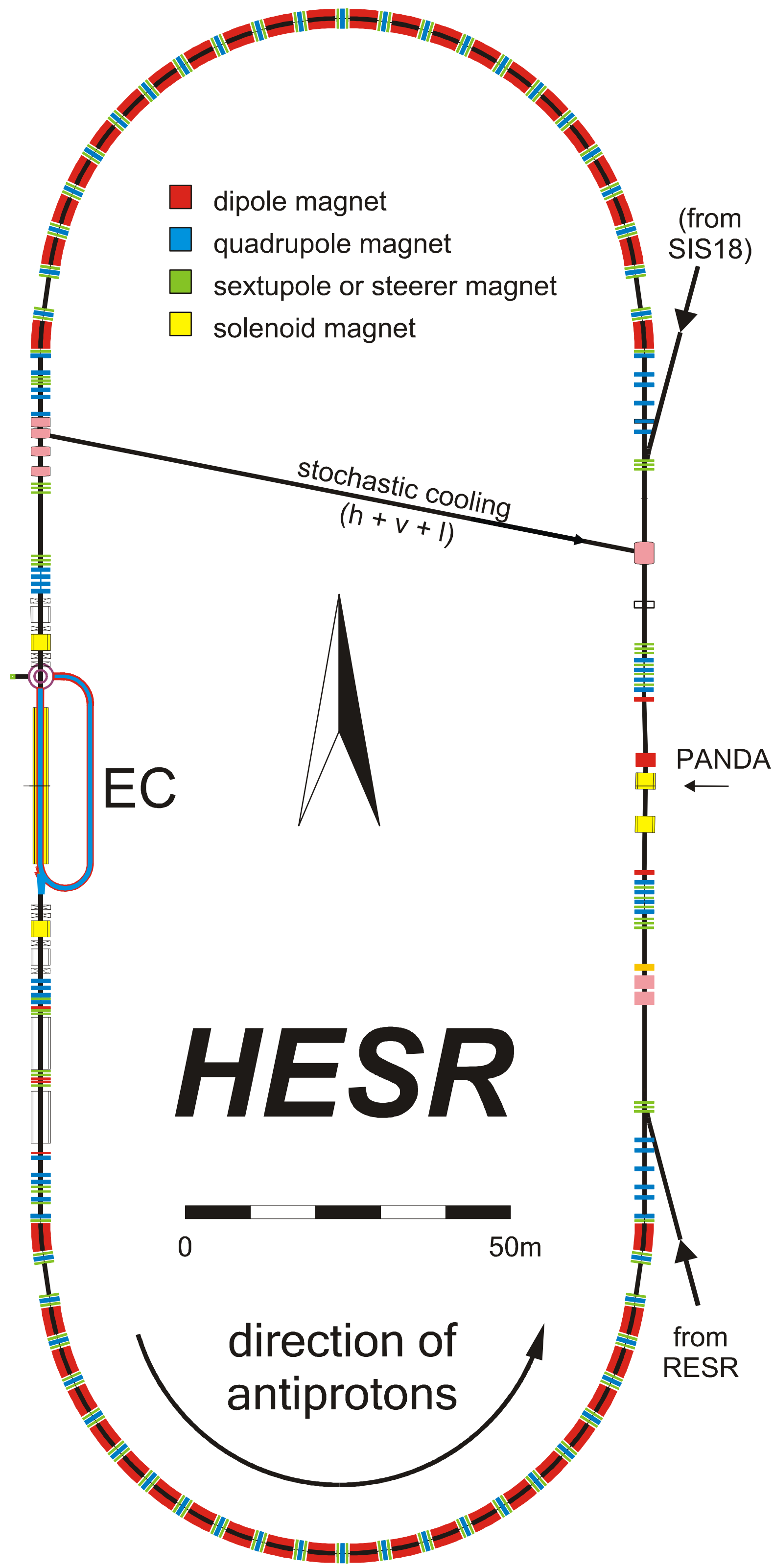
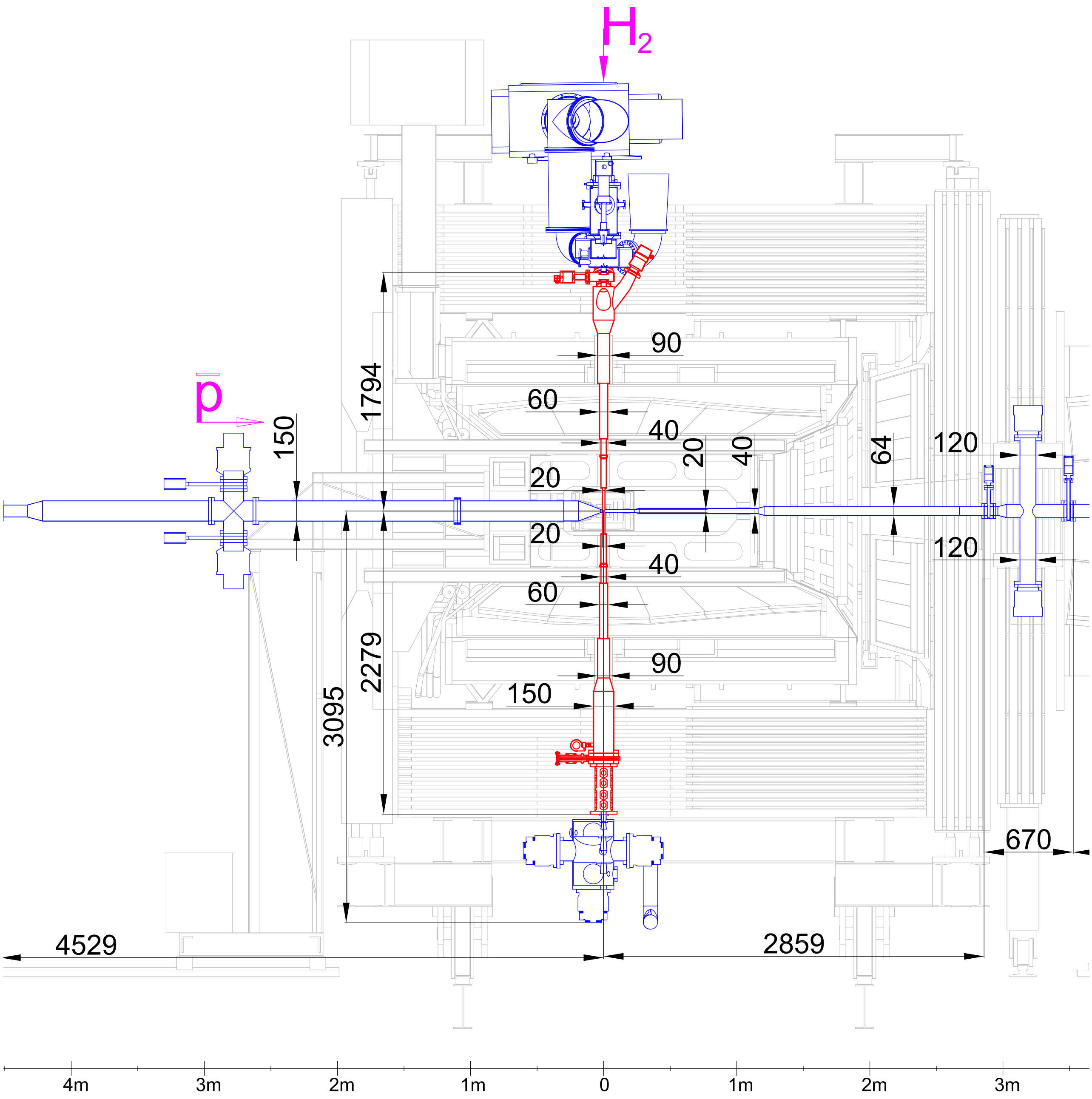
Counteracting Trapped Ion Effects in the HESR

1. Introduction
2. HESR Layout
3. The Ionization Process
4. Potential Well of the Antiproton Beam
5. Beam Neutralization by Trapped Ions
6. Clearing Electrodes
7. The Arcs (Dipole Magnets)
8. PANDA Target Region
9. Electron Cooler (EC)
10. Summary and Conclusions

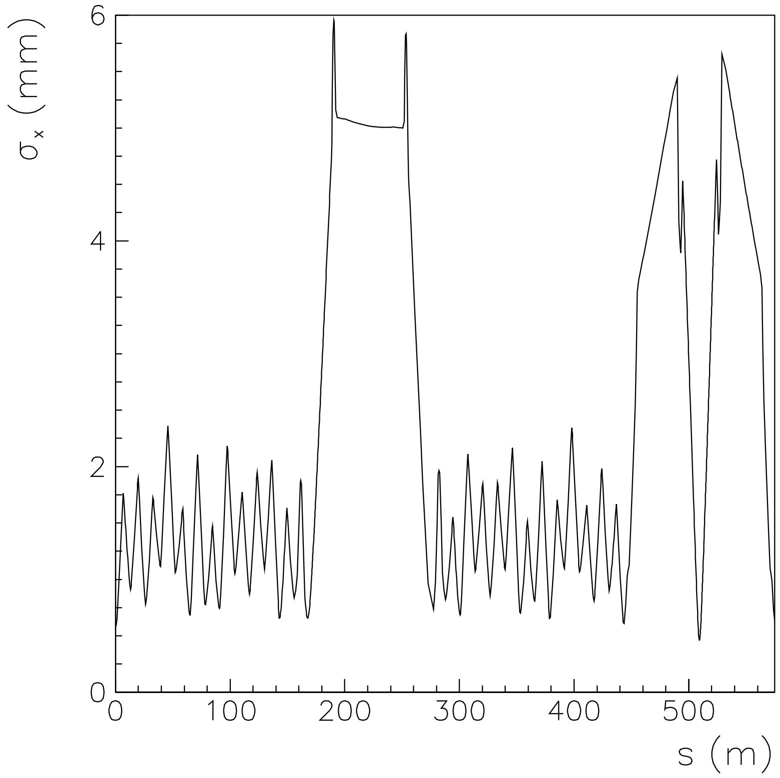
Layout of the HESR

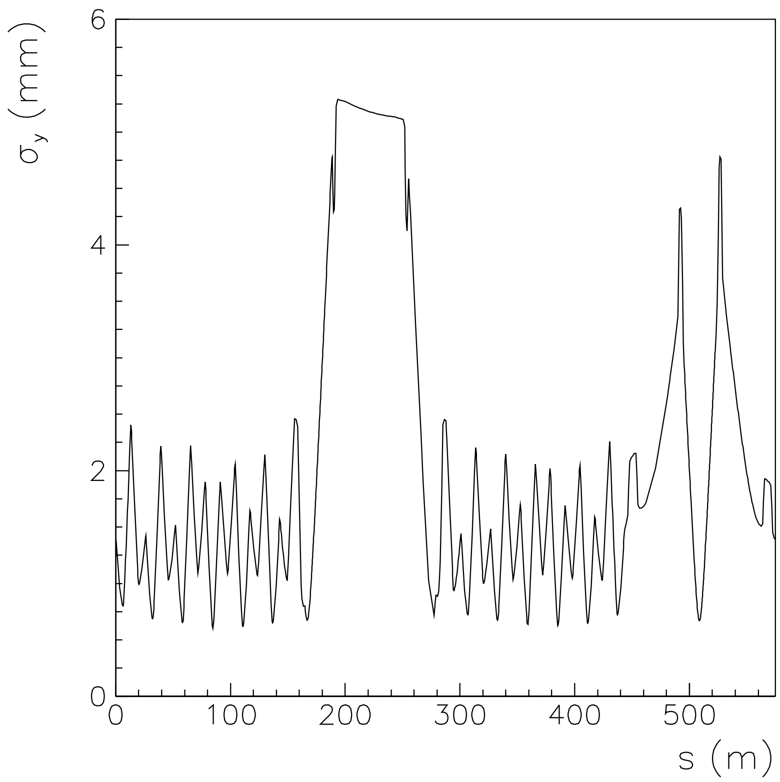


Panda Target and Spectrometer



Beam Envelopes





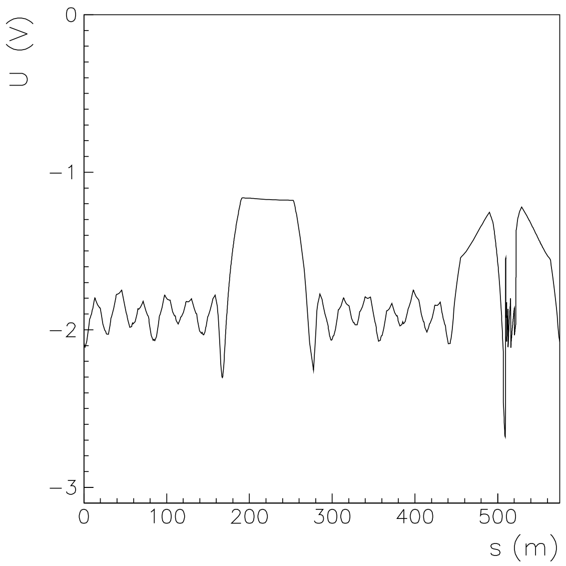
Potential Well of the Antiproton Beam

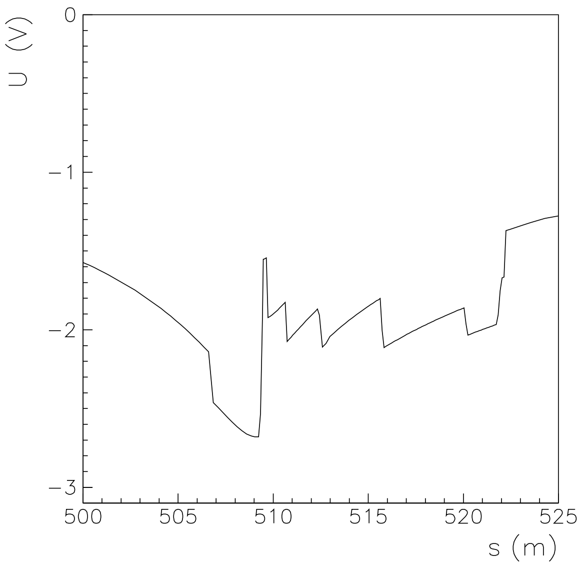
Central Potential Depth

$$U(s) = U(0,0,s) = \frac{\lambda}{4\pi\epsilon_0}\left[\gamma + \ln\left(\frac{2\,r_c^2}{(\sigma_x+\sigma_y)^2}\right)\right], \qquad (1)$$

Transverse Electric Field near Beam Center

$$\begin{aligned} E_x(x,y) &= \frac{\lambda}{2\pi\epsilon_0}\frac{1}{(\sigma_x+\sigma_y)}\frac{x}{\sigma_x} \\ E_y(x,y) &= \frac{\lambda}{2\pi\epsilon_0}\frac{1}{(\sigma_x+\sigma_y)}\frac{y}{\sigma_y}. \end{aligned} \qquad (2)$$





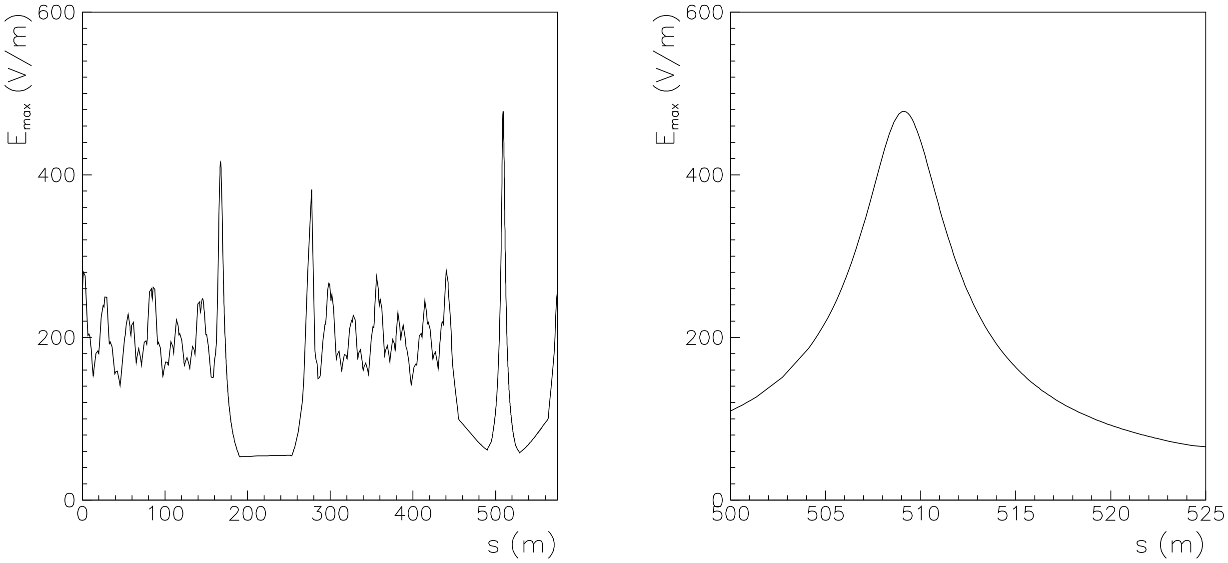
Central beam potential $U(s)$ assuming the standard optics, $L_1 = 0.9C$, $p_{\bar{p}} = 15$ GeV/c, $N_{\bar{p}} = 1.0 \cdot 10^{11}$ and $\eta = 0$.

Transverse Electric Field of the Beam

Clearing electrodes near the inner surface of the beam tube

Clearing electric field: 2250 V/m

Clearing electrodes every 5 m and near potential minima



Upper limit E_{max} of the transverse electric field of the antiproton beam assuming the standard optics, $L_1 = 0.9C$, $p_{\bar{p}} = 15$ GeV/c and $N_{\bar{p}} = 1.0 \cdot 10^{11}$.

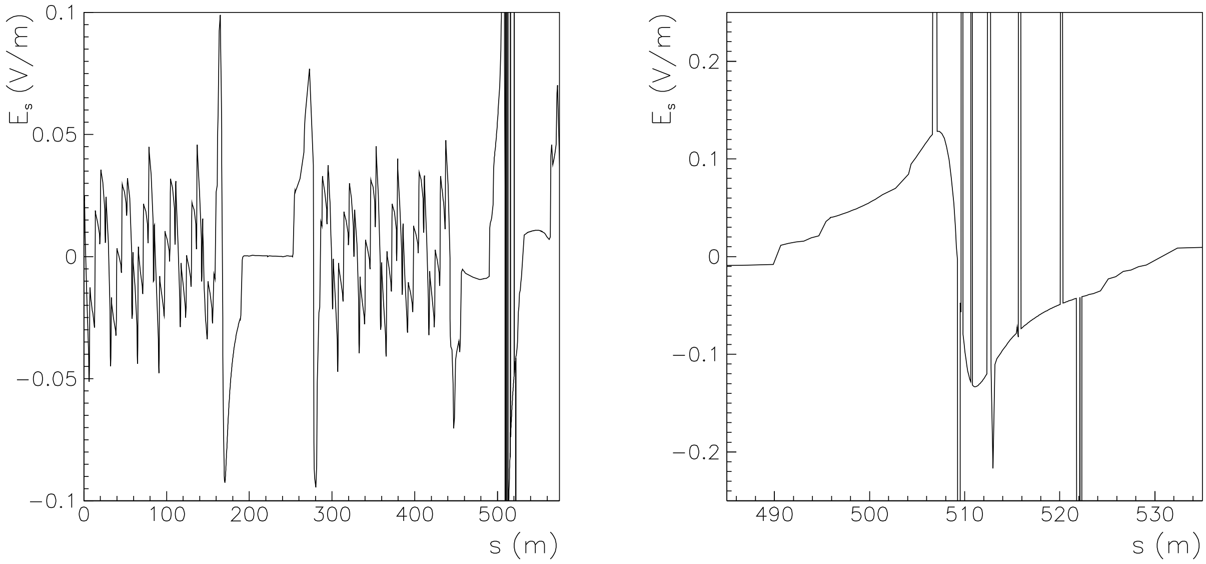
Longitudinal Electric Field

Longitudinal Electric Field E_s, Longitudinal Acceleration a_s, Clearing Time T_c

$$E_s = -\frac{U_{i+1} - U_i}{s_{i+1} - s_i} \tag{3}$$

$$a_s = \frac{e}{m} E_s \tag{4}$$

$$T_c = \sqrt{\frac{2l}{a_s}}. \tag{5}$$



Longitunal electric field component E_s of the antiproton beam assuming the standard optics, $L_1 = 0.9C$, $p_{\bar{p}} = 15$ GeV/c and $N_{\bar{p}} = 1.0 \cdot 10^{11}$.

Production Time, Clearing Time and Neutralization

Production Rate $R_{p,i}$ and Production Time $T_{p,i}$ of Ion i

$$R_{p,i} = \sigma_i \rho_{m,i} \beta c. \tag{6}$$

$$T_{p,i} = \frac{1}{R_{p,i}}. \tag{7}$$

Clearing Rate $R_{c,i}$ and Clearing Time $T_{c,i}$

$$T_{c,i} = \frac{1}{R_{c,i}}. \tag{8}$$

Local Neutralization $\eta_i(s)$

$$\eta_i(s) = \frac{L_1}{C} \frac{T_{c,i}(s)}{T_{p,i}(s)} = 0.9 \frac{T_{c,i}(s)}{T_{p,i}(s)}. \tag{9}$$

$$\eta(s) = \sum_{i=1}^{n} \eta_i(s) \tag{10}$$

Ionization

Ionization Cross Section (Bethe's Formula)

$$\sigma = 4\pi \left(\frac{\hbar}{m_e c}\right)^2 \left\{ M^2 \left[\frac{1}{\beta^2} \ln\left(\frac{\beta^2}{1-\beta^2}\right) - 1\right] + \frac{C}{\beta^2} \right\}, \tag{11}$$

$$4\pi \left(\frac{\hbar}{m_e c}\right)^2 = 1.874 \cdot 10^{-24}\ \mathrm{m}^2. \tag{12}$$

Ionization cross sections

$p_{\bar{p}}$ (GeV/c)	$\sigma(H_2)$ (m^2)	$\sigma(CH_4)$ (m^2)	$\sigma(H_2O)$ (m^2)	$\sigma(CO)$ (m^2)
1.500	$2.16 \cdot 10^{-23}$	$1.12 \cdot 10^{-22}$	$8.60 \cdot 10^{-23}$	$9.37 \cdot 10^{-23}$
3.825	$1.87 \cdot 10^{-23}$	$9.88 \cdot 10^{-23}$	$7.61 \cdot 10^{-23}$	$8.35 \cdot 10^{-23}$
8.889	$2.00 \cdot 10^{-23}$	$1.07 \cdot 10^{-22}$	$8.27 \cdot 10^{-23}$	$9.11 \cdot 10^{-23}$
15.000	$2.12 \cdot 10^{-23}$	$1.15 \cdot 10^{-22}$	$8.84 \cdot 10^{-23}$	$9.78 \cdot 10^{-23}$

Ionization Rate

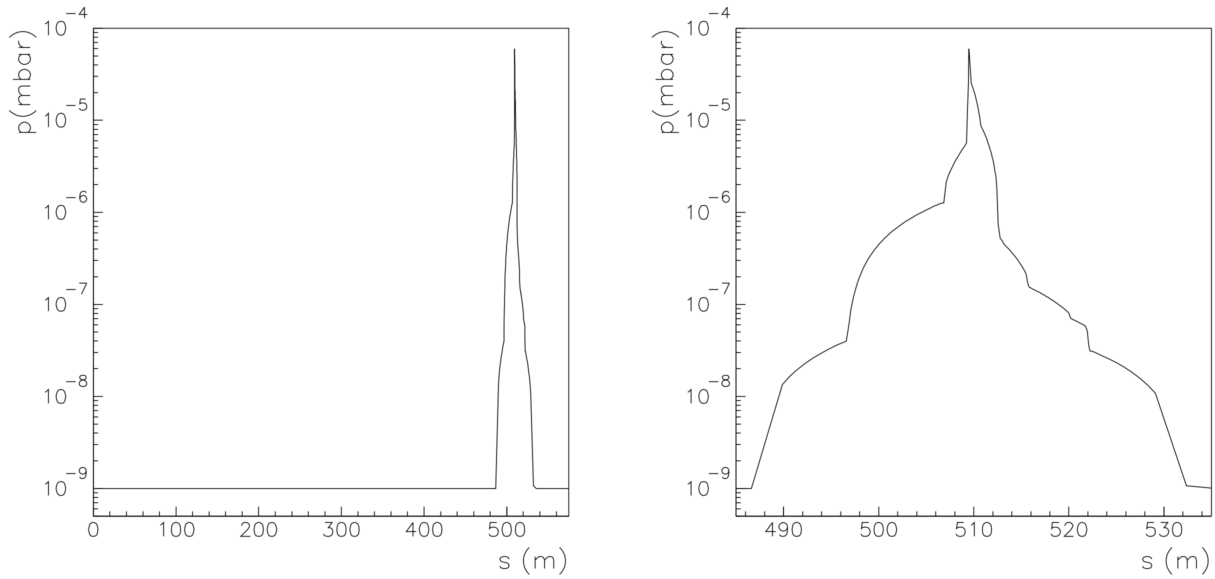
$$\frac{dN_{ion}}{dt} = \sigma N_{\bar{p}} f \rho_m C = N_{\bar{p}} \sigma \rho_m \beta c. \tag{13}$$

With $N_{\bar{p}} = 1.0 \cdot 10^{11}$ at 15 GeV/c and $\rho_m(H_2) = 2.47 \cdot 10^{13}\ \mathrm{m}^{-3}$

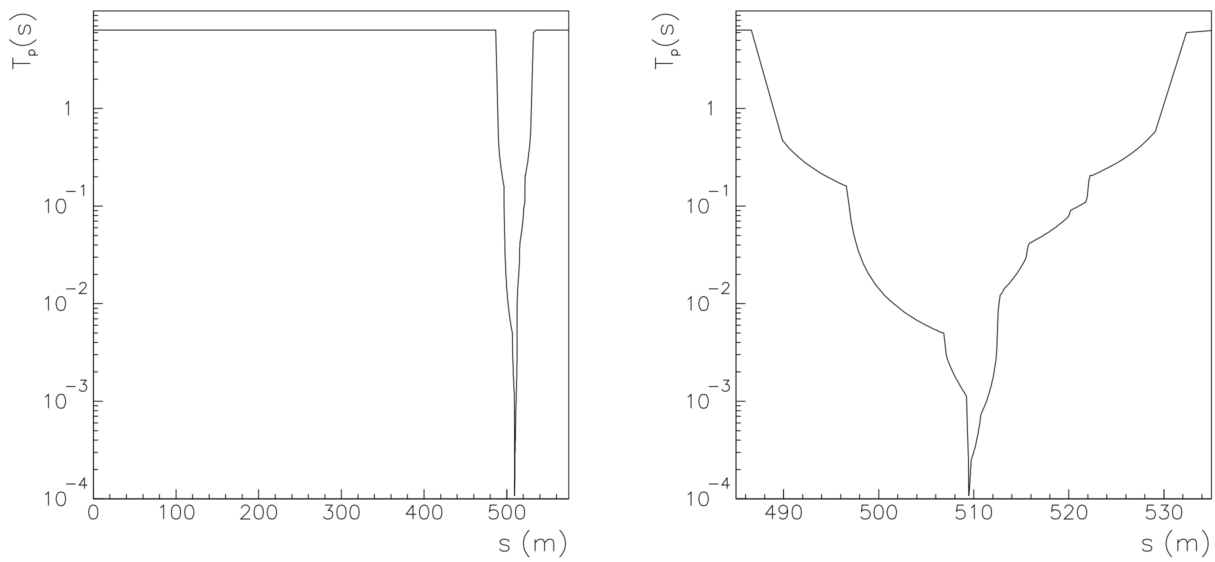
$$\frac{dN_{ion}}{dt} = 1.57 \cdot 10^{10}\ \mathrm{s}^{-1}. \tag{14}$$

$p = 1.0 \cdot 10^{-9}$ mbar: Full neutralization within 6.4 s (if no clearing)!

Residual Gas Pressure and Production Time T_p



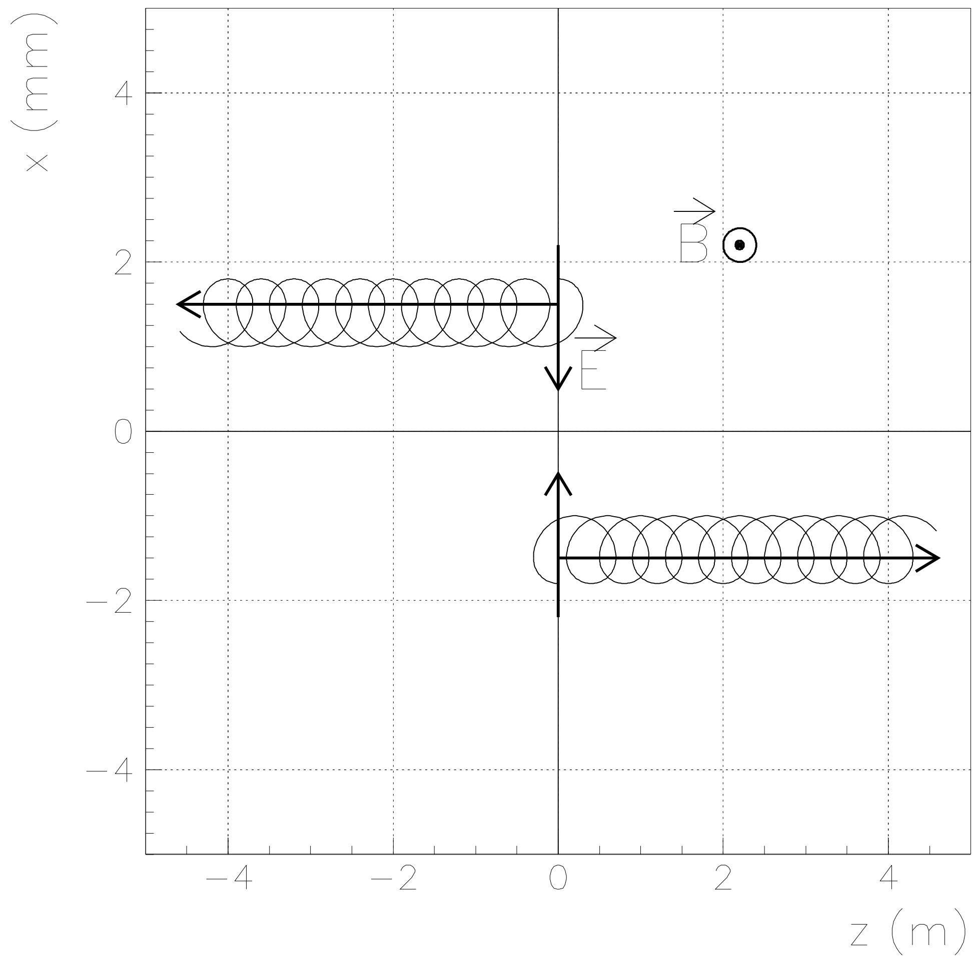
Vacuum pressure $p(s)$ **without NEG coating and heating jackets in the arcs**.



Cross-Field Drift Velocity in Dipole Magnets

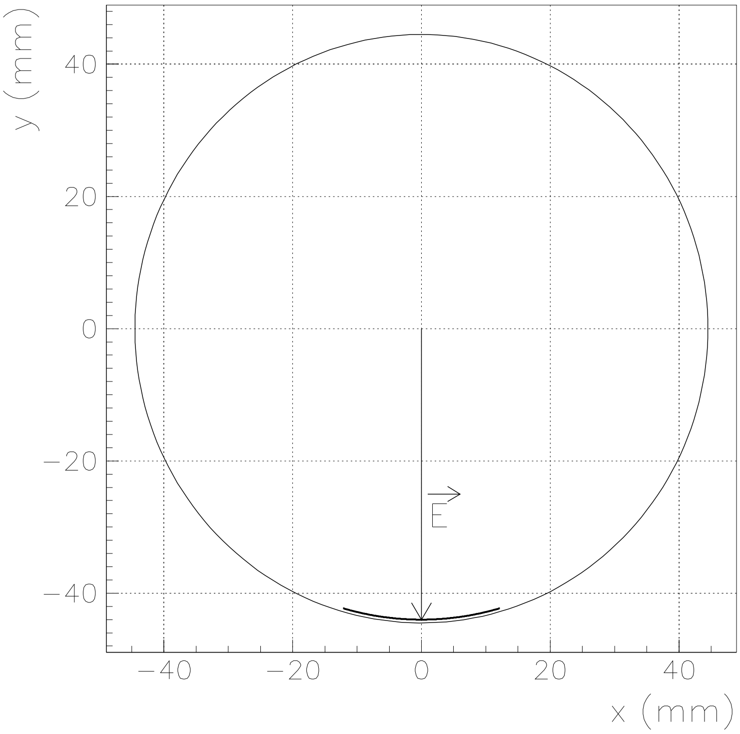
Ions with velocity $v_\perp$ to $\vec{B}$ perform cyclotron motions
Electric field $\vec{E}$ of the $\bar{p}$-beam and magnetic field $\vec{B}$ yield
cross field drift velocity $\vec{v}_D$:

$$\vec{v}_D = \frac{\vec{E} \times \vec{B}}{B^2}, \quad |\vec{v}_D| = \left| \frac{E_x}{B_y} \right| . \tag{15}$$



HESR Dipole Fields: 0.17 - 1.7 , $N_{\bar{p}} = 1.0 \cdot 10^{10}$.
Mean E_x: 2.2 - 6.9 V/m
Mean v_D: 12.9 - 4.1 m/s

Continuous Clearing Electrodes

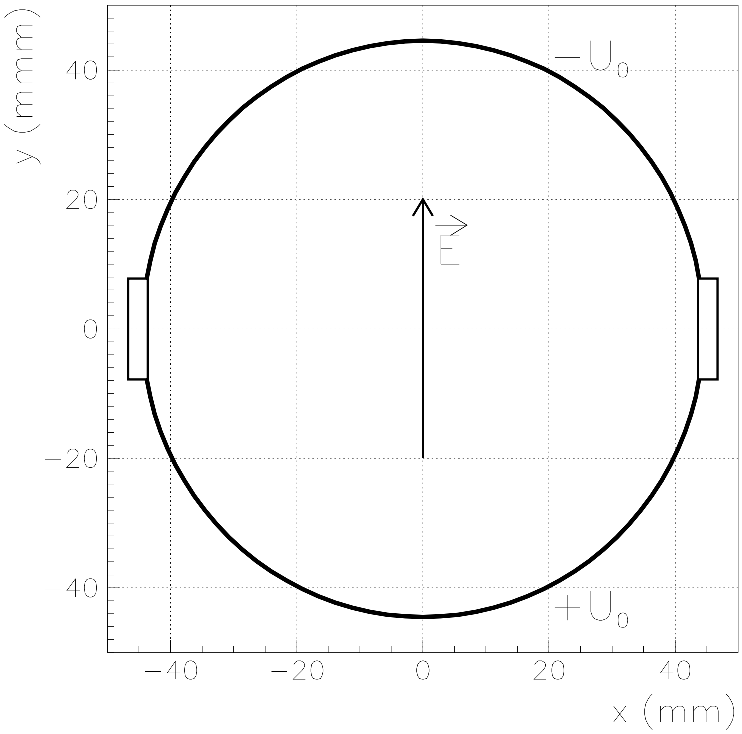


A 0.1 mm thin and 30 mm wide isolating Al_2O_3 layer can be deposited at the bottom of the beam pipe using plasma spraying. On top of the isolating layer a 25 mm wide highly resistive thick film coating with a few 10 μm thickness is applied. The highly resistive coating on top of the dielectric can be realized using commercially available thick film pastes from Heraeus. Reference: Fritz Caspers (CERN)

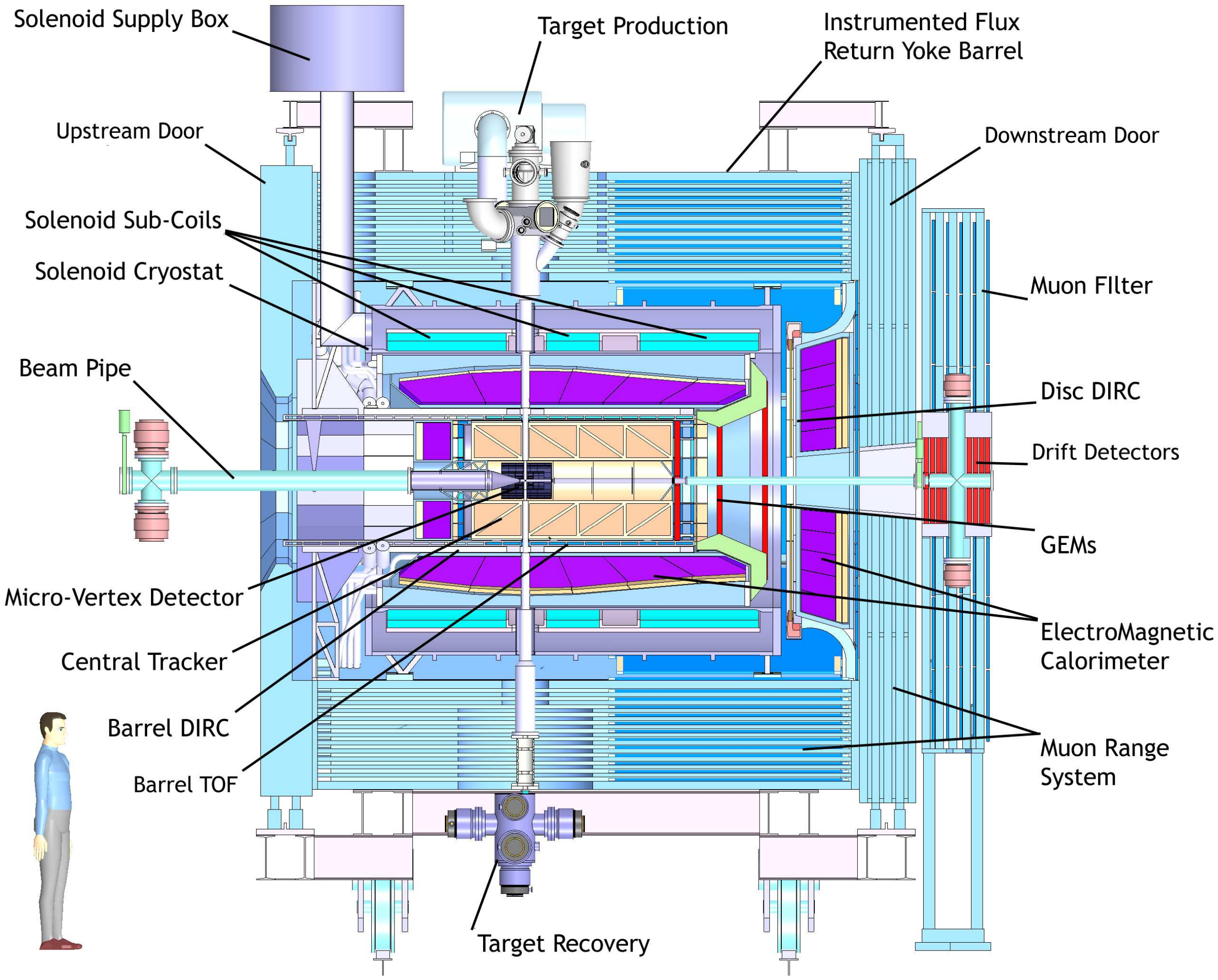
The surface resistance $R_{surface}$ of the highly resistive layer must be higher than the free space impedance $Z_0 = 377\ \Omega$ but small enough that the voltage drop along the electrode is not too high. If $R_{surface} \gg Z_0$ the layer is "invisible" to the electromagnetic waves and the longitudinal and transverse impedance budget is not seriously affected!

The length of such an electrode can be a few meters. It can be installed in straight sections and in magnetic dipole sections. The clearing voltage can be applied by feedthroughs at one or both ends of the electrode. Clearing voltages up to -1.0 kV are possible. **Clearing voltage of -1.0 kV yields electric fields of -640 V/m in the center of a 89 mm wide beam pipe.**

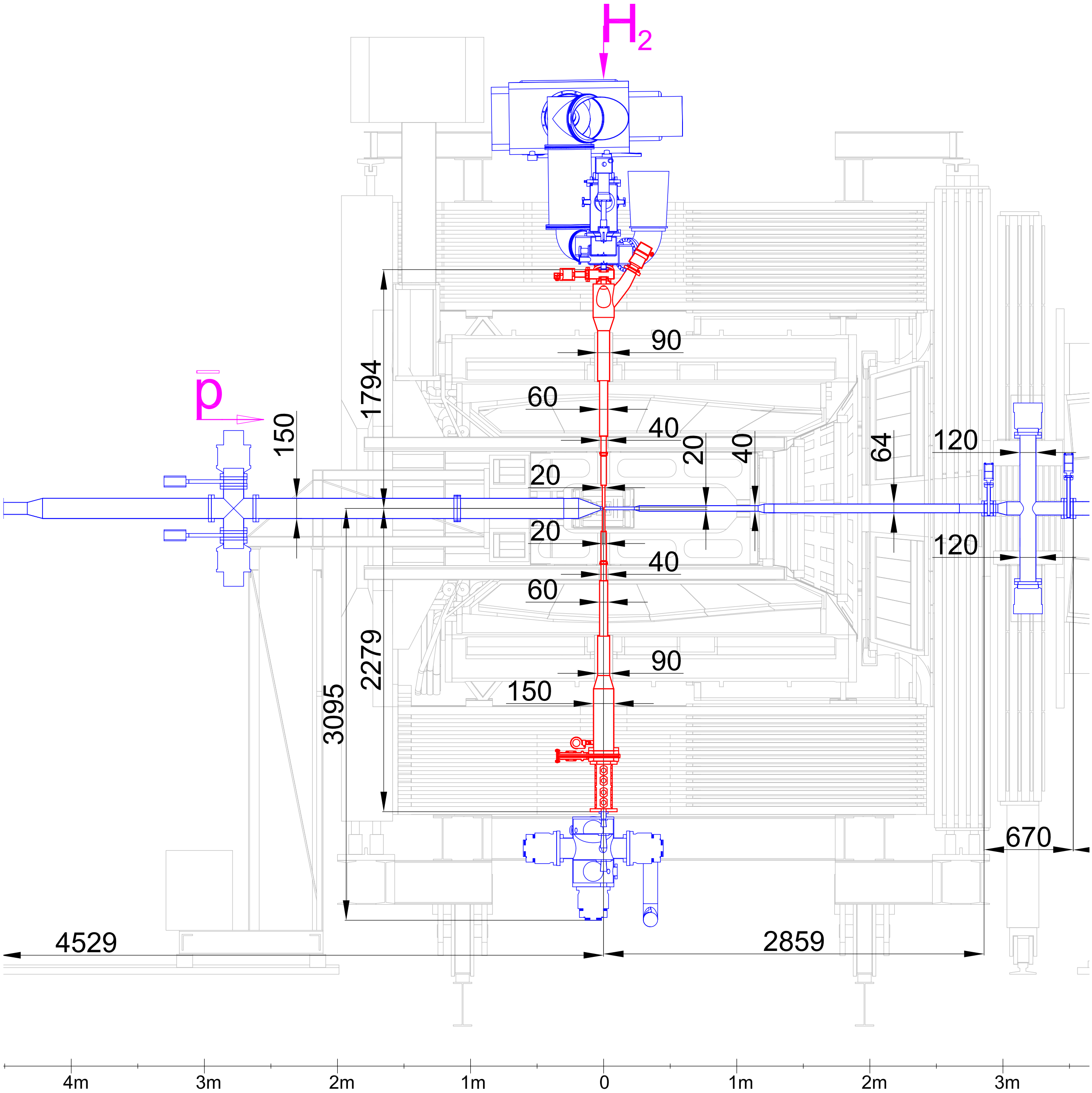
Continuous Clearing Electrodes



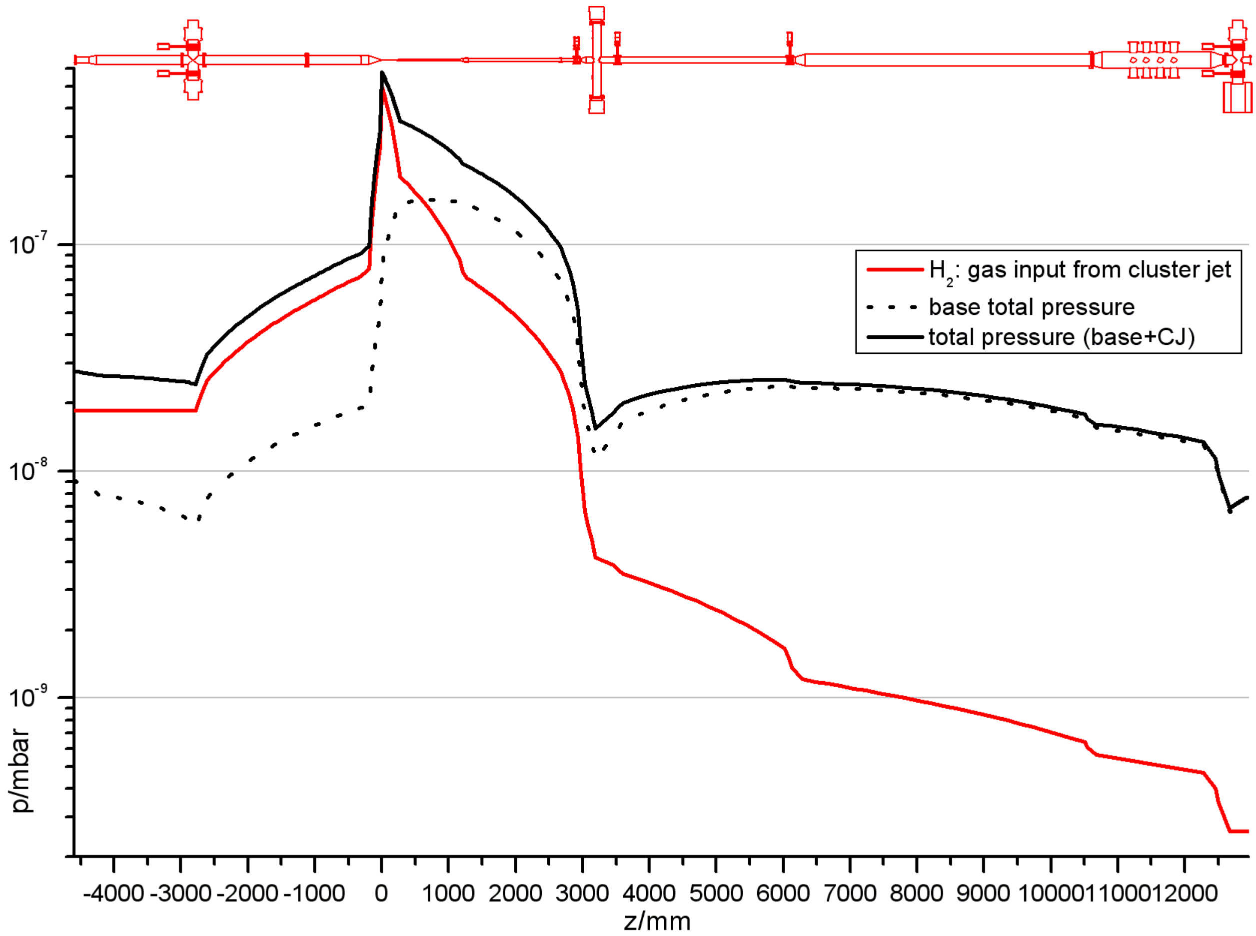
Panda Target and Spectrometer



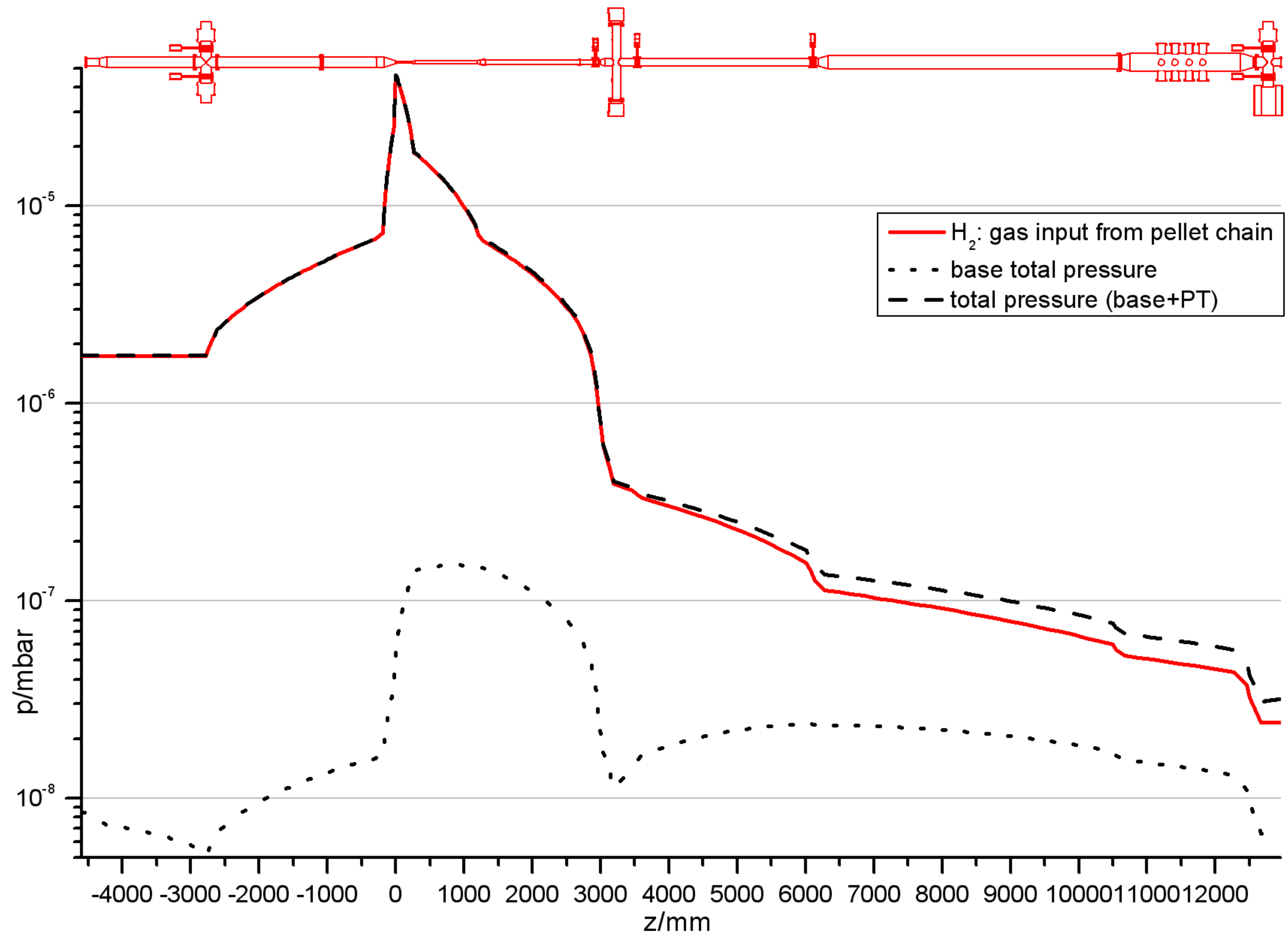
Panda Target and Spectrometer



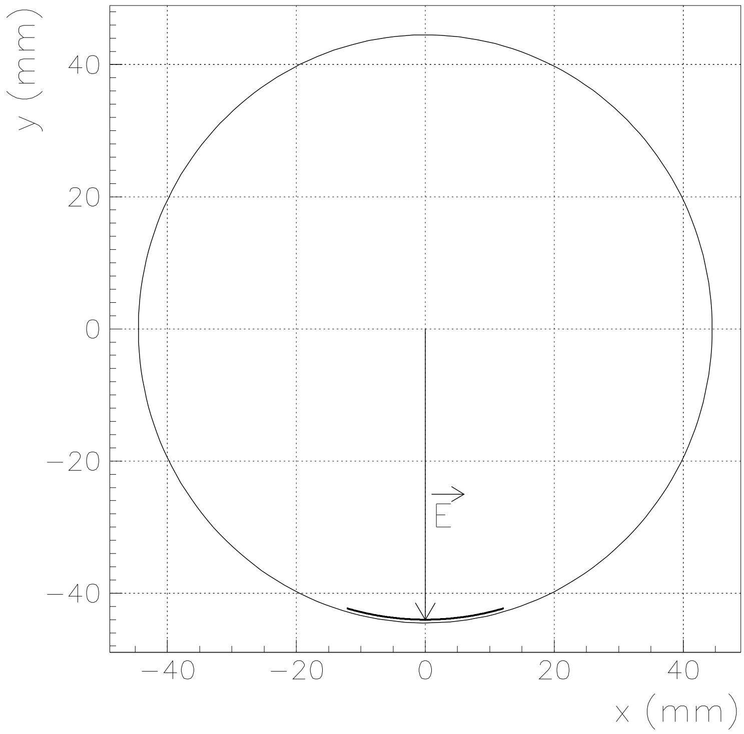
Pressure Profile Cluster-Jet

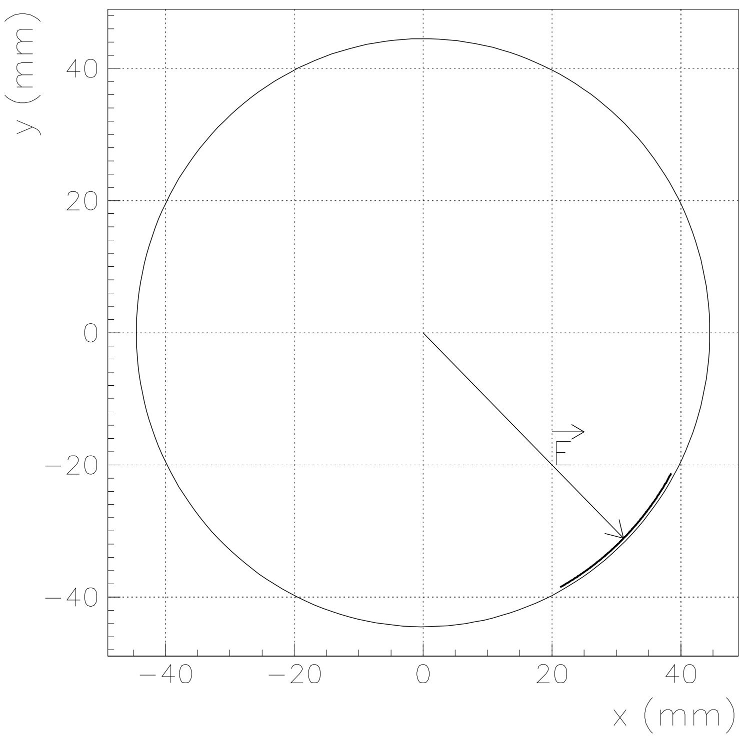


Pressure Profile Pellet Target

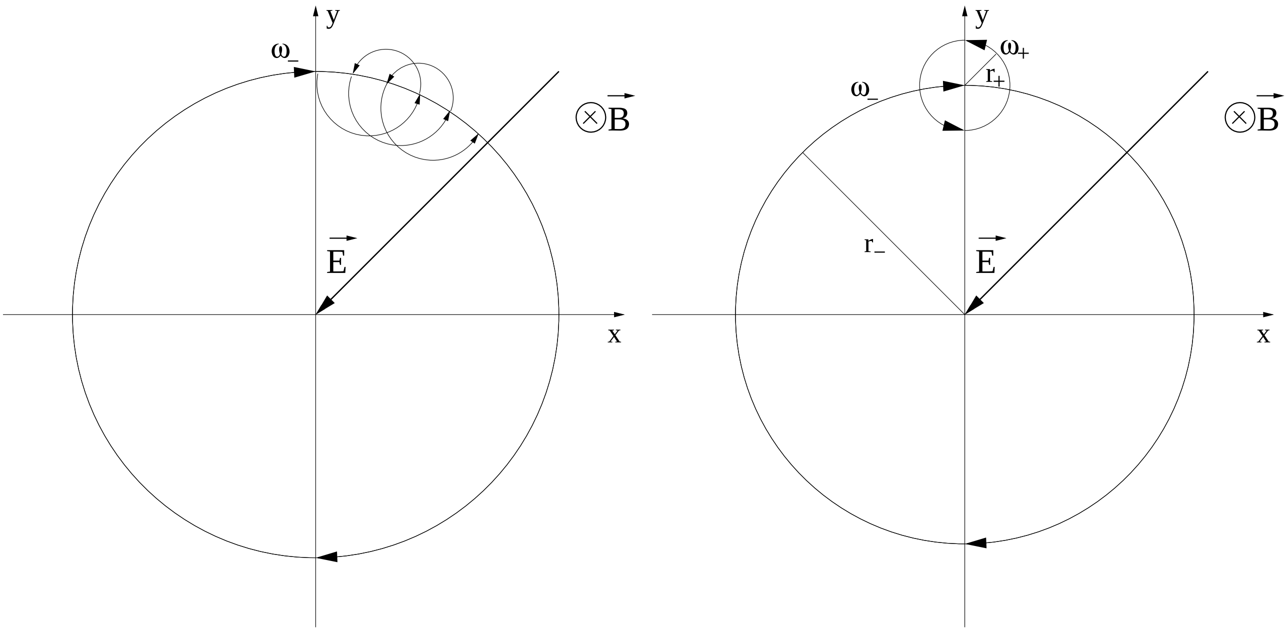


Continuous Clearing Electrodes near Panda





Motion of Trapped Ions in a Solenoid



$$\omega_c = \frac{q}{m}B,$$

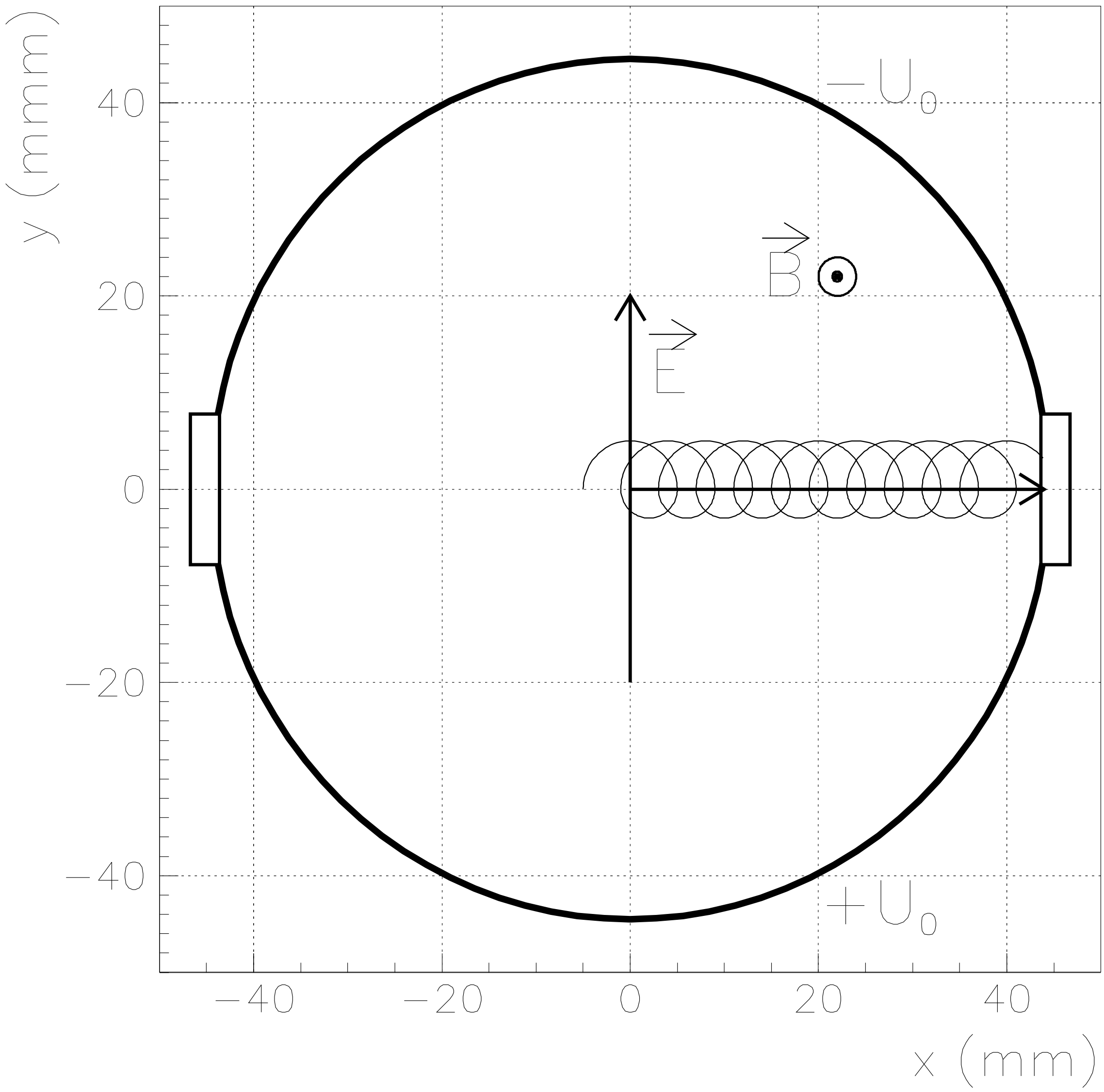
$$\omega_b^2 = \frac{q}{m}E_0 = \frac{q}{m}\frac{|\lambda|}{2\pi\epsilon_0}\frac{1}{a^2}, \quad (|\vec{E}| = E_0\,\rho),$$

$$\omega_+ = \frac{\omega_c}{2} + \sqrt{\left(\frac{\omega_c}{2}\right)^2 + \omega_b^2}, \quad \text{(modified cyclotron motion)}$$

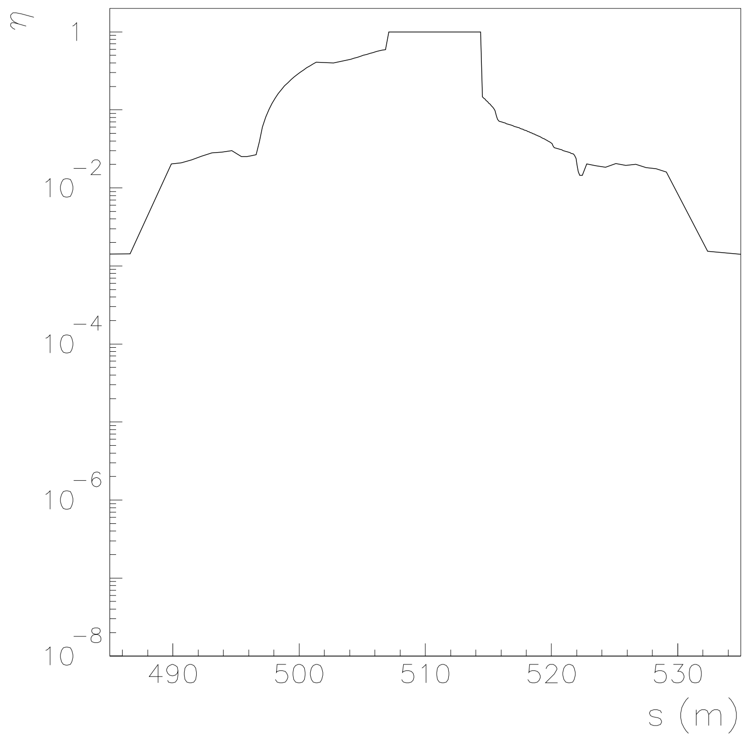
$$\omega_- = \frac{\omega_c}{2} - \sqrt{\left(\frac{\omega_c}{2}\right)^2 + \omega_b^2}, \quad \text{(magnetron motion)}$$

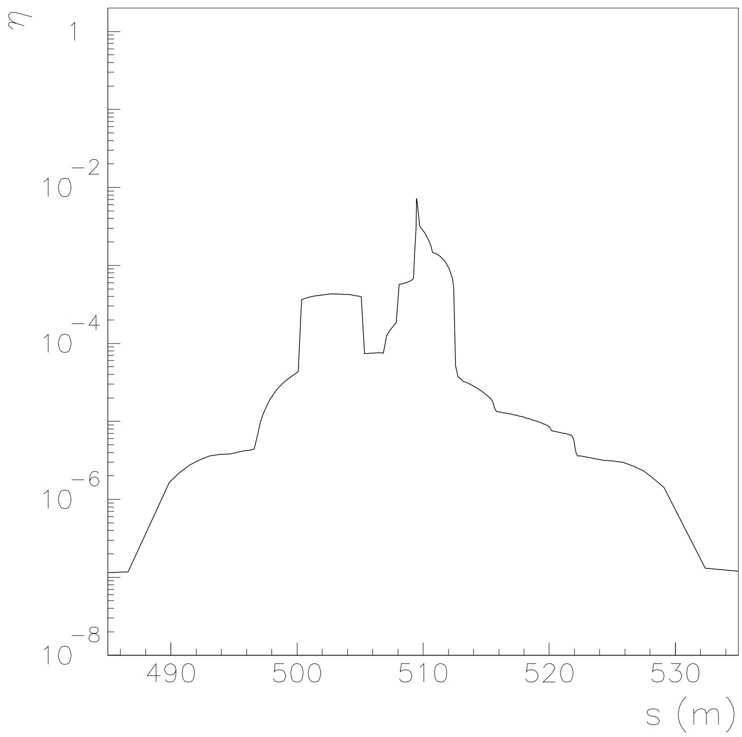
$$v_- = r_-\,\omega_- = -r_-\frac{\omega_b^2}{\omega_c} = -r_-\frac{E_0}{B} = -\frac{|\vec{E}|}{B} = \frac{\vec{E}\times\vec{B}}{B^2}. \qquad (16)$$

Continuous Clearing in a Solenoid



Neutralization $\eta(s)$: Single vs. Continuous Clearing

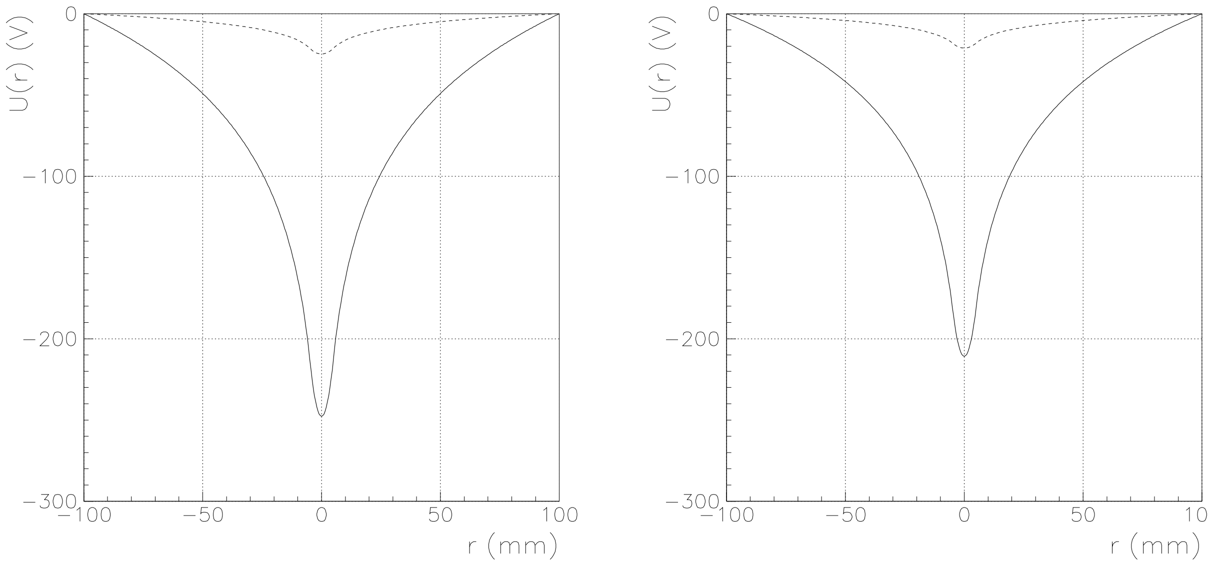




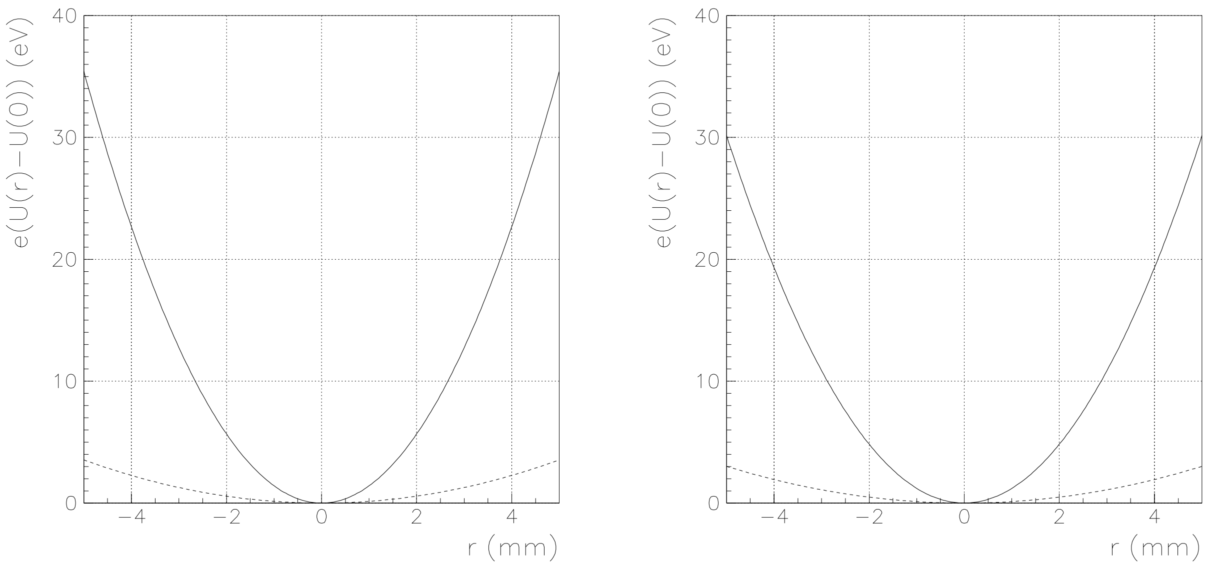
Electron Cooler

1. Kinetic energy of electrons: 0.45 - 4.5 MeV
2. Momentum range of antiprotons: 1.5 - 8.9 GeV/c
3. Electron current: 1.0 A
4. Magnetic field of solenoid: 0.2 T
5. Field straightness: $B_r/B < 10^{-5}$
6. Length: 24 m

Drawbacks of the EC: Space-Charge Potential

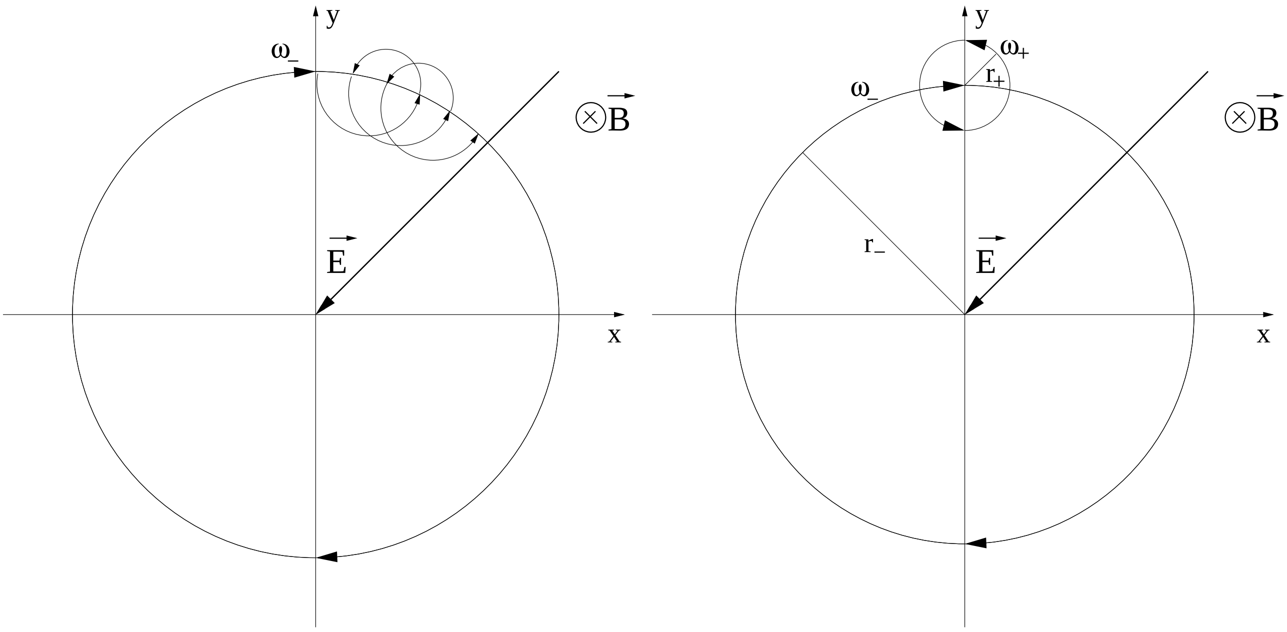


Space charge potential $U(r)$ of the electron beam ($I_e = 1.0$ A, $a = 5$ mm, $r_c = 100$ mm). Full line: Beam neutralization $\eta = 0.0$. Dashed line: Beam neutralization $\eta = 0.9$. Left: Nominal kinetic energy 0.45 MeV. Right: Nominal kinetic energy 4.5 MeV.



Variation of the electron energy due to the space-charge potential $U(r)$

Azimuthal Cross-Field Drift Velocity



$$
\begin{aligned}
\omega_c &= \frac{q}{m} B, \\
\omega_b^2 &= \frac{q}{m} E_0 = \frac{q}{m} \frac{|\lambda|}{2\pi\epsilon_0} \frac{1}{a^2}, \quad (|\vec{E}| = E_0\, \rho), \\
\omega_+ &= \frac{\omega_c}{2} + \sqrt{\left(\frac{\omega_c}{2}\right)^2 + \omega_b^2}, \quad \text{(modified cyclotron motion)} \\
\omega_- &= \frac{\omega_c}{2} - \sqrt{\left(\frac{\omega_c}{2}\right)^2 + \omega_b^2}, \quad \text{(magnetron motion)} \\
v_- &= r_-\, \omega_- = -r_- \frac{\omega_b^2}{\omega_c} = -r_- \frac{E_0}{B} = -\frac{|\vec{E}|}{B} = \frac{\vec{E} \times \vec{B}}{B^2}. \qquad (17)
\end{aligned}
$$

Drawbacks of the EC Space-Charge Potential

Relative energy and momentum deviations due to space-charge effects assuming negligibly small neutralization ($\eta \approx 0$).

T_e (MeV)	$\Delta T_e/T_e$	$\Delta p_e/p_e$
0.45	$7.87 \cdot 10^{-5}$	$5.14 \cdot 10^{-5}$
1.5	$2.07 \cdot 10^{-5}$	$1.65 \cdot 10^{-5}$
2.5	$1.22 \cdot 10^{-5}$	$1.04 \cdot 10^{-5}$
3.5	$8.64 \cdot 10^{-6}$	$7.66 \cdot 10^{-6}$
4.5	$6.70 \cdot 10^{-6}$	$6.08 \cdot 10^{-6}$

Electron beam rotation v_{az} due to space-charge effects assuming negligibly small neutralization ($\eta \approx 0$).

T_e (MeV)	ω_+ (s^{-1})	ω_- (s^{-1})	$v_{az}(a)$ (m/s)	$v_{az}(a)/\beta_e c$
0.45	$1.87 \cdot 10^{10}$	$4.00 \cdot 10^{6}$	$2.00 \cdot 10^{4}$	$7.89 \cdot 10^{-5}$
1.5	$8.94 \cdot 10^{9}$	$8.01 \cdot 10^{5}$	$4.00 \cdot 10^{3}$	$1.38 \cdot 10^{-5}$
2.0	$7.16 \cdot 10^{9}$	$5.07 \cdot 10^{5}$	$2.54 \cdot 10^{3}$	$8.64 \cdot 10^{-6}$
2.5	$5.97 \cdot 10^{9}$	$3.50 \cdot 10^{5}$	$1.75 \cdot 10^{3}$	$5.93 \cdot 10^{-6}$
3.5	$4.48 \cdot 10^{9}$	$1.96 \cdot 10^{5}$	$9.81 \cdot 10^{2}$	$3.30 \cdot 10^{-6}$
4.5	$3.59 \cdot 10^{9}$	$1.25 \cdot 10^{5}$	$6.25 \cdot 10^{2}$	$2.10 \cdot 10^{-6}$

$$v_{az}(r) = \omega_- r = \frac{1-\eta\gamma_e^2}{\gamma_e^2}\frac{I_e}{\beta_e c}\frac{1}{2\pi\epsilon_0}\frac{1}{B}\frac{r}{a^2}. \quad (18)$$

$$v_{az}(a) = \omega_- a = \frac{1-\eta\gamma_e^2}{\gamma_e^2}\frac{I_e}{\beta_e c}\frac{1}{2\pi\epsilon_0}\frac{1}{B}\frac{1}{a}. \quad (19)$$

$$v_{az}(a) = 0 \text{ if } \eta = 1/\gamma_e^2 \text{ (optimum!)}. \quad (20)$$

What is the Optimum Neutralization of the EC?

$\Delta p_e/p_e$ and $v_{az}(a)/(\beta_e c)$ for $\eta \approx 0$.

T_e (MeV)	γ_e	η	$\Delta p_e/p_e$	$v_{az}(a)/(\beta_e c)$
0.45	1.88	0	$5.24 \cdot 10^{-5}$	$7.89 \cdot 10^{-5}$
1.5	3.94	0	$1.65 \cdot 10^{-5}$	$1.38 \cdot 10^{-5}$
2.5	5.89	0	$1.04 \cdot 10^{-5}$	$5.93 \cdot 10^{-6}$
3.5	7.85	0	$7.66 \cdot 10^{-6}$	$3.30 \cdot 10^{-6}$
4.5	9.81	0	$6.08 \cdot 10^{-6}$	$2.10 \cdot 10^{-6}$

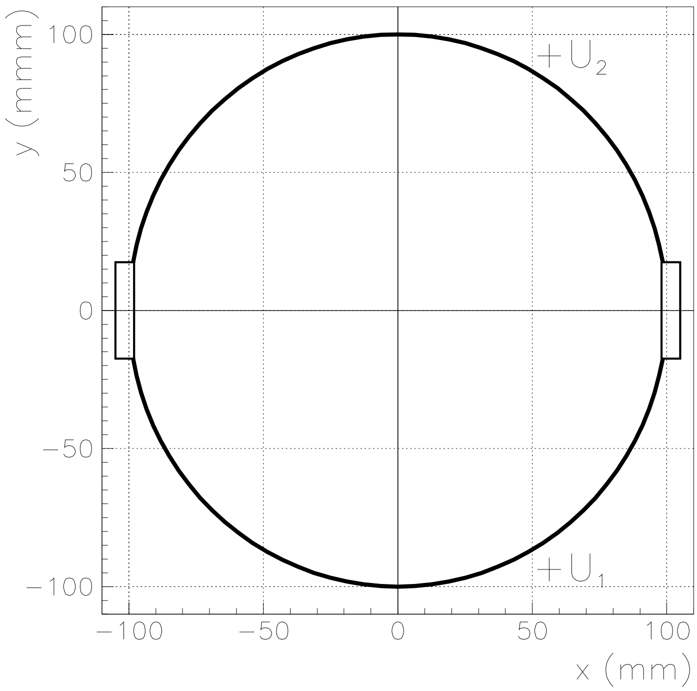
$\Delta p_e/p_e$ and $v_{az}(a)/(\beta_e c)$ for $\eta = 1/\gamma_e^2$.

T_e (MeV)	γ_e	η	$\Delta p_e/p_e$	$v_{az}(a)/(\beta_e c)$
0.45	1.88	0.283	$3.69 \cdot 10^{-5}$	0
1.5	3.94	0.0646	$1.54 \cdot 10^{-5}$	0
2.5	5.89	0.0288	$1.01 \cdot 10^{-5}$	0
3.5	7.85	0.0162	$7.54 \cdot 10^{-6}$	0
4.5	9.81	0.0104	$6.02 \cdot 10^{-6}$	0

$\Delta p_e/p_e$ and $v_{az}(a)/(\beta_e c)$ for $\eta = 1$.

T_e (MeV)	γ_e	η	$\Delta p_e/p_e$	$v_{az}(a)/(\beta_e c)$
0.45	1.88	1	0	$2.00 \cdot 10^{-4}$
1.5	3.94	1	0	$2.00 \cdot 10^{-4}$
2.5	5.89	1	0	$2.00 \cdot 10^{-4}$
3.5	7.85	1	0	$2.00 \cdot 10^{-4}$
4.5	9.81	1	0	$2.00 \cdot 10^{-4}$

Neutralization Electrodes for EC



Neutralization electrodes at entrance and exit of EC as used at LEAR: Instead of extracting the ions which are produced by ionization of the residual gas in the EC, the ions are reflected and stored in the EC.

The optimum neutralization is reached if $\eta = 1/\gamma_e^2$.

The continuously produced surplus ions can be removed by shaking the ions with a sine-wave signal applied to a transverse kicker ('LEAR shaker'), see next transparency.

Stabilization of Optimum Neutralization $\eta = 1/\gamma_e^2$

Taking the neutralization in the expression for the bounce frequencyb ω_b into account the equations for the modified cyclotron frequency ω_+ and the magnetron frequency ω_- may be written in the following form,

$$\omega_\pm = \frac{\omega_c}{2} \pm \sqrt{\left(\frac{\omega_c}{2}\right)^2 + (1-\eta\gamma_e^2)\omega_b^2(\eta = 0)}. \quad (21)$$

If the neutralization η tends towards $1/\gamma^2$ (i.e. $\eta \rightarrow 1/\gamma^2$) we have

$$\omega_+ \rightarrow \omega_c \quad \omega_- \rightarrow 0. \quad (22)$$

That means the magnetron motion around the beam center tends to zero and we are left with the pure cyclotron motion around the magnetic field lines.

In order to achieve a stable neutralization with $\eta = 1/\gamma^2$ one can use the **Ion-Cyclotron-Resonance (ICR) heating** of the ions by adjusting exactly the cyclotron resonance frequencies. In the HESR EC nine beam position monitors are foreseen. These position monitors can also be used as shakers by applying the RF voltages to pairs of position pick-up electrodes. The surplus ions which are continuously produced are heated up resonantly. The ion cyclotron resonance occurs exactly at $\eta = 1/\gamma^2$, i.e. when $\omega_+ = \omega_C$.

Table: Cyclotron frequencies $f_c = \omega_c/(2\pi)$ and bounce frequencies $f_b = \omega_b/(2\pi)$ in the HESR EC for $I_e = 1.0$ A, $B = 0.2$ T and $a = 5.0$ mm.

Ion	f_c (kHz)	f_b (kHz) at 0.45 MeV	f_b (kHz) at 4.5 MeV
H_2^+	1525	$\sqrt{1-\eta\gamma_e^2} \times 1854$	$\sqrt{1-\eta\gamma_e^2} \times 1710$
CH_4^+	191	$\sqrt{1-\eta\gamma_e^2} \times 655$	$\sqrt{1-\eta\gamma_e^2} \times 605$
CO^+	109	$\sqrt{1-\eta\gamma_e^2} \times 495$	$\sqrt{1-\eta\gamma_e^2} \times 457$

Summary and Conclusions

1. Ionization of Residual Gas Molecules
2. Single vs. Continuous Clearing Electrodes
3. Continuous Clearing Electrodes in the Dipoles
4. Continuous Ion Clearing near Panda Target
5. Electron Cooler: Optimum Neutralization $\eta = 1/\gamma_e^2$
6. Stabilization of EC Neutralization: ICR Heating