

Experience with polarized hydrogen molecular source

Dmitriy Toporkov

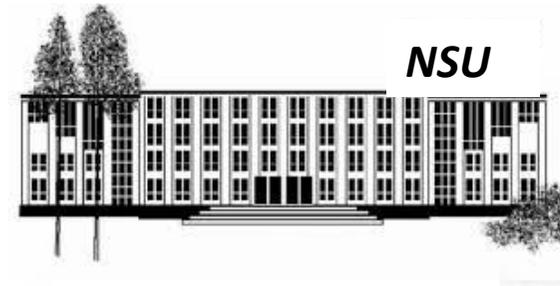
Budker Institute of Nuclear Physics,
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Novosibirsk, Russia.

Workshop on Nuclear Fusion with Polarized Fuel
October 2-3, 2017, Ferrara
Conference room at Hotel Europa

BINP



NSU



Sources of polarized atoms

The sources of polarized atoms (ABS) have been developed from the early 50th. Clausnitzer was the first who got a polarized proton beam using an ABS with quadrupole focusing magnets. The intensity of polarized atomic beam was approximately

10^{11} at/sec.

[G. Clausnitzer, R. Fleischman, H. Shopper, Zs. F. Physik 144 (1956) 336]

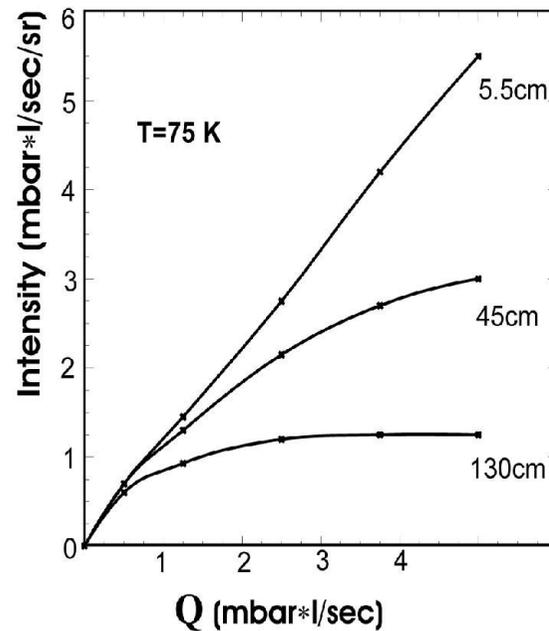
Since there fast developing of this technique now reached the limit in the intensity of polarized atoms. The best sources deliver about

10^{17} at/sec

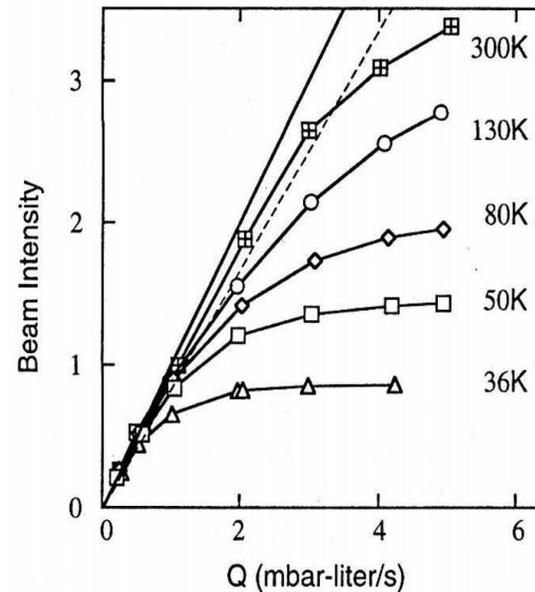
Parameters and intensity for different ABS

ABS	$\Omega_{\text{geom.}}(\text{sr}) = \pi r_{\text{mag.}}^2 / l_{\text{n-mag.}}^2$	$\Omega_{\text{mag.}}(\text{sr}) = \pi \mu B / kT_{\text{nozzle}}$	$\Omega_{\text{average}} = \Omega_{\text{g.}} \Omega_{\text{m.}} / (\Omega_{\text{g.}} + \Omega_{\text{m.}})$	Intensity H / D at/sec
Wisconsin ABS NIMA336(1993)410	$2.86 \cdot 10^{-2}$	$3.74 \cdot 10^{-2}$	$1.62 \cdot 10^{-2}$	$8.6 \cdot 10^{16}$ total H $6.7 \cdot 10^{16}$ d10mm H
FILTEX ABS NIMA343(1994)334	$2.38 \cdot 10^{-2}$	$2.95 \cdot 10^{-2}$	$1.31 \cdot 10^{-2}$	$8.1 \cdot 10^{16}$ d10mm H
HERMES ABS NIMA496(2003)277	$1.73 \cdot 10^{-2}$	$3.16 \cdot 10^{-2}$	$1.12 \cdot 10^{-2}$	$6.6 \cdot 10^{16}$ d10mm H $5.0 \cdot 10^{16}$ D
ETH ABS (NIKHEF) electromagnets NIMA378(1996)40	$2.5 \cdot 10^{-2}$	$3.31 \cdot 10^{-2}$	$1.42 \cdot 10^{-2}$	$2.6 \cdot 10^{16}$ d 12mm H $1.6 \cdot 10^{16}$ D
ETH ABS (NIKHEF) perm. magnets NIMA455(2000)769	$2.29 \cdot 10^{-2}$	$5.1 \cdot 10^{-2}$	$1.58 \cdot 10^{-2}$	$7.6 \cdot 10^{16}$ max H $6.4 \cdot 10^{16}$ d 12mm H $4.5 \cdot 10^{16}$ D
Cryogenic ABS NIMA495(2002)8	$4.3 \cdot 10^{-2}$	$5.3 \cdot 10^{-2}$	$2.37 \cdot 10^{-2}$	$7.9 \cdot 10^{16}$ total H $8.2 \cdot 10^{16}$ D
RHIC ABS NIMA536(2005)248 NIMA556(2006)1	$2.36 \cdot 10^{-2}$	$5.48 \cdot 10^{-2}$	$1.65 \cdot 10^{-2}$	$12 \cdot 10^{16}$ total H
ANKE ABS NIMA721(2013)83	$3.14 \cdot 10^{-2}$	$5.8 \cdot 10^{-2}$	$2.04 \cdot 10^{-2}$	$7.5 \cdot 10^{16}$ d 10mm H $3.9 \cdot 10^{16}$ D

At large distances or low temperature of the beam intrabeam scattering limits the intensity.



FILTEX ABS, 1991



T.Wise et al. NIMA 336(1993) 410

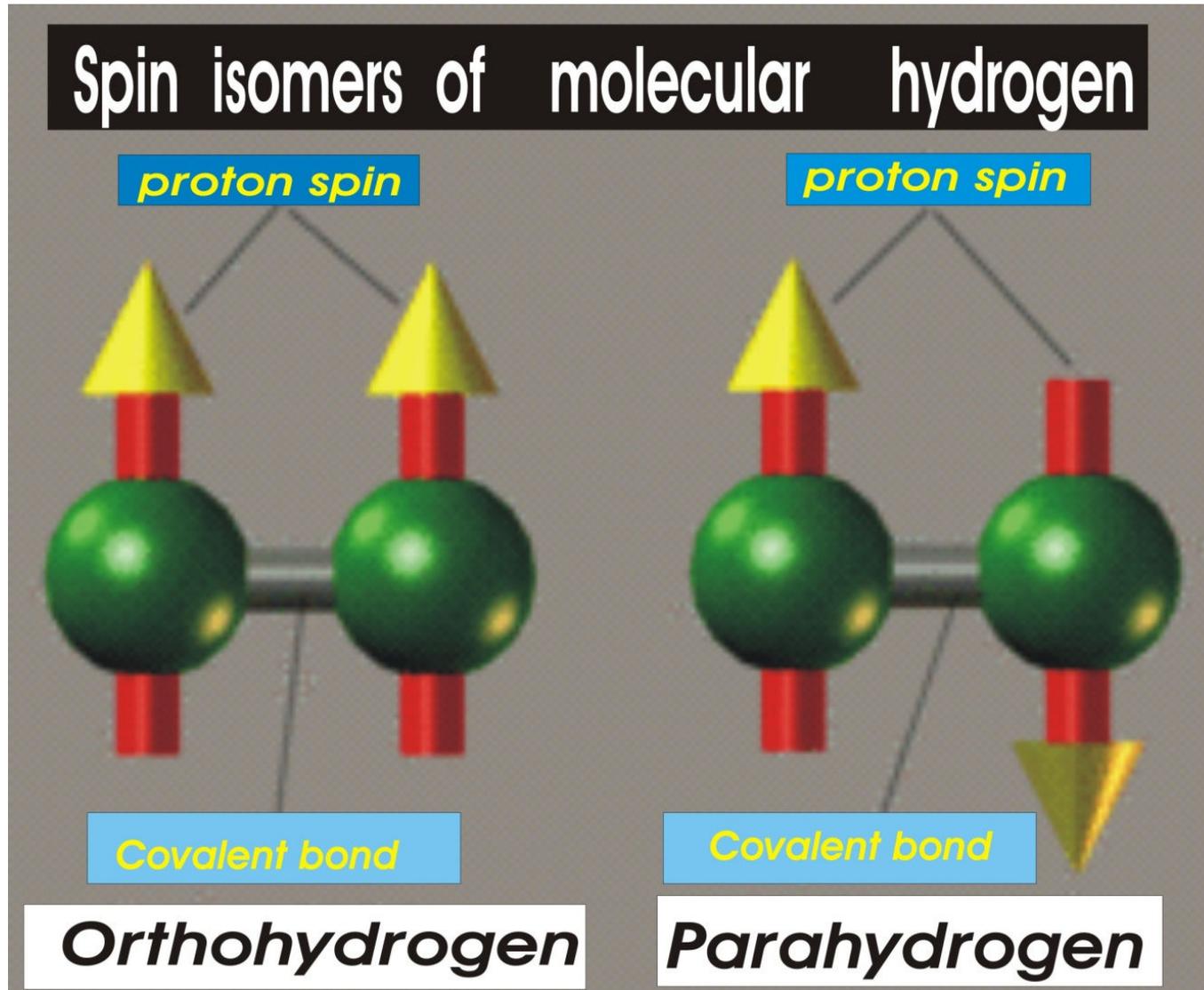
Intensities of the free hydrogen molecular beams.

R. L. Garwin (Rev. Sci. Instrum. 29 (1958) 374) proposed to produce a beam of polarized protons by using a conventional Stern-Gerlach separation of hydrogen molecules.

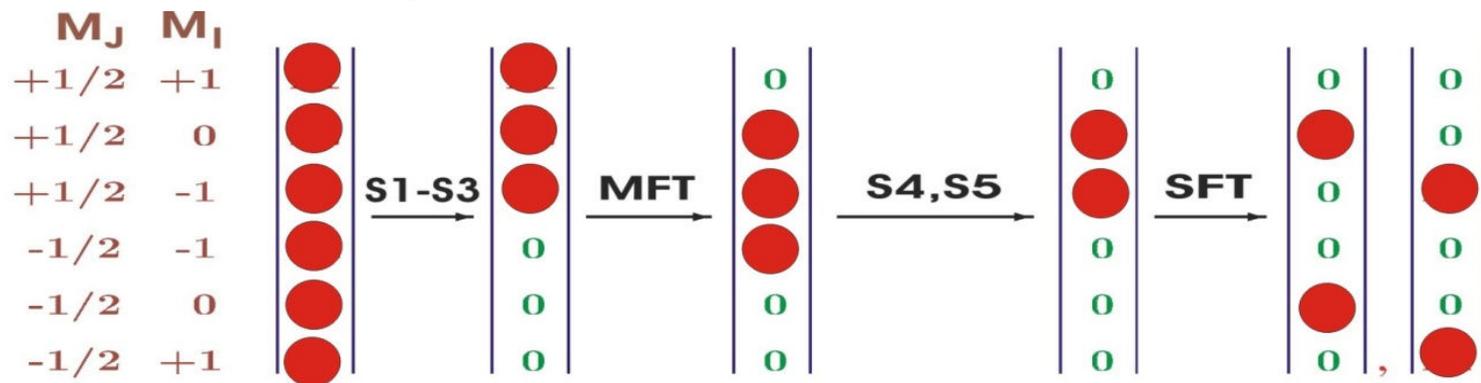
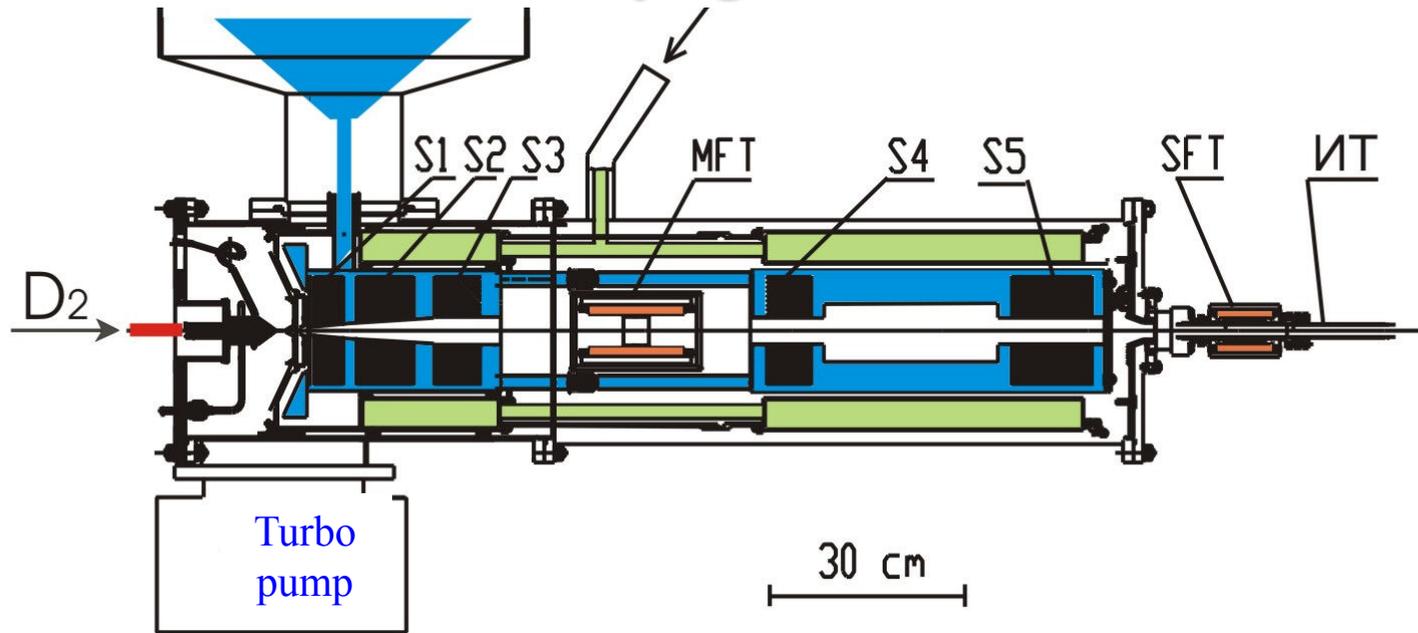
In 1998 we have suggested to obtain polarized hydrogen and deuterium molecules using the superconducting multipole magnets.

u.V. Shestakov, D.M. Nikolenko, I.A.Rachek, D.K. Toporkov, and V.F. Dmitriev, in Proc. of 13th Intern. Symp. on High Energy Spin Phys., Protvino, Russia. (1998) 415.

Ortho and parahydrogen



Novosibirsk Cryogenic Atomic Beam Source

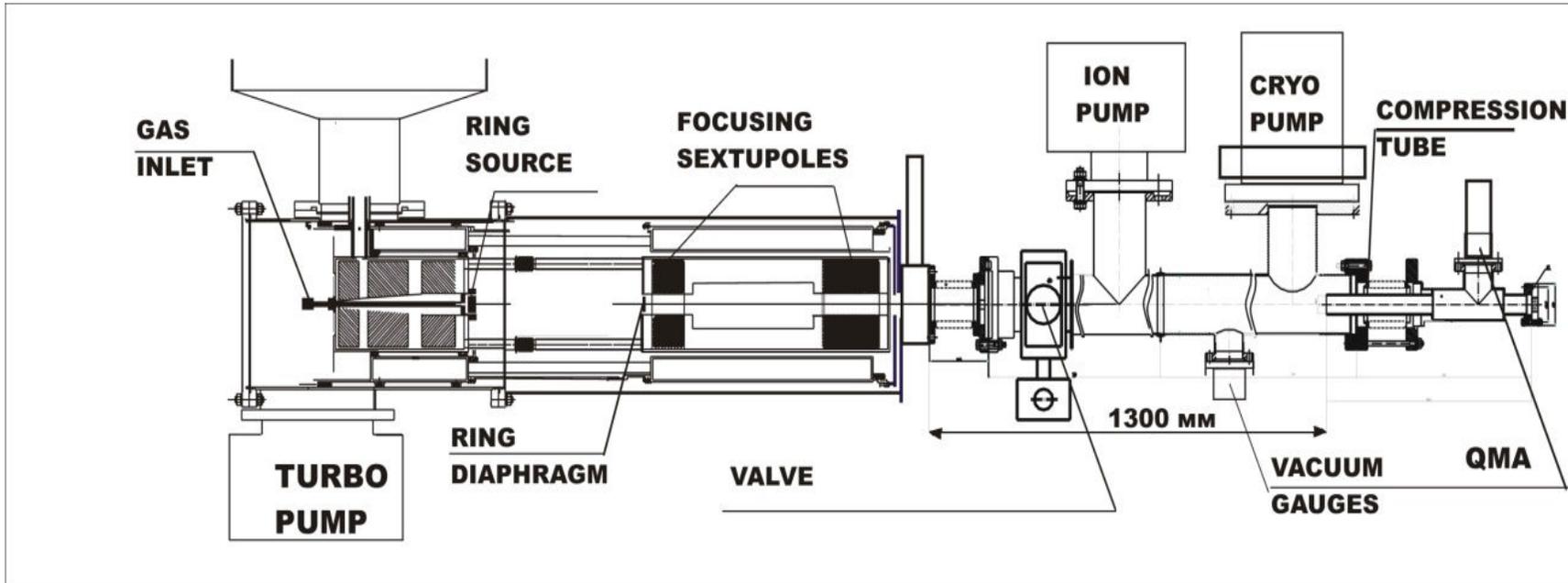


Tensor polarization
Vector polarization

$$P_{zz} = 1 - 3n_0 = -2, +1.$$

$$P_z = n_+ - n_- = 0.$$

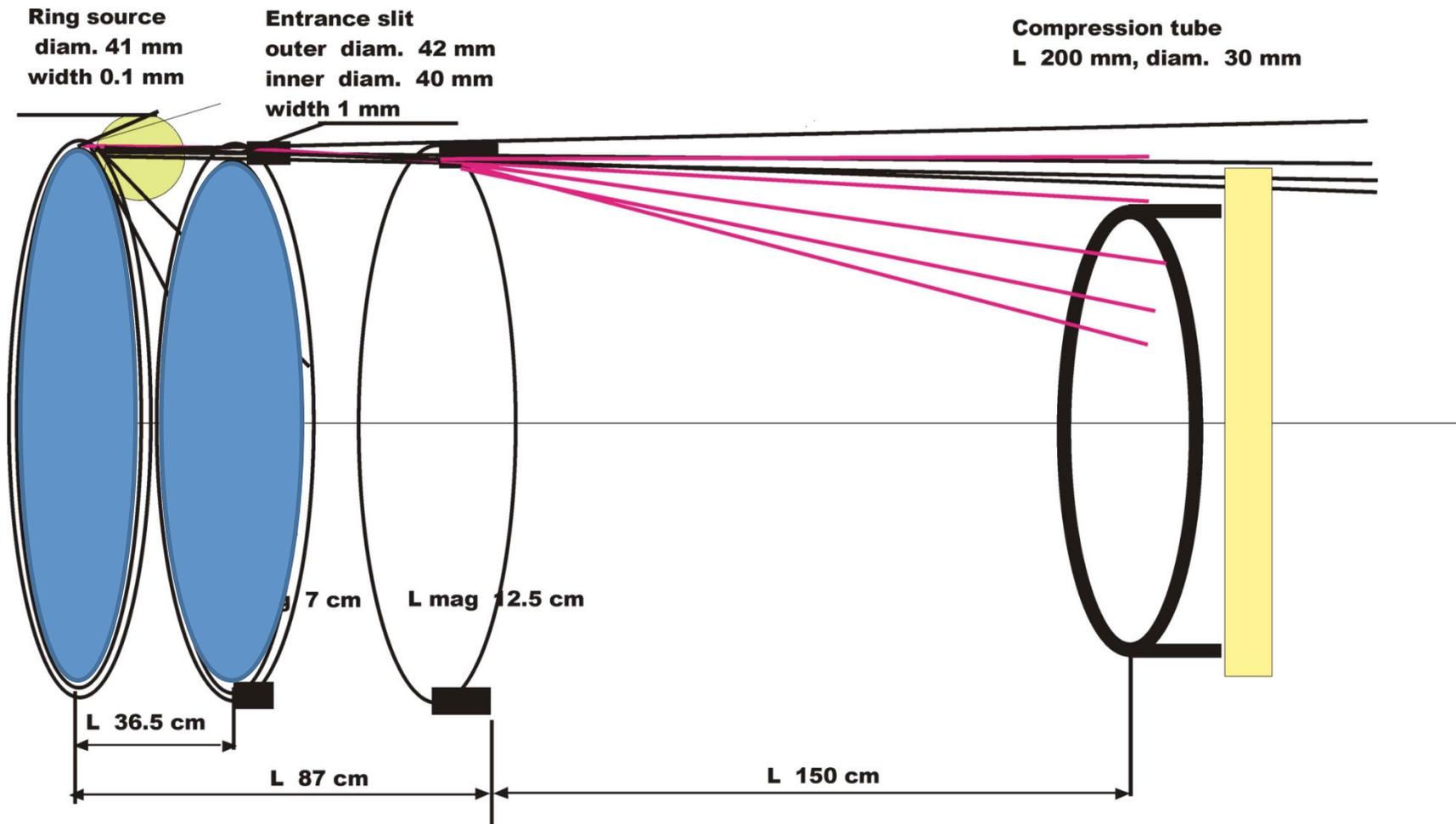
Experimental setup to obtain polarized molecules



The source of polarized hydrogen molecules at the test bench

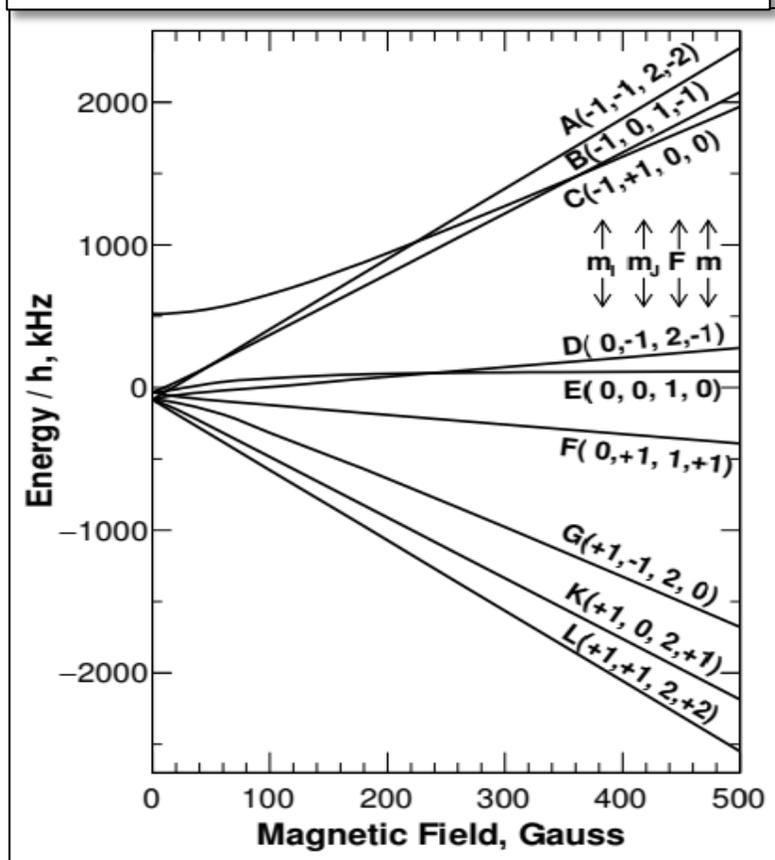


Polarized molecules source based on existing cryogenic ABS

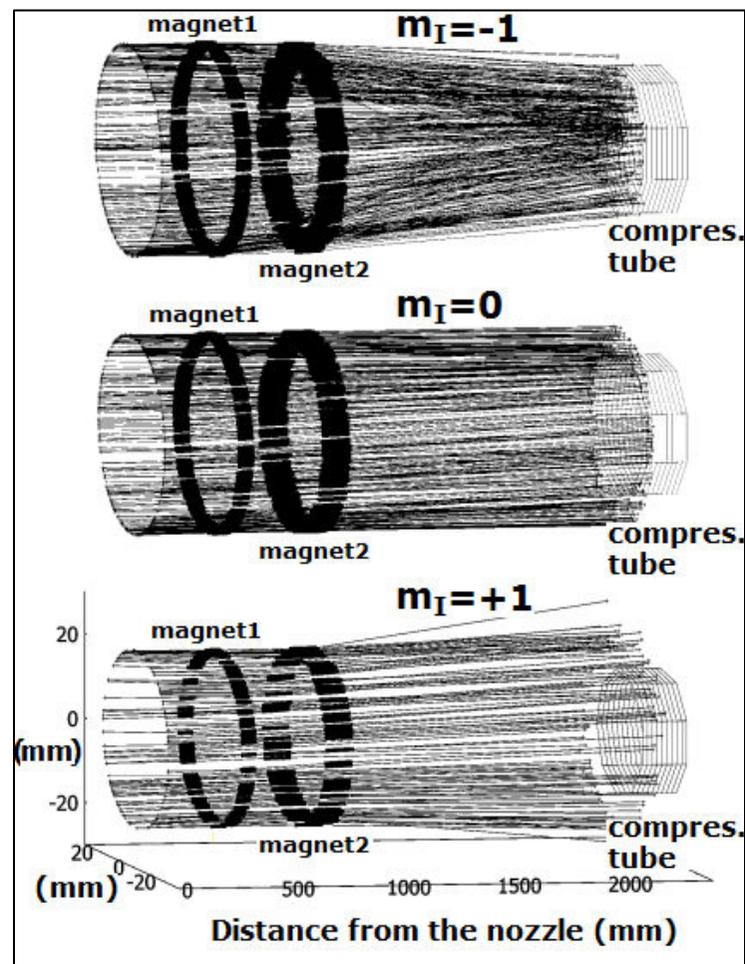


Monte Carlo simulation

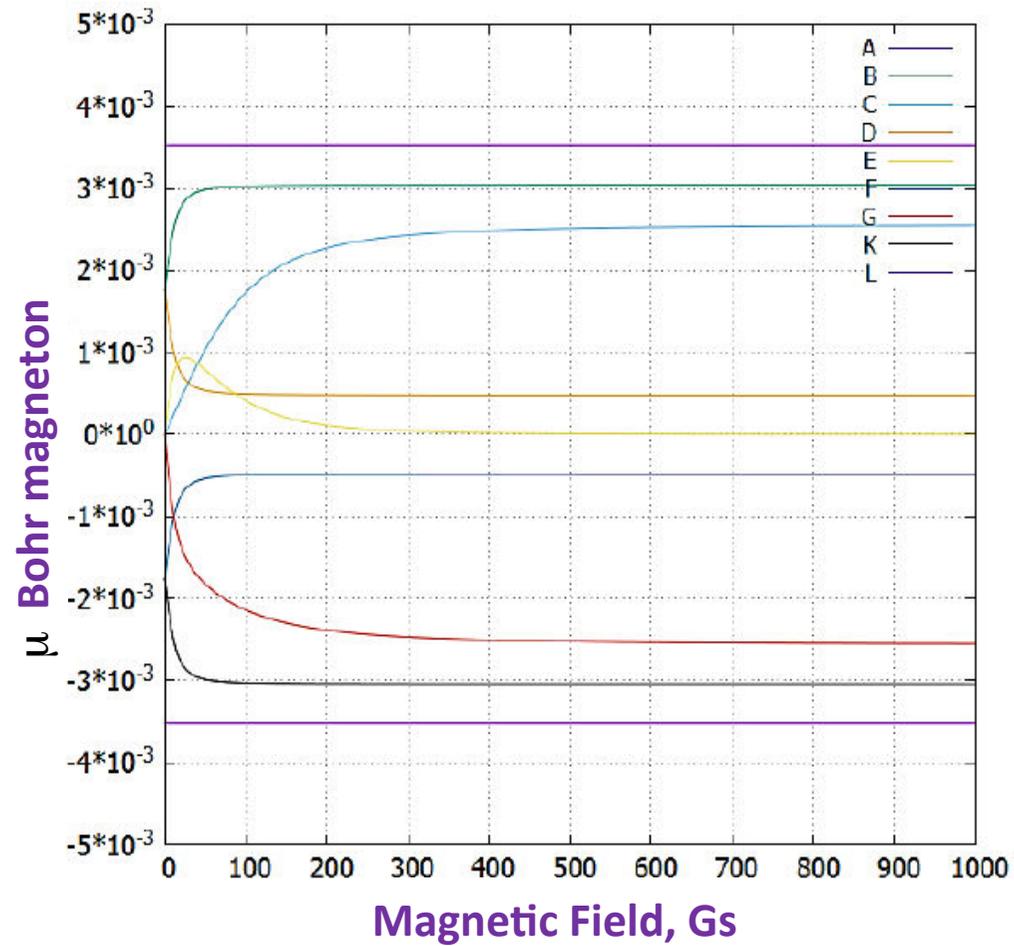
Energies of H_2 states as a function of magnetic field.



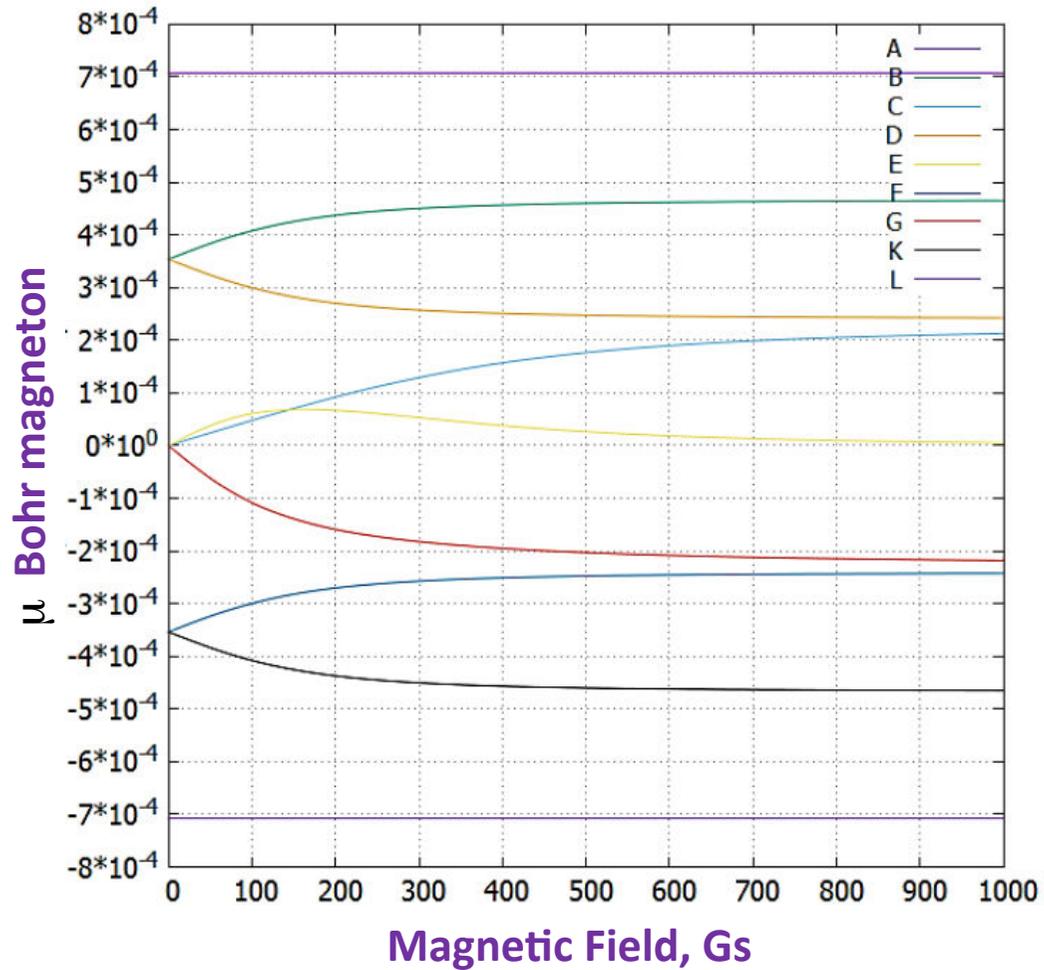
Only molecules in the states **A, B, C** with $m_I = -1$, which are focused by the field can enter the CT.



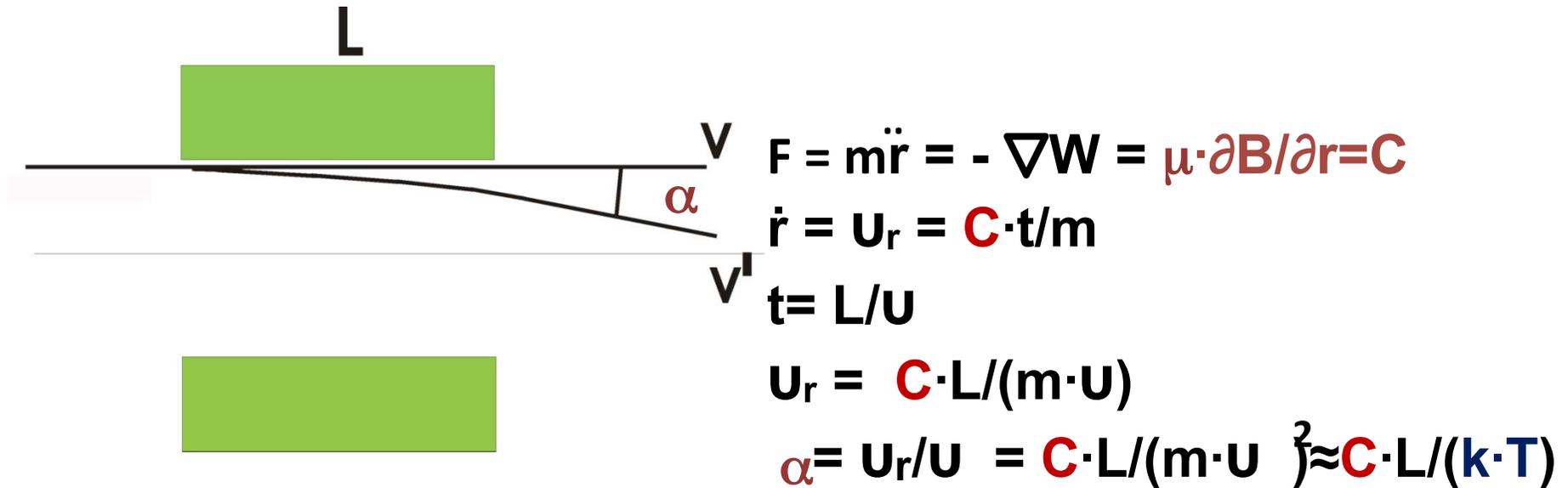
Magnetic moment of molecule H_2



Magnetic moment of molecule D_2

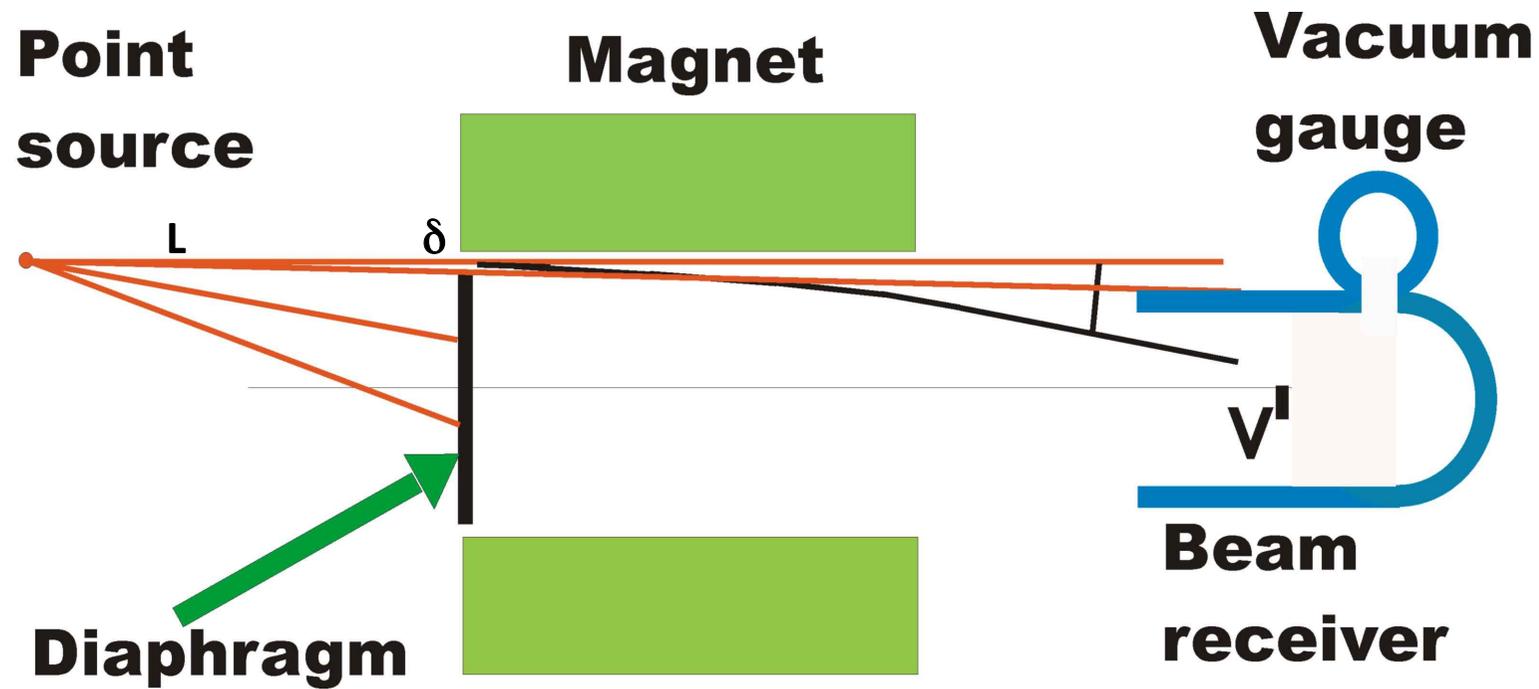


Geometry selection



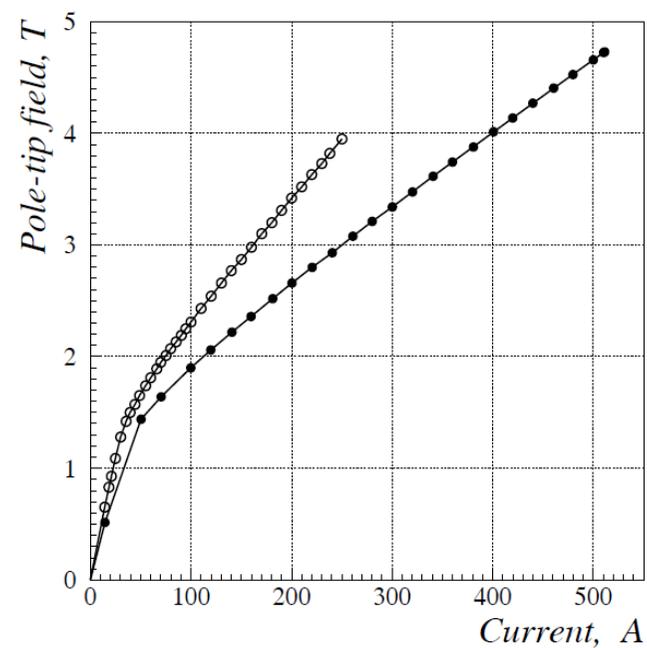
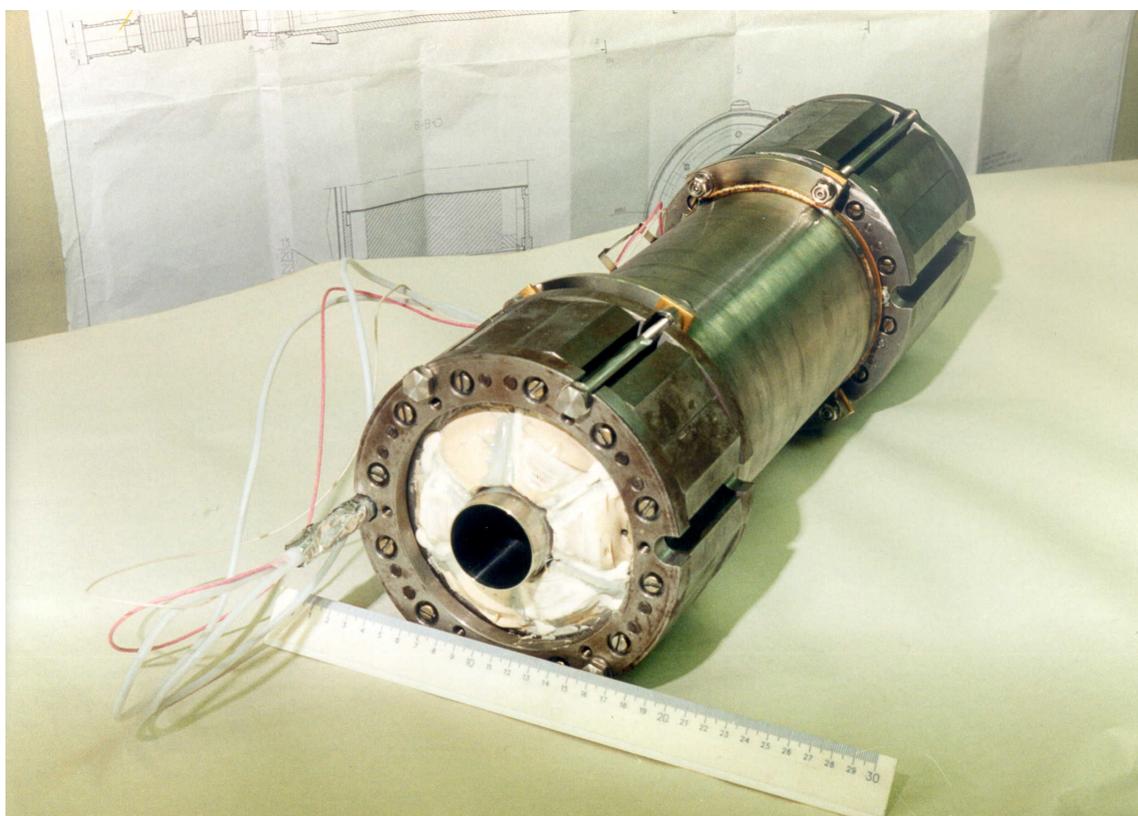
For our case $\mu = 2.5 \cdot 10^{-3} \mu_B$, $T \approx 8K$, $L = 19.5 \text{ cm}$, $\partial B / \partial r = 32 \text{ kG/cm}$,

$$\alpha = 1.3 \cdot 10^{-3} \text{ rad}$$

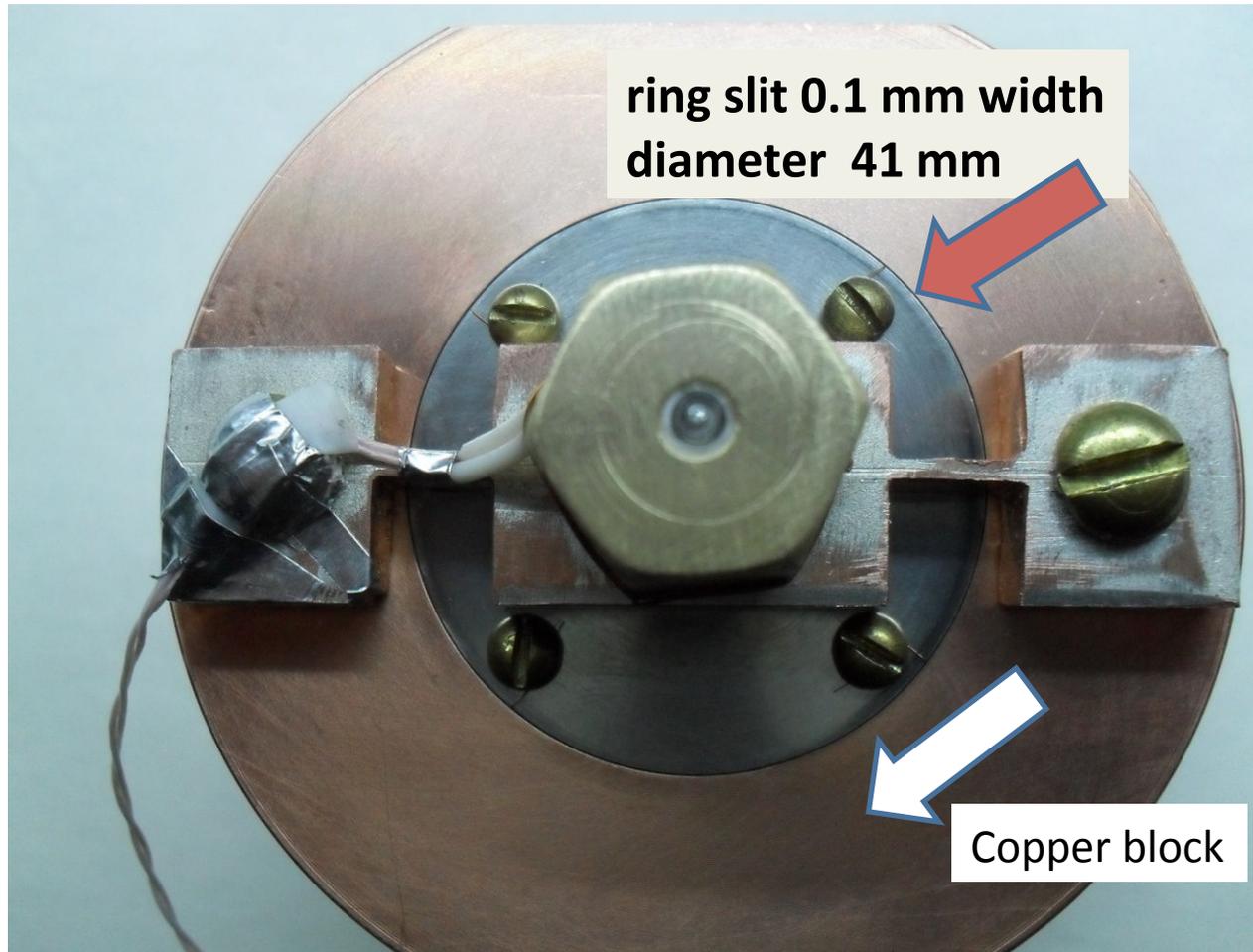


$$\alpha = \delta/L = 1/365 = 2.3 \cdot 10^{-3}$$

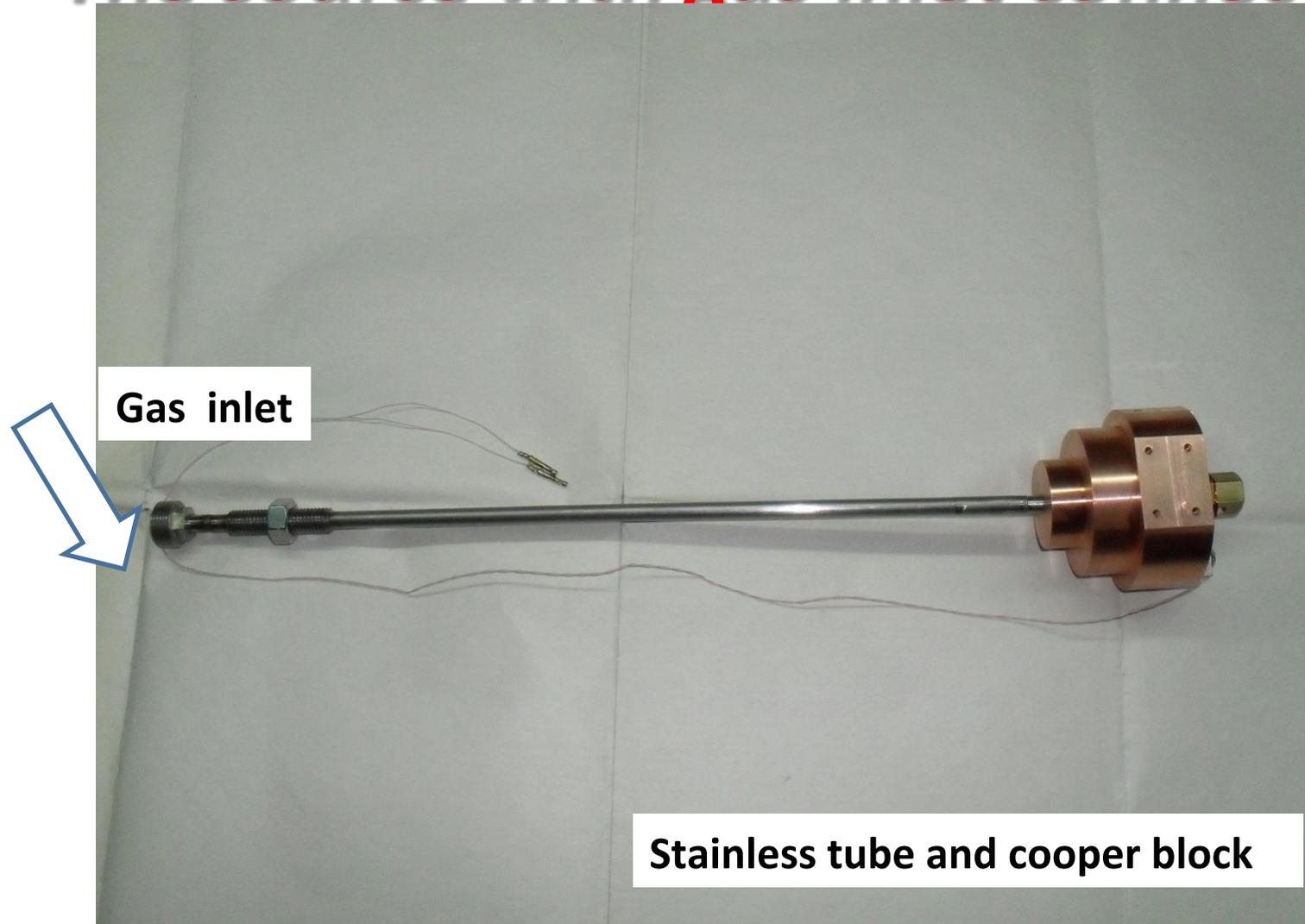
Superconducting sextupole magnets with constant aperture 42 mm inner diam. used in ABS



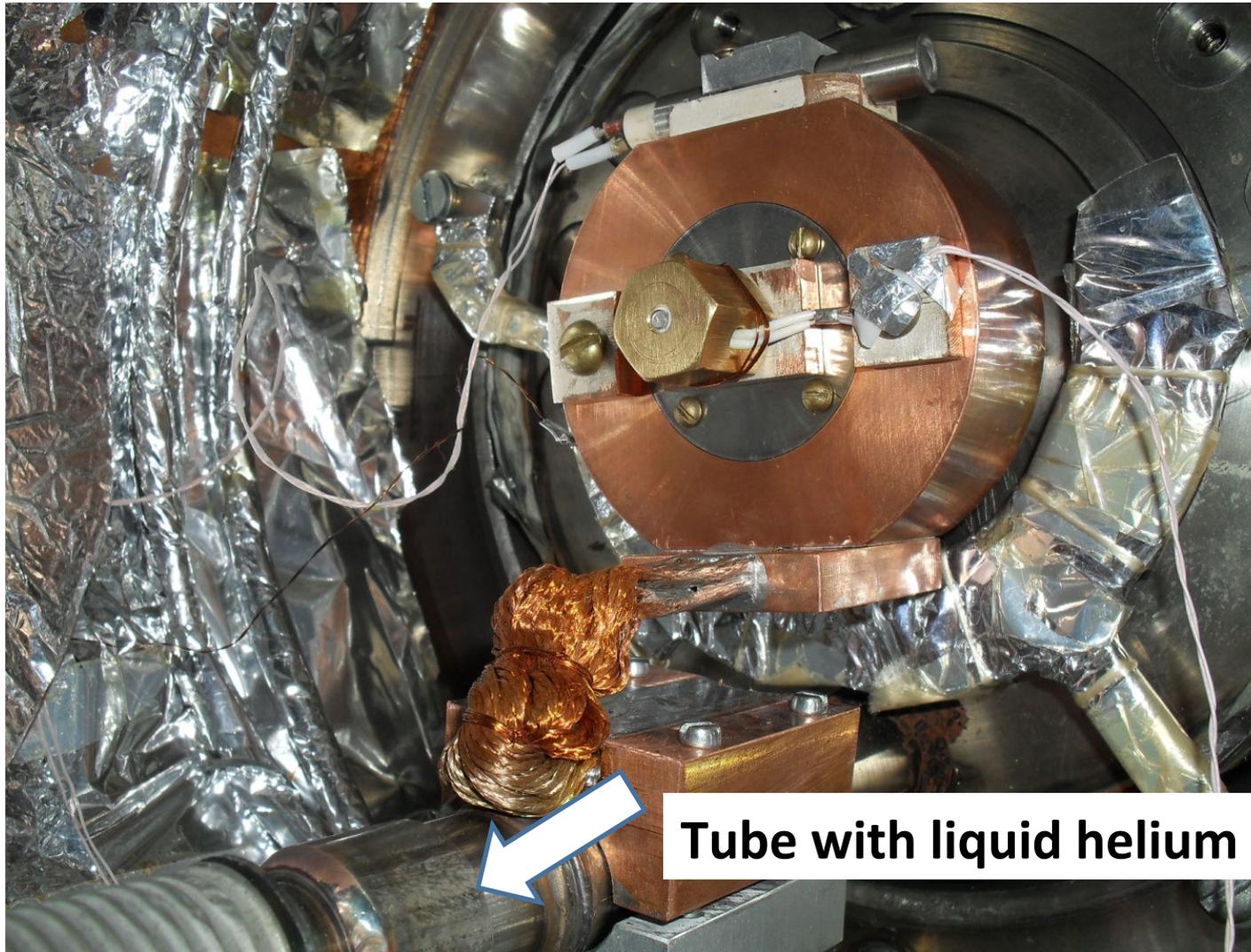
Source of cold hydrogen molecules



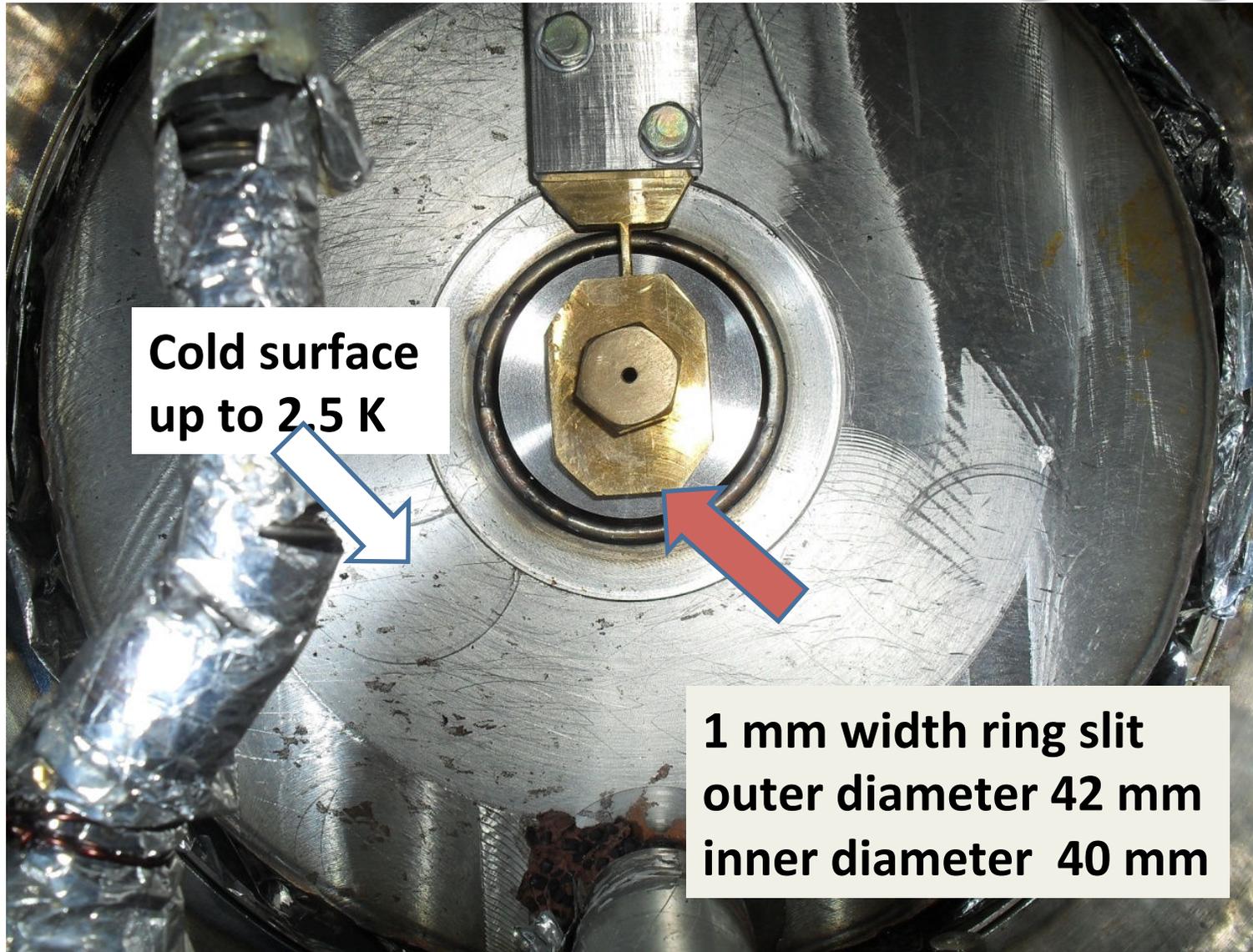
The source with gas inlet connected



Source installed inside the ABS



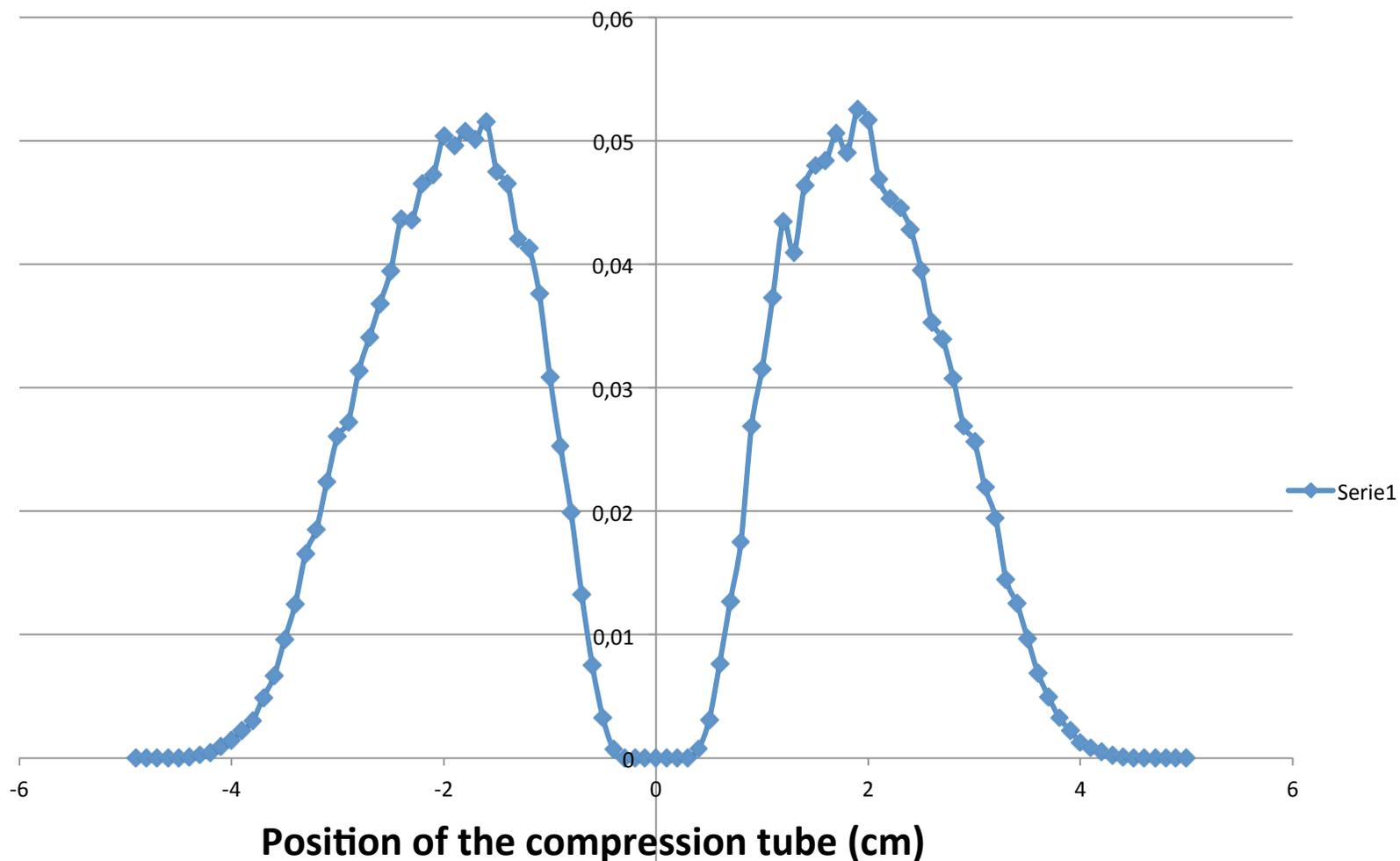
The entrance slit to a focusing magnet



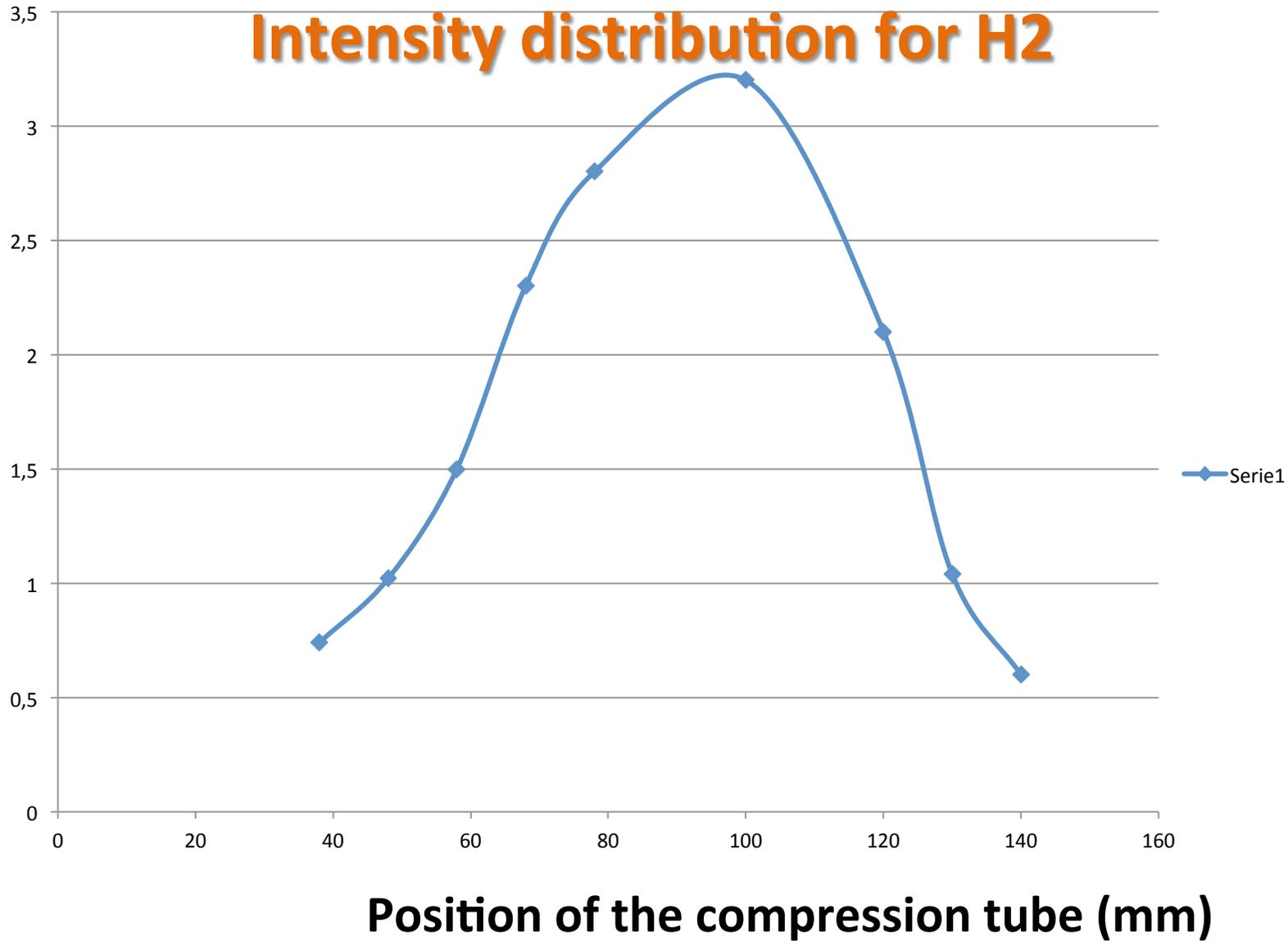
**Cold surface
up to 2.5 K**

**1 mm width ring slit
outer diameter 42 mm
inner diameter 40 mm**

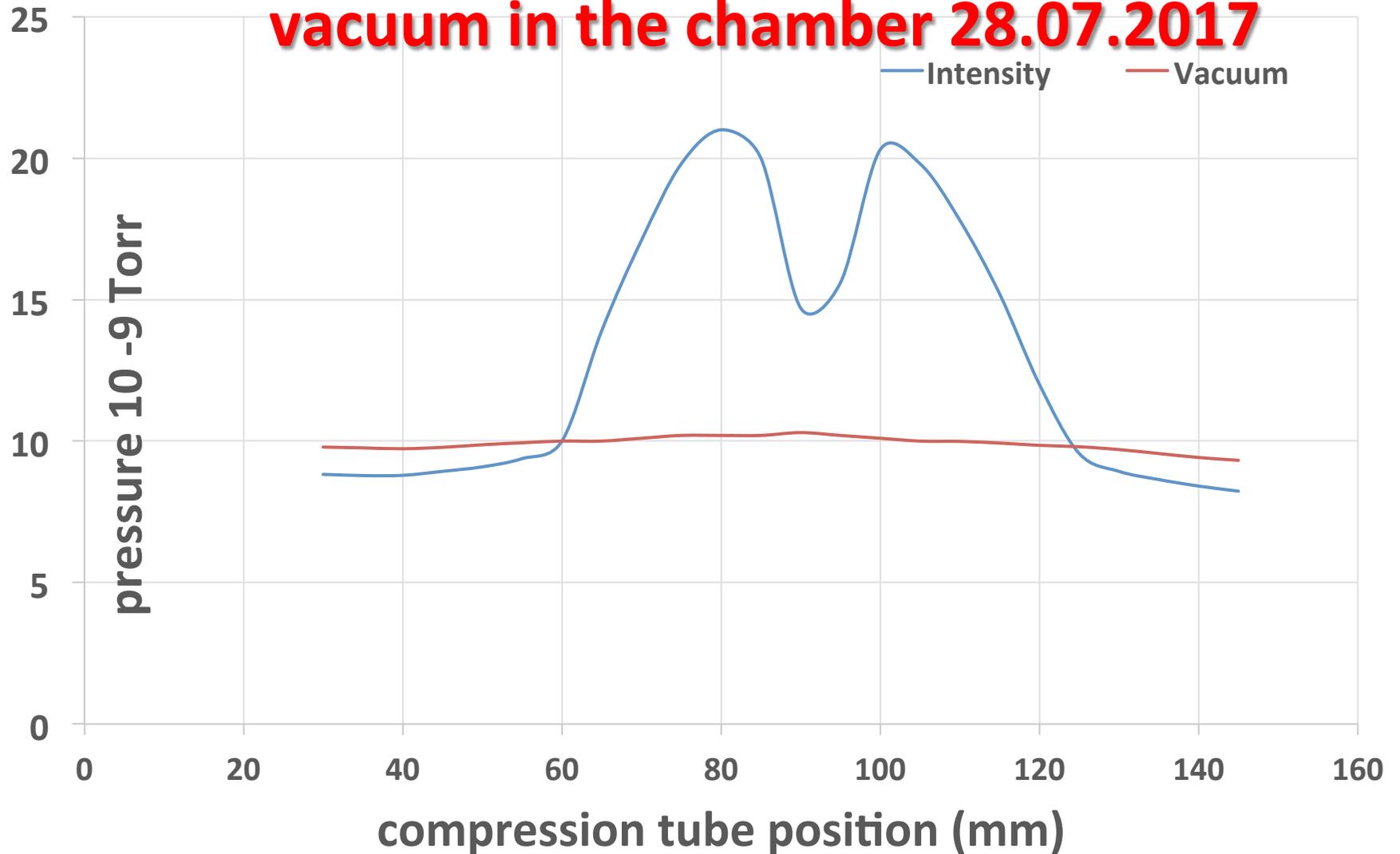
Distribution of the beam intensity at compression tube location (simulation)



No beam intensity measured by compression tube at the beam axis in the assumption that molecules touched the cold surface are pumped.

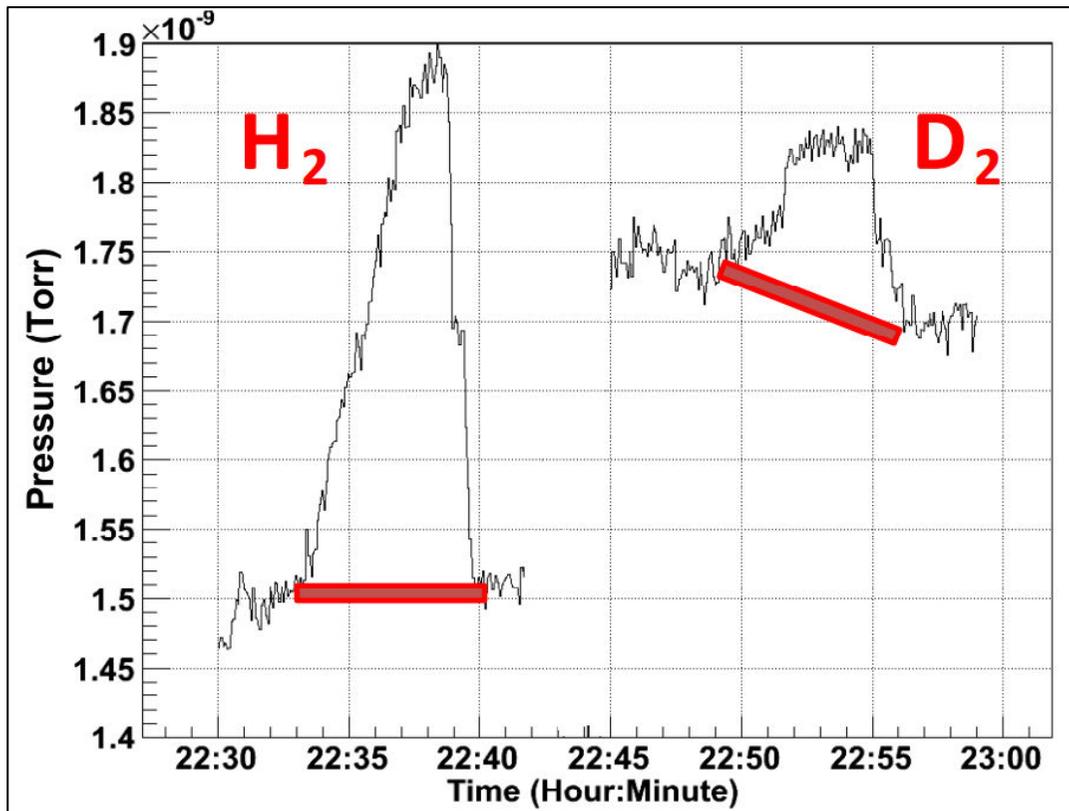


Intensity distribution of CO₂ beam and vacuum in the chamber 28.07.2017



Experimental results :: comparison of focusing efficiency H_2 and D_2

The flux of the focused deuterium molecules is lower since the magnetic moments of D_2 molecules are much smaller than those of H_2 molecules.

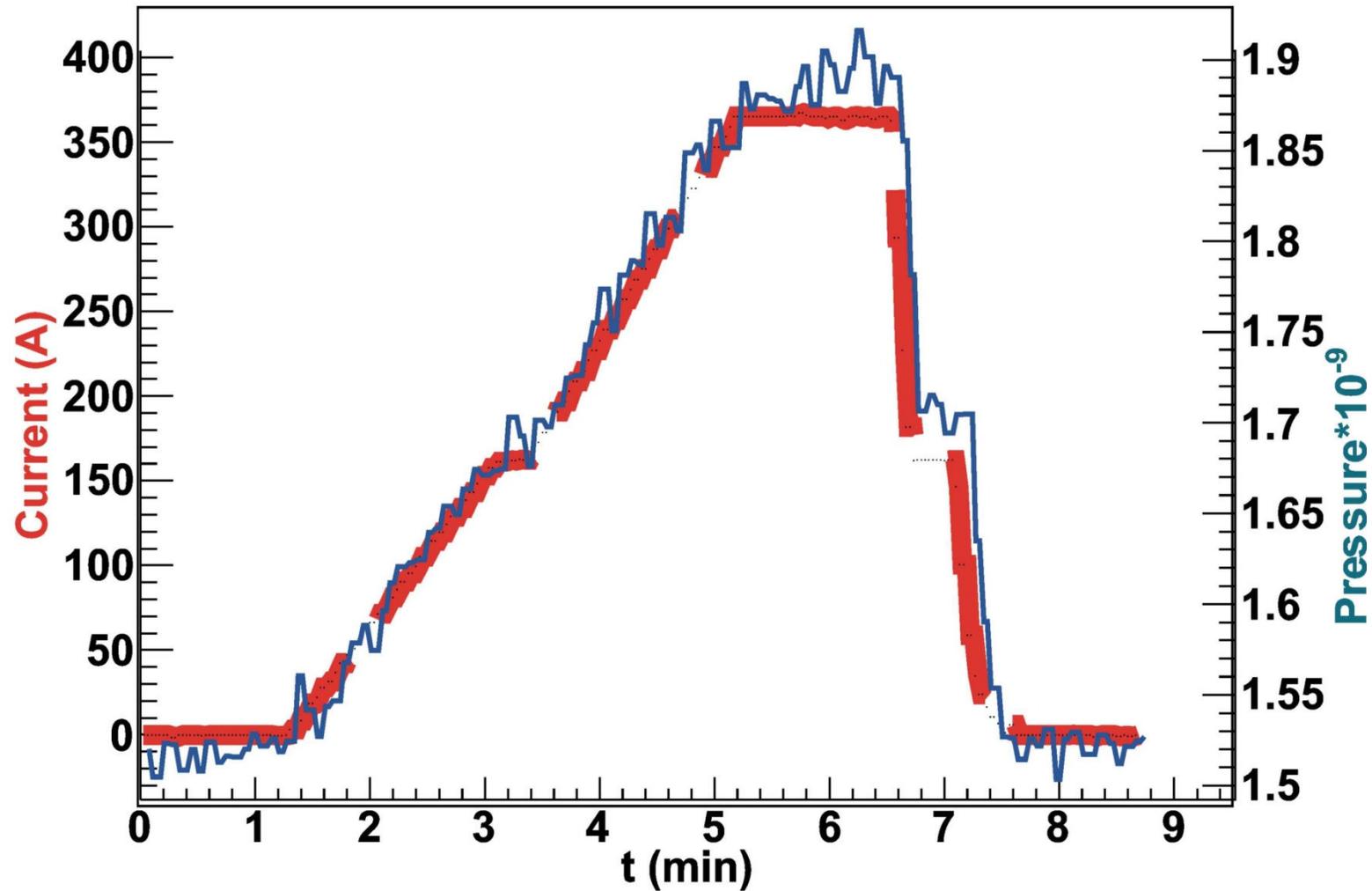


**Magnetic moment of H_2
is $2.5 \cdot 10^{-3} \mu_B$**

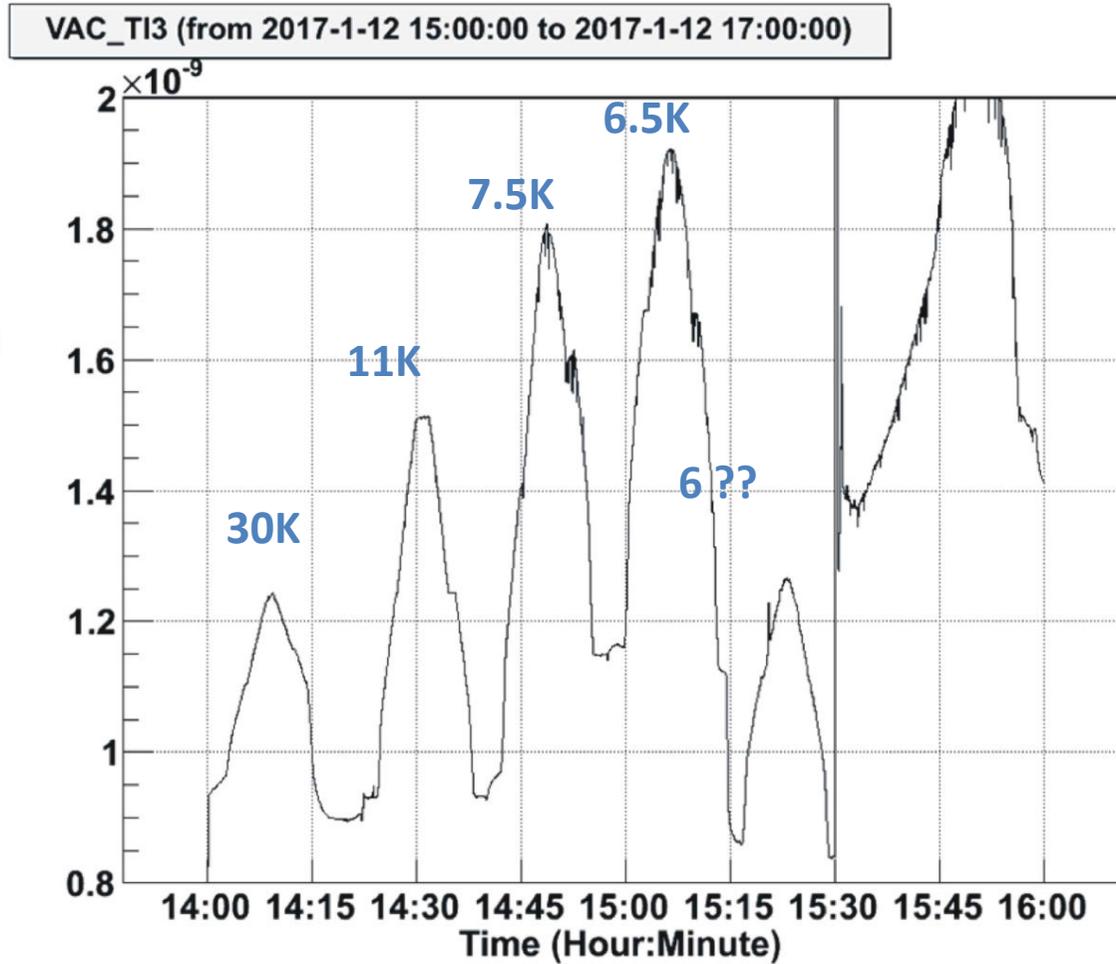
**Magnetic moment of D_2
is $6.5 \cdot 10^{-4} \mu_B$**

The measured flux of polarized deuterium molecules is about 5 times smaller than the flux of hydrogen molecules. The geometry of the source was not optimized to get the highest flow of D_2 .

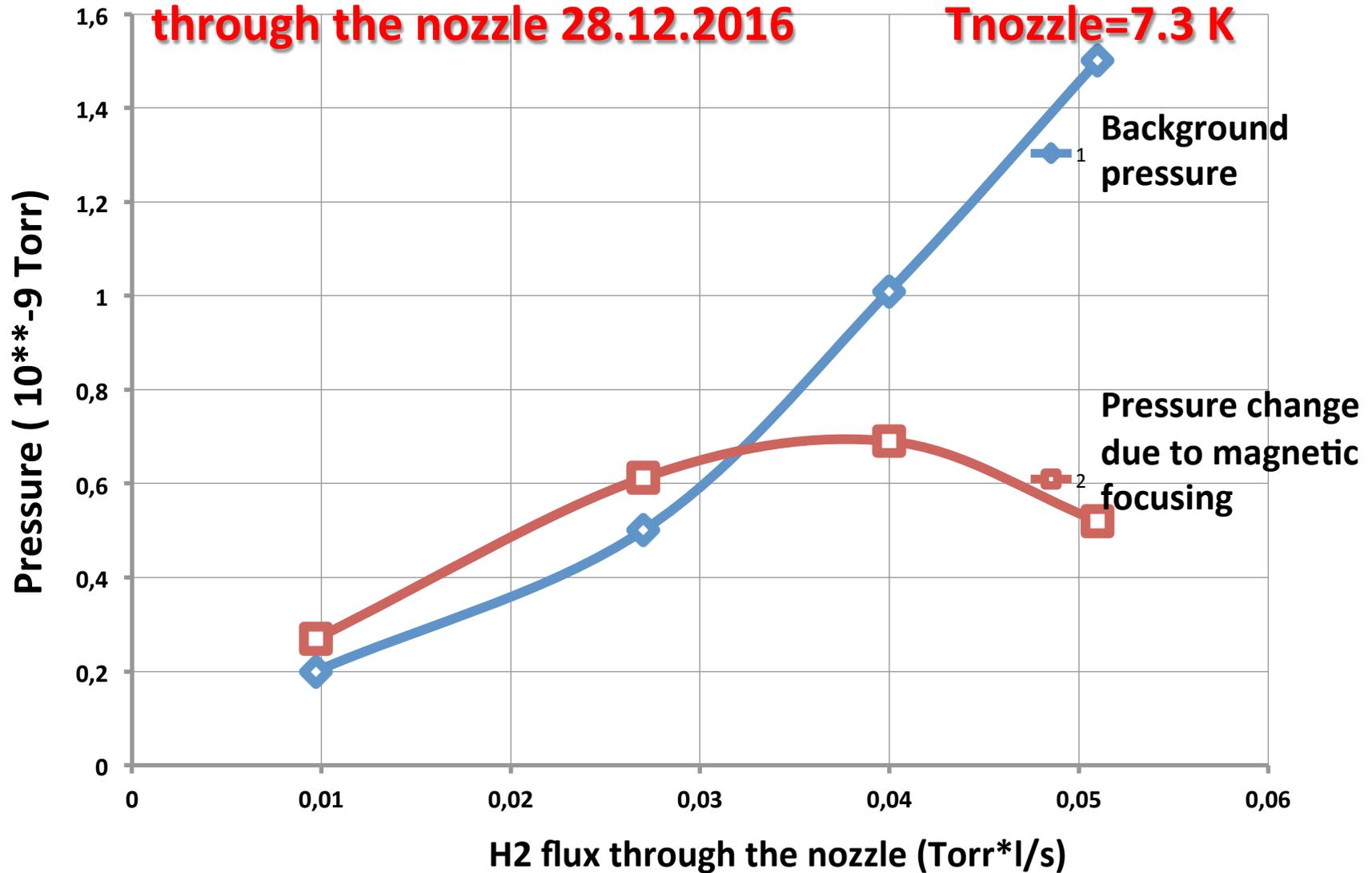
Correlation between the magnetic field and the intensity of the focused beam

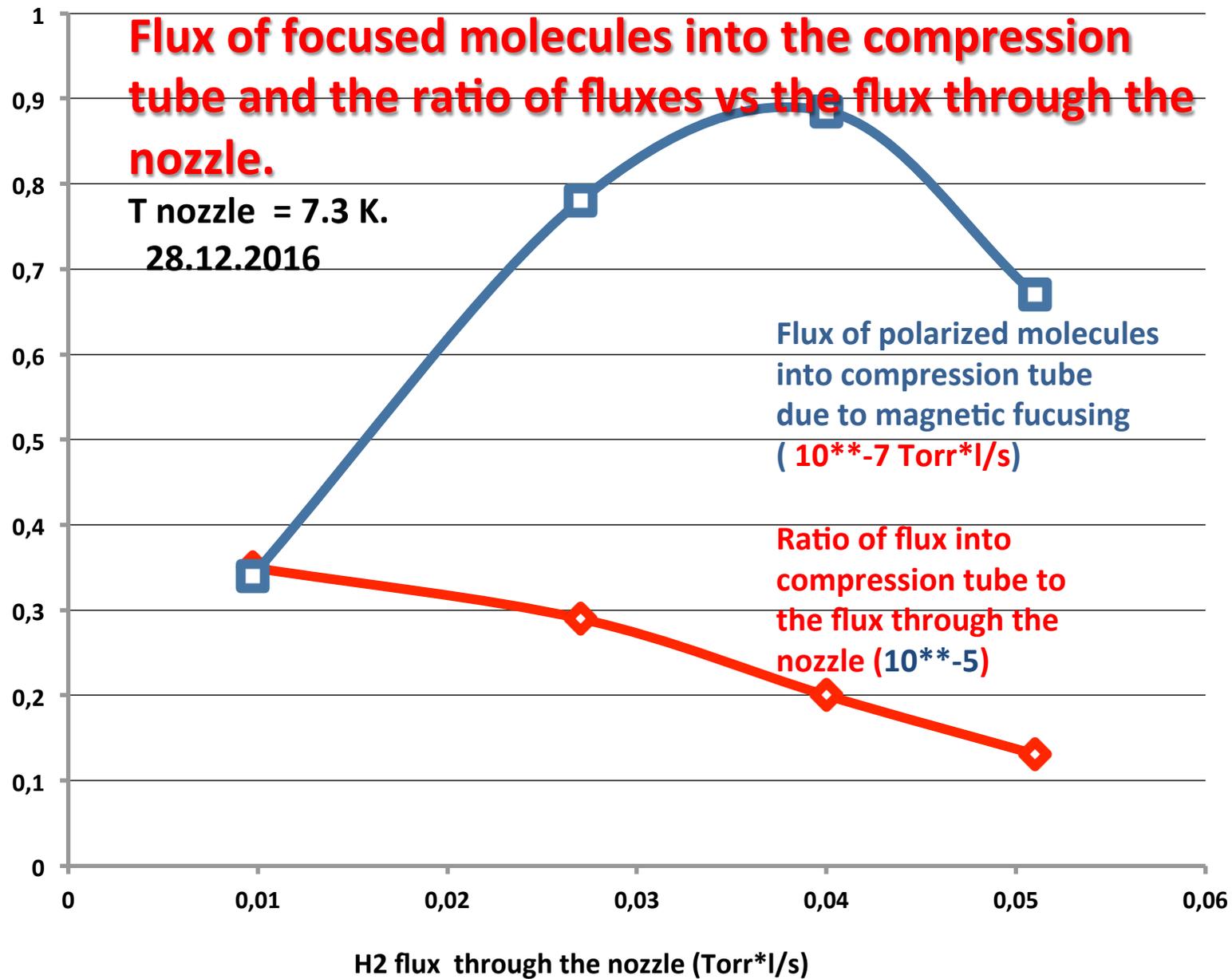


Intensity of the H2 beam while ramping the magnet for different nozzle temperature (computer screen)



Background pressure in compression tube and pressure change due to magnetic field vs the flux through the nozzle 28.12.2016





Monte Carlo simulation

Maxwell–Boltzmann velocity distribution at 8 K for hydrogen

$\cos(\theta)$ intensity distribution from the source

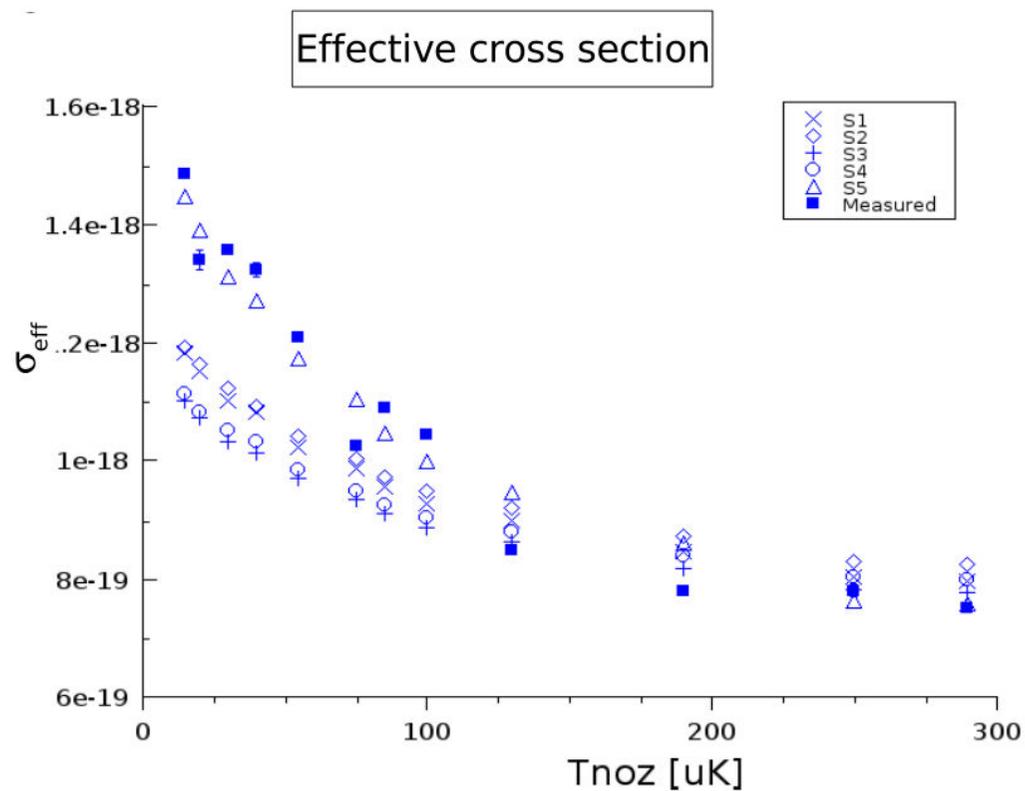
Flux of focused molecules into the compression tube

$$Q_{\text{comp. tube}} = 2.1 * 10^{-6} Q_{\text{nozzle}}$$

Experiment (comp. tube in a center position)

$$Q_{\text{comp. tube}} = (3 - 1) * 10^{-6} Q_{\text{nozzle}}$$

Comparison between experimental data and calculations



Luca Barion
Istituto Nazionale di Fisica Nucleare

RestGas attenuation measurements 10

Estimation of the attenuation

The intensity of the beam in the forward direction with an attenuation taken into account may be written as

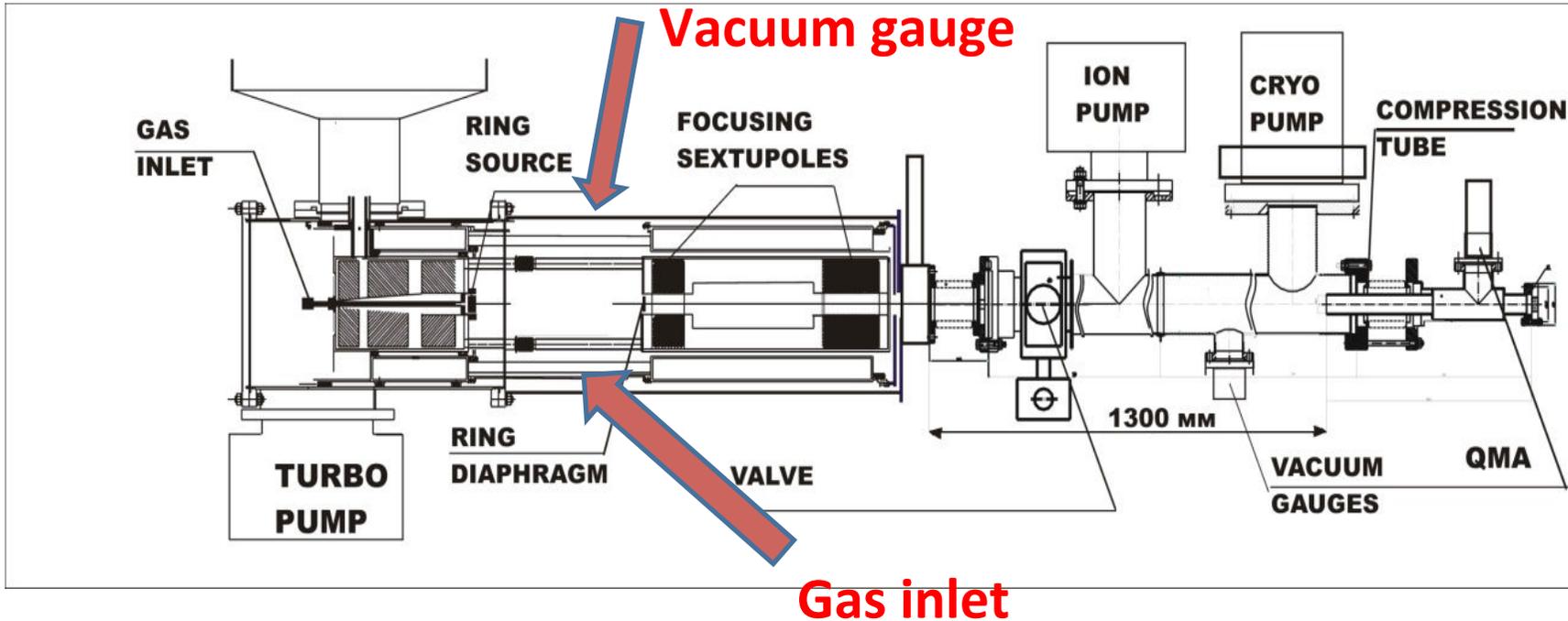
$$dI(0) / d\Omega = k \cdot S \pi \cdot \sigma \cdot L \cdot X \cdot \exp(-X),$$

where $X = n \cdot \sigma \cdot L = Q_0 / S \cdot \sigma \cdot L$ is dimensionless quantity. The pumping speed of hydrogen on cold cryosurfaces (area is about of 400 cm²) in this region may be estimated as $\approx 6 \cdot 10^{**6}$ cm³/s.

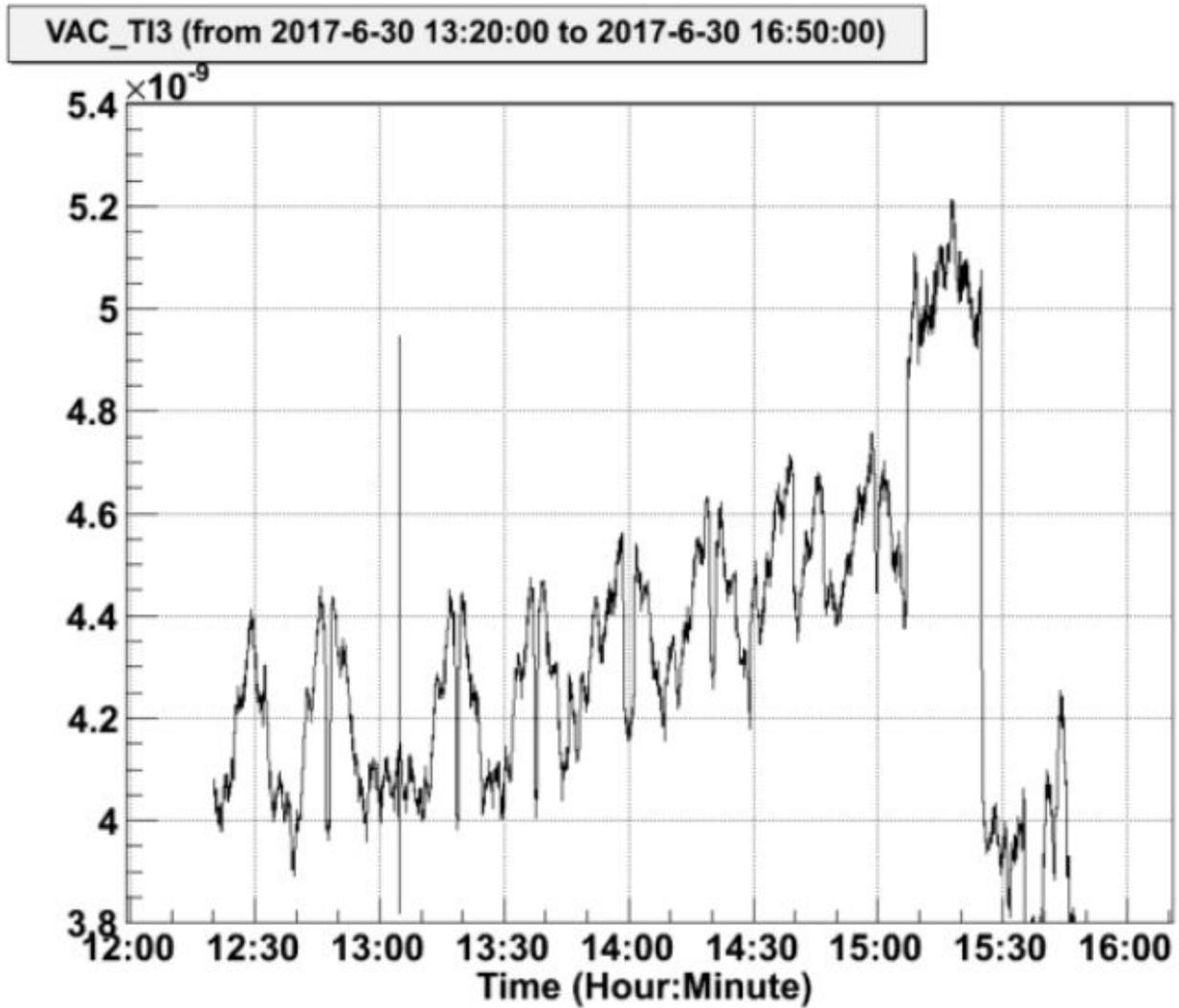
$\sigma = 1.5 \cdot 10^{-14}$ cm² for 80 K molecular beam and we can get $Q_{\max} \approx 10^{**19}$ mol/s ≈ 0.3 Torr·l/s.

We have to put $\sigma = 1.5 \cdot 10^{-13}$ cm²

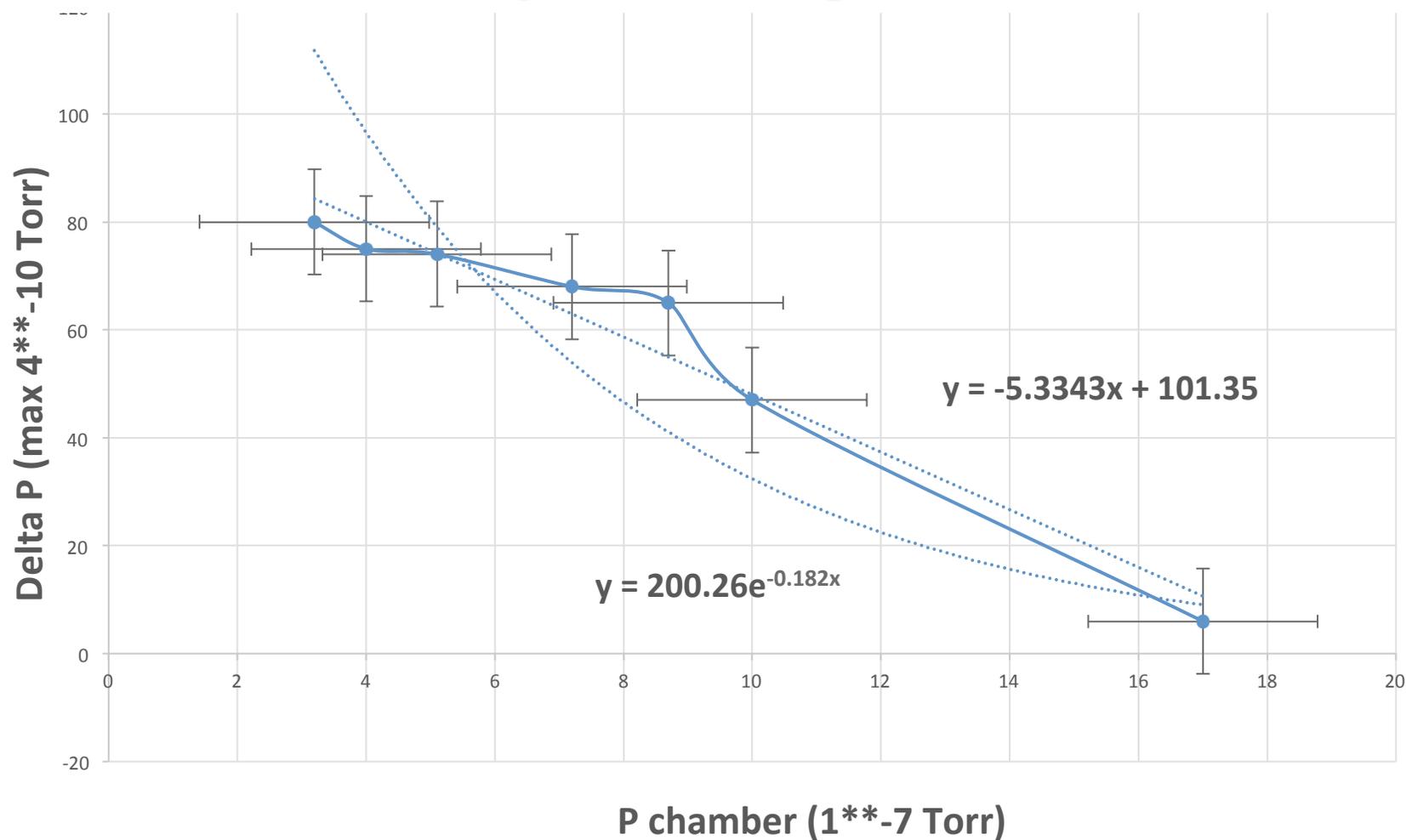
Experimental setup to obtain polarized molecules



Attenuation of polarized orthohydrogen beam by residual gas (computer screen)



Attenuation of polarized orthohydrogen beam by residual gas

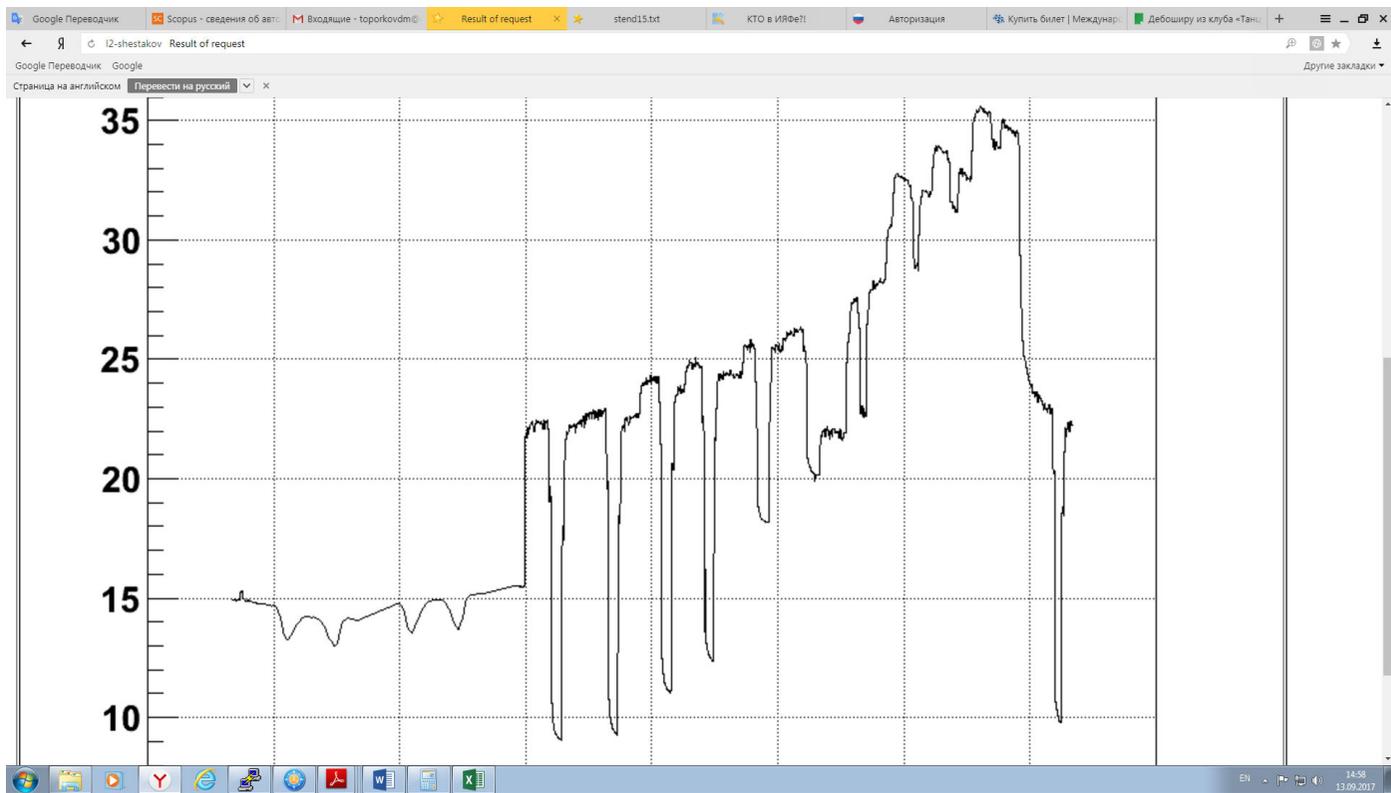


Cross section estimation

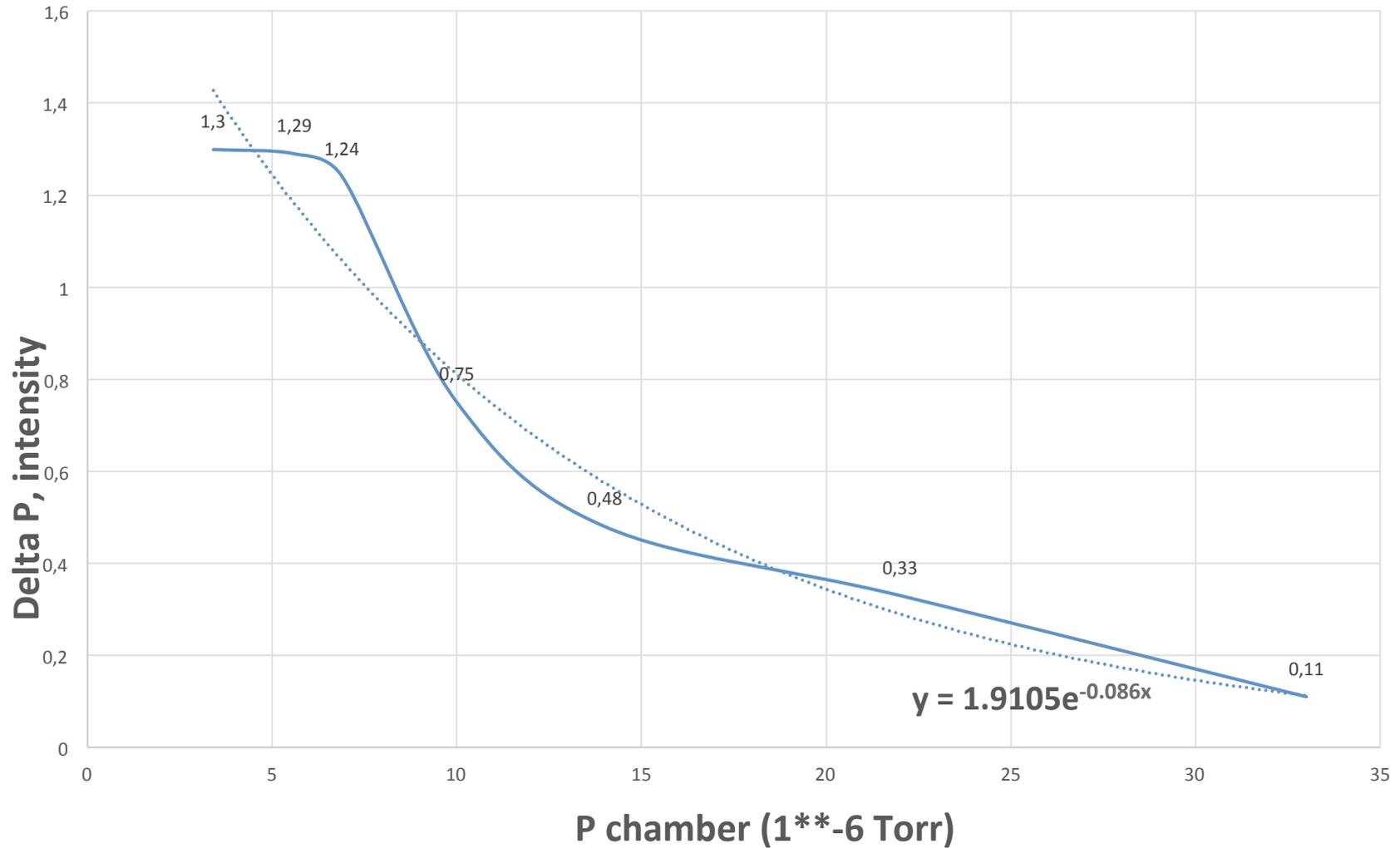
$$L \cdot n \cdot \text{Sigma} = 33 \cdot 3.2 \cdot 10^{16} \cdot 2.5 \cdot 10^{-7} \cdot \text{Sigma} \cdot X = 0.182 \cdot X$$

Assuming $T_1 = 30\text{K}$ $\text{Sigma} = 2.2 \cdot 10^{-13} \text{ cm}^2$

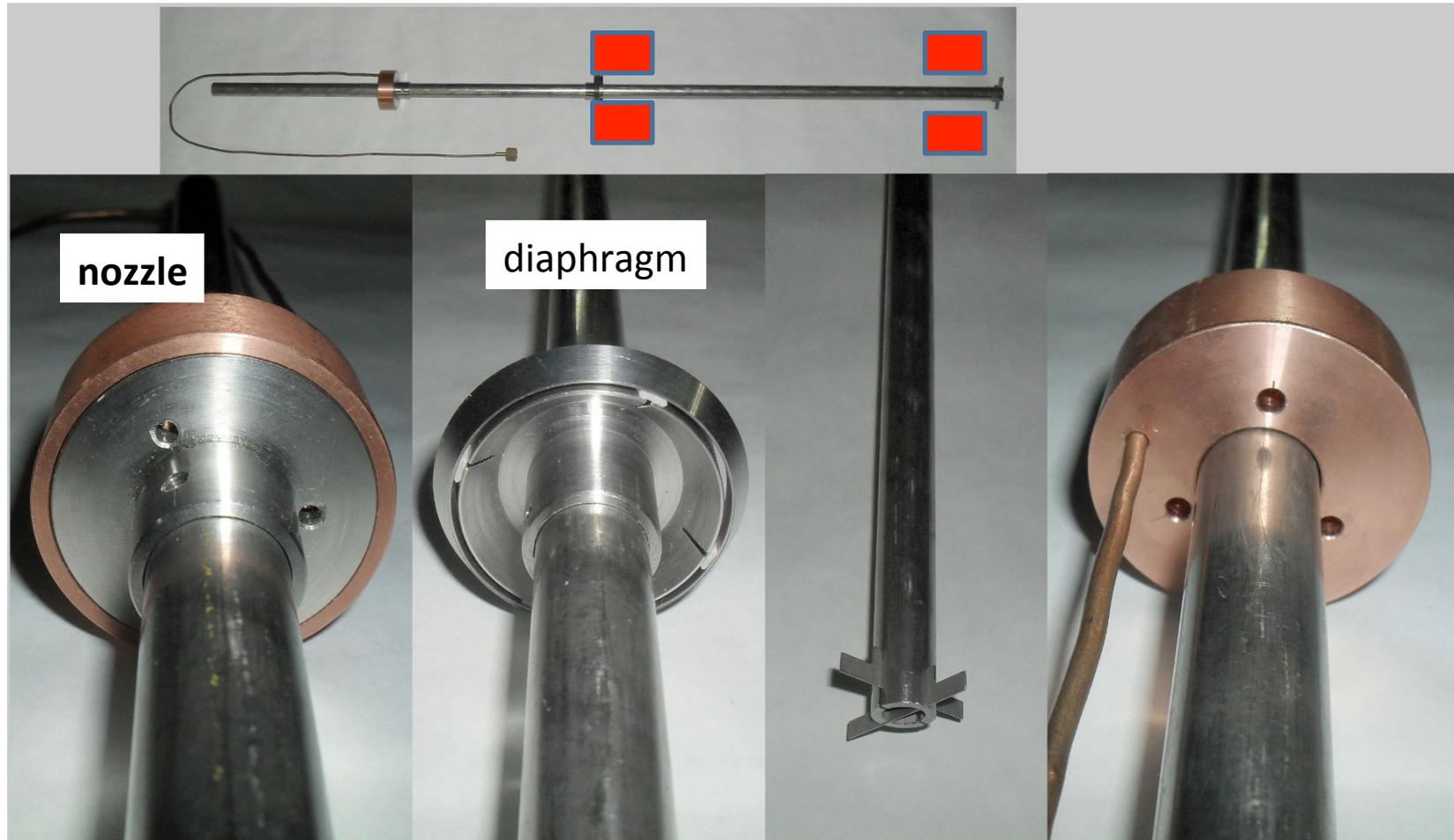
similar to estimation before!!!



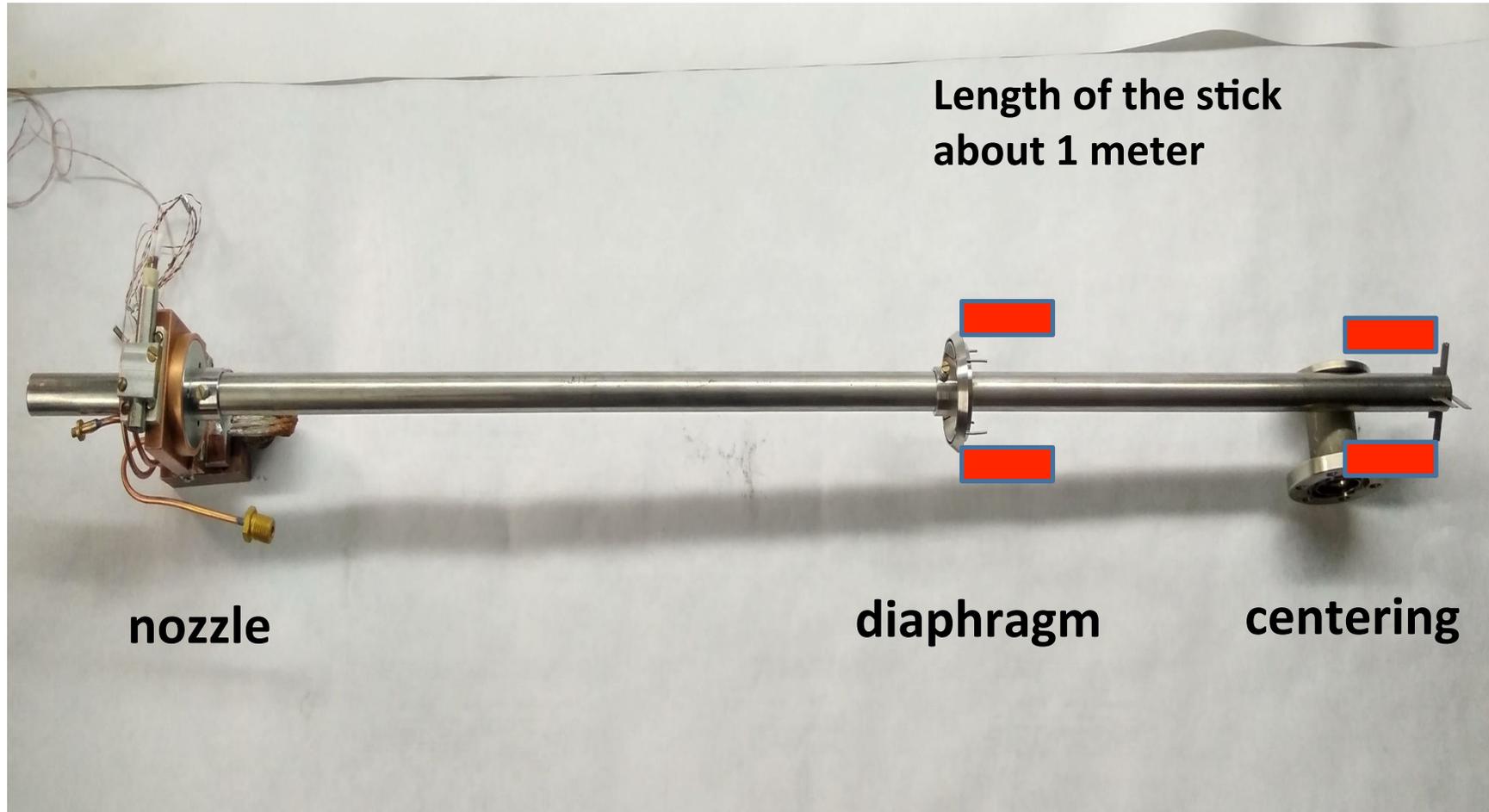
Attenuation of CO2 beam 28.07.2017



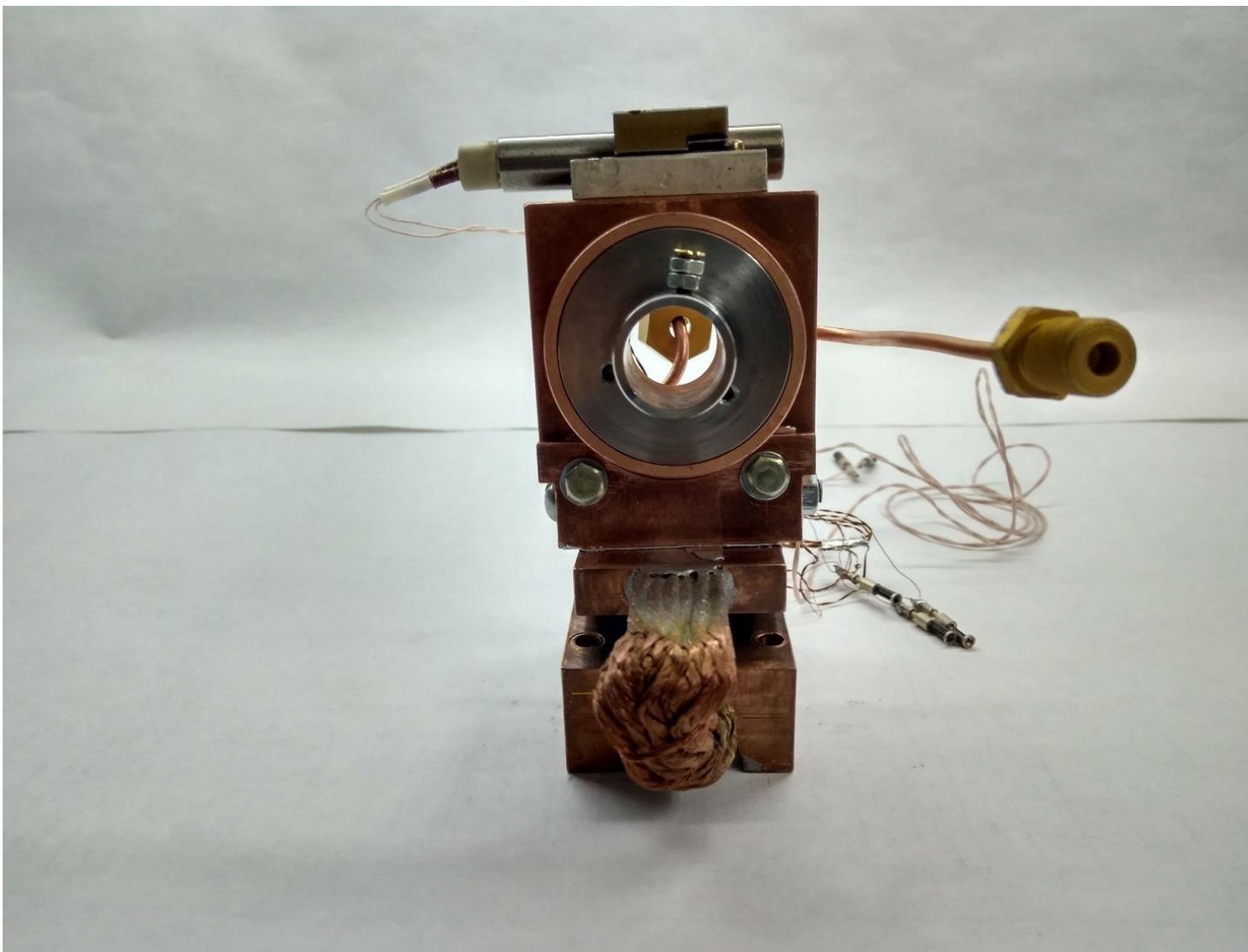
New system for the nozzle and diaphragm installation



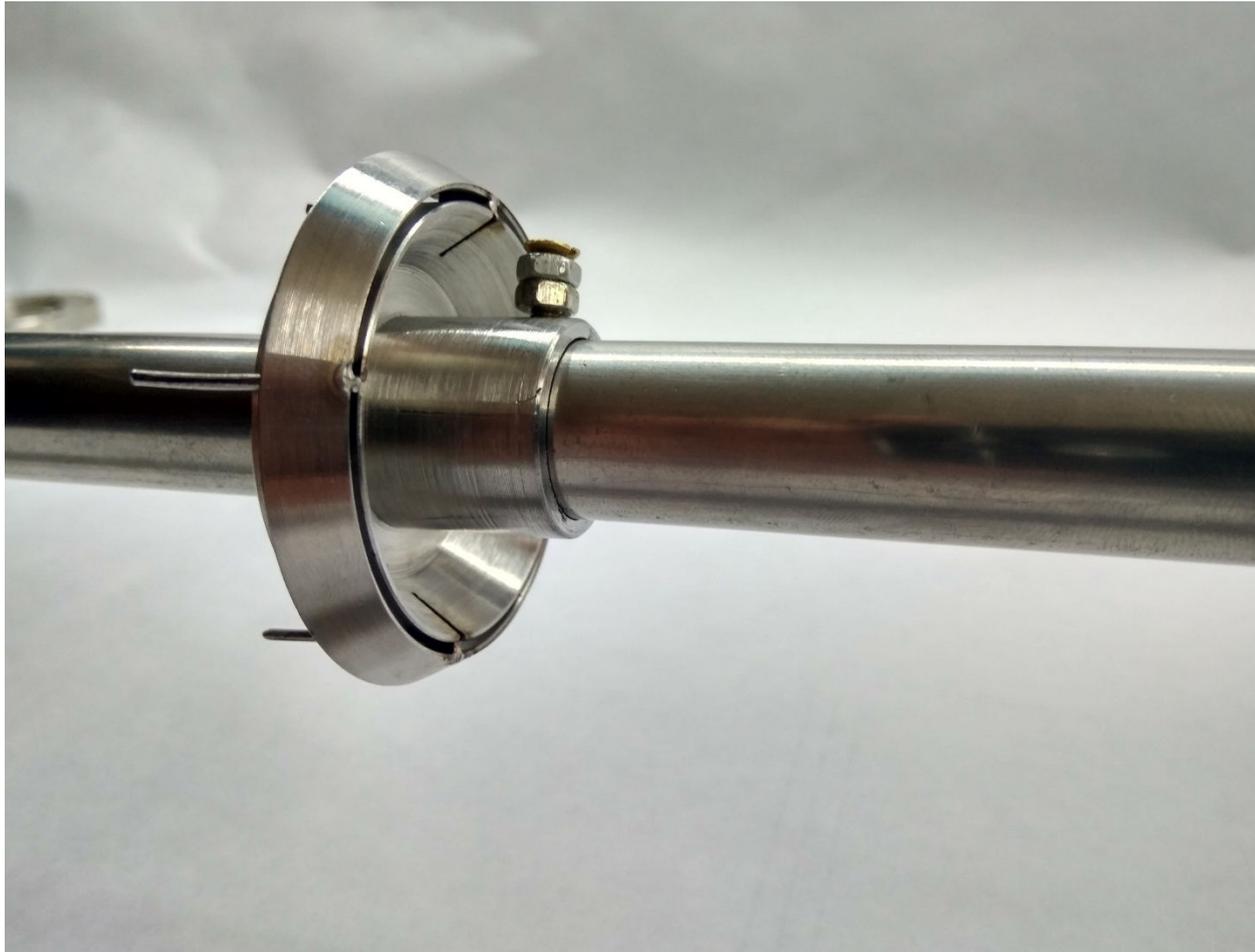
Alignment of the elements



NOZZLE



DIAPHRAGM



CENTERING

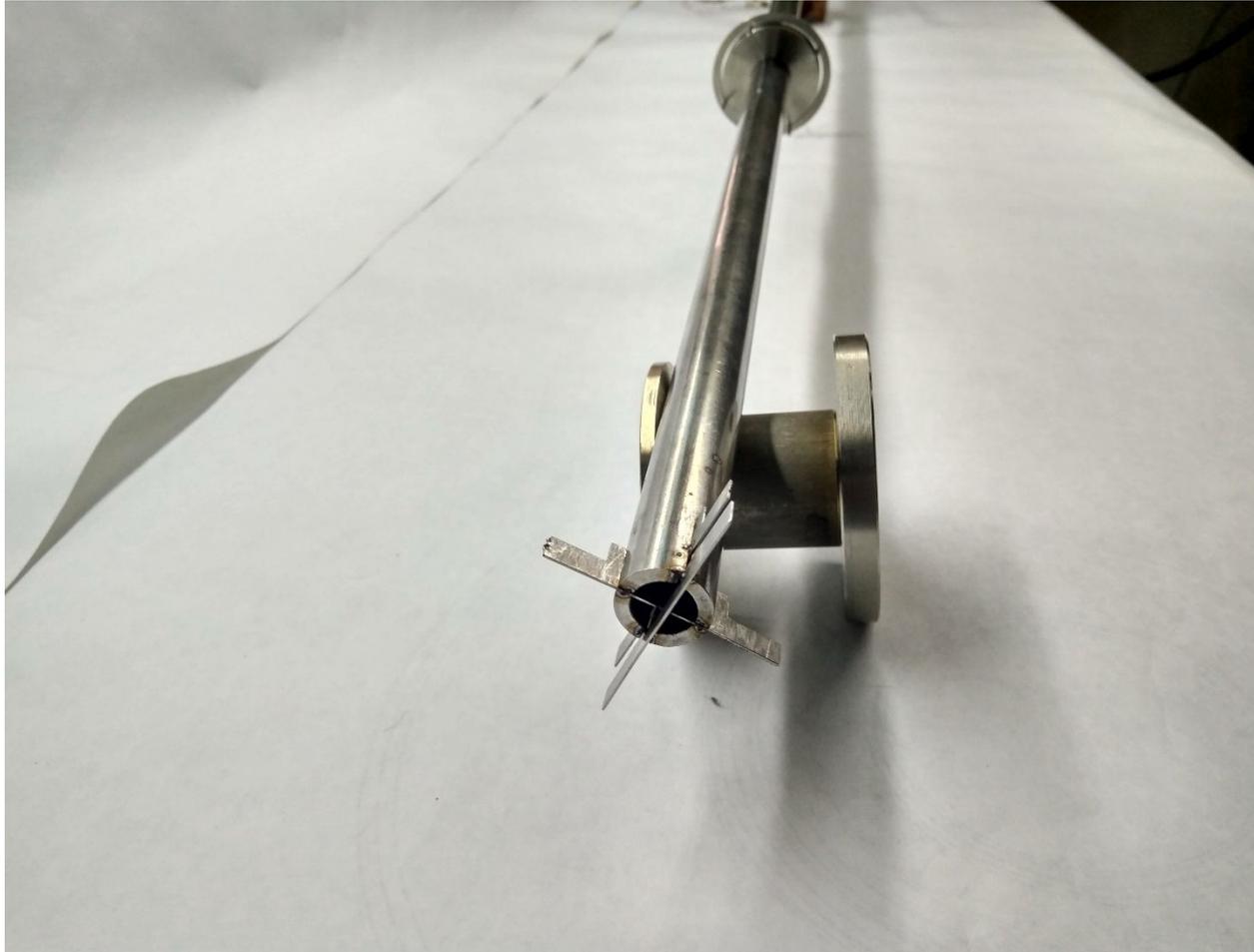
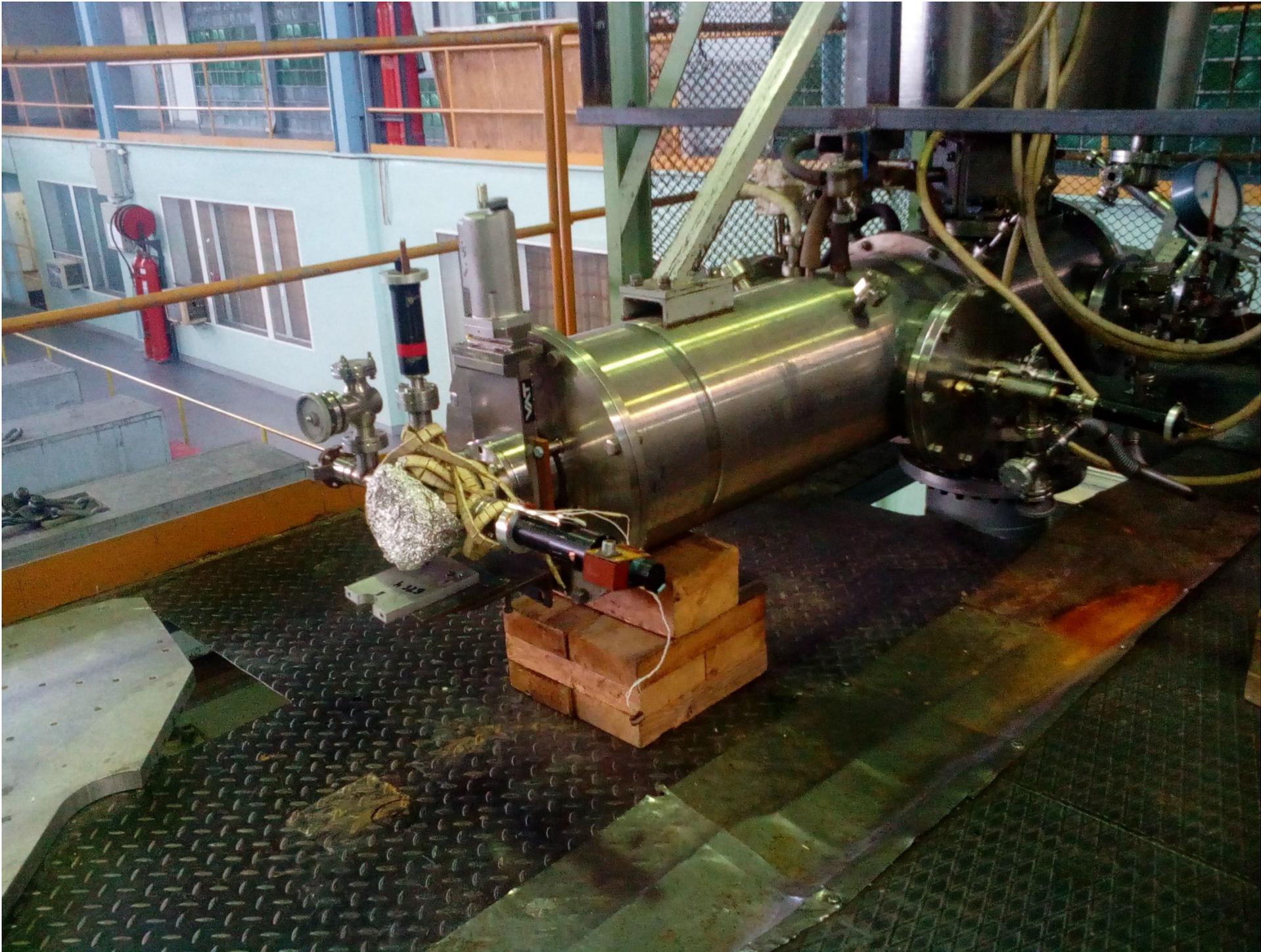
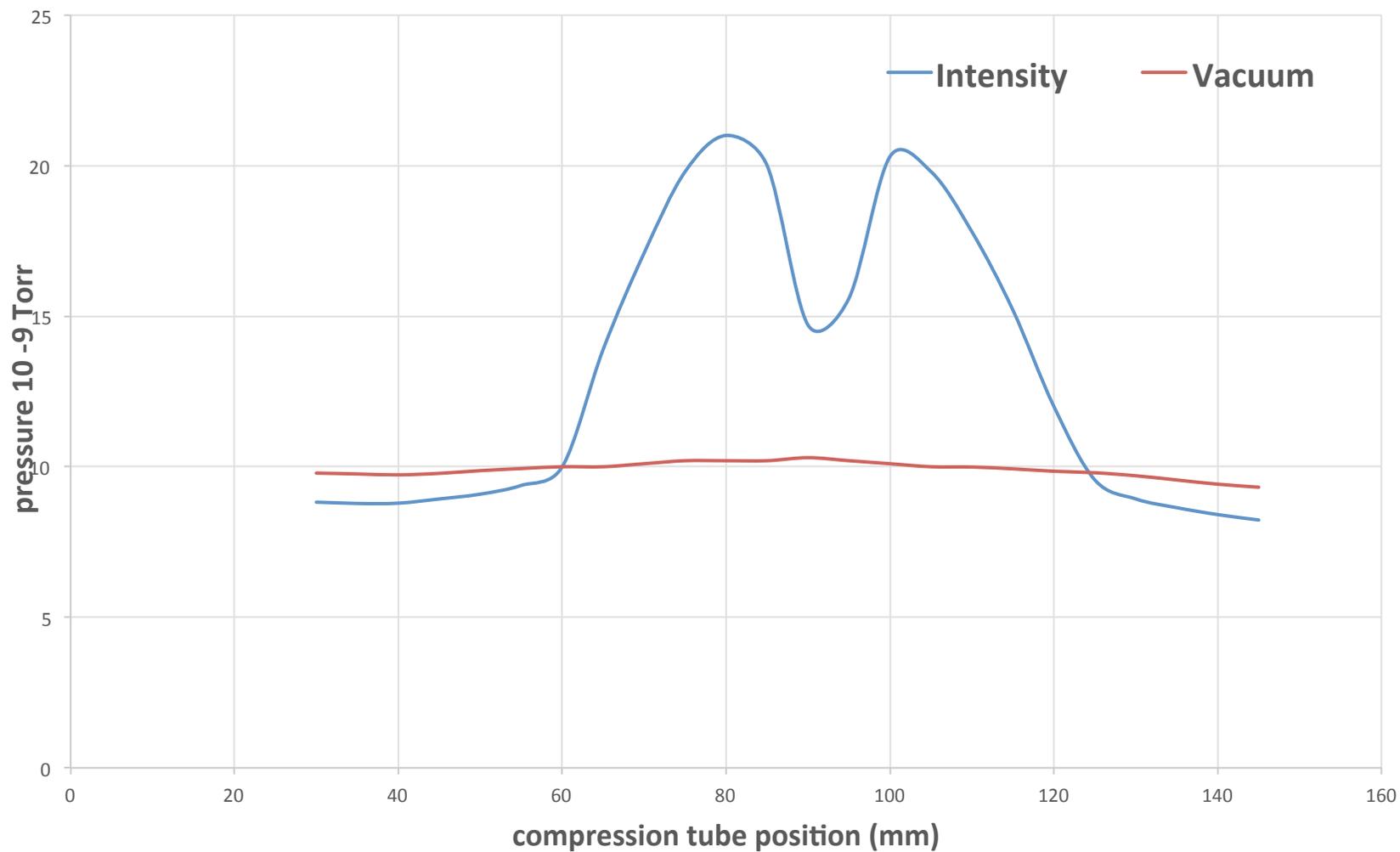


Photo of the nozzle from the exit of the magnet





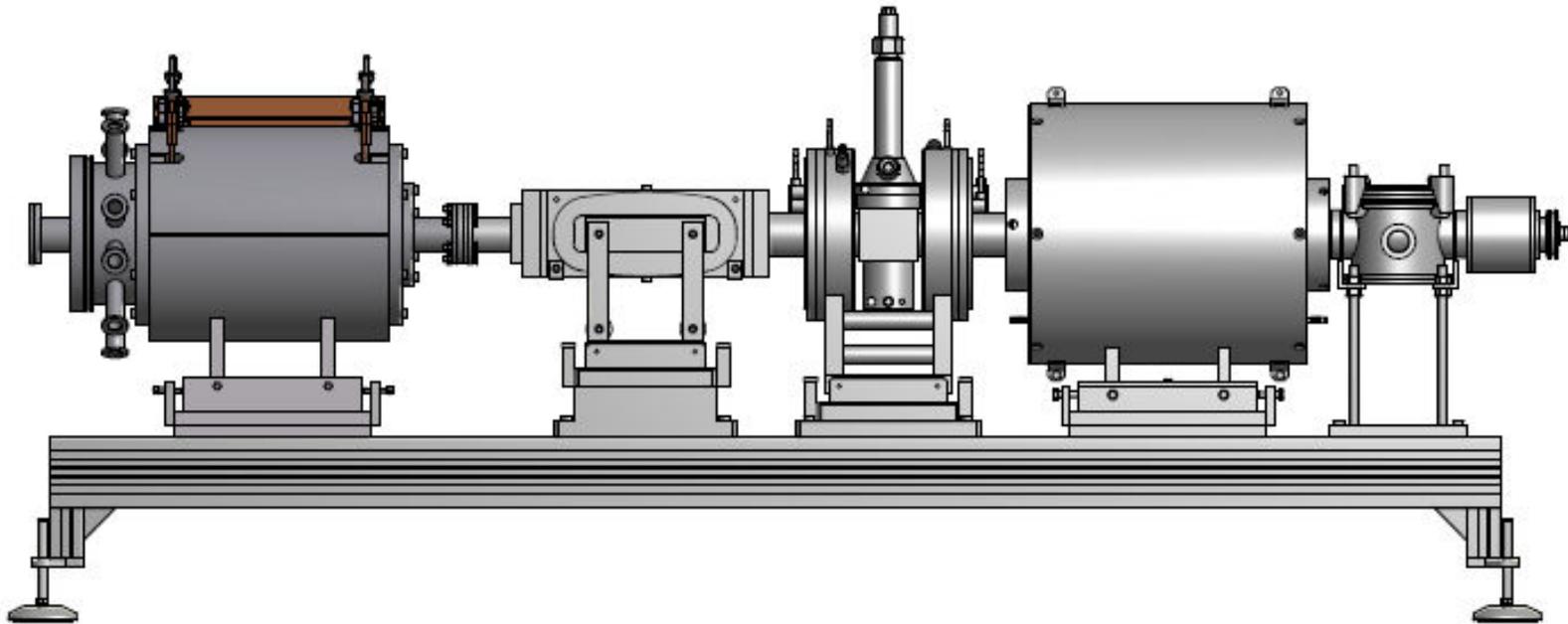
Intensity distribution of CO2 beam and vacuum in the chamber 28.07.2017



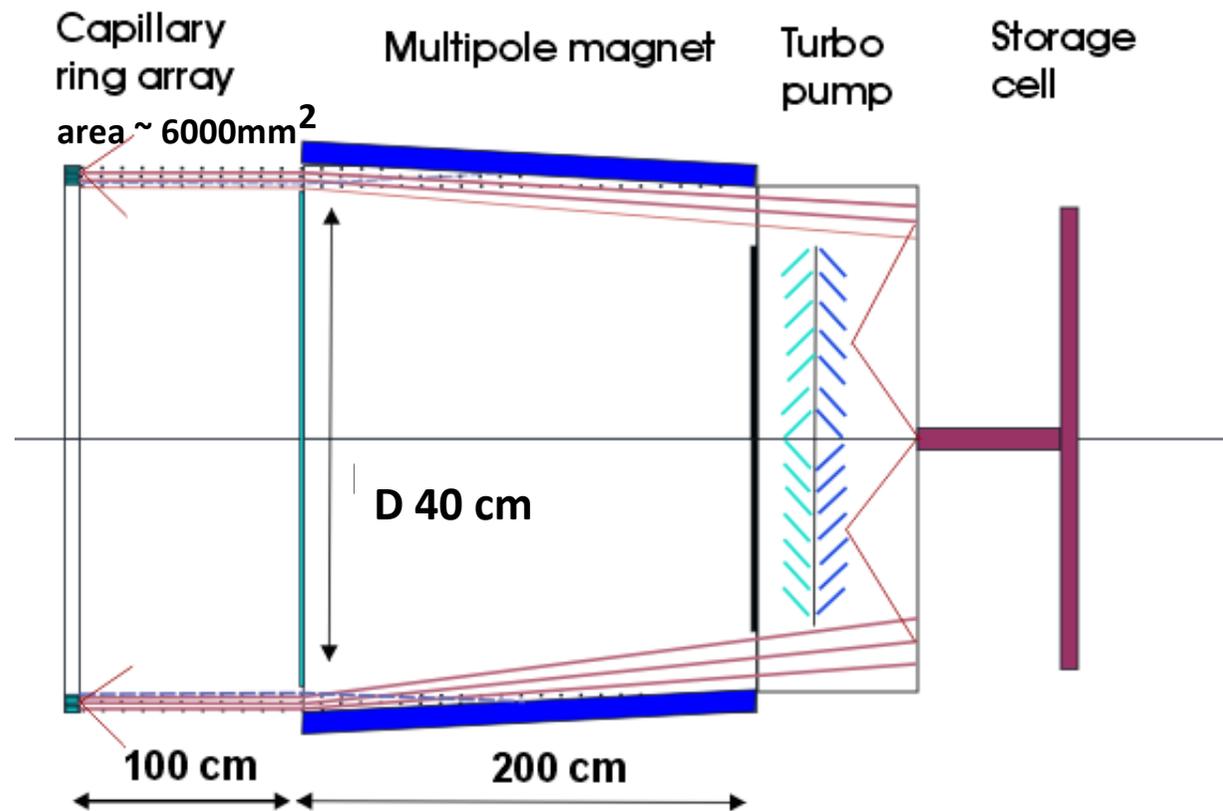
Future prospect

- Understanding the process of molecules reflection from the cold surface
- Measurement of the polarization of molecules using Lamb-shift polarimeter
- Directivity of the molecular beam from the nozzle
- Design prototype of a new source

Lambshift polarimeter

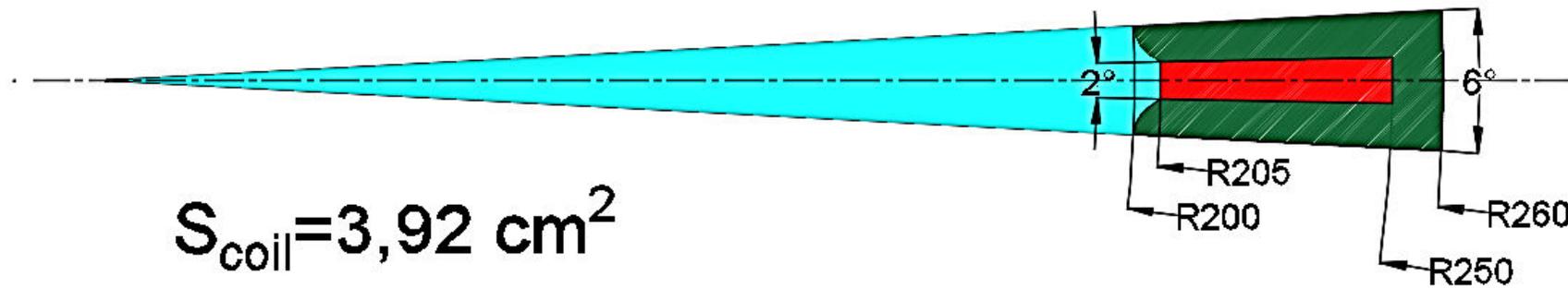


Possible setup of future polarized hydrogen molecules source



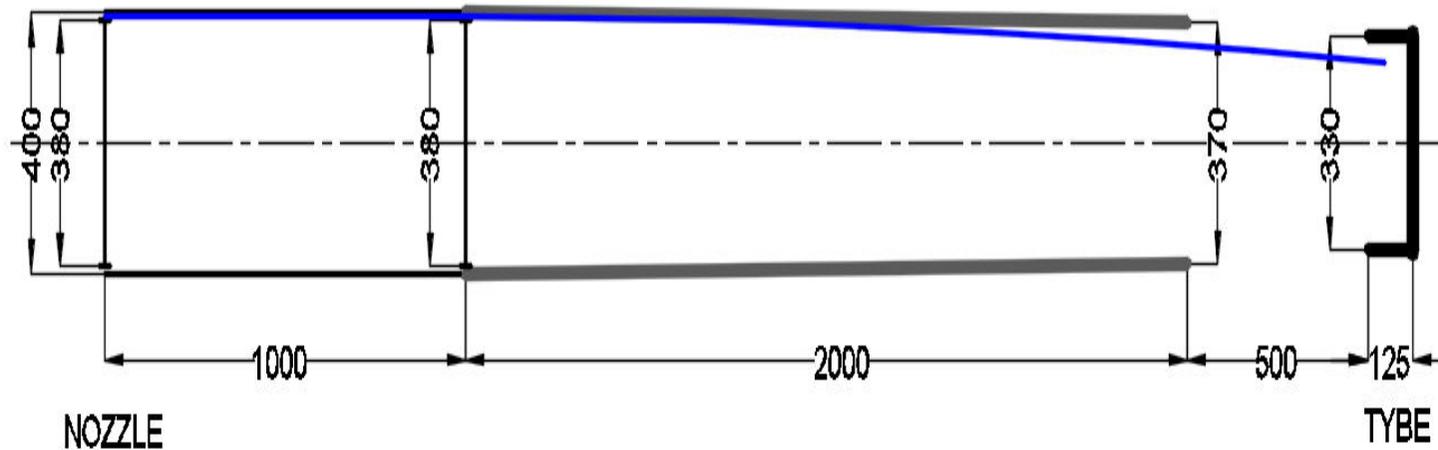
Geometry of 60pole magnet

1/60 MAG

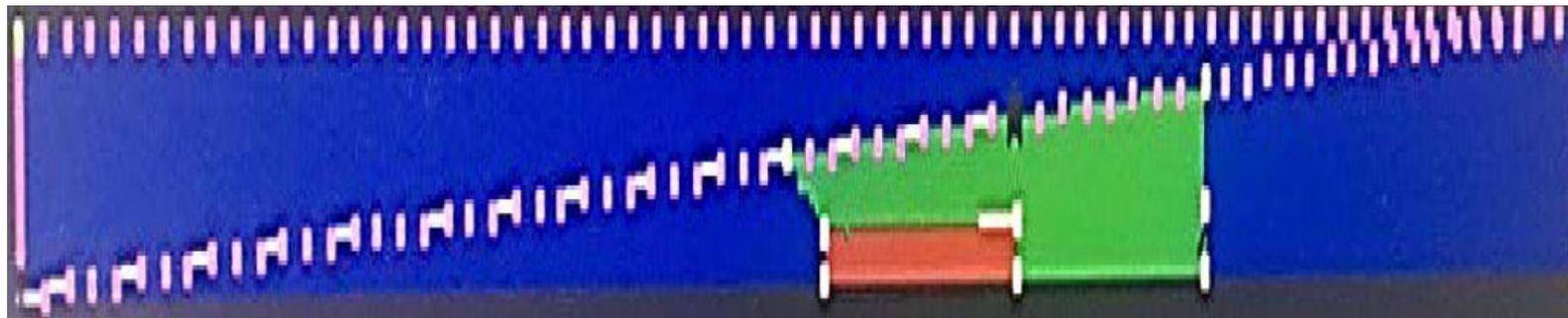
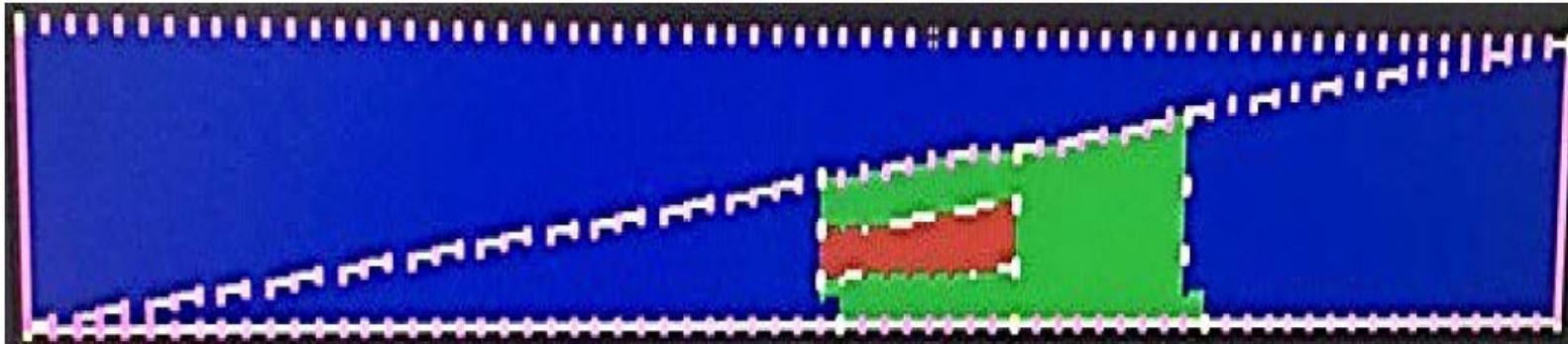


* dimensions are in (mm)

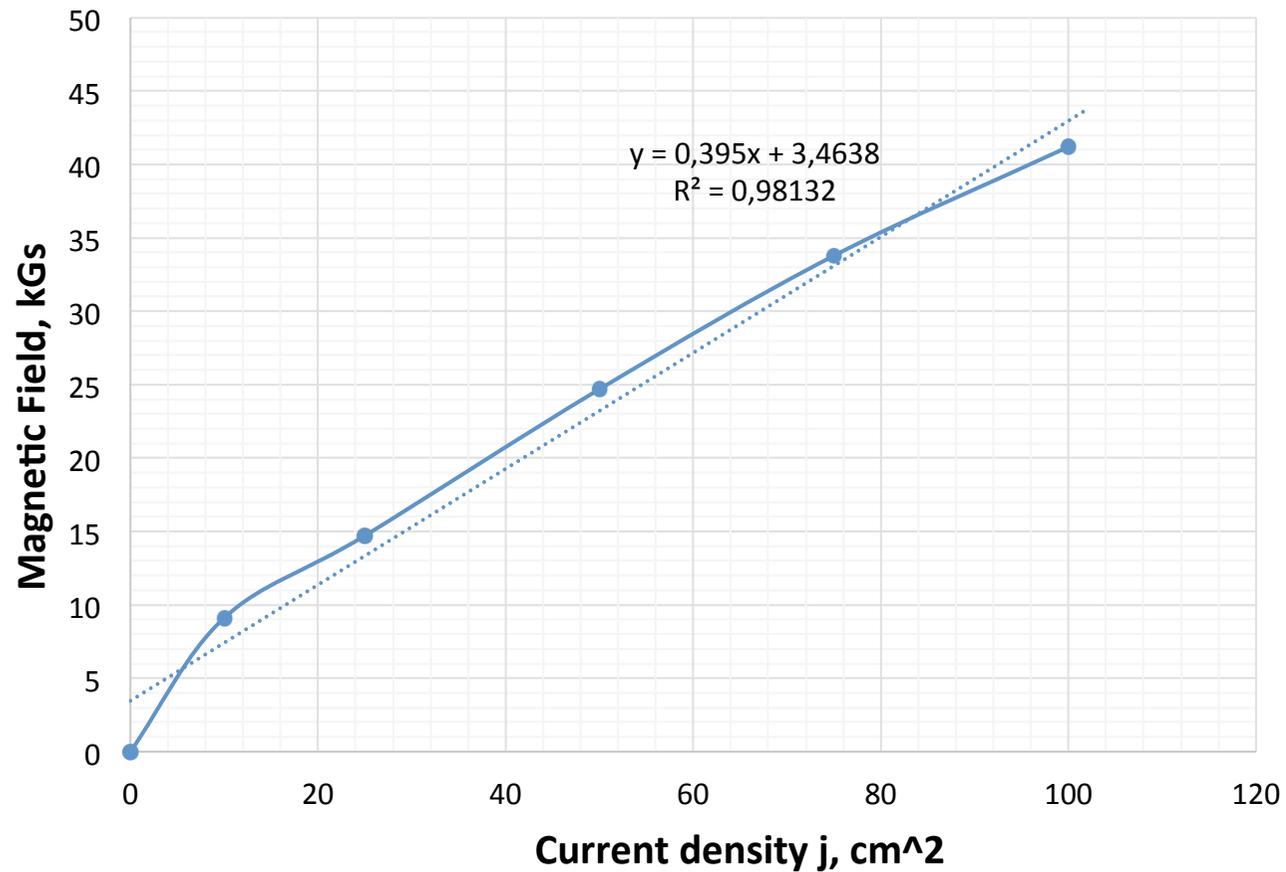
60-pole MAG



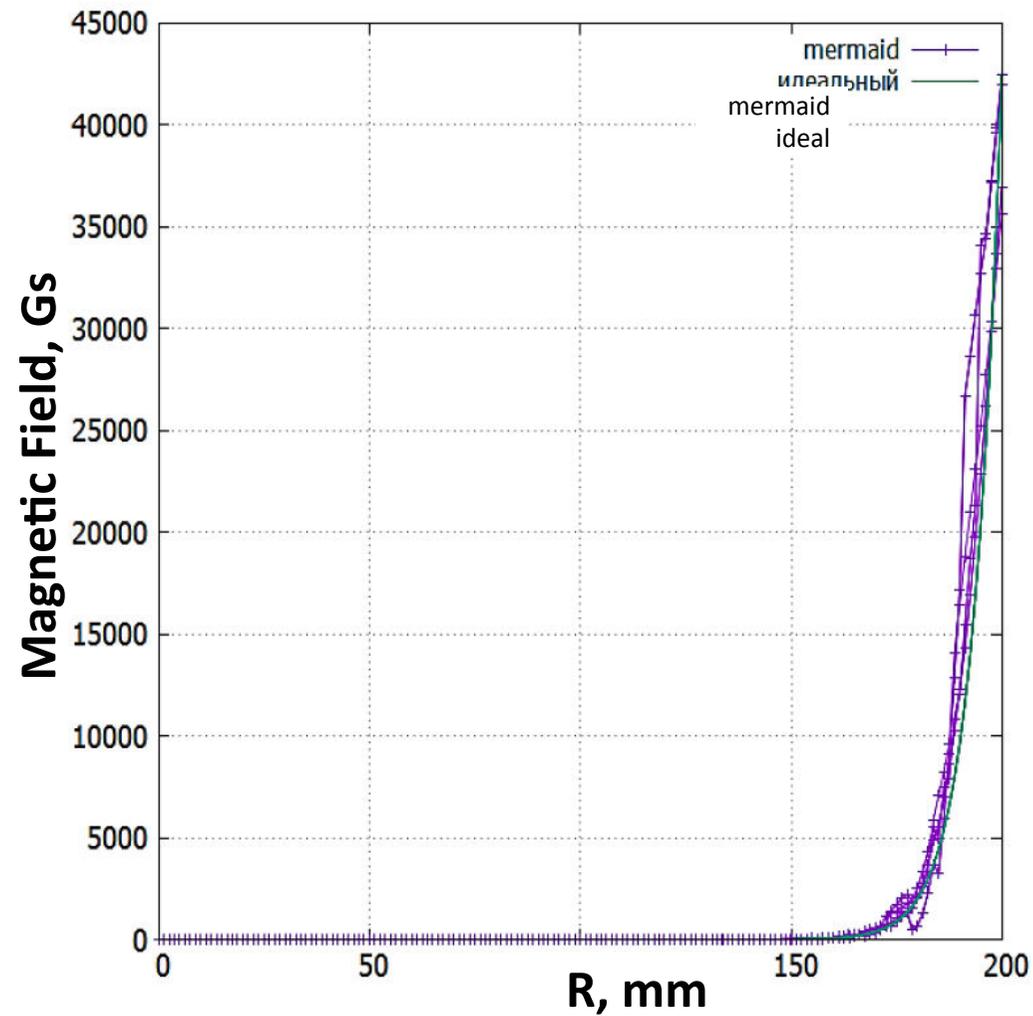
Geometry of the magnet for code MERMAID



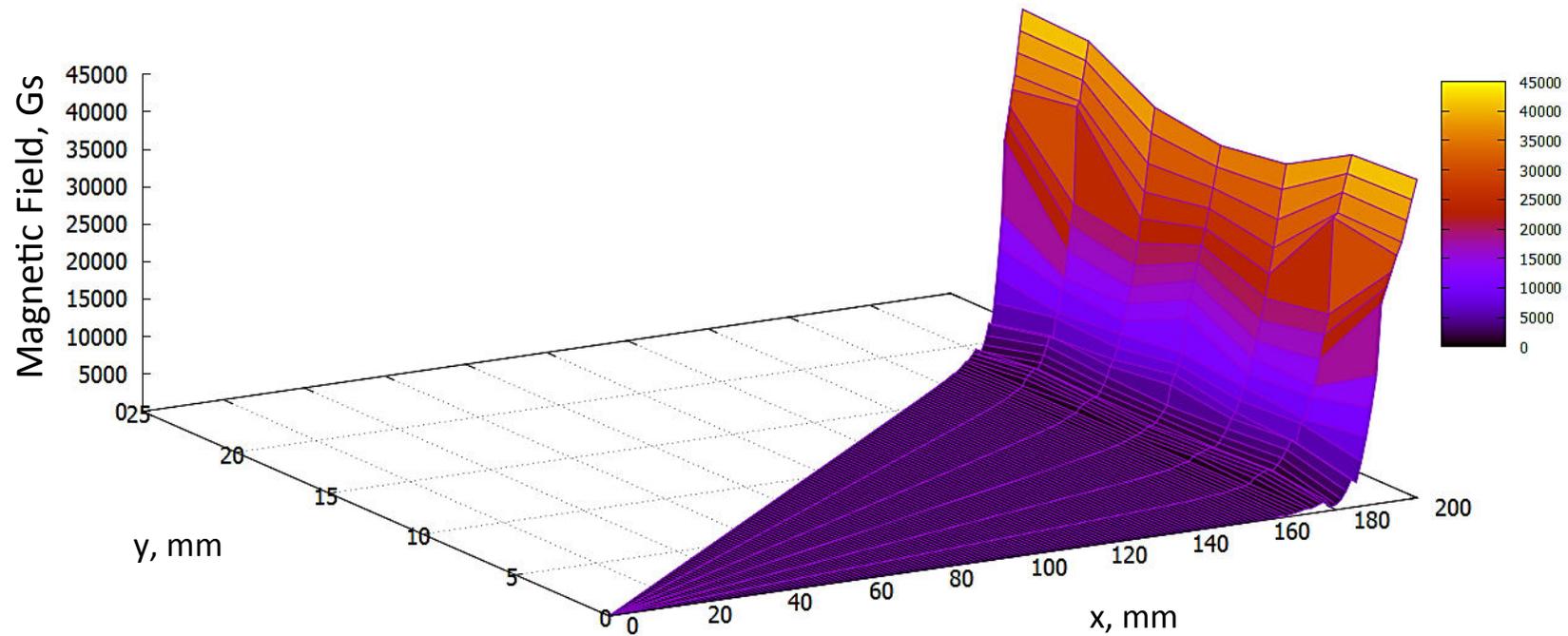
The dependence of the magnetic field on the current density



60pole magnet magnetic field

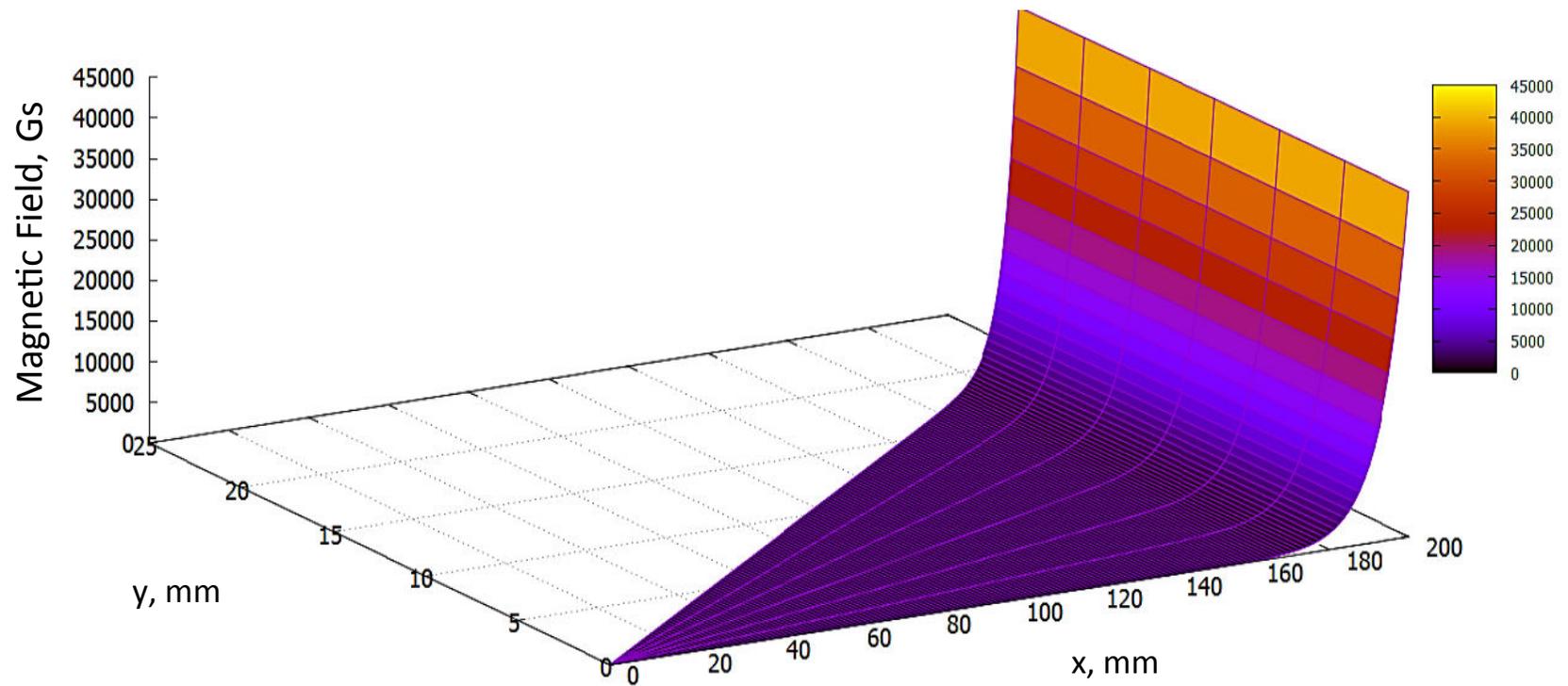


Mermaid modeling Magnetic Field plane $(rcos(\varphi); rsin(\varphi))$



Ideal Magnetic Field

plane $(r\cos(\varphi); r\sin(\varphi))$



Monte Carlo simulation of the motion of molecules results

at the exit of the magnet

molecule	2.94×10^{17} total	$N_{\downarrow mag}$ in	$N_{\downarrow positive}$ mag out / $N_{\downarrow nozzle}$	$N_{\downarrow zero}$ mag out / $N_{\downarrow nozzle}$	$N_{\downarrow negative}$ mag out / $N_{\downarrow nozzle}$	$N_{\downarrow all}$ mag out / $N_{\downarrow nozzle}$	$P_{\downarrow z}$ mag out	$P_{\downarrow zz}$ mag out	$FM_{\downarrow 1}$ mag out	$FM_{\downarrow 2}$ mag out
$H_{\downarrow 2}$ ($T=8$)							in the beam receiver			
molecule	2.94×10^{17} total	$N_{\downarrow mag}$ in	$N_{\downarrow positive}$ tube / $N_{\downarrow nozzle}$	$N_{\downarrow zero}$ tube / $N_{\downarrow nozzle}$	$N_{\downarrow negative}$ tube / $N_{\downarrow nozzle}$	$N_{\downarrow all}$ tube / $N_{\downarrow nozzle}$	$P_{\downarrow z}$ tube	$P_{\downarrow zz}$ tube	$FM_{\downarrow 1}$ tube	$FM_{\downarrow 2}$ tube
$H_{\downarrow 2}$ ($T=8$) K P_{loss}			4.60476e-05	0	0	4.60476e-05	1	1	1357	1357

Conclusion

- The measured flux of focusing molecules is close to the expected one
- **More investigation should be done to get optimal molecular flux from the CABS**
- **This and further investigation will be done under the joint RSF-DFG grants № 16-42-01009 and № BU 2227/1-1**

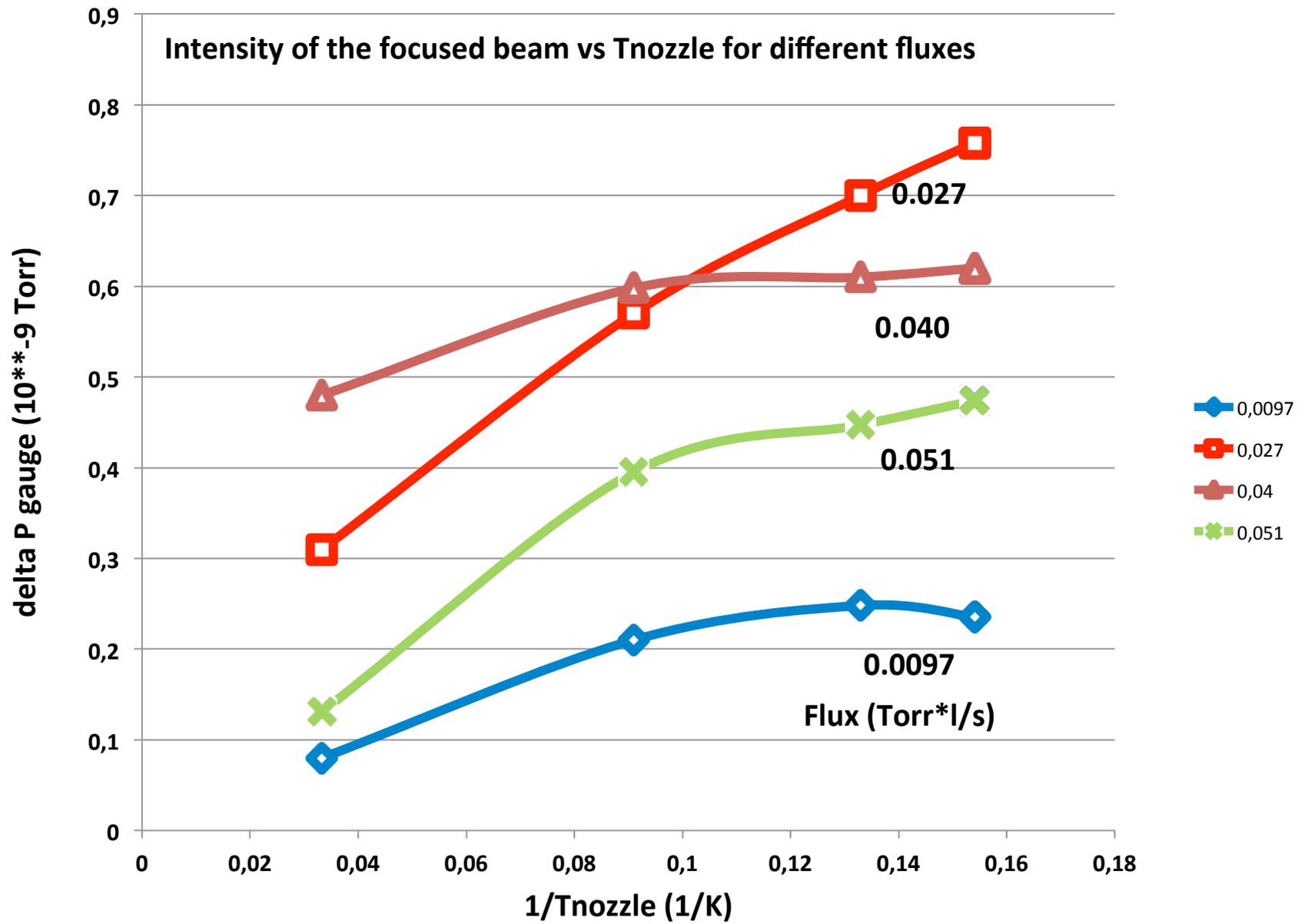
A team working on polarized molecular source



03.10.2017

Experience with PMS D.Toporkov

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Intensity of the focused beam vs flux for different T nozzle

