Towards a first measurement of the free neutron bound beta decay hydrogen atoms at a high flux beam reactor throughgoing beam tube

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Two- body neutron decay

$n \rightarrow H + \overline{\nu}$

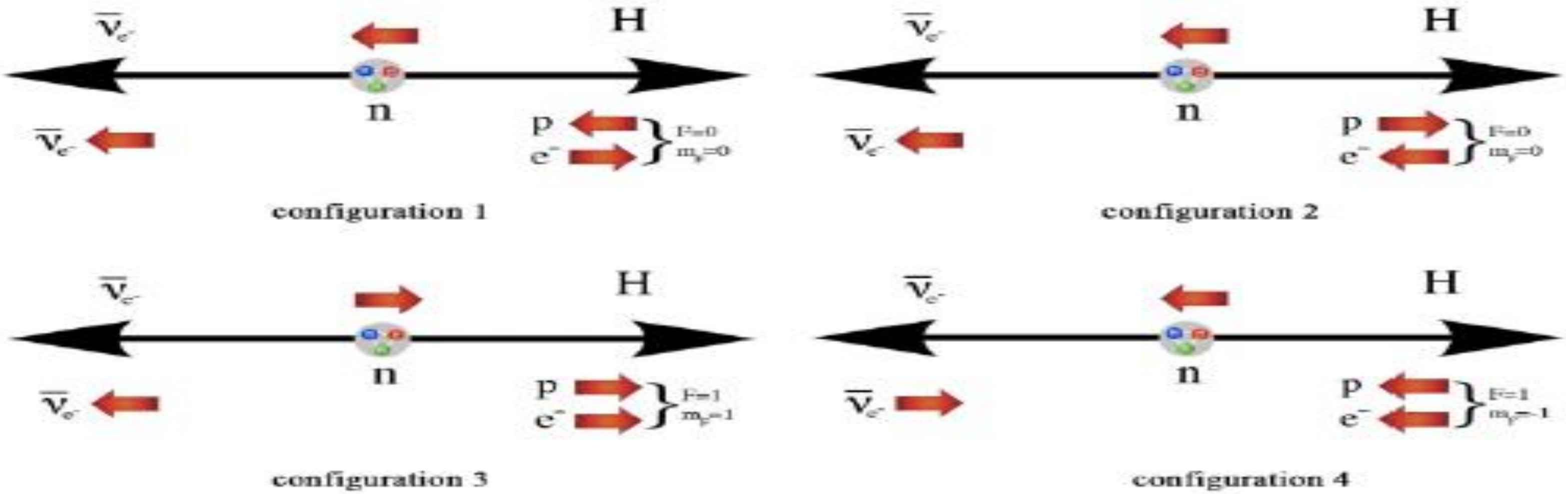
$T_H = 325.7$ eV, $\beta = 0.83 \cdot 10^{-3}$, BR $= 4 \cdot 10^{-6}$

Four hyperfine spin states exist

(L. L. Nemenov, Sov. J. Nucl. Phys. 31, 115 (1980), L. L. Nemenov and A. A. Ovchinnikova, Sov. J. Nucl.Phys. 31, 659 (1980), W. Schott et al., Eur. Phys. J. A30, 603 (2006))

83.2 % H(1s), 10.4 % H(2s)

Hyperfine spin states



Configurations 1 – 3 within SM ($H(\overline{\nu})$ = 1), population probabilities (44.14 %, 55.24 %, 0.622 % for gS = gT = 0) given by X = (1 + gS) / (λ - 2 gT), λ = gA / gV = -1.2761 (+14 −17) (D. Mund, B. Märkisch, M. Deissenroth, J. Krempel, M. Schumann, H. Abele, A. Petoukhov, and T. Soldner, Phys. Rev. Lett. 110, 172502 – Published 23 April 2013)

table 1

i	$\bar{\nu}$	n	p	e^-		$W_i(\%)$	F	m_F	$\|m_S m_I\rangle$
1	$\leftarrow$	$\leftarrow$	$\leftarrow$	$\rightarrow$	Fe/GT	$44.14 \pm .05$	0,1	0	$\|+-\rangle$
2	$\leftarrow$	$\leftarrow$	$\rightarrow$	$\leftarrow$	GT	$55.24 \pm .04$	0,1	0	$\|-+\rangle$
3	$\leftarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	Fe/GT	$.622 \pm .011$	1	1	$\|++\rangle$
4	$\rightarrow$	$\leftarrow$	$\leftarrow$	$\leftarrow$	Fe/GT	0.	1	-1	$\|--\rangle$
2’	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\leftarrow$	Fe/GT	0.	0,1	0	$\|-+\rangle$
1’	$\rightarrow$	$\rightarrow$	$\leftarrow$	$\rightarrow$	GT	0.	0,1	0	$\|+-\rangle$

V-A, S,T added

$$A = \langle f|S|i\rangle \propto \Psi_n(0) G \cos\theta_c \bar{u}^m(p)\gamma_\alpha(1+\gamma_5)u^n(-q)\cdot$$

$$\cdot \quad \bar{u}^r(p_p)\gamma_\alpha(g_V + g_A\gamma_5)u^s(p_n)\delta(Q+q-p_n) \qquad (2)$$

$$dW_A \propto \Sigma A\bar{A}^\dagger \cdot \delta(Q+q-p_n)d\mathbf{Q}d\mathbf{q} \qquad (3)$$

$$W_A \propto \sum_{n=1}^{\infty} |\Psi_n(0)|^2 \propto n^{-3}(L=0) \qquad (4)$$

$$W_A \propto (G^2\cos^2\theta_c/a_B^3)(\Delta - m)^2(1+3\lambda^2) \qquad (5)$$

$$W_\beta \propto G^2\cos^2\theta_c\Delta^5(1+3\lambda^2) \qquad (6)$$

$$\Delta H \propto G\cos\theta_c \sum_{i=S,T} \bar{\psi}_p Q_i(g_i + g_i'\gamma_5)\psi_n\bar{\psi}_e Q_i\psi_{\bar{\nu}} \qquad (7)$$

$W_i, i = 1 ... 3$

$$W_1 = 2C((1-\lambda) + g_S + 2g_T)^2 \quad (8)$$

$$W_2 = 8C(\lambda - 2g_T)^2 \quad (9)$$

$$W_3 = 2C((1+\lambda) + g_S - 2g_T)^2 \quad (10)$$

$$\sum_{i=1}^{3} W_i = 1, C^{-1} = 4((1+g_S)^2 + 3(\lambda - 2g_T)^2) \quad (11)$$

table 2

Table 2. W_i(%) for various g_S and g_T.

config. i	$g_S = 0, g_T = 0$	$g_S = 0.1, g_T = 0$	$g_S = 0, g_T = 0.02$
1	44.114	46.44	43.40
2	55.24	53.32	55.82
3	.622	.238	.780
4	0.	0.	0.

$W_i, i = 1 \ldots 4, H_{\bar{\nu}}$

$$W_1 = \frac{(\chi - 1)^2}{2(\chi^2 + 3)}, W_2 = \frac{2}{\chi^2 + 3}, W_3 = \frac{(\chi + 1)^2}{2(\chi^2 + 3)},$$

$$\chi = (1 + g_S)/(\lambda - 2g_T)$$

$$Left - right\, symmetric\, V + A\, model\; x = \eta - \zeta, y = \eta + \zeta :$$

$$W_4 = \frac{(x + \lambda y)^2}{2(1 + 3\lambda^2 + x^2 + 3\lambda^2 y^2)}, H_{\bar{\nu}} = \frac{1 + 3\lambda^2 - x^2 - 3\lambda^2 y^2}{1 + 3\lambda^2 + x^2 + 3\lambda^2 y^2}$$

$$(J.Byrne, Eur.Phys.Lett.\mathbf{56}(2001)633)$$

$$for\, \zeta = 0, x = y = \eta = .036 : W_4 \approx \frac{\eta^2 (1 + \lambda)^2}{2(1 + 3\lambda^2)} = 8.1 \cdot 10^{-6}$$

$$H_{\bar{\nu}} \approx 1 - 2\eta^2 = 1 - \frac{4(1 + 3\lambda^2)}{(1 + \lambda)^2} \cdot W_4 = .997$$

aim

$$Present\,values: |g_S| \leq 6 \cdot 10^{-2} (C.L. 68\%),$$

(E. G. Adelberger et al., PRL 83(1999)1299).

$-0.0026 < g_T / g_A < 0.0024$ (C.L. 95 %)

(R. W. Pattie, Jr., et al. PRC 88, 048501 (2013)

$$\eta \leq .036, |\zeta| \leq .03 (C.L. 90\%)$$

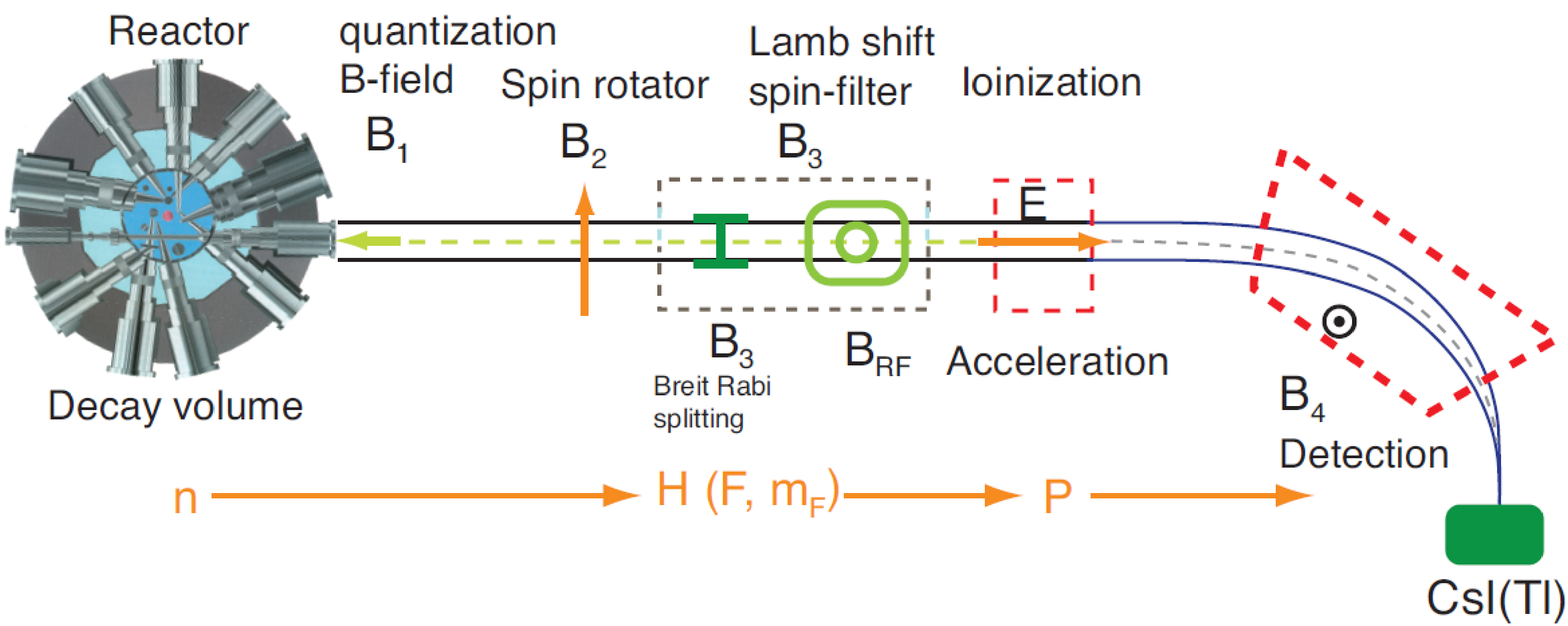
(A.Gaponenko et al., PR D71(2005)071101),

(J. R. Musser et al., PRL 94(2005)101805).

g_S upper limit should be reduced by a factor 10

H_ν should be measured within 10^{-3}

principal setup



Frm2 SR6 beam tube neutron and gamma flux

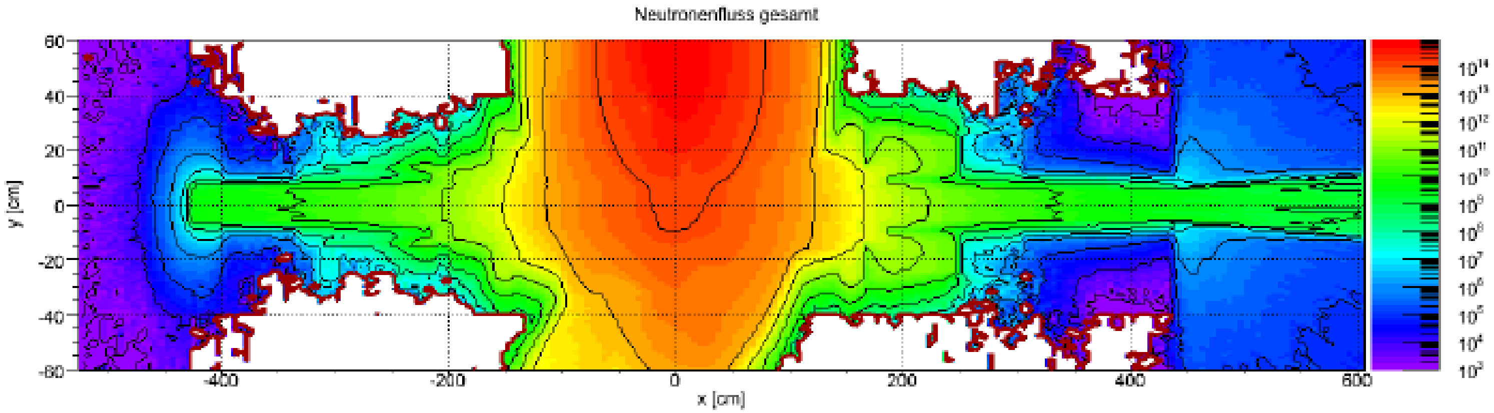


Abb. 28: Neutronenfluss in der horizontalen Ebene auf Höhe der Strahlachse des SR6

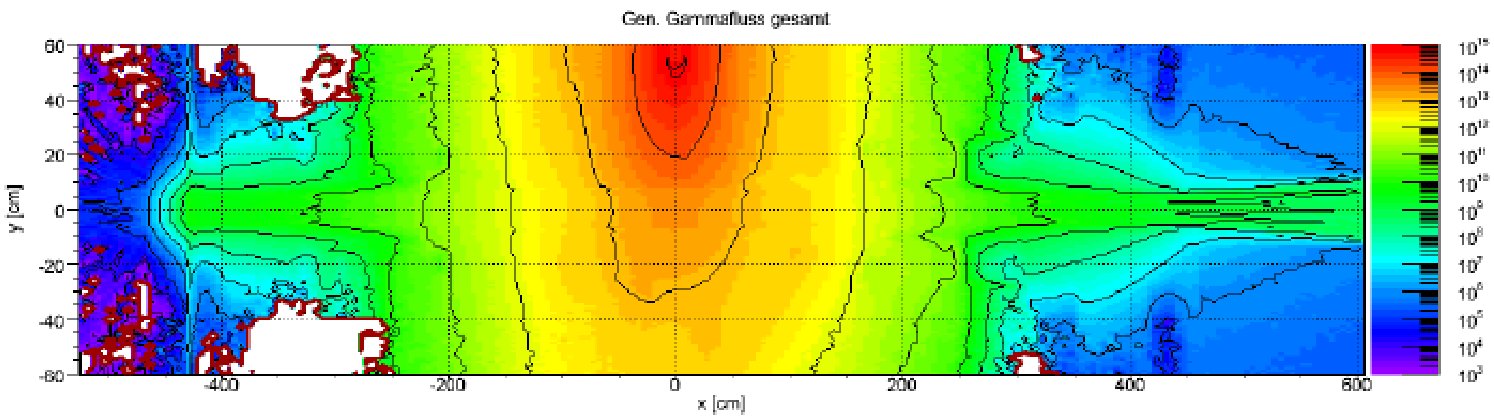


Abb. 29: Gammafluss in der horizontalen Ebene auf Höhe der Strahlachse des SR6

$T_n < 0.6$ eV, $E_\gamma < 0.5$ MeV

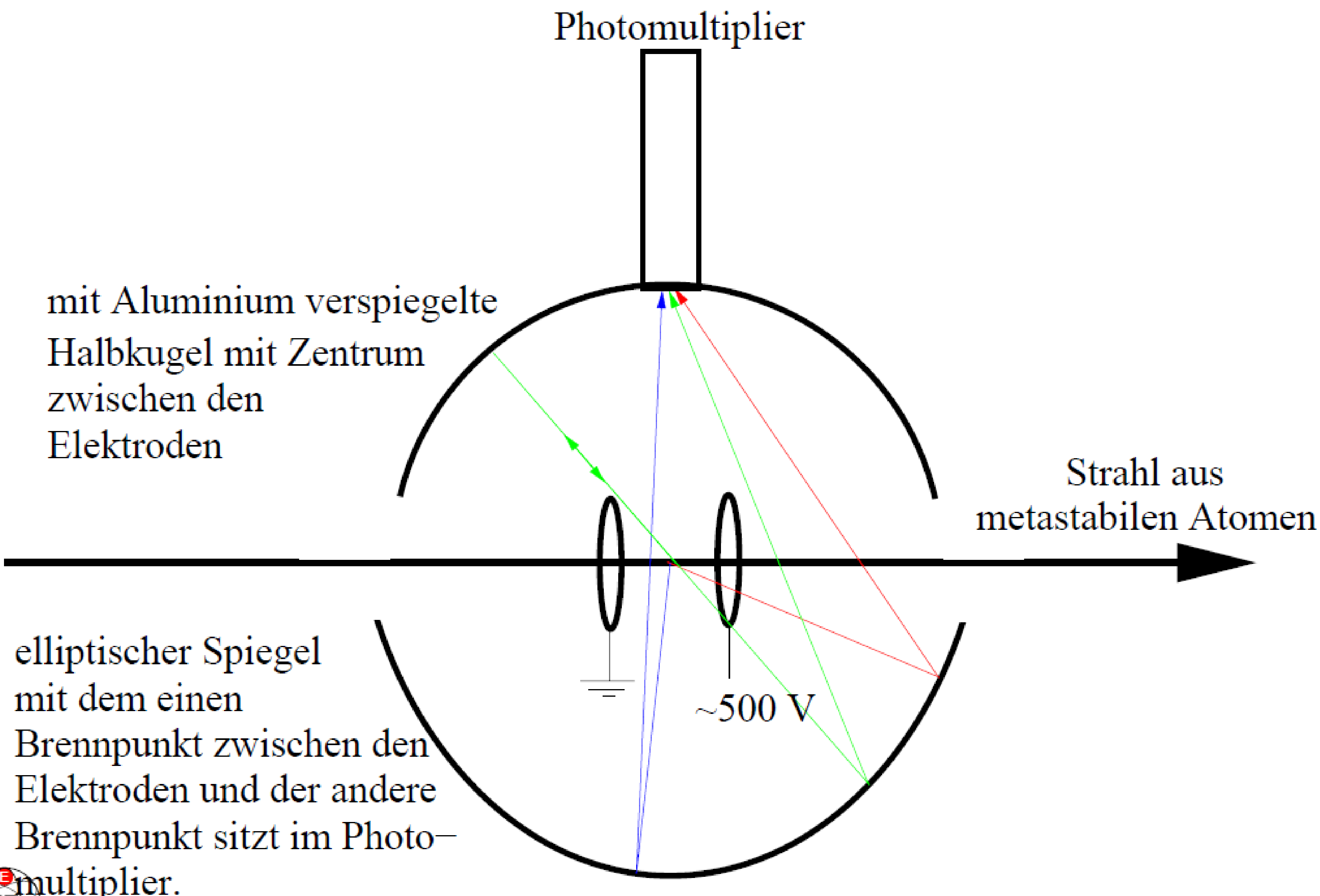
H(2s) detection

Measuring by quenching and Lyman- α detection(PM, channeltron)

Charge exchanging to H^- within an Ar cell, selecting the H^- from H(1s) by $\vec{E}_4$, accelerating by $\vec{E}_2$ and focusing the H^- with a magnet. spectrom. onto a detector(CsI(TI), SDD)

Ionizing H(2s) to p using two transverse CW laser beams within curved mirror resonators and an $\vec{E}$ field, selecting the p by $\vec{E}_4$, accelerating by $\vec{E}_2$ and focusing the p with a magn. spectr. onto a detector(CsI(TI), SDD)

coated mirrors



H(2s) ionization by two laser beams

After the spin filter the H(2s) can be ionized by two crossed CW laser beams with curved mirrors

($\lambda_1(2s \rightarrow 10p)$ =379.68 nm, **Ti-sapphire**

$\lambda_2(10p \rightarrow 27d) = 10.560\mu$m) **$CO_2$**

and an $\vec{E}$ field.

The resulting proton can be analyzed by $\vec{E}_4$, accelerated and focused by $\vec{E}_2$, bent by $\vec{B}_4$ and detected, e. g., by a CsI(Tl) crystal.

2s-10p-27d H(2s) ionization

$$Doppler\,shifted\,frequency\,\nu' = \nu\frac{\sqrt{1-\beta^2}}{1+\beta\cos\phi}\,for\,\phi = \pi/2$$

$$\nu' = \nu\sqrt{1-\beta^2}\,(2^{nd}\,order)$$

$$\Delta\nu'/\nu = \beta^2/2 = -3.44\cdot 10^{-7}\,for\,H(2s)(\beta = 0.83\cdot 10^{-3})$$

$$\frac{d\nu'}{\nu} = -\frac{\beta\,d\beta}{\sqrt{1-\beta^2}} = -6.06\cdot 10^{-9}\,for\,d\beta = 0.73\cdot 10^{-5}$$

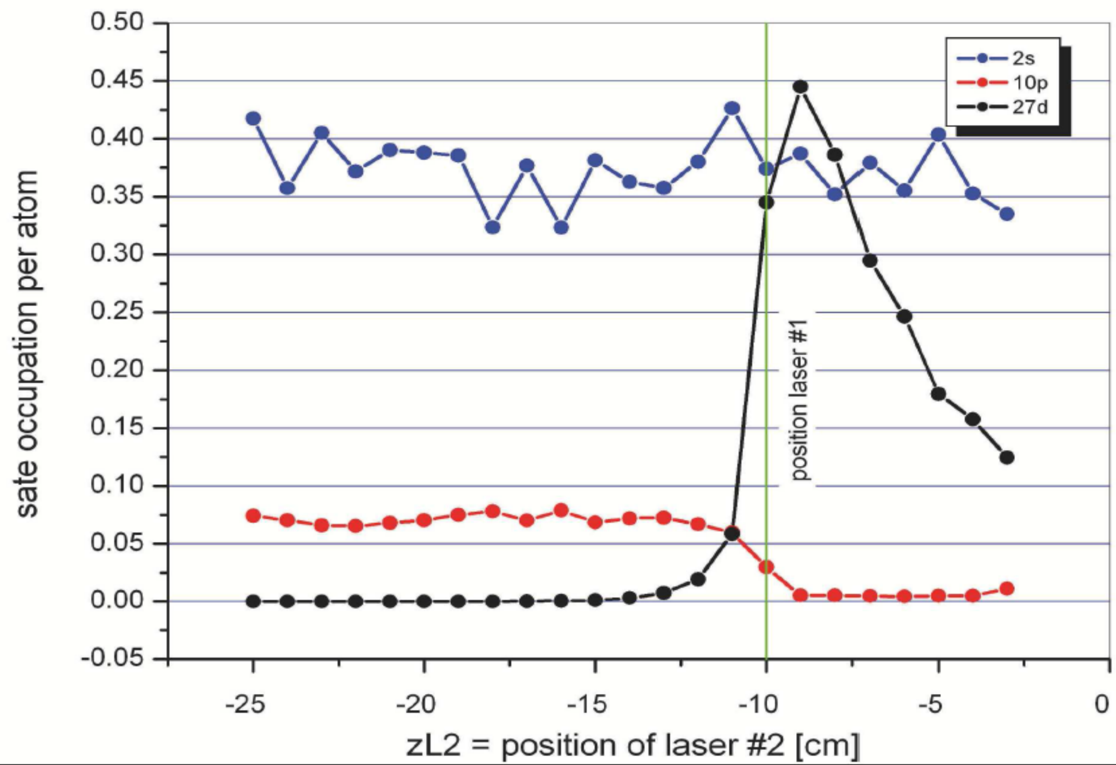
$$d\nu' = -4.785\cdot 10^{6}\,s^{-1}\,for\,\nu_{2s-10p} = 7.896\cdot 10^{14}\,s^{-1},$$

$$d\phi = (d\nu'/\nu)/\beta = -7.3\cdot 10^{-6},\,i.e.,$$

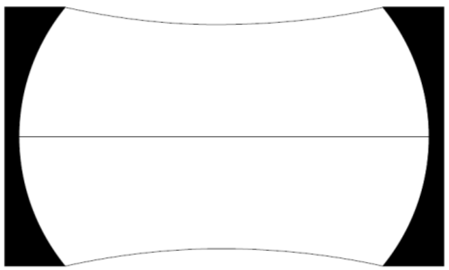
$$the\,photons\,must\,be\,perpendicular\,to\,the\,H(2s)$$

2s-10p-27d occupation, T=300 K

Power within resonators: 20 kW(laser 1), 100 W(laser 2)



Neutron Boui



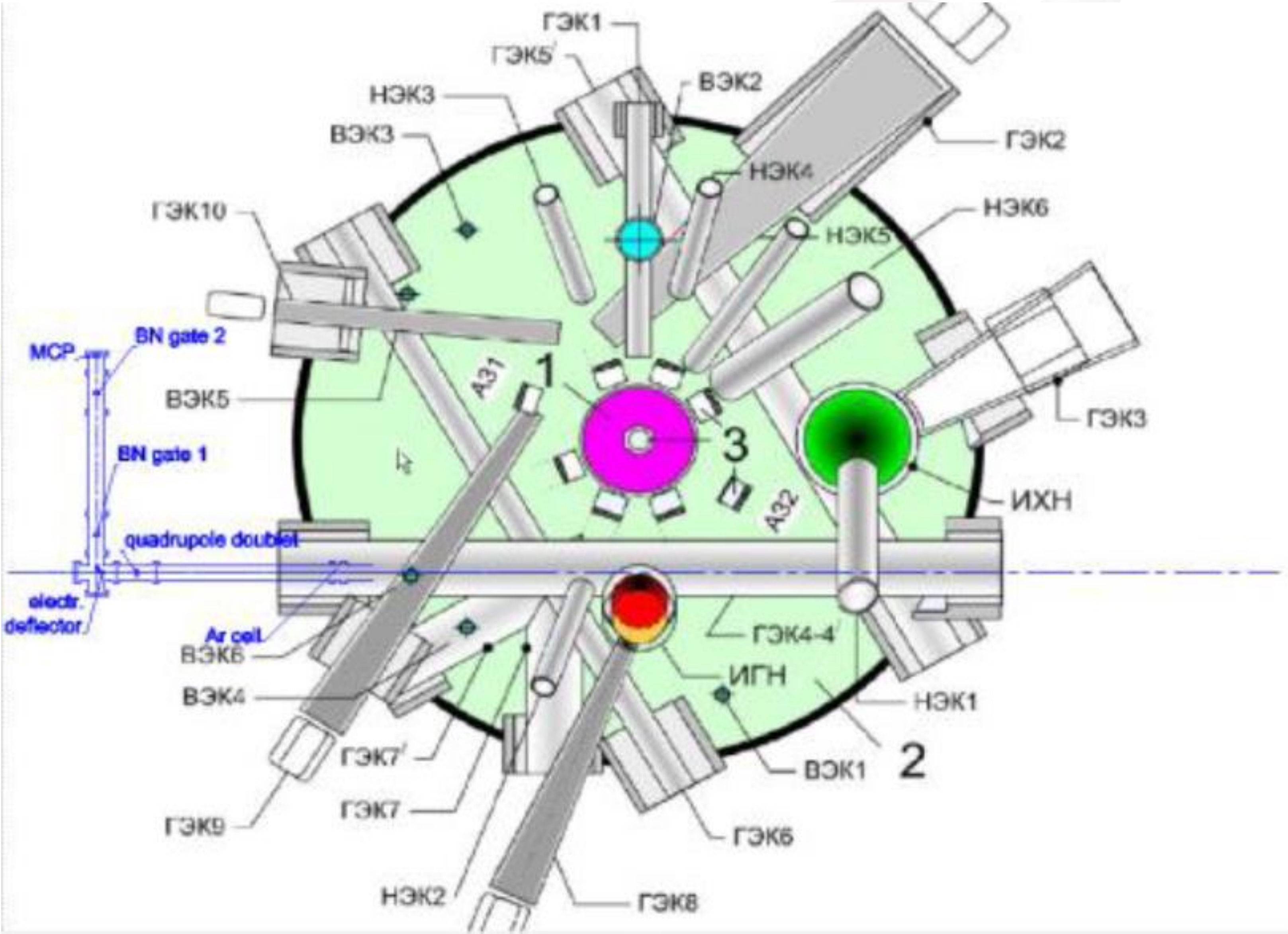
Pin R Pin E R

$$E = (1 - R)^{-1} \approx 10^6$$

First step

BOB monoenergetic H atoms are to be measured, e. g., at a throughgoing beamtube (PIK) using an Ar gas cell (H(2s) → H^- , F. Roussel et. al., PRA 16, 1854 (1977)), electrostatic focusing elements, a pulsed electric deflector, a Bradbury Nielsen (BN) gate chopper and an MCP

PIK experimental setup



H(2s) + Ar → H^{-} + Ar^{+} cross section

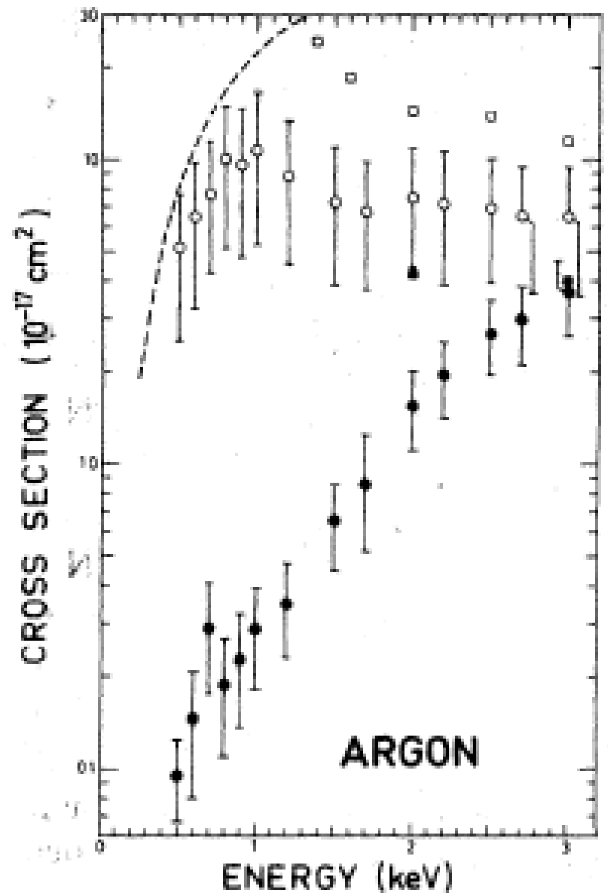
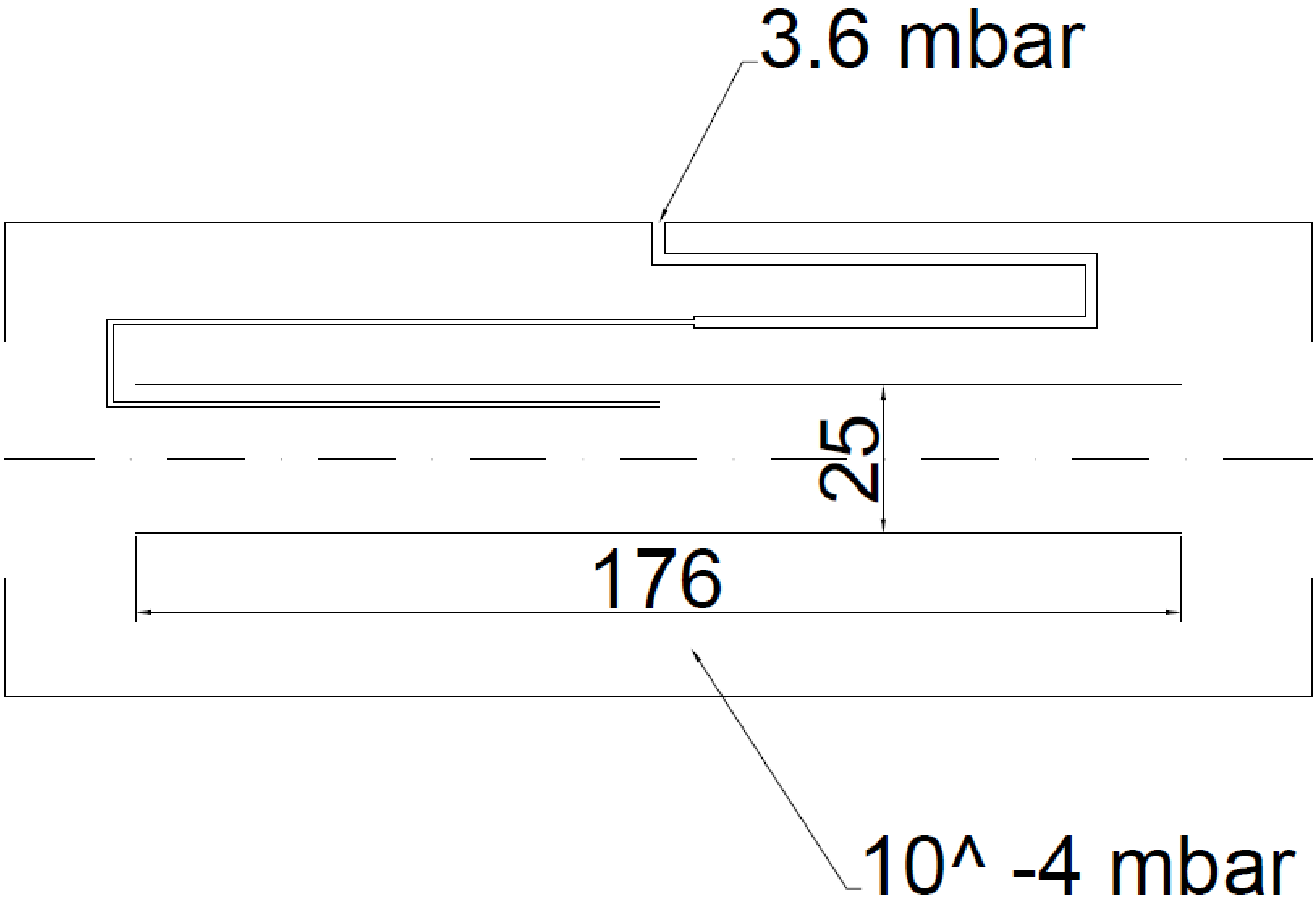


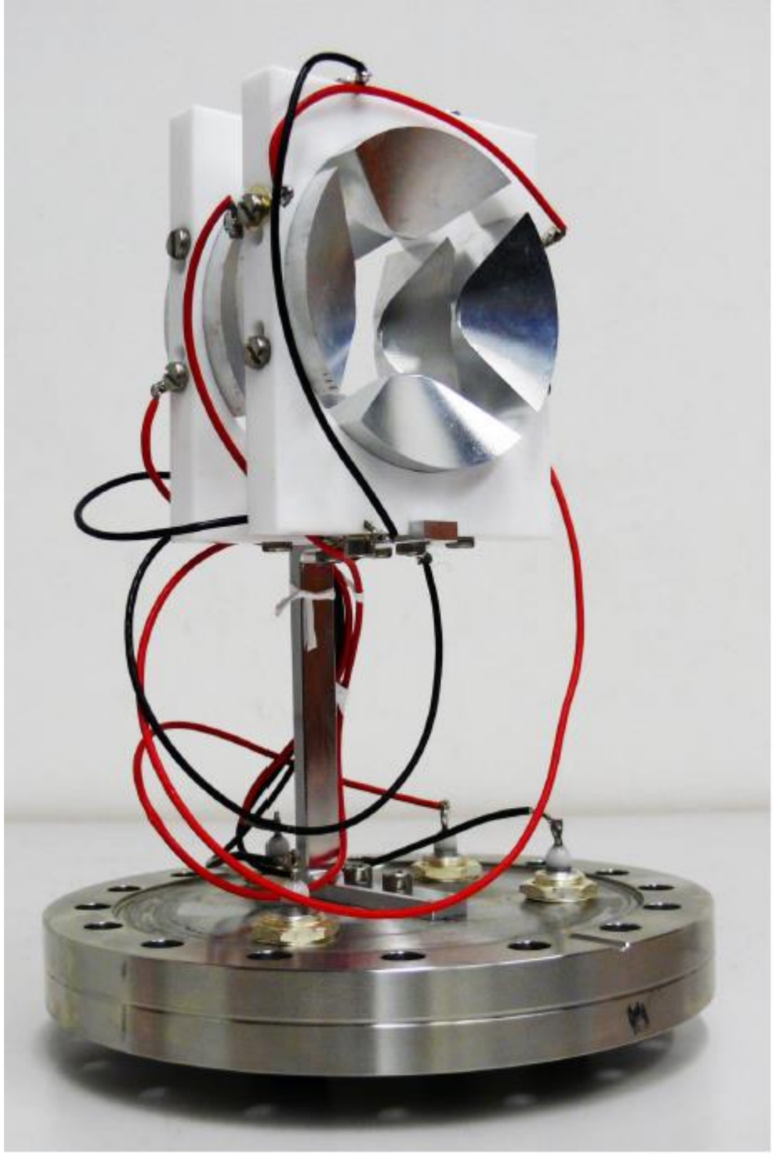
FIG. 10. Electron-capture cross sections for H ($1\,^2S$) and H ($2\,^2S$) in argon (55-mrad detector's acceptance angle). σ_{g^-}: ●, present work; ■, Williams.[5] σ_{m^-}: ○, present work; □, Dose and Gunz[7] recalibrated; ---, theoretical calculation by Olson.[14]

σ ($T_{H(2s)}$ = 0.33 keV) ≈ 5 · 10^{-17} cm^2

Ar cell schematically

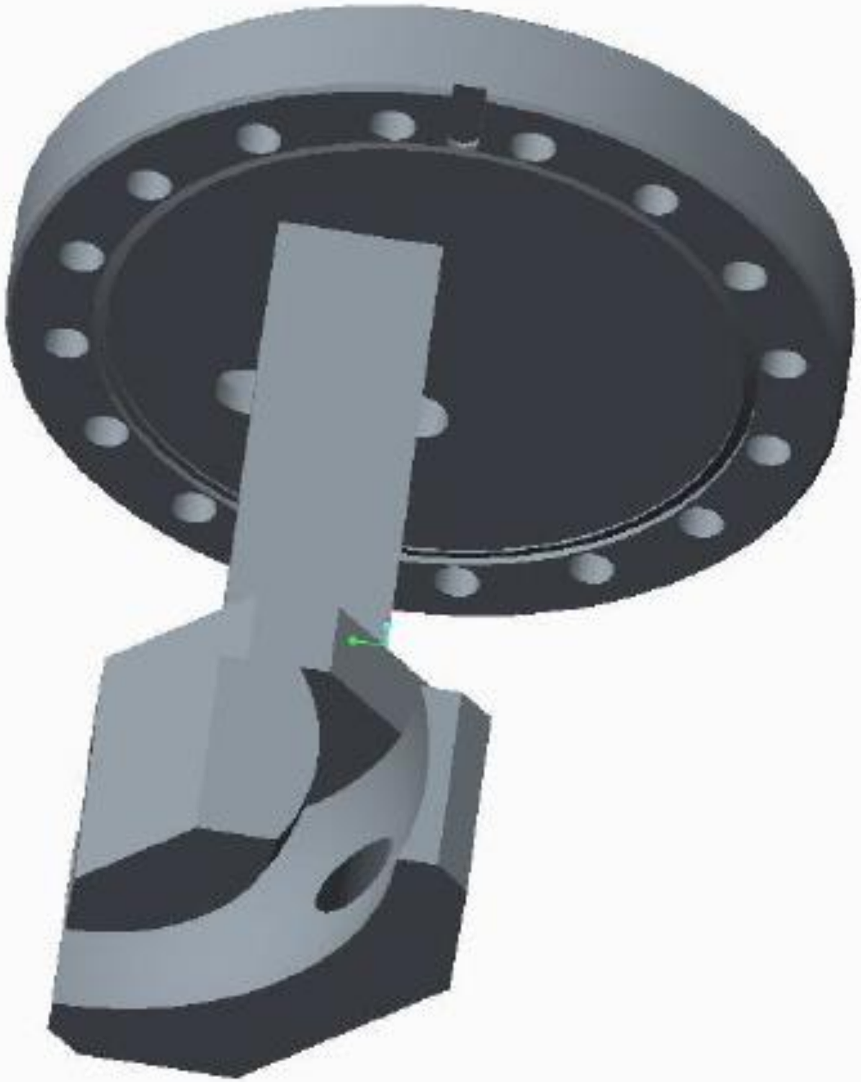


Electrostatic quadrupole doublet



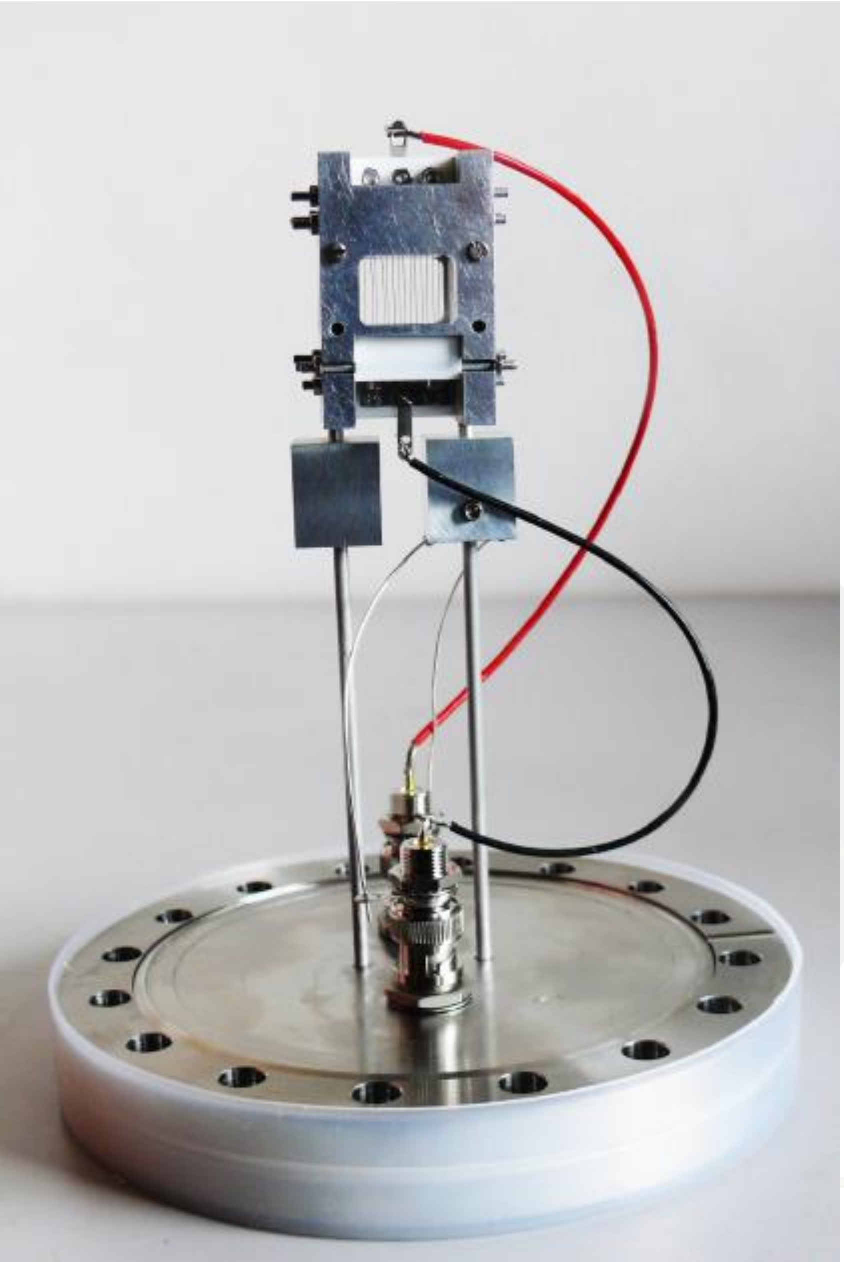
Φ 3 cm aperture

Pulsed electric deflector



2 cm x 4 cm aperture

Bradbury Nielsen gate chopper



$1.76\,cm \times 1.26\,cm$ aperture BN gate

Expected H^- rate

$\dot{N}_H = BR \left(\int \phi(z)\, \Omega(z)\, dV \right) / (4\pi\, \tau_n\, v_n) =$

$= BR\, \theta_1^2\, r_s^2\, \pi\, z_n\, \bar{\phi} / (2\, \tau_n\, v_n) = 7.3\ s^{-1}$

with $\theta_1 = 0.14$ (8°), $r_s = 1.5$ cm, $z_n = 0.5$ m,

$\bar{\phi} = 10^{14}\ cm^{-2}\ s^{-1}$, $\dot{N}_{H(2s)} = 0.73\ s^{-1}$

p ($l_m = 0.176$ m, $\sigma = 5 \cdot 10^{-21}\ m^2$) = $8.4 \cdot 10^{-3}$ mbar

P (H(2s) → H^-) = $n_{Ar}\ \sigma\ \Delta z = 0.18$, $n_{Ar} = 2 \cdot 10^{20}\ m^{-3}$

$\dot{N}_{H-} = 0.13\ s^{-1}$

P (H(2s) → H^+) = 0.45 (2 laser)

$\dot{N}_{H+} = 0.33\ s^{-1}$

g_S

The g_S statistical error is

$$(\delta g_S)_{stat} = (\frac{\partial g_S}{\partial W_3})_{g_S=6\cdot 10^{-2},\, g_T=0} \cdot (\delta W_3)_{stat} =$$

$$= \frac{\lambda(\chi^2+3)^2}{-\chi^2+2\chi+3} \cdot \sqrt{\frac{W_3}{N}}.$$

$$With\,(\delta g_S)_{stat} = 6\cdot 10^{-3} (\chi \approx 1/\lambda, W_3 = 3.683\cdot 10^{-3})$$

N = 4.4 · 10^4 results ($\dot{N}_{H+}$ = 0.33 s^{-1}),
i. e., 1.5 d measuring time

$H_{\bar{\nu}}$

The $H_{\bar{\nu}}$ statistical error is

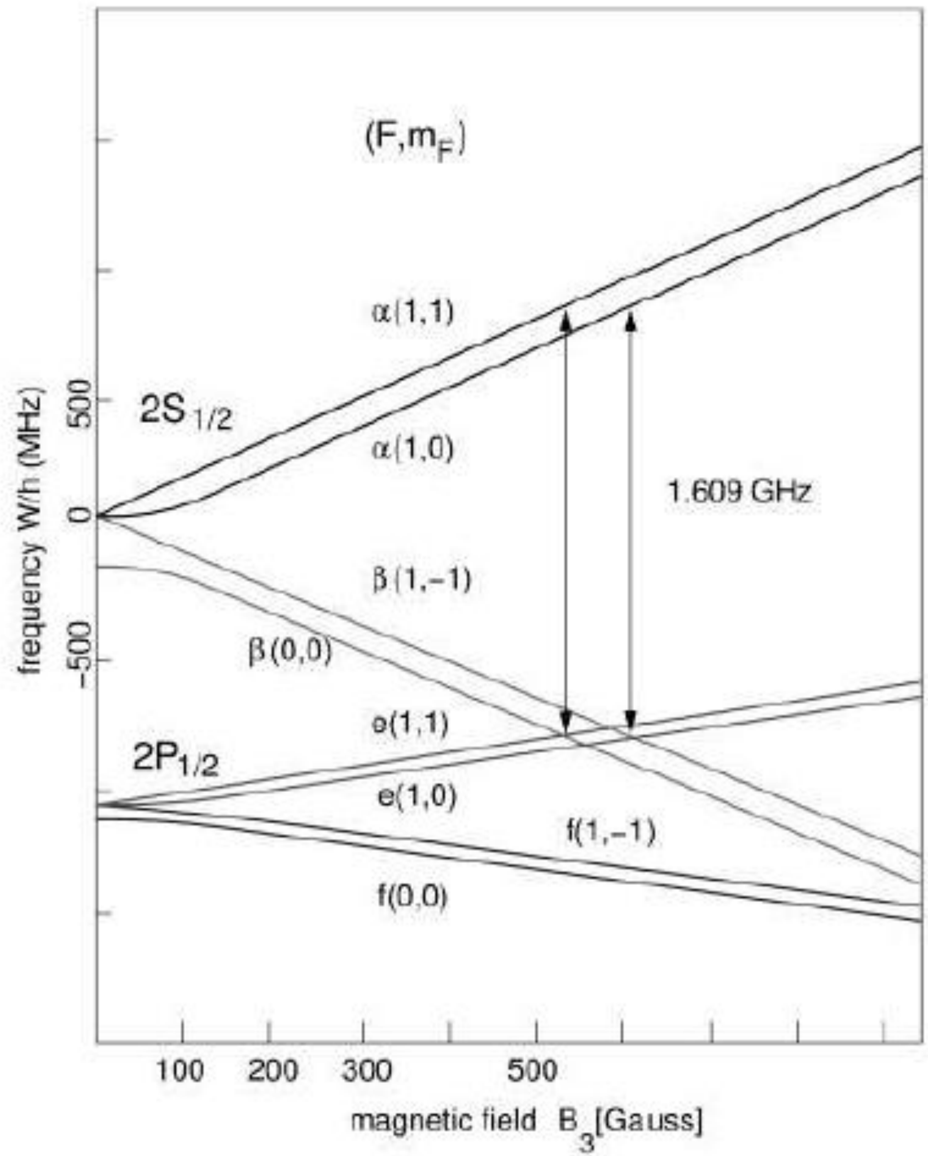
$$(\delta H_{\bar{\nu}})_{stat} = \frac{4(1+3\lambda^2)}{(1+\lambda)^2} \cdot \sqrt{\frac{W_4}{N}}. \quad With$$

$$(\delta H_{\bar{\nu}})_{stat} = 1 \cdot 10^{-3}$$

$$(\eta = .036,\ W_4 = 8.1 \cdot 10^{-6},\ H_{\bar{\nu}} = .997)$$

$N = 8.3 \cdot 10^5$ results ($\dot{N}_{H+} = 0.33\ s^{-1}$),
i. e., 29 d measuring time

Breit- Rabi diagram of the 2 $S_{1/2}$ 2 $P_{1/2}$ hyperfine splitting



$\alpha-,\beta$ -states

$$|\alpha 11\rangle = |++\rangle$$

$$|\alpha 10\rangle = \cos\theta|+-\rangle + \sin\theta|-+\rangle$$

$$|\beta 1-1\rangle = |--\rangle$$

$$|\beta 00\rangle = \sin\theta|+-\rangle - \cos\theta|-+\rangle,$$

$$tan2\theta = B_c/B, B_c = 63.4\,Gauss(2S)$$

$$N_{\alpha 10} = N_1\cos^2\theta + N_2\sin^2\theta$$

$$N_{\beta 00} = N_1\sin^2\theta + N_2\cos^2\theta$$

χ

χ obtained by measuring $v_{\alpha\beta} = N_{\alpha 10}/N_{\beta 00}$ or $v_{\alpha\alpha} = N_{\alpha 11}/N_{\alpha 10}$

$$v_{\alpha\beta} = \frac{(\chi-1)^2\cos^2\theta + 4\sin^2\theta}{(\chi-1)^2\sin^2\theta + 4\cos^2\theta}, \quad v_{\alpha\alpha} = \frac{(\chi+1)^2}{(\chi-1)^2\cos^2\theta + 4\sin^2\theta}$$

$$with\,\chi\,either\quad \chi = 1 \pm 2\sqrt{\frac{\sin^2\theta - v_{\alpha\beta}\cos^2\theta}{v_{\alpha\beta}\sin^2\theta - \cos^2\theta}}\quad or$$

$$\chi = \frac{-(1+v_{\alpha\alpha}\cos^2\theta) \pm 2\sqrt{v_{\alpha\alpha}(1-v_{\alpha\alpha}\sin^2\theta\cos^2\theta)}}{1-v_{\alpha\alpha}\cos^2\theta}$$

W_4

W_4 obtained by measuring $v_{\beta\beta} = N_{\beta 1\text{-}1} / N_{\beta 00}$

$v_{\beta\beta} = N_4 / (N_1 \sin^2\theta + N_2 \cos^2\theta) =$
$= 2 N_4 / (N_1 + N_2 - \cos 2\theta\, (N_1 - N_2))$

for $B \ll B_c$, $2\theta \approx \pi/2$, $\cos 2\theta \approx 0$
$v_{\beta\beta} = 2 N_4 / (N_1 + N_2) \rightarrow W_4 \approx (1/2)\, v_{\beta\beta}$

for B large, $\cos 2\theta \approx 1$
$v_{\beta\beta} = N_4 / N_2$

n > 2 background(1)

$$W(4s \to 2s) = 2 \cdot W(4s) \cdot W(4s \to 3p) \cdot W(3p \to 2s) \cdot$$

$$\cdot W(\Delta j = 0) W(\Delta j = \pm 1) = 3.07 \cdot 10^{-4}$$

$$W(4s) = 1.3\%, W(\Delta j = 0) = 2/5, W(\Delta j = \pm 1) = 3/5$$

$$W(4s \to 3p) = A_{4s3p}/(A_{4s3p} + A_{4s2p}),$$

$$W(3p \to 2s) = A_{3p2s}/(A_{3p2s} + A_{3p1s})$$

$$W(5s \to 2s) = 2 \cdot W(\Delta j = 0) W(\Delta j = \pm 1) \cdot W(5s) \cdot$$

$$\cdot (W(5s \to 4p) \cdot W(4p \to 2s) + W(5s \to 3p) \cdot W(3p \to 2s)) =$$

$$= 2.18 \cdot 10^{-4}, W(5s) = .7\%$$

$n > 2$ background(2)

$$\Sigma = W(4s \to 2s) + W(5s \to 2s) = 5.25 \cdot 10^{-4}$$

$$.44\,\Sigma = 2.32 \cdot 10^{-4} \to \text{config. 4}$$

$$.55\,\Sigma = 2.90 \cdot 10^{-4} \to \text{config. 3}$$

being 7.9 % of W_3 ($\approx dW_3$)
background eliminated by ionizing these $(n>2)s$ H atoms using a λ = 1.458 μm laser

Mockup setup

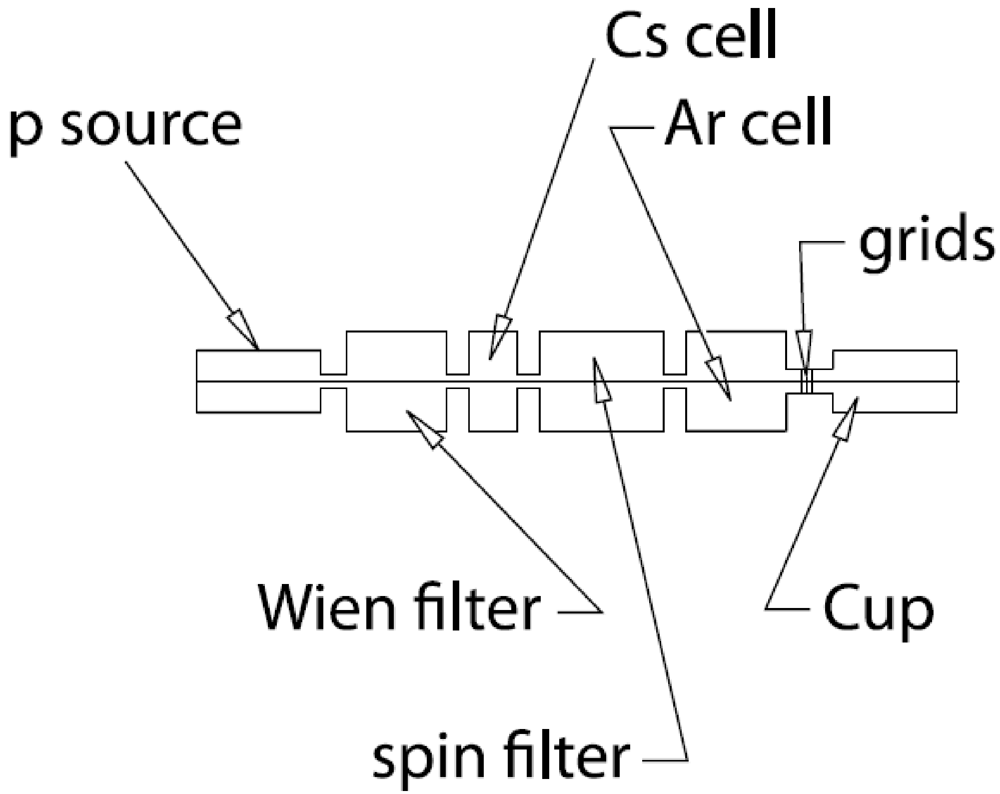


Figure 1: Sketch of the mockup setup to measure the kinetic energy difference of H^- ions produced by charge exchanged H(2s) and H(1s) atoms within an Ar cell.

W.Schott et al., MLL Annual Report 2014,

(https://www.mll–muenchen.de/forschung/atomphysik/index.html)

Cup H^- current vs. spin filter magnet current

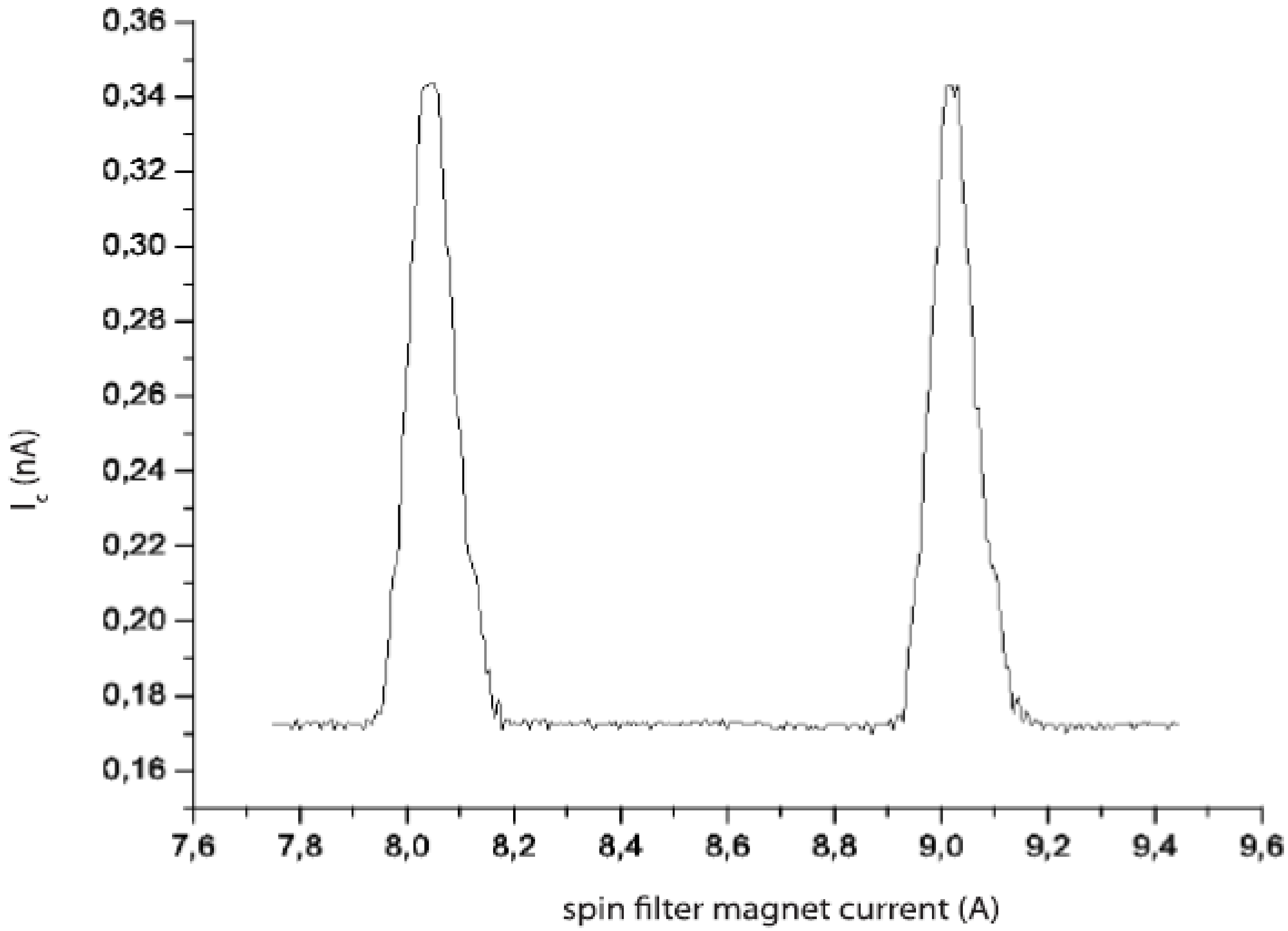


Figure 2: Cup H^- current I_c vs. spin filter magnet current. At the peak setting H(2s) and H(1s) atoms appear behind the filter, whereas at the valley setting(between the peaks) only H(1s) remain.

Cup current vs. counter field grid voltage

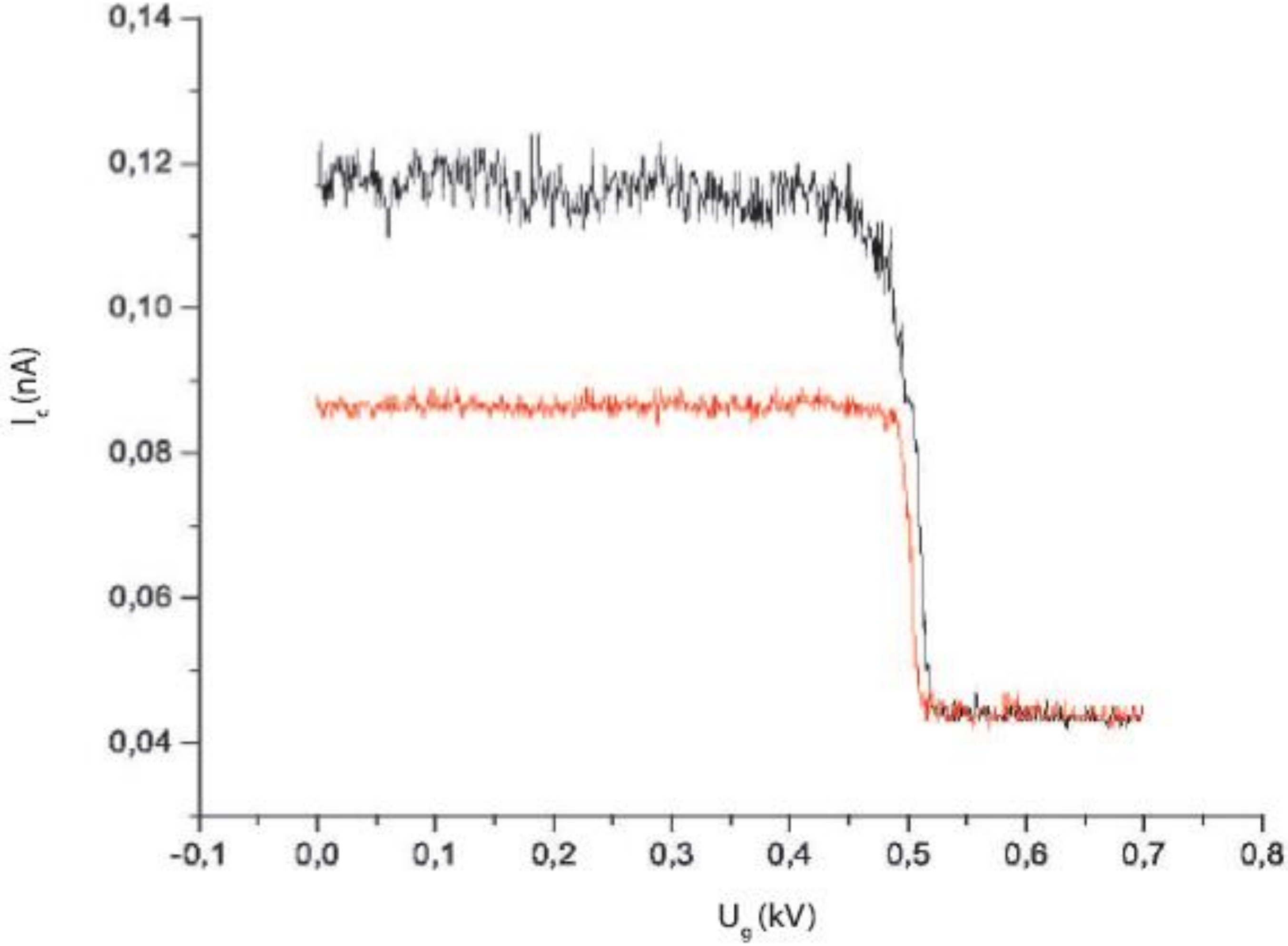


Figure 5: I_c vs. counter field grid voltage U_g. Upper curve: H^- from H(1s) and H(2s). Lower curve: H^- from H(1s).

Differentiated I_c vs. counter field grid voltage U_g.

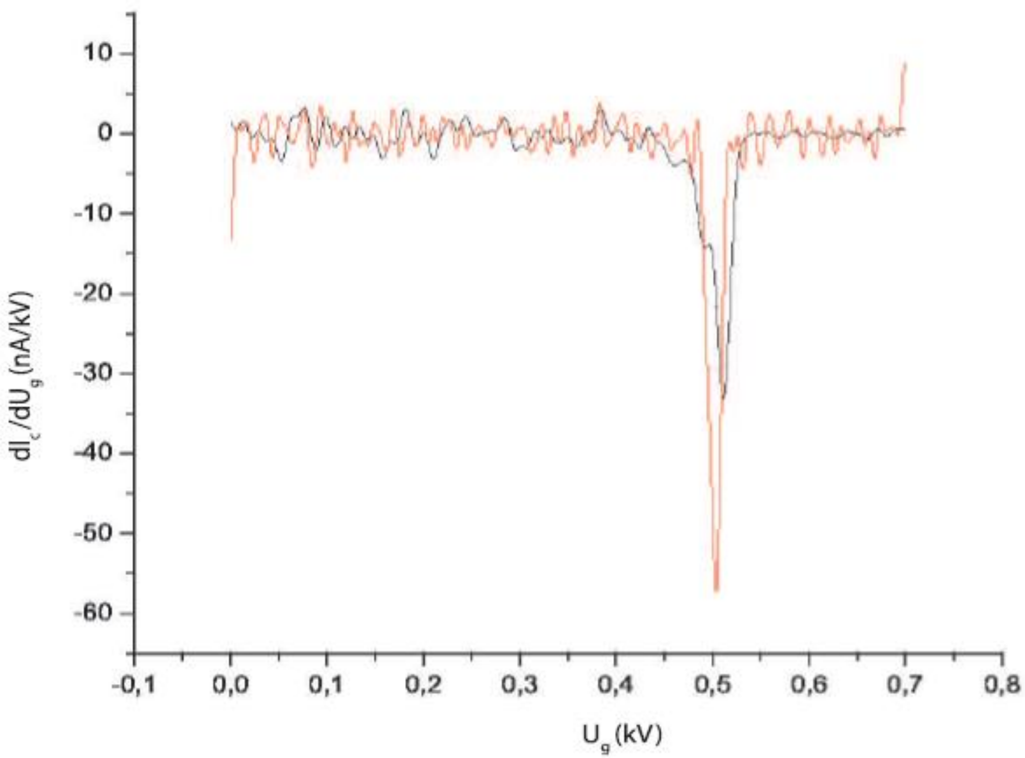


Figure 6: dI_c/dU_g vs. U_g. a. Narrow single peak: H^- from H(1s). b. Wider double peak: H^- from H(1s) and H(2s).

Difference between T_{H-} and T_H

H(2s): T_{H-} = T_H + 10.2 eV =
= 335.9 eV

$dT_H = E_0 \beta\, dv/c = 5.7$ eV

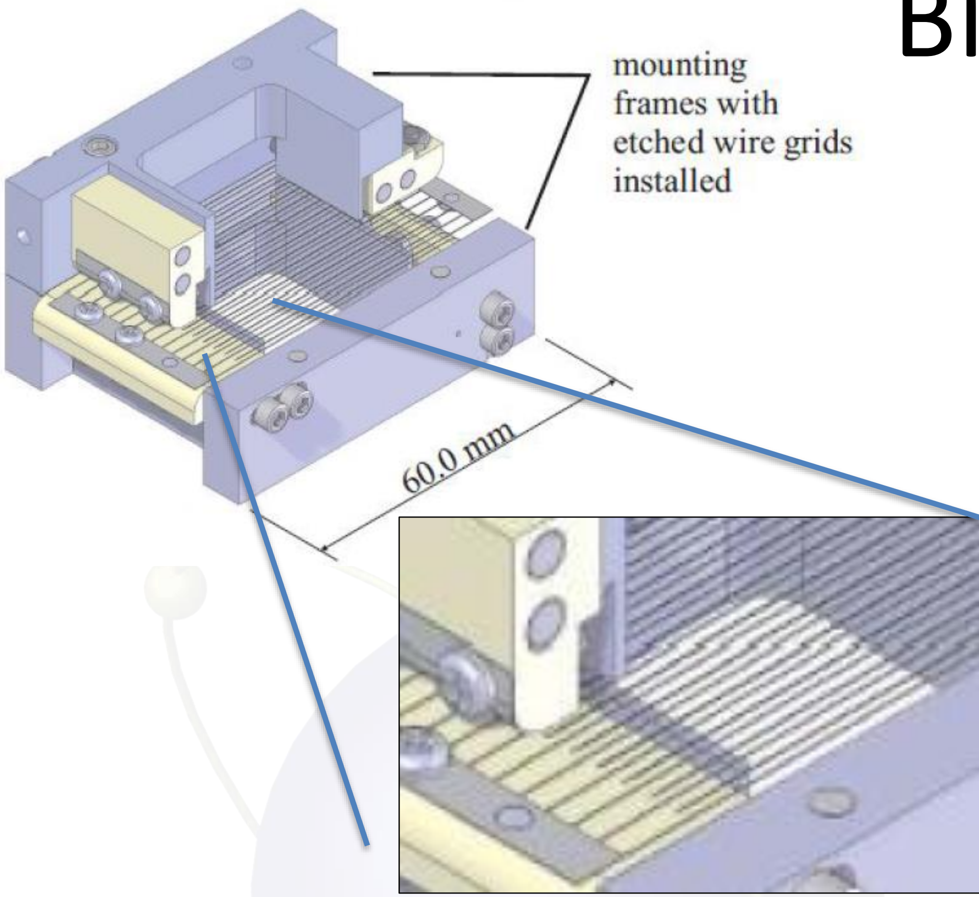
$\Delta t / t = -(1/2)\, \Delta T_H / T_H$, $t = 4$ µs

at s = 1m, $\Delta t = 63$ ns

A TOF spectrometer (BN gate chopper)

- Technique: Use two electric grid systems (fast switchable)
  - Principle as for neutron chopper system
  - „close“ means electric field „on“: deflecting H^- or quenching of H(2s)
  - „open“ means no field: H^- or H(2s) survives passage
- Operation of two gates spatially separated by 1m using fast HV pulsing technique
  - FPGA based fast logical system drives HV source
  - Generates pulse-pattern with variable pulse length („open“ time), delay time between the two electric systems and repetition rate
  - Typical rise time of HV pulse: 10ns
  - Typical gate time: 200-500ns
  - Typical driving voltage: 200-500V

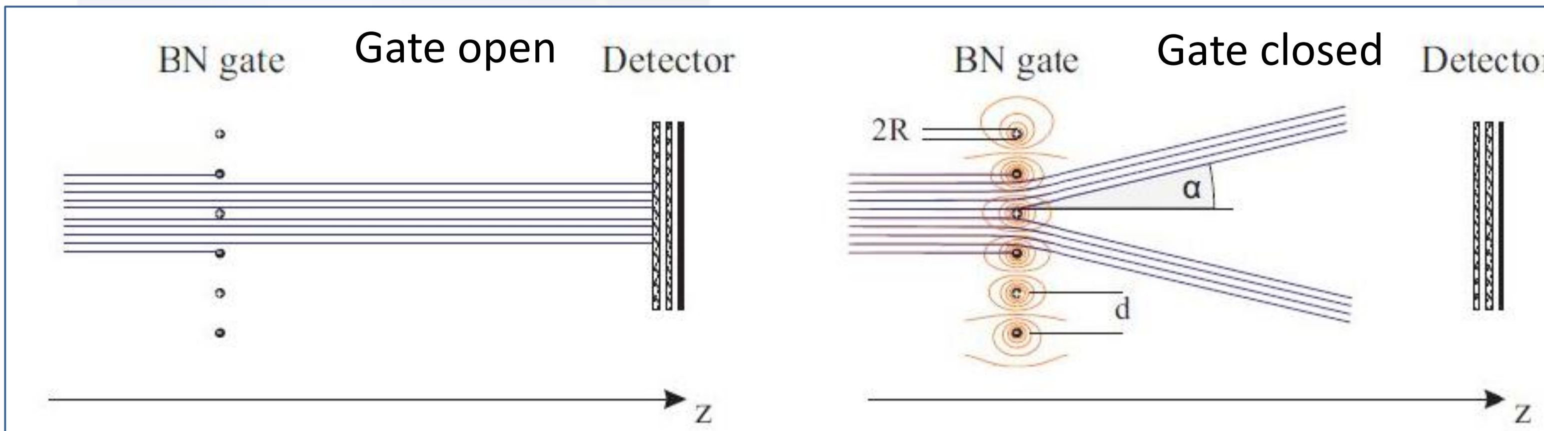
BN Gate



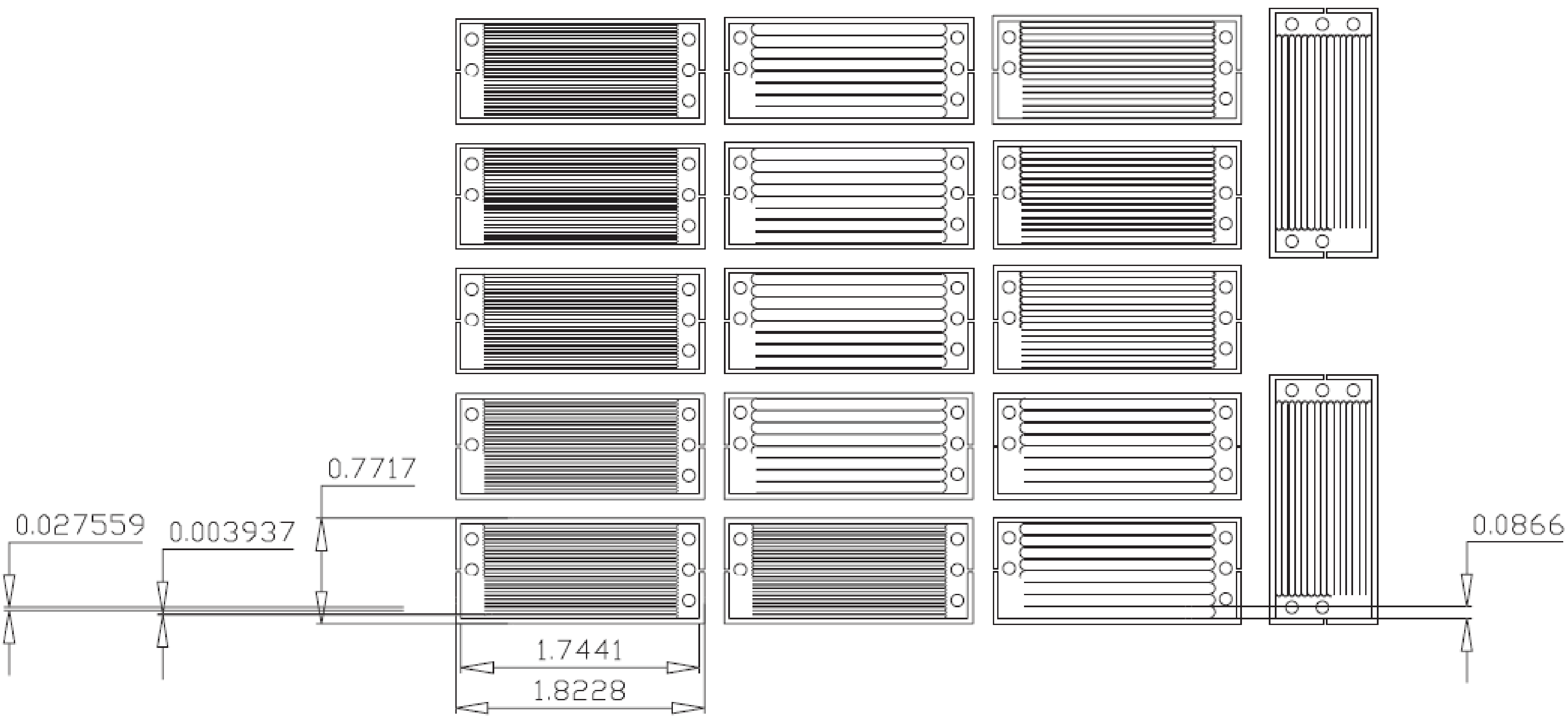
How the BN gates functions:

- HV_{Typ} = 250 V /grid (HV_{max} = 500V)
- use two grids intercalated in one plane
  - HV_1 = +250 V
  - HV_2 = -250 V

Example: charged particles

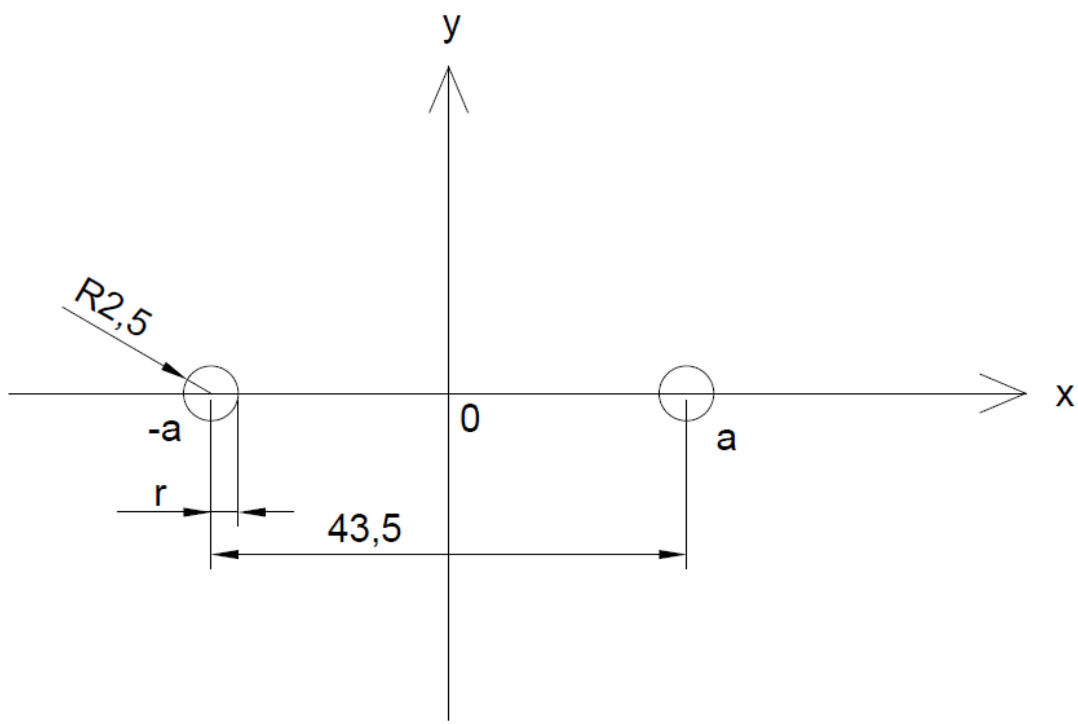


BN gate photo- etched grid



Newcut 434 East Union St. Newark, NY 14513, USA

Grid dimensions (mil)



$\alpha = \pi\, q\, U_{wire} / (2T_{H-} \ln (1/ \tan(\pi / (4a/r)))) = 22.3°$,
$U_{wire} = \pm 200$ V, $2a = 43.5$ mil, $2r = 5$ mil

T. Brunner et al., Int. Journal of Mass Spectrometry, vol. 309, 1 January 2012, p. 97- 103.

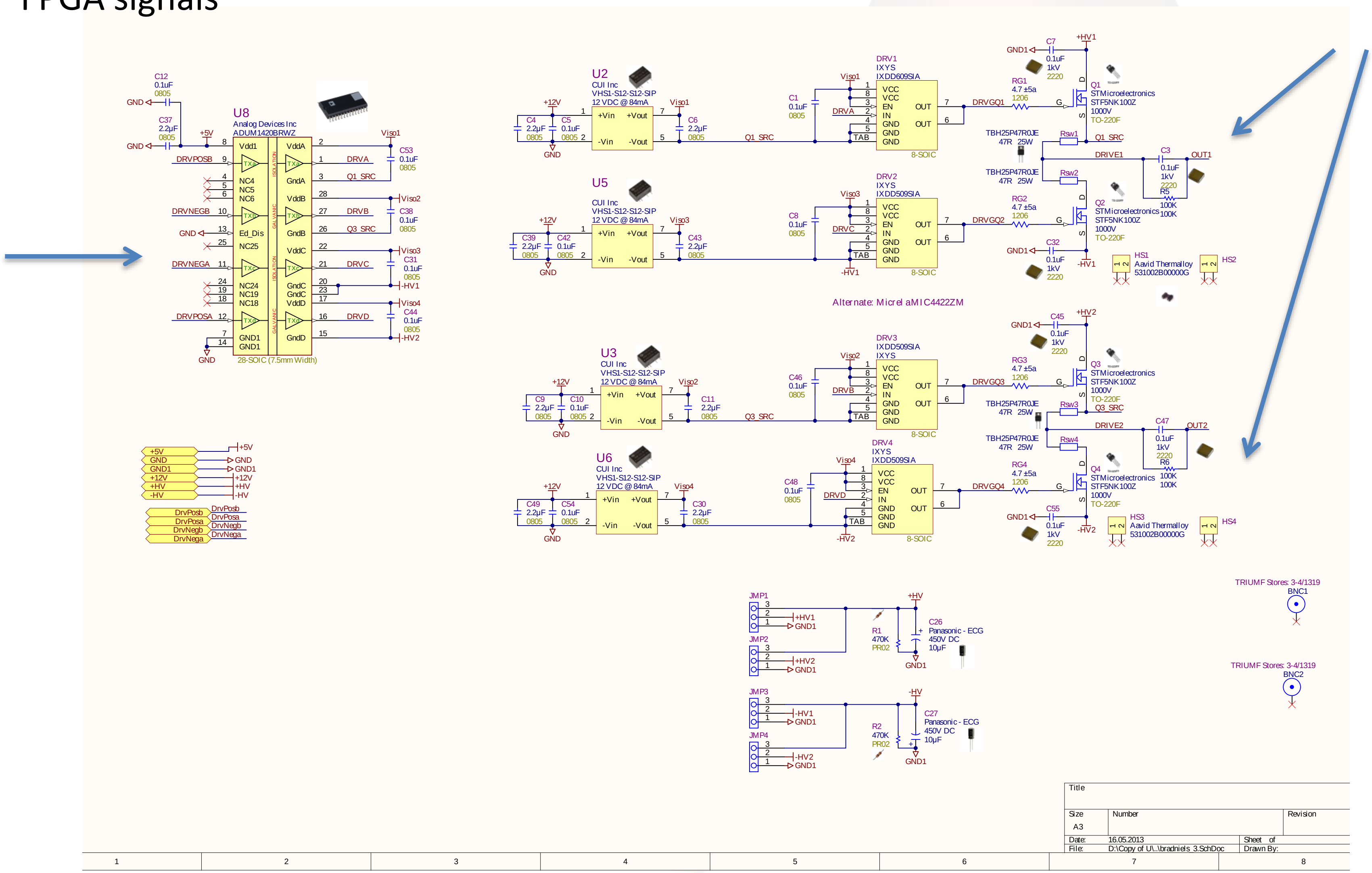
Pulse generation for BN gate grids

FPGA signals

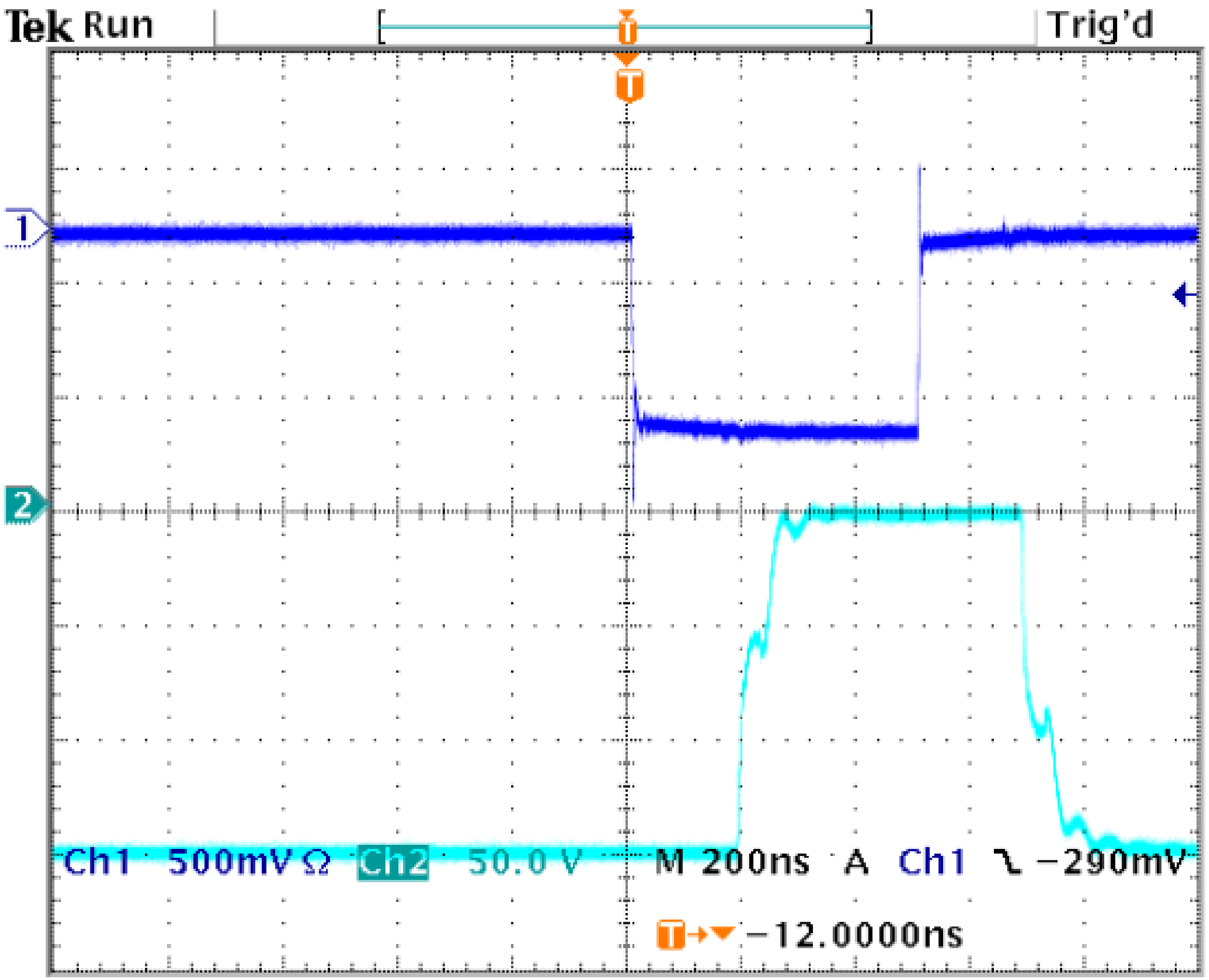
DC/DC converter

FET driver

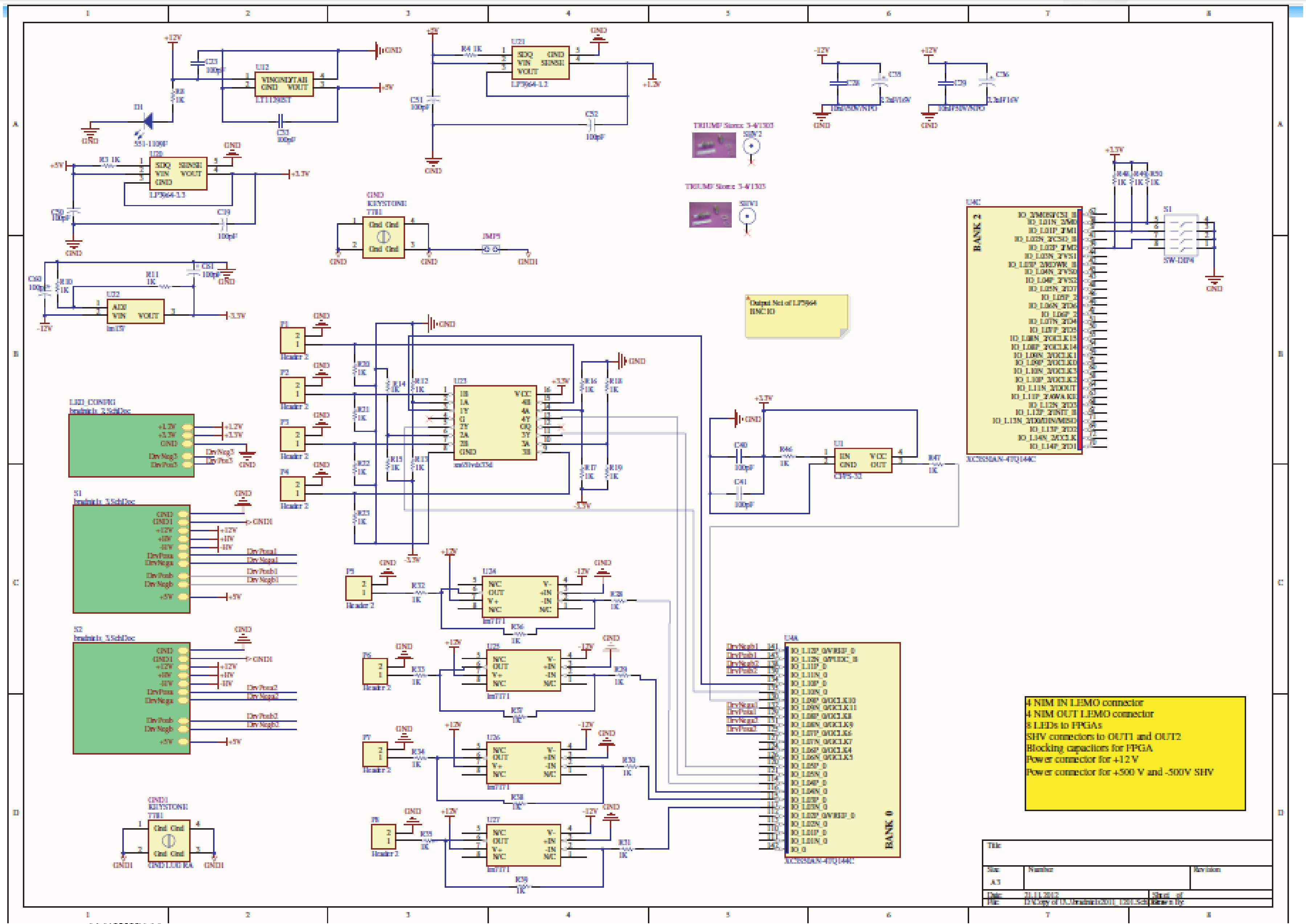
HV pulse generation



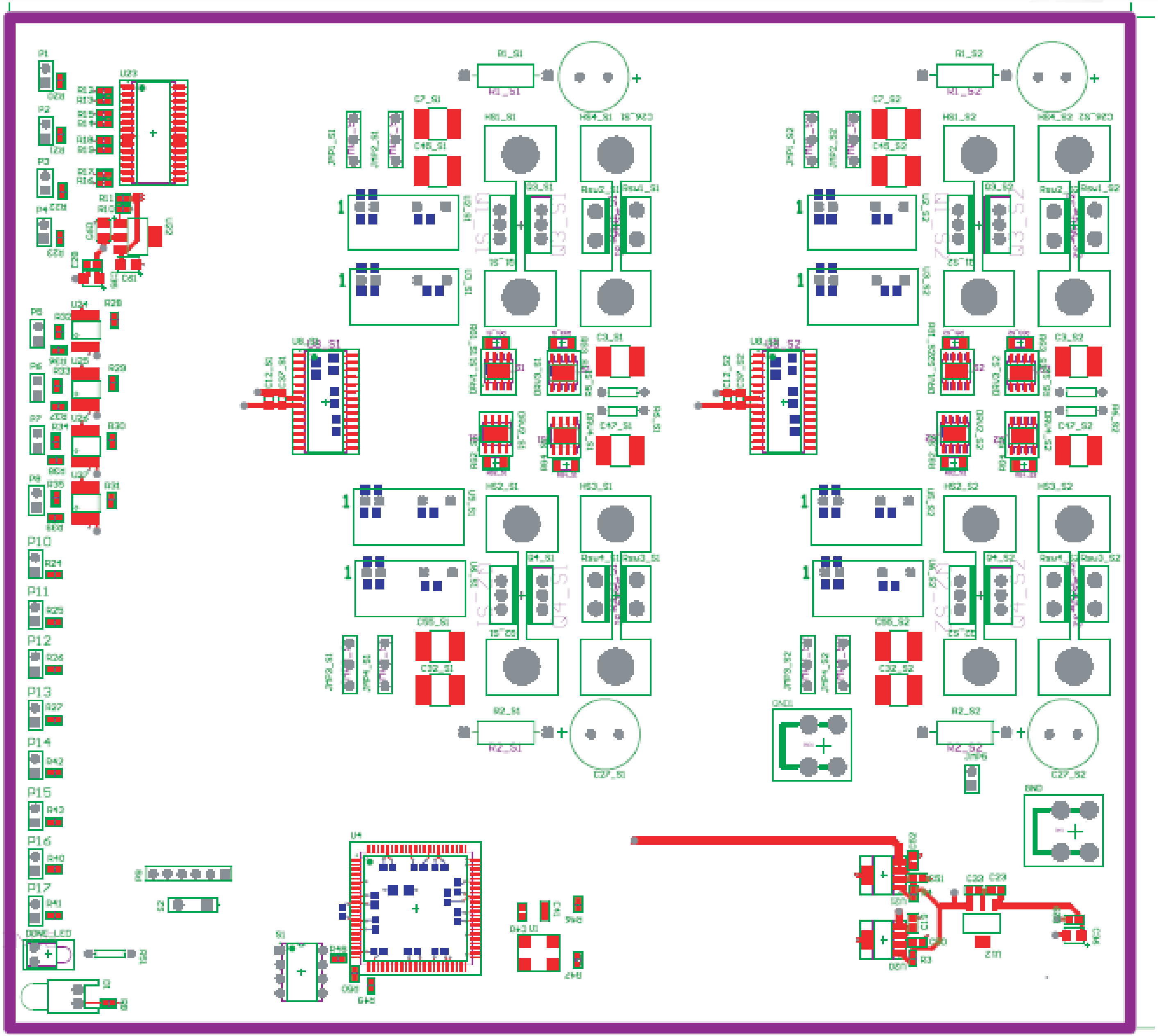
BN gate trigger NIM signal, BN gate pulse



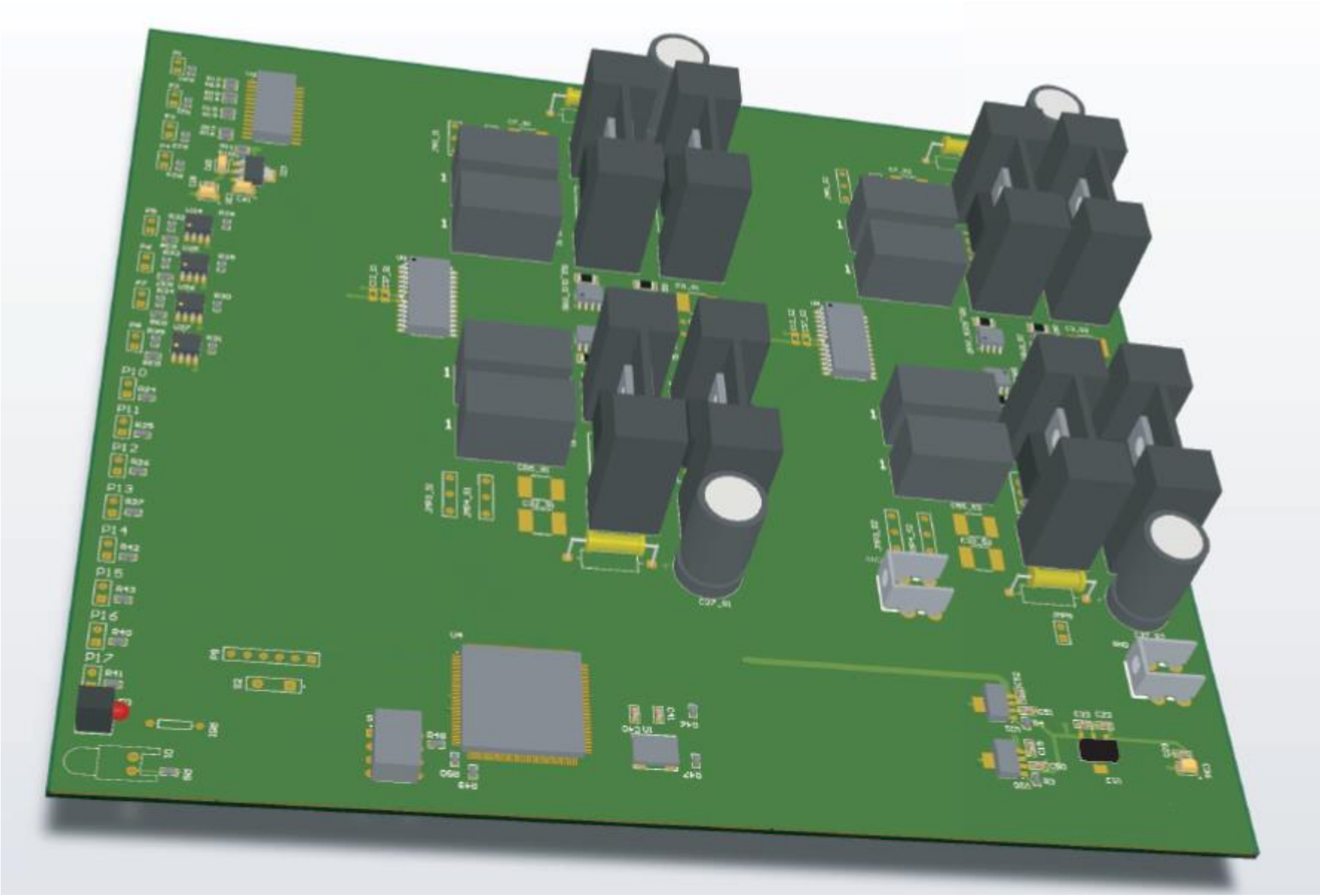
FPGA structure, schematics



2D pcb



3D pcb



BN gate chopper setup without active focusing

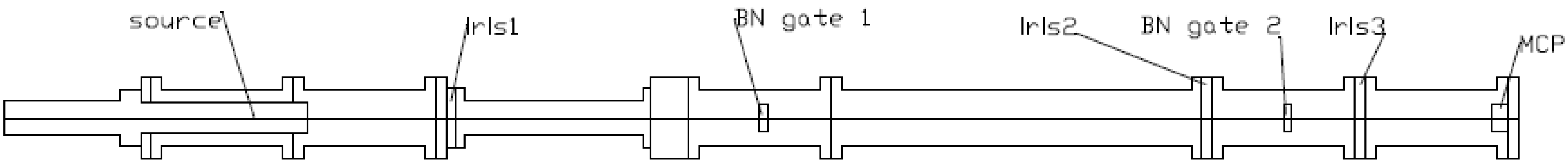
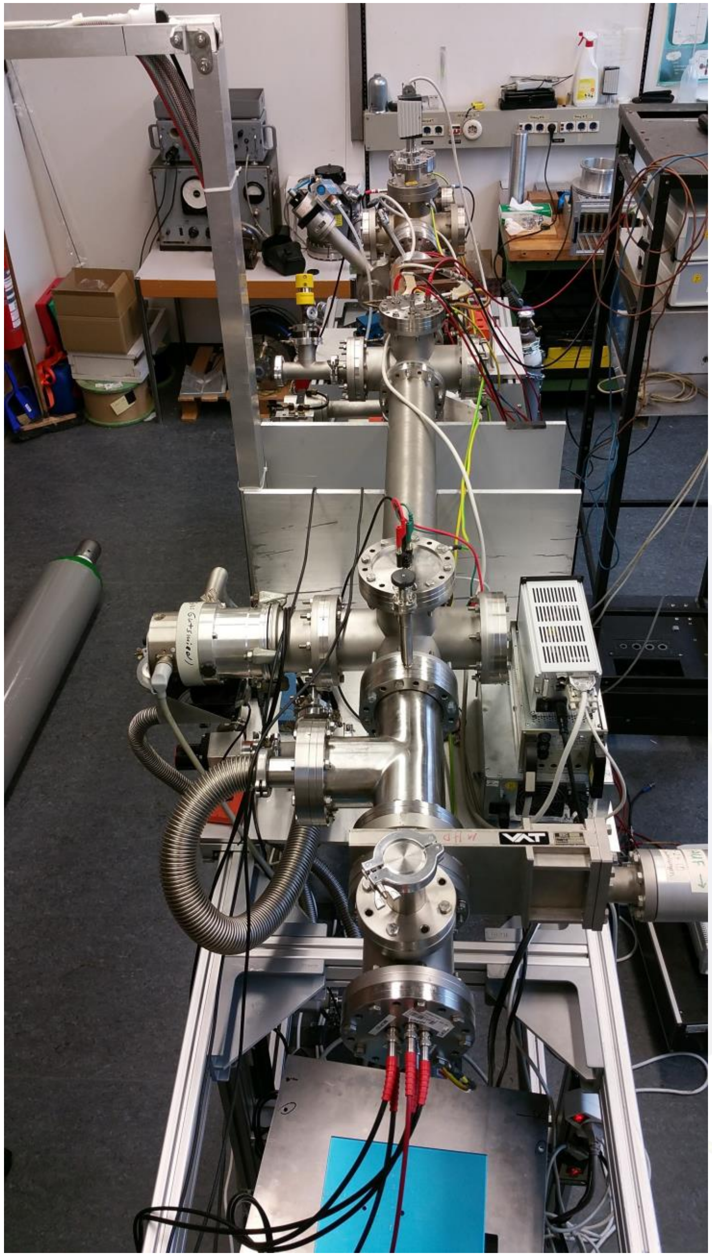
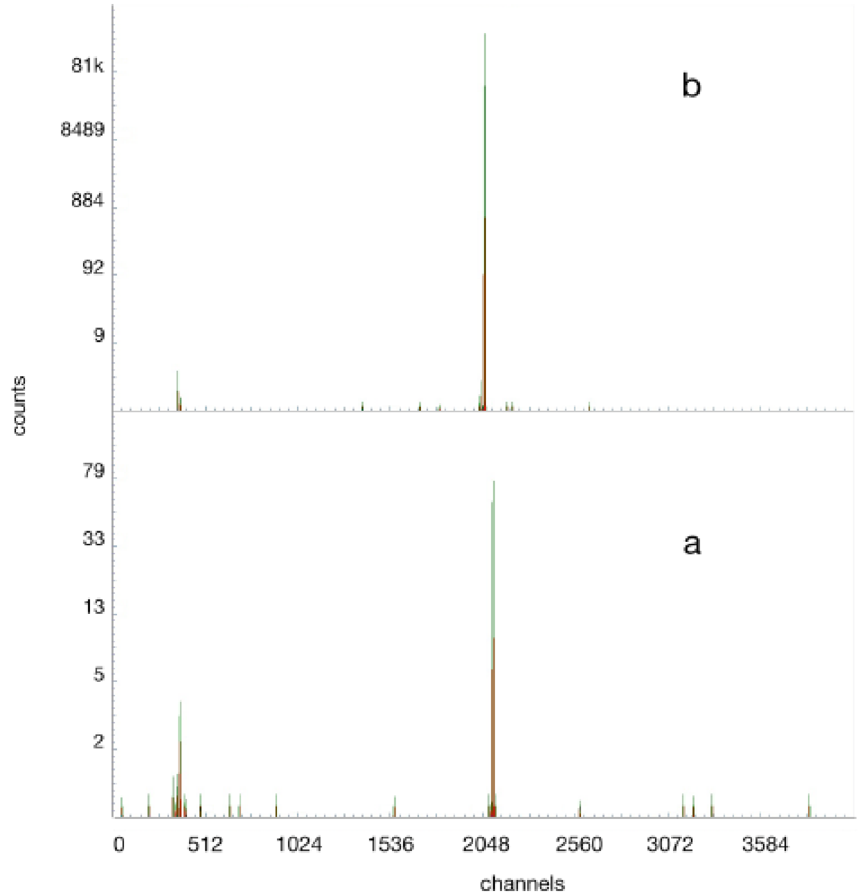


Photo of the chopper setup



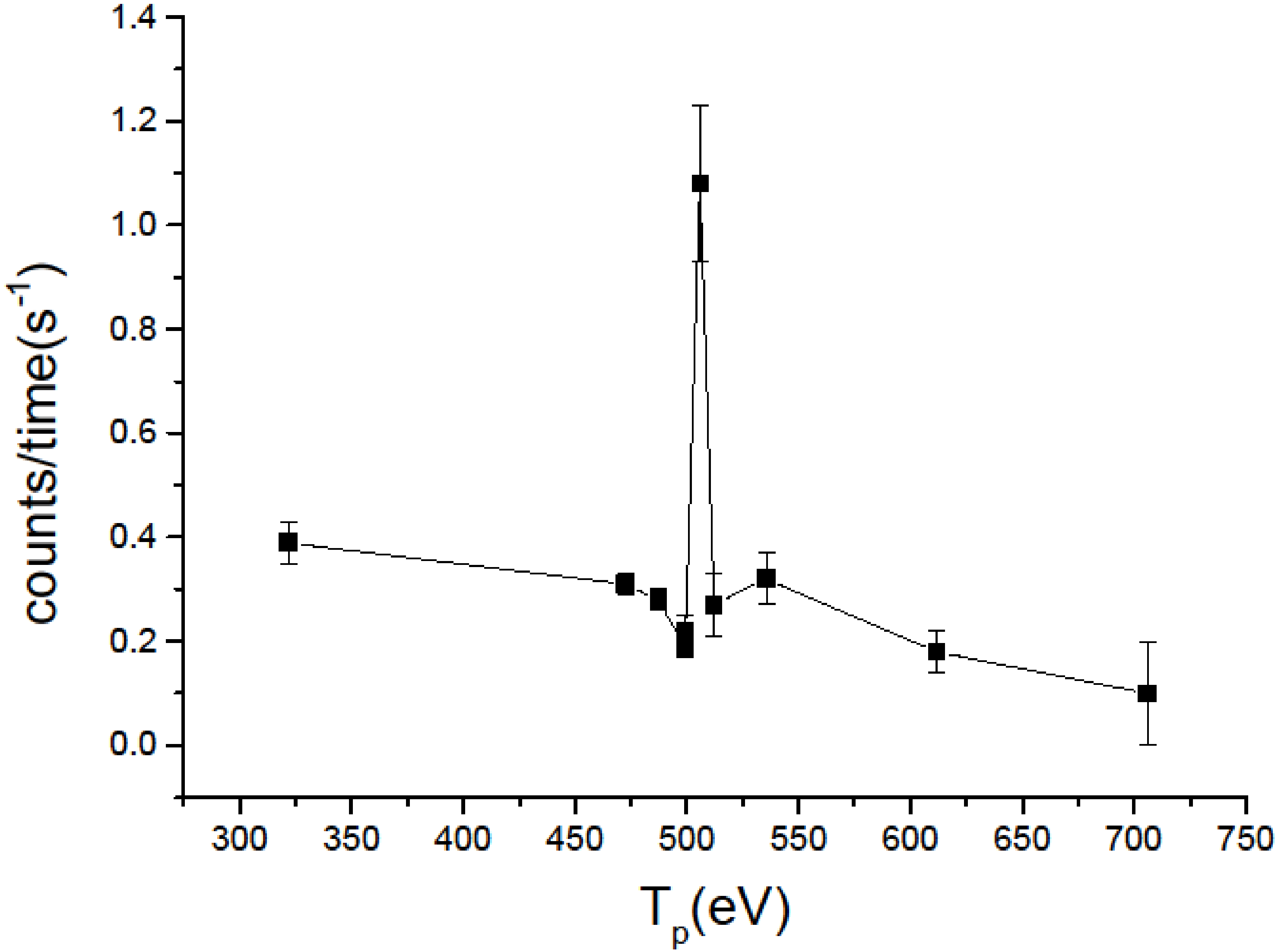
The two BN gates are positioned in the CF100 cross pieces, the MCP is in the foreground

Protons passing the BN gates pulse slopes

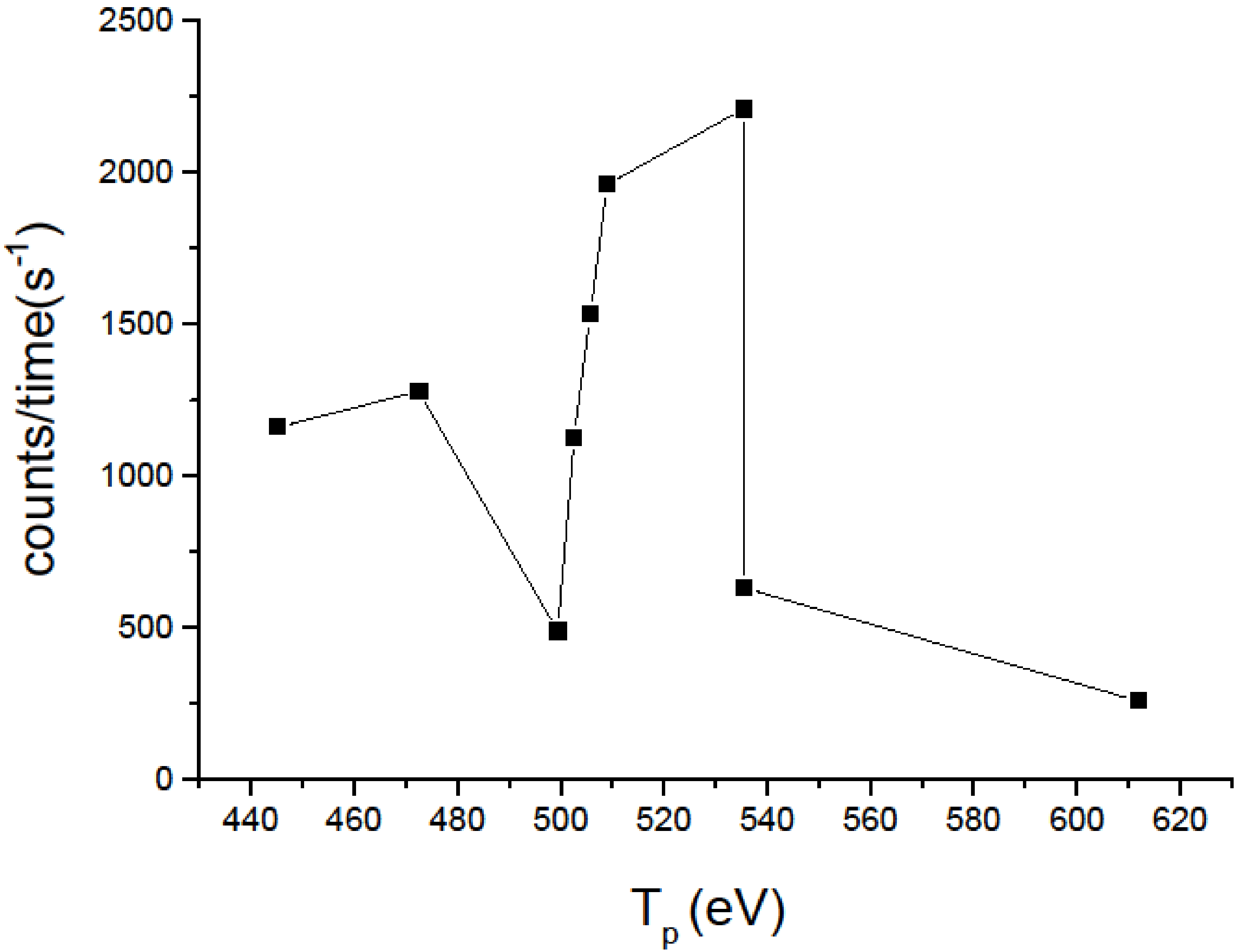


500 eV proton TOF spectra. ± 300 V grid voltages. ϕ1 mm Iris1, ϕ5 mm Iris2, ϕ1 mm Iris3 diameters. a. Source H_2 pressure $5 \cdot 10^{-4}$ mbar. Spike width 1.57 channels corresponding to dt = 3.83 ns and dT = 1.21 eV. b. Source H_2 pressure $5 \cdot 10^{-3}$ mbar. 1.09 channels wide, dt = 2.66 ns, dT = 0.92 eV.

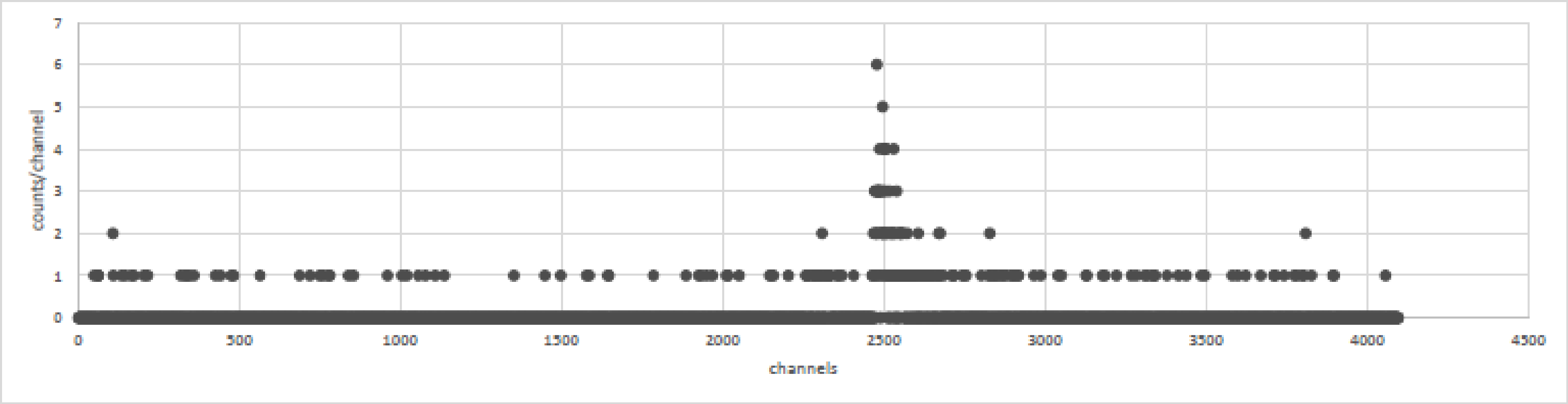
Proton source line profile at $p_{H2} = 5 \cdot 10^{-4}$ mbar



Proton source line profile at $p_{H_2} = 5 \cdot 10^{-3}$ mbar

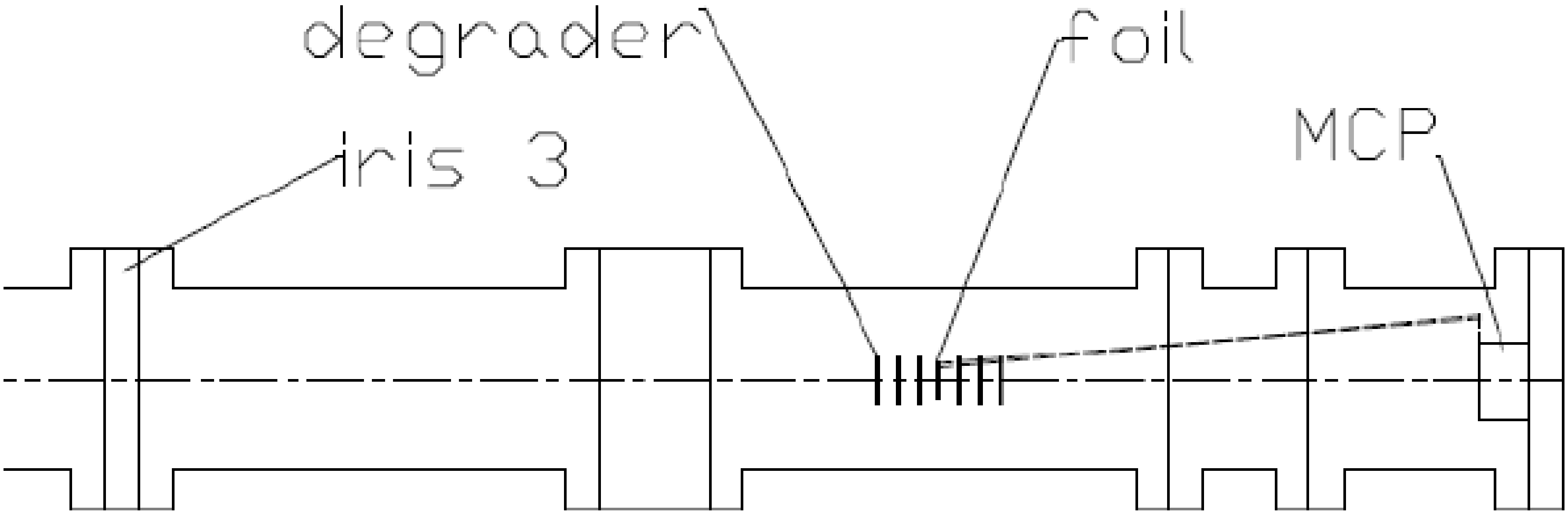


500 eV p TOF spectrum at $p_{H2} = 4 \cdot 10^{-4}$ mbar



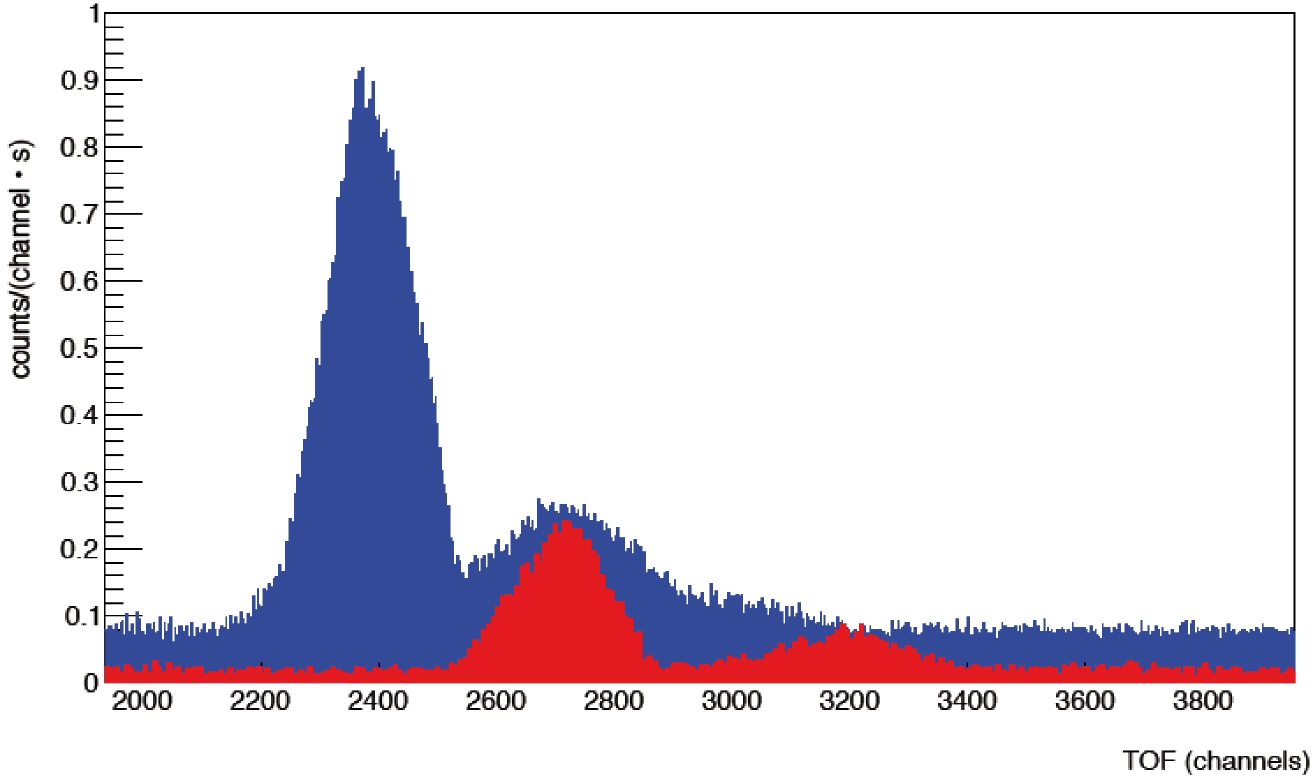
± 300 V BN gate chopper grid voltages.
ϕ1 mm Iris1, ϕ5 mm Iris2, ϕ5 mm Iris3 diameters

Secondary electron yield measurement



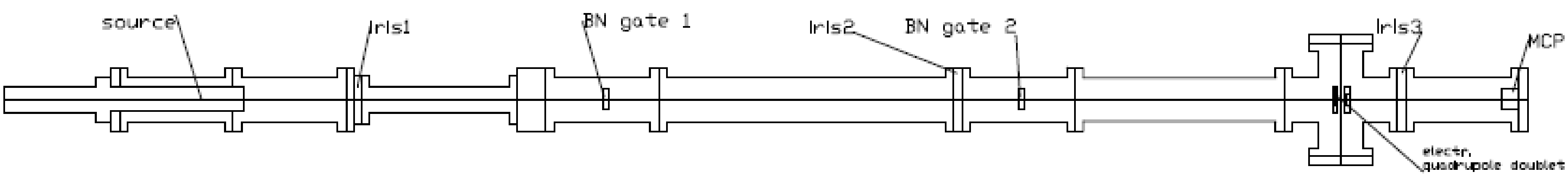
BN gate chopper setup modified by a degrader. Protons of keV energy pass thin foils of carbon, silver and plastics coated with MgO or LiF. The produced keV secondary electrons are measured by an MCP.

TOF spectra at $p_{H2} = 3 \cdot 10^{-3}$ mbar

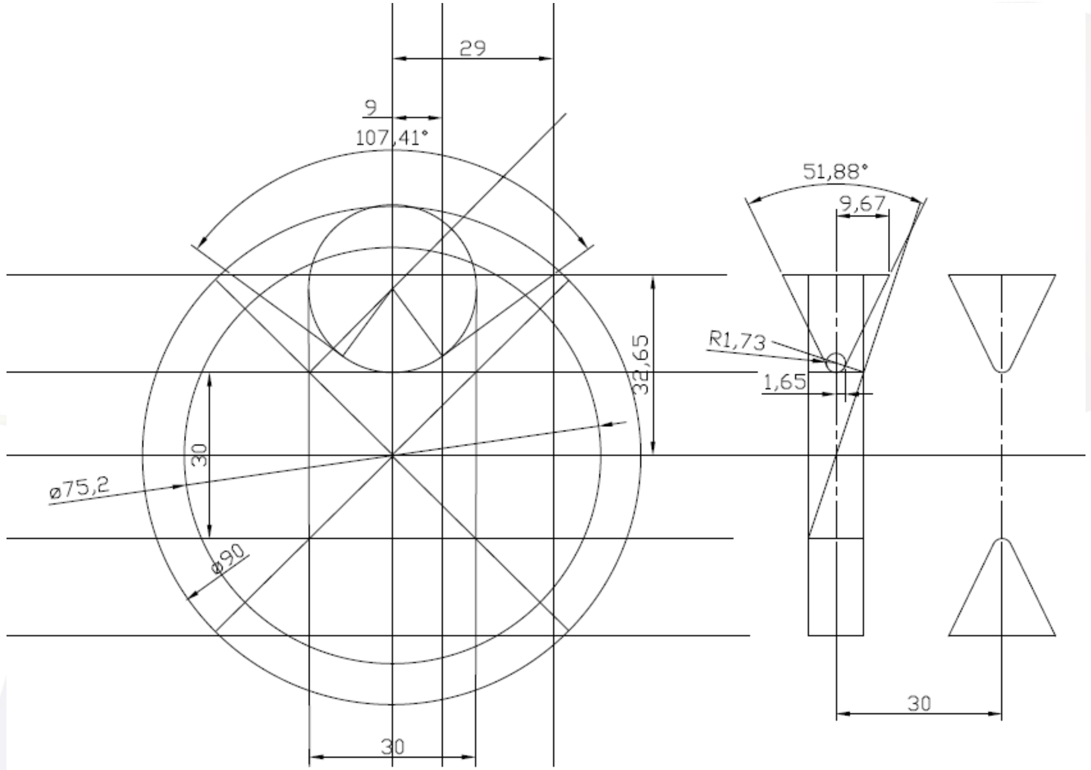


± 300 V BN gate chopper grid voltages. ϕ5 mm Iris1, Iris2, Iris3 diameters. Blue. 18 keV sec. electrons, produced by 18.5 keV protons, having hit a 17 μg/cm² C foil coated with 10 Å LiF. Red. Open zero voltage foil frame 500 eV protons. 3.1 electron/ incident p.

Electrostatic focusing using a quadrupole doublet



Electrostat. quadrupole doublet, schematically



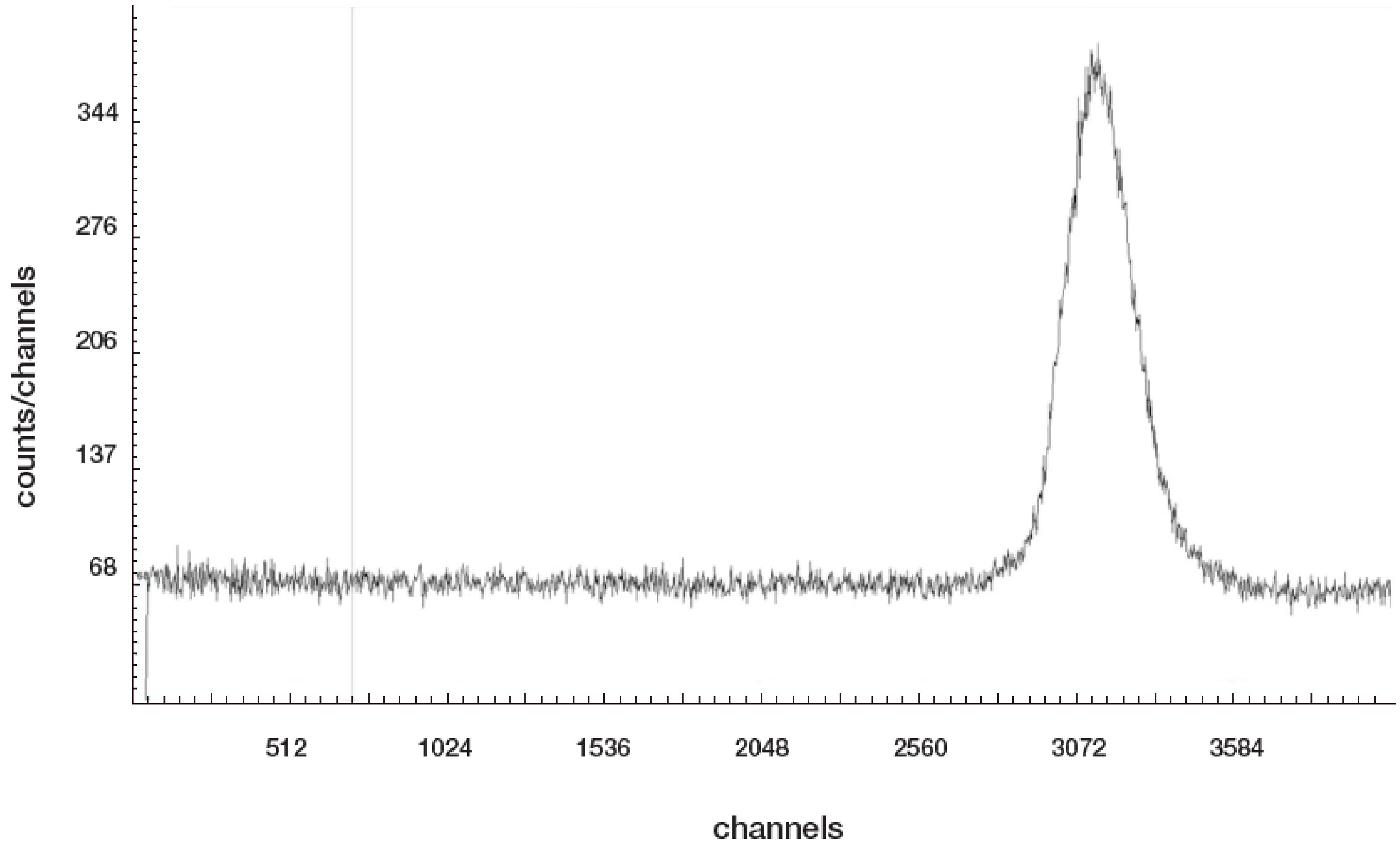
Q1, Q2: L=1cm, aperture radius r=1.5cm, l=3cm, Q1: $1/f_1 \approx k_1^2 L$; $k_1 = r^{-1}\sqrt{(\Phi_1/U_s)}$, Q2: f_2, k_2, Φ_2, for $f_1 = f_2 = f$, $\Phi_1 = \Phi_2 = \Phi$, doublet focal length f^*

$$1/f^* = 1/f_1 - 1/f_2 + l/(f_1 f_2), \quad f^* = r^4 U_S^2/(L^2 \Phi^2 l) = f^2/l,$$

$$l_1 = f^2/l - |f|, \quad l_2 = f^2/l + |f|$$

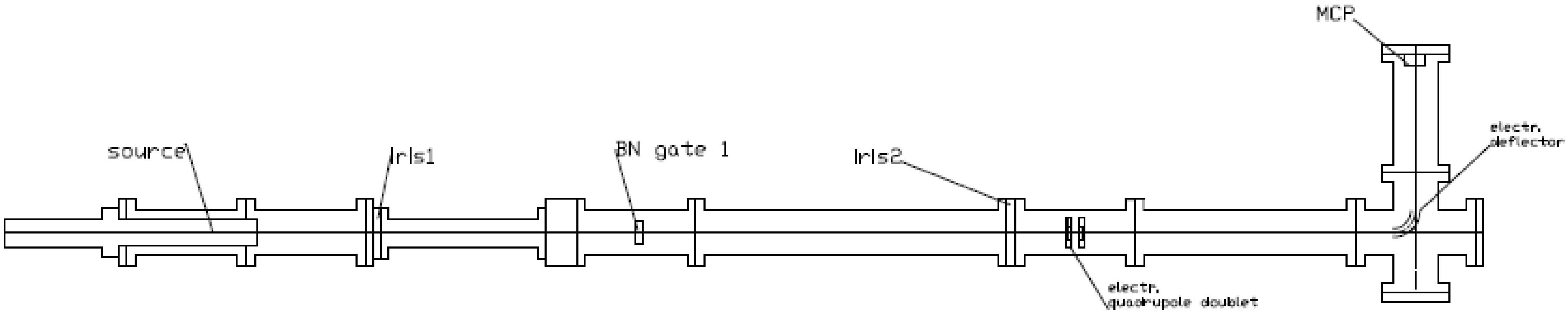
K. G. Steffen, *High Energy Beam Optics* (Intersience Publishers, New York, London, Sydney, 1965) 24 - 29

Quadrupole doublet focused 500 eV p TOF spectrum

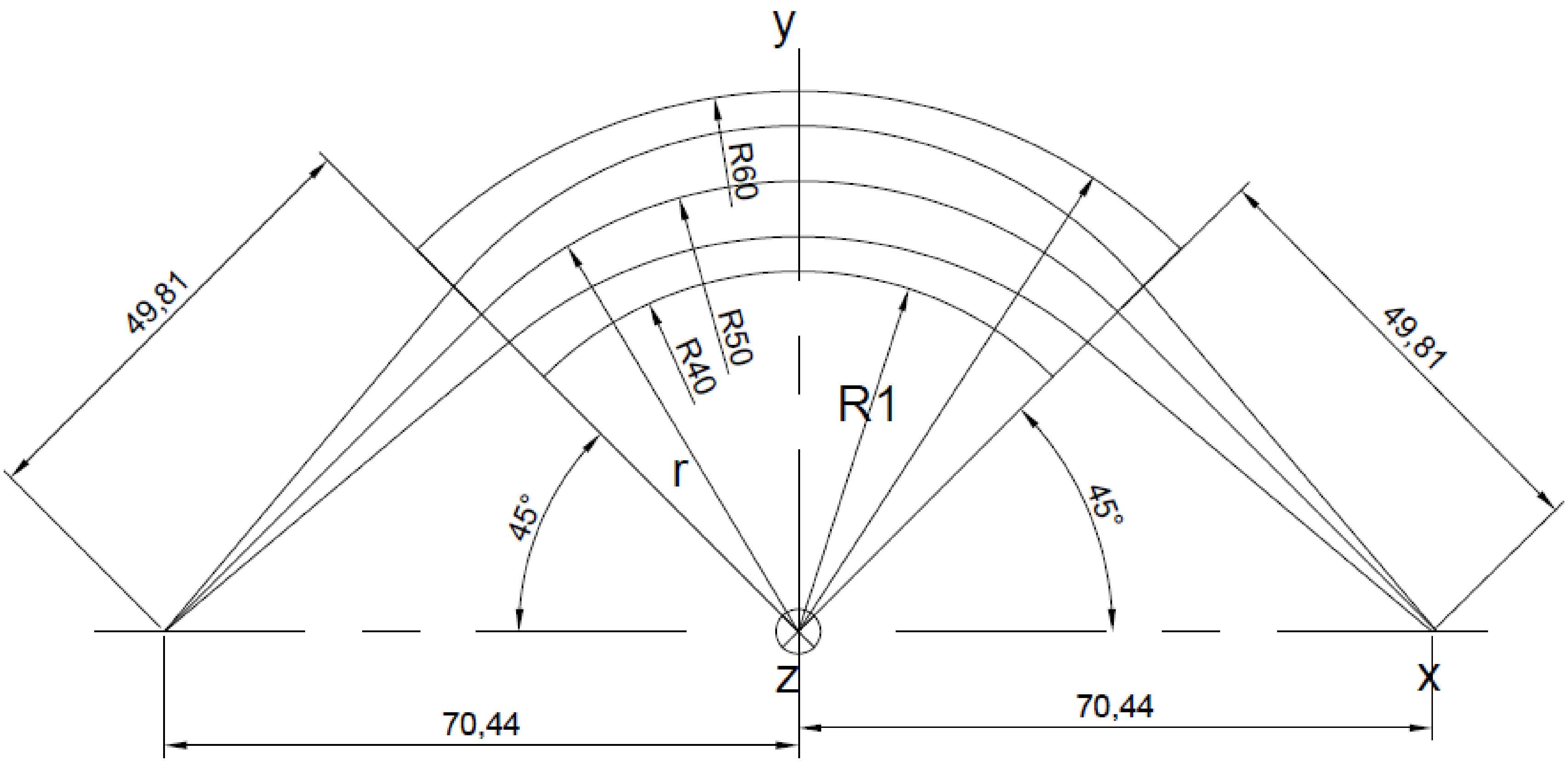


$p_{H2} = 7 \cdot 10^{-3}$ mbar. ± 300 V BN gate chopper grid voltages. ϕ5 mm Iris1, Iris2, Iris3 diameters.

Q doublet focusing onto an electric deflector

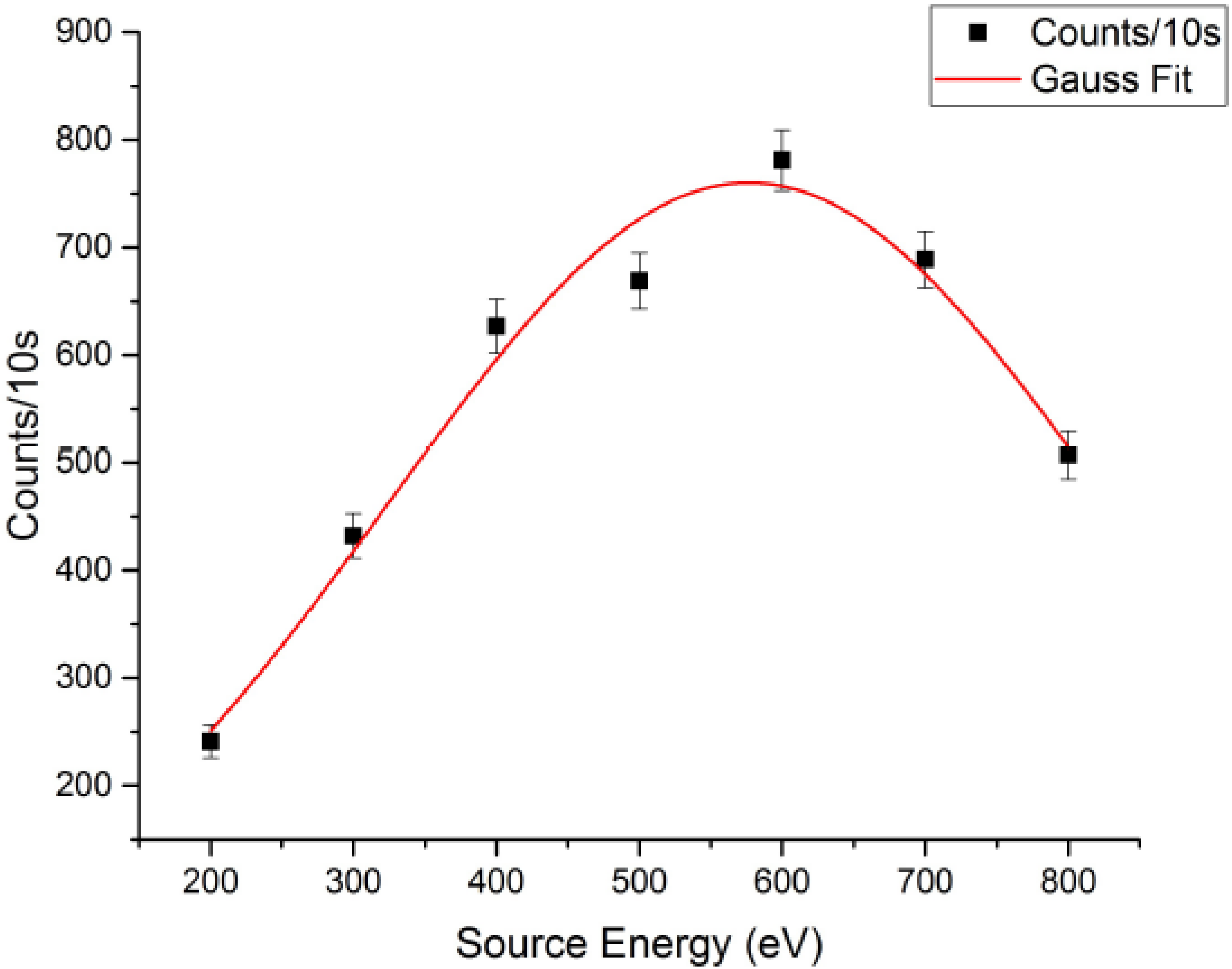


Electric deflector, schematically

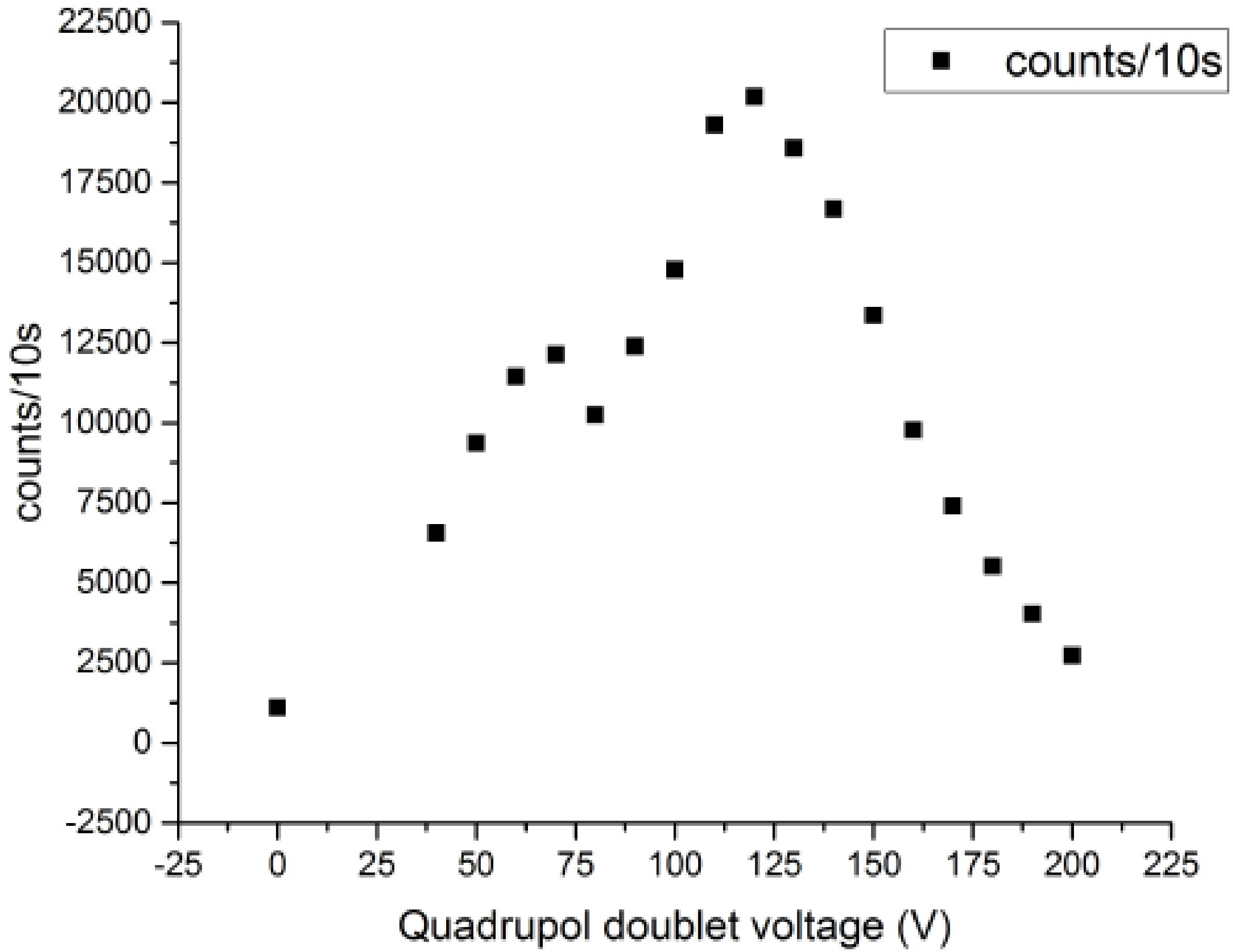


Two electrodes radii R1 and R2, reference particle radial coordinate r. Double- focusing with focal points in horizontal (x- y) and vertical planes being at the same position. $E(r)=UR_1 R_2 /(r^2 (R_2 – R_1)) = 2T/(qr)$, $T=500$ eV, $r=5$ cm, $R_1 = 4$ cm, $R_2 = 6$ cm, $U=416.8$ V

Deflector dispersion



Deflected intensity vs. Q doublet voltage Φ



T=500 eV, U/2 = ± 220 V

Outlook

Functioning: BN gate chopper with electrostatic Q doublet focusing and electric deflector

H(2s) detection by charge exchanging in Ar cell

Measurements: BOB H(1s) and H(2s) atoms (Ar cell, focusing element, deflector, BN gate chopper, MCP)

BOB H(2s) hyperfine state population probability (spin filter, Ar cell etc.)

$N_{\alpha 11}/ N_{\alpha 10} \rightarrow \chi\ (g_S, g_T)$

$N_{\beta 1\text{-}1}/ N_{\beta 00}$, $N_{\beta 1\text{-}1}/ N_{\alpha 10}$, $N_{\beta 1\text{-}1}/ N_{\alpha 11} \rightarrow W_4\ (H_\nu)$