POWER COUPLER DEVELOPMENTS FOR HIGH INTENSITY LINACS

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Abstract

This paper reviews the RF power coupler developments for high intensity superconducting linacs. Pulsed high intensity proton linacs, continuous wave (CW) heavier ion linacs and energy recovery linacs (ERL) require high power couplers at various frequencies. The paper focuses on developments for which average power is mostly above 30 kW.

PULSED H^+/H^- LINACS

The development of superconducting high intensity pulsed proton linacs with duty cycles in the 1-10% range requires RF couplers to deal with high peak power, since cavities are foreseen to run at high gradient with high peak currents. The projects driving the choice of the coupler parameters are the European Spallation Source ESS [1] and the Superconducting Proton Linac Study (SPL) at CERN [2]. The average power is high enough that RF dissipation aspects have to be dealt with, both for thermal stability when the couplers are integrated on a cavity inside a cryostat, and for integrity of the components such as the ceramic window. The characteristics are more demanding than for the SNS with a nominal peak power for 550 kW, aiming to the 0.9 to 1.2 MW range.

Most couplers developed as of now share common characteristics: they rely on a single coaxial RF window acting as a vacuum barrier at room temperature, also called warm window. The vacuum side of the ceramic is coated with TiN to reduce secondary electron generation in case of multipactor activity in the window and prevent charge build-up. Due to the frequency range they lie in (500 MHz to 1 GHz) a waveguide to coaxial transition ensures the connection to the power RF network rectangular waveguide. The inner conductor can be biased using DC high voltage to alter the electron activity behavior. To prevent potential problems with high power handling, bellows are generally avoided, because they are difficult to cool. Therefore active cooling of the outer conductor connecting to the cavity using He-gas is chosen to minimize the heat leak to the liquid He bath.

The coupler instrumentation is of utmost importance for efficient and safe conditioning, then later for operation. During processing, the RF power increase is generally controlled comparing the pressure in the coupler to a threshold of the order of 10^{-7} mbar. The pressure measurement serves as the primary interlock but is not fast enough to protect the coupler. Fast interlocks are provided by an electron pick up, and an arc detector installed close to the window. A large fraction of couplers developed at various frequencies are similar to KEK design for Tristan SC cavity later successfully adapted for KEK-B coupler which transfers daily the highest average power of 350 kW CW to a beam and operates for more than a decade [3].

Having a single warm window separated from the cavity axis by a typical distance of 0.5 m brings constraints on the design of cryomodules especially if they host more than two cavities, assembled in a clean room to form a string, together with couplers. Indeed the cavity string has to be inserted as a whole in the module vessel. This method is the most successful to avoid contamination of the SRF cavity surface which reduce their performance.

SNS

The 805 MHz couplers for the elliptical cavity section of the SNS designed on the KEK-B basis [4]. The warm window consists in a ceramic disk matched using chokes both on the inner and outer conductor. The cold part of the coupler is a 50 Ω coaxial line 96 mm in outer diameter (OD). It is a double walled stainless steel enclosing a 3 bar He gas heat exchanger, copper plated on the RF inner surface. The doorknob transition to the rectangular waveguide is equipped with a capacitor on which DC biasing is applied when needed.

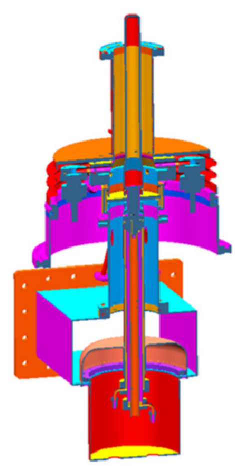


Figure 1: SNS power coupler.

The SNS coupler is the only example in high intensity pulsed linacs for which test and beam operation performance is available with high statistics. All 84 production couplers have been conditioned to 650 kW 1 ms pulses at 60 Hz in travelling wave mode (TW), and 600 kW in standing wave mode (SW) under all phase condition with the same duty cycle. A fraction of couplers were conditioned at Jlab up to 1 MW in TW [5]. In the linac, operation does not require a forward power in excess of 300 kW. It is worth noting that none of the SNS couplers have failed. The current RF power handling capability is sufficient for the SNS power upgrade [6], but the operation revealed that some of the existing couplers were causing a thermal instability in several cavities end groups. The latter are build from reactor grade Nb with low thermal conductivity. One possible improvement is to reduce the thermal load coming from the coupler through a better cooling of the antenna a lower radiation from its tip. The remote control of the He cooling of each outer conductor will be implemented to cure the inhomogeneous flow among couplers fed from the same 5K gas source [7].

J-PARC

Although the development of the SRF modules of the J-PARC linac has been already completed, it must be mentioned since its 972 MHz couplers are derived from the KEK-B design and exceeded their design specification of 300 kW 3ms 25 Hz, being tested up to 370 kW at this duty cycle, both in TW and SW mode. A high peak power test was conducted using 0.6 ms pulses up to 2.2 MW in TW [8].

CEA-Saclay Developments

CEA-Saclay has developed a 704 MHz coupler [9] based on KEK-B coaxial window design in the framework of EU R&D programs for future proton injectors at CERN and SPL. The outer conductor connecting the window to the cavity is a double walled stainless steel cylinder, 100 mm in diameter, incorporating gaseous He cooling channels. It has been copper coated at CERN using magnetron sputtering. A doorknob transition ensures the connection between the air side of the window and the WR1150 waveguide network (Fig. 2). Biasing the inner conductor is possible but has not been used during tests.

This coupler was originally meant to run at 250 kW peak power with a 10% duty cycle, but since the RF design permits a much higher power handling, the cooling scheme was designed accordingly, aiming at 1 MW peak power, 10% duty cycle. Two separate cooling circuits are built in the coupler, one for the whole inner conductor, one at the periphery of the ceramic disk. The inner channel cools the antenna tip, the inner part of the ceramic, and the air part of the coaxial line in that order. Water cooling has been preferred upon forced air since or conduction cooling it is able to limit the temperature increase at the antenna tip to 1 K in fully reflected conditions even at the maximum average power. This minimizes the radiative heat transfer to the cavity.

One pair of couplers has been built, conditioned up to 1.2 MW 10% duty cycle on the room temperature test stand in TW, 1 MW in SW [10]. One of the coupler has been assembled on a 5-cell beta 0.47 cavity and operated in the horizontal test cryostat Cryholab at 1.8 K. The cavity can be driven on tune in pulsed mode up to 45 kW forward power, and 180 kW during the filling time. To test the coupler at a higher power, the cavity was detuned with respect to the RF frequency. In this case, the power is fully reflected during the whole RF pulse. A maximum forward power of 1 MW was reached using 2 ms pulses repeated at 50 Hz. This regime was sustained for several hours keeping the coupler and cavity in thermally stable [11]. Despite not having been specifically designed for this use, the couplers have been conditioned and operated in horizontal position.

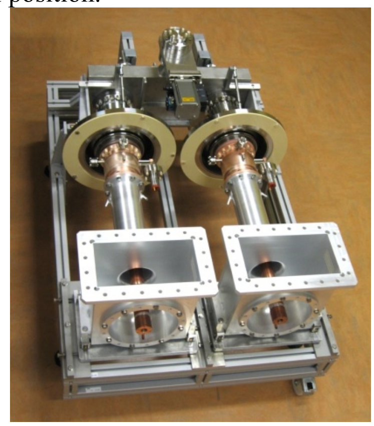
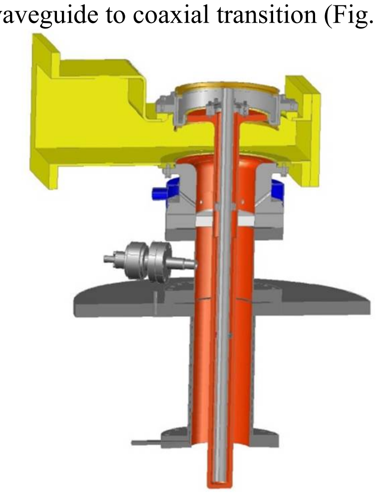


Figure 2: CEA-Saclay 704.4 MHz coupler pair.

CERN Developments

In the framework of the SPL study, other designs are pursued at CERN based on the proven brazing and construction technology developed in-house [12]. The first uses a ceramic disk window of the same type as used on SPS couplers. The RF matching is obtained using the WR1150 waveguide to coaxial transition (Fig. 3).



Figurre 3: SPS type disk window design for SPL at CERN.

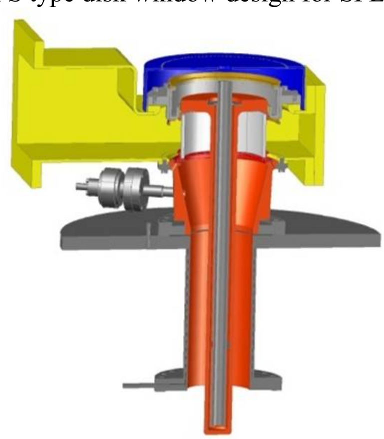


Figure 4: LHC type window coupler for SPL.

The other design studied at CERN is based on a cylindrical window and uses the brazing technology and mechanical design developed for LHC. The window is located in the waveguide to coaxial transition and combined with a step in the rectangular guide to achieve the RF matching (Fig. 4). For both design the antenna and window are air cooled. Prototypes for each model are being fabricated at CERN, to be tested with high power at Saclay in 2011.

HINS at FNAL

Part of the development of a 325 MHz spoke resonator cryomodules for the High Intensity Neutrino Source (HINS) H^- linac programme [13] is the prototyping and test of power couplers. This coaxial coupler differs from the ones described earlier. It is designed to transmit a lower average power and this permits the use of a cold disk window and bellows on the outer conductor on the cavity side. A second window is at room temperature and the connection to the power RF source employs standard coaxial lines. One pair of prototypes has been conditioned up to 700 kW with 3 ms pulses at 2 Hz [14].

CW ION LINACS

High intensity continuous proton or deuteron linacs are less demanding in terms of maximum power. Most of the corresponding couplers share the RF design chosen for the couplers described above, single window and transition to RF network allowing the biasing of the antenna and more importantly the cooling of the antenna. The APT coupler developed in the late 90's departed from those generally encountered characteristics [15], being a two-window coupler first specified for 210 kW CW RF power at 700 MHz. Prototypes built with both fixed coupling and variable coupling have been tested up to 1 MW CW on a room temperature test bench in TW and 850 kW in SW [16].

FNAL Project-X

After departing from a pulsed linac to a CW machine with 1 mA beam current, project-X ICD-2 is not strictly spekaing a high intensity linac [17], but the coupler developments recently started are closely related to other FPCs presented in this paper. For the different sections and options of the linac, couplers at 325 MHz for spoke resonators, 650 MHz and 1.3 GHz for elliptical multicell cavities are needed. At the more advanced stage of design is the 30 kW CW 1.3 GHz coupler for which a very simple layout is put forward using a single disk window at room temperature. It is compatible with a standard ILC type module with a claimed low manufacturing cost [17].

IPN-Orsay Developments

The proton linac application which requires a continuous beam intensity of several tens of mA is Accelerator Driven System (ADS). The activity in EU is focused on demonstrating the concept of a reliable CW proton linac around the Myrrha, EU programs Eurotrans. The design of the 704 MHz 150 kW CW coupler for elliptical multicell cavities is very similar to SNS and Saclay couplers. The main difference lies in the diameter of the coaxial line on the cavity side which is 80 mm. The cooling of the cold outer conductor relies on a supercritical He (3 bar, 6K) counter flow heat exchanger [18]. The coupler prototypes have been build and are ready for conditioning with a 80kW IOT amplifier.

The coupler development at IPN-Orsay also focuses on 352 MHz couplers for spoke resonators in the framework of Eurisol [19]. The spoke coupler is a single disk matched window design installed on a coaxial 3" 1/8 50 Ω line, capable of transmitting 20 kW (Fig. 5). It is connected to a coaxial transmission line on the emitter side.

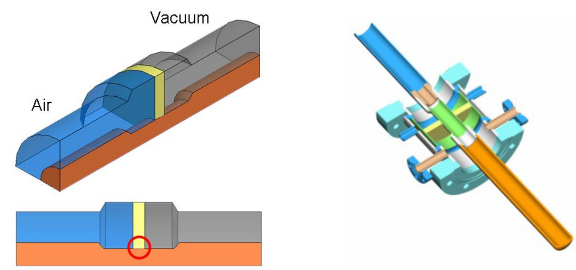


Figure 5: Geometry of the IPN Orsay 352 MHz power coupler.

Two prototypes have been built and conditioned in TW mode up to 10 kW. A test in vertical cryostat has been carried out on the spoke resonator and reached 5 kW.

IFMIF-EVEDA

The higher average power requirements of the IFMIF 125 mA deuteron accelerator for material irradiation are driving the design of the 175 MHz 200 kW CW power coupler for the SC half-wave resonators (HWR). In the EVEDA phase the power needs are reduced to 70 kW, but the couplers have to follow the ultimate specifications of IFMIF and be tested at 200 kW in TW [20].

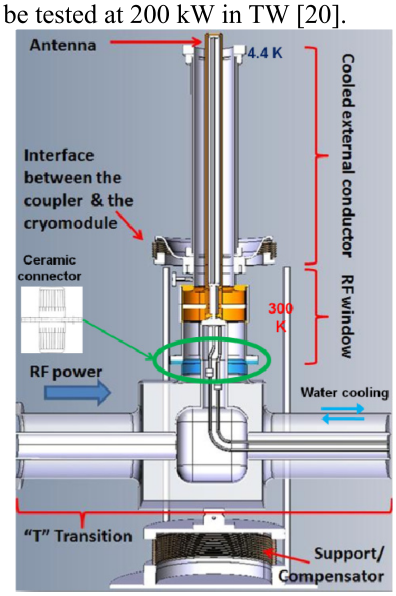


Figure 6 : The IFMIF coupler layout.

The single disk window is located outside the cryomodule in the larger diameter 6” 1/8 coaxial line. It is matched using steps on the inner and outer diameter of the line. A specific “T” transition ensures the connection between the window and the coaxial power network. The third branch of the T is equipped with a short circuit which serves as the insertion path for the antenna and window water cooling circuit (Fig. 6). The cooling of the coaxial outer conductor connected to the cavity is derived from the 704 MHz Saclay coupler described before. The first pair of prototype is currently being fabricated in industry.

ENERGY RECOVERY LINACS

Design constraints for SRF ERL accelerating systems are different from ion linacs. Beam brightness preservation along the accelerator prevents the use of a single FPC per cavity, but a pair of them symmetrically arranged is used in a systematic way, in order to preserve the EM field symmetry. The higher power requirements concern the injector module which has to accelerate the full beam intensity of the order of 100 mA, without the possibility to resort to the energy recovery scheme, therefore with low loaded Q cavities.

Cornell ERL

The development of the 1.3 GHz Cornell ERL was one of the first attempt to start from the TESLA TTF technology to push it towards high power CW operation. The power couplers are derived from the TTF-III couplers [21] designed for 3.2 kW average power to enable CW operation at 50 kW. They retain the concept of combining two cylindrical windows, one at 80 K the other in the coaxial to waveguide transition (Fig. 7). However for better power handling, the impedance of the cold coaxial part is raised from 50 to 60 Ω, and the outer conductor enlarged to 62 mm in diameter. The cold window was also enlarged in diameter. The antenna length is adjustable in a 15 mm range.

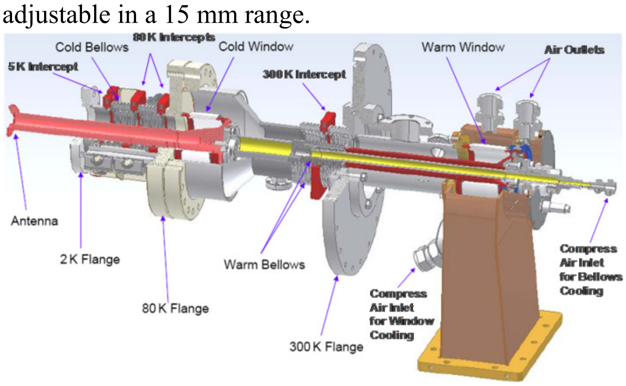


Figure 7: Schematic view of the Cornell ERL injector coupler.

The cooling has also gone through major modification in two phases. The first prototypes used bellows in the cold part with 5 K and 80 K thermal intercepts to minimize thermal leaks on the cavity and air cooling in the warm window and bellows [22]. They showed good RF performance but unexpected temperature rise was observed in the warm part. A second series of coupler was built with improved cooling of the warm part.

The couplers were tested on a LN_2 cooled cryostat enclosing the coupling cavity up to 61 kW in CW and 85 kW in pulsed mode [23]. The injector cryomodule with its 5 two-cell cavities has been tested with beam [24].

The FPCs of the main linac cryomodule also derive from the TTF-III architecture but use a different approach than for the injector cryomodule since they have to sustain 5 kW CW in full reflection. The bellows are located around the cold window to provide mechanical compliance, therefore the outer conductor connected to the cavity is much simpler [25].

Daresbury International Cryomodule Collaboration

The ALICE ERL cryomodule is being upgraded, and the power couplers are part of the elements which are replaced. The new couplers are modified Cornell ERL injector FPCs suitable for the required power of 30 kW CW [26]. The coupler length modification for the ALICE module assembly reduces the number of bellows and number of thermal intercepts on the cold part. The couplers conditioning is underway in pulsed and CW mode. A power of 5 kW is already exceeded in CW, and unexpected heating of the warm part is being investigated [27].

KEK CERL

The Compact ERL [28] injector module hosts 2-cells 1.3 GHz cavities driven by a pair of coaxial couplers carrying each 170 kW. The window is of the Tristan and KEK-B type (Fig. 8). The window and antenna are cooled by water, the outer conductor is cooled with 5 and 80 K intercepts but no bellows are used. The expected static heat leak at 2 K is 2 W per coupler, compared to 0.2 W for the Cornell design employing bellows in addition to the thermal intercepts.

Figure 8: The disk window of CERL coupler.

Prototypes have been conditioned up to 100 kW CW forward power in TW, and it is planned to aim at the maximum power available from the 300 kW klystron [29].

BNL

The BNL 703.75 MHz 0.5 A ERL is one of the most demanding for power couplers. Also it is the only ERL project using a different frequency than 1.3 GHz to overcome beam breakup issues. The superconducting RF gun generating the beam must be operated at high gradient to produce a high brilliance beam. The power transferred to the beam is 1 MW CW using two FPC rated at 500 kW, however the couplers have been designed for 1 MW CW. They are inspired from the SNS design, with a higher cooling capability. The antenna, window, air-side outer conductor and doorknob transition are water cooled. The prototypes are being prepared for their conditioning at BNL.

AKNOWLEDGMENTS

The author thanks the collegues who helped by providing data: Sang-Ho Kim, Mircea Stirbet, Eric Montesinos, Vyacheslav Yakovlev, Emanuel Rampnoux, Hassen Jenhanni, Sergey Belomestnykh, Joseph Orrett, Eiji Kako and Ilan Ben-Zvi.

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