ISSUES FOR A MULTI-BUNCH OPERATION WITH SPARC C-BAND CAVITIES

D. Alesini[2], M. Migliorati[1,2], A. Mostacci *[,1,2], L. Palumbo[1,3], B. Spataro[2], C. Vaccarezza[2]
[1]Sapienza University, Roma, Italy, [2]INFN-LNF, Italy, [3]INFN-ROMA1, Italy

Abstract

SPARC C-band traveling wave cavities were originally designed for the SPARC energy upgrade in the single bunch operation mode. In the context of a gamma source based on Compton backscattering and based on the SPARC C-band technology, we investigated the issues related to the use of these structures in the multi-bunch operation mode. Several beam configurations have been considered and the effects of transverse and longitudinal long range wakefields on beam dynamics have been studied. In the paper we present the results of these studies and, in particular, the issues related to transverse beam break-up that could prevent the multi-bunch operation. Possible HOM damped structures are also proposed.

INTRODUCTION

In the context of the Compton Gamma-ray Source of ELI-NP, the Romanian pillar of the European Extreme Light Infrastructure, an European proposal is under preparation. The machine is expected to achieve the Gamma-ray beam specifications of an energy tunable between 1 and 20 MeV, narrow bandwidth (0.3%) and high spectral density, 10^4 photons/sec/eV [1]. The proposal relies on compact, high gradient C-band sections which will be tested at SPARC.

In this paper we first review the C-band accelerating structures, originally designed for SPARC energy upgrade. Afterwords we focus on the issues of the acceleration of long bunch trains, in particular on transverse beam break-up. With a theoretical approach we will show the potential danger of dipole modes and thus we propose a structure with high order mode damping.

C-BAND CAVITIES FOR SPARC

SPARC energy upgrade relies on the use of C-band cavities [2]; a discussion of the main issues concerning this upgrade can be found in Ref. [3]. The structure is a Constant Impedance (CI) traveling wave (TW) device [4] working on the $2\pi/3$ accelerating mode; the main parameters are summarized in Table 1.

The single cell has been designed to reduce the peak surface electric field and reach an average accelerating gradient of 35 MV/m in realistic operational conditions. The large iris radius (7 mm) allows better pumping speed and higher group velocity to shorten the RF pulse and reduce the average power and discharge probability. The maximum surface field results 100 MV/m (HFSS simulations) which is a safe value for a discharge-free operation.

Table 1: C-band Accelerating Structure Relevant Parameters

Parameter	Value
Frequency	5.712GHz
Type	TW, $2\pi/3$, CI
# of cells	73
Cell length	17.5mm
Structure length with couplers	1.4m
Iris radius	7mm
Group velocity/c	0.0283
Field attenuation	0.22/m
Series impedance (E_{acc}^2/P_{in})	34MΩ/m^2
Filling time	150ns
$E_{s,peak}/E_{acc}$	2.2
Pulsed heating @ E_{acc}=35MV/m	$< 1°$C
Max. average accelerating field	52MV/m
Average diss. power @ 10Hz	60W

The design relies on the waveguide coupling, in alternative to the cell coupling, as shown in Fig. 1; such a scheme has been proposed at SLAC for the high gradient X-band cavities [5]. Its main advantage is that the RF field on the coupling slot edge is weaker than in case of the cell coupling. This reduces the risk of discharge and excessive heating of the in-out slots. The RF power is applied symmetrically onto the beam pipe by means of the waveguide splitter depicted in the picture. In this way, the dipole component of the field is completely canceled in the coupling cell.

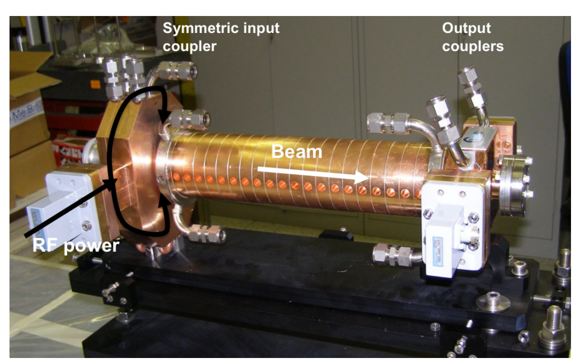

Figure 1: C-band prototype.

* Andrea.Mostacci@uniroma1.it

CUMULATIVE BEAM BREAK-UP (BBU)

As a bunch in a beam pulse (like a slice in a bunch) is displaced from the axis of the axis-symmetric accelerating structures, transverse deflecting modes are excited in the cavities (analogously to short range wakefields in single bunch beam break-up).

The trailing bunches are then deflected by the wakefield forces whether they are on-axis or not. The angular deflections transform into displacements through the transfer matrices of the focusing system and these displaced bunches will themselves create wakefields in the downstream cavities of the linac. The subsequent bunches will be further deflected leading to a beam blow-up.

Such effect was observed at SLAC back in 1966. As a first estimate, we used a semi-analytical approach by Mosnier [6] to show that for our C-band cavities a dumping of High Order transverse Mode (HOM) is necessary.

We are concerned with the transverse equation of motion for a whole bunch (ignoring internal structures); the current is composed of a train of bunches with identical charges (Q_b) evenly spaced by period T, which is an integer number of RF periods of the accelerating mode. The bunches are considered to be rigid macroparticles, like delta-functions, separated by period T; we assume that all the bunches are injected with the same initial offset x_0.

All the cells of the TW structure are assumed identical and we considered only the dipole mode in each cell. Rigorously the Mosnier approach requires that many betatron oscillations are performed in the linac and the BBU remains moderate within a betatron oscillation.

The transverse wakefield force experienced by bunch k, spaced kT from the first bunch, depends on the transverse wakefield generated by the preceding bunches (and thus by their displacement). The long range transverse wakefield is a high order deflecting mode, identical in all the cavities of the structure, identified by the frequency ω_{HOM}, the filling time T_f (or quality factor Q) and R/Q.

Reference [6] writes the equation of motion in term of the z-transform, instead of the Laplace transform since the displacement $x(kT, s)$ of the k bunch at the position s is a discrete function of time. Then the solution can be retrieved with a perturbation method, that is with an expansion into a series of the driving wakefield force.

The 0-order solution is given for a vanishing driving force, i.e. a pure betatron oscillation (that is the unperturbed motion). It is the motion of the first bunch which is not affected by any wakefield because of causality. The n-th order solution is driven by the wakefield excited by the solution of the order $n-1$. Thus the 1-st order solution is computed from the motion of the first bunch and affects all the bunches, except the first one; it means that the n-th order solution affects only bunches of index larger then n. Therefore the summation can be stopped at the M-th order of a train of M bunches.

Being β_0 the (assumed constant) betatron function, $\gamma(L)$ the energy at the exit of the linac ($s = L$), on can define the dimensionless BBU strength as

$$a(L) = \frac{Q_b \beta_0}{2G} \omega_{HOM} R/Q \ln\left[\frac{\gamma(L)}{\gamma_0}\right], \quad (1)$$

where G is the accelerating gradient (in V/m), γ_0 is the energy at the Linac entrance and ω_{HOM} is the resonant frequency of the high order mode. For $a \ll 1$ the series expansion can be stopped to the first order term, while if the BBU strength parameter a is moderate, it is sufficient to keep only few terms of the summation.

In the z-domain the n-th order solution can be determined analytically, but its inverse z-transform is, in general, not possible in closed analytical form. Therefore, Mosnier proposed to use an asymptotic technique valid when the blow-up is strong or to perform the inverse transform upon the n-th order solution in order to compute the transient solution.

In any case the transient term decays with the time constant of the deflecting mode (i.e. $T_f = 2Q/\omega_{HOM}$). It is worth noting that the beam displacement diverges if the period of the HOM is multiple of the bunch spacing (i.e. $\omega_{HOM} T = 2p\pi$ with p integer) as it physically sounds.

It can be shown that a steady state solution exists; it is identical to the unperturbed one except that the betatron phase exhibits an additional term proportional to the BBU strength a. It depends on the decay time of the wakefields and it is reached for an infinite bunch train. Therefore the motion is bounded; it is a consequence of the previous assumption of the moderate BBU during one betatron oscillation, which is true for most of the practical cases.

Figure 2 shows the normalized transverse position at the Linac exit for each bunch in the train, i.e.

$$\left[x_{(kT,L)} - x_{(\infty,L)}\right] / \left[\left(\frac{\beta_{(L)}}{\beta_0}\right)^{1/2} \left(\frac{\gamma_0}{\gamma_{(L)}}\right)^{1/2} x_0\right], \quad (2)$$

being k the bunch number and $x_{(\infty,L)}$ the steady state solution reached for long trains; $x_{(kT,L)}$ is the solution stopped at the order n equal to ne number of bunches. The dashed lines represent the asymptotic solution valid for large BBU strength as obtained with the steepest descent method [6]. Table 2 summarizes the parameters used in the calculations which assume a constant β along the Linac $\beta_L = \beta_0$.

Figure 2 clearly shows that the BBU may prevent the multibunch operation. From Eq. 1, one can reduce the bunch charge Q_b or the betatron function β, i.e. increasing the focusing strength. A better approach is to remove the problem by dumping the dipole mode, i.e. reducing its R/Q or its filling time T_f (that is the mode quality factor Q) by improving the EM design.

DAMPED STRUCTURES

The two main approaches to wakefield suppression are heavy damping and moderate damping together with strong detuning in the cell frequencies [8]. We propose to adopt the first solution, that is each cell can be strongly coupled

ISBN 978-3-95450-115-1

Table 2: Parameter List Used in the BBU Estimate of Fig. 2.

Parameter	Value
$\beta_L = \beta_0$	5m
G	30MV/m
L	25m
γ_0	80MeV
$f_{HOM} = \omega_{HOM}/2\pi$	8.398GHz
R/Q	0.26 MΩ/m^2
Q	11000
Q_b	250pC
T	15ns
$a(L)$	0.669

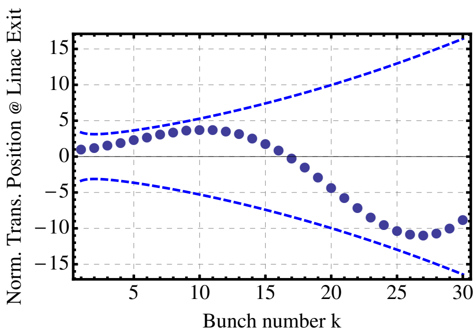

Figure 2: Normalized transverse position (Eq. 2) at the exit of the linac because of the BBU.

with waveguides to allow dipoles modes to propagate in the waveguide and dissipate into a load. Such a solution is very similar to the one adopted for CLIC [8].

The main advantages are a strong damping of all modes above waveguide cut-off, the possibility of tuning the cells and of a good cooling. The drawbacks are the need a 3D milling machine and the presence of multipole field components (octupole) which are anyway not critical, at least for CLIC case. An optimized design has been done, resulting in the electric field shown Fig. 3, while the main structure parameters are given in Table 3.

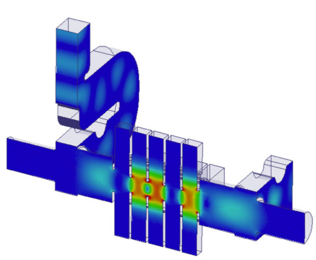

Figure 3: Electric field in the damped C-band section.

A preliminary mechanical design has been already produced, as shown in Fig. 4. The fabrication procedure will be the same adopted for the un-damped structure; the input/output couplers are fabricated separately and joined to the cells by a vacuum flange. We foresee to build a prototype with a reduced number of cells to test the effectiveness of the dipole mode damping including the absorbing material performances and to test the vacuum properties of the structure with absorbing material. The prototype will allow also to perform the low power tests and the tuning of the structure as well as to test its high gradient performances.

Table 3: C-band damped accelerating structure relevant parameters for an input power of P_{in}=40MW and repetition frequency of 100Hz.

Parameter	Value
Type	TW, $2\pi/3$, CI
Frequency	5.712 GHz
Cell length	17.5 mm
Structure Length	1.5 m
# of cells	85
Iris radius	6.5 mm
Group velocity/c	0.022
Field attenuation	0.31/m
Series impedance (E^2_{acc}/P_{in})	45MΩ/m^2
Filling time	230ns
$E_{s,peak}/E_{acc}$	2.1
E_{acc} (average)	34MV/m
Pulsed heating	7°C
Average dissipated power	1.2kW

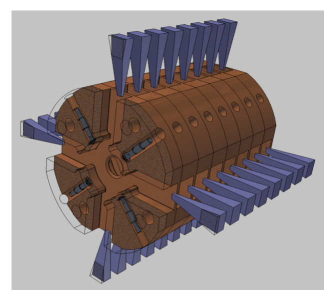

Figure 4: Mechanical drawing of the damped section.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Commission under the FP7-INFRASTRUCTURES-2010-1/INFRA-2010-2.2.11 project TIARA (CNI-PP). Grant agreement no. 261905.

REFERENCES

[1] C. Vaccarezza et al., Proc. of IPAC12, TUOBB01 (2012).
[2] D. Alesini et al., Proc. of IPAC11, MOPC013 (2011).
[3] R. Boni et al., Proc. of IPAC10, THPEA006 (2010).
[4] T.P. Wangler, *RF Linear Accelerators*, Wiley, NY (2008).
[5] C. Nantista et al., SLAC-PUB-10575 (2004).
[6] A. Mosnier, CERN 95-06, p. 481 (2005).
[7] A. Citterio et al., Proc. of IPAC11, MOPS076 (2011).
[8] R. Jones, Phys. Rev. ST-AB 12 (2009) 104801.