High average power fundamental input couplers for the Cornell University ERL: requirements, design challenges and first ideas

S. Belomestnykh, M. Liepe, H. Padamsee, V. Shemelin, and V. Veshcherevich

Laboratory for Elementary-Particle Physics, Cornell University, Ithaca, NY 14853

9 September 2002

This paper is intended to set general requirements for the fundamental RF power couplers under development for the Cornell University ERL project, specify major design challenges, consider design options, describe general approach to some calculations and present first ideas.

1. Coupler requirements and design challenges

There are three different coupler types to be developed for the Cornell University ERL: for a buncher cavity, for five injector cavities and for five linac cavities. The buncher cavity is a normal-conducting single-cell cavity made of copper. It serves to produce an energy spread of about 10 keV in a σ_{gun} = 12 ps, 500 keV bunch coming from the gun so that the bunch will be shortened to σ_{injector} = 2.3 ps in a drift space between the buncher cavity and the first injector cavity. The five injector cavities are superconducting 2-cell niobium structures. They provide 500 kW (limit is set by the input power coupler specifications) of RF power to the beam. Consequently the permitted beam current depends on the injector energy and varies from 100 mA at 5 MeV to 33 mA at 15 MeV. The five linac cavities are superconducting 9-cell TESLA-style niobium cavities. Each cavity is operated at an accelerating gradient of 20 MV/m. The RF parameters of the buncher, injector and linac cavities [1] are listed in the table below. Some numbers in this table are preliminary as we are still working on the final designs. An overview of the ERL RF system can be found elsewhere [2].

Table 1: RF parameters of ERL cavities.

	Buncher cavity	Injector cavity	Linac cavity
Frequency, MHz	1300	1300	1300
Energy of particles, MeV	0.5	0.5 to 5 (15)	5 (15) to 100
Number of cells per cavity	1	2	9
R/Q, Ohm	210.5	218.4	1036
Q_0	2×10^4	$\geq 5\times10^9$	$\geq 10^{10}$
Q_{ext} nominal	2×10^4	4.6×10^4	2.6×10^7
Q_{ext} range	–	4.6×10^4 to 4.1×10^5	8×10^5 to 4×10^7
Cavity gap voltage, MV	0.12	1 (3)	20.8
Installed RF power per cavity, kW	20	150	20

The beam passes the buncher cavity at the RF wave null so that beam power is zero. Therefore the buncher cavity coupling to a transmission line is determined only by the cavity wall losses and the coupler is fixed with $Q_{\text{ext}} = 2\times10^4$. On the other hand, there will be strong reactive beam loading [2], which will have to be compensated by cavity detuning for optimal match. However, without beam the frequency of the buncher cavity is off by 114 kHz, requiring 14 kW of RF power for an accelerating voltage of 120 kV. It turns out that the best choice would be to detune the buncher cavity halfway [2]. This reduces the required power to 6 kW at 120 kV and leaves enough power overhead to raise the cavity voltage up to 200 kV for experiments with higher bunch charges. The coupler hence should be designed for a standing wave (SW) operation with maximum forward power of 20 kW (installed power).

The other two coupler types must be adjustable. The injector cavity coupler has to deliver 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 4.6×10^4 to 4.1×10^5 or factor of 9. This coupler should be designed to withstand an RF power up to 150 kWCW in traveling wave (TW), the installed RF power per cavity.

Two factors determine requirements to the linac cavity coupler: the need of high-pulsed-power processing (HPP) and the amount of microphonic noise [1]. Necessity to reach peak electric field of 80 MV/m during HPP with 1.5 MW of RF power and pulse length of 250 μs dictates the lower limit of $Q_{ext} = 8\times10^5$. The microphonic detuning of the cavity resonant frequency sets the upper limit of the external quality factor. For a chosen detuning value of 25 Hz (peak), the optimum Q_{ext} is equal to 2.6×10^7. We hope that utilizing piezo-electric tuners will reduce the effect of microphonics and allow us to increase Q_{ext} to save RF power. That is why we set the upper limit to 4×10^7. The installed RF power is 20 kW per cavity and, because of zero beam loading in energy recovery mode, practically all incident power is reflected back from the linac cavities. Thus the linac coupler should be designed for a forward power level of 20 kWCW with full reflection.

In summary, the main design challenges to the ERL fundamental RF power couplers are:

- High average RF power (up to 20 kW SW for buncher and linac, 150 kW TW for injector)
- Very strong coupling (4.6×10^4 for injector)
- Wide range of variable coupling (factor of 9 for injector and factor of 50 for linac)
- Minimizing transverse kick to the beam to avoid emittance growth
- Design of a multipacting-free (or almost multipacting-free) complex 3D structures

2. *Design options*

There are two possible coupler design options: a waveguide coupler or a coaxial coupler. Their major pros and cons are listed in Table 3. Though waveguide couplers can handle RF power better than coaxial ones, several high average power coaxial couplers have been developed recently. Also, coaxial couplers have in general smaller heat leak and it is relatively easy to modify multipacting power levels by changing the diameter and/or impedance of a coaxial line. On the other hand, the larger size of a waveguide coupler means higher pumping speed and the absence of the center conductor makes the design simpler and cooling easier. So, taking into consideration all these arguments, it seems that it is to a large extent a matter of taste, machine/cavity specific requirements and availability of ceramics and of an acceptable prototype design to decide which coupler/window design to choose.

Table 3: Pros and cons of waveguide and coaxial couplers.

	Pros	**Cons**
Waveguide	• Simpler design • Better power handling • Easier to cool • Higher pumping speed	• Larger size • Bigger heat leak • More difficult to make variable
Coaxial	• More compact • Smaller heat leak • Easier to make variable • Easy to modify multipacting power levels	• More complicated design • Worse power handling • Require active cooling • Smaller pumping speed

A number of high average RF power couplers and windows have been developed at different laboratories around the world. Some of the most relevant to our case designs are listed in Table 2. Both waveguide and coaxial designs are used in different configurations (see recent review of the field in [3]), but only few of the couplers are variable.

Table 2: Fundamental RF power couplers and windows.

Facility	Frequency	Coupler type	RF window	Max. power	Comments
LHC [4]	400 MHz	Coax variable (60 mm stroke)	Cylindrical	Test: 500 kWCW 300 kWCW	Traveling wave Standing wave
PEP-II [5]	476 MHz	WG fixed	Disk WG	Test: 500 kWCW Oper: 225 kWCW	RF window test Forward power, HER [6]
CESR [7] (B-cell)	500 MHz	WG fixed	Disk WG	Test: 450 kWCW Oper: 300 kWCW 360 kWCW	RF window test Beam power Forward power
KEK-B [8] (SC cavity)	509 MHz	Coax fixed	Disk coax	Test: 800 kWCW Oper: 380 kWCW	
LEDA [9]	700 MHz	-	Disk WG	Test: 800 kWCW	Similar to PEP-II window
APT [10] (SC cavity)	700 MHz	Coax variable (±5 mm stroke, 2×10^5 to 6×10^5)	Disk coax	Test: 1 MWCW 850 kWCW	Traveling wave Standing wave (fixed coupler)
SNS [11, 3] (SC cavity)	805 MHz	Coax fixed	Disk coax	Test: 2 MW peak 22 kW average	similar to KEK-B 720 kW @ 1 ms, 30 pps,
JLab FEL [12]	1500 MHz	WG fixed	Planar WG	Test: 50 kWCW Oper: 30 kWCW	RF window test, very low ΔT
TESLA [13] (TTF2 & TTF3)	1300 MHz	Coax variable (17 mm stroke, factor of 20: 10^6 to 2×10^7)	Cylindrical	Test: 1.8 MW peak (4.68 kW average) 250 kW peak (3.3 kW average)	TW, 1.3 ms pulse @2 Hz @10 Hz

3. Calculating multipacting, external coupling, transverse kick and emittance growth

To efficiently design couplers to specified parameters one has to develop and use appropriate calculating tools. In this section we describe tools that we use in assisting fundamental RF coupler development. Multipacting might be one of the major RF system performance limiting factors. Multipacting phenomena in coaxial couplers can be studied with MultiPac [14] software package, which became recently available free of charge for scientific community. Cavity multipacting will be studied with MultiPac and MPS [15]. Finally, multipacting zones in rectangular waveguides can be calculated both analytically and numerically [16, 17]. At this point it is less obvious to us what one can use for 3D calculations in such places as waveguide to coaxial line transition and cavity-coupler interface although there are couple of programs available [18].

Several methods have been developed in recent years to calculate external coupling to RF cavities using computer codes (see description of some of them in [19, 20, 21, 22, 23, 24].) We adapted one of the methods for waveguide coupler calculations [25] with MAFIA and CST Microwave Studio™ [26]. The calculation requires two computer program runs to calculate standing wave fields for two different boundary conditions (perfect electric and perfect magnetic walls) at the same reference plane in the transmitting line connected to the cavity. Then one calculates two quantities, Q_1 and Q_2, such that $Q_{ext} = Q_1 + Q_2$ (see detail explanation in [23]).

Asymmetry of the fundamental power coupler (as well as HOM couplers) geometry leads to non-zero transverse electric and magnetic fields on the cavity axis and results in the transverse kick to the bunch passing the coupler. A comprehensive study of this effect can be found in [27]. Because of the finite bunch length different parts of the bunch experience different kicks which in turn generates emittance growth. Let us first explain how one can calculate the transverse kick. We will follow M. Dohlus' approach as it is explained in [28, 29], but will use somewhat different notation. The integrated normalized transverse field strength can be written as

$$v_{\mathrm{t}} = \frac{V_{\mathrm{t}}}{V_{\mathrm{acc}}} = M_1 \cdot v_{\mathrm{in}} + M_2 \cdot v_{\mathrm{out}},$$

where M_1 and M_2 are the coupling constants for the normalized incoming and outgoing waves, v_{in} and v_{out}. The coupling constants can be determined using results from exactly the same two program runs as that needed for the Q_{ext} calculation. One can reconstitute the incoming traveling wave by combining the two standing wave solutions in quadrature with appropriate normalization and then calculate the transverse kick as it is illustrated in Figure 1.

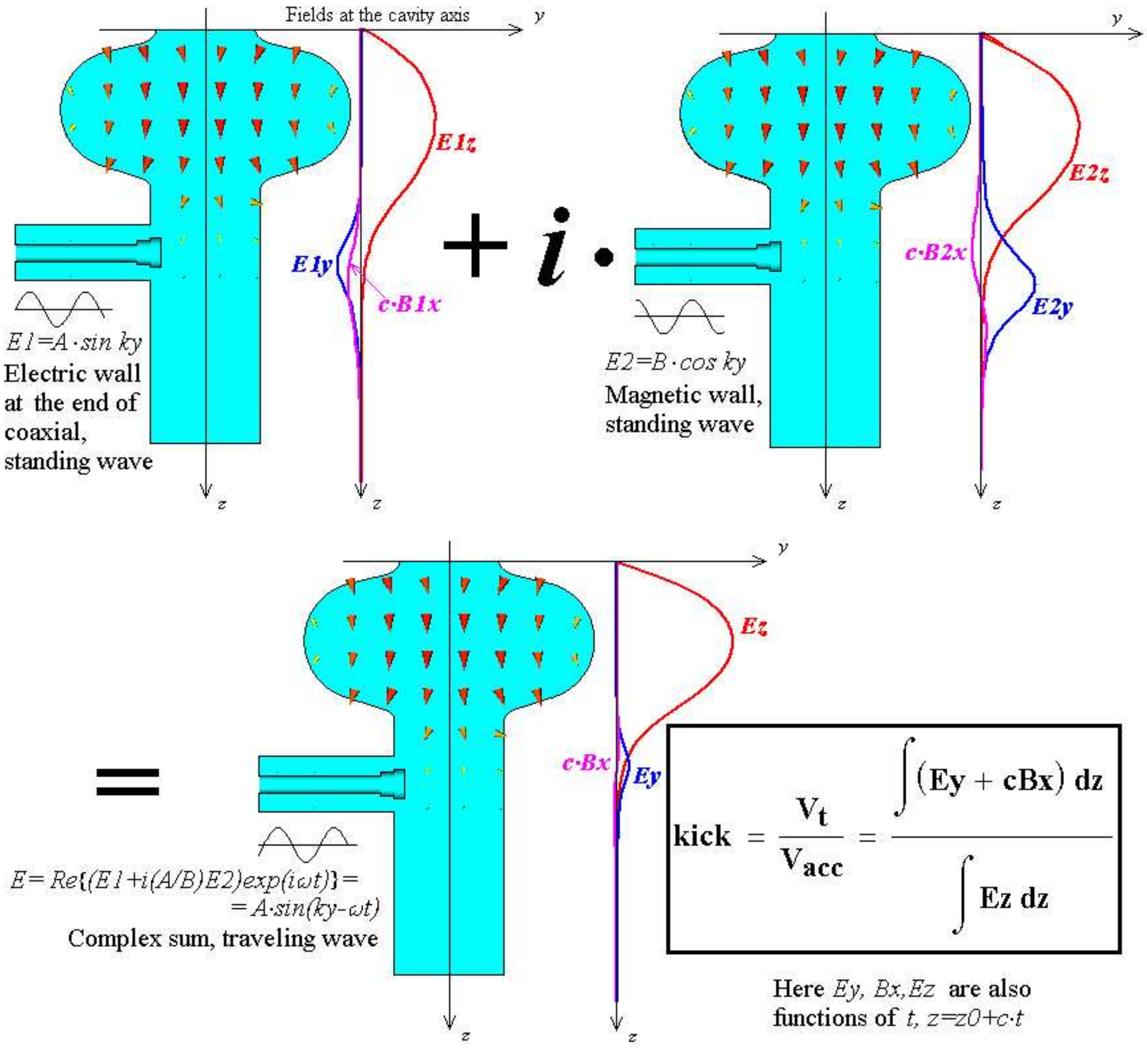

Figure 1: Illustration to the coupler kick calculation.

The first coupling constant is then determined by

$$M_1 = \frac{v_\mathrm{t}}{v_\mathrm{in}}.$$

Similarly one can reconstitute outgoing traveling wave to calculate the second coupling constant. Finally, in the stationary case [29] the incoming and outgoing waves are fully determined by the running conditions (beam current I_b, beam phase relative to maximum acceleration φ_0,accelerating voltage V_acc, operating frequency ω) and the cavity parameters (Q_ext, R/Q, and the cavity detuning $\delta\omega$):

$$v_\mathrm{in} = \frac{I_\mathrm{b}\, R/Q \cdot Q_\mathrm{ext}}{2V_\mathrm{acc}}\left(\cos\varphi_0 + i\sin\varphi_0\right) + \frac{\beta+1}{2\beta}\left(1 + i\tan\psi\right),$$

$$v_\mathrm{out} = -\frac{I_\mathrm{b}\, R/Q \cdot Q_\mathrm{ext}}{2V_\mathrm{acc}}\left(\cos\varphi_0 + i\sin\varphi_0\right) + \frac{\beta+1}{2\beta}\left(\frac{\beta-1}{\beta+1} - i\tan\psi\right),$$

$$\tan\psi = 2Q_\mathrm{L}\,\frac{\delta\omega}{\omega}.$$

Now, knowing the coupling constants and the formulae for the traveling waves, one can easily calculate the transverse kick for any combination of running conditions and the cavity detuning. For a reflection free operation ($v_\mathrm{out} = 0$) it is necessary that

$$\tan\psi = -\frac{I_\mathrm{b}\, R/Q \cdot Q_\mathrm{L}}{V_\mathrm{acc}}\sin\varphi_0\ ,$$

and

$$I_\mathrm{b} = \frac{V_\mathrm{acc}}{R/Q \cdot Q_\mathrm{ext}\cos\varphi_0}\,\frac{\beta-1}{\beta}.$$

The kick received by the center of a passing bunch depends on the relative phase φ_0 between the bunch and the RF voltage:

$$\alpha = \frac{p_\mathrm{t}}{p} = \frac{eV_\mathrm{acc}}{pc}\,\mathrm{Re}\left(v_\mathrm{t} e^{i\varphi_0}\right),$$

where p is the longitudinal momentum, p_t is the transverse momentum due to the RF coupler. This kick can be easily compensated. We are interested here in a kick change along the bunch, from head to tail, which leads to the transverse emittance growth. The normalized transverse emittance growth can be estimated, assuming that before kick $\alpha = 0$ and $d\sigma_\mathrm{t} = 0$, from [30]

$$d\varepsilon_\mathrm{n,t} = d\sigma_{\mathrm{t}'} \cdot \sigma_\mathrm{t} \cdot \gamma\beta,$$

$$d\sigma_{\mathrm{t}'} = \frac{d\sigma_{\mathrm{p_t}}}{p} = \left|\frac{dp_\mathrm{t}}{d\varphi}\right|_{\varphi=\varphi_0} \frac{2\pi\sigma_\mathrm{z}}{\lambda_\mathrm{RF}}\,\frac{1}{p}.$$

Here σ_t and $\sigma_{\mathrm{t}'}$ are the bunch sizes in the transverse plane t, σ_z is the bunch length, λ_RF is the RF wavelength. The derivative of the transverse momentum on phase is

$$\frac{dp_\mathrm{t}}{d\varphi} = \frac{eV_\mathrm{acc}}{c}\,\mathrm{Re}\left(\frac{dv_\mathrm{t}e^{i\varphi}}{d\varphi}\right) = \frac{eV_\mathrm{acc}}{c}\left[-\mathrm{Re}(v_\mathrm{t})\cdot\sin\varphi - \mathrm{Im}(v_\mathrm{t})\cdot\cos\varphi\right].$$

In the end we get

$$d\varepsilon_{\mathrm{n,t}} = \sigma_{\mathrm{t}} \frac{2\pi\sigma_{\mathrm{z}}}{\lambda_{\mathrm{RF}}} \frac{eV_{\mathrm{acc}}}{E_0} \left| \mathrm{Re}(v_{\mathrm{t}}) \cdot \sin\varphi_0 + \mathrm{Im}(v_{\mathrm{t}}) \cdot \cos\varphi_0 \right|$$

(here E_0 = 0.511 MeV is the rest mass energy of electron). This formula, of course, gives only a rough estimate of the emittance growth for a bunch on axis and does not take into account transverse dependence of electromagnetic fields. Computer simulations are necessary for a more precise evaluation of the emittance growth.

There are several possibilities to completely or partially cure transverse kick from the fundamental RF power coupler and associated with it emittance growth. We list several of them below and will discuss some implementations in following sections.

- An azimuthally symmetric coupler
- Two identical couplers opposite each other (a “double-coupler”)
- Symmetrizing stub opposite to an input coupler
- Alternate input power couplers in adjacent cavities
- Using larger beam pipe
- Non-protruding antenna

Our design goal is to allow a maximum emittance growth of no more than 10% total for five superconducting cavities. Then for the injector parameters listed in Table 3 below and for the bunch on crest (φ_0 = 0) we get a requirement for the imaginary part of the coupler kick

$$\left|\mathrm{Im}(v_{\mathrm{t}})\right| \le 1.57 \times 10^{-3}.$$

It turns out that it is possible to satisfy this requirement. For example, a coaxial coupler with quarter wave transformer, larger beam size than that of TESLA structure and non-protruding antenna (see section 4.2) has imaginary part of the kick about two times smaller than this value.

Table 3: ERL injector parameters for the emittance growth calculations.

$\varepsilon_{\mathrm{n,t}}$	=	1	mm·mrad
σ_{t}	=	2	mm
V_{acc}	=	1	MV per cavity
λ_{RF}	=	231	mm
σ_{z}	=	0.6	mm

4. *First ideas for ERL fundamental power couplers*

4.1 Buncher cavity coupler

The normal-conducting buncher cavity will operate at the cavity gap voltage up to 0.2 MV (Table 1). Detuning required for the fast beam turn-on will cause a strong mismatch without beam and therefore the design power should be set to 20 kW in standing wave. To reduce power dissipation in the cavity walls, the buncher cavity shape has to be optimized for maximum shunt impedance – hence there are re-entrant nose cones (Figure 2) and coupling at the cavity equator. An advantage of this kind of coupling is a reduced coupler kick as the coupler is far from the beam axis. We chose a coaxial loop coupler (Figure 3) with a cylindrical window at the waveguide to coaxial line transition (similar to the “warm” window in the TTF3 coupler).

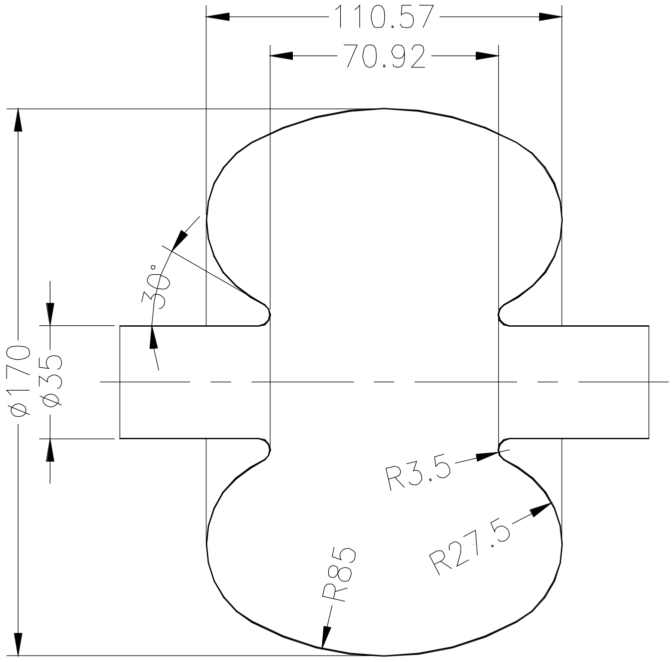

Figure 2: Buncher cavity.

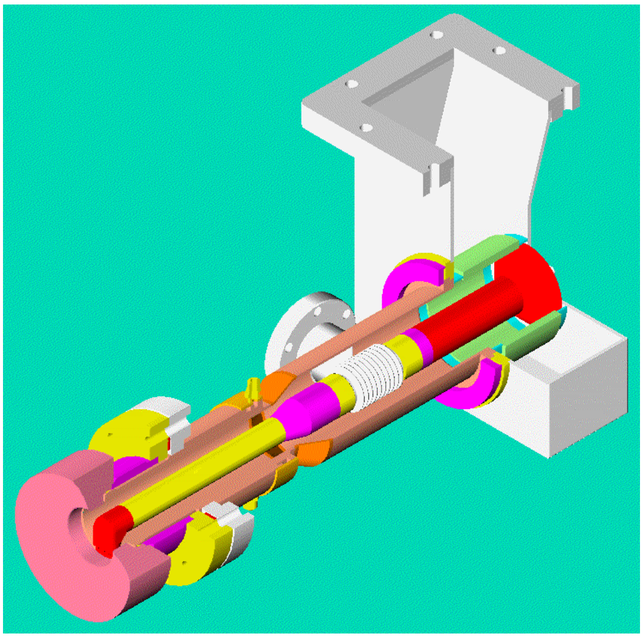

Figure 3: Buncher cavity input coupler.

4.2 Injector cavity coupler

The injector cavity coupler is the most challenging of all ERL fundamental power couplers. The injector cavity will provide 100 kW of RF power to accelerate a beam with an average current up to 100 mA. The coupler should be adjustable to accommodate different beam loading at different injector energies (see Table 1): Q_{ext} ranges from 4.6×10^4 to 4.1×10^5. There are several high average power couplers and windows which have demonstrated the possibility to handle high average power and can serve as design examples in developing the injector cavity coupler. We discuss some of them below. In this section we will only briefly describe our first ideas and results. More details will be presented in the follow-up papers.

A double-coupler at 700 MHz was developed for the APT superconducting cavities [10]. The coupler is coaxial with adjustable coupling and a double RF window (Figure 4). It was tested up to 1 MWCW in traveling mode and up to 850 kWCW in standing mode. Although this coupler design has several desirable features like good pumping speed near the ceramic window and a center conductor cantilevered off of a shorting plate that is easy to cool, its design is very complicated and costly due to high average power need [31].

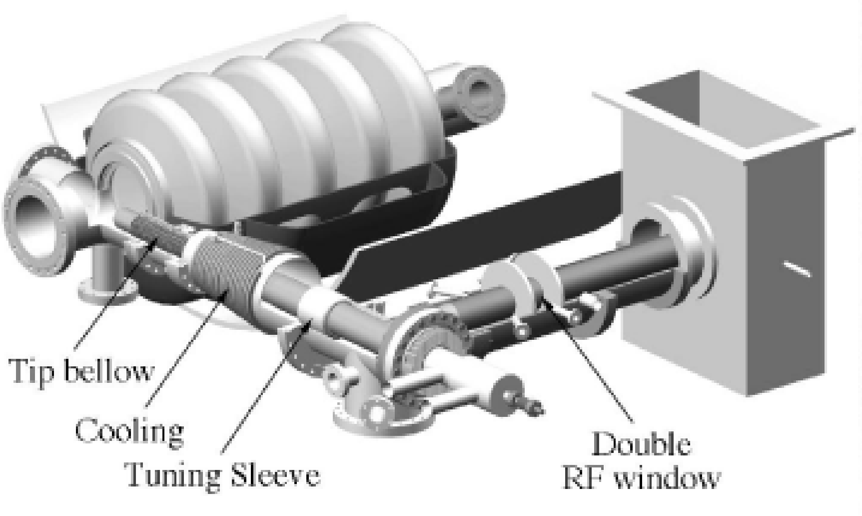

Figure 4: APT cavity with fundamental input coupler [10].

The other interesting design of a 704 MHz 300 kWCW coupler was proposed at Saclay [32]. It employs a coaxial antenna coupler with a waveguide RF window and vacuum waveguide to coaxial line transition. Although this design has fixed coupling, it is not difficult to make it adjustable (Figure 5). The original design considers use of a window similar to that used at Cornell [33]. At least two other windows of different designs (Figure 6) that can be used in such a coupler have been built and tested. A 714 MHz window for the LEDA accelerator was tested up to 800 kWCW [9]. A 1500 MHz CEBAF superconducting cavity window modified for the Jefferson Lab FEL was tested up to 50 kWCW (limited by the available RF power source) with very low temperature rise of the ceramics [12].

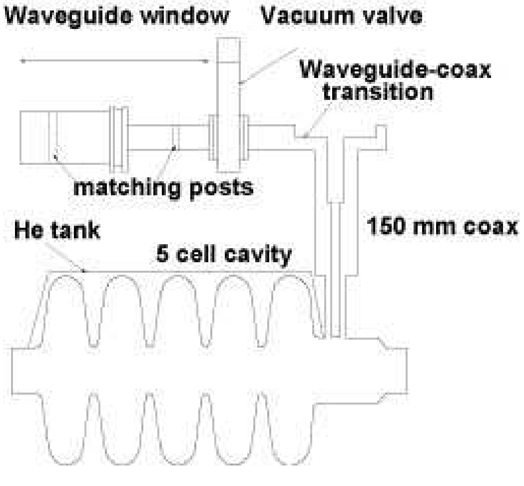

Figure 5: Saclay 704 MHz Power Coupler for a High Intensity Proton Linear Accelerator [32].

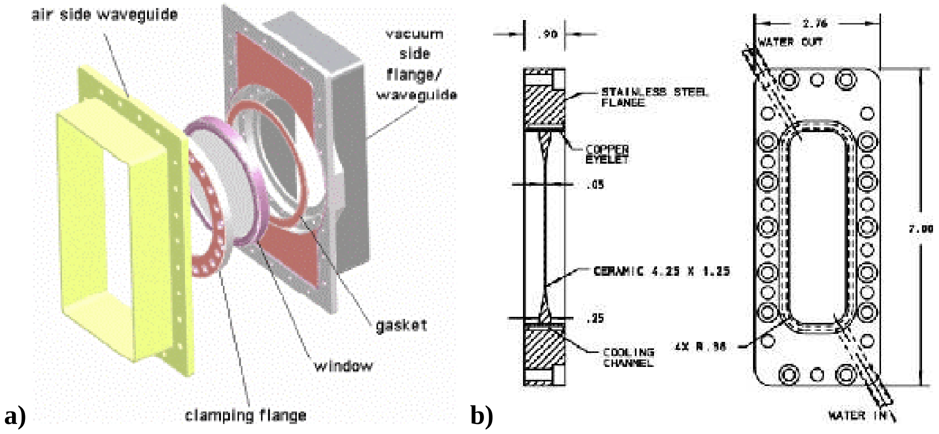

Figure 6: Waveguide windows: a) LEDA window [9]; b) Jefferson Lab FEL window [12].

The major drawback of these coupler designs as well as many others is that windows are located outside cryostats and therefore must be attached after the cryostat assembly. This makes possibility of cavity contamination more likely and makes it more difficult to achieve high gradients. To assure cleaner assembly some couplers (for example, TTF and CEBAF) have cold windows close to the cavity. The second, warm window, is then necessary to protect gas cold surfaces from the contact with air. It also provides additional protection to the superconducting cavities in case of the ceramic leak. Disadvantages of using two windows are: more complicated coupler design and possible gas condensation on the cold ceramics. It is possible, however, to avoid the cold window complication. W.-D. Moeller proposed [34] a concept of TESLA coupler design with only one window: the "cold" window is moved further out to the edge of the cryostat thus becoming warm while still remaining inside so one can assemble it with the cavity in the clean room prior to insertion into the cryostat. To reduce contamination in case of the ceramic leak one can use a Kapton™ barrier similar to the one used on Cornell cryomodules and fill the space between the two windows with clean nitrogen gas.

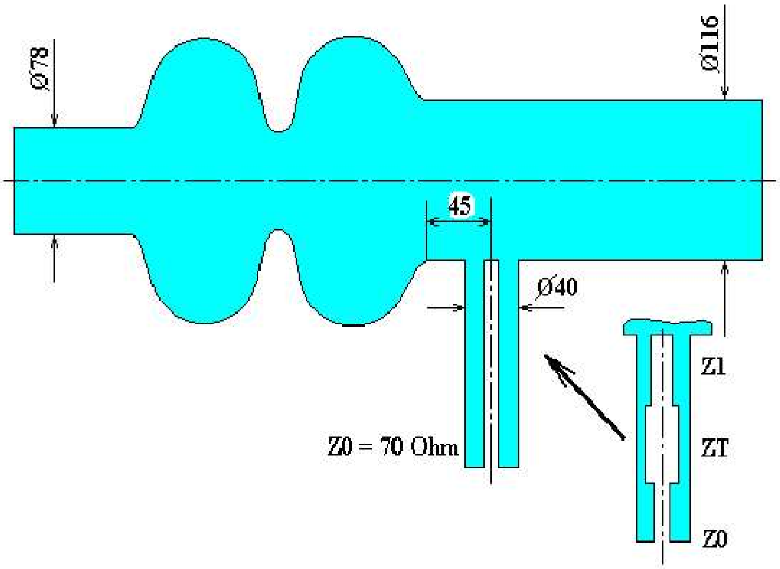

Figure 7: Coaxial coupler with quarter-wave transformer.

Our main goal in designing a fundamental input coupler for the injector cavity is to reach the desired coupling strength with minimal transverse kick to the beam. Because we plan to use TESLA cavities and cryostats in the main linac structure, it was natural to use one of the TESLA designs as a starting point for the injector cavity/coupler/cryostat design. First we took TTF3 coupler dimensions and tried to modify the coupler/cavity interface. The approach here was to enlarge the beam pipe for better coupling while keeping the antenna tip flush with the beam pipe surface, but we could not reach $Q_{\rm ext}$ with a reasonable beam pipe size. To further enhance coupling one can use a quarter-wave transformer (Figure 7). However, there is now standing wave at the transformer location and a possibility of multipacting in the low-impedance ($Z_T \approx 30$ Ohm) part. One can alleviate multipacting problem by increasing the coaxial line diameter from 40 mm to, say, 60 mm, which will also help in average power handling, but an unpleasantness of having a standing wave pattern still remains.

The other very attractive idea that we had briefly explored is a hybrid waveguide-coaxial coupler (Figure 8). This way to couple RF power to a cavity should not create any transverse kick and there should not be any wake fields harmful to beam (if the beam is traveling from left to right on the picture). However, our calculations showed that the presence of the waveguide created a field asymmetry and consequently a transverse kick to the beam. The field symmetry can be improved by elongating the coaxial part to allow higher-order modes (HOMs) generated by the waveguide to coaxial line transition to attenuate better and/or by choosing the design of the transition that generate minimal amount of HOMs. There are also other uncertainties in this proposal that require extensive studies: higher-order mode excitation by the beam, coupling strength tuning, waveguide connection to the cryostat, etc. Though we still like this idea, we abandoned it for the ERL project and decided to use a “simpler” approach of a double-coupler. One clear advantage of the double-coupler is that each of its couplers has to provide two times weaker coupling as a single-coupler and has to transmit twice as less power to the beam. For the first iteration of the double-coupler design we use a 60 mm coaxial line. As far as power handling is concerned, we will follow the advise of B. Dwersteg who in [36] indicated weak points of the TTF couplers and suggested ways to fix them. Careful studies of the coupler alignment tolerances, thermal load estimate and establishing a coupler tune-up procedure are under way and will be reported elsewhere.

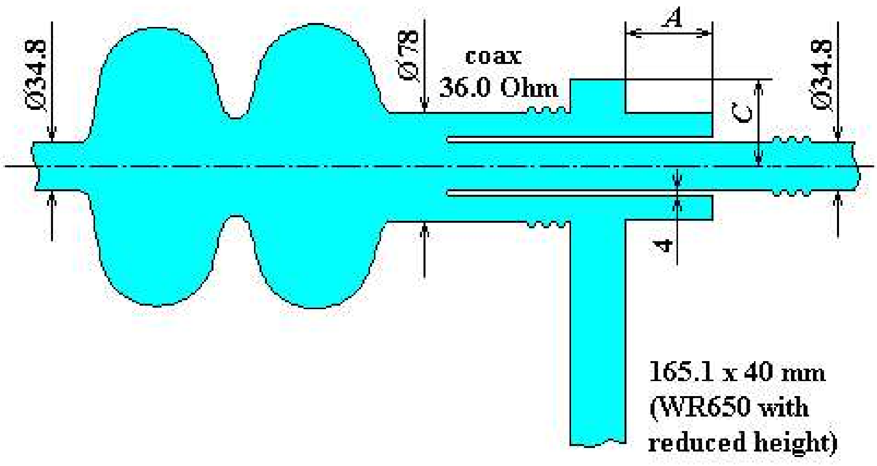

Figure 8: Waveguide-coaxial coupler.

4.3 Linac cavity coupler

As we mentioned above, the linac cavities are 9-cell TESLA cavities, operating at an accelerating gradient of 20 MV/m in CW mode. The coupler of this cavity must be able to withstand forward power of 20 kW with full reflection and provide adjustability of $Q_{\rm ext}$ from 8×10^5 to 4×10^7. Also, in the HPP mode forward power will reach 1.5 MW with 250 μs pulse length. The input power couplers developed for TESLA cavities meet spec for pulsed power. The coupling range is very close to our goal and can easily be extended by making slight modification to the coupler design and adding a 3-stub waveguide transformer. Thus the only parameter that does not meet the spec is average power: the TTF2 coupler was tested up to 4.68 kW average power in traveling wave mode, the TTF3 coupler (Figure 9) is designed for the same average power of 5 kW. Although many TTF couplers have been tested already, the ultimate power limit was never explored and none of the couplers was destroyed during testing or in operation. As part of collaborative effort of several laboratories and industry to develop high CW power couplers at 1300 MHz it was proposed [34] to perform a study of ultimate power limit of the TTF3 coupler (a destruction test).

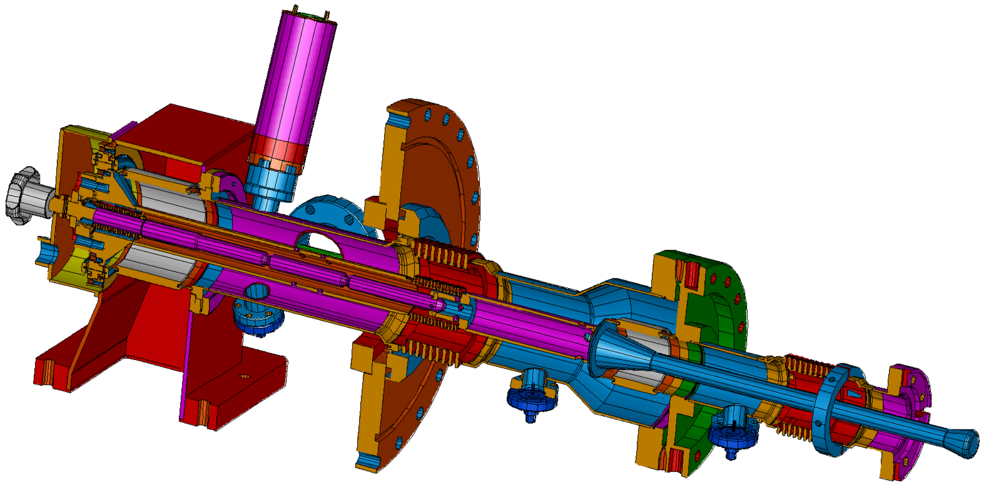

Figure 9: The TTF3 input power coupler [13].

More coupler developments are under way for TESLA [35]. The TTF4 input power coupler is developed for the TESLA 4-cavity superstructure (7-cell cavities). This coupler has a bigger diameter of outer conductor (80 mm versus 40 mm in the cold part and 60 mm in the warm part of the TTF3 coupler) and as a result is believed to be multipactor-free. This coupler should be able to handle average power of about 20 kW [36]. The TTF5 design (for the two 9-cell cavity superstructure) has the outer conductor diameter of 60 mm in both warm and cold parts and is designed for average power of about 10 kW [36]. We intend to adapt one of the TTF coupler designs for our linac cavities, possibly with minor modifications to improve the average power handling. Also, emittance growth will have to be checked with computer simulations.

5. Summary

We considered general requirements and design challenges for the fundamental RF power couplers of the Cornell ERL cavities. Main design challenges are: high average RF power (up to 20 kW SW for buncher and linac, 150 kW TW for injector); very strong coupling (4.6×10^4 for injector); wide range of coupling variability (factor of 9 for the injector and factor of 50 for the linac); minimizing transverse kick to the beam to avoid emittance growth; designing of a multipacting-free (or almost multipacting-free) complex 3D structures. We considered pro and cons of the two major design options – coaxial and waveguide couplers – and concluded that neither of them has clear advantage and that the choice should be dictated by machine/cavity specific requirements and availability of suitable ceramics and an acceptable prototype design. Both waveguide and coaxial designs are used in laboratories around the world, but only few of the couplers are variable. We compiled a list of most relevant designs in Table 2.

We briefly described some calculating tools that we use in assisting fundamental RF coupler development and in greater details discussed evaluating coupler kick to the beam and associated emittance growth. Several possibilities exist to completely or partially cure this phenomenon: an azimuthally symmetric coupler; a double-coupler; symmetrizing stub; alternated input power couplers in adjacent cavities; enlarging the beam pipe; using non-protruding antenna.

Finally, we presented first ideas for the ERL fundamental power couplers: a coaxial loop coupler for the buncher cavity, a TTF-style coupler for the main linac cavities. Several options were considered for the injector cavity coupler: single coaxial coupler with enlarged beam pipe, single coaxial coupler with enlarged beam pipe and transformer, waveguide-coaxial coupler, – before we settled on the double-coupler as a more practical approach. Detailed description of our studies of different coupler geometries will be presented elsewhere.

References

[1] *Study for a proposed Phase I Energy Recovery Linac (ERL) Synchrotron Light Source at Cornell University*, ed. by S. Gruner and M. Tigner, CHESS Technical Memo 01-003 and JLAB-ACT-01-04 (4 July 2001).

[2] S. Belomestnykh and M. Liepe, "RF Parameters and Field Stability Requirements for the Cornell ERL Prototype," to be published as Cornell LEPP ERL Note.

[3] I. Campisi, "Fundamental Power Couplers for Superconducting Cavities," presented at the 10th Workshop on RF Superconductivity, Tsukuba, Japan, 2001.

[4] H. P. Kindermann, M. Stirbet, " The Variable Power Coupler for the LHC Superconducting Cavity," *Proceedings of the 9th Workshop on RF Superconductivity*, Santa Fe, NM, November 1999, pp. 566-569.

[5] M. Neubauer et al., "High-Power Testing of PEP-II RF Cavity Windows," *Proceedings of the 5th European Particle Accelerator Conference*, Sitges, Barcelona, Spain, June 1996, pp. 2059-2061.

[6] P. McIntosh, private communications (May 2002).

[7] S. Belomestnykh and H. Padamsee, "Performance of the CESR Superconducting RF System and Future Plans," presented at the 10th Workshop on RF Superconductivity, Tsukuba, Japan, 2001.

[8] Y. Kijima et al., "Input Coupler of Superconducting Cavity for KEKB," *Proceedings of the 7th European Particle Accelerator Conference*, Vienna, Austria, June 2000, pp. 2040-2042.

[9] R. A. Rimmer et al., "A High-Power L-Band RF Window," *Proceedings of the 2001 Particle Accelerator Conference*, Chicago, IL, June 2001, Vol. 2, pp. 921-923.

[10] E. N. Schmierer et al., "Results of the APT RF Power Coupler Development for Superconducting Linacs," presented at the 10th Workshop on RF Superconductivity, Tsukuba, Japan, 2001.

[11] K. M. Wilson et al., "The Prototype Fundamental Power Coupler for the Spallation Neutron Source Superconducting Cavities: Design and Initial Results," presented at the 10th Workshop on RF Superconductivity, Tsukuba, Japan, 2001.

[12] V. Nguyen et al., "Development of a 50 kW CW L-Band Rectangular Window for Jefferson Lab FEL Cryomodule," *Proceedings of the 1999 Particle Accelerator Conference*, New York, NY, March 1999, Vol. 2, pp. 1459-1461.

[13] W.-D. Moeller, "High Power Coupler for the TESLA Test Facility," *Proceedings of the 9th Workshop on RF Superconductivity*, Santa Fe, NM, November 1999, pp. 577-581.
W.-D. Moeller, private communications (2002).

[14] P. Yla-Oijala, D. Proch, "MultiPac – Multipacting Simulation Package with 2D FEM Field Solver," presented at the 10th, Workshop on RF Superconductivity, Tsukuba, Japan, 2001.

[15] A. V. Grudiev et al., "Simulation of Multipacting in RF Cavities and Periodical Structures," *Proceedings of the 1997 Particle Accelerator Conference*, Vancouver, Canada, June 1997, pp. 2609-2611.

[16] V. Shemelin, "Multipactor Discharge in a Rectangular Waveguide with Regard to Normal and Tangential Velocity Components of Secondary Electrons," Cornell LNS Report SRF 010322-03 (2001).

[17] R. Geng et al., "Multipacting in a Rectangular Waveguide," *Proceedings of the 2001 Particle Accelerator Conference*, Chicago, IL, June 2001, Vol. 2, pp. 1228-1230.

[18] F. Krawczyk, "Status of Multipacting Simulation Capabilities for SCRF Applications," presented at the 10th Workshop on RF Superconductivity, Tsukuba, Japan, 2001.

[19] N. Kroll and D. Yu, "Computer Determination of the External Q and Resonant Frequency of Waveguide Loaded Cavities," *Particle Accelerators*, v. 34, p. 234 (1990).

[20] W. Hartung and E. Haebel, "In Search of Trapped Modes in the Single-Cell Cavity Prototype for CESR-B," *Proceedings of the 1993 Particle Accelerator Conference*, Washington, DC, March 1993, pp. 898-900.

[21] M. Prome, "Conceptual Studies for a High Power Proton Linac," *Proceedings of the LINAC-94 Conference*, Tsukuba, Japan, 1994, p. 146.

[22] P. Balleyguier, "A Straightforward Method for Cavity External Q Computation," *Particle Accelerators*, v. 57, pp. 113-127.

[23] P. Balleyguire, "External Q Studies for APT SC-Cavity Couplers," *Proceedings of the LINAC-2000 Conference*, Monterey, CA, August 2000, pp. 133-135.

[24] D. Li et al., "Calculations of External Coupling to a Single Cell RF Cavity, *Proceedings of the LINAC-98 Conference*, Chicago, IL, August 1998, pp. 977-979.

---

[25] V. Shemelin and S. Belomestnykh, "Calculation of the B-cell Cavity External *Q* with MAFIA and Microwave Studio," Cornell LEPP Report SRF 020620-03 (2002).
[26] CST GmbH, Darmstadt, Germany, http://www.cst.de/.
[27] Zenghai Li, "Beam Dynamics in the CEBAF Superconducting Cavities," PhD Dissertation, the College of William and Mary, VA, March 1995.
[28] M. Dohlus, "Kicks of the input couplers for the TESLA cavities," transparencies from the TESLA Collaboration Meeting, Orsay, April 2000.
[29] M. Dohlus, S. G. Wipf, "Numerical Investigations of Waveguide Input Couplers for the TESLA Superstructure," *Proceedings of the 7th European Particle Accelerator Conference*, Vienna, Austria, June 2000, pp. 2096-2098.
[30] M. Zhang and Ch. Tang, "Beam Dynamic Aspects of the TESLA Power Coupler," *Proceedings of the 1999 Particle Accelerator Conference*, New York, NY, March 1999, pp. 2769-2771.
[31] E. Schmierer et al., "Design of the Spoke Cavity ED&D Input Coupler," presented at the 10th Workshop on RF Superconductivity, Tsukuba, Japan, 2001.
[32] G. Devanz et al., "Preliminary Design of a 704 MHz Power Coupler for a High Intensity Proton Linear Accelerator," *Proceedings of the 7th European Particle Accelerator Conference*, Vienna, Austria, June 2000, pp. 2031-2033.
[33] M. Pisharody et al., "High Power Window Tests on a 500 MHz Planar Waveguide Window for the CESR Upgrade," *Proceedings of the 1995 Particle Accelerator Conference*, Dallas, TX, June 1995, Vol. 3, pp. 1720-1722.
[34] Workshop on 1.3 GHz Couplers for CW Operation at Power Levels between 10 and 100 kW, ACCEL Instruments GmbH, Bergisch Gladbach, Germany, April 9, 2002.
[35] W.-D. Moeller, "Performance of TTF Couplers at Pulsed Operation," presented at the Workshop on 1.3 GHz Couplers for CW Operation at Power Levels between 10 and 100 kW, ACCEL Instruments GmbH, Bergisch Gladbach, Germany, April 9, 2002.
[36] B. Dwersteg, "Couplers for Superconducting Cavities at 1.3 GHz High CW Power," presented at the Workshop on 1.3 GHz Couplers for CW Operation at Power Levels between 10 and 100 kW, ACCEL Instruments GmbH, Bergisch Gladbach, Germany, April 9, 2002.