THE CERN ACCELERATOR SCHOOL

Reliability & Tolerance Case for ADS

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THE CERN ACCELERATOR SCHOOL

1. Basics of reliability theory

2. European ADS Demonstration: the MYRRHA project
3. The reference ADS-type accelerator
4. MYRRHA linac design & tolerance cases
5. Conclusion

Definition of reliability (1)

- Standard **definition of reliability**

« The probability that a system will perform its intended function without failure under specified operating condition for a stated period of time »

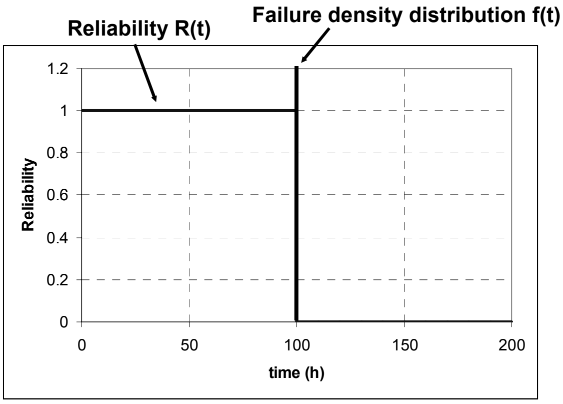
- A functional definition of failure is needed.
- The system's operating conditions must be specified.
- A period of time, or **MISSION time**, is needed.

Definition of reliability (2)

- Mathematically, the **reliability function** R(t) of a system is the probability that the system experiences no failure during the time interval 0 to t

- Example (ideal & simple world):

- Systematic failure after 100h of operation
- Mission time is essential !
  R=100% if t<100h
  R=0 if t>100h



- The **failure density** f(t) of a system is the probability that the system experiences its first failure at time t (given that the system was operating at time 0)

Reliability function

- From the failure density distribution f(t), one can derive:

 - the failure probability F(t), probability that the system experiences a failure between time 0 and t:

$$F(t) = \int_0^t f(x)dx$$

 - the **reliability function R(t)**

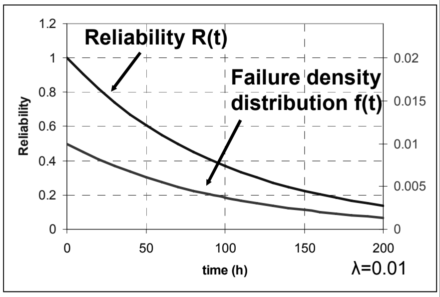
$$R(t) = 1 - F(t) = \int_t^\infty f(x)dx$$

- Ex. using an exponential distribution for f(t) (simple, very commonly used)

$$f(t) = \lambda\, e^{-\lambda t}$$

$$F(t) = \int_0^t \lambda e^{-\lambda x}.dx = 1 - e^{-\lambda t}$$

$$R(t) = \int_t^\infty \lambda e^{-\lambda x}.dx = e^{-\lambda t}$$



Failure rate function

- Another important concept is the **failure rate function λ(t),** $\lambda(t) = \frac{f(t)}{R(t)}$

 which predicts the number of times the system will fail per unit time at time t

- Using an exponential distribution for f(t), the failure rate is CONSTANT: the device doesn't have any aging property

$$\lambda(t) = \frac{f(t)}{R(t)} = \frac{\lambda e^{-\lambda t}}{e^{-\lambda t}} = \lambda$$

(λ=0.01 failure/hour in our previous example)

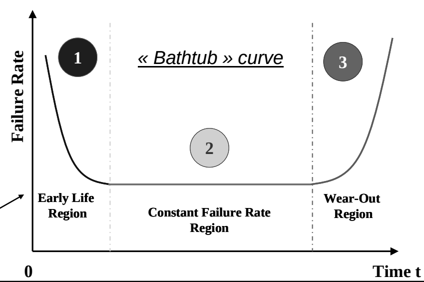
- More complex distributions can be used for f(t), leading to more realistic failure rate functions:

- Normal distribution → $f(t) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t-\mu)^2}{2\sigma^2}}$

- Lognormal distribution → $f(t) = \frac{1}{\sqrt{2\pi}\sigma t} e^{-\frac{(\ln t-\mu)^2}{2\sigma^2}}$

- Weibull distribution → $f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^\beta}$

- ...



Mean Time To Failure MTTF

✹ The **Mean Time To Failure (MTTF)** of a system is the average time of operation of the system before a failure occurs. This is usually the value of interest to characterize the reliability of a system.

$$MTTF = \int_0^\infty t f(t).dt = \int_0^\infty R(t).dt$$

✹ Using an exponential distribution for f(t) – constant failure rate λ – the MTTF is simply:

$$MTTF = \int_0^\infty e^{-\lambda t}.dt = \frac{1}{\lambda}$$

(MTTF=1/0.01=100 hours in our previous example)
(note that R(MTTF) is always 1/e = 36.8%)

Very convenient ! -> if MTTF is know, the distribution is specified ☺

✹ The **Mean Time Between** (2 consecutive) **Failure (MTBF)** is generally the metrix being used for repairable systems. MTBF = MTTF only for constant failure rate.

Maintainability & Availability

✹ When a system fails, it has to be repaired (or changed). **Maintainability** is the probability of isolating and repairing a fault in a system within a given time.

✹ The same formalism can be used, leading to the definition of the **Mean Time To Repair (MTTR),** which is the expected value of the repair time.

✹From Reliability & Maintainability, the **Availability function A(t)** of the system can be calculated. It is the probability that the system is available at time t.

✹ For long times, it converges towards the **steady-state availability**:

$$\bar{A} = \lim_{t \to \infty} A(t) = \frac{MTBF}{MTBF + MTTR} = \frac{system\ uptime}{system\ uptime + system\ downtime}$$

Common techniques for reliability analysis (1)

✹ **Reliability Block Diagram (RBD)**

- Made of individual blocks, corresponding to the system modules

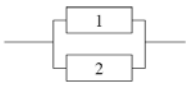
- Blocks can be connected in:

  - **Series**: when any module fail, the system fails

$$R = \prod R_i \qquad \frac{1}{MTBF} = \sum \frac{1}{MTBF_i}$$

(valid only for constant failure rate)

  - **Parallel**: redundant modules



$$R = 1 - \prod (1 - R_i)$$

  - **K-out-of-n system**: requires at least k modules out of n for sytem operation
  - Etc.

Example of RBD analysis

From P.Pierini, L.Burgazzi, Reliability Engineering and System Safety 92 (2007) 449–463

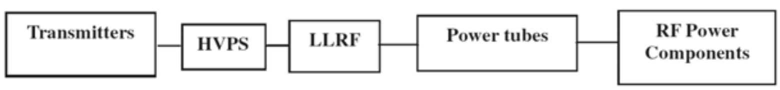


Fig. 1. RBD model for RF system.

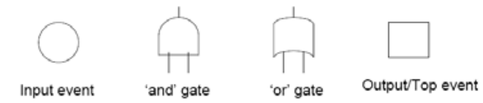
Table 4
Reliability and availability results for RF system (for a standard mission time of 168 h)

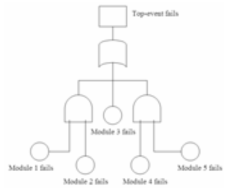
Component	MTBF (1/h)	MTTR (1/h)	Failure rate (1/h)	Reliability	Availability
Transmitters	10000	4	1.0E-4	0.98	0.99
High-voltage power system	30000	4	3.3E-5	0.99	0.99
Low-level radio frequency	100000	4	1.0E-5	0.99	0.99
Power amplifiers	50000	4	2.0E-5	0.99	0.99
Power components	100000	4	1.0E-5	0.99	0.99
1 comp./system	5769	4		0.97	0.99
60 comp./system	96	4		0.17	0.96

Common techniques for reliability analysis (2)

- **Fault tree analysis**

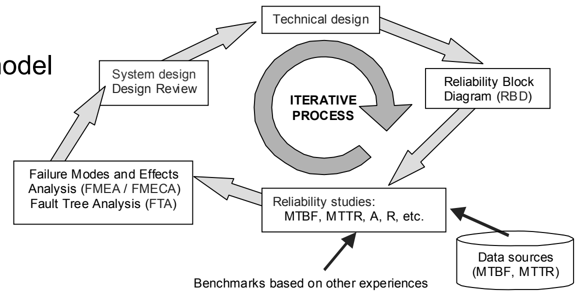
Shows which combination of failures will result in a system failure





- **Monte Carlo simulations**

Statistical evaluation of a reliability model



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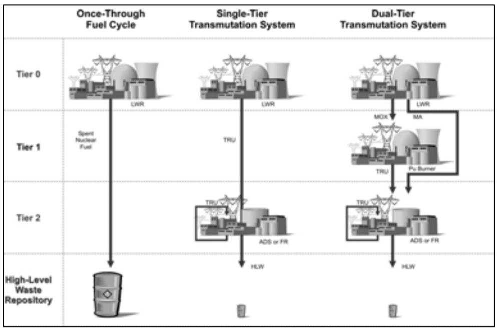
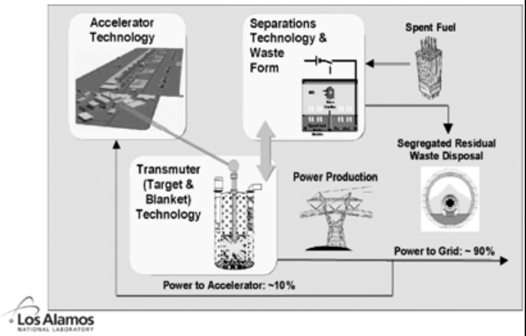
ADS (Accelerator Driven Systems)

- About 2500 tons of spent fuel are produced every year by the 145 reactors of EU
- **Partitionning & Transmutation (P&T) strategy**: reduce radiotoxicity and volume of long-lived nuclear wastes (Am-241 in particular) before geological storage
- **ADS sub-critical system**: reference solution for a dedicated "transmuter" facility





ADS in the European & French context → 2010

- (FR) **Law « Bataille » n° 91-1381, 30 december 1991**
=> French roadmap for research on radioactive waste management

- (EU) ETWG report on ADS, 2001
- (EU-FP5) **PDS-XADS** project (2001-2004)
- (EU-FP6) **EUROTRANS** programme (2005-2010)
- (FR) **Law n°2006-739, 28 june 2006**
=> Following-up the law « Bataille », with focus on sustainability

Article 3 (...) 1. La séparation et la transmutation des éléments radioactifs à vie longue. Les études et recherches correspondantes sont conduites en relation avec celles menées sur les nouvelles générations de réacteurs nucléaires mentionnés à l'article 5 de la loi n° 2005-781 du 13 juillet 2005 de programme fixant les orientations de la politique énergétique ainsi que sur les réacteurs pilotés par accélérateur dédiés à la transmutation des déchets, **afin de disposer, en 2012, d'une évaluation** des perspectives industrielles de ces filières et de mettre en exploitation un **prototype d'installation avant le 31 décembre 2020** ; (...)

The MYRRHA project

MYRRHA Project

Multi-purpose hYbrid Research Reactor for High-tech Applications At Mol (Belgium)

Development, construction & commissioning of a new large fast neutron research infrastructure to be operational in 2023

➊ ADS demonstrator

➋ Fast neutron irradiation facility

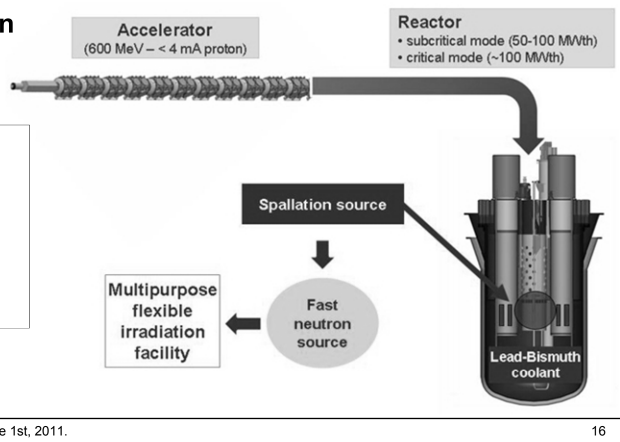
➌ Pilot plant for LFR technology

MYRRHA as an ADS demonstrator

Demonstrate the physics and technology of an Accelerator Driven System (ADS) for transmuting long-lived radioactive waste

- Demonstrate the **ADS concept** (coupling accelerator + spallation source + power reactor)
- Demonstrate the **transmutation** (experimental assemblies)

Main features of the ADS demo
50-100 MWth power
k_{eff} around 0.95
600 MeV, 2.5 - 4 mA proton beam
Highly-enriched MOX fuel
Pb-Bi Eutectic coolant & target



MYRRHA as a fast spectrum irradiation facility

- All **European irradiation Research Reactors** are about to close within 10-20 years
- The **RJH** (Réacteur Jules Horowitz) project, is presently the only planned MTR (Material Tests Reactor), and provides mainly a thermal spectrum
- MYRRHA is the **natural fast spectrum complementary facility**

Réacteurs de recherche européens

Pays	*Réacteurs de recherche*	*Age en 2015 (ans)*
Belgique	*BR2 à Mol*	*52*
Hollande	*HRF à Petten*	*54*
Norvège	*HRP à Halden*	*55*
France	*Osiris à Saclay*	*49*
Suède	*R2 à Studsvik*	*Mis à l'arrêt en 2005*
République tchèque	*LVR15 à Řež*	*58*

Main applications of the MYRRHA irradiation facility

Test & qualification of innovative fuels and materials for the future Gen. IV fast reactor concepts

Production of neutron irradiated silicon to enable technologies for renewable energies (windmills, solar panels, electric cars)

Production of radio-isotopes for nuclear medecine (^{99}Mo especially)

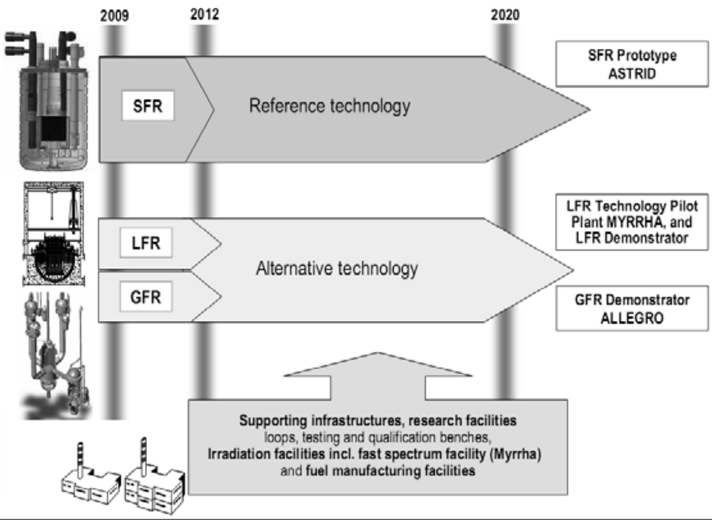
Fundamental science in general (also using the proton linac by itself !)

MYRRHA as a Gen.IV demonstration reactor

Serve as a technology Pilot Plant for **liquid-metal based reactor concepts** (Lead Fast Reactors)

European commission scope for the development of Gen.IV advanced reactor systems demos

(ESNII roadmap)

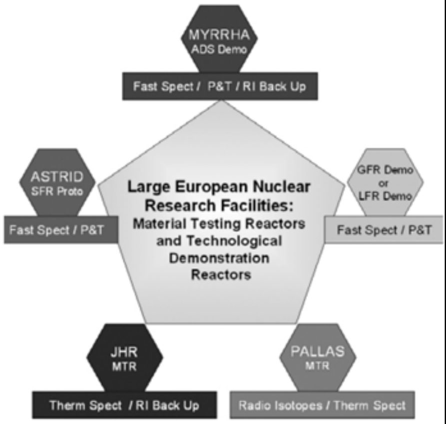


SNETP
Sustainable Nuclear Energy Technology Platform

MYRRHA in brief

MYRRHA is considered as **a strategic stone**:

- for **SCK●CEN**, as a replacement for the BR2 reactor (shut-down in 2026)
- for the European picture of **Material Testing Reactors**, as a complement to the RJH
- For the future of **sustainable nuclear energy**, as an ADS demonstrator & a strong support to the development of Gen. IV reactors

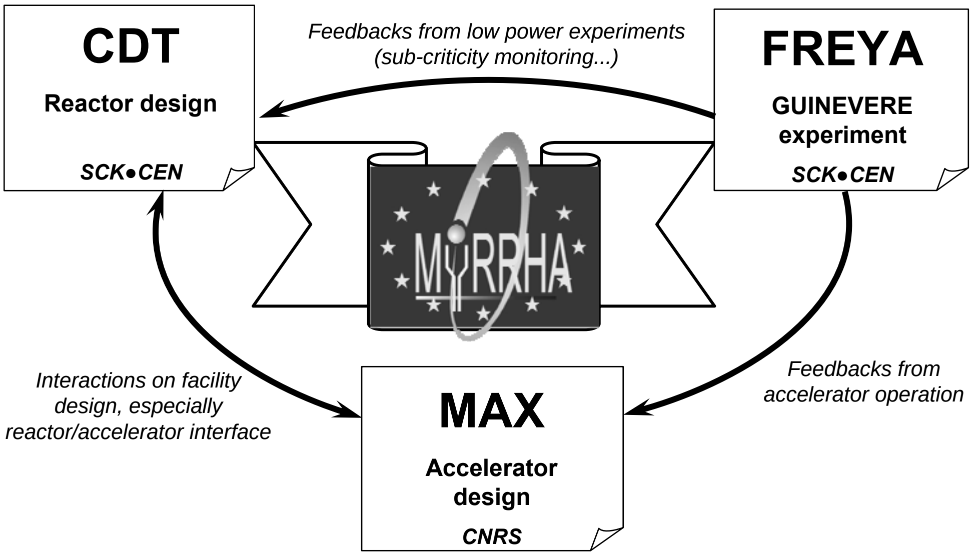


SNETP
SUSTAINABLE NUCLEAR ENERGY TECHNOLOGY PLATFORM

MYRRHA official key dates

- **1998**: first studies
- **2002**: pre-design "**Myrrha Draft 1**" *(350 MeV cyclotron)*
- **2002-2004:** studied as one of the 3 reactor designs within the **PDS-XADS FP5 project** *(cyclotron turns into linac, fault-tolerance concept is introduced)*
- **2005:** updated design "**Myrrha Draft 2**" *(350 MeV linac)*
- **2005-2010:** studied as the XT-ADS demo within the **FP6 IP-EUROTRANS** *(600 MeV linac conceptual design, R&D activities w/ focus on reliability)*
- **2010:** MYRRHA is on the **ESFRI list**, and is **officially supported by the Belgium government** at a 40% level (384M€, w/ 60M€ already engaged)
- **2010-2015:** Engineering design, licensing process, set-up of the international consortium, w/ support from the **FP7 projects CDT, FREYA & MAX**
- **2016-2019:** construction phase
- **2020-2023:** commissioning and progressive start-up
- **2024**: full exploitation

MYRRHA within FP7: 2011 - 2014



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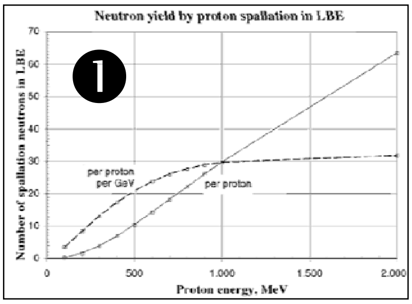
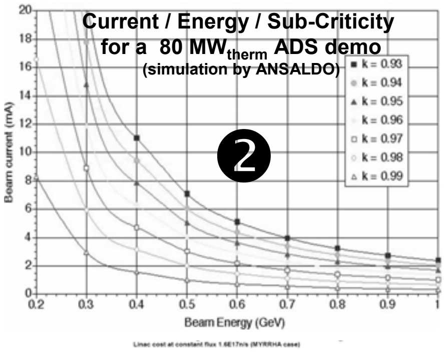
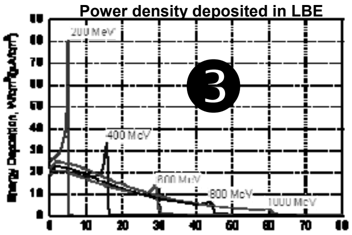
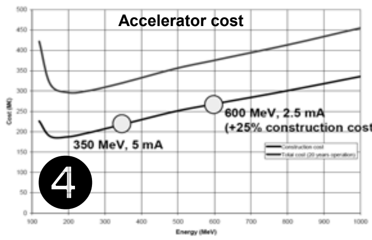
Proton beam energy / intensity requirements





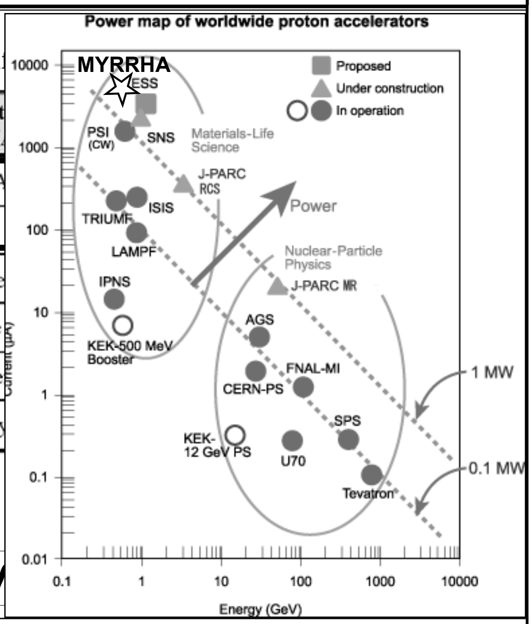




Proton beam specifications

Proton beam general initial speci

	Transmuter demonst (XT-ADS / MYRRH
Proton beam current	2.5 mA (& up to 4 mA
Proton energy	600 MeV
Allowed beam trips nb (>1s)	~ < 5 per 3-month ope
Beam entry into the reactor	Vertically from above
Beam stability on target	Energy: ±1% - Curre
Beam time structure	CW (w/ low frequency



High power CV

Proton beam specifications

Proton beam general initial specifications within EUROTRANS

	Transmuter demonstrator (XT-ADS / MYRRHA project)	**Industrial transmuter (EFIT)**
Proton beam current	2.5 mA (& up to 4 mA for burn-up compensation)	~ 20 mA
Proton energy	600 MeV	800 MeV
Allowed beam trips nb (>3s)	~ <10 per 3-month operation cycle	~ < 3 per year
Beam entry into the reactor	Vertically from above	
Beam stability on target	Energy: ±1% - Current: ±2% - Position & size: ±10%	
Beam time structure	CW (w/ low frequency 200μs beam "holes" for sub-criticality monitoring)	

Extreme reliability level !

High power CW accelerators

Reliability specifications

- **Beam trips longer than 3 sec** to avoid thermal stresses & fatigue on the ADS target, reactor & fuel assemblies (and to provide good plant availability)

  => Present specification = **less than 10 beam trips per 3 month operation cycle**

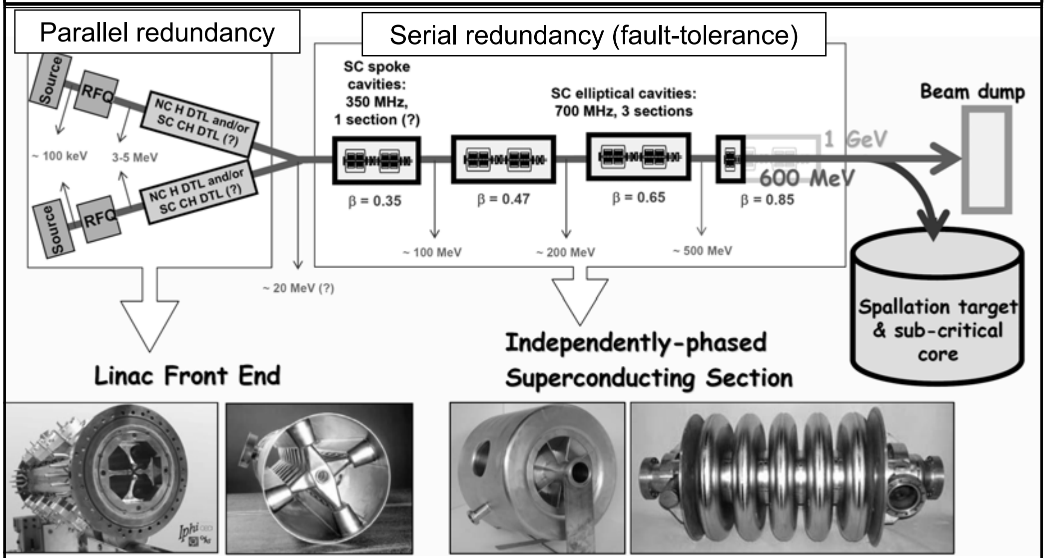
  - Mission time : 2190 h
  - Goal for MTBF : about 250h
  - Goal for reliability parameter : unconstrained (R(2190h) is nearly null)
  - Goal for availability : about 85% (given that the reactor restart time is 48h, A~250h/300h)

- Until now, the reliability goal of the accelerators was 'we do the best we can'. With ADS, the **reliability is for the first time a CONSTRAINT**, and the reliability level (in fact the MTBF) is about **1 to 2 orders of magnitude more severe** than present state-of-the-art
- On the contrary, availability level is in-line with present high-power proton accelerators (SNS, PSI..)

Reliability: impact on accelerator design

- Reliability guidelines have to be followed during the ADS accelerator design:
  - **Strong design** ("overdesign")
    - Perfectly safe beam optics to ensure a low-loss machine, typically $<10^{-6}$ per meter (beam dynamics basic rules for space-charge management & beam halo minimization)
    - Operation points far from technological limitations (importance of R&D !)
    - Make it as simple as possible (ancillary systems, C&C ...) & avoid « not-so-useful » complicated elements (HOM couplers?, piezo tuners?...)
  - **Redundancy** in critical areas for reliability
    - Serial redundancy where possible (the function of the failed element is replaced by retuning other elements with nearly identical functionalities = « Fault-tolerance »)
      Ex. fault-tolerant modular SC linac, solid-date RF amplifiers...
    - Parallel redundancy otherwise (where 2 elements are used for 1 function -> expensive !)
      Ex. spare injector…
  - **Repairability** (on-line repairability where possible)
    - Repairability = engineering issue which deserves attention during the whole design phase
    - Efficient maintenance scheme

Generic scheme of the European ADS accelerator



Modular & upgradeable concept – Maximized electrical efficiency – Optimized for reliability

Reliability spec – from the reactor side (1)

- Present specifications inspired from the **PHENIX reactor** (fast, Na liquid metal)
  - PHENIX spec. (20 years operation)
    - Fast stops (210s) : < 600 (200 effective)
    - Emergency stops (SCRAM 0.7s) : < 200 (100 effective)
    - Total => **10 stops / 3 months effective**
  - PHENIX maintenance showed that a few elements (heat exchangers) didn't tolerate thermal transients → **CAUTION !!**

- Simulations performed to assess the number of admissible thermal shocks lead to <u>very different results</u>, o.o.m. => **1000 stops / 3 months** → **OPTIMISM !**
  - U.S study (AAA project)
  - JAEA study (ADS 800 MWth)
  - AREVA analysis for XT-ADS
  - SCK*CEN study for MYRRHA

Trips	Allowed Number	
	/ cycle	/year
< 10 seconds	800	2500
10 seconds – 5 minutes	80	250
> 5 minutes	8	25

Reliability spec – from the reactor side (2)

- **DOE white paper on ADS** (September 2010)

Accelerator and Target Technology for Accelerator Driven Transmutation and Energy Production

H. Aït Abderrahim[h], J. Galambos[d], Y. Gohar[a], S. Henderson[c*], G. Lawrence[e], T. McManamy[d], A. C. Mueller[g], S. Nagaitsev[c], J. Nolen[a], E. Pitcher[e*], R. Rimmer[f], R. Sheffield[e], M. Todosow[b]

[a]Argonne National Laboratory
[b]Brookhaven National Laboratory
[c]Fermi National Accelerator Laboratory
[d]Oak Ridge National Laboratory
[e]Los Alamos National Laboratory
[f]Thomas Jefferson National Accelerator Facility
[g]CNRS-IN2P3, France
[h]SCK•CEN, Mol, Belgium
[*]Co-chairs

September 17, 2010

It seems that a compromise is still to establish in the ADS reactor community...!

Some more or less "fuzzy" points =>
- data of irradiated steel T91 & 316L,
- impact of oxyde layer errosion/corrosion by LBE on cladding embrittlement,
- strategy for LBE cooling management during trips,
- needed time for start-up procedures after a trip
- ...

Finding #6: Recent detailed analyses of thermal transients in the subcritical core lead to beam trip requirements that are much less stringent than previously thought; while allowed trip rates for commercial power production remain at a few long interruptions per year, relevant permissible trip rates for the transmutation mission lie in the range of many thousands of trips per year with duration greater than one second.

Reliability – from the accelerator side (1)

- Most of **nowadays proton accelerators** are not (yet) optimised for reliability
  - MTBF is in the order of a few hours typically
  - Several trips / day are experienced

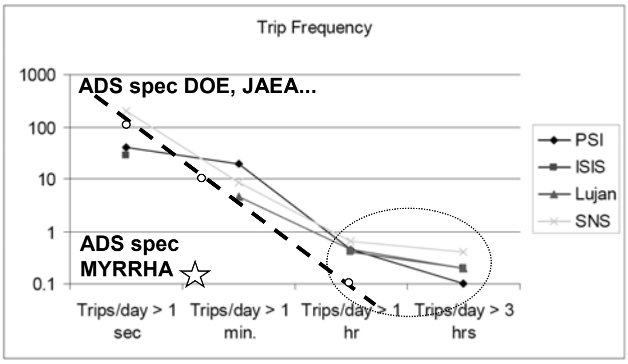


Figure 6. Trip frequency vs. trip duration for high power proton accelerators.

J. Galambos (SNS) - HB2008

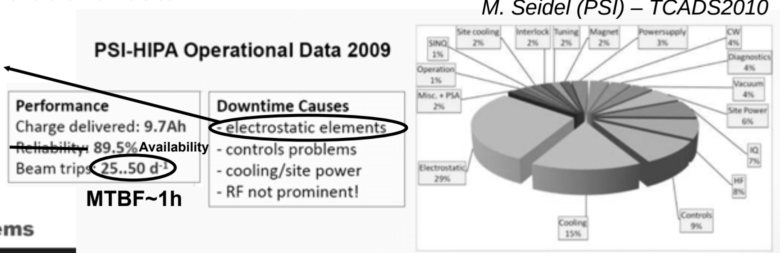
- DOE reliability spec. more or less compatible with state-of-the art (except for long trips)
- MYRRHA / PHENIX spec. 2 orders of magnitude more severe

Reliability – from the accelerator side (2)

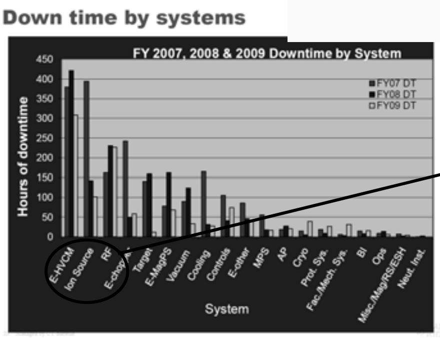
- PSI and SNS **operational data**

M. Seidel (PSI) – TCADS2010

Typical failure cause of HP cyclotrons



MTBF~1h



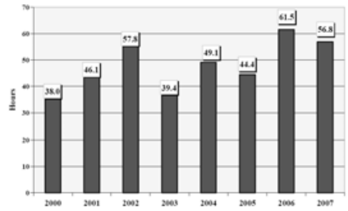
Failures mainly come from:

- **Injector**
- **RF chains**

S-H. Kim (SNS) – TCADS2010

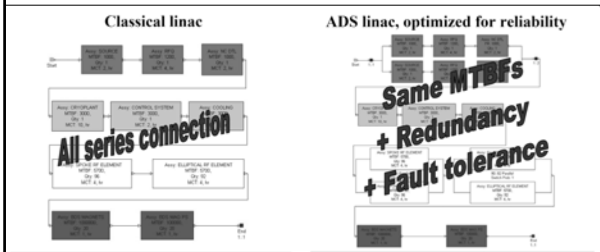
Reliability – from the accelerator side (3)

- From the present situation, a very high **progression margin** exists
  - Since a few years, the accelerator community is more and more sensitive to reliability/availability aspects (e.g. dedicated workshops)
  - Light sources do quite well since a few years (ex: ESRF facility reaches MTBF > 60 h)
  - MYRRHA preliminay reliability analysis showed that the goal is not unrealistic if the reliability rules are applied



L. Hardy (ESRF) - EPAC2008

Figure 1: Evolution of the Mean Time Between Failures.



Classical linac	
System MTBF	31.19 hours
Nb of failures (3 months)	**70.23**
Steady State Availability	86.6 %

ADS linac, optimized for reliability	
System MTBF	757.84 hours
Nb of failures (3 months)	**2.89**
Steady State Availability	99.5 %

➲ **"analysis of the analysis"**

- Fault-tolerance (& redundancy) can really improve the situation, by about one order of magnitude (but of course, @ a certain cost)
- The obtained *absolute* figures remain highly questionable (very few reliable MTBF data, high complexity of the system not fully modeled)
- A much more detailed analysis is recommended
- In any case, a few years of commissioning and training will be needed once the machine is built

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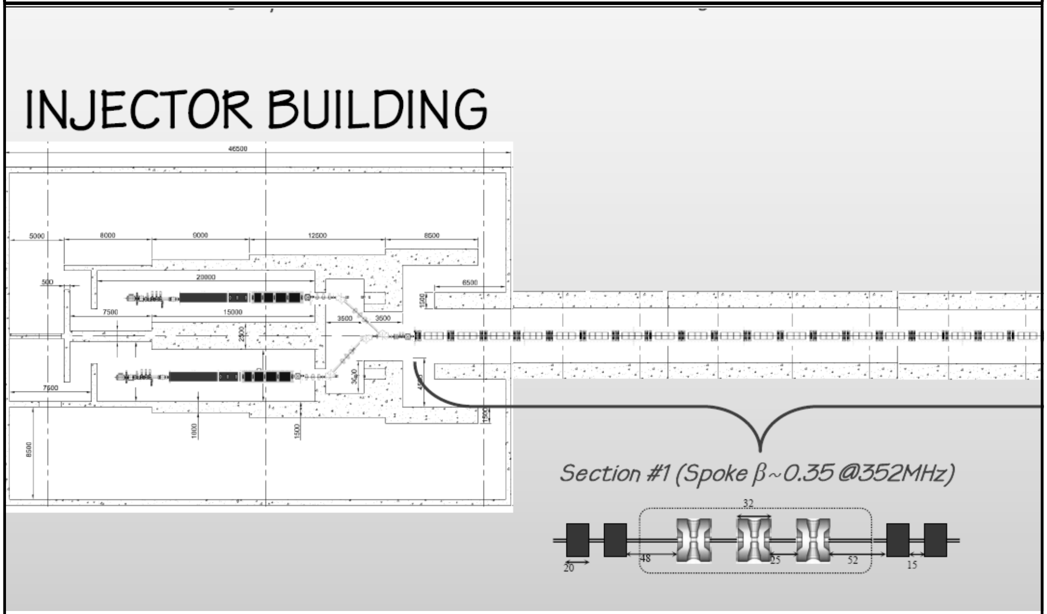
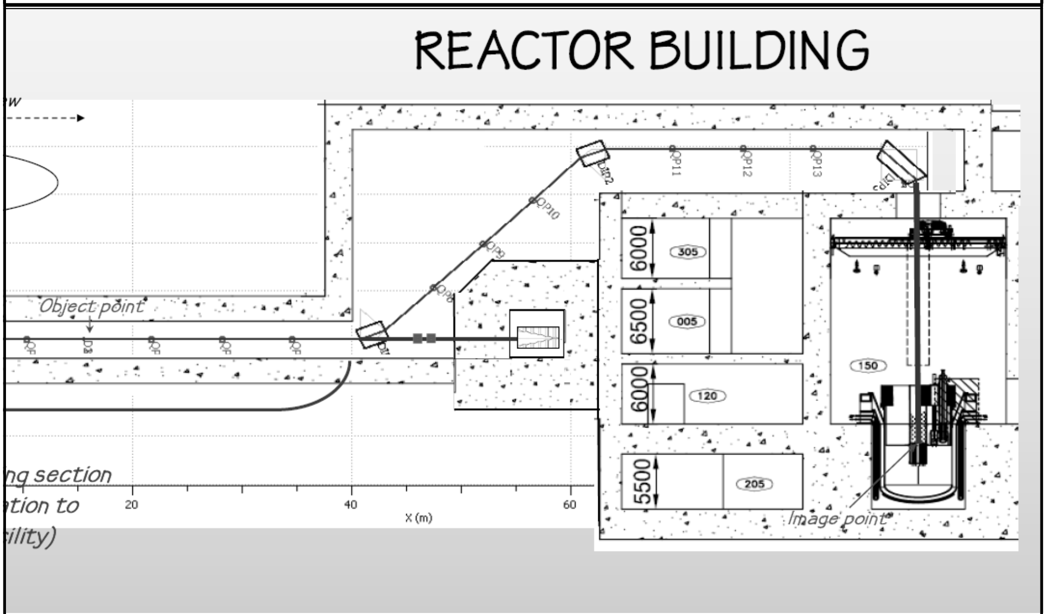
5. Conclusion

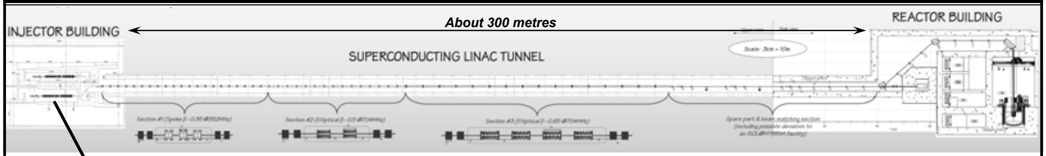
The MYRRHA linear accelerator

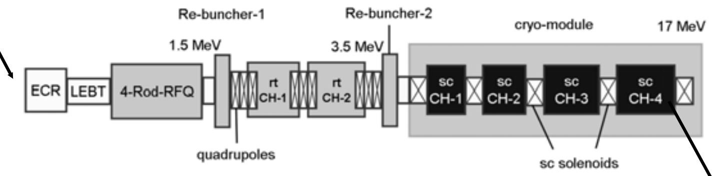


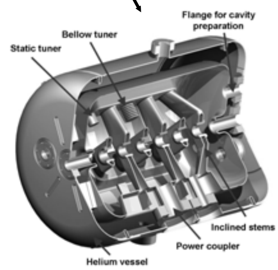
The MYRRHA linear accelerator



The 17 MeV injector: present design

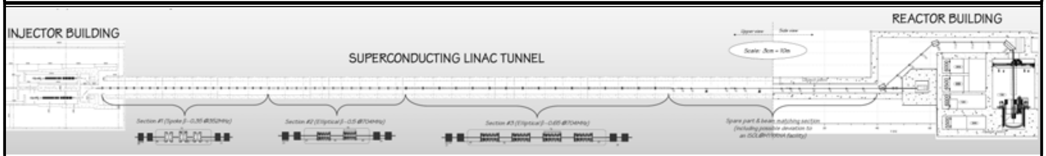


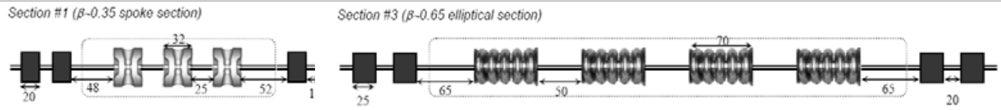




- ECR proton source (5 mA, 30 kV) + **176 MHz RFQ**
- « Booster » with 2 copper & 4 superconducting 176 MHz **CH cavities up to 17 MeV**
- **Very efficient solution** at these very low energies (>1 MeV/m energy gain)
- A back-up 352 MHz design is looked at in parallel
- A 2nd redundant injector is foreseen in case of failure

The main 17 - 600 MeV LINAC: present design

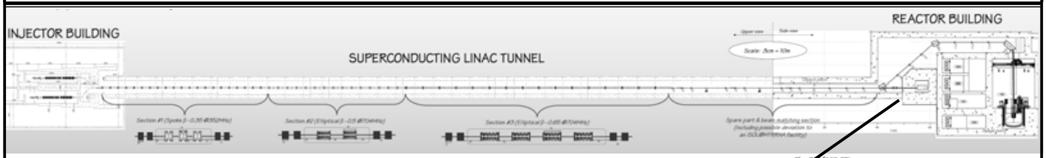




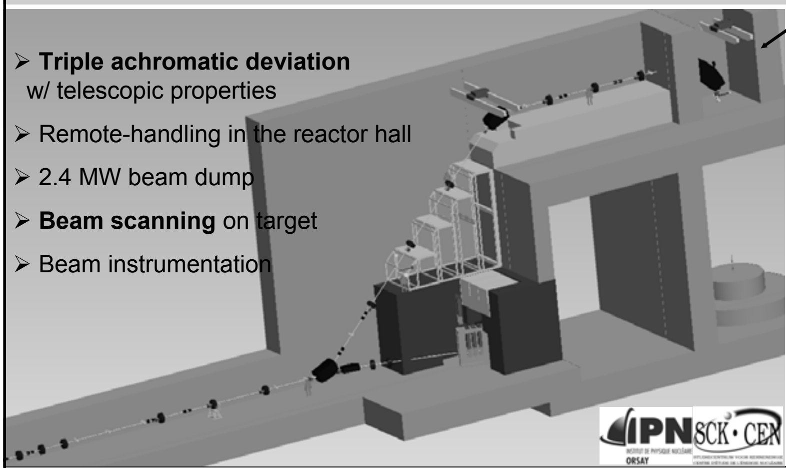
- « **Spoke** »-type superconducting cavities * 63 (352 MHz, family #1)
- **Elliptical** superconducting cavities * 94 (704 MHz, families #2 et #3)
- Total length: 215 metres
- Modular accelerating structures **independently powered**
- Capability of on-line **fault-tolerance**
- Comfortable **margin** for operating points (50mT B_{pk}, 25MV/m E_{pk})

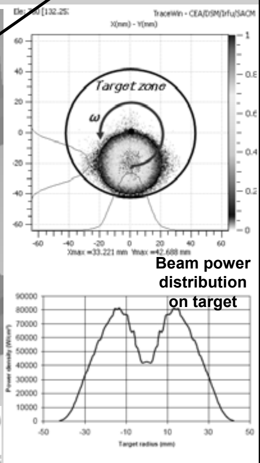
Section number	1	2	3
Input energy (MeV)	17.0	86.4	186.2
Output energy (MeV)	86.4	186.2	605.3
Cavity technology	Spoke 352.2 MHz	Elliptical 704.4 MHz	
Cavity geometrical β	0.35	0.47	0.66
Cavity optimal β	0.37	0.51	0.70
Nb of cells / cavity	2	5	5
Focusing type	NC quadrupole doublets		
Nb of cavities / cryomodule	3	2	4
Total nb of cavities	63	30	64
Acc. field (MV/m @ opt. β)	5.3	8.5	10.3
Synchronous phase (deg)	-40 to -18	-36 to -15	
5mA beam loading / cav (kW)	1 to 8	3 to 22	17 to 38
Section length (m)	63.2	52.5	100.8

Final beam line to reactor: present design



- **Triple achromatic deviation** w/ telescopic properties
- Remote-handling in the reactor hall
- 2.4 MW beam dump
- **Beam scanning** on target
- Beam instrumentation



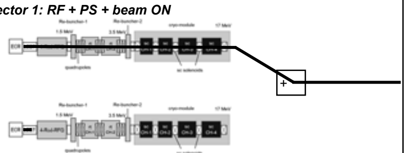


Tolerance cases: injector

- Tolerance case in injector is based on the use of a **switching magnet**
  - Laminated steel yoke (to prevent Eddy current effects) + suited power supply

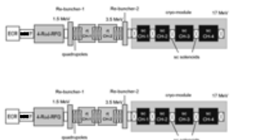
❶ Initial configuration

Operational injector 1: RF + PS + beam ON



Warm stand-by injector 2: RF+ PS ON, beam OFF (on FC)

❸ The fault is localized in the injector

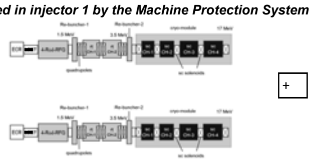


The switching magnet polarity is changed (~1s)

Need for an efficient fault diagnostic system !

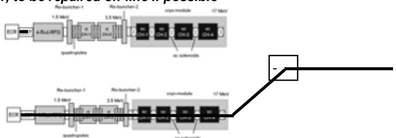
❷ A fault is detected anywhere

Beam is stopped in injector 1 by the Machine Protection System @t_0



❹ Beam is resumed

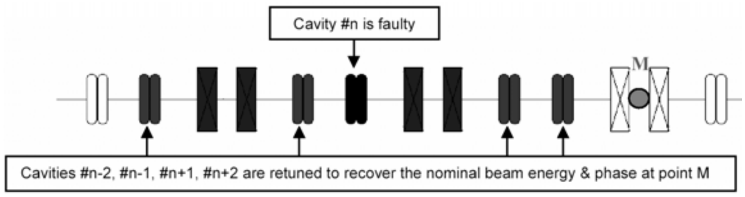
Failed injector 1, to be repaired on-line if possible



Injector 2 operational (@t_1 < t_0 +3sec)

Tolerance cases: main SC LINAC (1)

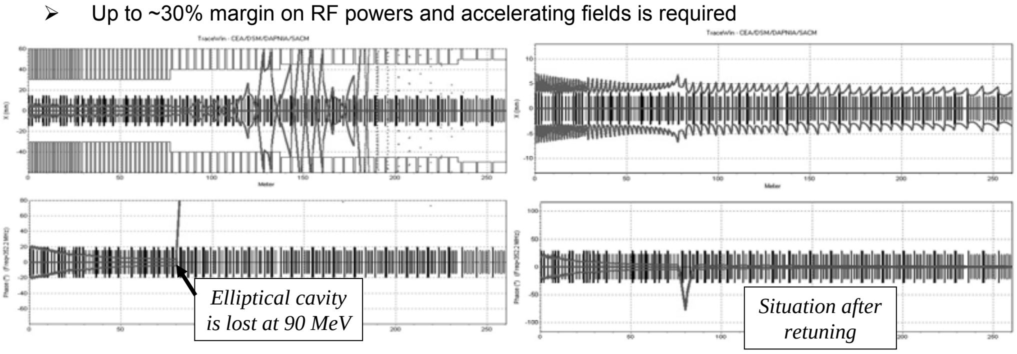
- Tolerance case in LINAC is based on the use of the **local compensation method**
  - If a SRF cavity system fails & nothing is done → beam is lost (β<1)
  - If adjacent cavities operation points are properly retuned → nominal beam is recovered



- Such a scheme requires:
  - **Independently-powered RF cavities**, good velocity acceptance, moderate energy gain per cavity & tolerant beam dynamics design
  - **Operation margins** on accelerating fields & RF power amplifiers
  - **Fast fault-recovery procedures** to perform the retuning within 3 seconds

Tolerance cases: main SC LINAC (2)

- With an appropriate retuning, the beam is recovered **in every cavity-loss case** without any beam loss (100 % transmission, small emittance growth), and within the nominal target parameters.
  - From 4 to 6 surrounding cavities are used
  - Up to ~30% margin on RF powers and accelerating fields is required

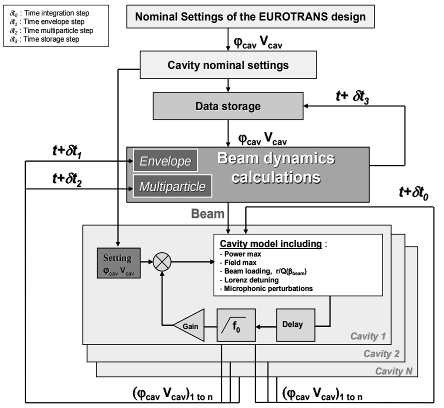


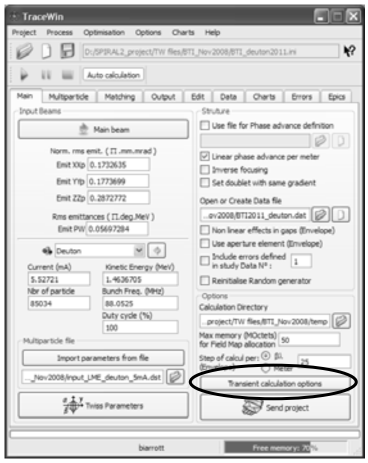
- Such a scheme is **implemented in the SNS** to deal with OFF cavities (but using a global LINAC retuning)

Tolerance cases: main SC LINAC (3)

- Simulation code has been developed to be able to **analyse the behaviour of the beam during transients** (coupling TraceWin / RF cavity control loop)

J-L. Biarrotte, D. Uriot, “Dynamic compensation of an rf cavity failure in a superconducting linac”, Phys. Rev. ST – Accel. & Beams, Vol. 11, 072803 (2008).





Tolerance cases: main SC LINAC (4)

- Example: beam transient behaviour during a cavity failure (no retuning)

➢ Beam envelopes evolution just after the failure

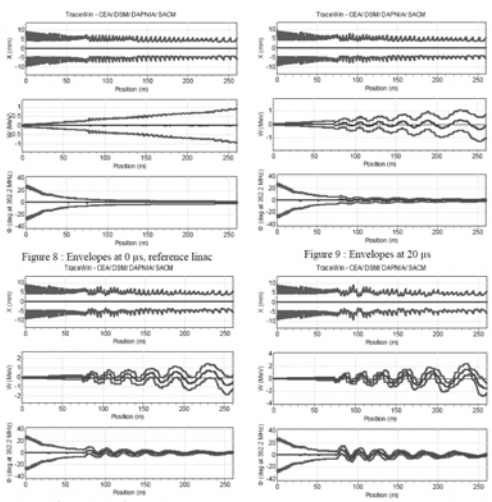


Figure 8 : Envelopes at 0 µs, reference linac

Figure 9 : Envelopes at 20 µs

Figure 10 : Envelopes at 50 µs

Figure 11 : Envelopes at 100 µs

➢ Location of beam losses @t_0 + 220µs

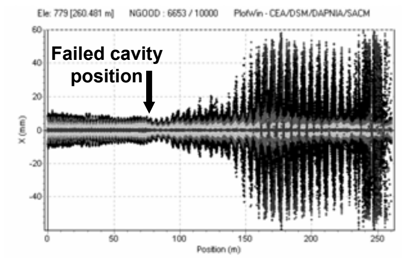


Figure 12 : Transverse beam distribution at 220 µs, in red are plotted the losses

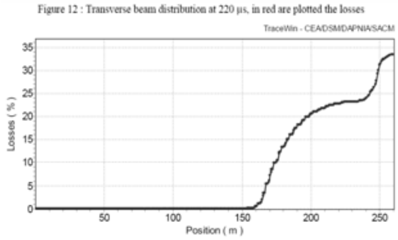
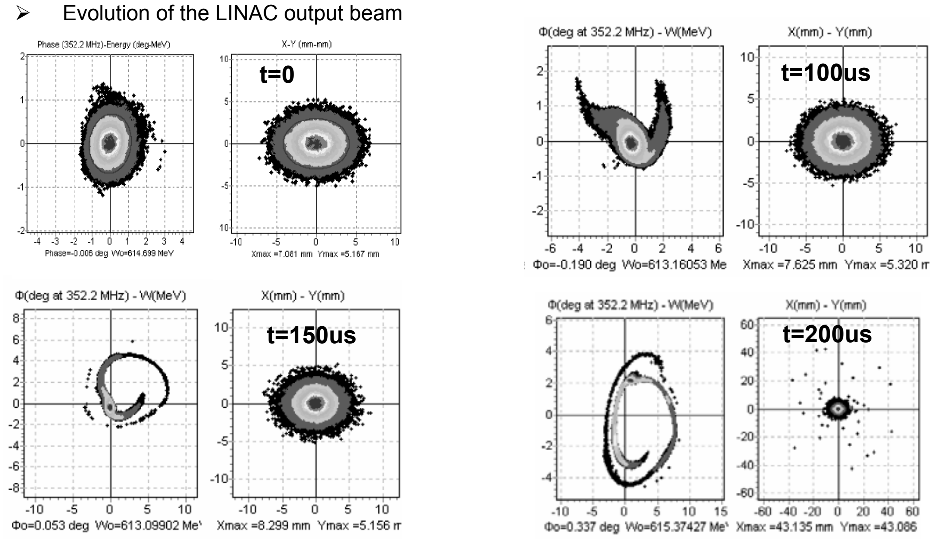


Figure 13 : Losses along the linac at 220 µs.

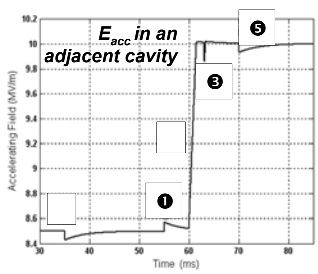
Tolerance cases: main SC LINAC (5)

- Example: beam transient behaviour after of a cavity failure (no retuning)
  - Evolution of the LINAC output beam



Tolerance cases: main SC LINAC (6)

- From this, a **fast fault-recovery procedure** has been settled for the on-line recovery procedure of accelerating systems failures



❶ A failure is detected anywhere

→ Beam is stopped by the MPS in injector at t_0

❷ The fault is localized in a SC cavity RF loop

→ Need for an efficient fault diagnostic system

❸ New field & phase set-points are updated in cavities adjacent to the failed one

→ Set-points previously determined at the commissioning & stored in the LLRF systems FPGAs

❹ The failed cavity is detuned (to avoid the beam loading effect)

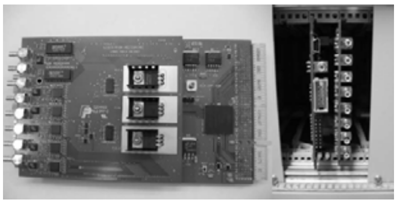
→ Using the Cold Tuning System (possibly piezo-based)

❺ Once steady state is reached, beam is resumed at $t_1 < t_0$ + 3sec

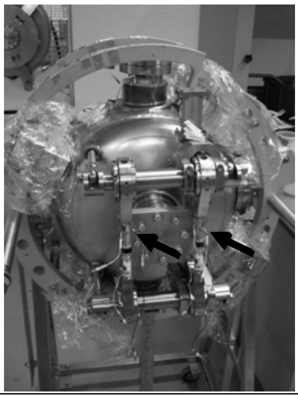
→ Failed cavity system to be repaired on-line if possible

Tolerance cases: main SC LINAC (7)

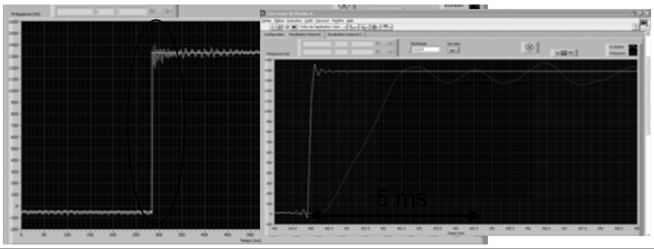
- Development of a new generation **digital LLRF system** suited to such procedures



- a FPGA chip, able to process the feedback control algorithms,
- several ADCs and DACs, to convert the received and produced signals,
- a RAM memory, used to store set-points or save operating parameters,
- a serial bus, to communicate with the general control/command system,
- a fast serial bus, to communicate with adjacent boards.

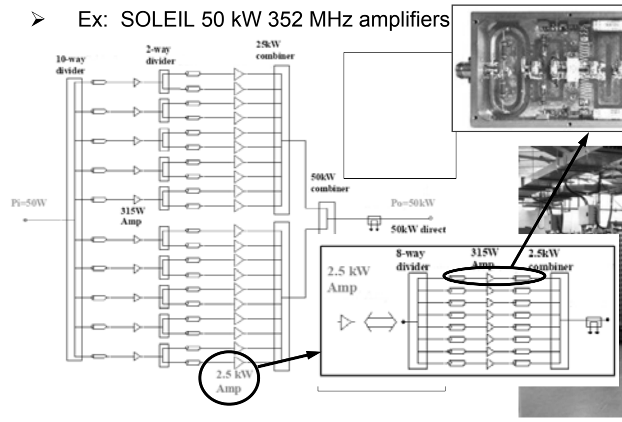


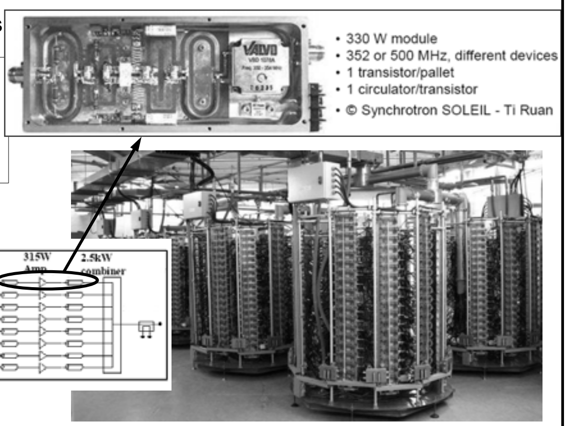
- Development of a reliable **piezo-based Cold Tuning System** for fast detuning/retuning of cavities



Tolerance cases: RF amplifiers (1)

- Tolerance case for RF amplifiers is based on the use of **solid-state technology**
  - Extremely modular solution, based on combination of elementary modules (pallets of few 100s W) → Inherent redundancy
  - Well adapted to CW operation w/ moderate peak power demand (i.e. MYRRHA)
  - Ex: SOLEIL 50 kW 352 MHz amplifiers





Tolerance cases: RF amplifiers (2)

- Operational advantages of **solid-state amplifiers**
  - No High Voltage, no high power circulator
  - Simple operation
  - Longer life times than tubes (MTBF >> 50000h), stable gain with aging
  - Possibility of reduced power operation in case of failure
  - Simplicity of maintenance due to redundancy
  - On-line repairability is possible (hot-pluggable pallets)

- Baseline solutions are existing at **176 MHz, 352 MHz, and even at 700 MHz**, thanks to TV transmitters technology

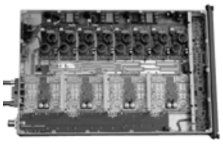


Figure 8 – HARRIS liquid cooled UHF transmitter[30].

Analog power levels up to 62.8 kW – Fully broadband PA modules (470 to 862 MHz with no adjustment) – 1:1 PA module to power supply redundancy – Hot-pluggable linear RF amplifier modules with integral soft-fail distributed power supplies – Automatic restart after AC mains interruption; returns to previous operational mode – Straightforward control, monitoring and in-depth diagnostics with easy-to-use, color touch screen – Harris® eCDi, Web-enabled remote GUI interface – Rugged, reliable construction – Liquid-cooled RF amplifiers, DC power supplies, RF combiners and reject loads to minimize air-conditioning costs

- Same redundant concepts can be applied to **DC power supplies**, etc.

1. **Basics of reliability theory**
2. **European ADS Demonstration: the MYRRHA project**
3. **The reference ADS-type accelerator**
4. **MYRRHA linac design & tolerance cases**

5. *Conclusion*

Conclusions

- **Reliability ≠ Availability !!!**
- With ADS (& the MYRRHA project), **reliability is for the first time a requirement** for the accelerator, not only a wish...
- The goal MTBF (about 250h) is <u>very ambitious</u> but seems reachable, given that:

1. Focus is made on reliability concepts during the whole design phase: **overdesign** / **redundancy** / **repairability**
2. **Tolerance cases** are implemented to the maximum extent, which implies especially the development of an efficient **fault diagnostic systems**
3. A sufficiently long period of **commissioning and practice** is foreseen during the early life of the MYRRHA machine

> ***My usual personal message to the MYRRHA team:***
> ***"We (accelerator community) can not reasonably promise the present required reliability spec. (10 trips/ 3 months) before at least a few years of commissioning & tuning of the MYRRHA machine. Please anticipate this in the reactor design."***

Chosen www ressources

- **Reliability theory:**
  <u>http://www.weibull.com/</u>
- **MYRRHA project:**
  <u>http://myrrha.sckcen.be/</u>
- **Proc. of Accelerator Reliability Workshops:**

  ARW-2002 (Grenoble): <u>http://www.esrf.eu/Accelerators/Conferences/ARW/</u>
  ARW-2009 (Vancouver): <u>http://www.triumf.info/hosted/ARW/</u>
  ARW-2011 (Cape Town): <u>http://www.arw2011.tlabs.ac.za/arw2011/</u>
- **MYRRHA accelerator design:**
  <u>http://ipnweb.in2p3.fr/MAX</u>