Study of the TESLA preaccelerator for the polarised electron beam

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Abstract

In the mainframe of the TESLA Technical Design Report a study of the polarised electron beam preaccelerator has been made. The bunching of electrons delivered by a polarised electron source is described and results of simulations are given. The acceleration of the beam with room temperature cavities and its transport to and through a superconducting linac up to 500 MeV is also studied. The polarised electron source itself is not described. Necessary initial values of beam parameters are only assumed.

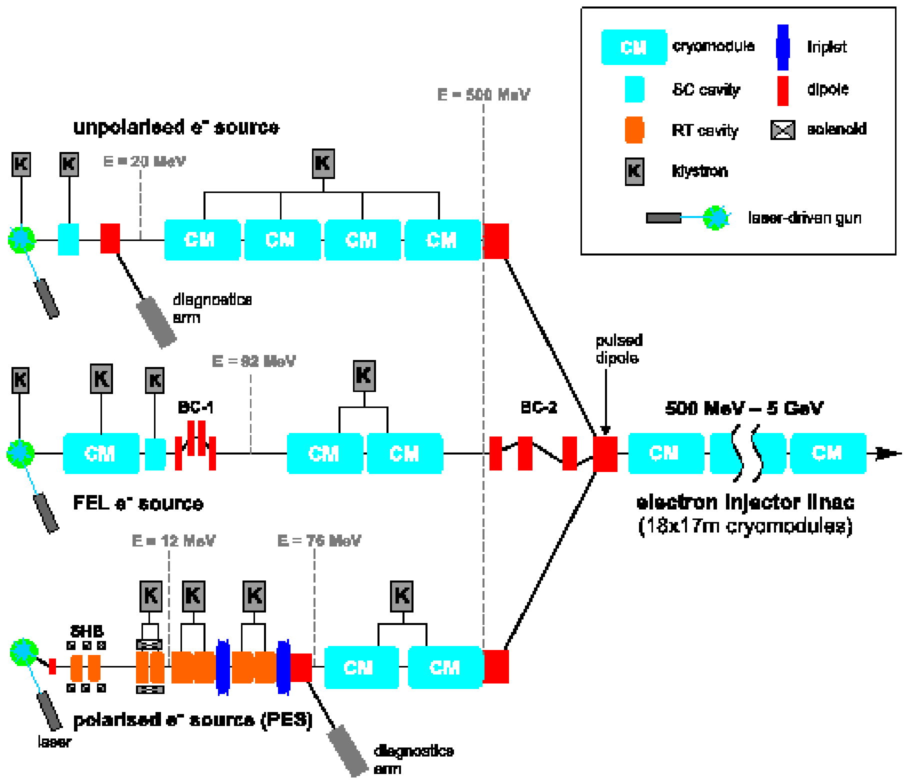

Figure 1 : Schematic of the TESLA injector complex. This report deals with the bottom injector linac

1 Introduction

TESLA will comprise three preaccelerators, for respectively the unpolarised electron beam, the FEL beam and the polarised electron beam. Particles will be separately and independently produced and preaccelerated up to 500 MeV, then injected into a common superconducting (SC) 5 GeV linac (fig. 1). Each beam therefore requires a particular study. The particularity of the polarised electron beam is that present polarised electron sources (PES) deliver low energy electrons (about 100 keV) that cannot be injected directly into a SC cavity because solenoids are required for their transverse focusing. RF guns as polarised electrons sources are not considered as operational yet. It is therefore necessary to accelerate them using room temperature (RT) cavities until the divergence of the beam is small enough that continuous focusing is no longer required. In addition, because of the low energy and space charge forces, the bunches delivered by the gun cannot be as short as necessary to produce a small energy spread. A prebunching and bunching system is therefore required, as in conventional electron injectors.

As a TESLA PES has not been designed yet, it was suggested to base this study on the parameters of the PES proposed for the NLC collider project [1], which is specified to deliver the same bunch charge (Table 1).

2 Initial beam parameters

Table 1 : Proposed specifications for TESLA and NLC polarised electron sources

Parameters	units	TESLA	NLC
Charge per bunch in linac	nC	3.2	3.5
Charge per bunch at gun	nC	4.5	
Bunch FWHM at gun	ns	2	0.7
Cathode bias	kV	-120	
Edge emittance	π mm.mrad	8	
Edge emittance (normalised)	π mm.mrad	5.6	
Beam radius	mm	12	
Envelope angle	mrad	10	
Peak current	A	2.25	6.4
Bunch # per pulse		2820	90
Bunch spacing	ns	337	1.4
Pulse length	μs	950	0.13
Repetition rate	Hz	5	120

We have adopted the same values as NLC for the beam parameters at the output of the gun such as electron energy, envelope radius and angle. The TESLA time structure, however, is quite different and, because of the much longer macropulse, will require a specifically developed laser [6] to control the gun emission. It seems that the TESLA PES will eventually deliver bunches of 2 ns rather than of 700 ps for NLC. As a result, it was not possible to use the NLC scheme for the prebunching section : Lower frequencies had to be chosen for the prebunching cavities for which we followed roughly the design of the S-Band collider Test Facility injector [3]. In case 700 ps bunches could be obtained, another scheme using SHB cavities of higher frequencies has also been studied (see appendix).

Here, the transverse emittance was also taken the same as for NLC which, given the smaller peak current resulting from the longer bunch, is a conservative assumption.

3 The prebunching section

3-1 Layout and main parameters

We use two sub-harmonic prebunching cavities (SHB) working at one-twelfth and one-third of the fundamental injector linac frequency, i.e. 108 and 433 MHz respectively. The distance between their axes is 200 cm and that between the second cavity axis and the buncher entrance is 38 cm (fig. 4).

Simulations with PARMELA have been performed assuming an initially uniform longitudinal distribution of charges, the length of which corresponds to a 2 ns pulse. A gaussian distribution does not significantly change the results. The initial rms phase extension is 270° of the 1.3 GHz period. The optimum modulating peak voltages are found to be 40 kV and 44 kV respectively. The bunches are compressed to 97° rms at the entrance to the second cavity and to 30° rms at the buncher entrance (Table4, fig. 5 and 6).

3-2 Power requirements and beam loading

The TTF experience with injector #1 [4] provides us with a good reference : A 216 MHz prebuncher cavity, made of stainless steel with copper deposited inside, did currently produce a 50 kV voltage in 2 ms pulses, at a 10 Hz repetition rate. Its shunt impedance was R_s = 6.2 MΩ and the unloaded quality factor was $Q_0 = 2.4\ 10^4$. A 400 W peak power was then required for that voltage. In scaling these parameters like $f^{-1/2}$ one can derive the following table (Table 2).

In assuming a critical coupling, we can also calculate the filling time, given by

$$t_f = \frac{2Q_0}{\omega(1+\beta)}$$

and the beam loading for a 9.5 mA peak current, given by

$$V_b = R_s i \frac{1}{1+\beta}$$

Table 2 : Parameters of subharmonic buncher cavities

Cavity #	F MHz	Voltage kV	R_s MΩ	Q_0	P W	t_f µs	V_b kV
1	108	40	8.8	$3.4.10^4$	220	14	42
2	433	44	4.4	$1.7.10^4$	360	25	21

In order to perform, right from the beginning of the beam pulse, the correct bunching, filling times will have to be reduced, e.g. by increasing the coupling factor. A trade-off will be found with the required RF power level. The phase and the amplitude regulations will compensate for the residual transient variations. As it was made in TTF injector #1, a fast phase shift of the RF during the transient beam loading can be added.

4 The bunching section

4-1 Choice of the RF structures

By accelerating the 120 keV incoming electrons with a high gradient one can limit the emittance growth caused by space charge forces. The cavities to be used, however, have to withstand 1 ms long RF pulses and a 0.5% duty cycle which imply severe thermal constraints. The requirement for RT cavities capable of high gradient and high average power also appears in the design of the positron pre-accelerator (PPA) — the linac that follows the e^+/e^- conversion target in TESLA. For that purpose, the Moscow INR group has proposed and studied new RF structures, the so-called CDS cavities [5]. Beside a high shunt impedance, they can dissipate 30 kW/m and have large beam apertures. Two cavity types have been defined, the characteristics of which are summarised in Table 3. Given the development work that such cavities require it is clear that using them here as building blocks, is recommended and will increase the machine reliability.

Table 3 : Main characteristics of RT accelerating CDS cavities

Parameters	units	Type #1	Type #2
RF frequency	GHz	1.3	
Structure type		SW	
Dissipated power	MW	< 4	
Aperture	mm	52	
No of cells per section		5	17
Shunt impedance	MΩ/m	31.92	35.38
Accelerating gradient	MV/m	< 14.88	< 8.5
Length	m	0.576	1.96

Because of the non-relativistic velocity of the incoming electrons (β[120 keV]=0.59), a $\beta < 1$ structure had to be considered. We have examined the case of a 5-cell cavity with a 12 MV/m gradient. Without space charge, it was found that a $\beta = 0.98$ structure could capture a significantly larger range of input phase and that a still smaller β would cause an excessive energy spread (fig. 2). However, with space charge no advantage was found to any $\beta < 1$ value. With less cells in the cavity, we might have found an optimum β with a smaller value, but that would have resulted in too a different structure than the one of PPA. In addition, the β =1 5-cell structure has the advantage of remaining efficient even if it is eventually operated at a higher RF gradient than 12 MV/m or if the PES works with a voltage higher than 120 kV. We then chose the "standard" β =1, 5-cell CDS cavities as a buncher element.

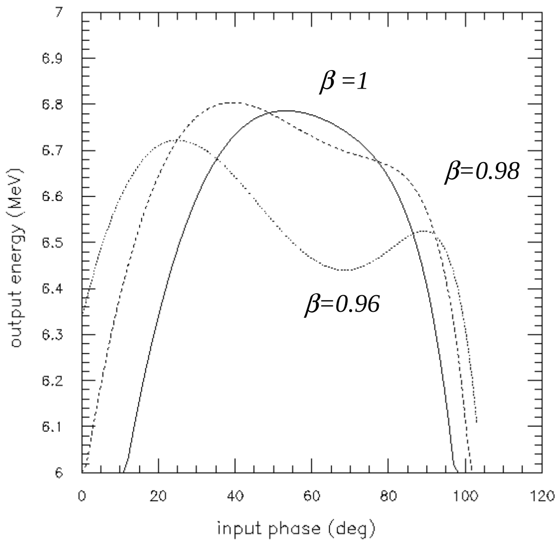

Figure 2: Energy gain vs input phase in a 5-cell room temperature CDS cavity for different β values. Accelerating gradient is 12 MV/m, incident energy is 120 keV

4-2 Buncher layout

The bunching section we propose is comprised of 2 type #1 β =1 cavities separated by a distance of λ/2 (115.3 mm), and sharing the power of one TESLA 10 MW klystron. To provide a safety margin simulations have been made with only 12 MV/m. The accelerating field distribution on axis of one such cavity is represented in fig. 3. In the code PARMELA, we described it by mean of a Fourier series, taking into account, both sides, the short fringe field. Coefficients are written in a file rather than in the code itself.

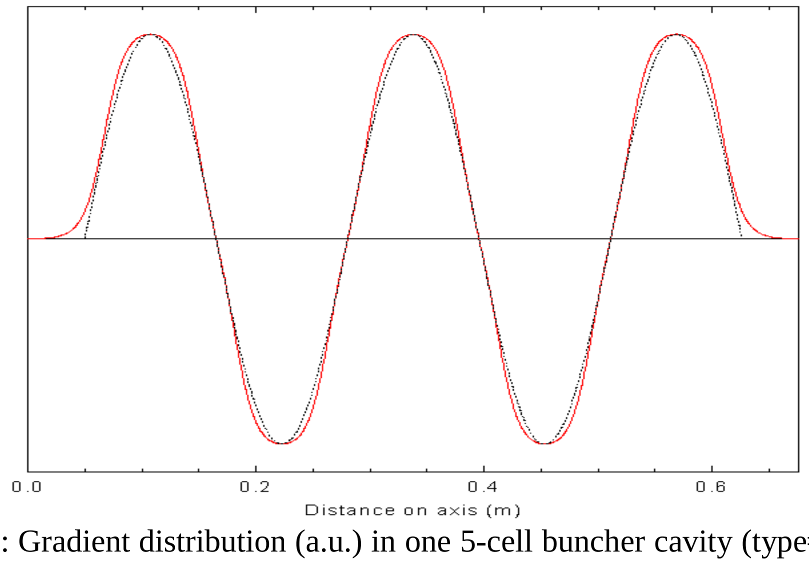

Figure 3: Gradient distribution (a.u.) in one 5-cell buncher cavity (type#1 CDS cavity) used for the PARMELA simulations. The dotted line represents a sine variation

4-3 Focusing scheme

In the NLC proposal the gun is placed at a 20° angle to the injector axis. This has technical advantages like permitting the polarisation measurement, protecting the gun vacuum, allowing installation of a second gun that can be a backup PES or a thermoionic gridded gun. So we could also adopt this layout. In order however, to simplify the simulations, we have supposed a straight 75 cm long drift space between the source and the prebuncher cavity, with one solenoidal lens in the middle (fig. 4). That lens is used to focus the beam into the prebunching cavity. At the waist, a Brillouin field is started to ensure a laminar flow. In the final design, some bunch lengthening could result from a longer path but it was neglected in this study.

The simulations have been performed first in using a magnetic field distribution along the axis made of "rectangular" steps. Several computer runs were used to determine the various parameter dependencies for that field, allowing to optimise the beam envelope and to achieve the minimum transverse emittance. Then a more realistic, continuous distribution was found (fig. 8). It starts from about 50 Gauss after the first prebuncher, increases linearly to about 130 Gauss at the buncher entrance and then increases sharply to 500 Gauss over the length of the two buncher cavities. Steep transitions are necessary to fulfil Brillouin conditions. A study with fields produced by real shielded solenoids has not been made yet.

4-4 Simulations results

Simulation results obtained with PARMELA, at several locations, are summarised in Table 4. Several characteristic plots are shown on fig. 5, 6 and 7 and beam size and bunch length evolutions along the axis are shown in Fig. 8

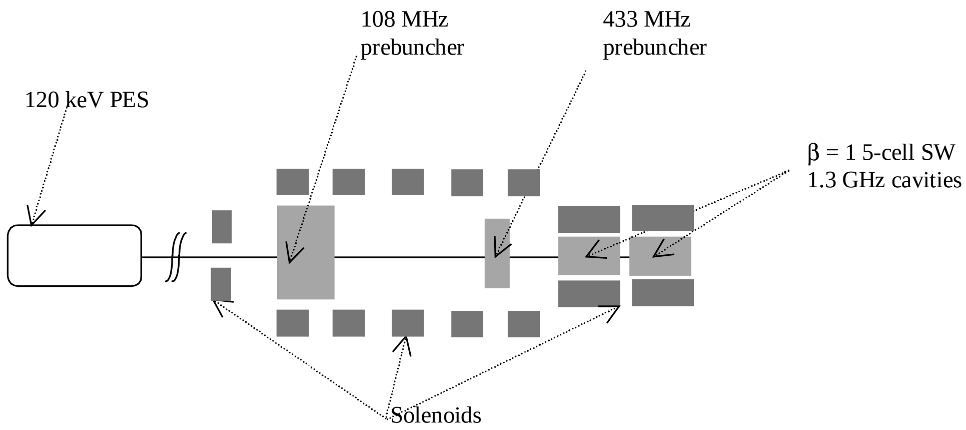

Figure 4 : Sketch of the prebunching and bunching sections

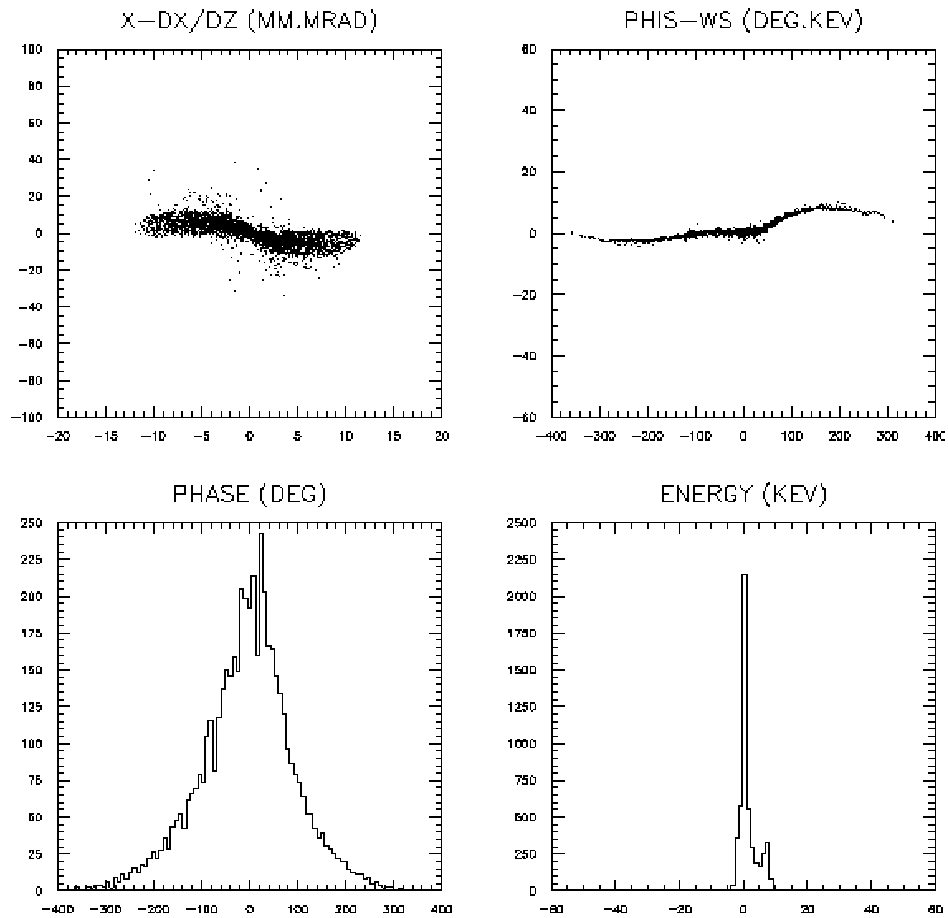

Figure 5 : Simulation results after first prebunching drift space

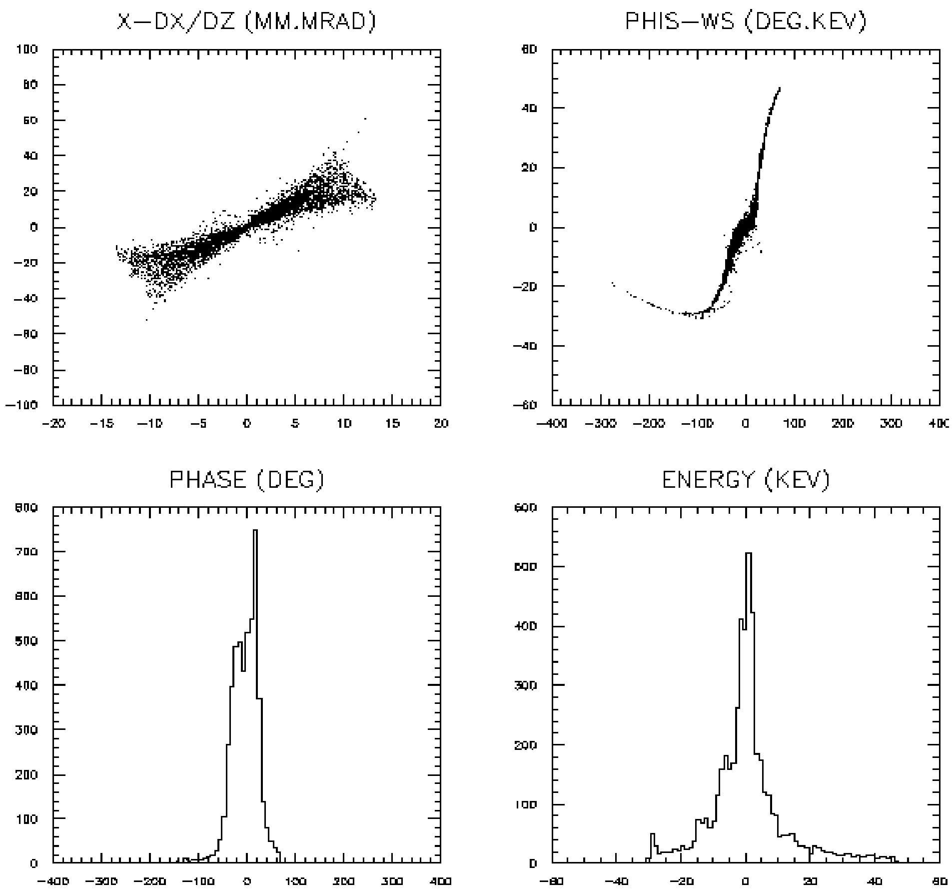

Figure 6 : Simulation results after second prebunching drift space

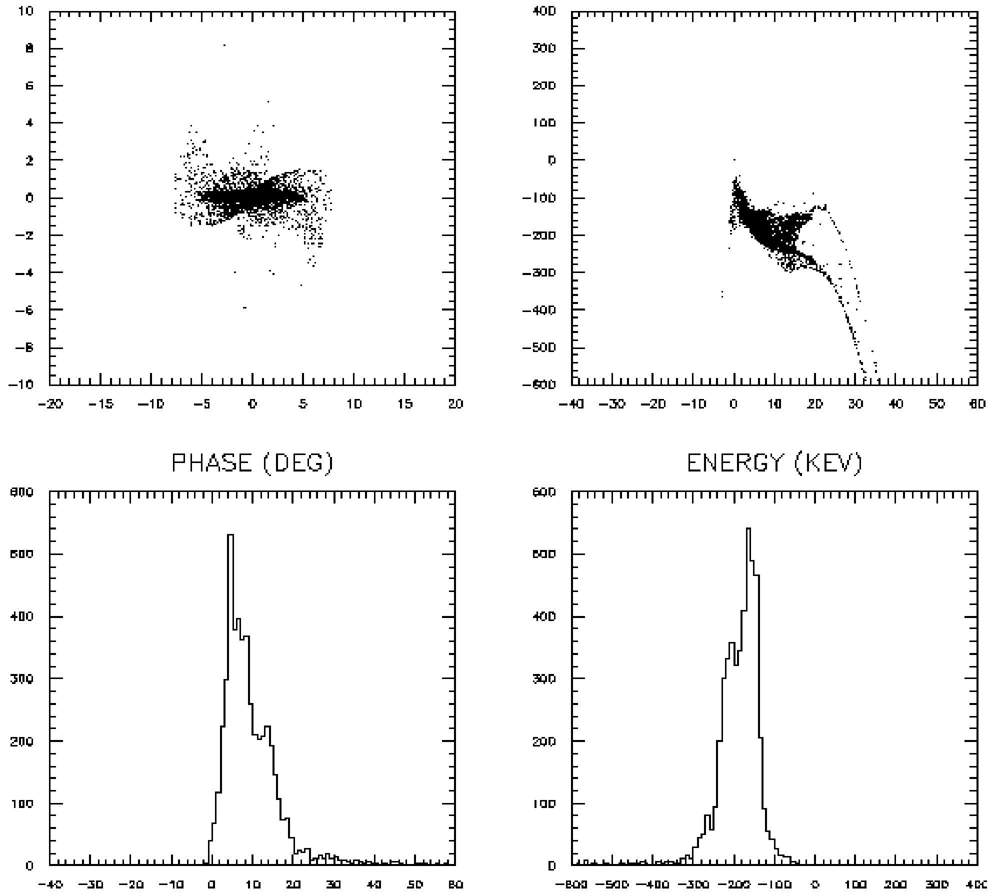

Figure 7 : Results of PARMELA simulations at end of the bunching section. Beam energy is 11.3 MeV. Results are summarised in Table 4

Table 4 : Summary of simulation results at exit of different sections

Parameters	units	Gun	Prebunch. #1	Prebunch. #2	Buncher
Distance from gun	m	0	2.8	3.1	4.5
Energy	MeV	0.12	0.12	0.12	11.3
Phase extension (rms)	deg	270	97	30	5.3
Energy spread (rms)	keV	0	2.8	12	45
Normalised emittance (rms)	π mm.mrad	4	15	22	42.5
Beam size σ_x	mm	4.9	5	6	2.6
Beam angular spread σ_{xp}	mrad	4	6	15	0.7

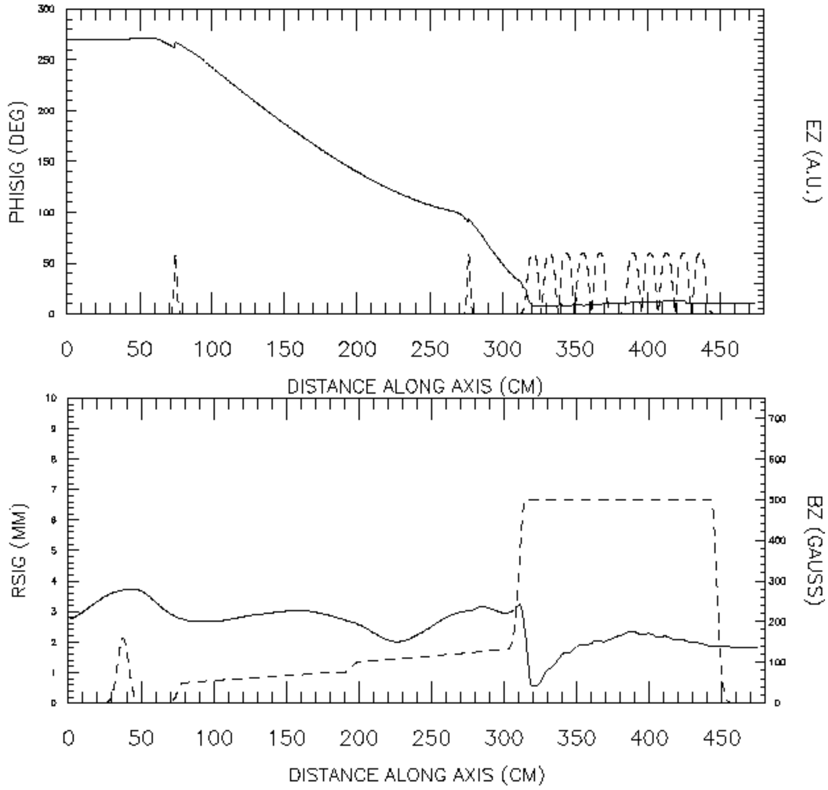

Figure 8 : RMS bunch length (top) and rms beam radius (bottom) along the prebunching and bunching sections (solid lines). In dotted lines, gradient distribution in a.u. (top) and magnetic focusing field distribution (bottom) are shown.

5 Acceleration by RT cavities prior to injection into the SC linac

5-1 Choice of energy

The choice of the beam energy for injection into the first cryomodule of the injector linac can be made by the criteria of the non-normalised beam emittance, which must be small enough to allow an easy transport of the beam through it. As a goal, we have chosen a non-normalised emittance of 0.5 mm.mrad, corresponding to the TTF injector normalised emittance of 20 mm.mrad for 8 nC bunches at 20 MeV.

At the buncher exit, the beam energy is ~12 MeV. For the required further acceleration, we will use 17-cell PPA cavities (type #2), which provide more energy than the 5-cell ones (Table 3).

One pair of such cavities — powered with one standard 10 MW klystron — can give an energy gain of 32 MeV. Table 5 shows the expected beam emittance after one, two or three such units. One unit, resulting in a beam energy of 44 MeV, is sufficient to adiabatically damp the initial emittance to below the required 0.5 mm.mrad; using a second such unit, up to 76 MeV, provides a large and sufficient margin.

Table 5 : Transverse emittance at end of RT cavities for beam of increasing energy

	E (MeV)	Norm. Emittance (mm.mrad)	Un. Emittance (mm.mrad)
TTF injector	20	20	0.5
PES + Buncher	12	42.5	1.74
+ 1 klystron	44	42.5	0.49
+ 2 klystrons	76	42.5	0.28
+ 3 klystrons	108	42.5	0.20

5-2 The 500 MeV superconducting linac

To achieve the required energy of 500 MeV, the SC linac has to provide 424 MeV to complement the 76 MeV from the room temperature section. A conservative choice is to use two standard TESLA cryomodules of 12 cavities each, since the required average gradient is then only 17.8 MV/m. One 10 MW standard klystron only is sufficient to power both modules with each arm supplying 12 cavities (fig. 9). Because of the lower energy than in the main TESLA linac, the cryomodules must be equipped with doublets instead of quadrupoles as in standard modules. One could also imagine to use three 8-cavity modules of the TTF type (see appendix, fig. A-4).

5-3 The RT–SC transition matching beamline

A spectrometer arm installed between the RT section and the SC linac will permit to independently operate and tune the former. Two triplets, either side of the dipole, are required for matching the beam into the SC linac with a 90° phase advance per module. The center of the first one is placed at 1.2 m from the RT linac exit and the second one 4.5 m farther. The total distance between the RT and the SC linacs is 11.6 m. A triplet is also necessary between the pairs of RT type #2 cavities (fig. 9). The resulting beam envelope is shown in fig. 10.

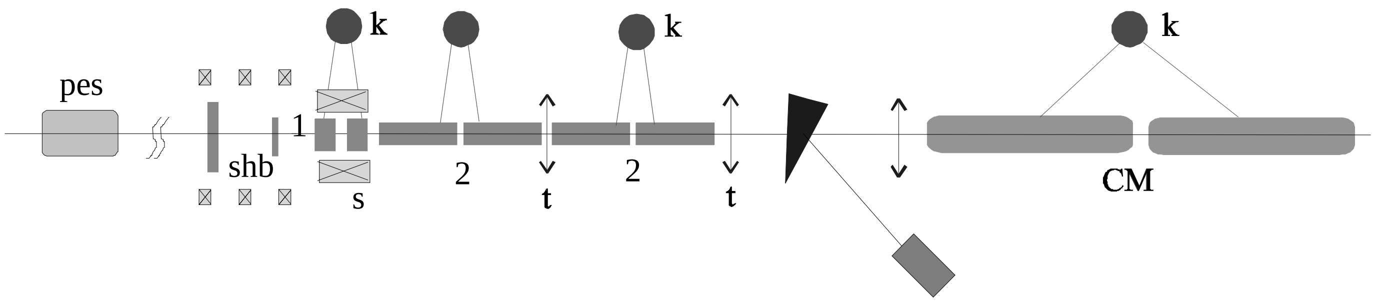

Figure 9: Layout of the proposed 500 MeV preaccelerator for polarised electrons. k: 10 MW klystrons; pes: polarised electrons source; shb: subharmonic prebunchers 108 and 433 MHz; 1: 5-cell RT cavities; 2: 17-cell RT cavities; s: solenoids; t: triplets; CM: cryomodules

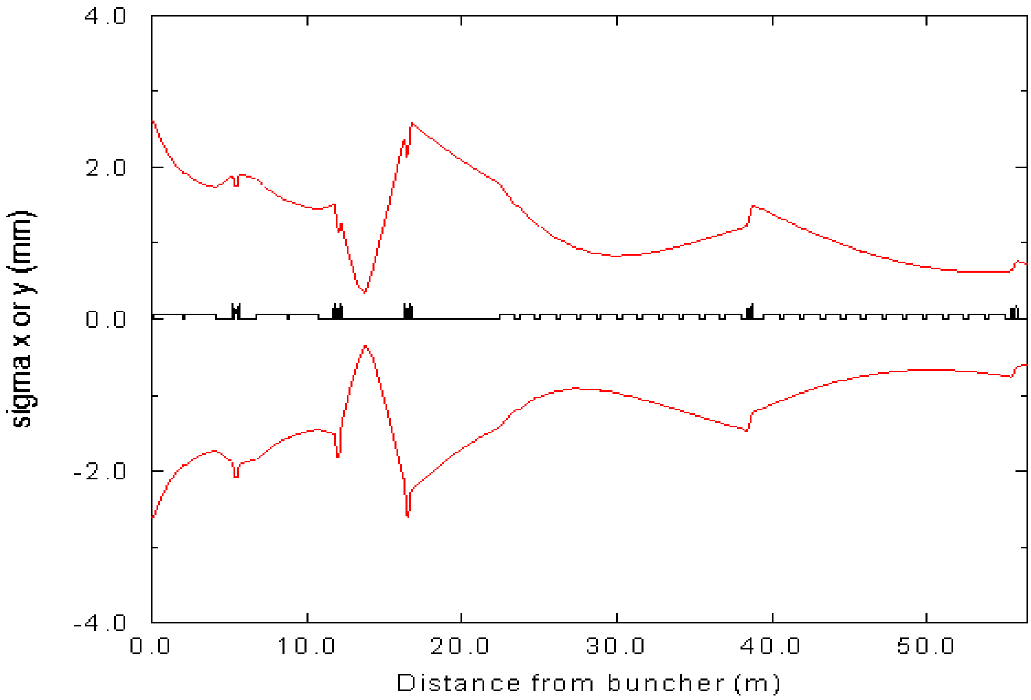

Figure 10 : Beam envelope through RT and SC linacs. Origin is at the buncher exit. Cryomodules are equipped with doublets. Gradient in cavities is 17.8 MV/m

6 Conclusion

This report describes a possible scheme for the pre-acceleration of polarised electrons up to 500 MeV in order to inject them into a 5 GeV linac, then into TESLA. It must be reminded however that the study was started with beam parameters of a polarised electron source different from the one that will eventually be used. As it was explained, a shorter initial bunch length could justify a very different prebunching system. An example is given in the following appendix. What is demonstrated by these two examples is that, despite very different initial beam parameters and prebunching systems, the rest of the linac can have the same structure and still fulfil satisfactory performances as a pre-accelerator. Of course, the final parameters of the 500 MeV beam will depend on the initial bunch length and initial emittance. As it will appear in the appendix, the shorter initial bunch length results in a more compact prebunching system and in a better final emittance.

7 Acknowledgements

Authors wish to thank B. Aune for useful discussions. Thanks are also due to V. Paramonov for providing us with useful informations.

References

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APPENDIX

Another possible scheme for the prebunching section

A 1 : Introduction

The scheme described in previous pages has been mainly determined by the assumed minimum length of the bunches delivered by the PES, i.e. 2 ns. This number itself, also results from assumptions made about the laser that will control the photocathode emission [6]. It must not be excluded however, despite the very long TESLA macropulse, that designers eventually succeed in obtaining shorter bunch lengths, e.g. 700 ps, as short as the one envisaged in the NLC design report [1]. In this case, a better scheme for the prebunching system has been studied which was inspired by the NLC proposal. It has the advantage of using smaller cavities placed at smaller distances, one from each other and from the buncher. Main results are given.

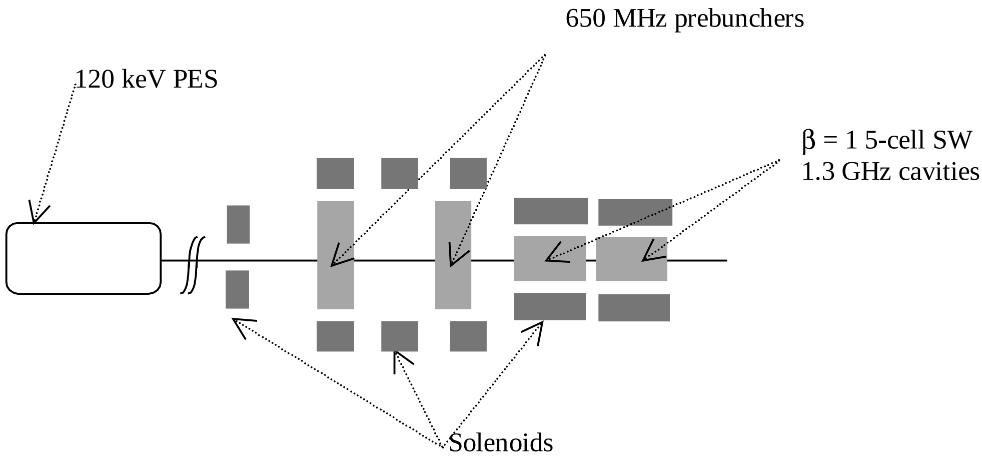

Figure A-1: Sketch of the prebunching and bunching system proposed for 700 ps gun bunches

A 2 : Description

Two subharmonic prebuncher cavities are used, which work at 650 MHz. (fig. A-1 and Table A-1). The bunching section is the same as in the previous scheme, i.e. two SW, CDS type #1, $\beta = 1$ cavities, operated at 12 MV/m and surrounded by solenoids. The focusing field distribution is slightly different (fig. A-3). It starts from 100 Gauss after the first prebuncher, increases linearly to about 200 Gauss, then sharply to 500 Gauss over the first prebuncher cavity. The predicted performances at the buncher exit are better, in particular the transverse emittance which is twice smaller (Table A-2 and fig. A-2). Consequently, the rest of the linac can remain the same as in the previous scheme, i.e. accelerate the beam in four 17-cell RT, CDS type #2, $\beta = 1$ cavities up to 76 MeV, before injection into a SC linac up to 500 MeV.

We have simulated the adaptation and the transport through this linac, in using three TTF-type, 8-cavity cryomodules that could be used instead of the 12-cavity standard TESLA modules. They are equipped with doublets (fig. A-4) instead of quadrupoles as in TESLA modules. The distance between the two pairs of RT cavities is 2.6 m and is 7 m between the RT and the SC linacs. The phase advance is 90° per module.

Table A-1 : Main parameters of the proposed buncher

Parameters	units	
Distance between SHB's	cm	74
Distance SHB #2 to buncher	cm	42
SHB's frequency	MHz	650
SHB voltages (cavity #1/#2)	kV	22/46

Table A-2 : PARMELA results at buncher #2 exit

Parameters	units	result
Energy	MeV	11.9
Charge	nC	3.2
Phase extension rms	°	4.7
Energy spread rms	keV	40
Emittance rms normalised	π mm.mrad	22.5
Beam size σ_x	mm	1.3
Beam angular spread σ_{xp}	mrad	0.7

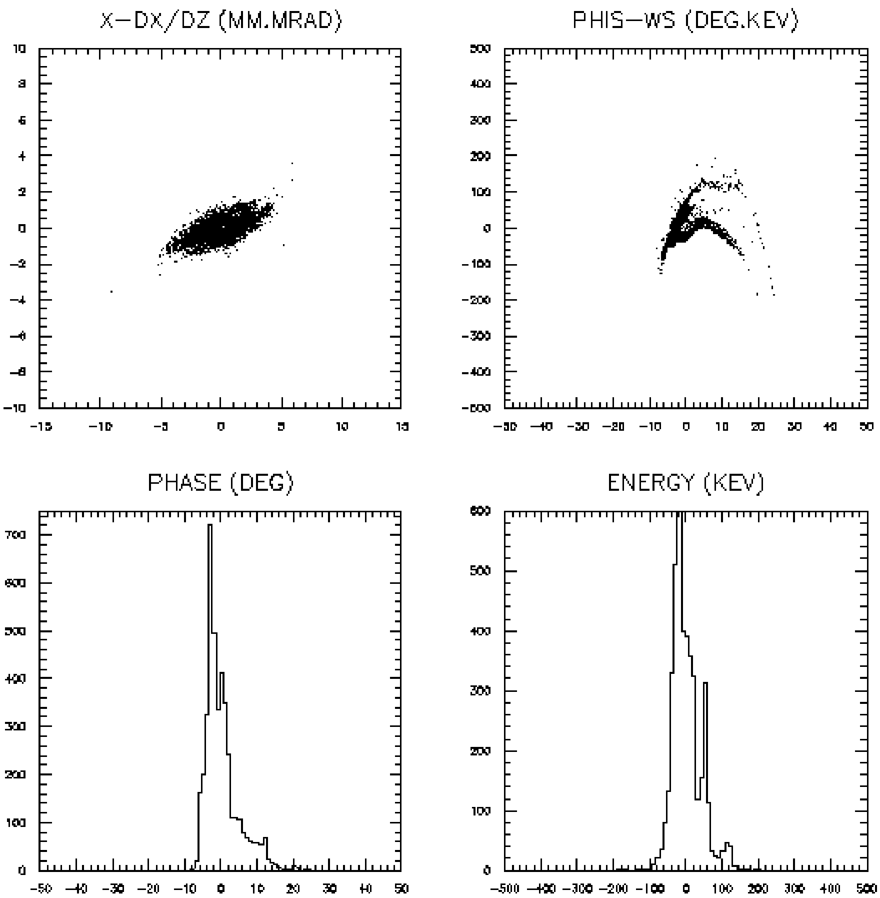

Fig.A-2 : PARMELA plots at end of the bunching section. Beam energy is 12 MeV

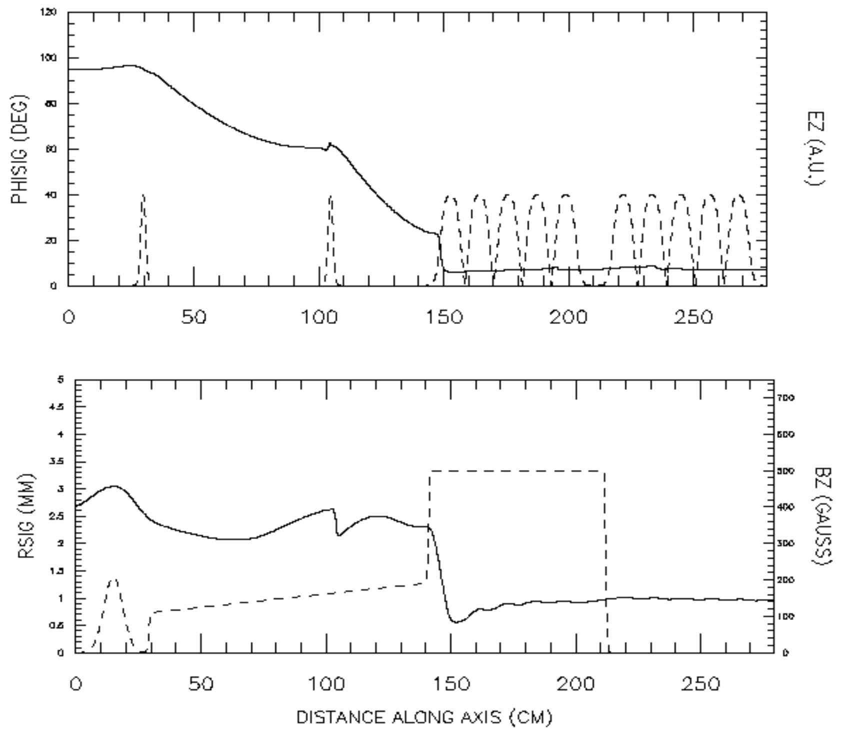

Figure A-3 : RMS bunch length (top) and rms beam radius (bottom) along the prebunching and bunching sections (solid lines). Gradient distribution in a.u. (top) and magnetic focusing field distribution (bottom) are shown (dotted lines).

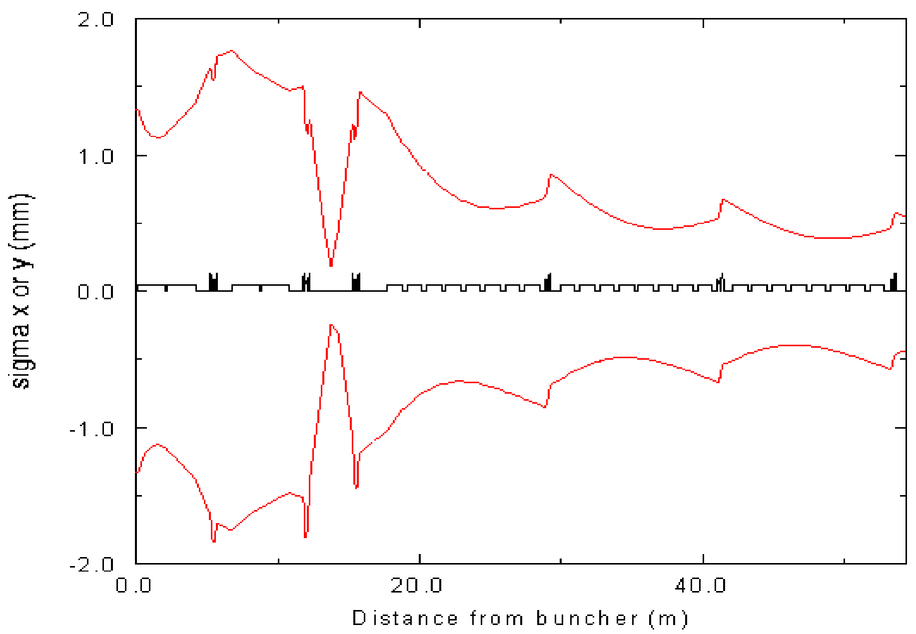

Figure A-4 : Beam envelope through RT linac and SC modules. Three 8-cavity TTF modules with doublets are assumed instead of two12-cavity TESLA modules as in the previous scheme (figure 9). Origin is at the buncher exit. Gradient in cavities is 17.8 MV/m