Abstract

International Fusion Material Irradiation Facilities is an initiative for developing materials able to resist the conditions in the inner walls of a fusion reactor. The most critical aspect is that one concerning to the 14 MeV neutron flux they have to deal with, which is about 10^{17} neutron m^{-2} s^{-1}.

The larger period fusion reactors are working without replacements the more efficient they will result, so continuous flux has to be delivered to the target as long as possible, testing materials in the hardest conditions in order to validate them for proper operation in the reactors. With this aim, availability of the facilities has to be maximized, and RAM analysis becomes a very useful tool. This study will be performed with RiskSpectrum®.

In the following text the accelerator facilities of IFMIF will be studied. The following issues will be explained in this report:

- The elaboration of a brief but consistent database of failure rate and repairing time.
- The adaptation of a FMEA.
- The modelization of a Fault tree.
- A first RAM analysis.

The desired availability of 88% will be achieved with this model and this data. Despite that, this is a first model in which updates will have to be made as the design goes deeper in detail. For instance, redundancies are not being considered, since they are not a matter of study in the present state-of-arts.

Critical components are the Heater and the Vacuum Pumping System in the Radiofrequency Quadrupole, and Diagnostics in both the Low and High Energy Beam Transport line. Except for the case of the Heater, these are not components but systems, and it is not strange their importance is bigger than importance associated with basic events referred to simpler components. These items have to be studied to go deeper in detail, enabling an analysis in which they are not basic events but gates containing more detailed failure modes.

Operational validated data from the supplier is specially recommended for the Heater.

Parametric studies are made of elements which have moderated importance but are numerous, such as Radiofrequency windows and amplifiers.

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1. Glossary

BPM	Beam Position Monitor
CDA	Concept Design Activity
CDR	Comprehensive Design Report
CIEMAT	Centro de Investigaciones Energéticas, Mediambientales y Tecnológicas
cw	continuous wave
ECRIS	electron cyclotron resonance ion source
EF	Error Factor
FC	Fraction contribution
FEEL	Fusion Energy Engineering Laboratory
FMEA	Failure modes and effects analysis
Fpy	full power year
He	helium
HEBT	High energy beam transport
HWR	Half-wave resonators
IEA	International Energy Agency
KEP	Key Element Technology Phase report
keV	kiloelectron-volt
LEBT	Low energy beam transport
LHe	Liquid Helium
Li	Lithium

mA	miliamperes
MeV	Megaelectron-volt
MTBF	Mean time between failures
MTTR	Mean time to repair
nc	Normal conducting
Pka	Primary knock-on atoms
Q	Unavailability
Q (t)	Time dependant unavailability
QWR	quarter-wave resonators
RF	Radio frequency
RFQ	Radiofrequency quadrupole
RAM	Reliability, availability and maintainability analysis.
Sc	Superconducting
T	Tesla

2. Preface

This project has been developed since March to December of 2009. Getting involved in a project related with nuclear fusion energy was the first motivation. Moreover, many aspects in this project are pioneering technology in accelerators field, such as the development of a high current continuous wave beam or the utilization of superconducting half-wave resonators. However, this also has some drawbacks, since little data is available and some parameters have to be extrapolated or imported from other technologies with the consequent uncertainties that this method introduces.

Updates, in the phase we are at (December 2009), could be made daily. This is why this is considered a first model, on which a trial and error procedure can be performed in order to achieve a model deeper in complexity and with more accurate data step by step. In fact, this could be understood as an improvement to the CDA model, since it has into account the accelerator as a whole. All the systems involving each part are included in the fault tree of that part, not considering, for instance, radiofrequency system as one thing and vacuum system as another not related one, since some components, as RF windows involve both radiofrequency and vacuum tasks.

A feedback with those institutes involved in the designing task is needed in order to have updated information in the model that lead to useful results these institutes can take advantage of.

3. Introduction

This text explains a first Reliability, Availability and Maintainability analysis (known as RAM) of the IFMIF accelerator.

A RAM analysis is a tool with which designers can see the performance of the possible layouts of a certain system and the components they are developed with, in order to make the optimal election to minimize the down time of an accelerator, in this case.

For doing a RAM analysis three main inputs are needed:

- A model of the accelerator.
- Reliability Database of every component.
- Failure modes and effects analysis (FMEA).

Despite the last two items were difficult to get, all the provided information has been properly referenced. The model was designed taking into account the initial concept design activity (CDA)[1] and the different modifications that have been introduced at KEP[2] (key element technology phase report), CDR[3] (Comprehensive design report). In some parts, more updated alternatives have been like considered, for instance in the Linac. [4]

This still is a first model and modification in the design should be followed by (or preceded by) the corresponding change in the fault tree and subsequent RAM analysis.

3.1 Objectives

The objective of this project is:

- The elaboration of a brief but consistent database of failure rates and repairing times.
- The adaptation of a FMEA.
- The modelization of a new Fault tree, based on the previous two steps.
- A first RAM analysis.

The program with which the last two objectives were performed is Risk Spectrum®. It allows a gate design of a fault tree and running different analyses on it.

3.2 Scope

The scope of this work has evolved from its start in March of current year 2009. It pretended to be a deeply detailed RAM based on a fault tree that could be developed up to very basic components. However, this detailed design is still being developed and institutes do not have that kind of information. Even a detailed FMEA has not been developed or studied in most of the systems. Collecting the failure data and building the fault tree have been the main aim of this project and it has been done knowing, as said before, that this model will have to be modified step by step. Good criterion on the designing of it could lead to important savings in cost, time and environmental impact, avoiding the construction of systems that would induce such unavailability that cannot be used in IFMIF.

3.3 IFMIF

The International Fusion Material Irradiation Facility, also known as IFMIF, is an international scientific research program designed to test materials for suitability for use in a fusion reactor. IFMIF is a joint project of Japan, the European Union, the United States, and Russia, and managed by the International Energy Agency (IEA). It will use a particle accelerator-based neutron source to produce a large neutron flux, in a suitable quantity and time period to test the long-term behavior of materials under conditions similar to those expected at the inner wall of a fusion reactor. These are:

- 14 MeV neutron flux of
- 10^{17} n s^{-1} m^{-2} providing a damage rate of
- 20 dpa/fpy

The facilities designed for this (they will be explained with more detail later) are the following:

- Accelerator facility.
- Target facility.
- Test facility.
- Conventional facility.
- Central control & common facilities.

In order to reproduce a reactor in continuous operation, materials have to be irradiated as much time as possible, being the availability an issue of paramount importance in IFMIF. Then, an overall availability of 70% required for International Fusion Material Irradiation Facilities distributed as follows:

System	Required	Calculated
Accelerator facilities	88.0%	87.65%
Target facilities	95.0%	95.08%
Test facilities	97.5 %	98.3%
Conventional facilities	99.5 %	99.73%
Central control & common facilities	99.5 %	99.5%

Table 3.1 Required and calculated availabilities for the different facilities in IFMIF.[5]

It has also been included in Table 3.1 the availability obtained with previous calculations. [5] The multiplication of this availability values would mean an availability of 80.7%, but it have to be taken into account the different scheduled maintenance periods, which are a short weekly maintenance of 8 hours, and an annual large stop of one month.

The following is an overview of main facilities in IFMIF:

3.3.1 Accelerator facility

Two parallel linear accelerators provide a 125 mA deuteron continuous-wave beam each (total of 250 mA), at 40 MeV. Operation in parallel provides redundancy and lowers the R+D effort that building a 250 mA accelerator would have meant.

The beam power is 10 MW. This is such an important flux, and particles repel each other. Moreover, deuterons are twice as heavy as protons, so focusing the beam will be a technological challenge. Focusing is especially critical in IFMIF for this reason and because the first thing needed to enhance the availability is to reduce beam loss at accelerator walls to the minimum.

The Accelerator is divided in six main parts, which are briefly explained next:

- Ion source.

It generates deuterons in continuous wave mode (cw) at 100 KeV of energy. Different kinds of ion source have been studied, but the ion source studied here is an Electron Cyclotron Resonance Ion Source (ECRIS), which had good behavior under 160 hours tests.[3]

An ECRIS works as follows: First, gas is injected in a chamber, called the Plasma Chamber. Then, it is heated up with microwave radiation. In the chamber an electron cyclotron resonance magnetic field is applied. The microwave radiation ionizes the gas, so free electrons become abundant and the magnetic field makes that free electrons are kept in the chamber, describing helicoidal orbits. This way electrons are kept for a time long enough to collide against new atoms and ionize them, getting important quantities of ions (of deuterium, in this case) that can feed a continuous wave beam. Electrodes are placed at one edge of the chamber to extract the ions, giving them an energy of 100keV. With this technology, heavy highly ionized particles can be generated.

Figure 3.1 Electron Cyclotron Resonance Ion Source for IPHI in CEA, Saclay [6]

- Low Energy Beam Transport

In this section the beam generated by the ion source is focused to be injected in the Radiofrequency quadrupole. It is formed of three quadrupoles which have to match the beam to the RFQ input needs. This is necessary both to provide optimal acceleration and to avoid activation of its walls.

Quadrupoles are the optical elements used to focus the beam in the transverse directions. They have an inherent problem: when focusing one direction (namely, X) they defocus the perpendicular one (Y). Then the usage of triplets, or at least doublets, is necessary for providing focus in both directions. Although the second quadrupole defocus the focalization of the first one, the overall result is a focusing improvement in both directions.

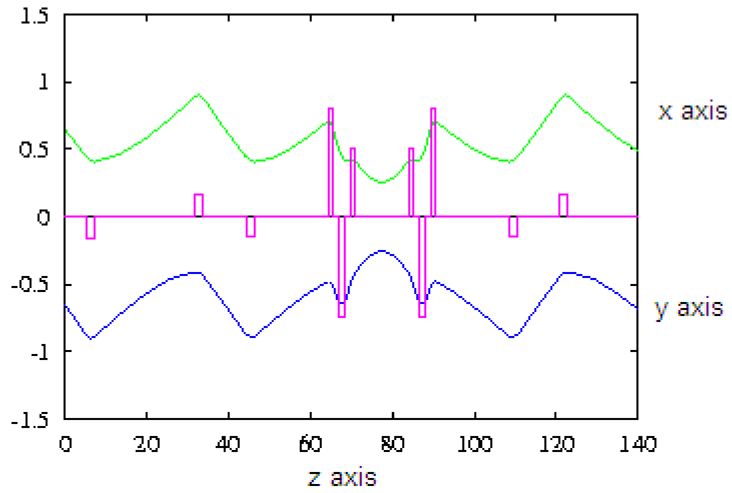

Figure 3.2 Focusing-Defocusing lattice in x-y axis[7]

- Radio frequency quadrupole.

In the Radiofrequency quadrupole (RFQ) the beam is accelerated from 100 KeV to 8 MeV and bunched, reducing the halo around the beam. The aim of this pre-acceleration is the optimization of the drift tube Linac section, which needs an input with this energy for taking profit of the 175 MHz frequency it is fed with. Along this cavity, not only acceleration is given to the beam, but also transverse and longitudinal focusing.

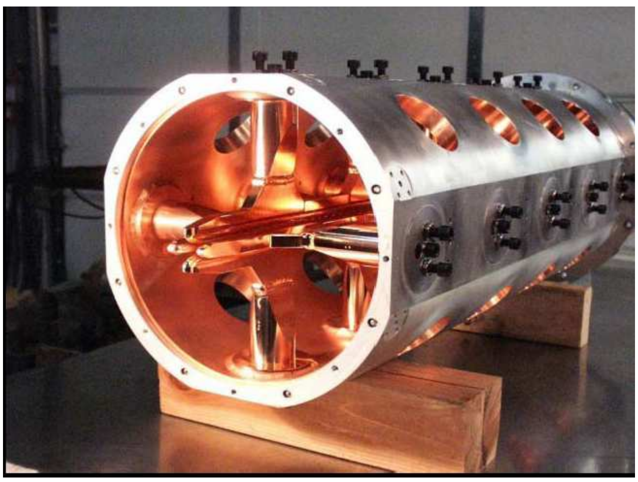

Figure 3.3 Example of RFQ cavity[8]

An easy way of reducing the number of particles in the halo is spreading them against the walls of the cavity. Care has to be taken for avoiding this spreading at the downstream part of the RFQ, since the more energetic they are, and the more problematic they can result.

- Matching section

Next part is a still not defined matching section between RFQ and the Linac. Its function will be a even more accurate adaptation for the Linac input than that of the RFQ.

- Linac

The Linac is the main and more complicated part of the accelerator, where the beam is accelerated from 8 to 40 MeV. This is the part were more modifications from the initial design have been taken into account. The alternative chosen for this study is a superconducting (sc) Linac with Half-wave Resonators (HWR).

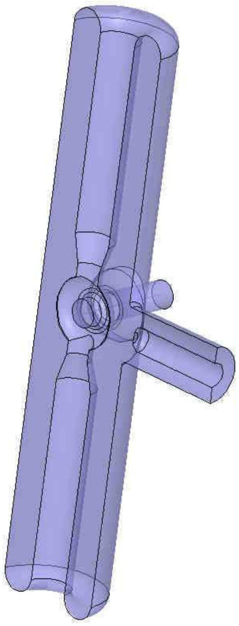

Figure 3.4 Half-wave Resonator Section. [4]

A Half-wave resonator (Figure 3.4) is a cavity made to match its measures with half the wavelength of the electric field in it. These way a resonance is generated and the amplitude is enhanced, and the energy associated to it (and transmitted to the particles) is much higher.

These cavities have to be kept under cryogenic conditions. With this aim, there have been designed the cryomodules, in which both the cavities and solenoid packages will be housed.

The accelerator is formed by four cryomodules. In each of them there is an insulating vacuum avoiding heat transfer between cryogenics and room temperature environment. There is a variable number of solenoid packages and cavities per cryomodule.

The so-called solenoid packages are focusing elements in which there is a superconducting magnet (fields of up to 6 T), a couple of steering coils and a couple of Beam Position Monitors (BPM). Obviously, superconducting magnets need cryogenic temperatures also. Their working Temperature is 4.2K, and it will be reached with Liquid Helium (LHe) cooling technology.

The reason why superconducting magnets is needed is the large current and power in the accelerator. The repulsion of deuteron ions is important in these conditions and magnetic fields needed are intense.

As Table 3.2 shows, solenoid packages are placed after every cavity in first cryomodule, after every 2 in the second one and after every 3 in last two.

Cryomodule	# Cavities	# Sol. Pack.
1	8	8
2	10	5
3	12	4
4	12	4

Table 3.2 Cavities and solenoid packages per cryomodule.

Each of these components (either solenoid package or resonator) has its own He tank. This is an important issue seen from the maintainability point of view. Problems concerning a single element will be solved without affecting the others, so bringing the accelerator back to operational conditions will be easier and faster.

In each He tank the contained component is kept in a biphasic He bath (a bath changing its phase is the best way of transferring heat). In Figure 3.5, a 3D view of the first cryomodule (with 8 cavities and 8 solenoid packages) can be seen.

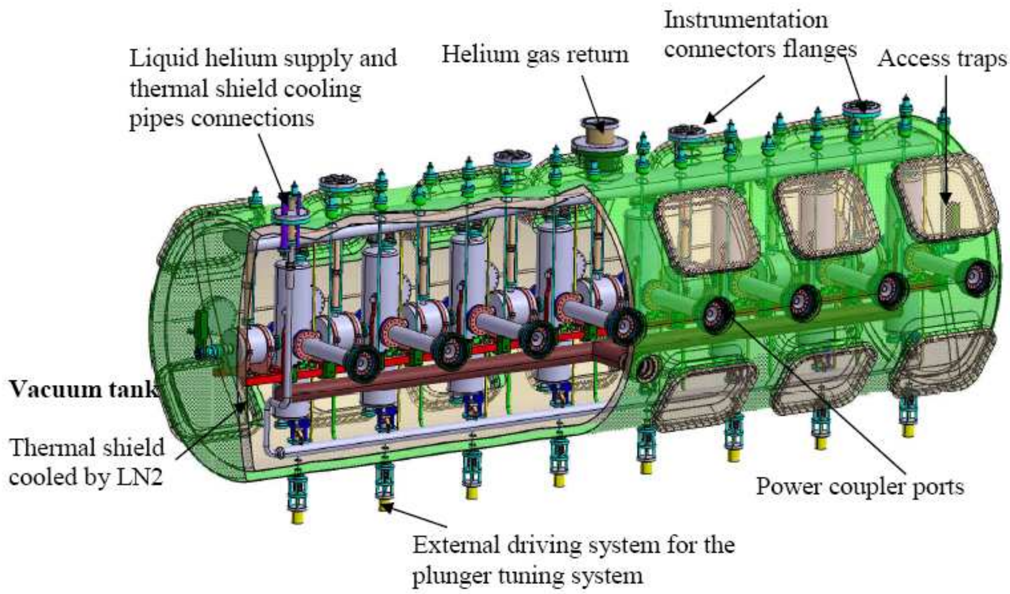

Figure 3.5 First cryomodule 3D view. [4]

Choosing a superconducting option has some drawbacks, such as the need of cryogenic conditions or insulation vacuum. Anyway, there is an important power saving (superconducting means less resistance and less power losses) and length reduction of the beam line compared with Alvarez Drift Tube Linac considered in CDA.

Other aspects as availability improvement due to possible operation under single cavity failure have not been taken into account in this first conservative model. [9]

- High Energy Beam Transport

HEBT drives the beam from the Linac to the target. This is the longest part of the accelerator, and it is critical since highest energetic particles (40 MeV) are driven through it. Moreover, the footprint on target is very specific (rectangular 20 cm X 5 cm) and it has to be obtained in this section [10]. Another function of the HEBT is avoiding recoiled particles to go upstream and damaging the accelerator elements or inner walls. The former is achieved with higher order magnets (octupoles and duodecapoles) while the latter is made by bending the beam with dipoles. By Lorentz's force, a dipole that bends a deuteron going downstream to the right will bend a deuteron going upstream to the right, too, but it would have to be bent to the left to follow the way upstream, so this is a good solution. Since bending radius depends on the velocity of the particles and it is not perfectly uniform (there has to be a longitudinal focusing effort) an important amount of particles will be deposited here and cooling will be especially important. [10]

3.3.2 Target facility

The deuterium beam, accelerated to 40 MeV collides against a liquid lithium target. This may induce a reaction in which high energy neutrons are produced, in a range peaked around 14 MeV. Since the deuteron beam has a high current and the cross section of the reaction is substantial, the flux of neutrons is high enough to reproduce a nuclear fusion energy reactor environment.

The lithium is provided through a loop that recycles it constantly. Its capacity is 21 m^3. These facilities have to purify, chill and monitor the Li flux constantly, to prevent any radiological hazard, and structure erosion. Moreover, Li has to be perfectly isolated from air and water, to avoid combustion. Vacuum conditions around this system are designed to prevent this from happening.

3.3.3 Test facility

The test facilities consist of test cells where the nuclear fusion reactor environment has to be reproduced. There are four different areas depending on the neutron flux they get:

High flux: higher than 2 MW/m^2, rising to temperatures between 250 ºC and 1000ºC. The induced damage higher than 20 dpa/fpy (displacements per atom/ full power year).

Medium flux: Rising to temperatures between 250 ºC and 1000ºC. Damage between 1 and 20 dpa/fpy.

Low flux: Temperature between 80K and 780K. Damage between 0,1 and 1 dpa/fpy.

Very low flux: Temperature between 4K and 570K. Damage between 10^{-2} and 10^{-1} dpa/fpy.

Since materials in and around the test cells may be highly activated, remote handling is needed for manipulation and maintenance operations, both at test cells and PIE (post-irradiation examination) facilities. The range of temperatures also implies cryogenic system necessarily.

3.3.4 Others

Although new technology is being developed, experience says that common failures in support systems are the cause of a great part of the unavailability of the system.

First, the above mentioned facilities have to be placed in any building, the so-called conventional facilities. They have also to be supported by some systems which will be slightly described below.

Conventional facilities are, mainly, the building in which all other facilities and its services will be housed. There will be a single main building, in which all the above mentioned facilities will be, and smaller separated buildings will house support services.

The support services also included in the conventional facilities are:

- Heat extraction system: needed to cool down different parts of the accelerator, the lithium loop and the test cells.
- Power distribution: Each facility needs a high reliability feed to operate safely and efficiently.
- Ventilation and air conditioning: It has to ensure air quality for all the areas where personnel have continuous access. It also has a radiological protection function.
- Water system: Providing water both for operation (demineralized) and domestic use.
- Radioactive waste treatment facilities: Keep activated pieces and liquids for the established time, until primary cooling and proceed in the convenient way in each case.

An important system that should be considered apart is the central control system. The control function will be centralized in a single control room. It will be supported by some instrumentation, monitors, sensors and other ancillary. Despite some automatic responses are designed to be triggered from each system, in general conditions all the control will be performed from the control room.

4. Database

The elaboration of a database was not an objective at first, but it was necessary since failure rate data is difficult to get and no substantially wide database was available. Tests are only run on certain parts, and the rates found in papers and other documentation refer to very specific parts and it is difficult to have a broad view. Sometimes, data refers to systems as a whole and not to components, so it is too general to be taken into account.

Two parameters have been used to define the unavailability. These are the failure rate (λ) and the mean time to repair (MTTR). Since some analyses are series of time dependent simulation (Monte Carlo) a probability distribution of these parameters should be considered.

MTTR is usually distributed as a Gaussian, but taking into account the little data available concerning to it, and the huge variability (the MTTR of the same component depends a lot on the location, environment or vacuum conditions, operating temperature…) its distribution is out of the scope of this first study. Indeed, since operational experience in many systems of this kind of accelerators is little and failure rates are generally big, most MTTR are estimations. Only years of accumulated experience among different accelerators will provide reliable information. It has been chosen a small standard deviation value, compared with the lowest MTTR value. The reason why the definition of the parameters is kept with the Gaussian distribution although it is useless in this study is to make it easier for later updates.

A lognormal distribution has been adjusted to the failure rate, because it is the type of function that best represents the expected electrical and mechanical failures rates, as they can be thought as the multiplicative product of many independent random variables, each of which is positive. No expected early failures have been modeled as single components will be tested before their installation.

ACCELERATOR (A)			Fail. Rate (1/h)	Error factor	MTTR (h)	Main Ref.
element	**code**	**function**				
cable	ACASP####G	supply power	**2,40E-06**	**11,13**	**10**	15, 17, 23
channel (clogging)	ACHCO####G	cooling	**9,40E-06**	**20,89**	**2**	23,30
cold connection	ACCVA####G	vacuum	**1,43E-08**	**34,97**	**10**	15,24,27
control system	ACSCN####G	control	**3,33E-04**	**8,55**	**2**	13,15,17,21
cooling	ACOCO####G	cooling	**3,33E-04**	**3,33**	**2**	13,14,21
diagnostics	ADIDI####G	diagnostics	**4,75E-04**	**5,14**	**24**	11,27
electrical connection	AECCN####G	control	**5,00E-05**	**500,00**	**24**	17,18,26,28
feedthrough	AFGVA####G	vacuum	**5,00E-05**	**14,80**	**12**	24,29
gas pipes	AGPCO####G	cooling	**2,00E-09**	**2,86**	**10**	23,27
H2 delivery	AH2IN####G	injection	**2,80E-05**	**138,97**	**10,5**	23,27
He tank connections	AHCCO####G	cooling	**1,43E-08**	**13,99**	**10**	15,24,27
He tank weld	AHWVA####G	vacuum	**1,00E-08**	**20,00**	**10**	20,24,25
heater (chiller)	AHECO####G	cooling	**8,00E-04**	**400,00**	**24**	16,23,27
high voltage power supply	AHVSP####G	supply power	**1,67E-05**	**62,50**	**24**	11,15,30
LHe pipes	ALPCO####G	cooling	**5,00E-07**	**250,00**	**10**	15,23,30
llrf	ALLCN####G	radiofrequency	**1,00E-05**	**10,00**	**1**	14,15
Passthrough (elect. Con.)	APTVA####G	vacuum	**1,22E-05**	**10,00**	**24**	14,15,27
pickup/connectors	APUSP####G	supply power	**5,00E-08**	**1,80**	**24**	29,30
pipe (leakage)	APICO####G	cooling	**1,20E-09**	**8,33**	**10**	20,23
power supply	APSSP####G	supply power	**1,86E-04**	**10,30**	**1**	13,14,16,27
pump	APUCO####G	cooling	**2,80E-05**	**1,75**	**10,5**	15,23,24
rf amplifiers (tube)	AAMRF####G	radiofrequency	**9,09E-05**	**30,30**	**8**	11,12,14,15,19,21
rf transport	ARTRF####G	radiofrequency	**1,00E-06**	**10,00**	**10**	17,31
rf window	ARWVA####G	vacuum	**1,22E-05**	**30,50**	**24**	14,15,27
sealing	ASGVA####G	vacuum	**5,00E-07**	**10,00**	**10**	24,27
temperature sensor	ATSCO####G	cooling	**7,00E-07**	**14,43**	**3**	23,24,30
vacuum pumping	AVPVA####G	vacuum	**8,00E-04**	**17,39**	**24**	24,27
valve	AVAVA####G	vacuum	**1,54E-07**	**19,44**	**24**	14,24,27
valve	AVACO####G	cooling	**2,60E-06**	**1,17**	**4**	23
valve operation	AVAIN####G	injection	**1,25E-04**	**10,00**	**1,7**	20,23
warm connection	AWCVA####G	vacuum	**5,71E-09**	**10,51**	**10**	24,27
weld	AWGVA####G	Vacuum	**6,00E-08**	**8,33**	**10**	20,24,25

Table 4.1 IFMIF Accelerator failure rate and MTTR database.

The parameter with which de deviation from the mean is defined is the error factor (EF). Some data was available with its error factor [30]. In the other cases (the most) it has been calculated with:

$$EF_1 = \frac{\lambda_{high}}{\lambda_{mean}};$$ Eq. 4.1

$$EF_2 = \frac{\lambda_{mean}}{\lambda_{low}};$$ Eq 4.2

Where λ_{mean} stands for mean failure rate, λ_{high} for a higher value of the rate, often from different bibliography, and λ_{low} for a lower one, under same conditions.

The election criterion followed was choosing the one calculated from operational data when possible. When both or none did so, the bigger EF was chosen.

Since it was only understood as a mean and its extension was not large, Microsoft Excel® was considered a useful tool, and no software specific for databases was used.

A hard task of comparing available data from CDA, CDR and KEP to many others was made leading to a solid database, especially referring to the failure rate. The parameters used for this model are the shown in Table 4.1. On the right hand side there are the references to the documents from which data of each basic event was extracted.

In the second column a code can be seen. This is the codification used for RiskSpectrum® basic events and it is convenient to explain it in this report.

4.1 Codification

Having a common codification for every system in IFMIF is an advantage for understanding and exchange of information. Previously, a codification was developed for the basic events of the target facilities in [4]. In this text a slight change is proposed to the previous referenced, since it makes it easier to recognize the function that basic events have and to search them if necessary. The notation used is the following:

S	CC	FF	IIII	M
system	component	function	Part(1) + spare(1) + number(2)	Failure mode

Table 4.2 Codification of basic events for IFMIF.

A ten-characters code gives us all the information of the basic event.

The modification is introduced in the function characters (FF). They were defined as two numbers and have been used as two letters in this project. This makes the codification more intuitive, and logical. The only logical correlation of functions (of the components of the accelerator, in this case) and numbers would be numbering the functions as they appear along the beam. However, the creation of a fault tree is made step by step as information is provided and further functions can be considered upstream when an important part of the model is already made, so functions should be renumbered or numeration would be useless. Moreover, as only two numbers are dedicated to name the function only 100 functions can be described. Letters, properly used, can provide an idea of the function by only reading two of them. Furthermore, possible updates need no modification of current notation.

component	**CC**
cable	CA
channel (clogging)	CH
cold connection	CC
Cooling system	CO
Diagnostics	DI
Electrical connection	EC
Feedthrough	FG
Gas pipe	GP
H2 delivery	H2
He tank connections	HC
He tank weld	HW
Heater (chiller)	HE
High voltage power supply	HV
LHe pipes	LP
Low level Radiofrequency	LL
Passthrough	PT
Pick-up/connectors	PK
pipe (leakage)	PI
Power supply	PS
Pump	PU
RF amplifiers	AM
RF cavity	CV
RF coupler	CR
RF transport	RT
RF window	RW
Sealing	SG
Solenoid package	SP
Temperature sensor	TS
Vacuum pumping system	VP
Valve	VA
Warm Connection	WC
Welding	WG

Table 4.3 Components codified for IFMIF Accelerator model.

Here a brief explanation of the codification is presented:

S: Letter to design the system or facility of the basic event. Along this project it will always be A, referring to Accelerator.

CC: Two characters referred to the component name. All components considered in this study are included in Table 4.3.

FF: Two letters giving an idea of the function of the component or the function that failure of the component could lead to miss (for example, rupture of RF window means vacuum loss). The main accelerator functions are exposed in Table 4.4.

Function	**FF**
Control	CN
cooling	CO
Diagnosis	DI
Focus beam	FB
Injection	IN
Radiofrequency feed	RF
Supply power	SP
Vacuum	VA

Table 4.4 Functions codified for IFMIF Accelerator model.

IIII: First letter refers to accelerator part. Second will be X along this project, since its function is to identify components on use from spare ones, which will be named with correlated letters A, B,… The last two are numbers: an index to distinguish components from each other.

Accelerator part	**I**
ion source	I
LEBT	L
RFQ	R
Linac (drift tube linac)	D
HEBT	H

Table 4.5 Accelerator parts codified for IFMIF Accelerator model.

M: failure mode. Along this project will always be global failure, G.

5. FMEA

As said in the preface, a FMEA (Failure mode and effect analysis) is necessary for the development of a fault tree. This is a study in which the failures of components are analyzed in order to know their contribution to unavailability of the accelerator. Further studies can be made to determine wrong operation parameters that could lead to less power delivery to target, but here attention is put in components which failure means beam loss.

The FMEA guide used is [32], that was developed by INFN, CEA, CNRS, ENEA and IBA, most of them also working for IFMIF. In that guide are considered the modes by which accelerator can lead to wrong operation, but only those that have severity 3 on beam, which means no beam on target, have to be considered for the availability analysis. It also has to be considered that the state-of-arts does not allow to go deep into details, since final configurations and redundancies are not known, yet.

Moreover, this is a first study and further failure modes can be considered in future, while others can be omitted since demonstration shows they do not lead to beam loss or the failure rate they are associated is demonstrated to be negligible.

The following is a brief explanation of the components which failure is studied. Then Table 5.1 shows the failure modes considered of the different components.

COMPONENT	CODE	CAUSE
Cable (HVPS)	ACASPIX01G	Ageing
		Insulation loss
		Short circuit
Cable (magnet)	ACASPIX02G	Insulation loss
	ACASPLX##G	Failure to reach RF field
	ACASPRX01G	Ageing
	ACASPDX##G	Radiation exposure
	ACASPHX##G	
Channel (clogging)	ACHCORX01G	Loss of water circulation
Cold connections	ACCVADX##G	Leak when P>Pcrit. Beam vacuum loss
Control system	ACSCNIX01G	Human error and different components failure
	ACSCNLX01G	
	ACSCNRX01G	
	ACSCNDX01G	
Cooling (dipole)	ACOCOHX##G	Loss of water cooling system

COMPONENT	CODE	CAUSE
Cooling (confin. magnet)	ACOCOIX01G	Insufficient cooling. Overheating
Diagnostics	ADIDILX01G	Human error and different components failure
	ADIDIHX01G	
Electrical connection (CS)	AECCNIX01G	Bad electrical connection in protection and control system
	AECCNDX01G	
Feedthrough	AFGVARX01G	Lechanical break. Vacuum loss
	AFGVADX17G	Mechanical failure. Beam vacuum loss
Gas pipes	AGPCODX01G	Leak. Insulation vacuum loss
h2 injection system	AH2INIX01G	H leak in the injection system. Possible ignition.
He tank connection	AHCCODX01G	Leak. Insulation vacuum loss
Heater/chiller	AHECORX01G	h/c failure. Loss of temperature control
High voltage power supply	AGVPSIX01G	Sparks
		Power supply failure
		Insufficient cooling
		Accidental disconnection
Injection valve	AVAINIX01G	Failure in valve operation. Valve closed
Liq. He Pipes	ALPCODX01G	Leak. Insulation vacuum loss
Low Level RF	ALLRFRX01G	Failure in LLRF control system
Passthrough	APTVADX18G	Mechanical break. Insulation vacuum loss
Passthrough (electrical)	APTVADX01G	Mechanical break in electrical passthrough
Pick up/connectors	APKSPRX01G	Broken. (failure to reach RF field)
Pipe (leakage)	APICORX01G	Loss of water circulation
Power supply (magnet)	APSSPIX01G	Power supply failure
	APSSPLX##G	
	APSSPRX01G	
	APSSPHX##G	
Pump	APUCORX01G	Loss of water circulation
RF amplifier (ion source)	AAMRFIX01G	Power supply of RF device
		Amplifier failure
		Cooling system failure
RF amplifier	AAMRFRX01G	Modulator failure
	AAMRFDX01G	Power supply
		Power coupler failure
		RF pick-up failure
		Short in the power coupler antenna
RF transport	ARTRFRX01G	Failure in rf feed
	ARTRFDX01G	
RF window	ARWVAIX01G	Rupture. vacuum loss
	ARWVARX01G	
	ARWVADX##G	

COMPONENT	CODE	CAUSE
Sealing	ASGVARX01G	Leak. Beam vacuum loss
	ASGVADX##G	
Temperature sensor	ATSCORX01G	Loss of temperature control
Vacuum pumping	AVPVARX01G	Wear out
		Loss of power
		Mechanical failure
		Cooling system failure
		Electronics failure
Valve (cooling)	AVACORX01G	Mixing valve failure
Valve (vacuum)	AVAVADX18G	Leak in valves
Warm connections	AWCVADX##G	Leak in connections. Loss of Beam Vacuum
	AWCVAHX##G	
Welding	AWGVADX##G	Leak on a cavity weld. Beam vacuum loss
	AWGVARX01G	Leak. vacuum loss
welding (beam vacuum)	AWGVAHX##G	Leak in weldings. Loss of Beam Vacuum
Welding (insulation vac)	AWGVADX18G	Insulation vacuum loss

Table 5.1 IFMIF Accelerator Failure Mode Effects.

The following is an explanation for more clarity of the components which failure mode has been considered:

Cable: The cable failure modes considered refer to those feeding the High Voltage power supply and the coiling cable of electromagnets and superconducting magnets.

Channel: The clogging of a water channel would hamper the cooling of the RFQ.

Cold connections: It is referred to connections under cryogenic conditions. The leaks in them mean the loss of the beam line vacuum.

Control system: failures in control system are critical and often difficult to be detected. Control system is complex and further detail is recommended for proper definition. Human error is an important factor during operation.

Cooling: This basic event refers to the cooling in two magnetic devices:

- The first is the confinement magnets in the ion source. The microwave radiation for heating the plasma also heats them up and a efficient cooling system is needed.

- The others are HEBT dipoles. Especial care has to be taken in these devices since bending is not perfect and beam loss in them is important.

Diagnostics: Beam goes through these devices, so their radiation exposure is constant. This is why the components in them are more likely to fail and are more difficultly repaired or replaced. Further study is recommended and robustness is especially needed here.

Electrical connection: Failures referred to the electrical connections in the control system, which can be critical in actively controlled parts of the accelerator.

Feedthrough: Conductions that connect vacuum areas with vacuum pumping devices out of them.

Gas Pipes: Pipes conducting He in gaseous state.

H_2 injection system: It feeds the plasma chamber with H_2. There is hazard of combustion or explosion of H_2. Conditioning is very important.

He tank connection: Connections to the cryogenic helium tanks from the insulation vacuum involving them in the cryomodules.

Heater/Chiller: It is the main element for control of temperature. Its malfunction, as will be shown later, is critical.

High Voltage Power Supply: Refers to the HVPS in the ion source. Further configuration study is recommended since more detailed operational data is available.

Injection valve: Failure in the aperture of the valve feeding the gas to the plasma chamber.

LHe pipes: Pipes conducting He in liquid state.

Low Level Radiofrequency: tuning device for matching radiofrequency to the accelerator needs.

Passthrough: Penetrations through which electrical, cryogenics, and vacuum connections are made.

Pick up/connectors: Electrical plug to feed RFQ.

Power supply: The power feed of the magnets. Have to reach the needed field to focus the beam.

Pump: device to circulate water in the RFQ cooling system.

RF amplifier: tube amplifiers that generate the electrical fields in the cavities or the ion source.

RF transport: coaxial transporting the RF power from the amplifier to the cavity.

RF window: radiofrequency passthrough in the cryomodules. It has to minimize losses and ensure the maintenance of vacuum and cryogenic conditions inside them.

Sealing: Elements that ensure the vacuum lines are perfectly hermetic.

Temperature sensor: Thermocouples in the RFQ cooling system.

Vacuum Pumping System: system that ensure the vacuum in RFQ cavity. Further study is recommended since RFQ is a long complex section and ensuring vacuum conditions may be complicated.

Valve: elements permitting or avoiding the pass of liquids and gases through them. They are especially important in the vacuum and cooling systems.

Warm connections: connections out of cryogenic environments.

Welding: Leaks in vacuum environments may be produced for wrong welding. Proper testing is recommended before installation.

6. Fault tree

The fault tree is the confluence between the failure data, the FMEA, and the knowledge of the accelerator. When all that information was collected (in fact, while it was being collected, since there are updates constantly and the beginning could not be delayed until all data was available) some shaping effort had to be made. The objective is to represent as accurately as possible the configuration of the accelerator, but avoiding details that provide more confusion than information. The more progress is made in the design and demonstration, the deeper the model can be developed. Studying first on this fault tree the behavior of the accelerator under parameter or configuration changes, as under redundancies, can help the designers to know in which way improving effort is more efficient and focus on it.

As commented at the beginning of this report, this fault tree takes into account, part by part, all the systems that provide unavailability. This is a top-bottom or array-to-leaves design. This meant conferring the convenient ranks to the systems and component that could be subdivided in more specific basic events. Sometimes, such subdivisions were impossible, so there are some incoherencies in the model caused by the fact that systems such as vacuum pumping system are basic events and in the same branch a simple magnet is a gate from which power supply and coiling cable hang.

First thing is showing the working interface symbols:

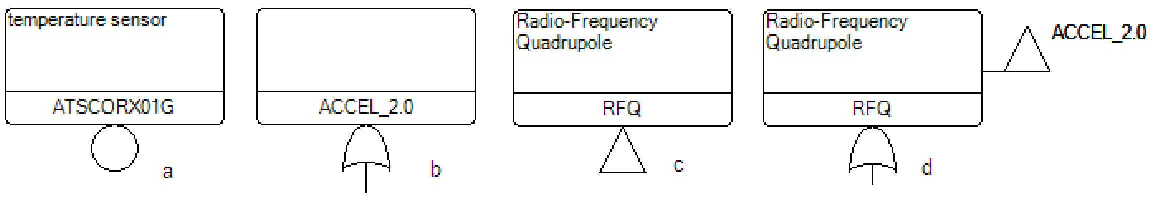

Figure 6.1 RiskSpectrum® gates. a) basic event gate. b) OR gate. c) Transfer gate (from array to branch). d) Transfer gate (from branch to array).

Gate *a* corresponds to basic events, i.e. the leaves in the fault tree model. Gate *b* is a typical OR gate, it is unavailable if any of its branches is unavailable. Gate *c* is a link to a branch fault tree which hangs from it. Using transfer gates makes the model easier to be understood. If the top gate of a fault tree is connected to a more generic one it looks like gate *d*.

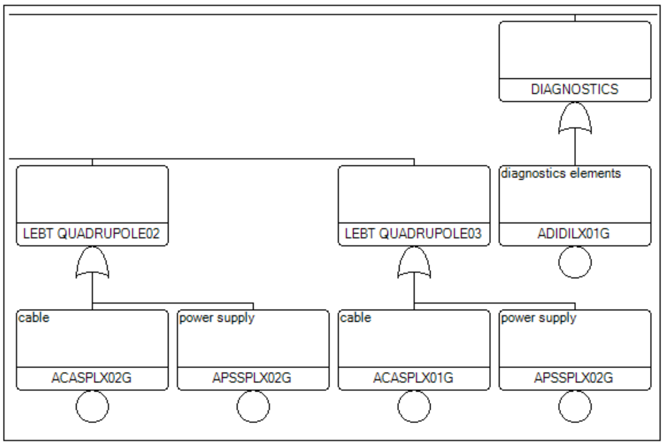

Figure 6.2 Section of IFMIF LEBT fault tree.

In Figure 6.2 a cut of the LEBT fault tree can be seen. This cut has been chosen to reflect the mentioned problem: simple electromagnets are gates, fed by basic events as detailed as a power supply and a coiling cable, whereas complex diagnostic devices are considered basic events.

Incoherence concept is related to the failure rate divergence of elements in the same level of a fault tree.

As an example, let's check figure 6.3. Consider the unavailability of a basic event is the number in its box. At gate X the failure rate is much lower than that of basic event Y. This makes the presence of the branch hanging from gate X is not necessary and its presence is an incoherence in the model.

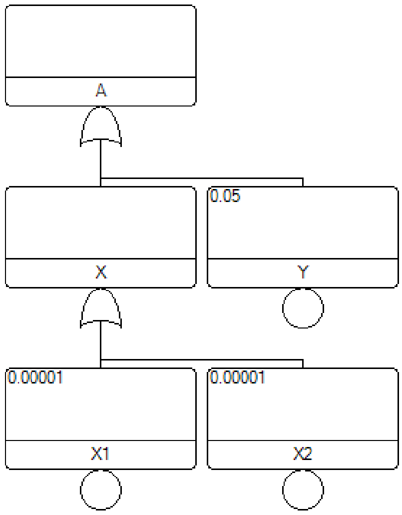

Figure 6.3 Incoherent fault tree example.

Despite that, the presence of incoherence has not been corrected in the fault tree because, as design activities progress, some basic events will become gates and coherence may be achieved. If the experience shows that any branch is actually incoherent, it can then be taken away. Until then, the presence of this components, although little important in their contribution to unavailability, provide valuable information of the accelerator layout, and keeping them makes the accelerator description more complete.

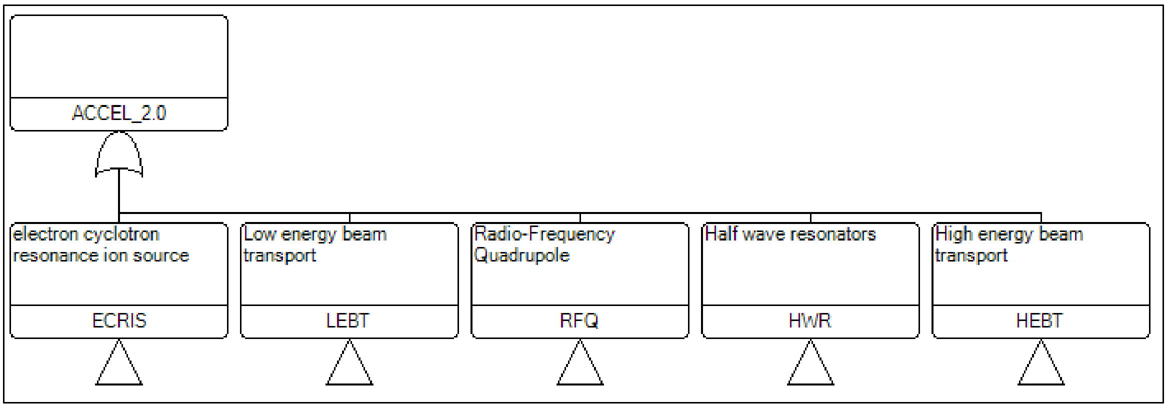

Figure 6.4 IFMIF Accelerator fault tree top gate.

Figure 6.4 shows the top fault tree. Each part is designed as a different fault tree in which each system involved in it is considered. All the fault trees are shown in Appendix A.

7. RAM Analysis

7.1 Basic concepts

The basic concepts necessary for the understanding of the RAM study are:

- Unavailability of A: Probability that A is failed at a given time point.
- Failure rate of A (h^{-1}): Probability that A fails per hour.
- Mean time to repair of A: Time estimated from the failure of A until beam operation is restored.
- Sensitivity of A: Variation on the total unavailability associated to variations on A parameter.
- Importance of A: Fraction of total unavailability caused by unavailability of A.
- Uncertainty of A: The probability variation associated to the fact of having limited knowledge on a parameter A.

7.2 Reliability and availability analysis

7.2.1 First results

The RAM Analysis (Reliability, Availability and Maintainability) is the final step of this project. Once the fault tree was built, departing from the database and the FMEA, different analyses were run on the model.

As mentioned in IFMIF presentation, two kinds of maintenance stops are programmed. Then, there have been simulations defined for the study of each case. The first and main is a simulation of 160h operation runs (one week is 168 hours and the 8 hours of scheduled maintenance are subtracted). However, maintenance activities on some elements cannot be performed during such a short period, since they are in a vacuum environment or at cryogenic temperatures. It is not possible to bring those elements to room conditions, do the maintenance and bring them back to operating conditions in 8 hours. This is why simulations of uninterrupted operation for eleven months have also been run. The results were very similar for both cases and only data of the first one will be explained here, since the time intervals in which interesting events occur are more important compared to the analysis time, and consequently they are easier to analyze visually with graphics, as shown in Figure 7.1. In 160h case (up) availability tend asymptotically to 88.05%. In the 8000h (down) one it tends to 88.04%. First diagram is more graphically informative than second.

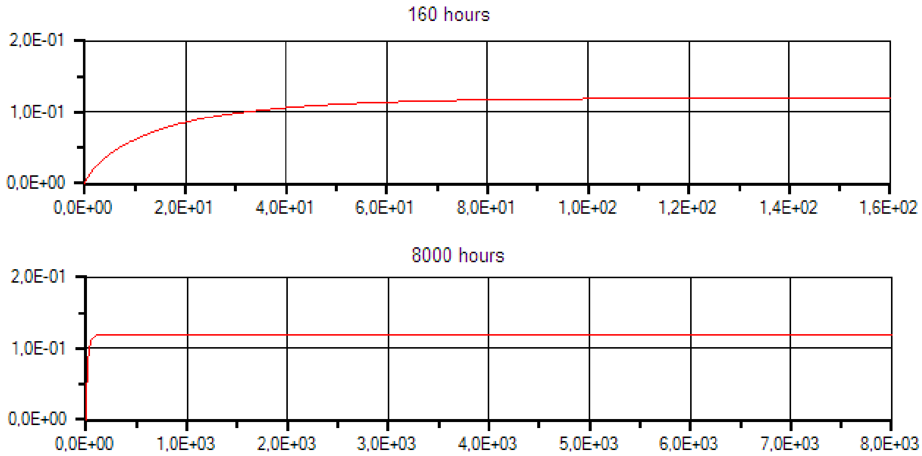

Figure 7.1 Time evolution of unavailability for WEEK simulation (160 hours, up) and for YEAR (8000 hours, down).

From now on, all the reported results will be referred to 160h, namely WEEK, simulation. Some analysis options were changed for more strength of the results. Number of simulations per analysis was raised from 1000 to 10000. The default analysis stays at a first order approximation and it has been changed to third order of approximation, too. This did not mean a significant increase in calculating time nor substantial results variation. The obtained results on the analysis run over the different fault trees are presented in next table:

	Availability	5%	95%
ACCEL_2.0	0,88	0,9754	0,735
ECRIS	0,99532	0,99917	0,99023
HEBT	0,9816	0,99542	0,9521
HWR	0,9505	0,99609	0,846
LEBT	0,9877	0,99795	0,9649
RFQ	0,96	0,99827	0,9112

Table 7.1 Availabilities of IFMIF accelerator and its main parts with the 90% confidence interval.

The first column gives the more substantial information of this project. It is the rate of operating expected time over the scheduled operation time. All the results are consistent with bibliography and total accelerator availability perfectly matches the desired value.

The first row refers to the total accelerator availability. It has to be exposed that this number has not been sought. The degree of coincidence with the desired value is impressive, it only differs in 0.04% (the actual obtained value is 88.04%), but no modification (at all) of the model has been made to get this value. Quite the contrary, completely new design of the fault tree brought to such a result, giving both results (the obtained with CDA and the obtained here) consistency and reliability.

On the other hand, its consistency depends on the consistency of all the previous steps. As modifications are made on the design and operation data is collected the model should be corrected, getting accuracy step by step. Nowadays, the most of the weakness of the model is associated to the MTTR.

The other rows report the availabilities calculated from the independent fault trees of each part.

7.2.2 Time dependency

The evolution of unavailability with time is an interesting study. The first thing to do is considering the time dependent unavailability. This way the variability of the parameters can be controlled with the error factor and standard deviation associated to them. The error factor introduced made that unavailability of different components shifted among the desired range. Again, the changes in the results were little.

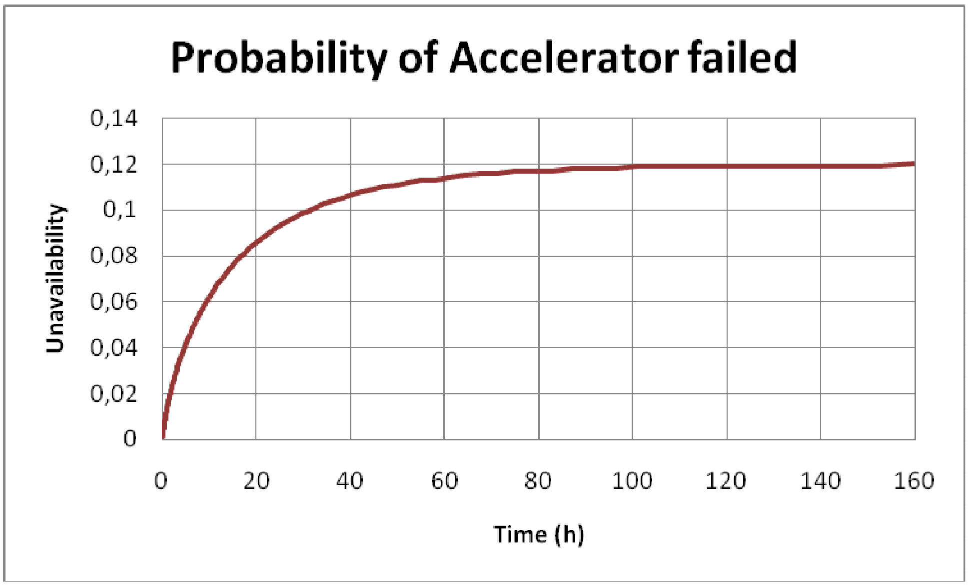

Figure 7.2 Accelerator unavailability temporal evolution.

Checking the figure 7.2 it is noticeable that during the first 80 hours there is the most important raise in the probability of the accelerator is failed. Passed that time availability is almost constant. It is easily explained since unavailability evolves as a constant minus a negative exponential function. The exponential tends to zero as time increases and the constant value is the remnant.

$$Q(t) = \frac{\lambda}{\lambda+\mu} \cdot \left[1 - e^{-(\lambda+\mu)\cdot t}\right]; \qquad \text{Eq. 7.1}$$

where λ stands for failure rate and μ for the inverse of mean time to repair.

Physically, this means that the lower a failure rate is, the bigger the μ will be compared to it and the smaller the constant remnant value will be. For the same reason, the time dependency is all in μ. Then it is logical that unavailability tends to the constant value in MTTR scales of time. As MTTR of basic events in LEBT are bigger than those in ECRIS, the unavailability of the former evolves more slowly.

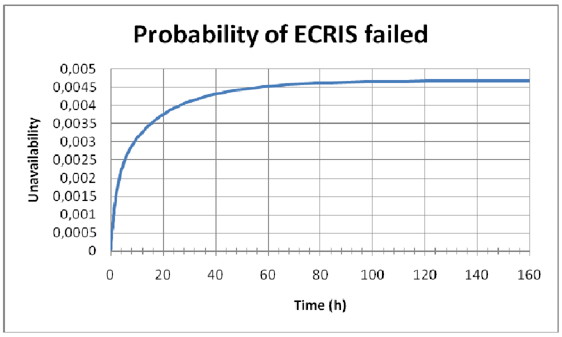

Figure 7.3 Ion source unavailability temporal evolution.

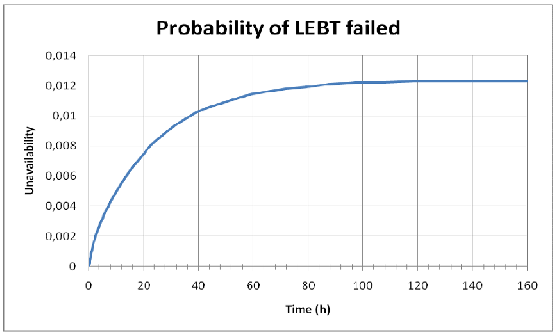

Figure 7.4 LEBT unavailability temporal evolution.

7.3 Importance analysis

It is possible to identify the basic events that have greater importance to the global unavailability by analyzing the minimal cut set analysis. The goal of the minimal cut set analysis is to generate the so-called minimum cut sets of the fault tree and to perform a point-estimate quantification of the top event. A minimal cut set is a combination of events, which cause the top event to occur, and the term “minimal” means that if any of those events is removed from the set, the top event does no longer occur. Since basic events are considered independent in RS and all the gates are OR gates, any basic event out means no-beam. The adaptability of the model makes possible future modifications where MCS are a bunch of basic events, using AND Gates.

The importance is the percentage of the total unavailability due to a single basic event. In this study, the fractional contribution (FC) variable has been chosen to describe the importance. The FC is calculated as:

$FC = 1- (1/I^R_i)$; Eq. 7.2

where the I^R_i is the risk decrease factor. The risk decrease factor is calculated as

$I^R_i = Q_{top}/Q_{top}(Q_i=0)$; Eq. 7.2

in other words, the fraction between the accelerator unavailability and the accelerator unavailability with the MCS that contain the unavailability of basic event “i” in zero. That means all the MCS that contain the basic event “i” do not cause accelerator unavailability. A low FC value (zero is the minimum) indicates that basic event “i” has a weak influence on total unavailability; whereas a high FC value indicates a strong relationship between those MCS that contain the basic event and the accelerator unavailability. In conclusion, the FC is a good indicator of the portion of the unavailability due to a basic event "i" unavailability.[33]

	Basic event	FC	Description
1	AHECORX01G	14,10%	Heater/chiller. RFQ cooling system
2	AVPVARX01G	14,10%	Vacuum pumping system. RFQ
3	ADIDILX01G	8,39%	Diagnostics. LEBT
4	ADIDIHX01G	8,39%	Diagnostics. HEBT
5	AECCNDX01G	0,88%	Electrical Connection. DTL control system
6	AECCNIX01G	0,88%	Electrical Connection. ECRIS control system
7	AAMRFDX39G	0,54%	RF Amplifiers. DTL RF System
8	AAMRFDX40G	0,54%	RF Amplifiers. DTL RF System

Table 7.2 main basic events ordered per Factor Contribution

7.4 Critical component identification

In table 7.2 the basic events with biggest FC are presented. There are two main basic event which have a 14,10% of total unavailability contribution. Engineering effort should firstly be focused on checking the quality of this result and studying ways of reducing the influence. This could be made reducing either the failure rate or the mean time to repair. Another path that is convenient to take into account is the introduction of redundancies.

Among the more important, it has to be highlighted the importance of the RFQ cooling system chiller. The other basic events with FC > 1 are referred to systems, so as their design detail improves their influence can be reduced. Anyway, diagnostics devices are radiated by the beam, so they are critical elements to be repaired, in case of failing.

A thing that is not noticeable without certain knowledge of the model is the influence of the RF amplifiers. Only two of them have been exposed in Table 7.2, but from number 7 to 48 ordered by FC are the 44 RF amplifiers that feed the accelerator. The 0,54% of influence of each of them means a total FC of 23,72%, being the biggest value. A parametric study is made on their MTTR and also on the MTTR of the RF windows (there also are 44 of them), since they are industrial components, product of mass-production, and a parameter change in them may mean important variations in the overall result.

7.5 Sensitivity analysis.

The sensitivity is the variable that represents how the variation in the top gate can be caused by variations in the parameters of basic events. Then this is a independent study on each parameter, not considering the basic events as a whole. It has been calculated as the fraction between $Q_{top,u}$ (the unavailability of the model considering the parameter ten times higher, sensitivity factor = 10) and $Q_{top,l}$ (the unavailability of the model considering the parameter ten times lower). A low sensitivity value (the minimum value is 1) indicates that the variation in the basic parameter does not affect the global unavailability; whereas a high sensitivity value indicates that little variations in the parameter mean high variations in the final result. In conclusion, sensitivity explains the evolution under parameters changing. [33]

This study is based on two different measurements, the sensitivity and the before studied importance.

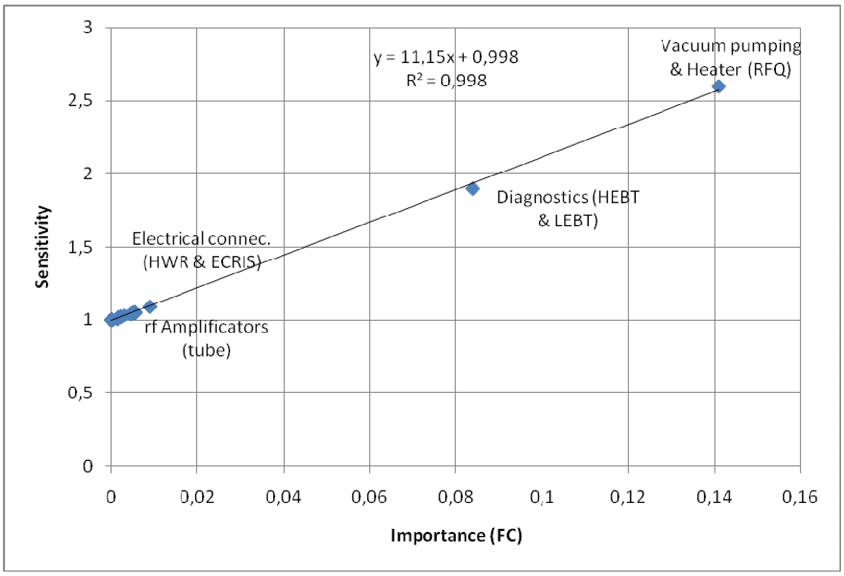

Figure 7.5 Accelerator sensitivity vs Importance

The main reason for doing this kind of graphic analysis is detecting any element which has a low importance but a high sensitivity, which would fall in the encircled area in figure 7.6

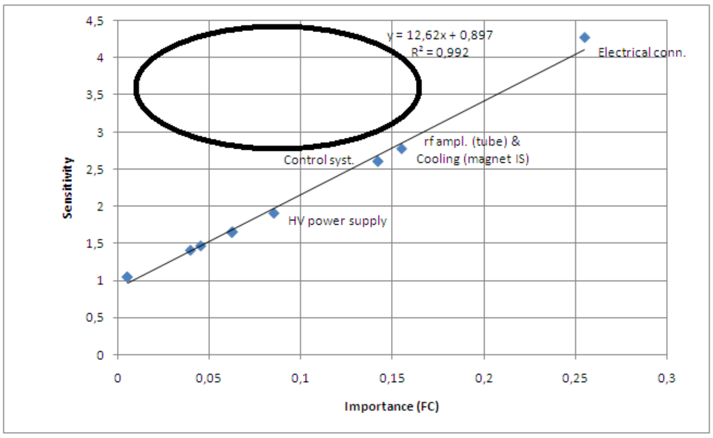

Figure 7.6 ECRIS sensitivity vs Importance.

Such values would mean an anomalous behavior of the model under the parameters they are referred to. The low importance they would have associated would not be a reliable information, since overall values are very sensible to little change in them. None of such elements are present in the model. However, basic events with high importance have associated extremely large sensitivites, as seen in LEBT.

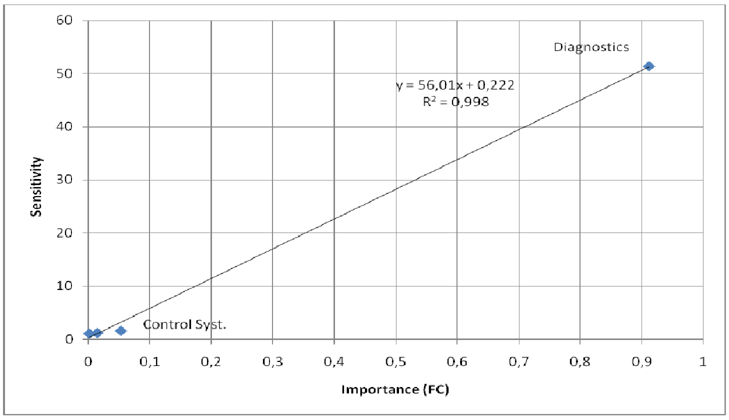

Figure 7.7 LEBT sensitivity vs Importance.

Almost all the importance in LEBT fault tree is associated to its Diagonostics. The sensitivity of this fault tree to its parameters is very important (compare with values on Figures 7.5 And 7.6)

Similar behavior are observed in the RFQ under the Vacuum pumping system and the heater/chiller and in HEBT under the same Diagnostics device

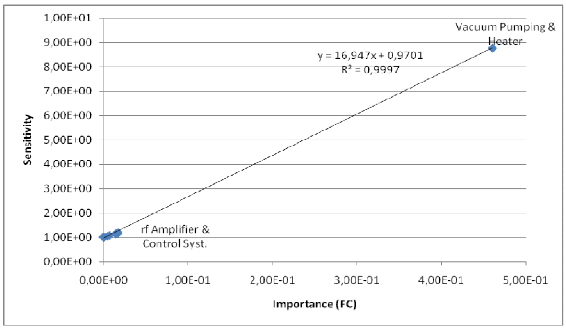

Figure 7.8 RFQ sensitivity vs. Importance.

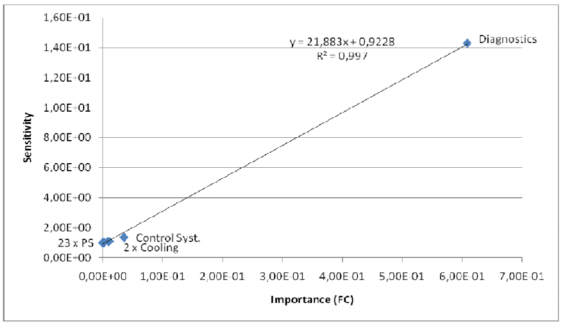

Figure 7.9 HEBT sensitivity vs. Importance.

HEBT and LEBT Diagnostics are exactly the same in this model. The difference in the sensitivities in each case is a consequence of the rest of the tree. LEBT is the simplest part of the accelerator, so it is logical that a critical device, such as Diagnostics, has a paramount importance in its availability.

Diferent basic events are considered independent in RiskSpectrum®. Due to this consideration it can be seen in Table 7.2 that their importance in the complete accelerator fault tree is the same.

It can be concluded that the simpler a tree is, the bigger the sensitivities of each parameter are, so the effective sensitivity should be measured in the complete accelerator fault tree.

7.6 Parametric analysis

A parametric analysis is the study of the parameters of a basic event. The parameter is changed and the analysis is run to compare with the results of the model.

Two of such analyses were made on the model. The first one was changing the RF Window MTTR from 24 hours to 48. The second was changing the RF Amplifiers MTTR from 8h to 4h.

These are examples of the way that maintenance effectiveness and spare part availabilities should be studied on the model.

7.6.1 RF Window. MTTR 48 hours.

Radiofrequency window is an element that is likely to be critical since it is the way of feeding the RF power from the amplifiers, at room conditions, into the cryomodule, which has the cryogenics in an insulation vacuum. Its rupture would mean a loss of vacuum. Pressure should be raised for reparation and lowered again for operational temperature to be reached. Such procedure, added to the typical reparation time, could have many complications and a discrete parameterization of this fact is studied here.

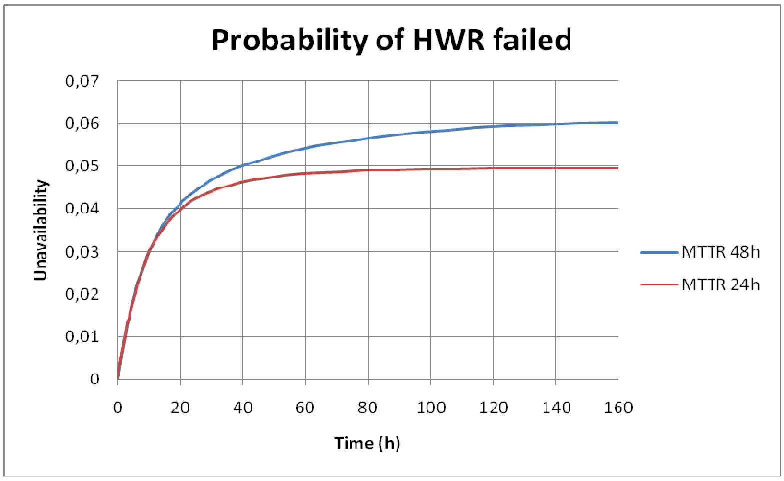

Figure 7.10 HWR unavailability under Parametric study of RF Window MTTR.

In figure 7.10 can be appreciated both the different time evolution and the value tendency on the two cases. As explained before, the higher the mean time to repair is, the slowlier that unavailability tends to a constant asymptothical value (exponential evolution). In fact, it is not clear in this graphic how close to the asymptothical value is the unavailability reached at 160 hours. In figure 7.11 are represented the first 1000 hours of a year simulation. There it can be observed that, past the first 200 hours, unavailability is constant at almost the same value as it was in the previous one, about 6%.

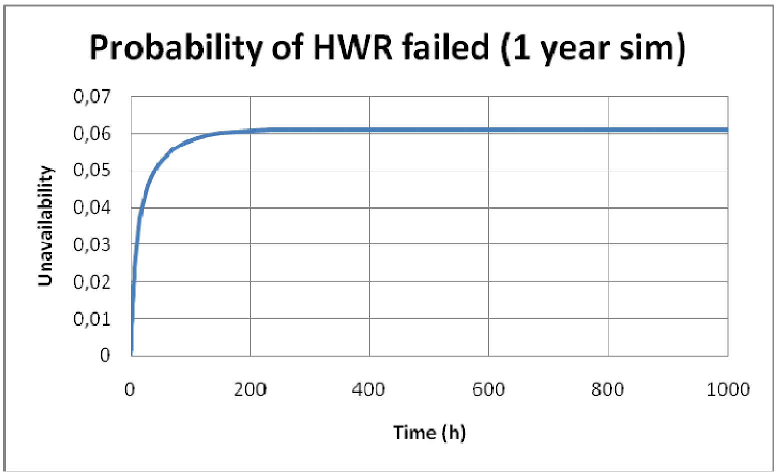

Figure 7.11 First 1000 hours of YEAR simulation with RF windows MTTR 48 hours.

The first conclusion hat could be extracted is that systematic complications in RF windows reparations (i.e. an error in design) would lead to an increase of the Linac unavailability of 1% which is an important amount but less than expected.

	FC	Sens.
48 HOUR	0,375	2,62
24 HOUR	0,306	3,02

Table 7.3 Importance and sensitivity of each value of RF window MTTR.

It can be highlighted that an FC increase does not mean an increase in sensitivity but a decrease. In this case, the more efficiently the reparation is made, the more sensitive it is to deviations on the parameter, so an even further improvement would mean even more noticeable effects. Since experience in different accelerators says this is usually a critical element and examining these results, some attention on it is worthable.

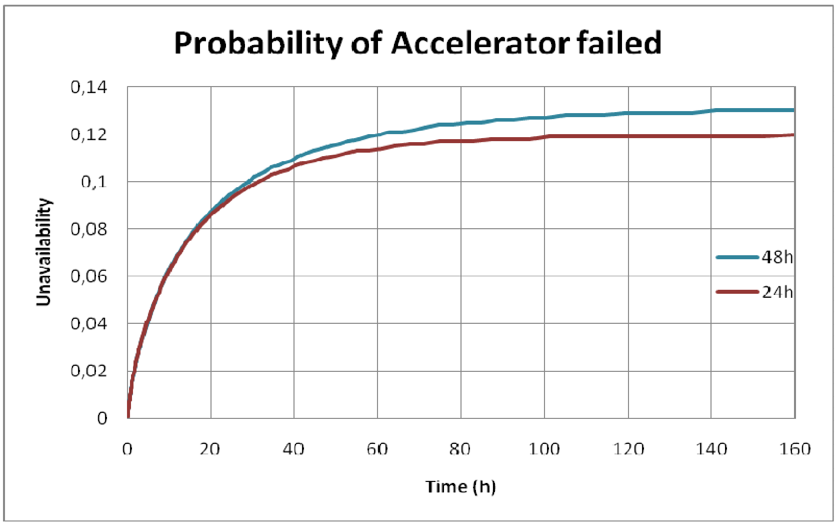

Figure 7.14 Unavailability of Accelerator with different RF Windows MTTR values. The increase leads to an unavailability 13%.

7.6.2 RF Amplifiers. MTTR 4 hours.

Radiofrequency amplifiers are the devices that feed the RF Power for the Linac to accelerate the beam. Modular design, where any of them can be easily substituted, is purposed in [4]. A proper mechanization of such contributions could mean an important improvement in availability. The following is a parametric study reducing the MTTR from 8 hours to 4. This element needs no special temperature or vacuum conditions which contribute to enlarge the down time, so this is considered an achievable MTTR.

In this case there is a significant difference with previously analyzed one. Both the importance and the sensitivity are reduced. Despite this, such a reduction means an increase in availability of 1,5%, a bigger difference than in the previous study (there, there was a reduction of 1%). This means that the other parameter referred to the same basic event, this is, the failure rate, is more important in this case. The more that a device failure occur, the more important its repairing time is. The failure rate of the amplifiers is almost one order of magnitude bigger than the one of RF windows.

	FC	Sens.
4 HOUR	0,426	7,28
8 HOUR	0,595	10,9

Table 7.4 Importance and sensitivity of each value of RF window MTTR.

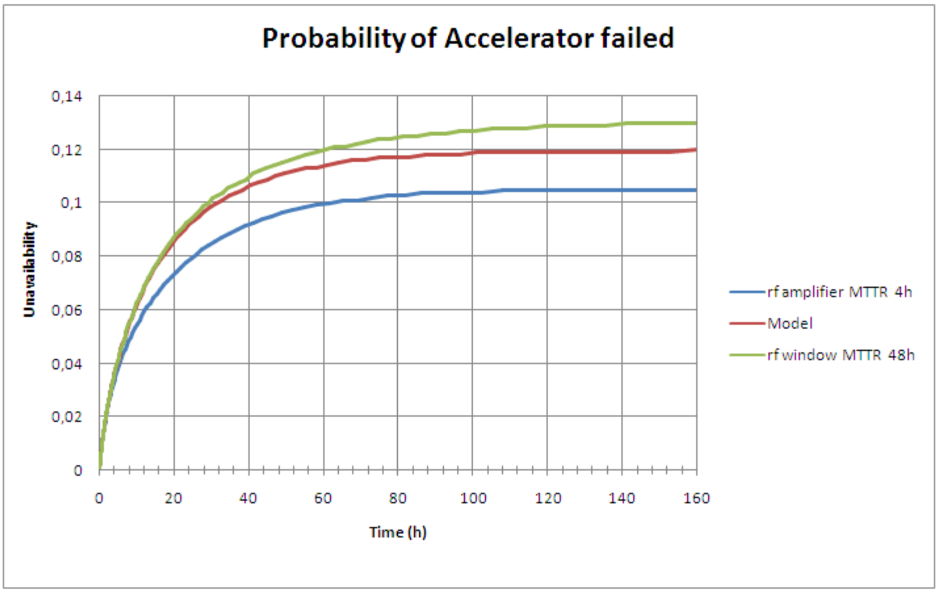

Table 7.15 Comparison of the model unavailability and the two parametrical analyses results.

7.7 Uncertainty analysis

Although all the provided availability results are given as a value, they move inside a range indeed. RiskSpectrum® calculates the probability distribution of unavailability of each tree. It also gives the mean value and the values over which the 5% and the 95% of the data are (this two values give the 90% confidence interval). All the uncertainty analyzed is referred to the failure rates, since MTTR variability has been blocked, as exposed in Chapter 4.

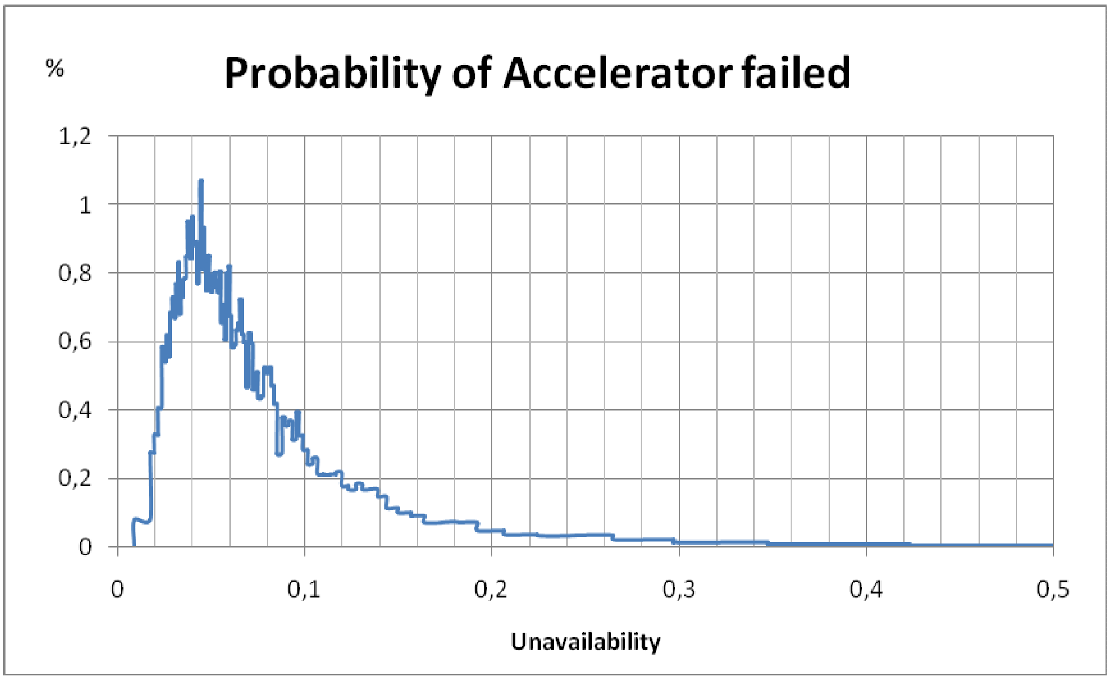

Table 7.16 Probability distribution function of accelerator.

On the horizontal axis lays the unavailability divided in differential intervals. On the vertical axis it's the probability that the unavailability falls in each interval. Most of the times the unavailability will be lower than the mean, but there are large tails on the right of the graphics.

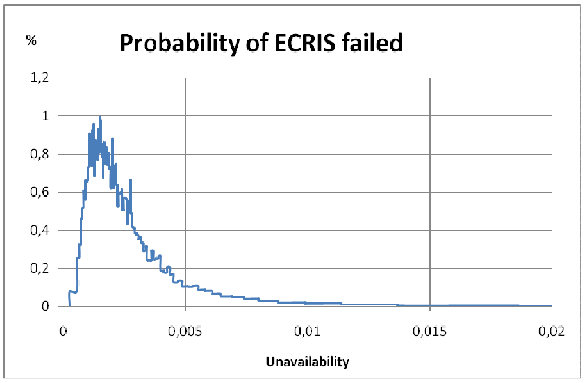

Figure 7.17 Probability distribution function ECRIS.

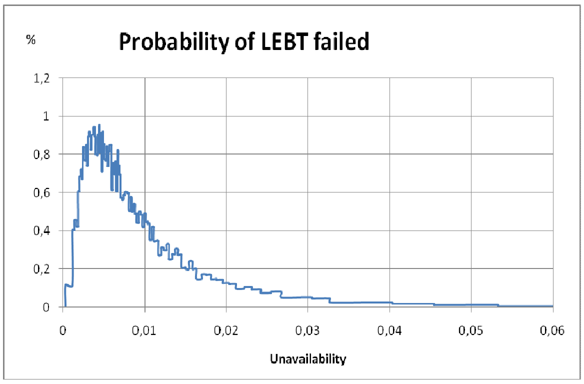

Figure 7.18 Probability distribution function LEBT.

The uncertainty analysis is made qualitatively. RFQ and DTL have sharper shapes, what means low uncertainty.

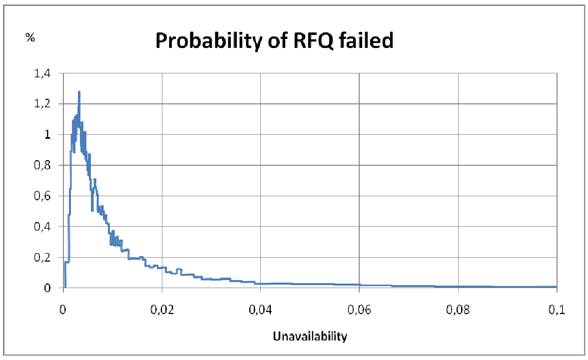

Figure 7.19 Probability distribution function RFQ.

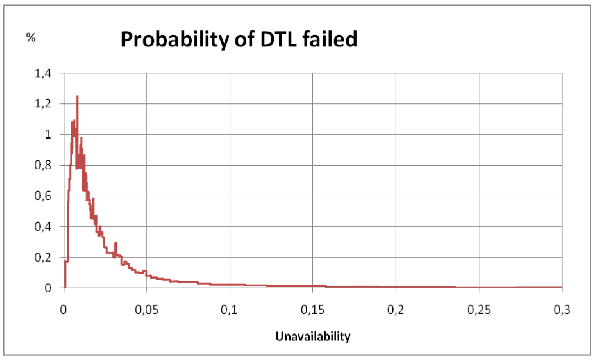

Figure 7.20 Probability distribution function DTL.

All the peaks are well below the mean values, so in most cases the unavailability values given in the report will be overestimations. In some rare cases there will be large unavailability periods which will be statistically compensated.

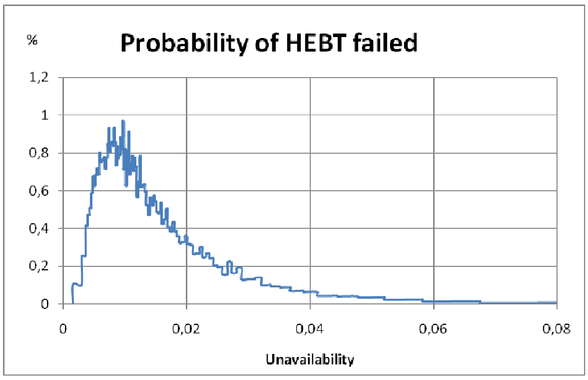

Figure 7.21 Probability distribution function HEBT.

Conclusion

This model is in consonance with the expected value from CDA previous analysis. It should be noted that they are different from its base, since this one has been developed not from the CDA model but from a completely different fault tree, born from adapting a FMEA to the actual layout and with failure data from other laboratories, using operational data when possible.

The calculated availability is 88.04%. Running a completely new model and getting such a number was a huge satisfaction. Despite this, it has to be noticed this is a first model in which updates will have to be made as the design goes deeper in detail. Things considered now as basic events can turn into branches as their components are specified.

The availability of spare elements is a critical issue, where the cost of the not used element has to be compared with the cost of having no beam in case of its failing. This comparison can be made considering different MTTR's on this model whether there is availability of spare elements or not.

Critical components are the Heater and the Vacuum pumping system in the Radiofrequency Quadrupole, and Diagnostics both in Low and High Energy beam transport. Except for the heater case, these are not components but systems, and it is not strange their importance is bigger than the importance associated with basic events referred to simpler components. These items have to be studied to go deeper in detail, enabling an analysis in which they are not basic events but gates containing more detailed failure modes.

Operational validated data from the supplier is specially recommended for the heater.

Parametric analyses showed that changes in Mean Time To Repair of RF window and RF amplifiers had significant consequences (around 1% of overall availability) but lower than expected.

The model is a good approximation, given the state of arts, to the accelerator failure mode and failure data.

Acknowledgements

This project would not have been possible without the collaboration of my directors, Javier Dies and Carlos Tapia, and the other people working on FEEL during last year, José Carlos Rivas, Anna Calvo and especially Javier Abal, who has worked shoulder to shoulder in each and every step of it, having an essential feedback that brought to this result. Also thank Carlos Gil, Mirko Gegundez and Carlos Gil their help with planes and Júlia Cantavella her review of the text.

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APPENDIXES

A. Fault tree

B. Cost

C. Environmental impact study

D. Parameters definition and calculations.

B. Cost

Cost of this project is associated to the hours invested in it. My availability has been variable along the duration of the project, mainly caused by the simultaneous studies of physics I am involved in. The Table B.1 shows time dedicated along the different terms and the cost derived from a non experienced engineer working on it.

PERIOD	months	hours/day	hours
March-May	3	3	198
June	1		10
July-September	2,5	8	440
September-December	3	5	330
TOTAL			978
		x25 €/hour	
Engineering COST			**24450**

Table B.1 Time dedicated and estimated cost.

There is a cost associated to the amortization of RiskSpectrum®. The price of each license is 3000€ for University projects developments (considerably cheaper than private sector licenses). Although it is for an indefinite time, it is considered to become obsolete in 3 years, approximately, so using it for a year rises the project cost by 1000 €, as seen in table B

YEAR	License amortization	Remaining value
0		3000
	1000	
1		2000
	1000	
2		1000
	1000	
3		0

Table B.2 License amortization.

Engineering cost	24450
License amortization	1000
TOTAL	**25450**

Table B.3 Total cost

C. Environmental impact

Developing a fault tree becomes an environmentally important issue when taking into account testing saving and the effort focusing associated to it.

Guiding the investment with a previous RAM analysis means saving materials and large quantities of energy. It can be avoided prototype construction, testing infrastructure and powering, and further useless series construction. The quantification of this saving is too complex. Depending on the importance that is given to previous RAM analysis and the extension of its utilization among the Institutes involved in this project the reduction of environmental impact can be simply energetic saving or the saving in large amounts of materials.

For instance, in this project it has been studied the half-wave resonator alternative for the Linac. The initial alternative was an Alvarez type Drift Tube Linac. However, the HWR option uses superconducting technology, which means very low losses, but before the construction phase, this study was asked. It has been demonstrated that the same availability can be achieved with this technology. If the contrary had been observed all the subsequent phases could have been saved.

	HWR	ALVAREZ
Cu dissipation (MW)	-	3.74
Heat load (W) @ 4K	900	-
Efficiency	0.003	0.6
Total (MW)	0.30	6.23

Table C.1 Power consumption comparison of the two Linac options. [4]

In the aspect referred to the developing area of this project, it has been done with low power consumption computers. Moreover, no fungible material but paper was used, and it only was in the unavoidable cases.

D. Parameters definition and calculations

The mean time between failure (MTBF) is the inverse of the failure rate, and it is defined as

$$MTBF \equiv T = \int_0^\infty R(t)\cdot dt \qquad \text{(Eq. D.1)}$$

where R is the reliability and t is time.

In CDA [3] it is assumed that reliability evolution is given by the exponential:

$$R = e^{-F\cdot t} \qquad \text{(Eq. D.2)}$$

Where F is the failure rate.

The availability (a) is defined as:

$$A_1 = \frac{T_1}{T_1+\tau} = \frac{\frac{T}{m_1}}{\frac{T}{m_1}+\tau} \quad A = \frac{T}{T+\tau} \qquad \text{(Eq. D.3)}$$

where τ =MTTR is the mean time to repair.

D.1- System with basic events only

Defined a system S_1 formed by m_1 masic events with equal parameters F, T i τ and with no redundancies, F_1, R_1 i A_1 are given by the following equations:

$$F_1 = m_1 \cdot F \qquad \text{(Eq. D.4)}$$

$$T_1 = \frac{1}{F_1} = \frac{T}{m_1} \qquad \text{(Eq. D.5)}$$

$$R_1 = R^{m_1} = e^{-m_1\cdot F\cdot t} = e^{-F_1\cdot t} \qquad \text{(Eq. D.6)}$$

$$A_1 = \frac{T_1}{T_1 + \tau} = \frac{\frac{T}{m_1}}{\frac{T}{m_1} + \tau} \qquad \text{(Eq. D.7)}$$

D.2- System with basic events and redundancies

Defined a system S_2 with m_2 elements and p_2 redundant parts, reliability R_2 and availability A_2 are given by next equations:

$$R_2 = e^{-m_2 \cdot F \cdot t} \left\{ \sum_{k=0}^{p_2} \frac{(m_2 \cdot F \cdot t)^k}{k!} \right\} = e^{-F \cdot t} \left\{ \frac{(F \cdot t)^k}{k!} \right\} \qquad \text{(Eq. D.8)}$$

$$A_2 = \frac{\frac{p_2 + 1}{m_2} \cdot T}{\frac{p_2 + 1}{m_2} \cdot T + \tau} = \frac{T_2}{T_2 + \tau} \qquad \text{(Eq. D.9)}$$

D.3- System formed by subsystems

Defined a system consistent in n subsystems: $S_1, S_2, \ldots, S_n$, the reliability R_s , availability A_s , MTBF T_s and the MTTR $F_S = \sum_{i=1}^{n} F_i \ \tau_S$ are given by:

$$R_S = \prod_{i=1}^{n} R_i \qquad \text{(Eq. D.10)}$$

$$A_S = \prod_{i=1}^{n} A_i \qquad \text{(Eq. D.11)}$$

$$T_S = \int_0^{\infty} \prod_{i=1}^{n} \left[e^{-F_i \cdot t} \left\{ \sum_{k=0}^{p_i} \frac{(F_i \cdot t)^k}{k!} \right\} \right] dt = \frac{1}{F_S} \int_0^{\infty} e^{-x} \left[\prod_{i=1}^{n} \left\{ \sum_{k=0}^{p_i} \frac{1}{k!} \left(\frac{F_i}{F_s} X \right)^k \right\} \right] dx \qquad \text{(Eq. D.12)}$$

Where reliability F_S is given by

$$F_S = \sum_{i=1}^{n} F_i \qquad \text{(Eq. D.13)}$$

Now, using a function g(x)defined as:

$$g(x) = \prod_{i=1}^{n} \left\{ \sum_{k=0}^{p_1} \frac{1}{k!} \left(\frac{F_1}{F_S} x \right)^k \right\} = \sum_{j=0}^{\sum_{i=0}^{n} p_i} c_j \cdot x^j \qquad \text{(Eq. D.14)}$$

Eq. D.12 is given by:

$$T_S = \frac{1}{F_S} \int_0^{\infty} e^{-x} \cdot g(x) \cdot dx = \frac{1}{F_S} \sum_{j=0}^{\sum_{i=0}^{n} p_i} \left(j! c_j \right) \qquad \text{(Eq. D.15)}$$

And according to Eq. D.3, MTTR τ_S is:

$$\tau_S = T_S \left(\frac{1}{A_S} - 1 \right) \qquad \text{(Eq. D.16)}$$

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