Physical principles of atomic beam production and diagnostic methods (the APol Absolute polarimeter project)

V.E. Larionov, V.B. Dunin, N.V. Dunin, V.V. Fimushkin, K.A. Ivshin, M.V. Kulikov, L.V. Kutuzova, N.M. Piskunov, A.N. Solovev,

Joint Institute for Nuclear Research, Dubna, Russia

A.N. Zelensk, Yu.N. Filatov

Moscow Institute of Physics and Technology, MIPT, Dolgoprudnyi

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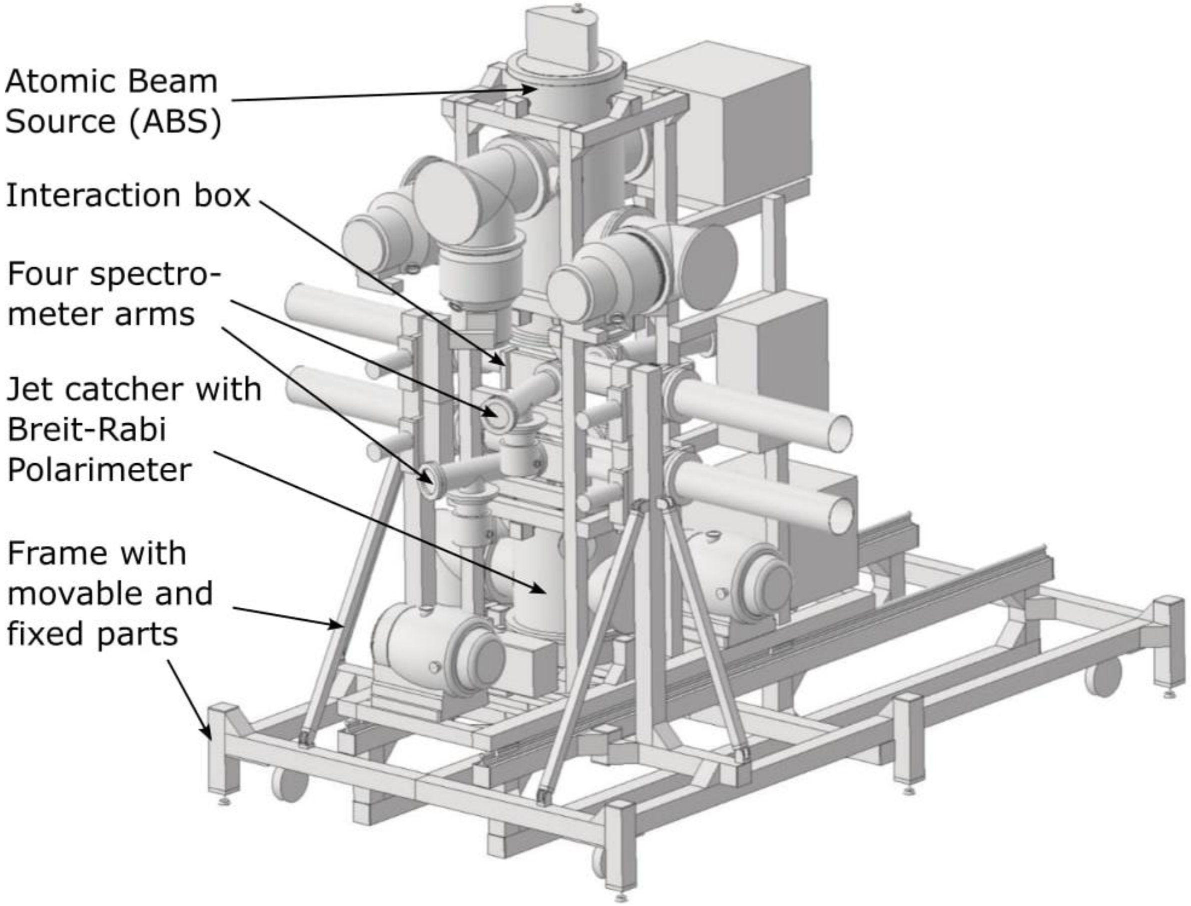
NICA Absolute Polarimeter (Apol)

To measure absolute values of proton or deuteron polarization at NICA collider rings an Absolute Polarimeter Apol with the internal polarized atomic hydrogen/deuterium jet target is being built



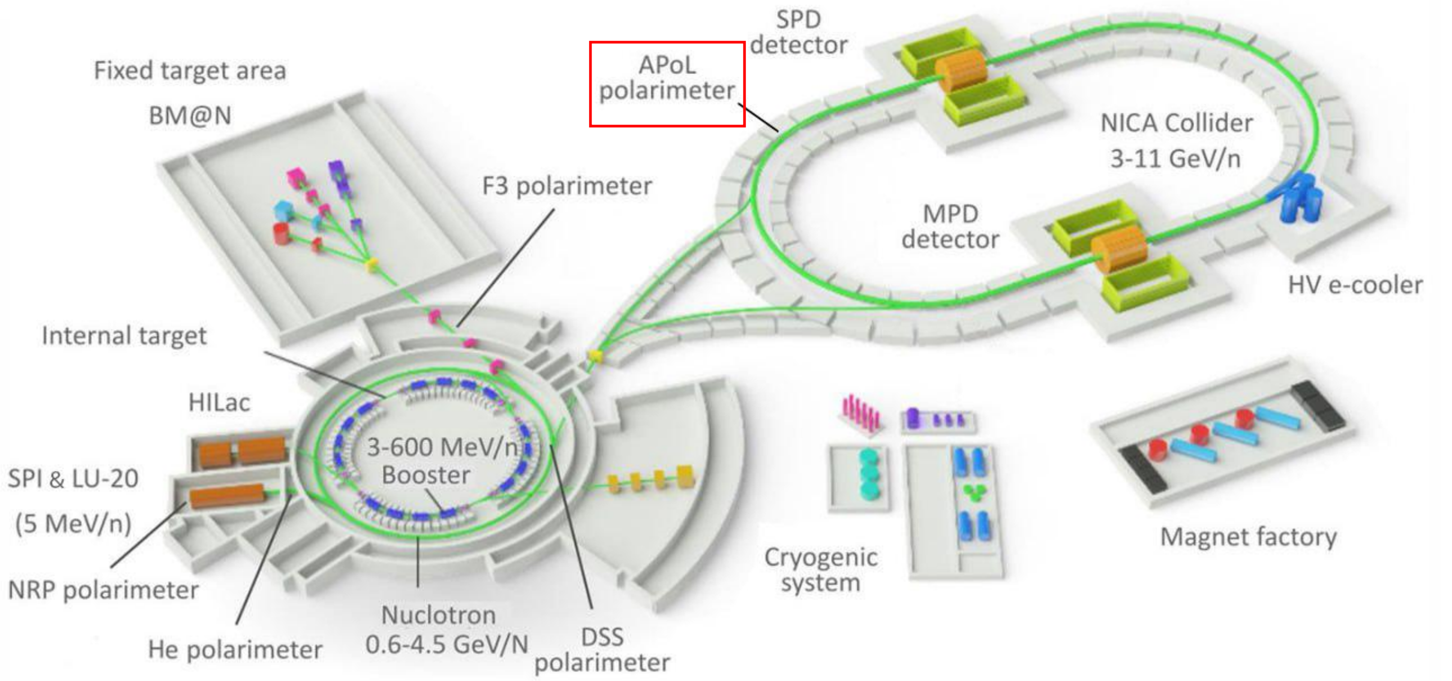
DOI: 10.1088/1742-6596/1435/1/012038

Main tasks for Apol

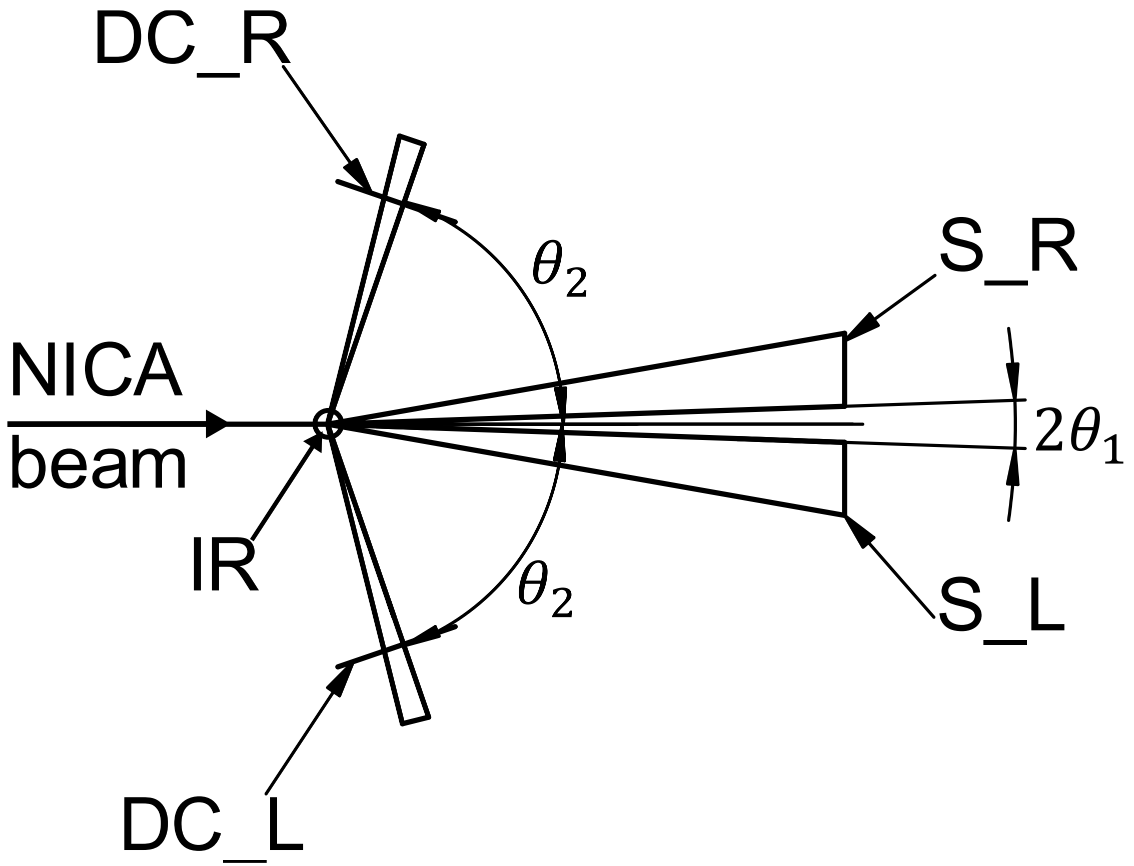
1. Beam polarization measurment in tuning of the NICA polarization control system

2. Determination the effect of disturbing Collider devices on beam polarization

3. Monitoring the degree of beam polarization during operation of the Collider



The operating principle: analyzing power and scattering asymmetry



IR - Interaction Region
DC – Drift Chamber
S - Scintillation Counters

beam energy range: **3..11 GeV**
recoil particle energy: **200 MeV**
recoil particle registration angle (in lab system): **75°**
A_N range: **20% .. 8%**

$P_{beam} = \frac{\varepsilon_{beam}}{A_N}$ - beam polarization,

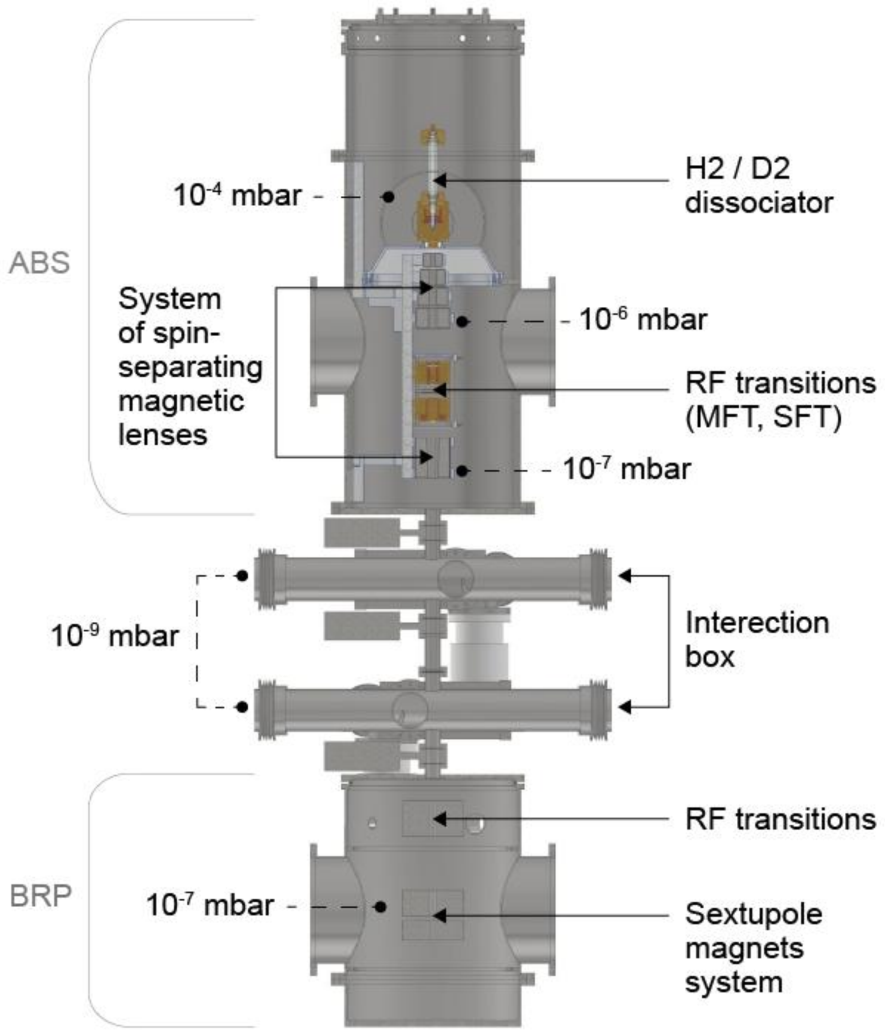
$A_N = -\frac{\varepsilon_{target}}{P_{target}} = \frac{\varepsilon_{beam}}{P_{beam}}$ –

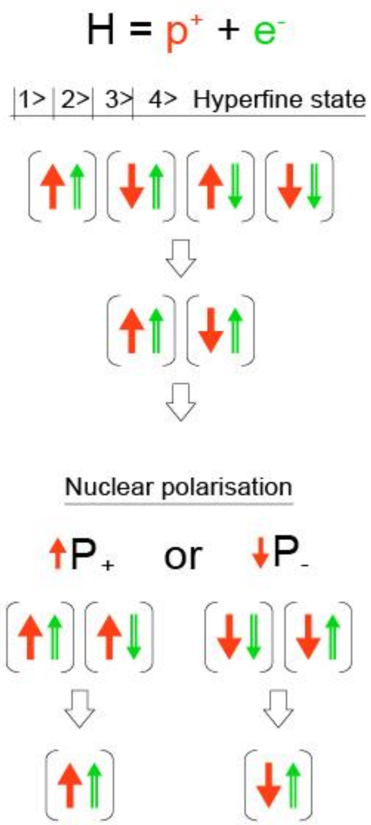
analizing power of the polarimetric reaction

$$P_{beam} = -P_{target}\frac{\varepsilon_{beam}}{\varepsilon_{target}}$$

$$\varepsilon = \frac{\sqrt{N_\uparrow^L * N_\downarrow^R} - \sqrt{N_\uparrow^R * N_\downarrow^L}}{\sqrt{N_\uparrow^L * N_\downarrow^R} + \sqrt{N_\uparrow^R * N_\downarrow^L}}$$

Design and operating principle of the Apol





1. **Beam formation:** The atomic beam is collimated and focused by a beam formation system.

2. **First spin-filtering stage:** Spin-separating magnetic lenses remove atoms with a **negative** electron-spin projection.

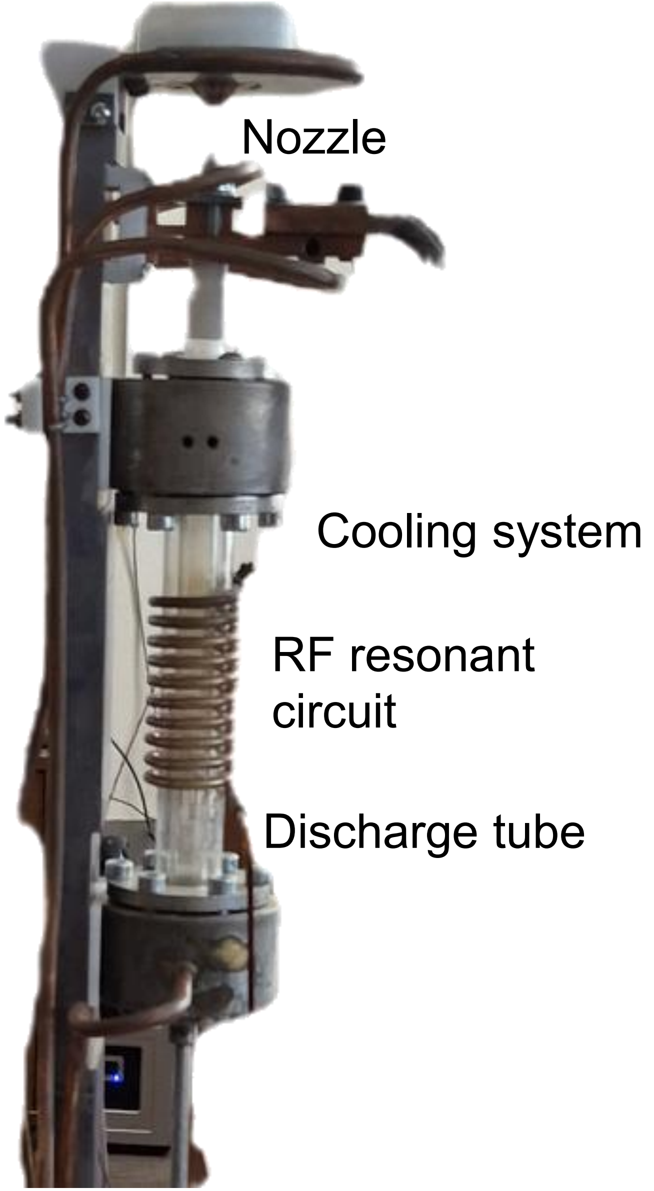
3. **Hyperfine transitions:** A hyperfine transition unit drives resonant transitions: *state 2 → 3* .

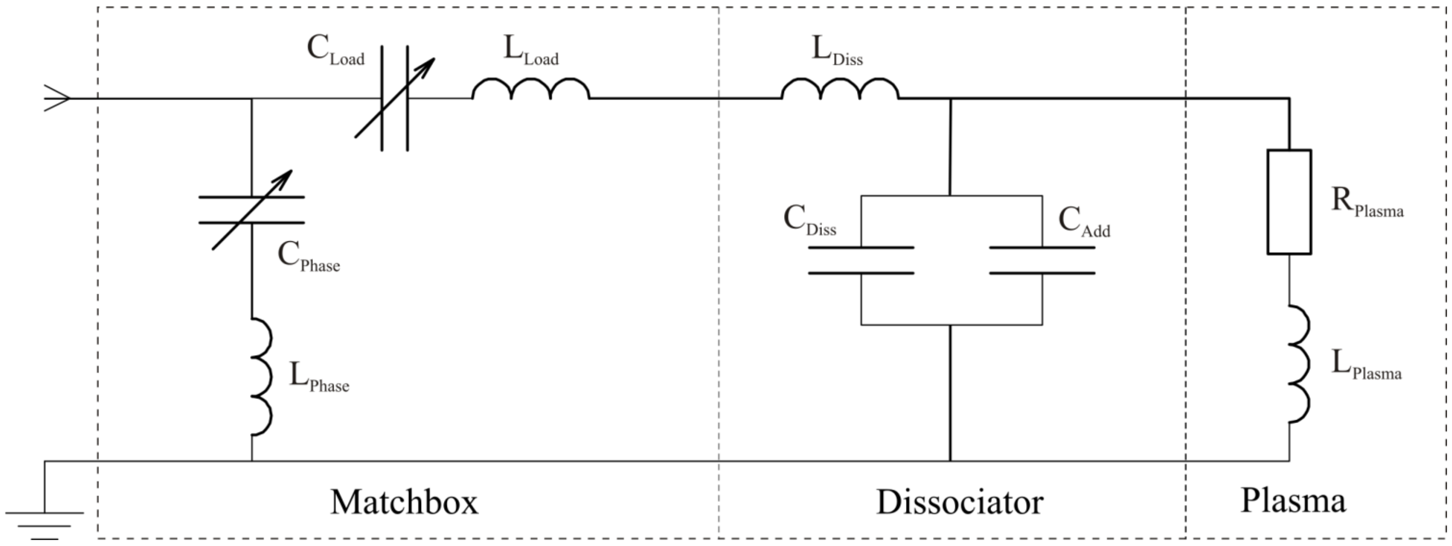
4. **Second spin-filtering stage:** Atoms with negative spin projection are filtered out again.→ **Result:** $P_z = 1$.

5. **Interaction region:** The fully polarized beam enters the interaction zone where it meets the target.

6. **Detection and polarimetry**
   1. **Elastically scattered atoms** → recorded in a drift chamber.
   2. **Unscattered atoms** (passing through without interaction) → directed to the Breit–Rabi polarimeter for target polarization measurement.

RF - dissociator Apol

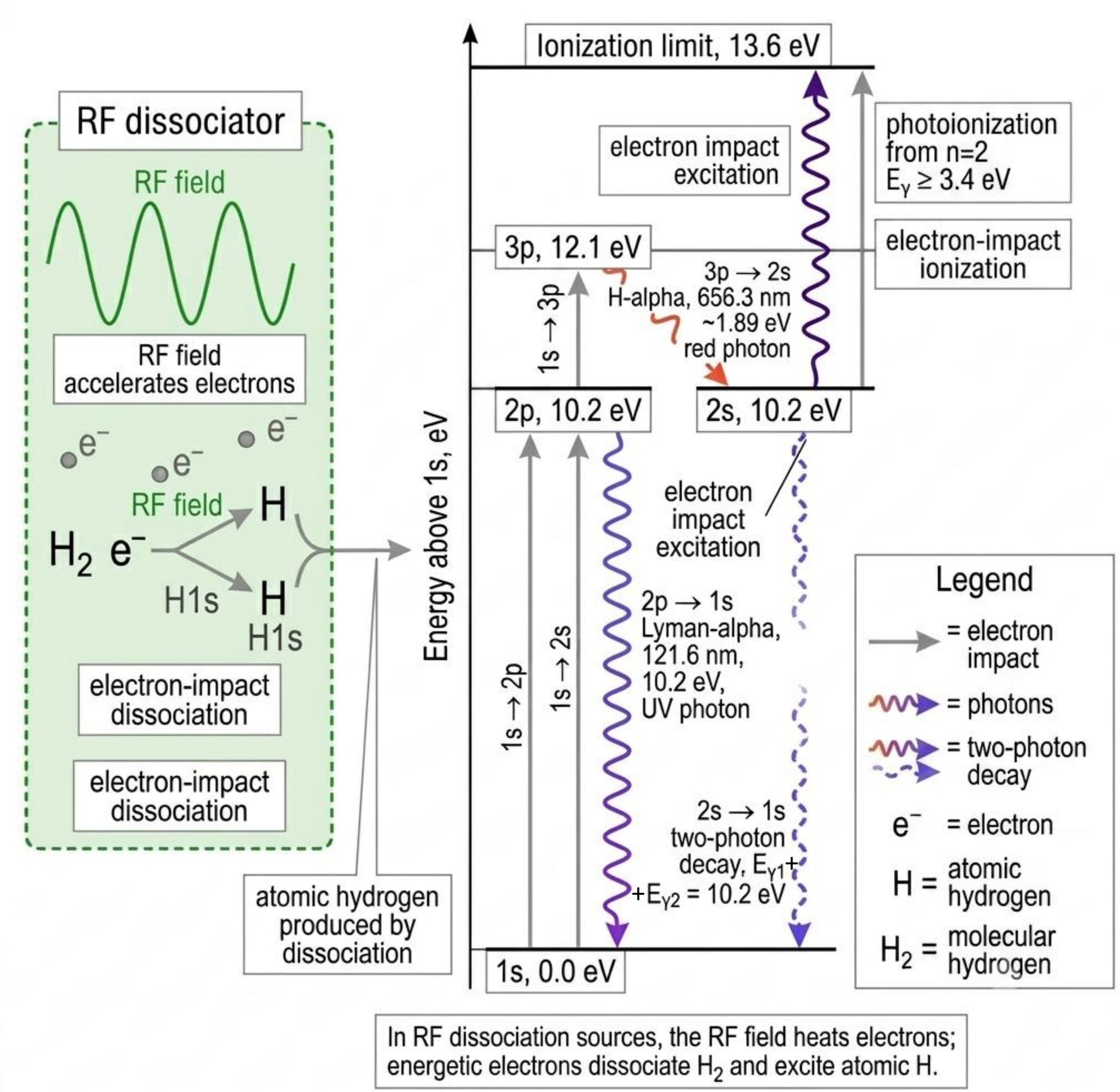


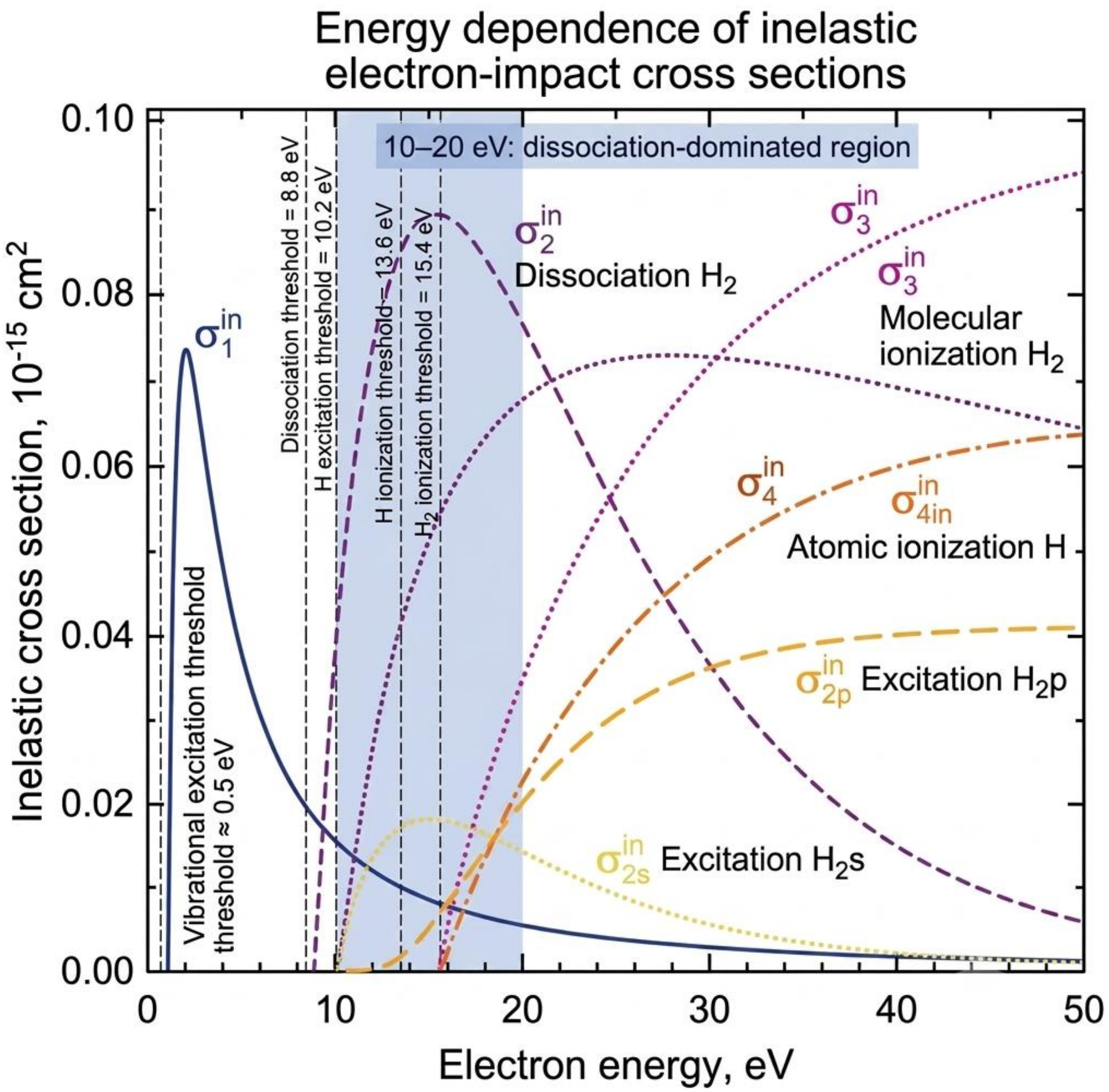


Dissociator Main Components:

- Discharge tube – glass tube with RF plasma; dissociates H_2 / D_2 into atoms
- RF resonant circuit – adjustable capacitor; matches plasma impedance
- Cooling system – water-alcohol jacket around the tube; prevents overheating
- Nozzle – cryogenically cooled; forms supersonic atomic beam
- Tuning – capacitance adjustment maintains low SWR for efficient power transfer

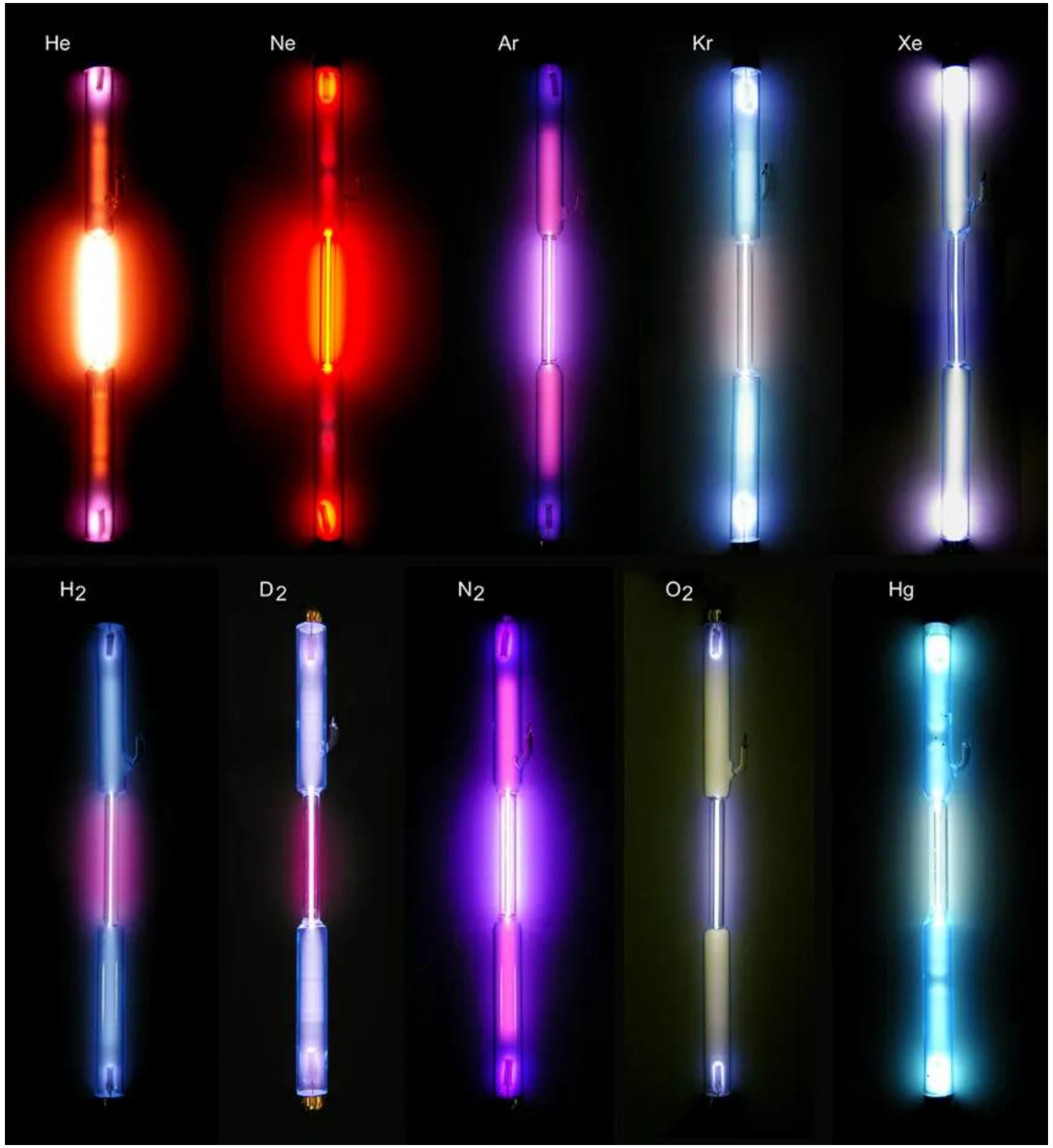
Operating principle of the RF – dissociator





N. Koch, PhD Thesis, University of Erlangen-Nürnberg (1999).

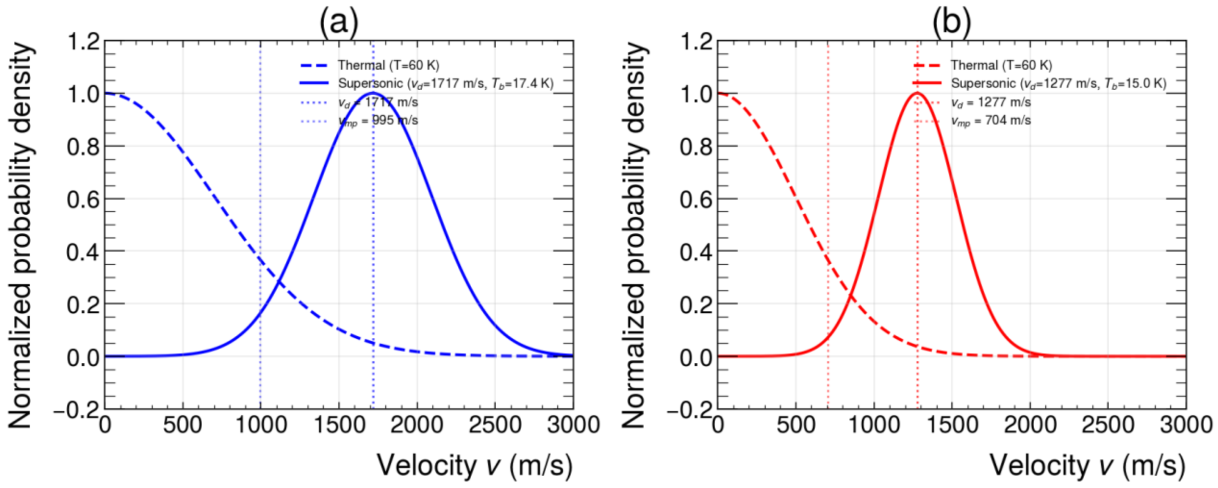
Operating principle of the RF – dissociator



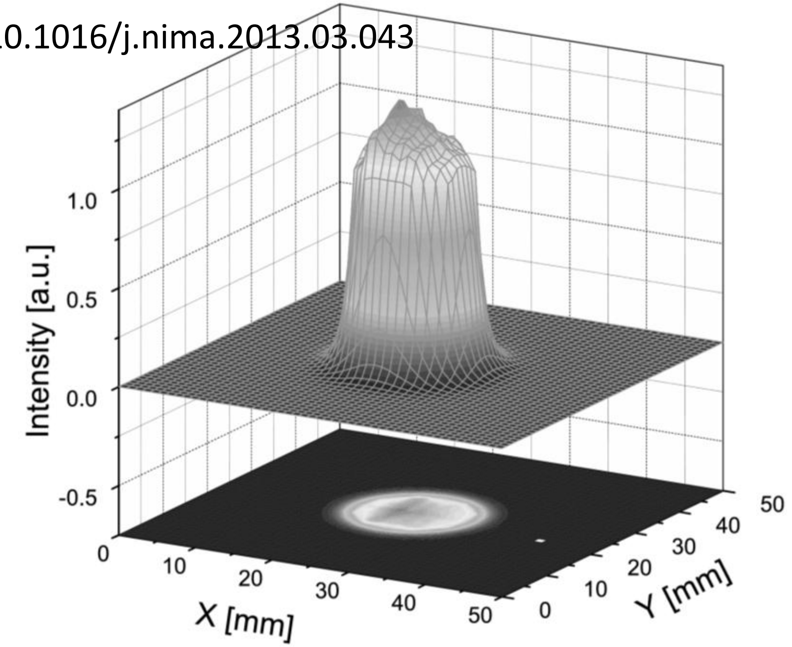
Balmer-alpha emission gives the plasma a purple colour.
Spectroscopy doesn't use for precise measurements.
But colour changes can warn us about pressure or power problems.
It's a quick diagnostic sign.

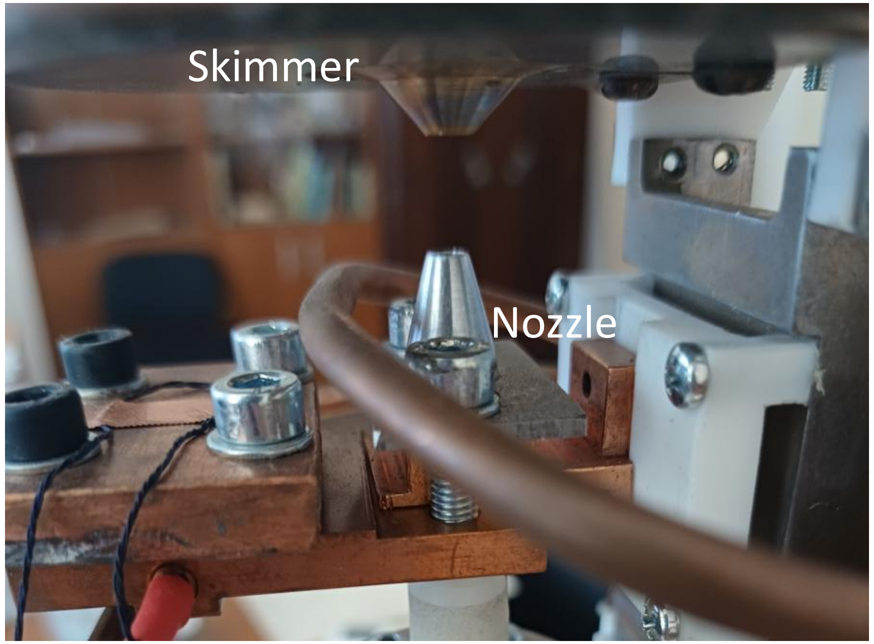
DOI 10.31857/S0044002724030094

Operating principle of the RF – dissociator



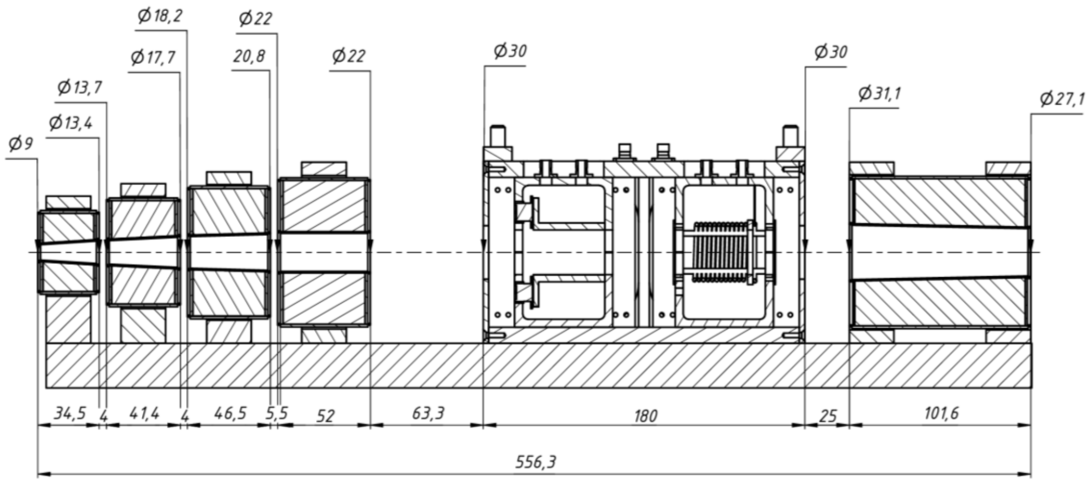
https://doi.org/10.1016/j.nima.2013.03.043





The gas from the dissociator goes through a cooled nozzle – this reduces thermal motion. Adiabatic expansion makes the flow supersonic with a narrow velocity spread. A skimmer selects the central part and reduces angular divergence. The result is a well-collimated beam – essential for the efficient operation of the magnetic system.

Apol multipolar magnetic system



1. **Polarizer assembly:**The beam enters the multipole magnetic lens system and RF units – the polarizer of the APOL setup.

2. **Stern–Gerlach spin selection:** The magnetic lenses focus and defocus atoms according to their electron-spin projection (Stern–Gerlach effect).

3. **Electron-spin-polarized beam**
After magnetic filtering, the beam (now polarized in electron spin) enters the RF cells.

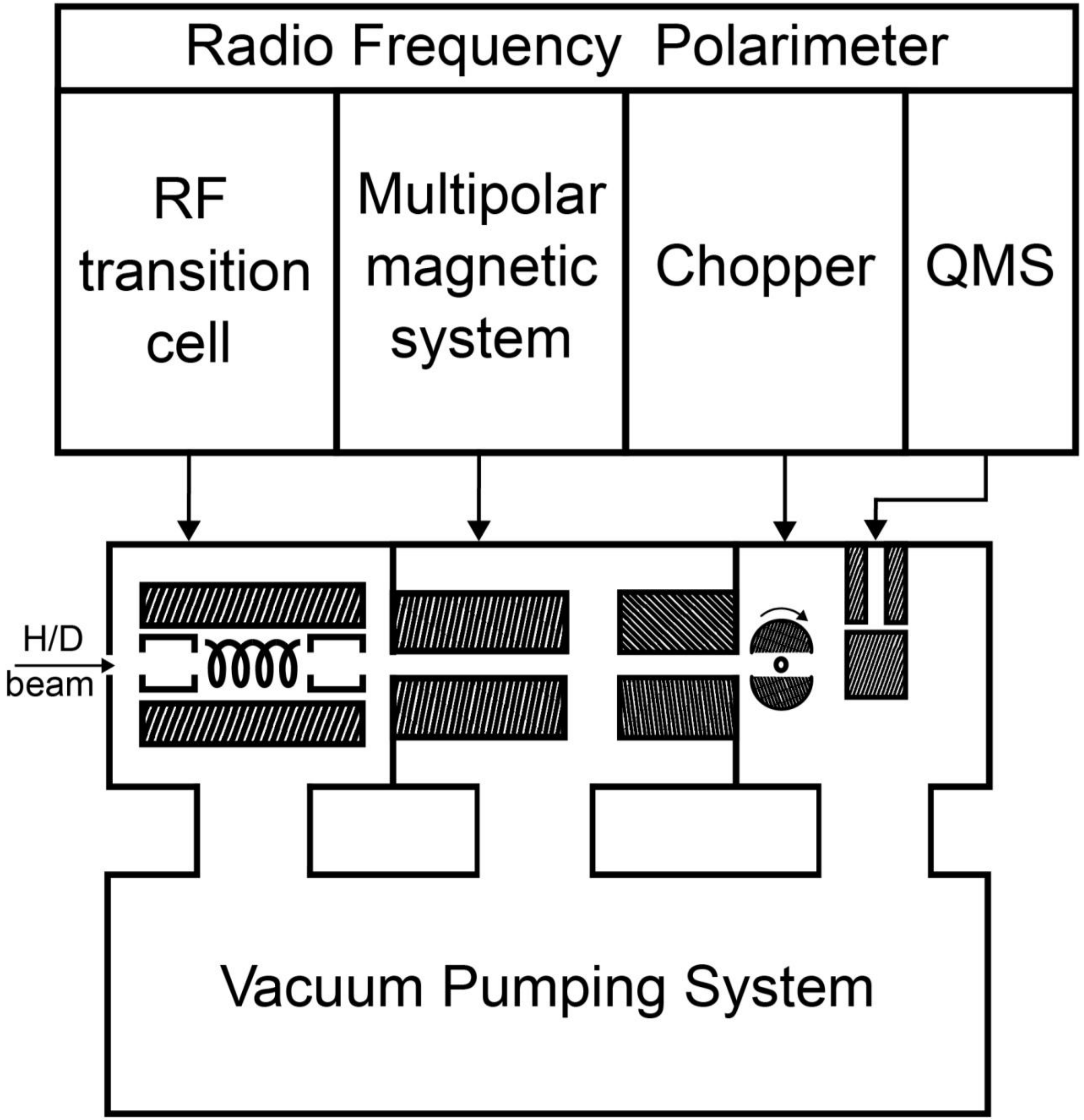
4. **Zeeman splitting:** Inside the RF cells, a static magnetic field splits the hyperfine levels into individual sublevels via the Zeeman effect.

5. **RF-induced transitions:** An **alternating (RF)** magnetic field drives resonant transitions between these Zeeman sublevels.

The magnetic system was based on the design of the RHIC absolute polarimeter magnetic system.

https://doi.org/10.1063/1.2888110

Breit-Rabi Polarimeter



1. RF transitions. The atomic beam enters the RF cell, where the radiofrequency field induces a selective redistribution of the hyperfine level populations (transitions between magnetic sublevels are induced).

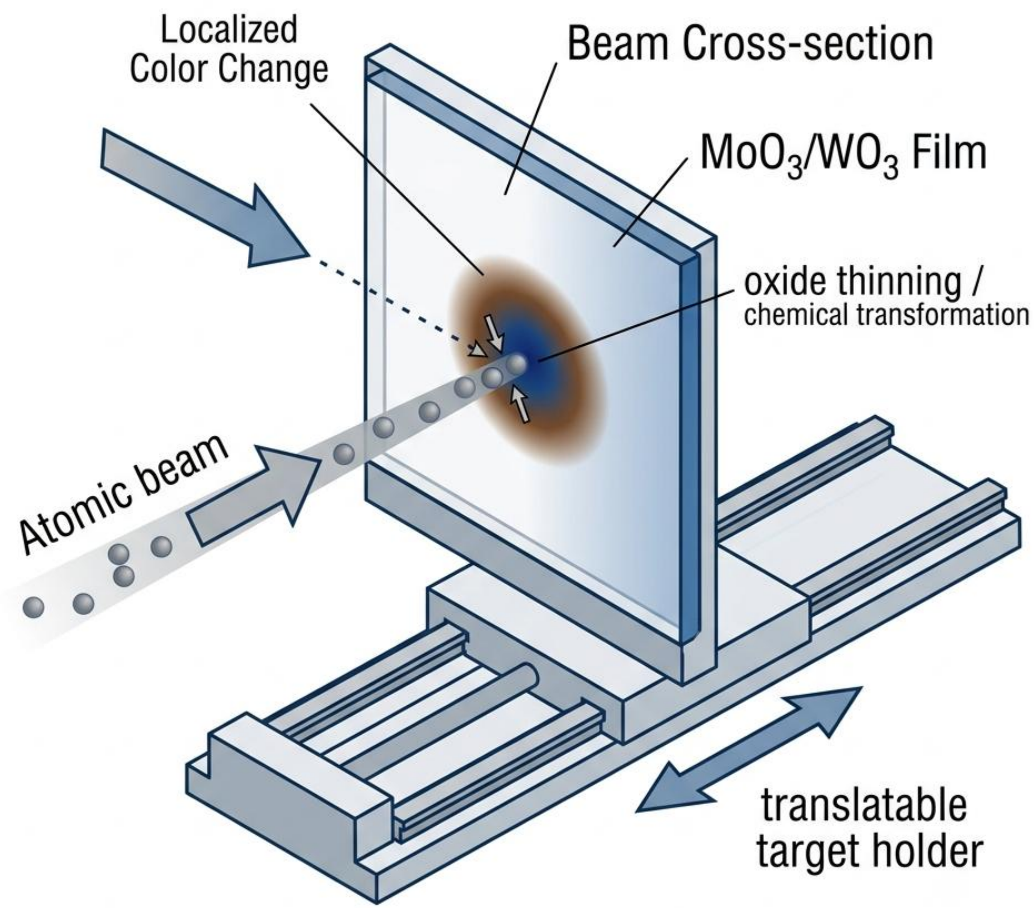
2. Spin separation. The beam then passes through spin-separating magnetic lenses (sextupoles), where atoms with a positive spin projection are focused, while those with a negative projection are deflected and discarded.

3. Detection. The focused atoms enter a quadrupole mass spectrometer (QMS), which registers the intensity; to account for the background of residual gas, the beam is periodically blocked by a chopper.

4. Polarization calculation. By sequentially switching the RF transitions and recording the intensity spectrum, a system of equations is constructed. Solving it yields the populations of all four states and determines the nuclear and electronic polarization degrees.

Beam profile diagnostics

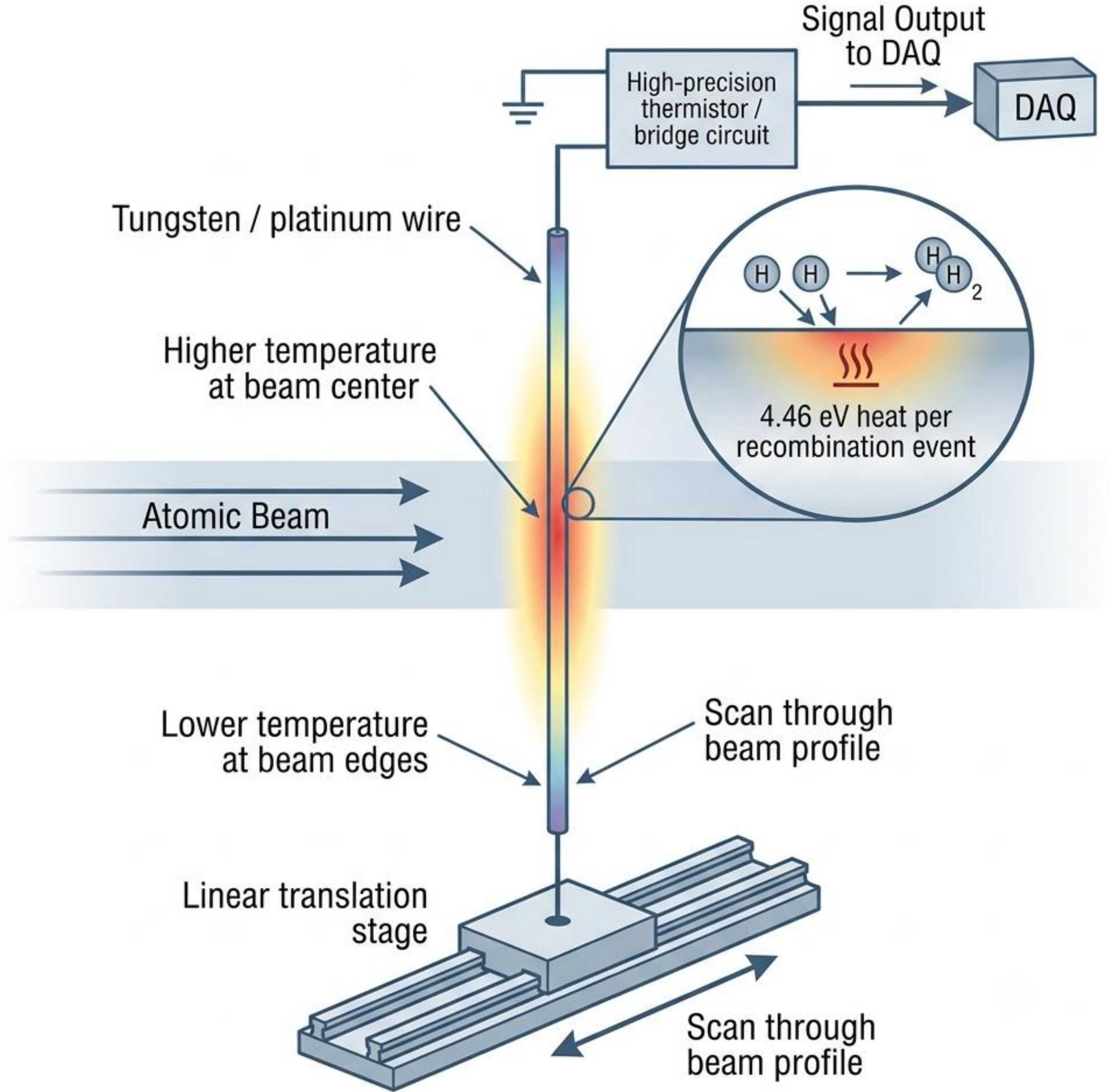
Beam visualization using thin films of transition metal oxides



http://inis.jinr.ru/sl/NTBLIB/28-02-2020/JINR-B1-9-7470.pdf

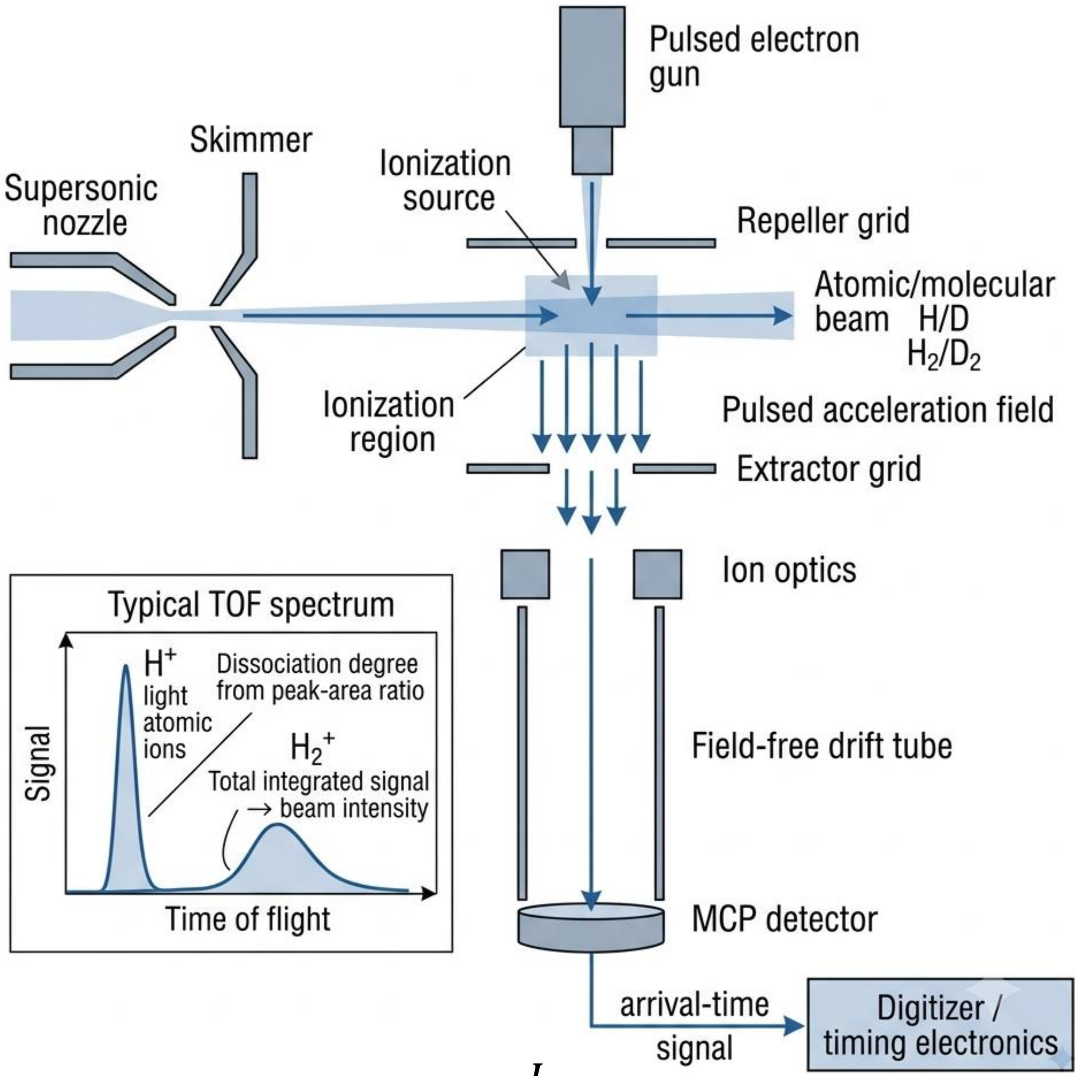
https://doi.org/10.1016/j.nima.2013.03.043

Calorimetric Wire Detector

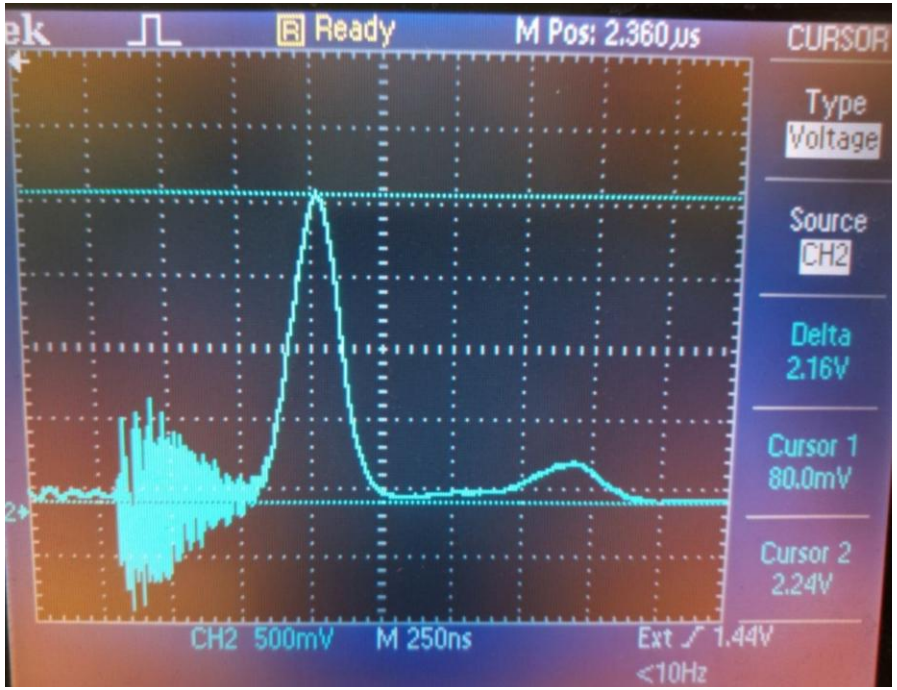


https://doi.org/10.48550/arXiv.2501.01268

Dissociation degree measurement - TOF

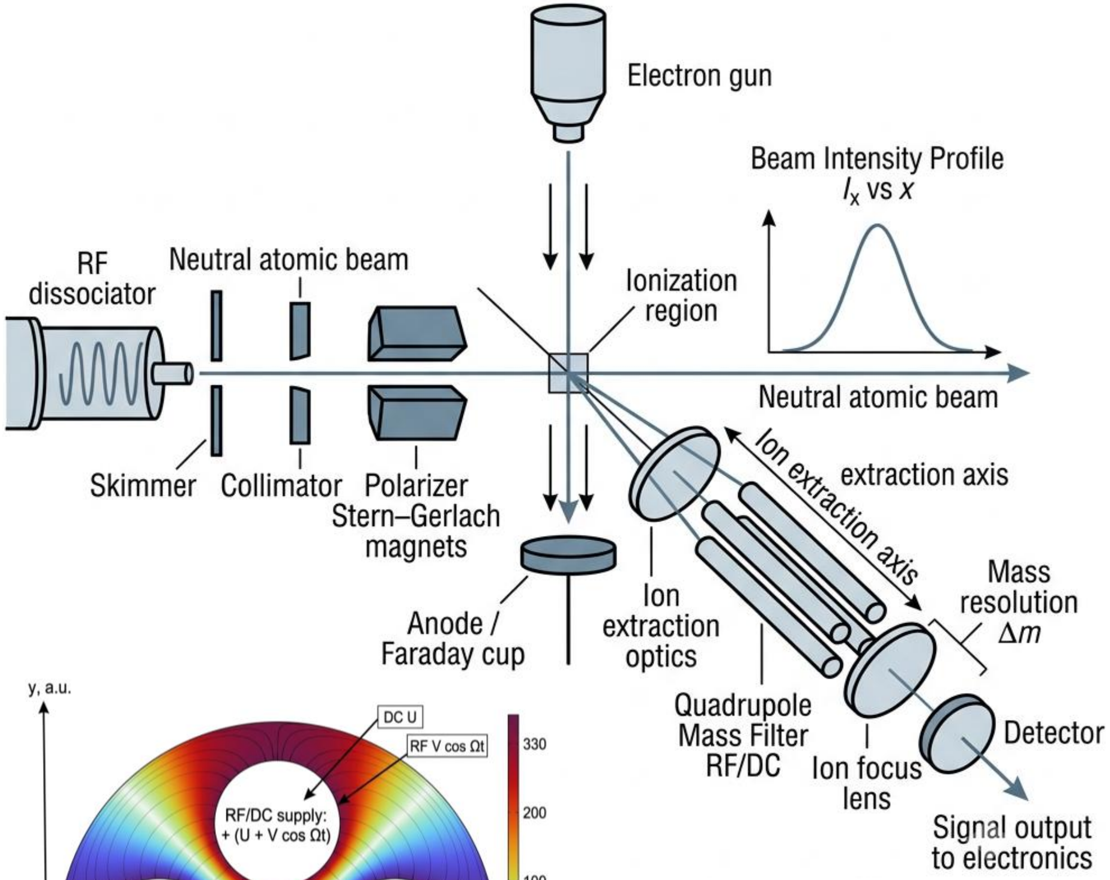


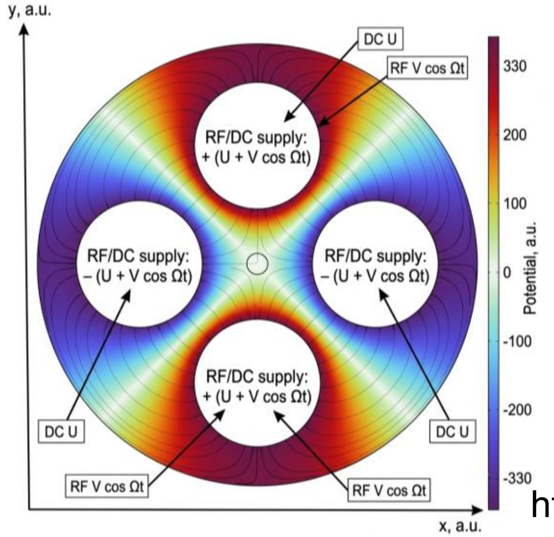
$$\alpha = \frac{I_H}{I_H + 2I_{H_2}}$$



1. **Ionization and acceleration**: The neutral beam (H and H_2) is ionized by a pulsed electron gun in the ionization region.
2. **Mass separation**: An electric field accelerates the ions, which are separated by mass in a field-free drift tube (light H^+ ions travel faster than heavy H_2^+ ions).
3. **Ion detection**: Detector records the time of flight (TOF), and the dissociation degree is calculated from the ratio of the peak areas of H^+ and H_2^+

Dissociation degree measurement – Cross- beam QMS





$$\alpha = \frac{I_H}{I_H + 2I_{H_2}}$$

https://doi.org/10.1016/j.nima.2013.03.043

1. **Ionization**: The neutral beam is ionized by an electron beam in the ionization region, producing positive ions (H^+ and H_2^+).

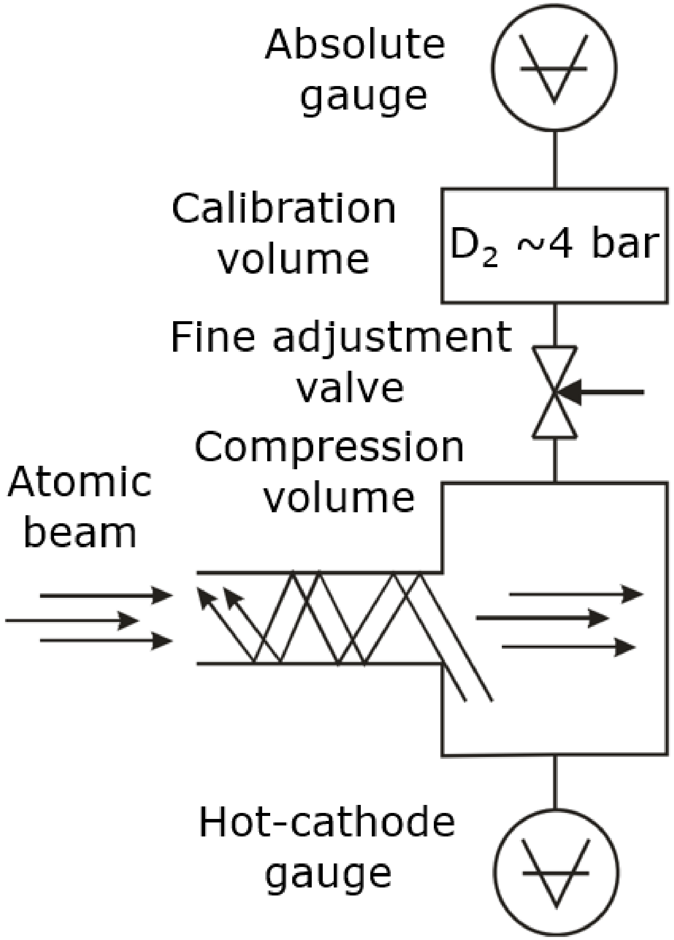
2. **Extraction of ions**: The ions are extracted from the ionization region using ion optics and directed into the mass filter.

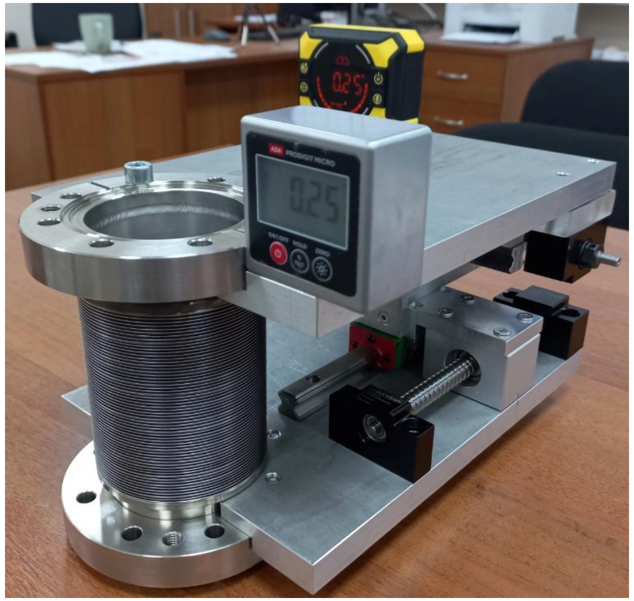
3. **Filtering by RF/DC field according to m/z**: The quadrupole mass filter uses the RF/DC field to filter ions based on their mass-to-charge (m/z) ratio, sequentially selecting either H^+ or H_2^+.

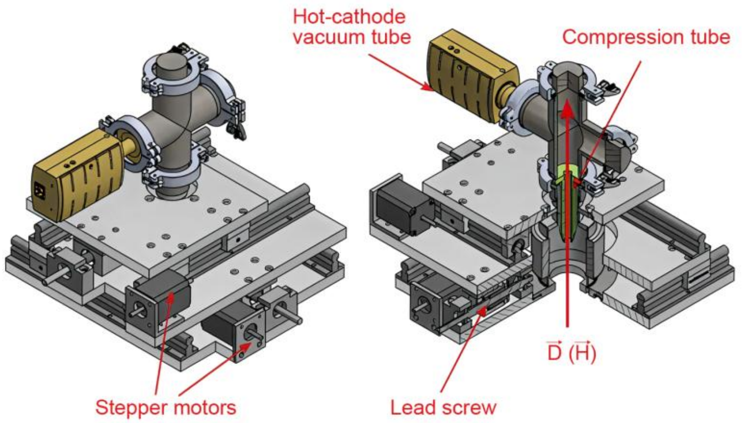
4. **Ion detection**: The filtered ions are registered by the detector, and the ion current is measured to obtain the intensities I_H and I_{H_2}, which are used to calculate the degree of dissociation.

Crossed-beam QMS and TOF cannot measure absolute beam intensity without prior calibration using a compression tube

Beam profile measurement – Compression tube







DOI 10.17586/2226-1494-2025-25-2-366-372

1. **Beam injection:** The atomic beam enters a tube and passes through it with practically **no wall collisions** (due to low pressure and small collision cross-section).

2. **Entry into compression volume:** The atoms then reach a closed compression volume.

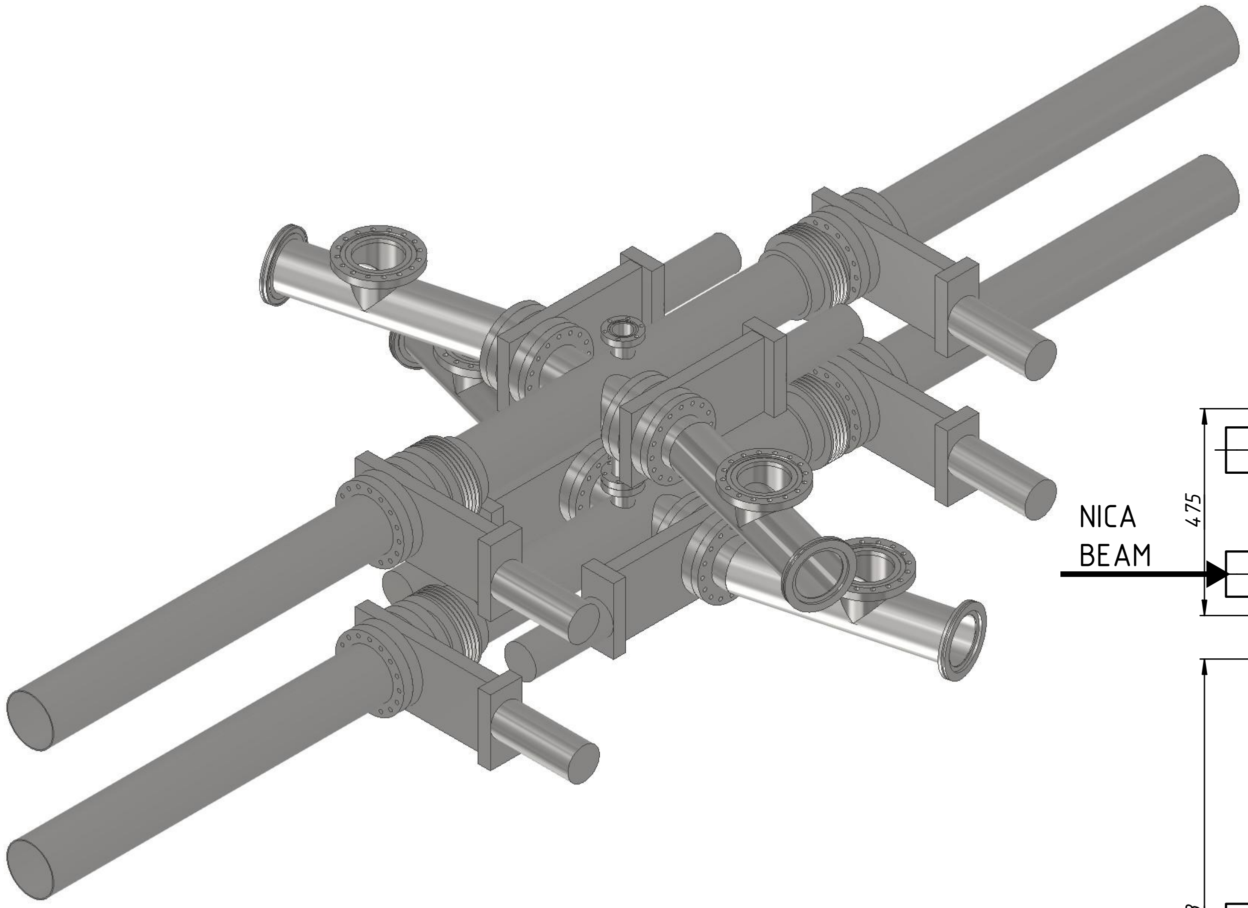
3. **Recombination and thermalization:** Inside this volume, atoms recombine into molecules on the walls or thermalize.

4. **Pressure increase:** These processes lead to a gradual rise of pressure in the confined space.

5. **Equilibrium condition** The pressure continues to increase until **dynamic equilibrium** is established between the incoming atomic flux and the outgoing gas flow.

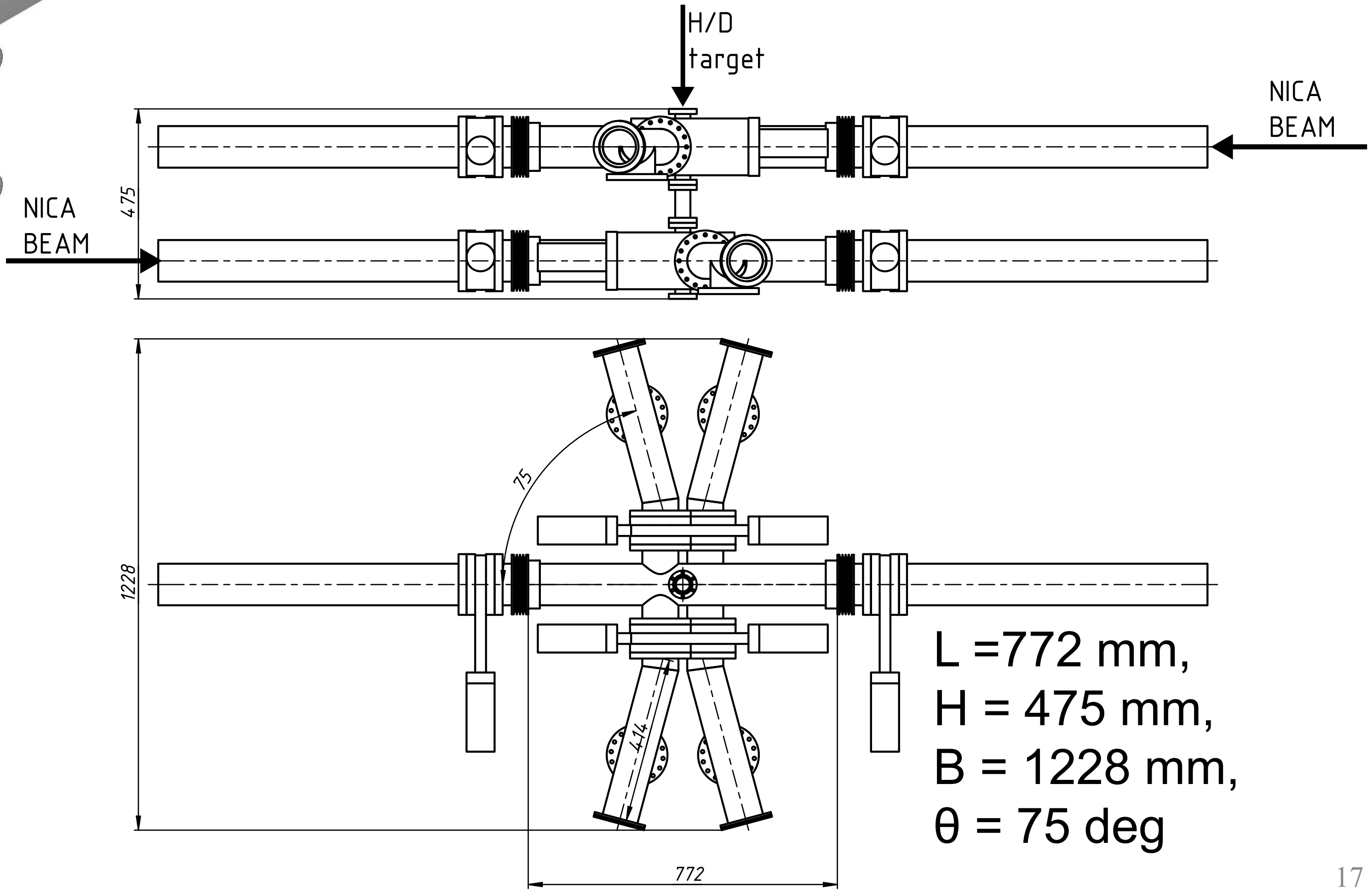
Thank you for your attention!

APol interaction box



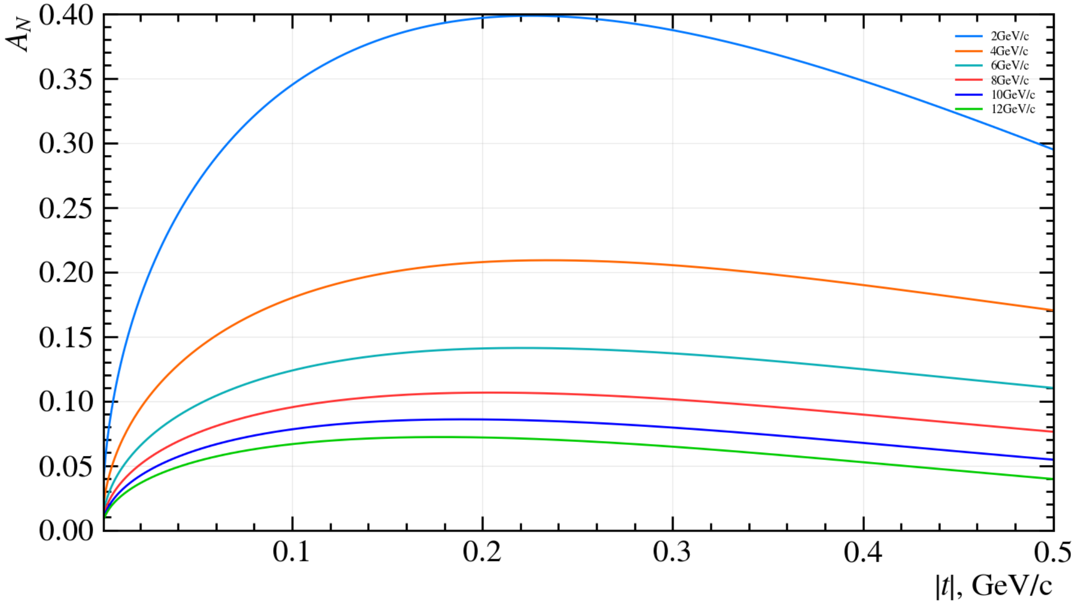
APol interaction box 3D Model

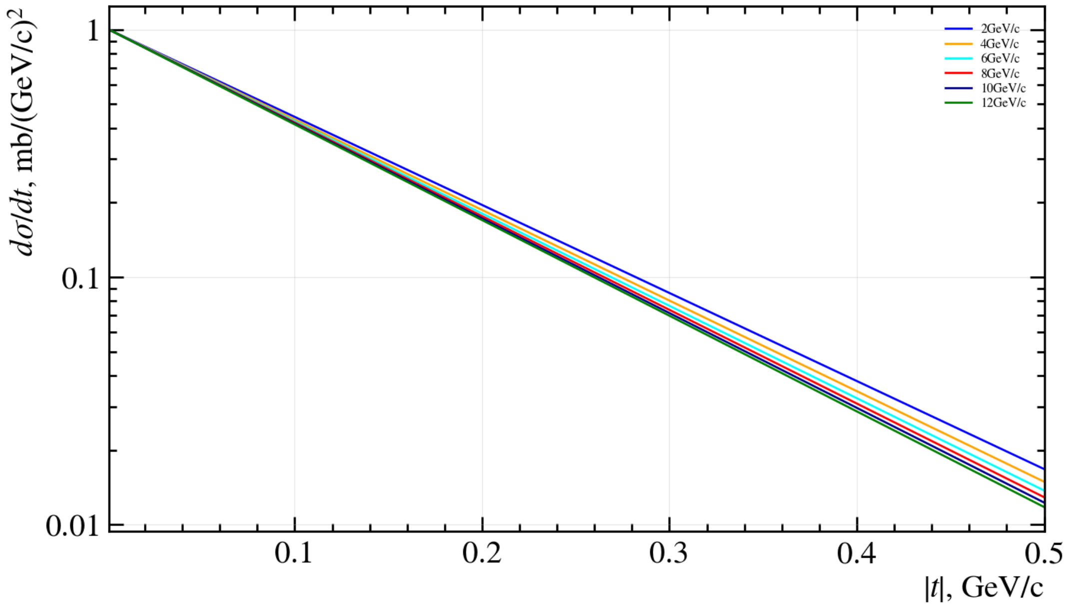
General assembly drawing of the APol interaction box

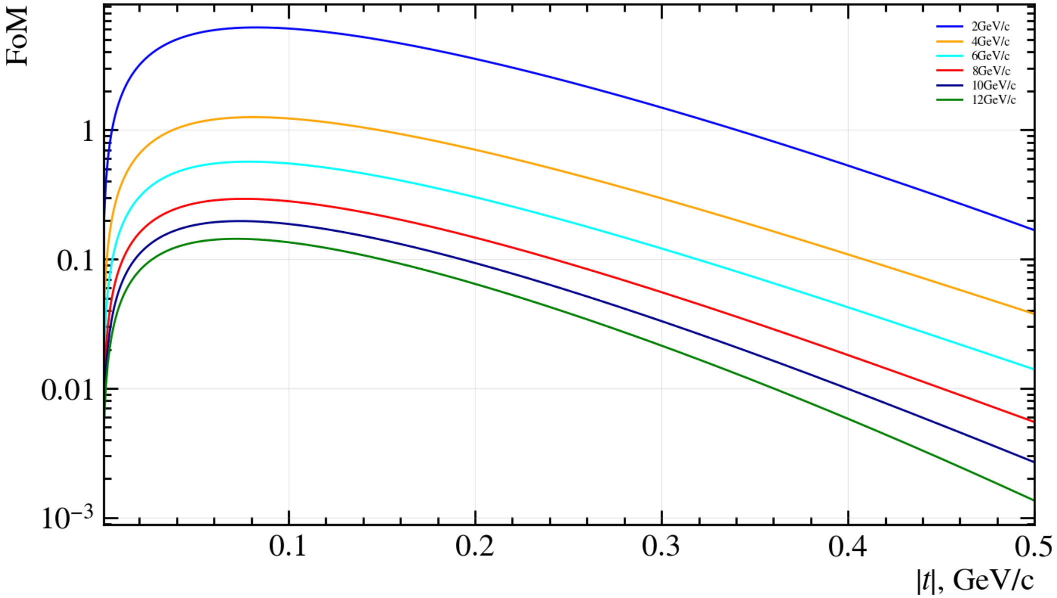


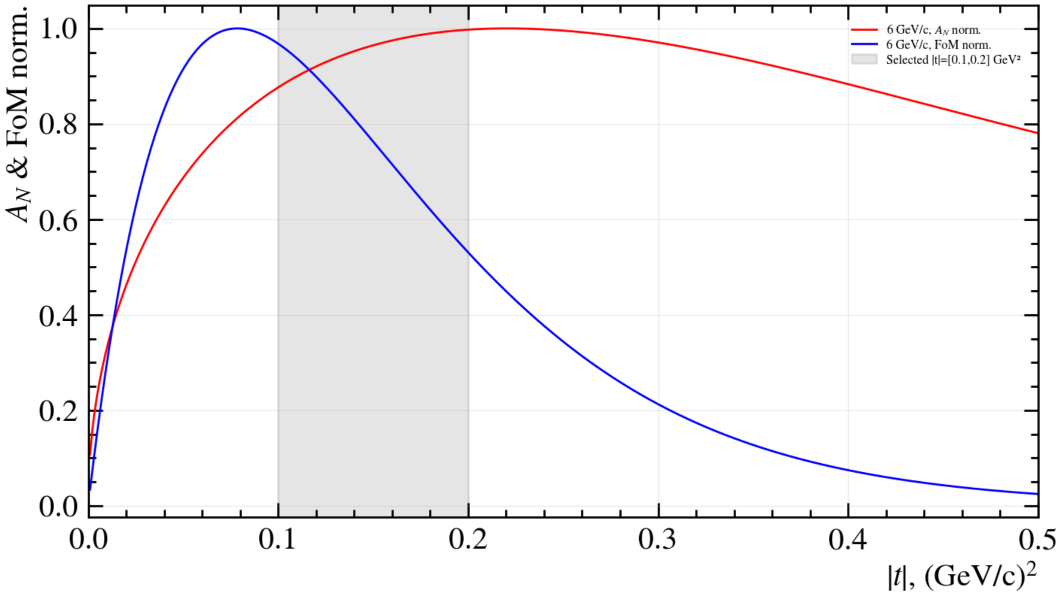
L =772 mm,
H = 475 mm,
B = 1228 mm,
θ = 75 deg

The operating principle: analyzing power and scattering asymmetry



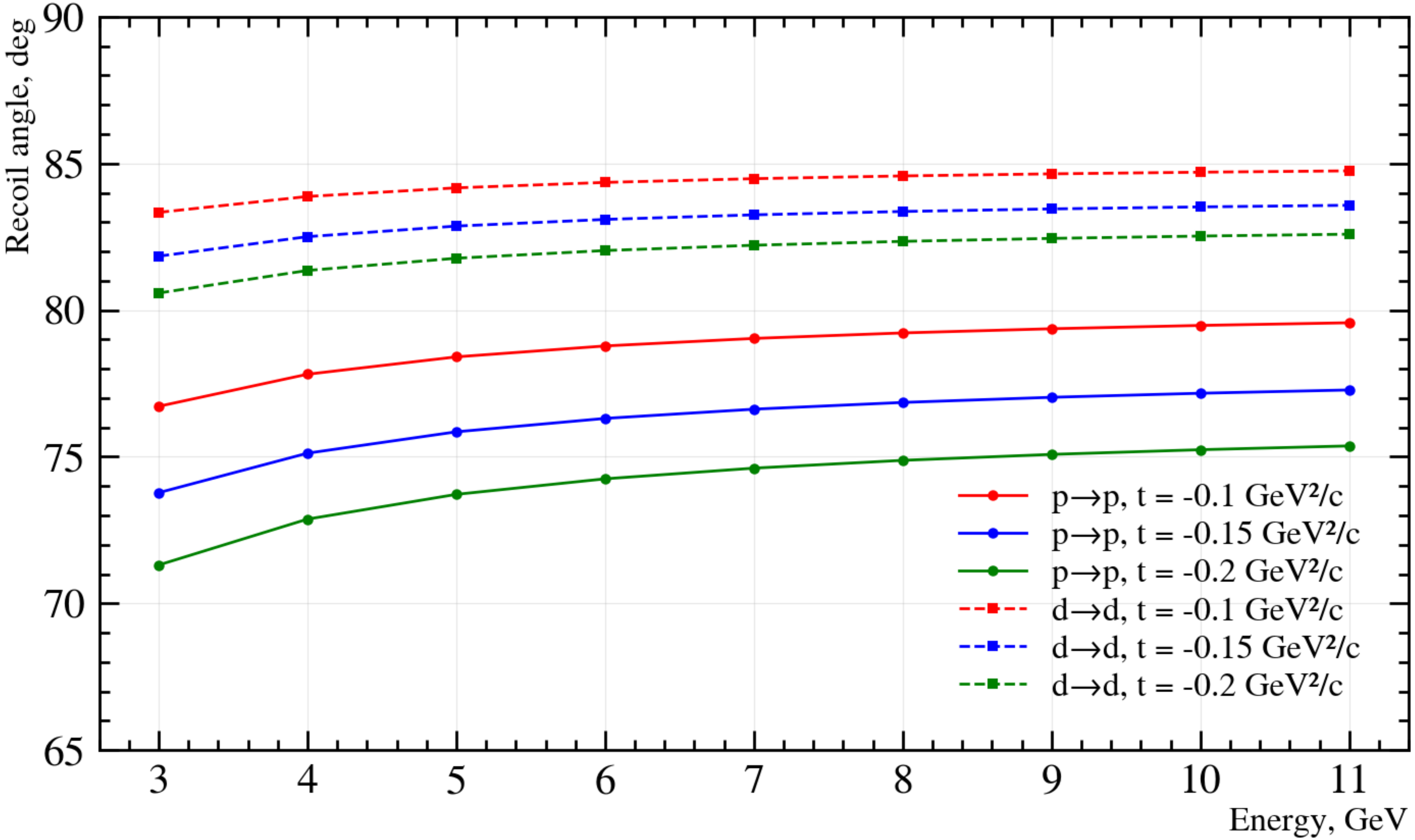






https://doi.org/10.1155/2015/914170

Proton/deuteron scattering angle



$$t = -4\left(p^* * \sin\frac{\theta}{2}\right)^2$$

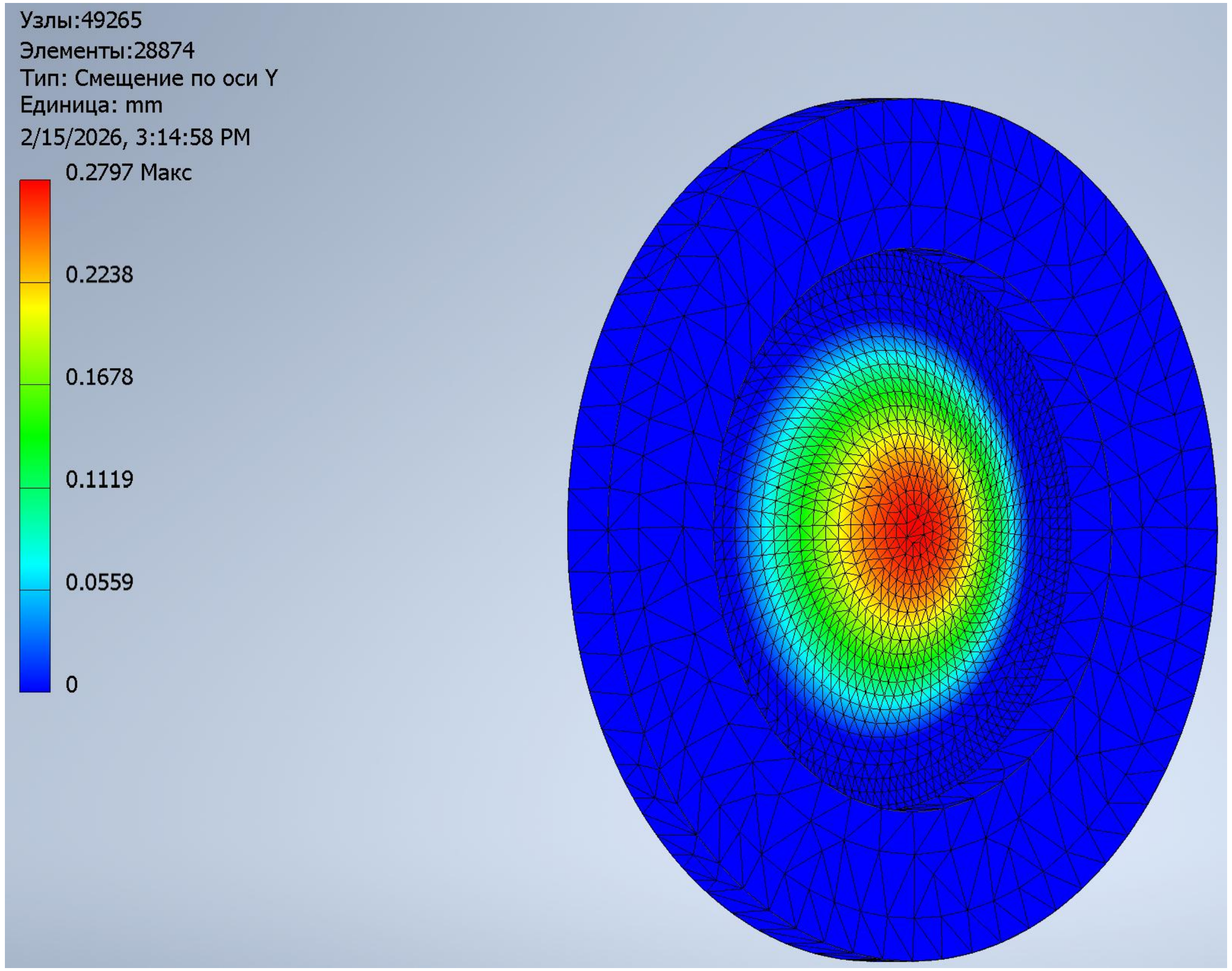
$$\tan\vartheta = \frac{p^* * \sin\theta}{\gamma_{cm}(\beta_{cm}E_{cm} - p^* * \cos\theta\ )}$$

$$\gamma_{cm} = \frac{E+m}{\sqrt{s}}$$

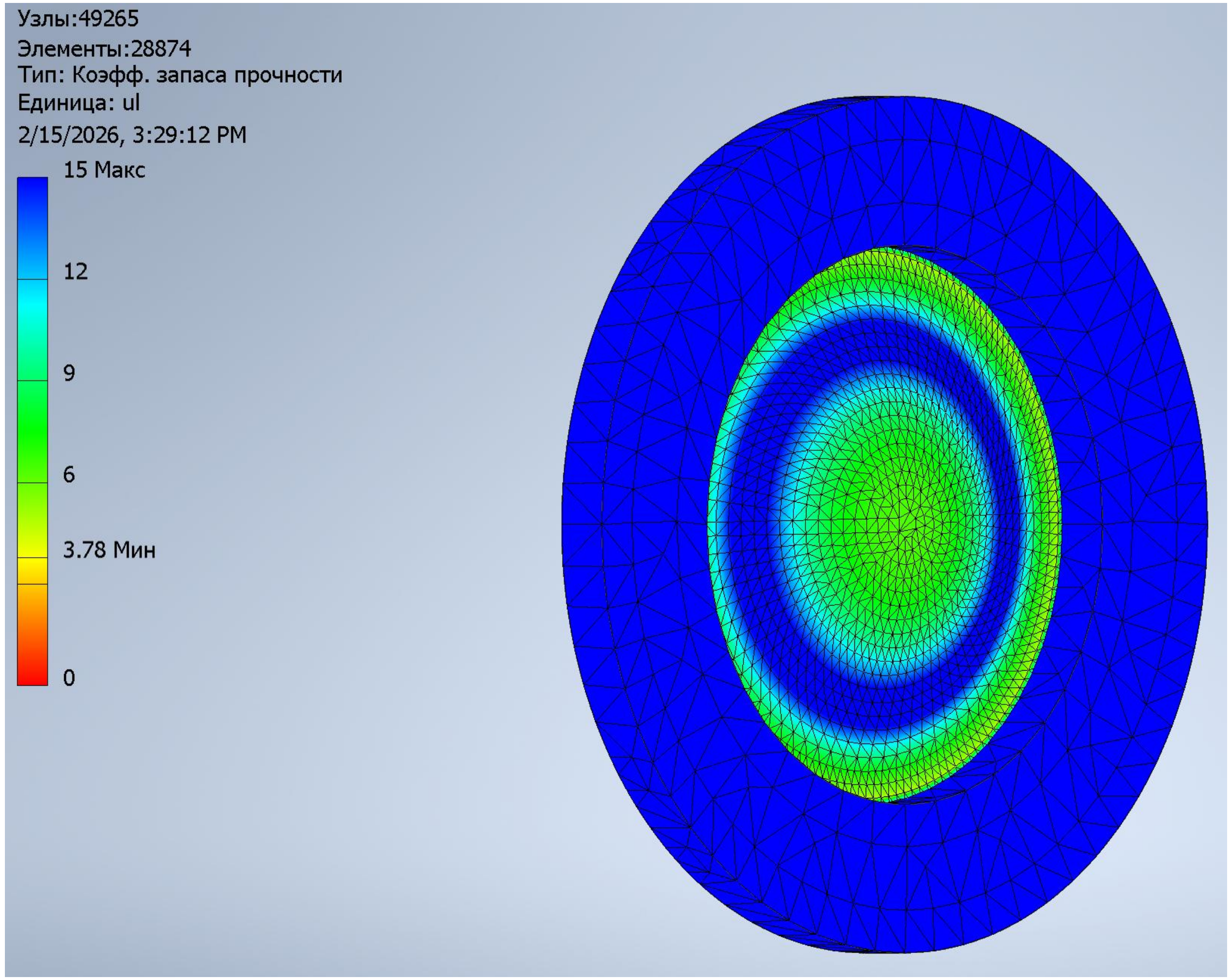
$$\beta_{cm} = \frac{p}{E}$$

p^* is the particle momentum in the center-of-mass frame (CM frame), θ is the scattering angle in the CM frame, and $p_\perp$ is the transverse momentum. The emission angle of the recoil particle in the CM frame is 180° - θ .ϑ is the angle in the laboratory coordinate system

Calculation of the membrane safety margin

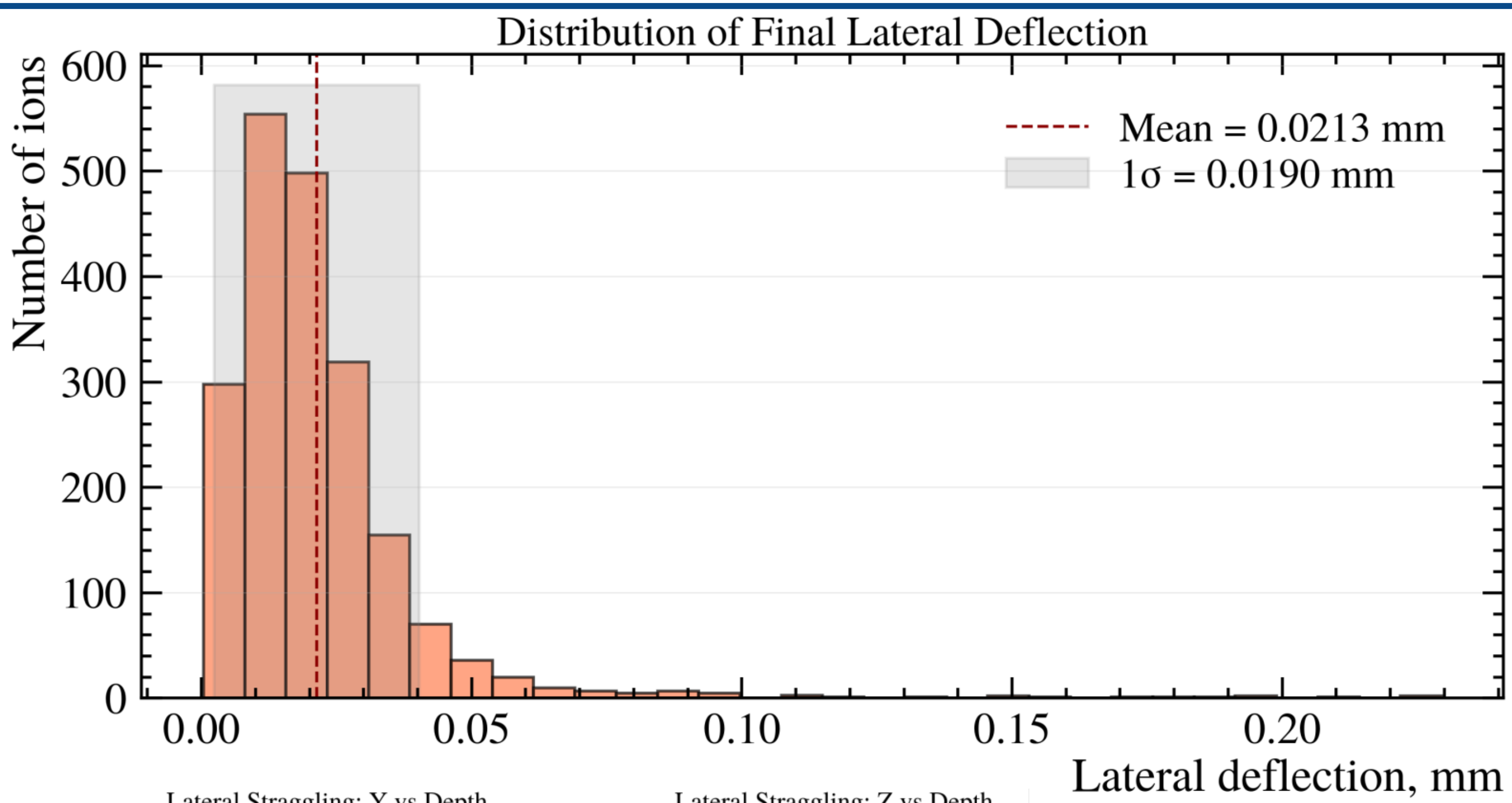


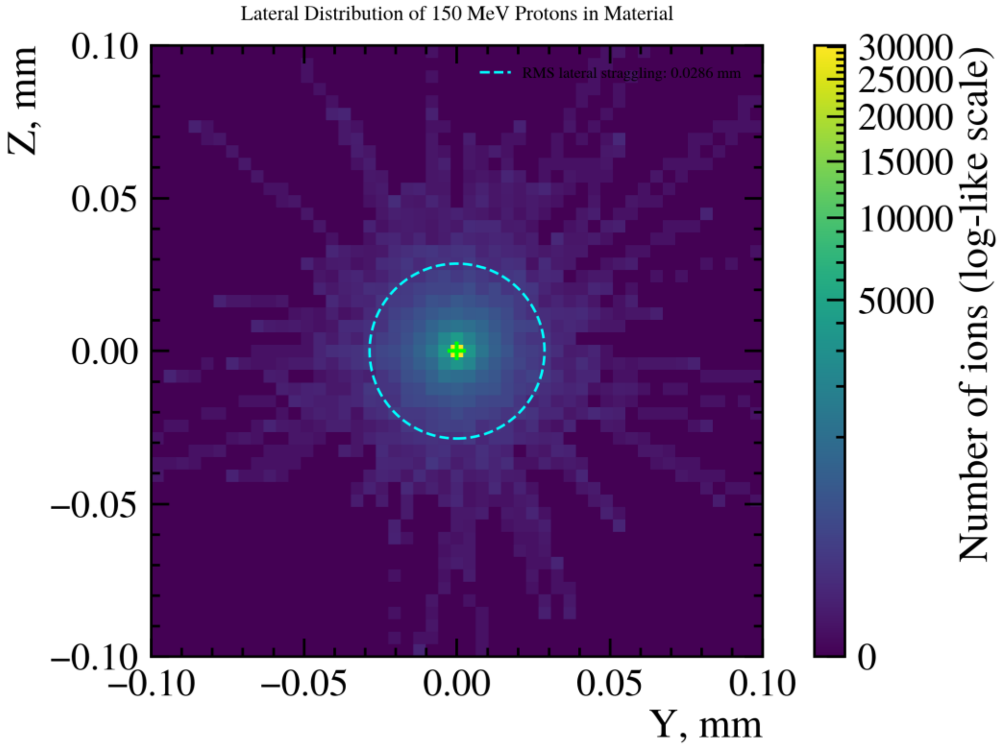
Calculation of the membrane displacement along the pressure axis
Pressure of 1 bar
Maximum displacement of 0.28 mm

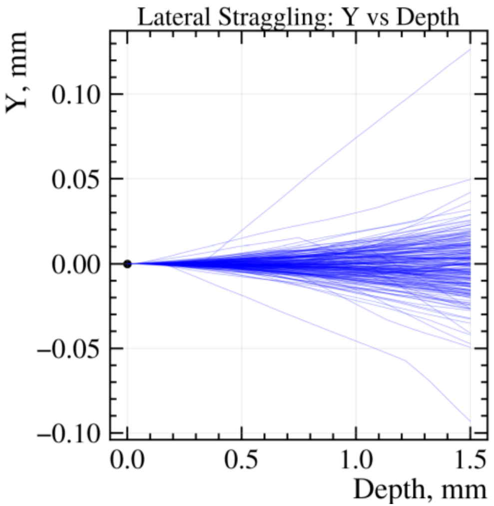


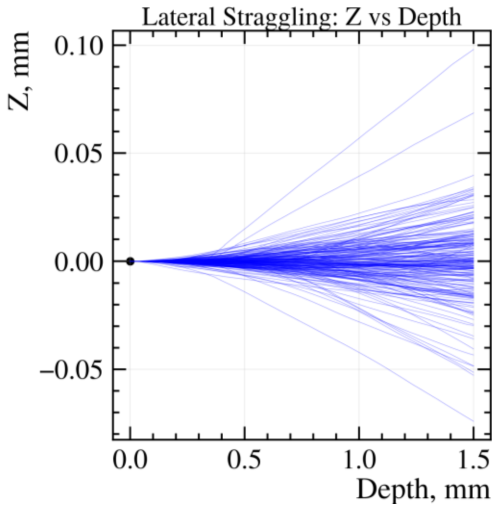
Calculation of the membrane safety margin
Pressure of 1 bar
Minimum safety margin of 3.48 (unitless)

Mean longitudinal straggling in titanium





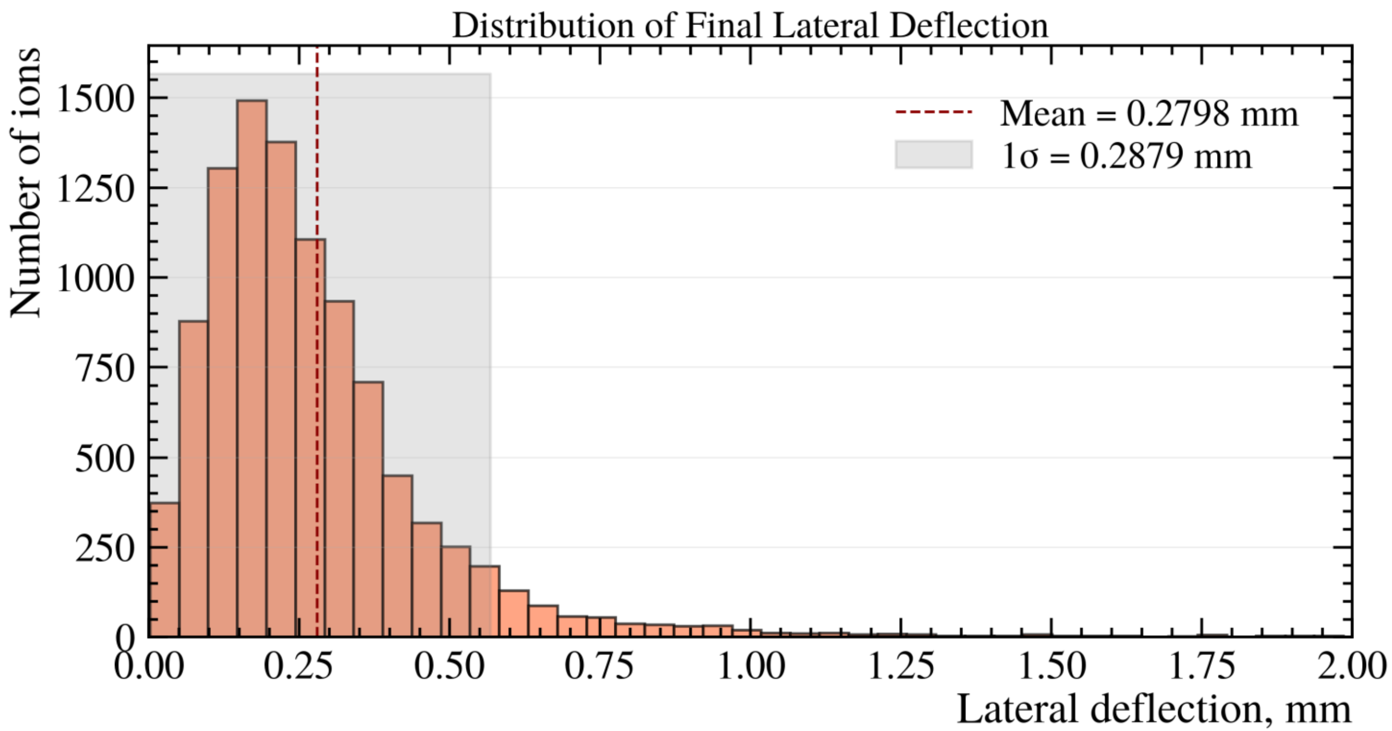


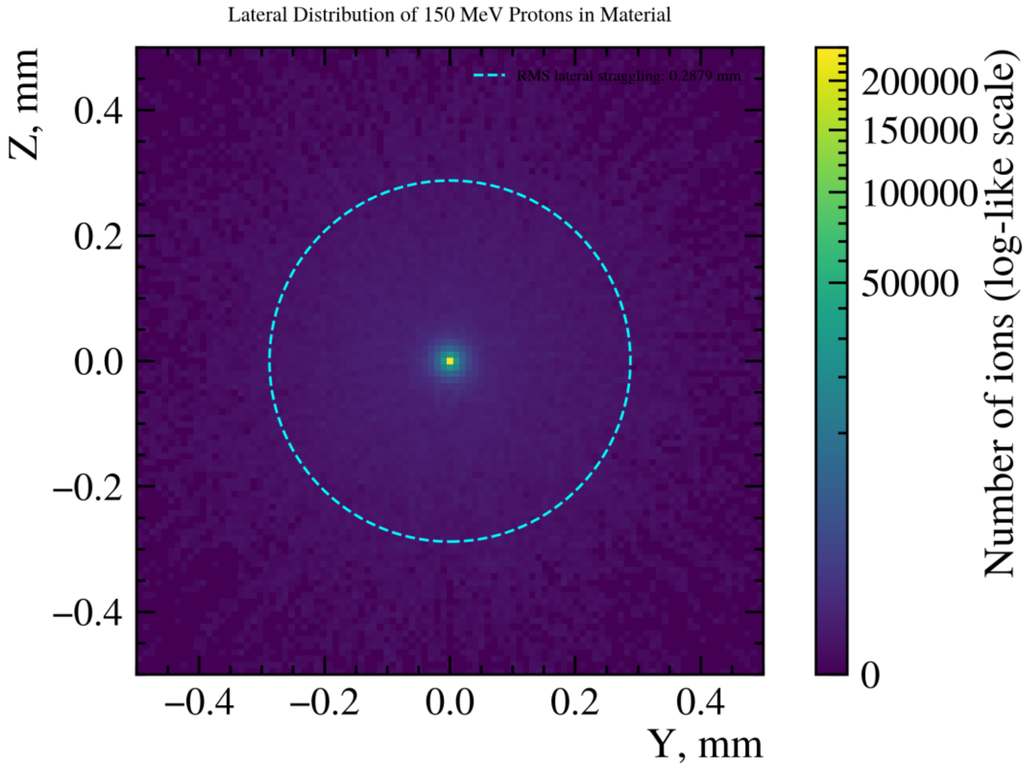


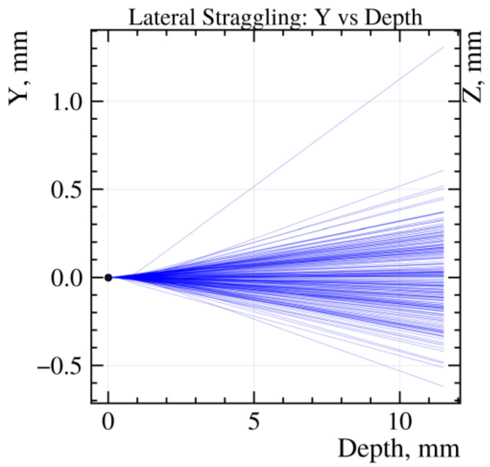
$$\left\langle \frac{dE}{dx} \right\rangle = 3.2 \pm 0.5\ MeV/mm$$

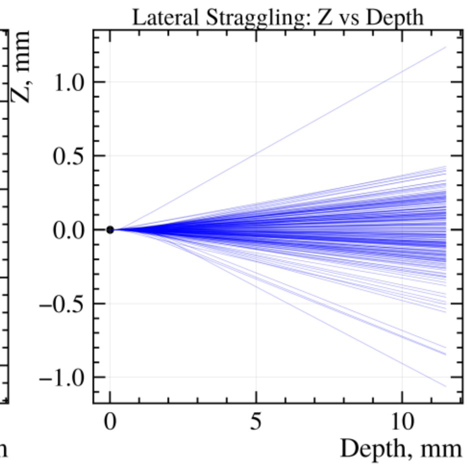
Mean lateral straggling $= 0.0213 \pm 0.0190\ mm$

Mean longitudinal straggling in titanium and in air





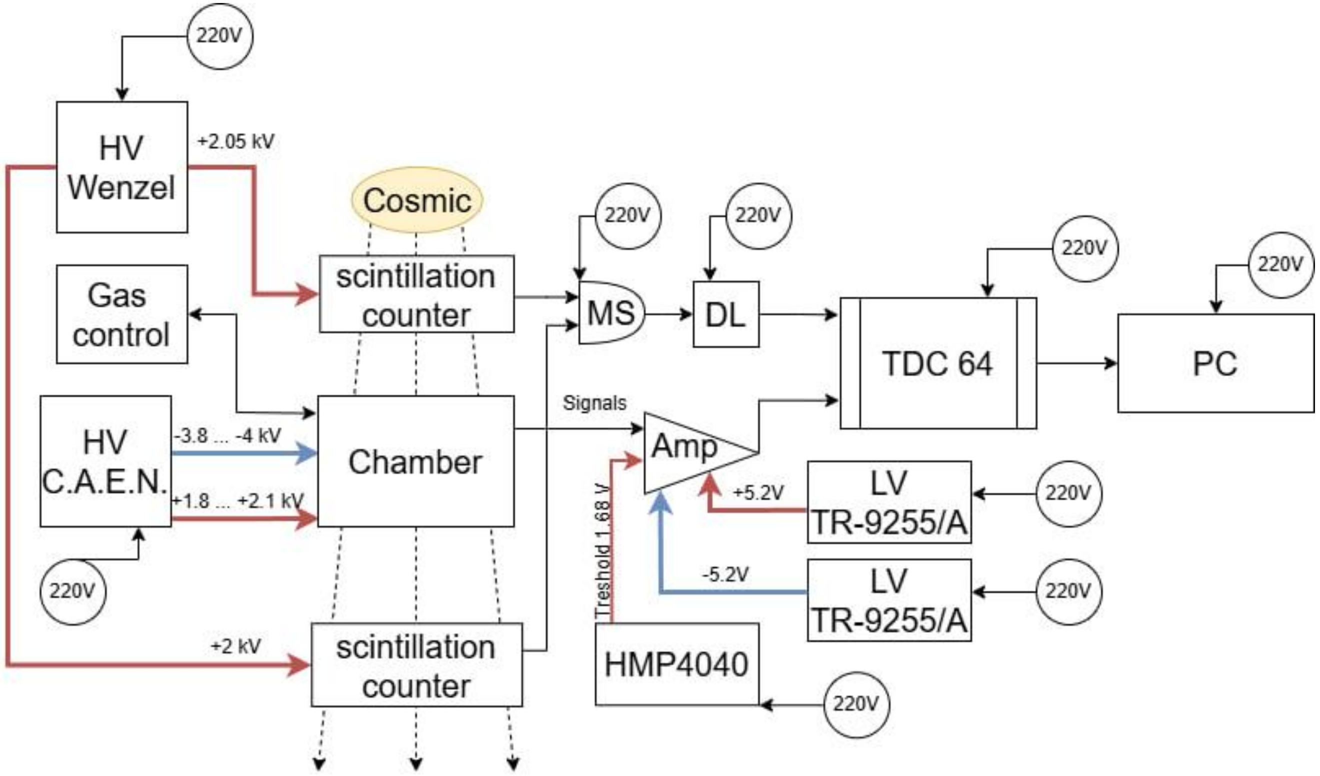




$$\left\langle \frac{dE}{dx} \right\rangle = 2.6 \pm 1.28\ MeV/mm$$

Mean lateral straggling $= 0.283 \pm 0.287\ mm$

Drift chamber



LV - low voltage source

HV - high voltage source

TDC - time to digital converter

DL - delay scheme

MS - matching scheme

Состав газовой смеси:
Ar - 55
$Ar+C_2H_5OH$ - 35
Iso - 20

•DOI: 10.1134/S1063779624700758

•DOI: 10.1016/0029-554X(77)90326-3

Measurement time estimate

Ohlsen G.G. "Polarization Transfer and Spin Correlation Experiments", Reports on Progress in Physics, 1972

$R = L \cdot \sigma_{\mathrm{FoM}} \cdot \varepsilon$ - the event rate

ε - the detection efficiency

L - the luminosity

$\sigma_{\mathrm{FoM}} = \int_{t_{min}}^{t_{max}} A_n^2 \cdot \frac{d\sigma_{el}}{dt} dt$ -the figure-of-merit cross section

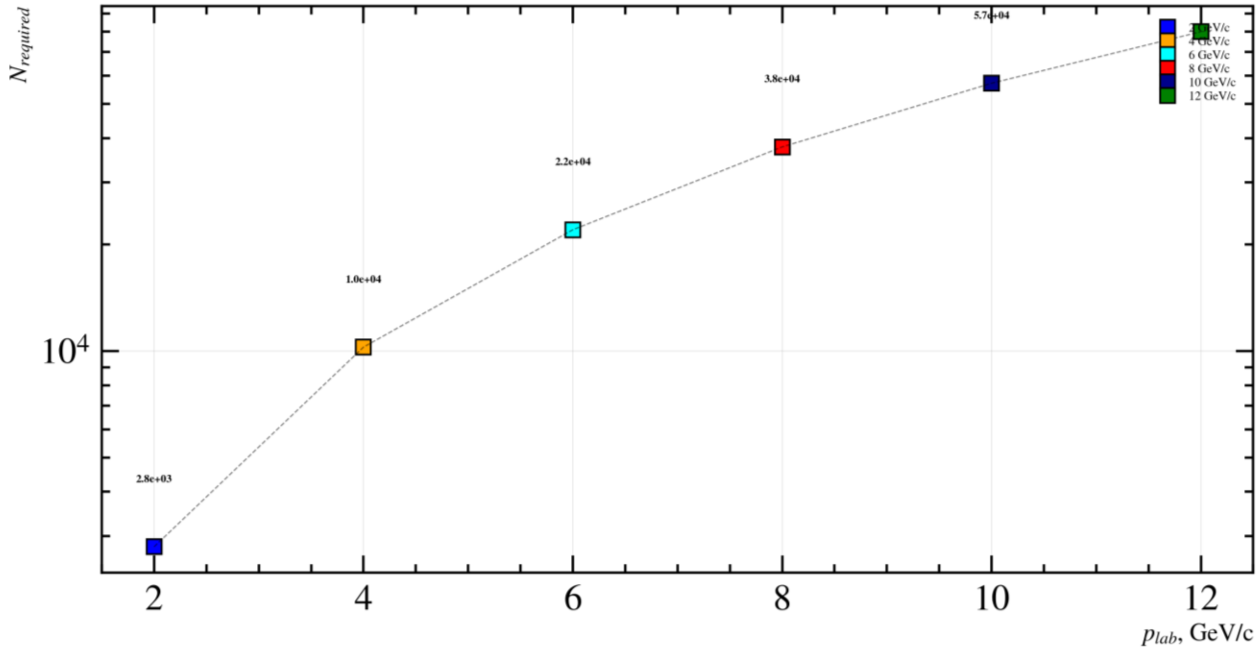
$N_{\mathrm{req}} = \frac{1}{A_N^2 \cdot (0.05)^2} = (0.05 \cdot A_N)^{-2} = R \cdot T$ - the number of the events needed to measure AN with the accuracy of 5%

$T = \frac{N_{\mathrm{req}}}{R} = \frac{1}{L \cdot A_N^2 \cdot (0.05)^2 \cdot \int \frac{A_n^2 d\sigma}{dt} dt \cdot \varepsilon}$ - the time needed to measure AN with the accuracy of 5%.

p_lab (GeV/c)	<A_N>	max(A_N)	σ_el (mb)	σ_FoM (mb)	N_required (5%)	Rate (s^{-1})	Time (s)
2	0.3782	0.3968	3.485329	0.49039717	2797.00	2.21E+03	1.27
4	0.1975	0.2076	2.555263	0.09795553	10255.00	4.41E+03	2.33
6	0.1348	0.1407	2.410361	0.0430866	22020.00	1.94E+03	11.35
8	0.1029	0.1065	2.062802	0.02154839	37753.00	9.70E+02	38.92
10	0.0837	0.0858	2.035945	0.01408132	57145.00	6.34E+02	90.13
12	0.0707	0.0721	2.011782	0.00997115	79931.00	4.49E+02	178.02

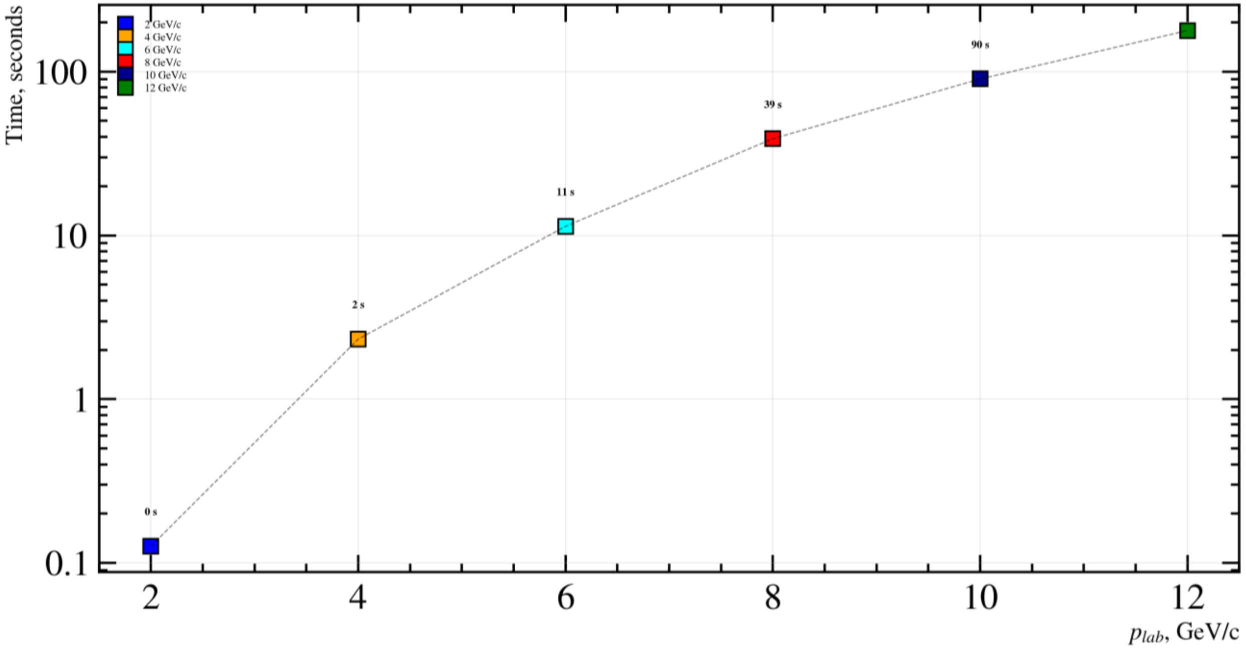
Cross-sections and analizing powers: Spinka H, Colton E, Ditzler W R, Halpern H, Imai K, Stanek R, Tamura N, Theodosiou G, Toshioka K and Underwood D 1983 NIMA 211 239-261

Measurement time estimate

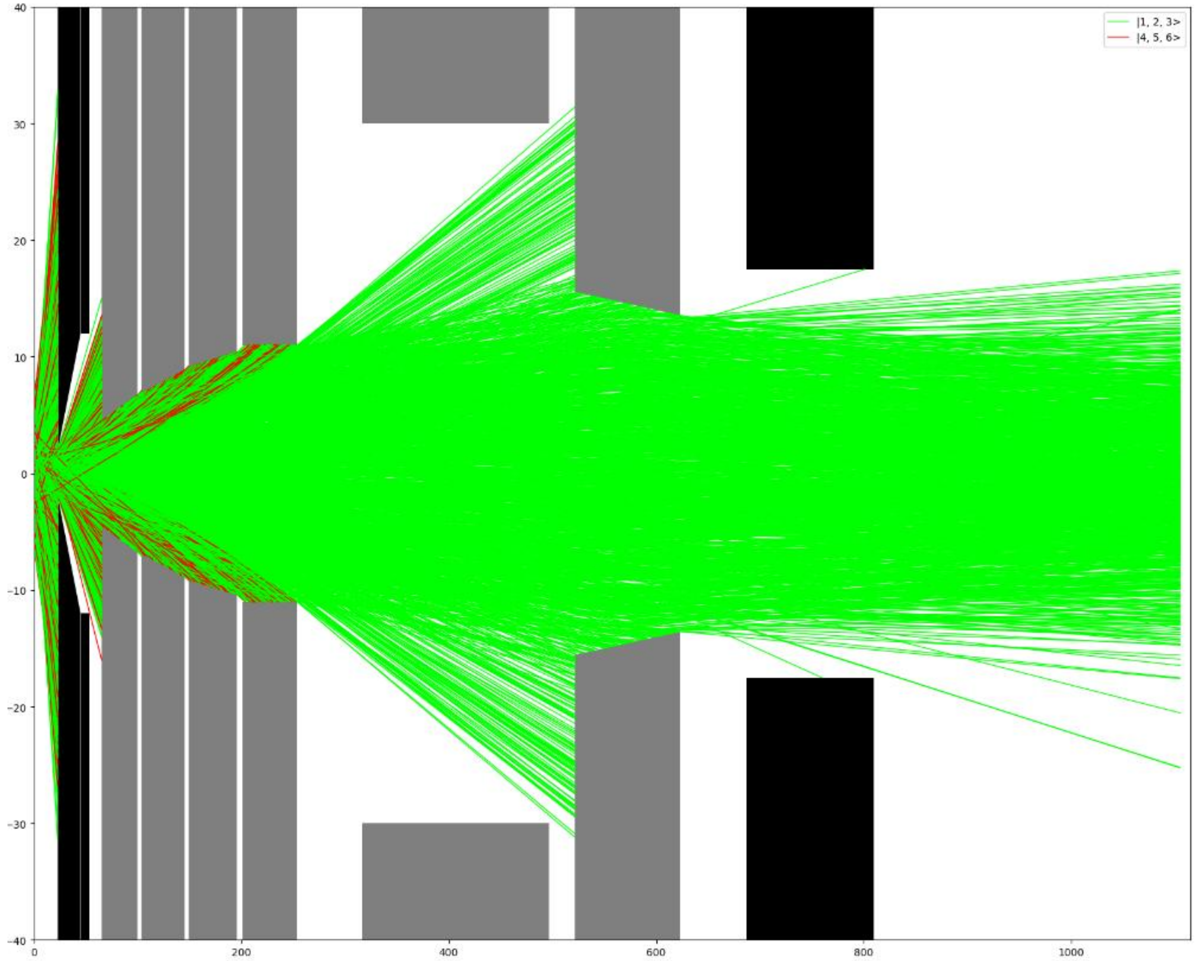


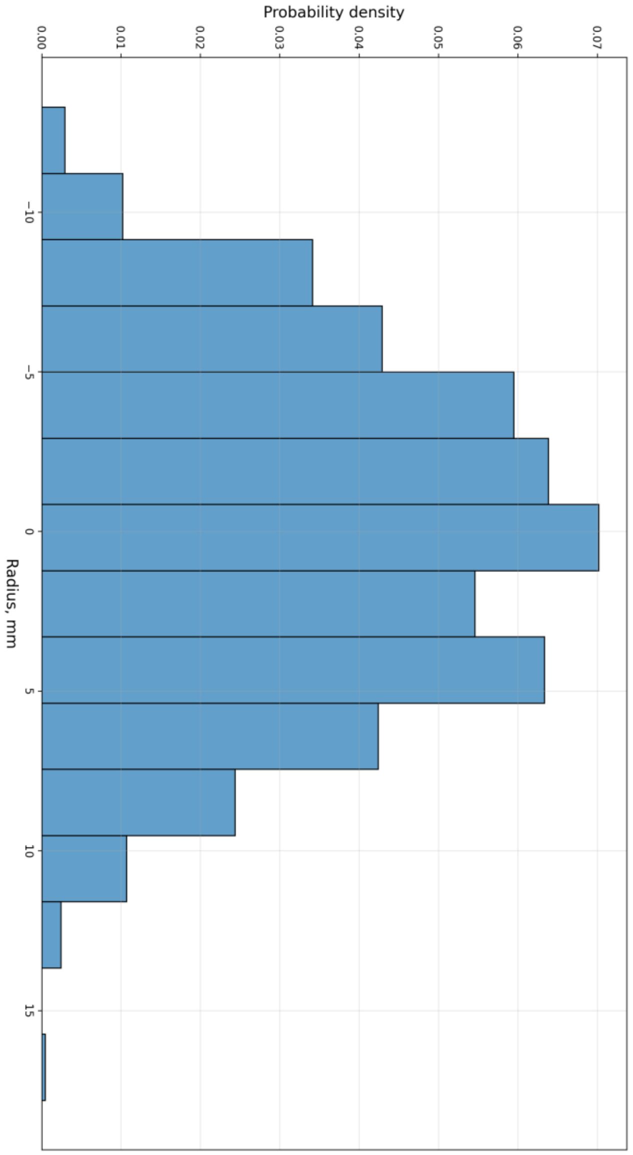
Dependence of the number of events required to measure the analyzing power with 5% accuracy on the momentum of incident protons

Dependence of the event collection time required to measure the analyzing power with 5% accuracy on the momentum of incident protons



Calculation atomic beam profile





$$\text{Intensity} = \frac{N_{end}}{N_{start}} * 100\%$$

Intensity_p = $(0.21 \pm 0.02)\%$

Intensity_d = $(0.09 \pm 0.01)\%$

Dencyti H_jet = $(1.52 \pm 0.15) * 10^{12}$

Dencyti D_jet = $(0,643 \pm 0.07) * 10^{12}$

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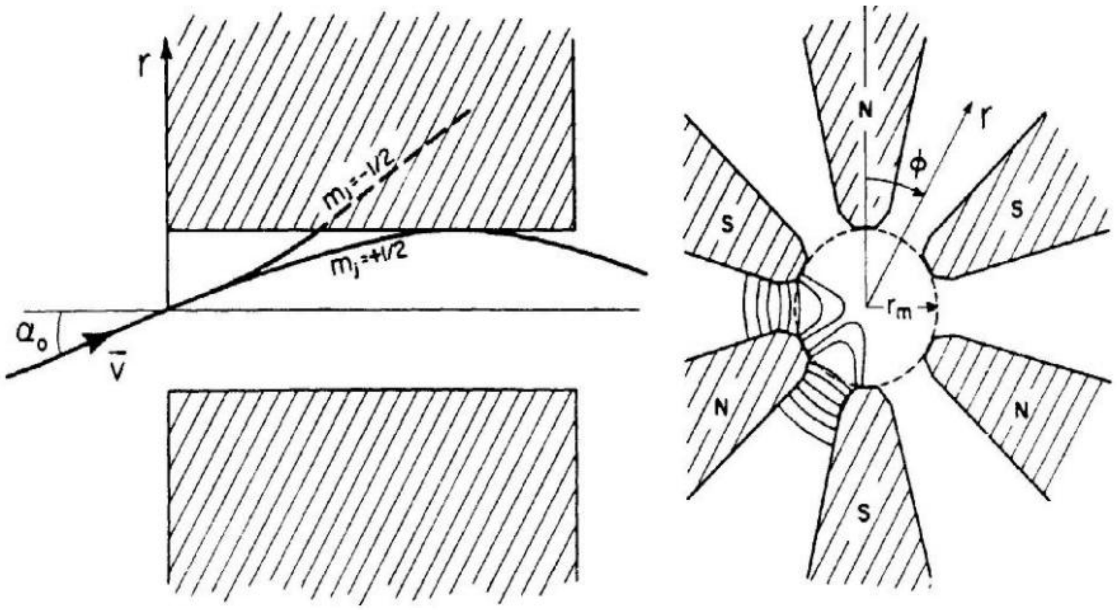
Multipolar magnetic system



A sextuple magnet used in ABS. An atom flying into a magnet with r = 0 at an angle α_0 is shown on the left; several lines of force are shown on the right

1. $$\frac{d^2\vec{r}^{\,1}}{dt^2} = \frac{1}{m}B_0\left(\frac{N}{2}-1\right)\frac{(\mu_e+\mu_d)}{r_0^{\frac{N}{2}-1}}\, r^{\frac{N}{2}-2}$$

2. $$\frac{d^2\vec{r}^{\,2}}{dt^2} = \frac{1}{2m}\left(\mu_d - \frac{-A_d\mu_c+\mu_c^2B}{\sqrt{9A_d^2-2A_d\mu_cB+\mu_c{}^2B^2}}\right)B_0\left(\frac{N}{2}-1\right)\frac{r^{\frac{N}{2}-2}}{r_0^{\frac{N}{2}-1}}$$

3. $$\frac{d^2\vec{r}^{\,3}}{dt^2} = \frac{1}{2m}\left(-\mu_d - \frac{A_d\mu_c+\mu_c^2B}{\sqrt{9A_d^2+2A_d\mu_cB+\mu_c{}^2B^2}}\right)B_0\left(\frac{N}{2}-1\right)\frac{r^{\frac{N}{2}-2}}{r_0^{\frac{N}{2}-1}}$$

4. $$\frac{d^2\vec{r}^{\,4}}{dt^2} = -\frac{1}{m}B_0\left(\frac{N}{2}-1\right)\frac{(\mu_e+\mu_d)}{r_0^{\frac{N}{2}-1}}\, r^{\frac{N}{2}-2}$$

5. $$\frac{d^2\vec{r}^{\,5}}{dt^2} = \frac{1}{2m}\left(-\mu_d + \frac{A_d\mu_c+\mu_c^2B}{\sqrt{9A_d^2+2A_d\mu_cB+\mu_c{}^2B^2}}\right)B_0\left(\frac{N}{2}-1\right)\frac{r^{\frac{N}{2}-2}}{r_0^{\frac{N}{2}-1}}$$

6. $$\frac{d^2\vec{r}^{\,6}}{dt^2} = \frac{1}{2m}\left(\mu_d + \frac{-A_d\mu_c+\mu_c^2B}{\sqrt{9A_d^2-2A_d\mu_cB+\mu_c{}^2B^2}}\right)B_0\left(\frac{N}{2}-1\right)\frac{r^{\frac{N}{2}-2}}{r_0^{\frac{N}{2}-1}}$$

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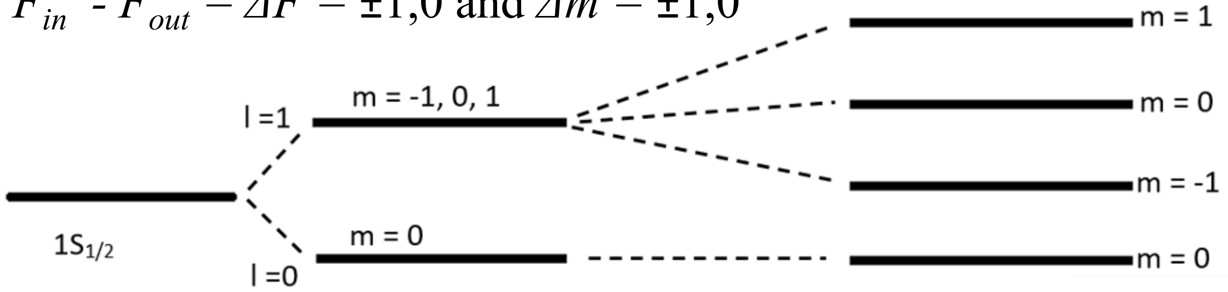
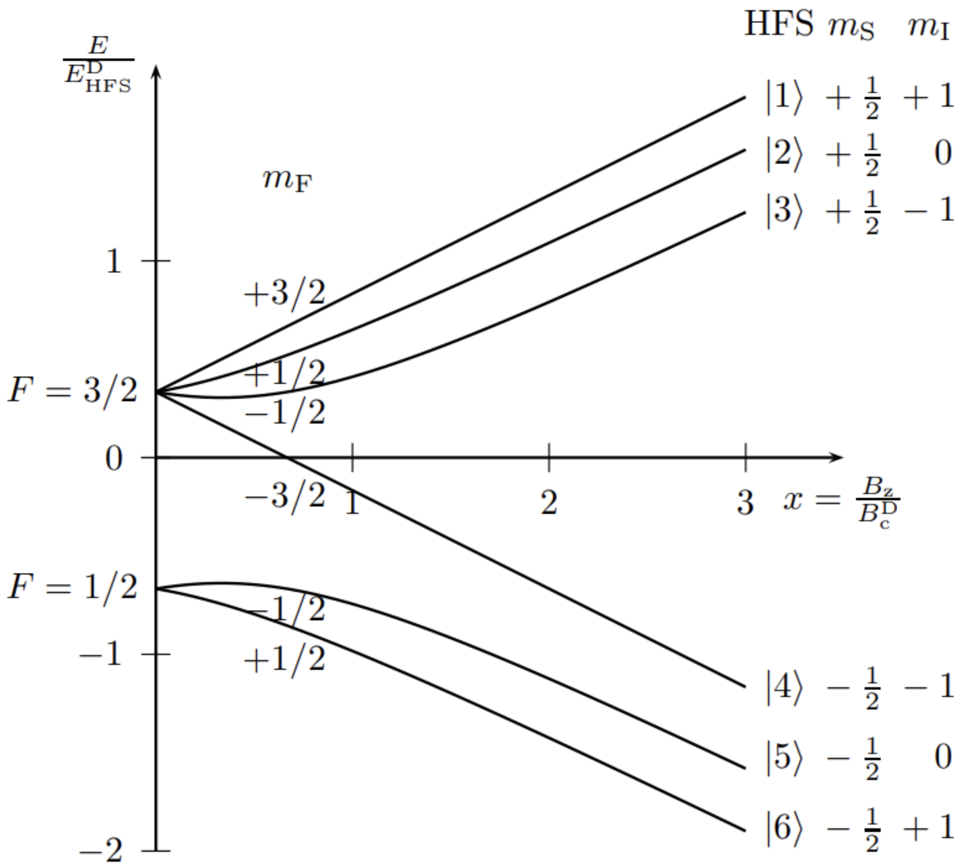
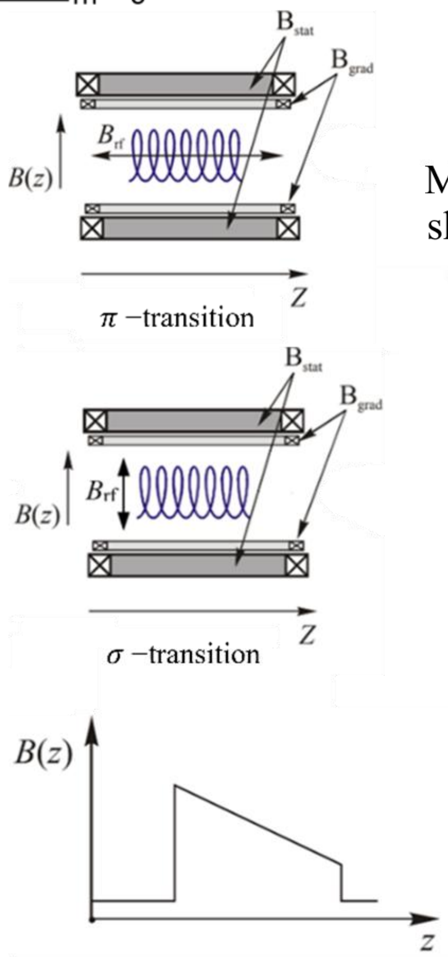
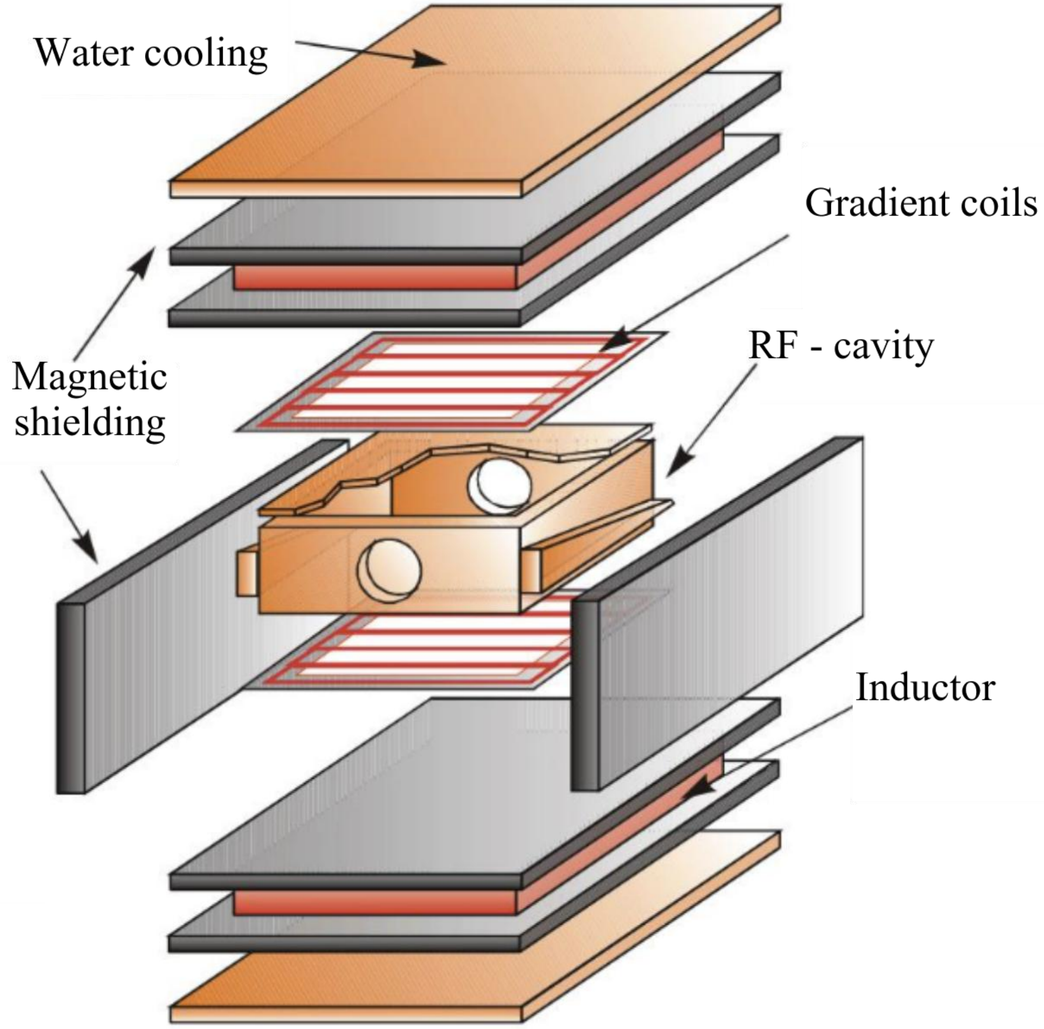
Radio - frequency transition cells

$F_{in} - F_{out} = \Delta F = \pm 1{,}0$ and $\Delta m = \pm 1{,}0$









Atomic beam measurement

- **Compression tube** – absolute method for measuring the integral beam intensity (atoms/s) by recording the pressure rise rate in a closed volume due to atomic recombination into molecules; serves as the primary calibration standard.
- **Quadrupole mass spectrometer (QMS)** – relative method for separate detection of atomic and molecular components, enabling determination of the dissociation degree; calibration is required for absolute values.
- **Time-of-flight mass spectrometer (TOF-MS)** – provides parallel detection of all masses in a single cycle, eliminating errors from intensity drift during scanning; well suited for dynamic measurements.
- **Calorimetric wire detector** – measures the 2D beam profile via the thermal effect of heterogeneous atomic recombination on a metal surface (Au/W); offers high spatial resolution.
- **Thin films of transition-metal oxides (MoO_3, WO_3)** – qualitative method for profile visualisation: atomic hydrogen reduces the oxides with a colour change, allowing fast assessment of beam position and shape during alignment.
- **Breit–Rabi polarimeter** – measures the nuclear and electron spin polarization of the atomic beam via RF-induced transitions between hyperfine sublevels, followed by magnetic spin separation in sextupole lenses and detection with a quadrupole mass spectrometer (QMS). By sequentially sweeping the RF frequency and recording the intensity spectrum, the populations of all four hyperfine states are extracted from a system of equations, giving absolute values of both nuclear and electronic polarization (dimensionless, from –1 to +1). This method is essential for characterising spin-dependent processes and does not require external calibration for polarisation, though the QMS intensity calibration is needed for absolute flux.

- **Combined use** of these methods provides comprehensive beam characterisation: intensity, dissociation degree, spatial distribution and nuclear polarization.