THE DESIGN OF A PROTOTYPE RF COMPRESSOR FOR HIGH BRIGHTNESS ELECTRON BEAMS

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Abstract

The generation of high brightness electron beams with longitudinal length less of 1 ps is a crucial requirement in the design of injectors for new machines like the X-ray FEL facilities. In the last years the proposal to use a slow wave RF structure as a linear compressor in this range of interest, to overcome the difficulties related to magnetic compressors, has been widely discussed in the accelerator physics community.

In this paper we will review the work carried out in the last 2 years and focused on the design a RF compressor based on a 3 GHz copper structure. The rationale of the conceptual design along with a description of the main experimental activities will be presented and a possible application of such a scheme to the SPARC project will be discussed.

INTRODUCTION

The strategy to attain high brightness electron beams delivered in short (sub picosecond) bunches is based on the use of RF Linacs in conjunction with RF laser driven photo-injectors and magnetic compressors. The formers are needed as sources of low emittance high charge beams with moderate currents, the latter are used to enhance the peak current of such beams up to the design value of 2-3 kA by reduction of the bunch length achieved at relativistic energies (> 300 MeV). Nevertheless problems inherent to magnetic compression such as momentum spread and transverse emittance dilution due to the bunch self-interaction via coherent synchrotron radiation have brought back the idea of bunching the beam with radio-frequency (rf) structures.

Such a type of bunching (named velocity bunching) has been experimentally observed in laser driven rf electron sources[1]. Velocity bunching relies on the phase slippage between the electrons and the rf wave that occurs during the acceleration of non ultra relativistic electrons.

It has been recently proposed to integrate the velocity bunching scheme in the next photoinjector designs using a dedicated rf structure downstream of the rf electron source [2]. The basic idea is to develop a rectilinear RF compressor, based on slow wave RF fields, that works indeed as a standard accelerating structure which simultaneously accelerates the beam and reduces its bunch length.

BASIC RF RECTILINEAR COMPRESSOR THEORY

The figure of merit for the compression may be defined as the ratio between the initial phase spread and the final one at the extraction. A simple model for the compression process may be developed analyzing the motion equations for an electron travelling in a rf structure. The phase extent at the extraction is a function of the initial energy spread and of the phase at the injection. A suitable tuning of the latter will result in an increase of the compression value.

A remarkable improvement of this scheme may be obtained whenever a beam, slower than the synchronous velocity, is injected into an rf structure at the zero acceleration phase, allowing it to slip back in phase up to the peak accelerating phase, and is extracted at the synchronous velocity.

A detailed mathematical treatment of this process may be found elsewhere [2]. The basic behaviour of the RF compressor may be easily understood thinking about an iris loaded TW structure designed to sustain a wave whose phase velocity is slightly lower than c (i.e. where we have that $k = k_0 + \Delta k = \frac{\omega}{c} + \Delta k$ with the detuning parameter. $\Delta k << k_0$). In such a structure the velocity of the beam will match that of the wave when the resonant beta and gamma can be well approximated by the expressions: $\beta_r = 1 - \frac{c\Delta k}{\omega}$ and $\gamma_r = \sqrt{\frac{\omega}{2c\Delta k}}$, where beta_r is the normalized phase velocity of the wave.

If beta_r is smaller than 1 the beam may advance in phase (i.e. slip forward on the wave) and the phase contour plots in the [γ,ξ] phase space (ξ is the phase of the wave as seen by the beam) become closed curves. Figure 1 shows the phase compression picture achieved assuming the injection at ξ=0 and the extraction at $\gamma=\gamma_r$. The analytical expression for this phenomena becomes

$$\frac{1}{\gamma_r} - \alpha \cdot \cos(\xi_{ex}) = \gamma_0 - \beta_r \sqrt{\gamma_0^2 - 1} - \alpha \qquad (1)$$

which shows that the extraction phase ξ_{ex} is a function of the injection conditions and the wave parameters. Using this expression it may be shown that compression values in excess of 9 may be obtainable and that the whole compression process may be tunable in this range acting on the wave parameters.

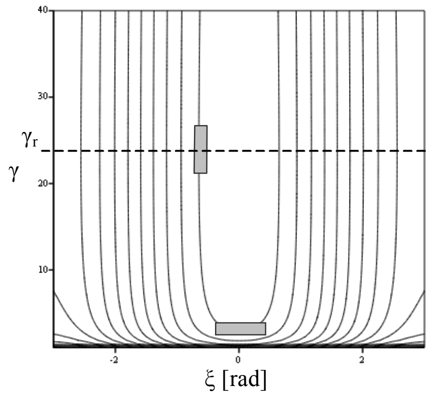

Fig. 1: Phase space plots of a slow RF wave

A PROTOTYPE SLOW WAVE RF COMPRESSOR

In 2003 we started a two years development program aimed at the design and construction of a slow wave TW structure which can be used as a prototype for a RF compressor.

The Italian SPARC injector project [3], whose target is the development of an ultra-brilliant beam photo injector for future SASE FEL based X ray sources, foresees the possibility to use a source like the one above discussed and we used its parameters as a general reference to define the scientific case to study. Table 1 shows the main parameters which we used for our investigations:

Parameter	**Value**
Frequency of the wave structure	2856 MHz
Linac structure	TW
Accelerating gradient	20 MV/m
Initial energy	5.7 MeV
Extraction energy	14 Mev
Compression factor (at 130 MeV)	7
RF pulse repetition rate	1÷10
Bunch length	10 ps

Table 1: Reference parameters for the study of the RF compressor

The expression (1) shows that the rf structure parameter which provides the metric of the compression process in a slow wave structure is the phase velocity (vf). In an iris loaded TW structure the phase velocity may be expressed as:

$$\frac{dv_f}{v_f} = \frac{df}{f} \cdot \left(1 - \frac{v_f}{v_g}\right)$$

The above relation shows that the v_f can be controlled by changing the excitation frequency or, in a equivalent way, by detuning the structure.

The first period of our study has been devoted to the analysis of the way to detune in a controlled fashion the structure.

A preliminary analysis between possible alternatives showed that a thermal induced detuning of the rf structure, at a fixed exciting frequency, may be a suitable solution. The feasibility of this approach depends both on a detailed study of the compression factor as a function of the structure temperature and on a new design of the cooling system of the structure which takes into account all the requirements.

To investigate the effects of the temperature on the compression process we started evaluating the typical parameters of a standard SLAC structure. The required compression factor of 7 results in a change of the order of 1‰ of the phase velocity that is equivalent to a variation of the order of 0.6 °C in the temperature of the structure. This calls for a system able to control in real time the temperature set point with a resolution at least five times smaller (0.12 °C) both in term of sensibility and of stability. The RF power load on the structure, computed using the beam parameters of table 1, is of the order of 1.1 kW. The resolution required to the control system in such a situation was evaluated against the usual cooling plant specifications and in a survey of the available industrial components to be used as the building block of the new cooling facility. We evaluated that it would be too much difficult to achieve such a performance mainly due to the requirements in terms of stability. We decided to move toward a new TW structure designed to support slow waves and with the goal to decrease of a factor of 3 the thermal sensitivity, so that the required phase velocity modulation will ask for a temperature variation of the order of 2 °C. Table 2 shows the main parameters of the new structure (referenced as ALMA 5) which we propose for the RF compressor.

	SLAC Mark IV	**Alma 5**
Cell radius (mm)	41.24	42.48
Iris radius (mm)	11.30	15.40
Disk thickness (mm)	5.84	5.9
Cell length	35	35
Frequency (MHz)	2856	2856
Mode	2π/3	2π/3
Q	13200	13205
Shunt impedance (MOhm/m)	53	41
Vg/c	0.0122	0.0341
ΔT (equivalent to 1‰ V_f)	0.6 °C	2.0 °C
RF power required for a 3 meter long structure (MW)	-	66MW

Table 2: Main parameters of the Alma 5 TW structure

The group velocity has been increased of a factor of 3 to fulfil the requirement on thermal sensitivity. The subsequent decrease in shunt impedance has been considered acceptable since the maximum gradient required to the structure is lower than that of standard SLAC cavities. The last row in the table shows the power required to the Klystron that feeds the structure. This parameter has been carefully taken into account in the design since, in principle, we may accept higher values of the group velocity (and consequently have a more comfortable thermal control) but this will results in an incompatibility with the RF power available for the SPARC project.

Using the parameters above reported a set of simulations have been carried out using codes as Homdyn and Astra to verify the behaviour of a full scale model composed of a slow wave structure followed by two standard SLAC cavities. The results have been plotted in fig. 2 and they show that the compression factor obtainable is at least a factor of two higher with respect to the result available using standard SLAC structures. The dependence of the compression factor on the thermal stability is of the order of 20% for 0.1 °C while for standard SLAC structures it is 3 times more.

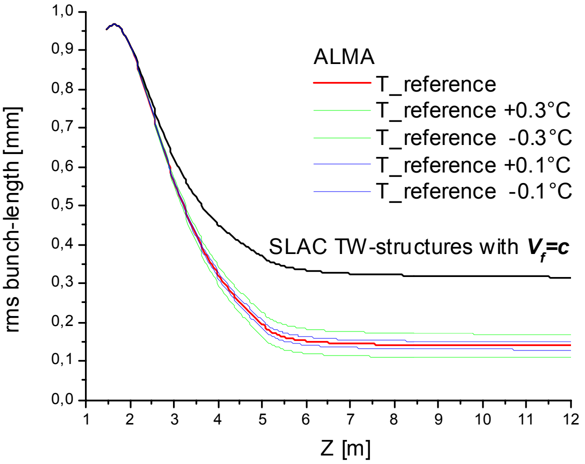

Fig.3: Simulations of the compression process

The mechanical design of the cell has been carried out taking into account the requirements due both to the brazing process and to the tuning. The results of the studies about the effects of the allowed machining tolerances have shown that a maximum error of 0.5° will be obtained. Such a value may be corrected using dinging holes, foreseen in the body of the cells, during the tuning process. Measurements carried out using aluminium based cells confirmed this predicted behaviour.

The thermal control of the structure has been studied using finite elements analysis. The solution has been found embedding the channels for water flow within the cells body to take advantage of the whole copper mass available. The cooling water will be provided to the structure by a Neslab HX300 compact cooling unit. This refrigeration unit has been chosen as the basic element around which build the cooling plant. It provides the capabilities to handle a maximum power load of the order of 10kW with a stability of the operating point of 0.1 °C.

To study the real behaviour of the cooling plant a test bench has been prepared using a 3 meter long standard SLAC cavity thermal controlled by the HX 300 unit. The cavity has been thermal insulated from the outside to reproduce as close as possible the characteristics of the ALMA 5 cooling circuits. The RF power load has been simulated by a controlled resistive load. 20 temperature probes (Tc and RTD) have been installed on the cavity to measure the temperature in different points. A network analyzer measures in real time the resonant frequency of the structure which has been maintained under vacuum for the whole duration of the test.

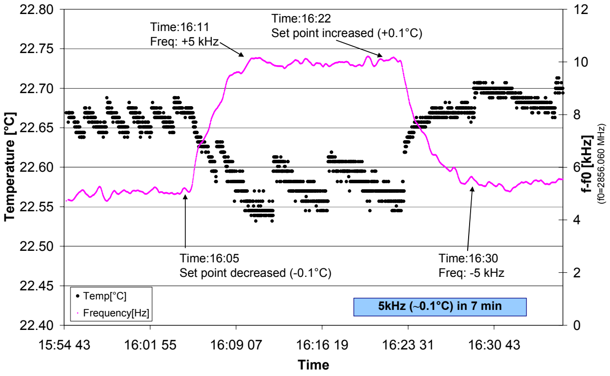

Fig.4: Temperature and frequency measurements

A significant measure is reported in fig. 4. The results show that the structure can be controlled with a stability better than 0.1 °C and that a change in the set point of the HX 300 controller of 0.1 °C is reflected in the structure within a few minutes. The RF behaviour of the structure is fully compliant with the simulations carried out using Superfish and Ansys.

CONCLUSIONS

The development of a prototype structure for a RF compressor is close to the final stage. The cell detailed design has been finished and it has been validated by preliminary tests on samples. A nine cells copper brazed structure will be available in August 2004 for an extensive set of measurements. The thermal control scheme has been defined and validated on a 3 meter long structure using the final components.

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