FUTURE HERA HIGH LUMINOSITY PERFORMANCE

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Abstract

After the design luminosity has been exceeded in the electron–proton collider HERA, the interaction regions are being rebuilt to obtain smaller β^* at the two interaction points (IP). This should increase the luminosity by about a factor of 4 yielding $L = 0.74 \times 10^{32}$ cm^{-2}s^{-1}. To achieve this, it can not be avoided that the beam–beam tune shift of the e–beam is increased and that the vertical β^* of the protons becomes comparable to the proton bunch length. This implies new beam dynamical conditions. In accelerator studies, the beam–beam limits of the two HERA beams have been explored and the new low emittance optics has been implemented and tested with a polarized positron beam. Based on these tests, the future performance limits of the HERA e–p collider is discussed.

1 LUMINOSITY UPGRADE

HERA exceeded its design goals in 2000 with a luminosity of $L = 0.2\times 10^{32}$ cm^{-2}s^{-1} and an integrated luminosity of 67 pb^{-1}. A large further increase in luminosity requires an upgrade of the interaction region (IR) since the beam cross sections at the IP are limited by the aperture in the low–β quadrupoles. Other ways of increasing the luminosity are not favorable since the lepton intensity is not far from being limited by the available rf power and there is no cost efficient way to increase the space charge–limited proton brightness in the acceleration chain.

The North and South IRs around the colliding beam experiments ZEUS and H1 have been rebuilt [1, 2] to move the first focusing magnets for electrons from 7 m to 2 m distance from the IP and to move the first focusing magnets for protons from 28 m to 11 m. The proton beam can now be strongly focused to $\beta_x^* = 2.45$ m and $\beta_y^* = 0.18$ m at the IP. The previous values have been $\beta_x^* = 7$ m and $\beta_y^* = 0.5$ m.

The new lattice is based on superconducting combined–function magnets installed inside the detectors to separate the beams completely after 8 m and to focus the electrons vertically. To avoid backgrounds for the experiments, the synchrotron radiation generated by these magnets is absorbed far from the IP, which requires sufficient apertures for the radiation fan in the IR magnets. The first lens for the protons is a new type of septum quadrupole which consists of a half quadrupole with a mirror plate. The new feature is a deep triangular cut–out in the mid–plane of the mirror plate for the lepton beam with a separation of only 60 mm from the proton orbit [3]. The magnets have high field quality of $\Delta B/B \simeq (2-3)10^{-4}$ @ $r = 13$ mm so that the dynamic aperture is not affected by field errors.

In order to make space for the superconducting magnets, the compensating solenoids in the detectors have been removed. The non–compensated solenoid fields affect the spin polarization of the lepton beam. Nevertheless, electron polarization can be maintained due to the newly installed spin rotator pairs which provide longitudinal polarization for H1 and ZEUS. The new nominal HERA parameters are:

	p	e
Energy–p/e (GeV)	920	27.5
Emit. hor/vert (nm)	5.1/5.1	20/3.4
β^* at IP hor/vert (m)	2.45/0.18	0.63/0.26
Aperture hor/vert (σ)	12/12	20/20
p per bunch and e-cur.	1.03$\cdot 10^{11}$	58 mA
Tune shift hor/vert (10^{-3})	1.6/0.4	34/51
Bunch Length (mm)	191	10.3

These parameters would lead to a luminosity of $0.74 \cdot 10^{32}$ cm^{-2}s^{-1} which includes a reduction by 0.92 due to the increase of the beta functions along the proton bunch during collision (the hourglass effect).

2 ACCELERATOR STUDIES

Before the upgrade, accelerator studies have been carried out to verify the new parameters and dynamical conditions [4]. The new low emittance optics of the leptons with a β–tron phase advance of 72° per FODO cell and an rf frequency shift of 300 Hz has been implemented and tested. The emittance value of 22 nm and the corresponding increase in specific luminosity was verified. The normalized dynamic aperture, one of the critical issues, was measured and was found to be similar as in the old $60°$ lattice ($A_x \approx 12\sigma_x$). High spin polarization of 60% has been obtained in this configuration. We conclude that there should be no problems with the new lepton optics [5].

In a beam–beam study, the protons were collided with lepton bunches of different intensities inducing 0.8 times as large proton beam–beam tune shift values than expected for the upgraded optics [6]. While there was an enhancement of a factor 2–4 in tail population ($x > 5\sigma_{px}$), the core of the proton beam and therefore the specific luminosity remained unaffected during 10 h of collisions. We thus conclude that there should be a sufficient margin in the proton beam–beam tune shifts.

The vertical beam–beam tune shift of the lepton beam will increase by 50% compared to the year 2000 operation. Therefore, the tune shift limit has been explored by

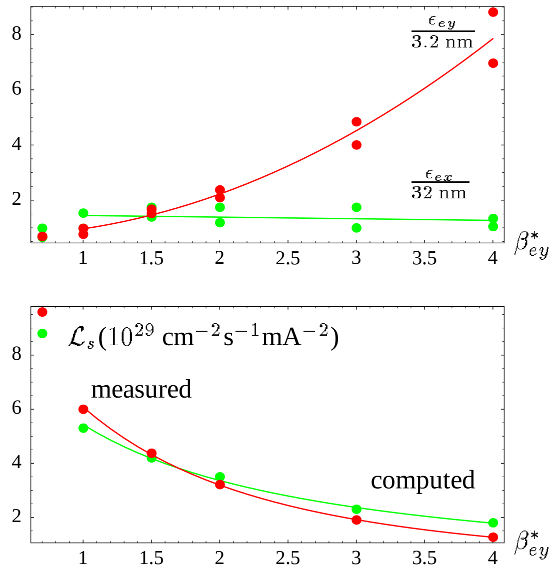

Figure 1: Top: Measured emittances of the lepton beam as a function of the vertical beta function. Bottom: Measured and computed specific luminosity.

increasing the lepton β^*_y [4c)]. Values of $\beta^*_{ex} = 2.5$ m (corresponding to the expected horizontal tune shift for 140 mA of protons) and $\beta^*_{ey}(\text{m}) \in \{1, 1.5, 2, 3, 4\}$ have been implemented and collided with a 90 mA proton beam. The beam sizes were not matched. We observed a monotonously increasing blow–up of the vertical lepton emittance with increasing β^*_y by factors up to 8. At the value of $\beta^*_{ey} = 1.5$ m which corresponds to a beam–beam tune shift of 0.069, the blow–up factor was 1.5. Figure 1 (top) shows the measured vertical emittance as a function of the beam–beam tune shift. Figure 1 (bottom) shows the measured specific luminosity and the luminosity computed from the measured beam emittances. These measurements justify that no emittance blow–up should be expected for the nominal values of the upgraded lattice.

All the critical beam dynamic issues for the HERA luminosity upgrade have been addressed in accelerator studies. There appears to be no beam dynamics problem to achieve the nominal parameters and there might be additional margin for a further increase in luminosity.

3 LUMINOSITY LIMITS

The upgraded lattice provides a physical aperture of 12σ for the protons, while it has been 10σ before the upgrade. The β–functions of the protons at the IP could thus be some 30% smaller than the nominal values yielding $\beta^*_{px} = 170$ cm, $\beta^*_{py} = 12.5$ cm. Thus, the new lattice permits proton β^*–functions as small or even smaller than the bunch length of the protons. The proton bunch length is ultimately limited by intra–beam scattering and grows slowly due to residual rf noise [7]. Currently it's RMS value is about 15 cm at the beginning of a store and reaches 28 cm after 10 h storage. This implies that maximum luminosity will be achieved with a noticeable variation of β along the bunch length. Also the electron beam could be focused stronger at the IP quadrupoles. This would however increase the chromatic error of these quadrupoles and decrease the dynamic aperture from $18\sigma_{ex}$ to roughly 12σ when the beta functions are reduced to $\beta^*_{ex} = 42$ cm,and $\beta^*_{ey} = 17$ cm. Several problems can occur when the electron and proton beta functions are pushed to these ultimate limits: (1) The fact that the bunch length of the protons is similar to the vertical beta function reduces the luminosity, (2) it influences the beam–beam tune shift, and (3) it changes the strength of resonances driven by the beam–beam force; (4) for proton emittances of 3.5π mm mrad, which have often been achieved in the past, the horizontal beam size of the proton beam becomes smaller than that of the electrons which enhances nonlinear effects on the electron beam.

For the smallest possible β^* values and for this small proton emittance, the luminosity, including an hourglass reduction factor, would ultimately be:

nominal: $\mathcal{L}$	reduction	ultimate: $\mathcal{L}$	reduction
$0.74 \cdot 10^{32}$	0.92	$1.3 \cdot 10^{32}$	0.86

Also the beam–beam tune shift can change due to the hourglass bunch–length effect. For HERA the beam–beam tune shift for particles in the center of the bunch and at the 5σ head or tail of the bunch are shown for the initial parameters with which operation will start in 2001. These are the nominal parameters with currents reduced to $0.73 \cdot 10^{11}$ protons per bunch and 50 mA of positrons. These shifts can be compared to those for the ultimate parameters with the smallest possible β^* and small proton emittances and to those for the extreme conditions of the performed accelerator studies:

	$\Delta\nu_{x0}$	$\Delta\nu_x^{5\sigma}$	$\Delta\nu_{y0}$	$\Delta\nu_y^{5\sigma}$
initial p	0.0016	0.00081	0.00044	0.00011
ultimate p	0.0022	0.00060	0.00059	0.00147
studies p	0.0022	0.0017	0.00061	0.00080
initial e	0.024	0.024	0.045	0.044
ultimate e	0.034	0.036	0.069	0.070
studies e	0.041	0.041	0.085	0.083

The tune shifts computed without consideration of the hourglass effect are indicated by an index 0.

The beam–beam resonances also change due to the hourglass effect. The formulas for the resonance strength contain high powers of the beta functions and some of the resonances can therefore strongly increase with increasing beta functions for particle collisions which occur not exactly at the IP but in the head or tail of the proton bunch. We therefore list the resonance strength computed without hourglass effect as well as the maximum resonance strength for particles between $\pm 5\sigma_s$ along the bunch. These numbers can be compared with the resonance strength which were encountered in the extreme conditions of the performed beam–

beam studies:

	initial	ultimate	studies
$\delta(4Q_{ex}+2Q_{ey})$	0.00020	0.00031	0.00045
$\delta(2Q_{ex}+8Q_{ey})$	0.000012	0.000018	0.000036

Other beam–beam resonances of reasonable order are not close to the lepton working point. For the protons there are 7th and 10th order resonances close to the working point. For these resonances maximum resonance strength over the bunch length can differ significantly from the resonance strength computed without the bunch–length effect. The strength (given in units of 10^8) for initial parameters, for ultimate parameters, and for the accelerator studies are indicated by the superscripts i, u, and s are:

	δ_0^i	δ_{max}^i	δ_{max}^u	δ_{max}^s
$\delta(10Q_{px})$	175	175	230	220
$\delta(8Q_{px}+2Q_{py})$	73	73	97	99
$\delta(6Q_{px}+4Q_{py})$	43	55	65	60
$\delta(4Q_{px}+6Q_{py})$	24	55	60	44
$\delta(2Q_{px}+8Q_{py})$	14	65	68	32
$\delta(10Q_{py})$	22	251	300	68
$\delta(14Q_{px})$	3.1	3.1	4.1	4.1
$\delta(12Q_{px}+2Q_{py})$	2.9	2.9	3.8	3.7
$\delta(10Q_{px}+4Q_{py})$	4.4	4.4	5.8	5.8
$\delta(8Q_{px}+6Q_{py})$	5.9	5.5	5.8	5.3
$\delta(6Q_{px}+8Q_{py})$	2.6	7.0	6.0	4.3
$\delta(4Q_{px}+10Q_{py})$	1.2	8.8	8.0	3.2
$\delta(2Q_{px}+12Q_{py})$	0.37	8.5	6.6	1.4
$\delta(Q_{py})$	0.33	22	22	1.7

Most of the resonance strength which would occur in the ultimate case have already been reached in our accelerator studies. The resonances which are stronger for ultimate parameters than in the studies would not be stronger without the bunch–length effect. Reducing the bunch length would therefore not only reduce the hourglass reduction of the luminosity, it would also reduce the resonance strengths to a level for which a stable operation of the proton beam under luminosity conditions was already demonstrated.

4 ULTIMATE LUMINOSITY

Since the beam dynamics seams to be acceptable for the smallest possible beta functions, the luminosity in HERA appears to be limited by the aperture of the protons in the low β–quadrupoles and by the dynamic aperture of the electron beam.

Under extreme conditions the hourglass effect can lead to a decrease of the luminosity with a reduction of β^*. For HERA this would happen for $\beta^*_{py} < 8$ cm. For the minimal $\beta^*_{py} = 12.5$ cm the luminosity is therefore reduced but not limited by the hourglass effect.

The vertical beam–beam tune shift of the leptons becomes $\Delta\nu_{ey} = 0.069$ and should be tolerable according to the beam–beam studies. The $12\sigma_{ex}$ electron dynamic aperture margin is small and it remains to be investigated whether this is sufficient. There is no reason not to achieve the full lepton beam current of 58 mA since the available rf power is sufficient. In order to reach the proton design intensity, many small improvements in the entire accelerator chain will be necessary. This requires much effort but is not fundamentally difficult the ultimate parameters which differ from the nominal parameter list would therefore be:

	p	e
Energy–p/e (GeV)	920	27.5
Emit. hor/vert (nm)	3.57/3.57	20/2.7
β^* at IP hor/vert (m)	1.7/0.125	0.42/0.17
Aperture hor/vert (σ)	10/10	12/12
Tune shift hor/vert (10^{-3})	1.7/0.5	47/69

With these ultimate values the luminosity could be as large as $L = 1.3 \times 10^{32} cm^{-2}s^{-1}$, which includes a noticeable hourglass reduction factor of 0.86. The required emittance coupling of the electron beam of 13.5% has been achieved under the extreme conditions of the mentioned accelerator studies, where the horizontal emittance was $\epsilon_{ex} = 32$ nm, since it was not reduced by an additional rf frequency shift but only by the $72°$ focusing scheme. If this ultimate coupling value can not be reached for $\epsilon_{ex} = 20$ nm due to emittance blowup, the ultimate luminosity might be several 10% smaller, so that $L = 1.3 \times 10^{32} cm^{-2}s^{-1}$ constitute upper limits of what can be reached. In order to get close to these values the full design beam intensities must be attained, there may not be any additional dynamic effects due to the beam–beam and the hourglass effect, the enhanced beta should not lead to intolerable synchrotron radiation tails inside the detectors, and the reduced dynamic aperture has to be sufficient for safe operation.

5 CONCLUSIONS

We conclude that the performance goal of the HERA luminosity upgrade of $L = 0.74^{32}$ cm^{-2}s^{-1} is not unrealistic and we are confident that it will be achieved. However we also conclude that it will be very difficult to obtain a substantially larger luminosity. A luminosity value of about $L = 1.3 \cdot 10^{32}$ cm^{-2}s^{-1} constitutes an upper limit, which willbe hard to reach. The available aperture margins however will be helpful to compensate a possible shortfall of beam intensity in the short term.

6 REFERENCES

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