BEAM DYNAMICS STUDIES FOR THE FAULT TOLERANCE ASSESSMENT OF THE PDS-XADS LINAC

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Abstract

In order to meet the high availability/reliability required by the PDS-XADS design, the accelerator needs to implement, to the maximum possible extent, a fault tolerance strategy that would allow beam operation in the presence of most of the envisaged faults that could occur in its beam line components. In this work we report the results of beam dynamics simulations performed to characterise the effects of the faults of the main linac components (cavities, focusing magnets...) on the beam parameters. The outcome of this activity is the definition of the possible corrective and preventive actions that could be conceived (and implemented in the system) in order to guarantee the fault tolerance characteristics of the accelerator. The PDS-XADS programme is funded by the EC 5th Framework Programme, under contract FIKW-CT-2001-00179.

Introduction

In current high-power accelerators, specific diagnostics are usually connected to all major accelerator components, continuously sending status information. Typically, when a component fails (i.e. its information status suddenly switches from “normal” to “faulty”), the beam is immediately shut down. Action is then taken to repair the faulty component, eventually leading to replacement of the hardware. After the maintenance, when accelerator operation is ready to resume, the procedure followed is the same for a new re-start, slowly ramping up in beam power. For most accelerators, the number of beam interruptions rapidly decreases with the trip duration time, thus maintaining an overall good level of availability. For most applications, despite the high number of short-duration breakdowns, the operation is not greatly affected, as a sufficiently high availability is preserved.

For an ADS application, however, any beam trip lasting more than a second will be considered as a major accelerator failure, leading to the reactor core shutdown. Thus, the philosophy prevailing on current machines to cope with component failures must be reconsidered, taking into account that requirement. In particular, for each failure analysis, the design should look at the ability to either maintain the beam under safe conditions, or to recover the beam through, in less than one second. This is a new feature, not required for any other accelerator application, which is quite specific to ADS linacs. In this paper*, we will develop this “fault tolerance” concept, and try to assess its practical implementation through beam dynamics calculations.

The PDS-XADS reference accelerator and the reliability requirement

Consecutive to the work of the European Technical Working Group on Accelerator Driven Systems [1], the Preliminary Design Study of an Experimental ADS (PDS-XADS) was launched in 2001. A large European collaboration supported by the EU within the Fifth Framework Programme performs these studies [2,3]. Five work packages (WP) cover the relevant issues; the WP3† is dedicated to the design of the high-intensity proton accelerator providing the neutron flux to the subcritical reactor via a spallation target [4,5]. The main specifications for this XADS accelerator system are summarised in Table 1.

Table 1. PDS-XADS proton beam specifications

Max. beam intensity	6 mA CW on target (10 mA rated)
Proton energy	600 MeV (includes 800 MeV upgrade study)
Beam entry	Vertically from above preferred
Beam trip number	Less than five per year (exceeding 1 second)
Beam stability	Energy: −1%, intensity: −2%, size: −10%
Beam footprint on target	Gas-cooled XADS: circular ˘ 160 LBE-cooled XADS: rectangular 10 · 80 MYRRHA: circular, “donut” ˘ 72

* This paper relies on the studies performed within the PDS-XADS programme, and on the corresponding internal reports: D9 (*Requirements for the XADS Accelerator & the Technical Answers*), D47 (*Accelerator: Feedback Systems, Safety Grade Shutdown & Power Limitation*), D48 (*Accelerator: Radiation Safety & Maintenance*), D57 (*Potential for Reliability Improvement & Cost Optimisation of Linac and Cyclotron Accelerators*) and D63 (*Definition of the XADS-class Reference Accelerator Concept & Needed R&D*).

† The following institutions collaborating within the WP3 are: ANSALDO (Italy), CEA (France), CNRS-IN2P3 (France, co-ordinator), ENEA (Italy), FRAMATOME ANP (France), FRAMATOME GmbH (Germany), FZ Jülich (Germany), IBA (Belgium), INFN (Italy), ITN (Portugal), University of Frankfürt (Germany).

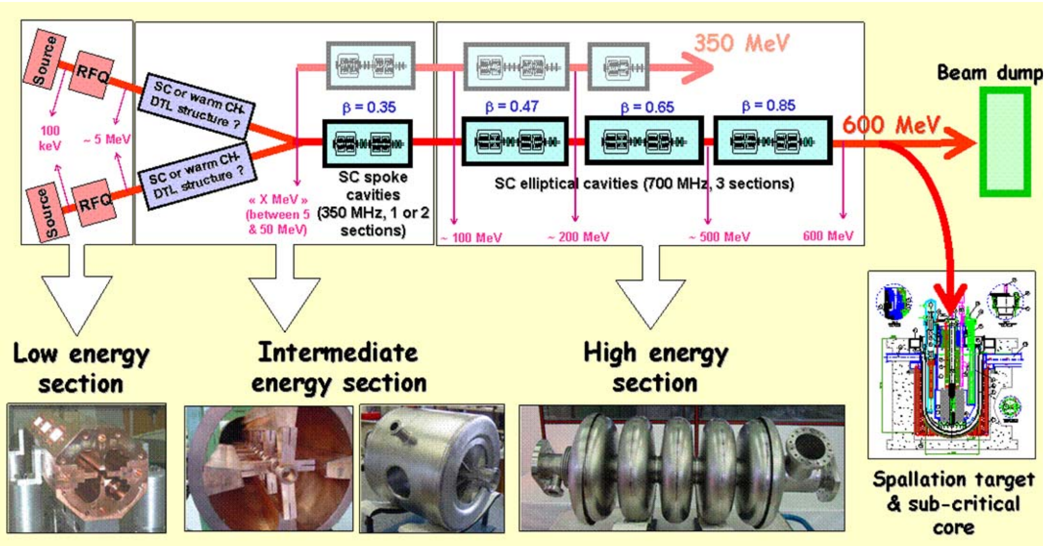
Table 1 notably highlights that a continuous beam operation with only a few (of the order of five per year) beam stops longer than approximately one second is considered to be mandatory for the successful demonstration of the ADS coupling. Given the state-of-the-art in the field of accelerator reliability [6], this requirement appears to be highly challenging.

From this extremely high reliability requirement, WP3 has assessed the corresponding technical answers [7], and a reference solution based on a linear superconducting accelerator with its associated doubly achromatic beam line has been worked out to some level of detail. No potential showstopper on the path for achieving an extremely reliable accelerator has yet emerged from the analyses performed [8,9]. From the reliability and availability specifications, it is clear that suitable design strategies had to be followed early in the conception stage of the XADS accelerator. The main guidelines that have been highlighted to drive the design are: a strong design (which makes extensive use of component de-rating and proper redundancy) and a high degree of fault tolerance (i.e. the capability to maintain beam operation within nominal conditions under a wide variety of accelerator component faults).

This fault tolerance concept is a crucial point in the design of the overall XADS accelerator in order to guarantee the few number of beam stops per year dictated by the target requirements. The state of the art in RF system technology is indeed not reliable enough to envisage an operation of the XADS accelerator during several months without any beam trip. At least a few tens of failures per year can be foreseen, due only to these RF systems, based on parts count reliability estimates. Therefore, even if a great effort can be directed at improving the MTBF of RF systems, it seems difficult to reach the reliability requirements without implementing any fault tolerance philosophy for the linac design.

The proposed reference design for the XADS accelerator, optimised for reliability, is shown in Figure 1. The injection section is composed of a "classical" proton injector (ECR source plus normal-conducting RFQ structure), followed by additional warm IH-DTL and/or superconducting CH-DTL up to a transition energy still to be defined (between 5 and 50 MeV). In this part, fault tolerance is guaranteed by means of a "hot stand-by" spare.

Figure 1. XADS reference accelerator layout: a doubled injector accelerator is followed by a fully modular spoke and elliptical cavity superconducting linac; the 350 MeV option corresponds to a smaller-scale XADS (MYRRHA project). Photos of typical cavity prototypes are shown in the lower part. From left to right: RFQ, CH structure, spoke, elliptical five-cell.



Above this transition energy, a fully modular superconducting linac brings the beam up to the final energy, using spoke and elliptical cavities. This section is designed to be intrinsically fault tolerant, meaning that an individual cavity failure can be handled at all stages without loss of the beam. This characteristic relies on the use of highly "de-rated" and independently-powered accelerating components, associated with a fast digital feedback system and adequate diagnostics.

In the following, the fault tolerance principle of this modular superconducting linac will be analysed by means of beam dynamics simulations. These calculations are performed using the TraceWin and PARTRAN codes developed in Saclay [10], and on the basis of the 5 MeV-600 MeV XADS reference linac layout presented in Table 2. In all cases, a 10-mA proton beam is considered, and the normalised rms emittance values at the input are assumed to be 0.27 π.mm.mrad in the transverse planes, and 0.39 π.mm.mrad in the longitudinal plane. Multi-particle calculations are performed using at least 10 000 particles and considering a Gaussian (truncated at 4σ) phase-space distribution.

Table 2. Layout of the 5 MeV-600 MeV XADS reference linac. Focusing is ensured by warm quadrupole doublets.

Accelerating sections	Frequency	No. of gaps per cavity	No. of cavities per lattice	Input energy	Output energy	No. of cavities
Spoke β = 0.15	352.2 MHz	2	2	5.0 MeV	16.7 MeV	36
Spoke β = 0.35	352.2 MHz	2	3	16.7 MeV	90.5 MeV	63
Elliptical β = 0.47	704.4 MHz	5	2	90.5 MeV	191.7 MeV	28
Elliptical β = 0.65	704.4 MHz	5	3	191.7 MeV	498.1 MeV	51
Elliptical β = 0.85	704.4 MHz	6	4	498.1 MeV	614.7 MeV	12

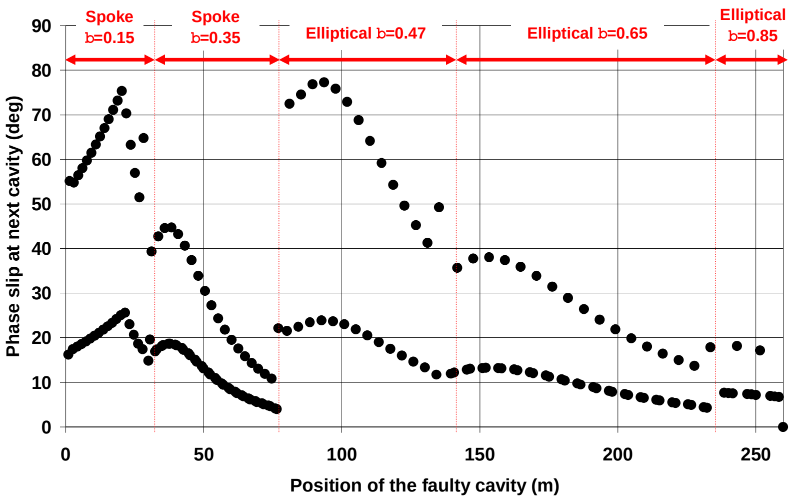
Consequences of the failure of a RF cavity

Let us assume in this section that the RF system fails to power a cavity somewhere in the linac, and that this cavity is immediately detuned to avoid any beam loading effect. This results in a loss of the energy gain provided by the failed cavity, and then in a beam longitudinal (phase-energy) mismatch at the entrance of the following cavity. Because we deal with a non-relativistic proton beam, this energy loss will imply a phase slip along the linac equal to $\delta\phi = 2\pi(\delta z/\lambda)(\delta\beta/\beta^2)$, increasing with the distance δz from the faulty cavity; β is the beam velocity (normalised to c), λ the RF wavelength and $\delta\beta$ the velocity loss (compared to the reference beam velocity) at δz [11].

Of course, the consequences of such a failure strongly depend on the position of the cavity in the linac, and on its operating conditions. The problem is more serious when the velocity of the particle is low, but also when the accelerating field and the operating frequency of the cavity are high. Figure 2 shows, for each cavity of the XADS reference linac, the phase slip induced at the entrance of the subsequent cavity if a cavity fails. It rapidly appears from this graph that the most critical sections of the accelerator towards the fault tolerance problem are the first β = 0.15 spoke section and the first β = 0.47 elliptical section.

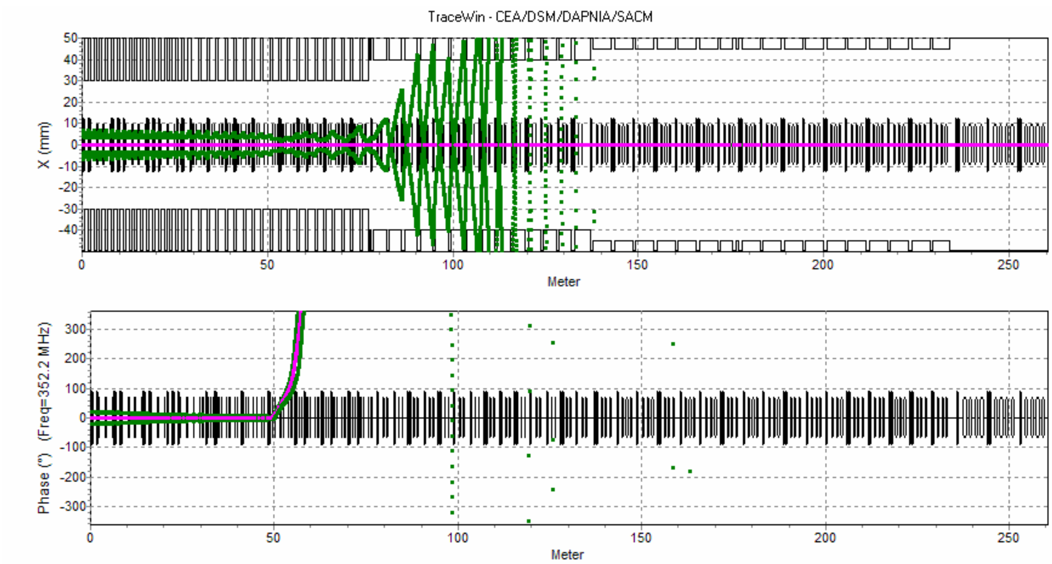
Another important parameter to be taken into account in the analysis is the longitudinal acceptance of the linac. The lower this acceptance (i.e. the higher the synchronous phase compared with the longitudinal size of the beam), the faster the fault-induced phase slip will offset the beam towards the phase instability region. One way to avoid the problem could thus be to lower both the synchronous phase (near the -90° bunching value) and the accelerating gain per cavity all along the linac, but this would lead to an unacceptable increase in linac length and cost.

Figure 2. Beam phase slip induced at the subsequent cavity as a function of the position of the faulty cavity in the linac. This phase slip is of course larger for a faulty cavity located at the end of a lattice.



In the XADS reference linac, where conservative but realistic synchronous phase and accelerating field values are used, simulations show that in almost every case, the fault of a cavity induces a sufficient phase slip to rapidly drop the beam out of the phase stability region. The beam can not then be correctly handled longitudinally in the subsequent cavities, and it is finally completely lost later in the linac (see example in Figure 3). This kind of behaviour with a final 100% beam loss is encountered for any cavity fault in the linac, except in the specific case of the first spoke cavity's failure (where only 40% of the beam is lost thanks to the low synchronous phase and the very low accelerating field used in this first cavity) and in the case of the last elliptical cavities' failure, at the very end of the linac, where the induced beam phase slip has no further consequences.

Figure 3. Beam envelopes (x-transverse, phase) in the 5 MeV-600 MeV XADS reference linac if spoke cavity #62 (40 MeV, 50 m) is lost and no compensation action is performed



Linac retuning after the failure of a RF cavity

From this first analysis, it is clear that in case of a cavity failure, some kind of retuning has to be performed. The aim of this retuning is to recover the nominal beam characteristics at the end of the linac, and in particular its energy, while ensuring the same level of transmission (and of emittance growth) as for the reference linac case.

To achieve this compensation, the general philosophy is here to re-adjust the accelerating fields and phases of the linac cavities to recover the required longitudinal behaviour of the beam. One simple way to achieve such a retuning is to compensate locally using the accelerating cavities neighbouring the failing one. This method especially has the advantage of involving a small number of elements, simplifying the retuning procedures and limiting the possible induced errors. This is illustrated in Figure 4: if cavity #n is faulty, the four surrounding cavities (#n-2, #n-1, #n+1, #n+2) are retuned to recover the nominal beam energy and phase at the end of the following lattice (point M). This can of course be performed with more (or fewer) cavities if necessary. Practically, the retuning of the cavities is undertaken acting only on their accelerating field amplitude and/or phase. On the transverse beam dynamics side, the gradients of the four focusing quadrupoles located inside the retuned lattices can also be adjusted if needed. Here again, more quadrupoles can be used if necessary.

This retuning must, of course, be performed properly in order to reach a reasonable compromise between the three following goals:

1) *Reaching the nominal energy and phase at point M (and consequently at the target).* In principle, this can be done simply by raising the accelerating field in the surrounding cavities (this is possible because the compensation is made both before and after the failed cavity; this is thus not true for the two first cavities of the linac). This method leads to a very acceptable situation (even at very low energies, see Figure 5), but of course, with such a basic retuning, some beam mismatch often appears both in the longitudinal and transverse planes, inducing emittance growth and halo creation.

2) *Avoiding any beam loss to ensure a 100% transmission, and keeping the emittance growth as low as possible*. This is undertaken first by trying to keep phase advances as smooth as possible, but also by limiting as much as possible the longitudinal size of the beam around the faulty cavity area, so as to maintain the whole bunch inside the phase stability region [this is mainly true in the low-energy sections, see Figure 5(b)]. To achieve all this, an adjustment of the RF phases in the retuned cavities and of a few quadrupole gradients is mandatory.

3) *Ensuring that the accelerating field of the retuned cavities (and the corresponding needed RF power) will not have to be increased too much compared with the nominal operation point*. We chose in the study not to exceed a +30% field increase in the cavities that leads to maximum allowed peak fields of E_{pk} =33 MV/m for the spoke sections (nominal "de-rated" operation point: 25 MV/m), and of B_{pk} = 65 mT for the elliptical sections (nominal "de-rated" operation point: 50 mT). Of course, the more cavities used for the retuning procedure, the more this field increase can be limited. Note that this requirement has been relaxed at the beginning of the linac where cavities are working at the very low peak field required by the nominal operation.

A reasonable compromise between these three requirements is not always easy to reach, especially in the very low velocity section (spoke b = 0.15) where the beam is "debunching" very rapidly at the fault cavity position, leading to halo creation and beam losses if a refined retuning is not carried out. In this case, a strong longitudinal focusing (i.e. high field increase, more than +30%) has to be performed in the retuned cavities to compensate for this effect, though not too much so as to maintain a good longitudinal matching.

Figure 4. Principle of local compensation to recover the beam energy and phase

Of course, in the case of the failure of cavity #1, cavities #2, #3, #4, #5 are used,
and in the case of the failure of the last cavity, the four preceding cavities are used.

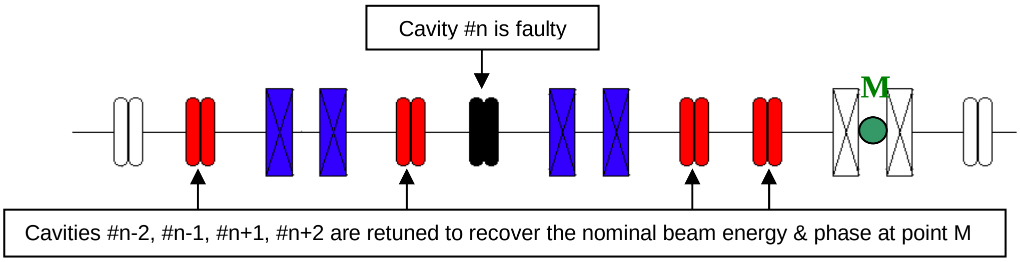
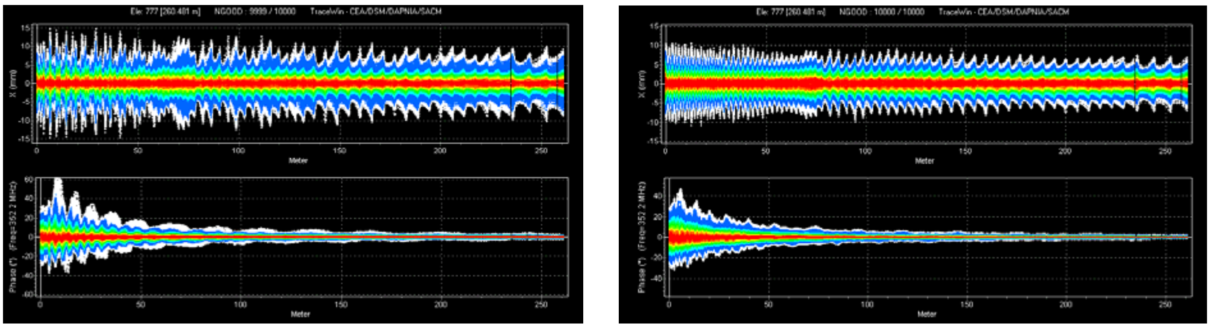


Figure 5. Multi-particle beam envelopes (x-transverse, phase) in the 5 MeV-600 MeV XADS reference linac if spoke cavity #4 (5.5 MeV, 3 m) is lost and compensation is achieved by: raising the field only in the four surrounding cavities (left), or applying the optimal tuning as reported in Table 3 (right).



Above 10 MeV, the situation becomes much easier. It is then always possible to recover the beam within the nominal parameters at the end of the accelerator without exceeding a +30% field rise, even if this limitation can be quite difficult to manage in the case where the number of cavities per lattice is small. The levels of emittance growth are always very low, and even meet the nominal values in the elliptical sections (see Table 3). Note that the situation is a bit more complicated when the faulty cavity is located at the transition between two sections (especially at the frequency change).

Based on these considerations, a systematic study of the XADS linac fault tolerance has been performed, optimising the retuned values to be applied for local compensation in the case of the failure of most of the linac cavities. Table 3 reports some of the obtained results. The conclusion of the study is that *in every case, with an appropriate retuning, the beam can be transported up to the high-energy end without any beam loss (100% transmission, reasonable emittance growth), and within the nominal target parameters.*

Case of a quadrupole failure

Calculations have also been performed to analyse the consequences of a quadrupole failure on the beam dynamics in the XADS reference linac. Here again, the consequences of such a failure depend on the position of the failed quadrupole. The situation is more critical in the sections where the safety ratio between the beam tube aperture and the beam size is smaller (see Table 4): the failure of one of the very first quadrupoles of the b = 0.15 spoke section leads to a beam loss of about 30%, the same

Table 3. Optimised retuning parameters and corresponding beam dynamics behaviour for a few cavity fault conditions. In all cases, the transmission is 100%. Note that the optimisation level can be different depending on the cases.

No. of 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 (%)	No. of retuned quads (bef + aft)
			Transv.	Long.					
0	–	Nominal	+5%	0%	–	–	–	–	–
1	SP 0.15	Nominal	+7%	+4%	0 + 4	+67%	19 MV/m	+67%	0 + 4
2	SP 0.15	Nominal	+9%	+12%	1 + 3	+90%	19 MV/m	+68%	0 + 4
3	SP 0.15	Nominal	+10%	+12%	2 + 3	+94%	21 MV/m	+56%	4 + 2
4	SP 0.15	Nominal	+9%	+4%	3 + 3	+46%	15 MV/m	+35%	2 + 4
19	SP 0.15	Nominal	+6%	+6%	2 + 3	+38%	24 MV/m	+48%	2 + 2
20	SP 0.15	Nominal	+9%	+4%	3 + 2	+37%	26 MV/m	+58%	2 + 2
35	SP 0.15	Nominal	+6%	0%	2 + 3	+20%	32 MV/m	+27%	2 + 2
36	SP 0.15	Nominal	+7%	+4%	3 + 3	+22%	34 MV/m*	+32%	2 + 2
37	SP 0.35	Nominal	+6%	0%	3 + 2	+22%	35 MV/m*	+34%	2 + 2
38	SP 0.35	Nominal	+7%	+6%	3 + 4	+29%	31 MV/m	+26%	2 + 2
39	SP 0.35	Nominal	+5%	+5%	4 + 2	+24%	36 MV/m*	+35%	4 + 2
61	SP 0.35	Nominal	+6%	+2%	2 + 3	+25%	31 MV/m	+26%	2 + 2
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
94	SP 0.35	Nominal	+6%	+2%	3 + 3	+16%	29 MV/m	+18%	4 + 2
95	SP 0.35	Nominal	+7%	-1%	3 + 3	+22%	31 MV/m	+29%	4 + 2
96	SP 0.35	Nominal	+5%	+1%	4 + 2	+21%	30 MV/m	+25%	4 + 2
97	EL 0.47	Nominal	+6%	0%	3 + 3	+18%	59 mT	+27%	4 + 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
110	EL 0.47	Nominal	+6%	0%	3 + 2	+20%	60 mT	+29%	2 + 2
123	EL 0.47	Nominal	+6%	0%	2 + 4	+20%	60 mT	+26%	4 + 2
124	EL 0.47	Nominal	+6%	0%	3 + 3	+19%	60 mT	+28%	4 + 2
125	EL 0.65	Nominal	+5%	0%	2 + 3	+18%	59 mT	+27%	4 + 2
126	EL 0.65	Nominal	+5%	0%	3 + 4	+21%	61 mT	+20%	4 + 2
127	EL 0.65	Nominal	+5%	0%	3 + 3	+21%	61 mT	+25%	4 + 2
146	EL 0.65	Nominal	+5%	0%	3 + 3	+18%	59 mT	+22%	4 + 2
147	EL 0.65	Nominal	+6%	-1%	3 + 4	+19%	60 mT	+22%	4 + 2
148	EL 0.65	Nominal	+6%	-1%	3 + 3	+20%	60 mT	+22%	4 + 2
173	EL 0.65	Nominal	+5%	0%	3 + 4	+17%	59 mT	+19%	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
176	EL 0.85	Nominal	+5%	0%	3 + 5	+18%	59 mT	+22%	4 + 2
177	EL 0.85	Nominal	+5%	0%	4 + 4	+18%	59 mT	+20%	4 + 2
178	EL 0.85	Nominal	+5%	0%	5 + 4	+18%	59 mT	+19%	4 + 2
179	EL 0.85	Nominal	+5%	0%	6 + 4	+17%	59 mT	+16%	4 + 2
184	EL 0.85	Nominal	+5%	0%	4 + 3	+17%	59 mT	+29%	2 + 2
185	EL 0.85	Nominal	+6%	0%	5 + 2	+19%	60 mT	+30%	2 + 2
186	EL 0.85	Nominal	+7%	0%	6 + 1	+21%	61 mT	+33%	2 + 2
187	EL 0.85	Nominal	+6%	0%	7 + 0	+25%	63 mT	+37%	2 + 2

* These values exceed the 33 MV/m maximum allowed value because the tuning acts on a cavity (#38) that is already working at 29 MV/m nominal conditions (this cavity is used for the transition matching between the two spoke sections).

Table 4. Beam losses for a quadrupole failure and for a doublet failure, and possible solutions to recover the beam

		Beam losses		After retuning (case of doublet failure)			
No. faulty quadrupole	**Section**	**Quadrupole failure**	**Doublet failure**	**No. of retuned quadrupole doublets**	**Beam losses**	**Transversal emittance growth**	**Longitudinal emittance growth**
1	Spoke 0.15	28%	0.33%	0 + 7	0.33%	More than 100%	More than 100%
2	Spoke 0.15	26%					
17	Spoke 0.15	18%	0.16%	3 + 3	0.02%	100%	10%
18	Spoke 0.15	22%					
35	Spoke 0.15	9.5%	0%	3 + 3	0%	20%*	-10%*
36	Spoke 0.15	12%					
37	Spoke 0.35	24%	0%	2 + 2	0%	66%*	-12%*
38	Spoke 0.35	22%					
55	Spoke 0.35	12%	0%	2 + 2 or 3 + 3	0%	12%	0%
56	Spoke 0.35	9%					
75	Spoke 0.35	7.5%	0%	2 + 2	0%	5%	0%
76	Spoke 0.35	6%					
77	Ellipt 0.47	0.3%	0%	3 + 3	0%	11%*	-2%*
78	Ellipt 0.47	1%					
89	Ellipt 0.47	3.5%	0%	2 + 2 or 3 + 3	0%	20%*	-10%*
90	Ellipt 0.47	3%					
103	Ellipt 0.47	0.6%	0%	2 + 2	0%	5%	0%
104	Ellipt 0.47	0.5%					
105	Ellipt 0.65	1%	0%	2 + 2	0%	7%	0%
106	Ellipt 0.65	1%					
121	Ellipt 0.65	0.5%	0%	2 + 2	0%	5%	0%
122	Ellipt 0.65	0.5%					
137	Ellipt 0.65	0%	0%	2 + 2	0%	5%	0%
138	Ellipt 0.65	0%					
139	Ellipt 0.85	0%	0%	3 + 1	0%	5%	0%
140	Ellipt 0.85	0%					
143	Ellipt 0.85	0%	0%	4 + 0	0%	5%	0%
144	Ellipt 0.85	0%					

* Emittance exchange in planes to coupling resonances.

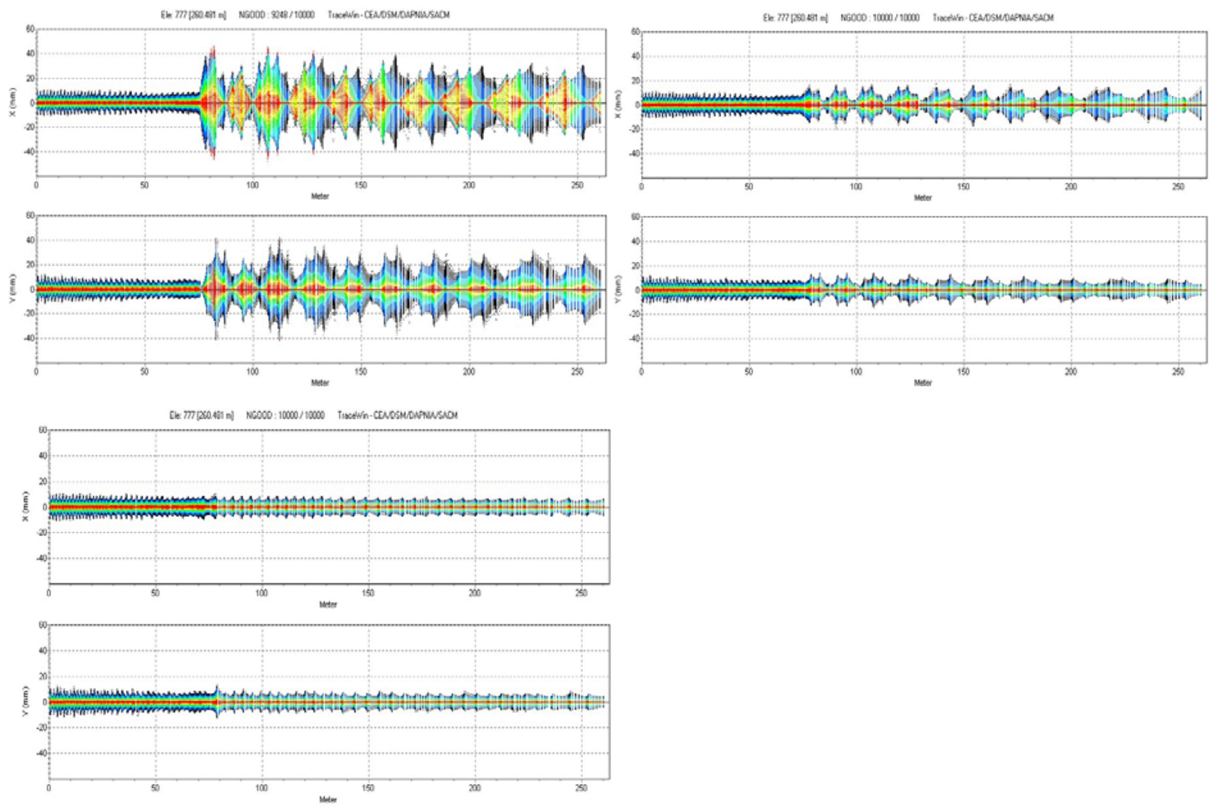
failure in the middle of the b = 0.35 spoke section only leads to a beam loss of about 10%, while the beam loss induced by a quadrupole failure in the elliptical sections is always lower than 5%. Of course, in every case, the beam is strongly mismatched in the transverse planes from the failure position up to the linac end, but the induced longitudinal mismatch is very small, as expected.

The second interesting conclusion is that in the case of a quadrupole failure, the situation is clearly better if the other quadrupole of the doublet is also switched off (see Figure 6). As a matter of fact, the induced mismatching in that case is better balanced between the two transverse planes than if nothing is done. *It is thus recommended to switch off the whole doublet if one quadrupole fails*.

Finally, with an adequate retuning of surrounding quadrupole doublets, it is possible to rematch the beam to the linac and obtain beam envelopes very similar to those of the nominal case. The situation is a bit more complicated in the very low energy section where we did not succeed in recovering a 100% transmission; the situation should probably be improved by including the MEBT quadrupoles (not modelled in the present study) in the matching procedure.

Figure 6. Beam envelopes in the 5 MeV-600 MeV XADS linac

Upper left – failure of quadrupole #75 (no correction), upper right – whole doublet is off (no correction), lower left – the four surrounding doublets are retuned



Conclusion and preliminary considerations for a full transient analysis of the problem

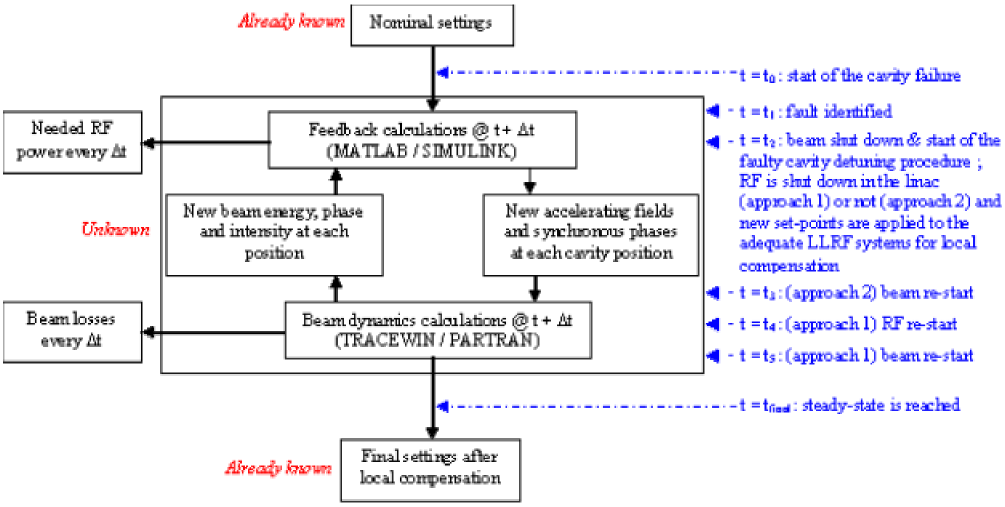
The systematic analysis performed to evaluate the fault tolerance capability of the XADS superconducting linac leads to the following conclusions:

- If a cavity fails and if nothing is done, the beam is (almost) always completely lost.
- If a cavity fails and if an appropriately rapid local compensation is done (retuning of a few surrounding cavities field and phase plus adjustment of a few quadrupoles gradients if needed), the nominal beam parameters at the target can be restored.
- If a quadrupole fails, it is advisable to switch off the whole doublet to limit the beam losses along the accelerator. For power supply failures it is thus convenient to power both quadrupoles in the doublet by a single power supply. The nominal beam parameters at the target can generally be restored by readjusting a few surrounding quadrupole gradients.
- The situation is substantially more difficult in the low-energy section of the linac (< 10 MeV).

This analysis is anyway not complete because it only takes into account the beam behaviour before the failure, and in the steady state after the local compensation. The remaining part of the problem consists now in the analysis of the transient state, assuming the beam is not switched off at the source during the fault compensation procedure, and in optimising the way the retuning procedure is carried out in order to minimise the possible integrated beam losses during these transients. In particular, this study will have to establish if, in case of a cavity fault, both RF and beam have to be switched off before re-starting (approach no. 1), or if RF has to be maintained while micro-switching the beam (approach no. 2).

Full analysis of the problem will really start in the 6th Framework Programme with the development of a new simulation code coupling both beam dynamics and RF feedback loop calculations. A first approach of such a "transient analysis" tool is summarised in Figure 7. R&D activities concerning superconducting cavities, to definitely demonstrate performances that ensure the "over-design" criteria necessitated by the reliability requirement, and on the development of adequate digital LLRF systems are also foreseen [12].

Figure 7. Proposed approach for a full transient analysis of the local compensation procedure



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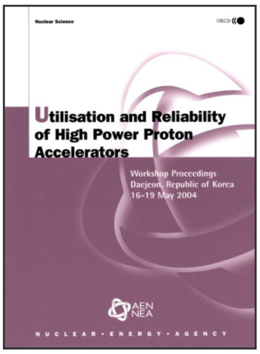
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