HIGH POWER COUPLERS FOR LINEAR ACCELERATORS

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Abstract

High power input couplers are a fundamental component of linear accelerating structures and, in particular, of superconducting structures. In fact, in this case, the power coupler's function is not only power transfer and vacuum separation but also includes the thermal transition and the integrity of the cavity cleanliness.

A lot of activity has been recently carried out in the framework of different project on both CW (KEK and Cornell) and pulsed (SNS and TTF) power couplers. Special attention has been devoted during the design phase to take care of the thermo-mechanical and electromagnetic performances, the multipacting thresholds, the preparation procedures and, last but not least, the cost which in the case of high energy linacs is a critical issue. In this framework not only the design phase but also the conditioning of the couplers has stimulated different studies.

Partial reviews of the existing designs and of the couplers characteristics will be presented taking into account the different challenges.

INTRODUCTION

The use of linear accelerators has been revaluated in the last decade in many different fields. The high energy physics community has recognised that a future lepton collider for precision studies will be a linear accelerator (ILC / CLIC); FEL linacs (in X, VUV and IR band) are being developed in different regions following either the traditional or the energy recovery configuration while neutron spallation sources, nuclear waste transmutation and tritium production are the main topics covered by the nuclear and material science communities. One point is shared between these very different projects: the need for high power to increase both the accelerating gradient of the linacs cavities (pulsed applications) and the beam current (CW applications). In this context a fundamental role has been played by the rapid advance of the superconducting (SC) cavity technology and its associated fields. The important effort on SC technology made during the last two decades has, in fact, driven the cavity performances near to the theoretical field limits. To attain these experimental results, the increase in accelerating gradients has to be supported by a similar enhancement of the auxiliary components performances, in particular of the interfaces.

Among them there have been different R&D programs on power couplers allowing the study, design, realisation and validation of different models.

As a baseline definition we can describe a coupler as a device that allows the transfer of power from the source to the cavity. In reality the couplers are one of the most critical components as they provide the interface between the cavity and the "external world". If, for example, we take into account the SC linac cavities, this implies ultrahigh vacuum (from environment to the machine pressure) and good thermal transition (from ~300K to 2K). Moreover the coupler must not limit the cavity performances. This implies that the coupler part integrated in the cavity has to respect all the tight cleanliness constraints imposed on SC cavities. In this context not only the design and construction, but also the preparation, mounting and pre-conditioning phases play a fundamental role for a successful operation of a coupler in a linear accelerator.

Long linacs projects (ILC for example), with a large number of cavities, need production, conditioning and installation of a large number of couplers. This requirement introduces the problem of the reduction of mass production costs as a real subject of dedicated R&D.

This paper will attempt to give an overview of the designs, models, technical solutions and problems associated with power couplers and of some of the projects concerning the above-mentioned activities. Applications to linacs will also be illustrated.

Being a review paper and owing to the wideness of the subject only few examples, chosen among the most meaningful, will be possible. Other excellent and extensive overviews on power couplers activities can be found in ref. [1],[2],[3].

POWER COUPLERS DESIGN

The perfect power coupler does not exist! Different design and technical solutions are usually taken into account depending on the required performances. Usually these are the result of a complex multi-parameter optimisation process. To simplify this process, first of all it is necessary to take into account the power coupler basic functions:

- RF - transferring of the power from the klystron to the cavity. At present very high power level are attained in the test stands (more than 2 MW pulsed and ~ 1MW CW)
- RF - matching of the source impedance with the cavity one (allowing flexibility) avoiding power waste by power reflection or by additive dissipation.
- Vacuum Science - separating the source vacuum from the cavity vacuum respecting the constraints given by both the pressure transition and the SC cavity cleanliness (remember: the coupler must not limit the cavity performances!). The transition is

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guaranteed by a ceramic window whose design minimises the internal power dissipation. In SC cavities, to prevent vacuum damages from affecting the cavity itself, the two-window solution is sometimes preferred.

- Thermal Engineering– acting as a thermal transition from the ambient to the cavity temperature. Limiting the RF thermal dissipation (dynamic load) and the consequent formation of "hot spots" and, as far as the SC technology is concerned, minimising the static load to reduce the wasted cryo-power.
- Beam Dynamics - minimising the effect on the beam dynamics (emittance dilution in sources and transverse kick in high energy linacs).
- Cost – in the framework of long linac and high numbers of cavities projects (XFEL, ILC etc) the financial part is a major issue. It is decisive also to simplify the coupler design to decrease the cost of the series production to a reasonable level.

How determinant each of these functions is in the design of a specific coupler is mainly defined by the choice of technology (warm or SC cavity) and of the beam characteristics (pulsed or CW mode, high accelerating gradients or high beam current, emittance requirements). Once the constraints imposed by these parameters are defined it is easier to choose the right design and techniques.

RF Design: Fields, Impedances, Coupling and Multipacting

The electromagnetic design optimisation is the most important step. The requirements in power, CW or pulsed, and in coupling, not only determine the coupler electromagnetic design, but they also have important repercussions on the choice of the materials and on the thermal design. Electromagnetic simulation codes providing the scattering matrix, such as HFSS® and Microwave studio®, are usually utilised.

There are two main options of couplers designs, the coaxial and the waveguide. The former, widely adopted in SC linacs, is more flexible as far as its dimensions are concerned (important at low frequencies), it can be easily adjusted varying the antenna penetration and usually has a smaller heat leak. The latter has a simpler design and better vacuum performances. At present waveguide power couplers are used quite exclusively in the very low energy part (sources, RF guns).

The electromagnetic design must be carefully assessed since the thermal and the multipacting behaviour also depends on it.

Ceramic windows are a critical design element: special attention must be paid to the reduction of the field on the ceramic window to avoid high absorption (= heating). Moreover, the ceramic has a high Secondary Emission Yield (SEY) that stimulates the mutlipacting activity. The choice of the window material and consequently of their dielectric constant is also critical for the impedance matching. This can be improved by additive elements (like chokes) at the ceramic window location.

Matching is very important to avoid reflected waves that could damage the klystron and standing waves that could result in strong temperature increase and high field electronic current emission. Usually coaxial couplers are designed as 50 Ohm lines both on the source and on the cavity side [4]. Other schemes, like a transition from 50 to 70 Ohm [2], can be applied. In the design phase the mismatching during the pulse transient has to be considered too. In fact, as the system is adjusted to take into account the beam loading, the cavity matching is not optimised during the pulse transient (with no beam). This creates SW patterns with higher electric fields that have to be evaluated. Furthermore the presence of the Lorentz force detuning shifts the SW patterns and the high field location.

The impedance matching is achieved not only by means of a careful geometrical design and selection of materials, but also by taking care of the coupler integration into the accelerating cavity. For this reason it is preferable to have the possibility to adjust the external Q factor (Qext) of the cavity by sliding the antenna (but considering the consequent resonant frequency shift of the system). This task implies a complex mechanical design especially for SC structures (e.g. using additive bellows on the antenna). Qext values can typically vary from 10^5 to 10^7 and adjustment ranges are typically of one order of magnitude. Different methods have been tested to evaluate the Qext and a good review can be found in [5].

The transition from the waveguide to the coaxial configuration is usually a doorknob design whose geometrical dimensions are optimised to reduce the return and insertion losses. A more complex design envisages the coaxial transition in the beam line to reduce the transverse kick [6]. This implies a minimisation of the H_{11} mode at the waveguide-coaxial transition to reduce field asymmetries.

A good RF contact must be guaranteed in the vacuum port reducing the gap at the flanges by using special gasket [7] if necessary, and in coating of the ceramic windows.

Increased electronic activity can suddenly be amplified at a given power threshold by a resonant avalanche phenomenon called multipactor. Multipacting electrons can strongly affect the electromagnetic design since the low order power thresholds must be carefully assessed to avoid sparks and coupler damage already during the conditioning process. This can be possible in simple structures, but very difficult in complex geometries like the bellows where the multipacting activity can be strong. The improved reliability of simulation codes [8, 9] recently extended to 3D geometry [10] allows corrections during the design phase varying the external diameter D, the frequency f or the impedance Z since the multipactor threshold varies following a $(f\ D)^4$ or a $Z\ D^4$ laws. Furthermore, it is important to stress that, compared to others RF structures, multipacting is strongly enhanced in couplers by the presence of the ceramic windows that usually present a high SEY (that for example for Alumina is ~ 8) and of bellows with very high field zones.

In certain ranges multipacting remedies do exist. Shifting of the resonant condition can be achieved by applying a bias on the central antenna in the coaxial couplers. In this case special attention has to be devoted to the antenna isolation and to the feedthrough. Fields can be extremely high in this zone raising the possibility of arcing and sparks. The bias polarity is important since it can in one sense suppress and in the other sense enhance the multipacting activity. In the waveguide option the same effect is obtained by applying a magnetic field. Concerning the ceramic emission, a coating with a low SEY material (usually Ti or TiN - SEY ~ 1) is mandatory.

Strong electric fields associated to the particle beam can also be responsible for field emission, electronic current increase and possibly for multipactor. A careful design will locate the windows away from the beam line of sight [11].

Thermal Design

The first step for the thermal design of a power coupler is evidently the correct choice of materials. This has to take into account not only the thermal dissipation, but one must choose also the cost of the system and so usually standard materials (austenitic Stainless Steel, Cu OFHC, Al_2O_3) and standard sizes for mechanical components.

For a SC system it is evident that the design is more complex. Stainless steel being a bad thermal conductor (~ 1W m^{-1} K^{-1} @ 10K), a copper plating of a few skin depths is imposed to reduce the Joule losses. Nevertheless, this thickness must be optimised since, if on the one hand it is important to evacuate the localised heating due to the dynamic losses (e.g. in bellows), on the other hand it is necessary to reduce the static loss in the cryostat and therefore the thermal flux from the environment.

The bellows (again!) play a very important role in this process of optimisation [12]. Their principal functions are to allow the sliding antenna Qext adjustment and an easier compensation of the thermal stresses during the cool down. But owing to their geometry they are also very good thermal resistors and a uniform and controlled copper plating is extremely difficult, if not impossible. All these considerations usually lead to many simulations with finite elements codes like ANSYS® or MAFIA®. Typical values for copper plating thickness are around several microns.

For CW couplers the high requirements in average power are demanding for the design of a cooling system. Usually the central antenna and the bellows can be water, gas or air cooled. Attention must also be paid to the thermal characteristics of the gaskets if the flange region proves to be a “hot zone”. For certain materials (like Aluminium for example) it is possible to have vacuum leaks starting from ~ 150 degrees. In this case copper gaskets are recommended.

Vacuum and Surface Aspects

Vacuum and surface technologies in power couplers play a very important role in the multipactor suppression and in the conditioning procedure. The study of the materials characteristics is fundamental: OFHC copper for plating is suitable and Al_2O_3 ceramic windows are frequently used. An extensive study on Alumina behaviour and on the impact on multipactor can be found in ref[13]. The use of ultra-pure alumina windows (99.5%), the avoidance of a MgO sintering binder and a high temperature and pressure process (HIP) to remove voids are suggested. Also if good results concerning the multipacting were obtained without TiN coating, this procedure is always recommended to avoid electron multiplication in the RF pulse transient.

The TiN coating of the window is actually a standard procedure in high power couplers ceramic windows since the SEY is strongly reduced by Titanium while the nitrification is often used to reduce the effect of oxidation. The coating thickness is some tents of nm and it is optimised to avoid power reflection. At present two different technologies are employed for coating: the evaporation [14] and magnetron sputtering [15].

Oil free pumping groups and hydrocarbon-free out-gassing elements (like Viton gaskets) are mandatory. If in situ baking is required it is recommended to use silicon wires instead of glass wool insulation stripes thus avoiding the presence of contaminating flakes. Also the cleaning, the mounting and the preparation procedure to assure the cleanliness of the different coupler parts are important for vacuum requirements. For this end special procedures are applied which will be illustrated later.

Beam Consideration. RF-GUN and Linacs Sources

The importance of the SW patterns due to the beam loading detuning has already been mentioned.

Another important parameter associated with the particle beam in the coupler design is the transverse kick. In fact, the coupler insertion being asymmetric with respect to the cavity axis, a dipolar electric field component appears to have the effect of a beam kick in the transverse plane. This can be evaluated by integrating the equation of motion taking into account the simulated electromagnetic field on the beam axis [16]. The remedy is to compensate this effect by alternating the coupler insertion on both sides of the beam propagation axis and, in the design phase, reducing the ratio between the coupler and the cavity diameter.

A peculiarity of linear accelerators is that, if we take into account a low energy beam like in the RF-GUN injector sources, the field asymmetry is responsible also for emittance dilution thus limiting the performance. An extensive paper about the coupler effect on sources can be found in [17]. Being normal conducting and therefore without heat leak problems the RF-GUN couplers are usually of the waveguide type. Emittance increase is reduced imposing a symmetric power distribution by a two “face to face” coupler configuration. Matching is usually done by a sliding short. An on-axis coaxial design has also been used for the Darmstadt Linac [6] and for the PITZ gun [18] with good results.

Industrial Studies for Very Long Linacs

The next generation of FEL x ray sources and the future project of a linear collider are examples of linac projects in which the mass production of accelerating cavities is determinant. In this case an industrialisation study of the coupler production is a very important task. At present a study has been launched on the XFEL project at DESY in collaboration with LAL-Orsay involving three different high technology industries. The original TTFIII coupler design has been re-analysed and modified to attain a significant cost reduction [19].

The review of the existing design entailed the relaxing of unessential tight tolerances, the minimisation of the number of assembly parts, the reduction of welding etc. The transfer to industry of TiN coating technology is also foreseen. The result of the study is supposed to give a full industrial plan for the production of 1000 couplers with the associated cost and risk analysis.

INTEGRATION IN SC STRUCTURES

Procedure for Cavity Assembly and Conditioning

Integration of a power coupler in a SC cavity linac is a major issue since the coupler has to guarantee that it will not affect the cavity performance. A detailed example is the description of the cleaning and assembly procedures for TTFIII couplers summarised hereafter [20].

Some of the cavity cleaning and preparation procedures, working in a class-10 clean room, are applied. An ultrasonic cleaning using a detergent is first performed. Usually detergent has hydrocarbons so it is necessary to rinse the couplers parts with ultra-pure water (~18 MOhm). This also ensures the removal of dust micro-particles. A continuous water resistivity check during the rinsing ensures that the chemical products are effectively washed out. Pure ionised nitrogen drying, blowing on a particle counter, also ensures the final removal of micro-particles. After these checks, the coupler can be mounted. Sometimes a vacuum oven is utilised to have a pre-baking before the clean room assembly. Mounting on the conditioning test bench is performed under laminar flow.

The exposure of the surfaces to the high power pulses is a gradual process called conditioning. The power is slowly ramped to the full power and pulse length while imposing different interlock thresholds applied to vacuum and electronic current diagnostics. This prevents rapid increase of the electronic activity that could damage the coupler. This process can be very time consuming (more than 80 hours per coupler pair) and expensive depending on different factors. Usually special test stands are utilised where couplers are mounted in pairs. These facilities are also used for R&D whose goal is to reduce the conditioning time as much as possible. To reach this goal an in-depth study of the conditioning procedures, constraints and parameters must be performed. Good results allow a conditioning time lower than 20 hours per pair [4][21][22].

After the conditioning the couplers are stored and mounted on a cavity where an additional in-situ baking can be performed. It is important that all these procedures allow for a rapid re-conditioning of the couplers once installed and for a full cavity performances utilisation. Excellent results were obtained on the TTFIII coupler. Mounted and tested on cavities on the test cryostat CHECHIA, the couplers were re-conditioned in less than 20 hours after opening in air, and allowed cavity gradient of the order of 30-35 MV/m.

SOME EXAMPLES OF POWER COUPLERS FOR LINACS : RECENT RESULTS AND ACTIVITIES

Some examples of different power couplers designs, that have already been illustrated in the previous text, and of their performances may give a better general view of this technology field.

CW couplers are usually used in very high beam current linacs. At LANL the APT project is intended to deliver a 100mA beam at 700MHz [11]. For this a 210 kW CW power transmission is required. A special design for coaxial couplers with central antenna gaseous cooling made it possible to obtain the impressive result of 1MW TW on a test stand.

Apart from proton machine also the ERL linacs require to drive high currents. For the Cornell ERL injector (100mA beam at 1.3 GHz) a coaxial coupler for SC cavities delivering 75kW CW has been developed [23]. At Daresbury the 4GLS project requires a ERL of 100mA at 1.3 GHz. Different couplers prototypes are being developed for the injector (50-100 kW CW), for a superconducting RF GUN (250-500 kW CW) and for the SC linac (max 20 kW CW) [24] .

For pulsed couplers the average power is not the central issue. A very high peak power is required to enhance the accelerating gradient and therefore the emittance properties. The SNS project at Oak Ridge is a superconducting H^- linac for condensed matter studies. A coaxial coupler of 50 Ohm impedance allowed one to deliver more than ~ 2 MW peak TW and 600 kW SW was obtained with a pulse length of 1.3 msec [7]. In the framework of the VUV and XFEL projects in DESY – Hamburg many different studies were performed on power couplers. The TTFIII model [21] has been chosen thanks to its reliability. It has been tested at LAL Orsay at 500kW peak power – 1.3 msec and more than 2 MW – 0.02 msec. This prototype has been recently chosen as baseline configuration design for the ILC project. In the meantime two different designs are being developed (TTFV and TW60) to reduce costs and conditioning time and to increase the transmitted power. In the framework of the ILC it is also mandatory to stress the innovative modular coaxial coupler design provided by KEK. The decoupling of the central antenna from the ceramic window allows one to avoid a delicate brazing procedure and to have more flexibility for possible damage repair. Transmission of the power is guaranteed by capacitive coupling at the ceramic transition. Very good results (2 MW peak at 1.5 msec - 3pps and less of 15h conditioning time) were recently obtained [25].

CONCLUSIONS

At present, the new generation of linac projects calls for increasingly high beam currents and accelerating gradients. This requirement can only be fulfilled if very high power can be produced and delivered to the accelerating cavity. The new generation of power coupler designs plays a major role in this context. The RF design is always determinant but, to obtain these results, increasing attention for the associated technology is mandatory. So a mixture of mechanical and thermal engineering and vacuum and surface science competences is required. At the same time the extremely strong constraints imposed by the SC cavities force to develop standard and reliable procedures, not affecting the cavity performances, also for cleaning, assembling and mounting phases. In the context of major projects, where the cost and therefore the number of produced couplers is determinant, it is necessary to develop simplified designs that could ensure the performances reducing the costs.

A peculiarity of power couplers for linacs is given by their design for low energy beams in sources and injectors. In this case the integration of the coupler and its effect on the beam emittance has to be carefully assessed in the design phase.

ACKNOWLEDGEMENTS

I would like to acknowledge all the colleagues that helped me to prepare this manuscript. Special thanks to T.Garvey for reviewing it and to W.D. Moeller, D. Proch, D.Kostin, I.Campisi, H.Matsumoto, K.Saito, E.Kako, C.Beard, S.Belomestnykh, E.Palmieri, P.Lepercq, S.Prat and H.Jenhani for suggestions and information.

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