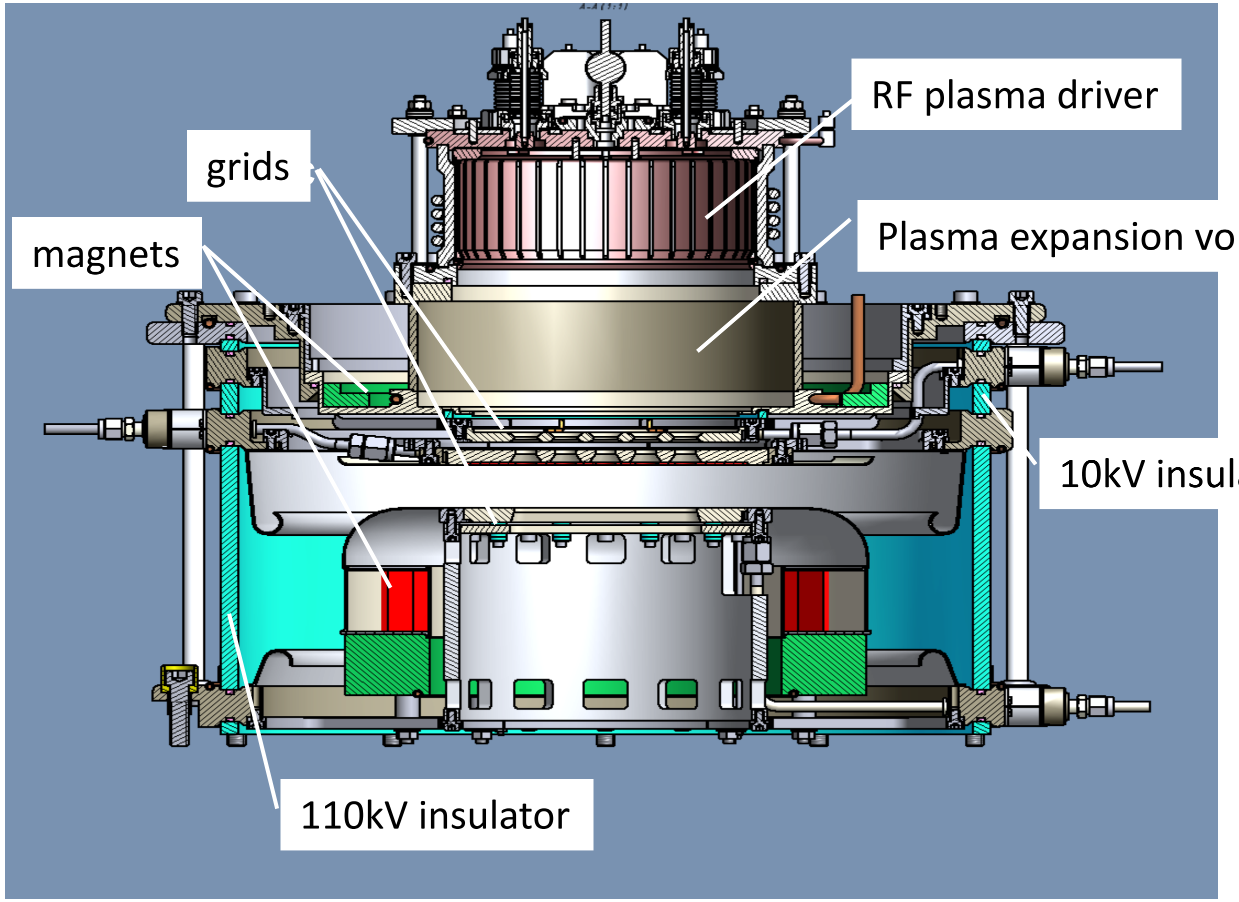


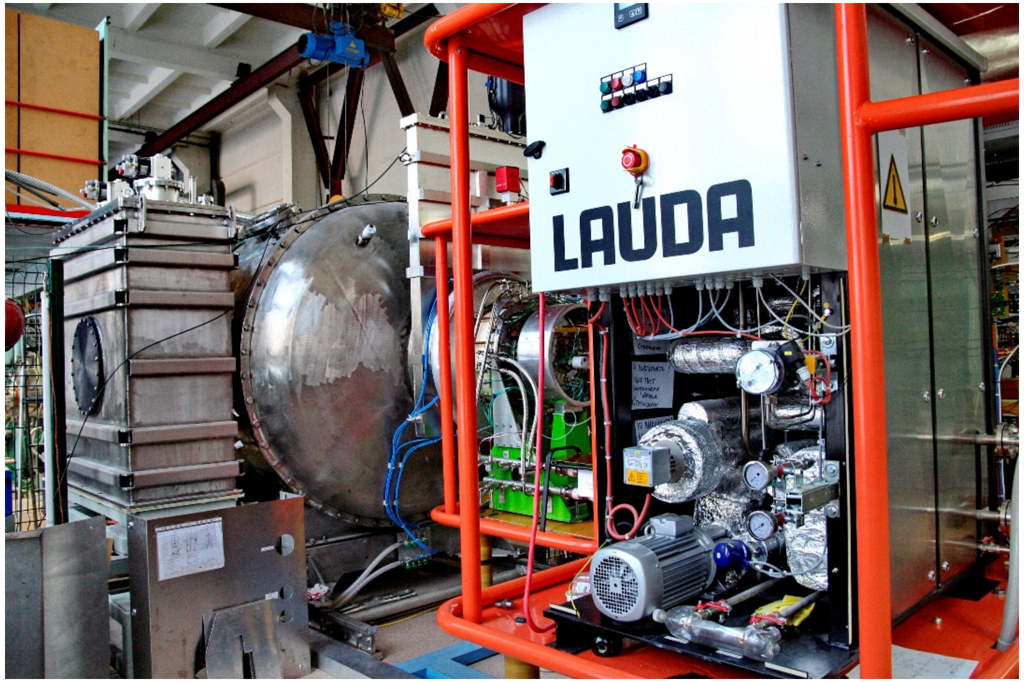
3 MW power supply

Low energy transport line and accelerating tube



120 keV, 1.5 A, 100 s negative ion source





A beam with energy 117 keV, current of 1.3 A, pulse duration of 20 s has been produced

Conclusions

- Development of neutral beams based on positive ions continues towards increasing of beams power and extending pulse duration to DC operation
- Development of high energy beams based on negative ions has been started with the new teststand

Thank you for attention!