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Synchrotron Radiation Power
from Insertion Quadrupoles onto LEP Equipment

A. Butterworth, G. Cavallari, M. Jimenez,

G. von Holtey

Abstract

Hot spots and leaks at vacuum transition pieces in the experimental straight sections at high beam energy have been shown experimentally as well as by simulation to be due to synchrotron radiation from the low-beta quadrupoles. The transition pieces can be effectively protected by collimators. However, when closed, the collimators themselves are hit by a very high flux of synchrotron radiation photons, amounting to several hundreds of Watts per mA of beam current. The power seen by the collimator jaw surface is strongly dependent on the horizontal closed orbit amplitude through the quadrupoles. Upper limits for asymmetric horizontal orbits in the even IP's are given in order to keep the incident power onto collimators below design values.

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1 Introduction

With the increase of the LEP beam energy, synchrotron radiation (SR) effects become ever more important. Effects from the increased radiation power from dipole and wiggler magnets on different machine components has been described in [1]. In this note the radiation from quadrupoles in the experimental straight sections is studied. The simulation program PHOTON [2] has been used to estimate the impact of SR-power from synchrotron radiation photons radiated in these quadrupoles onto vacuum elements and collimator surfaces along the LEP straight sections. The simulations were done for the present layout of IP4 or IP8, with $(102^\circ/90^\circ)$ -optics [3] and for various beam energies between 92 GeV and 100 GeV. Temperature measurements and radiation levels at vacuum transitions are reported for different settings of protection collimators and beam parameters.

2 Vacuum transition pieces

Over most of the first 70 m from the IP the vacuum chamber has a diameter of 158 mm or more. At this point a 15° -transition piece reduces the pipe diameter to 100 mm. This diameter is kept until the connection to the elliptical arc vacuum chamber, starting several meters upstream of QS11, about 240 m from the IP. Through the s.c. cavities, however, the inner free diameter is much larger than 100 mm and is reduced to the 100mm pipe inbetween the 10.8 m long modules by similar 15° -transition pieces.

The power density at the first 100mm transition from radiation of the low-beta quadrupoles is about 300 times larger than the radiation density along the downstream 100mm vacuum pipe. Including radiation from all upstream straight section quadrupoles and a flat horizontal orbit, PHOTON simulations find a value of 210 for this factor, or 310 if a horizontal closed orbit with $x^* = 0.2$ mrad is assumed.

In fact, temperatures of well above 100°C have been measured at the first 100mm transition during the energy ramp, when collimators are relatively open. With collimators closed during physics data taking, no or little heating is observed.

Simulation of collimator scans show that the SR-power onto the 100mm transition can be reduced to negligible values by closing the upstream horizontal (COLH.QS3B, 14 m upstream of the transition) and vertical (COLZ.QS3A, 5 m upstream) collimators to about ± 35 mm (Figure 1). Of the total 4.4 Watt per mA beam current with open collimators 97% arrive in the horizontal plane and 99% of the photons are radiated in the six low-beta quadrupoles QS0 and QS1. However, the obtained power of less than 5 W/mA is not sufficient to explain the observed temperature increase. The observed heating can be explained by introducing horizontal closed orbit deviations through the low-beta quadrupoles (see Figure 2). Orbits have been simulated by ‘kicking’ the beam at the IP, the starting point for tracking in PHOTON. With $x^* = 0.2$ mrad the power at the transition rises to 36.7 W/mA; with $x^* = 0.3$ mrad $P = 124$ W/mA, a factor of 28.4 increase. Again, the transition can be shielded by the two collimators used above (Figure 2). However, observed heating in the vertical plane, can not be explained by vertical asymmetric orbit amplitudes, nor by the vertical separation bumps.

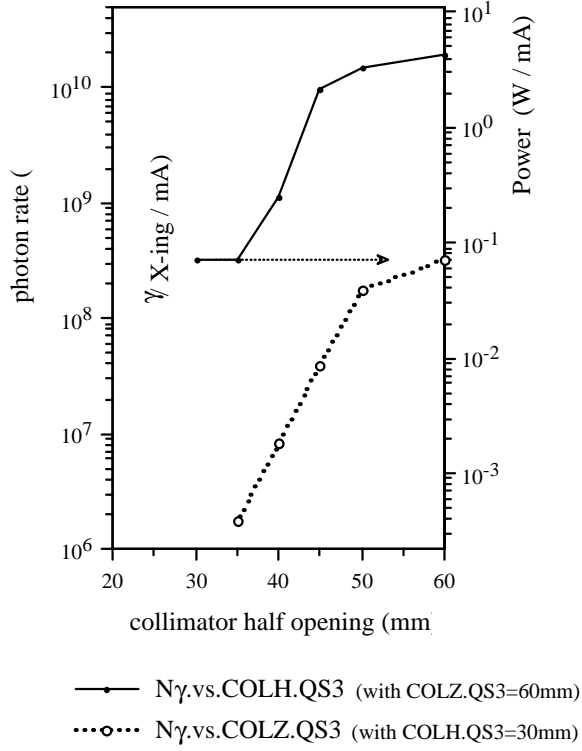


Figure 1: Simulated photon rate and SR-power onto the 100mm transition piece at 70 m from IP4 as function of horizontal and vertical collimator settings. (Ebeam= 94.5 GeV, $\beta_x^* = 2.5$ m, BT= 66%, flat horizontal orbit)

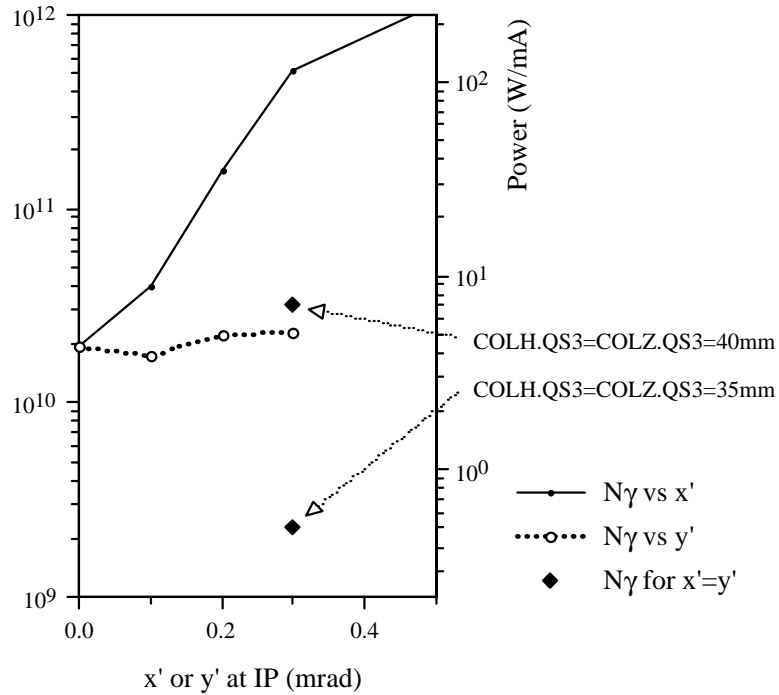


Figure 2: Simulated photon rate and SR-power onto the 100mm transition piece at 70 m from IP4 as function of horizontal and vertical closed orbit angles in IP4. (E_{beam} = 94.5 GeV, $\beta_x^* = 2.5$ m, BT= 66%, open collimators)

Temperature measurements at the first 100mm transition piece have been performed¹ for different settings of the two collimators and for varying beam and orbit conditions. Four temperature probes were positioned around the transition piece right of IP8: T1.int and T3.ext in the horizontal plane and T2.up and T4.down in the vertical plane.

Figure 3 shows the observed temperature changes when the horizontal COLH.QS3 and the vertical COLZ.QS3 collimators were opened and then progressively closed again. A sharp increase of the temperature on the lower side of the transition (T4.down) is observed as soon as COLZ.QS3 is opened. The temperature is drastically reduced by closing COLZ.QS3 from ± 50 mm to ± 45 mm and the heating completely halted with COLZ.QS3 = ± 35 mm. Temperatures on top of the transition (T2.up) and in the horizontal plane increase slowly over 20 to 30 minutes, starting with the opening of COLH.QS3. However, the maximum temperature increase at the horizontal probes is only 35 C^0 and is most likely mostly due to conduction from the hot region below the tube. After closing also the horizontal collimator to ± 35 mm, no heating is present anymore and all four temperature values approach each other and slowly cool down. While a small temperature increase from synchrotron radiation in the horizontal plane with well corrected orbits is expected from simulations, the observed strong heating at the lower side of the transition tube is not explained by the simulations done. In a second experiment the bunch train bumps were turned on to BT = 66% of their maximum value and the same temperature pattern were observed once the collimators were opened.

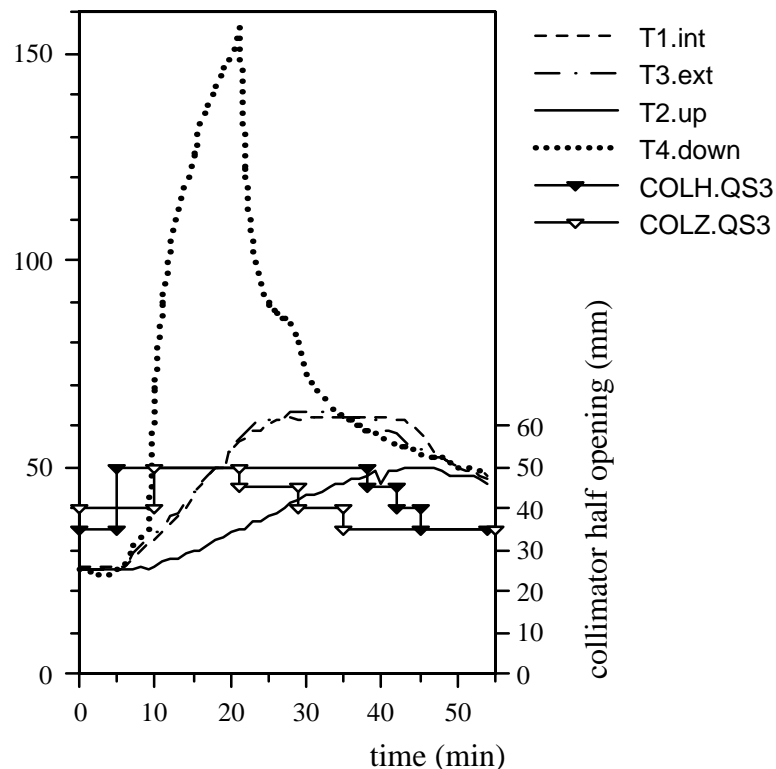


Figure 3: Temperatures measured at the 100mm-transition piece 70 m from IP8 as function of horizontal and vertical collimator openings.

¹ Beam conditions: fill #4676 (19/6/1998), high energy (102/90)-optics, $E_{\text{beam}} = 92\text{ GeV}$, $\beta_x^* = 2.5\text{m}$, four e^+ bunches of $350\mu\text{A}$, RF frequency shift of $\Delta f_{\text{RF}} = +100\text{Hz}$ from the “nominal central” value $352\,254\,170\text{ Hz}$, standard closed orbit corrections, vertical bunch train bumps BT = off, collimators at ‘ramp&squeeze’ settings.

In a third experiment the temperature T3.ext at the outside of the transition piece increased sharply from about 60 C° to 120 C° after installing an asymmetric orbit bump through the low-beta quadrupoles with $x^{*'} = 0.1$ mrad (first part of Figure 4). This behaviour is expected from simulation. Closing COLH.QS3 to ± 35 mm stops the radiation completely.

The fourth experiment, with a flat horizontal beam ($x^{*'} = 0$) and COLH.QS3 open (later part in Figure 4), showed a small temperature increase by 15 C° in the horizontal plane due to an enlarged horizontal beam emittance from 24.2 nm ($\Delta f_{RF} = +100$ Hz) to 37.7 nm ($\Delta f_{RF} = 0$ Hz).

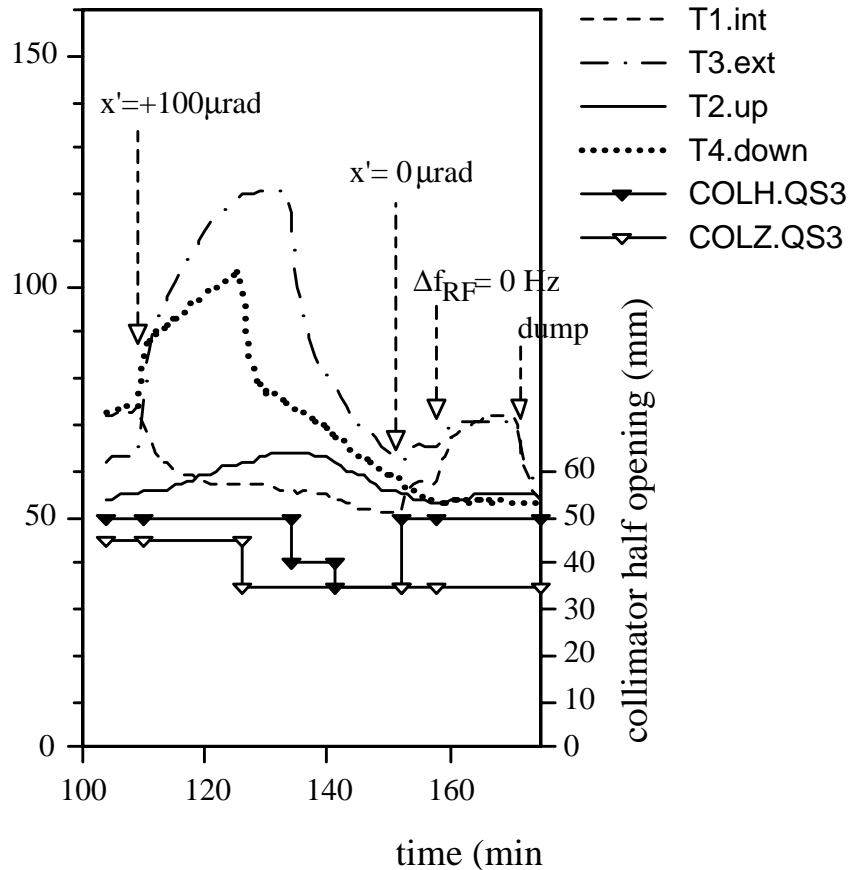


Figure 4: Temperatures measured at the 100mm-transition piece 70 m from IP8 for different orbit and machine settings.

High radiation values of up to 50 krad/h, that were measured at the 100mm vacuum transition at the downstream end of cavity module 273 in IP2 during the last part of the energy ramp, could be completely cured by further closing the horizontal collimators COLH.QS4² in IP2 during the ramp³. A similar effect is seen in the RF modules of all IPs (Figure. 5).

² Collimators COLH.QS4 and COLZ.QS4 in IP2 and IP6 have the same function as collimators COLH.QS3 and COLZ.QS3 in IP4 and IP8.

³ this experiment was performed on 11/8/1998 (fill 5016)

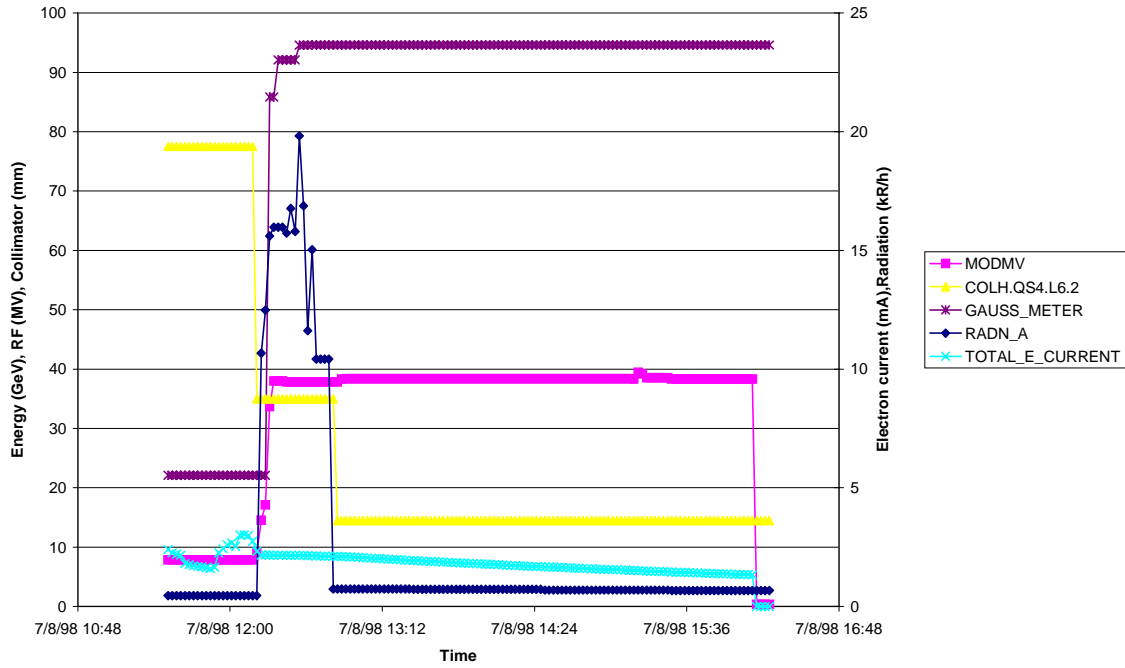


Figure 5a. Radiation level in unit 633 module 2 with collimator settings prior to 11 Aug 1998.

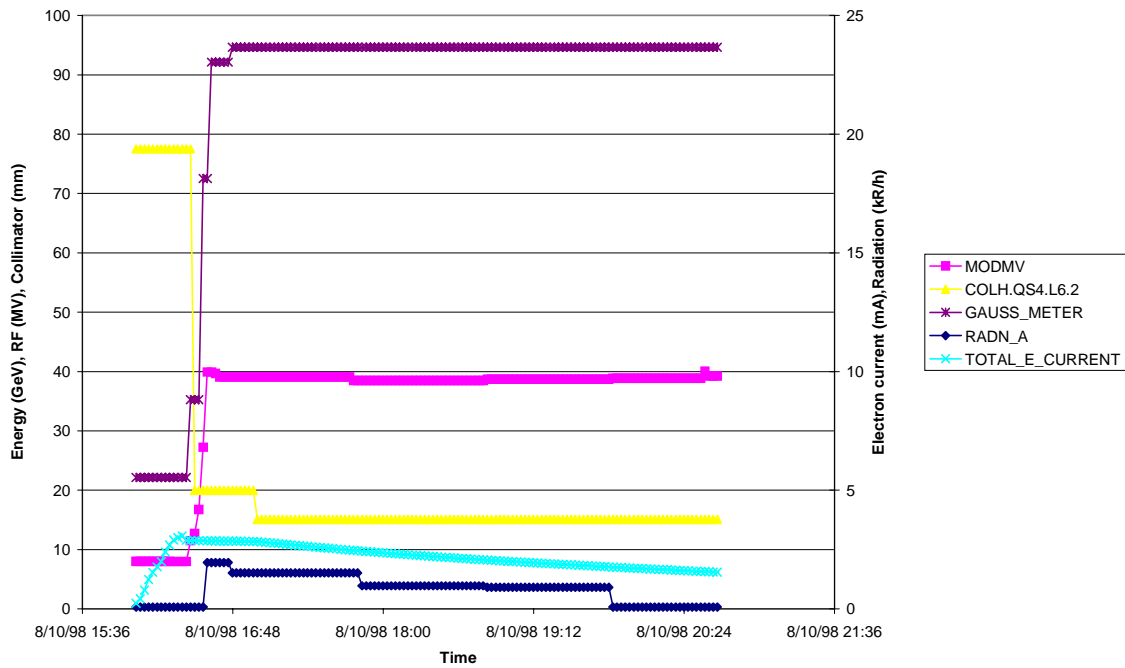


Figure 5b. Radiation level in unit 633 module 2 with collimator settings after 19 Aug 1998.

No temperature increase or radiation at 100mm transitions along the experimental straight sections have been observed since tighter settings for collimators COLH.QS3/4 and COLZ.QS3/4 are used during ‘ramp&squeeze’ (>19/8/1998). These collimator settings do not influence the machine performance during the energy ramp.

3 Collimators

Collimators in the experimental insertions are needed to protect the detectors from particle backgrounds [4], but with LEP2 beam energies they become in addition more and more important to protect LEP equipment from the increasing SR-power. However, this has the consequence that the collimator jaws themselves become the target of an increased number of SR-photons. Table 1 gives the simulated SR-power incident onto collimator front and inner surfaces in IP4 or IP8 for a beam energy of 100 GeV and for two cases of asymmetric horizontal orbits. The situation is very similar in interactions IP2 and IP6.

Name	Collimators in IP4 or IP8		Incident power (W/mA)	
	distance from IP (m)	half opening (mm)	$x'^* = 0$ mrad	$x'^* = 0.2$ mrad
COLH.QS1B	8.5	38.0	$\ll 0.1$	$\ll 0.1$
COLV.QS2	15.1	25.0	$\ll 0.1$	$\ll 0.1$
COLZ.QS2	21.3	45.0	$\ll 0.1$	$\ll 0.1$
W-absorber	55.7	78.0	0.6	9.6
COLH.QS3B	56.3	19.2	93.3	291.0
COLZ.QS3A	66.1	40.0	1.8	1.5
COLV.QS5	79.2	15.0	19.4	13.7
COLH.QS6	108.0	11.6	65.5	112.0
COLH.QS10	220.5	11.0	21.1	40.6

Table 1: SR-power received by collimator surfaces in IP4 or IP8 from a 100 GeV beam. (PHOTON simulations with (102/90)-optics and $\beta_x^* = 1.5$ m). Results for a ‘flat’ orbit and for a realistic asymmetric orbit in the horizontal plane are given. Collimators ‘COLH’ move in the horizontal plane, ‘COLV’ and ‘COLZ’ act in the vertical plane. The absorber has an inner bore of 156 mm. The collimator openings correspond to settings used for physics data taking with a nominal horizontal emittance of $\epsilon_x = 40$ nm.

The deposited power is high, particular for horizontal collimators. The LEP2 collimators COLH.QS3B and COLH.QS10 have been designed for maximum power deposition of 800 W, all other collimators (LEP1 version) are designed for 600 W [5]. For COLH.QS3B, which receives the highest radiation, this limit would be reached for a beam current of 8.6 mA with a completely flat horizontal orbit. As most photons are radiated in the low-beta quadrupoles, deviations of the orbit through these quadrupoles strongly increase the SR-radiation. An asymmetric orbit with an angle at the IP of $x'^* = 0.2$ mrad triples the power on the COLH.QS3B surfaces (Table 1) and reduces the current at which the design limit is reached to 3.1 mA. For all other collimators the maximum tolerable beam current is higher.

Figure 6 give the simulated incident SR-power onto front and inner surfaces of COLH.QS3B as function of asymmetric orbits in IP4. While the dependence on y'^* is relatively weak, the radiation power quickly rises with x'^* . For a beam current of 4 mA ($J_x=1$) the 800 W limit is reached with $x'^* = 0.20$ mrad at 94.5 GeV and with $x'^* = 0.15$ mrad at 100 GeV. Orbits with $x'^* = 0.2$ mrad are presently often observed during physics data taking, albeit with lower beam currents and smaller emittances. The 1.5 times smaller horizontal emittance ($J_x=1.5$) reduces the power at COLH.QS3B to about 60%.

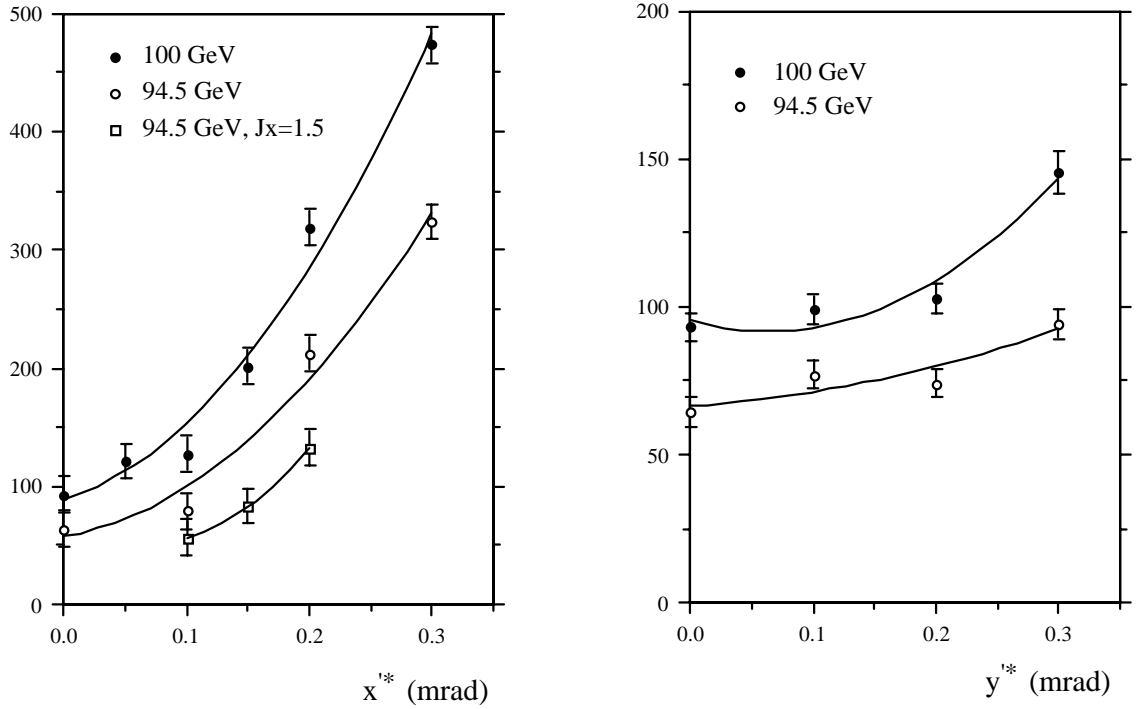


Figure 6: Simulated SR-power onto COLH.QS3B surfaces as function of the angle at the IP of a horizontal (left figure) and vertical (right figure) asymmetric orbit through the low-beta quadrupoles. Curves are for two different energies with $J_x=1$, (102/90)-optics and $\beta_x^*=1.5$ m.

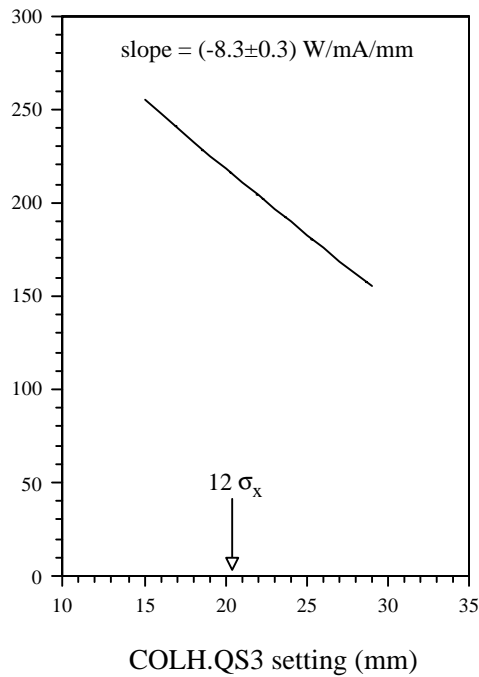


Figure 7: Simulated SR-power onto COLH.QS3B surfaces as function of the collimator half opening. The calculations were done for 100 GeV with $J_x=1$, (102/90)-optics and $\beta_x^*=1.25$ m, and with $x^*=0.2$ mrad.

The dependence of the power at COLH.QS3B on the collimator opening is plotted in Figure 7. The power can not be considerably reduced by further opening the collimator jaws. A setting of \bullet 22 mm is required during physics data taking in order to protect the SR-masks in the experiments from impact of direct SR-photons. About the same setting is needed to shadow vacuum transitions along the straight sections from SR-photons radiated in the low-beta quadrupoles.

4 Conclusion

Observed hot spots and high radiation signals on 100mm vacuum transition pieces in the experimental straight sections during energy ramping are due to the impact of very high rates of SR-photons from quadrupoles, in particular the low-beta quadrupoles QS0 and QS1. The transitions can be protected against this radiation by closing horizontal (COLH.QS3) and vertical (COLZ.QS3) collimators during the energy ramp.

Collimators, which are closed during ramp and physics data taking, are hit by high rates of SR-photons mainly from low-beta quadrupoles. These rates increase sharply if non-zero orbit amplitudes, particularly in the horizontal plane, exist in the low-beta quadrupoles. At beam energies above 90 GeV the absorbed SR-power can rise to several hundred Watt per mA beam current. LEP1 collimators are constructed for a maximum overall power deposition of 600 W, LEP2 collimators for 800 W. In order to stay below these upper limits, the horizontal orbit amplitudes through low-beta quadrupoles must be controlled to below threshold amplitudes. When expressed in terms of the angle x'^* of an asymmetric orbit in the IP, the threshold values for 4 mA beams are $x'^* \leq 0.2$ mrad at 94.5 GeV and $x'^* \leq 0.15$ mrad at 100 GeV.

Simulations suggest that the vertical collimators are hit much less and the dependence on vertical orbit deviations is much less critical. However, as the observed large temperature increase below the 100mm transition at 70 m from IP8 could not be explained by simulation, care has also to be taken at highest energies to keep the vertical orbit around the even IP's as flat as possible.

References

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- [6] R. Jung, private communication