Controlling coupler-kick emittance growth in the Cornell ERL main linac[*]

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Abstract

One of the main concerns in the design of a high brightness Energy Recovery Linac x-ray source is the preservation of beam emittance. Discussed is one possible source of emittance dilution due to transverse electromagnetic fields in the accelerating cavities of the linac caused by the power coupler geometry. This has already been found to be a significant effect in Cornell's ERL injector cavities if only one coupler per cavity is chosen. Here we present results of simulations for Cornell's main ERL linac with six possible coupler configurations and compare them with regards to total emittance growth after one complete pass through the linac. We explain why the sign of the phase between the transverse kick and the accelerating force alternates each cavity when the cavities are arranged in a mirror symmetric way. In this case each cavity with its coupler before the structure is followed by one where the coupler is placed after the structure. This leads to a cancellation of the emittance growth to acceptable values. We find that cavity detuning of individual cavities does not destroy this cancellation. Furthermore we analyze other methods of compensating coupler kicks and find that symmetrization of the cavity geometry in the coupler region with the addition of a stub opposite the coupler is very efficient.

INTRODUCTION

Time dependent transverse fields on the beam axis in the region of an accelerating cavity's power coupler are a possible source of emittance dilution. The coupler creates an asymmetry in the otherwise rotationally symmetric cavity, leading to non radially symmetric field profiles [1, 2]. Previous studies have found this effect to be significant in the injector cavities of the Cornell energy recovery linac (ERL) [3]. As a solution, a second input coupler was installed situated on the opposite side of the beam pipe, canceling the asymmetry and the transverse kick [4]. This approach, though effective, would be a technically challenging and expensive design for a large superconducting linac such as the Cornell ERL or the ILC. A solution to the emittance increase due to coupler kicks that does not include the addition of a second coupler would therefore be preferable.

It is common wisdom that emittance growth from coupler kicks can be strongly reduced by having the coupler location alternate from above to below the beam pipe so that the coupler kick from one cavity is compensated by that of the next. While this is correct, alternating the coupler location requires large technical changes in supercon-

Table 1: Parameters of the Cornell ERL cavities.

Frequency	1300 MHz
Number of Cells	7
Cavity Shape	TESLA type
Accelerating Voltage	15 MV/m
Q_0	10^{10}
Q_{ext}	$\in \{2 \times 10^7, 10^8\}$
Coupler Type	Coaxial
Coax Impedance	50 Ω

ducting cryomodules where cryogenic pipes are arranged parallel to a string of several cavities. We have shown [5] that cavities with high external Q have coupler kicks that change the sign of their phase when the coupler is moved from before to after the cavity, as long as one accelerates on crest. This implies that the emittance growth from one cavity can be canceled by the next, provided the coupler has been moved from before to after the cavity. All couplers can then be mounted on the same side of the beam pipe, and cryomodules become far simpler to construct.

We consider and compare the effects from six different coupler configurations: (**tf**) all couplers mounted on the **t**op of the beam pipe; all couplers placed in **f**ront of the cavity, (**ta**) all couplers mounted on the **t**op of the beam pipe; couplers **a**lternated from being placed in front of and behind the cavity, (**af**) couplers **a**lternated from being mounted on top of and underneath the beam pipe each cavity; all couplers placed in **f**ront of the cavity, (**aa**) couplers **a**lternated from being mounted on top of and underneath the beam pipe each cavity; couplers **a**lternated from being placed in front of and behind the cavity, (**mf**) couplers alternated from being mounted on top of and underneath the beam pipe each cryo**m**odule, or every ten cavities; all couplers placed in **f**ront of the cavity, (**dc**) **d**ouble **c**oupler arrangement with two couplers per cavity, equivalent to no transverse kick.

In addition to these six configurations we investigate the benefit of optimizing the placement of the coupler along the beam pipe and the addition of a symmetrizing stub opposite the coupler.

COUPLER-KICK EMITTANCE GROWTH

The electric and magnetic standing wave profiles in the cavity were computed with Microwave Studios (MWS) [6]. The Linac parameters used for simulations of the Cornell ERL are listed in Table 1.

The momentum change that is produced when a particle transverses an rf cavity along its central axis with $s = vt$,

is specified as

$$\Delta \vec{P} = q \int_{t_i}^{t_f} [\vec{E}_0(vt,t) + v\vec{e}_s \times \vec{B}_0(vt,t)]dt , \quad (1)$$

The vertical coupler kick κ_y is defined as the ratio of the complex vertical rf kick with the complex longitudinal kick:

$$\kappa_y = \frac{\Delta \vec{P}_y}{\Delta P_\parallel} . \quad (2)$$

The phase of the coupler kick, ϕ_c, is the difference between the phase of the the transverse kick and ψ, the phase of the accelerating kick.

A Gaussian distribution of particles with rms bunch length σ_t that experiences the coupler kick at a beta function β_y obtains an emittance growth of

$$\Delta \varepsilon_y = \frac{1}{2}\beta_y S^2 \sigma_t^2 , \quad (3)$$

$$S = \frac{\Delta E_0}{E}|\kappa_y|\omega \sin(\phi_c + \psi) , \quad (4)$$

where $\Delta E_0/E$ is the relative energy gain in the cavity and ω is its angular frequency.

Standing Wave Approximation: We will use the approximation that traveling waves in the coax excite standing waves in the cavity. Exact standing waves would be excited in the cavity if the energy leaving the cavity through the coupler per oscillation were zero. Correspondingly, this standing wave approximation is very good if the energy loss per oscillation is much less than the the total energy stored in the cavity. The ratio between these two energies is characterized by Q_{ext}. Simulations in MWS were run varying the depth of the inner conductor in order to match the Q_{ext} values of 2×10^7 and 10^8 [7].

We calculated realistic values for the coupler kick by integration through the field profiles simulated in MWS. With MWS one can compute $E\&M$ waves that correspond to operating the cavity without reflection, i.e. in the coupler they describe purely inward traveling waves. We denote the coupler kick of this operation mode as κ_y^+.

Alternating Coupler Position

In our MWS simulations the coupler is situated in front of the cavity. However, in configurations (af) and (aa) the coupler will alternate from being placed in front of and behind the cavity. It is therefore necessary to model the change in momentum due to a coupler kick κ'^+ supplied after the particle exits the cavity. Symmetry arguments and the resonance approximation can be used to show [5]

$$\kappa_y'^+ \approx (\kappa_y^+)^* . \quad (5)$$

The effect on emittance due to the coupler kicks from two consecutive cavities with one coupler before, the other

Table 2: Coupler kick parameters.

| | $Q_{ext} = 2 \times 10^7$ | | $Q_{ext} = 1 \times 10^8$ | |
	pre Cav	post Cav	pre Cav	post Cav
$|\kappa_y|10^4$	.9651	.9891	1.039	1.027
ϕ_c (rad)	2.838	-2.793	2.819	-2.816

(a) Small emittance growth configurations, $Q_{ext} = 2 \times 10^7$

(b) Large emittance growth configurations, $Q_{ext} = 2 \times 10^7$

(c) Small emittance growth configurations, $Q_{ext} = 10^8$

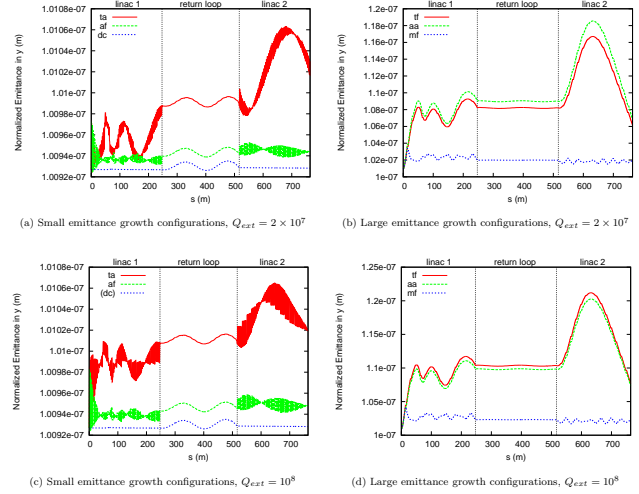(d) Large emittance growth configurations, $Q_{ext} = 10^8$

Figure 1: Normalized emittance in the y direction.

behind the cavity, i.e. configuration (ta), is then describe with Eq. (3) with

$$S \approx 2\frac{\Delta E_0}{E}|\kappa_y|\omega \cos(\phi_c)\sin(\psi) . \quad (6)$$

Operation on crest, or $\psi = 0$, leads to $\Delta \epsilon_y = 0$. The second coupler cancels the effects from the first similar to the cancellation from switching the direction of the beam pipe as in configuration (af). Therefore we find that alternating both the position and direction of the coupler kick as in configuration (aa) should lead to a double negation and thus large emittance growth.

Coupler kicks for the coupler after the cavity were also calculated with MWS, i.e. without assuming standing wave approximation. The phase of the coupler kicks and the respective magnitudes are shown in Table 2. The results illustrate the approximate complex conjugacy. This shows that the standing wave approximation is very good.

Shown in Fig. 1 are results of normalized emittances for the ERL lattice. Initial normalized emittance is 1×10^{-7}m. The Cornell ERL is split into two accelerating sections, labeled as linac 1 and 2, connected by a return loop. To compensate for overall transverse kicks, the necessary corrector coil strengths are computed and included in the lattice. The orbit distortion from the coupler kick can be significant, leading to about 1mm orbit distortion after the first 10 cavities. With increasing beam energy the orbit distortion diminishes.

As one might expect from our previous conclusion, the increase in normalized emittance is small for the (ta) and (af) configurations while larger for the (aa) configuration

Table 3: Coupler kicks for optimized coupler phase.

	$Q_{ext} = 2 \times 10^7$		$Q_{ext} = 1 \times 10^8$	
	pre Cav	post Cav	pre Cav	post Cav
$|\kappa_y|10^4$	.6037	.6066	.5943	.6043
ϕ_c(rad)	3.126	-3.013	3.129	-3.1

which has a nearly identical effect as the (tf) configuration. While alternating the direction of the coupler each cavity with all couplers in front as in configuration (af) has less of an effect on emittance than does the (ta) configuration, both effects are essentially negligible, comparable to no coupler kicks at all (dc). The (ta) configuration is therefore preferable as it is much easier to implement.

Whenever cancellations rely on symmetries, one has to investigate how sensitive the cancellation is to small deviations from ideal symmetry. Even identically constructed cavities will be detuned differently due to vibrations. The cavities reflection coefficients α will differ between cavities. However, we find in [5] with symmetry transformations and the standing wave approximation that the coupler kick is independent of the reflection coefficient to a good approximation for large Q_{ext}.

Minimizing Coupler Phase

An alternative method for minimizing emittance growth which does not depend on the alternating placement of the coupler entails manipulating the coupler kick such that its phase is 0 or π. As the change in emittance of Eq. (3) varies with S^2 and thus with $\sin^2(\phi_c + \psi)$, operation at $\psi = 0$ leads to low emittance growth for $\phi_c = 0$ or π. This method reduces the effects from each individual coupler and is effective no matter the configuration of couplers along the lattice.

The coupler kick phase is dependent on the distance the coupler is situated from the entrance of the cavity. In the previous simulations the coupler was positioned 4.5 cm from the entrance of the cavity. We find that moving the coupler out to a distance of 5.3 cm leads to a coupler phase of π for $Q_{ext} = 2 \times 10^7$ and moving out to a distance of 5.5 cm leads to a phase of π for $Q_{ext} = 10^8$. The coupler kick parameters are listed in Table 3. Figures 2 show the results of normalized emittance through the ERL lattice for all six coupler arrangements with these coupler parameters. The emittance growth is decreased substantially for all cases illustrating the large dependence of the emittance growth on the phase of the coupler kick.

Symmetrizing Stub

The above methods for reducing emittance growth, namely the alternating position of the coupler as in configuration (ta) and the phase minimization technique, all depend on operation on crest, $\psi = 0$. For some working modes of the Cornell ERL, it is preferable to operate slightly off crest. For such applications, an alterna-
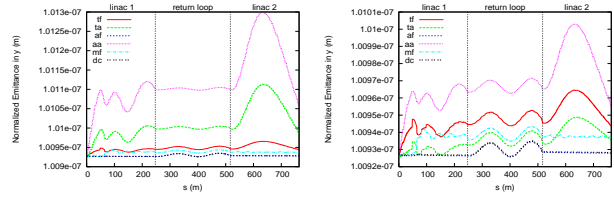

Figure 2: Normalized emittance in the y direction for the six coupler configurations for $Q_{ext} = 2 \times 10^7$ (top) and $Q_{ext} = 1 \times 10^8$ (bottom).
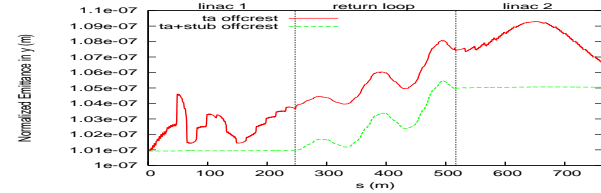

Figure 3: Emittance growth with off crest operation with and without symmetrizing stub.

tive method for reducing emittance growth is adding a stub across from the coupler. The stub is used to minimize the asymmetry in the beam pipe causing the transverse fields in the coupler region.

Simulations were run with configuration (ta) $9°$ off crest with the coupler placed 4.5 cm from the entrance of the beam pipe, i.e. the coupler phase was not minimized, to investigate the extent of the dependence of the emittance growth cancellation on ψ. A second simulation was run with the same configuration, $\psi = 9°$, but with a stub of only 1 cm depth added to the cavity. Results are given in Fig. 3. The addition of the very small stub eliminates emittance growth through linac1 and linac2 very effectively. The emittance increase in the return loop is independent of the coupler kicks.

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