Performance and running scenarios in the future

M. Meddahi, CERN, Geneva, Switzerland

Abstract

The modifications to the cryogenic system of LEP and the RF systems allow to establish new limits on the possible intensity and therefore on the luminosity performance. Together with the experience with the low emittance optics in 1998 and the expected beam-beam tune shifts, estimates can be made for the performance in 1999. Further changes to the horizontal and vertical beta function are discussed based on past experience and running scenarios are proposed for optimum performance within the boundary conditions. A few speculative remarks are made on running LEP in the year 2000.

1 BOUNDARY CONDITIONS

1.1 RF voltage and gradients

Cavities	Gradient (MV/m)	MV
272 Nb-Cu	6	2777
16 Nb	5	136
Cu-system	-	120
1 klystron off		- 81.7
Total		2951
Total available (96 % efficiency)		**2833**

Table 1: RF voltages with SC gradient at 6 MV/m

	$102°/90°$ **Jx = 1.0**	$102°/90°$ **Jx = 1.5**
Avail. Voltage	2833 MV	2833 MV
E$_{max}$ (GeV) ($\tau_q = 24$ h)	**97.0**	**96.5**

Table 2: Maximum energy for phase 1

The strategy for increasing the energy in 1999 and 2000 is described in [1]. During a first stage the superconducting accelerating gradient will be fixed to 6 MV/m, giving a total available voltage of 2833 MV (Tab.1). From this voltage we calculate the corresponding maximum energy for the $102°/90°$ optics and two different values of the horizontal damping partition number Jx (Tab.2). As a result, 96 GeV is proposed as the energy for this first stage. At a fixed energy, the gradient will then be slowly increased in order to prepare the next stage.

Cavities	Gradient (MV/m)	MV
272 Nb-Cu	6.5	3009
16 Nb	5	136
Cu-system	-	120
1 klystron off		- 88.5
Total		3177
Total available (96 % efficiency)		**3050**

Table 3: RF voltages with SC gradient at 6.5 MV/m

	$102°/90°$ **Jx = 1.0**	$102°/90°$ **Jx = 1.5**
Avail. Voltage	3050 MV	3050 MV
E$_{max}$ (GeV) ($\tau_q = 24$ h)	**98.8**	**98.3**

Table 4: Maximum energy for phase 2

During this second stage the gradient in the SC cavities will be fixed to 6.5 MV/m. From Tab.3 and Tab.4, 98 GeV is the proposed energy for the second stage.
The third stage will depend on the available SC accelerating gradient and it is proposed to aim for 7 MV/m. The corresponding available voltage (Tab.5) and the possible energy (Tab.6) lead to suggest an energy of 100 GeV.

1.2 Intensity limitations

The various intensity limitations were presented in details in 1998 [2, 3]. Only the modifications affecting the operation in 1999 are discussed here. More details can be found in [4].

Cavities	Gradient (MV/m)	MV
272 Nb-Cu	7	3240
16 Nb	5	136
Cu-system	-	120
1 klystron off		- 95.3
Total		3401
Total available (96 % efficiency)		**3265**

Table 5: RF voltages with SC gradient at 7 MV/m

	102°/90° **Jx = 1.0**	102°/90° **Jx = 1.5**
Avail. Voltage	3265 MV	3265 MV
E$_{max}$ (GeV) ($\tau_q = 24$ h)	**100.5**	**100.05**

Table 6: Maximum energy for phase 3

Units	Power (MW)
36 klystrons	36
1 klystron off	- 1
Cu-system	0.5
Total available (96 % efficiency)	**34.1**

Table 7: RF power

The total intensity limit ($2I_0$) from the RF power (P_{rf}) is given by $P_{rf} = (2I_0)U_0$ where U_0 is the energy loss per turn. The total available RF power is 34.1 MW (Tab.7) and the corresponding maximum intensity is summarized in Tab.8. This limit is above 10 mA.

The intensity limit by cryogenic cooling power was addressed during the workshop [5]. The cooling power at 4.5 K per module is given by :

$$P_{cm} = \frac{4(V(E_a))^2}{(R/Q)Q(E_a)} + \frac{R_m(\sigma_s)(2I_{tot})^2}{2k_b}$$

where $V(E_a)$ is the total voltage from one cavity (function of the accelerating gradient E_a), R/Q is the normalised shunt impedance, Q the quality factor of the cavity, R_m the loss impedance (function of the bunch length, σ_s) and k_b the number of bunches per beam. The first term describes the power required to cool the RF system (RF dissipation) and the second term describes the beam induced dynamic load. This limit has been modified from experience/measurements obtained during the 1998 run.

Recent measurements on SC cavities have shown that the linear dependence of the quality factor as a function of the accelerating gradient was too pessimistic. A new model (logarithmic and according to RF specifications) is assumed, yielding larger Q values at high gradients (Tab.9). As a consequence the cryogenics requirements are reduced and it allows to operate at a slightly higher energy and/or with an increased total current.

Loss impedance measurements performed on the SC cavities equipped with new field probe cables showed that the new cavities contributed much less to the impedance.

E(GeV)	96	98	100
U_0 (GeV)	2.48	2.70	2.92
$2I_0$ (mA)	13.7	12.6	11.7

Table 8: Maximum intensity from RF power

	Values of 1998	New values for 1999
Q (6 MV/m)[10^9]	3.2	3.2
Q (7 MV/m)[10^9]	2.3	2.85

Table 9: Quality factor

10 MΩ were measured instead of the 16 MΩ (for σ_s=9 mm) measured in 1997 with the cavities equipped with old field probe cables. The corresponding maximum possible currents tolerated by the cryogenics budget are above 10 mA (Tab.10).

As a conclusion, up to 100 GeV, the total intensity limit for 1999 is above 10 mA and is also limited to ≈1.0 mA/bunch from TMCI. Consequently, the proposed intensities for running in 1999 are 6 and 8 mA (with 4 bunches per beam) and 10 mA with 6 bunches per beam.

E(GeV)	96	98	100
2I (mA) ($J_x = 1$)	16.1	14.5	12.2
2I (mA) ($J_x = 1.5$)	15.8	14.1	11.5

Table 10: Maximum intensity from the cryogenics budget

1.3 Beam-beam limit

Fig.1 represents the maximum vertical beam-beam parameter (ξ_y) recorded for many 1998 fills as a function of the corresponding total intensity (intensity for which ξ_y was maximum). In Fig.2, ξ_y is averaged in bins of 0.1 mA. The two figures do not show any sign of beam-beam parameter saturation with increasing current.

This is also illustrated with the evolution of ξ_y during fill 5259 (Fig.3). As a result, it was proposed to use

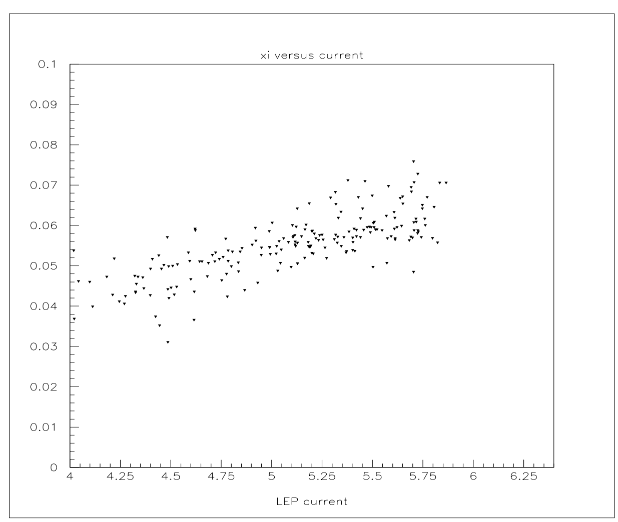

Figure 1: ξ_y as a function of the total current

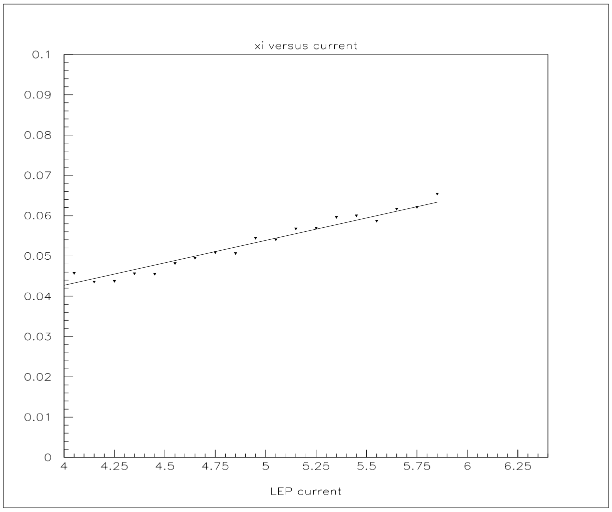

Figure 2: Average ξ_y in bins of 0.1mA vs current

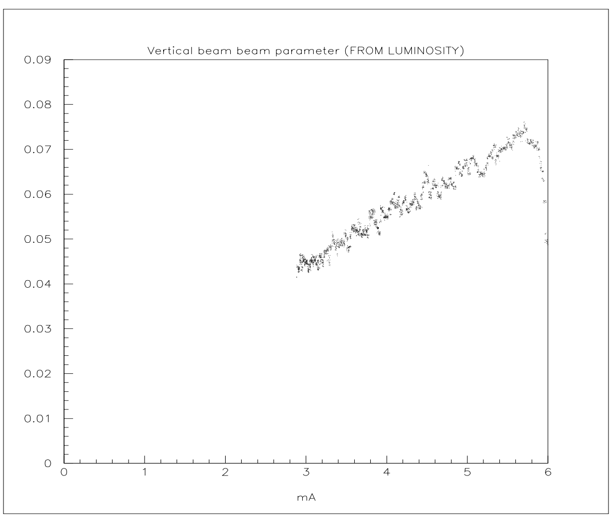

Figure 3: ξ_y for Fill 5259 vs current

a maximum beam-beam parameter of 0.08 for the performance estimate calculation. Such beam-beam parameter limit would be for example achieved with intensities described in Tab.11 for various energies (assuming 4 bunches per beam, an emittance ratio (κ) of 1.2 % and J_x = 1.5). Above these currents, beam blow up is expected and a way out would be to use more bunches per beam (i.e 6+6).

E(GeV)	96	98	100
$2I_0$ (mA)	8.1	8.6	9.1

Table 11: Maximum intensity at beam-beam parameter limit

1.4 Horizontal and vertical squeeze

During 1998, three different physics periods can be distinguished. During the first period (up to fill 5140), β_x^* = 1.5 m and β_y^* = 5 cm were used and both ξ_y and the peak luminosity were increasing, as the total current was increased (Fig.4, Fig.5).

For the second period (fills 5140-5262), β_x^* was squeezed to 1.25 m while β_y^* remained unchanged. Both ξ_y and the peak luminosity were increasing compared to the first period, without increasing further the total current.

Finally, from fill 5263 onwards, during the last physics period, β_y^* was squeezed to 4 cm while β_x^* remained unchanged. The result was a decrease of ξ_y and an increase of the luminosity compared to the second period, while the total current remained unchanged.

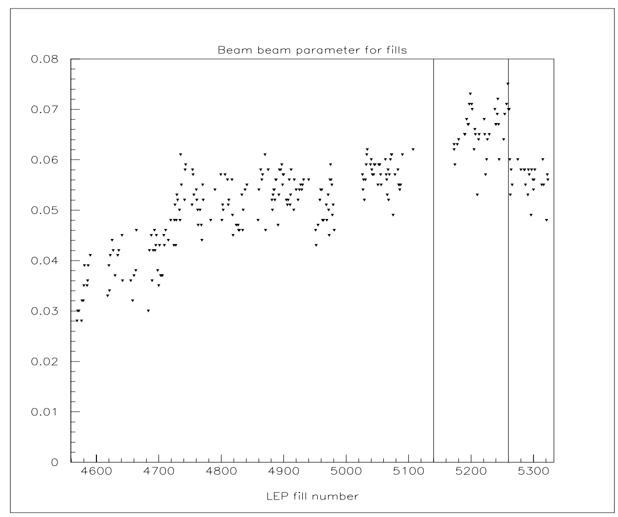

Figure 4: Beam-beam parameter as a function of fill number

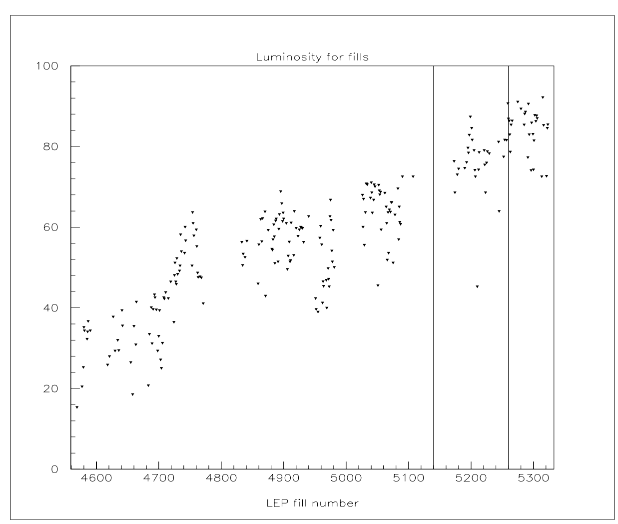

Figure 5: Luminosity as a function of fill number

In order to quantify these changes and to study whether the effects of the horizontal and vertical squeezes were as expected, one fill in each of the three physics periods is presented (Tab.12).

For the horizontal squeeze, for the same bunch intensity,

β_x^* m	β_y^* cm	ξ_y	ξ_x	Lum. $\times 10^{31}$	I/bunch μA	Δf_{rf} Hz
1.50	5	0.062	0.042	7.3	750	100
1.25	5	0.076	0.042	9.0	750	120
1.25	4	0.061	0.042	9.5	750	120

Table 12: Three fills during the different running periods

squeezing the horizontal beta value from 1m5 to 1m25 and increasing the RF frequency shift from 100 Hz to 120 Hz, is expected to yield 20 % increase in both the ξ_y and peak luminosity. Tab.13 shows that the expectations were effectively met.

β_x^* (m)	Meas. ξ_y(expected)	Meas.Lum. (expected) (10^{31} cm^{-2}s^{-1})
1.50	0.062	7.5
1.25	0.076 (0.075)	9.0 (9.0)

Table 13: Measured and expected ξ_y and peak luminositiy

For the same bunch intensity, and a vertical squeeze from 5 cm to 4 cm, one expects 11 % decrease in ξ_y and 11 % increase in luminosity. Tab.14 shows that the expectation were met in ξ_y and close in luminosity. The performance gain from the squeeze was also discussed in [6].

Possibilities to squeeze further the β^* have already been

β_y^* (cm)	Meas. ξ_y(expected)	Meas.Lum. (expected) (10^{31} cm^{-2}s^{-1})
5	0.076	9.0
4	0.068 (0.067)	9.5 (10.0)

Table 14: Measured and expected ξ_y and peak luminosity

addressed in [7, 8].

For the horizontal squeeze, background considerations due to the aperture in the horizontally focusing quads limit the maximum β_x^* through the following expression :

$$\frac{\beta_x^*}{\epsilon_x} > \frac{1.25}{46 \times 10^{-9}}$$

For J_x =1, the limit is 1.21 m at 100 GeV (Tab.15) which is very close to the operational value (1.25 m).

If one would like to always fit in the machine an optics with a J_x =1 and keep the same optics all the way up to 100 GeV, 1.25 m would be the right choice. Also, it was shown [9] that the background storms observed during physics fills and optimised by small horizontal tune change, are less severe for larger β_x^*, which would bring another argument to not further reduce this value.

Concerning a further reduction of the vertical beta func-

Energy (GeV)	96	98	100
ϵ_x(nm)	41	42.8	44.6
β_x^* min (m)	1.11	1.16	1.21

Table 15: Minimum β_x^* for different energy

tion, beam-beam effects are imposing a limit on the β_y^* in order not to affect the luminosity. This is the hour glass effect which was discussed for LEP in [10].

With $\beta_y^* \geq 2\sigma_l$ and for $\sigma_l = 1$cm , the limit on β_y^* is 2 cm, compared to the present value of 4 cm.

A further reduction has to be tested in order to study its feasibility in operation.

However an attempt to match the physics optics at $\beta_y^* = 3.5$ cm showed that β_y values were increasing in QS3-QS4 (200 m at collimator). Also, the necessary sextupole strength on SD1 severely increased (from KSD1=$-.35$ at 4cm to KSD1=$-.38$ at 3.5cm). This would limit this 3.5 cm optics to 94.4 GeV (max $-.036$). It has to be reminded that large value of the sextupole strength enhances excitation of non-linear resonances and increases the tune dependence with amplitude. Both effects reduce the dynamic aperture [11].

With the 3.5 cm optics, the non-linear chromaticity correction showed a reduced aperture in momentum $\Delta p/p = \pm 0.013$ (was $\pm$ 0.015) and it was demonstrated in [12] that further reduction of the β_y^* would lead to marginal momentum aperture.

In summary, it is recommended to use β_x^* of 1.25 m and β_y^* of 4 cm, at the start-up and through 1999.

2 PERFORMANCE ESTIMATE IN 1999

Tab.16 summarized the parameters used for the 1999 performance estimate. As can be observed in Fig.6 and Fig.7,

Energy (GeV)	96	98	100
Jx	1.5	1.5	1.5
V_{RF} (MV)	2833	3050	3265
ϵ_x (nm)	27.4	28.5	29.7
σ_s (mm)	10.8	11	11.2
β_x^* (m)	1.25	1.25	1.25
β_y^* (m)	0.04	0.04	0.04
Δf (Hz)	90	90	90
κ (%)	1.2	1.2	1.2

Table 16: Proposed parameters for 1999 with the $102°/90°$

the only performance limitations in 1999 will come from both the maximum possible current to be accumulated in LEP and from the achievable accelerating gradient.

The integrated luminosity L_{int} is given by $L_{int} = \eta\ L_0$ T with the global efficiency η = 0.2 or 0.15, L_0 the peak luminosity and T the total time considered. In Tab.17, three energy cases are treated (96, 98, 100 GeV) for three intensities (6, 8, 10 mA). For 6 mA, the expected integrated luminosity is $\approx$ 1.5 pb^{-1}/day, assuming a global efficiency of 0.20. While increasing the intensity and the energy, the global efficiency is expected to be reduced. At 8 mA the luminosity is constant with the energy E ($\approx$ 2 pb^{-1}/day), due to the fact that in the range of energies considered the ratio $\xi_y \times E$ is constant.

96 GeV	6 mA	8 mA	10 mA
L_0 /10^{30} ($cm^{-2}s^{-1}$)	92.5	145	170
L_{int} (pb^{-1})/day, η=.2	1.59	2.50	2.93
η=.15	1.19	1.88	2.20
98 GeV	6 mA	8 mA	10 mA
L_0 /10^{30} ($cm^{-2}s^{-1}$)	88.7	145	163
L_{int} (pb^{-1})/day, η=.2	1.53	2.50	2.82
η=.15	1.15	1.88	2.11
100 GeV	6 mA	8 mA	10 mA
L_0 /10^{30} ($cm^{-2}s^{-1}$)	85.2	145	156
L_{int} (pb^{-1})/day, η=.2	1.47	2.50	2.70
η=.15	1.10	1.88	2.03

Table 17: Performance estimate: $102°/90°$ Jx = 1.5

3 LIMITS AND ESTIMATE FOR 2000

In 2000, the maximum SC accelerating gradient will still remain a challenge and the cryogenic cooling power will start to limit the performances. This is illustrated in Fig.6 where for energies above 100 GeV, the 6 and 8 mA curves cut the cryogenics limit curve at 7.4 and 7.6 MV/m respectively.
The corresponding maximum energies for the SC gradient are summarized in Tab.18.

Tab.19 summarizes the maximum intensity from cryogenic cooling power, and it can be seen that the intensity decrease is very steep above 100 GeV.

E_a	7.2	7.4	7.6
E (GeV) ($J_x = 1$)	101.6	102.3	102.8
E (GeV) ($J_x = 1.5$)	101.1	101.8	102.3

Table 18: Maximum energy for different SC gradients

A word of caution has to be added regarding the maximum tolerable horizontal emittance in LEP (Tab.20). It remains to be demonstrated that a horizontal emittance of 47.3 nm at 103 GeV can be accommodated in the machine.

E(GeV)	100	102	103
2I (mA) ($J_x = 1$)	12.2	8.4	5.0
2I (mA) ($J_x = 1.5$)	11.5	7.1	1.4

Table 19: Maximum intensity from the cryogenics budget

E(GeV)	100	103
ϵ_x (nm) ($J_x = 1$)	44.6	47.3 !
ϵ_x (nm) ($J_x = 1.5$)	29.7	31.5

Table 20: Horizontal emittance for $102°/90°$ optics

4 CONCLUSIONS

The performance limitations in 1999 will depend on the maximum possible intensity and on the maximum reliable accelerating gradient. For 2000, the cryogenics cooling power will also be a limitation for energies above 100 GeV. For 1999, the following recommendations were made :

- Operate at 96 GeV, 98 GeV and aim for 100 GeV
- Use the $102°/90°$ optics with a J_x = 1.5, $\beta_x^* = 1.25$ m and $\beta_y^* = 4$ cm
- Start with a total intensity of 6 mA and then 8 mA using 4 bunches per beam
- When the total intensity available would exceed 8 mA, 6 bunches per beam could be considered.

Performance estimates are given for 1999 and with 6 mA the integrated luminosity is expected to be about 1.5 pb^{-1}/day. With 8 mA, 2 pb^{-1}/day are expected. However it is emphasized that for high intensity and high energy the global efficiency is likely to be reduced.

5 REFERENCES

[1] G. Geschonke; *Strategy for increasing the energy in 1999*; These Proceedings.

[2] D. Brandt, K. Hübner, S. Myers *On LEP Performance Limits in 1999 and 2000*; CERN SL/98-005 (DI).

[3] D. Brandt; *Performance and running scenarios in the future*; Proceedings of the eighth LEP performance workshop, Chamonix, January 27-30, 1998, and CERN SL/98-006 (DI).

[4] D. Brandt, S. Myers *LEP Performance Limits re-visited*; CERN SL/98-074 (DI).

[5] P. Gayet; *Cryogenics issues for LEP in 1999*; These Proceedings.

[6] M. Lamont; *Review of 1998*; These Proceedings.

[7] A. Verdier; *Reduction of* β^*; Proceedings of the seventh LEP performance workshop, Chamonix, January 14-17, 1997, and CERN SL/97-06 (DI).

[8] J. Gareyte; *LEP2 Optics : Options and Implications*; Proceedings of the eighth LEP performance workshop, Chamonix, January 27-30, 1998, and CERN SL/98-006 (DI).

[9] G. von Holtey; *Particle background in LEP experiments and beam tails*; These Proceedings.

[10] S. Myers; *Simulation of the beam-beam effect for* e^+ e^- *storage rings*; Nucl. Inst. and Meth. 211 (1983) 263-282, North Holland Publishing Company.

[11] D. Brandt et al; *A candidate low emittance lattice for LEP at its highest energies*; EPAC-98, Stockholm, June 1998 and CERN SL-98-030 (AP).

[12] A. Verdier; *Optics limits for the highest energy*; These Proceedings.

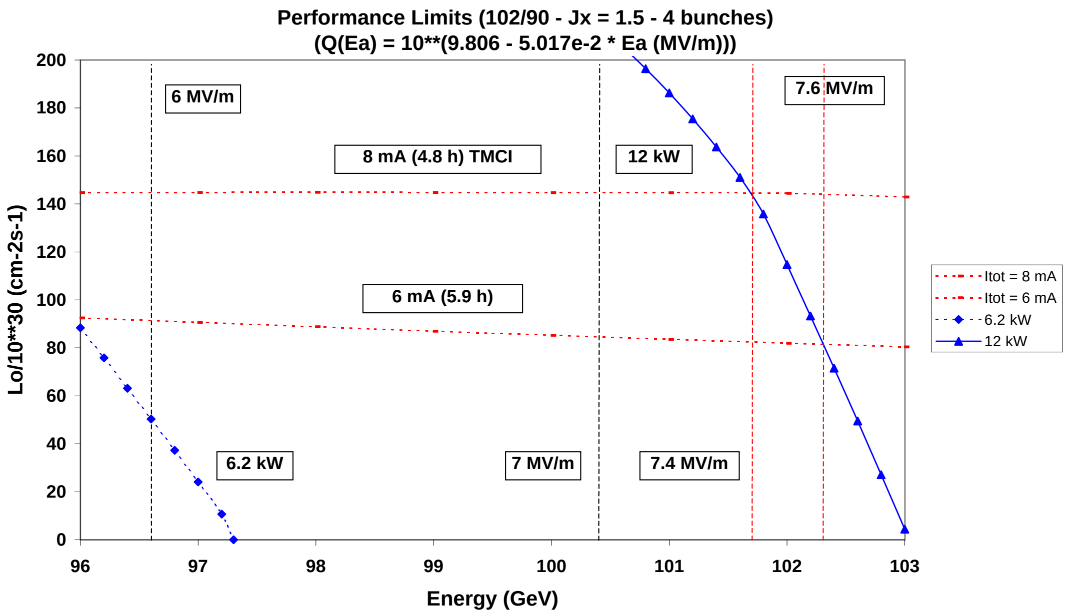

Figure 6: Performance limitations for 4 bunches

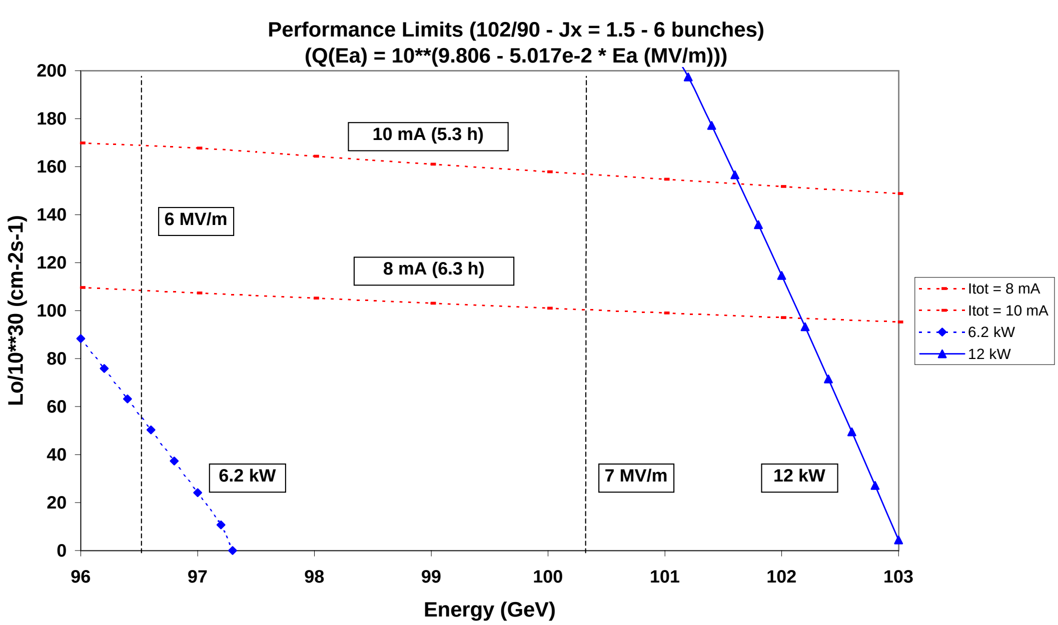

Figure 7: Performance limitations for 6 bunches