Reliability and Fault-Tolerance Strategy in the MYRRHA Superconducting Linac

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Accelerator Reliability Workshop
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Knoxville, Tennessee, USA

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

➊ Accelerator Driven System demonstrator

➋ Fast neutron irradiation facility

➌ Pilot plant for LFR technology

STUDIECENTRUM VOOR KERNENERGIE
CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

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

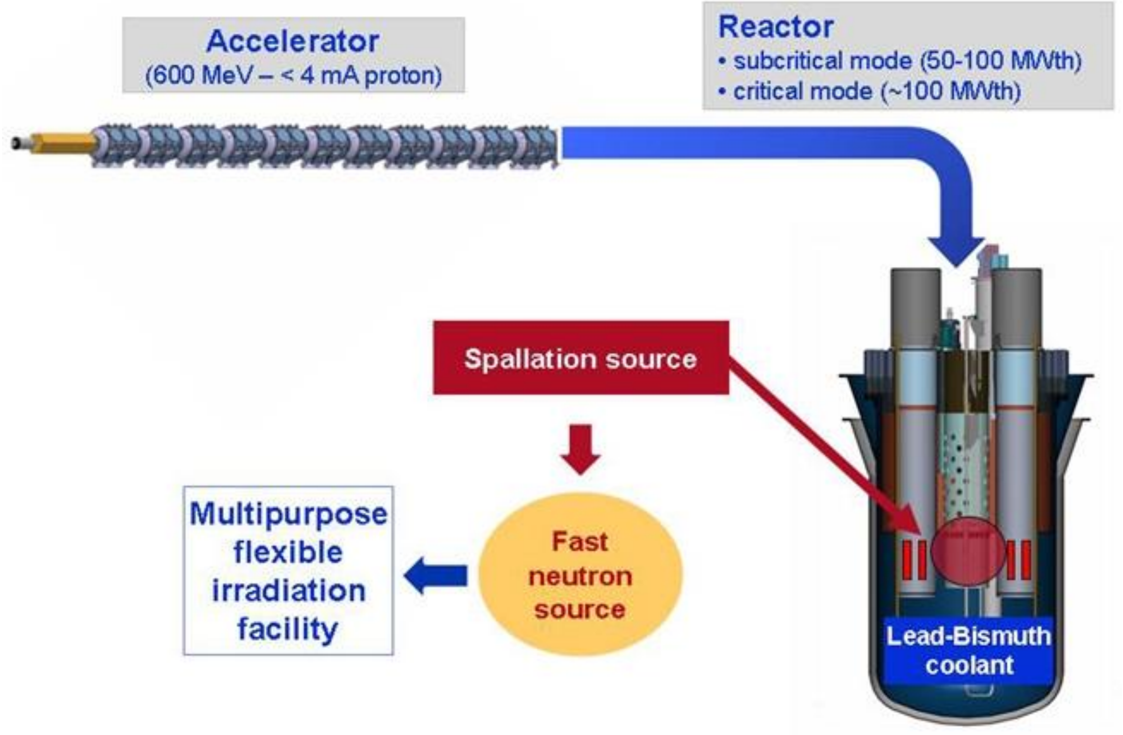
50-100 MW_{th} power

Highly-enriched MOX fuel

Pb-Bi Eutectic coolant & target

k_{eff} around 0.95 in subcritical mode

600 MeV, 2.5 - 4 mA proton beam



Accelerator
(600 MeV – < 4 mA proton)

Reactor
- subcritical mode (50-100 MWth)
- critical mode (~100 MWth)

Spallation source

Fast neutron source

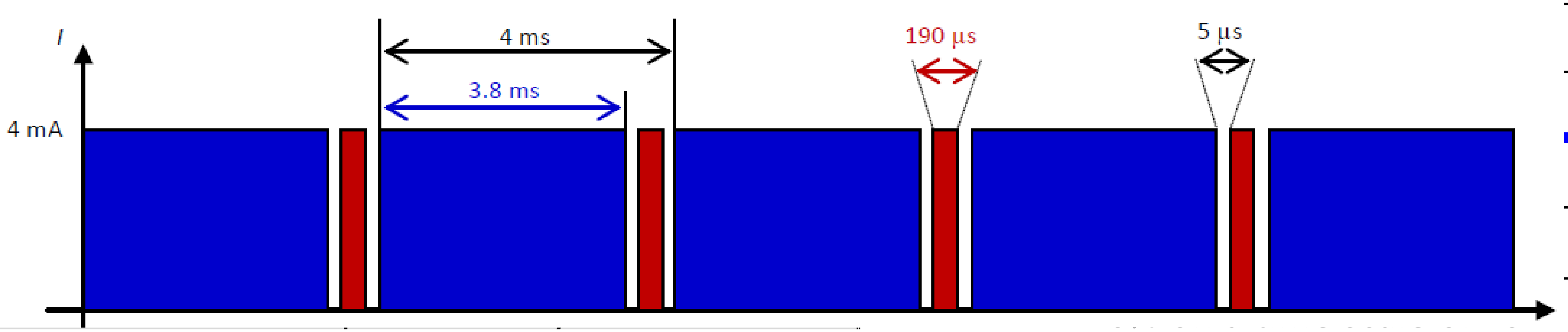
Multipurpose flexible irradiation facility

Lead-Bismuth coolant

Requirements for the Accelerator

High power proton beam (up to 2.4 MW)

Proton energy	600 MeV
Peak beam current	0.1 to 4.0 mA



Reference MYRRHA beam time structure for 2.4 MW operation:
-> long 4mA blue pulses are sent to the reactor (mean power is adjusting with pulse length)
-> short red ones are sent to ISOL (creating 200us beam holes for reactor subcriticity monitoring)

# of a	eriod
# of allowed beam trips on reactor longer than 0.1 sec	100 maximum per day
# of allowed beam trips on reactor shorter than 0.1 sec	unlimited

Extreme reliability level

Reliability Requirements

- **Beam trips longer than 3 sec** must be very rare:

➲ To minimise thermal stress & fatigue on the target window, reactor structures & fuel assemblies

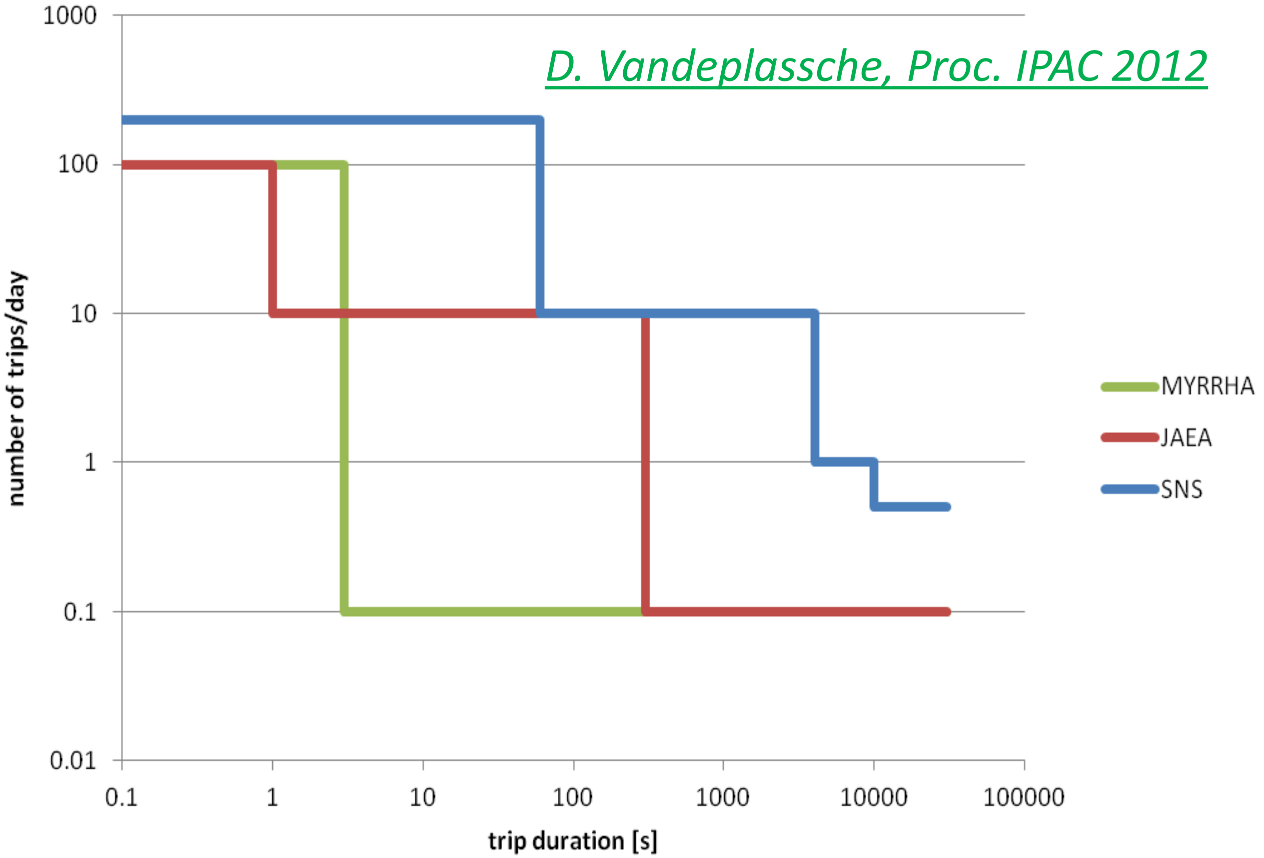
➲ To ensure an 80% availability – given the foreseen reactor start-up procedures

- **Present MYRRHA specifications:**

<10 beam trips per 3-month operation period (i.e. MTBF > 250h) – derived from the PHENIX reactor operation analysis

➲ Above present high power proton accelerator performances (PSI or SNS)

➲ Far above present ADS specifications in US or Japan – mainly based on simulations



D. Vandeplassche, Proc. IPAC 2012

Requirements for the Accelerator

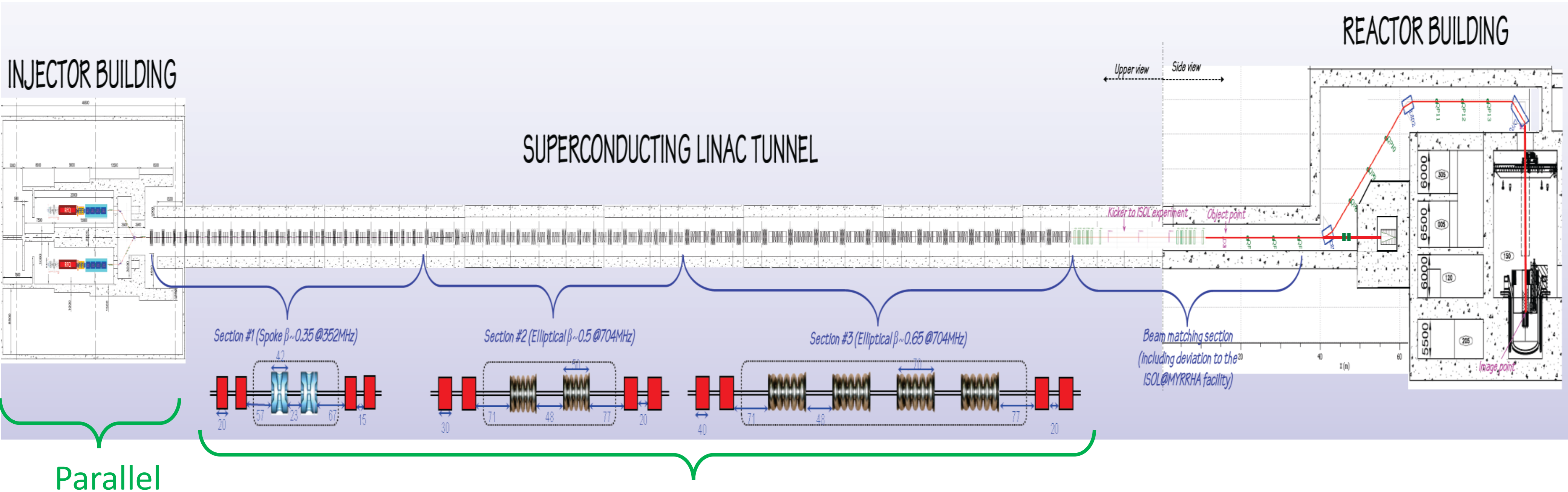
- **In any case, reliability guidelines are needed for the ADS accelerator design:**

➲ **Robust design** i.e. robust optics, simplicity, low thermal stress, operation margins…

➲ **Redundancy** (serial where possible, or parallel) to be able **to tolerate/mitigate failures**

➲ **Repairability** (on-line where possible) and efficient maintenance schemes

- **Layout of the MYRRRHA linac**



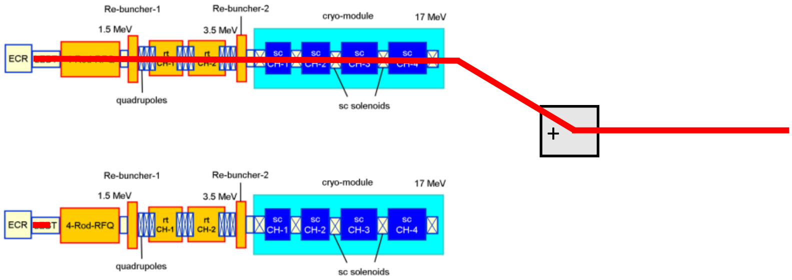
Parallel redundancy

Serial redundancy

Fault compensation strategy in the injector: Parallel Redundancy

❶ Initial configuration

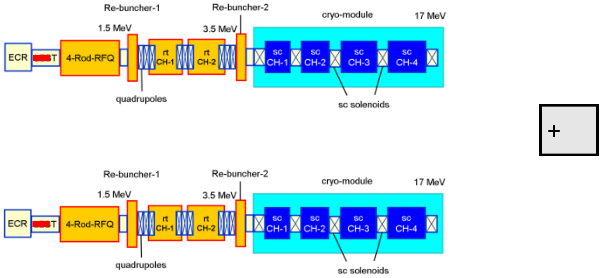
Operational injector 1: RF + PS + beam ON



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

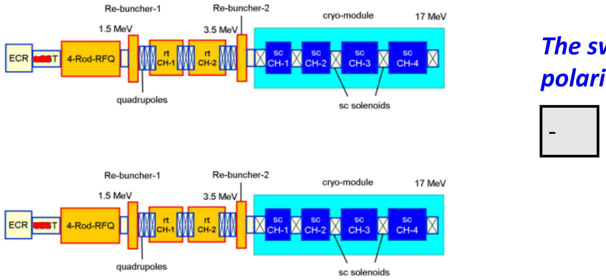
❷ A failure is detected anywhere

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



❸ The failure is localized in injector

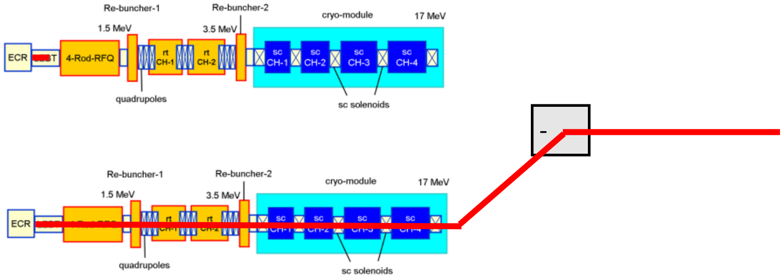
The switching magnet polarity is changed (~1s)



Need for an efficient fault diagnostic system !

❹ Beam is resumed

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



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

Fault compensation in the main linac: Serial Redundancy

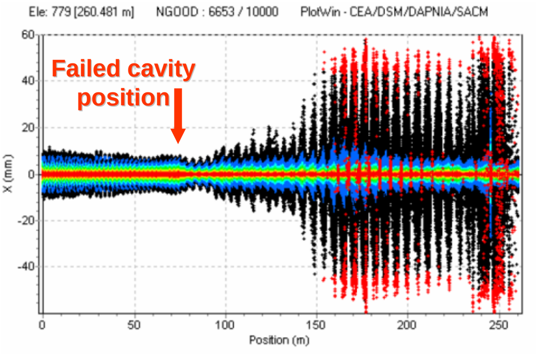


Figure 12 : Transverse beam distribution at 220 µs, in red are plotted the losses

❶ A failure is detected anywhere

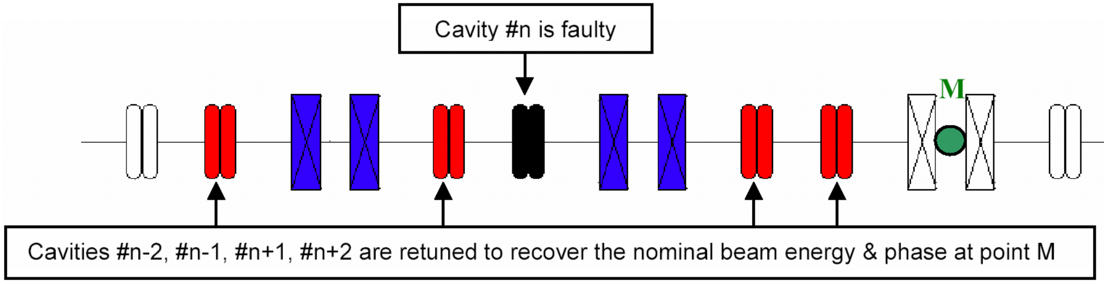
→ Beam is stopped by the MPS in injector at t_0

❷ The fault is localised in a SC cavity RF loop

→ Need for an efficient fault diagnostic system

❸ New V/ϕ set-points are updated in cavities (cryomodule) adjacent to the failed one

→ Set-points determined in advance: via virtual accelerator application and/or during the commissioning phase

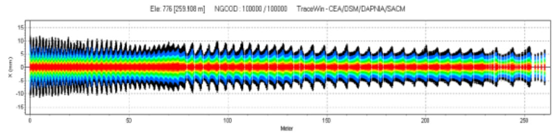


Cavity #n is faulty

Cavities #n-2, #n-1, #n+1, #n+2 are retuned to recover the nominal beam energy & phase at point M

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

→ Using the Cold Tuning System



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

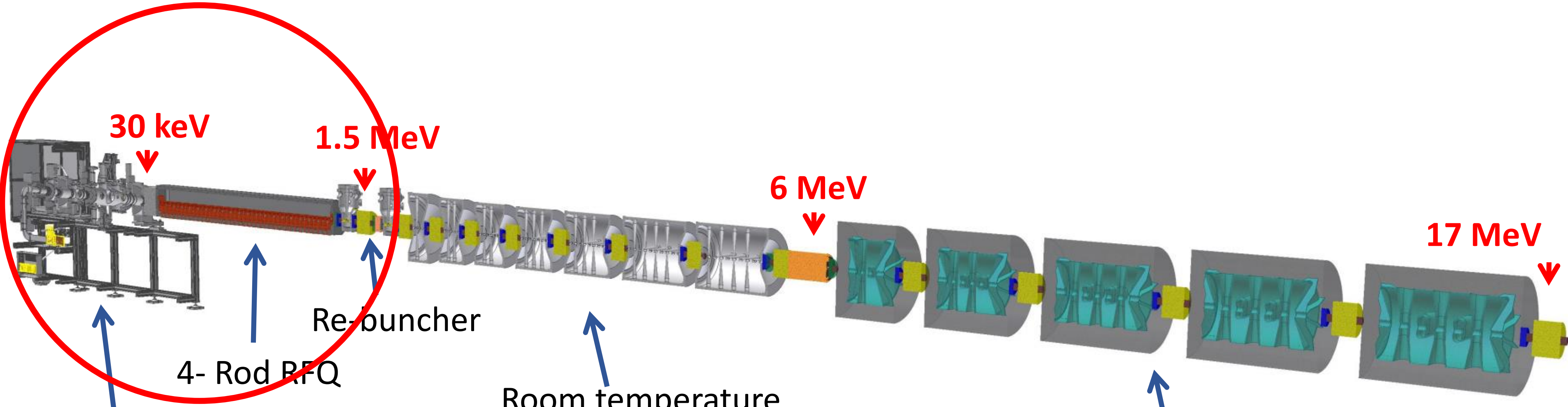
→ Failed RF cavity system to be repaired on-line if possible

MYRRHA Accelerator backgrounds & supporting projects

- **End 90's**: several collaborative R&D activities worldwide on ADS accelerators : *(APT/AAA, TRASCO, etc. w/ especially a CEA/CNRS/INFN collaboration)*
- **2001:** "The European roadmap for developing ADS for Nuclear Waste Incineration", European Technical Working Group on ADS *(chaired by C. Rubbia, ENEA)*
- **2002-2004:** MYRRHA is studied as one of the 3 reactor designs within the **PDS-XADS FP5 project** (coord. Framatome/AREVA): *cyclotron turns into linac, first reliability analyses show a need for fault-tolerance capability*
- **2005-2010:** MYRRHA is studied as the XT-ADS demo within the **EUROTRANS FP6 project** (coord. FZK): *600 MeV linac conceptual design, R&D activities w/ focus on reliability*
- **2010:** MYRRHA is on the ESFRI list, and officially supported by the Belgium government at a 40% level *(384M€, w/ 60M€ already engaged)*
- **2010-2014: MYRRHA accelerator advanced design phase supported by the EURATOM FP7 project : MAX (MYRRHA Accelerator eXperiment R&D)**
- 2015-2019: MYRRHA accelerator design and prototyping supported by Horizon 2020 - Research and Innovation Framework Programme: **MYRTE** (MYRRHA Research and Transmutation Endeavour) - WP2. Project just started.

The injector (30 keV to 17 MeV)

- **Dedicated R&D for the MYRRHA injector**



Room temperature CH-DTL cavities

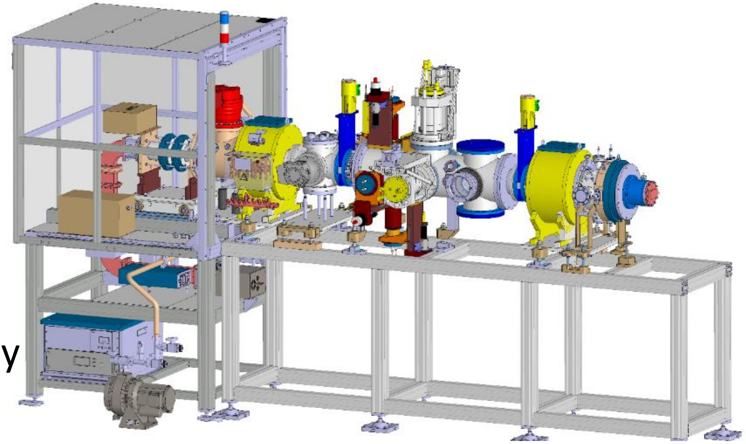
Low Energy Beam Transfer line (ECR proton source)

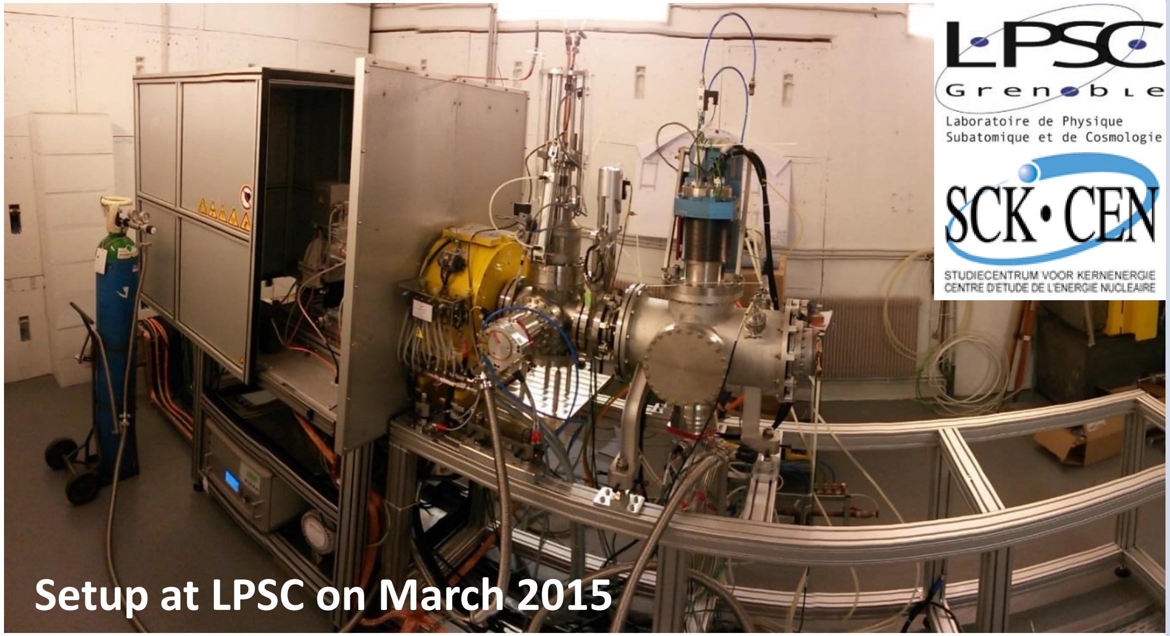
Superconducting CH cavities

R. Salemme et al., Proc. LINAC 2014
D. Mader et al., Proc. LINAC 2014

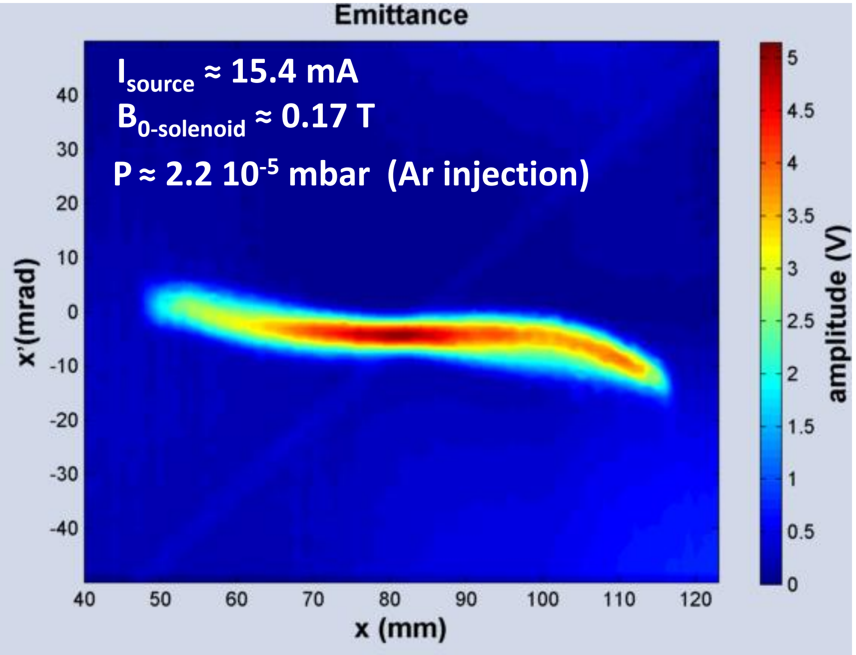
Low Energy Beam Transfer line (30 keV)

- First meters of the MYRRHA linac (initiate the construction)
- Compact design, with 2 solenoids & 1 electrostatic chopper.
- An accelerator mock up for:
  - ➲ Beam dynamics studies: i.e. space charge compensation
  - ➲ Reliability studies, with long run tests
  - ➲ To initiate the EPICS control system implementation & strategy





Setup at LPSC on March 2015



RFQ (30 keV to 1.5 MeV)

- 4-Rod RFQ at 176.1 MHz (4 meters long)

➲ Less expensive than a 4-Vane with more simple mechanical parts

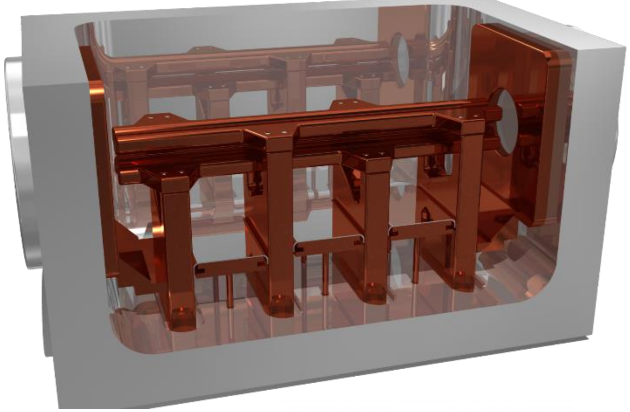
➲ Easier to tune than a 4-Vane

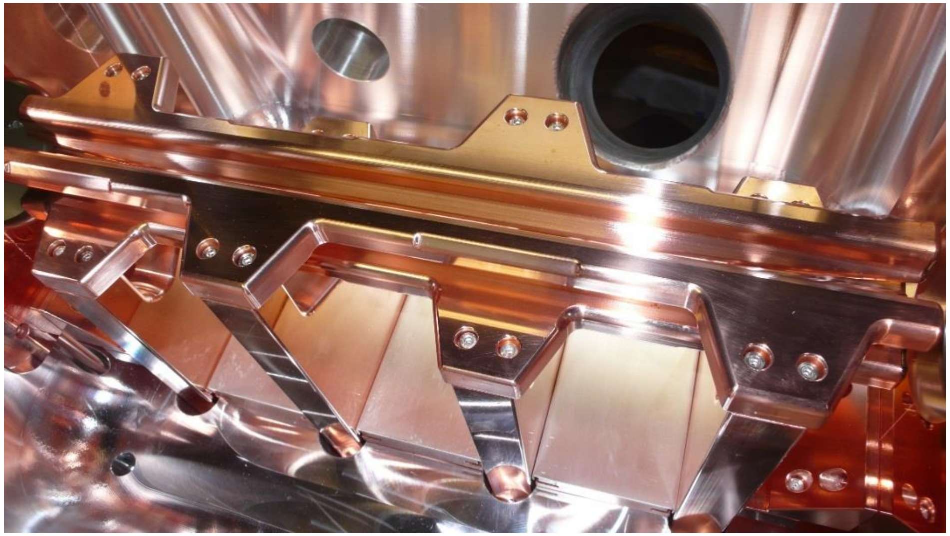
➲ Possibility to repair

➲ Need Particular attention for the cooling channel layout

Parameter	Value	unit
Frequency	176.1	MHz
Energy	1.5	MeV
Voltage	44	kV
Current	5	mA
R_p	67 (77)	kΩm
RF power	108	kW
P/L	25	kW/m

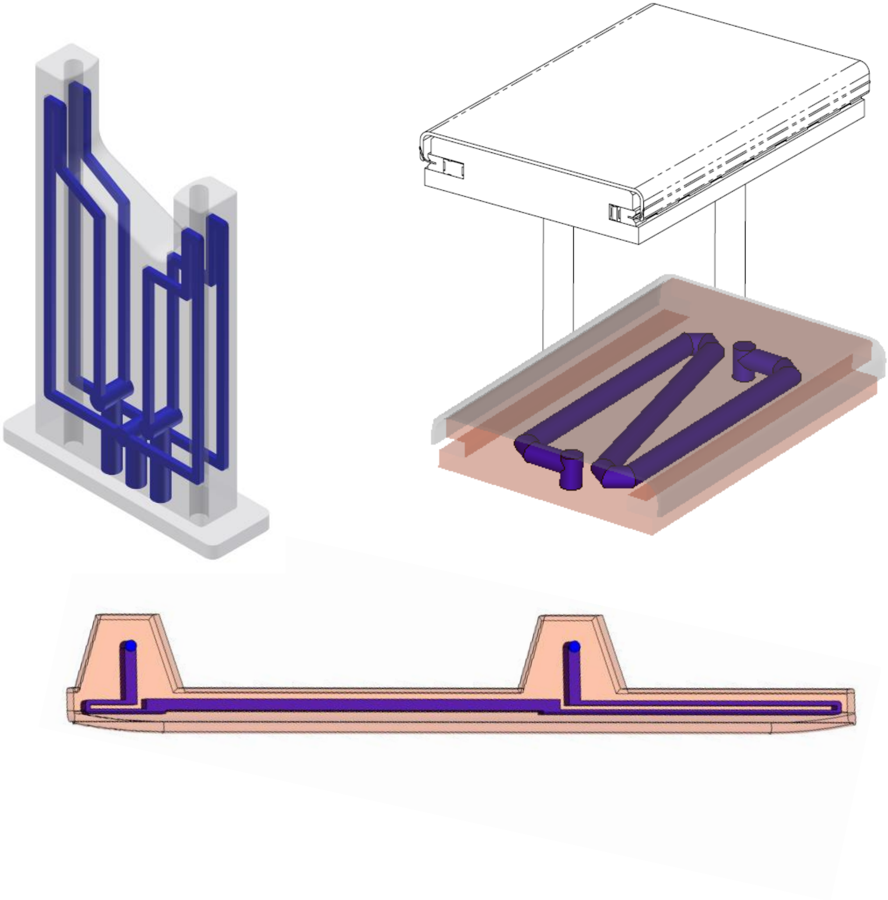
- A 0.4 meter prototype have been built and tested at IAP Frankfurt to validate the cooling channel layout



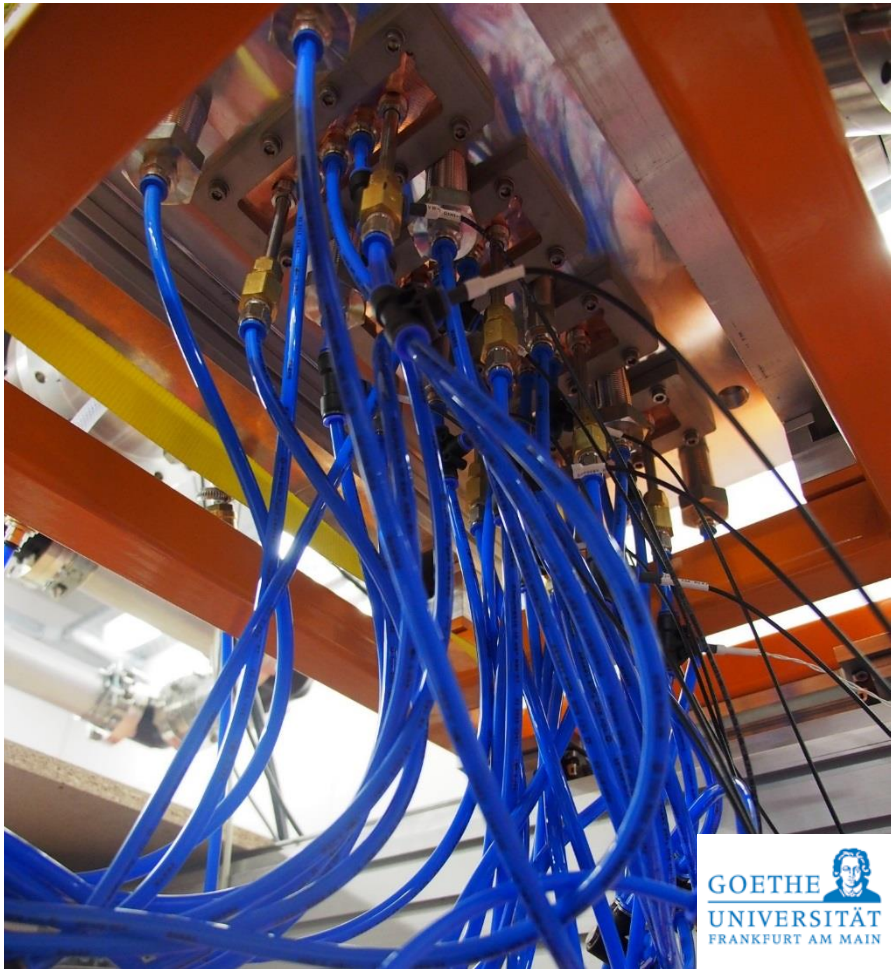


RFQ : cooling philosophy

- As much as possible
- Temperature distribution as homogeneous as possible

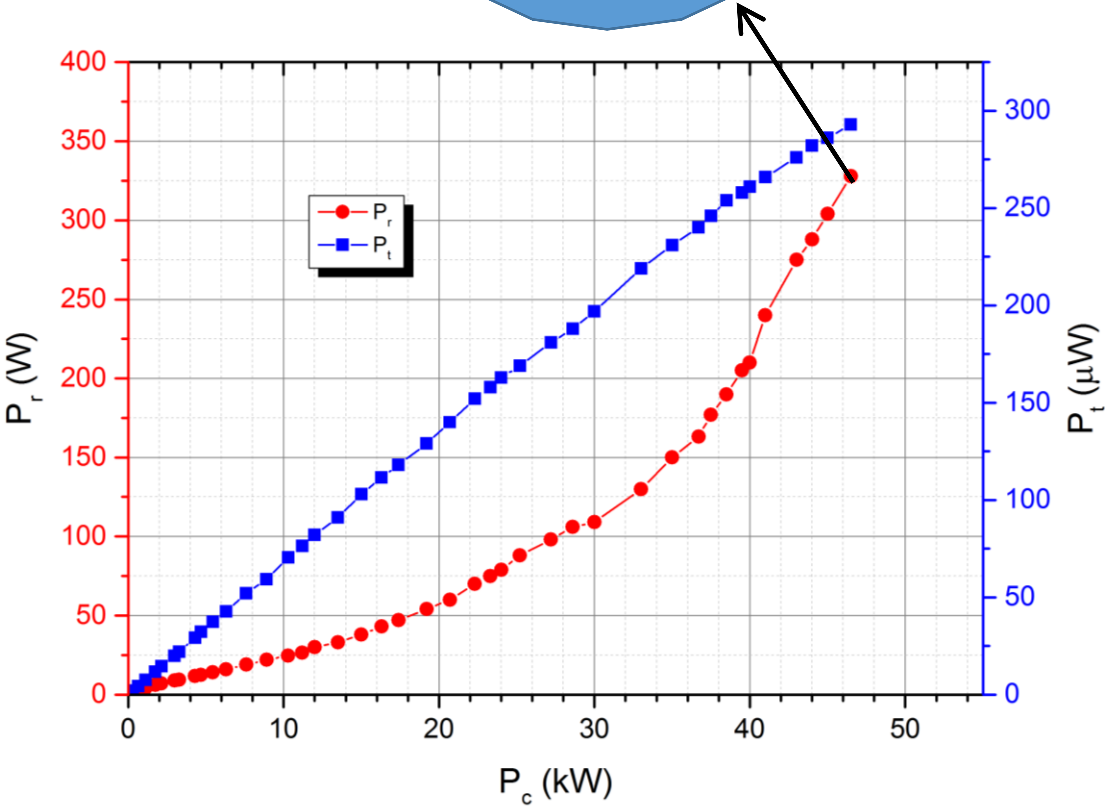


Courtesy of H. Podlech



RFQ prototype : RF power tests and first long run

P_{th}=116 kW/m
U=94.5 kV
E_p=29 MV/m

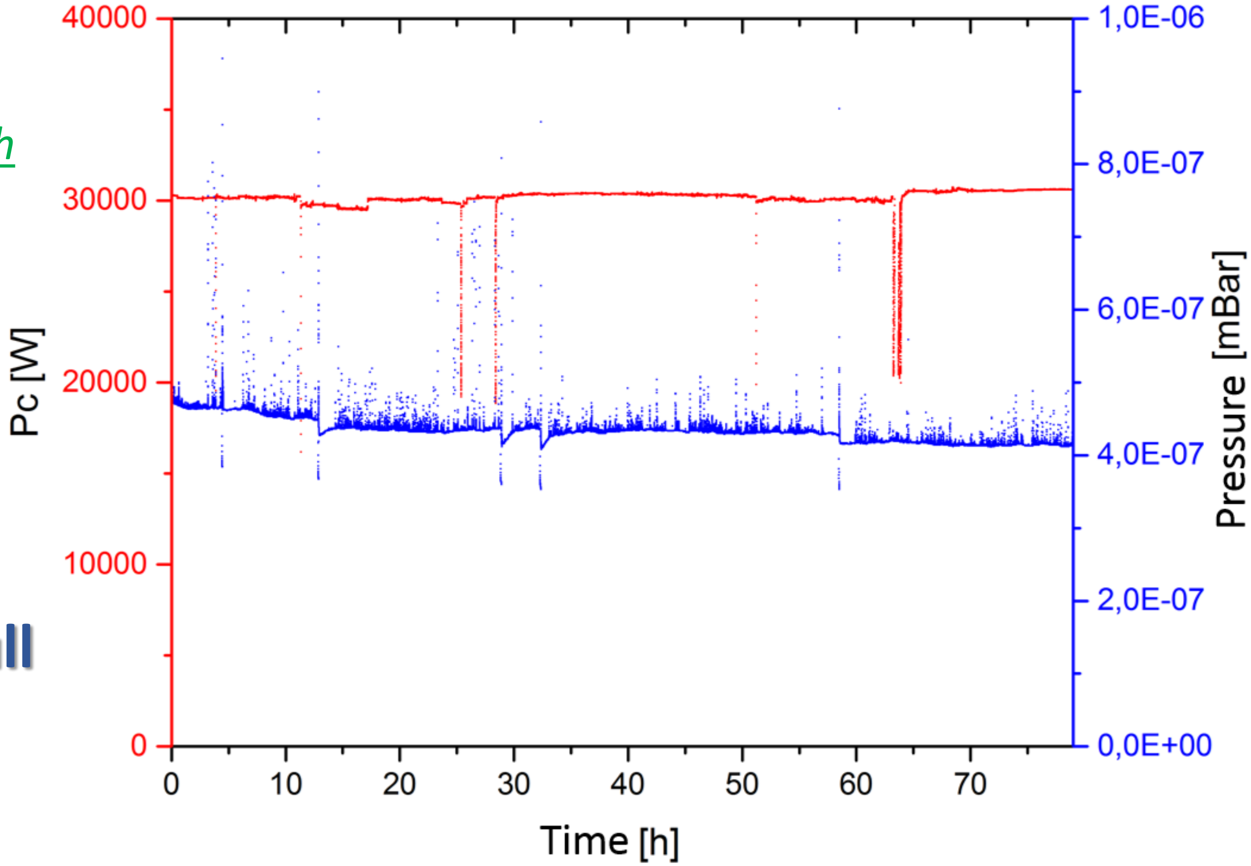


Courtesy of H. Podlech

Parameter	Value	unit
Frequency	175.5	MHz
L	400	mm
a	3.7	mm
ρ	3	mm
R_p (expected)	67	kΩm
R_p (measured)	77	kΩm
Q_0 (expected)	3750	---
Q_0 (measured)	4300	---
RF power (goal)	30	kW
P/L	75	kW/m

RFQ : First Long Run test of the prototype

- No amplitude control.
- Linear power density was 3 times higher than required for MYRRHA.
- Down Times:
  - ➲ One major due to amplifier shut down (40 min): internal error.
  - ➲ some short (>1 s) downtimes due to sparking
  - ➲ a few longer (1-20 s) due to high reflection. This can be avoided by using sufficient large circulators.



Courtesy of H. Podlech

- **Next step is the construction of the full RFQ (4 meters)**

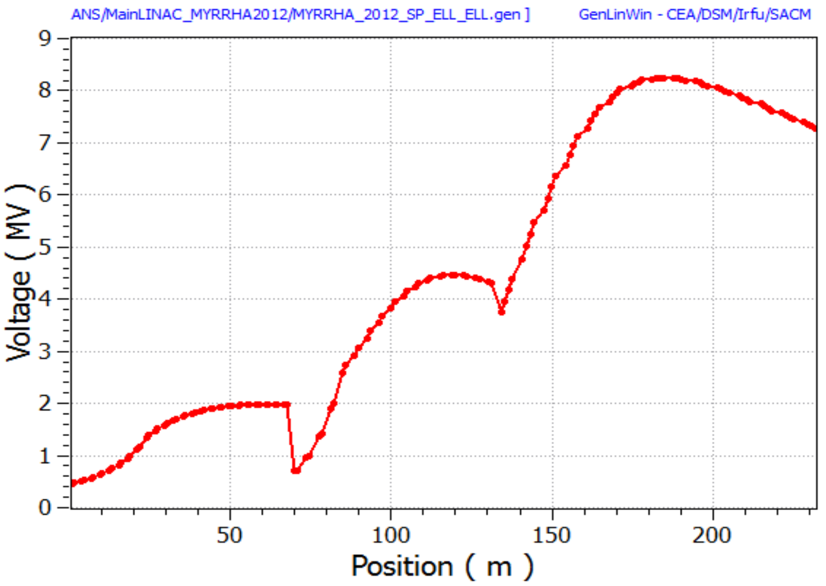
Main Superconducting Linac Design

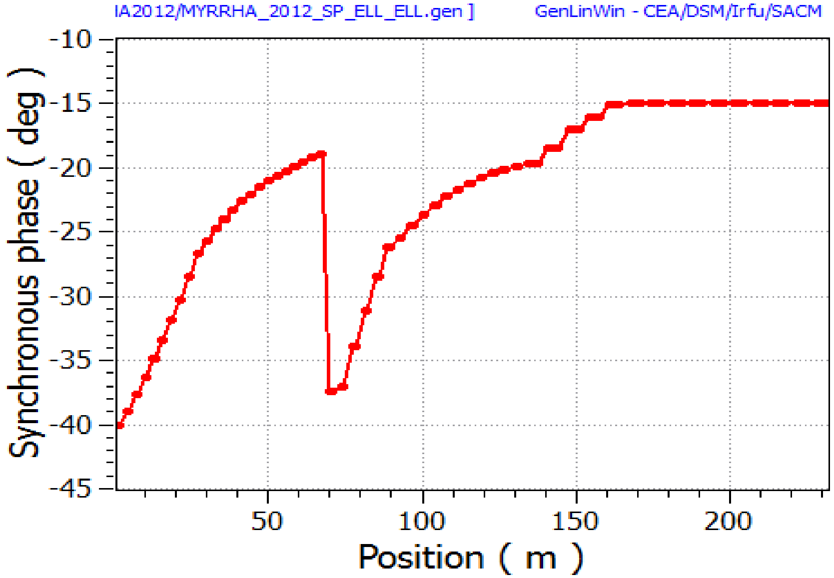
- **Enable E_{acc} increase by 30 %** for fault-compensation.
- “Smooth” phase advance variation : avoid SC-driven resonances, instabilities & emittance exchange.
- Large acceptance: enable the retuning scheme & avoid beam losses.

Section #	#1	#2	#3
E_{input} (MeV)	17.0	80.8	183.9
E_{output} (MeV)	80.8	184.2	600.0
Cav. technology	Spoke	Elliptical	
Cav. freq. (MHz)	352.2	704.4	
Cavity geom. β	0.35	0.47	0.65
Cavity optim. β	0.375	0.510	0.705
Nb of cells / cav.	2	5	5
Focusing type	NC quadrupole doublets		
Nb cav / cryom.	2	2	4
Total nb of cav.	48	34	60
Nominal E_{acc} (MV/m) *	6.4	8.2	11.0
Synch. phase (deg)	-40 to -18	-36 to -15	
Beam load / cav (kW)	1.5 to 8	2 to 17	14 to 32
Nom. Qpole grad. (T/m)	5.1 to 7.7	4.8 to 7.0	5.1 to 6.6
Section length (m)	73.0	63.9	100.8

*Eacc is given at β_{opt} normalised to L_{acc} = Ngap.β.λ/2

J-L. Biarrotte et al. Proc. SRF2013





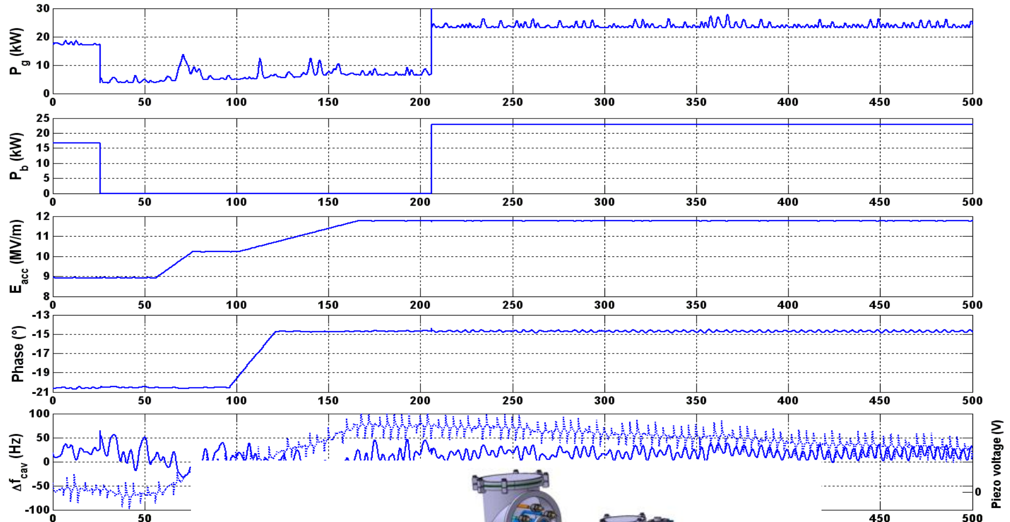
R&D for retuning procedures in less than 3 seconds

- Feasibility of the retuning procedures in less than 3 seconds

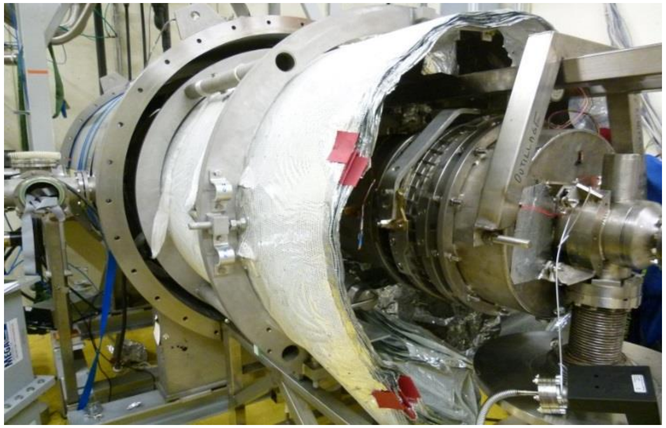
➲ Matlab Simulink Model : Cavity + feedback loops

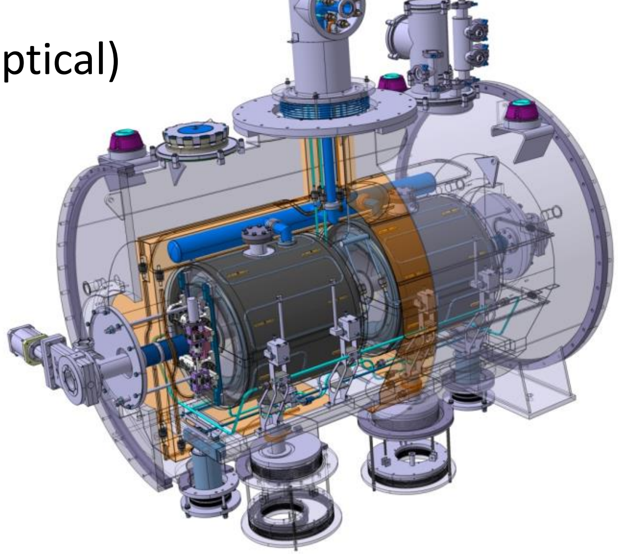
➲ feasible in less than 1 second

➲ But requires a fast frequency tuning system able to detune the cavity at a speed of 5 kHz/sec by at least 100*bandwidth (~ 10 kHz)



- Dedicated R&D on superconducting cavity (Spoke & 5-cell elliptical)

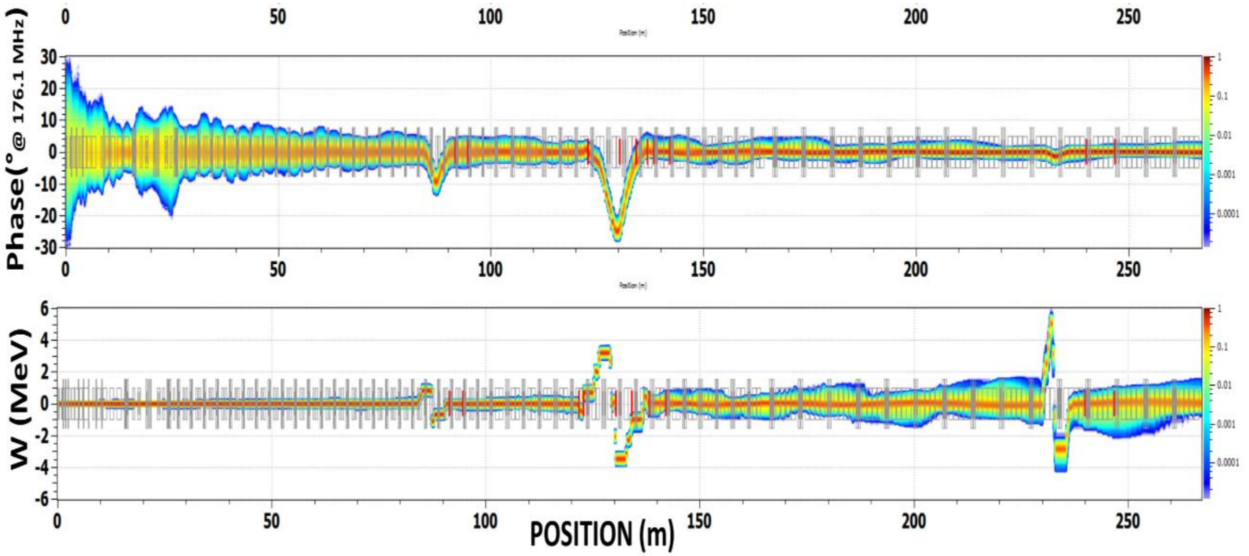




Beam studies for fault-recovery

- Example with multiple failures :

➲ Section #1: 1 Spoke cavity
➲ Section #2: 1 Cryomodule (i.e. 2 cavities)
➲ Section #1: 1 elliptical cavity



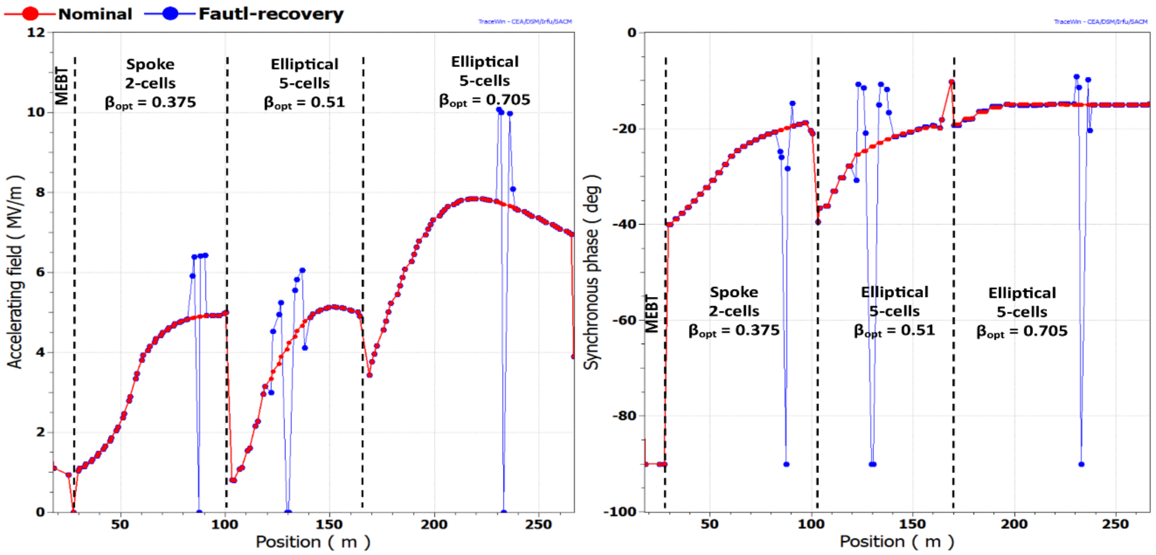
- Feasibility of beam retuning have been assessed but:

➲ A few critical scenario tested and identified (11).

➲ Most critical with 25 % of the cavity failed not tested

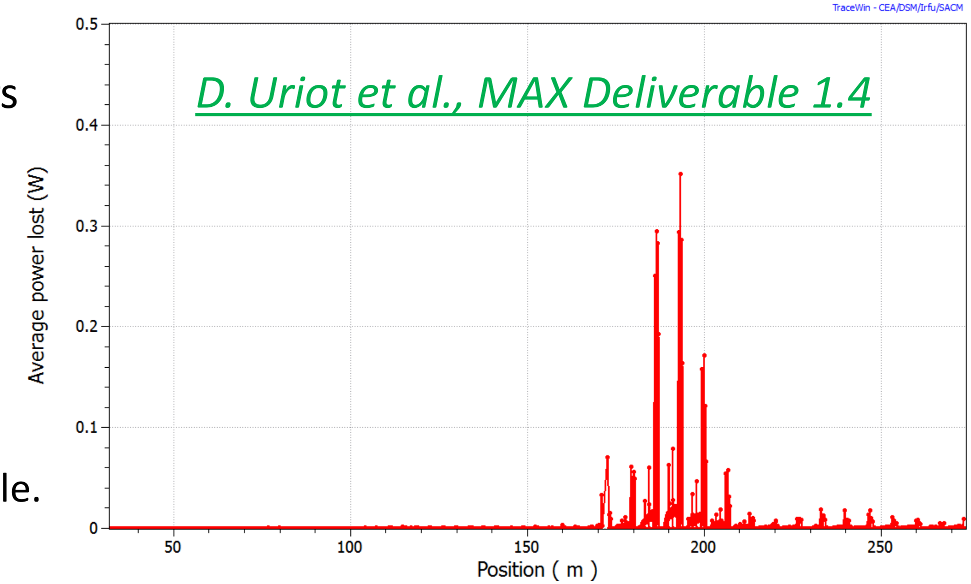
➲ Retuning simulations carried out with a “perfect linac” (No errors-homogenous E_{acc} distribution)

F. Bouly et al., Proc. Linac 2014



Fault recovery with errors

- Same example multiple failures example with errors (static and dynamic).
- 1000 linacs simulated with 10^6 macro-particles



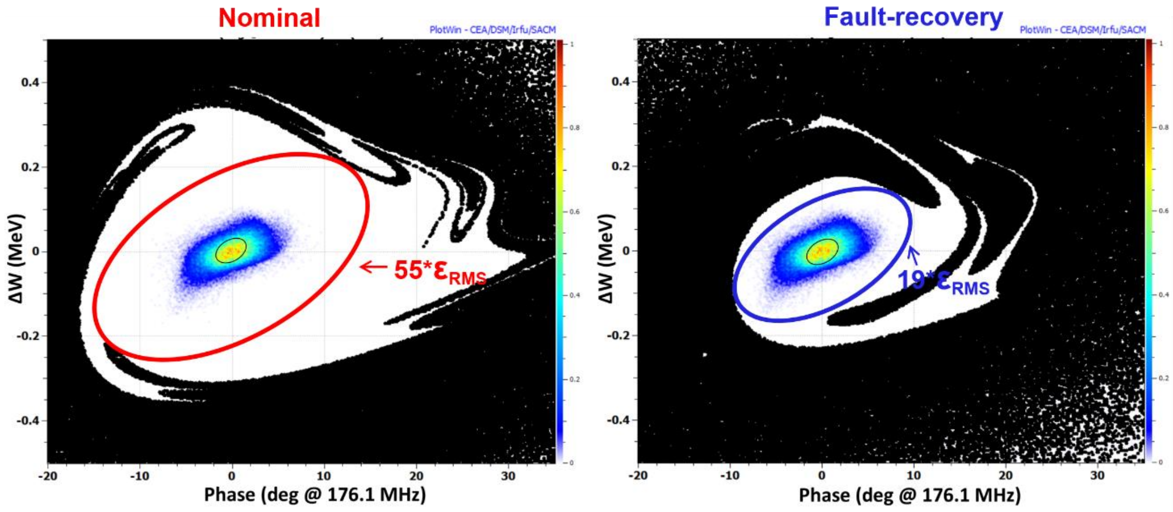
TraceWin - CEA/DSM/Irfu/SACM

D. Uriot et al., MAX Deliverable 1.4

- In the last section the losses are close by the acceptable limit of 1 W/m

➲ Emittance growth in section #2 with the failed cryomodule.

- Longitudinal acceptance is the key point for beam loss control
- Investigate to improve the method and find a less aggressive retuning scheme (use more cavities?)



Nominal

Fault-recovery

PlotWin - CEA/DSM/Irfu/SACM

Reliability Model of the full accelerator

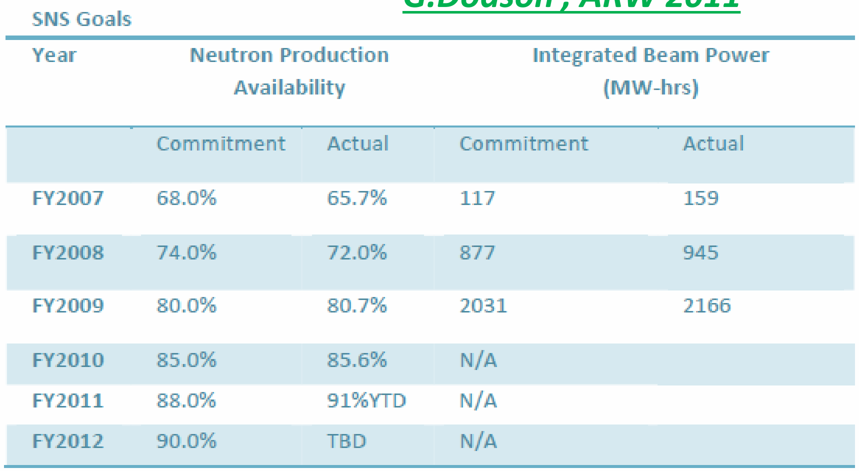
- 1st step: Development of a fault tree reliability model of the SNS

➲ SNS Design (Systems and Functions) - *SNS public info; SNS Design Control Documents (DCDs)*

➲ Reliability Data (Quantifying model)- Failure - MTTF and repair times – MTTR : SNS Operation team (SNS BlockSim model – **G. Dodson, J. Galambos**)

➲ SNS Operating Data: logbook (Benchmarking)

G.Dodson , ARW 2011



SNS Goals

Year	Neutron Production Availability		Integrated Beam Power (MW-hrs)	
	Commitment	Actual	Commitment	Actual
FY2007	68.0%	65.7%	117	159
FY2008	74.0%	72.0%	877	945
FY2009	80.0%	80.7%	2031	2166
FY2010	85.0%	85.6%	N/A	
FY2011	88.0%	91%YTD	N/A	
FY2012	90.0%	TBD	N/A	

- Good agreement between the model and operating data

➲ **73% availability of the SNS Linac *resulting from model is* confirmed by the availability *figures of the SNS from the* first years of SNS operation.**

- The reliability results show that the most affected SNS Linac parts/systems are:
  - Superconducting linac (SCL), Injector, Diagnostics & Controls
  - RF systems (especially the SCL RF system)
  - Power Supplies and PS Controllers

These results are consistent with the records in the SNS Logbook

A. Pitigoi, Workshop MAX-EUCARD2 , 2014

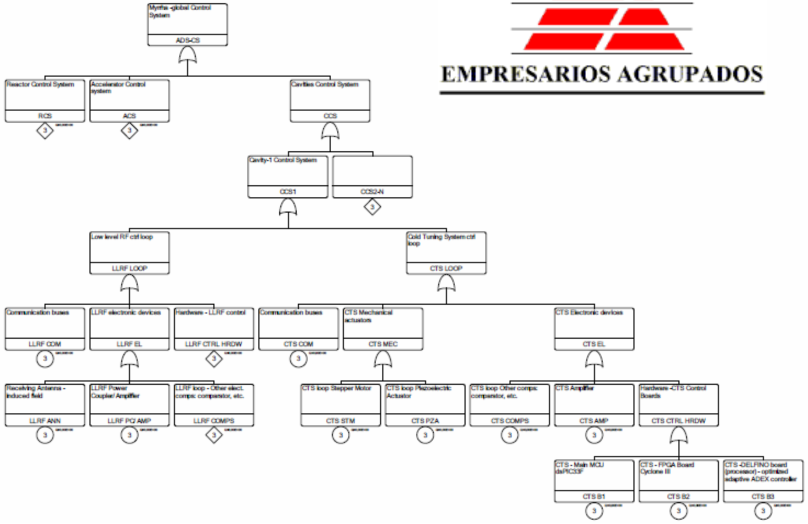
MYRRHA linac modelling

A. Pitigoi, Workshop MAX-EUCARD2 , 2014

• Overall approach

- Fault Tree, based on SNS model + Max design
- Basic Events: Component / Function failures
- Undeveloped Events/Systems: Reliability targets
- Reliability model: Availability / Failure frequency (Linac shutdown)
- Reliability Analysis: Design Optimization

EMPRESARIOS AGRUPADOS

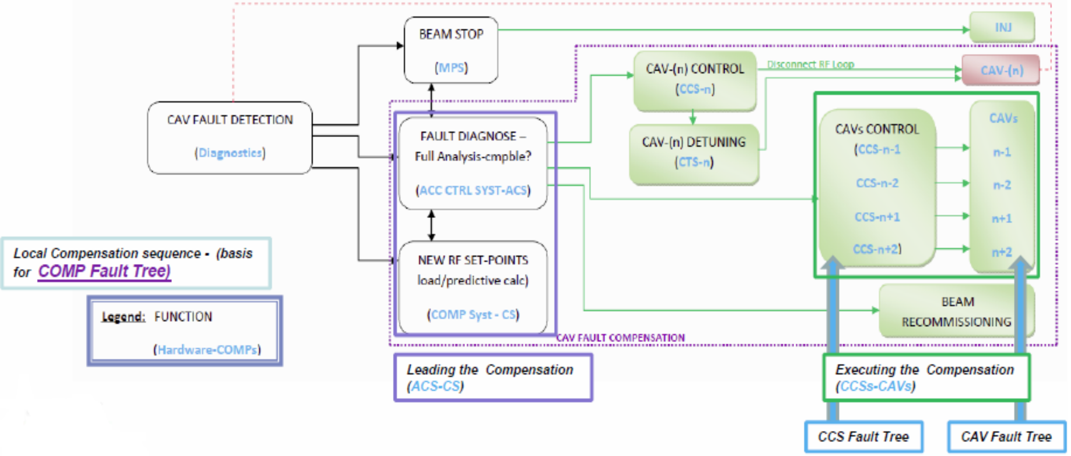


• Modeling Assumptions

- RF Systems: considered ⇔ SNS (except Klystrons, modulators) ← Solid state amplifier s (SSAs)
- AUX syst ⇔ SNS, modified for Myrrha (current design)
- Missing Reliability data
    - → Assumptions (Equipment overall Reliability data from manufacture

• Control system modelling

- Fault tree development (Myrrha control philosophy)
- Defined diagnostics included in the fault tree
- Missing datas: Diagnostics, acquisition, signal transmission…



Preliminary model: first results

- The Fault compensation scheme is effective, **but only if the linac has an intrinsic optimized reliability**

➲ First results gives ~550 trips/years with a “standard” (No-redundancy) linac (~70% availability)

➲ Fault compensation strategy enable to decrease the number of trips by ~100/year (parallel + serial redundancy)

➲ The MYRRHA goal : 40 trips/year (10 per 3-months period)

➲ Goal : ~140 trips/year for the standard linac → Reduce the number of compensation events

- Need for intelligent fail-over redundancy implementation in controllers

- A strong effort is needed for Diagnostics & controls systems developments: must be designed with a high level of reliability.

- Implement redundancy of systems, subsystems and components most affected by failures

CONCLUSIONS & PROSPECTS

- Within the MYRTE project (WP2) R&D will be strongly focused on the injector:
  - ➲ LEBT & RFQ construction and operation - SSAs & control systems R&D
  - ➲ A “Platform” for low energy proton beam dynamics
  - ➲ Dedicated to reliability studies (collecting failure datas, long run tests …)

- Improvements of the Fault compensation procedure:
  - ➲ Improve the methodology to calculate the cavity set points
  - ➲ Consider a “non-perfect” linac
  - ➲ Possibility to use more cavities to compensate one failure

- Improve the reliability tree model of the MYRRHA linac to anticipate, as best as possible, on the critical points for the linac detailed design

THANK YOU