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Current Dependent Pressure Rise at PEP-II LER*

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1 Abstract

A nonlinear current dependence pressure rise was observed in the Low Energy Ring (LER) of the PEP-II B-factory. The paper presents preliminary experimental results, discussion, and describes simple simulations which indicate that the pressure rise can be related to the beam induced multipacting [1].

2 Experimental observations

The PEP-II LER is the high current 3.1 GeV positron ring with approximately six-fold symmetry. Each section comprises two halves of an arc and a straight section. The arcs have 9×4.5 cm TiN coated aluminum elliptical beam pipe with an ante-chamber. A straight section is made out of 4" stainless-steel round beam pipes.

LER design current 2.14 A current is stored in the train of 1658 bunches with the nominal bunch spacing 4.2 ns, i.e. two rf buckets. At the present time, the maximum current achieved in the ring exceeds 1 A. Most of the experiments described below was carried out with the beam current up to 1A.

Fig. 1 shows dependence of pressure on current typical for all ion pumps in the ring. The pump #3091 is located in the middle of the arc and the pump #2091 is in the middle of a straight section. The pressure rise is more gradual in the arcs and quite sharp in the straight sections above a certain threshold value of current.

The measurements show that the pressure rise has several specific features.

1. It increases with current monotonically at low currents but the growth is not linear as would be expected from the synchrotron radiation (SR).

2. Except for the SR pedestal, the sharp pressure rise with current is observed above a certain threshold, which is about the same in the arcs and straight sections.

3. The threshold current and pressure at the given current depend on the bunch pattern in the train.

4. Non-linear pressure rise has not been observed in the electron PEP-II ring.

Pressure variation along the ring for 582 bunch fill is depicted in Fig. 2 for straight sections and in Fig. 3 for the arcs.

Pressure is calculated from the measured current of ion pumps. Each point on the graphs Fig. 3 and Fig. 4 represents reading of an individual high voltage power supply which is, in most cases, connected to more than one ion pump.

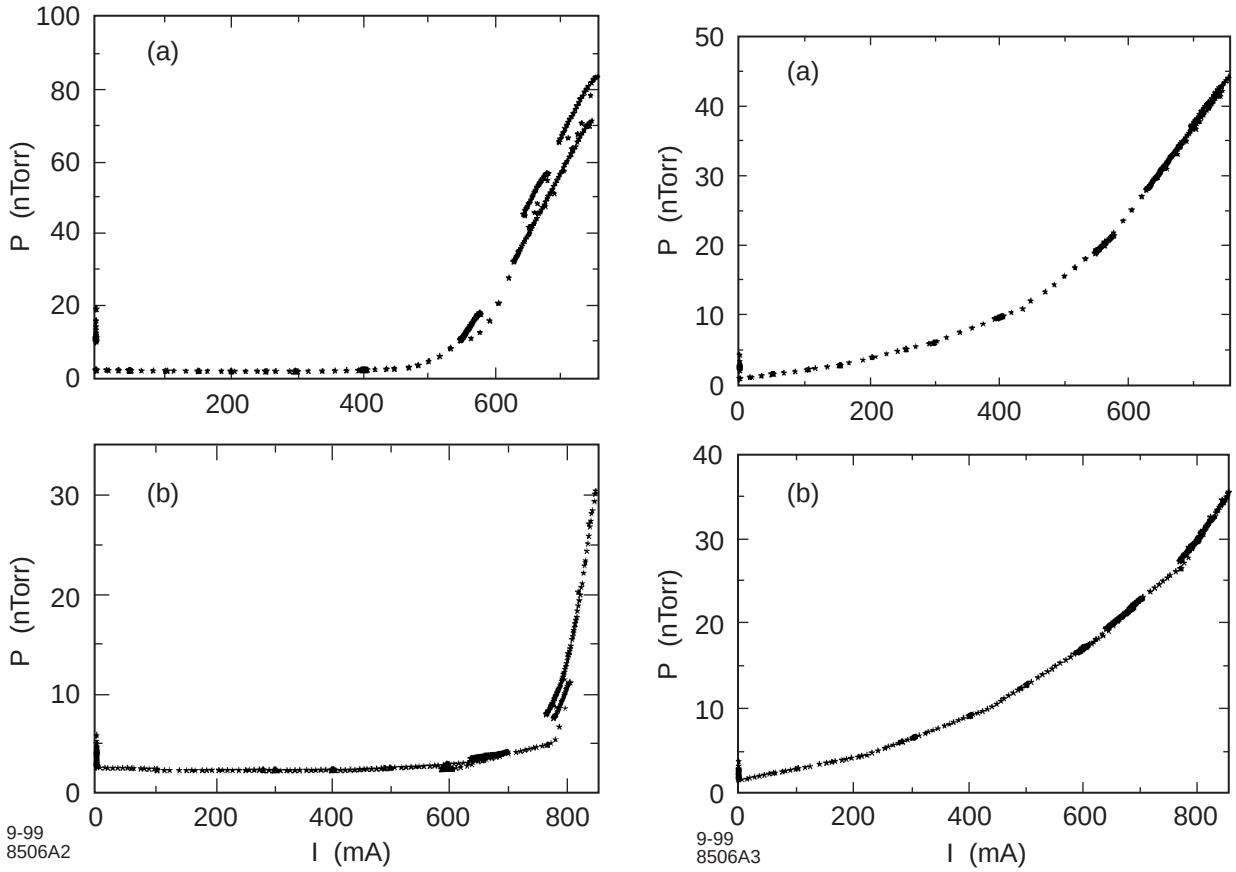

Figure 1: Dependence of pressure on beam current. Left column: pump is in the middle of the straight section. Right column: pump is in the arc. Number of bunches $n_b = 582$ (1a) and $n_b = 785$ (1b).

The dotted curves in the upper part of Figures 2,3 show the base pressure with no current in the ring. Two lower curves in each figure are dynamic pressure rise dP/dI for low current (0-200 mA) and the current 650 mA, above the threshold.

Three straight sections of the LER, number 4, 12, and 8, are "regular" straights without significant sources of the SR (bending magnets, wigglers, etc). For those straights and at low currents (0-200 mA), dynamic pressure dP/dI is significant in the beginning of the straight section, where there is a substantial photon flux from the last bends of an arc, and it decreases toward the end of the straights. At high current (650 mA) all "regular" straights demonstrate very high dynamic pressure rise, several times higher than that in the arcs, indicating that a mechanism different and larger than SR is responsible for this effect.

In the arcs, contrary to the straights, dP/dI at low and high currents are strongly correlated, as well as some correlation exists between dynamic pressure rise and the base pressure.

The current measured in the ion pumps may have, in general, an electron component which mimics the ion component. These two components were distinguished by measuring the decay rate of the pump current after the beam was aborted, see Fig. 4. Both ion and electron components of the pump current decay in time but the decay rate of the electron component is much higher. The relative magnitude of the drop of the pump current after beam abort is shown in the upper part of Figs. 2,3 (the curve with open square marks). The typical magnitude of this parameter in the arcs is about two, while it may be much higher for some pumps in the straights indicating that substantial electron component is present. This result is consistent with independent measurements of the electron component which was determined as the pump current remaining when ion pump magnet was taken off. "Magnet off" measurements show that the electron component in the LER arcs, where pumps are attached to the ante-chamber, is small, less than 1% of the total.

It is worth noting that, although the overall dependence of pressure on the beam current is monotonic, above the threshold knee it displays hysteresis-like hooks especially at the maximum current, because the time variation of the beam current was fast compared to the time constant with which pressure reaches the equilibrium.

3 Discussion

Generally, pressure rise with the beam current can be related to SR, gas desorption due to the wall temperature rise or gas desorption due to collisions of energetic electrons and ions with the beam pipe wall.

As it was mentioned above, SR gives only linear rise with the beam current. Temperature variations are slow and can not lead to effects which depend on bunch spacing.

The same is true for effects caused by ions. On top of this, the rate of ion production is relatively low. Indeed, the number of ions produced by the stored beam in collisions with residual gas per unit length per second is

$$\frac{d^2N_i}{dsdt} = \sigma_i n_g \frac{N_b}{\tau_b}, \tag{1}$$

and depends only on the average beam current. Here $\sigma_i \simeq 2$ Mbarn is ionization cross-section, N_b is the bunch population, n_g is density of the residual gas at normal (300 K) temperature related to pressure P,

$$n_g = 3.\,10^7 P\mathrm{cm}^{-3}\mathrm{nTorr}^{-1}, \tag{2}$$

and $c\tau_b$ is bunch spacing.
The number of the ions and ionization electrons produced in collisions with the residual gas at $p = 100$ nTorr, $n_b = 582$, and $I = 0.65$ A is $d^2N_i/dsdt = 3.1\,10^{12}\,s^{-1}m^{-1}$, and depends only on the average beam current.

At the same current 0.65 A, pressure at a straight section pump with the pumping speed 100 l/s is about 40 nTorr. Taking into account that the distance between pumps is about 7 m, one can obtain that the average out-gasing rate in this location is about $2\,10^{13}$ atom/(m s). It is about an order of magnitude higher than the ion production rate in collisions. Hence, primary ions and energetic electrons produced in inelastic collisions can not be responsible for observed pressure rise.

The secondary neutrals produced by ion impact with the wall can increase the pressure. With the high yield this process can lead to pressure instability. However, our estimate shows that, for the LER parameters, this does not take place [2].

Ionization electrons have high energy and are capable to produce neutrals but their direct flux to the wall is too low to explain the pressure rise.

The coupled-bunch transverse oscillations due to geometric wakes or due to beam-electron cloud interaction can enhance flux of electrons of the cloud to the wall. These electrons have low energy and it is not clear whether they can cause desorption of neutrals from the walls.

The only plausible process remained is the de-gasing due to impact with the walls of large number of energetic electrons produced in beam induced multipacting [1].

We assume that the yield of neutral atoms in electron collisions with the wall depends on the energy deposited to the wall.

There are quite a number of parameters defining the system: beam pipe radius b, bunch separation $s_b = 2\pi R/n_b$, transverse and longitudinal rms of the beam σ_x and σ_l, beam current I, and parameters defining secondary electron emission: average energy of the secondary electrons E_0, the threshold energy E^e_{th} at which the yield of electron production exceeds one, and the threshold energy E^A_{th} where the de-gasing takes place. The photon flux is different at different location in the ring and should also be considered as independent parameter.

Depending on these parameters, the system may behave quite differently. We specify therefore parameters relevant to the experiment: $b = 4.5$ cm, $\sigma_x = 0.1$ cm, $\sigma_l = 1$ cm, $E_0 = 10$ eV, $E^e_{th} = 200$ eV for TiN coated Al and stainless-steel walls, n_b in the range of 500 to 1600, I in the range from 0.5 to 2.0 A.

Primary electrons can be generated by ionization of the residual gas, and by the direct or scattered SR. By design, the number of photo-electrons in the beam pipe in the arcs is not very large. Nevertheless, the number of photo-electrons produced even by the large-angle SR emitted per bunch

$d^2N_e/ds/dt = (dN_e/ds)(c/s_b)$, is substantially larger than that due to ionization. Here

$$\frac{dN_e}{ds} = \eta_{e\gamma}\frac{cN_\gamma N_b}{s_{max}\, s_b}, \tag{3}$$

$\eta_{e\gamma} \simeq 0.1$ is number of secondary electrons per incident photon, $N_\gamma = (4\alpha_0\sqrt{3}/\pi)(b/h)\ln(s_{max}/s_{min})$ is number of photons per positron escaping the ante-chamber with full height h. The estimate for LER [3] gives , $s_{max} = 9$ m. $s_{min} = 3.5$ m, $N_\gamma = 0.045$, and $dN_e/ds = 6.8\,10^5\ 1/cm$. Then, for $n_b = 500$, $\frac{d^2N_e}{dsdt} = 4.6\,10^{15}\ cm^{-1}s^{-1}$. The energy of large angle photons in this estimate was taken to be large enough to produce secondary electrons, i.e. larger than the typical work function 4.5 eV.

The large drop of the ion current after beam abort in the beginning of the straight sections indicates that there is a substantial electron density, what is consistent with the high photon flux at these locations.

Even if 1% of primary photons propagate to the end of the straight section, they give flux of the photo-electrons larger than that due to ionization.

It is not clear whether such low-energy photons may directly cause desorption and increase of pressure. In the experiment, increase of pressure with current has a clear threshold what speaks against such an assumption.

The electron density at low currents depends mostly on the flux of SR photons. It is given by the density of primary photo-electrons and varies along the ring. At high currents, acceleration of electrons by the beam is essential for out-gasing and electron avalanche may be a dominant effect defining the electron density.

The threshold energy E^e_{th} for production of the secondary electrons is high, $E^e_{th} \simeq 200eV$. For $E > E^e_{th}$, the yield of secondary electrons is almost independent of the energy of primary electrons. We assume that this is also true for stainless steel straights and TiN coated Al arcs. (Without TiN, the yield for Al can be as high as $\eta = 1.5$ and E^e_{th} is lower, $E^e_{th} \simeq 40$ eV).

Simple simulations are carried out with a tracking PIC code for cylindrically symmetric case. It takes into account initial energy spread of photo-electrons, production of the secondary electrons in collisions with the walls, and the space charge effect of accumulated electron cloud. The code calcualtes the average density of the electron cloud and the energy deposited to the wall as function of number of bunches passing a given location. Between bunches, electron trajectory is radial and is defined by the space-charge of the accumulated electrons. A bunch gives a kick and generates new primary electrons. Primary photo-electrons are generated proportionally to the bunch population I/n_b at the beam pipe wall $r = b$ and uniformly distributed azimuthally and within energies $0 < E <= E_0$. Electrons reaching the wall produce secondary if their energy exceeds E_{th} or perish otherwise. Simulations use parameters $E_0 = 10$ eV, $E_{th} = 200$ eV, and consider train of 582 bunches ($s_b = 378$ cm).

The high SR flux was simulated by generating $4.4\,10^4 I/n_b$ electrons per bunch at $r = b$. Dynamic pressure in this case rises approximately monotonically with current. This can be explained by approximately uniform distribution of electrons due to initial energy spread of secondaries which, in its turn, produces different acceleration by the next bunch, as well as by the space charge force. Fig. 5 shows two cases corresponding to the electron-electron yield $\eta = 0.8$ and $\eta = 1.2$. The difference at low currents is small because the electron density is determined primarily by the photon flux and dependence on the yield is weak. Note that, generally, the average density of e-cloud in the beam pipe varies with current in different pattern compared to the energy deposited to the wall.

Electron avalanche produced in electron collisions with the wall is important at the end of straights where the SR flux is small. This mechanism is the most effective at resonance currents when time of flight between walls is multiple of the bunch spacing and if the yield $\eta > 1$. The most dangerous are one- and two-pass resonances. The one-pass resonance can take place at the current too high for PEP-II parameters. The main effect for PEP-II comes from two-pass resonances. The higher-order resonances corresponds to several oscillations of a particle before it hits the walls. They are smeared out due to initial energy spread of the secondary electrons, randomization of the 3D trajectories, the finite length of a bunch, and the space-charge effect. As a result, number of particles in resonances drops for multiple passes and such resonances are much less dangerous.

Multiplication of the secondary electrons with initial velocity $v_0/c = \sqrt{2E_0/mc^2}$ depends on the bunch spacing. For large bunch spacing $(s_b v_0/c) > 2b$, the secondary can reach the opposite wall before the next bunch comes in. Multiplication is suppressed for $s_b > 14.2$ m for $E_0 = 10$ eV, $b = 4.5$ cm, or, for equidistant bunches, $n_b < 155$. In this case, the energy deposited to the wall per ionization electron is proportional to I^2 and the total energy per bunch deposited to the wall is proportional to I^3.

For larger n_b, a secondary electron at the distance r from the beam gets another kick $v/c = 2N_b r_0/r$ from the following bunch. The threshold current can be estimated requiring that electron having initial $v_0/c = \sqrt{2E_0/mc^2} + 2N_b r_0/b$ at $x = -b$ hits the wall at $x = b$ before the second bunch arrives and has $E > E^e_{th}$. The last requirement is more stringent. Dependence of I_{th} on bunch spacing is depicted in Fig 6.

For a low photon flux, the secondaries are generated mostly in avalanche electron collisions with the wall. Results of calculations is shown in such a case in Fig. 7. It is calculated in the same way and with the same parameters as in Fig. 5 except that number of primary electrons generated per bunch was 100 times smaller.

At low currents, electron can be accelerated or slowed down depending on its distance from the beam axis. The electron cloud builds up and the

equilibrium which may be reached after 30-40 bunches as it was shown in simulations of the photo-electron instability [4].

The steady-state density n_0 can be estimated from condition of neutrality, $n_0 = N_b/(2\pi s_b b^2)$. The density n_0 is $n_0 = 1.7\,10^6$ cm^{-3} at $I = 1$ A. This condition is usually obtained replacing the kicks from the beam by the average potential $U_{beam} = -(2N_b e^2/s_b)\ln(b/r)$ and describing space charge effect by uniform distribution of the cloud with the density n. The total potential has maximum at $r/b = \sqrt{N_b/(2\pi n s_b b^2)}$. Then, for $n > n_0$, the maximum is at $r < b$ inside of the pipe and the potential barrier pushes the secondaries back into the wall.

Another estimate of the quasi-equilibrium density can be obtained assuming that the maximum density is reached when the potential of the cloud is equal to the average energy of the secondary electrons at the wall, $2\pi n e^2 b^2 = E_0$, provided the acceleration from the beam with LER parameters does not change energy E_0 much. The estimate does not depends on beam parameters but implies that there is mechanism (direct or scattered SR or electrons hitting the wall) responsible for the production of secondaries. The estimate gives $n = 0.56\,10^6$ cm^{-3}, smaller than condition of neutrality.

The deposited energy increases as I^2 provided the density of the cloud is constant. At large currents electrons located within the radius $r_{max} \simeq 2N_b r_0 s_b/b$, reach the wall in time between bunches. The deposited energy depends only on the bunch population:

$$\frac{dE_{wall}}{ds} = \int_{r<r_{max}} \frac{2}{mc^2}(\frac{eIZ_0}{4\pi})^2(\frac{s_b}{r})^2 2\pi n r dr, \tag{4}$$

or

$$\frac{dE_{wall}}{ds} = \frac{2}{mc^2}(\frac{eIZ_0}{4\pi})^2 2\pi n s_b^2 \ln(\frac{2N_b r_0 s_b}{b\sigma_x}). \tag{5}$$

Here, $Z_0 = 120\pi$ Ohms.

Therefore, the number of neutrals $d^2N_0/dtds \propto I^2 s_b$. For pumping speed S_{pump}, pressure scales as $S_{pump}P \propto \frac{dN_0}{ds\,dt}$, or $P \propto I^2 s_b$, and the dynamic pressure $dP/dI \propto N_b$ as in the experiment.

Let us add few more remarks.

Resonance condition for the avalanche is sensitive to the distance between the beam and the wall. A small radial shift of the beam may change the threshold current and change pressure dependence on current. Effect is local, and variation of the closed orbit around the ring may smear the resonance. This was confirmed in our simulations.

Results of simulations are sensitive to the order in which the primary electrons are generated and kicked by the parent bunch. They may be generated and move before the next bunch provides a kick, or the kick follows the electron production right away. In the first case, the initial energy spread distributes electrons at the different distances from the incoming bunch and the dependence on current is smoother than in the second case.

The electron cloud only in a very crude approximation can be considered as a quasi-static, see Fig. 8. Actually, a static cloud can not exist at all.

Electron trajectory depends on the initial position $r(0)$. Electrons with small $r(0)$ never change direction of their motion and hit the wall. Electrons with large $r(0)$ have a turning point and go to the opposite wall unless they are stopped by the next bunch. Parameter $\Omega/c = \sqrt{2\pi n r_0}$ (plasma frequency) sets a characteristic time of these oscillations. For $n_e = 10^6$ cm^{-3}, the frequency $\Omega/2\pi \simeq 6.3$ MHz.

The time variation of the density may lead to variation of the effective transverse wake-field of the e-cloud along the bunch and to the effective longitudinal wake-field.

It is also important to emphasize, that the electric field of the electron cloud and production of secondaries electrons may substantially reduce effective yield of the secondary electrons. Effect comes both from the build-up of the space-charge potential and from the surface cleaning by electron collisions.

It is worth comparing the situation in the electron and positron storage rings. The electron cloud of the positron machine is replaced in the electron machine by the ion cloud. The ions of the central region can be accelerated and hit the wall producing neutrals. There is, however, a substantial difference: ions are much slower at the same current and the equilibrium density is defined not by the condition of neutrality but by secondary ionization and beam-ion instability. As the result, the ion density is much lower.

The rising pressure deteriorate beam life time. Accumulated space charge with density n_{tot} works as a focusing quad increasing betatron tune ν by

$$\Delta\nu = (2\pi R)^2 \frac{r_0 n_{tot}}{4\pi\gamma\nu}. \tag{6}$$

For LER parameters, $\nu \simeq 36$, $\gamma = 6\,10^3$, the tune shift is $\Delta\nu = 0.5\ 10^{-8} n_{tot}$. The electron density of the order of 10^6 cm^{-3} gives tune shift smaller than the beam-beam parameter.

This explains why the pressure rise does not apparently affects the beam stability.

4 Conclusion and Remedies

Results of simulations are consistent with measurements and show that, at moderate currents, the pressure rise is related to the photo-electrons in the beginning, and to the avalanche electrons in the end of the straight sections. In the first case, the deposited energy growth as I^2 due to additional energy spread introduced by the space-charge of photo-electrons. In the latter case of small flux of photo-electrons, there is a sharp threshold defined by the geometry of the beam pipe and bunch spacing. Although dependence of

pressure on current is more monotonic in experiment than in simulations this can be explained as a result of additional smearing of the resonances in the 3D case.

At large currents, dramatic pressure rise is caused by de-gasing from the walls induced by avalanche electrons. The later can affect the yield of secondary electrons and neutrals. The surface cleaning by the SR and related change of the yield η in the beginning of the straight sections may be essential in explaining why the pressure at the end of the straight sections is higher than that in the beginning at high currents.

A solenoidal longitudinal field was suggested to confine secondary electrons at the walls. To make Larmor radius small, $r << b$, the magnetic field has to be strong enough,

$$B >> 2\,10^{-6}\,(\frac{I_{beam}}{[mA]})\,(\frac{\sigma_l\sqrt{2\pi}}{b^2})\ \text{Gauss m.} \tag{7}$$

For LER parameters, B of 3 Gauss would be enough.

Another criterion is given by condition of adiabaticity of the kick. If bunch length is large compared to the Larmor period,$eB\sigma_l\sqrt{2\pi}/mc^2 >> 1$, a Larmor radius is adiabat invariant and preserved. The Larmor circle in this case moves as a macroparticle. To avoid this, B should be small enough,

$$B << 700\ \text{Gauss.} \tag{8}$$

Another possibility is based on observation that pressure rise in the arcs is correlated with the base pressure. This suggest that running a beam with $n_b \propto 500$ and low current, where pressure rise is large, can help cleaning the wall surface at the acceptable background level in the detector.

During preparation of this paper, new experiments studying pressure rise in PEP-II were carried out. They will be presented in a separate publication.

References

[1] see, for example, O. Grobner, Beam Induced Multipacting, LHC Project Report 127, May 1997

[2] S. Heifets, J. Seeman, W.Stoeffl, Pressure stability under a pump failure, PAC, 1997

[3] S. Heifets, Study of Instability of PEP-II Positron Beam (Ohmi-effect and multipactoring), SLAC-PUB-95-6956, 1995

[4] M. Furman, G. Lambertson The electron-cloud instability in the arcs of the PEP-II positron ring, PEP-II AP Note 97.27, Nov. 1997

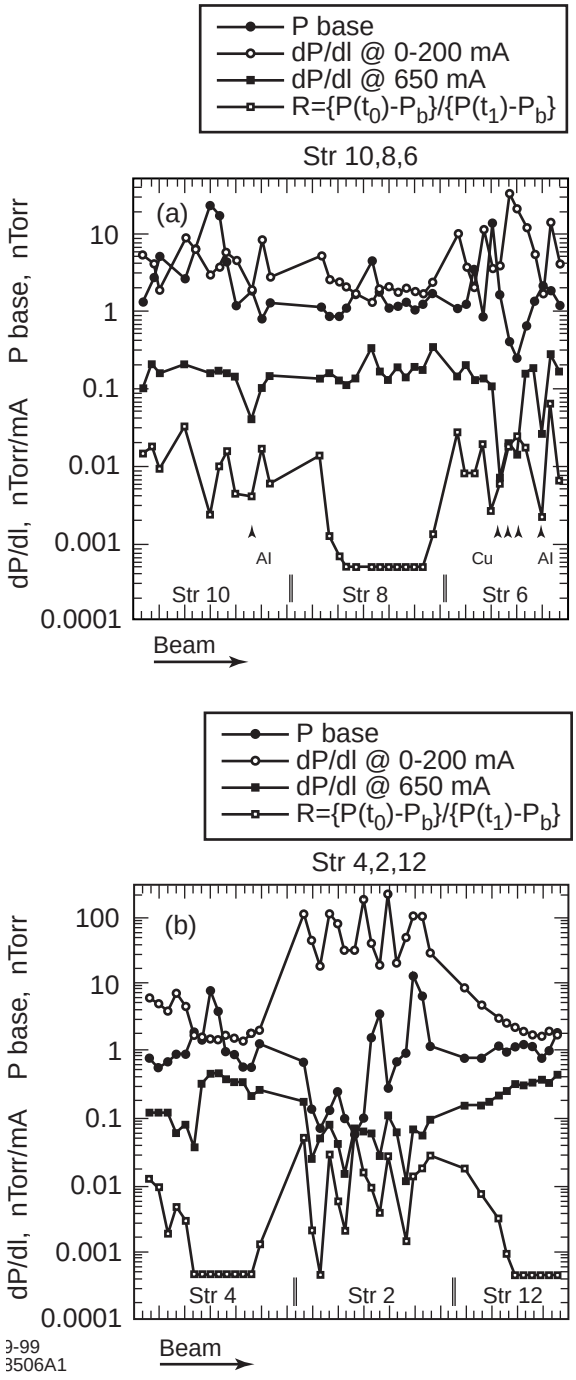

Figure 2: Variation of pressure P (upper curve), pressure drop, see text, (upper curve, open dots), and dynamic pressure rise dP/dI (two lower curves for low and high currents, respectively) along the straight sections in the ring. Fill of 582 bunches and 10% gap.

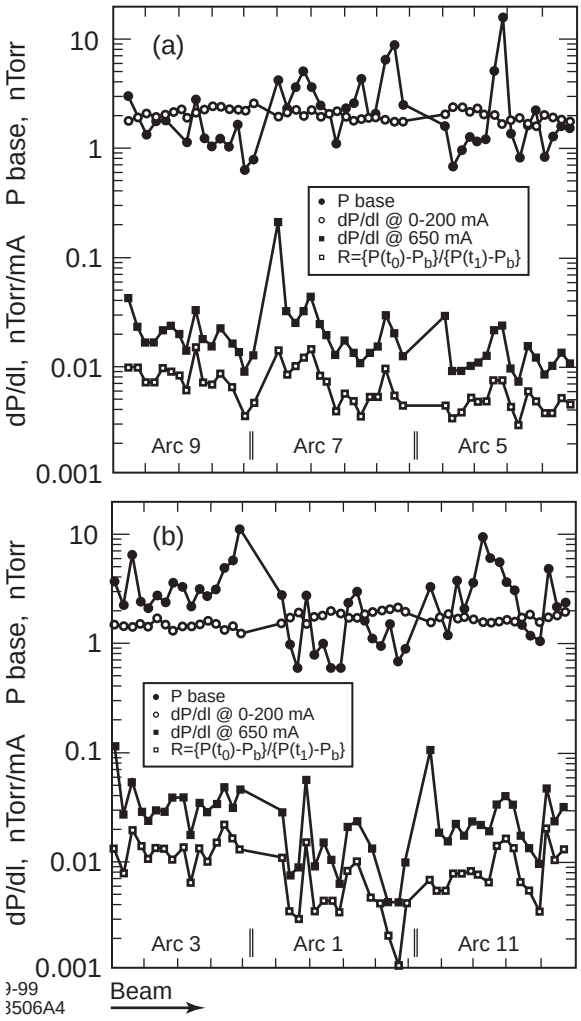

Figure 3: The same as in Fig. 2 but for the arcs 9, 7, 5 (top), and number 3,1,11 (bottom).

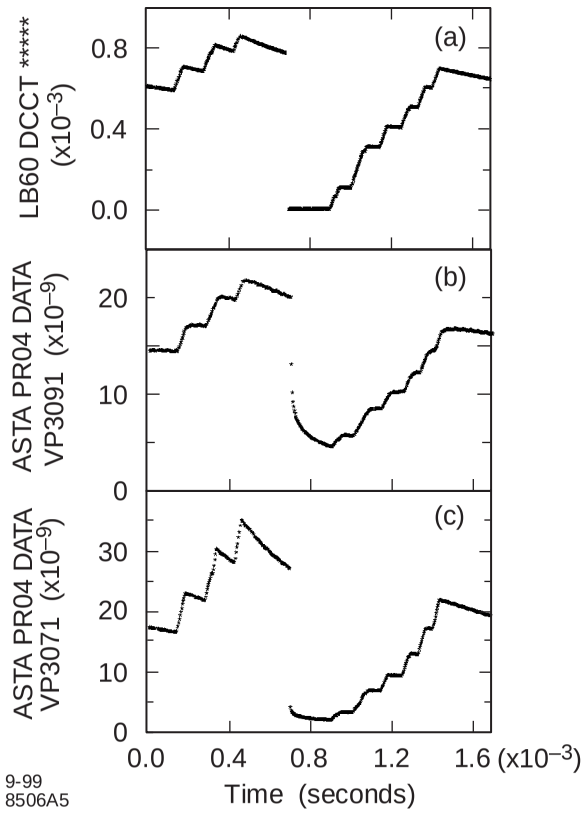

Figure 4: Variation of the ion pump current with time during the beam abort. (a): beam current vs time, (b): variation of the pump current in time for the case of pressure dominated by neutrals, (c): ion pump current vs time in the case of the pump current with substantial electron component.

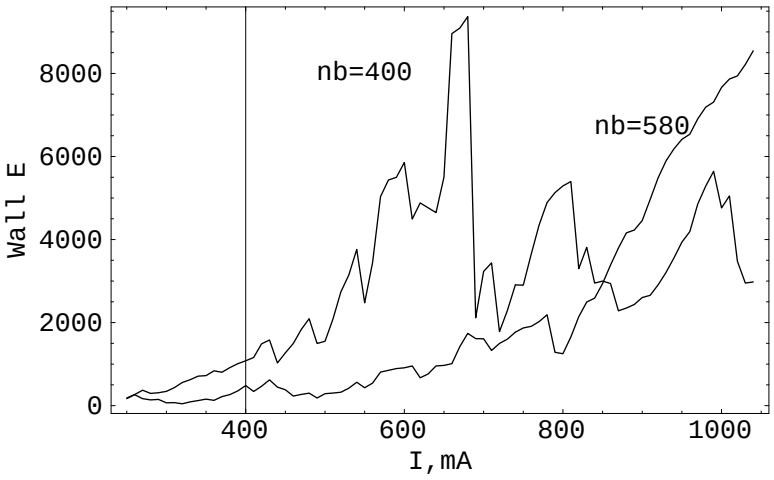

Figure 5: Energy deposited to the wall vs beam current. High flux, $\eta = 1.2$, $E_0 = 10$ eV, $E_{th} = 200$ eV, $b = 4.5$ cm for number of bunches $n_b = 400$ and $n_b = 580$.

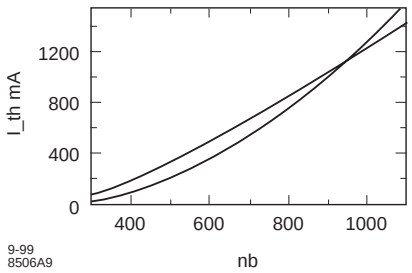

Figure 6: Threshold current vs number of bunches. Low curve: limit by time of flight, upper curve: limit by E_{th}. Current has to be above both curves. $E_0 = 5$ eV, $E_{th} = 200$ eV, $b = 4.5$ cm

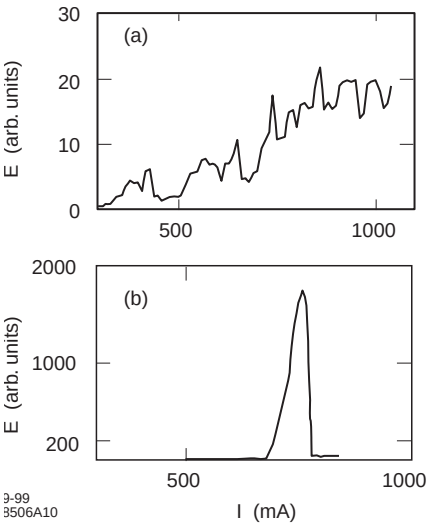

Figure 7: Energy deposited to the wall vs beam current. Low flux, $\eta = 0.8$ (a) and $\eta = 1.2$ (b). Note scaling. $n_b = 582$, $E_0 = 10$ eV, $E_{th} = 200$ eV, $b = 4.5$ cm.

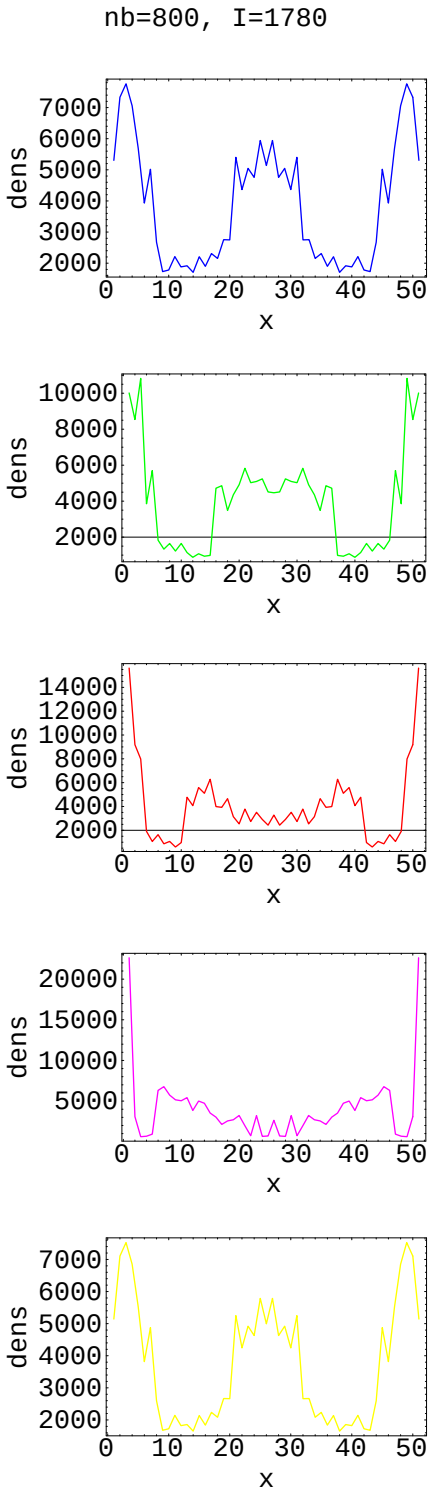

Figure 8: Variation of distribution of the electron cloud in time. Each snapshot is taken at 1/4 of bunch spacing.