Status of the Source of Polarized Deuterons (JINR Accelerator Complex)

V.V. Fimushkin, A. D. Kovalenko,

L.V. Kutuzova,

Yu.V. Prokofichev, V.P. Vadeev

Joint Institute for Nuclear Research, Dubna, Moscow region

A.S. Belov

Institute for Nuclear Research of Russian Academy of Sciences, Moscow

- The **SPD-project** assumes the development of the universal high-intensity **Source of Polarized Deuterons** (protons) using charge-exchange ionizer.
- The design output current of the **SPD** will be up to **10 mA** for ↑ D^+ (↑ H^+)
- The polarization will be up to 90% of the maximal vector (±1) & tensor (+1,-2) polarization
- The project is based on the equipment which was supplied within the framework of the Agreement between JINR & IUCF(Bloomington, USA)
- The project will be realized in close cooperation with INR of RAS (Moscow, Russia))

- The main purpose of the SPD-project is to increase the intensity of the accelerated polarized beams at the JINR Accelerator Complex up to

10^{10} d/pulse

- The JINR accelerator NUCLOTRON is accelerator of relativistic nuclei which will be upgraded to the NUCLOTRON-M in the coming three years. The accelerator has been created to work with proton beam with energy up to 12 GeV and nuclei up to 6 AGeV
- Now a plan to build a new accelerator - NICA collider of maximum energy $\sqrt{S_{NN}}$ =9 GeV is discussed at JINR. The NUCLOTRON-M will be first step to the NICA

- **The SPD-project includes the following stages:**
- **- development of the universal high-intensive Source of Polarized Deuterons (protons) using the charge-exchange plasma ionizer with the output current up to 10 mA D^+ (H^+) and polarization ~ 90 % from nominal vector polarization + (-) 1 and tensor polarization + 1,-2**
- **- modification of the linac preaccelerator hall (upgrading of the HV (400 kV) platform & power station**
- **- improvement of the preaccelerator tube vacuum with TMP**

- adaptation of the existing remote control system (console of LU-20 linac) of the polarized ion source under the high voltage
- complete tests of the source
- assembly of the designed source and equipment at the linac preaccelerator
- LU-20 runs with polarized beams & polarization measurements at the output of the linac (LU-20)

- **The estimations and first runs with the polarized deuterons from the source used up to now (0.4 mA D+ cryogenic source POLARIS) at NUCLOTRON show depolarizing resonances for accelerated deuterons are absent in all of energy range of accelerating**

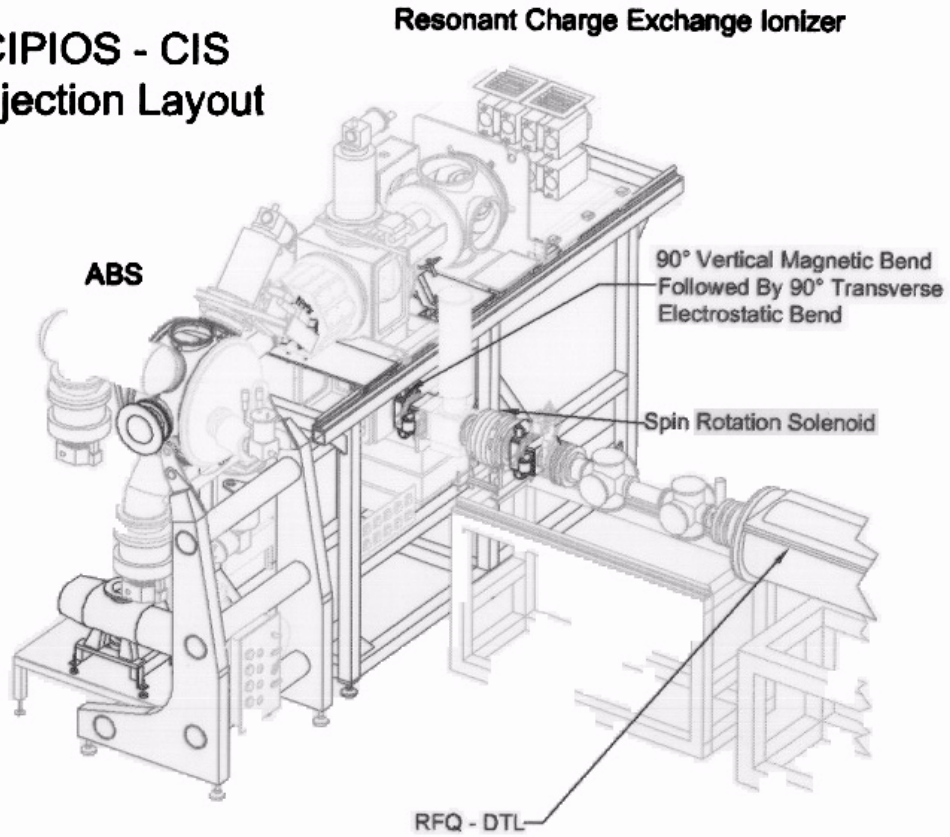
- The most labour-consuming and expensive work is development of the **Source of Polarized Deuterons** based on the equipment of **Cooler Injector Polarized IOn Source (CIPIOS)** developed at Indiana University Cyclotron Facility (IUCF, USA) in INR of RAS (Moscow) cooperation in 1999

- **CIPIOS** was intended for high-intensity negative polarized and unpolarized beams production

- **CIPIOS includes**
  - source of the polarized atoms using the permanent sextupole magnets (B= 1.4 T) for focusing and electron spin separation
  - radio frequency transitions units of nuclear polarization
  - resonant charge-exchange ionizer. The polarized ions are formed at resonant recharging of the polarized atoms and unpolarized ions in plasma by a highly efficient charge exchange reaction
  - spin orientation of negative **H^- (D^-)** ions at the output of **CIPIOS** is vertical

Cooler Injector Polarized IOn Source (CIPIOS)

CIPIOS - CIS
Injection Layout



Beam Properties

- Pulsed @ 1Hz to 4Hz
- 25 keV Beam Energy
- Polarized H^- or D^-
- Nominal polarization ≥ 80%
- ≈ 1.5 mA (peak) from source
- ≥ 25 mA (peak) unpolarized available

Characteristics of the source of negative polarized ions IUCF (CIPIOS):

- peak current of polarized ion beam H^- (D^-) - 1.8 (2) mA
- peak current of polarized ion beam H^- (D^-) - 40 (30) mA
- polarization H^- - 80-85%
- polarization D^-:

Type of polarization	Pz nominal	Pz measured	Pzz nominal	Pzz measured я
vector (+)	+1	0.909(31)	+1	0.891 (13)
vector (-)	-1	-0.684 (30)	+1	0.695 (14)
tensor(+)	0	0.003 (32)	+1	0.875 (13)
tensor (-)	0	0.020 (33)	-2	-1.591 (13)

- normalized emittance H^- (D^-) - 1.2 π mm mrad
- pulse duration – up to 500 microsec. @ 1-4 Hz from source
- energy of polarized ion beam - 25 keV

- The source CIPIOS has high reliability and high stability of polarization and intensity of the beam during of typically 1000 hours accelerator runs

- Scheduled stops are necessary for the cryocooler regeneration and dissociator unit every two weeks of continuous work

- CIPIOS also generates unpolarized beams of negative ions of hydrogen and deuterium with a current up to 30 mA

INR source of polarized protons

It is known that at INR the source of polarized protons with the charge-exchange plasma ionizer and the polarized atom storage in the ionization volume is developed.

Characteristics of polarized H^+ (H^-) ion beam of the INR source

H^+

Without polarized atom storage

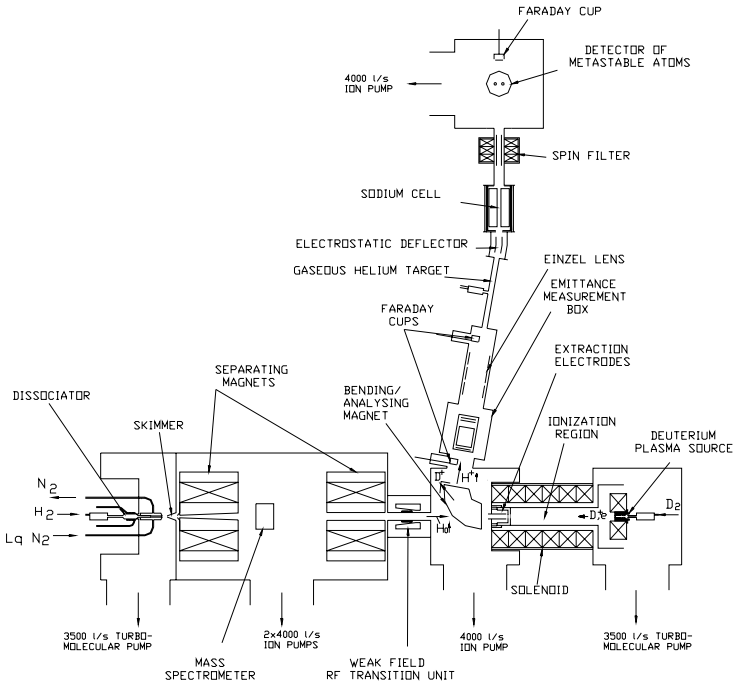
Intensity	6 mA
Polarization	85%

With polarized atom storage

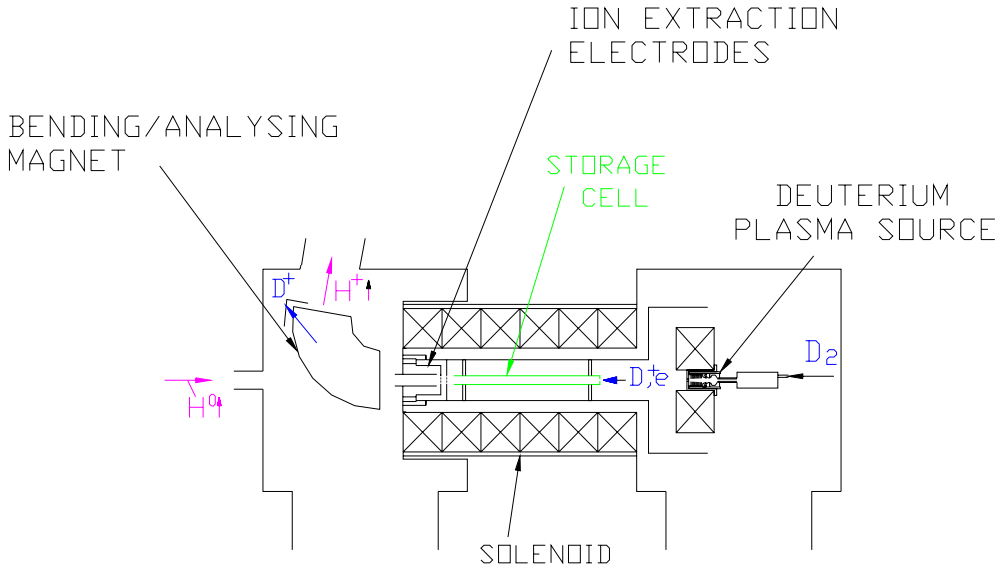
Intensity	11mA
Polarization	80%

H^-

Intensity	4 mA
Polarization	90%



Schematic layout of the polarized proton source
with nearly resonant charge–exchange plasma ionizer



Schematic diagram
of nearly resonant charge-exchange plasma ionizer
with a storage cell

The ionizer with storage of polarized atoms allows

- increase intensity of the polarized ion beam,
- reduce emittance of the polarized beam
- reduce considerably H_2^+ ion current which is difficult to be separated from polarized D^+ due to similar mass of the ions.

- At the **NUCLOTRON** one-turnaround injection is used.
- Transition to the re-charge injection of negative ions is not provided
- Therefore it is expedient to use the source of positive polarized deuterium ions

The higher intensity of the beam is reached for positive polarized ion sources with charge-exchange plasma ionizer in comparison with the source of negative polarized H^- (D^-) ions

SPD-project assumes to convert the charge-exchange ionizer of **CIPIOS** into the ionizer using storage of polarized deuterium atoms and production of **positive polarized deuterons** by resonance recharging in the hydrogen plasma

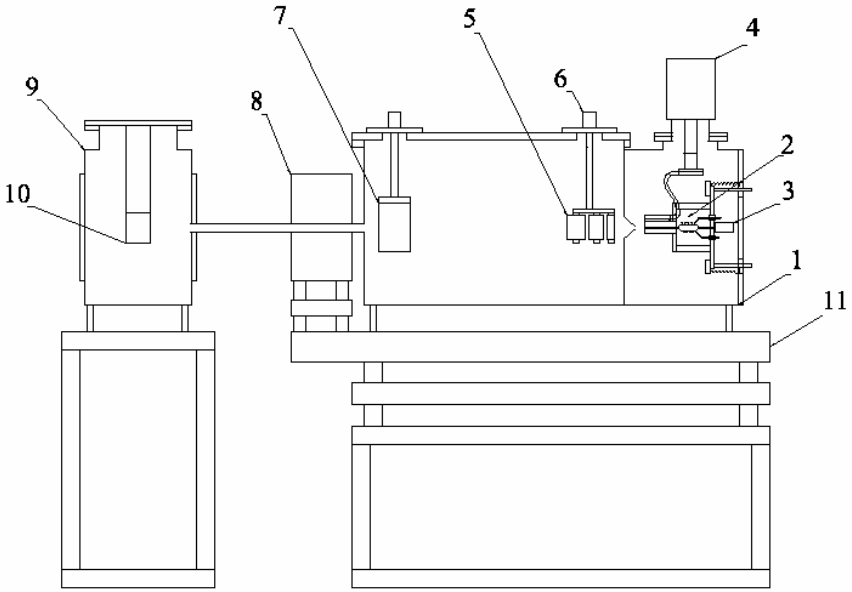
The elements of the source **CIPIOS** transferred from IUCF (USA) lack some equipment

- That is why we will need development and fabrication of the missing modules and parts for the future source.
- These are mainly elements of the Atomic Beam Source (**ABS**).
- In addition, acquisition of the missing equipment and instruments to the source as a whole is necessary.

- - vacuum chamber of the ABS and sextupole magnets
- - dissociator
- - channel of the atomic deuterium (hydrogen) beam cooling
- - pulse valve of molecular deuterium (hydrogen) injection into the dissociator bulb with the power supply of the pulse gas valve
- - high-frequency pulse generator with pulse power up to 5 kW operating in the 50 MHz self-excitation circuit
- - modulator of the high-frequency generator with the maximum voltage up to 4.5 kV and a pulse current up to 2 A

should be development

Scetch of the deuterium (hydrogen) Atomic Beam Source



- 1.vacuum chamber, 2. dissociator, 3.pulse gas valve, 4. cryocoooler, 5.permanent sextupole magnet assembly, 6. adjusting device of sextupole magnets, 7. RF-cells, 8.sextupole electromagnet, 9.mass spectrometr vacuun chamber, 10.time-of-flight mass spectrometer, 11.adjustable suppoprt

For optimization of the atomic beam intensity it is necessary

- - measure the **atomic beam density** in the pulse mode using the time-of-flight mass-spectrometer
- - measure the **atomic beam velocity distribution**
- - compute the **optimum location** of the permanent sextupoles

The **RF-transition units** will be checked and tuned with a sextupole electromagnet as an analyzing device

The designing and manufacture of **ABS** parts, optimization of the intensity of the atomic beams, and functional test of the cells of the nuclear polarization of deuterium (hydrogen) atoms will be performed under the agreement with **INR of RAS (Moscow)**

The purpose is to get atomic ***D*** beam with the pulse density of **2.5 ·10^{10}** at/cm^3 at the distance of **150** cm from the cooling channel outlet and the most probable velocity of **1.5 ·10^5** cm/s.

The work to be carried out at JINR includes

- - assembly and tests of the charge-exchange plasma ionizer, including the storage cell in the region of ionization and transportation of hydrogen plasma with the flow of unpolarized protons up to 100 mA through the storage cell
- - optimization of the ion-optical system up to 25 keV and transport of the high-current deuteron beam
- - long-term tests with the storage cell in the ionizer

It is necessary to develop electronic control system components for primary analysis and data acquisition and for fiber optic connection with the computer

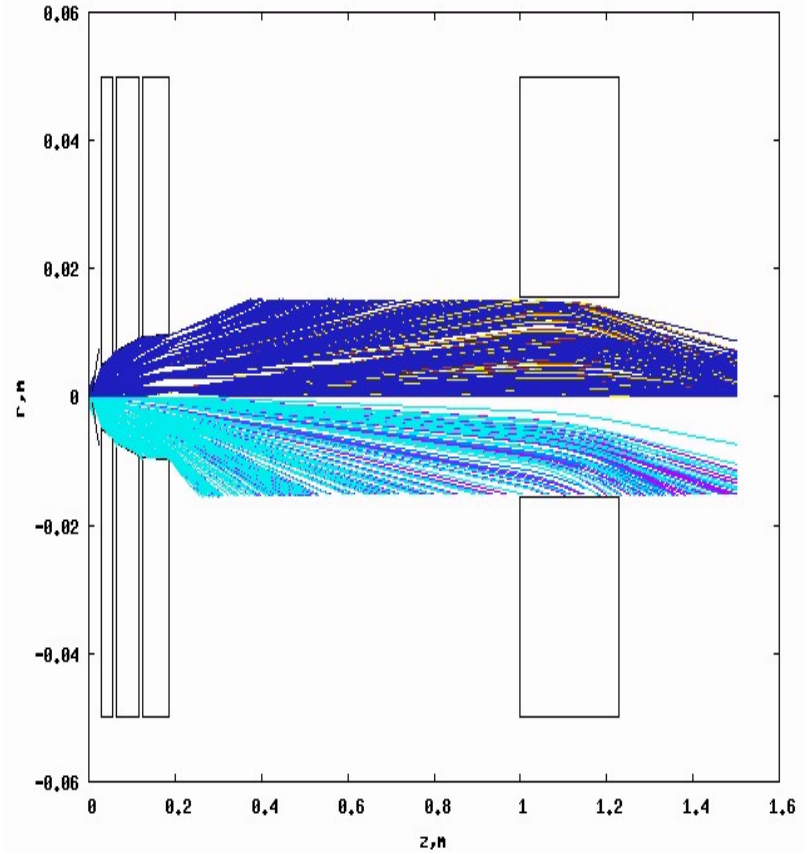
Status of the SPD project

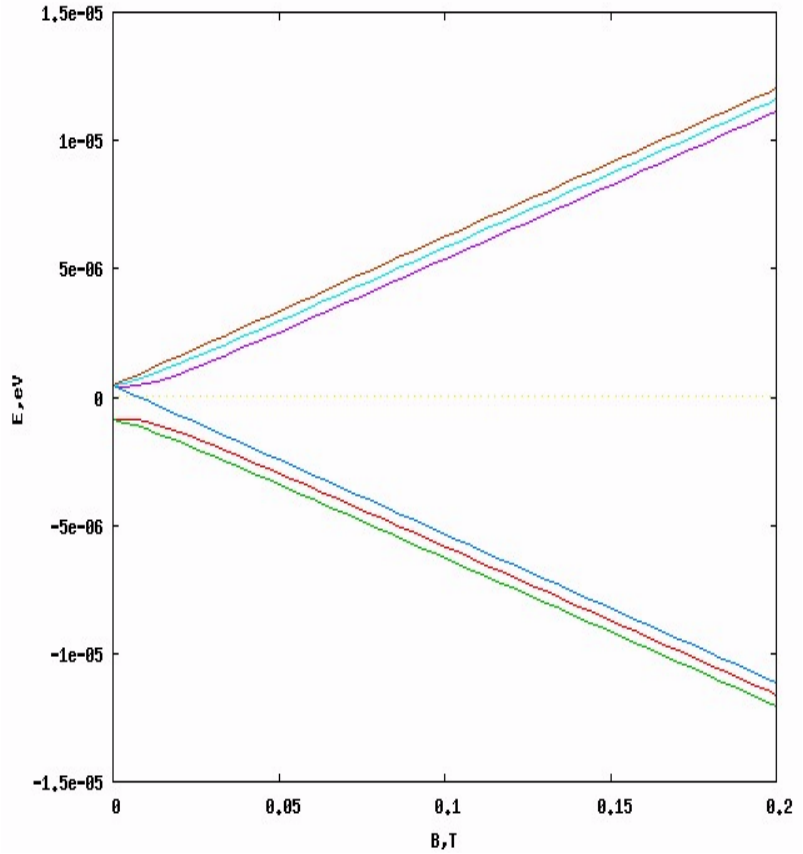
Now within the framework of the project and the JINR-INR Agreement the source of polarized atoms is under development at INR

The testbench for the charge-exchange ionizer is under preparation at JINR

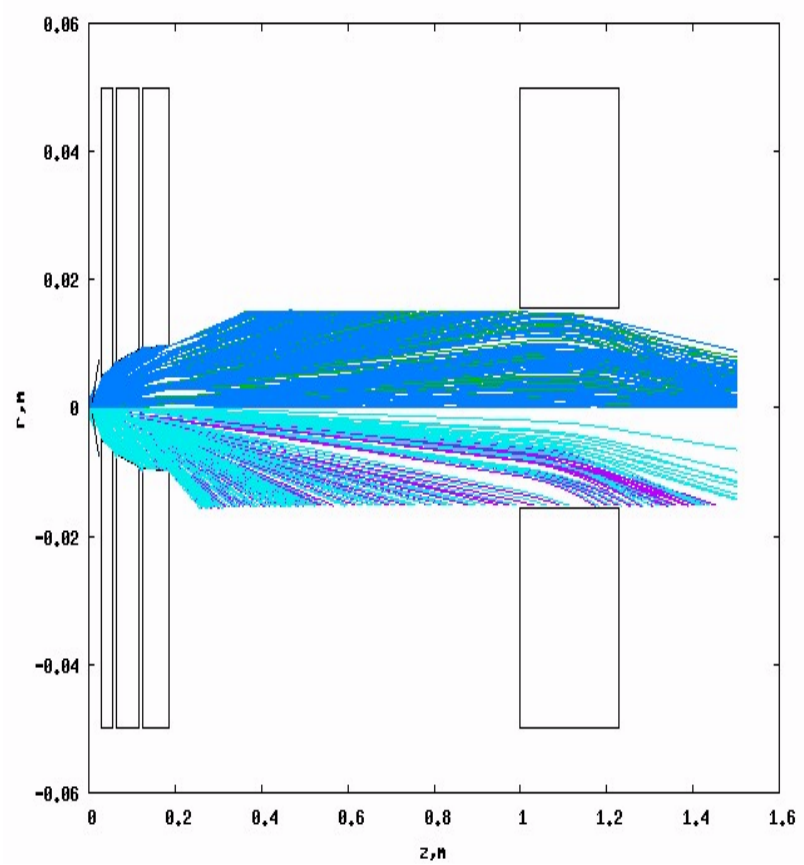
The missing equipment is to be purchased in the nearest future

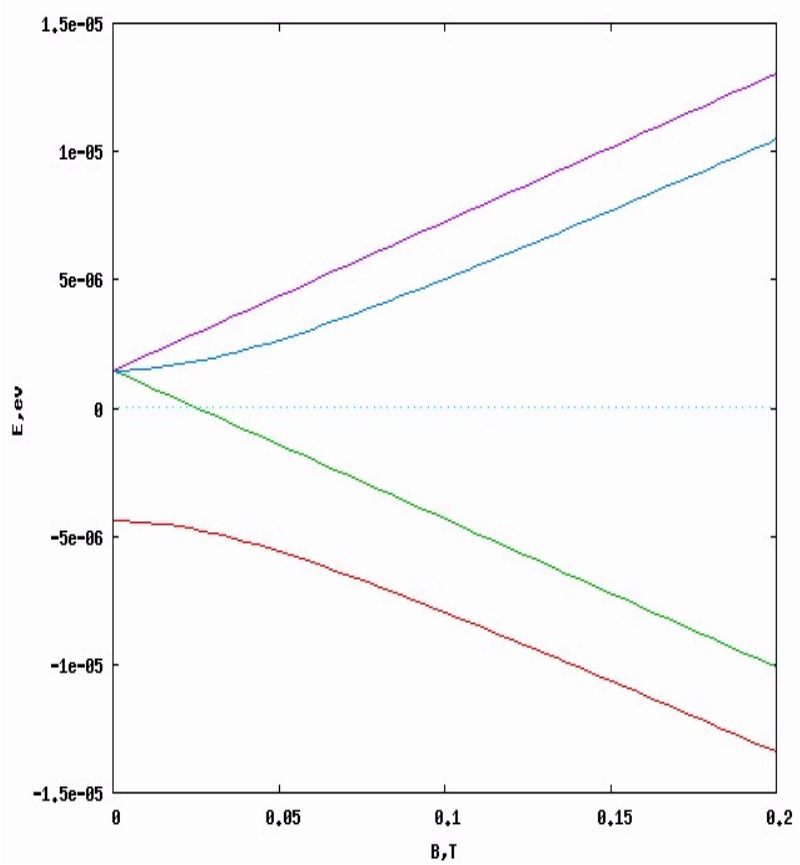
Dynamics of atomic deuterium beam downstream the sextupole magnets
& Atomic Deuterium Breit-Rabi diagram



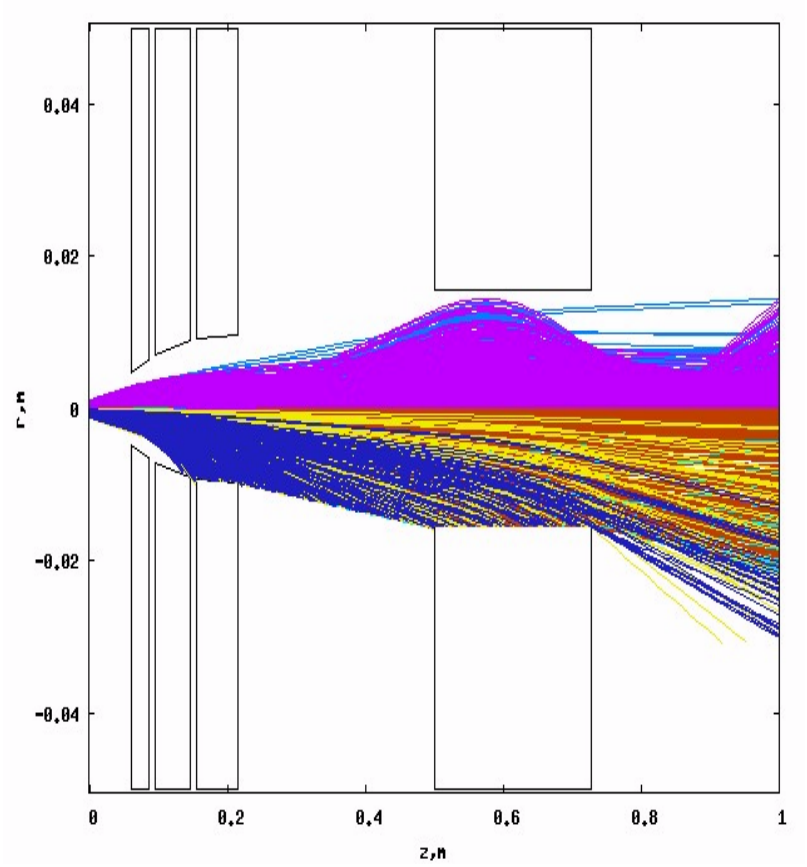


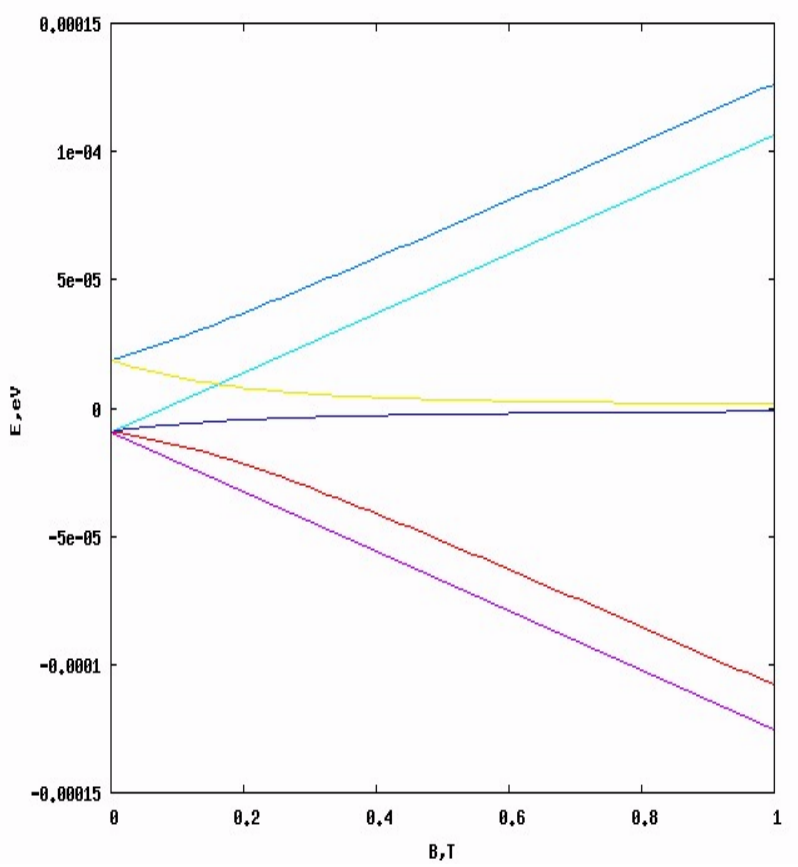
Dynamics of atomic hydrogen beam downstream the sextupole magnets
& Atomic Hydrogen Breit-Rabi diagram



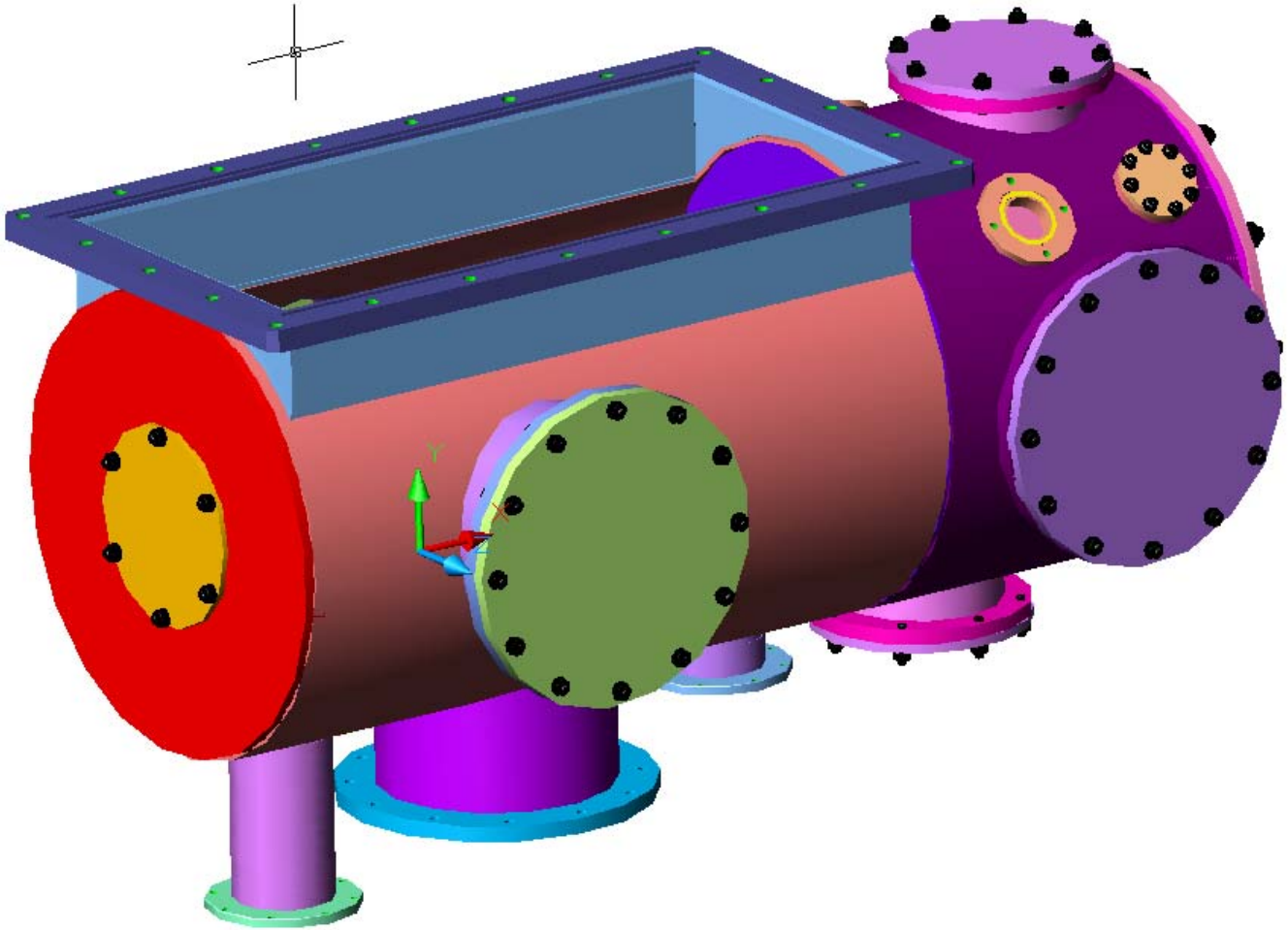


Dynamics of helium-3 beam downstream the sextupole magnets & Helium-3 Breit-Rabi diagram

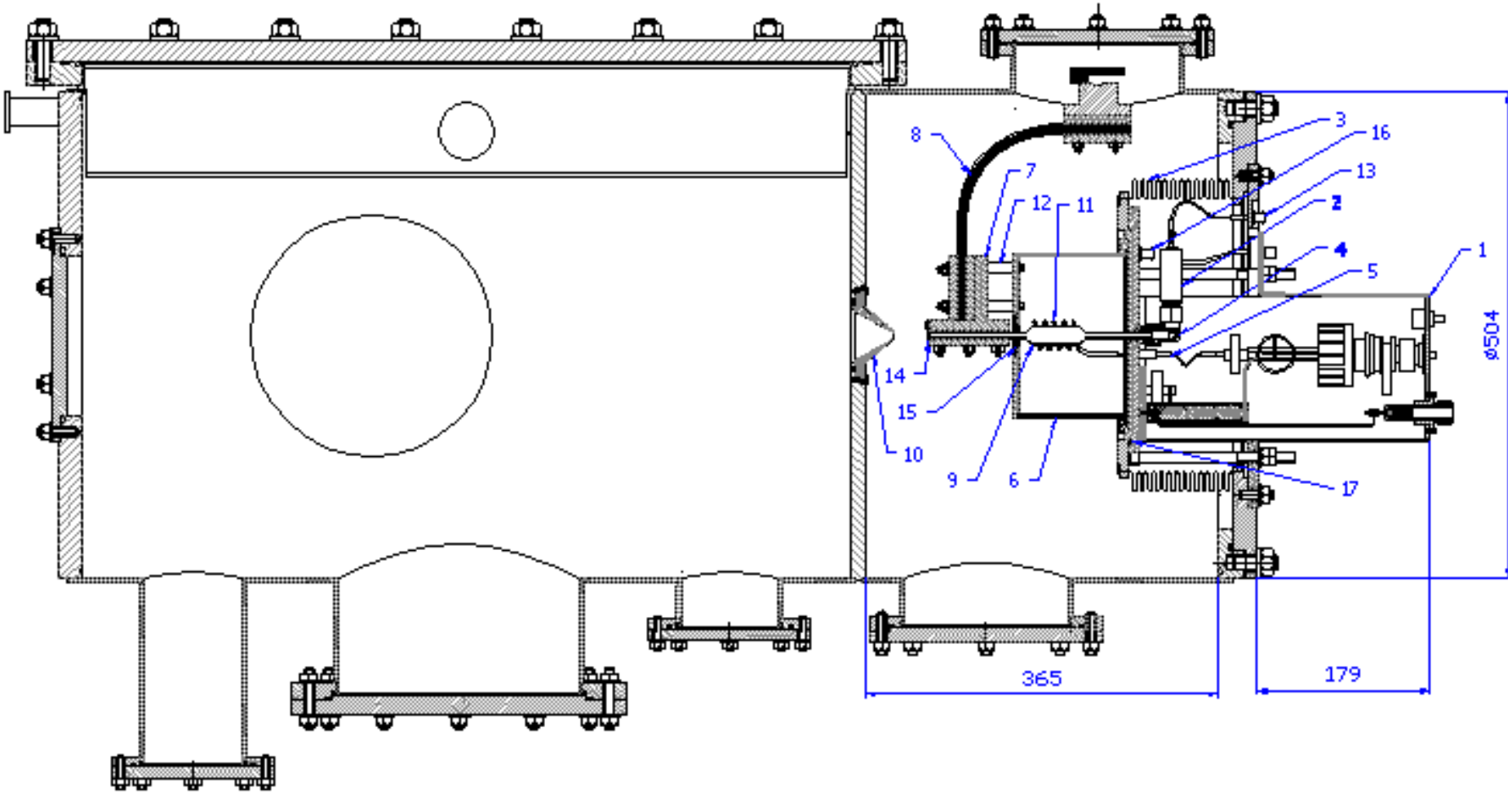




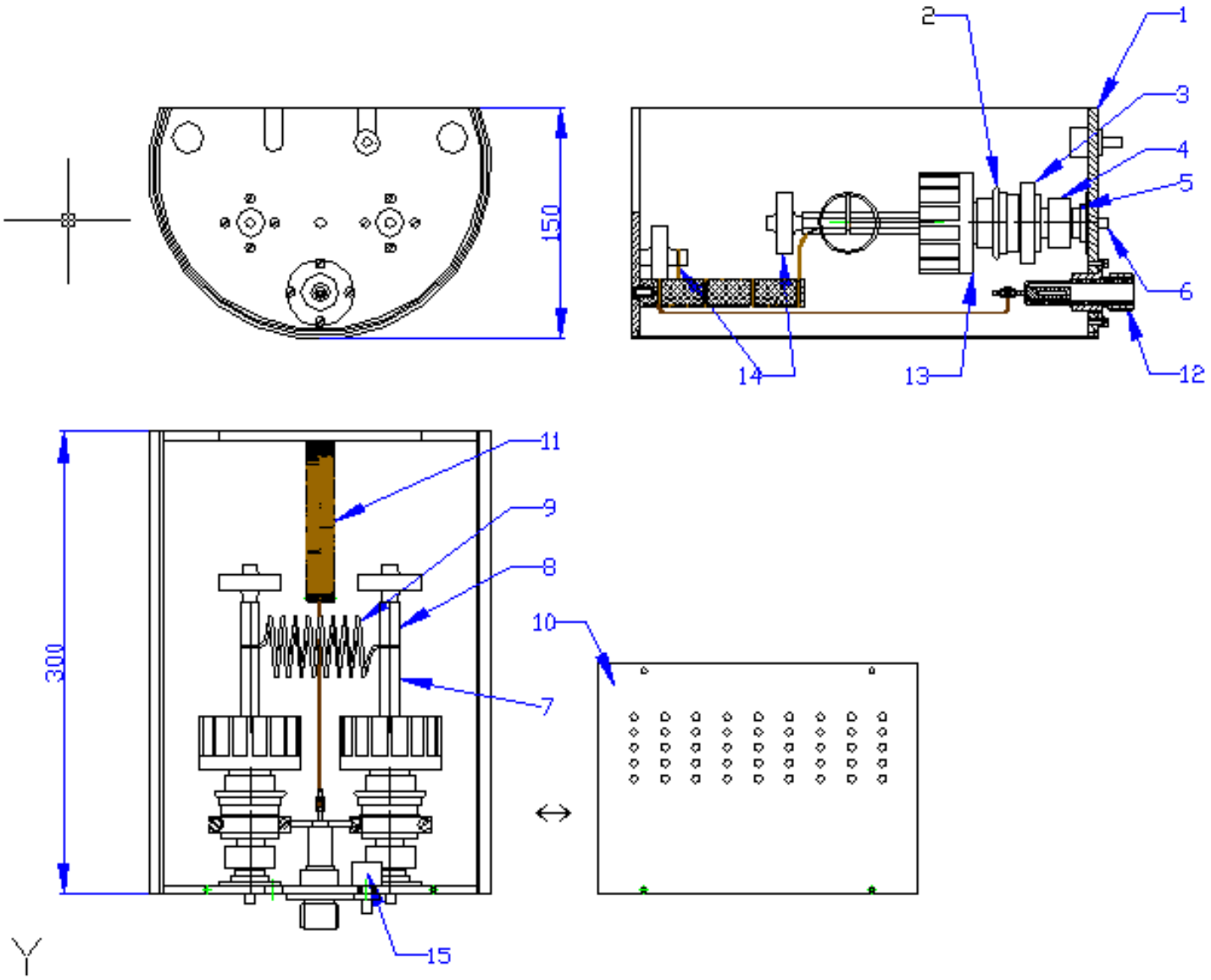
Vacuum chamber of the Atomic Beam Source



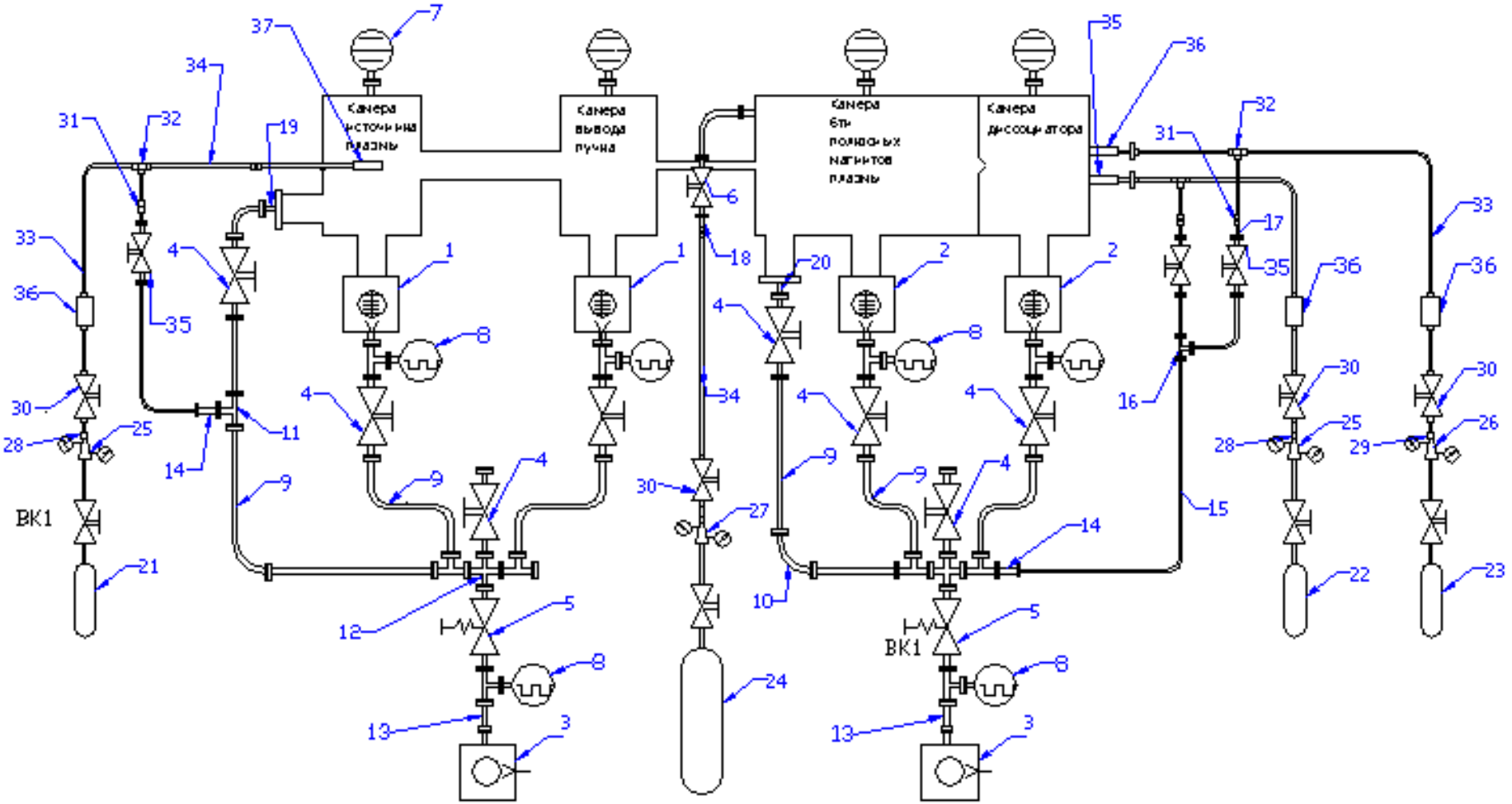
Dissociator chamber of the Atomic Beam Source



RF generator of the dissociator



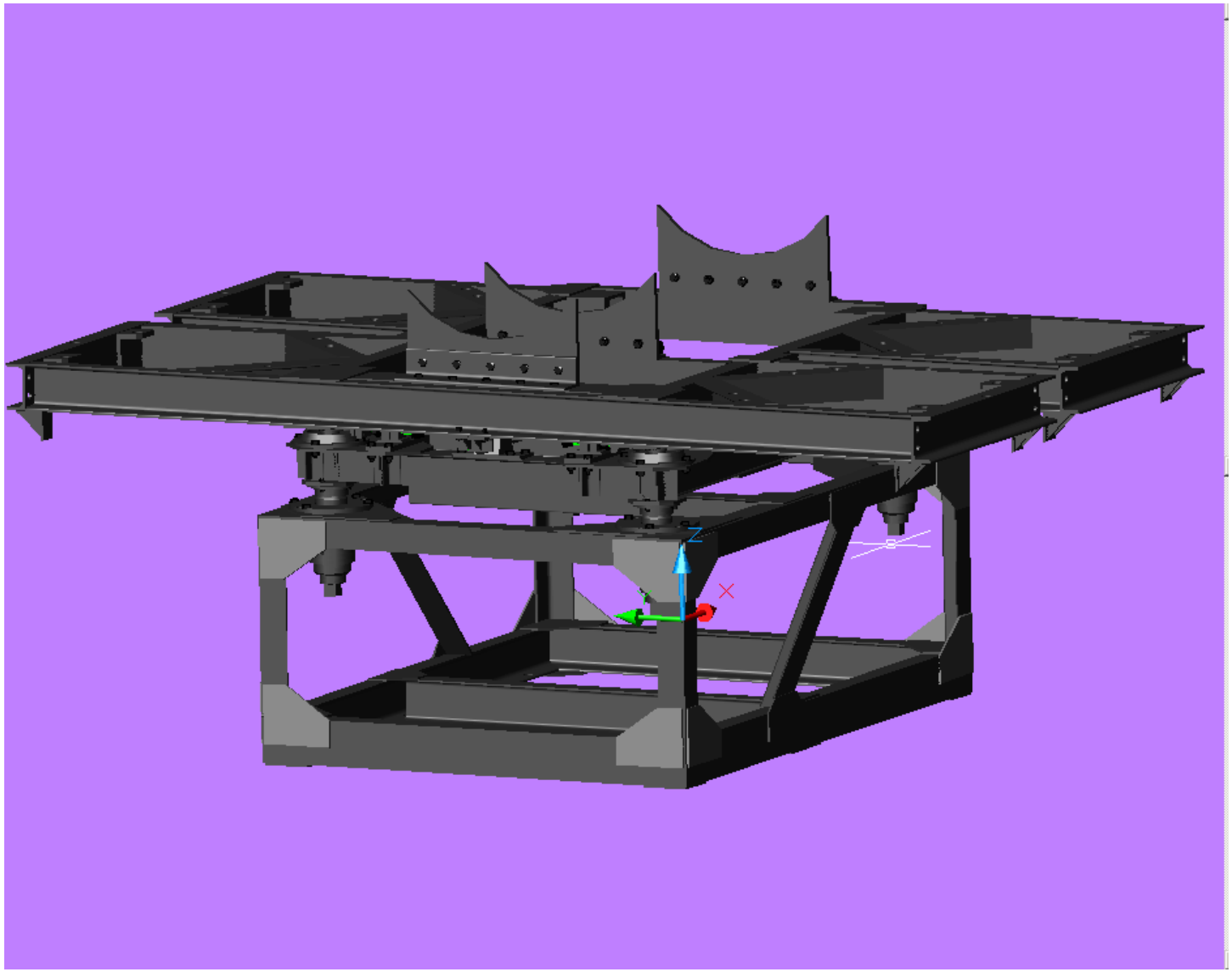
Vacuum pumping system of the Source of Polarized Deuterons



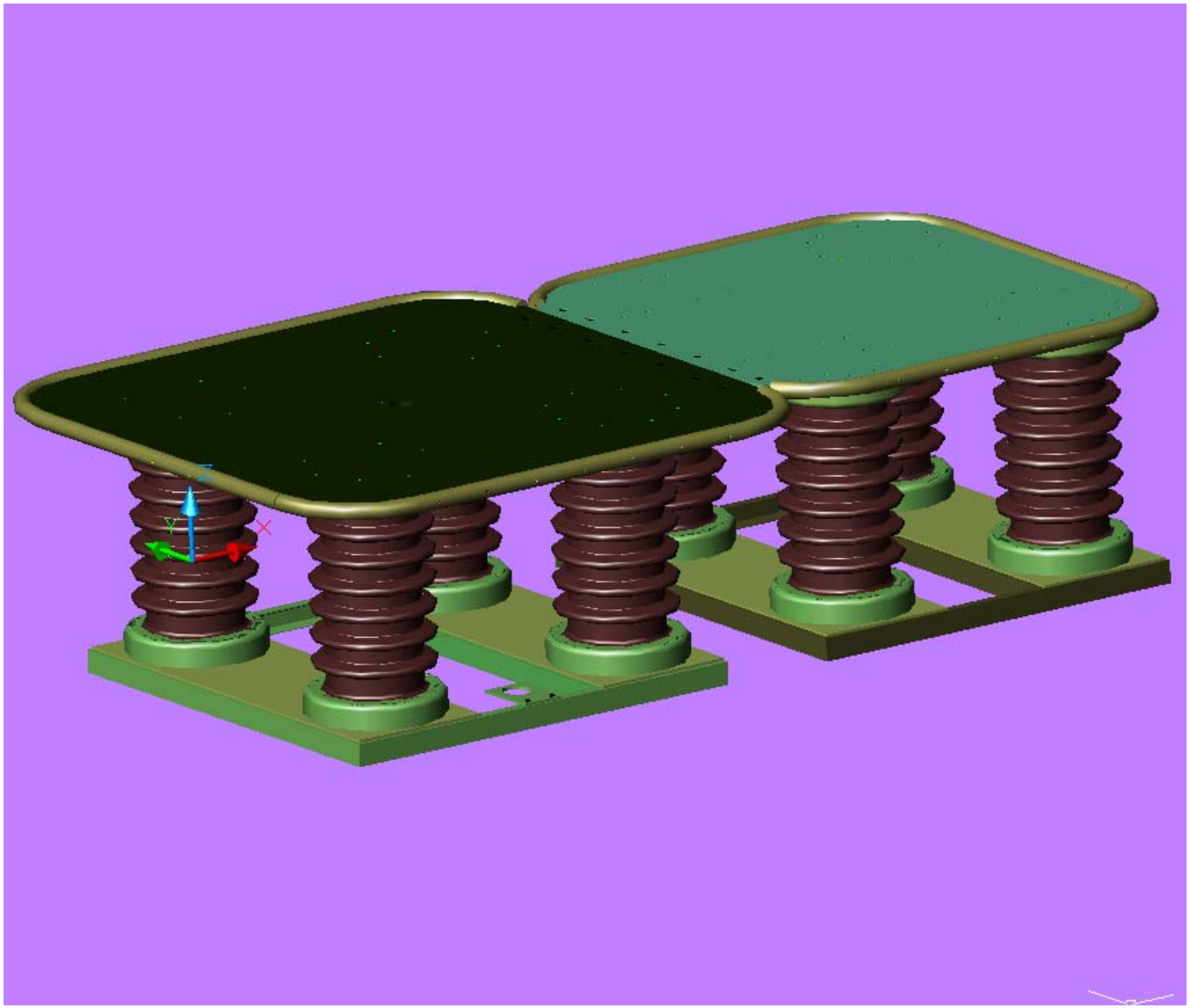
- **VARIAN**
- Pump, Turbo-V 3K-T, **2300** l/s H_2 , **2400** l/s He - 2 item
- Pump, Turbo-V 2K-G, **1600** l/s N_2 - 2 item

- **CTI - Cryogenics**
- Cryocooler, Model 1020 77K - **35W** first stage
- 20K - **12W** second stage

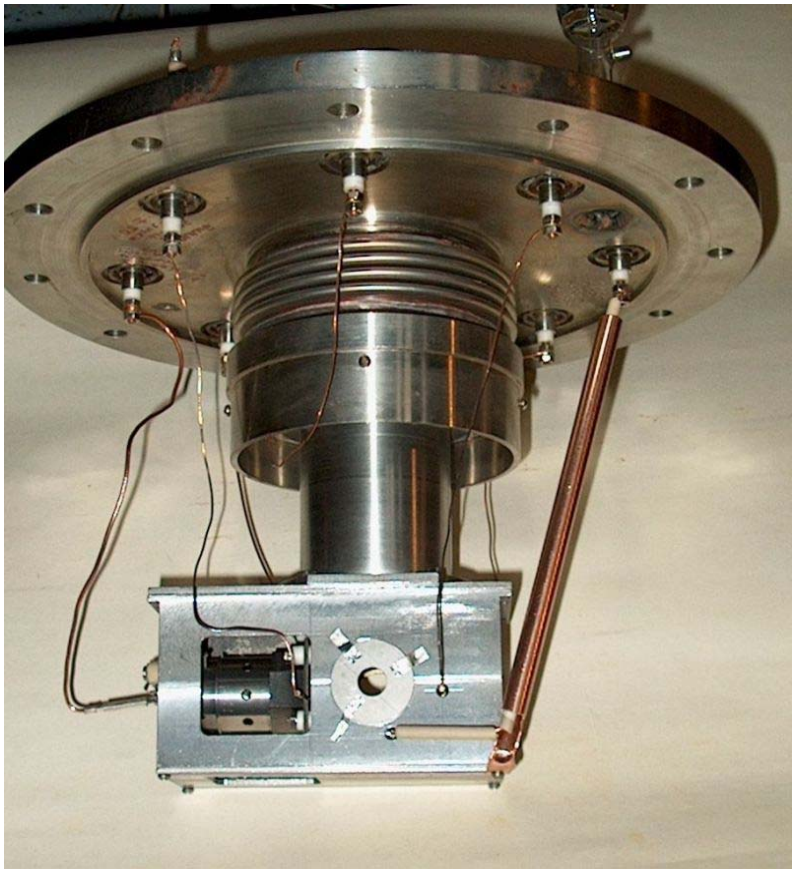
Adjustable support



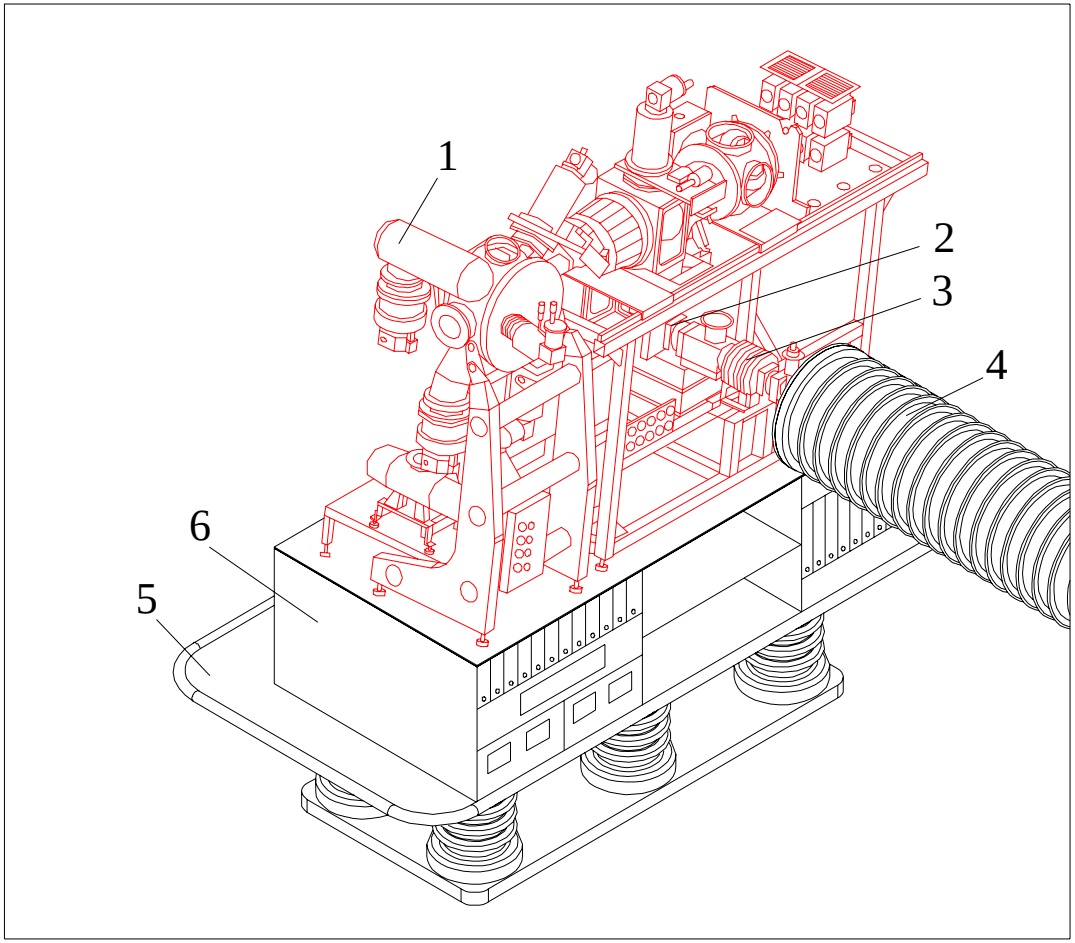
High-voltage terminal at the linac (Lu-20) (improvement)



Time-of-flight mass-spectrometer with cross-beam ionizer



Placement version of the polarized deuteron souce on the high-voltage terminal at linac (LU-20)



1. Assembly of the Source of polarized atoms and Charge-exchange plasma ionizer
2. Extraction unit
3. Spin-precessor
4. Preaccelerator tube
5. High-voltage terminal
6. Electronic and electrotechnical equipment of setup

- Resonant charge-exchange reaction is charge exchange between atom and ion of the same atom:

$$A^0 + A^+ \rightarrow A^+ + A^0$$

  - cross -section is of order of 10^{-14} cm^2 at low collision energy

- Charge-exchange between polarized atoms and ions of isotope relative the polarized atoms - to reduce unpolarized background

Nearly resonant charge-exchange reactions which can be used for polarized ion sources

$$H^0\uparrow + D^+ \Rightarrow H^+\uparrow + D^0$$
$$D^0\uparrow + H^+ \Rightarrow D^+\uparrow + H^0$$

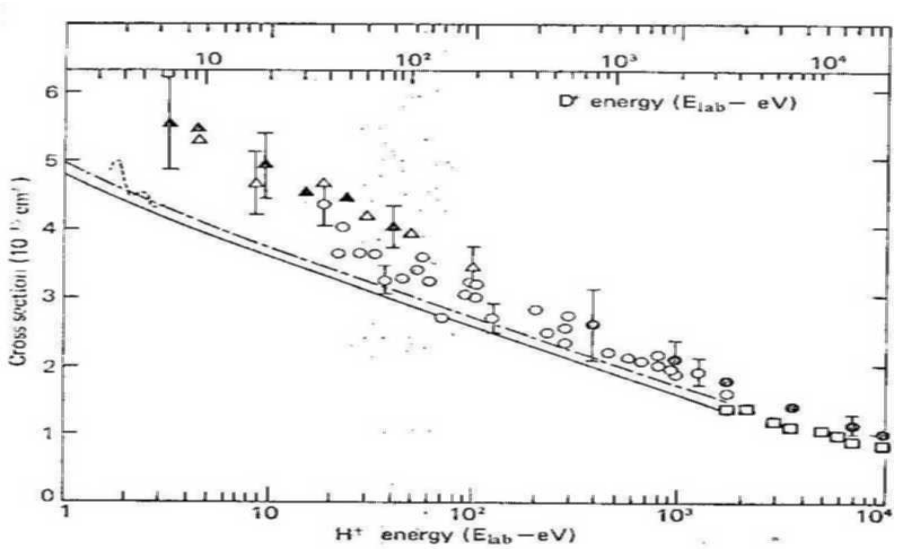
$$H^0\uparrow + D^- \Rightarrow H^-\uparrow + D^0$$
$$D^0\uparrow + H^- \Rightarrow D^-\uparrow + H^0$$

$$^3He^0\uparrow + {}^4He^+ \Rightarrow {}^3He^+\uparrow + {}^4He^0$$
$$^3He^0\uparrow + {}^4He^{++} \Rightarrow {}^3He^{++}\uparrow + {}^4He^0$$

Cross-section vs collision energy for process

$H^+ + H^0 \rightarrow H^0 + H^+$

$\sigma = 5 \cdot 10^{-15}$ cm^2 at ~10eV collision energy

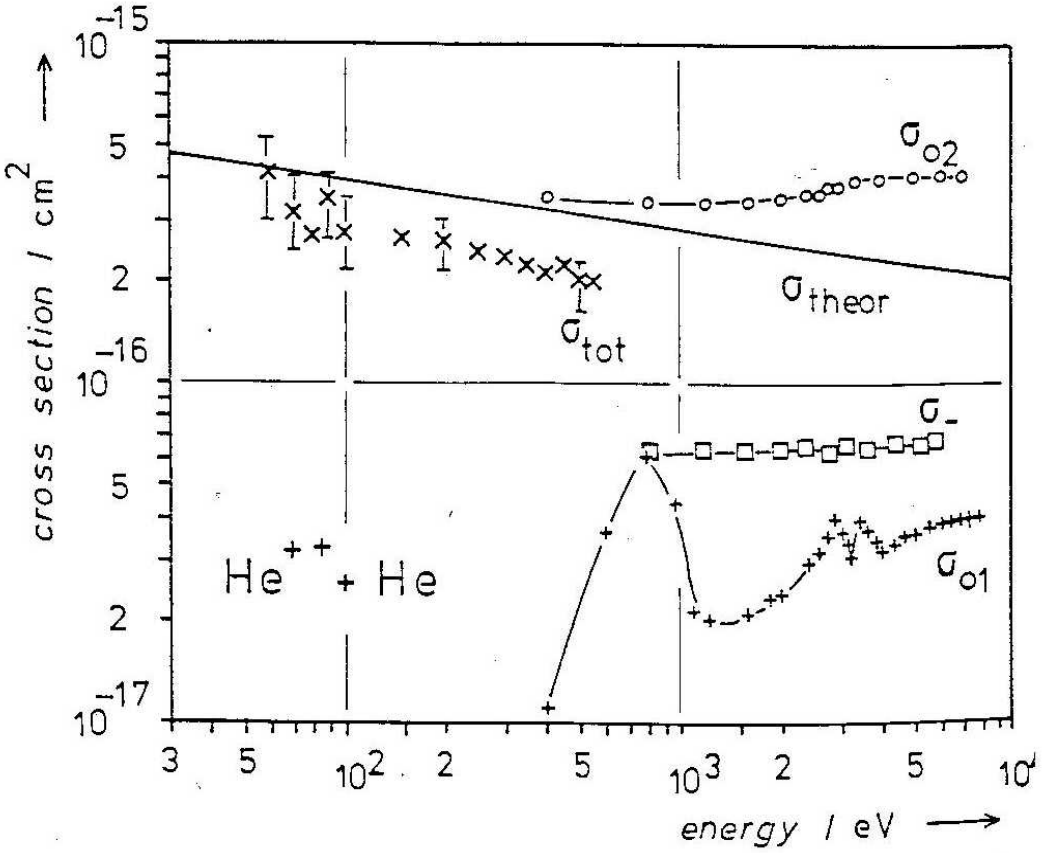


I-A3-Fig. 7 Cross section for charge transfer
$H^+ + H \rightarrow H + H^+$

Cross-section vs collision energy for process

$He^{++} + He^{0} \rightarrow He^{0} + He^{++}$

$\sigma = 5 \cdot 10^{-16}$ cm^2 at ~10eV collision energy



For the polarized ions production deuterium moves in an RF dissociator of the source of polarized atoms and hydrogen in a plasma source of ionizer, and the next reaction is used:

$$D^{\circ}\uparrow + H^{-} \rightarrow D^{-}\uparrow + H^{\circ}$$

Source POLARIS (JINR)

Transition	I	Pz	Pz^2 I	Pzz	Pzz^2 I
M (1 → 4)	1/2	-2/3	2/9	0	0
M (3 → 6)	1/2	2/3	2/9	0	0
M (2 → 6)	1/2	1/3	1/18	1	1/2
M (3 → 5)	1/2	1/3	1/18	-1	1/2

Source CIPIOS (IUCF)

Transition	I	Pz	Pz^2 I	Pzz	Pzz^2 I
M (1 → 4) M (3 → 5)	1/3	0	0	-2	4/3
M (1 → 4) M (2 → 6)	1/3	0	0	1	1/3
M (2 → 6) M (1 → 4)	1/3	-1	1/3	1	1/3
M (3 → 5) M (2 → 6)	1/3	1	1/3	1	1/3

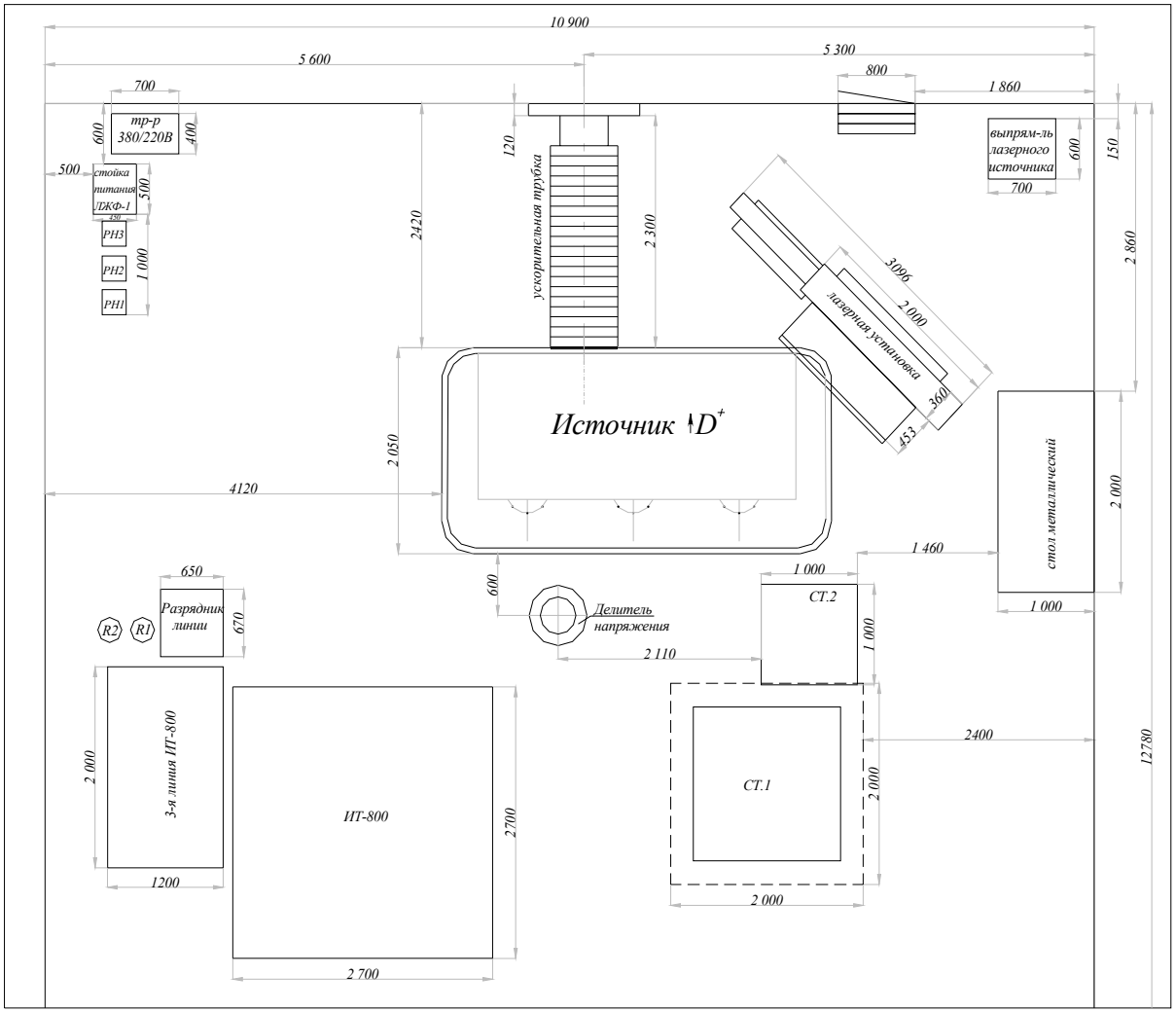
- **INR of RAS**

  - the source of the polarized protons with the charge exchange ionizer using a free atomic beam in ionizer and using a storage of the polarized atoms in the field of ionization is developed

- **Intensity and polarization of H^+ beam - 6 mA, 85%**
- **Intensity and polarization of H^+ beam with storage cell - 11 mA, 80%**

- **Storage cell is**
  - increase of the polarized ions beam intensity
  - decrease of polarized beam emittance
  - significant decrease of H_2^+ ion current

Plan of setup placing at linac hall



Characteristics of the INR polarized proton source

- ABS:
  - peak intensity of polarized atomic hydrogen beam is 2 $\cdot 10^{17}$ at/s
  - most probable velocity is 2 $\cdot 10^{5}$ cm/s

- Polarized proton beam:
  - peak current is 6 mA
  - polarization - 75-90 %
  - normalized emittance 2π mm mrad
  - rep. rate up to 10 Hz

- Unpolarized deutron current density - 250 mA/cm^2

- Polarized ions are produced in polarized ion sources via several steps process:
  - **polarization of neutral atoms** (atomic beam method or optical pumping)
  - **conversion of polarized neutral atoms into polarized ions** (ionization by electron impact, electron impact + charge-exchange, charge exchange, nearly resonant charge-exchange)

- Nearly resonant charge-exchange processes have large cross sections. This is base for high efficiency of polarized atoms conversion into polarized ions.