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DECAY RATES AND AVERAGE LUMINOSITY FOR THE BFI STORAGE RINGS

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1 Introduction

Recently CERN and PSI have established a study group, which investigates the possibility of building a B-meson factory called BFI in the ISR tunnel [1]. 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.

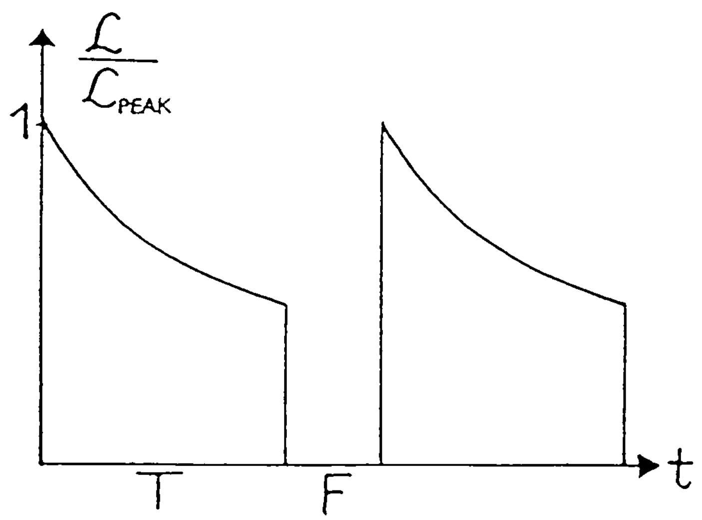

Figure 1: Luminosity decay in a collider (F=filling time, T=colliding time)

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 experimentalists 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 broken up into the injection times for the two beams, the preparation time F_{prep} 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.

c) Continuous filling: The beam losses are compensated by a "quasi continuous" injection of new particles during a supercycle of the PS-SPS complex. It can be shown that the injectors can provide the necessary number of particles per SPS supercycle in the interleaved mode, i.e. during the dead-time of the SPS between the proton cycles as is done for LEP. 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 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. η is given by the formula:

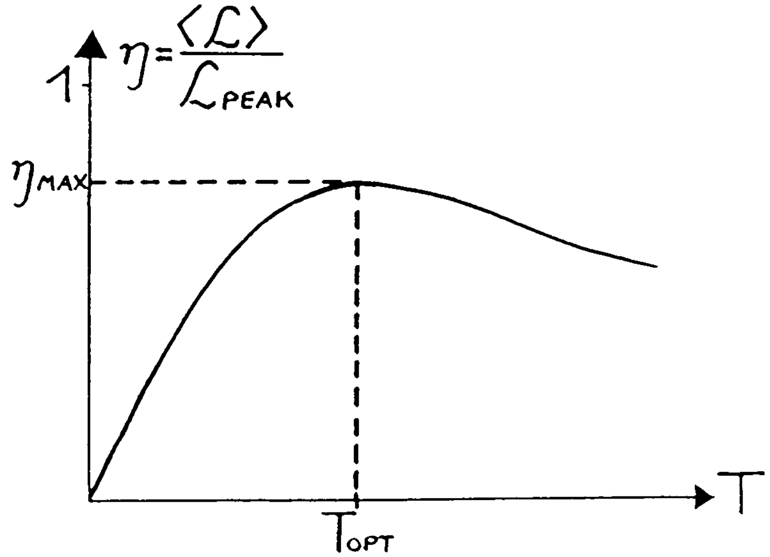

Figure 2: Relative average luminosity vs. colliding time T

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

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 [2],[3],[4]. In [4] 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.

For the BFI case we have looked at the following effects which can lead to beam decays:

- BBB has the highest cross section of all beam-beam effects and is the dominant off all effects leading to particle losses. For all cases considered, the corresponding lifetime is around 1-10 h. More details are explained in chapter 2.

- BGB due to a non-perfect vacuum is treated in chapter 3. Lifetimes for this effect are in the range of 5-10 h.

- Quantum lifetime: Particle losses due to synchrotron radiation occur, when a particle losses 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.

- Touschek effect: two particles inside the same bunch can exchange energy by Møller scattering. The particles can get lost, if the final energies after such a collision are outside the bucket [5]. Estimates indicate [6], 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.

Obviously BBB and BGB are the dominant processes. We have therefore neglected the quantum life time and the Touschek effect in our optimisation of the average luminosity.

In our case we have the new situation compared to the calculations in [2]-[4] 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 new 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 7 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 [3].

2 BBB 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 [7]:

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

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 the cases considered we took thus a constant value $\sigma_{bb} = 0.3 \cdot 10^{-24} cm^2$ (This is to compare with the cross sections in the order of $10^{-33} cm^2$ for the processes to be investigated with this collider). The initial lifetime (see chapter 6) is given by

$$\tau_i(0) = \frac{N_i}{n_x \sigma_{bb} \mathcal{L}(0)} \tag{3}$$

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

$$\tau_i(0) = 9.2h \, \frac{I_i \, [A]}{\mathcal{L} \, [10^{33} cm^{-2} s^{-1}]} \tag{4}$$

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.

3 BGB 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 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.

The estimates for the values of P_0, $\frac{dP}{dI}$ and k_{vac} are based on the experience from LEP [8], 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.	meaningless
P=poor vacuum	1.	10.	17.

Table 1: Vacuum parameters

4 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 after one year of operation, while the second case corresponds to a machine upgraded for ultimate luminosity. The third case is for operation with equal energies of the rings. In all cases two interaction points and a circumference of 963 m were assumed. The currents were taken from the latest parameter list [9].

From the initial decay rates $\dot{Y}_i(0)$ of the relative populations, as defined in chapter 6 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 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.

5 Injector parameters

The LEP injector chain is planned to be used as the BFI injector. This means in the cases of unequal beam energies (cases 1 and 3 in table 2) that the high

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

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 timetable. 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 $0.6\,s$ are 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). But also an operation interleaved (I) with the proton acceleration with 4 or 8 lepton cycles between the proton acceleration cycle and a total cycle time of $14.4\,s$ can be of interest. A more detailed description of the BFI-injection can be found in a special CERN report [10]. The present intensity limits are summarized in table 3.

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

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 limits for the stacking rates in the BFI colliders, which are summarized in table 5.

One sees, that for the 8 GeV electrons 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

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 limits for average stacking rates $\dot{I}$ [mA/min] in each BFI collider ring. Cycles of 1.2 s in PS, SPS.

electrons is given by the PS. For the positrons the stacking limit would come from the present EPA performance.

6 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 = electric charge and τ_{rev} = revolution time. Substituting N_i with 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

$$\begin{aligned} -\dot{Y}_1 &= A_{12}Y_1\,Y_2 + A_{G1}Y_1^2 + B_GY_1 \\ -\dot{Y}_2 &= A_{21}Y_1\,Y_2 + A_{G2}Y_2^2 + B_GY_2 \end{aligned} \tag{8}$$

with

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

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 average 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 an 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:

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

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 [4] is given by

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

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 [4].

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.

7 Results for the BFI colliders

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 3. 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 5. 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
```

7.1 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), injection process (fast filling or interleaved filling), 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 $\eta(T)$ as a function of running time T as well as the filling time $F(T)$. 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 EPA. All other columns should be self explanatory.

7.2 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. 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 poor vacuum is demonstrated in fig. 5a. Without any improvement of LPI the refill time would increase to 39 min, but topping-up looks quite feasible as seen in fig. 5c. For the interleaved mode the present LPI performance has to be improved by only a factor 1.5 to reach the PS limit, since EPA has 10.8 s time to accumulate positrons. With two e^+-cycles followed by two e^--cycles between two proton cycles the filling time for the e^--ring would be 39 min. But since the e^+-ring is already full after 29 min we can switch to 4 e^--cycles after this time and complete both fillings in 34 min. Including the 2 min preparation time, we have a total dead time of 36 min, which is relatively long. Topping-up however looks quite practical with 14 min after 2 h running. If one improves the LPI performance anyhow by a factor 6.5 in order to have a fast refill in the dedicated mode, then one is able to run in the interleaved mode without the accumulation of the positrons over 10.8 s. This gives the flexibility of having the e^--cycles in an arbitrary order to optimize the filling times and one has exactly the same stacking rates as before, with a total dead time of 36 min for a complete refill. Fig. 6a and 6b are thus valid for both alternatives for the interleaved mode.

Case 2 (asymmetric, $\mathcal{L} = 10^{34} cm^{-2} s^{-1}$):
With this high luminosity only short runs of 1 h or less are feasible. 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 the LPI needs an improvement by a factor of 13. In the interleaved mode the filling rates, beeing a factor 3 lower than in the dedicated mode, are comparable to the decay rates. The average luminosity drops somewhat as seen in fig. 8a and 8b. 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! In the interleaved mode we take again advantage of the accumulation of positrons over 10.8 s. 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).

8 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 developped 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 noticebly 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. Taking advantage of the 10.8 s accumulation time for positrons in EPA reduces the requirement for improvement in the positron production of LIL, which would make the interleaved mode very attractive. Reasonable injector parameter sets are summarized in table 7.

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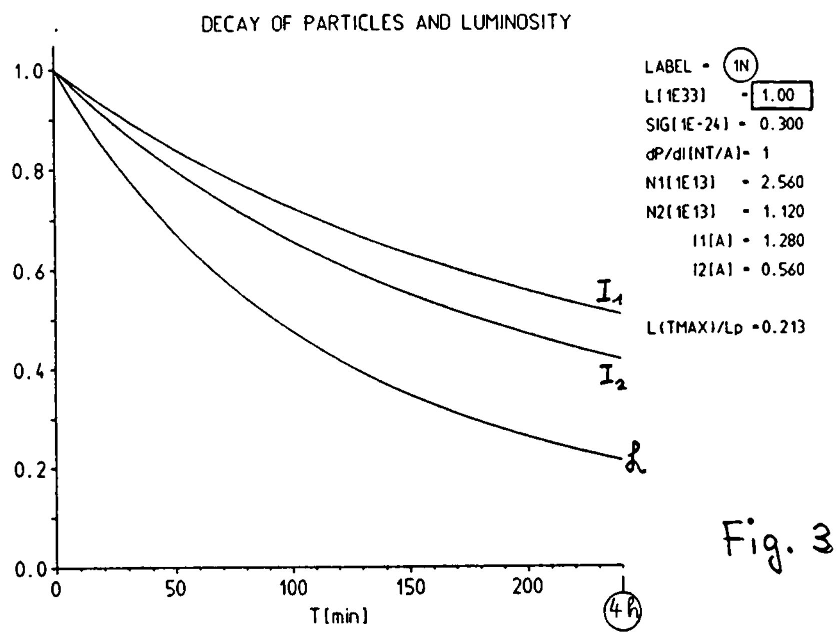

Fig. 3a

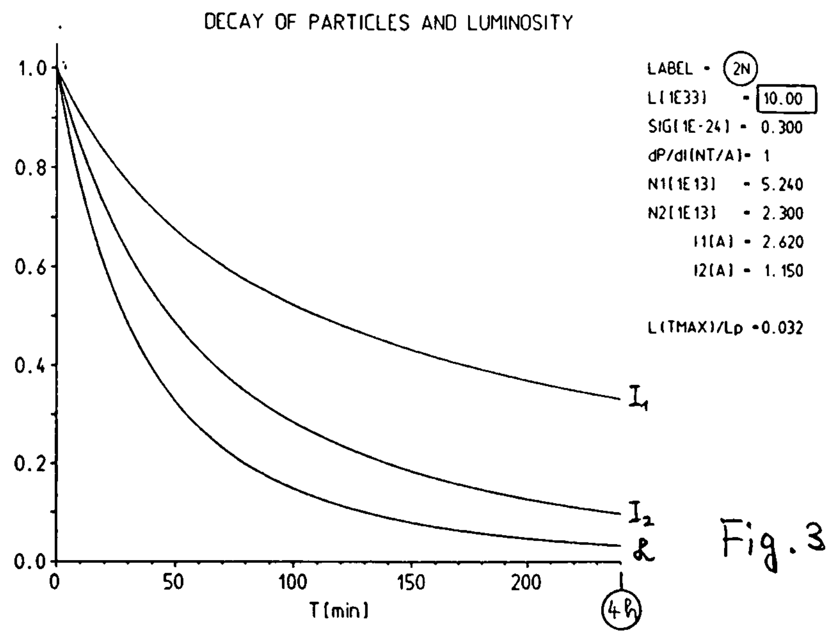

Fig. 3b

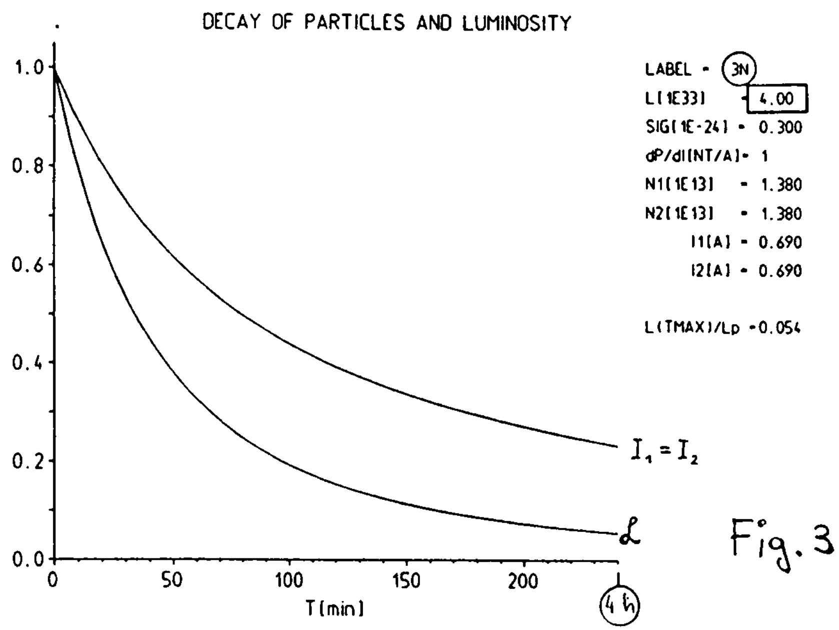

Fig. 3c

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

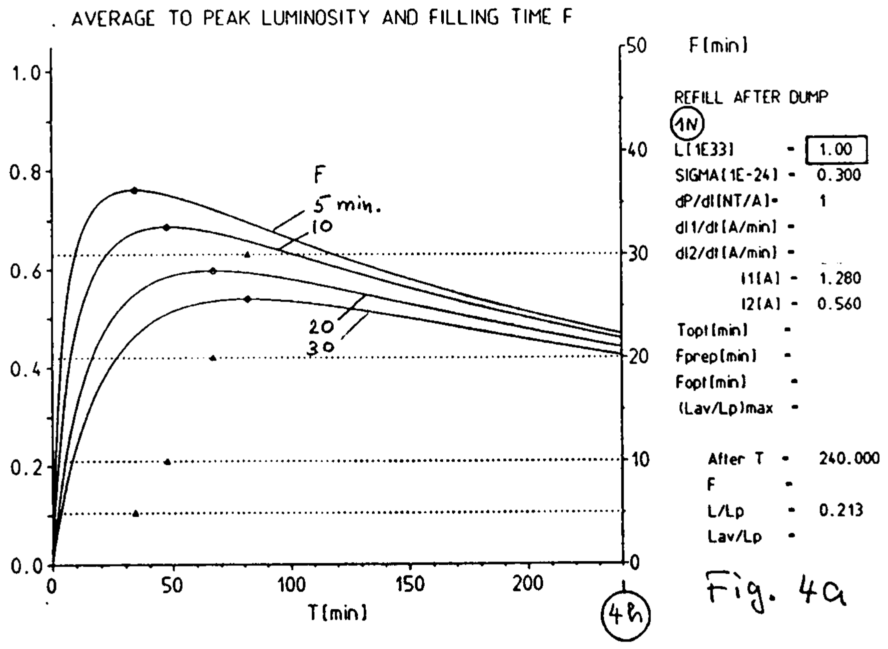

Fig. 4a

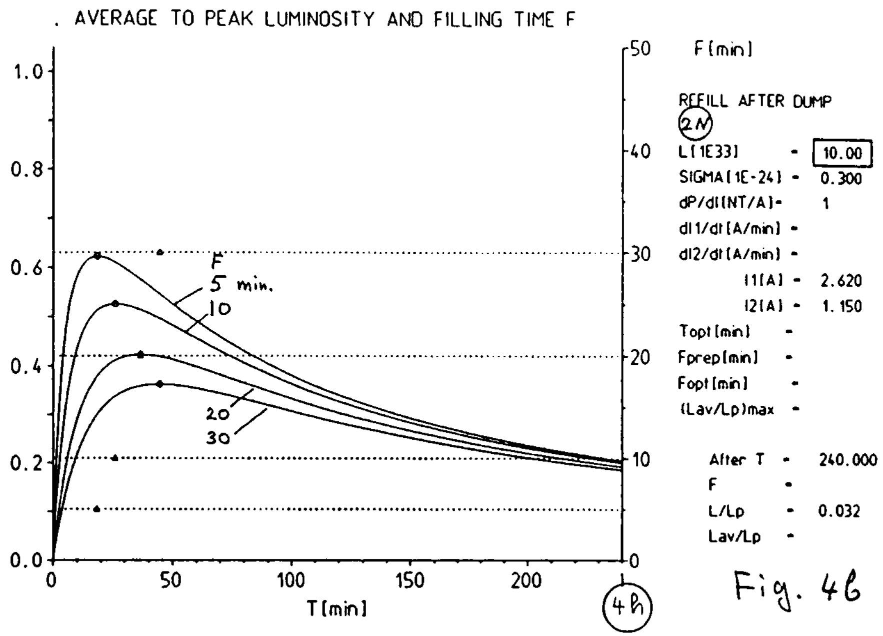

Fig. 4b

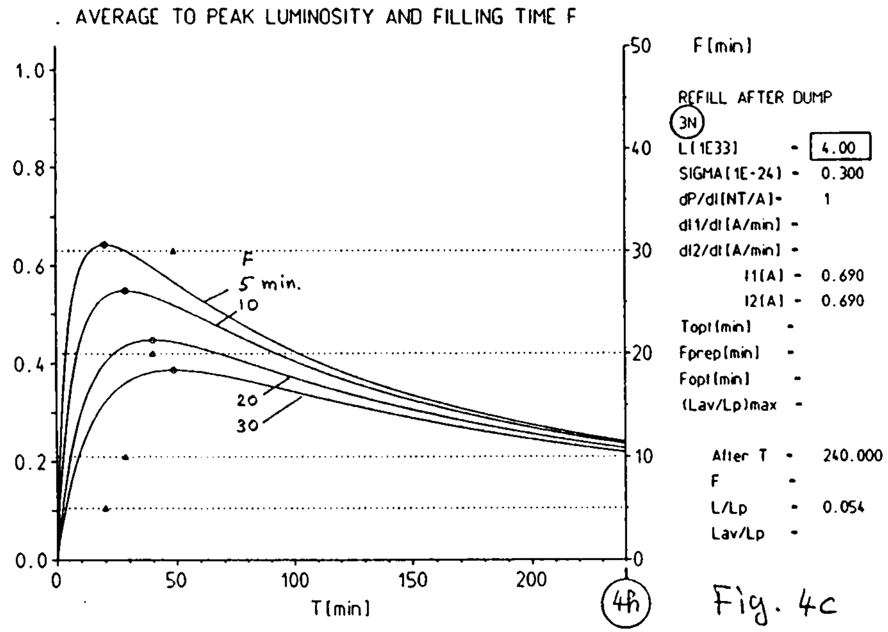

Fig. 4c

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

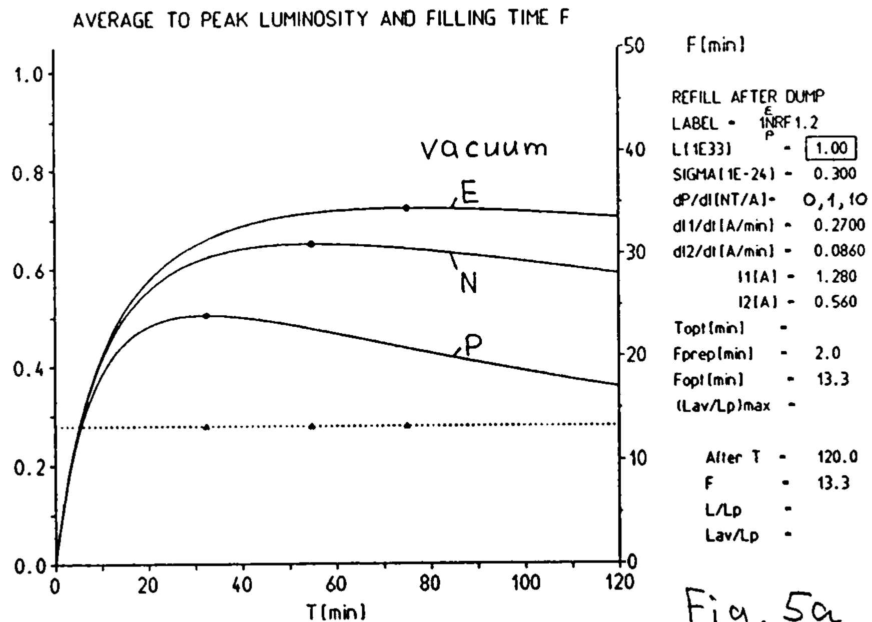

Fig. 5a

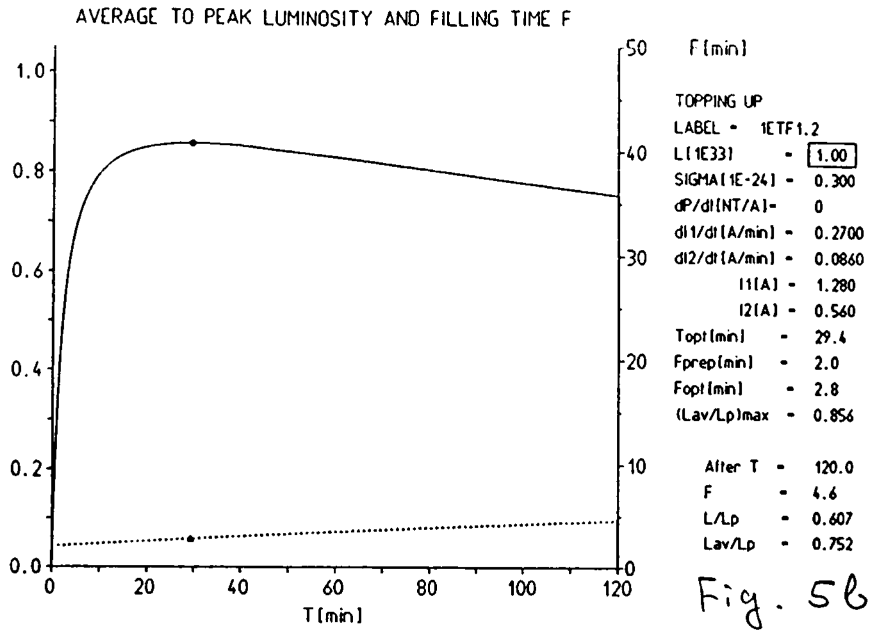

Fig. 5b

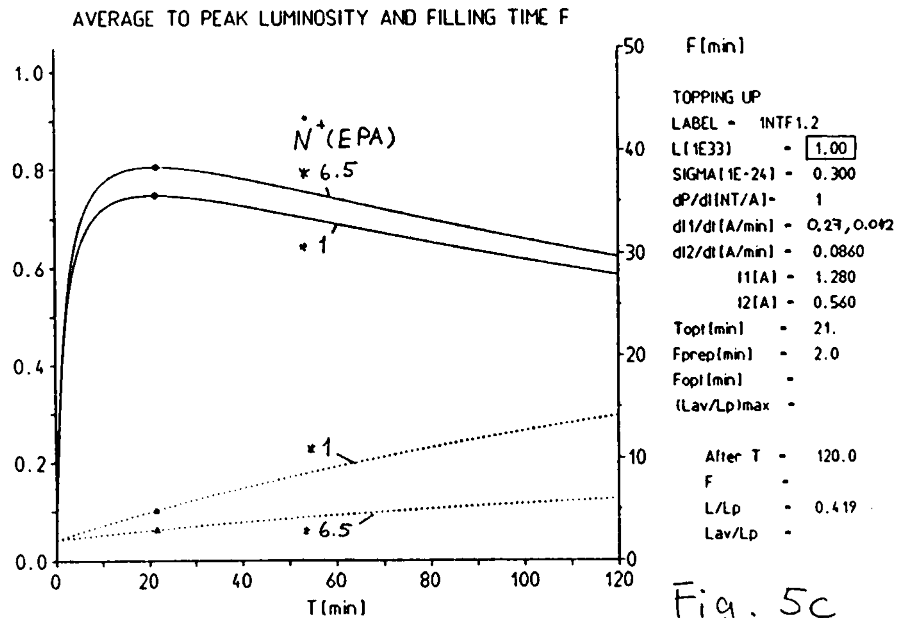

Fig. 5c

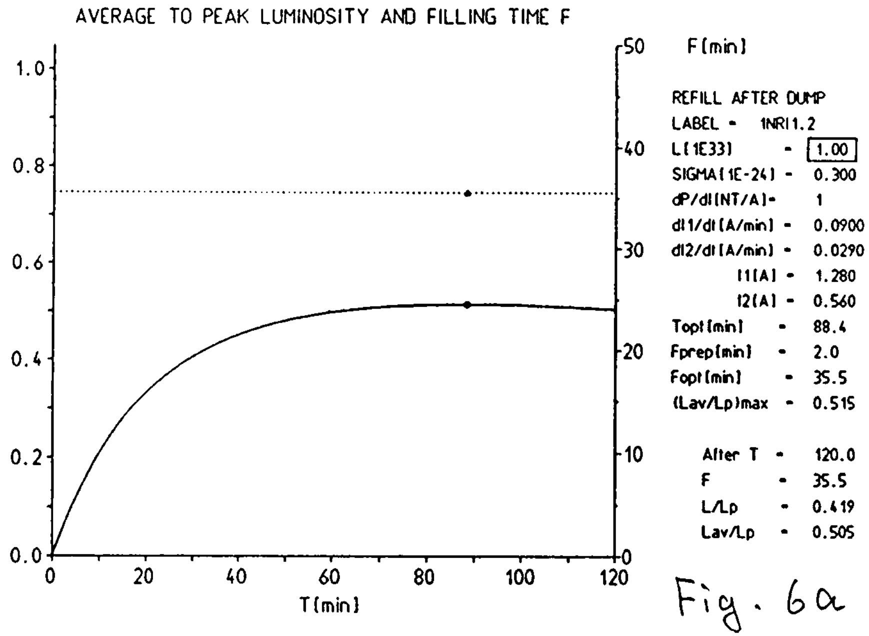
AVERAGE TO PEAK LUMINOSITY AND FILLING TIME F
F[min]
T[min]
REFILL AFTER DUMP
LABEL = 1NRI1.2
L[1E33] = 1.00
SIGMA[1E-24] = 0.300
dP/dI[NT/A]= 1
dI1/dt[A/min] = 0.0900
dI2/dt[A/min] = 0.0290
I1[A] = 1.280
I2[A] = 0.560
Topt[min] = 88.4
Fprep[min] = 2.0
Fopt[min] = 35.5
(Lav/Lp)max = 0.515
After T = 120.0
F = 35.5
L/Lp = 0.419
Lav/Lp = 0.505

Fig. 6a

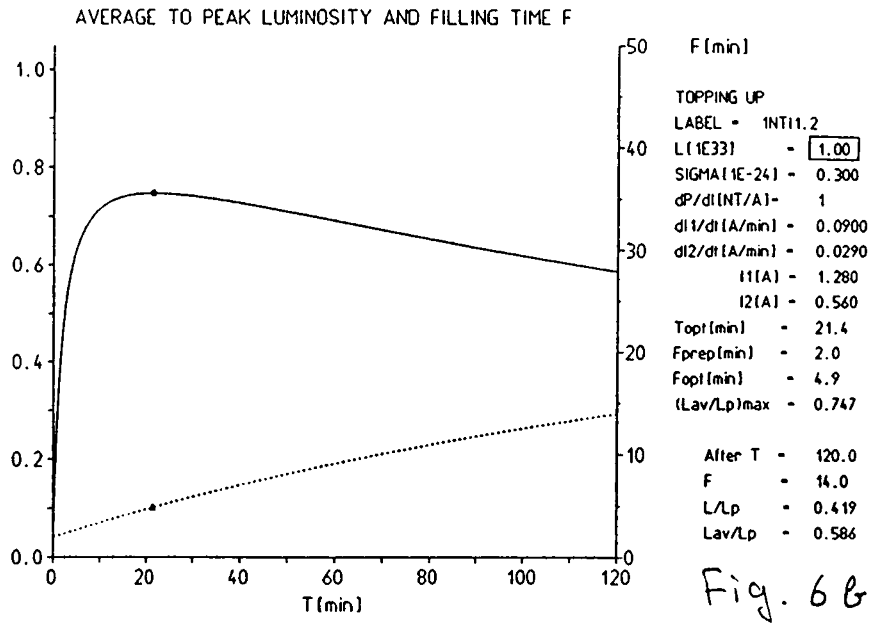
AVERAGE TO PEAK LUMINOSITY AND FILLING TIME F
F[min]
T[min]
TOPPING UP
LABEL = 1NTI1.2
L[1E33] = 1.00
SIGMA[1E-24] = 0.300
dP/dI[NT/A]= 1
dI1/dt[A/min] = 0.0900
dI2/dt[A/min] = 0.0290
I1[A] = 1.280
I2[A] = 0.560
Topt[min] = 21.4
Fprep[min] = 2.0
Fopt[min] = 4.9
(Lav/Lp)max = 0.747
After T = 120.0
F = 14.0
L/Lp = 0.419
Lav/Lp = 0.586

Fig. 6b

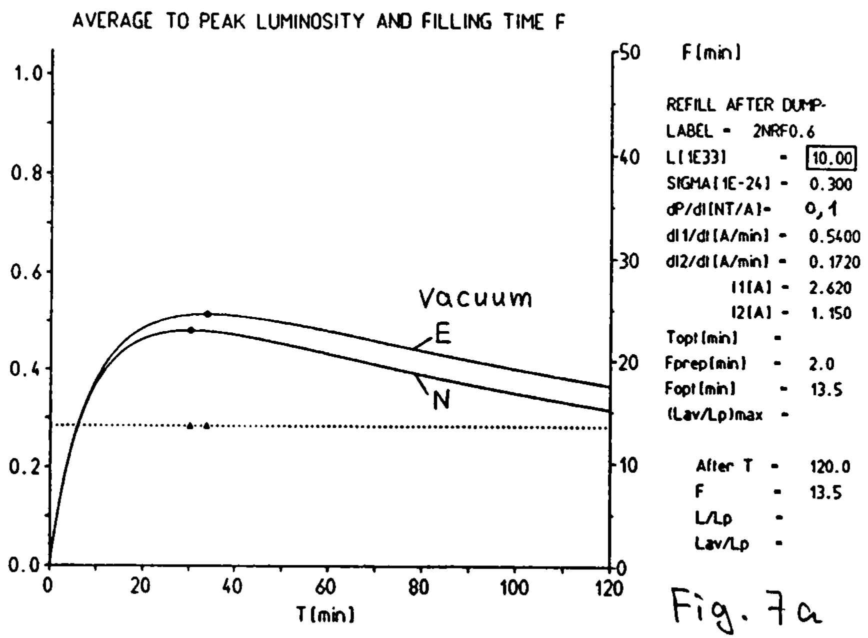

Fig. 7a

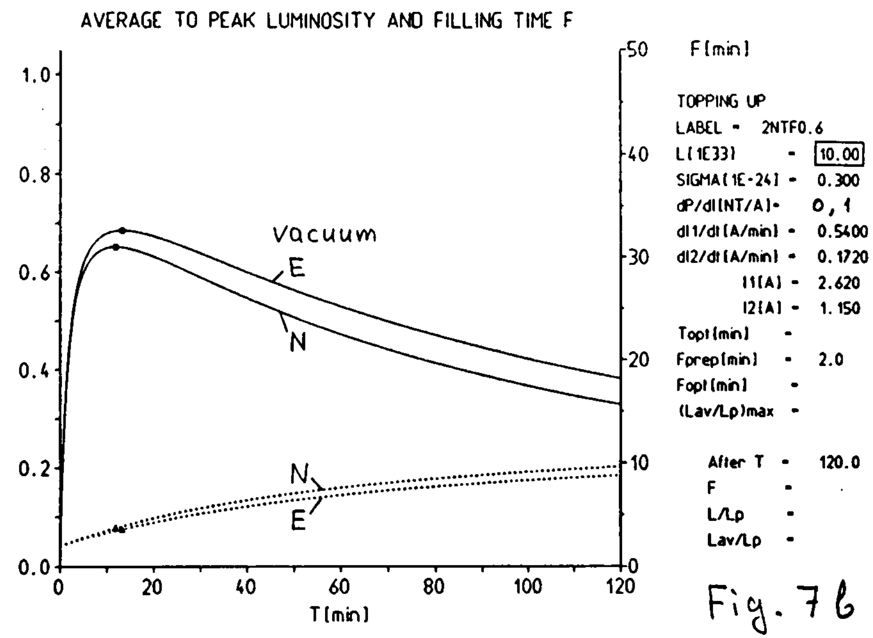

Fig. 7b

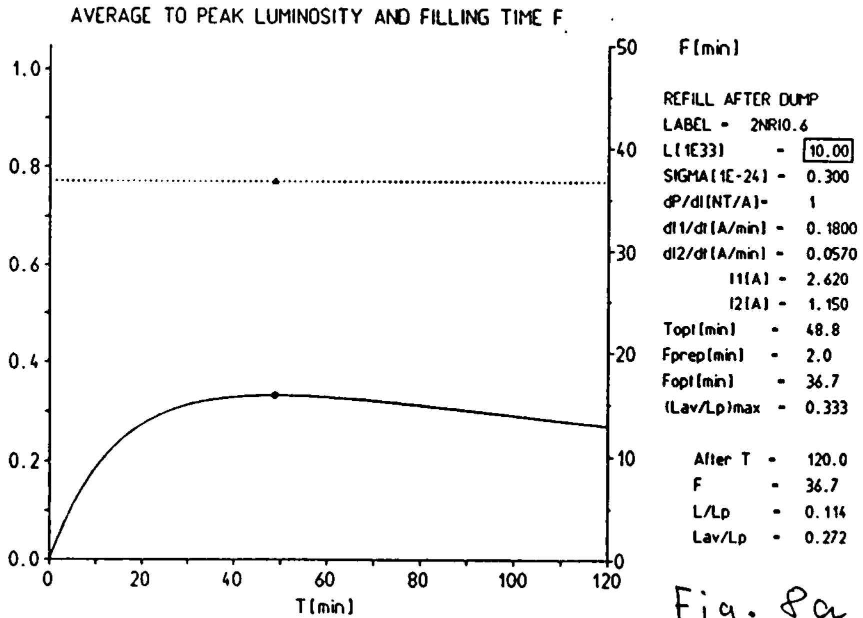

Fig. 8a

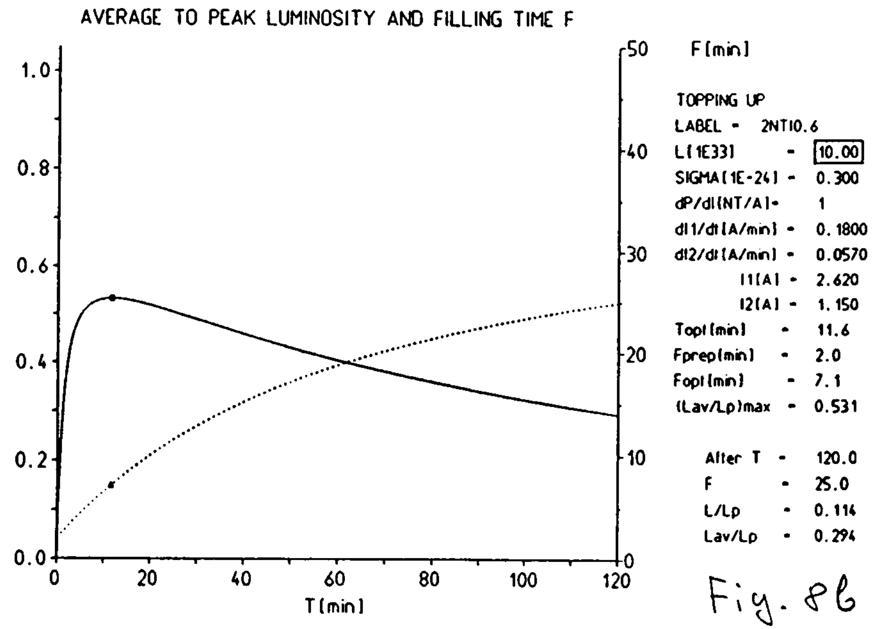

Fig. 8b

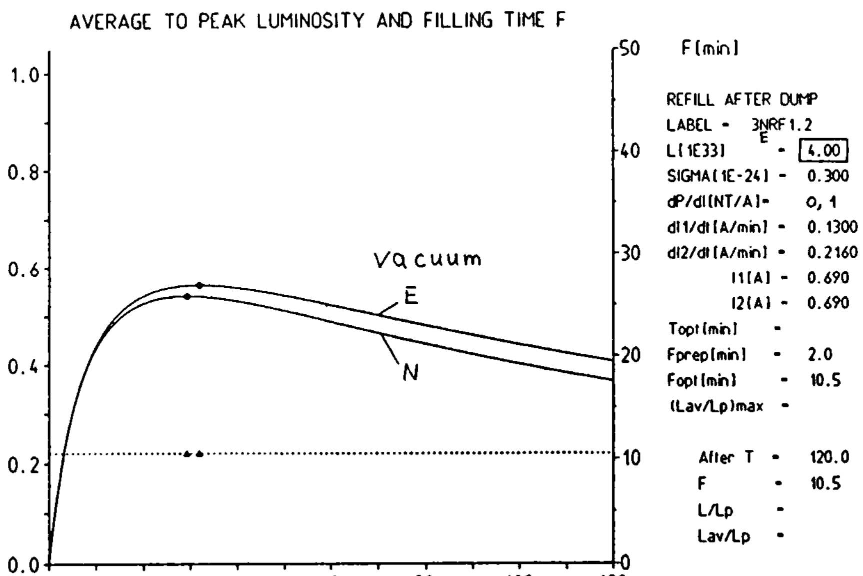

Fig. 9a

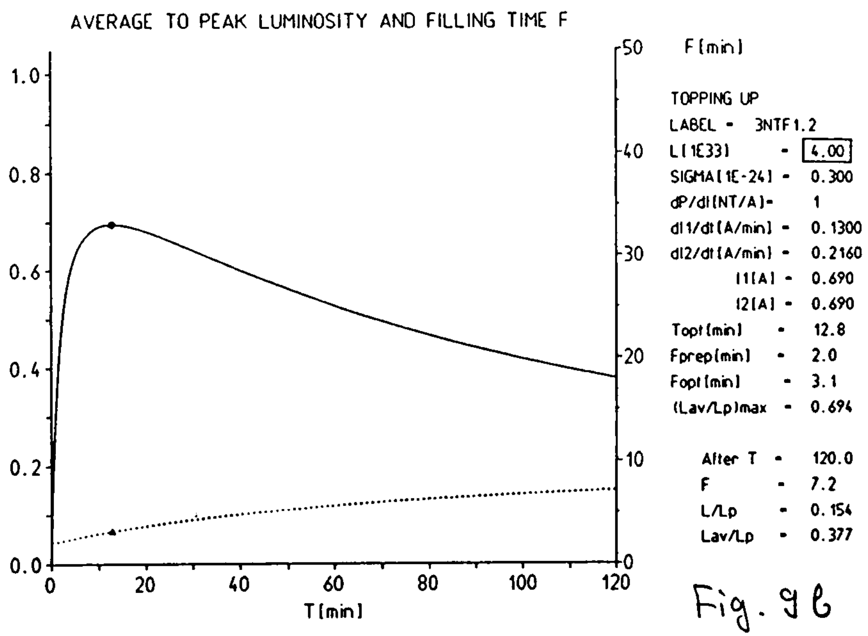

Fig. 9b

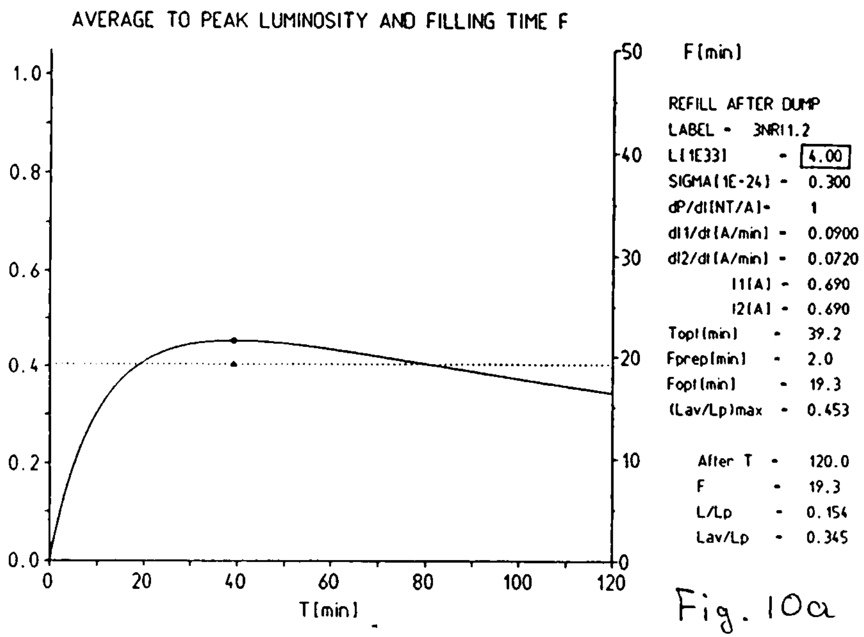

Fig. 10a

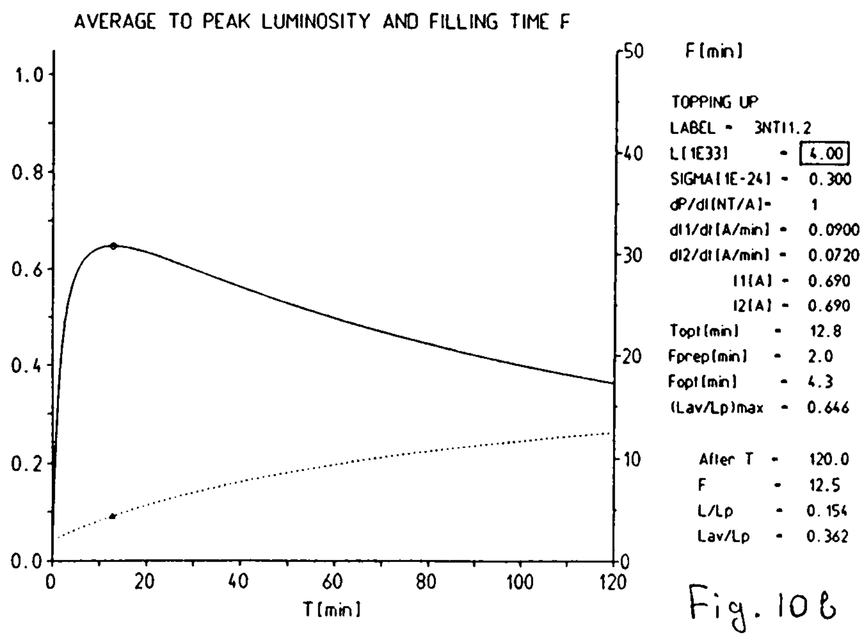

Fig. 10b

Average Luminosity for BFI colliders $\eta(T) = \frac{\langle \mathcal{L}(T) \rangle}{\mathcal{L}(0)}$ T = run time, F = fill time

8.3.1990

case	$\mathcal{L}$ $[10^{33}]$	I_1^+ [A]	I_2^+ [A]	improvement EPA(LPI) e^+	$\dot{I}_1^+$ [A/min]	$\dot{I}_2^-$ [A/min]	vacuum	filling mode	LABEL (vacuum case, fill mode, cycle)	η_{max}	T_{opt} [min]	F_{opt} [min]	after T=2h $\eta(2h)$	after T=2h F(2h) [min]	Figure	Comments
1 asym.	1	1.28	0,56	6.5	0.27 ↓ 5'	0,086 ↓ 6.5'	E	Ref. Ded.	1ERF1.2	0.72	75	13	0.70	13	5a	
							N	" "	1NRF1.2	0.65	55	13	0.59	13	"	
							P	" "	1PRF1.2	0.51	32	13	0.36	13	"	
							E	Top. Ded.	1ETF1.2	0.86	29	3	0.75	5	5b	
							N	" "	1NTF1.2	0.81	22	3	0.62	6	5c	
				1	0.042 ❘ 30'	0.086 ❘ 6.5'	N	" "		0.75	21	5	0.59	14	"	not much worse!
				1.5 ($pe^+e^+e^-e^-p$)	0.09 ❘ 14' +	0.029 ❘ 19'	N	Ref. Int.	1NRI1.2	0.51	88	36	0.50	36	6a	long filling
							N	Top. Int.	1NTI1.2	0.75	21	5	0.59	14	6b	
2 asym.	10	2.62	1,15	13	0.54 ↓ 5'	0.172 ↓ 7'	E	Ref. Ded.	2ERF0.6	0.51	34	14	0.37	14	7a	fast decay → runs ≈ 1h
							N	" "	2NRF0.6	0.48	30	14	0.32	14	"	
							E	Top. Ded.	2ETF0.6	0.68	13	4	0.38	9	7b	0.6 s cycle needed
							N	" "	2NTF0.6	0.65	12	4	0.33	10	"	
				13 ($pe^+e^+e^-e^-p$)	0.18 ❘ 15' +	0.057 ❘ 20'	N	Ref. Int.	2NRI0.6	0.33	49	37	0.27	37	8a	long filling
							N	Top. Int.	2NTI0.6	0.53	12	7	0.29	25	8b	
3 sym.	4	0.69	0.69	3	0.13 ❘ 5'	0.216 ❘ 3'	E	Ref. Ded.	3ERF1.2	0.57	31	16	0.41	10	9a	fast decay → runs ≈ 1h
							N	" "	3NRF1.2	0.54	29	10	0.37	10	"	
							N	Top. Ded.	3NTF1.2	0.69	13	3	0.38	7	9b	
				1.5	0.09 ❘ 8' +	0.072 ❘ 9'	N	Ref. Int.	3NRI1.2	0.45	39	19	0.35	19	10a	adequate filling
							N	Top. Int.	3NTI1.2	0.65	13	4	0.36	13	10b	

present limits. **EPA:** $8 \cdot 10^9\ e^+/s \cdot \text{bunch}$, PS: $5 \cdot 10^{10}\ e^+/\text{bunch}$, $4 \cdot 10^{10}\ e^-/\text{bunch}$, **SPS:** $1.6 \cdot 10^{10}\ e^-/\text{bunch}$

TABLE 6

Case	1		2		3	
$\mathcal{L}\,[cm^{-2}s^{-1}]$	$1 \cdot 10^{33}$		$10 \cdot 10^{33}$		$4 \cdot 10^{33}$	
Injector operation	Dedi-cated	Inter-leaved	Dedi-cated	Inter-leaved	Dedi-cated	Inter-leaved
e-cycling time	1.2 s		0.6 s		1.2 s	
SPS-involved	yes		yes		no	
LPI-improvement	6.5	1.5	13	13	3	1.5
e^+-accumulation over 10.8 s	no	yes	no	no	no	yes
proposed run time	2 h		1 h		1 h	
$\mathcal{L}(T)/\mathcal{L}(0)$	0.44		0.27		0.33	
refill time [min]	13	36	14	37	10	19
topping-up time	6	14	8	19	6	9
$\eta = \langle\mathcal{L}\rangle/\mathcal{L}(0)$ (for topping-up)	0.62	0.59	0.47	0.41	0.53	0.50

Table 7: Example of reasonable parameter sets