A LEPTON-PROTON COLLIDER WITH LHC

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Abstract

The luminosity and collision energy of lepton proton collisions using the LHC and a LEP-size storage ring is explored assuming proton-proton collisions in parallel. A model accelerator layout demonstrates that luminosities in the order of $L=10^{33}$cm^{-2}sec^{-1} should be possible.

PHYSICS MOTIVATION

Deep inelastic lepton-nucleon scattering (DIS) has been pivotal in resolving the structure of the proton and developing the field theory of strong interactions between quarks and gluons. With the first lepton-proton (ep) collider HERA, these investigations have been brought to the high energy frontier corresponding to the Fermi scale of a few hundreds of GeV. Major new results include the observation that electromagnetic and neutral and charged current weak interactions to become of comparable strength at squared 4-momentum $Q^2=10^4$GeV^2 transferred from the lepton to the proton, the discovery of a new regime of high parton densities at small momentum fractions x of the proton, a rather high proportion of diffractive events, about 10%, in which despite the violent character of the collision the proton remains intact and which may be related to the confinement of quarks, and the accurate measurement of the light and heavy quark as well as the gluon distributions in the proton. Deep inelastic scattering at HERA has been proven to be of the utmost importance for preparations for Large Hadron Collider (LHC) in the TeV scale of energy. Ep-scattering at higher energies is an obvious next step. DIS physics at TeV energies is the physics of the electron-quark sector in which resonant states may be observed and then studied in detail in a high luminosity ep collider. While the high density, low x physics has revealed a rich structure of the proton and of QCD, a further large step in energy is required for a detailed understanding of these phenomena. A third important aspect of TeV ep physics is the high accuracy one may obtain in the precision measurements of the gluon distribution, the beauty quark density in the proton and the strong coupling constant. The proposed ep collider at the LHC (LHeC) combines the 7 TeV proton beam with a new electron beam of about 70 GeV. This increases the accessible Q^2 and the luminosity by factors of 20, when compared to HERA. Physics up to $Q^2=10^5$GeV^2 can be explored extremely efficiently. The high design luminosity will also enable studies of new particles up to TeV energies possibly polarised lepton beams and thus a well defined initial state. Hence, the LHeC appears as a natural complement of the LHC and a linear e+e- collider.

PARAMETERS AND CONSTRAINTS

Since the luminosity which can be achieved in linac-ring ep colliders is limited to around $L=10^{31}$cm^{-2}sec^{-1} [1], we consider the luminosity which could be achieved in a ring-ring configuration at LHC. A lepton ring, to be installed above the superconducting magnets of the LHC, brings leptons into collisions with the LHC protons at one interaction point. Similar estimates have been performed previously [2, 3]. The present estimate makes use of the experience of high luminosity operation at HERA to estimate the luminosity of LHeC. The aim is to investigate the parameters required for a realistic LHeC with a centre of mass energy of 1.4TeV and with a peak luminosity of $L = 10^{33}$cm^{-2}s^{-1}. Proton-proton collisions take place simultaneously, which implies that the proton beam parameters for LHeC are determined by the existing LHC parameters. The proton parameters used in this study are taken from reference [4] (with the beam energy 7 TeV, the number of protons per bunch $1.67\cdot10^{11}$, the normalized beam emittance 3.75 μm, the bunch length of 7.5cm and the bunch spacing 25ns). In order to provide sufficient space for the detector, a magnet-free area of at least 2.4m is required in the interaction region. The aperture of the first accelerator lattice elements should allow for a detector acceptance angle of 10 degrees.

The luminosity of a circular high energy ep collider is $L = I_e N_p \gamma_p / (4\pi e \cdot \varepsilon_{Np} \cdot \sqrt{\beta_{xp}} \sqrt{\beta_{yp}})$ (I_e, the lepton beam current, N_p, the number of protons per bunch, γ_p, the Lorentz factor of the protons, ε_{Np} the normalized proton transverse beam emittance and β_{xp} β_{yp}, the values of the proton β-function at the interaction point, IP). It is assumed that the beam cross sections of the proton and lepton beams at the IP are equal, and that the beam-beam tune shift parameters are tolerable. With the proton parameters given, only the lepton beam current and the β-functions at the IP remain to be chosen to achieve $L = 1 \cdot 10^{33}$cm^{-2}s^{-1}.

The lepton beam current in a high energy lepton storage ring is limited by RF power. A power of $P_{rf}=$ 50MW for 5000 h operating time (≈86% of the LEP power consumption, 28% of the 1999 CERN site power consumption of 910GWh [5]) is considered as an upper limit. The maximum lepton beam current is then determined by the beam energy. With a 3000m bend radius, $E_e = 70$GeV, and $P_{rf} = 50$MeV it is 71mA. It remains to design the interaction region and a lepton accelerator lattice, which provides proton β–functions at the IP of $\beta_{xp}\beta_{yp}=1$m^2, matching the cross section of the lepton beam while providing sufficient dynamic aperture. Since the electron beam is naturally flat, whereas the proton beam is naturally round, the ratio of the horizontal to the vertical proton β-function at the IP is chosen to be 3.6 to ease matching the beam cross sections. For matched beam cross sections, the lepton emittance determines the lepton β-functions at the IP. The lepton beam emittance is constrained to a window limited by dynamic and geometric aperture considerations, beam-beam tune shift limitations, the so-called hourglass effect

due to the long proton bunches and parasitic beam-beam interactions which require a small beam divergence to help the beam separation. Based on these considerations, the emittances for the leptons are chosen to be ε_{xe}=7.6nm and ε_{ye}=3.8nm. This implies lepton β-functions of β_{xe}=12.7cm and β_y=7cm. The accelerator lattice consists of a FODO structure in the 8 arcs with a betatron phase advance of 72º per cell. In order to achieve the required emittance the number of cells in the arc of LHeC is increased from the LEP value of 290 to 376. The cell length is 60.3 m and the bending radius is 2997 m and the circumference is C =26659 m. The beam current of 71 mA is composed of 2800 bunches spaced by 25 ns with $1.40 \cdot 10^{10}$ particles per bunch. Beam instabilities are not expected to become an important performance limitation given that the single bunch currents are relatively modest. The expected total impedance, roughly estimated, is less than the impedance of LEP. A conventional active damper system could be used to damp coupled bunch oscillations if needed. Since the ATLAS and CMS detectors are assumed to remain active at their locations when the lepton-proton collider is operated, a bypass must be provided around them. There exist survey tunnels which are parallel with the LHC straight sections 1 and 5, which could be used for a bypass of the caverns which house the detectors. They have a distance of about 10m from the LHC beam axis and a length of about 100m. Two connection tunnels about 250m long and up to 2m in diameter would have to be drilled from the end of the arcs to connect to these tunnels.

INTERACTION REGION

A lepton-proton physics programme at the LHC would be unlikely to begin before the B-physics programme is completed. One may thus envisage locating the interaction region at IP8 where LHCB is housed.

To obtain small β, the low-β quadrupoles have to be close to the IP. This requires quick separation of the two beams outside the collision region. Separation by strong magnetic fields produces high power synchrotron radiation, which is problematic because of experimental backgrounds and heating of the vacuum system. The alternative, a large crossing angle, reduces the luminosity. The following scheme compromises between these difficulties: The lepton and proton bunch spacing is 25 ns. The two proton beams cross at the IP with a relative angle of 6mrad in the horizontal plane and a vertical separation. On of the proton beams collides with leptons collide at a horizontal angle of θ_c= 2mrad. At the first parasitic ep collision point at 3.72m longitudinal distance from the IP, the lepton and the proton beam are separated by about 7.8mm or 8.4σ of the horizontal lepton beam size which is considered sufficient to avoid potentially harmful parasitic beam-beam interactions. The length of the magnet-free space for the detector beam-pipe is assumed to be 2.4 m. The detector acceptance angle is 9.4º. The low-β quadrupoles for both protons and leptons are

assumed to be superconducting with a cold beam pipe and cold iron flux return. The focusing of the electrons is accomplished by a quadrupole triplet. The low-β quadruples are displaced by 0.25mm from the beam axis, which provides a 0.4mrad deflection of the lepton beam. The low-β triplet is followed by a separator dipole magnet with a field of 0.023T and 15m length which provides a 1.5mrad deflection. The beam separation at 22m, at the first proton low-β magnet, is 62mm. The proton beam passes off-centre through the lepton low-β triplet before entering the proton low-beta triplet which provides apertures of (15-20) mm, strengths of about 120T/m, and a total length of 45m. The first of these magnets is a septum half quadrupole as in the case of HERA. The width of the septum is 12mm. The return yoke of the first two quadrupole magnets accommodates a lepton beam pipe at room temperature. The beam separation at the third quadrupole is sufficiently large for the leptons to pass outside the cryostat. After the low-β triplet of the proton beam, the lepton beam is deflected by 5mrad vertically. The two proton beam orbits diverge to 80 cm separation. After the vertical deflection of the lepton beam, the protons are matched to their arc trajectory with three 10 m long superconducting dipole magnets. The interaction region is sketched in figure 1.

This arrangement accommodates the lepton β-function at the IP of β_{xe}=12.7cm and β_{ye}= 7cm. The peak values of the vertical and horizontal lepton β-functions amount to 906m and 269m. The chromaticity contributions from the IR are quite modest with values of ξ_{xIR}= -7 and ξ_{yIR}= -38, which is about 20% of the contributions of the arc. The proton β-functions at the IP are 1.8m and 0.5m with horizontal and vertical peak values of 2600m. The magnets provide apertures of at least 13.5 times the RMS beam size for protons and at least 20 times the RMS beam size for leptons. According to HERA experience [6], this is sufficient to avoid beam lifetime reductions or poor backgrounds.

The crossing angle of θ_c = 2mrad reduces the luminosity by a factor of 3.5. One can recover from this reduction if the proton beam is tilted around a vertical axis by θ_c/2. This can be accomplished using 500MHz RF resonators with a transverse deflecting field of 20.8MV. With β-functions of 708 m at the crab cavities, the transverse kick for 1-σ particles is 2.1 μrad. With a gradient of 3.4MV/m, the two crab cavity systems around the IP must have an active length of 6.1m each. The two crab cavities can be installed in the IR between 120m and 140m from the IP. The horizontal amplitude of the 'crabbed' trajectories is less than 0.3mm for 1 σ particles. The corresponding increase in aperture requirement is negligible.

In the beam separation bending fields (ρ=10^{4}m) synchrotron radiation of 9.1 kW with a critical energy of 76 keV is produced, which is transported within a fan of 1.9mrad horizontal opening angle and an RMS height of 2mm. Due to the crossing angle, the synchrotron radiation fan is tilted away from the proton beam and does not enter

the cold proton low-β quadrupole magnets. The linear power density reaches a maximum of 8 kW/cm at the location of the 1m-long absorber at 22m. No problems are expected from this level of radiation.

The superconducting low-β quadrupoles for the electron beam can be built using standard superconducting technology. The first two low-β quadrupoles for the protons are more challenging, because the lepton beam pipe has to pass through the cryostat of these magnets. The first lens is a septum quadrupole laid out as a superconducting half quadrupole. The radius of the half aperture is 30mm which provides a 15mm aperture for the beam. The left side half of the magnets is a standard superconducting quadrupole. The other half consists of magnetic iron with a gap for the lepton beam. The gradient achieved is 93T/m. The magnetic mirror plate works well up to a magnetic induction of 2.79T near the coil. Field calculations confirm that the magnet has a reasonable field quality and has no field in the gap containing the lepton beam.

BEAM-BEAM EFFECTS AND LUMINOSITY

The luminosity is recalculated from the design parameters. The 7.5cm bunch length of the proton beam causes a luminosity reduction to R=94 %. The crossing angle should not reduce the luminosity since it is compensated by the crab-tilt of the proton bunches. The so-called dynamic beta, the distortions of the β-functions in the core of the beam the beam-beam interactions decreases the lepton β-functions at the IP in the electron-proton case if the tunes are above the integer and below the quarter integer resonance. For Q_{xe}= 0.10 and Q_{ye} = 0.11 (similar to HERA-e tunes) one obtains a reduction of the electron β-functions from β_{xe}= 12.7 cm to β_{xe}=6.9cm, and from β_{ye} =7cm to β_{ye} = 7.3 cm. The beam-beam tune shift values which result from the parameters are $\Delta\nu_{x,y}$=0.048, 0.051 for leptons and $\Delta\nu_{x,y}$=0.003, 0.008 for protons. These large tune shifts in both planes are beyond

HERA experience and more studies are needed to verify whether they are tolerable. The long-range beam-beam tune shift parameters as calculated using the formulae in reference [7] are 0.0010, -0.0015 (leptons). The operational experience with long-range beam-beam effects in LEP [8] (at four instead of at one interaction point) indicates that there may be problems mainly due to beam-beam orbit effects. A somewhat larger crossing angle might be necessary to reduce the long-range beam-beam effect sufficiently. Further study is needed to confirm that a crossing angle of 2mrad is sufficient for 25 ns bunch spacing. Taking these effects into account the luminosity for I_e= 71mA, N_p= 1.68 10^{11}, ε_{xp}= 0.5 nm, ε_{xe}= 7 nm, ε_{ye} = 5 nm and R = 0.94 amounts to

$$L = \frac{I_e N_p \gamma_p R}{4\pi e \sqrt{\varepsilon_{xp}\beta_{xp} + \varepsilon_{xe}\beta_{xe}}\sqrt{\varepsilon_{yp}\beta_{yp} + \varepsilon_{ye}\beta_{ye}}}$$

$$= 1.1\cdot10^{33}\,cm^{-2}s^{-1}$$

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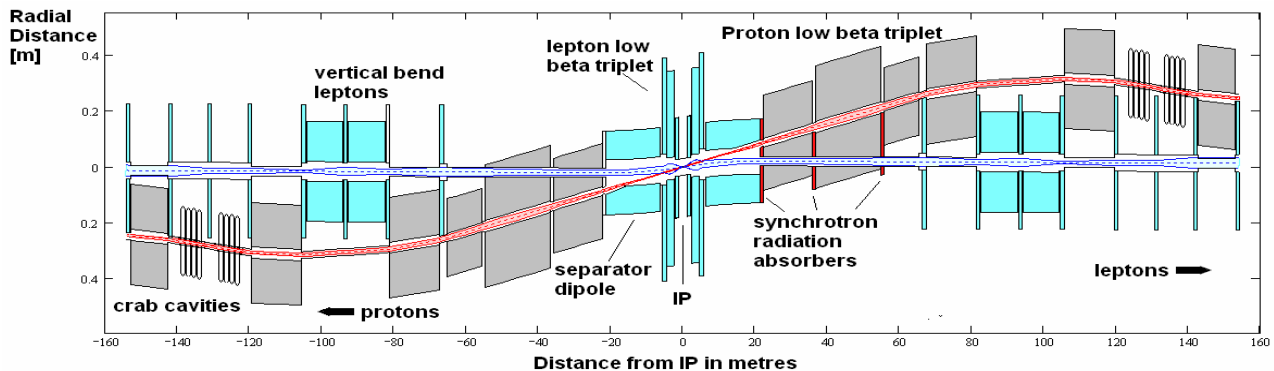
Figure1: Schematic top view of the ep IR. Shown are the magnet apertures and the beam envelopes (10 RMS beam sizes for protons, 20 RMS beam sizes for leptons). Note the distorted scale. The non-colliding proton beam is not