CLIC Note 352

DRIVE BEAM GENERATION FOR CLIC BASED ON 200 MHZ SC STRUCTURES

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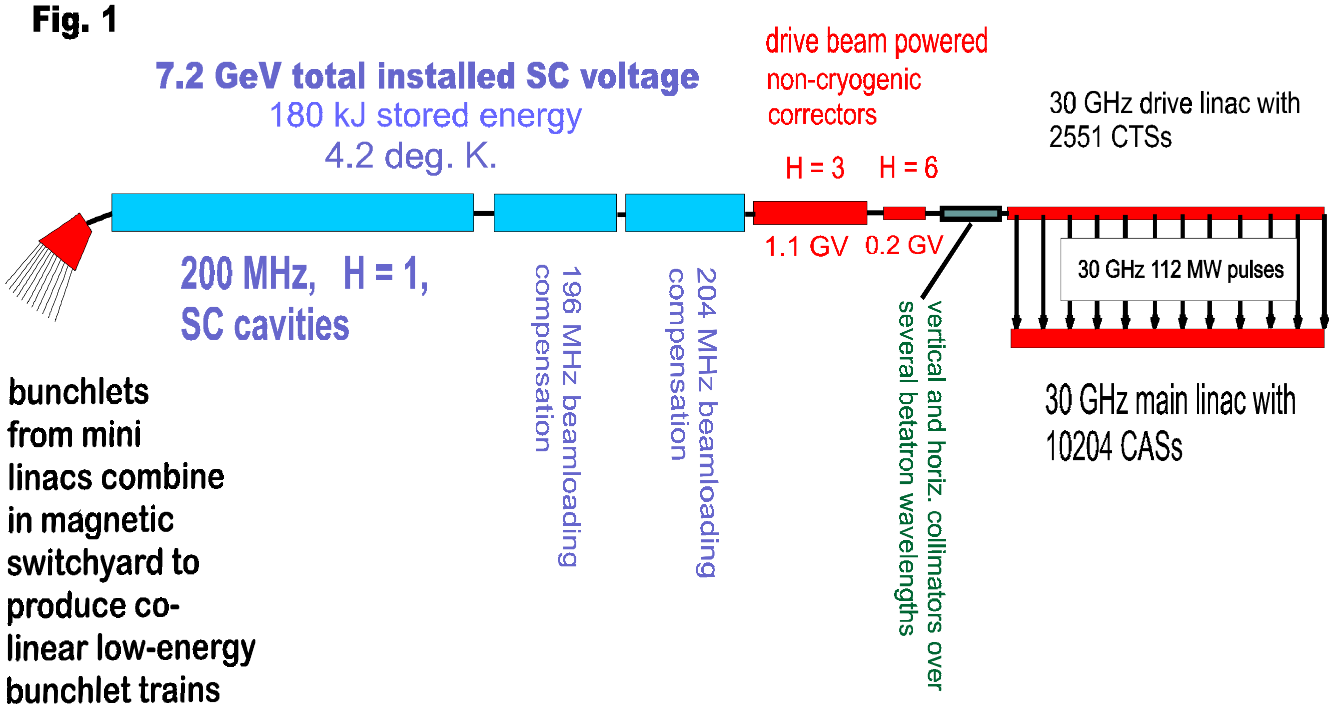
Fig. 1



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Abstract

The present note describes an RF power generation scheme for multibunch operation at 1 TeV CM and luminosity 10^{34} cm^{-2}s^{-1}. - The scheme is upgraded to use acceleration with 200 MHz SC cavities (instead of 352 or 250 MHz ones, but still with 6MV/m) in order to reduce the active SC linac length, for the required stored electromagnetic energy (180 KJ/linac), and hence also reduce the capital cost of drive beam generation. Furthermore an improved Q-value (7.8 10^9) [1], due to the lowered frequency, increases the overall efficiency.

Introduction

The purpose of each drive beam is to produce via 2551 CLIC Transfer Structures (CTSs) 30 GHz output pulses to power N_{CAS} = 10 204 CLIC Accelerating Sections (CAS) [2] of the main linac with the **provisional** parameters:

R/Q = 4875 Ohm/structure,
(circuit convention)
length ℓ = 0.49 m
Q = 3500
v_{gr} = 0.065 c
E_{acc} = 100 MV/m (loaded)
Spacing of multibunches = 0.667 ns
Multibunch charge = 0.64 nC

To deliver four 112.5 MW CAS input power pulses (4 CASs are fed by one CTS, N_{CTS} = 2551) the CTS main parameters can be chosen as follows:

R/Q = 5.2 Ohm/structure,
(circuit convention)
length ℓ = 0.92 cm
drain time d = 5 ns = 1/200 MHz
v_{gr} = 0.38 c
CTS internal power losses = 5 %,

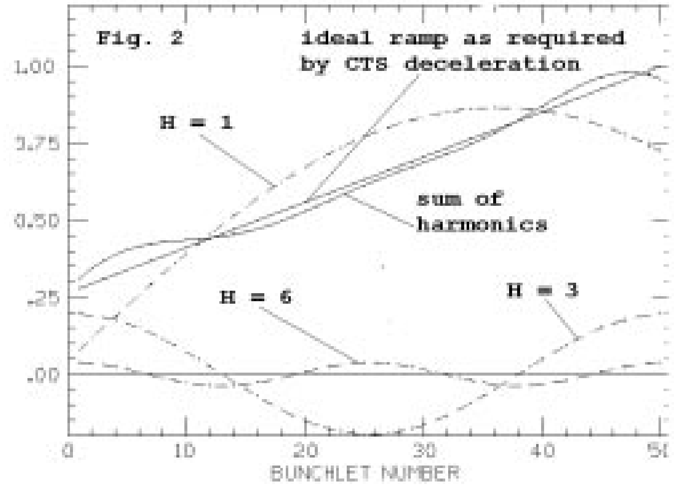
with CTS to CAS transmission losses of 10% and for a nominal bunchlet length of 0.6 mm rms. The maximum bunchlet intensity is 50 nC .

Bunchlet Trains

One drive beam consists of 13 bunchlet trains (of up to 50 bunchlets per train), obtained initially with a switch-yard (combining bunchlets from 10 parallel mini S-band linac pairs) [3],[4],[5] followed by the acceleration arrangement shown in fig. 1(shown for one drive beam only).

For the main acceleration of the drive beam essentially a single 200 MHz (H=1) SC linac (with beamloading compensation) followed by beam excited non-cryogenic H = 3 and H = 6 correctors has been studied.

Good drive beam to RF efficiencies are obtained through matching of the train energy profile to the decelerating wake pattern in the drive linac, such that at the end of the CLIC drive linac, the bunchlets are dumped at an almost equal and low average energy, say, 0.3 GeV but above 0.2 GeV to avoid electron losses . - With one train of 50 bunchlets per period the bunchlet deceleration varies from + 76 % to -76 % (of the mean value), because the structures yield energy between trains, see fig.3.



Figs 2 and 6 show that it is feasible to preshape the train energy profile to the deceleration ramp by proper phasing of the 200 MHz voltages in the SC cavities (7.2 GV installed) in conjunction with the H=3 (1.1 GV) and the small H=6 (.2 GV) correction

Following a suggestion by R.D..Ruth & K.A. Thompson[6] almost constant multibunch energies (±-0.2%, necessary to pass the CLIC final focus sections) are obtained by a specially shaped CTS output power pulse: the time shape is such that, prior to the passage of the multibunches, first the steady state of the CAS (with beamloading) is established (with the 6 first drive trains, or prefill trains, yielding a rising ramp) and then, during the passage of the multibunches, this state is maintained with a constant input power level (112.5 MW/CAS).

A computer optimisation program obtains the necessary multibunch acceleration precision by optimising the number of bunchlets and their charges of the 6 first (prefill) trains.

These trains have increasing numbers of bunchlets (30, 34, 40, 44, 48 and 50 bunchlets/train, see fig. 3) [7], combined with small variations of bunchlet intensities.

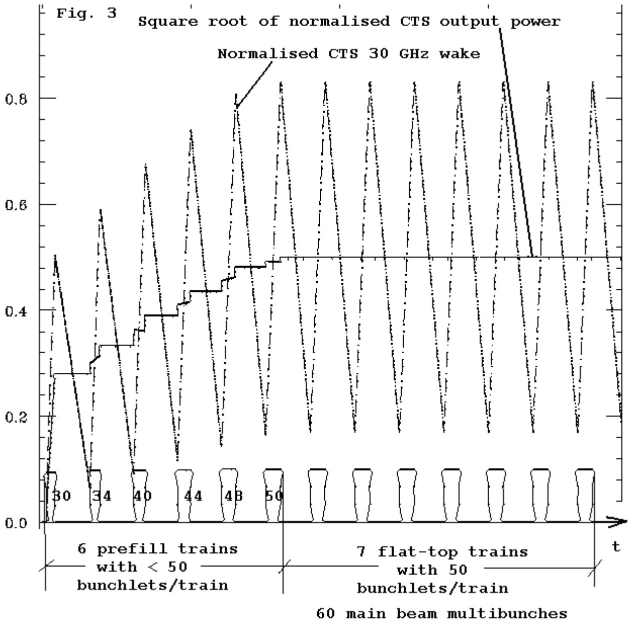


Fig. 3 indicates computer optimised bunchlet numbers, relative intensities (with respect to 50 nC), normalised 30 GHz CTS wake amplitudes (dashed, linear variations of ± 76 %) and the normalised CTS output amplitude.

The energy spread of the accelerated 60 multibunches of the main beam is 0.1 % rms.

Acceleration at 200 MHz and beamloading compensation

We focus the acceleration optimisation on the flat top trains (having the most severe deceleration); in particular on the compensation of the beamloading in the 200 MHz SC structures.

The voltage decrease of the fundamental frequency cavities (R/Q = 77.3 Ohm/m, circuit convention) has been compensated by two groups of cavities with slightly different frequencies (195.4 and 204.6 MHz); they produce a fractional beat during the passage of the drive beam, yielding low deceleration for the first prefill trains and high acceleration for the flat-top ones[8]. - During the compensation optimisation a beneficial (for drive beam to RF efficiency) voltage increase pattern for the prefilling trains resulted (see fig 4).

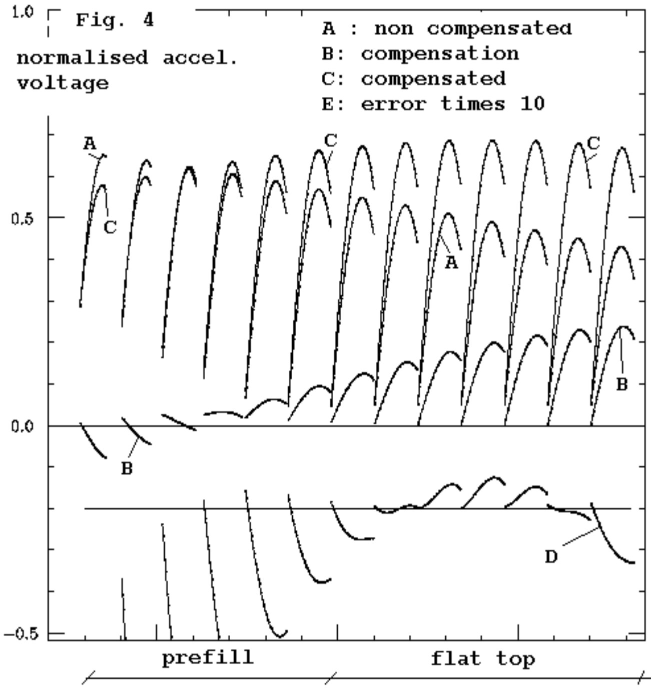


Fig. 4 Decrease of normalized(with respect to the sum of all installed cavity peak voltages) accelerating H = 1 voltage due to beamloading over 13 trains of bunchlets (upper full trace A). --Curve B shows the compensating voltage obtained as a fast beat between the 2 groups of compensating cavities with 43 % of the total installed voltage and frequencies 195.4 and 204.6 MHz. – Curve C is the compensated voltage.- Curve E indicates the resulting error with respect to an ideal constant voltage on the flat top.- Only the successive short phase intervals (of 120 deg.) populated by the bunchlets of each train are shown, whereas the remaining **unpopulated** 240° in each of the 13 periods have been **cut out**. The error with respect to the ideal H=1 oscillation is 0.01 rms.

Third and Sixth Harmonic Correctors

Fig. 2 indicates the specified acceleration ramp (matching the flat-top wake of one train) for any train of the flat-top and the synthesised one obtained with the fundamental, the third and the sixth harmonics.

Since in this synthesis the harmonic corrections (essentially necessary for the flat-top trains only) are anticipated as cavity excitation by the pretrains, the phase of the third harmonic will be 180 degrees (cosine) at the train centre and the phase of the sixth one zero. The two phases happen to be near to optimum, as can be seen from fig. 2.

Fig. 5a shows the fundamental H = 3 cavity mode as energised by the first prefilling trains (excitation occurs since these trains last less than one H = 3 oscillation period) with R/Q of 232 Ohm/m at .6 GHz. The geometry is scaled from the H = 1 structures.

The flat-top trains with 50 bunchlets lasting exactly one period cause no net change to the excitation. - The resulting field amplitude is 2 MV/m and the total active length 550 m (a shorter length should be obtainable with a higher R/Q structure).

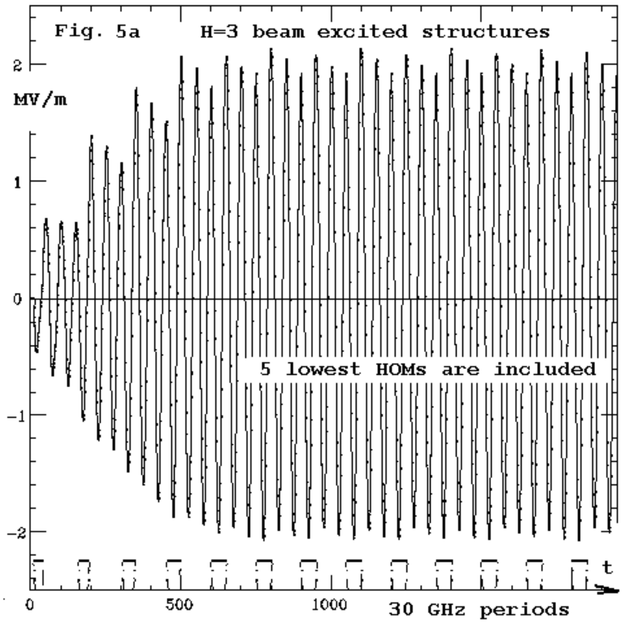
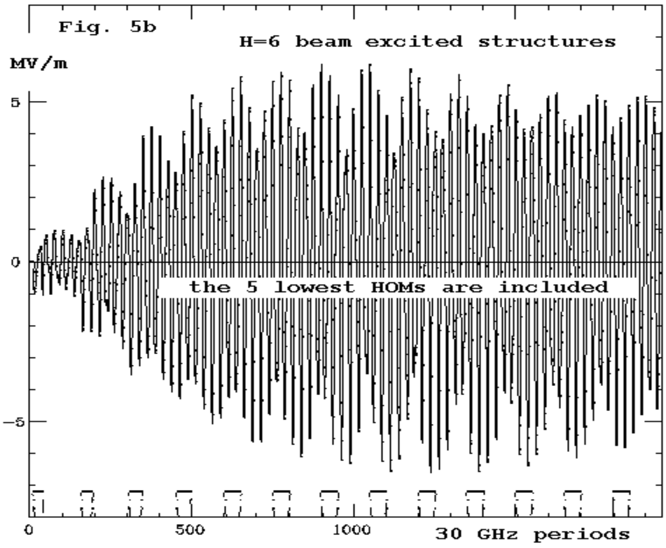
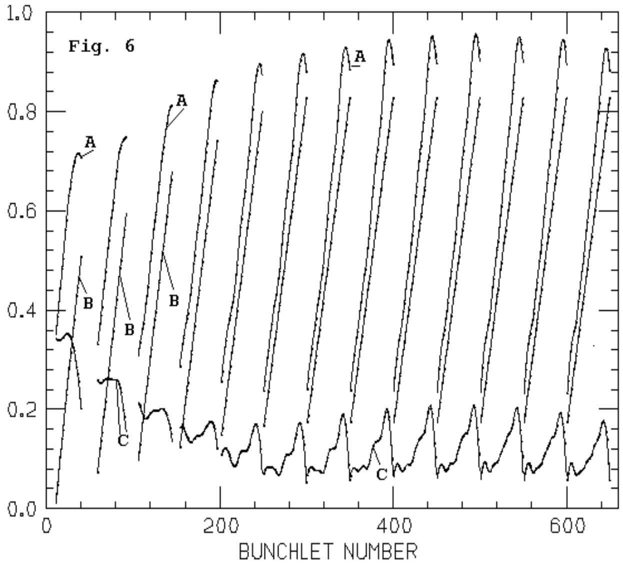


Fig. 5a H = 3 excitation by the prefill train pairs(upper trace). The drive train pairs (bottom trace) are also shown. - Only a small fraction (600J, 0.7 %) of one drive beam energy (90 kJ) is used for energising. Furthermore it is taken from the first trains which are underdecelerated in the CTSs of the drive linac. The voltage obtained is 2 MV/m. The 5 lowest HOMs of the 600 MHz cavity are included.



Figs 5b shows the voltages obtained with the sixth harmonic cavity (again its 5 lowest HOMs are included).

Fig. 5b: Excitation by the 6 prefill trains of H = 6 structures. The following flat top trains, lasting each exactly 2 periods of oscillation, cause no net change to this excitation.



A:initial energy, C:final energy, B: CTS deceleration
The curves are valid for bunchlet centres

Finally fig.6 shows for the bunchlet centres of all trains the total deceleration wake amplitude of the CTSs . The average deceleration amplitude for the flat-top trains is

$$0.93 N_{CTS} q_{train} (R/Q)_{CTS} \omega/2 = 2.91 \text{ GV}$$

corresponding to 0.5 along the normalised vertical axis.

Furthermore fig. 6 indicates the bunchlet initial energies (at the beginning of the decelerating drive linac) and final ones (before dumping). The initial energies are the result of the accelerations/ decelerations in the three types of cavities (SC H = 1, warm H = 3 and H = 6, approximately anticipated in fig. 1).

These necessary initial bunchlet energies (to survive to the end of the drive linac as outlined under the chapter **Bunchlet trains**) are given by a computer optimised linear combination of curve C (H = 1, 7.2 GV peak installed) of fig. 4 and the harmonic excitations of figs. 5a (H = 3, 1.1 GV peak) and 5b (H = 6, 0.2 GV peak).

The final energies are the initial ones minus the decelerations in the transfer structures of the drive linac.

Above graph permits the calculation of the drive beam to 30 GHz efficiency by dividing the area between the two curves by the area underneath the upper curve and multiplying with the bunchlet form factor 0.93 as well as the CTS internal loss factor 0.95. The value found is 74%.

Dynamic tracking computations by J. Riche [9] following the bunchlets through the decelerating drive linac have demonstrated their survival without any damping in the CTSs (of the transverse beam break-up mode).

A concept for a large aperture CTS with damping exists. Mafia calculations [10] indicate that the needed R/Q of 5.7 Ohm/m is obtainable with an aperture of 40 mm .

Note that the harmonic cavities are inexpensive because they are non-cryogenec; furthermore they do not need adjustable tuning nor input- or output couplers. After the passage of a pulse the small amount of energy taken from the pretrains is absorbed in the cavity walls.

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Cryogenics

We follow investigations by K. Hübner [11] and I. Wilson[12] for LEP2 structures at 6 MV/m, 352 MHz and $Q = 4 \ 10^9$ with static losses of 29.5 W/m and dynamic losses 32.3 W/m.

For the 200 MHz structures (still 6 MV/m) static losses per metre are estimated to be approximately 20 % [13] higher than for the 352 MHz ones, and the Q-value to be $7.8 \ 10^9$ [1] instead of $4 \ 10^9$ at 4.2 deg K.

Taking into account by a factor 3/4 the yo-yoing stored RF energy level between pulses (the cavities yielding about half their energy to the passing drive beam), the dynamic losses should be 20 W/m and the static ones 35.4 W/m. The total power to be absorbed at 4.2 degrees K is 133 KW for 2400 m of active SC linac length.

Applying a cryo-factor 225 [13] for large scale cooling to 4.2 degrees K, we obtain a total mains consumption of 29.9 MW for the cryogenics of the two CLIC drive beams.

Efficiencies

The most important assumptions, leading to an overall (wall plug to main beam) efficiency of 11.2 %, are illustrated in fig. 7a for the 1 TeV cm case. RF and mains power level indications are for both collider beams.

Unfortunately, due to beamloading in the 200 MHz SC cavities, it is difficult to accelerate more than 13 drive trains corresponding to 60 multibunches.

The **Switchyard** [3],[4],[5]

The purpose is to create from 10 mini linac pairs with photo guns operating at 3 GHz and delivering 25 nC bunchlets above trains of 50 nC bunchlets. The linac energies would be spread evenly between 28.3 and 56.6 MeV.

The arrangement is used in two ways: a) to double the bunchlet intensity by making two bunchlets of different energies come together both longitudinally and transversely at the exit of a sprectrometer type magnet, and b) by arranging for many successive bunchlet pairs to produce the high intensity colinear bunchlet trains.

Fig. 7: Efficiencies

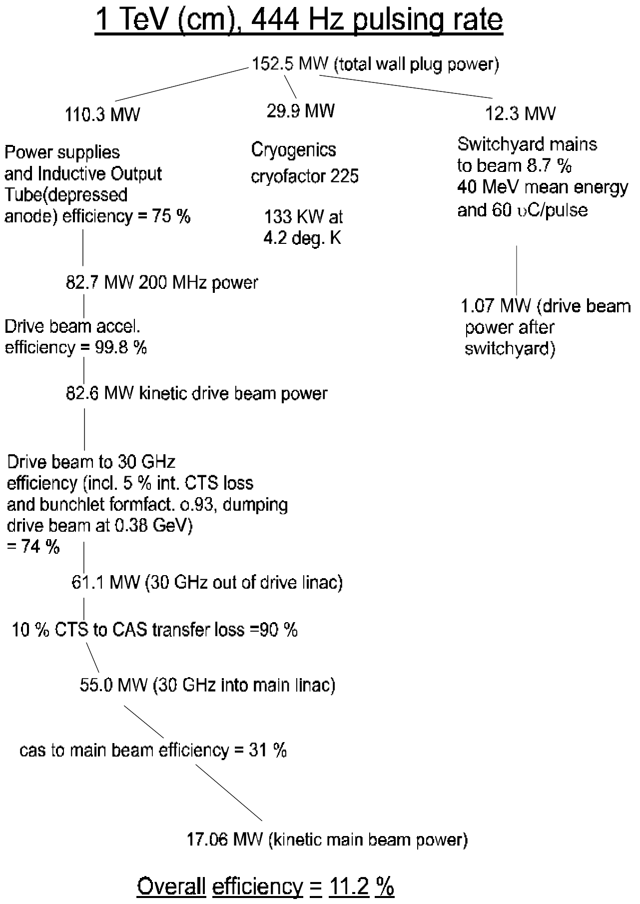
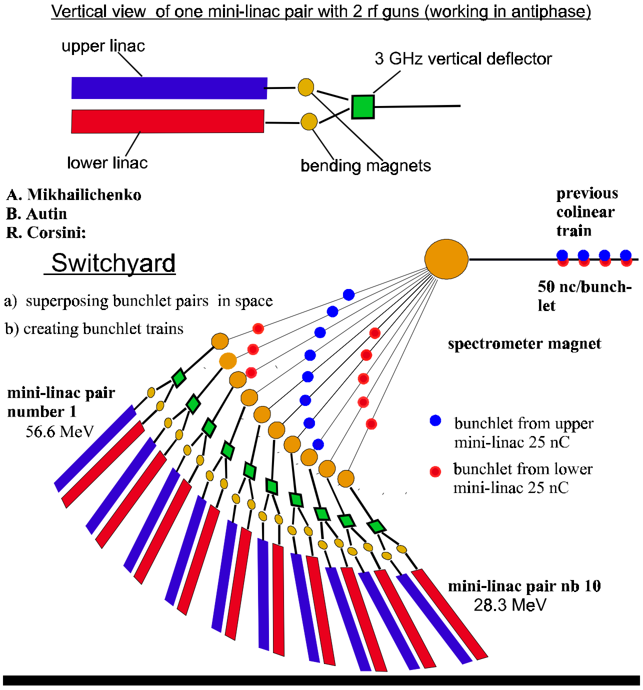


Fig. 8a

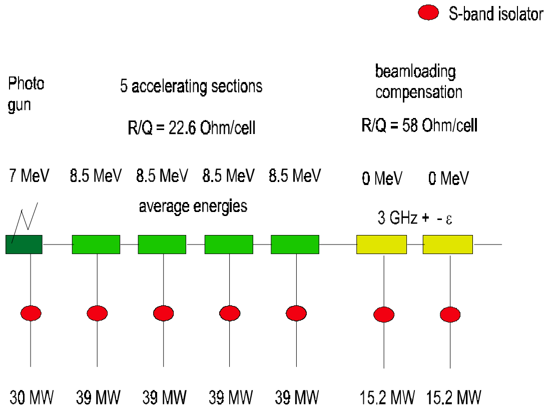


The scheme is illustrated in fig. 8a. Each vertically arranged mini-linac pair is followed by a bending magnet and a 3 GHz vertical deflector in order to place bunchlets from the 2 linacs in the central plane. Typically upper linac 1 and lower linac 5 could have their bunchlets combined at the exit of the spectrometer magnet. 33.3 ps later upper linac 2 and lower linac 6 could have their bunchlets combined; and so forth. Per train of 50 bunchlets each linac would fire five times. The large linac charge per pulse of 1.63 μC could be handled by low R/Q (23 Ohm/cell) 3 GHz standing wave structures with a high initial gradient (50 MV/m). Beamloading compensation would be obtained with the standard fast beat method [14], using two further frequencies.

An eleventh linac pair should be foreseen with each switchyard for redundancy.

Fig. 8b: Details of single mini linac from channel 5

S-band, standing wave, Π cells, 50 MV/m,
22.6 Ohm/cell (circuit convention)
4 cells/cavity (as Rudi Bossarts CTF booster structure, but with lowered R/Q).



- Structure fill time: 1660 ns

- Total charge accelerated 1625 nC/pulse, only a 1000nC gun design exists!

- Possible KLYSTRON: Thomson TH 2153 boosted to 150 MW peak and 80 kW mean power (this possibility is not certain!)..

- 216.4 MW pulsed power per mini-linac.

- Assuming 1 db distribution loss, we need 8.7 GW total installed S-band peak power, corresponding to 58 Klystrons with modulators but without pulse compression.

- 444 Hz pulsing modulators difficult but not impossible (P. Pearce)

- Optimistic mains to drive beam efficiency: 8.7 % (R. Bossart), total mains power: 12.3 MW for both switchyards.

Fig. 8b shows a tentative concept of one mini-linac of pair number 5. The main accelerating structures are extrapolations of R. Bossarts CTF1 booster sections[15] to low R/Q values to accomodate the large accelerated charge of 1625 nC/pulse. The S-band photo guns would be a major challenge as well as the modulators, pulsing at 444 Hz and studied by P. Pearce[16], for the boosted 150 MW TH 2153 Thomson klystrons .

RF Power Sources

A European manufacturer of klystrons (EEV) is presently developing a CW Inductive Output Tube at 178 MHz for power levels above 1 MW. The same manufacturer indicates that at 200 MHz and 1 MW a depressed collector version should have a target efficiency of 85 %.

For the switchyard S-band klystrons from both Thomson (TH2153) and Toshiba (E3712 type) have been considered. Both need development, the main problem being the average power due to the 444 Hz pulsing.

Conclusions

In this simple proposal for drive beam generation most of the capital investment would be for 200 MHz SC cavities (with their power sources and cryostats at 4.2 deg. K), containing the necessary stored energy (~ 360 kJ total) for acceleration of 2 complete drive beams (of ~ 180 kJ total).

The main disadvantages of the scheme seem to be:

a) significant amount of RF and cryogenics hardware for complete drive beam generation complex, corresponding to about 8 times the hardware of the LEP2 upgrade.

b) high mini-linac charge/pulse of 1625 nC.

c) overall efficiency of only 11.2 %, essentially because of the limited stored RF energy in the 200 MHz structures, which through beamloading limits the number of drive bunchlet trains per pulse.

d) although the CTS beam aperture is large (40 mm), serious damage can be caused by drive beam losses in the CTSs since the single drive beam contains up tp 90 KJ of kinetic energy; smaller losses can deform the CTSs thus increasing transverse wakes [17].

A fail-safe concept (against damage in the drive linac by high-energy electrons) could consist of vertical and horizontal scrapers, distributed over several betatron wavelengths upstream of the drive linac, combined with aperture restrictions between CTSs.

High-energy electrons, contained in the tolerated emittance (defined by the scrapers), would mostly reach the linac end [9]; mainly less dangerous low-energy ones (say, <300 MeV) would hit the aperture restrictions between CTSs, such that only a small fraction of the electron energy is deposited in the CTSs (via showers) [18], see fig. 1.

Alternatively, to protect the CTSs even further, several scraping sections could be arranged along the drive linac.

The main advantages of the 200 MHz drive beam generation scheme appear to be:

a) simplicity: no long drive beam transport lines, no 180 and 90 deg. arcs and no fast kickers as in other concepts. - The drive beam generation process (except for the switchyard) thus occurs over a limited and perfectly straight length of about 1.4 km (including SC cavities, magnets and straight sections) followed by the colinear 30 GHz power extraction in the drive linac (see fig. 1).

b) acceleration in mainly large-aperture (38 cm) 200 MHz SC structures causing low wakes.

c) only 35 kW/m of 200 MHz CW input power for the SC cavities.

The eleven 3 GHz mini-linac pairs, upstream of the switchards, delivering each up to 130 bunchlets of 25 nC per pulse, seem a difficult challenge; the development work can however be attempted in the modest framework of the CERN TEST FACILITY (CTF). – Multipacting in the 200 MHz SC cavities should be investigated. - Cavity tune changes due to ponderomotive forces, periodic with the 444 Hz pulsing, may be acceptable thanks to the shortness (<70 ns) of the drive pulse compared with the structure vibration period [18].

Acknowledgments

The author is indebted to R. Bossart (S-band standing wave structures and efficiency), C. Johnson (drive beam dynamics and CTS deformations with beam losses), P Pearce (modulators, 200 MHz and S-band powering) and A. Riche (drive beam dynamics and checking of general parameters) for many clarifying discussions and suggestions.

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