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Injection and Accumulation Studies

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Introduction, aim

To study injection and accumulation efficiencies and try to explain present performances:

- by examination of the behavior of the stored beam with injection bumpers and kickers pulsing
- by measurement of the injection and accumulation efficiencies versus bumper amplitude, kicker amplitude and residual oscillation amplitude.

These measurements were performed during the last term of 1988.

1. Studies of a stored beam life time under injection conditions

In all these measurements we have used an e^+ beam of 4.10^{10} e^+ in one bunch. The injection hardware was pulsed every 80 ms as usual under operational conditions.

1.1 Life time versus injection bump (HR.BSW) amplitude

The injection bumpers (HR.BSW) are set to produce a closed orbit (C.O.) deformation localized in injection septum area, The beam lifetime versus injection bumper current is measured in order to get information on the aperture available for the stored beam at the septum. Injection bumpers are pulsed approximately for 8 ms every 80 ms. Beam lifetime is measured through the beam current transformer readings or directly from the analog signal, depending on the time scale of the losses.

When the injection bump is ON, the tails of the transverse beam distribution are removed, and some diffusion , to recover equilibrium, takes place. We assume at this stage that this diffusion process is slow in respect to 8 ms and fast in respect to 72 ms , leaving the beam recover its equilibrium distribution between two shots of the HR.BSW.

Under these conditions with $I = I_0 e^{-\frac{t}{\tau}}$ $\tau = life\ time$

we have (1) $$-1/\tau = \frac{1}{I}\frac{dI}{dt}$$

which can be measured directly from our data. In table 1 below, we can find beam lifetime in s versus HR.BSW current in A.

Table 1 : Life time versus injection bumpers amplitude

HR.BSW current(A)	Bump at septum(mm)	Life time(s) measured	Space calculated from bumps(mm)	Space calculated from losses(mm)
4.7	34.8	1320	5.5	5.2
4.8	35.5	342	4.8	4.7
4.9	36.3	37	4.0	4.1
5.0	37.0	3.7	3.3	3.1
5.1	37.7	0.73	2.6	1.9

The injection closed orbit is only moved in the septum area where there the limiting aperture is. The injection septum (HIP.SMH33) is located at 48 mm inwards from the central orbit. From the closed orbit measurements in the vicinity of HIP.SMH33, we can infer a horizontal C.O. position of $-$ 7.7 mm. The effect on C.O. of the HR.BSW at 500 MeV for the operational tunes (Qh = 4.60 , Qv = 4.37) at HIP.SM33 is $x_s = 7.4\,mm/A$. So the available aperture at the septum level is

$$d_{sp} = 40.3 - 7.4 \times I_{BSW} \quad (2)$$

These values can also be found in Table 1 col. 4

During the 'ON' period of the HR.BSW, the beam is close to HIP.SMH33 and all particles having a horizontal betatron amplitude larger than the clearance 'a_1'. will be lost. With a gaussian betatron amplitude distribution in normalized horizontal phase space

$$g(a) = \frac{a}{\sigma_a^2}\, e^{-\frac{a^2}{2\sigma_a^2}}$$

With $\sigma_a = \frac{\sigma_x}{\beta_x}$ we intercept, if N_i particles are initially in the beam

$$N(a) = N_i \int_{a_1}^{\infty} g(a)\, da = N_i\, e^{-\frac{a^2}{2\sigma_a^2}} \quad (3)$$

With the τ definition given before and τ_{rep} being the repetition time of the bumpers (here 80 ms) we get

$$\tau = e^{\frac{a^2}{2\sigma_a^2}}\, \tau_{rep} \quad (4)$$

In table 1 col.5 we show the clearance deduced from the life time with $\sigma_x = 1.17\,mm$, which is very close to the experimental one deduced from the geometry and the bumper current in col. 4

Figure 1 shows the measured life time versus clearance calculated from HR.BSW current and the theoretical life time for the same clearance with our nominal horizontal equilibrium emittance . The agreement is good and one can use expression (2) to find available aperture at injection. For these studies , where we have used 2.0 A in HR.BSW , the admittance will be $48\pi\ 10^{-6}$ rad.m . With the present (November 88) C.O. at -7.7 mm at septum and operational conditions (i.e. 1.5 A in HR.BSW) horizontal admittance at injection is $62\pi\ 10^{-9}$ rad.m. It can be compared with the design value of 85π 10^{-6} rad.m for which it was assumed no C.O. distortion and a current of 1.875 A in HR.BSW.

To get nominal acceptance, with the present C.O.(November 88) one must not work with more than 0.8 A in HR.BSW .

1.2 Beam life time versus fast bump by injection kickers

These measurements are done with a stored beam of 4 x 10^{10} positrons in 1 bunch. We measure the beam life time versus injection kicker amplitude, producing a fast (50 ns) and localized C.O. deformation at a repetition time of 80 ms, producing a fast closed orbit bump at HIP.SMH33 .

Injection bumpers are set to 2 A, as in previous measurements producing a closed orbit bump of 14.8 mm at HIP.SMH33 .

The beam life time is evaluated with the same method as in 1.1. At each shot of the kickers a small segment in the horizontal betatronic phase space is cut. Between 2 shots, i.e. during 80 ms we assume as an approximation that the beam recovers its equilibrium distribution. Table 2 shows the dependance of beam life time versus injection kickers amplitude in kV (column 1 and 2).

Table 2: Beam life time versus equal injection kickers amplitudes

HR.KFI Voltage(kV)	Displacem. in mm at HIP.SMH33	Calculated clearance mm	Lifetime s measured	Theoretical clearance losses mm	Corrected Displacement at HIP.SMH33	Corrected space from KFI mm
12.0	20.3	5.2	>3000	>3000	19.3	6.2
13.0	22.0	3.5	1215	4.4	20.8	4.6
14.0	23.7	1.8	20	3.0	22.5	2.9
14.5	24.6	0.9	2.55	2.2	22.3	2.1
15.0	25.5	0.0	0.62	1.3	24.2	1.3
15.5	26.3	−0.8	0.24	0.5	25.0	0.5

From the geometry of injection, of the closed orbit and of the injection bump , we can calculate the displacement and the distance (called "clear." for clearance in table 2) between the displaced orbit and the inner side of the injection septum. It is shown in col.2 of table 2. From this we get the expected clearance called "calculated clear." in col.3 .

Calculation of clearance from losses

We assume here a gaussian beam from which, in the normalized horizontal transverse phase space, we cut a chord characterized by a position of the rope on the x axis at a_1. At each shoot we cut on one side all particles having $x > a_1$. The losses N_1 after one shot are given by

$$N_1 = \frac{N_0}{2}\left[1 - \frac{2}{\sqrt{\pi}}\int_0^{a_1} e^{-\frac{z^2}{2\sigma_x^2}} \frac{dz}{\sqrt{2}z}\right] = \frac{N_0}{2}\left[1 - erf\left\{\frac{a_1}{\sqrt{2}\,\sigma_x}\right\}\right]$$

(5) Under these conditions, the life time is given by

$$\tau = \frac{2\,\tau_{ref}}{1 - erf\left\{\frac{a_1}{\sqrt{2}\,\sigma_x}\right\}}$$

With $\sigma_x = 1.17\,mm$, we have worked out what has to be the clearance between the bumped C.O. and the septum providing the same life time as measured . It is shown table 2 col.5 as "Theoretical clearance from losses". Figure 2 shows calculated life time as a function of clearance .

If we compare col. 3 and 5 of table 2, discrepancies are obvious, The calculated bumped C.O. at the septum is found too far from the center. As we have found a good agreement in our first HR.BSW measurements, we cannot accuse the closed orbit or HR.BSW calibration. It seems that injection kickers are providing less displacement than foreseen.

Let us look at the position for 15.5 kV: we are close to the heart of the beam, and the measurements are very sensitive to position errors. If we believe the clearance deduced from losses , which is 0.5 mm, we can infer that the value of -0.8 mm calculated from injection kickers calibration is wrong and must be 0.5 mm. It corresponds to an error in calibration of the injection kicker of 5.2% less, which is not dramatic (error in calibration, relative tuning between kicker pulse and bunch ....). Recalculating clearance with this new calibration gives column 7 of table 2 in which we find now a very good agreement with column 5 over all the KFI voltage range . Figure 2 shows measured life time versus corrected clearance which exhibits good agreement with the theoretical values .

We can conclude that apart from this calibration factor on the injection kicker, which will have to be checked, the beam behaves as expected .

1.3 Beam life time versus stored beam oscillation amplitude

Injection can be performed with an unbalanced, a balanced scheme or a mixture between these two. In an unbalanced scheme the two injection kickers do not provide the same eflexion. They are adjusted such that the admittance required by the injection process is minimized. The disadvantage is that the stored beam is performing a coherent oscillation all around the ring which leads to beam loss at higher stored current. In the balanced scheme, both kickers have the same amplitude and the stored beam is not disturbed outside the bump. An unbalanced scheme will provide, even with big or mismatched beam, fast initial accumulation rate, but will lead to saturation later. On the contrary, a balanced scheme will provide a smaller initial accumulation rate but will allow to reach other intensity limitations than given by the injection process

As in operation, in these measurements we use an unbalanced scheme, i.e. we pulse the 2 injection kickers with different amplitudes but we do not inject. We observe the life time of the stored beam versus its amplitude at the septum. Injection bumpers are still at 2 A as in 1.2.

According to previous tests (see 1.2 of this note) and operation, we will set HR.KFI31 (first kicker seen by the positron beam) to 12 kV and HR.KFI11 (last one seen by the positron beam) will be varied between 12 to 25 kV. In the same way as before, we will pulse the injection kickers and bumpers every 80 ms and measure the beam life-time versus HR.KFI11 amplitude. On the beam, the resulting betatron oscillation amplitude at the septum is given by the difference between the 2 kicks, as they are at a 2 π distance in betatron phase space. In table 3 one find the results of our measurements. On the first line we have written ranges because between 11 to 21 kV on HR.KFI11 there is no effect on beam life time. For the kicker calibration we have used the usual factors disregarding the calibration correction found in 1.2 .

Table 3: Beam life time with varying betatron oscillations HR.KFI31 = 12 kV

HR.KFI11 (kV)	Oscillation ampl. (mm)	life time (in s)	Clearance calc. from HR.KFI11
11 to 21	1.6 to 14.5	>3000	25.5 to 10.40
22.0	16.1	570	8.7
23.0	17.7	510	7.1
24.0	19.3	330	5.4
25.0	20.9	2	3.7

We can compare qualitatively these results to the results of 1.2 in table 2 , we can see that we have now a non "infinite life time" if the beam passes at 19.3 mm of the slow bumped closed orbit . This is due to 2 facts

1. Here we have an oscillation and we cut a ring in the transverse phase space in place of a segment

2. Due to oscillations, we have a blow up of the beam which is not damped enough between 2 shots (60 ms damping time and 80 ms between kickers shots) and the distribution of it must be far from a Gaussian.

On the other hand, we can say that with 21 kV i.e. 14.5 mm of horizontal oscillation, the dynamic aperture is not a limiting factor . It must be larger than 27 π 10^{-6} rad.m if we use as amplitude 14.5 mm plus 4 x σ of the beam.

2. Studies of the behaviour of the injected beam

In this chapter we will use a positron beam coming from LIL-W. To avoid errors arising from the contribution of $\Delta p/p$ to the betatron injection process, we limit the momentum spread to $\pm$ 0.5% by collimation at slit HIP.SLT22 in the LIL - EPA transfer line. The injection will be set first on axis, i.e. without residual oscillations to find optimum conditions.

As in the previous chapter injection bumpers will be set at 2 A, providing a 14.8 mm closed orbit bump at the septum.

2.1 Injection efficiency versus injected beam oscillation

No trapping will be done during these measurements. The RF cavity in EPA is OFF. Injection efficiency η_{inj} is defined as the ratio of the number of e^+ seen in HR.UMA11 at the 10th turn after injection to the number of particles seen in HIP.UMA22, last detector in LIL - EPA transfer line.

With axial injection, in this series of measures the best η_{inj} was 91% with HR.KFI11 = 30 kV and a residual horizontal oscillation amplitude X_{oscill} of 3 mm due to the 30 kV limit in HR.KFI11 (pushed this year to 35 kV).

The measurements are summarized in table 4 and drawn on figure 3.

Table 4: Injection Efficiency versus HR.KFI11, HR.KFI31 = 0 kV, HR.BSW = − 2 A

KF11 kV	η_{injc} %	X_{oscill} at SMH33 mm	clearance from beam to HIP.SMH33 mm
30	91	3.0 mm	22.5 mm
25	90	11.0 mm	14.5 mm
20	80	19.1 mm	6.4 mm
18	77	21.3 mm	4.2 mm
16	65	25.6 mm	0
14	46	28.8 mm	−3.3 mm
12	21	32.0 mm	−7.5 mm

Using figure 3, we guess the range of HR.KFI11 producing at the beginning a few percents of loss, and at the end driving to a 50% loss. It corresponds to half the size of the mismatched incoming beam , oscillating in the machine and scraping on the septum. This range is shown in figure 3. The accuracy is not very good but gives a value of 10 to 11 kV corresponding to 16 to 17.8 mm of beam envelope radius yielding with $\beta_x = 13.65\,m$ at HIP.SMH33 to $\varepsilon_x = 19$ to $23\ \pi 10^{-6}$ rad.m which is about 4 times the expected positron emittance.

If the injected beam had the same aspect ratio in phase space as the stored beam, its ε_x would be $19-23\pi\ 10^{-6}$ rad.m . Since the positron linac emittance is expected to be $5\ \pi\ 10^{-6}$ (= acceptance of LILW section 25/26), we conclude that the beam is horribly mismatched. This is in good agreement with 1987 measurement of $\varepsilon_x = 21\ \pi\ 10^{-6}$ rad.m done with HR.SLH11 (PS/LPI Note 87-33), showing that the beam was not adapted as planned at design stage.

2.2 Accumulation efficiency versus residual oscillation of the stored beam

The accumulation efficiency η is the ratio of the number of particles accumulated in EPA, measured with a DCCT (HR.TRA83). The incoming number of particles is measured in HIP.UMA22 (magnetic pickup and integrator) in the LIL − EPA transfer line. As these measurements are made with very different electronic systems, absolute mesurements are difficult and we will use relative variation of η with respect to the best value. The RF voltage was set to 40.0 kV.

2.2.1 Variation of HR.KFI11

On figure 4 one can see typical accumulations in one bunch every 80 ms with HR.BSW = – 2A, HR.KFI31 = 12 kV and HR.KFI11 varying from 16 to 29 kV. the reference case is the one with 27 kV. The best initial accumulation efficiency under these conditions lies between 72 to 90% depending on UMA22 estimation (analolg or digital) still with $\frac{\Delta p}{p} \leq 0.5$ %. The variation of $\frac{\eta}{\eta_{max}}$ versus HR.KFI11 is shown in table 5 and on figure 5.

Table 5

Relative efficiency of accumulation versus injection kicker amplitude

HR.KFI11 (kV)	$\frac{\eta}{\eta_{max}}$	Stack oscill. amplitude (mm)	Incoming beam oscillation (mm)
16	42	6.4	25.6
18	62	9.7	21.3
20	76	12.9	19.1
22	97	16.1	15.9
24	100	19.3	12.7
26	96	22.6	8.6
27	95	24.2	7.8
28	52(?)	25.8	6.2
29	32(?)	27.4	4.6

The curve on figure 5 can be explained (photo 1 and 2 of figure 4)

1. For HR.KFI11 increasing from 16 kV to 22 V, the increase of accumulation efficiency is linear . We infer that the loss in this range is from the incoming beam because we know that no loss occurs from stack when its amplitude of oscillation is less than 19.3 mm as shown under 1.3. Considering 2.1 too, we have the confirmation that for an incoming beam oscillation lower than 19 mm, most of it is injected (with the data of table 4, comparisons are difficult, because they only take into account the first 10 turns and not the following RF trapping).

2. Around 24 kV (see photo 3 of Figure 4) where is the best accumulation rate, the stack is not affected by the oscillation of 19 mm (cf. table 3) and the incoming beam is well injected with an oscillation of 10 mm to 12 mm. At this value, the horizontal betatron phase requirement for injection is s 18 π 10^{-6} rad.m or 15.5 mm radius at HIP.SMH33 ,which is consistent with the value found in 2.1 (cf. table 4).

3. Increasing to more than 26 kV (see photo 4 of Figure 4) the stack is performing oscillations larger than 22 mm. According to table 3, it will be scraped and with the intensity lost being proportional to the number of particles present, we will go to a saturation explaining the curvature of the accumulated current versus time.

The EPA injection design values are based on a perfect C.O., a current in HR.BSW of 1.875 A and voltages in HR.KFI11 and 31 equal to 15 kV . This is a balanced injection scheme , because the stacked beam do not oscillate and the oscillations are performed only by the incident beam. It requires for the injection process 85 π 10^{-6} rad.m. In this case, the incident beam is around 64 mm inwards the axis of the vacuum chamber and has a radius of 5 mm.

In our case with the C.O. of -7.7 mm at HIP.SMH33 we are forced, with the values of 2 A choosen for HR.BSW, o lower HR.KFI31 to 12 kV to avoid the injection septum scraping the stack. As the incomming beam has not the upright ellipse needed, it has to be withdrawn from the inner septum edge at around 73 mm inwards from the axis of the vacuum chamber, needing more injection kick with HR.KFI11 (24 kV). The kick of HR.KFI11, will not only put the stack back to the bumped C.O. but will induce an oscillation of the same amplitude and opposite phase to the one used to bring the stack close to the injection septum just before injection. Now the stack oscillate at the limit of injection admittance as well as the incoming beam: this is an unbalanced injection scheme.

2.2.2 Variation of HR.KFI31

This is a cross-check of 2.2.1 measurements. We set HR.KFI11 (which affects the stored and the injected beam) to 24 kV giving a maximum injection efficiency for the incoming beam. HR.KFI31 which only effects the stored beam will be varied from 12 to 16 kV. Figure 6 shows the photo of accumulation with HR.KFI31 at 14, 15 and 16 kV.

At each shot of the HR.KFI31 a segment will be cut in the transverse phase space from the stored beam by HIP.SMH33. If we increase HR.KFI31, the stored beam will be cut more and more and we will go to saturation as in 2.2.1.

In table 6 we have summarized the main results. In col. 3 the saturation level is expressed as the ratio of the accumulated current at saturation, to the accumulated current at the first injection. Col. 4 in fact is the loss on the stack at equilibrium used for σ_x calculations. In col 5 and 6 we give the clearance for the stacked beam at first pass in front of the septum (i.e. in presence of the fast bump by HR.KFI31) and for the following passes.

Table 6

HR.KFI31 kV	Stack jump at HIP.SMH33 1st pass – mm	Saturation level	Percentage loss at saturation level	Clearance at HIP.SMH 33 1st pass – mm	Clearance at HIP. SMH33 other pass – mm	p	σ calculated mm
14	22.6	6.3	15.9	2.9	9.4	1.0	2.9
15	24.2	3.3	30.3	1.3	11.0	0.5	2.6
16	25.8	2.1	47.6	∼0	12.6	–	ind.

If we look at figure 6 we can try to have an estimation of the stored beam emittance after 80 ms of damping. If we compare the clearance available at first pass (col. 5 of table 6) and for oscillation (col. 6 – table 6) we can conclude that losses are due mainly to the first pass. From the losses, using formula (5) and graphic interpolation (see figure 7) we can deduce a clearance in terms of $p = \text{clearance} / \sigma_x$ (see column 7 of table 6) and by knowing p and the value of the clearance , access to σ_x shown in col 8 which will be the σ of the beam after 80 ms of damping. These measurements are obviously not very accurate but are consistent between each other. For comparison equilibrium horizontal emittance has a $\sigma_x = 1.17\,mm$.

Conclusions

The behaviour of the beam is well understood, and in particular the impossibility where we are now of injecting with a balanced scheme, which is linked to the incomming beam characteristics and to the C.O. and the excessive bumps. It is obvious, for having EPA in good order, even if our performances are correct, that the C.O. has to be corrected . Modifications of the injection settings taking into account the distorted C.O. at injection septum, will be tried and checks performed .

The injected beam, as seen in previous studies is far from the right matching and some suspicion exists on its position at the output of the injection septum. Proper matching has to be done and checks on beam position performed during studies. It has to be noted that in our machine the quad at the end of LILW foreseen for the matching of LILW to EPA has an insufficient range. The matching section at the beginning of LILW FODO will have to be used until a technical solution for a matching section between LILW and EPA has been found.

With the beam lifetime we have found good agreement between measurements and slow bumps (HR.BSW) calibration. With the fast bumps calibration, a discrepancy of 5% has been seen. The possible origin, amplitude or timing mistuning will have to be identified .

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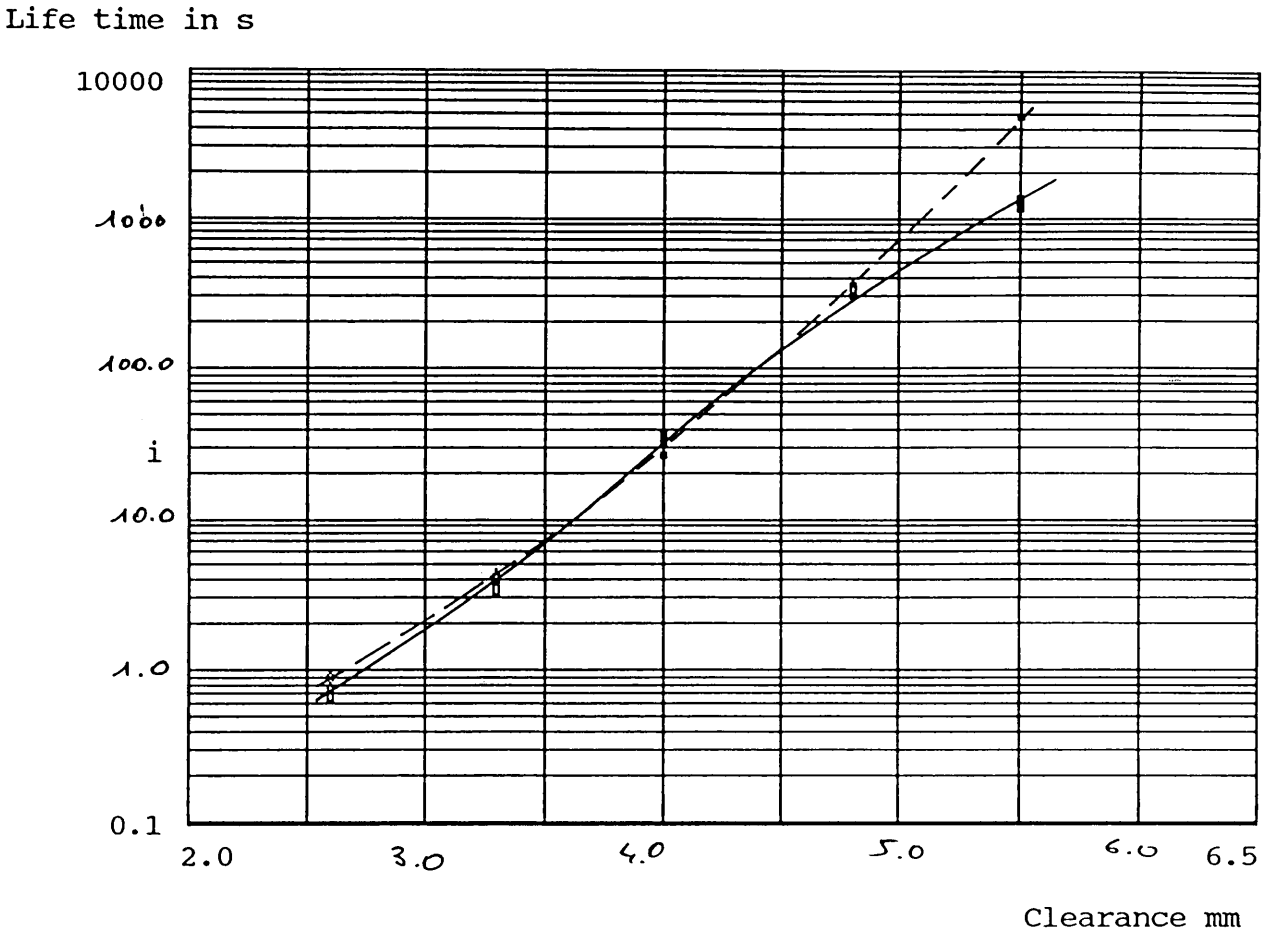


Figure 1:

Life time of stacked bumped beam versus clearance at HR.SMH33

Squares = measured life time in s _____

Diamond = theoretical life time in s – – – –

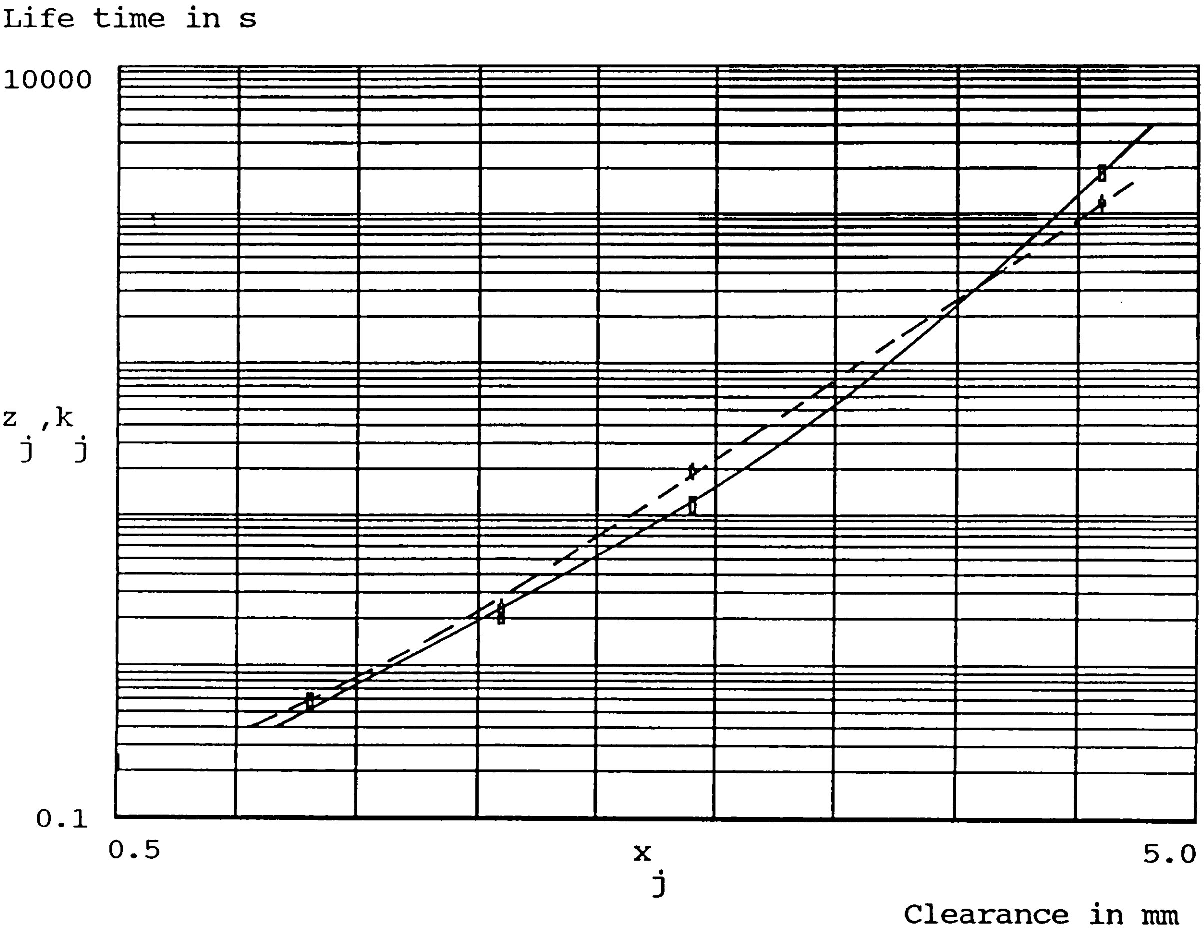


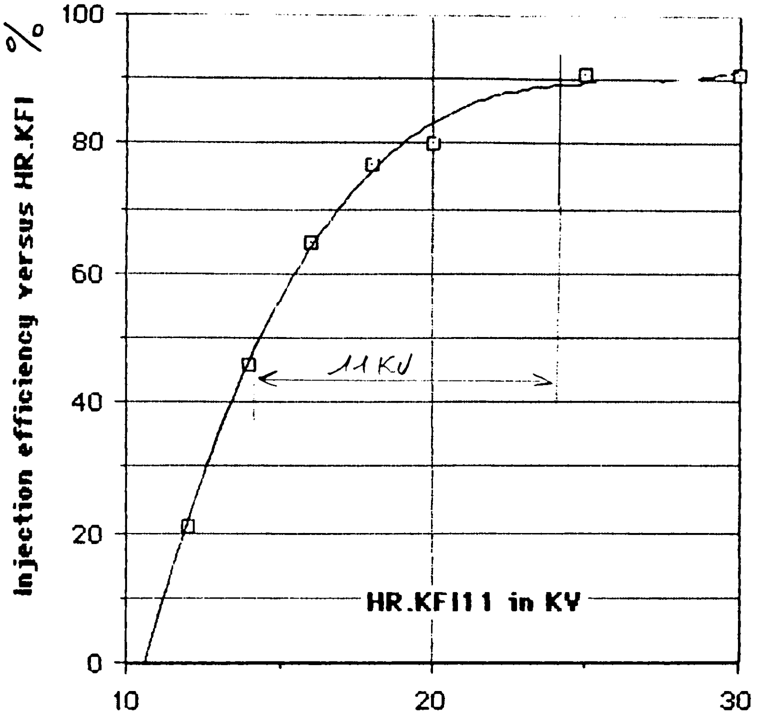
Figure 2:

Life time of kicked beam (fast localized bump produced in the injection kickers)

versus corrected clearance at HIP.SMH33

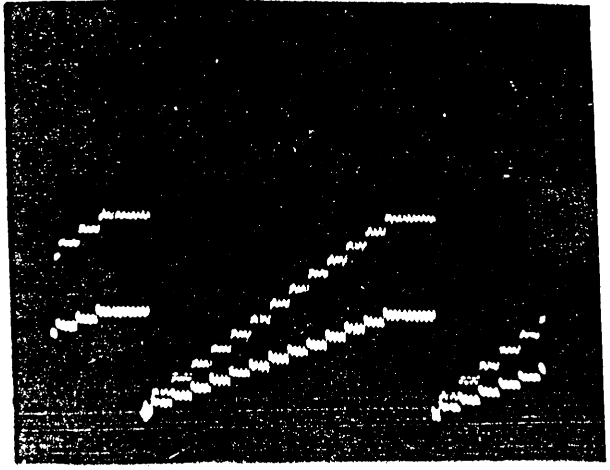
Squares: measured data ____

Diamond: calculated data – – – – –

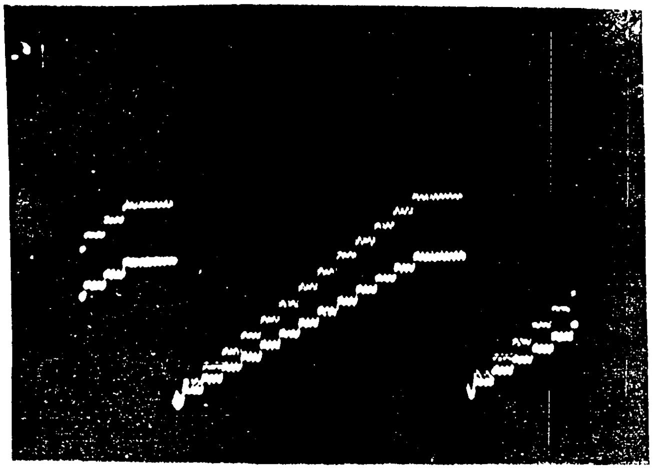


Injection efficiency versus HR.KFI in KV

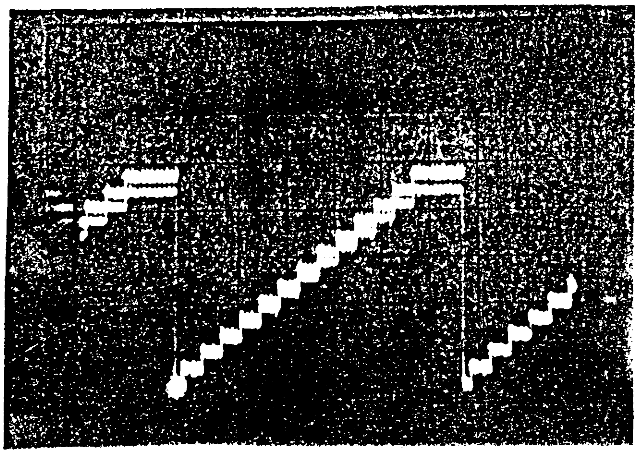
Figure 3



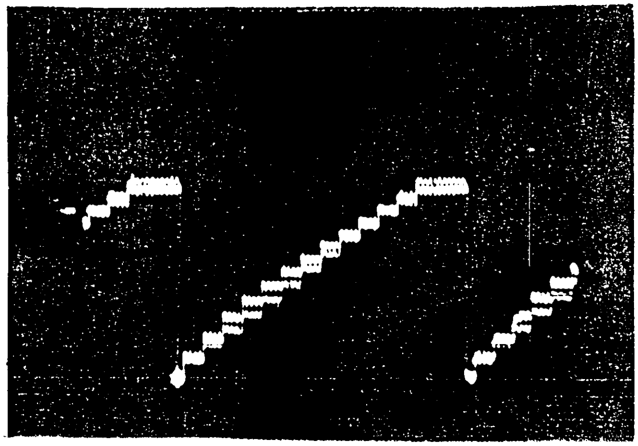
HR.KFI11 = 16 kV



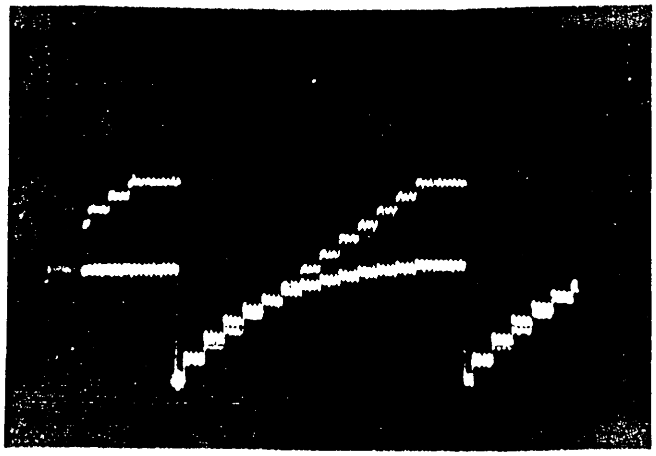
HR. KFI11 = 18 kV



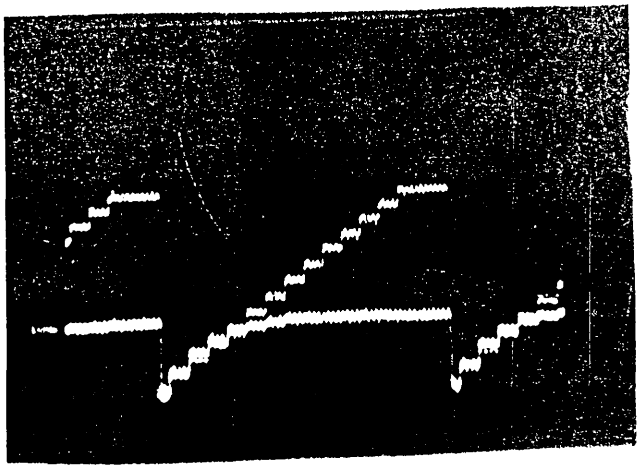
HR. KFI11 = 22 kV



HR. KFI11 = 27 kV



HR. KFI11 = 28 kV

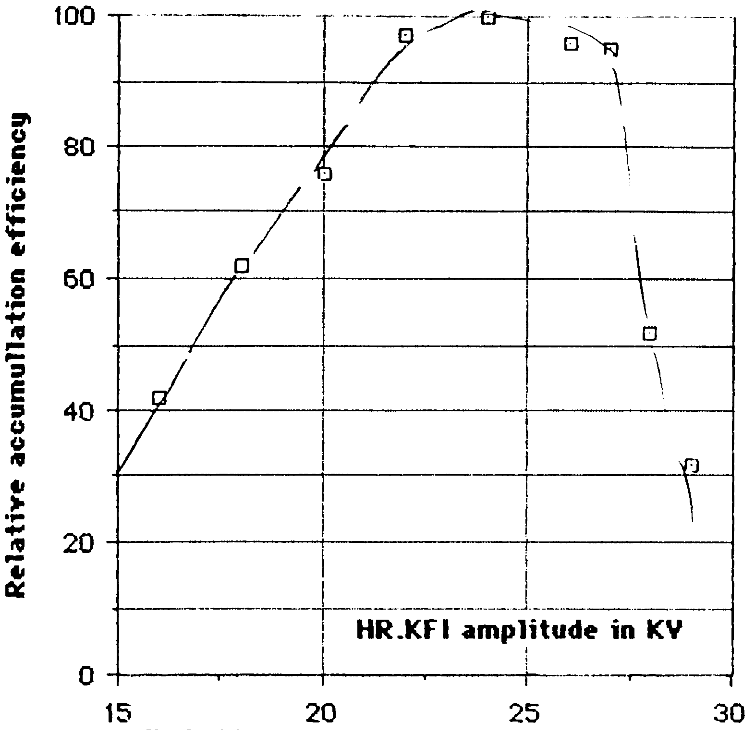


HR. KFI11 = 29 kV

Figure 4

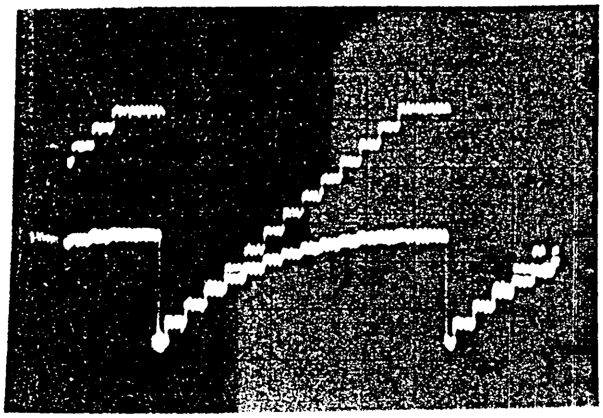
Typical accumolation of e^+

HR. BSW = -2 A HR. KFI 31 = 12 kV
1 injection every 20 ms
HR. KFI11 from 16 to 29 kV

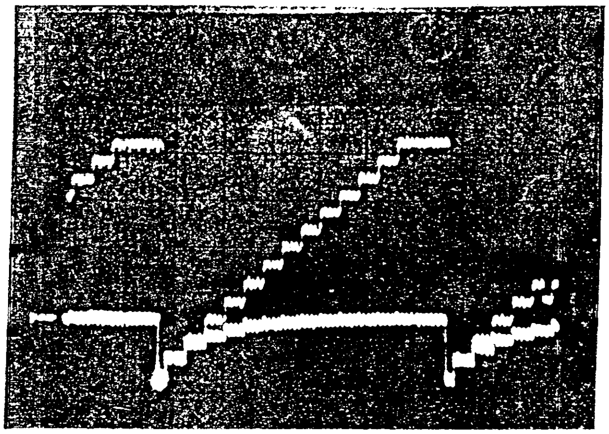


Relative accumulation efficiency
versus HR.KFI amplitude

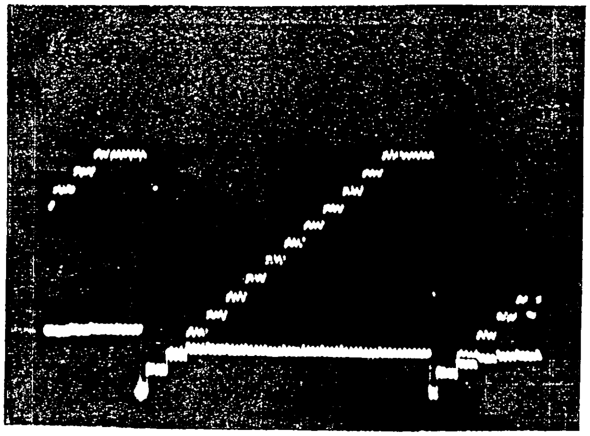
Figure 5



HR KFI31=14kV



HR. KFI31=15kV



HR.KFI31=16kV

Figure 6

Saturation of accumulation versus HR.KFI31
For HR.KFI11= 24kV HRBSW=-2A
1 injection every 80 ms