PS/RF/Note 97-11 (MD)
12 August 1997

FIELD EMISSION MEASUREMENTS ON RFQ2 AND RECALIBRATION OF THE VANE VOLTAGE

M. Vretenar

1. RE-ANALYSIS OF RFQ2 CALIBRATION

A calculation of the RFQ2 beam transmission as function of the vane voltage has recently been done with the beam tracking code PARMILA and reported in [1]. The simulation is compared here (Figure 1) with two sets of measurement data, the first one collected in 1990 at the RFQ test stand and the second one in 1994, after the installation of the RFQ2 at Linac2. We recall here that the RF voltage between the RFQ electrodes (vanes) defines its focusing strength and therefore its transmission.

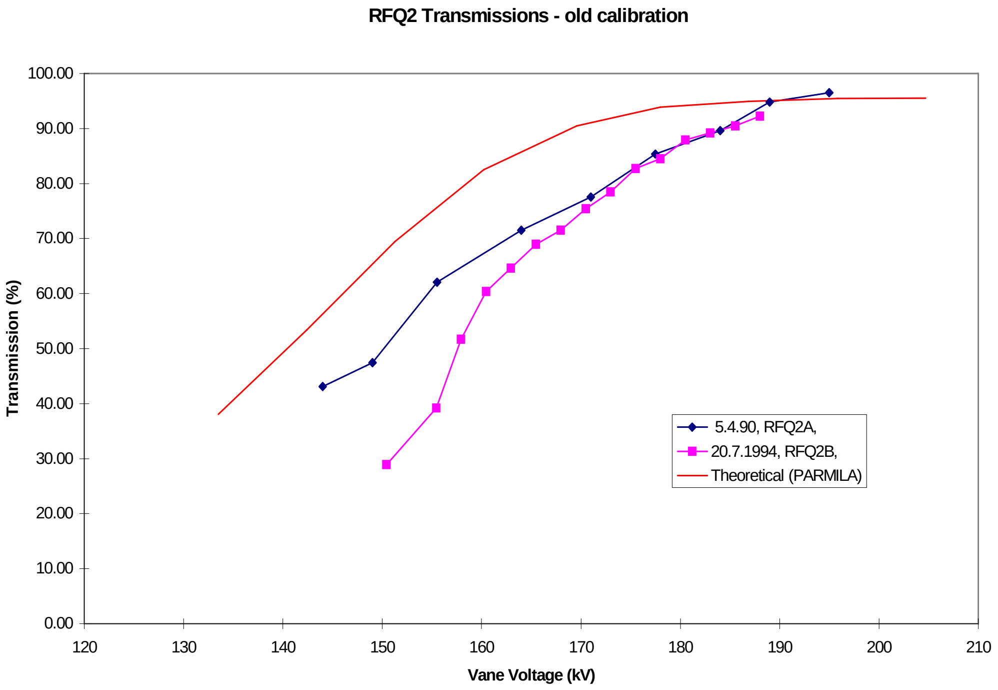

Figure 1: Theoretical and measured transmission of RFQ2 as function of vane voltage (old calibration)

There is a clear disagreement between calculated and measured data. However, the slope of the linear part of the curves is nearly the same, indicating that an offset could have slipped into the calibration of the RFQ vane voltage. The simulation code is considered as very reliable, while the cavity voltage calibration is a process more tricky and subject to errors. Nevertheless, a 10% offset is large enough to justify a more detailed analysis of the calibration process.

The calibration was done by taking the R/Q calculated by the 2-D RF simulation code Superfish, then multiplied by the measured Q-value in order to obtain the shunt impedance R. The nominal vane voltage given by the beam dynamics simulations, $V_0 = 178$ kV, was then used to calculate the corresponding nominal power P as $P = V_0^2/R$ (we use the linac definition of shunt impedance). Once this power was going into the cavity, the “RFQ Amplitude” as acquired through the control system was registered as the nominal RFQ level. This is the voltage on a monitoring loop inside the cavity, detected and processed in the RF chain, and proportional to the vane voltage.

Some errors can affect this calibration, mainly the accuracy of the 2-D code in the determination of the correct R/Q and the accuracy of the power measurement. 2D simulations usually give precise enough results for cavities like the RFQ2, where the end cells are no more than a small perturbation. Model measurements of R/Q always showed values very close to the computed ones in the limit of the measurement error. The vane modulation, not considered by Superfish, also contributes to the cavity capacitance and therefore to R/Q, but its effect can be estimated from the detuning due to the modulation to be less than 1%. The power going into the cavity is measured through a directional coupler and an RF detector whose calibrations were carefully checked in the laboratory. Altogether, these sources of calibration error can add up to a maximum of a few percent.

The only reasonable hypothesis to justify a 10% offset in the calibration is that “something else” was taking power from the generator, i.e. that the power we were measuring was not all going to establishing the voltage across the vanes, but that a certain amount of it was going elsewhere. It could be going to another mode, or to electrons. Other modes were never observed in the RFQ2, while electrons can be produced by many processes (multipactor, losses of beam on the vanes, etc.) and then absorb power from the generator. However these processes have a random behaviour and oscillations or instabilities should have been observed in the RF signals.

A more stable behaviour can instead correspond to electrons produced by field emission induced on the RFQ vanes by the RF voltage. Under this assumption, at high voltages, some electrons could be extracted by the electric field from the vane at negative RF potential and then accelerated to the adjacent positive vane, absorbing power from the generator thus disturbing power measurement and calibration.

Re-analysing the old measurements with a new technique can prove the field emission hypothesis. In a system where the power goes only to the right cavity mode, the power is by definition proportional to the square of the voltage. By plotting P vs. V^2, where V is the voltage on the monitoring loop as acquired through the control system, not necessarily calibrated but proportional to the vane voltage, one could look for deviations from this simple law. Luckily enough, in the old RFQ2 logbooks there were some set of data (input power at different voltages) taken in the past, at the time of the RFQ calibration, that could be plotted in the new way. Figure 2 shows $P(V^2)$ for a measurement done at the RFQ test stand in 1990. Together with the measured points, a straight line interpolates the first five points. At powers beyond 300 kW, we see a clear deviation from the straight line, i.e. the "signature" of field emission.

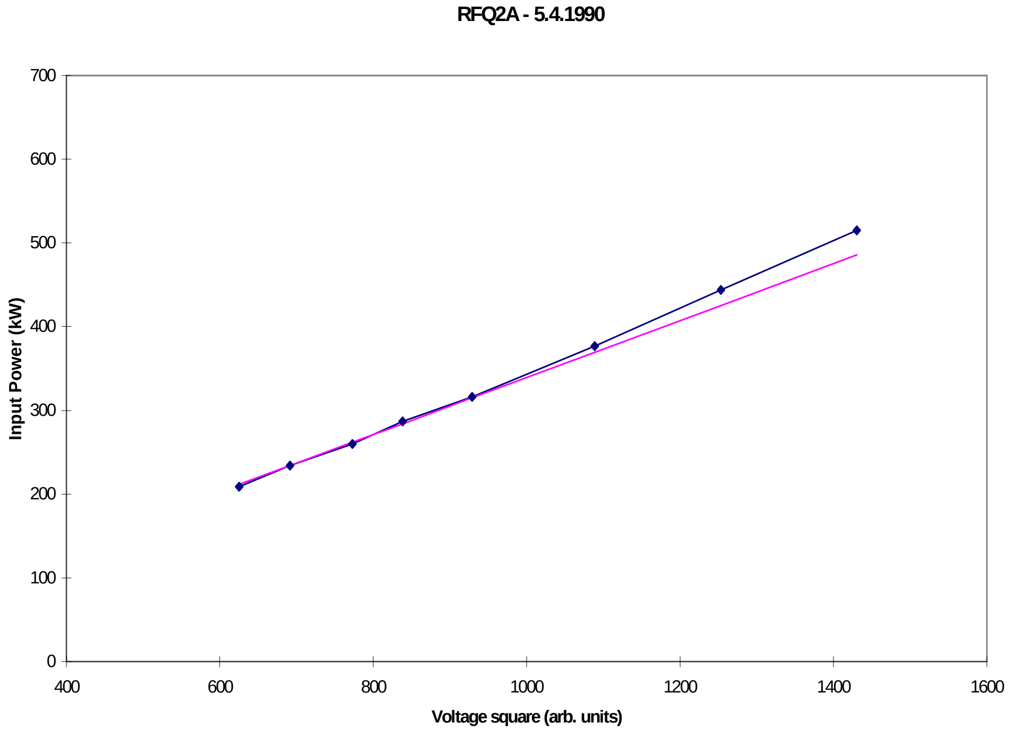

Figure 2: Input Power vs. vane voltage (arbitrary units) square for the RFQ2, 1990 measurement

Field emission current (also referred to as "dark current") is a well-known problem in electron linac cavities, where due to the short pulse length the field can be pushed to very high level [2]. It is usually not observed in proton cavities, where the long pulses forbid high fields.

In the RFQ2 case this was not only an unexpected phenomenon, but it could not be observed, as is usually the case, from the rise of reflected power. The RFQ2 is overcoupled to the generator, in order to be matched for a proton beam of 200 mA, making that the field emission loading was actually decreasing the reflected power.

Moreover, the field emission loading in an RFQ can be high even for small electron currents. The small gap between opposite RFQ vanes (5mm, 0.3% of the wavelength) makes that all the electrons produced get the energy corresponding to the full voltage (the transit time factor is 1 even for electrons produced at rest energy).

Field emission is strictly related to RF breakdown (high field emission is considered as a pre-breakdown phenomenon), and to the maximum field achievable. However, the physical mechanism and the eventual quantitative relationship are still matter of discussion [3] [4]. The RFQ2 was subject to many breakdowns after accidental oil pollution in 1990, and then again immediately before and after the installation at Linac2. An analysis of field emission would give a new insight for understanding its unstable behaviour and could give some hints in order to achieve a better operating condition.

2. FIELD EMISSION MEASUREMENTS ON RFQ2

A high electric field on an electrode surface reduces the width of the potential barrier that confines the conduction electrons inside the metal. When the field is sufficiently high some electrons can tunnel through the barrier. The process is statistical, but when the thickness of the potential barrier is of the order of the Planck electron wavelength, the probability of crossing the barrier becomes so high that huge electron currents can come out of the electrode. A quantum-mechanics analysis of field emission is due to Fowler and Nordheim [5] and gives for the emitted current density J (A/m^2) the following formula, valid at temperature $T = 0$ and with some simplifications on the electron band structure:

$$J(E) = \frac{1.54 \cdot 10^{-10}}{\phi} \cdot E^2 \cdot \exp(-\frac{3.21 \cdot 10^{-9} \cdot \phi^{3/2}}{E})$$

Here ϕ is the metal work function in eV and E the surface electric field in V/m.

Loew and Wang have calculated a useful form of the Fowler-Nordheim formula for RF-varying field and standard temperature [3]. They introduce a local field enhancement factor β, which takes into account the surface imperfections, roughness, marks and impurities, all increasing the effective surface field. For a copper electrode (ϕ = 4.65 eV) the current density is:

$$J(E) = 4.83 \cdot 10^{-11} \cdot (\beta \cdot E)^{2.5} \cdot \exp(-\frac{6.55 \cdot 10^{10}}{\beta \cdot E}) . \qquad (1)$$

The exponential term in (1) makes that the highest β spots dictate the emission behaviour of large surfaces. Typical values found by Loew and Wang for electron linac cavities are between 40 and 80. Taking for example $\beta = 60$, the field emission curve looks like in Figure 3.

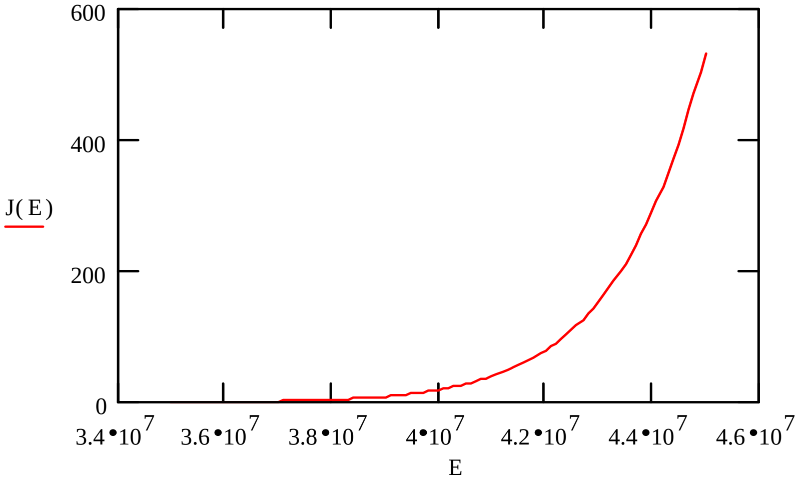

Figure 3: Field emission current density (A/m^2) vs. Electric Field (V/m), $\beta = 60$

We see a threshold for high electron production, due to the rise-up of the exponential term, at a field around 43 MV/m (in a more general way, at $\beta E \approx 2.6$ GV/m). This is 20% higher than the maximum RFQ2 surface field, 35 MV/m, indicating that the RFQ2 should normally operate in a region free from field emission. Nevertheless, an enhancement factor β much higher than the standard values would explain a high field emission level.

The overall field emission current can be calculated from the curves $P = \mathrm{f}(V^2)$, but beforehand a new calibration factor has to be determined, by applying the standard calibration procedure at a power level certainly free from field emission, for example at half the nominal. A new calibration measurement done on the RFQ2 during a dedicated MD showed that the nominal vane voltage corresponds to a command value for the RFQ Amplitude of 3820 mV, 8.5% higher than what was believed before to be the nominal level, 3520 mV. Once the new ratio between RFQ Amplitude and vane voltage V has been found, the field emission current at a voltage V can be calculated as:

$$I(V) = \frac{1}{V}\left[P(V) - \frac{V^2}{R}\right]$$

Once the correct calibration factor has been determined, this formula can be applied also “retroactively” to old sets of measurement data, to find the level of field emission present in the past. Three sets of data were taken for analysis, referring to the two identical units of RFQ2 that were produced, the RFQ2A and the RFQ2B. Two were found in the old logbooks, a 1990 measurement on RFQ2A and another measurement on the RFQ2B done in February 1993, immediately after its installation at Linac2 (unfortunately, only three points were taken at that time). A third set of data was taken during two MD sessions on the RFQ2, on May 7 and 14, 1997. Figure 4 shows the overall field emission current as function of vane voltage in the three cases.

This gives a clear evidence of the presence of high field emission current in some period of the RFQ2 history, sometimes as high as 250 mA. Whereas in the present situation the RFQ shows appreciable field emission only beyond 180 kV.

By plotting $\ln(I/V^{2.5})$ as function of $1/V$ one can draw the so-called Fowler-Nordheim plot. If the emission follows the F.- N. formula, the measured points should fall on a straight line, whose slope is inversely proportional to the enhancement factor β. Knowing the numerical factor in the exponential term of (1), we can derive from the measurements an effective value of β. The plot for the three sets of data and the corresponding β's are shown in Figure 5. Actually the data refer to two different versions of RFQ2, RFQ2A and RFQ2B.

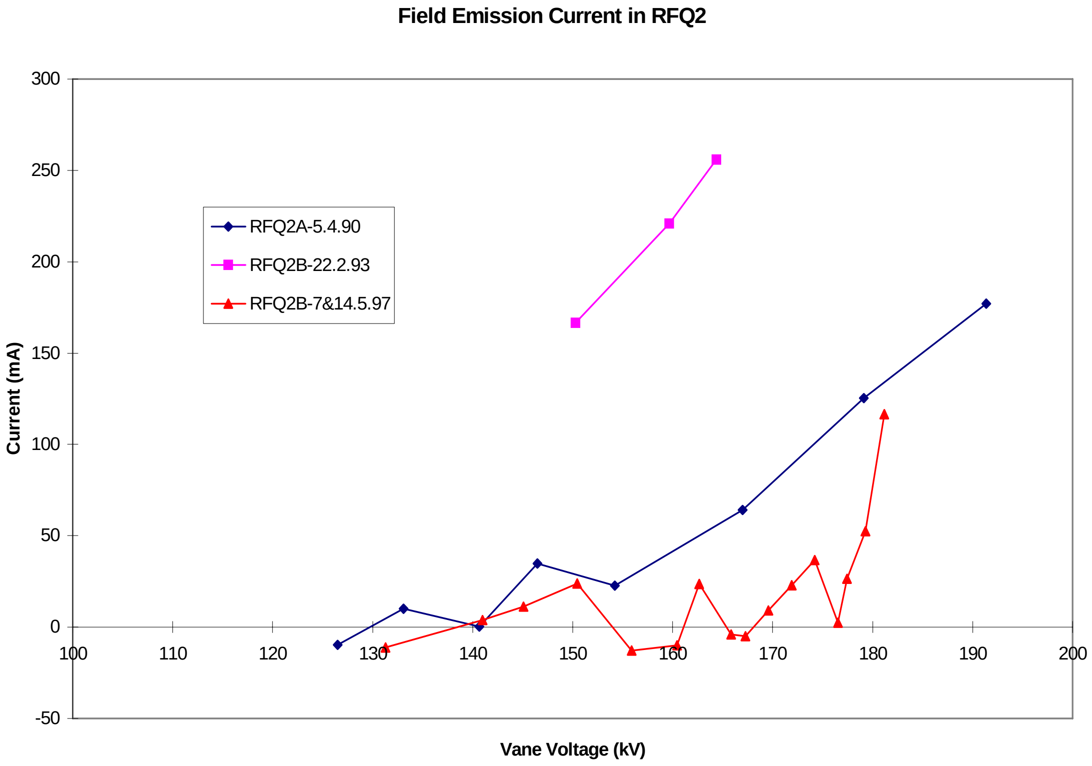

Figure 4: RFQ2 Field Emission Current vs. Vane Voltage

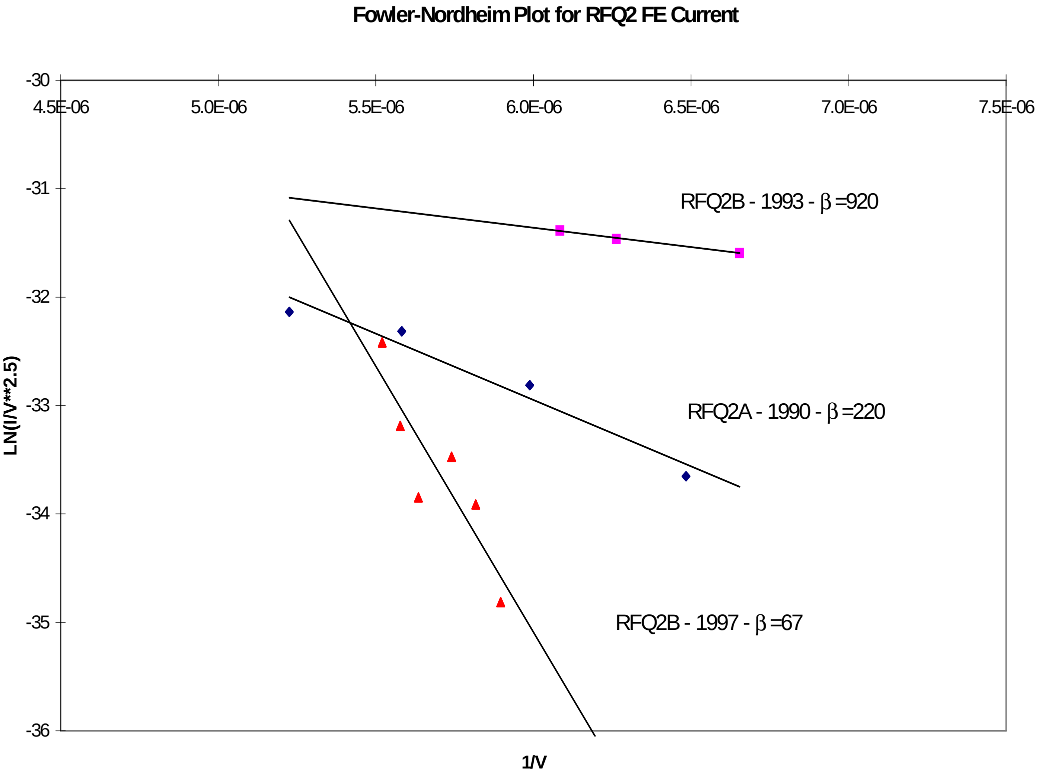

Figure 5: Fowler-Nordheim Plot for RFQ2 Field Emission

The 1990 set of data, taken immediately after the first RFQ2, was delivered from the workshop has $\beta = 220$. Compared to a standard β-value between 40 and 80, it indicates either a bad finishing or some pollution of the surfaces, due to the long exposure of the cavity in the workshop (no clean room was available at the time) or to some more recent pollution from the vacuum system.

The $\beta \approx 920$ measured immediately after the installation of the second RFQ at the linac (1993), although less precise because measured only on 3 points, indicates that the RFQ was heavily polluted (the surface finishing was the same as for the first RFQ). Actually, in 1993 the RFQ2 operation was disturbed by many breakdowns, making it impossible to operate at the (old) nominal level and forcing to decrease its voltage (with consequent loss in transmission) to a safe value. During the 1994 shutdown, the RFQ was carefully inspected, and a defective vacuum pump was found and immediately replaced. This pump was responsible for the diffusion of oil vapours into the cavity. The field emission measurement shows how the oil layer deposited on the vanes induced a very high enhancement factor and a huge level of field emission.

The third curve, corresponding to the present status, shows a $\beta = 67$, falling in the standard values. It indicates that after the removal of the source of pollution and some years of stable operation at high voltage, the vane surfaces slowly eliminated the oil layer.

Using the new calibration factor, one can redraw the transmission curves of Figure 1. The agreement is now good (Figure 6).

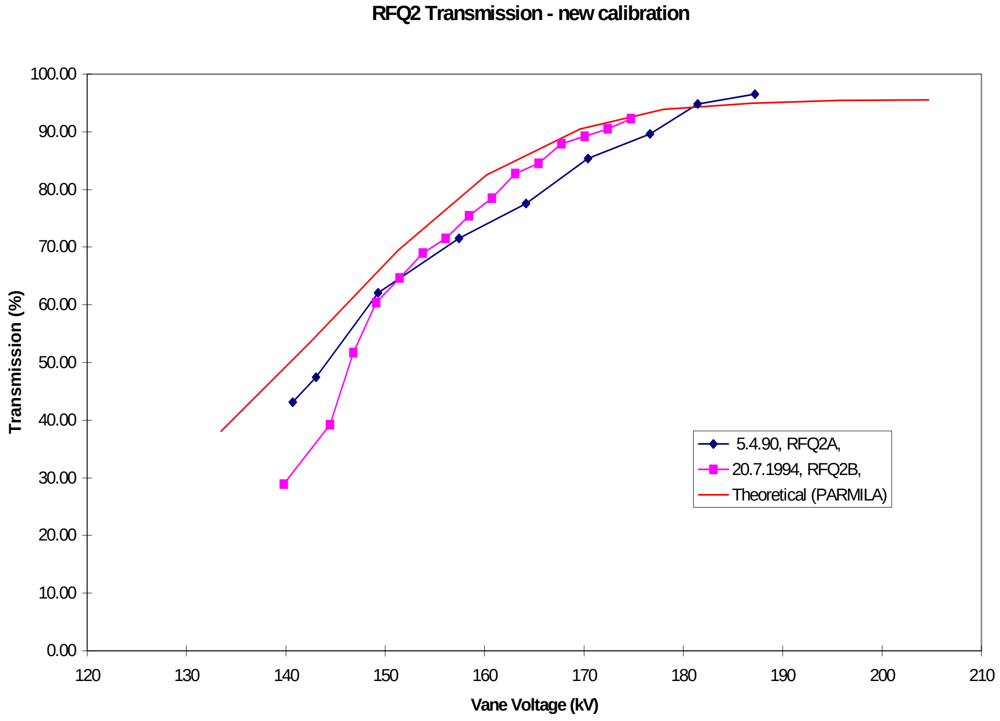

Figure 6: RFQ2 transmission as function of vane voltage, simulation and measurements (new calibration)

3. CONDITIONING OF THE RFQ TO A HIGHER VOLTAGE

The recalibration and the field emission measurements indicate that:

1. The RFQ2 must be operated at a higher voltage to improve beam transmission.
2. The RFQ2 can be operated at a higher voltage, now that field emission has virtually disappeared and therefore field emission related breakdowns should be largely reduced.

However, the RFQ2 was never operated regularly at the new nominal voltage, thus making a further cavity conditioning necessary. This was done between May and June 1997, in parallel with the normal Linac2 operation. The reduced number of beam users after the SPS fire incident allowed a certain amount of RFQ breakdowns, with consequent loss of beam.

Starting from the original RFQ Amplitude of 3500 mV, the RFQ level was increased by steps, and then the number of breakdowns was counted by a small Windows-based application program, running on an office PC and acquiring the RFQ level from the control system “passerelle”. At each step in voltage, the probability of breakdown occurrence increases, and in fact we noticed a sharp rise in the amount of breakdowns per day registered by the program. However, after a few days at the new level, the rate decreased allowing for another step in voltage. Finally, we stopped at the level of 3700 mV, still 3.2% lower than the nominal. After a few weeks at this level, breakdowns virtually disappeared.

As a consequence of this re-conditioning process, and after some adjustments of the focusing in the transfer line, the linac current delivered to the booster was increased from 145 mA to 160 mA.

In the future, another conditioning round is foreseen to go up to the nominal voltage. This should give a further increase in current, however less spectacular than the previous one due to the fact that we are approaching saturation of the transmission curve (Figure 6).

6. ACKNOWLEDGEMENTS

This work started from the simulations of A. Lombardi, who has also been very helpful in many discussions.

5. REFERENCES

[1] B. Couturier and A. Lombardi, Proposal for a new Proton Injector for LINAC2, PS/HP/Note 97-06.
[2] R. Bossart, J.C. Godot, H. Kugler, J.H.B. Madsen, A. Riche, J. Stroede, RF-Gun Construction, Tuning and High-Power Tests, Proc. EPAC Conference, Berlin, 1992 and CERN/PS/92-19 (LP).
[3] G.A. Loew and J.W. Wang, Field Emission and RF Breakdown in Copper Linac Structures, Particle Accelerators, 30 (1990), 225.
[4] H. Matsumoto, Dark Currents, Proc. of the XVIII Int. Linac Conf., Geneva, 1996, p.626-630.
[5] R.H. Fowler and L.W. Nordheim, Proc. Roy. Soc. A 119, 173-181 (1928).