OPTIMUM CHOICE OF RF FREQUENCY FOR TWO BEAM LINEAR COLLIDERS

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Abstract

Recent experimental results on normal conducting RF structures indicate that the scaling of the gradient limit with frequency is less favourable than was believed. We therefore reconsider the optimum choice of RF frequency and iris aperture for a normal conducting, two-beam linear collider with E_{CMS}=3 TeV, a loaded accelerating gradient of 150 MV/m and a luminosity of $8{\cdot}10^{34}cm^{-2}s^{-1}$. The optimisation criterion is minimizing RF costs for investment and operation with constraints put on peak surface electric fields and pulsed heating of accelerating structures. Analytical models are employed where applicable, while interpolation of simulation program results is used for the calculation of luminosity and RF structure properties.

INTRODUCTION

The rational for the use of high frequency, normal conducting linac technology for linear colliders in the multi-TeV regime like CLIC [1] has been discussed in [2] and earlier by [3]. However, there it is assumed that the increase of obtainable accelerating fields with frequency as observed in the 3-12 GHz range [4] continues for even higher frequencies. This assumption was not confirmed by recent experiments [5], which indicate rather a saturation of the attainable field for an electric surface field-strength E_S of about 300 MV/m independent of frequency. Another important limitation comes from cavity surface damage due to pulsed surface heating ΔT by the magnetic RF surface field H_S. Recent measurements indicate that the pulsed heating must be limited somewhere in the range of 40 to 120 K for copper cavities [6]. Based on these informations the optimum RF frequency and accelerating structure iris opening a/λ in terms of costs is computed for a two beam linear collider like CLIC. The center of mass energy E_{CMS}, mean accelerating gradient G and effective luminosity L_1 in a 1% energy bin are assumed to be those of the present CLIC design, i.e. 3 TeV, 150 MV/m and $3.3{\cdot}10^{34}cm^{-2}s^{-1}$.

ASSUMPTIONS

The assumptions below are used for the optimisation:

RF- structures

The structure geometry parameters are determined by the condition that for a given a/λ the cell geometry giving the highest shunt impedance R_S' for a surface to accelerating field ratio $E_S/G\leq2$ should be chosen. To determine these geometries a large number of cases have been computed with the code URMEL. The results are compiled in table 1 with the definition of the geometry parameters in fig. 1. It is apparent that for larger apertures the cell-to-cell phase advance has to be decreased to keep the surface field small at the expense of reduced Q values. The cell parameters of table 1 are applied to the middle cell of the structure and the variation of R_S' and Q along the structure is neglected. Although the URMEL calculations as listed in table 1 are performed for cells without higher order mode damping, the effect of the damping is taken into account by applying a fudge factor of 0.8 to Q and a factor of 1.41 to H_S/G. These are typical values for the CLIC accelerating structures presently under consideration [7]. The length of the RF structure is determined by the requirements that the group velocity varies linearly along the structure, fulfilling the constant gradient condition for half the nominal beam current. The ratio of group velocity at the structure input to output is fixed to 3. These choices of parameters seem to be a good compromise for RF to beam efficiency, maximum field at zero beam current and technical feasibility.

Table 1 Travelling wave structure cell parameters, which give highest R_S' for $E_S/G\leq2$. The parameters are given for a synchronous frequency of 30 GHz. The scaling behaviour with frequency is indicated in the 2nd row.

a mm	φ deg.	d mm	ε	B mm	E_S/G	H_S/G 1/kΩ	R_S' MΩ/m	R_S'/Q kΩ/m	Q	v_G/c %	$\sqrt{\langle W_T'^2\rangle}$ kV/C/m^2	ν_1 GHz
$1/\nu$	1	$1/\nu$	1	$1/\nu$	1	1	$\nu^{1/2}$	ν	$\nu^{-1/2}$	1	ν^3	ν
1.00	144	0.6	1.2	3.91	1.96	2.55	192.8	40.9	4714	0.6	1.85	46.03
1.25	144	0.7	1.4	3.98	1.97	2.75	165.0	35.3	4675	1.3	1.39	43.79
1.50	144	0.9	1.4	4.08	1.98	3.03	137.7	30.1	4574	2.0	1.05	41.68
1.75	135	1.0	1.4	4.22	2.00	3.24	115.2	26.7	4322	3.8	0.85	39.75
2.00	108	0.9	1.4	4.38	2.00	3.34	93.0	25.3	3681	7.6	0.76	38.13
2.25	90	0.9	1.4	4.57	1.97	3.62	69.2	22.2	3117	10.5	0.63	36.93
2.50	72	0.8	1.4	4.76	1.98	3.86	50.5	19.6	2582	13.3	0.52	36.12
2.75	72	0.9	1.8	5.00	2.00	4.21	41.2	16.4	2514	16.2	0.38	35.28
3.00	60	0.9	1.8	5.30	2.00	4.84	26.3	13.5	1945	17.9	0.29	34.48

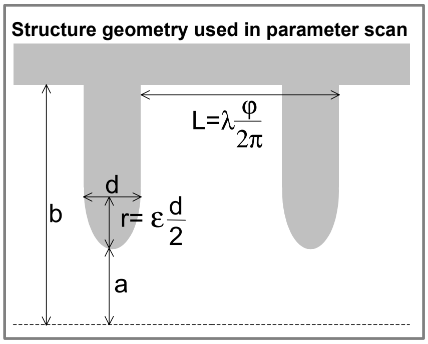

Fig. 1 Definition of geometry parameters for table 1.

Bunch charge and spacing

The bunch charge Q_B and bunch-length σ_Z are optimised according to the criteria described in [8] with the constraints that the total energy spread is kept ≤1% and the transverse short-range wakefield at a distance σ_Z behind the bunch center is kept at a constant value taken from the present CLIC design. A gaussian bunch shape is assumed and the longitudinal and transverse short-range wakefields are computed with the formulae given in [9]. The RF phase is fixed at 12^0 off crest.

The bunch spacing is obtained by the requirement that the long-range wakefield strength should be kept constant. The rational for this is, that for given linac length and alignment tolerance the emittance growth due to transverse wakefields should be approximately constant if the wakefield strength is kept constant. Since the bunch charge is already determined as described above, only the bunch spacing can be adjusted to fulfil this condition. This spacing is worked out by computing for each geometry of table 1 the rms strength $\sqrt{\langle W_T'^2\rangle}$ and the 1st synchronous dipole mode frequency of the transverse long-range wakefield ν_1 with the code ABCI. These values are listed in the two last columns of table 1. Assuming an exponential damping in time with a damping time of $\tau=Q/\pi\nu_1$, where the quality factor of the first dipole passband Q is assumed to be 20, the bunch distance needed to keep the long-range wakefield strength constant at a reference value W_{REF} given by the present CLIC design can be estimated as:

$$\Delta t_B \approx \frac{\tau}{2}\log\left(\frac{\langle W_T'^2\rangle}{W_{REF}^2}+1\right)$$

Luminosity

The effective luminosity L_I scales in the multi TeV regime like $\sim P_{MB}/\sigma_Z^{1/2}$ if the vertical beam size at the IP σ_Y^* is kept constant and the horizontal beam size σ_X^* is adjusted to an optimum value [2]. P_{MB} is the mean power of the main beam. However, as pointed out in [8] this optimum value cannot be reached for all possible combinations of bunch charge and length due to limitations of the damping ring and the beam delivery system. Fig. 2 shows the deviation from this scaling as a function of bunch charge computed with the program GUINEA-PIG.

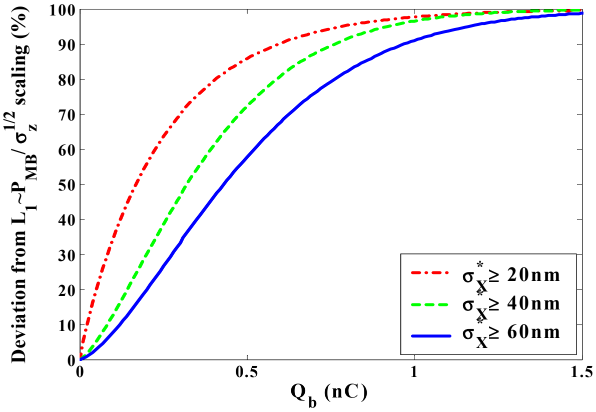

Fig. 2 Deviation from $L_I \sim P_{MB}/\sigma_Z^{1/2}$ scaling due to constraints on σ_X^* for σ_Y^*=0.7nm.

Pulse length and repetition rate

The pulse length is determined by the condition that the maximum pulsed surface heating is kept constant at ΔT=80 K and the repetition rate is adjusted in a manner to keep the effective luminosity L_I constant.

Costing

To estimate the dependence of overall costs on ν_{RF} and a/λ we assume that the dependency of main linac and tunnel costs on theses quantities is small, since G and therefore the total linac length is kept constant. Implicitly it is also assumed that the strength of focusing systems and alignment tolerances are kept constant. Therefore the main cost dependence comes from the RF power source and here more specifically from the drive beam accelerator. The two main contributions are the costs for electricity and the investment costs for the RF source needed to power the drive beam accelerator. Supposing that the drive beam scheme is sufficiently flexible to have constant wall plug to (high frequency) RF efficiency $\eta_{\text{Plug-RF}}$ of 40% [1], we compute the electricity costs for a ten-year period with 5000h of running a year as

$$C_E = P_{MB} / (\eta_{Plug\text{-}RF}\cdot\eta_{RF\text{-}MB})\cdot 5000\text{h}\cdot 10\text{y}\cdot 0.06\ \text{SFr/kWh}$$

With $\eta_{RF\text{-}MB}$ the RF to main beam power transfer efficiency computed for each combination of ν and a/λ. For the power source investment it is assumed that the source can be broken up in klystron/modulator units delivering 4 kJ RF energy per pulse each, with a unit cost estimated from past experience [10] of

$$C_U = 1.725\ \text{MSFr} + 0.012\ \text{MSFr}\cdot\nu_R[\text{Hz}]$$

where ν_R is the repetition frequency. Hence the total investment cost for this power source is given by

$$C_I = C_U\cdot E_{CMS}\cdot Q_B\cdot N_B / (\eta_{RF\text{-}MB}\cdot\eta_{RFDM}) / 4\ \text{kJ}$$

With N_B the number of bunches per pulse and η_{RFDM} the drive beam RF to main beam RF power transfer efficiency. The present CLIC value of η_{RFDM}=68% has been assumed. The total cost of the drive beam power source is given by

$$C_{\text{Total}} = C_E + C_I$$

RESULTS

Putting all together we get the drive beam power source cost as shown in fig. 3 and fig. 4. The curves in fig. 3 are computed without constraints on σ_x^* , while $\sigma_x^* \geq 60$ nm is imposed for the case shown in fig. 4. At the present status of the damping ring and beam delivery system design this latter case is the more realistic assumption. For each frequency the a/λ that minimises total costs has been chosen. In the unconstrained case this leads to a constant a/λ of 0.15. In the constrained case a/λ increases almost linearly from 0.15 at 14 GHz to 0.275 at 42 GHz. For the unconstrained case C_E is almost constant and C_I decreases monotonically with frequency. For the more realistic constrained case a flat cost minimum is achieved for the frequency range 22-26 GHz. Table 2 compares parameters that correspond to the cost minimum of fig. 4 with the present CLIC parameters[*]. The improvement in RF source cost is not dramatic, however, the optimised case has the additional advantage of reduced electric surface field and pulsed surface heating for the main linacs in comparison with the present CLIC reference design.

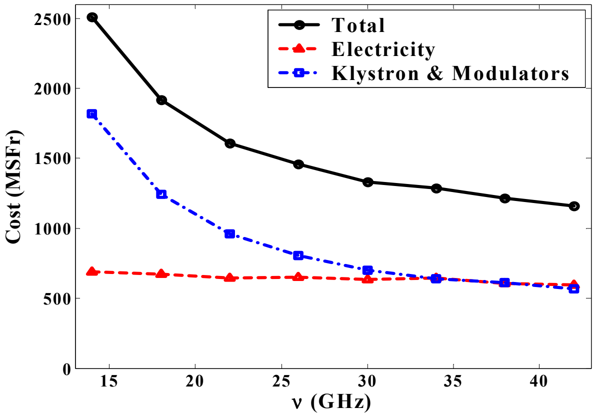

Fig. 3 Costs of power source with unconstrained σ_x^*.

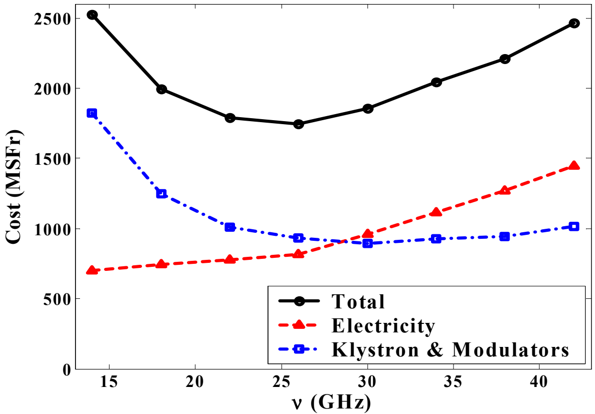

Fig. 4 Costs of power source with $\sigma_x^* \geq 60$nm.

CONCLUSION

Although the faith that higher frequencies automatically lead to higher achievable accelerating fields has vanished in recent years, the argument that high frequencies are favourable for TeV class linear colliders is still valid for budget reasons. The optimum frequency depends on the limitations on the achievable IP beam size. In the CLIC case this optimum is at the present design state at about 22-26 GHz with an a/λ of 0.175-0.2. If progress in the design of the damping ring and beam delivery system allows for smaller IP beam size, this optimum will shift to higher frequencies. Further studies are necessary to investigate the impact of parameters on the other components of the drive beam complex, the injector chain, damping rings, main linacs and beam delivery system.

Table 2 Present CLIC and optimised parameters

	present	optimised
E_{CMS} (TeV)	3	3
G (MV/m)	150	150
σ_Y^*./ σ_X^*.(nm)	0.7 / 60	0.7 / 60
L_1 (10^{34} cm^{-2} s^{-1})	3.3	3.3
ν_{RF} (GHz)	30	26
a/λ (averaged)	0.2	0.2
Q_B (nC)	0.64	0.92
σ_Z (μm)	35	44
Δt_B (ns)	0.66	0.77
T_{Puls} (ns)	103 ns	49 ns
ν_{rep} (Hz)	100	150
P_{AC} (MW)	319	280
η_{RF-MB} (%)	23.1	24.6
C_E (MSFr)	890	820
C_I (MSFr)	1270	930
C_{Total} RF source (MSFr)	2160	1750

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[*] Same power source cost model has been applied for both cases.