A Broad-Band (0.2-8MHz) Multiple-Harmonic VITROVAC®-Filled Acceleration Structure

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Abstract

Higher or multiple-harmonic acceleration drives in synchrotrons are desirable, when passing the transition point, applying stochastic cooling on a bunched beam, or for many other longitudinal beam manipulations, as bunch stretching or compression. As proof-of-principle, virtually arbitrary, digitally synthesised voltage wave forms, employing contents up to fourth harmonic in the range 0.2-8MHz, could be generated at the gap of *one single* (symmetric re-entrant) cavity, filled with discs of the novel amorphous metal VITROVAC®. Although broad band, its shunt impedance is of the same order as for standard, ceramic-ferrite filled cavities; a 10 kW amplifier produces voltages in the kV-range. As relevant examples, we achieved a flat-top wave form suitable for the transition (± 27° at ~ 10^{-3} error), a fourth-order flattened bucket for bunched-beam cooling, a harmonic bucket with linear restoring force, and a rapid rf-phase jump. The compact cavity system should be well suited for any proton device operating in this frequency range, and also for therapy-oriented rings.

1. Introduction

The generation of more than one rf harmonic with stationary phase relation has long been an issue with accelerators. Beam dynamics with non-harmonic accelerating voltage offers substantial flexibility and, oftentimes, attractive advantages to beam particle acceleration, manipulation, and storage. A variety of technical approaches has been employed. They commonly require a number of separate rf-cavities. Since these cavities will have to be phase aligned in order to obtain a stationary acceleration voltage pattern in the time domain, this is one of the main obstacles which have not permitted wider use of non-sinusoidal acceleration wave forms. Any combination of more than two harmonics is virtually ruled out by the ensuing technical phase-lock problems. In addition, such systems would not permit frequency tuning, as required when accelerating (especially heavier) ions to medium energies. With the use of a specific ferro-magnetic cavity filling, VITROVAC®,[1] we are able to overcome any of these technical issues for frequencies below about 10 MHz. The potential for use at higher frequencies is presently under investigation.

2. Beam Dynamics

Beam gymnastics with anharmonic potentials permit adiabatic beam pulse shaping, or to tackle the passage of transition in circulating accelerators by longitudinal dynamics alone. An idealised linear force law is also of interest. For technical reasons due to the (digital) synthesis of the low-level wave forms, we have restricted ourselves at this point to using the fundamental, the second, and the fourth harmonic,[2] hereafter referred to as three-octave harmonics. This approach permits exact phase fidelity between these three harmonics under any condition including frequency ramping. Finally, compared to ceramic ferrite-filled cavities, the new broad-band characteristics allow also much more rapid rf changes in time, as, e.g., a phase jump for conventional gamma-transition techniques.[3]

2.1. linear force law

With a common sinusoidal force law, only small amplitude synchrotron phase oscillations will obey the same frequency, while larger amplitudes will soften down to zero-frequency at the separatrix. This phase mixing may be desirable; on the other hand, by imposing a linear force law, a rigid rotation in phase space can be achieved, leading to one single synchrotron frequency (although at random phase) of all beam bunch particles. Limiting the harmonic content to three-octaves, we obtain a force law linear between ± 90°, with an asymptote $45/64\phi V_o$:

$$V(\phi) = V_o \left(\sin\phi - \frac{5}{32}\sin 2\phi + \frac{1}{256}\sin 4\phi\right) \qquad (1)$$

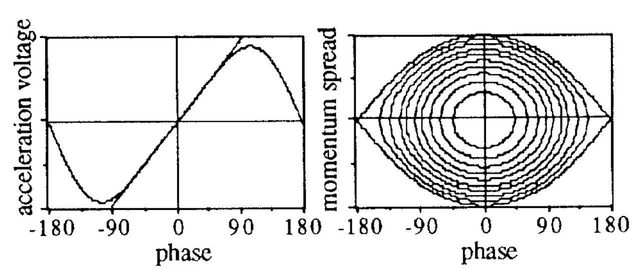

Fig. 1: "Linear" force law and phase space, computed for three-octave harmonics

2.2. stochastic cooling force law

Stochastic cooling of a bunched beam meets with substantial technical difficulties due to the resulting large coherent mode contribution in the noise spectrum. Moreover, the cooling force quenches, when, be it during the cooling process or for other reasons, particles become or are concentrated at the centre of the bucket, where rigid phase rotation is prevalent, see Sect. 2.1., and the necessary phase-space mixing ceases to be effective. A suitable "lawn-chair" shaped accelerating wave form with a flattened (zero-slope) portion at the phase-space centre, however is able to remedy this situation considerably, by introducing there a spread in synchrotron frequency. Wei [4] studied stochastic cooling under such a lawn-chair shaped voltage law. He pointed out, that, conversely, such a voltage law will reduce cooling efficiency of a fully-filled bucket with high occupancy away from the phase space centre. Our digital signal synthesis system [2] can, in principle, combat this problem by bringing up the harmonic content with time, as needed, so as to match to optimum cooling efficiency at any time. We put for the lawn-chair voltage law:

$$V(\phi) = V_o \left(\sin\phi - \frac{5}{8}\sin 2\phi + \frac{1}{16}\sin 4\phi\right) \quad (2)$$

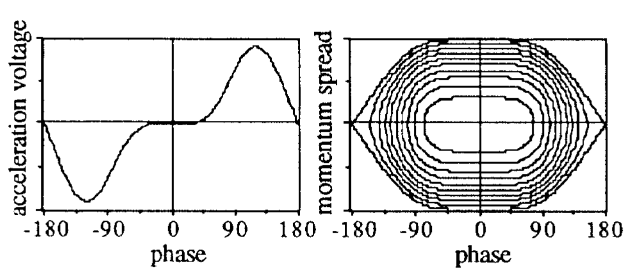

Fig. 2: "lawn-chair" force law and phase space, computed for three-octave harmonics

2.3. beam pulse shaping

More generally, on an adiabatic time scale, i.e. during a time of many synchrotron oscillation periods, the particle beam pulse assumes a shape imposed by the bunching or accelerating potential.[5] Beam bunch shaping with two harmonics has been employed at various accelerators, e.g. the CERN PS Booster.

2.4. transition energy passage

In the vicinity of the transition point, all particles will circulate in the ring with the same frequency, regardless of their momentum deviation. Thus, with a classical *sinusoidal* voltage law, late-comers will experience a larger voltage than the design particle, but will remain late-comers; i.e. phase focusing ceases to function, and the momentum spread will be increased. Now, a *time-constant* voltage impose the same energy gain on all particles, but cannot be realised with rf techniques. Rather, a wave form with flattened peak voltage may be used. This new method to tackle the transition crossing problem directly in longitudinal phase space was pioneered by J. Griffin at Fermilab.[6] Omitting space charge effects, the entire bunch (momentum spread $\pm\delta_{max}$) will sweep in time t during the passage over part of the phase space, and also will distort due to second order effects in time, t, and momentum deviation, δ:

$$\Delta\varphi(t,\tau,\delta) \approx 2\pi h f_\infty \delta \beta_{o,o} \left\{ \frac{(\tau^2 - t^2)\,\dot{\gamma}}{\gamma_{T,o}^3} - \frac{(\tau+t)\delta}{\gamma_{T,o}^2}\left[2\alpha_1 + 3\beta_{o,o}^2\right] \right\} \quad (3)$$

The non-linear passage time is denoted by τ;[6][7] velocity of the design particle and transition energy at the passage point are $\beta_{o,o}=\beta(\delta=0,t=0)$, and $\gamma_{T,o}=\gamma_T(\delta=0)$, resp. Otherwise standard notation is used.[6][7] The minimum flat-voltage portion must thus span over a phase width of $\pm\Delta\varphi(\tau,\tau,\delta_{max})$. COSY, Jülich, will have to pass transition in order to attain its maximum design energy. Here, the various scenarios suggest that $\Delta\varphi \sim 30°$ should (although barely) be sufficient.[8] With three-octave harmonics, the voltage law

$$V(\phi) = V_o \left(\cos\phi - \frac{5}{16}\cos 2\phi + \frac{1}{64}\cos 4\phi\right) \quad (4)$$

produces maximum flatness for $\varphi \to 0°$, with a deviation (from absolute flat) of less than 0.2% for $\Delta\phi = \pm 30°$.

3. CAVITY AND POWER AMPLIFIER SYSTEM

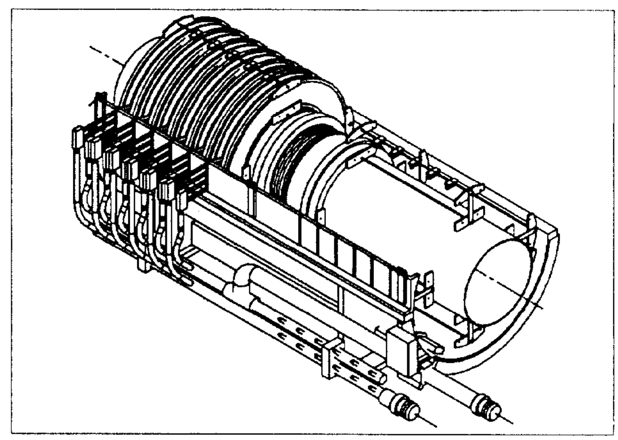
Fig. 3: cut-away drawing of cavity, showing inner and outer conductor, toroids, cooling ducts and polarisation bars

The system consists of a co-axial, re-entrant symmetric (push-pull) singlegap cavity, see Fig. 3, similar in dimensions and geometry of the acceleration systems used at LNS and COSY.[9] It is loaded with 24 toroids of material 6025F, of VAC. A push-pull amplifier is housed underneath, employing two tetrodes TH541, 10kW each, of Thomson Tubes Electroniques. Presently, the power amplifier is being upgraded to two 50kW TH120 tubes. Peak amplitudes in excess of 2kV may routinely be generated at the accelerating gap. The system is described in detail in [1]. Depending on the capacitive gap load, the system has a natural (zero-bias current) resonant frequency of about 500 kHz, and may be tuned with a bias current of only some 5 Amperes to 10 MHz.

The striking features, compared to similar cavities of traditional ceramic ferrite loading,[9] are (a) the low bias currents required, and (b) the much broader resonance impedance pattern *without the loss of peak impedance*, i.e. 500Ω (at 500kHz) and 230Ω (at 10MHz). By broad band, we thus mean several octaves *at one and the same (i.e. constant) bias current*. One could speculate, that this broad-band property is due to an rf-wavelength λ roughly independent of frequency inside the cavity, providing a $\lambda/4$-match at a wider range around the resonance frequency. This would require an approximate scaling law for the product of the permeabilities $\mu\varepsilon \propto 1/f^2$, while a skin-depth caused reduction in permeability due to flux exclusion would require about $\mu \propto 1/\sqrt{f}$. In any case, although very real, this intriguing effect is not well understood at this point and awaits further study. The broad-band (at fixed-bias current) behaviour can be exploited when driving simultaneously several harmonics, or for rapid changes in rf parameters.

4. Test Performance and Results

The tests results described here were obtained with this cavity system without beam. The gap voltage was monitored directly with a voltage divider. The three frequency components were generated by digital synthesis.[2] Their amplitudes and phases were adjusted to achieve the wave forms of Equs. (1), (2), and (3). The zero-slope regions of cases (2) and (3) permit precision tests for the performance of the anharmonic drive, and showed generally agreement to the low-level input waveform within a fraction of a percent. The measurements were taken with a Tektronix DSA602 digital signal analyser. The step-down ratio of the voltage divider was 1:1133, thus 1mV on the oscilloscope traces below correspond to 1.133V at the acceleration gap inside the cavity.

4.1. lawn-chair wave form

Figure 4 shows the flat (zero-crossing) segment of the measured rf voltage versus time (or phase). Deviation from flatness in the zero-slope part is less than 0.2%, compared to a peak voltage of 750mV resp. 850V at the gap.

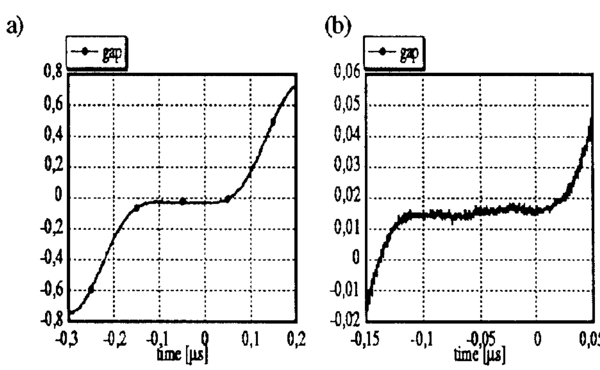

Fig. 4: lawn-chair voltage law actually realised at the gap: (a) 200mV, 100ns per div; (b) 10mV, 50ns per div.

4.2. flattened-top wave form

Figure 5 shows the flat (top) segment of the measured rf voltage versus time (or phase). Deviation from flatness in the zero-slope part is 0.05%, compared to a (positive) flat-top voltage of 0.98V resp. 1.1kV.

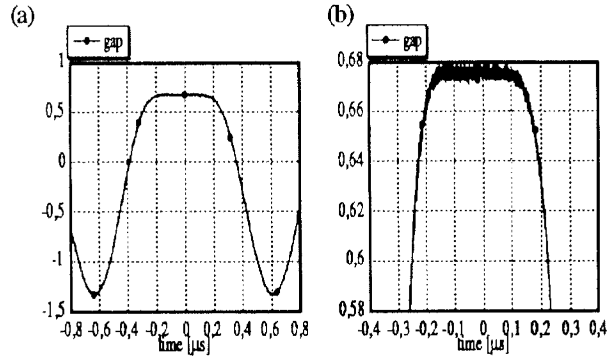

Fig. 5: flattened-top voltage law actually realised at the gap: (a) 500mV, 200ns per div; (b) 2mV, 100ns per div.

4.3. rapid 180°-phase jump

Figure 6 shows a rapid phase jump in time, completed in a few rf cycles.

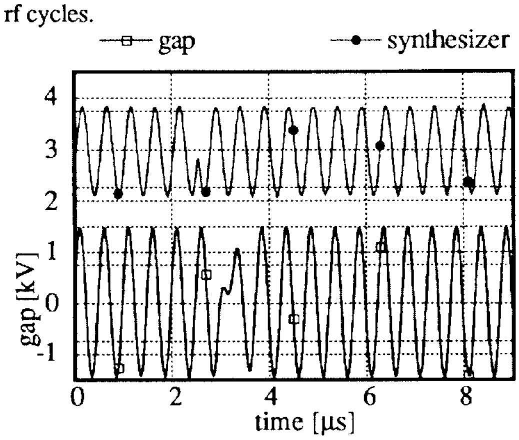

Fig. 6: rapid phase jump actually realised at the gap

On the basis of our tests, beam experiments are envisioned on COSY to test the actual beam dynamics.

5. Acknowledgements

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6. References

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