Electrical power of ring-linac options for LHeC

Anders Eide

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Laboratory for Particle Accelerator Physics

2008

1 – Introduction

The Large Hadron electron Collider (LHeC) is a proposed hadron-lepton (electrons and positrons) collider that is being considered to complement and extend the physics reach of the LHC. It should run at the same time as hadron collisions take place in the LHC experiments. The LHCb interaction point is the most likely candidate for the LHeC detector.

The physics motivation for the LHeC includes more precise interpretation of data from LHC, due to an improved knowledge of the parton distribution functions of protons, and the expectation of new physics such as leptoquarcks [13].

This report discusses the electrical power demand (RF-power + cryogenic power) for operation of the ring-linac options for LHeC.

2 – Options for the lepton accelerator

Two possible main options are being explored for the lepton accelerator. The first is an electron/positron storage-ring accelerator in the LHC-tunnel with a nominal energy of 60 GeV, resulting in a center-of-mass energy of 1.3 TeV in the collisions, and a luminosity in the range of 10^{33} $cm^{-2}s^{-1}$. One of the potential problems with the storage-ring option is that it require bypasses of more than 10 m to avoid the LHC experiments, but this is resolvable.

The second candidate is an electron linac in a separate tunnel, possibly with even higher energies (up to 2 TeV center-of-mass energy), but with lower luminosity than the ring option. The reduction in luminosity for a ring-linac collider is a result of the electrons only taking part in a single collision. The ring-linac option also has the advantage of allowing a high polarization (~80%) of the leptons, and it makes it fairly easy to obtain the desired emittance, e.g. an emittance that matches the LHC-beam's normalized emittance of 3.75 µm (may be improved by planed LHC injector upgrades – namely Linac 4, SPL and PS2), as there is no synchrotron radiation in the linac, but adiabatic damping. The tunnel, cavities and other equipment and technology developed for an LHeC linac can perhaps later be used for an ILC-type collider.

Three different ring-linac designs are considered: a normal conducting linac, a superconducting pulsed linac and a superconducting continuous wave linac, as well as energy recovery options for the two last cases.

2.1 – Normal conducting linac

A pulsed normal conducting linac does in general have a much lower efficiency in the transfer of power from the RF waveguide to the beam than superconducting machines. However, as there is no cryogenics system to supply, it can still be competitive in luminosity at low power.

For the LHeC a normal conducting linac is expected to give a too low luminosity and it is only treated superficially here. The calculations presented are derived from numbers from the CLIC design, although the CLIC beam parameters are probably the most difficult to use for collisions with the LHC.

2.2 – Superconducting pulsed linac

The use of superconducting (s.c.) cavities obviously enhances the efficiency of the power transfer from the RF-cavities to the beam. This as a result of the reduction of wall-loses in the cavity to almost zero.

However, the efficiency does not, in the pulsed case, become 100% nor, in most cases, even close to this ideal value. As an example the XFEL design assumes an efficiency of less than 50%. The reason for the losses is that in a pulsed linac one has to recreate the RF-wave before every pulse. This results in a filling time, given by the difference between the RF and the beam pulse length, where the power input does not contribute to the beam acceleration. The efficiency of a machine can thus be calculated from the ratio t_B/t_{RF} where t_B is the beam pulse length, t_{RF} the RF pulse length

The filling time scales as 1/I, where I is the beam current. Which means that the efficiency can be rescaled from some reference machine with

$$\eta = \frac{t_B}{t_B + (t_{RF,ref} - t_{B,ref})\frac{I_{ref}}{I}}$$

where the parameters are defined as above. The parameters with the index *ref* indicates the values from the machine design used as reference [14].

This RF to beam efficiency gives the beam current

$$I = \frac{P}{E} - \frac{t_{RF,ref} - t_{B,ref}}{t_B} I_{ref}$$

where E is the electron energy and P the beam power. This gives the (to me somewhat surprising) result that the RF to beam efficiency term, caused by the build up time of the pulse, only reduce the luminosity of collisions by a constant independent of the beam power.

In the following calculations I have assumed a 10 Hz pulse frequency and 1 ms pulse length, giving a duty factor (d.f.) of 1%. This might be too high (a factor two higher than for ILC) due to limitations on the power which can be provided by the klystrons and coupled to the cavities (at a reasonable price level), but this is not further discussed here.

2.3 – Superconducting continuous wave linac

The possibility of a continuous wave (c.w.) linac is a result of the significant reduction of wall losses with the introduction of super conductivity. There are still a few residual losses though, resulting in a heat load to the structure, and the power needed to maintain the temperature at 2 K in the cavities poses a serious drawback for this option. It is therefore chiefly considered in some energy recovery scheme.

2.4 – Recirculating linac

A recirculating s.c. linac will reduce the cryogenics power by the number of passes through the linac. Of course we also have to take into consideration the synchrotron losses, given by

$$\Delta E = C_\gamma \frac{E^4}{\rho}$$

where ρ is the radius and with the constant $C_\gamma = 8.858 \times 10^{-5}$ m/GeV^3 [1]. For a 70 GeV machine a reasonable diameter is 1 km with five passes, i.e. four circulations. This gives an energy loss of 1.6 GeV to synchrotron radiation in the last circulation where the electrons have an energy of about 55 GeV.

To obtain larger energies in a recirculating linac one has to increase the arc to control synchrotron radiation losses and this give an ultimate energy limit around the maximum energy in LEP at 100 GeV, with the last couple of circulations inside the LHC tunnel.

A recirculating linac option might have more problems obtaining the emittance wished for and must also include additional electrical power for bending and focusing magnets. These factors are ignored here. Recirculation is only considered with c.w. mode

2.5 – Energy recovery

It is possible to recover most the energy put into the beam by decelerating the particles after the collision with the LHeC. This can be done either by transferring the beam back to a recirculating linac and decelerate the beam through the same number of passes as it was originally accelerated through, or by the use of two opposing linacs where the beam is accelerated in one and decelerated in the other. The last option also increase the luminosity by a factor two assuming interaction of beams from both linacs with the two LHC beams.

The recirculating linac with energy recovery seems to be difficult to realize due to the imbalance of the energy caused by synchrotron radiation losses. This problem is not discussed here.

The two linacs option is a very tempting alternative as it could yield a much higher luminosity for a given power input. It will also make a beam dump unnecessary, which can otherwise be a serious challenge.

There are some drawbacks though, in addition to the fact that the energy recovery scheme in it self will need a lot of R&D. The tunnel length and cryogenics system etc. will of course increase by a factor two. There might also be some new challenges concerning the beam interaction points and, since the center of mass moves with the proton beam, two detectors are needed, one in each direction.

Energy recovery can also be done with a pulsed s.c. linac, as the pulse will last much longer than the time the beam needs to pass through the entire linac. I have assumed 95% energy recovery for both pulsed and c.w. linacs.

3 – Cryogenics

To obtain an estimate for the cryogenic power we used the numbers from the systems planed for the ILC and XFEL accelerators. These designs were as expected correlated (apparently the ILC system is based on XFEL's), but for ILC somewhat better efficiencies are assumed.

The cryogenics system consists of three helium circuits kept at different temperatures. The innermost, of liquid helium at 2 K, is enveloped by a 5-8 K circuit and finally the outer one operates at 40-80 K. The ILC and XFEL accelerating gradients and heat loads in terms of electrical power are given in Table 1.

Table 1: Cryogenics system parameters

	Accelerating gradient [MV/m]	Duty factor	Static heat load [W/m]	Dynamic heat load [W/m]
XFEL[1]	23.6	0.65%	410	781
ILC[2]	31.5	0.75%	337	728

[1] [4] [2] [5]

The dynamic heat load is proportional to the square of the accelerating gradient [15] which means that a rescaling of the power estimate can be obtained from

$$P = L_S \eta \frac{E}{g} + \frac{L_{D,ref} g^2 D}{g_{ref}^2 D_{ref}} \eta \frac{E}{g}$$

where L is the heat load of the cryogenics system (static and dynamic), D is the duty factor, g the accelerating gradient and η the efficiency (E/g = length of linac).

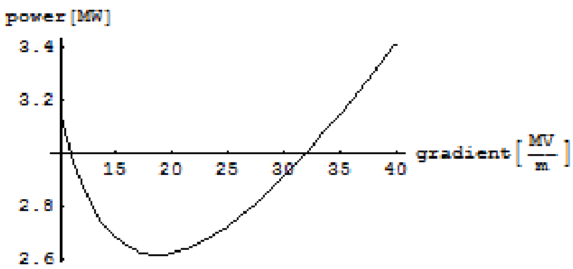

Figure 1: Plot of cryogenic power vs. accelerating gradient for a 1% duty factor 70 GeV linac with minimum at 19 MV/m

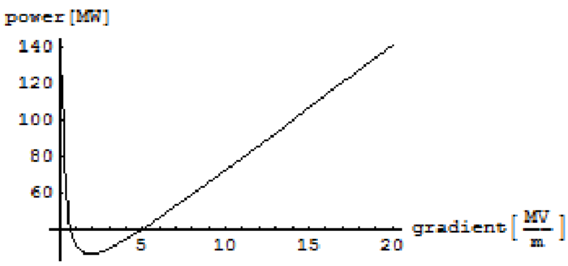

Figure 2: Plot of cryogenic power vs. accelerating gradient for a c.w. 70 GeV linac with minimum at 2 MV/m

We understand from the equation that the cryogenics power will be much higher with a c.w. operation than with a pulsed machine. The increased significance of the dynamic part cause the optimal gradient to be much lower for c.w., i.e. it becomes 2 MV/m rather than 19 MV/m (see Figures 1 and 2), and, because of the increased proportion of power going to cryogenics, approaching this optimum becomes much more important, as shown in Figure 3.

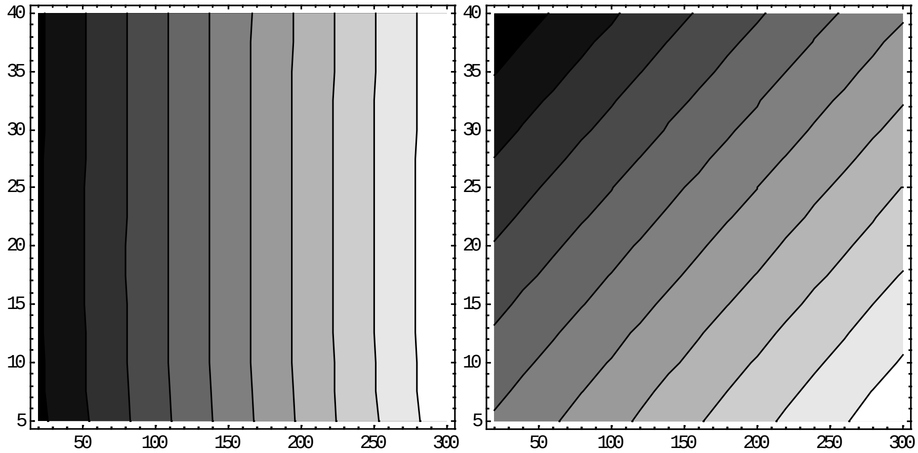

Figure 3: Qualitative contour plots of how the luminosity evolves as a function of AC-power [MW] (x-axis) and gradient [MV/m] (y-axis) for a 1% duty factor linac (left) and for a c.w. linac (right). Light colors signify high luminosity.

I have in the following calculations assumed a 30 MV/m gradient for the pulsed and a 10 MV/m gradient for the c.w. s.c. linac.

The cryogenic power is influenced by the RF-frequency, but this relation is fairly complicated. As the frequency of the ILC and XFEL designs is 1.3 GHz I have assumed the same for the LHeC linac. However, the Superconducting Proton Linac (SPL) will run at 700 MHz, a decision that was made to be able to operate with higher beam current. It might be an advantage for the LHeC electron accelerator to operate at this energy as well and I have therefore included some crude calculations at this frequency, with the assumption that the reduction of the RF-frequency by almost a half also halves the cryogenic power. This is based on an argument presented by Trevor Linnecar and Joachim Tuckmantel, but it is very simplified, especially for the pulsed linac, where the rescaling is very complex. The idea is that at half the frequency the cavity area is increased by a factor four, the number of cavities is reduced by a factor two and the surface resistance by a factor four, hence the cryogenic power could be reduced by a factor two [17].

4 – RF-efficiencies

To calculate the efficiency of the power transfer from wall plug to the beam I looked up estimates from other linacs, namley the Electron Laboratory for Europe (ELFE), the Continuous Electron Beam Accelerator Facility (CEBAF), the International Linear Collider (ILC) and the European X-ray Free Electron Laser (XFEL), (shown in Table 2) and assumed similar numbers. Unfortunately it turned out to be difficult to obtain numbers for some of the machines and so most of the calculations are based on estimates done for ILC and XFEL.

Table 2: Some parameters from other s.c. linac designs (of these only CEBAF has been in operation)

		ELFE[1]	**CEBAF**[2]	**ILC**[3]	**XFEL**[4]
Wall plug → Klystron				83%	75%
Klystron → RF		~50%	~45%	65%	65%
Transport to cavities		91%	~88%	93%	94%
RF → Beam		83%	~32% (?)	62%	46%
Cells /cavity		4	5-9	9	9
Length	[m/cavity]	1.7	3	1	1
Q_0		$>2.7\times10^9$	10^9-10^{10}	10^{10}	$>10^{10}$
R/Q	[Ω/m]	270		1000	1000
Duty factor		cw	cw	0.75%	0.65%
Beam current	[μA]	100	200	45	30
Pulse length (beam)	[ms]			~1	0.65
RF Pulse length	[ms]			1.6	1.4
RF-frequency	[MHz]	350	1500	1300	1300
Gradient	[MV/m]	7.3	19-22	31.5	23.6
Main linac length	[km]	1.8		2 x 11.5	1.7
Particle energy	[GeV]	25 (3.5/pass)	12 (2.2/pass)	250	20

[1][6] [2][8,16] [3][5] [4][4]

I used 50% wall plug to RF efficiency for all the schemes considered (from XFEL and ILC estimates). I further assumed 100% RF to beam efficiency for the cw schemes and used the efficiency equation in chapter 2.2 for the pulsed machine. For the normal conducting linac a wall plug to beam efficiency of 10% is used [7].

5 – LHC parameters

The beam parameters of the LHC obviously influences the collision luminosity. As the LHeC will not be built before 2015, and as there are several planed upgrades of the LHC before this time, it seems reasonable to assume somewhat better parameters than what is currently expected. In addition it may be possible to adjust some parameters to optimize for the ring-linac option, in particular to squeeze the β*. The numbers used in the following calculations of luminosity are shown in Table 3 together with the parameters expected after LHC commissioning this fall.

Table 3: LHC proton beam parameters

		Nominal operation 2009[1]	Assumed for LHeC[2]
Proton energy	[GeV]	7000	7000
Number of particles per bunch		1.15×10^{11}	3.4×10^{11}
Transverse normalized emittance	[μm]	3.75	3.75
Optical β-function at IP (β*)	[m]	0.5	0.1
Bunch spacing	[ns]	25	25

[1][3] [2][10,15]

6 – The luminosity

The optics and bunch spacing of the electron beam is assumed to be exactly matched to the proton beam [12]. The luminosity is thus calculated from

$$L = \frac{I_e N_p}{4\pi e \beta^* \epsilon}$$

where N_p is the number of protons per bunch, ε the proton beam chromaticity and β* the betatron function in the interaction point [1]. The electron beam current I_e is

$$I_e = \frac{P_{AC} - P_{cryo}}{E} \eta_{RF}$$

where E is the electron energy, P_{AC} the total electrical power, P_{cryo} the cryogenic power and η_{RF} the total wall plug to beam efficiency. The formulas and values used to calculate the cryogenic power and the RF-efficiency are given in the appropriate sections above.

The physics motivation for the LHeC puts a lower limit on the luminosity at 10^{32} $cm^{-2}s^{-1}$.

7 – Results

The results are presented as plots of the luminosity as a function of the electrical power, or, in Figure 7, the energy.

The luminosity as a function of the total electrical power is shown in Figure 4 with an RF-frequency of 1.3 GHz and in Figure 5 rescaled to 700 MHz.

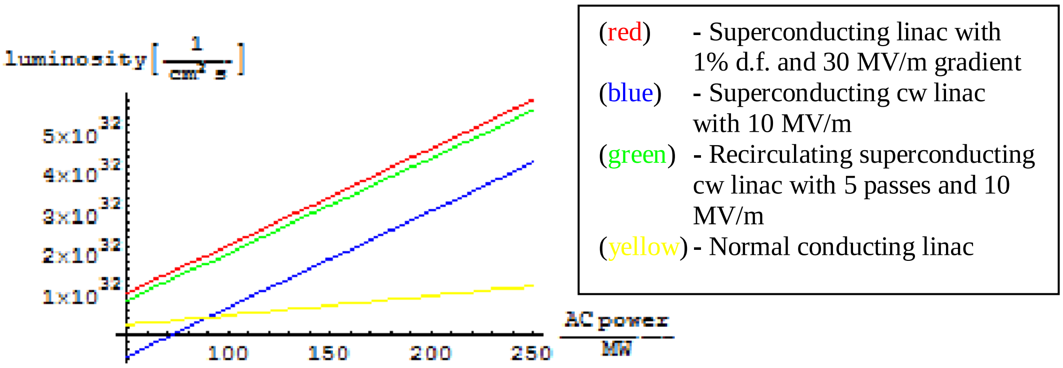

Figure 4: Luminosity of LHeC with 70 GeV electrons and 1.3 GHz RF-frequency for different linac schemes

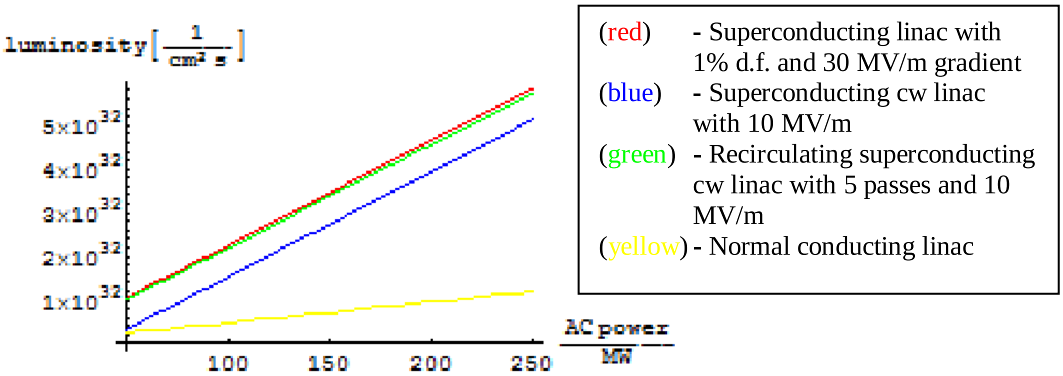

Figure 5: Luminosity of LHeC with 70 GeV electrons and 700 MHz RF-frequency for different linac schemes

Figure 6 shows the luminosity with the opposing linacs energy recovery scheme implemented.

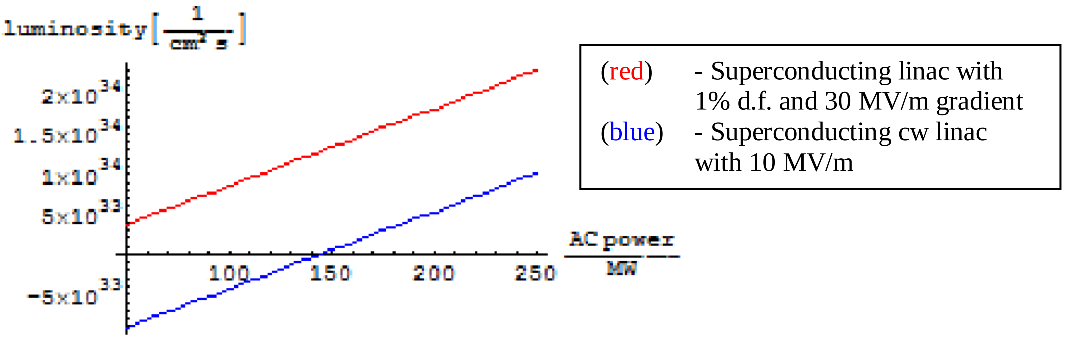

Figure 6: Luminosity of LHeC with 70 GeV electrons and 1.3 GHz RF-frequency assuming 95% energy recovery

Lastly Figure 7 shows how the options develop at higher energies.

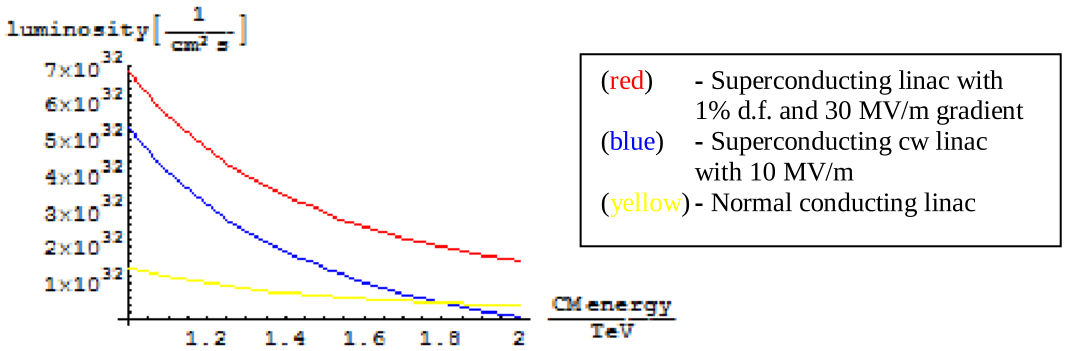

Figure 7: Luminosity of LHeC as a function of the center of mass energy of the collisions with 150 MW total electrical power for the electron acceleration and 1.3 GHz RF-frequency in the electron linac

8 – Conclusion

The results of this study (Figures 4-7) suggests that the s.c. pulsed linac gives the highest luminosity per unit of electrical power. To obtain the minimum required luminosity of 10^{32} $cm^{-2}s^{-1}$ this scheme need an electrical power of about 50 MW while the cw linac need about 125 MW. Figure 7 indicates that the pulsed linac is even more advantageous at higher energies. The length of the pulsed linac is assumed to be one third of that of a cw linac at the same energy and so construction costs may be smaller as well.

At 70 GeV electron energy the recirculating scheme give a luminosity that might be as high or perhaps slightly higher than the pulsed linac (if the RF-frequency of the linac should be 700 MHz a new more detailed calculation of these options is needed to investigate this), but it has the unfortunate drawback of having an upper limit in energy and of being difficult to upgrade after operation has started.

I have throughout this study made a lot of assumptions and simplifications, commented on in this report as they are made, that should be elaborated in a more detailed study. In addition I have ignored the power demand of all systems not affiliated with either the cryogenics or the main accelerating power, i.e. focusing magnets, beam dump, vacuum pumps etc. At least some of these systems (e.g. beam dump) may be very important when comparing different schemes and should also be looked on.

9 – References

[1] Helmut Wiedemann, *Particle Accelerator Physics*, 3rd ed. Springer, 2007

[2] David H. Whittum, *Introduction to Electrodynamics for Microwave Linear Accelerators,* SLAC, 1998

[3] Brüning et al. *LHC Design Report Volume I*, CERN, 2004

[4] Altarelli et al. *The Technical Design Report of the European XFEL*, DESY, 2007

[5] Phinney et al. *ILC Reference Design Report Volume 3 – Accelerator,* SLAC, 2007

[6] Burkhardt et al. *ELFE at CERN: Conceptual Design Report*, CERN, 1999

[7] Braun et al. *Updated CLIC Parameters 2005,* CERN, 2006

[8] Arrington et al. *The Science and Experimental Equipment for the 12 GeV Upgrade of CEBAF*, Jefferson Lab, 2005

[9] Leonid Rivkin, *Introduction to particle accelerators,* lecture notes, 2007

[10] Hans Braun, *LHeC: Linac -Ring Option*, DIS08 (London), 2008

[11] Frank Zimmermann, *Scenarios, merits and challenges for a linac-ring ep collider based on LHC*, internal report, 2007

[12] Swapan Chattopadhyay, *Thoughts on LHeC: A 70 GeV (e-) X 7 TeV (p) Collider At a luminosity of* $10^{\wedge 33}\ cm^{-2}s^{-1}$, internal report, 2007

[13] Emmanuelle Perez, *Physics Beyond the Standard Model at LHeC*, DIS07 (Munich), 2007

[14] Hans Braun, private communication

[15] Frank Zimmermann, private communication

[16] Swapan Chattopadhyay, private communication

[17] Trevor Linnecar, private communication