Optimisation of Accelerator Reliability for ADS: Example of SC Cavities and the Associated RF Power Couplers

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Abstract. In order to limit as much as possible the number of thermal shocks in the spallation target and the reactor core, ADS-class accelerators require an extremely high reliability of less then 5 beam-trips per year. The recent European (FP5) Study PDS-XADS has established the following to be the main parameters for reliable accelerator operation: use of derated and redundant components, intrinsic fault tolerance and a dedicated maintenance strategy. In this paper the progress of certain aspects of reliability studies done at the Institute of Nuclear Physics in Orsay will be presented. The low level RF fast feedback system for the SC cavities operation, providing the necessary beam stability, will be discussed. Also the conceptional design of the RF power coupler that requires a high level of robustness is given.

1. Introduction

The main objective of the recently accomplished "Preliminary Design Study - eXperimental Accelerator Driven System" (PDS-XADS) project [1, 2] was to demonstrate the feasibility of coupling accelerator technology with nuclear reactor technology leading to an ADS for nuclear waste transmutation. This 3-year project was launched in 2001 as a part of EU's 5th Framework Programme (FP). A special working package (WP3) was dedicated to the accelerator design. This work will now continue in 6th FP, on an enlarged-scale as the integrated project EUROTRANS involving 48 organizations from 14 European countries.
The reference accelerator concept elaborated by PDS-XADS is reported elsewhere in the present proceedings in more detail [3]. Here we recall some prominent features: it is a high-intensity superconducting (SC) proton-linac, delivering a beam on a spallation target to provide an external neutron flux source for the sub-critical core. Its specifications are given in Table 1.

TABLE 1: Main specifications for XADS linac

Final proton beam energy	600 MeV (delivering 15 neutrons/proton)
Proton beam current	• 6 mA max. on target • 10 mA rated
Beam time structure	Continuous wave (CW)
Main additional specifications	The concept must stay valid for a 1 GeV, 20 mA industrial machine
	Less then 5 beam trips (>1 sec) per year

The structure of the accelerator contains three main parts: the "low-energy section" (up to 5 MeV) containing the injector, the "intermediate section" (up to 100 MeV) containing either a room-temperature solution based on a DTL structure, or a cold solution using SC resonators (or possibly both), and the "high-energy section" made of SC multicell elliptical cavities.
A special requirement of an XADS accelerator is to suffer less then 5 beam-trips per year. This is a consequence of a necessity to limit as much as possible the number of thermal shocks in the spallation target and the reactor core. Today's technologies result in machines having at least a few tens of failures per year, only due to the RF systems, hence a need for a thorough R&D program on accelerator reliability. The main parameters for reliable

accelerator operation are use of derated and redundant components, intrinsic fault tolerance and a dedicated maintenance strategy [4].

This paper presents progress on two aspects of accelerator reliability studies: the fault tolerance feasibility with the design of a low level RF fast feedback system for SC cavities, and the conception of RF power couplers requiring a high level of robustness.

2. Low Level RF Fast Feedback System

RF power system supplies energy to the cavity to accelerate the beam. Main purpose of the low level RF fast feedback system is to provide sufficient field stability (typically no less than 1% amplitude and 1˚ phase) that would avoid beam losses. Moreover SC cavities that have a very high quality factor, given that they are made of relatively thin niobium walls are sensitive to few additional perturbations such as Lorentz force or microphonic vibrations capable of altering cavity's resonant frequency sufficiently to induce beam instabilities. These are some of the reasons why low level RF fast feedback systems are necessary in any accelerator; however their importance is increased in ADS type accelerators due to following reasons:

- increasing the reliability of the RF system by making it integrated and digital;
- improving the overall reliability by creating a fault tolerant accelerator;
- the need to measure the reactor criticity, which imposes a beam structure with 200 μs gaps every second, requiring RF control systems able to quickly compensate for beam mode changes.

In order to explain the fault tolerance principle, we first describe what happens in a case of a cavity failure.

Modularity being a substantial feature of reliability, XADS design foresees one RF power source per cavity. Thus in a case of a RF system failure only one cavity is lost. This induces a loss of energy gain that translates as a phase slip along the linac equal to $\delta\varphi \approx 2\pi\,(\delta z/\lambda)\,(\delta\beta/\beta^2)$ [1] in the area between the faulty cavity and the first one to follow it, after which it increases rapidly with the distance δz [5], β is the beam velocity (normalized to c), λ the RF wavelength and $\delta\beta$ the velocity loss (compared to the reference beam velocity) at δz. The consequences of this kind of failure depend on the position of the cavity, and are more serious when β is low, or when cavity's accelerating field and operating frequency are high. Longitudinal acceptance needs also to be taken in count. The lower it is, the faster the failure-induced phase slip drives the beam towards the phase instability region.

According to simulations XADS reference linac that uses conservative but realistic values for synchronous phase and accelerating gradient, in the case of cavity failure has a sufficient phase slip to promptly constrain the beam out of the phase stability region. This routine generates a 100% beam loss for almost any cavity fault in the linac.

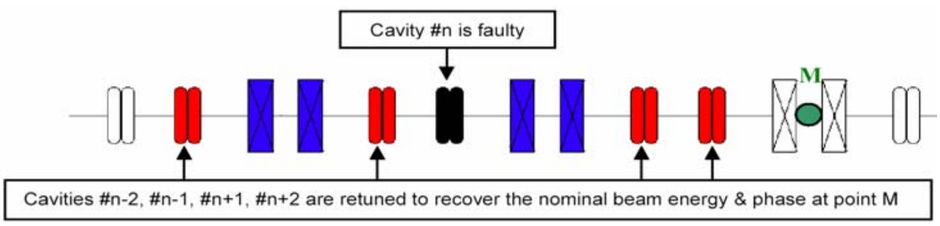

FIG. 1. Localised compensation method.

[1] This expression can be used for phase slip because we are dealing with a non-relativistic proton beam.

A fault tolerant linac can avoid beam loss using a localised compensation method to deal with such a problem. This method consists of retuning a certain number of cavities surrounding the defective one in order to recover the nominal beam characteristics at the end of the linac.
If the cavity #n fails, the neighboring #n-2, #n-1, #n+1 and #n+2 are retuned in a manner to assure conciliation among following goals: 1) reach nominal energy and phase at point M, and consequently at the target; 2) limit the induced beam mismatch to ensure a 100% transmission and keep the emittance growth as low as possible; 3) ensure that we do not exceed a 30% accelerator field rise in the cavities as compared with their nominal "derated" operation point. If needed, more neighboring cavities can be used. The adjustment of focusing quadrupoles located inside the retuned lattice is used for transverse beam dynamics compensation. Table 2 shows retuning values for several cavities of our linac specifying their position, type and β value (SP: spoke, EL: elliptical). [6]

TABLE 2: Sample of the retuning values for each cavity failure

# faulty cavity	section	Final energy	Emittance growth (%)		Number of retuned cavities (before + after)	Max ΔEacc (%)	Max E_{pk} (SP) or B_{pk} (EL)	Max ΔPower (%)	Nb of retuned quads (before + after)
			Transv.	Long.					
0	-	Nominal	+ 5 %	0 %	-	-	-	-	-
1	SP 0.15	Nominal	+ 7 %	+ 4 %	0 + 4	+ 67 %	19 MV/m	+ 67 %	0 + 4
4	SP 0.15	Nominal	+ 9 %	+ 4 %	3 + 3	+ 46 %	15 MV/m	+ 35 %	2 + 4
62	SP 0.35	Nominal	+ 6 %	0 %	2 + 2	+ 26 %	31 MV/m	+ 28 %	2 + 2
63	SP 0.35	Nominal	+ 5 %	+ 1 %	3 + 2	+ 25 %	31 MV/m	+ 27 %	2 + 2
98	EL 0.47	Nominal	+ 6 %	0 %	3 + 2	+ 23 %	62 mT	+ 31 %	4 + 2
109	EL 0.47	Nominal	+ 6 %	0 %	3 + 3	+ 20 %	60 mT	+ 28 %	4 + 2
174	EL 0.65	Nominal	+ 5 %	0 %	3 + 3	+ 18 %	59 mT	+ 22 %	4 + 2
175	EL 0.65	Nominal	+ 5 %	0 %	4 + 4	+ 17 %	59 mT	+ 18 %	4 + 2
186	EL 0.85	Nominal	+ 7 %	0 %	6 + 1	+ 21 %	61 mT	+ 33 %	4 + 0
187	EL 0.85	Nominal	+ 6 %	0 %	7 + 0	+ 25 %	63 mT	+ 37 %	4 + 0

Carrying out this method demands specifically designed low level digital RF fast feedback system. The pattern of such a system is shown on fig. 2.

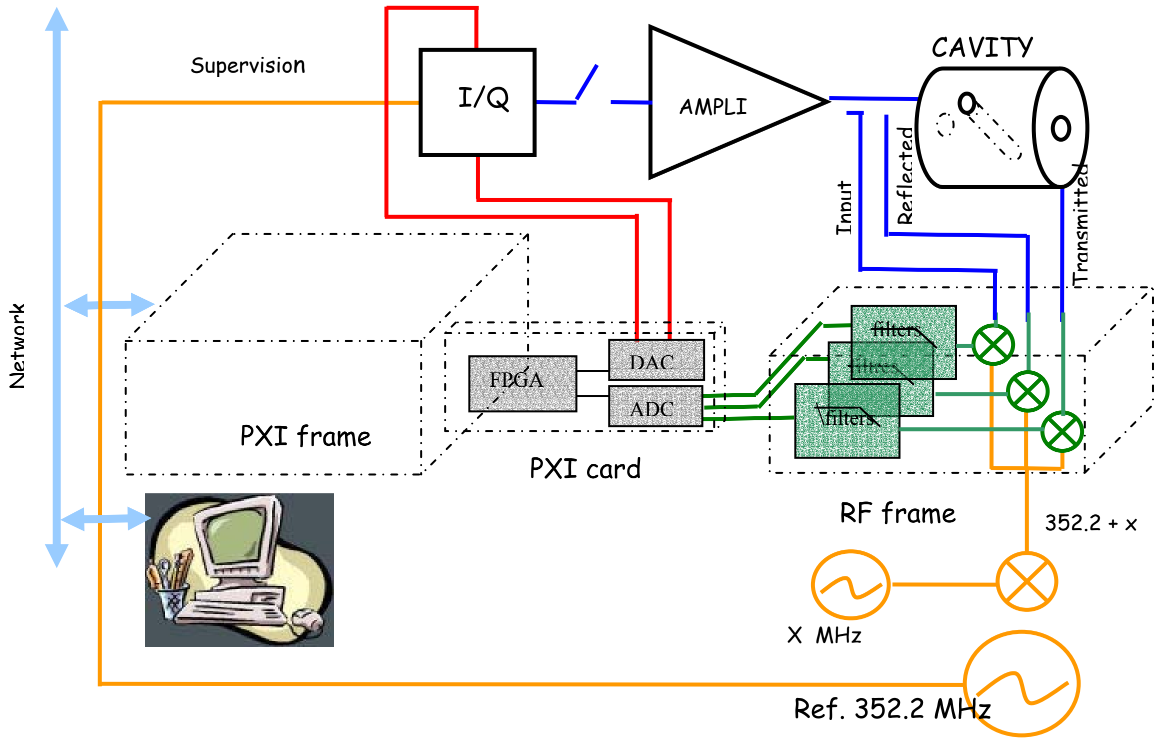

FIG. 2. Scheme of the low level digital RF fast feedback system

By measuring transmitted power of the cavity, the system is able to detect any discord between reference values and the ones ongoing in the cavity and correct them using a fast proportional loop. Measurements of input and reflected power can also be used for reacting on a cold tuning system or to operate a variable coupler.
Localised compensation method needs also to inter-connect each cavity's LLRF system into a network, in order that when a breakdown of one cavity is established through a system of fault diagnostics, the neighbouring cavities' reference set-points change.
Further studies are starting in the frame of the EUROTRANS project to precisely design such a LLRF system, and analyse the relevant scenarios and procedures to be implemented in order to make the localised compensation method possible.

3. Conception of the RF Power Coupler

Couplers are essential components of RF power systems and therefore of accelerator structure. Their function is dual: transfer of energy from an RF generator to a SC cavity at a suitable rate, and to act as boundary separating the vacuum of the SC cavity from the atmospheric pressure of the transmission line. Figure 3 illustrates a typical RF power coupler. It consists of three major parts: 1) upstream part which is a transmission line connecting the power source to the ceramic window; 2) ceramic window that is the barrier separating the vacuum of the SC cavity from the atmospheric pressure of the transmission line; 3) downstream part containing an antenna which penetrates the cavity and concludes energy transmission process by creating an EM wave in the cavity.

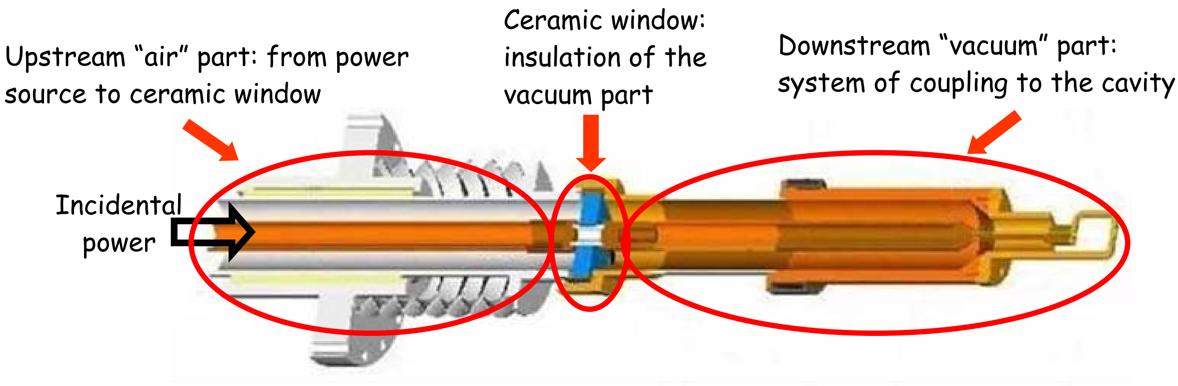

FIG 3: Scheme of an RF power coupler

Design of an RF power coupler for a SPOKE type cavity [7] is under development. Coupler requirements for such cavity are:

- an EM wave with a frequency of 352.2 MHz,
- power transmission up to 20 kW (nominal value 10 kW),
- electrical capacitive coupling for CW operation.

The ceramic window is considered as the most delicate part of the coupler on account of its air/vacuum separation role, but also due to the thermo-mechanical constraints it suffers. As a separator, the window must be permeable to electromagnetic radiation with no sizeable power losses due to reflection or dissipation. Window design must take into account technologies of materials, surfaces, vacuum, electromagnetic design, gas dynamics, and manufacturing methods. The importance of correct window design is accentuated by the consequence of its failure, the braking of vacuum that leads to an immediate beam shutdown, which represents obvious "fault **in**tolerance" behaviour.

Conception of the window begins with electromagnetic calculations that have been made easier by computer codes such as HFSS and MAFIA. These codes allow complete modelling of the field distribution of the coupler/cavity fields' interfaces thus guaranteeing optimum coupling. In order to achieve optimum coupling and insure window robustness, we studied several different geometry configurations, some of which are shown on figure 4.

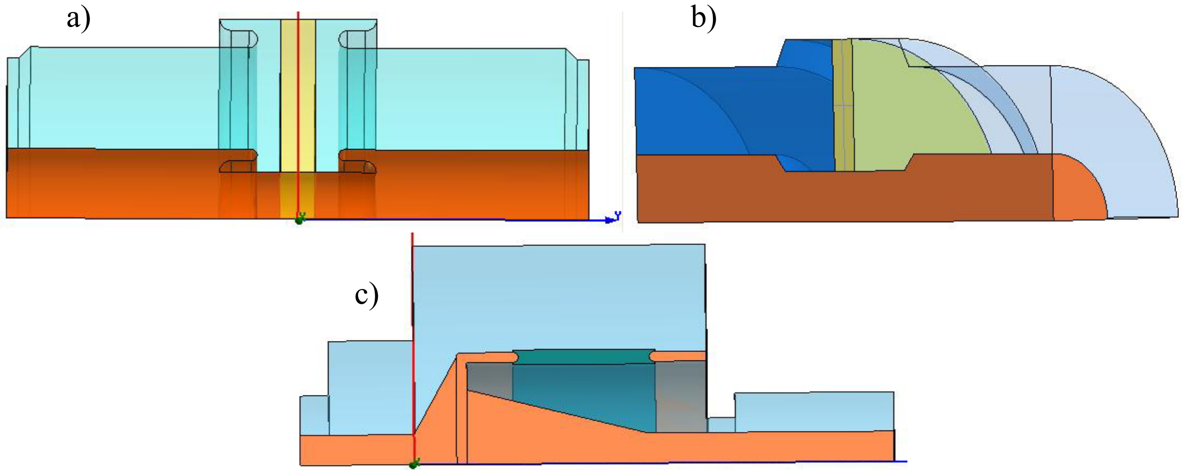

FIG. 4: Several window geometries: a) disk with chokes; b) disk without chokes; c) cylinder

The choice of the window geometry must be based on a reasonable compromise between minimising electric field on the surface of the window (E_{surf}) in order to avoid multipacting phenomena, minimising power losses in the window (heating), and a balance between large enough band-width and small enough reflected power (S_{11}). Table 3 summaries main parameters for different window types calculated with HFSS software.

TABLE 3: Comparison of main parameters for different window types

Window type	Disk with chokes	**Disk without chokes**	Cylinder	"Guide/coaxial"	"T"
S_{11} (dB)	-55,4	**-58**	-45,17	-60	-40,2
Band-width (MHz)	>1000	**760**	410	6	8
E_{surf} max (V/m)	$1{,}18.10^5$	**$1{,}24.10^5$**	$1{,}50.10^4$	$1{,}24.10^4$	$2{,}30.10^4$
Losses (W)	60	**71,75**	68,2	147	33
% P_{losses}/ $P_{incident}$	0,30%	**0,36%**	0,34%	0,74%	0,17%
Window volume (mm^3)	$2{,}86.10^4$	**$1{,}65.10^4$**	$8{,}11.10^4$	$1{,}61.10^6$	$1{,}37.10^5$
Voluminal losses (W/mm^3)	$2{,}10.10^{-3}$	**$4{,}34.10^{-3}$**	$8{,}41.10^{-4}$	$9{,}14.10^{-5}$	$2{,}41.10^{-4}$

Mechanical properties of the coupler must also be evaluated since window design relies on a delicate ceramic-to-metal brazing. This is why simplicity of fabrication is also taken into consideration. Based on all these considerations we choose to continue development of the window "disk without chokes". Details of these calculations can be found in reference [8].
The next step in our study will be to perform thermal calculations. As the RF power must reach the cold SC cavity, end parts of the transmitting line must be able to undergo thermal barrier between room temperature and the SC needed temperature of 2-4.5 K. This feature of coupler conception brings tight requirements on geometries and very subtle balances among static and dynamic heat loads placed on the refrigeration system. Thus couplers must employ materials that provide large thermal resistance to uphold the large thermal gradients without

introducing additional RF losses. Here we would also use numerical calculations to optimise our design, knowing that the most delicate part of thermal calculation resides in avoiding the loss of cavity's SC quality due to the thermal loading.

4. Conclusion

The integrated project EUROTRANS maintains its course within the 6^{th} European FP. The final goal is to be ready to launch an eventual construction of the machine at the end of 2008. In the meanwhile R&D program on reliability is pursued, focusing amongst other items on the ones presented in this paper.

Regarding the low level RF fast feedback system, further developments consist of manufacture of the integrating digital system for a single cavity. Tests of the system are planned for summer 2005. This is followed by development of a fault-diagnostics system jointly with a study of feasibility of connecting individual LLRF systems into an interactive network.

On the subject of the power coupler for a spoke cavity, the thermal calculations as well as a mechanical study need to be included into design, in order for the construction and testing of the cavity to meet the schedule goal of first half of 2006.

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