SPACE CHARGE EFFECTS STUDIES FOR THE ESS COLD LINAC BEAM PROFILER

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Life Science

Material Science

Imaging

Fundamental Particle Physics
Why a non-interceptive beam profiler?

**REQUIREMENTS for the BEAM TRANVERSE PROFILER:**

- Stand high proton beam intensity \( I_{\text{peak}} = 62.5 \text{ mA}, P_{\text{peak}} = 125 \text{ MW} \)
- Have minimum impact on the proton beam (avoid \( H^+ \) scattering/induced nucl. reactions)
- No cooling forseen
- Provide enough statistics (capability of measuring 1 profile per pulse at nominal vacuum conditions)
- The total measurement error in the RMS extension of the beam must amount to less than \( \pm 10\% \). (ESS L4 requirement)

**TRANSVERSE PROFILE MEASUREMENTS FOR:**

- supporting the tuning of the beam
Working principle and issues:

IPM: Ionisation Profile Monitor

- The proton beam ionises the residual gas
- $E$ separates $e^-$/ionised molecules
- Charge collection on read-out

SPACE CHARGE EFFECTS:

POSSIBLE CORRECTION METHODS

- Add magnetic field $\times$
- High electric field $\times$
- Software correction $\checkmark$
Space charge effect estimation:

General idea:

- A Gaussian bunch with charge $Q_b$ is moving with velocity $v_b$ along the z-axis in the lab. frame $K$.
- The bunch is at rest w.r.t. the co-moving frame $K$.
- The $\Phi$ generated by $Q_b$ is calculated in the co-moving frame $\rightarrow \nabla^2 \Phi(\bar{x}, \bar{y}, \bar{z}) = -\frac{1}{\epsilon_0} \rho(\bar{x}, \bar{y}, \bar{z})$.
- The $E$ field generated by $Q_b$ is calculated in the co-moving frame $\rightarrow \vec{E} = -\nabla \Phi$.
- Through Lorentz transformations, the $E$ field in $K$ is translated into an electromagnetic field in $K$.

$$E = \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix} = \begin{pmatrix} \gamma_b \bar{E}_x \\ \gamma_b \bar{E}_y \\ \beta_b \bar{E}_z \end{pmatrix}, \quad B = \begin{pmatrix} -\gamma_b \beta_b \bar{E}_y/c \\ \gamma_b \beta_b \bar{E}_x/c \\ 0 \end{pmatrix} = \frac{\beta_b}{c} \begin{pmatrix} -E_y \\ E_x \\ 0 \end{pmatrix}.$$  

- $\mathbf{F} = Q_0 \left( \mathbf{E} + \mathbf{v} \times \mathbf{B} \right) \Rightarrow$ acceleration $\Rightarrow$ speed $\Rightarrow$ displacement $\ldots$ therefore trajectory of $Q_0$ in the $elm$ field generated by $Q_b$.

Implementation (ESS core + CEA development & optimisation):

- $10^4$ test particle $Q_0$ are generated in the center of the IPM and tracked as described above.
- The SCE is given by the difference between the initial and final RMS of the $Q_0$ distribution.
Parameters on which SCE depend:

- Beam “structure” (intensity, spatial spread, energy)?
  - Energy: [90, 2000] MeV
  - Current peak: 62.5 mA
  - Pulse length: 2.86 ms
  - Pulse frequency: 14 Hz (duty cycle 4%)
  - Bunch frequency: 352.31 MHz

- E field?

- Nature of the tracked ion ⇒ residual gas composition?
  - Nominal gas composition: \( \text{H}_2 \) (79%), CO (10%), \( \text{CO}_2 \) (10%), \( \text{N}_2 \) (1%)

- Initial momenta distribution of electrons/ionised molecules?
Beam energy influence:

\[ E_y = 300 \text{kV/m} \]
\[ \sigma_y = \sigma_z = 2 \text{mm} \]

In reality, for some parameter combinations, the lower the energy the larger the SCE.

- Less SCE for larger beams.
- Less SCE for \( \text{H}_2^+ \).
Electric field influence:

- $E_p = 90 \text{ Mev}$ (previous worst case scenario)
- $\sigma_x = \sigma_y = \sigma_z = 2 \text{ mm}$ (average beam size in Spoke)
- Ideally homogeneous $E_y$

- Less SCE for $H_2^+$.
- Less SCE for higher electric fields.
Initial momenta influence (1/2):

GARFIELD++ simulations

Electrons:
- Azimuthal angle $\varphi$ uniformly sampled in $[0, 2\pi)$
- Emitted preferentially orthogonally to the $z$ axis
- Ionised molecules (assumption):

$$v_e = \frac{m_{ion}}{m_e} v_{ion}$$
Initial momenta influence (2/2):

\[ E_p = 90 \text{ MeV} \]
\[ \sigma_x = \sigma_y = \sigma_z = 2 \text{ mm} \]
Homogeneous \( E_y = 300 \text{ kV/m} \)

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<th></th>
<th>( \text{final } H_2^+ )</th>
<th>( \text{final } e^- )</th>
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<td><strong>Std Dev</strong></td>
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✅ Less SCE for \( H_2^+ \).
Electric field homogeneity influence:

COMSOL simulations of the EI field in the IPM:

- The value of the resistors was optimized with COMSOL in order to get the best electric field uniformity
- Different sets of resistors were chosen for different potential difference configurations

Potential field map example:
Electric field homegeneity influence:

\[ E_p = 90 \text{ Mev} \]
\[ \sigma_x = \sigma_y = \sigma_z = 2 \text{ mm} \]

Realistic electric field

- The chosen set of resistors create, in such a case, a “focusing” electric field, which Oppose to SCE.
Conclusions:

TO MINIMIZE THE SCE

- IPM used in ion configuration
- Initial momenta distribution unimportant only for massive ionisation products
- High electric field
- Properly “chosen” real electric field.

IF MEASURES TO MINIMIZE THE SCE ARE FOLLOWED, NO CORRECTION IS NEEDED TO MEET THE L4 ESS REQUIREMENTS

REMINDER:
the total measurement error in the RMS extension of the beam must amount to less than ± 10%. (L4 ESS requirement)
Conclusions:

THANK YOU FOR YOUR ATTENTION