FEASIBILITY STUDY OF SUB-HARMONIC EXTERNAL BUNCHER FOR THE 75 MHZ HEAVY ION RFQ

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Abstract

All RF accelerators require bunched beam at the injection due to limited phase acceptance of accelerators. The RFQs being the only accelerator with 2π phase acceptance over one RF period. The internal bunching of RFQ though very efficient leads to longer structure length with higher power consumption. The beam quality can be improved by using an external buncher for heavy ion RFQs which needs to be designed fulfilling the requirements of nuclear physics experiments. The suitability of f/n (n=1,…., 5) sub-harmonic external buncher is studied by simulation in combination with heavy ion RFQ and presented. Analytical expression derived for optimum bunching distance taking transit time factor into account is discussed. The power level for each fourier analyzed harmonic is calculated and algoritmn to realize such buncher is presented.

INTRODUCTION

Designing heavy ion RFQ's in shorter length requires special techniques in the design process. One such technique is to separate the bunching from the acceleration process. The concept is to replace the internal adiabatic buncher with very small longitudinal electric field. As the external buncher is not used for acceleration, smaller bunching voltage are applied and focussing channel lengthened so as to achieve a smaller energy spread, longitudinal emittance and time structure.

HARMONIC BUNCHER

A saw-tooth voltage waveform (see Fig. 1) is ideal for a buncher but is difficult to generate. Buncher can be a single-gap or multi-gap type. Single-gap bunchers using a sinusoidal waveform are the most frequently used bunchers and they typically bunch about 50% of the original DC beam whereas multi-harmonic bunchers capture as much as 60–80%, depending upon the number of harmonics (see table 1) used.

Table1: Voltage coefficients and bunching efficiencies for a one, two and three harmonic buncher

Harmonics	U1	U2	U3	η (%)
1	0.63662	0	0	50
2	0.55133	0.27566	0	67
3	0.45	0.3183	0.15	75

So, in the case of heavy ions, a single-gap multi-harmonic buncher or a double-drift buncher is most beneficial. Double-Drift Buncher (DDB) is of the type where the two bunchers are separated in space and the second buncher is driven at twice the frequency of the first. A double drift system (as incorporated in BARC-TIFR Pelletron Accelerator Facilty) is equivalent to the superposition of several harmonics for approximating a linear voltage.

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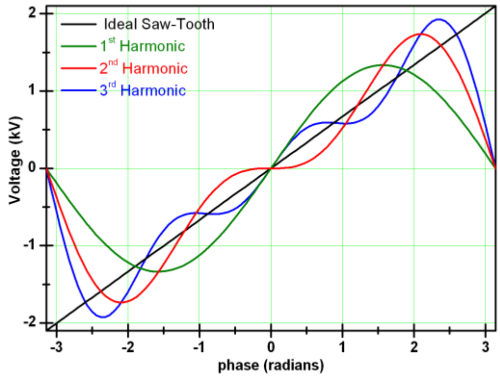

Figure 1: Saw-tooth voltage waveform generation using harmonics.

Single gap multi-harmonic buncher as proposed and used at ATLAS [1] is obtained by combining the fundamental wave with its various higher harmonics. Another type of buncher used at PIAVE [2] also uses a similar design of buncher but with resonant lines (1st and 3rd harmonic at one grid and 2nd harmonic at other grid) which have to be tuned according to the frequency.

F/N EXTERNAL BUNCHER STUDY

Accelerators are tools used to study nuclear properties and many experiments (e.g. time of flight) require bunch spacing of 100 ns. A sub-harmonic buncher upstream heavy ion RFQ is used to fulfill this requirement subject to beam dynamics studies. The 75 MHz Heavy Ion RFQ [3] at Pelletron Accelerator Facility (PAF), Mumbai is designed to accelerate ions with q/m of 1/7 from 10 keV/A to 575 keV/A. Suitability of f/n (n=1,…., 5) sub-harmonic external buncher in combination with heavy ion RFQ is studied using LIDOS[4] software.

Analytical Expression

The ideal saw-tooth waveform is represented by the Fouries series with infinite harmonics given by

$$U(\varphi) = (2U_0/\pi)\, F(\varphi), \quad F(\varphi) = \sum_{n=1}^{n=3} (-1)^{n+1} \frac{\sin(n\varphi)}{n} \qquad (1)$$

The analytical formula derived for optimizing buncher to RFQ distance (***s***) is (see Eq. 2)

$$s = \beta\lambda \frac{\varphi}{2F(\varphi)} \frac{E(keV/u)}{(Z/\zeta)U(kV)} \qquad (2)$$

where β = v/c, v being the velocity of incoming ions, φ/F(φ)is inverse of transit time factor (TTF), φ is the phase which maximizes F(φ), Z/ζ is the ratio of atomic number to mass number for the respective ions. The peculiar feature of this analytical expression lies in the TTF which takes into account the harmonic content as well.

Simulation Studies

The 75 MHz heavy ion RFQ design was optimized using LIDOS software with an f/n (n=1,…,5) third harmonic external buncher, 'f' being the RFQ frequency. For this study, the pre-buncher fundamental frequency was varied from f/5 = 15 MHz to f = 75 MHz. The transmitted (Trans.) and accelerated fraction (Accel.) is plotted as a function of buncher frequency (see fig. 2). The buncher to RFQ distance for various buncher frequencies was calculated using equation (2). From the study it is inferred that below f/2 external buncher frequency, longitudinal losses in RFQ increase due to 'n' bunch formation which move out of the separatrix (see fig. 3).

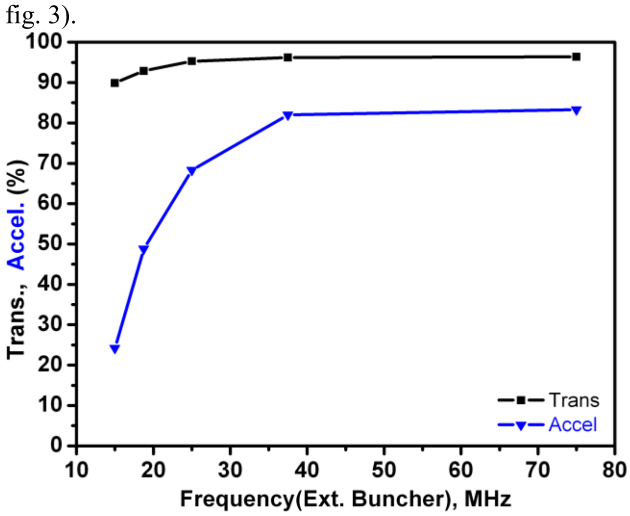

Figure. 2: Long. Transmission with freq.

HARMONIC POWER LEVEL

For the pre-buncher, it is required to generate a saw-tooth waveform given by

$U(\phi) = (U_0 / \pi)\,\phi$, $U_0 = 2.1$ KV, q/m = 1/7

$U(\phi) = 0.66845076\,\phi$

This wave form is generated by using three harmonics with fundamental mode at **75 MHz**.

Hence $U(\phi) = (2\,U_0 / \pi)\,F(\phi)$

$$U(\phi) = U_0[0.63662\sin(\phi) - 0.31831\sin(2\phi) + 0.212207\sin(3\phi)]$$

The total RF power required, $P \propto U^2(\phi)$

power in the product term should be zero

i.e. $\sin(\phi)\sin(2\phi), \sin(2\phi)\sin(3\phi), \sin(\phi)\sin(3\phi)$

$$\text{Hence, } P \propto 0.405285 U_0^{\,2}[\sin^2(\phi) + 0.25\sin^2(2\phi) + 0.111\sin^2(3\phi)]$$

At the peak, $\phi = 135^0$

$P \propto 0.405285\, U_0^{\,2}[0.5 + .25 + 0.055555]$

Desired power level in each harmonic is

fundamental mode = $0.5/0.805555 = 62.069$ %

second harmonic = $0.25/0.805555 = 31.034$ %

third harmonic = $0.055555/0.805555 = 6.897$ %

Possible Methodology

The saw-tooth waveform can be generated by summing the fundamental to 3rd harmonics Fourier components. Two phase locked loops operating with a reference frequency of 75 MHz generate the fourier components of saw-tooth waveform with repetition frequency of 75 MHz. They are combined at signal level, amplified and used to power the buncher cavity. The resultant saw-tooth waveform is feedback regulated by I/Q regulation of its individual Fourier components. Pickup probes inside buncher cavity monitor the waveform and provide feedback for I/Q regulation.

CONCLUSION

It is established that a third harmonic saw-tooth waveform has a 75% theoretical bunching efficiency compared to 50% for a single harmonic buncher (see table 1). Based on simulation studies, a single-gap third harmonic buncher with 75 MHz as the fundamental mode is the most suitable option for our RFQ. Below f/2 sub-harmonic frequencies, longitudinal losses in RFQ increase substantially causing loss of beam.

REFERENCES

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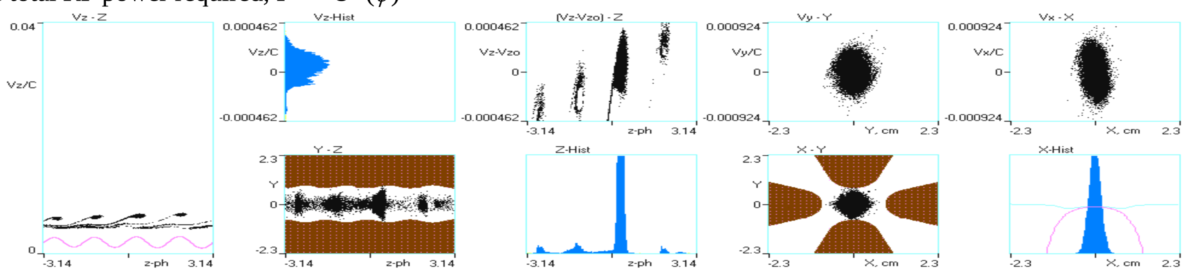

Figure 3: Four bunch formation in case of f/4 third harmonic external buncher –RFQ combination.