ON INCREASING HERA LUMINOSITY

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Abstract

The Luminosity of the HERA lepton proton collider is limited in part by the bunch length of the protons of 20cm. This limitation is expected to be removed by the installation of the new damper system which will control longitudinal coupled bunch instabilities of the proton beam [1] thereby avoiding the bunch lengthening by a factor of two. This opens new possibilities for increasing the luminosity in HERA since the beta functions at IP for both leptons and protons can be lowered by about 20% without noticeable reduction of the corresponding luminosity by the so called hourglass effect [2]. While the beta function of the proton ring could be reduced with the help of the quadrupoles in the low beta section only, the reduction of the beta function of the lepton ring up to this value of 20% cannot be done by the same means without significant loss of dynamic aperture. A more intricated use of the beam-beam focussing (dynamic beta) is required in order to achieve the desired beam spot size at the IP's. The price to pay here is an additional beam-beam beta beat as well as a distortion of the non-linear chromaticity compensation, which may lead to enhanced synchro-betatron resonances.

This paper represents an overview about available margins and given constraints for more luminosity gain in HERA under the new conditions.

PROTONS

During acceleration, the proton bunch length evolves under the influence of adiabatic damping and RF voltage ramping on one hand and longitudinal coupled bunch instabilities caused by impedances in HERA on the other hand. The first effect results in the continuous decrease of the bunch length. The coupled bunch oscillations are suppressed by the Landau damping as long as the bunch length is sufficiently large. As soon as the bunch length decreases below a critical value, which for HERA-p is slightly smaller than 20cm, the instability sets in and endures until the bunch reaches a certain length which is considerably larger than the bunch length just before the onset of instability. As a result the bunch arrives at the end of the acceleration with a length of 20cm or more. To solve this problem the new damper system has been installed during the last shutdown [1] which suppresses the longitudinal coupled bunch oscillations and thus prevents the bunch lengthening. It has been demonstrated that the theoretically possible lengths of 13cm [3] could be achieved after the damper system has been adjusted properly.

Aperture Margins for Protons

The limitations for the proton beta function at the IP's are given mainly by the aperture margins in the low beta quadrupole magnets. Acceptable proton background conditions require an aperture which is able to accommodate at least 10 RMS sizes (σ) of the beam. HERA luminosity running 2005 was performed with the average horizontal and vertical beam emittance of 4.6nm which results in the aperture margin of 12σ in the low beta section and thus 20% more than required limit. Further reduction of the beta function at IP's did however less sense because of the hourglass effect. Since the bunch lengthening could be avoided now, the usage of the full aperture can be considered.

Intra Beam Scattering.

The intra beam scattering (IBS) becomes a serious problem under the new conditions. The first experiments with the new damper system have shown that the 13cm short bunches lengthen quickly as the result of IBS and reach a length of 20cm already 1.5 hours after the acceleration.

A possible improvement can be achieved by increasing of the circumferential RF voltage U. The 208MHz RF system in HERA-p is presently operated with ~600kV but allow increase of the circumferential voltage by a factor of up to three. The simulations based on the Piwinski model [4] have shown that the IBS rate could be significantly reduced, so that the bunch length of 20cm would be reached only after 6 hours of the luminosity running (fig. 1). Moreover, a further luminosity gain is expected due to the shorter bunches which scale with $U^{-1/4}$.

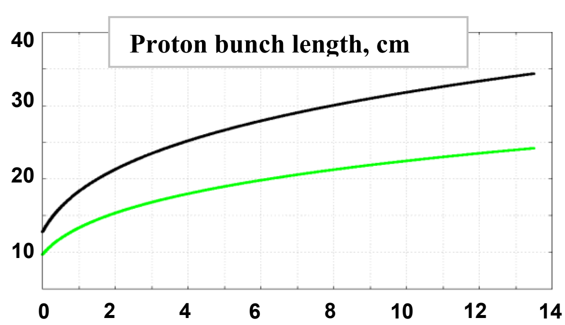

Figure 1: Simulations of the proton bunch length during the luminosity run for U=600kV (black line) and for the case if the circumferential RF voltage has been increased by o factor of 3 (green line).

LEPTONS

The **HELUM72SM** optics for the lepton beam which has been used in the luminosity running 2005 provides aperture margin of 18σ in the low beta sections. However the reduction of the lepton beam size cannot be achieved by a smaller beta function only because of the significant increase of the chromaticity of the low beta section and a corresponding dramatic reduction of the dynamic aperture. Therefore only partial reduction of the lepton beam spot at IP's by means of the nominal beta from 63cm to 55cm is intended in the new optics.

Dynamic Beta

The other possibility to reduce the lepton beam spot at the IP without significant loss of the dynamic aperture is making use of the dynamic beta. The dynamic beta results from the beam-beam interaction at the IP's. For leptons with a small betatron amplitude compared to the size of the p-beam at the IP, the beam-beam force acts in a very good approximation as an additional quadrupole. The effective quadrupole becomes however weaker for particles with large amplitudes. This way the large increase of chromaticity in the low beta section is restricted only to the particles in the beam core and thus the dynamic aperture remains unaffected.

Nominal and Alternative Working Point

The nominal working point **Q_x=0.127, Q_y=0.17** provides appropriate dynamic beta for the electron beam. For the positrons an alternative working point **Q_x=-0.127, Q_y=-0.17** (mirror tunes) suits better. The nominal tunes for electrons and mirror tunes for positrons are then the starting point for the softening of the beam-beam beta beat compensation.

Beam-Beam Beta Beat

The **HELUM72SM** optics intends the rigorous beam-beam beta beat compensation, which is accomplished by proper phasing of two IP's [5]. If one wants to make use of the dynamic beta, this condition should be abolished. The price to pay here is an additional beam-beam beta beat and an enhanced chromatic beta beat with possible enhancement of synchro-betatron resonances.

The rigorous beam-beam beta beat compensation is given by choice of the phase advance between IP South and IP North equal to π/2. Such an arrangement provides a compensation of the half integer stop-band and a beta beat free zone in the half of the ring between IP North and IP South and localises the beta beat only to the other half of the ring. This compensation is a by-product of a scheme to compensate the chromatic beta beat by cancellation of the contributions for the two interaction regions North and South. Experience has shown that nonlinear chromaticity is the major cause for strong synchro-betatron resonances in the vicinity of the desired working point. This arrangement is therefore most favourable for stable operating conditions.

In order to make use of the additional focussing caused by the beam-beam interaction one has to soften the rigorous beam-beam beta beat compensation. Thus it is planed to change the phase advance in the new optics for electrons from 0.5π to 0.35π and for positrons after switching to mirror tunes from 0.5π to 0.65π. In both cases it would lead to reduction of the dynamic beta by about 25%.

The calculations of the corresponding change in the beta beat distribution show that one has to expect a beta beat with the amplitude of about 11% in the section IP North → IP South (former "free zone") and about 5% additional beta beat in the other half of the ring.

Non-Linear Chromaticity Compensation

The non-linear chromaticity of the two colliding beam interaction regions cancels in the **HELUM72SM** optics due to appropriate choice of the phase advance [5]. Since the phase advance changes the distortion of the intrinsic non-linear chromaticity compensation takes place in the new optics. The calculations of the off-energy beta beat for a particle with the energy deviation of $1\sigma_E$ indicate for example an additional beta beat of 6% equally spread out in the whole ring.

The non-linear chromaticity needs to be reduced by means of a more complex scheme of chromaticity compensating sextupole magnets. For the optics with a FODO cell phase advance of 0.4π as it is in **HELUM72SM** one has to introduce 5 sextupole families according to the rule **A-B-C-D-B** in order to compensate the non-linear chromaticity distortion [6].

Table 1: Nominal and Upgrade Parameters

	Nominal			Upgrade		
	e^+	e^-	p	e^+	e^-	p
Horizontal β-function at IP β_x, m	0.63	0.63	2.45	0.55	0.55	2.25
Vertical β-function at IP β_y, m	0.26	0.26	0.18	0.24	0.24	0.16
Horizontal tune	0.127	0.127		-0.127	0.127	
Vertical Tune	0.170	0.170		-0.170	0.170	
Phase advance IP S→N, 2π	0.25	0.25		0.325	0.175	
Dyn. Hor. β-function at IP β_{xdyn}, m	0.74	0.67		0.49	0.48	
Dyn. Vert. β-function at IP β_{ydyn}, m	0.49	0.30		0.204	0.204	
Horizontal beam size at IP, µm	122	116	100	99	98	96
Vertical beam size at IP, µm	38	30	28	25	25	26
Bunch length at IP, cm			20			10
Hour-glass reduction factor			0.919			0.95
Specific luminosity, $10^{30}mA^{-2}cm^{-2}s^{-1}$	1.79	2.16		2.49	2.51	

NOMINAL AND UPGRADE PARAMETERS

The table 1 represents the nominal and upgrade parameters. If all steps have done properly one may expect a luminosity win of 16% for electron running and about 39% for the positron running. The main part of the luminosity win for the positron running traces back however to switching to the alternative working point.

CONCLUSIONS AND DISCUSSION

Further increase of the luminosity gain in HERA could be achieved by reduction of the beam sizes of proton and lepton beam at the IP's. The strongest limitation for the beam size at IP is given by the aperture margins in the low beta section for protons and dynamic aperture limitations for leptons. The aperture margins for protons weren't exhausted to full capacity yet, because of the simultaneous reduction of the luminosity gain through the hourglass effect. Since this problem is expected to be removed after the installation of the new damper system, the reduction of the proton beta function at the IP's could be fulfilled up to limits given by the aperture margins in the low beta section.

The beam spot size of the lepton beam could be further reduced by making use of the dynamic beta. For this purpose the rigorous beam-beam beta beat compensation have to be softened. Unfortunately the non-linear chromaticity compensation would be in that case distorted as well. Both effects may lead to enhanced synchro-betatron resonances and thus to poor lifetime and poor background conditions. The further increase of the luminosity gain in HERA represents thus a subtle optimization problem to solve between the available margins and given constraints. Estimations show that an increase of peak luminosity by about 16% could be achieved.

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