EFFECTS OF THE RESIDUAL GAS SCATTERING IN PLASMA ACCELERATION EXPERIMENTS AND LINACS *

F. Broggi# , A. R. Rossi, A. Bacci, L. Serafini (INFN, Milano), A. Cianchi (INFN-Roma II, Roma), A. Clozza, G. Di Pirro (INFN/LNF), Frascati (Roma), Italy

Abstract

High vacuum has always been mandatory in particle accelerators. This is especially true for circular machines, where the beam makes thousands or millions turns, and beam lifetime is heavily affected by the residual gas scattering. In dimensioning the interaction chamber for a plasma accelerator experiment, because of gas jet operation, diagnostics and control devices foreseen, the problem of potential harmful effects of residual gas scattering on the beam dynamics should be addressed anyhow.

Simulations of the beam interaction with the residual gas have been performed with FLUKA code. The effects of different vacuum levels on the electron beam is reported and consequences on the beam quality in general are discussed.

INTRODUCTION

In a Plasma Accelerators experiment preservation of the electron beam emittance is a key factor for the quality of the produced beams.

Electron beam scattering by the residual gas is expected to increase the beam emittance leading to a degradation of the beam quality.

Typical pressures for accelerators are about 10^{-9} 10^{-10} mbar. Typical dimensions of an interaction chamber for plasma acceleration experiment are about one meter.

The gas jet for the beam-plasma interaction together with some other objects inside (diagnostics, moving feedthrough, etc.), can degrade the vacuum level.

A similar experiment [1] was run at a vacuum of about 10^{-3} mbar though in that experiment, the vacuum was not a critical factor.

The effect of the residual gas has been studied by evaluating the mean free path of the electrons, and the cross section for the main scattering processes (Coulomb scattering and bremsstrahlung scattering) showing a negligible effect up to 10^{-3} mbar. Then the effect has been evaluated with the FLUKA code [2,3] with 10 independent runs with 10^7 particle each.

No significant degradation occurs, in the interaction chamber, up to 10^{-3} mbar.

This unexpected result can be tested in the SPARC accelerator once the pressure level is increased from its operating values, in a section of the accelerator where the pressure increase does not damage accelerator elements (such as RF cavities). In this case, degradation of the beam of few part per million per meter is expected at pressure of 10^{-4} mbar.

BEAM PARTICLE LOSS BY RESIDUAL GAS SCATTERING

The probability that a scattering of a beam particle by residual gas occurs is

$$dP = dN_0 \frac{\sigma}{A} = n\sigma ds$$

Where :

A, ds element section and length

dN_0 number of atoms in the volume $dV = Ads$

n atomic density (atoms/m^3)

The variation of the particle number in the beam is : $dN = -NdP = -Nn\sigma ds$.

The number of scattered particles per unit path length and the scattering rate are :

$$\frac{dN}{ds} = -Nn\sigma \; ; \quad \frac{dN}{dt} = -Nn\beta c\sigma = -\frac{N}{\tau} \qquad (1)$$

where $\tau = \frac{1}{n\beta c\sigma}$ is the "beam lifetime", a parameter used in storage rings to indicate the beam time "availability".

The main mechanisms responsible for residual gas scattering and beam loss in a linac beam are the Coulomb scattering and the bremsstrahlung.

Before analyzing these two mechanism it is useful to determine the mean free path in a gas resulting from the kinetic theory of gas.

KINETIC THEORY OF GAS

From the gas law we have:

$$pV = \frac{2}{3} W_{av} = \frac{2}{3}\frac{1}{2} N_0 m v^2$$

where

p , V gas pressure and volume

N_0 number of molecules

W_{av} average kinetic energy of a molecule in the gas

m molecule mass

The r.m.s velocity of a molecule is $v \approx 1.73\sqrt{\frac{kT}{m}}$

with

k Boltzmann constant

T absolute temperature

*Work performed in the frame of the the FLUKA collaboration

#francesco.broggi@mi.infn.it : francesco.broggi@cern.ch

The mean free path is $\bar{\lambda} = \frac{1}{n\sigma}$ where σ is the cross section of the atom or molecule; if we take into account the relative velocity of the molecules, the mean free path becomes $\bar{\lambda} = \frac{1}{\sqrt{2}n\sigma}$; being $L = \frac{p}{kT}$ the gas molecular density at pressure p (Loschmidt number), we have $\bar{\lambda} = \frac{kT}{\sqrt{2}\pi d^2 p}$ where d is the mean molecular diameter.

If we consider a pure nitrogen biatomic gas, at a temperature of 300 K we obtain:

$$\bar{\lambda}[m] = \frac{1.38\cdot 10^{-23}\cdot 300}{\sqrt{2}\pi\left(2\cdot 0.75\cdot 10^{-10}\right)^2 101.325\, p[mbar]} = 4.1\cdot 10^{-4}\frac{1}{p[mbar]} \quad (2)$$

being 0.75 Angstrom both the nitrogen atomic and the covalent (for the N_2 molecule) radius, so at a pressure of 10^{-4} mbar the mean free path for N_2, is 4.1 m.

So far we considered the mean free path of nitrogen gas and the parameter indicates the mean path between two consecutive scattering of a molecule with two others.

We are interested in the scattering between an electron and the gas molecule whose mean free path is given by its density and temperature as from (2), but, considering the different dimensions of the electron, the mean free path of an electron in such a medium is increased by the ratio of the molecule radius and the electron one, neglecting the field spatial extension of the electron, since it is relativistic. So we can write:

$$\bar{\lambda} = \frac{kT}{\sqrt{2}\pi d^2}\cdot\frac{1}{p}\cdot\frac{d/2}{r_e} \quad (3)$$

Pressure of 10^{-4} mbar gives a mean free path of $1.1\times 10^5\, m$ and a cross section of 3.8×10^4 barn so the residual gas seems to have low effects for pressures of order of 10^{-4}-10^{-3} mbar for a relativistic electron beam over pathlength of about 1 m. As a matter of fact, being the scattering atoms density 2.45 x 10^{18} part/m^3 for p=10^{-4} mbar, according to (1) results

$$\frac{dN}{ds} = Nn\sigma = N\cdot 2.45\cdot 10^{18}\cdot 3.8\cdot 10^{-24} = N\cdot 9.3\cdot 10^{-6}$$

so about 14000 scattering occur for a nC beam in 1 m and about 93 are expected for a typical FLUKA run with 10^7 primary electrons.

BEAM LOSS MECHANISMS

The main mechanism responsible of residual gas scattering and beam loss in a linac are the coulomb scattering and the bremsstrahlung [4,5,6,7,8].

Coulomb Scattering

The cross section for the Coulomb scattering is

$$\frac{d\sigma_C}{d\Omega} = \left(\frac{2Zr_0}{\gamma}\right)^2 \frac{1}{\left(\vartheta^2 + \vartheta_1^2\right)^2} \quad (4)$$

where

ϑ. polar angle

Z charge of the scattering target

r_0 classic electron radius = 2.818x10^{-15} m

$\theta_1 = \frac{Z^{\frac{1}{3}}}{192}\frac{1}{\gamma}$ minimum scattering angle because of the atomic electron shielding effect

Integrating between θ_0, minimum angle at which an energy loss occurs, and θ_{max} we have:

$$\sigma_C = \frac{2\pi Z^2 r_0^2}{\gamma^2}\left(\frac{1}{\vartheta_0^2 + \vartheta_1^2} - \frac{1}{\vartheta_{max}^2 + \vartheta_1^2}\right) \quad (5)$$

If we consider Z=7, nitrogen or CO_2 gas, and a conservative value of θ_0=0, the relation gives:

$$\sigma_C = \frac{2\pi Z^2 r_0^2}{\gamma^2}\left(\frac{1}{\vartheta_1^2} - \frac{1}{\vartheta_{max}^2 + \vartheta_1^2}\right) = 2.5\cdot 10^5 \text{ barn} \quad (6)$$

So, from (1), about 380000 scattering for a 1 nC electron beam in 1 m, and about 600 scattering for a typical FLUKA run (10^7 particles run) are expected.

It follows that for a gas residual pressure of 10^{-4} mbar the beam degradation expected is about 0.06‰. A gas pressure of 10^{-2} mbar causes in one meter a beam degradation of about 0.5%. The degradation is even less if we consider only the kinetic theory of gas.

Bremsstrahlung

The cross section for bremsstrahlung scattering is

$$\frac{d\sigma_{brem}}{du} = \frac{16\alpha r_0^2}{3} Z(Z+1)\ln\left(\frac{184}{Z^{\frac{1}{3}}}\right)\frac{1-u+0.75u^2}{u} \quad (7)$$

With $u = \frac{\Delta E}{E}$ relative energy loss by radiation

The integrate cross section is

$$\sigma_{brem} = \int_0^1 \frac{d\sigma}{du}du \approx \frac{16\alpha r_0^2}{3} Z(Z+1)\ln\left(\frac{184}{Z^{\frac{1}{3}}}\right)\left(\ln\frac{1}{u_a} - \frac{5}{8}\right) \quad (8)$$

If we consider Z=7 and u_a=0.003 [4,7,8] we find $\sigma_{brem} = 4$ barn .

In terms of radiation length X_0 the cross section can be written $\sigma_{brem} = \frac{1}{nX_0}$ with n gas target density, so, for a pressure p=10^{-4} mbar we obtain:

$$\sigma_{brem} = \frac{1}{2.45\cdot 10^{18}\ 3\cdot 10^9} = 1.4\cdot 10^{-28} = 1.4 \text{ barn} \quad (9)$$

Either considering (8) or (9) the breemstrahlung cross section of order of few barn, much less than the Coulomb scattering, so it is negligible.

FLUKA RUNS

FLUKA runs with 30 MeV electron beam with zero emittance (0.2 mm beam radius no divergence) has been performed. The electron beam propagates for 1 m in air (different pressure values has been investigated), then the beam is dump on a screen with infinite absorption coefficient (black hole) to avoid backscattering.

The particles with different position/divergence, with respect to the initial conditions, are scored.

Five different runs of 10^6 particles each (repeated twice) and ten runs with 10^7 has been done.

The simulation has been carried out for different vacuum levels, from 10^{-2} to 10^{-9} mbar and for beam energy of 30 MeV, (the electron beam energy of PLASMONX plasma accelerator experiment and Thomson backscattering[9]), and for 150 MeV, the energy of the SPARC test facility [10]. A run at 100 GeV has been done too.

From the simulations the linear scaling of the number of scattered particles versus the residual gas pressure and versus the path length (relation (1)) is verified so this "rule of thumb" follows:

$$\frac{dN_{sc}}{ds} \approx (6.8 \pm 0.3) \cdot 10^{-2} N_0 p[mbar] \qquad (10)$$

So for a pressure of 10^{-4} mbar, from a typical FLUKA run with 10^7 particles, about 68 scattering events occur.

This value is about a factor 10 less than what expected by Coulomb scattering cross section evaluation, as from (6), where the cross section is overestimated (because of some conservative assumption about the integration extremes in (5) and (6)). Conversely the result is rather in good agreement with the elementary considerations from the kinetic theory of gas as from (3).

150 MeV SPARC Beam

As told before FLUKA runs with 30 and 150 MeV electron beam, (SPARC beam) agree with the rule (10).

It could be experimentally verified with the SPARC beam, by varying the residual gas pressure inside the beam pipe, by switching off the vacuum pumps.

Of course this could be done far away from the RF sections, in order to prevent dangerous discharges inside the cavities. A possibility is to use the secondary beam line (the one that will be dedicated to PLASMON-X or Thomson experiment, see Fig.1).

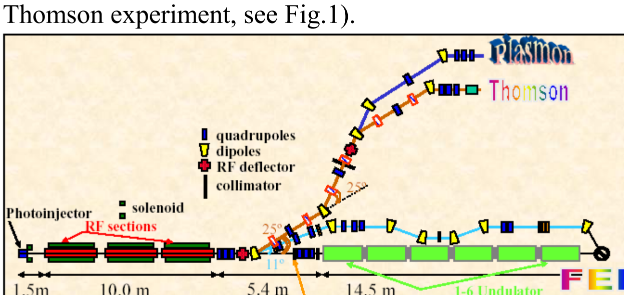

Figure 1: Schematic layout of the SPARC and related experiment area. The part dedicated to Plasmon-X and Thomson can be used to experimentally verify the calculations of this work

The beam degradation can be monitored by the usual beam diagnostics elements (beam screen to check the transverse dimensions, or emittance measurements via quad scan technique).

GeV SPARX Beam

SPARX is an X ray FEL facility[11] to be built in Rome at Tor Vergata University campus, with beam energy of 1-2.5 GeV. FLUKA runs at high energies confirm the rule (4), so the vacuum needs in the SPARX linac, preserved the operating conditions for the RF cavities and the beam quality needs for the FEL process, may be analyzed, once the benchmarking with the SPARC test facility beam will be satisfactory.

CONCLUSIONS

We considered the scattering of an electron beam by residual gas at different pressure. The main scattering mechanism are Rutherford scattering (the most important), and the bremsstrahlung (negligible).

The gas residual scattering can be a challenge for storage rings, but not for a linac where the beam runs only once or in dumping rings, where the beam runs for relatively short times [6], so a good vacuum level seems not necessary for the PLASMON-X or Thomson scattering experiment, neither in the SPARC linac, far away from the RF sections.

REFERENCES

[1] M.Galimberti, A.Giulietti, D.Giulietti, L.Gizzi, ″SHEEBA : A Spatial High Energy Electron Beam Analyzer″, Rev.Sci.Inst., 76 :053303,April 2005.

[2] A.Fasso`, A.Ferrari, J.Ranft, and P.R.Sala, "FLUKA: a multi-particle transport code", CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773.

[3] G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fasso`, J. Ranft, "The FLUKA code: Description and benchmarking", Proceedings of the Hadronic Shower Simulation Workshop 2006, Fermilab 6--8 September 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49, (2007).

[4] USPAS lecture N° 18, 26-Nov.2001.

[5] A.Wrulich ″Single Beam Lifetime″, CERN yellow rep. 94-01 p. 409, CAS, 5th General Accelerator Physics Course, 7 - 18 Sep 1992 - Jyväskylä, Finland.

[6] I.Reichel et.al "Thermal-Photon and Residual-Gas Scattering in the NLC Beam Delivery", SLAC-PUB-8012, Nov 1998.

[7] S.M. Seletsky, "Thermal Photon and Residual gas Scattering of the Electrons in the ILC RTML", SLAC-TN-06-007, Aug,15, 2006.

[8] A.Piwinski "Beam Losses and Lifetime", CERN yellow rep. 85-02 p. 432, CAS, 1st General Accelerator Physics Course, 3 - 14 Sep 1984 - Gif-sur-Yvette, Paris, France.

[9] D.Filippetto et al. Status of Thomson Source at *SPARC*/PLASMONX ", this conference.

[10] M.Ferrario et al. "Recent Results of the *SPARC* FEL Experiments ", this conference.

[11] L.Palumbo, "Status of the SPARX-FEL Project", this conference.