PRELIMINARY STUDY OF A CONVENTIONAL SCHEME FOR A TESLA INJECTOR

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- Juillet 1991 -

INTRODUCTION

Electron-positron linear colliders are now envisaged at energies of the order of one TeV by particle physicists . This new generation of machines will have to deliver very short and very intense bunches. In the context of the TESLA project, a preliminary proposal for the injector of such a machine has been reported by C. Pagani [1]. His scheme uses a superconducting rf-gun. In this paper we examine the possibility of using more conventional devices that could be part of a Test Facility in a very next future.

In the first part we mention the requiments of such a project and then we examine the existing installations that reach similar performances. Two solutions appearing to be interesting, we choose to investigate them further. Both use SC cavities. The first one, which is described in part II, consists in firstly prebunching the beam and then in sending it in accelerating SC cavities. The second scheme (part III) consists in firstly accelerating long bunches thanks to a "flat-topping" operation and then in compressing them as much as possible.

I. GENERAL CONSIDERATIONS

I-1. Specifications

The goal is to produce bunches of 5.10^{10} electrons, 1 mm long (i.e a 3 ps duration or 1.6 degree of an 1.3 GHz period), at 1 μs intervals. They must be delivered in macropulses of 1 ms repeated at around 10 Hz.

Photocathodes are now often envisaged for such bunch density but unfortunately they are considered as not operationnal in the immediate future so we choose not to include them in our study. This imposes the use of a classical electron gun i.e a thermionic cathode with electrostatic optics.

I-2. Review of existing models

A good way to start is to examine existing installations that reach similar specifications using such a gun. If we limit ourselves to 1.3 GHz systems, three injectors can be found in the litterature that deliver electron bunches in the 5.10^{10} range. They are :

- The EG&G linac in Santa Barbara [2].

- The Boeing F.E.L [3].

- The Argonne electron linac [4].

Although different in detail, the three systems use in fact the same set of devices, namely :

- A thermo-ionic cathode gun with 100 to 150 kV anode voltage delivering 1 to 3 ns pulses (a ns pulse and 5.10^{10} electrons correspond to an 8 A peak current).

- Several prebunching RF cavities working at subharmonic or harmonic frequencies. The first subharmonic frequency encountered is chosen low enough for the period to be much greater than the gun pulse duration.

- One capture TW section, phase velocity graded, with accelerating gradients of the order of 10 MV/m.

- One or more standard accelerating structures that increase the electron energy up to around 20 MeV. Bunch durations are then in the 20-50 ps range.

- Solenoidal focusing all along the beamline, including over cavities and accelerating structures.

- In addition to these common features the Argonne machine compresses its bunches further by using a magnetic bunching scheme at an energy of 22 MeV. The phase in the last accelerating structure is adjusted to produce an adequate time-energy correlation. This model is interesting because the bunch finally obtained meets our specifications exactly (Figure 1).
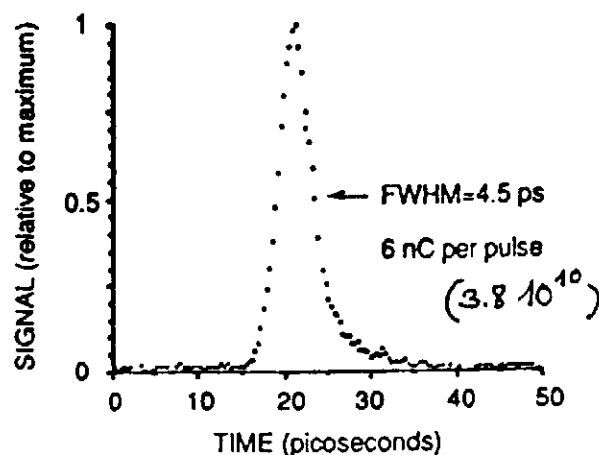

Figure 1

The shape of the pulse of the L-Band Linac of the Argonne National Laboratory [4].

I-3. Are these schemes possible solutions to the problem ?

All of these injectors work with RF pulses in the µs range and repetition rates of the order of 50-200 Hz. For 1 ms long pulses, it is clear that the utilization of these models would pose a problem of power limitation and power sources.

A practical limit of power dissipation in a RF cavity can be estimated from a figure given in a MAMI paper [5] as 22 kW/m for a 2.45 GHz structure (the MAMI Laboratory developped RF copper structures intended for CW operation). Since this limit should vary with the cylindrical external area of the cavity, i.e as (frequency)$^{-2}$, if we assume that RF peak power figures given for the Boeing scheme are typical (8.3 kW for the 108 MHz cavities and 6 kW for the 433 MHz one), one finds that prebunching cavities could still work even in a CW regime. Withstanding the corresponding gap voltages (respectively 42 and 39 kV) during 1 ms pulses without arcing would still be a problem that we disregard for now.

In addition, we note that rf power tubes are available commercially in this range of power and pulse length.

The real difficulty arises from the capture cavities, that need peak power of 3.5 MW to 11 MW. The highest peak power found for a commercially available klystron delivering 2 ms pulses is 2-4 MW. Therefore, it is not possible to duplicate the design of those working injectors precisely. Designing an adequate graded beta structure may not be impossible, but was not examined yet.

The solutions that we tried to investigate further are :

- Using similar scheme for prebunching, but finding a capture scheme using one or more superconducting cavities.

- A completely different scheme, using superconducting cavities for both the prebunching and the capture.

II. FIRST INVESTIGATION:

USING SC CAVITIES WITH CLASSICAL BUNCHING

II-1. Introduction

Using superconducting cavities solves the RF power limitation problem but introduces new difficulties. Because the number of particles per bunch is very high and the pulse already compressed, the impossibility of magnetic focusing along the SC capture cavity is a severe drawback. To overcome this difficulty we use short, single cells in order to reduce the distance without focusing where the beam radius increases tremendously. We also added superconducting solenoids as close as possible to each single cell. Another important problem is the goal of a very small bunch length. This implies high accelerating field but, on the other hand, we have to take into account that damping HOM's requires a large aperture resulting in large fringing fields which decrease the capture efficiency. To cope with these problems we use single cells instead of multicells. This permits the use of higher gradients, the variation of the pitch of the cells to match the acceleration, and the straightforward addition of focusing lenses. These single cells are presumed to be enclosed in one single cryostat in order to reduce drift spaces between them. As a result, magnetic lenses would also have to be superconducting. We choose an average accelerating field of 25 MV/m in order to insure an efficient capture. This high value is the admitted upper limit compatible with the state of the art.

Finally we tested with PARMELA a scheme relying on the following two options that we describe in detail below:
- prebunching with two subharmonic bunchers.

- a whole cryostat housing SC monocells and solenoids.

As the simulations presented here follow a previous study on MACSE dynamics [Internal report DAPNIA/SEA/R03], the RF frequency is 1.5 GHz. Results are expected to remain valid at 1.3 GHz.

II-2. Prebunching scheme

For the electron gun high voltage we found a good compromise at around 500 kV : low energies enable an efficient velocity modulation permitting large phase compression, while high energies reduce emittance growth from space charge forces. The bunches delivered by the gun have a total length of 1 ns which corresponds to 540° at 1.5 GHz. A good emittance 500 KeV electron gun delivering adequate current has already been reported [6].

The first subharmonic buncher works with an RF frequency $f_0/6$ (250 MHz). Because of high space charge effects and high beam velocity, the amplitude of the field in the buncher has to be large to produce an efficient velocity modulation. On the other hand, the buncher amplitude is limited by the RF power in the copper cavity and the induced energy spread. A good compromise for the accelerating voltage was found to be 120 kV. The distance between the two bunchers to get the best phase compression is 3.5 m. Over this distance solenoids are installed with a graded magnetic field to optimize the beam radial focussing. The phase spread which is achieved (210°) is still large in comparison with the phase acceptance of the capture cavity, so we need a second subharmonic buncher. We choose an RF frequency 499 MHz ($f_0/3$) for the second buncher. At this point the effect of space charge has increased by a factor of 2.5 so a total voltage of 85 kV is necessary to reduce the bunch length. The distance between the first and the second SC single cell is 1.3 m. This distance is divided as follows (Figure 2) :

- a 80 cm solenoid.
- a 20 cm drift space between superconducting and normal solenoids.
- a 22 cm superconducting solenoid.
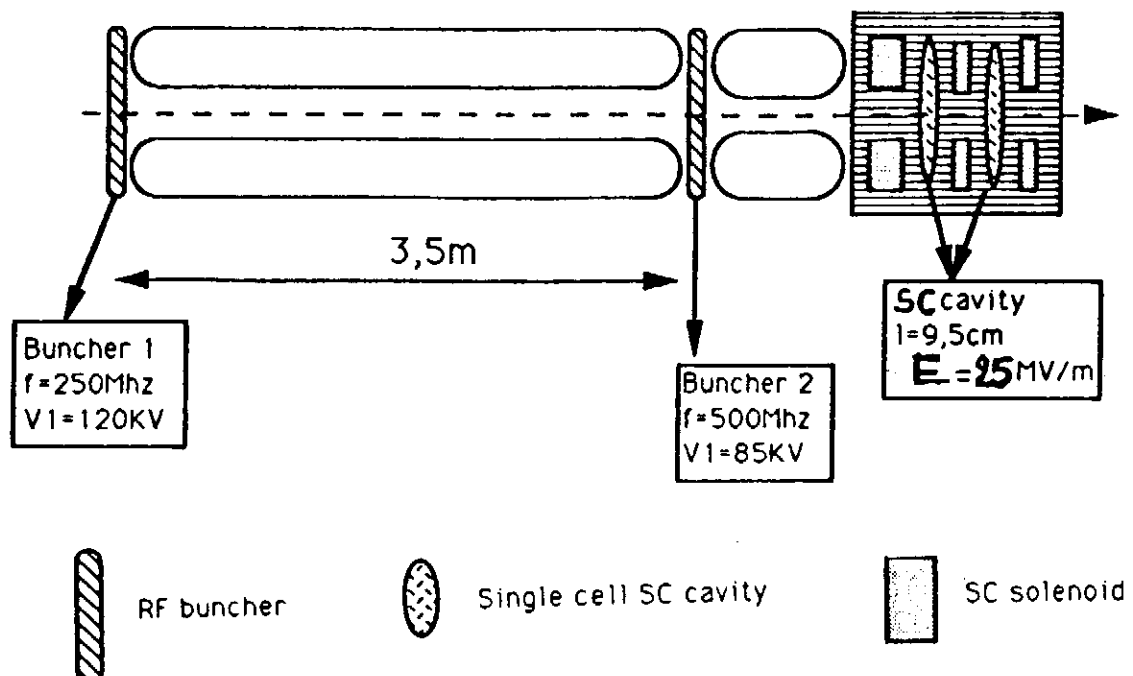- a 8 cm drift space between superconducting solenoid and single cell.

Figure 2

The injector design considered at first.

II-3. Capture Section

At the entrance of the first SC cavity, the phase extension is 120° and the beam has an average energy of 500 keV. To accelerate and bunch this beam further with high space charge, a high value of accelerating field is needed. We took a value of 25 MeV/m. The fringing field effects were included in the PARMELA calculations. The real cavity length is 9.5 cm (this value was optimized for the 500 KeV electrons) and the total active field extends over 19 cm. A total phase extension of 32° at the entrance of the second cavity is obtained. The energy is obviously very high (2.6 MeV) and the rms energy spread is 8%. The second cavity is used to reduce the bunch and the energy spread. Although there are three superconducting solenoids in the cryostat, one before the first mono-cell, one between and one after, the compression in the first monocell induces an important defocusing in the radial phase space and the rms beam radius reaches 15 mm in the solenoid between the cavities (Figure 3).

Figure 4 shows the final results at an energy of 2.94 MeV. The rms phase extension has been reduced to 10° (i.e. 5.5 mm), the normalized emittance is 4. 10^{-4} m.rad and the rms energy spread is 200 keV ($\Delta p/p = 7\%$).
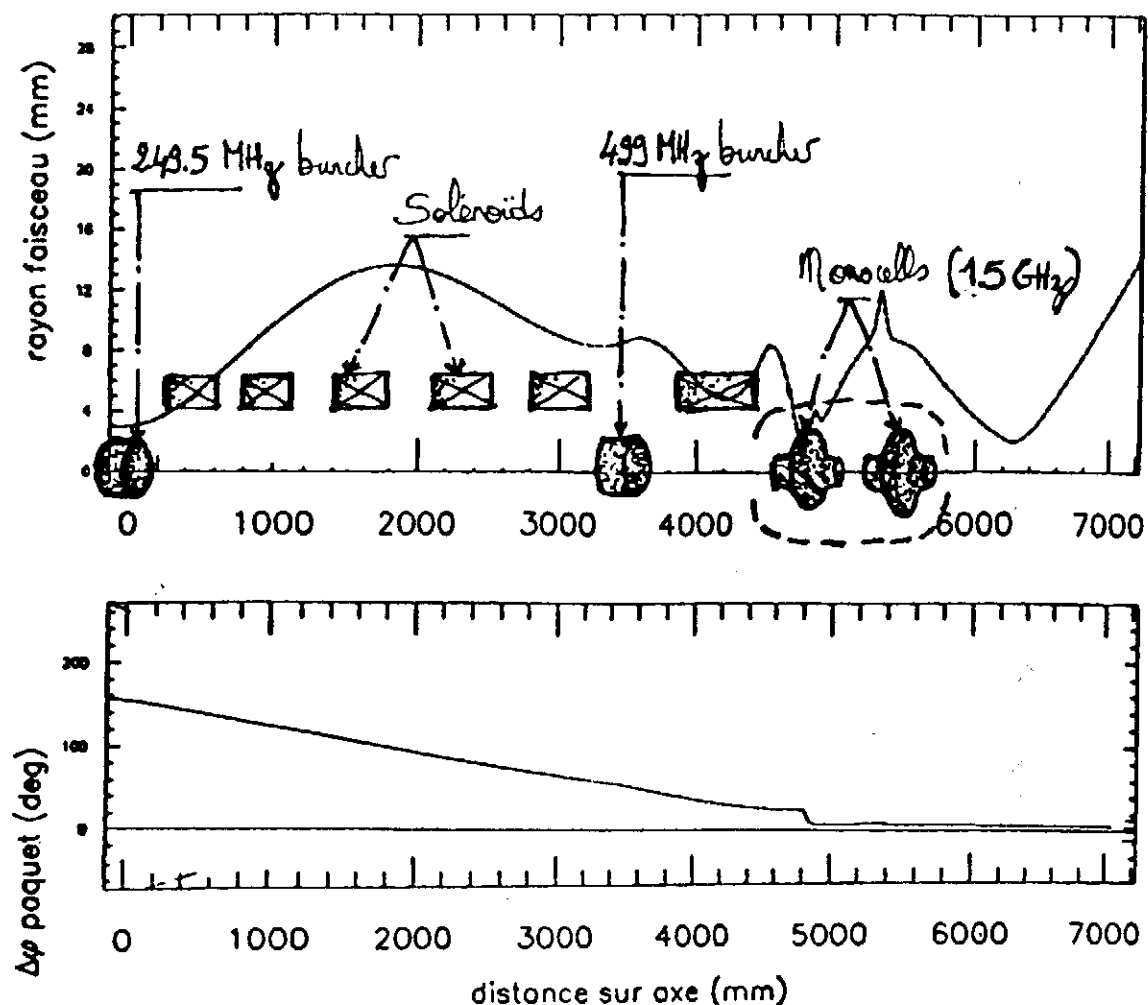

Figure 3

-a- The beam rms radius along injection.
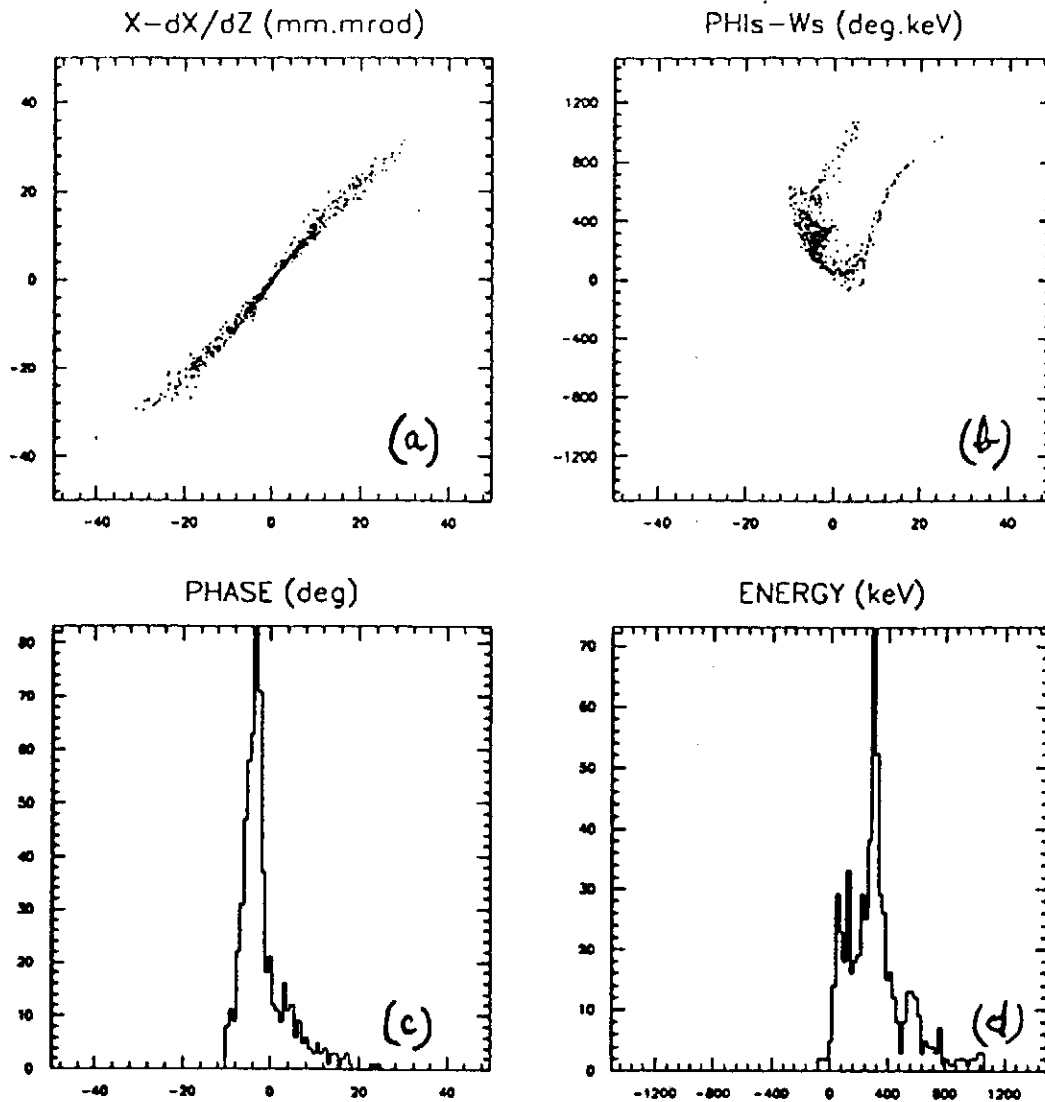-b- rms phase extension envelope as a function of the distance.

Figure 4

a) Radial emittance.
b) Longitudinal emittance.
c) Phase distribution spectrum.
d) Energy distribution spectrum.
(The z coordinate is 722cm, i.e 1.12 m after the cryostat)

II-4. Concluding remarks of this first investigation.

Considering only the rms phase length of the beam, which is the key parameter of this study, we are still a factor of 5 over the specification. In order to further decrease this value, a scheme including a magnetic buncher such as the one already in operation at Argonne [4] would be interesting to investigate.

III. SECOND INVESTIGATION :

STUDY OF A SCHEME USING "FLAT-TOPPING"

Ideas used in this section have been presented in a paper by T.Smith [7]. Some additionnal inspiration was provided by a project of injector for an F.E.L described in [6].

III-1. Phase space dilution in presence of space charge effects.

The degradation of the emittance of the beam is mainly caused by the phase dependence of the longitudinal and transverse forces of the accelerating RF mode, which causes phase space dilution : different electrons experience different rf phases as they pass through the cavity, thus they gain different amounts of energy and experience different transverse forces.

For very intense beams, space charge forces may also contribute significantly to the degradation of the emittance, especially in the capture section where both causes add their effects. As suggested by T.I. Smith [7], these problems can be reduced by the use of high gradient, harmonically resonant cavities. The principle is the following : The fields of a TM010-like fundamental mode are superimposed with those of the third harmonic mode to "flat-top" the cavity voltage gain versus phase curve (Figure 5-a). This leads to a greatly enhanced phase acceptance with no beam degradation. The growth of the transverse emittance is also reduced by flat-topping : from Maxwell's equations we know that the magnetic fields, which are largely responsible for the transverse focussing forces, arise from the time rate of change of the local electric field. Thus, flat-topping the electric field automatically minimizes the magnetic field, and the use of harmonics can reduce longitudinal and transverse phase space growth simultaneously .

One obvious method of reducing the magnitude of the space charge forces for a bunch of constant charge is to increase its dimensions, or at least not to decrease them. This implies low frequency operation, since the allowable beam dimensions scale with the operating wavelength. It also argues in favor of not prebunching the beam before the flat-topping operation. Bunches of 1 ns can be sent directly into flat-topping cavities, so that we achieve the equivalent of a high energy gun of about 1 MeV. Another method for reducing space charge effects is to accelerate the charge bunch as rapidly as possible in order to take advantage of relativistic effects. This argues in favor of high field gradients in the accelerating cavities.

There is a compromise to find for the diameter of the beam. If it is small, the growth of the transverse emittance due to rf fields effects is not important because all the particles experience the same transverse field envelope. But in this case the space charge forces are increased inside the small volume occupied by the bunch, and may degradate the beam and prevent efficient bunching.

PHIs – Ws (deg.keV)
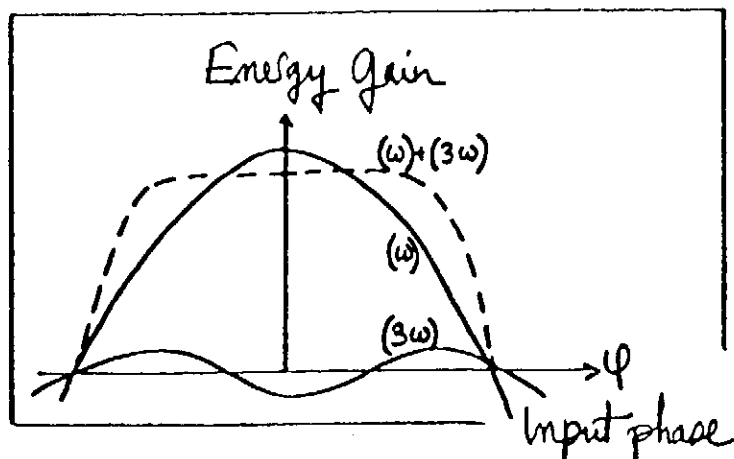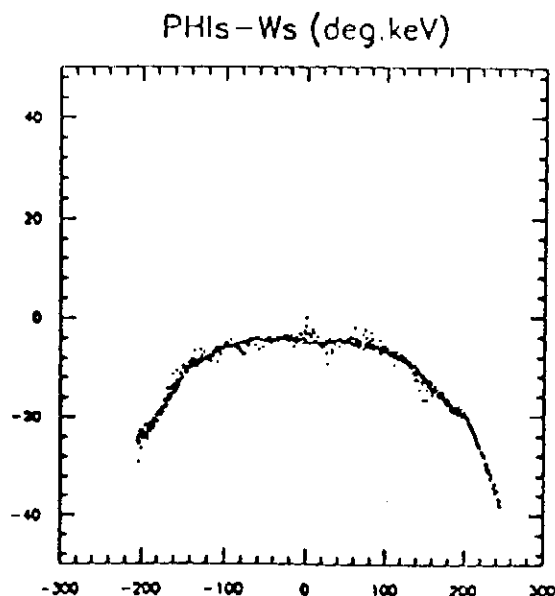
(a)   (b)

Figure 5

a) The principle of "flat-topping" : the fields of a fundamental mode are surimposed with those of the third harmonic mode in such a way that it "flat-tops" the cavity voltage gain versus phase curve.
b) The result of one PARMELA calculation taking into account the space charge forces. The average energy is 1 MeV.

III-2. The problem of the bunching operation.

Considering bunches of 1 ns delivered by the gun, the main problem to solve is the compression of its length. The two methods that are available and that could be combined are the bunching by an accelerating cavity operating at the zero energy gain point (velocity modulation), and magnetic compression.

If the energy gained in the flat-topping cavities is too high, the bunching afterwards by velocity modulation would be very difficult for two reasons :

a) A very high power would be required in the bunching cavity in order to create an appreciable energy dispersion in the bunches.

b) Above 1 MeV, the variation of the velocity as a function of the energy is very small so that, despite the fact that the space charge forces are very diminished, the bunching is not very efficient and needs long drift sections.

The magnetic compression cannot compress the phase extension of the beam by more than a factor of twenty. Thus it is not efficient enough to solve our problem. Furthermore, its efficiency strongly depends on the shape of the longitudinal emittance, which must be as linear as possible. This constraint is not easily respected when the space charge effects are dominant along the bunching drift.

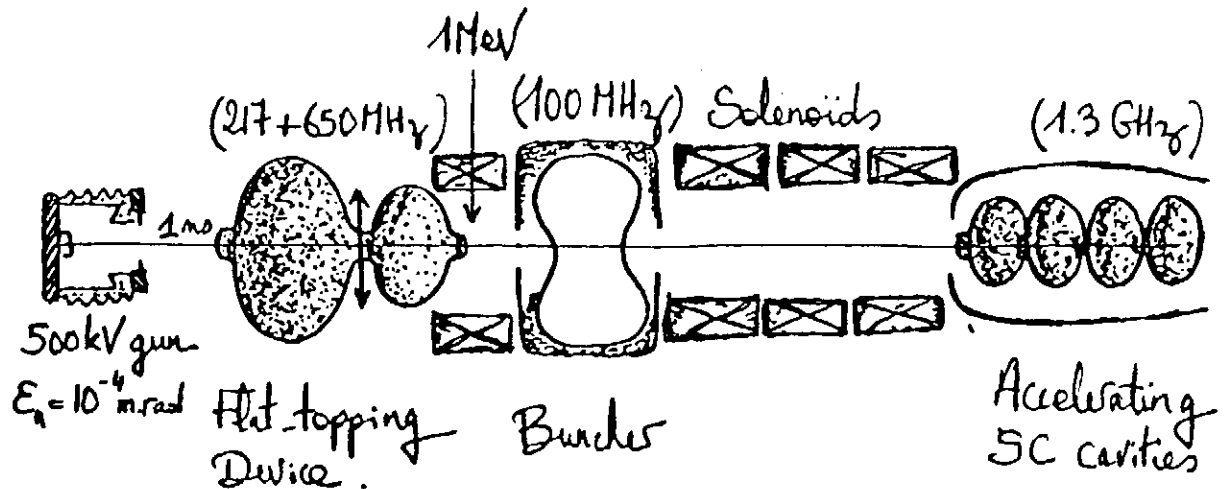Taking into account all these considerations, we have studied the following scheme (Figure 6):

Figure 6

Scheme of the second injector that we have studied.

III-3. The flat-topping operation.

The energy at the exit of the gun is assumed to be 500 keV. At this value of the energy (corresponding to a velocity of 0.86c) the flat-topping operation is simplified because the beam is almost ultrarelativistic. The 500 keV, 1 ns bunches are sent directly in the two "flat-topping" cavities separated by a focusing lens. The frequency of the fundamental cavity has been chosen equal to 216.67 MHz ($f_0/6$) so that the incoming bunch length is one fifth of the period. The second flat-topping cavity operates on the third harmonic (650 MHz) with a peak field level which is one third that of the first cavity (1.5 MV/m and 0.5 MV/m, respectively).

The ideal would be to have the highest field that is possible in these cavities in order to eliminate the space charge problem, but if the energy at the exit is too high the bunching operation is not feasible because a dispersion of the energy in the bunch is no more associated with a corresponding velocity modulation. This is why the field levels have been chosen so that the energy of the beam at the exit of the flat-topping cavities is only one MeV.

The effect of the flat-topping on the longitudinal emittance is given on figure 5-b. It seems to be quite satisfactory because the result is not very different from what it would be without space charge. The growth of the transverse emittance is only 45% (for an initial value of $1.1\ 10^{-4}$ m.rad). The energy dispersion is only about 20 keV, that is 2% for the relative dispersion. At this stage, the phase extension of the bunches is equal to its value at the entrance. There is no longitudinal compression at all. Thus, we must find a way to compress the bunch by a factor of 300 in order to get the desired 3 ps pulses.

III-4. The phase compressing operation.

At 1 MeV the space charge forces are diminished but still exist. The bunches are difficult to compress by a conventional bunching cavity since at this level of energy the velocity does not depend strongly on the energy (an increase of 100 keV in energy changes the velocity by only 0.8%). This means that we need very high power in the bunching cavity to create a strong energy modulation, and that the bunching drift will be long. Only one buncher is used (100 MHz). The length of the drift space is 6.70 m, the rms phase extension after bunching is 60° and the energy dispersion about 150 keV. At this stage we could envisage the addition of a magnetic bunching device but the shape of the longitudinal emittance is not very encouraging (Figure 7). Therefore we tried to inject the beam directly in

1.3 GHz accelerating single cell cavities with an accelerating field of 15 MV/m. The results at the exit of the first accelerating cavity are given in Figure 8. The exit energy is 2.91 MeV, the rms phase extension is 8° (i.e 4.4 mm), the normalized emittance is 6.7 10^{-4} m.rad and the energy dispersion is 350 keV ($\Delta p/p$ = 12%).
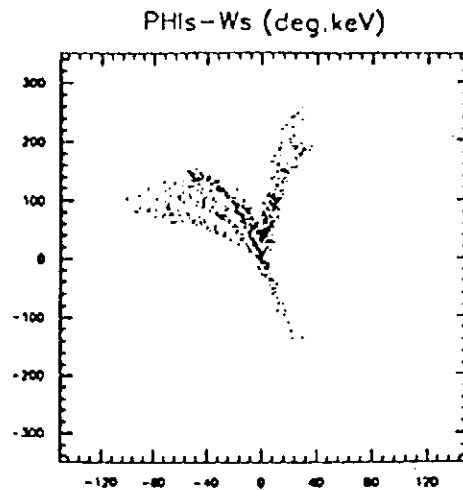
PHIs—Ws (deg.keV)

Figure 7

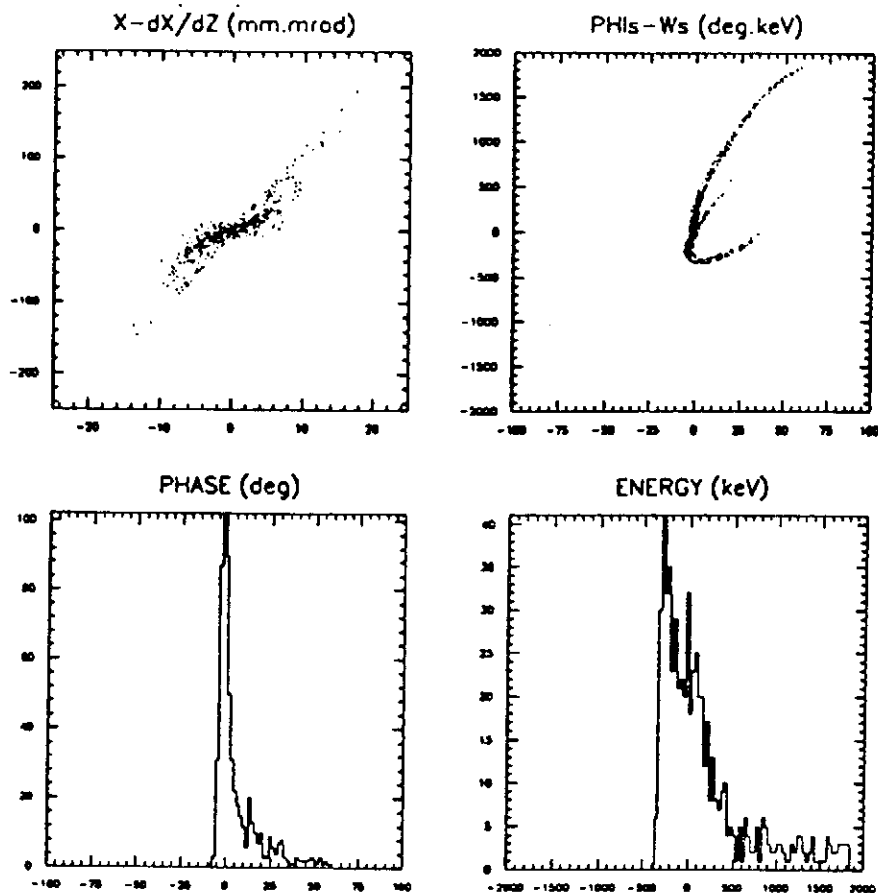*The shape of the longitudinal emittance after bunching.*

Figure 8

Results of the calculations at the exit of the first accelerating cavity.

III-5. Concluding remarks of this second investigation.

This scheme does not allow to reach easily the specification concerning the bunch length (4.4 mm instead of 1. mm) for the chosen charge (6 nC).

IV. GENERAL CONCLUSION.

We must insist on the fact that our study was not exhaustive. We have not considered all possible schemes and we did not examine all the aspects of the two solutions reported here. However, it is clear that we did not succeed in meeting the specifications given in I-1. Although the two schemes that we have tried are based on quite different principles, they lead to equivalent results : a bunch length that is a factor five larger than the length required. Now the question is : is there a parameter on which the constraint could be released?

If it is possible to increase the bunch length to a value of 5 mm, then one of the solutions discussed above can be pursued. If instead it is possible to reduce the charge requirement for the bunch by an order of magnitude, then calculations made for the MACSE project have shown that it is straightforward to build a conventional injector delivering 5.10^9 particles per bunch. With this approach, the injector for TESLA could be simplified considerably.

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