Progress on the CLIC Final Focus System

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Abstract

The Final Focus System has been adapted to the revised parameter list for CLIC [1]. It is expected that lower emittances are obtainable in the damping rings and the blowup in the main linac can be contained to 25 %. Then the luminosity is no longer limited by synchrotron radiation in the final quadrupoles, and a luminosity above $10^{33} cm^{-2} s^{-1}$ could be reached for bunches colliding head on. However, finite crossing angles are required so the disrupted beam can pass through a special aperture in the first interaction region quadrupole. The reduction of luminosity due to this crossing angle and due to unavoidable misalignments has been studied as function of bunch length with a particle tracking code. Two designs of quadrupoles are presently being evaluated, one based on permanent magnets, and the other on pulsed currents. Results of measurements on models are presented.

1 The revised beam parameters

The revised parameter list [1] assumes bunches of lower six-dimensional emittance. The normalized transverse emittances are reduced by a factor two compared to the previous assumptions

$$\begin{aligned} \epsilon_x &= 1.5 \times 10^{-6}\, m \\ \epsilon_y &= 0.5 \times 10^{-6}\, m \end{aligned} \tag{1}$$

and the bunch is a bit shorter with

$$\sigma_z = 170\, \mu m \tag{2}$$

The energy of each particle is given by its longitudinal position in the bunch. By careful balancing of the applied RF voltage and the wake potential one obtains a distribution with a spread less than 10^{-3} when asymmetric cuts are applied. [2]. Since about 15% of the particles are lost by the cuts, a total bunch population of 5.9×10^9 particles is required.

1.1 Energy profiles in DIMAD

The code DIMAD [3] allows ray-tracing of up to 10,000 (super-)particles through a beam line. Uniform and (truncated) Gaussian distributions are standard options of the program, but it has been necessary to implement more general distributions as well as the possibility to correlate particle energy with longitudinal position. Results with parabolic profiles were already reported in [4]. Non-symmetric profile functions were added by allowing asymmetric cuts of the longitudinal distribution.

1.2 Beam envelopes

The earlier lattice layout of the CLIC final focus system [4] has been retained, but the beam-envelopes were computed for the following input beta-values:

$$\begin{aligned} \beta_x^{(0)} &= 3.00\, m \\ \beta_y^{(0)} &= 3.24\, m \end{aligned} \tag{3}$$

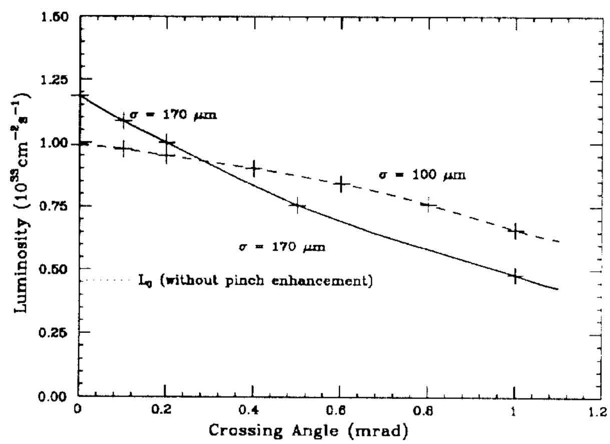

Fig.1:Luminosity dependence on crossing angle

These values correspond to the beta-values at the interaction point

$$\begin{aligned} \beta_x^* &= 4.8\, mm \\ \beta_y^* &= 0.58\, mm \end{aligned} \tag{4}$$

and, with the emittances given in Eq.(1), to the desired spot sizes of 12 x 60 nm.

The maximum extension of the beam is $\sigma_x = 83\, \mu m$ horizontally at the entrance of the last-but-one quadrupole, and $\sigma_y = 32\, \mu m$ vertically at the entrance of the last one. If one fixes the aperture of both quadrupoles in such a way that the pole-tip field is $B_0 = 1.4\, T$, the pole tip is at 9 σ horizontally and 15 σ vertically, which is a significant improvement with respect to the previous situation [4]

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2 Results from tracking simulations

The results reported in this section have been obtained by

- ray-tracing to second order with DIMAD of one or a few batches of 10,000 particles through the final focus beam line [4], taking into account synchrotron radiation in bends and quadrupoles
- processing the output distributions, split into two different beams of 5,000-particles each (electron and positron) colliding head-on, through a fast luminosity-calculation program with no beam-beam interaction
- simulating the pinch effect at collision with the CLIC beam-beam simulation program RBEAM [5]

Results for the intermediate values of beam energy, $E_0 = 250\,GeV$ and $E_0 = 500\,GeV$, have been included assuming that the normalized transverse emittances are fixed.

2.1 Optimization of the dipole strengths

The chromatic aberrations created by the final telescope are pre-corrected by sextupoles in 'chromatic correction sections' containing dipoles to create the necessary dispersion. An optimum dipole strength was found [6] by balancing the emittance growth due to synchrotron radiation, increasing with their strength, and the non-linear distortions, which decrease since the resulting higher dispersion leads to weaker sextupoles. The luminosities were computed without synchrotron radiation in the quads nor pinch enhancement since the optimal field should depend very little on both effects.

The optimization was done at three beam energies. For $E_0 = 1\,TeV$, the best field is $B_O = 245\,G$ which is the one chosen before [4]. At lower energies, where synchrotron radiation is weaker, the optimum dipole field is higher: about 340 G for 500 GeV, and almost 400 G for 250 GeV. The luminosity decreases only slightly for lower energy beams [6].

2.2 Luminosity dependence on crossing angle

For finite crossing angles, the ends of short bunches do no longer completely overlap during collision. Thus the luminosity in CLIC would decrease rapidly with increasing crossing angles as shown in Fig.1, computed with program RBEAM [5] for 2 beams of 5000 (super-)particles each tracked with DIMAD [3] through the CLIC Final Focus. With shorter bunches (e.g.$\sigma_z = 100\mu m$) the reduction is smaller, but the initial value is also reduced since the disruption is insufficient when the number of particles per bunch is kept constant.

The minimum required crossing angle is about 1 $mrad$, which yields a separation of $1.25mm$ at the face of the first quad (at $1.25m$ from the intersection), and thus permits the disrupted beam to clear the aperture of $1mm$ diameter. The disrupted beam is also larger (the emittance is increased by about one order of magnitude), and the horizontal gap needs to be widened vertically to let it pass without damage.

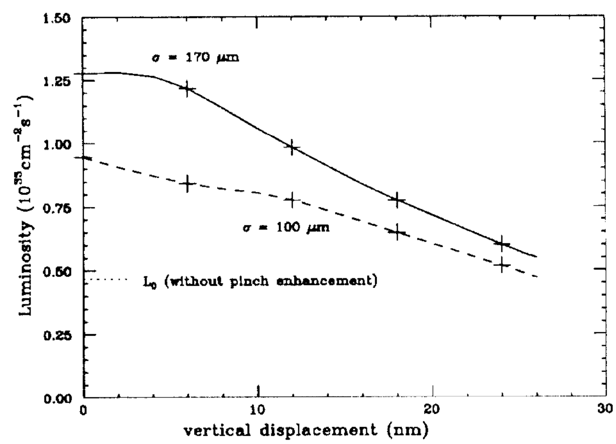

Fig.2: Luminosity dependence on displacement

For the standard bunch length of $0.17mm$, the luminosity reduction would be more than 50 %. For a slightly shorter beam of $0.1mm$, the reduction is only 35 %. A way to avoid this decrease is the use of transverse-deflecting "crab cavities" [7] which make the bunches collide over their full length even for a large crossing angle. However, the practical difficulties of keeping the required phase-stability for the deflecting modes for short bunches are considerable.

Small transverse displacements of the beam - e.g. due to jitter - are partially corrected by the attraction of the two beams as can be seen in Fig.2. However, as has been reported before [4], the inevitable misalignments of focussing elements and pick-up errors in the final focus channel will also lead to an increase of the beam size and a corresponding luminosity reduction.

3 Magnet Studies

A 25 mm long section of a permanent magnet quadrupole with iron-cobalt poles, based on a study presented previously [8], has been designed, and the components have been machined to the required sub-micron tolerances. Accurate assembly is achieved by the use of shallow precision wedges. The aperture is 1 mm in diameter, and initial results confirm the poletip field of about 1.4 T. A bench has been designed and constructed for the precise measurement of field quality and magnetic axis using the vibrating wire technique. While the model under test does not accommodate the passage of the disrupted beam entering at 1.25 mm from the axis, preliminary calculations indicate that only minor modifications would be required to achieve that goal.

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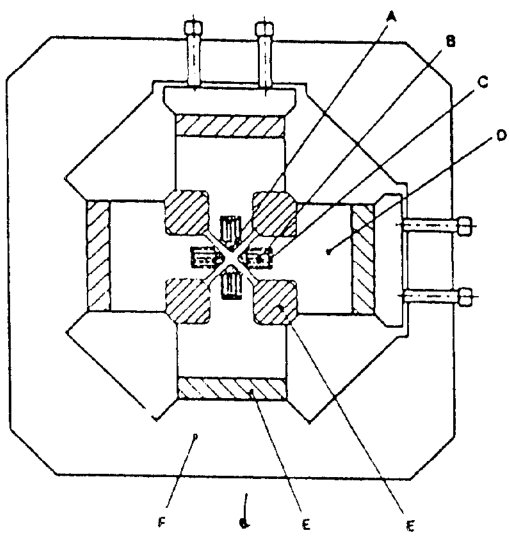

Fig.3: Cross-section of the pulsed quadrupole.
A...Copper conductor, B...Water cooling channel,
C...Stainless Steel jacket, D... Slotted SS support,
E...Ceramic spacers, F...Steel frame.

Alternatively, pulsed single conductor quadrupoles are being evaluated at CERN and elsewhere [9]. They permit higher surface fields than permanent magnets, allowing for either higher gradients, although not necessarily applicable for CLIC, or larger apertures. A scaled-up version of such a quadrupole (half aperture $A = 5\ mm$) has been built at CERN (see Fig.3) and was measured in the pulsed regime at the INP, Novosibirsk [10]

The results, given in Table 1, agree well with computations obtained by a finite element computer code [11] in the transient skin effect regime.

This table shows that sets of rather conservative parameters for single pulse operation can still be found at relatively large apertures.

The average power, at least for the elevated repetition rate of CLIC of 1.7 kHz, and thus the cooling of the quadrupole, becomes a limiting factor. A model conductor, a copper rod of 2×2 mm^2 cross-section extended into a comb-like array of cooling fins at one of its side faces has been built and its heat removal capacity been measured: a d.c. current of $I = 1.4\ kA (35 A/mm^2, 7.8\ kW/m)$ led to a modest temperature rise of the conductor above the cooling water of only $17^o\ C$. At such average powers dissipated in each conductor in the pulsed regime one can anticipate gradients of $2 \times 10^3\ T/m$ and $1 \times 10^3\ T/m$ for half- apertures of $A = 1\ mm$ and $A = 1.5\ mm$ respectively. Further problems resulting possibly from the pulsed

Table 1

Half aperture (mm)	1.0	1.0	1.5	2.0
Gradient (T/m)	1000	2000	1000	1000
Pulse duration (μs)	8	8	18	32
Peak current (kA)	4	8	9	16
Peak voltage (kV)	1.3	2.6	1.3	1.3
Energy/pulse (J)	~5.5	~22	~28	~88
Average power (kW)	9.4	37.5	48	150

Table 1: Parameters for a 1 m long quadrupole, scaled from the geometry of the tested model.

operation, like vibrations and field repeatability will have to be carefully considered. Also the passage of the opposite beams through the quadrupoles in the horizontal plane will have to be arranged, e.g. by displacing or removing the conductors in the horizontal plane [12].

4 Conclusions

Thanks to the reduced emittances in the new parameter list, luminosities in excess of $10^{33} cm^{-2} s^{-1}$ can now be reached in CLIC if the beams collide head-on. These luminosities can be maintained also at energies below 1000 GeV by slightly retuning the lenses. However, including the effects of finite crossing angles and transverse displacements of the bunches reduces the luminosities considerably. In addition to very careful alignment of the quadrupoles and pick-ups, a dynamical correction of the beam position will be required.

5 References

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