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Beam test of a harmonic kicker cavity

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Abstract. A harmonically resonant kicker cavity designed for beam exchange in a circulator cooler was built and successfully tested at the Upgraded Injector Test Facility (UITF) at Jefferson Lab. This type of cavity is being considered for the injection scheme of the Rapid Cycling Synchrotron at the Electron-Ion Collider, where the spacing of neighboring bunches demands very short kicks. Operating with five transversely deflecting modes simultaneously that resonate at 86.6 MHz and consecutive odd harmonics thereof, the prototype cavity selectively deflects 1 of 11 electron bunches while leaving the others unperturbed. An RF driver was developed to synthesize phase- and amplitude-controlled harmonic signals and combine them to drive the cavity while also separating the modes from a field-probe antenna for RF feedback and dynamic tuning. Beam deflection was measured by sweeping the cavity phase; the deflection waveform agrees with expectations, having sub-nanosecond rise and fall times. No emittance increase is observed. Harmonically resonant cavities like the one described provide a new capability for injection and extraction at circulators and rings.

1. Introduction

In circulating accelerators, the minimum bunch spacing needed to accommodate the rise/fall time of a kicker can limit the design options for the bunch train. Originally developed for the Circulating Cooler Ring, a hypothetical ring with 11 revolutions driven by an energy-recovery linac that was intended to be part of the Jefferson Lab Electron-Ion Collider [1], the harmonic kicker cavity offers a new option for applications where every nth bunch must be deflected [2]. One such application is the injection into the Rapid Cycling Synchrotron at the Electron-Ion Collider [3], where one out of four consecutive bunches is injected at a time; here, the bunch spacing is 1.6 ns, and each set of four bunches is followed by a gap of 12 µs, encouraging the use of a pulsed device but out of reach for a stripline due to the short bunch spacing.

A harmonic kicker is a transversely deflecting cavity that can be excited at multiple harmonic frequencies at the same time, allowing one to Fourier-synthesize any deflection waveform containing only these frequencies; the high Q of the modes compared to a stripline makes the drive power manageable, while pulsed drive is still possible if the gap between sets of bunches is sufficiently long. Figure 1 shows a model of the prototype reduced to the most important parts.

An example waveform providing a kick to 1 out of 11 bunches is shown in Fig. 2. The usefulness of this type of waveform is not characterized by its absolute flatness outside of the main peak but by the locations of its zero crossings or minor peaks, depending on design. While conceptually flexible, the mode structure of such cavities must be chosen according to the bunch timing of the intended application. Compared to placing multiple cavities with different

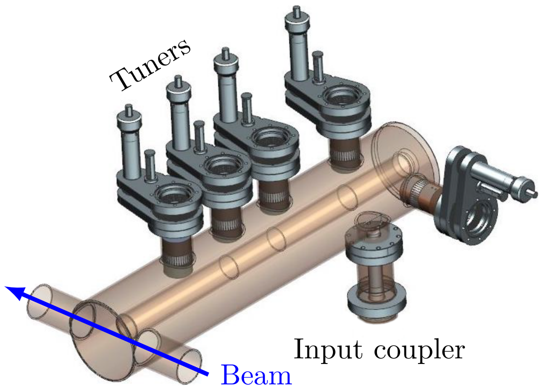

Figure 1. CAD model of a 5-mode harmonic kicker cavity. Five stub tuners are needed to tune all modes. The RF signal is coupled in through a single port; another port serves as the field probe (not shown here).

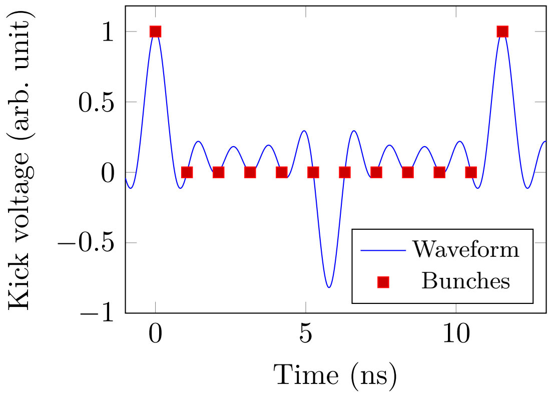

Figure 2. Kick action only on bunches at a bunch frequency equal to the fundamental of the kick waveform, $f_{\mathrm{HK}} = 86.6\,\mathrm{MHz}$; in this example, all 11 buckets are filled at a bunch frequency of $11 f_{\mathrm{HK}} = 952.6\,\mathrm{MHz}$.

resonant frequencies in series, combining the modes in one cavity has the upside of providing all the deflection in the same location, thereby avoiding bunch displacement due to the extra drift between cavities; however, note that only odd harmonics can readily be produced in a single cavity of this type.

Drawing from a diverse collaboration for fabrication [4], tuning [5], and drive-circuit design, we produced working prototypes of the cavity and the drive circuit and performed a beam test to verify the basic aspects of the cavity performance. The following sections describe the methods and results.

2. Harmonic Arbitrary Waveform Generator

The cavity is controlled by a specially designed drive circuit called the Harmonic Arbitrary Waveform Generator (HAWG). A synthesized RF source phase-locked to the master oscillator of the accelerator is used to generate an 86.6 MHz harmonic comb. The desired harmonic signals are divided from the harmonic comb onto individual channels using a harmonic combiner and divider [6]. Once isolated, each harmonic signal is phase- and amplitude-controlled using I/Q modulator ICs, amplified, and recombined to the cavity's drive antenna using a second harmonic combiner. While the cavity is designed for an input power of multiple kW, the present version of the HAWG provides 100 W per channel. With this power, the cavity produces its nominal deflection of $\sim 4\,\mathrm{mrad}$ at $6.5\,\mathrm{MeV}/c$.

Signals from the coupling antenna of the cavity are directed to a third harmonic divider where the harmonic signals are separated to individual I/Q demodulator ICs, allowing for both RF feedback and stub-tuner control for each mode.

3. Beam generation and synchronization

The beam test of the cavity was performed at Jefferson Lab's Upgraded Injector Test Facility (UITF). Designed to be accessible and reconfigurable with relatively little logistical effort, this accelerator delivers short (<1 ps) electron bunches at up to 8 MeV with an average current of 100 nA (limited only by radiation shielding). The beam is generated by a laser-driven DC photogun at 200 keV, ballistically bunched, and accelerated to the final energy by a compact, superconducting booster [7]. All RF elements run at $f_0 = 1497\,\mathrm{MHz}$; the signal pulsing the laser determines the bunch timing. In principle, the machine supports bunches at any subharmonic of f_0; also, configurable low-frequency (50–200 Hz) macropulses gating the drive laser can be set up regardless of bunch timing.

The frequencies useful for this experiment are determined by the cavity design. The cavity fundamental $f_{HK} \approx 86.6$ MHz is related to the machine base frequency f_0 by

$$\frac{f_{HK}}{f_0} = \frac{7}{121}. \tag{1}$$

The highest frequency that is a subharmonic of both f_{HK} and f_0 is $f_0/121 \approx 12.4$ MHz, making this frequency ideal for placing all bunches on the same cavity phase, whereas its 11th harmonic, $f_0/11 \approx 136.1$ MHz, could be used to probe all 11 phases of interest at the same time. The simplest way to measure the deflecting action of the kicker cavity is to send bunches at $f_0/121$; this way, all bunches are deflected the same, avoiding the complication of temporally selective detection downstream. The angle of deflection can then be measured as a function of relative phase by shifting the cavity waveform in time.

The frequencies needed for all RF systems (normally including the laser) come from the main RF synchronization chassis of the machine, which contains multiple independent phase-locked loops (PLLs) operating from a common 10 MHz reference. Because the $f_0/121$ signal needed for this experiment was not readily available from the laser PLL, we instead used a commercial frequency generator (CG635 by Stanford Research) synchronized to the same 10 MHz reference. Due to the nature of the frequency ratio, there is no way to produce the exact frequency with this generator, but with 16 digits of frequency resolution, the phase drift due to frequency mismatch is $< 0.1°$ per day.

Another CG635 set to the same frequency supplied the reference signal for the PLLs in the HAWG that generate all frequencies for the harmonic cavity, allowing for independent phase control of the HAWG with a single knob.

Apart from phase-synchronous RF drive of all components, an additional complication was the necessity for pulsed operation of the HAWG. While the device is designed for CW operation in principle, the duty cycle was limited to 10 % for this experiment as a precaution. In order to prevent bunches from being delivered with the cavity off, we operated the laser in macropulse mode with a pulse width of 400 µs and a delay of 100 µs with respect to the 50–200 Hz trigger signal, and gated the HAWG with a stretched copy of this trigger signal so that it would turn on sooner than the beam and turn off later, giving the cavity time to ring in. The timing is shown schematically in Fig. 3.

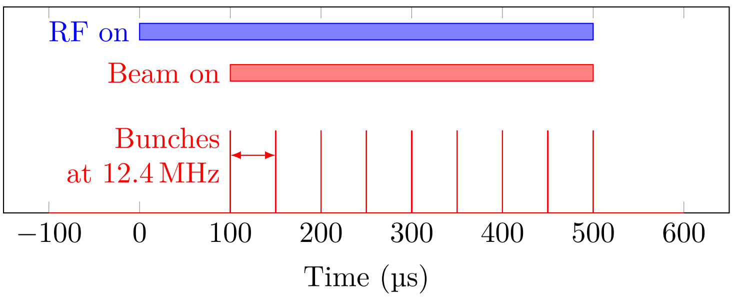

Figure 3. Macropulse timing for clean beam delivery while the cavity is on. Bunch spacing exaggerated for visual clarity.

The macropulse beam mode increases the bunch charge for the same average current, improving the signal-to-background ratio of the BPMs, which is too low for them to be sensitive in CW mode because of the average-current limitation of the UITF. On the other hand, because the macropulses are generated electro-optically with a finite contrast ratio of ≈ 250, very low macropulse duty cycles such as those needed for viewscreen-safe operation result in a high relative level of CW background during the nominally-off time window, obscuring the desired image on viewscreens after the kicker. This issue is not significant for other diagnostics because they can be used at higher beam duty cycles; also, the BPM data acquisition is gated to the macropulse signal and therefore insensitive to CW background.

4. Beam-line setup

For this experiment, we chose a beam momentum of 6.5 MeV/c for deflection angles $\leq$ 4 mrad at full HAWG output power. The deflection was detected by a pair of BPMs located downstream of the cavity. With the cavity off, the beam orbit was set up to be as flat as possible throughout this section and geometrically centered in the cavity. A pair of quadrupole magnets combined with a wire scanner located at the downstream end of the beam line was used to measure the transverse phase space; because the bunch frequency was chosen to place all bunches at the same kicker phase, the deflection from the kicker could be steered out with a pair of correctors, restoring the orbit through the emittance-measurement section. Figure 4 shows a schematic layout, while Fig. 5 shows a photo of the cavity installed in the UITF beam line.

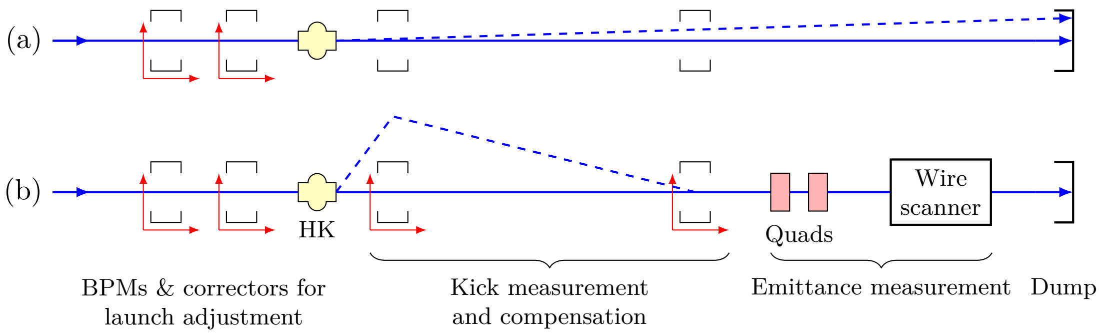

Figure 4. Conceptual sketch of the beam line for the kicker test. Part (a) shows the essential components of the setup for measuring only the deflection, while part (b) includes a kick correction with two steerers to restore the orbit for consistent quad scans. The dashed line represents the beam orbit with the kicker turned on; it is exaggerated for clarity in the bottom figure.

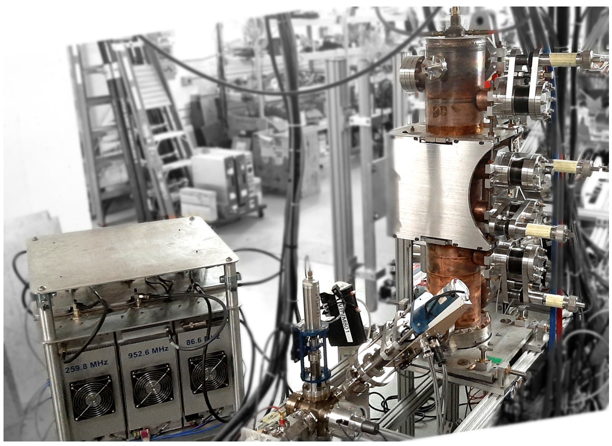

Figure 5. Harmonic kicker installed in the UITF beam line with the HAWG next to it.

5. Results

5.1. Deflection waveform

Due to time constraints, the beam test was performed without automatic stub-tuner control and RF feedback. However, after iterative matrix-based tuning of all modes and with temperature-regulated water flowing through the inner conductor of the cavity, we found that the frequency stability of all modes was well within the bandwidth. The limited RF duty cycle helped keep detuning due to RF heating to a minimum.

As a first test, we drove the cavity at half power per channel one mode at a time, the other amplifiers off, and scanned the HAWG reference phase to measure the deflection waveform at each frequency. The angle of deflection for each phase follows from the position signals of two subsequent BPMs located downstream of the cavity. Figure 6 shows an example of this measurement performed at the ninth harmonic, demonstrating the single-mode deflection is a clean sine wave.

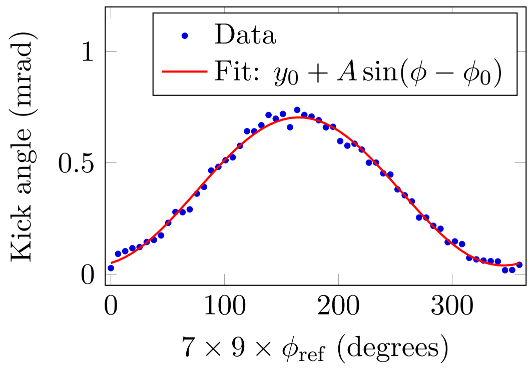

Figure 6. Deflection waveform with only the 9th harmonic (779.4 MHz) being driven at nominally 50 % output power. The phase ϕ_{ref} being scanned is that of the 12.4 MHz reference and is scaled up accordingly for clarity. The beam angle is not explicitly corrected to give zero with the cavity off. $y_0 = 0.372(3)$ mrad, $\phi_0 = 75.1(7)°$, $A = 0.333(4)$ mrad.

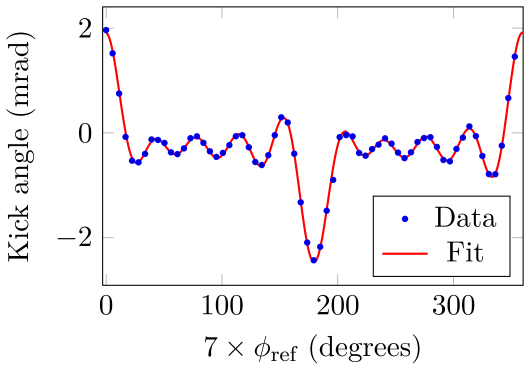

Figure 7. Deflection waveform with all five modes powered and optimized.

Having tested each mode individually, we powered all modes at the same time, measured the superposition waveform, and adjusted the phase and amplitude setpoints of the modes to give equal phases and amplitudes in the deflection waveform as determined by a fit of

$$f(\phi) = f_0 + \sum_{k=1}^{5} A_k \cos\left[(2k-1)\phi - \phi_k\right] \tag{2}$$

with $\phi = 7\phi_{\text{ref}}$. With all A_k equal and all $\phi_k = 0$, this would give the desired waveform shown in Fig. 2.

The waveform so obtained is shown in Fig. 7, its parameters listed in Table 1. While the waveform visually resembles the target, the numbers show a discrepancy in the highest mode. The dominant limitation preventing an accurate and reproducible synthesis of the target waveform is the lack of both tuning feedback and RF feedback in the present setup, causing the phases to wander. In practice, this is exacerbated by each phase being slightly interdependent

Table 1. Fit parameters for waveform in Fig. 7

k	A_k (mrad)	ϕ_k
1	0.47	1°
2	0.46	2°
3	0.46	4°
4	0.43	4°
5	0.38	−16°

with the corresponding amplitude due to imperfections of the RF elements in the HAWG, especially in the highest mode.

The adjustability of the modes turned out to be further limited by multipacting, which could be observed as a vacuum response and intermittent jumps in the cavity field for several different combinations of RF parameters. While our attempts to process out the multipacting between beam shifts were unsuccessful, it is not expected to be present at higher levels of drive power as needed for the beam momenta of practical applications.

5.2. Transverse phase space

As is the case for all deflecting cavities, the time-dependent deflecting field of the harmonic kicker will transform the spread of arrival times—i.e., the bunch length—into a spread of transverse angles, deteriorating the 2-d emittance if the bunch length is significant compared to the temporal slope of the field around the central bunch phase. Multipole components of the field will further affect the transverse phase space if the transverse beam size is significant. As a sanity check to verify that neither effect is visible with the default bunch length of the UITF and an optics setup that ensures $\sigma_{x,y} \ll 1\,\mathrm{mm}$, we performed quad scans at the end of the line at different cavity phases, correcting for the deflection with steering coils. The results are listed in Table 2, showing no measurable impact on transverse phase space regardless of kicker phase; the point at 0° is at peak deflection, whereas that at 15.4° is at maximum negative slope.

Table 2. Downstream Twiss parameters in the deflecting plane of the kicker

$7\phi_{\mathrm{ref}}$	α	β (m)	ϵ (nm)
off	-9.9	21.4	26.3
0°	-9.6	19.9	26.7
15.4°	-9.5	20.0	24.4

6. Conclusion

We successfully operated the harmonic kicker with all five modes and performed a beam-based measurement and optimization of the deflection waveform, finding no unexpected issues other than multipacting. We expect the technical limitations of the drive circuit to be fully resolved by ongoing development efforts, making harmonic kicker cavities a viable option for future accelerator designs.

Acknowledgments
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