Ions in Energy Recovered Linacs

The Good and the Bad

Todd I. Smith
Hansen Experimental Physics Laboratories
Stanford University
Stanford, CA 94305-4085
Todd.Smith@Stanford.edu
The Good

Characterization of a nondestructive beam profile monitor using luminescent emission

A. Variola,* R. Jung, and G. Ferioli

AB Division, CERN, CH-1211 Geneva 23, Switzerland

(Received 7 June 2005; revised manuscript received 7 August 2007; published 12 December 2007)

The LHC (large hadron collider) [LHC study group: LHC. The large hadron collider conceptual design [CERN/AC/95-05] is the future p-p collider under construction at CERN, Geneva. Over a circumference of 26.7 km a set of cryogenic dipoles and rf cavities will store and accelerate proton and ion beams up to energies of the order of 7 TeV. Injection in LHC will be performed by the CERN complex of accelerators, starting from the source and passing through the linac, the four booster rings, the proton synchrotron (PS), and super proton synchrotron (SPS) accelerators. One of the main constraints on LHC performance is emittance preservation along the whole chain of CERN accelerators. The accepted relative normalized emittance blowup after filamentation is 7%. To monitor the beam and the emittance blowup process, a study of different prototypes of nonintercepting beam profile monitors has been performed. In this context a monitor using the luminescent emission of gases excited by ultrarelativistic protons (450 GeV) was developed and tested in the SPS ring. The results of beam size measurements and their evolution as a function of the machine parameters are presented. The image quality and resolution attainable in the LHC case have been assessed. A first full characterization of the luminescence cross section, spectrum, decay time, and afterglow effect for an ultrarelativistic proton beam is provided. Some significant results are also provided for lead ion beams.

PRSTAB 10, 122801(2007)
nondestructive beam profile monitor using luminescent emission

FIG. 3. (Color) The BPL experimental setup installed in the SPS ring: (1) vacuum tank, (2) the ports dedicated to the beam passage, (3) H and V optical windows for light extraction and beam imaging, (4) calibration reference screens, (5) H profile optical setup, (6) V profile optical setup, (7) optical channel for the counting experiment, (8) photomultiplier, (9) gas injecting channel.

Beam current (protons): 0.14A
Gas (N$_2$) pressure: 5 10$^{-7}$ Torr
Integration time: ~ 200 ms
Spatial resolution: ~20 µm

Beam sizes evolution during the ramp ranging from 14 to 450 GeV.

(a) Display of the beam scintillation path.
(b) Vertical profile obtained by projection on the horizontal axis on which the result of a Gaussian fit is superimposed. The measurement conditions were beam σ=676 µ, beam current 140 mA, 2x10$^{13}$ protons, beam energy=450 GeV, and nitrogen pressure=5 10$^7$ Torr.
The Bad

• Ion Trapping. If it occurs it will:
• Change the electron optics around the ERL,
• Increasing the electron beam emittance and
• Degrading the FEL performance
Ion clearing in an ERL
Georg H. Hoffstaetter, Matthias Liepe
Laboratory for Elementary Particle Physics,
Cornell University, Ithaca/NY, USA

Abstract
The rest-gas in the beam-pipe of a particle accelerator is readily ionized by effects like collisions, synchrotron radiation and field emission. Positive ions are attracted to electron beams and create a nonlinear potential in the vicinity of the beam which can lead to beam halo, particle loss, optical errors or transverse and longitudinal instabilities. In an energy recovery linac (ERL) where beam-loss has to be minimal, and where beam positions and emittances have to be very stable in time, these ion effects have to be avoided. Here we investigate three measures of avoiding ion accumulation: (a) A long gap between linac bunch trains that allows ions to drift out of the beam region, a measure regularly applied in linacs; (b) a short ion clearing gap in the beam that leads to a time varying beam potential and produces large excited oscillations of ions around the electron beam, a measure regularly applied in storage rings; (c) Clearing electrodes that create a sufficient voltage to draw ions out of the beam potential, a measure used for DC electron beams and for antiproton beams. For the parameters of the X-ray ERL planned at Cornell University we show that method (a) cannot be applied, method (b) is technically cumbersome, and (c) should be most easily applicable.

NIMA A 557 (2006) 205–212
Simple, linear theory. Assume uniformly charged disk like bunches, relativistic beam, bunch length $l_b$, bunch radius $a$, beam current $I$, bunch frequency $f_b$, distance between bunches $\lambda_b$ ($\lambda_b = c/f_b$).

$q = \text{electron charge/bunch} = I/f_b = n_e e$

$E_e(r) = \text{electric field in bunch} = (I/f_b) r/(2\pi \varepsilon_0 a^2 l_b)$

$F_e(r) = \text{force on singly charged ion} = -eE_e(r)$

For a fully neutralized beam the ion charge between electron bunches is equal to the electron bunch charge. Let $\phi$ be a parameter indicating the degree of neutralization ($0 \leq \phi \leq 1$). Assume the transverse ion distribution is the same as that of the electron beam (i.e. uniform, hard edge radius $a$)

$q_i = -fq$

$F^*_{e}(r) = \text{force on singly charged ion in the bunch} = F_e(r)(1 - \phi l_b/\lambda_b) \sim F_e$

$F_i(r) = \text{force on ion between electron bunches} = -\phi F_b(l_b/\lambda_b)$

Note: Although $F_i$ is small, if the beam is fully neutralized ($\phi = 1$), the average force over the interval between two bunches is equal in magnitude to that over one bunch.
Ion Trapping
Do we have to worry?

Assume that an impulse approximation is adequate:

$$
\Delta \dot{y}_e (r) = F_e \frac{\Delta t_e}{m_i} = - \frac{2n_e c r_p}{A_i a^2} r \\
\Delta \dot{y}_i (r) = F_i \frac{\Delta t_i}{m_i} = \theta \frac{2n_e c r_p}{A_i a^2} r
$$

where $r_p = \text{classical proton radius} = \frac{e^2}{(4\pi\varepsilon_0 m_p c^2)} = 1.525 \times 10^{-18} \text{ m}$

The response of an ion to the passing of a bunch can be written in matrix form as:

$$
\begin{pmatrix}
    y_1 \\
    \dot{y}_1
\end{pmatrix}_e =
\begin{pmatrix}
    1 & \frac{l_e}{c} \\
    -\alpha & 1
\end{pmatrix}
\begin{pmatrix}
    y_0 \\
    \dot{y}_0
\end{pmatrix}
$$

$$
\alpha = \frac{2n_e r_p c}{A_i a^2}
$$

Similarly, the interval between bunches acts as:

$$
\begin{pmatrix}
    y_1 \\
    \dot{y}_1
\end{pmatrix}_i =
\begin{pmatrix}
    1 & \frac{\lambda_b}{c} \\
    \beta & 1
\end{pmatrix}
\begin{pmatrix}
    y_0 \\
    \dot{y}_0
\end{pmatrix}
$$

$$
\beta = \frac{2\theta n_e r_p c}{A_i a^2}
$$

The combination forms a FODO channel, familiar in both electron and photon optics.
Ion Trapping
Do we have to worry?

One full cycle (electron bunch-gap) is described by

\[
\begin{pmatrix}
  y_1 \\
  \dot{y}_1
\end{pmatrix}_c = \begin{pmatrix}
  1 & \frac{\lambda_b}{c} \\
  \beta & 1
\end{pmatrix} \begin{pmatrix}
  1 & \frac{l_e}{c} \\
  -\alpha & 1
\end{pmatrix} \begin{pmatrix}
  y_0 \\
  \dot{y}_0
\end{pmatrix}_c = \begin{pmatrix}
  1 - \alpha \frac{\lambda_b}{c} & \frac{l_e + \lambda_b}{c} \\
  \beta - \alpha & 1 + \beta \frac{l_e}{c}
\end{pmatrix} \begin{pmatrix}
  y_0 \\
  \dot{y}_0
\end{pmatrix}_c
\]

This describes stable (bounded) motion if the absolute value of trace of the matrix is <2.

\[-2 < 2 + \beta \frac{l_e}{c} - \alpha \frac{\lambda_b}{c} < 2 \quad \text{or} \quad 4 > \alpha \frac{\lambda_b}{c} - \beta \frac{l_e}{c} = \frac{2n_e r_p}{A_i a^2} (\lambda_b - \theta l_e)\]

Ignoring $\phi l_b$, an ion will be trapped only if

\[
A_i \geq \frac{1}{2} \frac{n_e r_p}{a^2} \frac{\lambda_b}{\lambda_b} = \frac{1}{2} \frac{I}{I_A} \left( \frac{\lambda_b}{a} \right)^2 \frac{m_e}{m_p}
\]

where $I_A = 17,000A$ and $m_p/m_e = \text{proton-electron mass ratio} = 1836$
Ion Trapping

Do we have to worry?

An ion will be trapped if

$$A_i \geq \frac{1}{2} \frac{I}{I_A} \left( \frac{\lambda_b}{a} \right)^2 \frac{m_e}{m_p} = I \left( \frac{\lambda_b}{a} \right)^2 \times 1.6 \times 10^{-8} A^{-1}$$

<table>
<thead>
<tr>
<th>I</th>
<th>$\lambda_b$</th>
<th>a</th>
<th>$A_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 ma</td>
<td>4 m (75 MHz)</td>
<td>1 mm</td>
<td>2.6x10^{-3}</td>
</tr>
<tr>
<td>100 ma</td>
<td>40 cm (750 MHz)</td>
<td>1 mm</td>
<td>2.6x10^{-4}</td>
</tr>
<tr>
<td>1 A</td>
<td>40 cm (750 MHz)</td>
<td>1 mm</td>
<td>2.6x10^{-3}</td>
</tr>
</tbody>
</table>

All ions are trapped in each case!!

Since it appears that we’ve had ion trapping all along, it can’t be a big issue, can it? Unfortunately, it’s not that simple.
Ion Trapping

It’s going to happen—Now can we worry?

Not yet—maybe the trapped ions won’t do anything bad.

**Emittance Growth?**

Assume the ion charge density is parabolic with the same radius \( a \) as the electron beam. The ion charge between electron bunches is \( q \), the same as the charge in an electron bunch. The ion charge density and electric field are given by:

\[
\rho(r) = \frac{2q}{\pi a^2 \lambda_b} \left(1 - \left(\frac{r}{a}\right)^2\right)
\]

\[
E(r) = \frac{qr}{\pi \varepsilon_0 a^2 \lambda_b} \left(1 - \frac{1}{2} \left(\frac{r}{a}\right)^2\right)
\]

Using an impulse approximation, estimate the effect of this electric field on a relativistic electron beam (no self-space charge forces) of radius \( a \) and zero initial emittance (zero divergence) as it travels a distance \( L \)

\[
x'(r) = \frac{\dot{x}(r)}{c} = \frac{F(r)}{\gamma m_0 c} \frac{L}{c}
\]

\[
\varepsilon_{nrms} = \gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}
\]
Ion Trapping

Now we can worry!

Emittance Growth!

\[ \varepsilon_{\text{rms}} = \frac{2}{5} \frac{1}{\sqrt{21}} \frac{I}{I_A} L \]

After 10 m, the rms emittance has grown to:

<table>
<thead>
<tr>
<th>I(A)</th>
<th>( \varepsilon_{\text{rms}} ) (( \pi m m m m r ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>50</td>
</tr>
<tr>
<td>0.1</td>
<td>5</td>
</tr>
<tr>
<td>0.01</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Time for neutralization by \( \text{H}_2 \) at \( 10^{-9} \) torr is 3.4 seconds

Initial phase space grows to this, with this rms ellipse
Ion Trapping
It’s a problem-What can be done?

a) “long” gaps between trains of bunches. With room temperature kinetic energies, ions will hit the walls in \( \sim 10 \mu s \) after the electron beam vanishes. If a 1 \( \pi \) mm mr emittance growth can be tolerated, then the electron pulse train could perhaps consist of 60 ms (3.4/50) bursts followed by 10 \( \mu s \) gaps. The duty cycle is probably OK, but the RF transient problem is tough.

b) “short” clearing gaps between trains. It may be possible to have short gaps spaced so that a gap in an accelerating beam and one from a decelerating beam are in the main linac at the same time. The RF transient in the main linac is solved, but not in the injector.

c) Place electrostatic clearing electrodes at beam waists where the ions congregate. (How many, where should they be placed, are the field gradients realistic?)

d) Jiggle the electron beam as it goes around, preventing ions from finding a resting place. (How can this be made to work in the wiggler?)

Try to get a reasonably complete understanding of the issues.