A High-Power Multiple-Harmonic Acceleration System for Proton- and Heavy-Ion Synchrotrons

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Abstract

A novel acceleration system for the (simultaneous) application of higher or multiple-harmonics in proton or heavy-ion synchrotrons has been developed for various uses, e.g. the passage of the transition point, applying stochastic cooling on a bunched beam, or for other longitudinal beam manipulations as bunch stretching or compression. The system consists of a coaxial cavity filled with the ferritic amorphous metal VITROVAC® of VAC, Hanau, in lieu of the conventional ceramic materials. In its current configuration, it can support a frequency range of 0.2-8MHz. Amplifier modules for both 10 and 50kW are available to produce gap voltages in the kV-range. By means of digital synthesis techniques, virtually arbitrary voltage waveforms with harmonic admixtures up to fourth order can routinely be generated at the cavity gap. As illuminating examples we achieved at high precision a flat-top wave form suitable, e.g. for the transition crossing, a linearized force law at the center of the bucket, and a fourth-order flattened bucket for bunched-beam cooling. The compact cavity system should be well suited for any synchrotron operating in this frequency range. Actual installation of such a system is projected for the medium energy device COSY Jülich, and the therapy-oriented ring TERA.

1. INTRODUCTION

Traditionally, acceleration systems in proton and heavy ion synchrotrons employ coaxial re-entrant cavity configurations with ceramic ferrite filling with figure-eight,[1],[2] dipole or quadrupole ferrite polarisation.[3] Such systems are frequency tuneable, while narrow-band, and may be phase-locked to the beam, producing a single harmonic of the particle revolution frequency in the ring. In contrast, the admixture of more than one rf harmonic with stationary phase relation opens up considerable flexibility and attractive advantages in manipulating beam dynamics, and has, therefore, been of long-standing interest with rf acceleration in synchrotrons.[4] A variety of technical schemes have been employed for such "non-harmonic" approaches. Due to the narrow-band cavity characteristics, they commonly require a number of separate rf-cavities producing the various harmonics. Such cavities have to be precisely frequency and phase aligned in order to obtain a stationary acceleration voltage pattern in the time domain, a technical complication restricting the use of more than two harmonics and usually ruling out the wider use of non-sinusoidal acceleration waveforms. We combined a specific ferro-magnetic cavity filling, VITROVAC®,[5] with novel digital signal processing (DSP) techniques [6] to tackle, and, by-and-large, overcome many of these technical issues for frequencies below about 10 MHz.

While not required by the high-power and cavity part, we restricted ourselves at present to generate gap-voltage waveforms using the fundamental, the second, and the fourth harmonic. This approach simplifies the signal generation techniques, resulting in exact phase fidelity between these three harmonics under any condition including frequency ramping. Thus, we may generate voltage waveforms at the gap of the general form

$$V(t) = V_1 \sin(\omega_o t+\phi_1) + V_2 \sin 2(\omega_o t+\phi_2) + V_4 \sin 4(\omega_o t+\phi_4) \ . \quad (1)$$

Correcting schemes for beam loading effects have not yet been considered in detail, but appear to be feasible. Due to the overall broad-band design, their remedy should be possible by DSP procedures alone, *without* the need of further fast-reacting high-power amplifier stages. [2]

2. BEAM DYNAMICS FOR SPECIFIC WAVEFORMS

Beam gymnastics with anharmonic rf potentials permit adiabatic beam pulse shaping,[4] bunched beam stochastic cooling,[7] or tackling the passage of transition in circulating accelerators by longitudinal dynamics alone.[8] An idealised linear force law may also be of interest for beam studies. Finally, the broad-band characteristics allow, as well, much more rapid rf changes in time, as, e.g., a phase jump for conventional gamma-transition techniques.[9]

Our system is not restricted to the common choice in Equ. (1), $\phi_1=\phi_2=\phi_4=\phi$. With this choice, however, we get a potential function in longitudinal phase space of the form

$$V(\phi) = V_1 \sin\phi + V_2 \sin 2\phi + V_4 \sin 4\phi \quad . \quad (2)$$

2.1. linear force law

By imposing a linear force law, e.g. a rigid rotation in phase space can be achieved, leading to one single synchrotron frequency (although at random phase) of all beam bunch particles. We can obtain a force law linear between ± 90°, with an asymptote $45/64\phi V_o$ at the phase space center when choosing in Equ. (2) V_2/V_1 = - 5/32, and V_4/V_1 = 1/256 .

2.2. stochastic cooling force law

A "lawn-chair" shaped accelerating waveform with a flattened (zero-slope) portion at the phase-space center increases the spread in synchrotron frequency. This can overcome cooling force quenching for particles concentrating at the center of the bucket, where rigid phase rotation is prevalent and mixing ceases to be effective.[7] For the lawn-chair voltage law, we may put in Equ. (2) V_2/V_1 = - 5/8, and V_4/V_1 = 1/16.

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. Beam bunch shaping with two harmonics has been employed at various accelerators, e.g. the CERN PS Booster.

2.4. transition energy passage

Tackling the transition crossing directly in longitudinal phase space was proposed by J. Griffin at Fermilab.[8] For instance, the minimum flat-voltage portion for the transition passage of COSY, Jülich, must span over a phase width of at least $\Delta\phi \sim \pm 30°$.[8] Choosing V_2/V_1 = - 5/16, and V_4/V_1 = 1/64 in Equ. (2) results in a deviation (from absolute flat) of less than 0.2%.

3. ACCELERATING SYSTEM

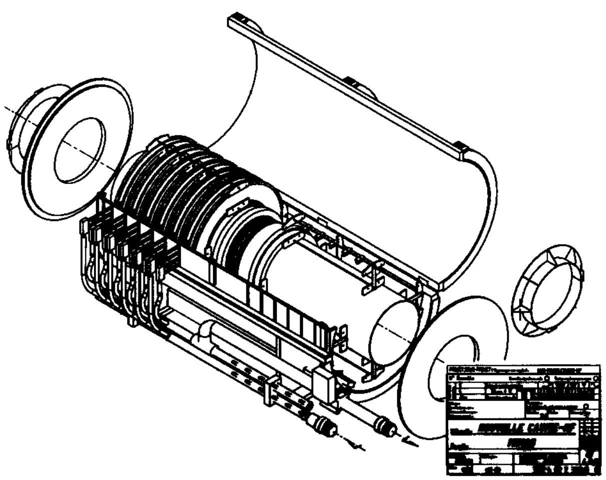

Fig. 1: cut-away drawing of cavity, showing inner and outer conductor, toroids, cooling ducts and polarisation bars

3.1. accelerating cavity

The cavity is of the coaxial, re-entrant symmetric (push-pull) single-gap type, see Fig. 1. In dimensions and design, it is roughly similar to the LNS-developed systems used at SATURNE and COSY.[1] It is, however, loaded with 24 toroids of the material VITROVAC® 6025F of VAC, with an eight-turn "figure-eight" polarisation winding. 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 3 MHz.

In Fig. 2, the (low-level) gap impedance of the-filled cavity is plotted vs. frequency for various bias currents. The actual total gap impedance is twice that of Fig. 2. It shows a marked broad-band characteristic at fixed bias current without major loss of peak impedance. The cavity characteristics are compared in Table I to the LNS and COSY system with conventional ceramic ferrite loading.

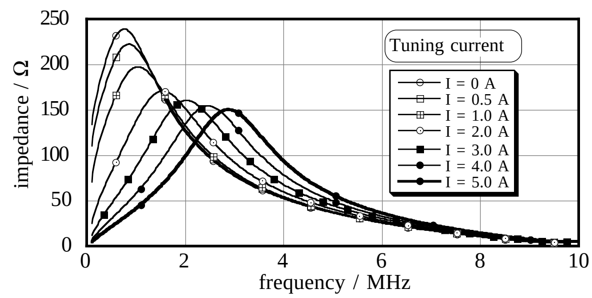

Fig. 2: gap impedance of the VITROVAC®-filled cavity (one-half cavity) vs. frequency for various bias currents.

	LNS and COSY cavity	VITROVAC-cavity
filling material	ferrite 8C12	VITROVAC 6025F
manufacturer	Philips, NL	VAC, Germany
number of rings	46	24
tuning current	- 20 to 70 A	0 to 10 A
frequency range	0.3 - 2 MHz	0.2 - 8 MHz
resonance width	< 50 kHz	~ 2 MHz
total gap impedance		~ 2 kΩ ~ 500 Ω
180°-jump within	10 to 50 rf periods	2 rf periods

Table I: comparison of characteristics of VITROVAC®-filled cavity with standard, ferrite-loaded cavity.

3.2. two alternative power amplifier modules

Two separate drawer-type amplifier modules, both in push-pull configuration, have been developed to fit directly underneath the cavity for closest possible coupling. The two cavity halves are fed completely independently. For both modules, the same driver/preamplifier configuration, again separately for both cavity halves, may be used. A π-type 50Ω driver coupling network into the main amplifier modules ensures broad-band behaviour at constant group delay. The lower-power system with a total of 10kW rf power employs two tetrodes TH541 of Thomson Tubes Electroniques. Peak amplitudes in excess of 2kV may routinely be generated at the accelerating gap. The system has been described in detail in [5]. For higher gap voltage, a second, high-power alternative has recently been developed, which uses two TH120 tubes featuring a total of 50kW rf power, similar to the LNS and COSY power amplifier systems.[1] Operating tests of this system are presently underway.

3.3. digital low-level signal synthesis and control

The low-level signal synthesis generates the composite waveform by suitably superposing fundamental and higher harmonic components, see Fig. 3. At its heart, a set of custom numerical controlled oscillators (NCO) are used, however with the provision of a variable-frequency common clock, rather than a large phase accumulator used in commercial NCOs. This leads to rigid frequency relations at any time in order to generate the harmonics. An arbitrary real-time digital phase correction via multipliers produces a phase fidelity to within 0.02°, while, similarly, an arbitrary real-time digital amplitude correction of 16 bit resolution is possible. Finally, fixed separate analog attenuation of the various harmonic components set the range of the desired admixtures. Our approach permits preserving the waveform shape in the time domain also under frequency ramping. Further, it also opens up the possibility of a real-time digital signal control, similar to the method as was demonstrated for the single-frequency component system at COSY.[10]

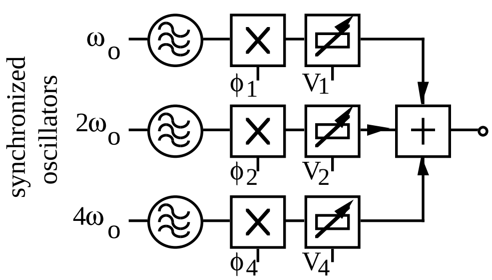

Fig. 3: signal synthesis scheme of harmonic composite

4. TEST PERFORMANCE AND RESULTS

The present test results were obtained with this cavity system without beam, operating at max. 10kW rf power. The gap voltage was monitored directly with a voltage divider.

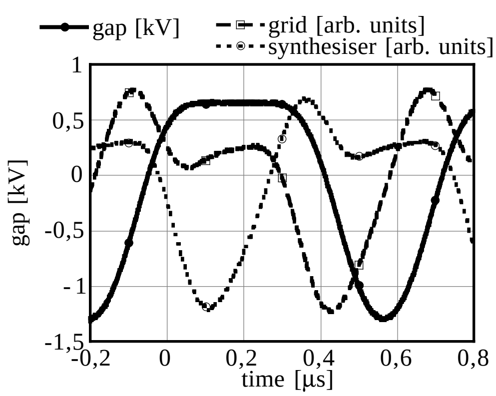

Fig. 4: digitally synthesized waveform, and actual waveform at tube grid and cavity gap

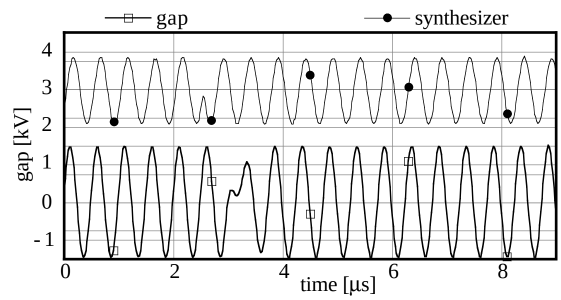

Fig. 5: rapid phase jump actually realised at the gap

Suitable transition waveforms (See 2.4) are shown in Fig. 4. To exemplify the digital signal synthesis performance, Fig. 4 shows also the low-level signal as originally synthesized, and the signal after passing through the driver and amplifier chain. The phase delays are adjusted such, that they compensate the delays incurred by the entire analog chain, including the cavity itself, to result in the desired waveform at the gap.

Figure 5 shows a rapid phase jump of 180° in time, completed in a few rf cycles. This is to be compared with the at least ten cycles needed for sign reversal with a conventional cavity (Table I). [9]

5. CONCLUSIONS AND OUTLOOK

The combination of a broad-band high-power acceleration structure and a digital synthesizer capable of producing precisely composed real-time voltage waveforms with higher harmonic content promises interesting acceleration experiments and performance enhancement in proton and heavy-ion synchrotrons.

Installation of the rf structure presented here, or of a similar system, is intended for both the medium-energy synchrotron COSY-Jülich, and for TERA in Italy, the proposed ring for cancer therapy,[11] for which a collaboration has been set up between LNS and the TERA project with validation tests about to make place at Saclay.

Some issues remain yet to be solved. To increase maximum gap voltage, as needed for COSY, a higher-power amplifier module is put into operation, with which first results were obtained with sinusoidal waveforms. This is to be followed by tests with added higher harmonics.

The signal processing system is presently being upgraded to actually allow for real-time control, or feed-back, of phase and amplitude, probably also for the higher harmonics.

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