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Decay Rates and Average Luminosity of a B-Factory in the ISR Tunnel

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Abstract

The different effects contributing to the decay of the electron and positron beam are discussed and the coupled differential equations describing this decay in an asymmetric B-factory are given. The effect of the vacuum pressure rise by gas desorption owing to synchrotron radiation is taken into account.

These equations can be solved numerically and the average luminosity can be calculated as function of the running time T for data taking with the filling time F as parameter. The proper choice of T for a given F can optimize the average luminosity.

Examples relevant for the B-factory in the ISR tunnel are given, taking into account the constraints of the LEP injector chain, which is proposed to be used also for this collider.

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Contents

1 Introduction

Recently CERN and PSI have investigated the possibility of building a B-meson Factory in the ISR tunnel (BFI) [1,2]. Electrons and positrons would be stored in separate rings and this collider facility could operate in either an asymmetric mode (3.5 GeV e^+ vs. 8 GeV e^-) or in a symmetric mode (5.3 GeV e^+ and e^-). The main goal and also difficulty for such a machine is to obtain a luminosity which is one or two orders of magnitude beyond the values reached with existing machines.

The subject of this note is to investigate the effects of beam decay and injector performance on the luminosity. The details of the injection process are given in the main report on BFI [1] and in the references quoted in it. Some parameters used in this report are slightly different from the final parameter list [1]. The reason is that this report is based on work done at an early stage when the BFI parameters were still evolving. This report is the corrected version of an earlier working document [3].

We have learned from a recent CALTECH report that F.C. Porter, CALTECH has been working along similar lines [4].

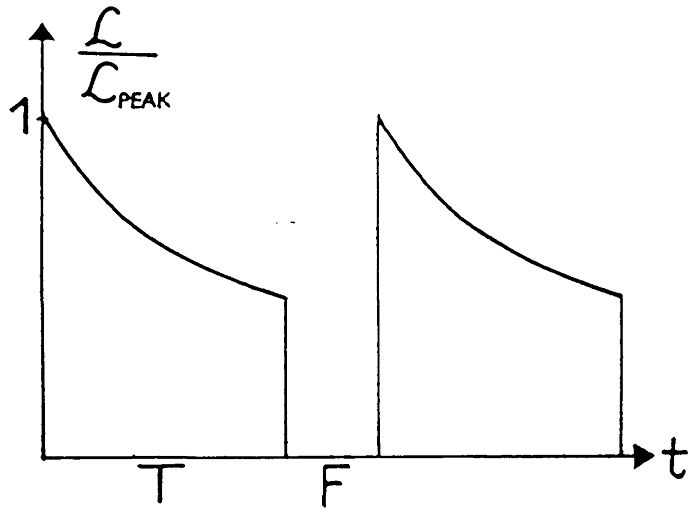

Figure 1: Luminosity decay in a collider (F=filling time, T=colliding time)

In a storage ring the beam currents decay after a fill due to particle losses caused by several effects. For fixed beam parameters the luminosity is proportional to the product of the intensities in the two beams and has thus an even stronger decay rate. To compensate this decay a periodic refill of the storage rings is clearly needed. For the experimentalist the key number is the average event rate and thus the average luminosity $\langle \mathcal{L} \rangle$, which depends on the useful running time T between two fillings and the filling time F, which cannot be used for physics. The filling time can be subdivided into the injection time for the two beams, the preparation time for switching off and on the detectors and for the final beam adjustments. A schematic curve for the time dependent luminosity is shown in fig. 1.

The filling time and thus the average luminosity depends on the filling mode of the storage rings. We distinguish the following main modes:

a) Refill: After a dump of the remaining stored particles the rings are completely refilled.

b) Topping-up: After each running period the circulating beams are supplemented by injecting new particles to bring the luminosity back to its peak value. This mode reduces the filling time especially for relatively short running times. It is the preferred mode of operation.

c) Continuous filling: The beam losses are compensated by a "quasi continuous" injection of new particles. It can be shown that the injectors can provide the necessary injection rate (see section 3). However, it is not clear whether this continuous filling mode is acceptable for BFI. Since injection with the beams in collision that are close to the beam-beam limit is hardly conceivable, the beams must be separated in the interaction points in a time short to the injection interval ($5s$) embedded in the supercycle of the CERN Super Proton Synchrotron (SPS) and brought into collision again very quickly after injection. Whether the beam steering can be done with sufficient precision in this short time, and whether this periodic moving of the beams and the adding of the particles can be done with tolerable background for switched-on detectors, remains to be seen. For this reason a continuous filling is not examined in detail for the moment.

For given fill parameters one can optimize the ratio η of average to peak luminosity by an appropriate choice T_{opt} of the running time T. This ratio is given by the

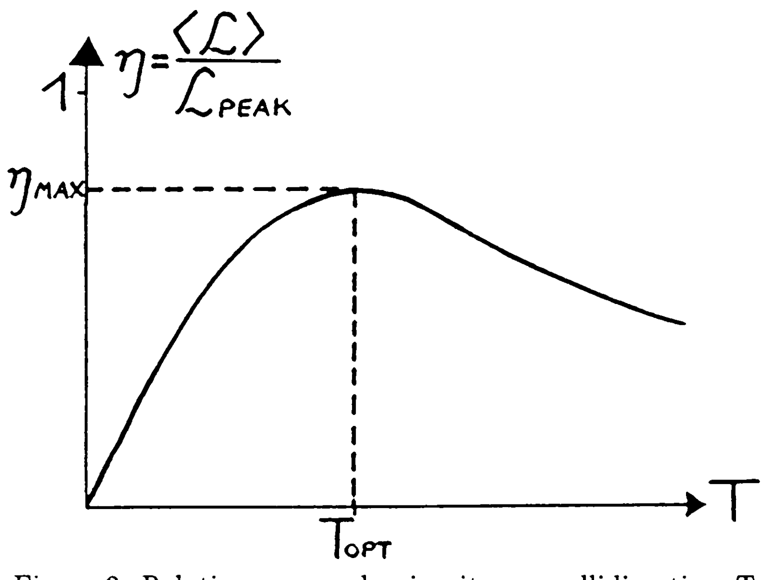

Figure 2: Relative average luminosity vs. colliding time T

formula:

$$\eta(T) = \frac{\langle \mathcal{L} \rangle}{\mathcal{L}_p} = \frac{1}{F + T} \int_0^T \frac{\mathcal{L}(\tau)}{\mathcal{L}(0)} \, d\tau \qquad (1)$$

A schematic curve for $\eta(T)$ is shown in fig. 2. The optimization of the average luminosity has been treated for LEP in three reports [5,6,7]. In [7] the effect of Beam-Beam Bremsstrahlung (BBB) and Beam-Gas Bremsstrahlung (BGB) on the beam decay was taken into account and an analytic solution was presented. We follow this approach but extend it taking into account that the currents and the beam energies can be very different in the two rings. Detailed numerical examples are worked out for a variety of combinations of operating modes and of filling modes of BFI.

2 Beam Decay

The following effects which can lead to beam decay have been considered:

- Beam-beam Bremsstrahlung (BBB) has the highest cross-section of all beam-beam effects and is nearly always the dominant of all effects leading to particle losses. For all cases considered, the corresponding beam lifetime is around 1-10 h.
- Beam-gas bremsstrahlung (BGB) due to a non-perfect vacuum leads to beam lifetimes in the range of 5-10 h.
- Quantum lifetime: Particle losses due to synchrotron radiation occur, when a particle loses so much energy by the emission of radiation quanta that it leaves the stable bucket area. The corresponding quantum lifetime is given by

  $$\tau_q = \frac{\tau_\epsilon}{2}\frac{e^r}{r}$$

  where

  $$\begin{aligned} \tau_\epsilon &= \text{energy damping time (a few ms)} \\ r &= \frac{1}{2}\left(\frac{\Delta}{\delta_\epsilon}\right)^2 \\ \Delta &= \text{rel. bucket (half) height}(\approx 4-5\cdot 10^{-3}) \\ \delta_\epsilon &= \frac{\sigma_\epsilon}{E} = \text{energy spread}\,(\approx 0.6\cdot 10^{-3}) \end{aligned}$$

  For the BFI the quantum lifetime τ_q is longer than about 100 h and can be neglected in all cases.
- Touschek effect: A collision of two particles inside the same bunch can lead to a transfer of transverse momenta into longitudinal momenta by Møller scattering. The particles can get lost, if the final energies after such a collision are outside the bucket [8]. Estimates for the asymmetric machines indicate that the Touschek lifetime for BFI is of the order of 20h for the low energy ring and much more for the high energy ring. This is valid for the lower luminosity option as well as for the high luminosity option [10]. Since the energy of the positrons is higher in the symmetric option, the Touschek lifetimes are very long in this case.

The Touschek effect can be neglected, except in the case of the positrons in the basic option, which have a relatively long lifetime (see table 2) and where the Touschek effect would reduce the lifetime by 25%. This should be taken into account in a more refined analysis at a later stage.

In our case we have the new situation compared to the calculations in [5,7] that the energies, and more important the currents, can be very different for the two rings. The BBB couples the intensities of the two beams and an analytic solution for the decay curves is not possible in general. Therefore we have written a computer code named LUMIFILL solving the general case of the beam decays and calculating the average luminosity for the two filling modes "refill" or "topping-up" (see chapter 5 for the details). We assumed that the beam cross-section at the interaction point would be constant during a physics run. Although we do not consider it for this report, we point out that a higher average luminosity would be obtained, if the cross-section of the beam were gradually and appropriately reduced during a physics run keeping the beams always close to the beam-beam limit. This has been done in ADONE and would make the luminosity decay slower [6].

2.1 Beam-beam bremsstrahlung

The cross section for particle losses due to beam-beam bremsstrahlung

$$e^+ + e^- \longrightarrow e^{+\prime} + e^{-\prime} + \gamma$$

was computed with the formula given in [11]:

$$\sigma_{bb} = \sigma_0 \, f(\gamma, \Delta) \tag{2}$$

with

$$\begin{aligned}
\sigma_0 &= \frac{16}{3} r_e^2 \, \alpha = 3.1 \cdot 10^{-27} cm^2 \\
f(\gamma,\Delta) &= [2\ln(2\gamma) - 0.5][\ln\frac{1}{\Delta} - \frac{5}{8}] + 0.5\,[\ln\frac{1}{\Delta}]^2 - 0.8\ln\frac{1}{\Delta} - 0.2 \\
\Delta &= \text{relative bucket (half) height } (\approx 0.4 - 0.5\,\%) \\
\gamma &= \frac{E}{mc^2} = \text{relativistic factor}
\end{aligned}$$

This cross section depends very weakly on the energy and the bucket height. For all the cases considered we took thus a constant value $\sigma_{bb} = 0.3 \cdot 10^{-24} cm^2$ (This should be compared with the cross sections in the order of $10^{-33} cm^2$ for the processes to be investigated with this collider). The initial beam lifetime (see chapter 4) is given by

$$\tau_i = \frac{N_i}{n_x \sigma_{bb} \mathcal{L}} \tag{3}$$

N_i is the total number of particles in ring i and n_x is the number of interaction points. For the BFI case with $n_x = 2$ we have the numerical values

$$\tau_i = 9.2h \, \frac{I_i\,[A]}{\mathcal{L}\,[10^{33} cm^{-2} s^{-1}]} \tag{4}$$

I_i is the beam current in ring i and $\mathcal{L}$ is the initial luminosity. This formula shows, that the beam with the higher intensity (in our case the $3.5\,GeV$ e^+-beam) lives longer, because each BBB-event consumes one particle from each beam and the strong beam has more of them.

2.2 Beam-gas bremsstrahlung

The effect of the residual gas due to beam-gas interaction can be described by three parameters, the static pressure P_0 without beam, the dynamic pressure $\frac{dP}{dI} \cdot I$ due to gas desorption induced by synchrotron radiation and the k_{vac} value, which is the product of total pressure and lifetime. The energy dependence of $\frac{dP}{dI}$ and k_{vac} is neglected, since it is rather weak in the region we considered.

For the vacuum behaviour we assumed three cases (see table 1). The first one corresponds to the vacuum performance one expects after one year of operation, the second one is the ideal case of no beam-gas interaction and the third one is for the case of a rather poor vacuum as could prevail during startup.

The estimates for the values of P_0, $\frac{dP}{dI}$ and k_{vac} are based on the experience from LEP [12], taking into account the effects of BGB and inelastic scattering.

Case	P_0 $[nTorr]$	$\frac{dP}{dI}$ $[nTorr \cdot A^{-1}]$	k_{vac} $[nTorr \cdot h]$
N=normal vacuum	1.	1.	17.
E=excellent vacuum	0.	0.	—
P=poor vacuum	1.	10.	17.

Table 1: Vacuum parameters

2.3 Main ring parameters and initial lifetimes

For the calculations three cases of operation for the main rings were taken into account (see table 2). The first case is the performance of the machine with unequal energies which should be reached fairly early, while the second case corresponds to a machine upgraded for ultimate luminosity. The third case is for operation with equal energies of the rings[1]. In all cases two interaction points and a circumference of 963 m were assumed.

From the initial decay rates $\dot{Y}_i(0)$ of the relative populations, as defined in chapter 4 one can get the so called initial lifetimes $\tau_i = -\dot{Y}_i(0)^{-1}$. For the lifetime of BBB alone we take equation 4 and for BGB alone we take from table 1 the case of a normal vacuum. Combining BBB and BGB one gets for each ring the initial lifetime as

$$\frac{1}{\tau_i} = \frac{1}{\tau_{i_{BBB}}} + \frac{1}{\tau_{i_{BGB}}}$$

Since the luminosity is given by the product of the two populations Y_1 and Y_2 one

[1] The symmetric option presented in the final report [1] has a luminosity of $6 \cdot 10^{33}\,cm^{-2}s-1$ and higher beam currents.

obtains an initial luminosity lifetime τ_{lum} as:

$$\frac{1}{\tau_{lum}} = \frac{1}{\tau_1} + \frac{1}{\tau_2}$$

The initial lifetimes for the three cases are shown in table 2.

Case	1 (asym.)		2 (asym.)		3 (sym.)	
$\mathcal{L}\,[cm^{-2}s^{-1}]$	$1 \cdot 10^{33}$		$10 \cdot 10^{33}$		$4 \cdot 10^{33}$	
	e^+	e^-	e^+	e^-	e^+	e^-
E [GeV]	3.5	8.0	3.5	8.0	5.3	5.3
I [A]	1.28	0.56	2.62	1.15	0.69	0.69
τ_{BBB} [h]	11.8	5.2	2.4	1.1	1.6	1.6
τ_{BGB} [h]	7.5	10.9	4.7	7.9	10.1	10.1
τ_i [h]	4.6	3.5	1.6	1.0	1.4	1.4
τ_{lum} [h]	2.0		0.6		0.7	
$-\dot{I}$ [mA/min]	4.6	2.7	27	19	8.2	8.2

Table 2: Main ring parameters, initial lifetimes and initial current decay

3 Injector parameters

The LEP injector chain [9] is planned to be used as the BFI injector. It consists of the LEP Injector Linac (LIL) providing either positrons or electrons for the Electron-Positron accumulation ring (EPA). The Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) form the rest of the injector complex.

In the case of unequal beam energies (cases 1 and 2 in table 2), the BFI high energy ring will be filled with electrons of $8\,GeV$ using the chain LIL-EPA-PS-SPS-PS, while the low energy ring only needs LIL-EPA-PS to bring the positrons to $3.5\,GeV$. In the symmetric energy case, LIL-EPA-PS with an upgraded PS r.f.-system is used for both rings. There are various schemes for the operation of the injection chain, which differs in the number of bunches and the cycling pattern. The most favoured schemes are based on the use of 8 bunches in the PS and SPS. The present cycling time for lepton acceleration is $1.2\,s$ but with some changes also $0.6\,s$ is achievable. The operation of the chain can be dedicated to the injection in the BFI. We call this mode the "dedicated" or "fast filling" (F). As for LEP, the interleaved operation (I) with 4 or 8 lepton cycles between the proton acceleration cycle and a total cycle time of $14.4\,s$ is however the preferred mode. A more

EPA	$0.8 \cdot 10^{10}\, e^+\, s^{-1}$·bunch^{-1}, $11 \cdot 10^{10}\, e^-\, s^{-1}$·bunch^{-1}	8 bunches
PS	$5 \cdot 10^{10}\, e^+$ bunch^{-1}, $4 \cdot 10^{10}\, e^-$ bunch^{-1}	8 bunches
SPS	$1.6 \cdot 10^{10}\, e^-$ bunch^{-1} ($\sigma_z \leq 8\,cm$)	8 bunches

Table 3: Present production limits in the CERN injectors

detailed description of the BFI-injection can be found in a special note [13]. The present intensity limits are summarized in table 3.

EPA to PS PS to SPS	PS to SPS to BFI	Stacking in BFI
80 %	90 %	30 %

Table 4: Transfer efficiencies

Using the transfer efficiencies listed in table 4 one can calculate the corresponding upper limits for the stacking rates in BFI brought about by the downstream machines. They are summarized in table 5. One sees that for the 8 GeV electrons

Injector	Filling			
	Fast		Interleaved	
	e^+	e^-	e^+	e^-
	continuous cycles		2 cycles	2 cycles
EPA	42	>600	31	>100
PS	270	216	45	36
SPS	-	86	-	14.4
decay rate of case 2	-27	-19	-27	-19

Table 5: Present upper limits for average stacking rates $\dot{I}$ [mA/min] imposed by the machines in the injection chain. Cycles of 1.2 s in PS, SPS.

the SPS is the bottleneck due to its longitudinal instability, and we assume that the SPS will always run at its production limit. In the symmetric case the SPS is not needed, and the limit for the 5.3 GeV electrons is given by the PS. For the positrons the stacking limit would come from the present positron production of LIL determining the EPA stacking rate. An improvement of the LIL performance is possible (see section 5).

The last line of table 5 gives the current decay rates in case 2 (table 2). Since they are smaller than the minimum stacking rate in the dedicated mode, we conclude that the injector performance would be sufficient for "continuous" injection.

4 Differential equations for the beam decay

The decay rates for the two separate rings are given by the two differential equations

$$\begin{aligned} \frac{dN_1}{dt} &= \left.\frac{dN_1}{dt}\right|_{BBB} + \left.\frac{dN_1}{dt}\right|_{BGB} \\ \frac{dN_2}{dt} &= \left.\frac{dN_2}{dt}\right|_{BBB} + \left.\frac{dN_2}{dt}\right|_{BGB} \end{aligned} \tag{5}$$

with N_i the number of particles in ring i. The decay rates due to BBB can immediately be derived from the definition of the luminosity

$$\left.\frac{dN_1}{dt}\right|_{BBB} = \left.\frac{dN_2}{dt}\right|_{BBB} = -n_x\, \sigma_{bb}\, \mathcal{L}(0)\, \frac{N_1(t)\, N_2(t)}{N_1(0)\, N_2(0)} \tag{6}$$

where n_x is the number of interaction points, while the decay rates due to BGB are given by

$$\left.\frac{dN_i}{dt}\right|_{BGB} = \frac{-1}{k_{vac}} \left(\frac{e}{\tau_{rev}} \frac{dP}{dI} N_i^2 + P_0 \, N_i \right) \tag{7}$$

with e = elementary electric charge and τ_{rev} = revolution time. Substituting for N_i the relative populations

$$Y_i \equiv \frac{N_i(t)}{N_i(0)}$$

in (5) gives together with (6) and (7) the two differential equations

$$\begin{aligned} -\dot{Y}_1 &= A_{12} Y_1 \, Y_2 + A_{G1} Y_1^2 + B_G Y_1 \\ -\dot{Y}_2 &= A_{21} Y_1 \, Y_2 + A_{G2} Y_2^2 + B_G Y_2 \end{aligned} \tag{8}$$

with

$$\begin{aligned} A_{12} &\equiv \tfrac{n_x \sigma_{bb} \mathcal{L}(0)}{N_1(0)} \quad , \quad A_{21} \equiv \tfrac{n_x \sigma_{bb} \mathcal{L}(0)}{N_2(0)} \\ A_{G1} &\equiv \tfrac{1}{k_{vac}} \tfrac{dP}{dI} I_1(0) \quad , \quad A_{G2} \equiv \tfrac{1}{k_{vac}} \tfrac{dP}{dI} I_2(0) \\ B_G &\equiv \tfrac{P_0}{k_{vac}} \end{aligned}$$

The relative luminosity $l(t)$ is defined as $\frac{\mathcal{L}(t)}{\mathcal{L}(0)}$ and given by

$$l(t) = Y_1(t) \cdot Y_2(t) \tag{9}$$

Hence with (1) the ratio η of average luminosity to peak luminosity in terms of relative populations is given by

$$\eta(T) = \frac{1}{F+T} \int_0^T Y_1 \, Y_2 \, dt \tag{10}$$

An analytic solution of (8) and thereby a closed expression of (10) exists only in the two special cases where either $A_{G1} = A_{G2} = B_G = 0$ (no BGB=perfect vacuum) or $A_{12} = A_{21} = 0$ (no beam decay due to BBB). In the first case (without BGB) one can use the relation

$$\left.\frac{dN_1}{dt}\right|_{BBB} = \left.\frac{dN_2}{dt}\right|_{BBB} \tag{11}$$

due to the fact that every BBB-collision eats up one particle from each beam. With equation (11) one can reduce the two coupled equations in (8) to a single one of the type $-\dot{y} = Ay^2 + By$ and gets the result:

$$\begin{aligned} Y_1(t) &= \left[(1+r) \exp(\frac{t}{\tau r}) - r \right]^{-1} \\ Y_2(t) &= \frac{1}{r+1} (1 + rY_1) \end{aligned} \tag{12}$$

with

$$r \equiv \frac{N_1(0)}{N_2(0) - N_1(0)} \quad \text{and} \quad \frac{1}{\tau} \equiv n_x \sigma_{bb} \frac{\mathcal{L}(0)}{N_2(0)}$$

which leads to

$$\eta(T) = \frac{\tau\, r}{(F+T)(r+1)} \left[1 - \frac{\exp(-\frac{T}{\tau\, r})}{1 + r\,(1-\exp(-\frac{t}{\tau\, r}))}\right] \tag{13}$$

In the second case (no BBB) the coupling of the two equations vanishes and the solution derived in [7] is given by

$$Y_{1,2}(t) = \left[\left(1 + \frac{\tau_b}{\tau_{1,2}}\right) \exp(\frac{t}{\tau_b}) - \frac{\tau_b}{\tau_{1,2}}\right]^{-1} \tag{14}$$

with

$$\frac{1}{\tau_{1,2}} \equiv \frac{e}{\tau_{rev}} \frac{N_{1,2}(0)}{k_{vac}} \frac{dP}{dI} \quad \text{and} \quad \frac{1}{\tau_b} \equiv \frac{P_0}{k}$$

the corresponding η is given by equation (10), but we suspect that there is no analytical solution, except for the case $N_1(0) = N_2(0)$ as shown in [7].

In all other cases (8) can only be solved by numerical means. This is done in a new Fortran program LUMIFILL with a Runge-Kutta algorithm. With the results obtained with this algorithm for $Y_{1,2}$ the integral in (10) is evaluated. The curves of $Y_1(t)$, $Y_2(t)$, $l(t)$ and $\eta(T)$ are plotted versus time t respective running time T. The results obtained are the subject of the next chapter.

5 Results for the BFI collider

The computer code LUMIFILL was used to calculate the beam decays and the average luminosity for some typical cases of the BFI proposal. Table 2 shows the parameters of the cases 1,2,3 corresponding to different luminosities. The vacuum effects were taken into account as explained in chapter 2. As a reference we took "normal vacuum" (=N), but some calculations were done without vacuum effects as well (E=excellent vacuum). To see the effect of poor vacuum (=P) we run case 1 under these conditions. In cases 2 and 3, where the luminosity is highest, one has to have at least "normal vacuum", otherwise the beam decays too fast.

The average luminosity depends on the choice of the filling method, as explained in chapter 1 and 3. We have considered the filling modes "Refill" (=R) and "Topping-up" (=T) for the main ring. For the injector complex we took the "Interleaved" (=I) operation and the "Dedicated" or "Fast Fill" (=F) operation into consideration.

All computer runs are labeled with a code which is constructed in the following way:

```
Label= 1ERF0.6
       2NTI1.2
       3P| | |
       ||| cycle time
       |||operating mode
       ||filling mode
       |vacuum
       case
```

5.1 Specification of computer runs, selection of representative cases

Each run of the computer code LUMIFILL consists of two parts: First one has to specify a variety of parameters like the Luminosity $\mathcal{L}$, the static and dynamic pressure P_0 and $\frac{dP}{dI}$, the BBB cross section σ_{bb} and the stored currents I_1 and I_2. The program then calculates and plots the decay curves for the currents and the luminosity. Figures 3a, 3b, 3c show the result for the standard cases 1,2,3 with "normal" vacuum. Next one has to specify the filling process with: filling mode (refill or topping-up), the stacking rates $\dot{I}_1$, $\dot{I}_2$ and preparation time F_{prep} (assumed as 2 min). The code then calculates and plots the average to peak luminosity $\eta(T)$ and the filling time $F(T)$ as a function of running time T. The optimum running time T_{opt} to reach the maximum of η is also indicated on the plot. Figures 4a,b,c show $\eta(T)$ for our cases 1,2,3 with the filling time F as a free parameter. From all possible combinations of the above parameters we had to restrict ourselves to a few representative examples, which are summarized in table 6. The column with the improvement factor for e^+ shows the ratio between required and present positron production rate for LIL. The filling rates $\dot{I}$ are averages over the corresponding supercycle. The numbers below the arrows under $\dot{I}$ are the refilling times of the individual rings. In case of a refill, the first column labelled F gives the refilling time plus 2 min for detector manipulation; in case of topping-up, it is the time needed to replace the particles lost during T_{opt}, plus 2 min for the detector. All other columns are self explanatory.

5.2 Discussion of different cases

Case 1 (asymmetric, $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$):
With this luminosity long running times are possible. After 2 h we have 44% and after 4 h still 21% of the initial luminosity (Fig. 3a). Operation of the injector complex could proceed in the following way: The lepton cycles are left at 1.2 s and the LEP preinjector (=LPI consisting of LIL and EPA) is improved by a factor of 6.5 in order to have short filling times. In the "dedicated" mode topping-up is achieved in typically 6 min and even a complete refill is possible in 13 min. Average luminosity ratios are in the range of 60 to 80%. The effect of vacuum quality is illustrated in fig. 5a for refilling in dedicated mode. Without any improvement of LPI the refill time would increase to 39 min, which is too long. However, the routine performance with topping-up would be surprisingly little effected as seen in fig. 5c.

Also for the interleaved mode, the present LPI positron performance has to be improved by a factor 6.5. If this were not done, the positrons would have to be accumulated during the proton cycle and the refilling time of the positron ring would become 29 min instead of 15 min, which was judged to be too long. Table 6, however, shows both possibilities: the preferred case $pe^+e^+e^+e^+p....pe^-e^-e^-e^-p$ with LPI improved by a factor 6.5; the case $pe^+e^+e^-e^-p$ with e^+ collection during the p-cycles and LPI improved only by a factor 1.5. Please note that the time needed to refill both rings simultaneously and the effective injection rate (averaged over F) during topping-up is the same for both operation modes. The only difference is in the time needed to refill the positron ring alone. The refilling time of both rings together can be found under F in table 6 in the lines referring to refills. In the lines referring to topping up, the first F is the filling time pertaining to optimum running time T_{opt}; the second column labelled F refers to a running time of 2 h.

Since the performance with topping-up is very satisfactory and since the interleaved mode hardly interferes with the other uses of PS and SPS, this combination of filling mode and operating mode is the preferred one (Fig. 6b).

Case 2 (asymmetric, $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$):
With this high luminosity only short runs provide a good average luminosity. For example after 1 h the luminosity decayed already to 27% of its peak value (see fig. 3b) and the average luminosity drops to a 40-60% level (fig. 7a,b). For acceptable filling times the e^--cycles have to be shortened from 1.2 to 0.6 s and LPI needs an improvement by a factor of 13. In the interleaved mode the filling rates, being a factor 3 lower than in the dedicated mode, are comparable to the decay rates. The average luminosity drops somewhat compared to the dedicated mode as seen in fig. 8a and 8b, but remains competitive. Increasing the number of bunches in the PS and SPS from 8 to 16 could make the interleaved mode even more attractive with refilling times of about 20 min.

Case 3, (symmetric, $\mathcal{L} = 4 \cdot 10^{33} cm^{-2} s^{-1}$):
In this case the luminosity decays almost as fast as in case 2, but the stored currents are substantially lower. In addition, we do not need the SPS in this case and the filling times are thus shorter than in case 2 and an e^--cycle of 1.2 s is quite adequate (Fig. 9a and 9b pertain to the refilling mode). In the interleaved mode we take advantage of the accumulation of positrons over 10.8 s during the proton cycle. Improving LPI by a factor of 1.5 and operating with two e^+-cycles followed by two e^--cycles gives reasonable filling times of 10 to 20 min. (see fig. 10 a,b).

6 Conclusions

The CERN injector complex with LIL-EPA-PS-SPS gives acceptable filling rates for the BFI collider rings, provided that LPI is upgraded by an amount which depends on the case considered.

We developed a computer code LUMIFILL which calculates the decay rates for currents and luminosity, taking into account the dominating losses by Beam-Beam-Bremsstrahlung (BBB) and Beam-Gas-Bremsstrahlung (BGB). This code calculates as a function of running time T the average luminosity and filling time for a complete refill and topping-up.

The calculations have shown, that for the initial design goal of $10^{33} cm^{-2} s^{-1}$ for the luminosity useful run times are about 2 h or less, while for higher luminosities the physics runs should be shorter than about 1 h. Topping-up is the filling mode to be recommended, because the filling times are noticeably shorter and the average luminosity is higher. For long running times obviously the difference to a refill becomes smaller.

In the interleaved mode, the stacking rates are a factor 3 lower than in the dedicated mode, because the PS and the SPS can accelerate leptons only during the 4.8 s between two proton cycles, but the average to peak luminosity is nearly as good as in the dedicated mode. The most reasonable cases are underlined in the last column of table 6.

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Table 6 - Synopsis of numerical results

case	$L/10^{33}$ $\left[\frac{1}{cm^2 s}\right]$	I_1^+ [A]	I_2^- [A]	e+ Improvement factor of LIL (LPI)	I_1^+ [A/min]	I_2^- [A/min]	vacuum	filling mode	LABEL vacuum filling-case/mode/cycle	η_{max}	T_{opt} [min]	F [min]	for T = 2h: η	for T = 2h: F [min]	Figure
1) asym.	1	1.28	0.56	6.5	0.27 ↓ 5'	0.086 ↓ 6.5'	E	Ref. Ded.	1E RF 1.2	0.72	75	13	0.70	13	5a
							N	" "	1N RF 1.2	0.65	55	13	0.59	13	"
							P	" "	1P RF 1.2	0.51	32	13	0.36	13	"
							E	Top. Ded.	1E TF 1.2	0.86	29	3	0.75	5	5b
							N	" "	1N TF 1.2	0.81	22	3	0.62	6	5c
				1	0.042 ↓ 30'	0.086 ↓ 6.5'	N	" "	1N TF 1.2	0.75	21	5	0.59	14	"
				6.5	0.09 ↓ 15'	0.029	N	Ref. Int.	1N RI 1.2	0.51	88	36	0.50	36	6a
				1.5	0.045 ↓ 29'	0.014 ↓ 19.5'	N	Top. Int.	1N TI 1.2	0.75	21	5	0.59	14	**<u>6b</u>**
2) asym.	10	2.62	1.15	13	0.54 ↓ 5'	0.172 ↓ 7'	E	Ref. Ded.	2E RF 0.6	0.51	34	14	0.37	14	7a
							N	" "	2N RF 0.6	0.48	30	14	0.32	14	"
							E	Top. Ded.	2E TF 0.6	0.68	13	4	0.38	9	7b
							N	" "	2N TF 0.6	0.65	12	4	0.33	10	"
				13 (pe⁺.e⁺.e⁻.e⁻p)	0.18 ↓ 15'	0.057 ↓ 20'	N	Ref. Int.	2N RI 0.6	0.33	49	37	0.27	37	8a
							N	Top. Int.	2N TI 0.6	0.53	12	7	0.20	25	**<u>8b</u>**
3) sym.	4	0.69	0.69	3	0.13 ↓ 5'	0.216 ↓ 3'	E	Ref. Ded.	3E RF 1.2	0.57	31	10	0.41	10	9a
							N	" "	3N RF 1.2	0.54	29	10	0.37	10	"
							N	Top. Ded.	3N TF 1.2	0.69	13	3	0.38	7	9b
				1.5	0.09 ↓ 8'	0.072 ↓ 9'	N	Ref. Int.	3N RI 1.2	0.45	39	19	0.35	19	10a
							N	Top. Int.	3N TI 1.2	0.65	13	4	0.36	13	**<u>10b</u>**

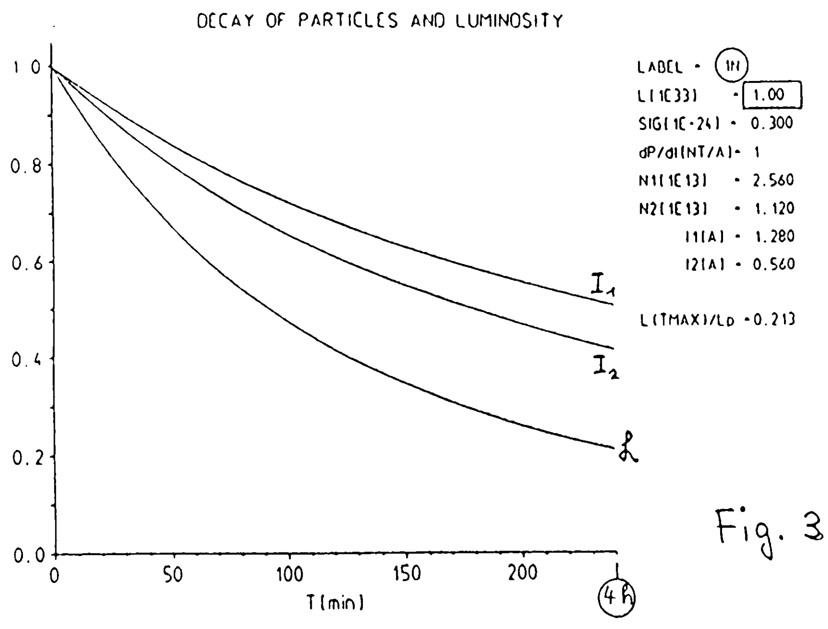

Fig. 3a

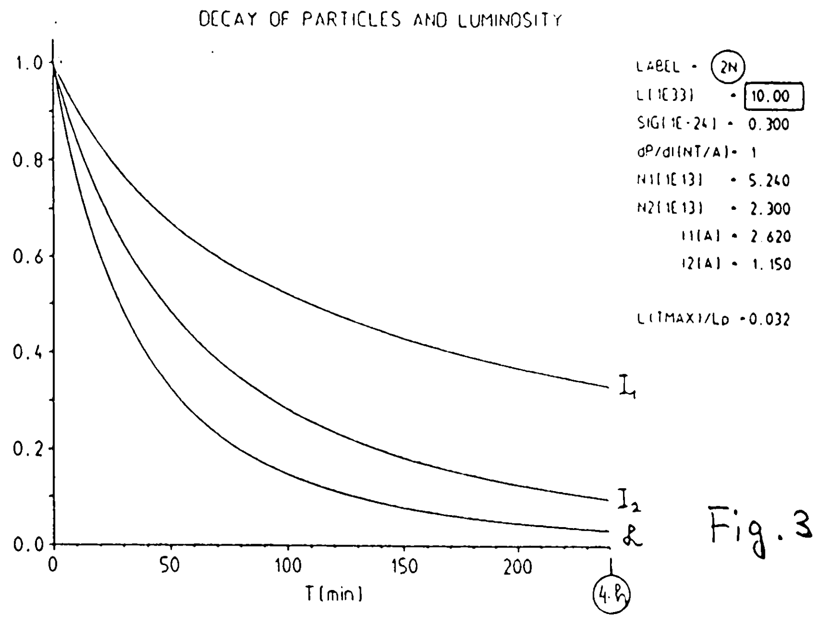

Fig. 3b

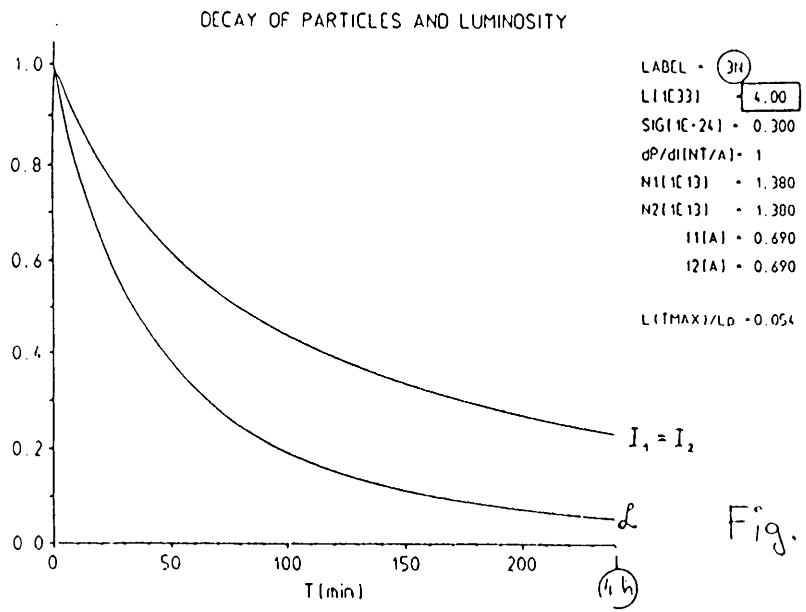

Fig. 3c

DECAY CURVES FOR CASES 1,2,3
WITH 'NORMAL' VACUUM (N).

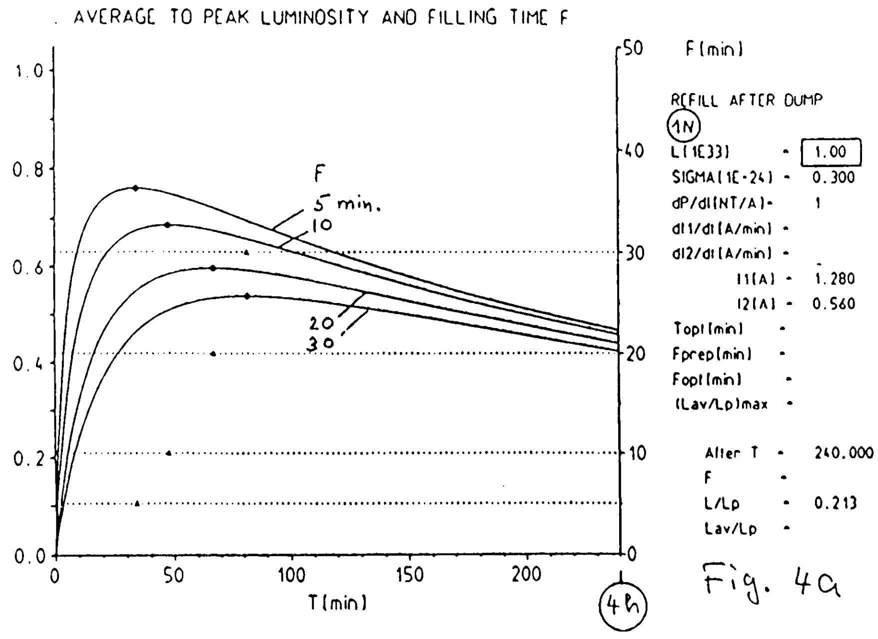

Fig. 4a

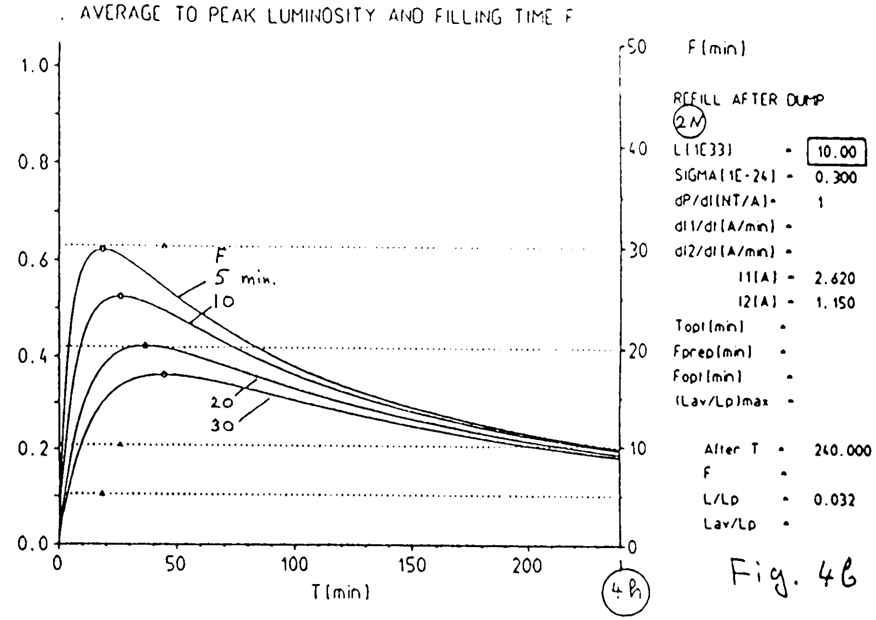

Fig. 4b

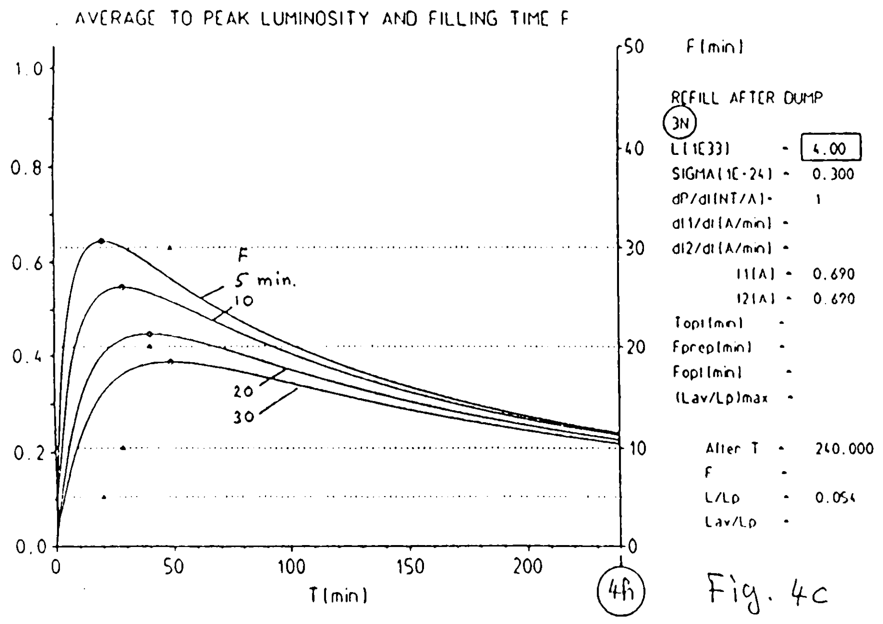

Fig. 4c

$\eta(T) = \bar{L}/L_{peak}$ = AVERAGE TO PEAK LUMINOSITY FOR CASES 1,2,3 WITH DIFFERENT REFILLING TIMES F.

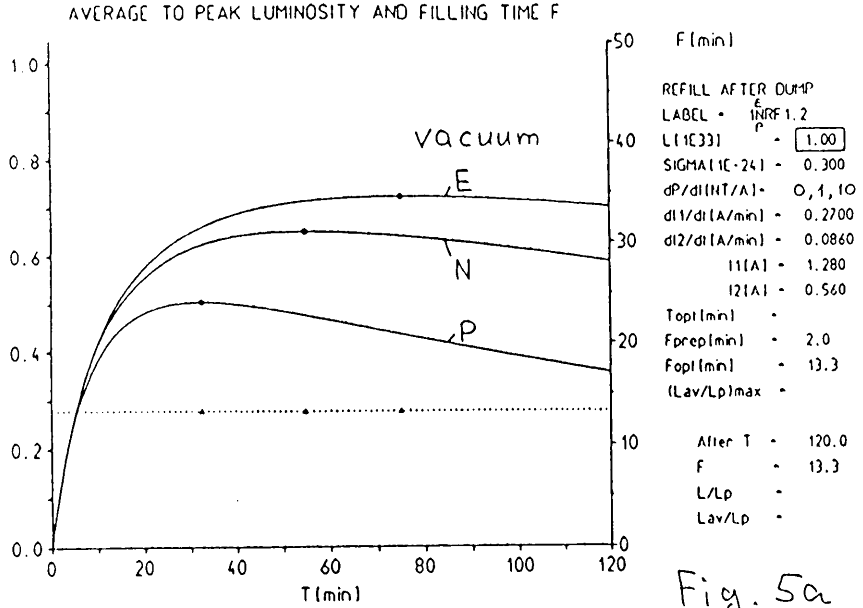

Fig. 5a

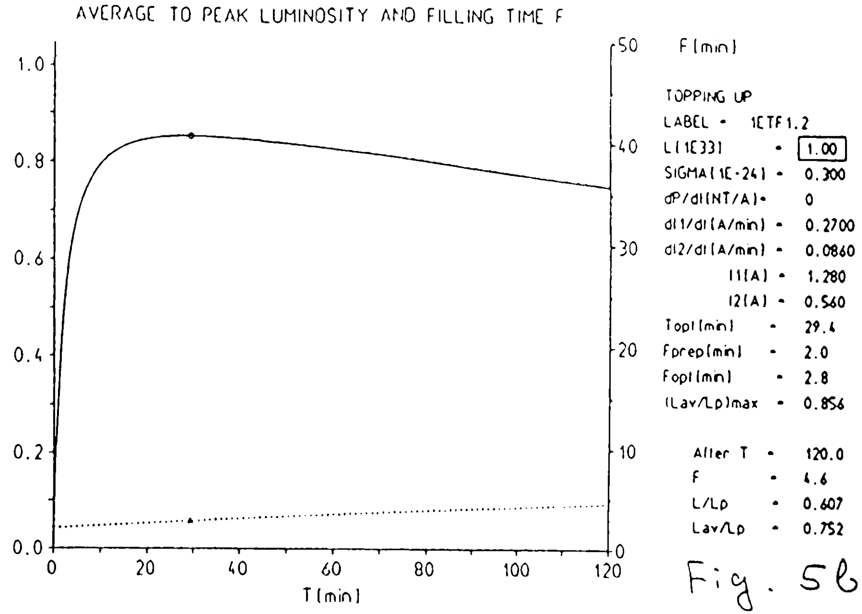

Fig. 5b

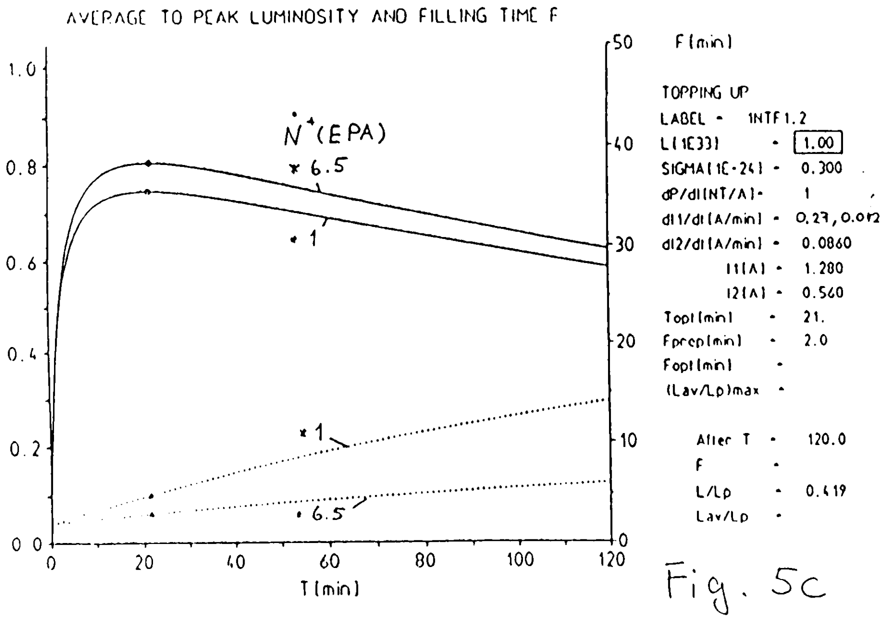

Fig. 5c

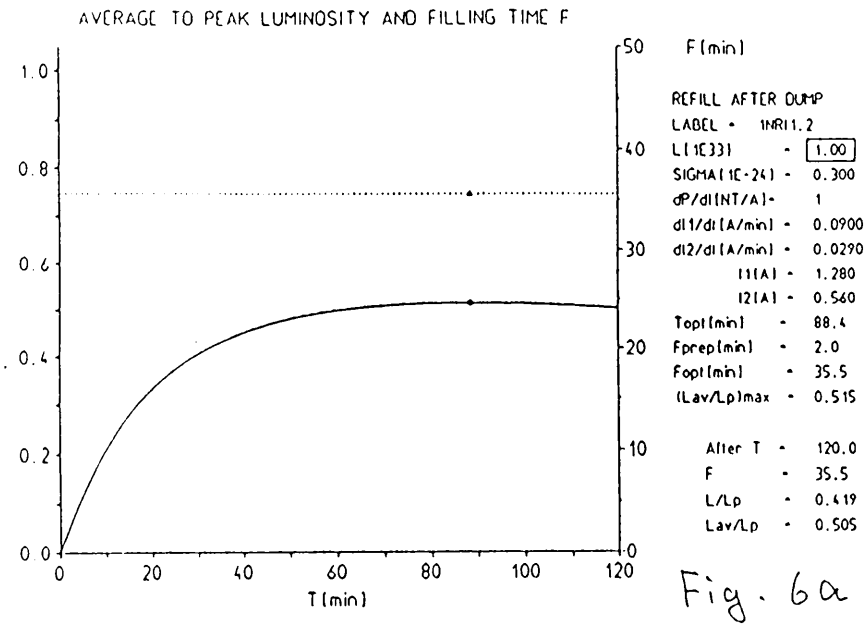
AVERAGE TO PEAK LUMINOSITY AND FILLING TIME F
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
T(min)
50
40
30
20
10
0
F(min)
REFILL AFTER DUMP
LABEL = 1NR11.2
L(1E33) = 1.00
SIGMA(1E-24) = 0.300
dP/dI(NT/A)= 1
dI1/dt(A/min) = 0.0900
dI2/dt(A/min) = 0.0290
I1(A) = 1.280
I2(A) = 0.560
Topt(min) = 88.4
Fprep(min) = 2.0
Fopt(min) = 35.5
(Lav/Lp)max = 0.515
After T = 120.0
F = 35.5
L/Lp = 0.419
Lav/Lp = 0.505

Fig. 6a

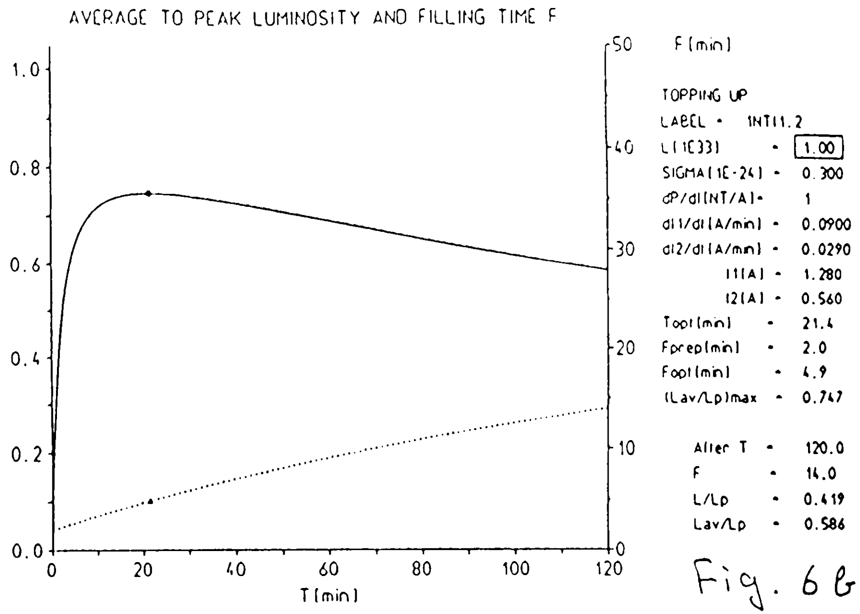
AVERAGE TO PEAK LUMINOSITY AND FILLING TIME F
1.0
0.8
0.6
0.4
0.2
0.0
0
20
40
60
80
100
120
T(min)
50
40
30
20
10
0
F(min)
TOPPING UP
LABEL = 1NT11.2
L(1E33) = 1.00
SIGMA(1E-24) = 0.300
dP/dI(NT/A)= 1
dI1/dt(A/min) = 0.0900
dI2/dt(A/min) = 0.0290
I1(A) = 1.280
I2(A) = 0.560
Topt(min) = 21.4
Fprep(min) = 2.0
Fopt(min) = 4.9
(Lav/Lp)max = 0.747
After T = 120.0
F = 14.0
L/Lp = 0.419
Lav/Lp = 0.586

Fig. 6b

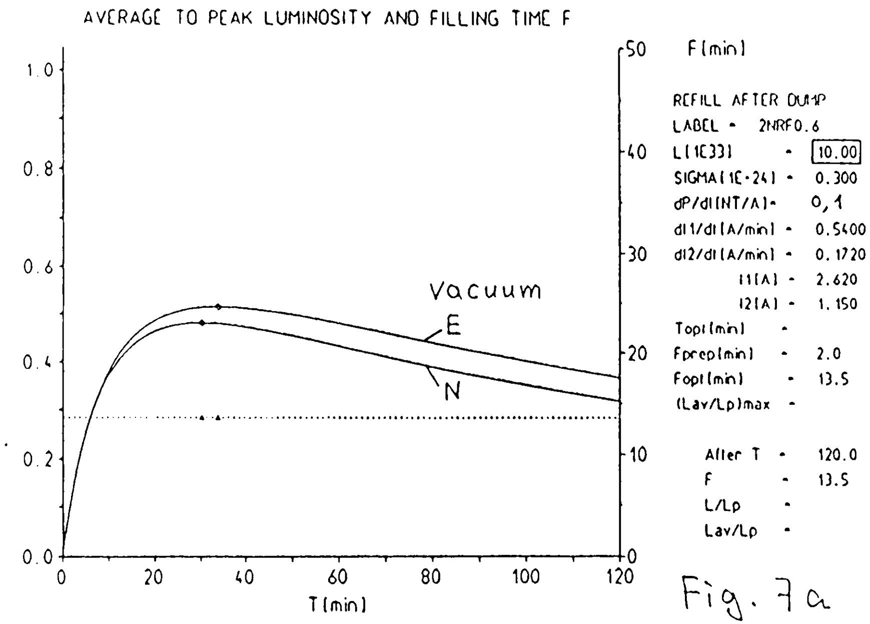

Fig. 7a

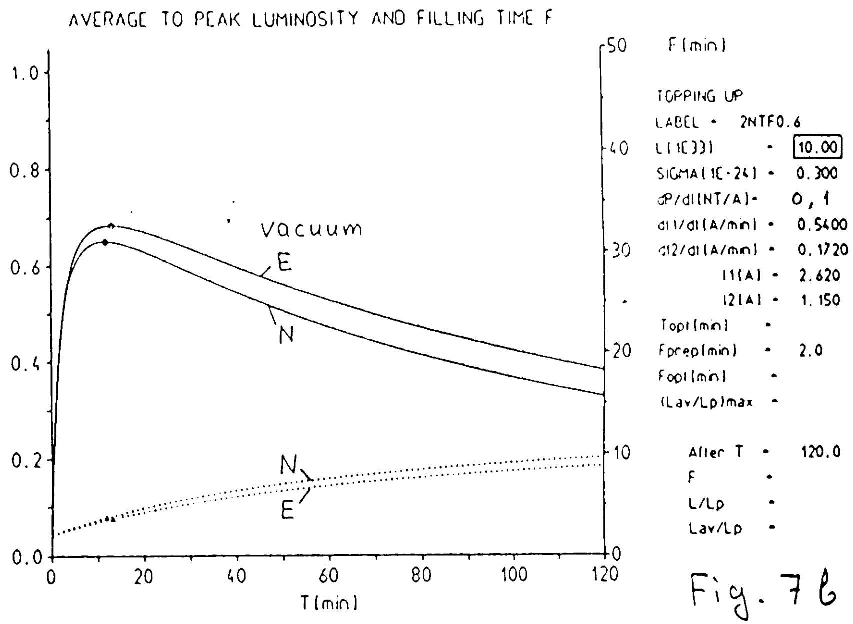

Fig. 7b

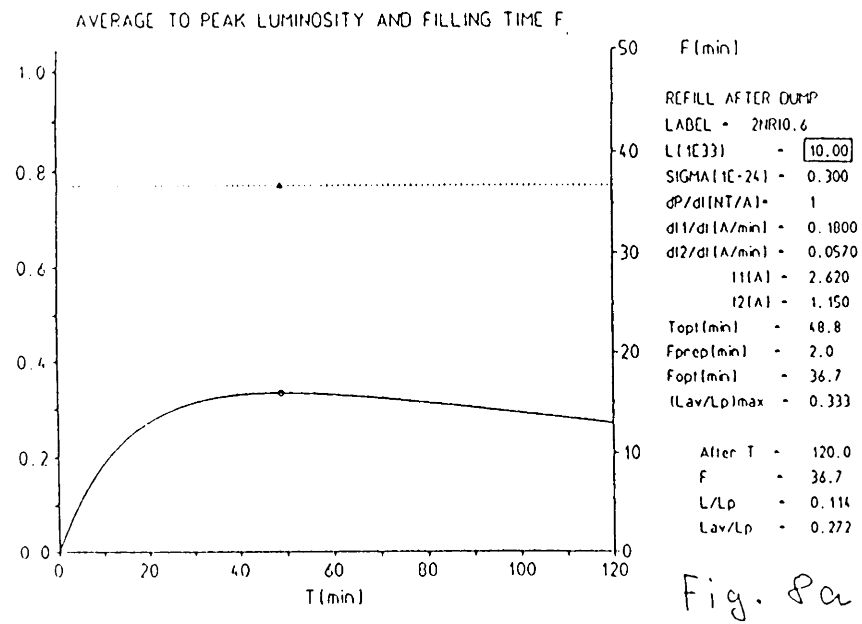

Fig. 8a

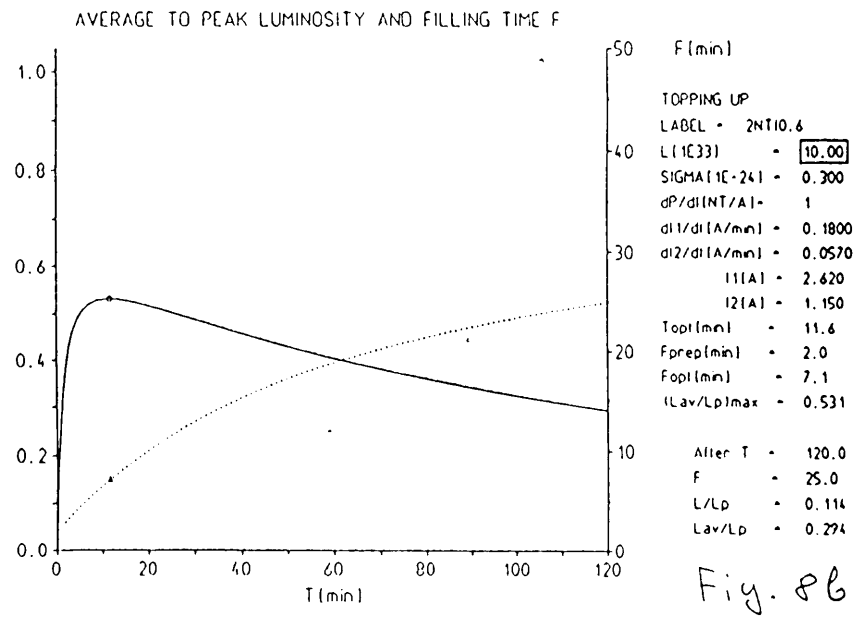

Fig. 8b

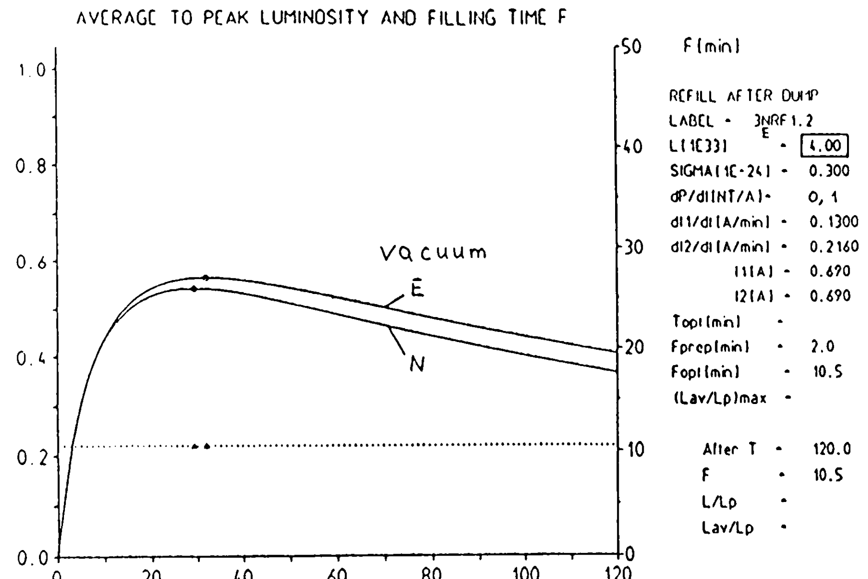

Fig. 9a

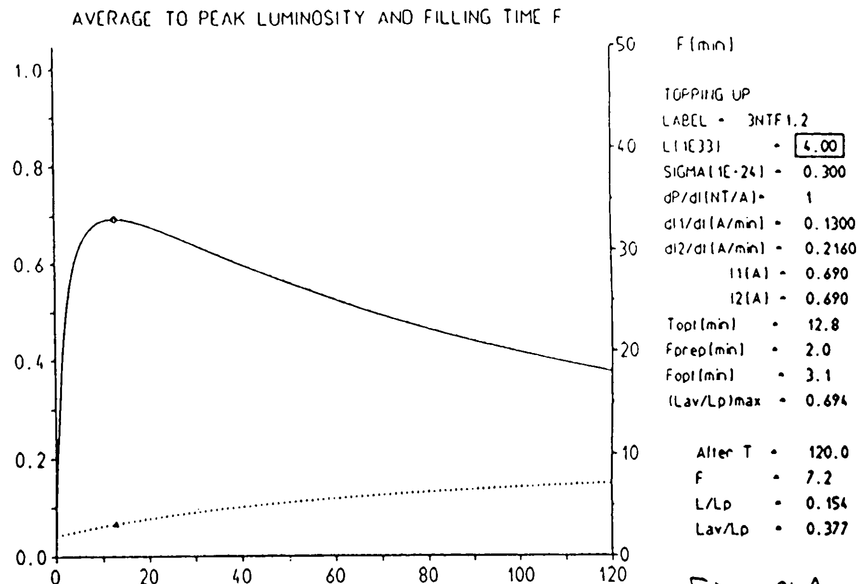

Fig. 9b

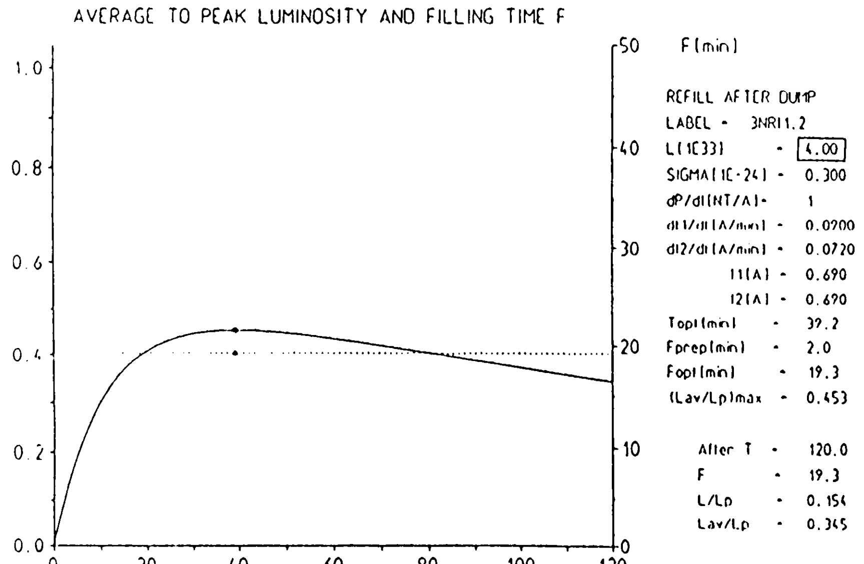

Fig. 10a

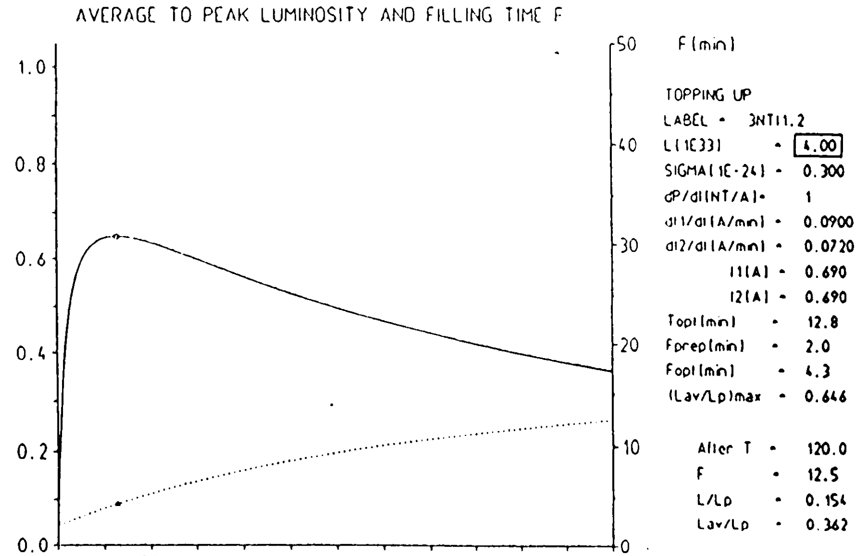

Fig. 10b