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University of Wisconsin-Synchrotron Radiation Center TECHNICAL NOTE	**File No.** 214	**Page** 1
Subject: Use of Rf Transverse Kicker to Provide Injection and Extraction of Particle Beams into Existing Circular Accelerator Structures with Current Multiplication	**Author(s):** **Legg, R**	
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Abstract

This note describes a scheme for injecting and extracting particle bunches from a source through a circular accelerator structure (a storage ring) using rf cavities producing transverse kicks. The scheme provides for re-circulating multiple passes through the circular structure to allow for effective current multiplication, and then recovering the beam through the source structure to minimize the source power requirements. The scheme is also attractive because it reduces the amount of source current required in the primary accelerator structures, mitigating the beam breakup issues [1] and easing the beam loss aperture and minimum beta requirements [2].

Introduction

Circular structures have been the work horses of the synchrotron radiation business for several decades, however in the last ten years the concept of an Energy Recovered Linac which utilizes the much lower emittance possible when the lattice structure no longer defines the beam emittance, has made steady progress. One of the major hurdles in making the transition to an ERL type source is cost. The driver alone is estimated to cost $100M before civil costs, beamlines or instrumentation is considered. It would be very advantageous to convert an existing storage ring facility to use an ERL driver in order re-use the existing site, staff, beamlines, etc. In order to do this a scheme which allows bunches to be injected into and extracted from an existing particle storage ring is desired. Additionally, since the beam in the storage ring takes many turns to “damp” to the ring’s intrinsic emittance, it would be very advantageous to re-circulate several passes of the injected beam in order to maximize the circulating current in the bending magnets and insertion devices, so long as the number of turns does not get so large that the beam’s emittance is diluted.

To do this, it is suggested that a pair of rf cavities designed to operate in the TEM dipole mode at a frequency that is one-quarter of the ring’s rf frequency, but 180 degrees out of phase with each other, be used to impart a transverse kick to bunches from the driver linac, FIGURE 1.

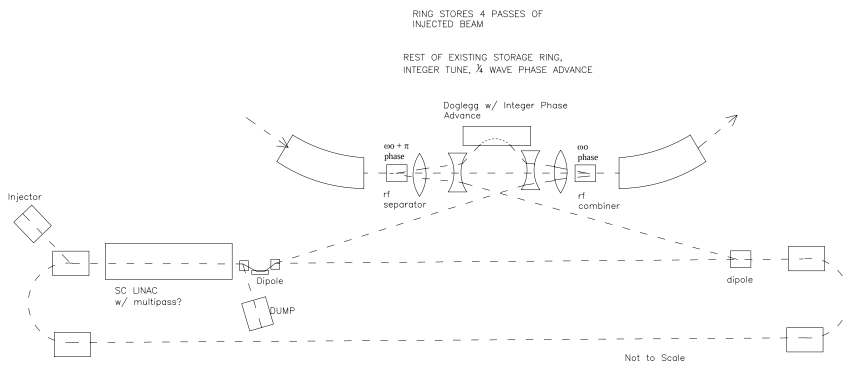

FIGURE 1

The bunch is given an oblique trajectory to the first cavity which is set at +90 degrees phase to kick the bunch onto the ring's central orbit. The bunch circumnavigates the ring and reaches the second rf cavity which has a phase advance of 180 + 90 degrees from the exit of the first cavity. Since the first cavity was at 90 degrees and imparted a kick, this cavity is at zero crossing, so the bunch coasts by on its way back to the first cavity. The phase advance from the second cavity to the entrance to the first is zero degrees, so the bunch coasts through the first cavity again to start a second pass through the ring. The bunch again goes around the ring and now the phase in the second cavity is 180 + 90 + 90 degrees with respect to the first cavity, or at the original +90 degrees. The bunch receives a transverse kick from the second cavity which is in the same direction as the original injection kick which diverts the bunch through a magnetic chicane which brings the bunch back to the first cavity with no additional phase advance, where it receives a kick of equal amplitude, but opposite sign due to the difference in phasing between the two cavities. This completes the four bump chicane, and puts the bunch back on the central orbit of the ring. The bunch again goes around the ring and is now at 180 + 270 degrees with respect to the original transverse kick, putting it on a zero crossing. The bunch drifts through the first kicker for a fourth time and goes around the ring where it reaches the second cavity with a phase advance of 180 + 360 degrees with respect to the original kick. This kicks the bunch back out of the ring toward the original ERL driver where a dipole steers the beam back onto an orbit for eventual energy recovery.

To clarify the pattern of kicks, refer to TABLE 1.

	INJECT	Pass 1	Pass 2	Pass 3	EXTRACT
Cavity 2		Zero Crossing	$+ 90^o$	Zero Crossing	-90^o
Cavity 1	$+ 90^o$	Zero Crossing	-90^o	Zero Crossing	

TABLE 1

This same pattern could be extended to allow n passes through the ring by setting the phase advance around the ring, to π/n and designing a dipole to reflect the trajectory of the incident beam. This scheme is complicated by requiring that the rf frequency of the separators be reduced to the ring rf frequency divided by n in order to keep each bunch in a bucket of the main rf frequency so incoherent synchrotron energy losses can be restored each time around the ring. There is the added problem that extracting the bunch from the ring becomes much more complicated due to the shallow extraction angles (π/n). Finally going to higher numbers of passes through the ring does not increase the stored current, which is limited by the charge per bunch and the number of buckets available in the main rf system. The only true advantage derived by going to more than four passes through the ring is the reduction in repetition frequency required by the injector which affects the average current from the injector and the associated drive laser average power. This reduction is at the expense of the emittance and bunch length dilution caused by putting the beam through the ring n times.

Cavity Design

The rf cavities used to kick the beam must be operated in the CW mode in order to maintain the amplitude and phase stability necessary to keep the bunches on the designated orbit. The cavity must be strong enough in order to produce a large offset for extraction and injection to be accomplished in a reasonable distance given the stay clear requirements of the beam. The CEBAF rf separator [3] produces 100 microrad of kick at 1 GeV from 400 watts of rf power. Assuming it can be scaled, 20 kilowatts would produce a 5 mrad kick in a 1 GeV beam. This is an extreme example however and would require a much improved cavity cooling scheme, but it does demonstrate that a large transverse kick using a conventional cavity is possible.

The other possible rf separators are the SRF separator cavities used at TESLA [7] or the proposed cavities for LUX [8]. Both these kickers are much larger though and offer relatively low transverse gradients. The Fourier system described in [7] might be interesting for much larger machines or if arbitrary injection/extraction pulse trains were desired.

Optics Design

The optics design of the merge point are challenging from the standpoint that small betas are desirable in order to minimize the effects of errors in the synchronization of the two kicker cavities and the main rf system, but large betas are desirable to maximize the effectiveness of the kicks in injecting and extracting the beam from the ring. To minimize the size of the rf kick needed, a defocusing quadrapole element downstream of the kicker cavity is used to magnify the kick. For bunches drifting through the two cavities at zero crossing, a triplet magnet set is used to maintain focusing in the merge region and to preserve the phase advance between the two rf cavities. For example, if the kicker produces a 3 mrad kick which is doubled in the downstream quadrapole, the beam will still only be 3 cm off axis after a 5 meter drift. To finish the extraction of the bunch either a second rf kicker, a septa magnet or a very long drift section is required. Since an additional focusing element is necessary to complete the triplet, just invoking a drift will simply shift the problem to the magnet designer looking for a scheme to allow the beam to get past the magnet. Similarly, a quad is necessary after the last dipole prior to the injection point in order to allow it to be placed far enough from the nominal beam path to avoid interfering with the kicker cavity or ring hardware.

Multiple beam effects are caused by using cavity kickers to produce multiple orbits in the ring [4]. The first is that differences in kicks between the two cavities cause an increase in the effective emittance of the beam as seen by the beamlines on the ring, since the error in the difference in amplitudes of the two rf kicks shows up as a transverse beam position difference between the various passes of the beams in the ring. Unless the detector can differentiate between the position of individual bunches, it will detect a larger transverse beam. For example, if the maximum betatron amplitude is 30 m in the ring and the beam sigma is 0.3 mm (PITZ gun)[5], then to keep offsets which show up as an effective emittance dilution under 1%, the cavity kicks must be matched to within (1%)(0.3mm)/ (30m) = 10E-4 mrad. This would require the rf phase and amplitude error when added in quadrature to be less than 10E-5 for a 10 mrad kick. This is about 0.2 degree or 3E-3 in cavity power. This is well within the capabilities of a CW rf control system. However, for very small transverse beams, or rings with much larger maximum betas, this scheme may be very challenging from an rf control standpoint.

The other effect caused by using rf kickers is that because of the electron bunches' finite length, there is a differential transverse kick across the length of the bunch as the bunch occupies a finite rf phase length in the cavity. The error looks like $A\sin(\omega+\omega_{bunchlength}/2)$ where A is the amplitude of the kick, ω is the phase of the cavity at the arrival of the bunch and $\omega_{bunchlength}$ is the bunchlength in rf degrees of the kicker cavity. For example, for a 125 MHz kicker cavity producing a maximum 3 mrad kick on a 1 psec long bunch, the difference in the kick at the front and back of the bunch is, (3 mrad) sin (90^o + 1e-12 sec (360^o/8e-9sec)), or about 1 nanoradian. This effect is mitigated by the second cavity operating 180 degrees out of phase with respect to the first cavity, so the effects cancel to the first order, with the second cavity producing a kick of the same magnitude but opposite sign.

The final effect which impacts the bunch length is the change in path length as the bunch energy changes with synchrotron radiation emission; or momentum compaction in storage rings. This effect gives rise to the synchrotron frequency in rings, where the bunches circulate for many millions of revolutions, as the electrons in the bunch slosh back and forth between the restoring force of the rf cavity and the synchrotron radiation losses [6]. In the case where rf kickers are used to inject and extract beams and only a few revolutions are made in the ring, there isn't time for oscillations to build up. If at APS, for example, the momentum compaction is about 0.003, and E_{loss}/E_{beam} is roughly 1E-3, then the change in bunchlength is roughly, 3e-6 times the revolution period. For APS the change in bunchlength from normal synchrotron radiation is almost 11 femtoseconds per revolution, so if 4 passes were stored in the machine from an ERL driver, the bunchlength might change by 44 femtoseconds before the bunch was extracted back into the driver. This is much smaller than the calculated increase of 20 femtoseconds per pass from Incoherent Synchrotron Radiation (ISR) and Coherent Synchrotron Radiation (CSR) [4]. This might be unacceptable for certain very short bunch experiments, however, by adjusting the momentum compaction of the lattice [2], some compensation for this term could be achieved.

Conclusion

A technique for injecting and extracting bunches from a CW linac into and out of an existing storage ring is described. The system allows a low frequency source to fill multiple revolutions in a ring limited only by the frequency of the ring rf system and the beam quality dilution caused as the beam recirculates in the ring. This system should allow operation of existing rings at higher average currents with lower emittance and bunchlength.

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