A HIGH POWER CW INPUT COUPLER FOR CORNELL ERL INJECTOR CAVITIES*

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Abstract

A conceptual design of the input coupler for superconducting injector cavities of Cornell ERL project is presented. The injector cavities are two-cell structures operating at 1300 MHz in CW mode. The coupler has a symmetric design to accommodate requirements for small transverse kick, high RF power delivery to the cavity, and high coupling value. It consists of two identical antenna type couplers symmetrically attached to a beam pipe of the cavity. Each of these individual couplers has to deliver at least 50 kW of CW RF power to the beam. The coupler has a variable coupling. Q_{ext} varies from $4.6{\times}10^4$ to $4.1{\times}10^5$. The symmetric design of the coupler dramatically reduces the transverse kick, a critical requirement for the ERL project. Individual couplers design is based on the design of TTF-III TESLA couplers but it has been significantly modified for requirements of ERL injector cavities.

INTRODUCTION

The project of Energy Recovery Linac (ERL)—a challenging ultra-high brightness X-ray source of a new generation—is in the R&D stage at Cornell University and Jefferson Laboratory [1], [2], [3]. It should be a CW 100 MeV machine with high average current (100 mA). Superconducting 1300 MHz RF structures will be used in the main linac and injector of this project. A goal of the ERL project is achieving a 2 μm emittance for a bunch charge q of 77 pC and 0.2 μm for 8 pC at the undulator location. This implies emittances of about 1 μm and 0.1 μm in the injector for the two different bunch charges.

A high brightness injector [4] is a key element of this machine. It includes a 500 keV DC photoemission electron gun, a conventional buncher, and five two-cell superconducting RF cavities. The injector cavities should accelerate the beam to a nominal energy of 5.5 MeV (1 MeV per cavity) with minimal emittance dilution. It requires delivering 500 kW power to the beam (100 kW for each cavity). Operation with acceleration to about 15.5 MeV (3 MeV per cavity) is also planned at a reduced average current (33 mA), limited by the total RF power available. All five two-cell cavities will be mounted in a single cryomodule [5].

REQUIREMENTS TO THE INJECTOR CAVITY COUPLER

The parameters of the injector cavities are summarized in Table 1. The injector cavity coupler has to deliver

Table 1: Parameters of the injector cavities

Energy of electrons, E	0.5 to 5.5 (15.5) MeV
Beam current, I_0	100 (33) mA
Frequency, f	1300 MHz
Number of cells per cavity, N_c	2
Q_0	$\geq 5{\times}10^9$
Q_{ext}, nominal	$4.6{\times}10^4$
Q_{ext}, range	$4.6{\times}10^4$ to $4.1{\times}10^5$
R/Q	218 Ohm
Cavity voltage, V	1 (3) MV
RF power per cavity, P	150 kW

100 kW of RF power to the beam and provide matching conditions for a cavity gap voltage of 1 through 3 MV and corresponding beam currents of 100 through 33 mA. Thus the external Q factor range is $4.6{\times}10^4$ to $4.1{\times}10^5$ or a factor of 9. This coupler should be designed to withstand an RF power up to 150 kW CW in traveling wave (TW), the installed RF power per cavity.

The main design challenges to RF power coupler of the injector cavity are:

- High average RF power (up to 150 kW TW)
- Very strong coupling ($Q_{ext} = 4.6{\times}10^4$)
- Wide range of variable coupling (factor of 9)
- Minimizing transverse kick to the beam to avoid emittance growth
- Multipacting-free (or almost multipacting-free) design

COUPLER DESIGN

We considered different options of the coupler design [6]. Finally, we chose a twin coaxial coupler [7], [8]. It consists of two identical antenna type couplers symmetrically attached to a beam pipe of the cavity (see Fig. 1). With this approach only a half of the full RF
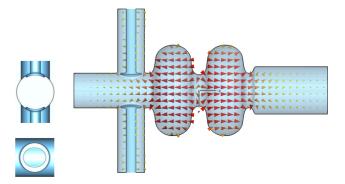

Figure 1: Input coupler in the injector cavity.

power goes through a single coupler and twice as less coupling is necessary ($Q_{ext} = 9.2 \times 10^4$). Another excellent feature is a good transverse field symmetry, which is very important for the ERL requirements—no more than 10 % of the emittance growth due to injector cavities.

As individual couplers we decided to use the TTF III couplers [9] modified to meet our requirements. It is rather natural because we plan to use TESLA cavities and cryostats in the main linac structure. We took into account some of the B. Dwersteg's advices given in [10].

The cold part of the original coupler was completely redesigned. Instead of a 40 mm 70 Ω coaxial line, a 62 mm 60 Ω line was chosen for getting a stronger coupling and better handling the high power. It is also multipacting-free in the full power range [7]. The coupler has a larger profiled antenna tip to provide a strong coupling. The travel range of the antenna was increased to 15 mm for getting the required coupling variation (see Fig. 2). In the cold window a bigger ceramic cylinder is used (similar to the one used in the warm window but with a reduced height). The weakest points of the TTF III coupler at high power levels are the bellows in the warm coaxial line. At the power of 50 kW the bellows temperature would reach 400 K on the outer conductor and 375 K on the inner conductor. This problem is solved in the new design by providing air cooling of both bellows of the warm coax line. For realizing the cooling of the outer conductor bellows, an additional edge-welded bellows unit is added to the design. It encloses the regular bellows and an air flow is established in the space between the two bellows. The diameter of inner coaxial line in the warm part of the coupler is slightly increased (from 27 mm to 28.8 mm). The general design of the coupler is shown in Figure 3.

Figure 4 shows the S_{11} parameter of the coupler in a frequency range for different coupling (and different bellows extension/compµression). The coefficient $ki = 0.7$
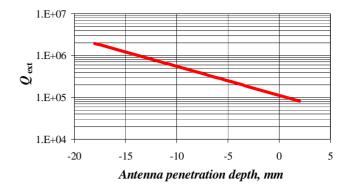

Figure 2: Dependence of Q_{ext} of a single coupler on the penetration of the antenna tip into the cavity beam pipe. The Q_{ext} of a twin coupler is twice as low.

corresponds to the weakest coupling and $ki = 1.1$ corresponds to the strongest coupling (ki is the relative length of the inner conductor bellows). Geometry of the coupler is optimized for obtaining compromised low reflection in the whole range of coupling variation.

Figure 5 and Figure 6 show electric and magnetic fields in the coupler.

The coupler has to deliver RF power to a super-conducting cavity, i. e. it is a part of the cryogenic system. Table 2 shows the values of heat loads of a single coupler to the cryogenic system.

Table 2: Injector cavity coupler heat loads

	Static	At 50 kW (CW, TW)
To 1.8 K	0.05 W	0.2 W
To 4.2 K	0.30 W	2.0 W
To 70 K	6.80 W	31 W

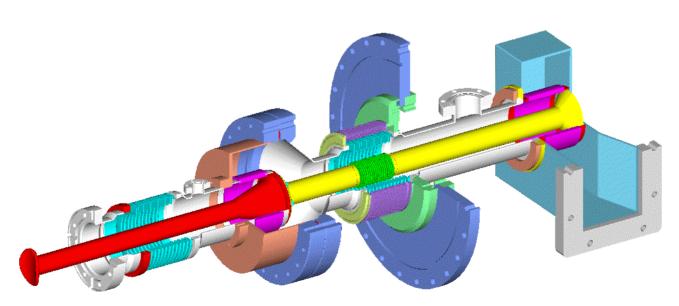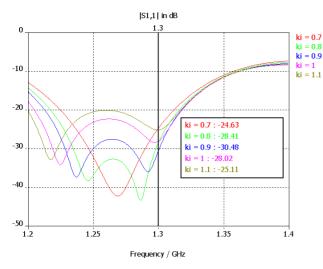

Figure 3: 3D view of the injector cavity coupler.

Figure 4: Reflection of the coupler in a frequency range at different coupling (coupling increases from weak to strong when *ki* varies from 0.7 to 1.1).
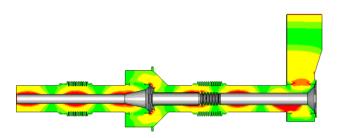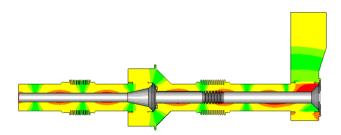

Figure 5: Electric fields in the coupler.

Figure 6: Magnetic fields in the coupler.

FIELDS SYMMETRY AND BEAM DYNAMICS

The twin coupler design gives an excellent transverse field symmetry on the beam axis. There can be only residual transverse fields due to antennae position errors and errors of power and phase balance between two single couplers.

Figure 7 shows the distribution of transverse fields along the beam axis for 1 mm difference of antenna penetration depths of two couplers (for the strongest coupling where the response to position errors is maximal). The 3D computer code CST Microwave Studio® [11] was used for field calculations. The fields
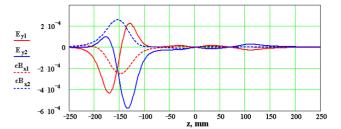

Figure 7: Normalized transverse fields on the axis of the injector cavity for a relative penetration depth error of 1 mm. The coordinate $z = 0$ corresponds to the cavity center. E_{y1}, B_{x1} and E_{y2}, B_{x2} were calculated respectively for shorted and open coupler.

are normalized to the maximum accelerating field E_{zm} on the axis. Integrating the fields, one can calculate the transverse kick for different coupler errors [7], [8]. The results are summarized in Table 3. For a comparison, the transverse kick of a single coupler is also presented in the table.

Table 3: Relative transverse kick (normalized to the maximum accelerating voltage) due to twin coupler errors.

Error in:	Error value	Transverse kick
Relative penetration depth	1 mm	2.2×10^{-4}
Relative phase	1°	7.0×10^{-4}
Relative power	1 %	4.5×10^{-5}
Single coupler		3.0×10^{-3}

The influence of an injector cavity on beam dynamics was simulated using the 3D computer code ASTRA [12]. The results are shown in Table 4.

Table 4: Beam emittance growth due to RF focusing and kick in the injector cavity with a single coupler and with a twin coupler.

	q [pC]	V_{acc} [MV]	ε_0 [µm]	σ_z [mm]	σ_x [mm]	emittance growth
single input coupler	77	1	1.0	0.6	2.0	6 %
	77	3	1.0	0.6	0.9	3 %
	8	1	0.1	0.6	0.6	16 %
	8	3	0.1	0.6	0.3	28 %
twin input coupler	77	1	1.0	0.6	2.0	4 %
	77	3	1.0	0.6	0.9	1 %
	8	1	0.1	0.6	0.6	4 %
	8	3	0.1	0.6	0.3	1 %

One can see from these estimates that coupler kick contribution is not important for nominal bunch charge of

77 pC but becomes noticeable in the case of ultra-low 0.1 μm emittances. For cavity with the twin coupler the emittance growth governs solely by RF focusing.

CONCLUSION

A preliminary design of the input coupler for the Cornell ERL injector cavity has been done. Based on the TTF III TESLA coupler design, it is developed for a much higher CW power operation. A twin coupler design has a very good field symmetry and meets stringent requirements of the ERL project.

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