Calculations on high-energy electron cooling in the HESR

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PANDA requires luminosity of $2 \times 10^{31} - 2 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ in $\bar{p}p$ collisions with $10^{10} - 10^{11}$ stored antiprotons.

This requires internal target thickness $4 \times 10^{15} \text{ cm}^{-2}$.

Only known internal target which meets this requirement is hydrogen pellet target:
Pellet flux diameter can be varied by choice of a “skimmer” between 1.5 and 3 mm. We decided to do present computations with $2R = 3$ mm.

Target thickness $4 \times 10^{15}$ cm$^{-2}$ is achieved if $\langle h \rangle = 4$ mm.

This corresponds to 15,000 pellets/s $2r_p = 30$ µm.
CHOICE OF BEAM SIZE AT TARGET

\[ \rho_{\text{eff,mean}} = \frac{\langle \mathcal{R} \rangle}{\sqrt{2\pi}\sigma_x} \int_{-R}^R 2\sqrt{R^2 - x^2} \exp \left( -\frac{x^2}{2\sigma_x^2} \right) dx \]

where

\[ \langle \mathcal{R} \rangle = \frac{4}{3} \pi r_p^3 \rho; \quad \mathcal{R} = 4.3 \times 10^{22} \]

\[ \rho_{\text{eff, max}} = \frac{\mathcal{R}}{2\pi\sigma_x\sigma_y} \int_{-r_p}^{r_p} \int_{-\sqrt{r_p^2 - x^2}}^{\sqrt{r_p^2 - x^2}} 2\sqrt{r_p^2 - x^2 - y^2} \times \]

\[ \times \exp \left( -\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2} \right) dy dx \]

3.5

80 %

0.8 mm
**CHOICE OF BETA AT TARGET**

\[
\sigma_{\text{single scattering}} = \pi \left( \frac{2 r_e m_e c^2}{c p \beta} \right)^2 \cdot \beta_T \frac{\beta_T}{A}
\]

\[
A_x = \min \left( \frac{(44.5 \text{ mm})^2}{\beta_{x,\text{max}}}, \frac{(10 \text{ mm})}{\beta_{x,\text{T}}} \right)
\]

\[
A_y = \min \left( \frac{(44.5 \text{ mm})^2}{\beta_{y,\text{max}}}, \frac{(10 \text{ mm})}{\beta_{y,\text{T}}} \right)
\]

\[
\beta_{x,\text{max}} = \beta_{x,\text{T}} + \frac{300 \text{ m}^2}{\beta_{x,\text{T}}}
\]

\[
\beta_{y,\text{max}} = \beta_{y,\text{T}} + \frac{550 \text{ m}^2}{\beta_{y,\text{T}}}
\]
CHOICE OF BETA AT TARGET

mbarn

0 5 10 15 20

m

4 m          8 m                            16 m

target $\beta_{x,y}$

sigma (1.5 GeV/c)
sigma (3.8 GeV/c)
sigma (8.9 GeV/c)
sigma (15 GeV/c)
\[
\frac{(0.8 \text{ mm})^2}{\beta_{\text{target}}} = \begin{cases} 
0.16 \text{ µm} & (1.5 \text{ GeV/c}) \\
0.08 \text{ µm} & (3.8-8.9 \text{ GeV/c}) \\
0.04 \text{ µm} & (15 \text{ GeV/c}) 
\end{cases}
\]
effective length of electron cooler 20 m
electron current 1 A (0.2 A @ 1.5 GeV/c)
electron beam radius, uniform cylinder 5 mm
magnetic field in electron cooler 0.2 T
beta value at electron cooler (both H and V) 80 m (40, 160 m @ 1.5, 15 GeV/c)
transverse electron temperature (in centre of electron beam) 1 eV
Transverse gradient of electron velocity (in order to take envelope oscillations into account. The chosen value corresponds to a cyclotron radius of 0.1 mm, or 35 eV, at the edge of the electron beam) 7×10^{-8} s^{-1}
longitudinal electron temperature 0.5 meV
electron beam neutralization nil
cooling force model Parkhomchuk
rms. straightness of magnetic field lines 1×10^{-5}
hydrogen pellet target, pellet size 30 µm
pellet stream diameter 3 mm
vertical separation between pellets 4 mm
beta value (both planes) at target 8 m (4 , 16 m @ 1.5, 15 GeV/c)
nuclear reaction cross section 100, 70, 55, 50 mbarn @ 1.5 3.8,8.9, 15 GeV/c)
intra-beam scattering Martini model
barrier bucket voltage 200 V
barrier duration (relative to circumference) 10 %
NEED FOR EMITTANCE STABILIZATION
Experience from existing electron coolers is that it is easy to not align perfectly and get broad transverse distributions.

Experience is also that it is much more critical to align correctly to get small transverse beam than to get small $\Delta p/p$

Figure 1: A double peak horizontal beam profile for 250 MeV/u O$^{6+}$. The scale on the $x$-axis is in mm.
Effect of misalignment between electron beam and ion beam in CELSIUS: electron-cooled 200 MeV/u Ar$^{18+}$. Curves represent theoretical profiles (if constant diffusion rate) measured with magnesium-jet beam profile monitor.
**EMITTANCE STABILIZATION**

Transverse and longitudinal cooler rates @ 8 GeV for different tilts
Calculated aspect of the beam on the target for $10^{10}$ 8 GeV electron-cooled antiprotons on target

Calculated equilibrium transverse beam profiles of $10^{10}$ 8 GeV electron-cooled antiprotons on target in units of the initial rms. beam size of 0.56 mm
RESULTS

8.9 GeV/c, $10^{10}$ pbars

emittance of 50% of pbars

momentum spread of 90% of pbars

calculated lifetime 6,000 s
RESULTS

8.9 GeV/c, $10^{10}$ pbars, with stochastic as well as electron cooling

- Emittance of 50% of pbars
- Momentum spread of 90%
- Calculated lifetime 6,000 s
RESULTS

8.9 GeV/c, $10^{11}$ pbars (no stochastic cooling)

emittance of 50% of pbars

momentum spread of 90% of pbars
RESULTS

3.8 GeV/c, $10^{10}$ pbars

emittance of 50% of pbars

momentum spread of 90% of pbars

Beam lifetime 4,700 s
RESULTS

1.5 GeV/c, $10^{10}$ pbars

emittance of 50% of pbars

momentum spread of 90% of pbars

Beam lifetime 2,600 s
RESULTS

15 GeV/c, $10^{10}$ pbars

- Emittance of 50% of pbars
- Momentum spread of 90% of pbars
- Beam lifetime 7,000 s

Beam lifetime 7,000 s
RESULTS

15 GeV/c, $10^{10}$ pbars, with stochastic as well as electron cooling

emittance of 50% of pbars

momentum spread of 90% of pbars

Beam lifetime 7,000 s
CONCLUSIONS

“Square” beam spot with side 1.6 mm achieved with appropriate choice of beta values at target and tilting the electron beam (“Hopf bifurcation”).

90 % momentum spreads:

- 1.5 GeV/c \(1.3 \times 10^{-5}\)
- 3.8 GeV/c \(9.0 \times 10^{-6}\)
- 8.9 GeV/c \(3.4 \times 10^{-5}\) with stochastic as well as electron cooling
- 15.0 GeV/c \(3.7 \times 10^{-5}\)