LUMINOSITY UPGRADE OF HERA

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Abstract

After six years of operation the electron proton collider HERA had reached a luminosity of $1.4 \cdot 10^{31}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, very close to the design value. We present an overview on the HERA upgrade project that pursues the goal to further increase the luminosity three-fold by the year 2000. The increase is achieved by reducing the beam cross sections at the IP to $120 \times 30\,\mu\mathrm{m}^2$ (RMS values). If furthermore design currents can be reached in both machines the improvement factor is up to 5. The upgrade involves a complete rebuild of the interaction regions as well as lattice modifications in the electron ring. Major issues of the project are superconducting magnets that will be installed inside the colliding beam detectors, unconventional normalconducting magnets, the handling of synchrotron radiation in the IR, and electron beam dynamics.

1 CONCEPT AND PARAMETERS

HERA is a 6.3 km long electron/proton collider, presently running at 27.5 GeV for the electrons and 920 GeV for the protons. The proton machine uses superconducting magnets in the arcs. The machine is equipped with four interaction regions (IR's), two of them for electron proton collisions with the detectors ZEUS and H1. The HERA luminosity can be written as follows:

$$\mathcal{L} = \frac{N_p I_e}{4\pi e \varepsilon_x^p \sqrt{\beta_x^p \beta_y^p}} \tag{1}$$

Here it has been assumed that both beams are matched, i.e. $\sigma^e_{x,y} = \sigma^p_{x,y}$. This condition is necessary to minimize the effect of the beam-beam interaction. For the electron beam a linear tuneshift limit of 0.04 should not be exceeded, whereas the proton beam suffers from nonlinear diffusion caused by the beam-beam force in case the electron beam is too small. Furthermore it holds $\varepsilon_x^p = \varepsilon_y^p$ for the proton beam emittances. It is difficult to decrease the proton emittances or to increase the proton bunch population N_p due to limitations in the pre-accelerator chain. The electron current I_e is limited ultimately by the available RF power. The most promising way to increase the luminosity is therefore the reduction of the spotsizes by stronger focusing, thus smaller β-functions $\beta^{p,e}_{x,y}$. In case of the electron beam a reduction of the beam emittance is anticipated in addition. The emittance reduction is achieved by increasing the phase advance per FODO cell from $60°$ to $72°$ and a combined shift of the RF frequency. Details on the parameter choice for the electron machine as well as implications on the beam dynamics can be found in [1].

The limitations for this way to increase the luminosity are mainly given by aperture restrictions and the beam-beam tune shift for the electrons. Additional limitations are caused by the so called hourglass effect for the protons since the vertical β-function comes close to the longitudinal beam size, and dynamic aperture problems for the electrons. Smaller β-functions at the interaction point (IP) imply a steeper increase of the beam dimensions with distance from the IP:

$$\sigma(s) = \sqrt{\sigma_0^2 + \varepsilon^2 s^2/\sigma_0^2} \approx \frac{\varepsilon}{\sigma_0} s \tag{2}$$

Consequently the spotsize at the IP is limited by the available aperture in the final focus quadrupoles and the distance to the IP at which those quadrupoles can be installed. The linear beam-beam tuneshift for the electrons is given by the following expression:

$$\begin{aligned} \Delta\nu^e_{x,y} &= \frac{r_e N_p \beta^e_{x,y}}{2\pi\gamma_e(\sigma^p_x + \sigma^p_y)\sigma^p_{x,y}} \\ &= \frac{r_e N_p \sqrt{\beta^p_{x,y}}}{2\pi\gamma_e \varepsilon^e_{x,y}\left(\sqrt{\beta^p_x} + \sqrt{\beta^p_y}\right)} \end{aligned} \tag{3}$$

Here r_e is the classical electron radius and γ_e the relativistic factor. The beam matching condition has been used to obtain the second line. As one finds from (3) the tuneshift can always be controlled by an appropriate choice of the electron beam emittance. After fixing the emittance, the beam sizes can be matched by adjusting the electron β-functions, which is possible as long as the available aperture allows this.

The concept of the HERA upgrade is based on an early separation of the two beams with combined function magnets that are installed inside the experimental detectors, 2 m from the IP. The following electron final focus magnets are passed by both beams. The first exclusive proton focusing magnet is positioned at 11 m distance, which has to be compared with a distance of 26 m at which it is installed in the present scheme. A summary of the upgrade parameters is shown in table 1, details are discussed in [2]. The luminosity can be raised by a factor 4.7 compared to the original HERA design. This assumes that design currents can be stored in both machines, which has to be achieved by independent improvements. The present machine has already achieved the original design luminosity, even without the full beam intensity, by pushing the aperture margins of the final focus quadrupoles to a considerably larger extend than foreseen for the upgrade (which provides space for 12 rms widths of the proton beam, compared to 9 rms widths in the present HERA operation). Since the parameters for the

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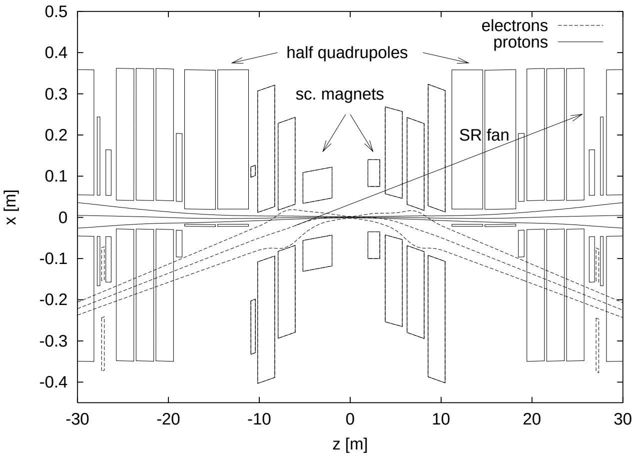

Figure 1: Schematic layout of the upgraded HERA interaction region. Beam envelopes of the proton beam ($12\,\sigma$) and the electron beam ($20\,\sigma$) are indicated.

HERA upgrade have been chosen it was possible to raise the p-beam energy from $820\,$GeV to $920\,$GeV in routine operation. This further improved the specific luminosity. The luminosity upgrade parameters and aperture margins are still based on the larger 820 GeV p-beam emittance. All magnets, however, are strong enough for $920\,$GeV operation. For these reasons the luminosity upgrade parameters appear to be sound (if not conservative). Further improvement of specific luminosity by pushing the aperture margins and exploiting the smaller p-beam emittance may be feasible.

	e-Beam	p-Beam
energy [GeV]	30	820
beam current [mA]	58	140
emittance [nm]	22	$5000/\gamma$
emittance ratio $\varepsilon_y/\varepsilon_x$	0.18	1
beta-function β_x^* [m]	0.63	2.45
beta-function β_y^* [m]	0.26	0.18
spot s. $\sigma_x \times \sigma_y$ [μm^2]	118×32	118×32
rms b. length [mm]	15	130
bb tune shift/IP $\Delta\nu_{x,y}$	0.027, 0.041	0.002, 0.0005
min. aperture [σ]	20	12
Luminosity	$7.00 \cdot 10^{31}$cm^{-2}s^{-1}	

Table 1: Goal parameters for the HERA upgrade.

The layout of the IR should not only allow electron/proton collisions but also positron/proton collisions. In that case the separator magnets switch polarity, and consequently the proton beam receives a small kick in the opposite direction, when compared to the electron case. In the present machine lattice this kick is compensated locally by special septum corrector magnets. However, this comfortable solution costs luminosity because it increases the distance between the IP and the focusing magnets. For the upgrade we adopted an unconventional solution that foresees to move the IP transversally by $8\,$mm for positron operation. With this offset the p(e$^+$) beam penetrates the p(e$^-$) beam at the end of the second proton final focus quadrupole. At this position we install a small septum like dipole magnet that corrects the remaining angle. The positron orbit is matched to the electron orbit by small transverse movements of the electron final focus magnets, which can be done without modifying the vacuum system.

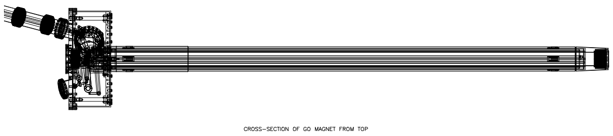

Figure 2: Left superconducting magnet, GO, top view (courtesy: BNL).

2 NEW COMPONENTS

Superconducting magnets. The early beam separation and focusing of the electron beam is done with superconducting magnets. We use two types of sc. magnets, left and right from the IP. The magnets are being designed and manufactured at BNL [3]. Because of the absent iron yoke those magnets can be build with very small outer diameters but relatively large apertures, which is important for the safe passage of synchrotron radiation (SR). The small outer diameter makes it possible to install the magnets directly inside the detectors. Both magnets have four coils: horizontal dipole, vertical dipole, quadrupole and tilted quadrupole. The vertical dipole is used for orbit correction and the tilted quadrupole for coupling correction of the electron beam.

Normalconducting magnets. In total we need 56 new magnets for the HERA interaction region. Most of the new magnets are being build at the Efremov Institute in St. Petersburg, Russia [4]. Many of these magnets have special features, resulting from the close beam orbits of the two machines, or synchrotron radiation issues. Examples are the electron final focus magnets that exhibit gaps between the coils to provide space for the SR fan and NEG pumps above and below the beam pipes. The first two proton quadrupoles are half quadrupoles with mirror plates to let the electron beam pass closely without affecting it. Another example is the above mentioned septum dipole magnet for the proton beam which has stringent requirements for the stray field that the electron beam experiences, at a distance of only $120\,$mm from the protons.

Vacuum system. Totally $448\,$m of UHV vacuum system have to be build new for the HERA upgrade. Since the beam separation is done in the detector, background induced by beam-gas interaction is more critical now and consequently the requirements on the vacuum quality are higher. At every possible location we are planning to equip the chambers with NEG pumps. In addition there are getter pumps and Ti-sublimation pumps installed in-between the magnets. The synchrotron radiation has to be guided relatively far from the detector to avoid too much backscattered photons. On the electron-downstream side we have foreseen key-hole shaped stainless steel chambers which are up to 250 mm wide. From 11 m on the outer SR fan is transported in a separate pipe. The critical septum absorber is discussed in [5].

3 CRITICAL ISSUES

Synchrotron radiation. The bend radius of the beam separation magnets has been decreased from 1200 m to about 400 m. Consequently the total SR power in the IR is increased to about 28 kW. Since the beam separation is done inside the detectors it is not possible anymore to collimate SR before the beams enter the detectors, as it is done in the present layout. In the new scheme the SR has to pass the detector safely without loosing even small fractions in the detector area ($P_{\rm loss} < 10^{-8} \cdot P_{\rm tot}$). To predict or to guarantee such small losses without collimation is difficult since the particle distribution in the e-beam tails is not precisely known. We are planning to do detailed beam tail studies by scraper measurements in the present machine.

Particle background. Another implication of the beam separation in the detectors is that all low energy electrons, produced by bremsstrahlung interactions with residual gas molecules in the straight IR section, will ultimately hit the detector beam pipe and cause background. This qualitative difference to the present scheme would cause a large increase in the particle background. To reduce this effect the lattice incorporates a dispersive chicane upstream of the detectors to collimate low energy electrons. However, there are still some meters of beamline between this collimation scheme and the detectors, where the beam-gas induced background will depend sensitively on the achievable residual gas pressure.

Sc. magnets inside detectors. The installation of the sc. magnets inside the detectors has two unpleasant implications. One is that magnetic detector components disturb the field quality of the magnets. Simulations predict for the magnet on the right side in ZEUS a sextupole component of several 10^{-3}. According to the simulations this could be reduced to acceptable $2 \cdot 10^{-4}$ by installing purposely additional iron parts that symmetrize the geometry. It is planned to verify the simulations experimentally by field measurements in realistic environments. The second difficulty arises from the interaction of the magnet end fields with the detector solenoid fields. At H1 one expects a magnetic force of about 5000 N on one end of the left sc. magnet, which is much larger than the weight force of the magnet of about 750 N. Unfortunately the magnet cannot be fixed very rigidly in the detector environment. While the electron beam is ramped from 12 to 30 GeV we expect a vertical movement of the magnet of $700\,\mu$m. This motion has to be corrected by a ramp table for the vertical correction dipole.

Electron beam polarization. The electron machine of HERA operates routinely with polarized beam, typically $50\% - 60\%$, which is used by the internal fixed target experiment HERMES in hall east. Spin rotators are installed in the IR east to provide longitudinally polarized electrons at the IP. In order to minimize the depolarizing effect of the solenoid fields of the other detectors, so called anti-solenoids are installed next to them for local correction. Because of space requirements those correctors will be removed for the upgrade. The beam coupling has to be corrected non-locally by tilted quadrupoles. Additional spin rotator pairs will be installed in the north and south interaction regions, primarily with the purpose to provide longitudinally polarized electrons also for the ep experiments. Without the anti-solenoids these rotators become essential also for the over-all achievable polarization degree since a longitudinally oriented spin is not disturbed by a solenoid field. A further complication arises from the partial superposition of detector solenoid field with the dipole fields of the sc. magnets. In summary it will be more difficult to achieve comparable polarization levels as in the present machine.

4 SUMMARY AND SCHEDULE

The HERA upgrade is an ambitious project that tries to push the design of the interaction regions to the possible limits. The qualitatively new scheme to separate the beams already inside the detectors will make the machine operation more critical. To guarantee safe passage of more than 10 kW synchrotron radiation through the detectors the machine controls and interlocks have to be refined.

The projects makes good progress, all components are still on schedule and the first five normalconducting magnets have been delivered already to DESY. The shutdown for installation of components in the tunnel and modifications of the ep detectors is scheduled for May 2000 and will take about 9 months.

5 REFERENCES

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