STUDY AND DESIGN OF ROOM TEMPERATURE CAVITIES FOR AN RF COMPRESSOR PROTOTYPE

David Alesini+, Franco Alessandria*, Alberto Bacci*, Carlo De Martinis* , Massimo Ferrario+, Alessandro Gallo+, Dario Giove*, Fabio Marcellini+, Marco Mauri*, Luca Serafini*

+*INFN-LNF-Frascati* , **INFN-Milan and University of Milan*

Abstract

The generation of high brightness electron beams with sub-ps bunch lentgh at kA peak currents is a crucial requirement in the design of injectors for Linac based X-Ray FEL's. In the last years the proposal to use a slow wave RF structure as a rectilinear 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 the results in the design and study of a 3 GHz model structure will be presented.

INTRODUCTION

The need to produce high brightness electron beams delivered in short (sub picosecond) bunches has been driven recently by the demands of X-Ray SASE FELs, which require multi-GeV beams with multi-kA peak currents and bunch lengths in the 100-300 fs range, associated to normalized transverse emittances as low as few mm mrad. The strategy to attain such beams 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 the impact of magnetic compressors on the beam dynamics is quite relevant, with tendency to reduce the performances of the whole system in terms of the final beam brightness achievable [1].

In the last years, developing a previous work about a plasma buncher scheme, alternative option of compression based on slow wave RF fields has been proposed [2]. The basic idea is to develop a rectilinear RF compressor that works indeed as a standard accelerating structure which simultaneously accelerates the beam and reduces its bunch length.

RF RECTILINEAR COMPRESSOR THEORY

The great advantage of a rectilinear scheme is obviously the absence of curved path trajectories, in addition to the fact that compression is applied at moderate energies (from 10 to 100 MeV) leaving the Linac free from any further beam manipulation.

We briefly report the basic elements of the theory of RF compressor as outlined in ref.2.

The interaction between an electron and the longitudinal component E_z of the RF field in a RF travelling wave structure is described by the Hamiltonian

$$H = \gamma - \beta_r \sqrt{\gamma^2 - 1} - \alpha \cos\xi$$

where $\gamma = 1 + \frac{T}{mc^2}$ is the normalized energy of the electron, $\xi = (\omega t - kz - \psi_0)$ is the phase of the wave as seen by the electron (ψ_0 is the injection phase) and $\alpha = \frac{eE_0}{2mc^2 k}$ is a dimensionless parameter which represents the accelerating gradient.

If we consider a wave whose phase velocity is slightly lower than c, we have that $k = k_0 + \Delta k = \frac{\omega}{c} + \Delta k$ (where the detuning parameter is small i.e. $\Delta k << k_0$) and we can write for the resonant beta and gamma the expressions $\beta_r = 1 - \frac{c\Delta k}{\omega}$ and $\gamma_r = \sqrt{\frac{\omega}{2c\Delta k}}$.

The behaviour of the RF compressor may be easily understood looking at the phase contour plots in the [γ,ξ] phase space. As an example we have considered a wave of amplitude $\alpha = 0.65$ and resonant gamma $\gamma_r = 24$. This corresponds to a wave phase velocity of β_r=0.999.

In fig. 1 we plot a phase-space diagram showing that particles injected with a phase equal to $-\pi/2$ and an energy smaller than the resonant one, will slip back in phase while accelerated up to $\gamma = \gamma_r$. Due to the nature of phase lines the bunch will have a phase spread (i.e. a bunch length) smaller than the initial one. For the same reason a further acceleration would clearly tend to de-compress the bunch.

The figure of merit for the compression process may be defined as the ratio between the initial phase spread and the final one at the extraction. Values in excess of 10 may be reached in such a scheme. A proper matching of the beam into the accelerating section and an additional focusing provided by external solenoids has been shown by simulation to obtain a proper preservation of the transverse emittance as discussed in Ref. [3]

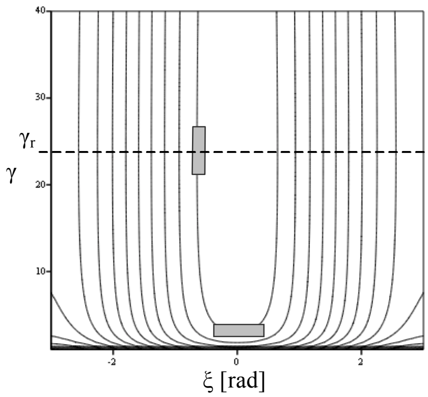

Fig. 1 Phase space plots of a slow RF wave

DESIGN OF CELLS FOR A SLOW WAVE RF COMPRESSOR

In the last year preliminary experimental investigations have been carried out using speed of light linac sections, which showed the validity of the velocity bunching concept[3]. In such a frame our group started an experimental activity aimed at the development of cells for the construction of a slow wave TW structure which can be used as a RF compressor. Table 1 shows the main parameters which we took as a reference for our investigations.

Table 1 Reference parameters for the study of the RF compressor

Parameter	**Value**
Frequency of the wave structure	2856 MHz
Linac structure	TW
Accelerating gradient	20 MV/m
Initial energy	6 MeV
Extraction energy	16 Mev
Compression factor	7
RF pulse repetition rate	1÷10
Bunch length	10 ps

The required compression factor calls for the availability of a structure able to control the phase velocity in the range between 0.999 c and c. In an iris loaded TW structure the equation:

$$(dvf / vf) = (df / f) \ (1 - vf / vg)$$

shows that the v_f can be controlled by changing the excitation frequency or, in a equivalent way, by detuning the structure. A suitable approach may be that to use a thermal control process that change the v_f at a fixed exciting frequency. The feasibility of such an approach has been initially studied referring to the typical parameters of a SLAC structure. The results obtained show that a change of the order of 1‰ of the phase velocity 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 with a resolution of the order of 0.06°C under a RF power load of the order of ~ 1.5 kW. We evaluated that it would be too much difficult to achieve such a performance and we tried to approach the problem with a new cell design. The goal was to obtain a structure able 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. The fact that the required accelerating gradient is lower with respect to a standard SLAC structure gave us a certain degree of freedom in the design as far as the shunt impedance figure is involved. Table 2 shows the main parameters of the new structure (referenced as ALMA 3) which we propose for the RF compressor.

Table 2 Main parameters of the Alma 3 TW structure

	SLAC Mark IV	**Alma 3**
Cell radius (mm)	41.24	42.60
Iris radius (mm)	11.30	15.40
Disk thickness (mm)	5.84	5.90
Cell length	35	35
Frequency (MHz)	2856	2856
Mode	2π/3	2π/3
Q	13200	13084
Shunt impedance (MOhm/m)	53	41
Vg/c	0.0122	0.0341
ΔT (equivalent to 1‰ Vf)	0.6 °C	2.0 °C
Tuning ring capability (MHz)	-	18
Tuning rod capability (kHz)	-	200

The mechanical design of the cell has been carried out in a complete fashion taking into account the requirements due to the cooling system and to the brazing process to join cells to give the final structure.

At the same time, at least for the first prototypes, we add frequency control capabilities to the cells both during the mechanical machining (using a tuning ring) and after the brazing (using a set of tuning rods). Such a feature has been foreseen to allow to control the influence of the achievable mechanical tolerances on the frequency response of the cells (a tolerance of 0.01 mm in the cell diameter gives an uncertainty of 370 kHz in frequency) and to provide a tuning tool for field adjustment.

The thermal control of this structure will be obtained using 8 channels for water flow. These channels have been machined within the cells body to provide a better heat exchange. The behaviour of this design has been verified under the expected RF power load using the finite element code Ansys. The results of this analysis show that the system will be suitable to match our requirements (fig. 2). The so far obtained thermal sensitivity allows to use a refrigeration unit with a control capability of the order of 0.1°C@45°C operating point. Such units are commercially available and we plan to use one of these as the basic building block of the thermal control setup.

To prove the reliability of the design and to gain experience on such a structure we machined a 4 cells aluminum prototype. The cells were stacked together using stainless steel threaded rods.

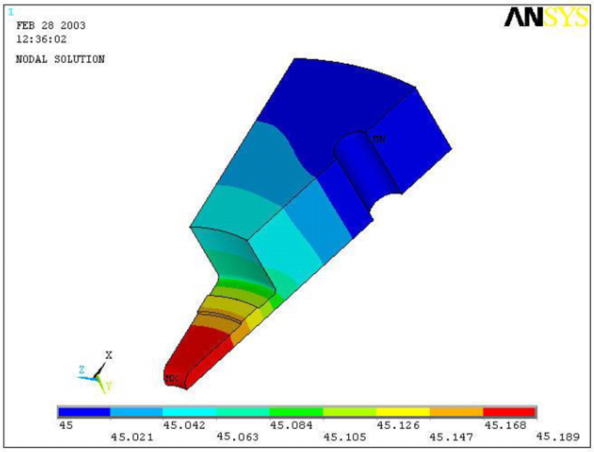

Fig. 2 Ansys simulation of the thermal behaviour of the ALMA 3 structure

The machining of these cells was simplified with respect to the final ones removing the cooling channels and the brazing grooves. The mechanical tolerances obtained were quite close to those required and this allowed to carry out significant measurements both on the single cell and on the set of the four cells.

The resonant frequency measurements on the single cells were in very good agreement with the expected values obtained with the code Superfish and confirmed the influence of the mesh value adopted in the numerical analysis (0.15 mm which gave us a frequency accuracy of the order of 100 kHz). For the sake of simplicity we started considering this assembly as a SW structure giving us the opportunity of sampling the dispersion curve at 4 points and to check field profile (Fig. 3).

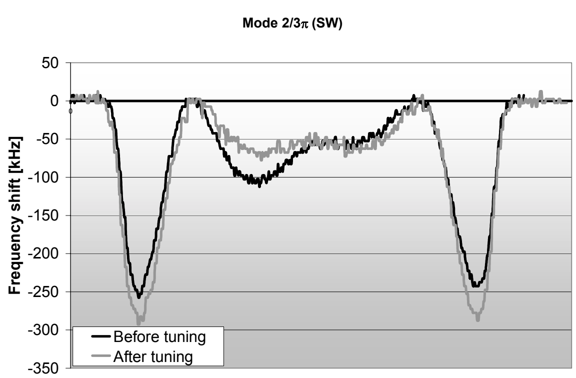

Fig.3 Measurements of the ALMA 3 structure accelerating field

The dispersion curve as a function of the cells temperature was measured using a test bench based on a laboratory oven. The internal size of the oven allows to position the 4 cells stack along with RF probes and temperature sensors to characterize the oven behaviour and to measure the cells temperature. Measurements were carried out in the range between 25 and 45 °C. The oven stability was of the order of 0.1 °C. The results (Fig. 4) proved a good agreement with the predicted behaviour of the phase velocity and gave the final validation of the whole design.

At the same time that we carry out the above described measurements, the OFHC copper to be used for the machining of a new 9 cells prototype has been forged by an Italian company according to our specifications. Great care has been taken to the control and measurement of the grain size of the bulk material (< 100 μm) in order to match the requirement for the brazing procedure. This process will be carried out at CERN and the whole cycle has been defined in agreement with CERN specialists.

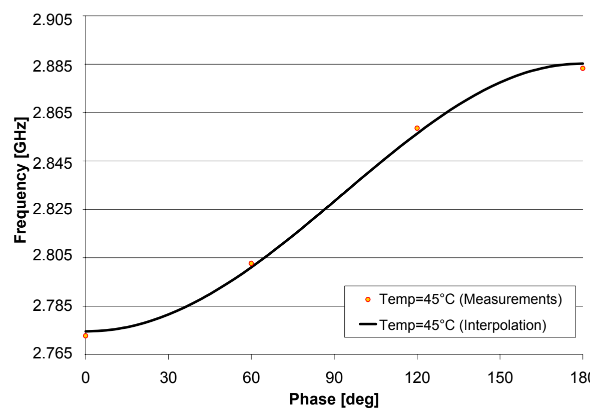

Fig. 4 Measurements of the ALMA 3 structure dispersion curve

CONCLUSIONS

The design of a new cell for a RF compressor working in the S-band has been completed and the measured performances of a first aluminum prototype have proven the feasibility of such an approach.

At this time the machining of the copper cells has been started and we plan to have a 9 cells brazed structure within the end of June 2003.

ACKNOWLEDGEMENTS

We would like to acknowledge very helpful discussions with M. Vretenar and S. Mathot (CERN), R. Boni (INFN-LNF) and the valuable support received in the experimental work by Luigi Gini and Carlo Uva (INFN-Milan) and Luciano Grilli (University of Milan).

REFERENCES

[1] P.Emma "Accelerator Physics Challenges of X-Ray FEL SASE Sources", EPAC2002, Paris, June 2002, p. 49

[2] L. Serafini et al. "Ultra-short Bunch Generation with a Rectlinear Compressor", PAC2001, Chicago, June 2001, p. 2242.

[3] M. Ferrario et al. "Recent Advances and Novel Ideas for High Brightness Electron Beam Production Based on Photo-Injectors" INFN-LNF 03/06P– 5 May 2003