Beam vacuum interactions II

Oswald Gröbner

O. Gröbner, CERN-Vauum group (ret.)
Present address: Schmiedgasse 5, 6020 Innsbruck, Austria
E-mail: Oswald.Groebner@chello.at
Oswald.Groebner@cern.ch
Specific ionisation of the residual gas

Ionisation of the residual gas by the high energy beam

$\sigma_p$ is the ionisation cross section

Ionisation cross-sections for high energy particles in units of $10^{-18}$ cm$^2$

$\sigma_p P_{\text{gas}} I_{\text{beam}}$

<table>
<thead>
<tr>
<th>Gas</th>
<th>26 GeV</th>
<th>7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$</td>
<td>0.22</td>
<td>0.37</td>
</tr>
<tr>
<td>He</td>
<td>0.23</td>
<td>0.38</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>1.2</td>
<td>2.1</td>
</tr>
<tr>
<td>CO</td>
<td>1.0</td>
<td>1.8</td>
</tr>
<tr>
<td>A</td>
<td>1.1</td>
<td>2.0</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>1.6</td>
<td>2.8</td>
</tr>
</tbody>
</table>

e.g. LHC arc: $I_p \sim 20$ nA/m at nominal current and density ($10^{15}$ H$_2$/m$^3$)
Power loss by nuclear scattering

Particles lost by nuclear scattering along the arcs of a machine can not be collimated and their losses occur uniformly distributed around the arcs

\[
P(w/m) = \frac{1}{c} \frac{IE}{\tau} = 0.93 \frac{I(A)E(TeV)}{\tau(h)}
\]

LHC design requires a nuclear-scattering life time of \( \sim 100h \)

LHC -> 0.1 W/m for two beams at ultimate current required gas density equivalent to \( 10^{15} \text{ H}_2/\text{m}^3 \)
Each W at 1.9 K \( \sim 500 \text{ W at RT} \) (Ph.L. lecture)
Space charge potential of the beam

Line density (particles/m), total current $I$

$$\lambda = \frac{I}{e\beta c}$$

Circular, concentric geometry, beam with uniform charge and radius $a$.

Electric field follows from Gauss law

Integrating the field gives the potential in the centre of the beam

$$V_b = \frac{e\lambda}{2\pi \varepsilon_0} \left[ \frac{1}{2} + \ln \left( \frac{r_p}{a} \right) \right]$$

ISR: $I = 20$ A, $r_p = 0.08$ m

$a = 0.01$ m

Electrons remain trapped in the potential well

![Graph of potential versus current](image.png)
Record book: the largest ionisation gauge

<table>
<thead>
<tr>
<th>Ionising beam current</th>
<th>10 - 60 A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge length</td>
<td>2 x 1km</td>
</tr>
<tr>
<td>Current resolution</td>
<td>20 pA</td>
</tr>
<tr>
<td>1-300 collectors &amp; true $&lt;P&gt;$ seen by beam</td>
<td></td>
</tr>
</tbody>
</table>

The integrated pressure around the whole machine requires a single electrode only.

!! LHC has a **bunched** beam therefore this system can not be used.

Further reading: ISR clearing current monitoring system, O. Grobner, P. Strubin, PAC1977_1376
Beam space charge neutralisation

Trapped charges neutralise the beam space charge and cause a tune shift and beam instabilities

The neutralisation factor is defined as
\[ \eta = \frac{n_i}{N_b} \leq 1 \]

\( N_b \) is the number of beam particles

\( n_i \) is the neutralising charge, i.e. electrons trapped in a proton beam, or positive ions trapped in an electron or antiproton beam.

Production rate \( (s^{-1} \text{ m}^{-1}) \) depends on gas density
\[ R_p = \beta c n_g \sigma_i \]

Equilibrium neutralisation
\[ \eta_{equ} = \frac{R_p}{R_c} \]
prop. to pressure!

The clearing rate \( R_c \) depends on the specific mechanism
Space charge neutralisation tune shift

Space charge due to neutralisation changes the focussing

\[
\Delta Q = \frac{1}{4\pi} \int \beta(s) k(s) ds
\]

\[
k(s) = \frac{e}{\gamma m_0 c^2} \frac{d\bar{E}}{dx}
\]

\[
\Delta Q = -r_0 R \langle \beta_x \rangle \frac{I_b}{e \beta c a^2 \gamma} \frac{1}{\gamma} = r_0 \frac{R}{Q_x} \frac{N_b}{2\pi a^2} \frac{\eta}{\gamma}
\]

For most accelerators a few \(10^{-3}\) neutralisation are harmful

For ISR-> \(\Delta Q \sim 20 \frac{\eta}{\gamma}\)
Ion stability in a bunched beam

Positive ions can be trapped in a bunched electron beam \( \rightarrow \) successive bunches give kicks to the ions

\[ \alpha \text{ attractive kick given by a bunch, } n \text{ number of bunches, } T \text{ revolution time} \]

\[ \alpha = \frac{4cr_0}{b(a+b)} A \frac{1}{n} = \frac{2cr_0}{a^2} A \frac{1}{n} \]

The ion motion is stable if

Ions with masses larger than a critical mass \( A_c \) accumulate

\[ -2 < Tr(M) < 2 \]

\[ -1 < \left(1 - \alpha \frac{T}{2n}\right) < 1 \quad \Rightarrow \quad \alpha_c = \frac{4n}{T} \]

\[ A_c = \frac{cr_0}{2a^2} \frac{N_b}{n} \frac{T}{n} = \pi r_0 \frac{RN_b}{a^2 n^2} \]

LHC: \( A_c \sim 10 \rightarrow \) electrons are ejected

LEP: 4 intense e- bunches \( A_c > 200 \)

e- rings all require a ‘clearing gap’
Proton-electron instability

Electrons oscillate in the potential well of protons -> excite protons to oscillate: coupled oscillators

Bounce frequencies:

\[ Q_p^2 \omega^2 = \frac{N_p r_e c^2}{\pi R a^2} \]
\[ Q_e^2 \omega^2 = \frac{r_p c^2 N_e}{\gamma \pi R a^2} \]

Stability limit for protons a few % neutralisation

\[ Q_p = \frac{(n-Q_e)^2 - Q^2}{2\sqrt{Q_e(n-Q_e)}} \]

e-p oscillations observed in the ISR and in many accelerators: ~80 MHz -> beam size increases!

Spectral lines -> harmonics of the revolution frequency.

With bad vacuum electron oscillations cover a wide frequency range

Single instability ~20 ms
Coulomb heating of trapped electrons

Multiple collisions with the beam -> beam heating

Momentum transfer depends on the velocity and the charge, not on the mass of the beam particle.

Physical limits on $b$: maximum allowed energy transfer and the condition that the electron can be considered stationary.

Energy transfer is inversely proportional to the mass of the particle -> for ions heating is very inefficient

\[
\Delta p(b) = \int_{-\infty}^{+\infty} eE(t)dt = \frac{2mc}{\beta} \frac{r_e}{b}
\]

\[
\Delta E(b) = \frac{(\Delta p)^2}{2m} = \frac{2mc^2}{\beta^2} \frac{r_e^2}{b^2}
\]

\[
\Delta E_{\text{max}} \Rightarrow b_{\text{min}} = \frac{r_e^2}{\beta^2 \gamma}
\]
Electron heating by multiple scattering (ISR)

\[ I_b = eN_b \frac{c}{2\pi R} \]

\[ \rho = \frac{N_b}{2\pi R \pi a^2} \]

\[ \Delta E(b) = \frac{2mc^2 r_e^2}{\beta^2 b^2} \]

\[ \frac{d^2 N_b(r)}{dt} = \frac{N_b}{2\pi R \pi a^2} \beta c 2\pi r dr \]

\[ \frac{d^2 E(r)}{dt} = \frac{2r_e^2 mc^2}{\beta} \frac{cN_b}{R \pi a^2} \frac{dr}{r} \]

\[ b_{\text{min}} = \frac{r_e}{\beta^2 \gamma} \]

\[ \frac{dE}{dt} = \frac{4r_e^2 mc^2 I_b}{ea^2} \ln \left( \frac{r_{\text{max}}}{r_{\text{min}}} \right) \]

Numerical example ISR:
- \( I = 20 \) A, \( R = 150 \) m, \( a = 0.01 \) m
- \( R_{\text{max}} = \text{vacuum chamber} = 0.04 \) m
- \( \gamma = 28 \). beam potential \( \sim 2\)kV
- Heating rate \( \sim 680 \) eV/s
- Clearing rate \( \sim 0.3/\)s
**Electron clearing by a bunched beam**

Electrons have 1/2000 the mass of a proton -> are not trapped in a bunched proton and positron beam

ISR: e-cloud build-up in a section with bad vacuum and without electrostatic clearing electrodes.

Bunching the ISR beam clears electrons
Ion impact energy

Ions are repelled by the positive space charge and hit the wall with a significant energy -> several keV

Bunched beams: heavy ions integrate the passage of many bunches and see an average field.
Light ions gain a more energy, since they see the peak field.
Final energy depends on the initial position in the beam

Ion energy in LHC

\[ M = 2, 4, 28, 44, 500 \]
Density increase by ions

Ions trapped in the beam contribute to the gas density

\[ d_g = \frac{P_g}{kT} \]

The ion density for a given degree of neutralisation will add to the neutral gas density

\[ d_i = \eta d_b \]

The beam density and the residual gas densities add up to give

\[ d_{\text{total}} = \eta \frac{I_b}{e} \frac{1}{\beta c a^2 \pi} + \frac{P_g}{kT} \]

e⁻ ring: \( I_b = 1 \text{A} \)
\( a = 0.002 \text{m} \quad d_b \sim 1.6 \times 10^{15} \text{m}^{-3} \)
\( P_g = 10^{-7} \text{Pa} \quad d_g \sim 2.4 \times 10^{13} \text{m}^{-3} \)

few% neutralisation will be a dominating contribution
Dust particle trapping

Trapping of ‘macroscopic’ (<10^{-6} \text{ m size}) dust particles has caused problems in several machines with negative beams: Antiproton accumulator, e^{-} ring in HERA and Super-ACO

Dust charges positively due to loss of electrons $\sim 10^6$ charges

Dust can remain trapped in the intense beam and cause lifetime degradation

Remedies are fast beam shaking to eject the ‘slow’ dust from the potential well

Origin of dust is not clear but evidence points to integrated sputter ions pumps in HERA e^{-} ring and to ion pumps mounted above the beam in LEP

HERA dust problem solved by replacing IP’s with linear NEG pumps.
Electron cloud

Key parameters

- Synchrotron radiation
- $Y(E,\phi)$ photoelectric yield
- $\delta(E,\phi)$ second. electron $Y$
- Second. electron energy
- residual gas ionization

- Photon reflectivity
- Beam pipe shape
- Bunch intensity and spacing
- External fields (magnetic, electric, space charge)
Electron cloud multipacting

The electric field of a bunch with the line density $\lambda$ and $\beta \sim 1$

$$E(r) = \frac{\lambda}{2\pi \varepsilon_0 r}$$

Momentum transfer by the bunch is independent on the bunch length $\tau$

$$\Delta p = eE\tau = \frac{e^2 n_b}{2\pi \varepsilon_0 cr}$$

Velocity gained by an electron

$$\Delta v = \frac{\Delta p}{m} = 2cr_e \frac{n_b}{r}$$

Condition for wall-to-wall multipactating

$$\frac{2r_p}{v} = t_{bb}$$

With $L_{bb} = ct_{bb}$ particles per bunch

$$n_b = \frac{r_p^2}{r_e L_{bb}}$$

$>>$ can occur also in a beam transfer line with a single pass
Gaussian beam

Gaussian density distribution

\[ E(r) = \text{const} \frac{1 - e^{-\left( \frac{r}{r_b} \right)^2}}{r} \]

Electrons move during the kick of a bunch

Integrating the equation of motion gives \( r(t) \), the velocity and energy

\[ m \ddot{r} = eE(r) \]

\[ \Delta W = \frac{m}{2} \frac{\dot{r}(\tau)^2}{2} = \frac{2mc^2}{e} r_e^2 \left( \frac{n_b}{r} \right)^2 \]

Energy (eV) of a stationary (red) and moving electron versus the initial radial position for different bunch length

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Beam vacuum interactions II
Effect of a dipole magnetic field

Cyclotron oscillations/bunch ~ 120
Cyclotron radius ~ 6 µm for 200 eV
F force by the proton bunch

SR photons -> median plane
Photoelectrons suppressed by the magnetic field.

Reflected photons reach top and bottom of the beam pipe ->
Low photon reflectivity is desirable to reduce photoelectrons which can move freely along the field lines.
Electron cloud in a dipole beam screen

Energy vrs. horizontal position

Horizontal multipacting range

Yield for different $n_b$

Bunch intensities $10^{10}$ per bunch
 Beam screen in an LHC dipole

Strip with saw tooth

ELECTRON CLOUD SCREEN (addition)

COOLING TUBES

MOLECULES

BEAM SCREEN 5 - 20 K

PHOTONS

SCATTERED PHOTONS

PUMPING SLOTS

MAGNET COLD BORE 1.9 K

BANDS OF CLOUD ELECTRONS
e⁻ cloud build up @ 25 ns bunch spacing
Spatial distribution / baffles to intercept electrons

CERN AT Division, Vacuum Group
Prepared by J.M. Jimenez

“Electron Cloud Induced Pressure rises in the SPS”
13th ICFA Beam Dynamics Mini-Workshop, 8 December 2003
Pressure increase due to BIM

Gas load, $Q_{\text{cloud}}$, is related to the power deposited by the electrons, $P_{\text{cloud}}$, to the molecular desorption yield, $\eta_e$, and to the average energy of the electrons in the cloud, $<E_{\text{cloud}}>$.

$$Q_{\text{cloud}} = k \frac{\eta_e P_{\text{cloud}}}{<E_{\text{cloud}}>}$$

LHC cooling limit: $P_{\text{cloud}} \sim 1 \text{ W/m} \rightarrow 10^{-6} \text{ mbar l/s/m}$
Reduction of BIM with beam dose

Beam scrubbing reduces the secondary electron yield and pressure rise

Running hours SPS

Photon dose in EPA

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Suppression of secondary electrons

True secondary electrons reflected electrons $E < 50$ eV are trapped by a weak solenoid field.

Between bunches, low energy electrons are confined close to the vacuum chamber walls by a weak external solenoid field.

Solenoid field in drift chambers

\[ r = \frac{mv}{eB} \]

\[ t_{cycl} = 2\pi \frac{m}{eB} \]

\[ r(m) = \sqrt{\frac{2m}{e} \frac{E(eV)}{B(T)}} \]

\[ t_{wall-wall} \sim \frac{\pi m}{eB} < \text{bunch spacing} \]

Radius (m) at 30 Gauss

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Field (Gauss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>100</td>
</tr>
<tr>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>150</td>
<td>20</td>
</tr>
<tr>
<td>200</td>
<td>1</td>
</tr>
</tbody>
</table>

LHC
KEKB

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Beam vacuum interactions II
Solenoids in quadrupoles are ineffective -> would require a much higher field
Beam pipe with antechamber

Synchrotron radiation is captured in the antechamber section.

C-magnet around antechamber traps photoelectrons.

Residual gas ionisation in the beam duct remains as an electron source.
Beam Duct with Ante-chamber

- Electrons in the beam channel
  - Photoelectrons decreased by factors at high current ($I_b \geq 1000$ mA).
  - The reduction was by orders at low current ($I_b \leq 100$ mA).
  - Multipacting seems to become important at higher current.

- Combination with solenoid field, and an inner surface with a low SEY will be required at higher current.

![Graphs showing electron current vs. LER beam current](image)

KEKB  (Y. Suetsugu)

2005.02.22  KEKB Review 2005 @KEK
The Secondary Electron Yield of TiZr and TiZrV NEG thin film coatings

- Normal PE (Primary Electrons) angle of incidence, 60 eV to 3 keV. PE ~ 5 \cdot 10^{-9} \text{ A}, pulsed, giving a total dose < 10^{-8} \text{ C/mm}^2 [1].
- TiZr and TiZrV thin film (1\text{µm}) deposited onto chemically polished copper substrates [2].
- An important $\delta_{\text{max}}$ decrease from above 2 to $<1.4$ already occurs after 2h at 200°C (TiZr) and 160°C (TiZrV), i.e. below the activation temperature [2].
- $\delta_{\text{max}} \sim 1.1$ after 2h at 250°C (TiZr) and 200°C (TiZrV) [2].

A. Rossi, presented at E-Cloud 04

Surface coatings have been applied to many vacuum systems
Conclusions

Numerous processes exist by which the beam and the residual gas interact. The walls and surface characteristics of the vacuum system have a vital influence.

In addition to static and dynamic out-gassing properties, also generation of electrons: photo- and secondary electrons are important.

Electron cloud effect with its consequences on beam dynamics has become a performance limiting effect in many accelerators.

Future vacuum system designs must put emphasis on surface properties of vacuum chambers and incorporate remedies for e-cloud effects to enable very high bunch currents and short bunch spacing.
Literature

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