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EFFECT OF RESIDUAL GAS ON ELECTRON BEAM IN LINACS

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Abstract

The design of the interaction chamber for PLASMON-X experiment at LNF include the vacuum level needed to preserve the characteristics of the interacting electron beam. At first sight, a very good vacuum (about 10^{-9} mbar) is needed as in all the electron accelerators. The evaluation of the scattering by the residual gas, performed with FLUKA, shows a negligible effect of the residual gas on a linac electron beam up to 10^{-3} mbar. As a matter of fact, the mean free path of the gas and of the electron in such poor vacuum is fairly long and the interaction probability low.

Evaluation of the residual gas effect are performed for the SPARC beam line and degradation of some part per million per meter at 10^{-4} mbar is foreseen.

A proposal to experimentally verify the simulation is made.

Work performed in the frame of the FLUKA collaboration and SPARC activity

1 INTRODUCTION

In a Thomson Backscattering (TB) experiment the electron beam emittance is a key factor for the quality of the produced photons.

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

Typical pressures for accelerators are about 10^{-9} 10^{-10} mbar. The dimension of an interaction chamber for TB or plasma acceleration experiment is about one meter.

The gas jet together with some other object inside (diagnostics, moving feedthrough, etc.), can degrade the vacuum level.

A similar experiment (Ref.1) had 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 (Ref. 2,3) with 10 independent runs with 10000 particles 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 (RF cavities). In this case, degradation of the beam of few part per million per meter is expected at pressure of 10^{-4} mbar.

2 BEAM PARTICLE LOSS BY RESIDUAL GAS SCATTERING

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

$$dP = dN_0 \frac{s}{A} = ns\,ds \qquad (1)$$

Where :

A element section

ds element length

ΔN_0 number of atoms in the volume $dV = Ads$

n atomic density (atoms/cm^3)

The variation of the particle number in the beam is : $dN = -NdP = -Nns\,ds$

So the number of particles scattered per unit path length is :

$$\frac{dN}{ds} = -Nns \qquad (2)$$

Switching to time, the scattering rate is :

$$\frac{dN}{dt} = -Nnbcs = -\frac{N}{t} \qquad (3)$$

where $t = \dfrac{1}{ncs}$ is the "beam lifetime", a parameter used in storage rings to indicate the beam time "availability".

The main mechanism responsible of residual gas scattering and beam loss in a linac beam are the coulomb scattering and the bremsstrahlung.

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

3 KINETIC THEORY OF GAS

From the gas law we have:

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

where

p gas pressure

V gas volume

N_0 number of molecules

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

m molecule mass

$nm = M$ gas mass

The r.m.s. velocity is $v \approx 1.73\sqrt{\dfrac{kT}{m}}$

with

k Boltzmann constant

T absolute temperature

The mean free path is $\overline{l} = \dfrac{1}{ns}$ with s cross section of the atom or molecule; if we take into account the relative velocity of the molecules, $\overline{l} = \dfrac{1}{\sqrt{2}ns}$

Being $L = \dfrac{p}{kT}$ the Loschmidt number (molecular gas density at pressure p) we have $\overline{l} = \dfrac{kT}{\sqrt{2}p\, d^2 p}$ where d is the mean molecular radius.

If we consider a pure Nitrogen biatomic gas, the mass of the molecule is $m = 28 \cdot 1.66 \times 10^{-27}\,kg \approx 4.65 \times 10^{-26}\,kg$.

Given mean velocity at a temperature of 300 K :

$$v \approx 1.73\sqrt{\frac{1.38 \cdot 10^{-23} 300}{4.65 \cdot 10^{-26}}} = 516\,\text{m/s}\,,$$

the mean free path is then (meter)

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

being 0.75 Angstrom both the Nitrogen atomic and the covalent (for the N_2 molecule) radius. At a pressure of 10^{-4} mbar the mean free path for N_2, is $\bar{l} = 4.1\,\mathrm{m}$ (4.1 cm at 10^{-2} mbar)

So far we considered the mean free path of Nitrogen gas and the parameter indicates the mean path between two consecutive scatterings 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 the last relation, 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

$$\bar{l} = \frac{kT}{\sqrt{2}p\; d^{2}}\cdot\frac{1}{p}\cdot\frac{d/2}{r_e} \tag{4}$$

For a pressure p $=10^{-4}$ mbar, the mean free path is $1.1\times10^{5}\,m$ while the cross section of 3.8×10^{4} barn .

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.

4 BEAM LOSS MECHANISMS

The main mechanism responsible of residual gas scattering and beam loss in a linac are the coulomb scattering and the bremsstrahlung (Ref. 4,5).

4.1 Coulomb Scattering

The cross section for the Coulomb scattering is

$$\frac{ds}{d\Omega} = \left(\frac{2Ze^{2}}{m_0 c^{2} g}\right)^{2}\frac{1}{\left(J^{2}+J_{1}^{2}\right)^{2}} \tag{5}$$

where

J polar angle

Z charge of the scattering target

r_0 classic electron radius = $2.818\mathrm{x}10^{-15}$ m

$q_1 = \frac{Z^{\frac{1}{3}}}{192}\frac{1}{g}$ 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

$$s = \frac{2pZ^2 r_0^2}{g^2}\left(\frac{1}{J_0^2 + J_1^2} - \frac{1}{J_{\max}^2 + J_1^2}\right) \approx \frac{2pZ^2 r_0^2}{g^2}\frac{1}{J_0^2} \qquad (6)$$

If we consider Z=7, Nitrogen gas, and a conservative value of θ_0=0, the relation (6) gives:

$$s = \frac{2pZ^2 r_0^2}{g^2}\left(\frac{1}{J_1^2} - \frac{1}{J_{\max}^2 + J_1^2}\right) = 6.2 \cdot 10^{-23}\ \mathrm{m}^2 = 2.5 \cdot 10^5\ \mathrm{barn} \qquad (7)$$

Being n=L the scattering atoms density (2.45 x 10^{18} part/m^3 for p=10^{-4} mbar) the total number of scattering per unit trajectory length is:

$\frac{dN}{ds} = Nns = N \cdot 2.45 \cdot 10^{18} \cdot 2.5 \cdot 10^{-23} = N \cdot 6.125 \cdot 10^{-5}$, about 380000 scattering for a 1 nC electron beam in 1 m, and about 60 scattering for a typical FLUKA run (10^6 particles run).

So 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 a beam degradation of about 1%.

4.2 Bremsstrahlung

The cross section for bremsstrahlung scattering is

$$\frac{ds}{du} = \frac{16ar_0^2}{3} Z(Z+1)\ln\left(\frac{184}{Z^{\frac{1}{3}}}\right)\frac{1 - u + 0.75u^2}{u} \qquad (8)$$

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

The integrate cross section is

$$s_{brem} \approx \int_0^1 \frac{ds}{du} du =\approx \frac{16ar_0^2}{3} Z(Z+1)\ln\left(\frac{184}{Z^{\frac{1}{3}}}\right)\left(\ln\frac{1}{u_a} - \frac{5}{8}\right) \qquad (9)$$

If we consider Z=7 and (Ref. 4) u_a=0.003 we find $s_{brem} = 6\ \mathrm{barn}$.

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

$$s_{brem} = \frac{1}{2.45 \cdot 10^{18}\ 3 \cdot 10^9} = 1.4 \cdot 10^{-28} = 1.4\ \mathrm{barn} \qquad (10)$$

Either considering the (9) or the (10) the breemstrahlung cross section is of order of few barns, more less than the Coulomb scattering, so it is negligible.

5 FLUKA RUNS

5.1 30 MeV electron beam energy

FLUKA runs with 30 MeV electron beam with zero emittance (0.2 cm 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,

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

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

From the simulations the linear scaling of the number of scattered particles versus the residual gas pressure and versus the path length (relation (2)) is verified so the following "rule of thumb" follows :

$$\frac{dN_{sc}}{ds} \approx (6.8 \pm 0.2) \cdot 10^{-2} N_0 p(mb) \tag{11}$$

So for a pressure of 10^{-4} mbar only some electrons per million will be scattered along 1 m of trajectory as calculated in section 4.1.

In Fig.1,2,3 and 4 the fluence of the electrons (track length density) for air pressure of 10^{-4},10^{-3}, 10^{-2} mbar and atmospheric pressure are shown.

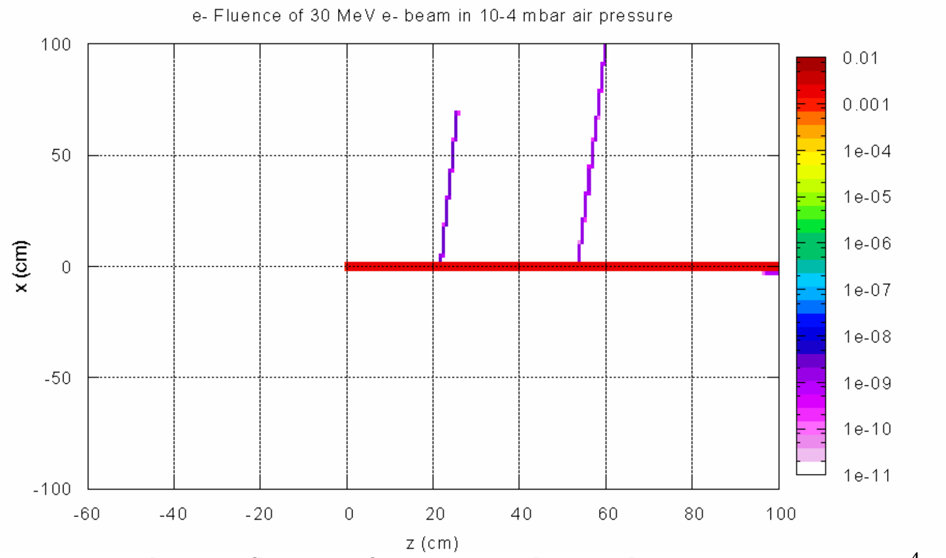

Fig.1 Electron fluence of a 30 MeV electron beam in 1 m air at 10^{-4} mbar.

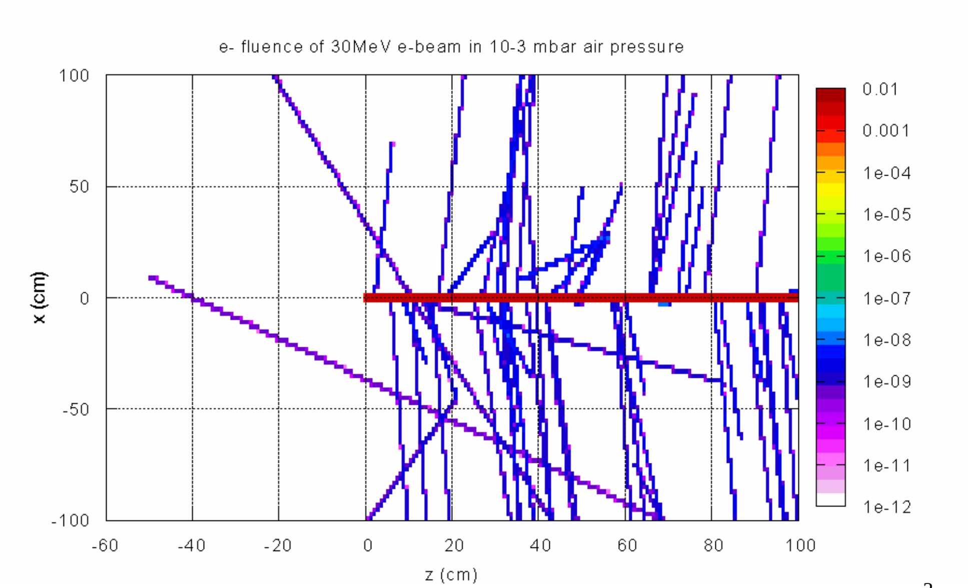

Fig.2. Electron fluence of a 30 MeV electron beam in 1 m air at 10^{-3} mbar.

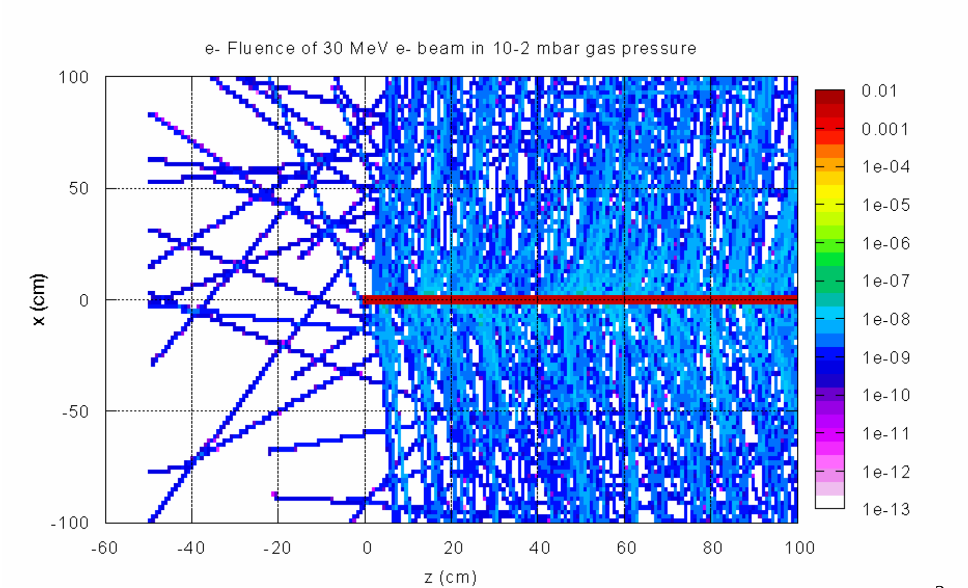

Fig.3. Electron fluence of a 30 MeV electron beam in 1 m air at 10^{-2} mbar

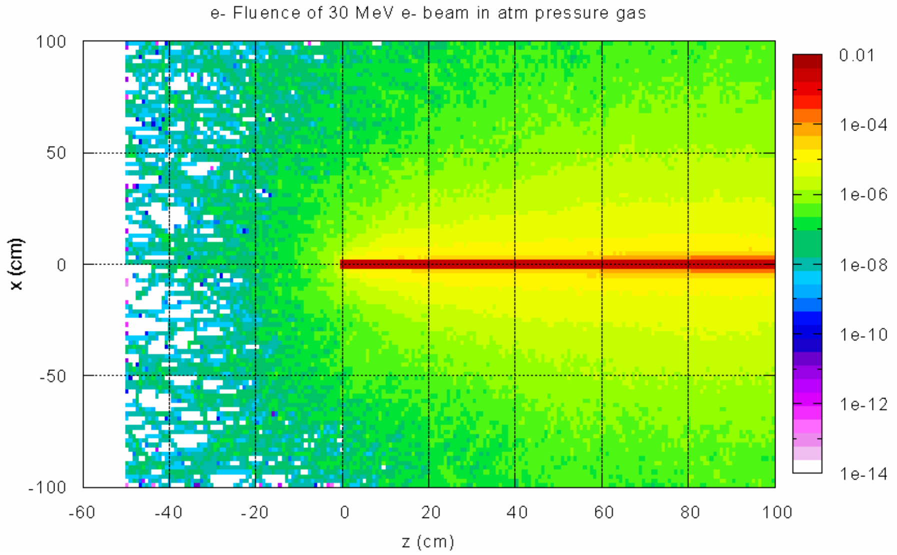

Fig.4. Electron fluence of a 30 MeV electron beam in 1 m air at atmospheric pressure.

In Fig 5, and 6 the beam spot after 1 m in air at 10^{-3} and 10^{-2} mbar air pressure is shown.

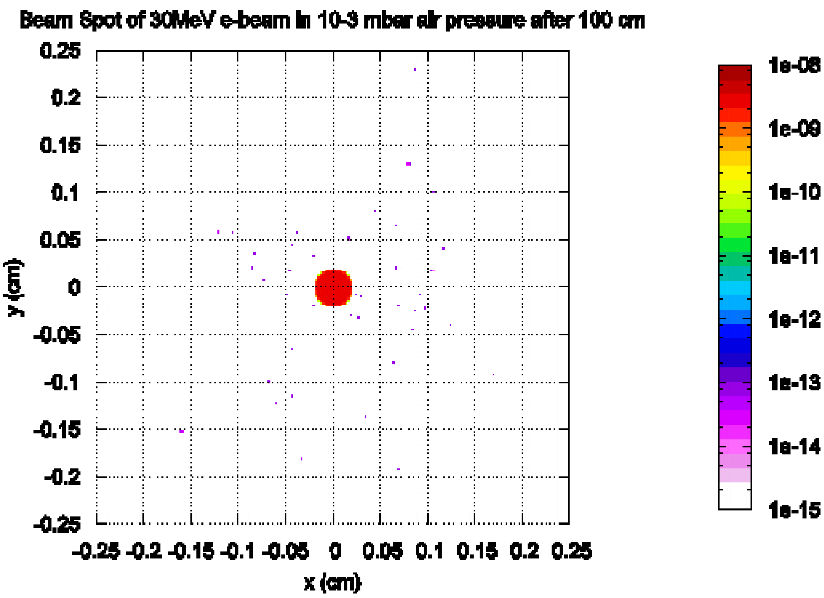

Fig.5. Beam spot of a 30 MeV, zero emittance electron beam after 1m in 10^{-3} mbar air pressure, the radius of the beam at origin is 0.2 mm.

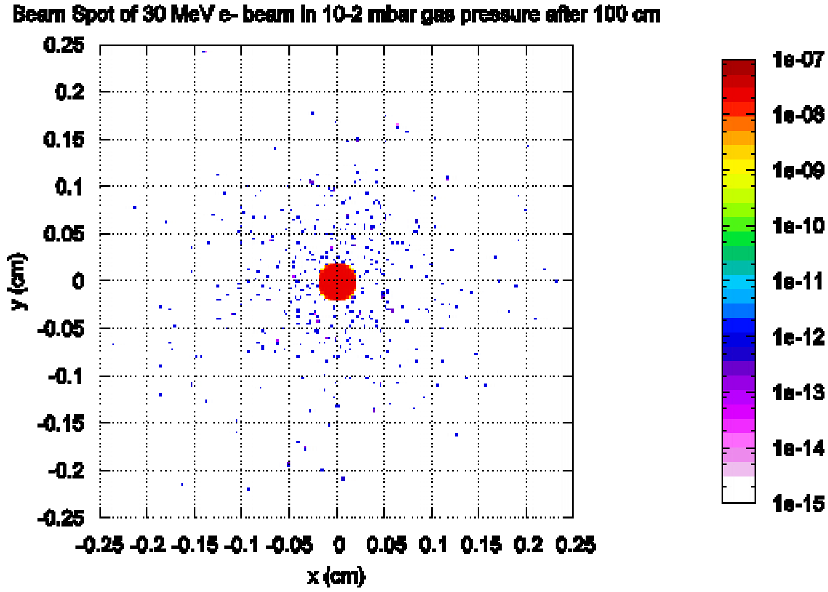

Fig.6. Beam spot of a 30 MeV, zero emittance electron beam after 1m in 10^{-2} mbar air pressure, the radius of the beam at origin is 0.2 mm.

For comparison the fluence of the electrons and of the photons at atmospheric pressure are shown in Fig 7 and 8.

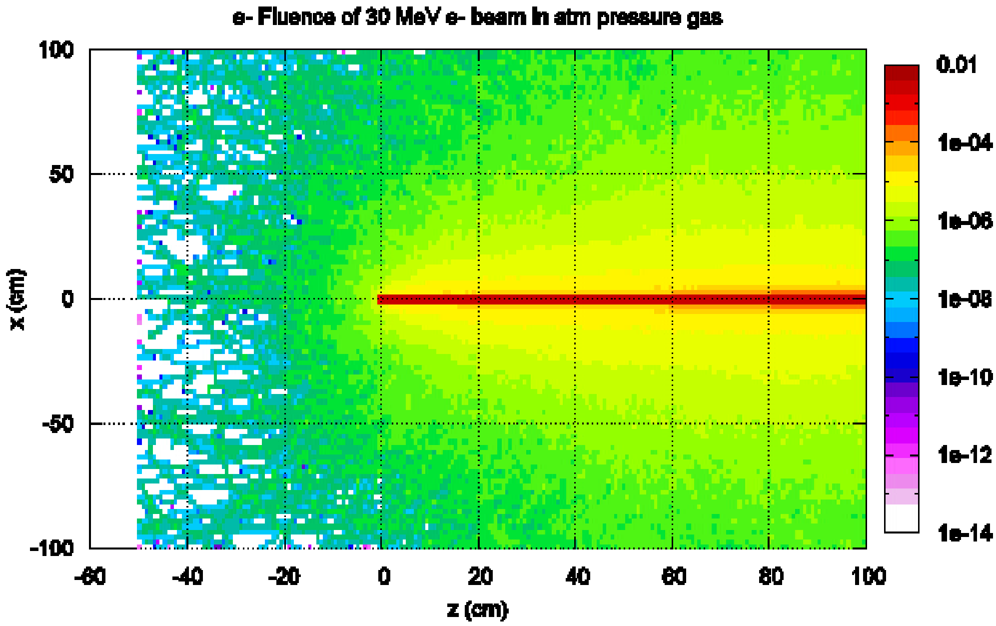

Fig.7. Electron fluence of a 30 MeV, zero emittance electron beam after 1 m at atmospheric pressure.

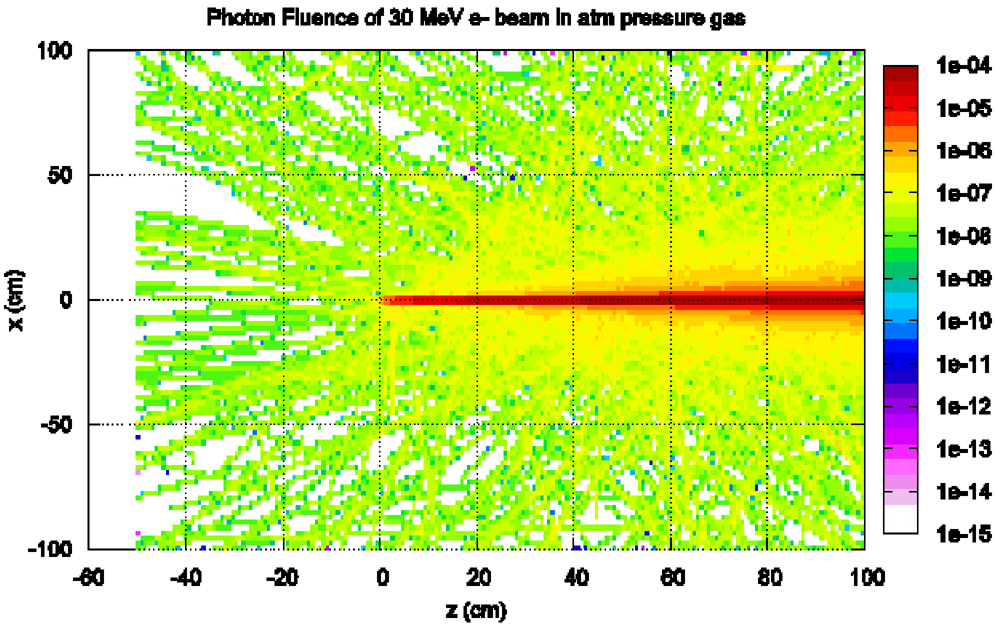

Fig.8. Photon fluence of a 30 MeV, zero emittance electron beam after 1 m at atmospheric pressure.

5.2 Energy Deposition

In Fig 9 and 10 the energy deposed in the air and in the vacuum chamber walls is shown.

The chamber is a stainless steel 2 mm thick parallelepiped with dimensions 1.0 x 1.0 x 2.5 m^3. The data refer to 5 different runs with 10^6 particle each (10^5 in the case of atmospheric pressure).

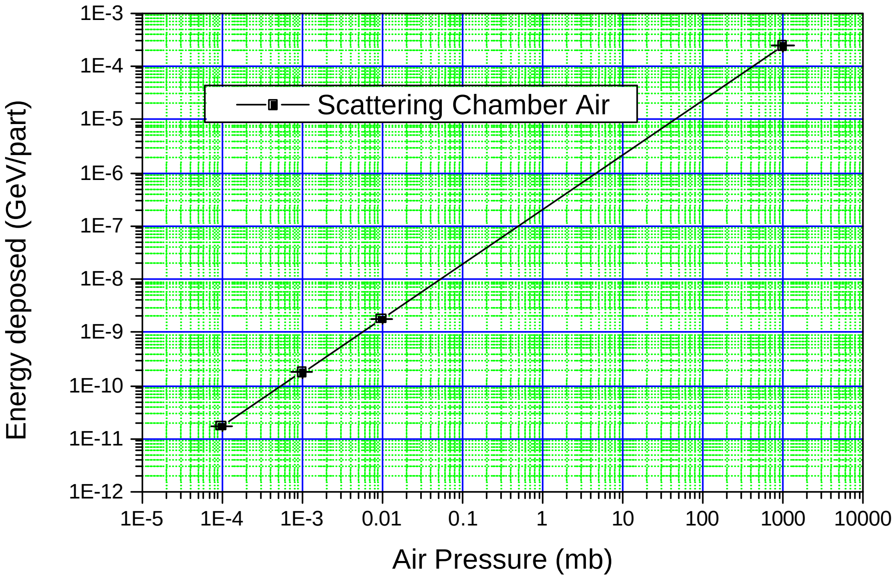

Fig.9. Energy deposed in the vacuum chamber air by a 30 MeV, electron beam at different air pressure.

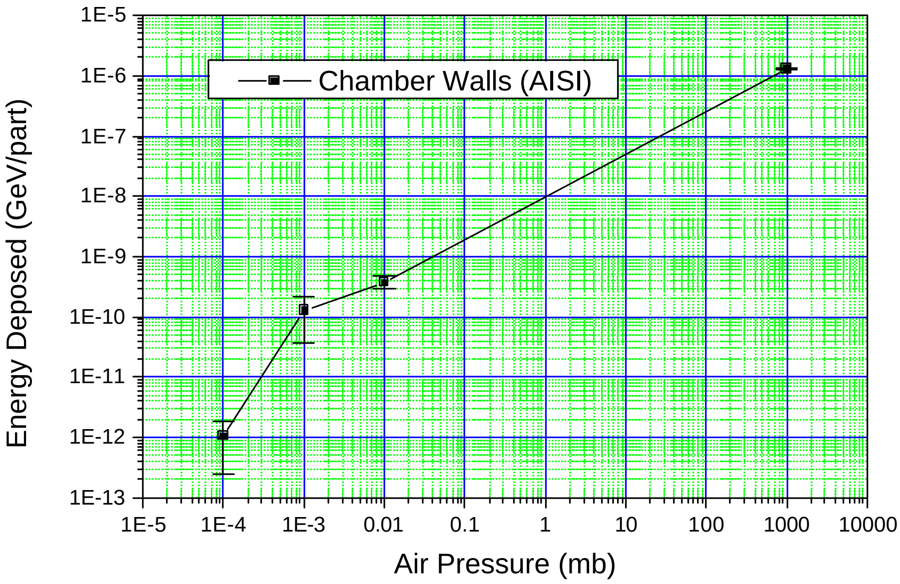

Fig.10. Energy deposed in the vacuum chamber walls air by a 30 MeV, electron beam at different air pressure in the chamber.

5.3 150 MeV SPARC beam

FLUKA runs with 150 MeV electron beam, (SPARC beam) agree with the rule (11).

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 discharge inside the cavities. A possibility is to use the secondary beam line (the one that will be dedicated to PLASMON-X experiment, see Fig.11)

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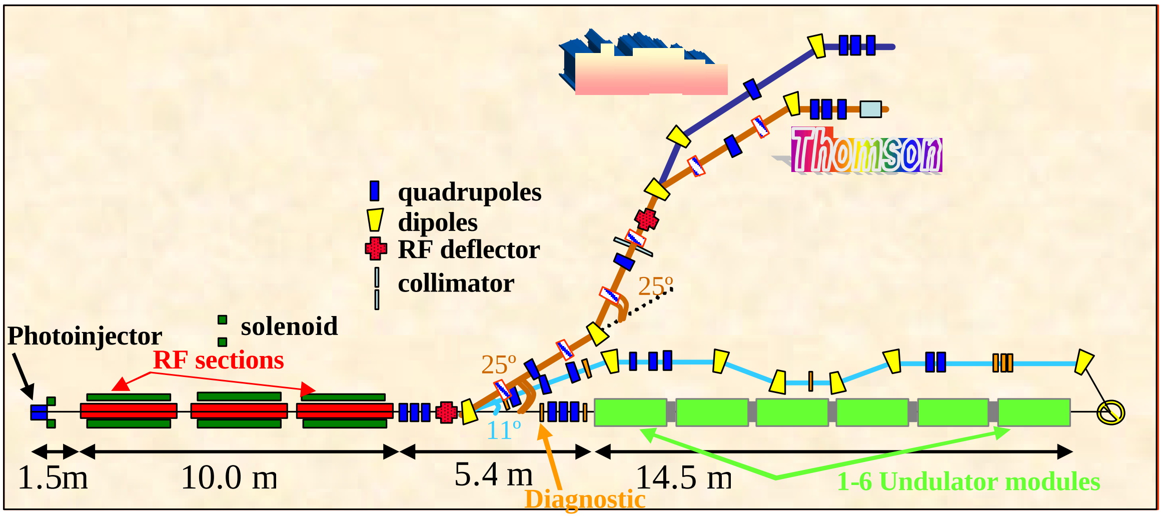

Fig.11. Schematic layout of the SPARC and related experiment area. The part dedicated to Plasmon-X and Thomson can be used to experimentally verify the calculations of this work.

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).

6 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 (Ref. 6), so a good vacuum level seems not necessary for the PLASMON-X or TB experiment, neither in the SPARC linac, far away from the RF sections.

7 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) A.Fasso`, A.Ferrari, S.Roesler, P.R.Sala, G.Battistoni, F.Cerutti, E.Gadioli, M.V.Garzelli, F.Ballarini, A.Ottolenghi, A..Empl and J.Ranft, "The physics models of FLUKA: status and recent developments", Computing in High Energy and Nuclear Physics 2003 Conference (CHEP2003), La Jolla, CA, USA, March 24-28, 2003, (paper MOMT005), eConf C0303241 (2003), arXiv:hep-ph/0306267.

(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) S.M. Seletsky “ Thermal Photon and Residual gas Scattering of the Electrons in the ILC RTML”, SLAC-TN-06-007, Aug,15, 2006.