Enhancing Accelerator Reliability with LLRF Digital Technology

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on behalf of EUROTANS WP 1.3 Accelerator design

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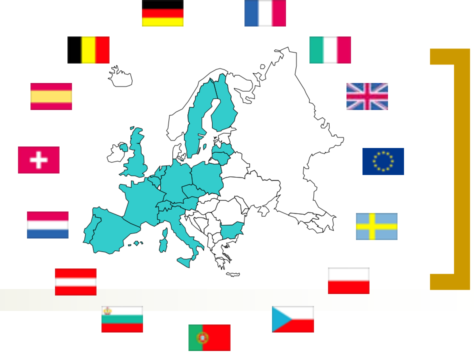
Overview

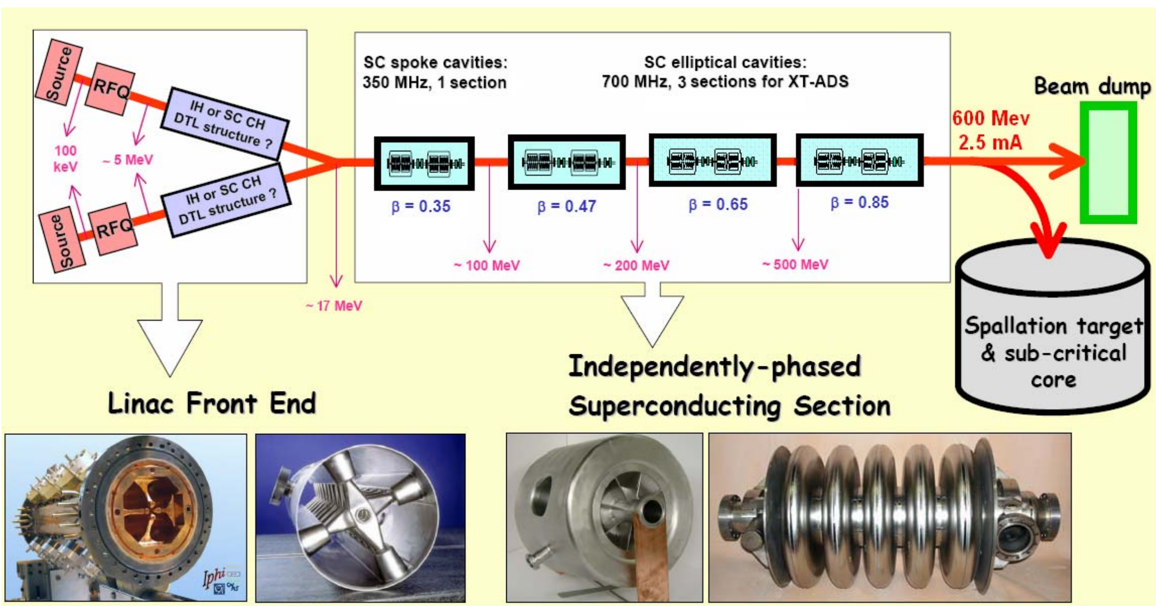
- EUROTRANS project: ADS for transmutation of nuclear waste
- Reliability key feature for ADS class accelerators
- Fault tolerant strategy
- Generic scheme for ADS LLRF digital feedback system
- LLRF digital system development for 352 MHz SPOKE cavities

ADS solution for nuclear waste transmutation



IP-EUROTRANS
- INTEGRATED PROJECT ON EUROPEAN TRANSMUTATION -

SIXTH FRAMEWORK PROGRAMME



WP 1.3: Accelerator design and development

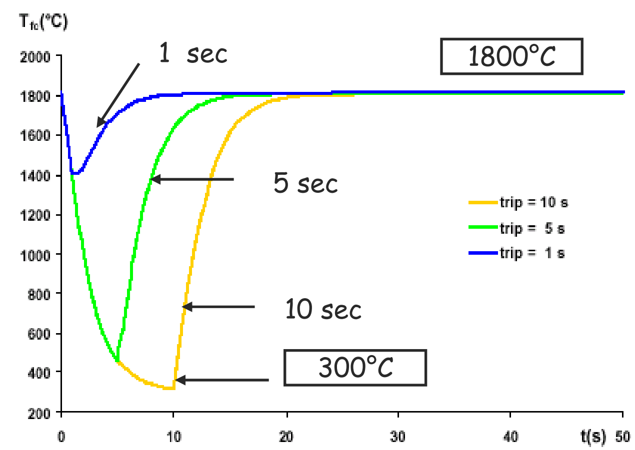
EUROTRANS goals:

Demonstration of technical feasibility of transmutation using an ADS

- Advanced design of an eXperimental facility demonstrating technical feasibility of Transmutation in an Accelerator Driven System (XT-ADS), and conceptual design of the European Facility for Industrial Transmutation (EFIT), DM1 DESIGN
- Provide validated experimental input from relevant coupling experiments of accelerator / spallation target / sub-critical blanket, DM2 ECATS
- Development and demonstration of the associated technologies, especially fuels DM3 AFTRA, heavy liquid metal technologies DM4 DEMETRA, and nuclear data DM5 NUDATRA

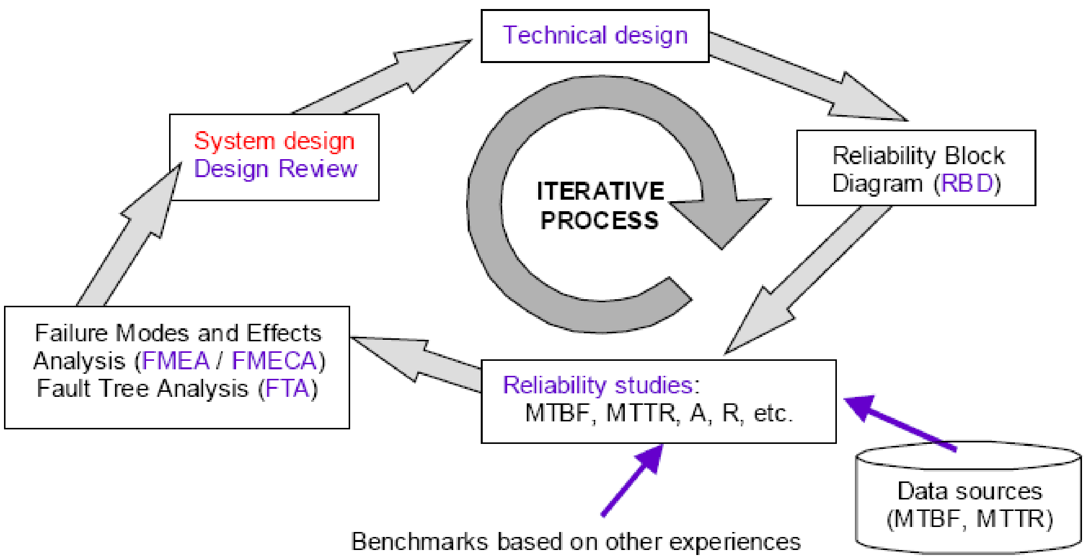
Accelerator reliability

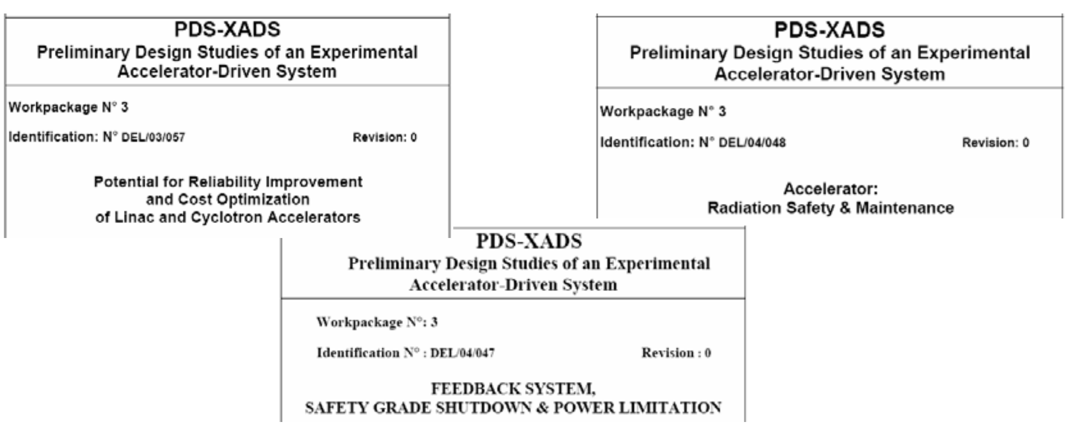
- Reliability ≠ Availability
  example: SILHI source 7 day run
- Accelerator is used to control fission reaction
  => CW beam structure
- The ADS challenge:
  - spallation source = worries about the stress on the target
  - ADS = spallation worries + stress induced on the reactor nuclear core
- Reactor core, and particularly the cladding, can only stand a few thermo-mechanical shocks per running cycle
  => request from reactor community for an accelerator with no more than 10 beam trips per year of over 1 second



Simulations of thermal transients in the sub-critical core

Designing a reliable machine





PDS-XADS
Preliminary Design Studies of an Experimental Accelerator-Driven System

Workpackage N° 3

Identification: N° DEL/03/057 Revision: 0

Potential for Reliability Improvement and Cost Optimization of Linac and Cyclotron Accelerators

PDS-XADS
Preliminary Design Studies of an Experimental Accelerator-Driven System

Workpackage N° 3

Identification: N° DEL/04/048 Revision: 0

Accelerator: Radiation Safety & Maintenance

PDS-XADS
Preliminary Design Studies of an Experimental Accelerator-Driven System

Workpackage N°: 3

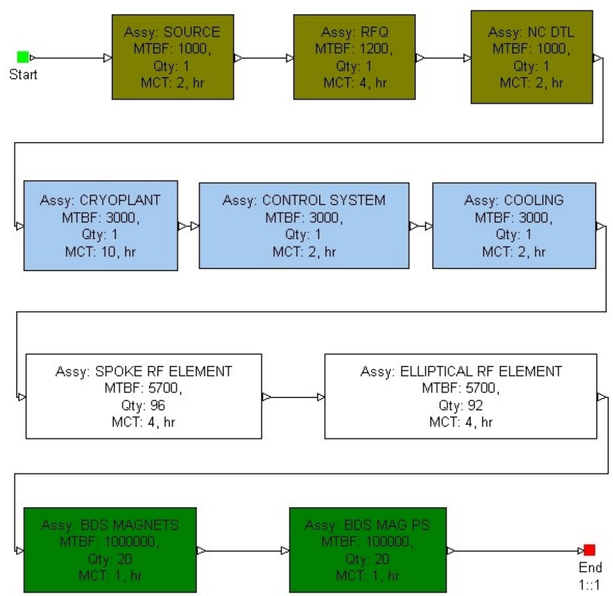
Identification N° : DEL/04/047 Revision : 0

FEEDBACK SYSTEM, SAFETY GRADE SHUTDOWN & POWER LIMITATION

- Defining reliability goals
- Use of RAMS software for formal accelerator reliability estimations
- Use of deductive and inductive reliability considerations
- Lumped components database
- MTBF considerations
- Redundancy of certain parts
- De-rated use of components
- Parts count

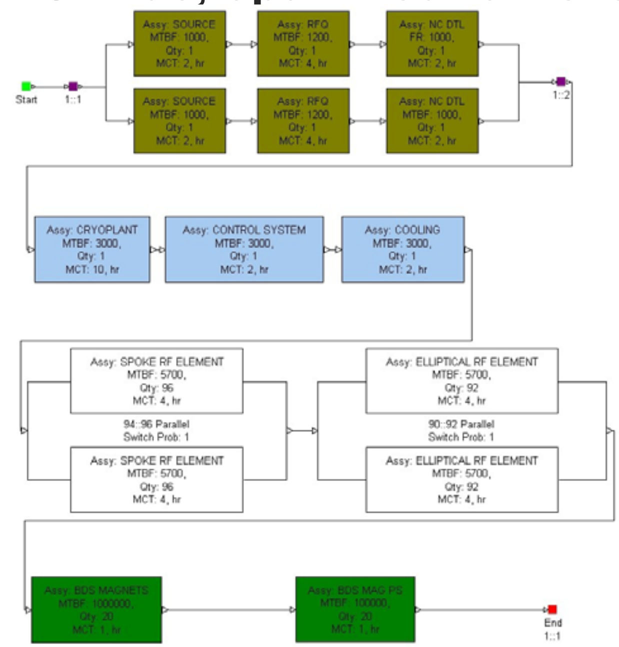
Designing a reliable machine

Classical linac



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

XADS linac, optimized for reliability

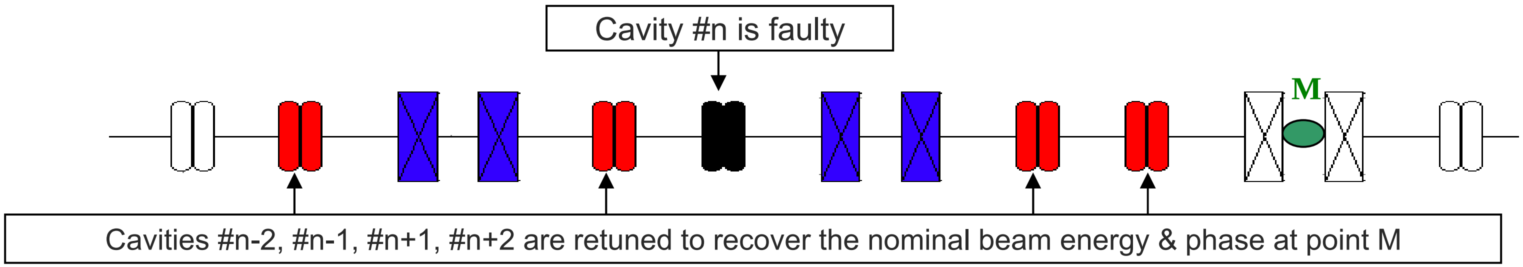


System MTBF	757.84 hours
Nb of failures (3 months)	**2.89**
Steady State Availability	99.5 %

P. Pierini, L. Burgazzi, “Reliability studies for a SC driver for an ADS linac”, Fifth International Workshop on the Utilization and Reliability of HPPA, SCK-CEN, Mol, Belgium, May 2007

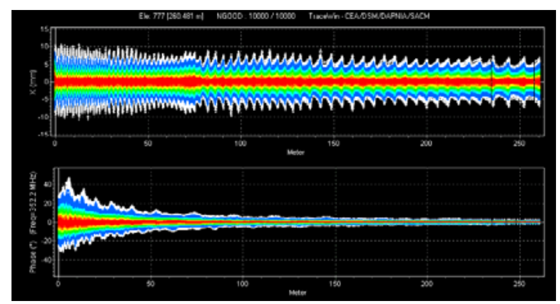
Fault tolerant accelerator

Local Compensation



Demonstrated from beam dynamics point of view

- Non-relativistic beam = phase slip as high as 80˚ in the following cavity
- Using 4 to 8 cavities
- Need of ~30% power and field margin
- Works for energies from 5 to 600 MeV, not so good results below 10/15 MeV



Multiparticle beam envelopes (x-transv., phase) in the XADS linac if spoke cavity #4 (5.5MeV, 3 m) is faulty and local compensation is performed

# faulty cavity	section	Final energy	Emittance growth (%) Transv.	Emittance growth (%) Long.	# of retuned cavities (bef + aft)	Max ΔEacc (%)	Max E_{pk} (SP) or B_{pk} (EL)	Max ΔPower (%)	# retuned quads (bef + aft)
1	SP 0.15	Nominal	+ 7 %	+ 4 %	**0 + 4**	+ 67 %	19 MV/m	+ 67 %	0 + 4
4	SP 0.15	Nominal	+ 9 %	+ 4 %	**3 + 3**	+ 46 %	15 MV/m	+ 35 %	2 + 4
35	SP 0.15	Nominal	+ 6 %	0 %	**2 + 3**	+ 20 %	32 MV/m	+ 27 %	2 + 2
61	SP 0.35	Nominal	+ 6 %	+ 2 %	**2 + 3**	+ 25 %	31 MV/m	+ 26 %	2 + 2
96	SP 0.35	Nominal	+ 5 %	+ 1 %	**4 + 2**	+ 21 %	30 MV/m	+ 25 %	4 + 2
125	EL 0.65	Nominal	+ 5 %	0 %	**2 + 3**	+ 18 %	59 mT	+ 27 %	4 + 2
174	EL 0.65	Nominal	+ 5 %	0 %	**3 + 3**	+ 18 %	59 mT	+ 22 %	4 + 2
186	EL 0.85	Nominal	+ 7 %	0 %	**6 + 1**	+ 21 %	61 mT	+ 33 %	2 + 2

Biarrotte et al., HPPA04, EPAC04

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Fault tolerant accelerator

Global Compensation

- Non relativistic beam -> velocity is energy dependent
- If a cavity fails, the beam arrives at downstream cavities later
- For SNS if an upstream cavity fails, the arrival time at downstream cavities can be delayed up to 5 ns
  - This represents over 1000 degrees phase setting of an 805 MHz RF cavity
  - Goal is to set the cavity to within ~ 1 degree

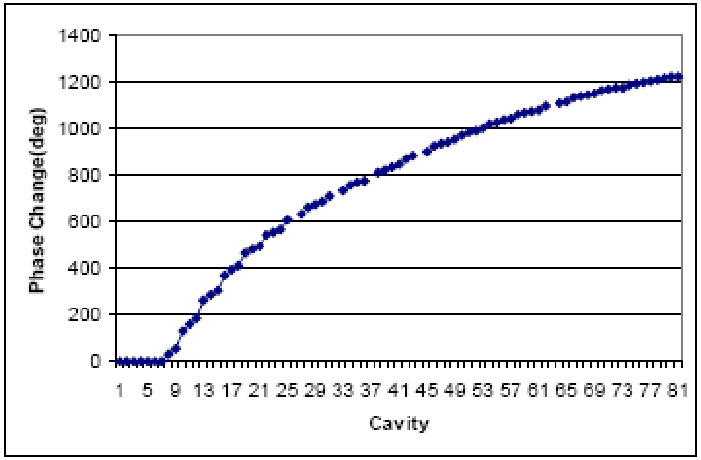


Figure 5: The predicted cavity phase setpoint change resulting from turning off cavity 7. The last cavity phase setpoint was checked with a phase scan and found to be within 1 degree of this prediction.

- High energy (> 200 MeV) & low mean current
- Recovery procedure duration = a few minutes

J. Galambos, S. Henderson, Y. Zhang, "A Fault Recovery System for SNS Superconducting LINAC", Proceedings of LINAC 2006

Fault tolerant accelerator

Scenario #1

- Fast fault detection and beam shut-down
- Fast access to a predefined set-point general database, or to the result of an appropriated longitudinal beam dynamics fast simulation
- Fast update and tracking of the new LLRF field and phase set-points
- Adequate management of the tuner of the failed cavity to put it off frequency
- Beam re-injection

Procedure duration induces beam gap of (theoretically) up to 1 second

<u>Work still to be done on technical issues:</u>

- Fast fault detection
- LLRF communication procedures
- Cold tuner fast management

Fault tolerant accelerator

Scenario #2

- Fast fault detection
- Fast access to a predefined set-point general database
- Fast update and tracking of the new field and phase set-points, based on the foreseen failed cavity transient behavior (pre-calculated tables), to recover quickly the nominal beam transmission and energy

Fast enough to avoid significant beam loss

- Slow update and tracking of new field and phase set-points with the same method while detuning the failed cavity to avoid the beam loading effect

Demonstrated from beam dynamics point of view

Fault tolerant accelerator

Failure of last spoke cavity: detection time = 75 µs correction step = 75 µs

- 40 correction steps are performed before stabilization @ 3ms
- Good emittance behavior, no beam losses during the procedure
- 6 cavities used with 50% Eacc margin available (with 8 cavities : 40%)

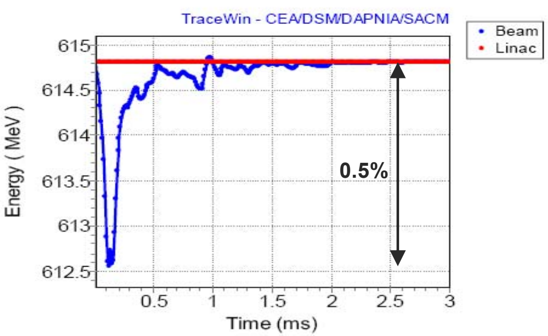


Figure 18 : Output beam energy

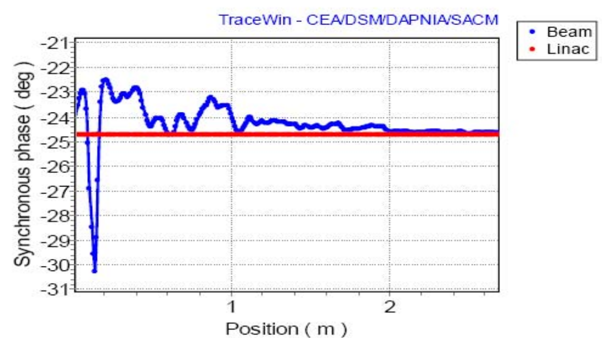


Figure 19 : Beam synchronous phase at last cavity

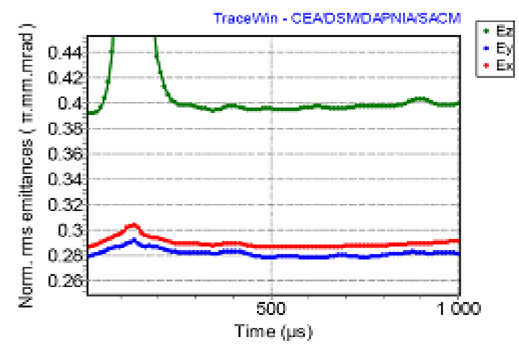


Figure 20 : Emittance evolution during the first ms

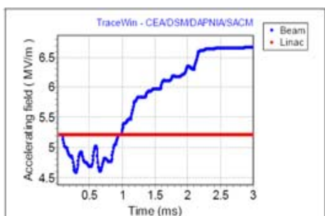


Figure 23 : Field in cavity #1

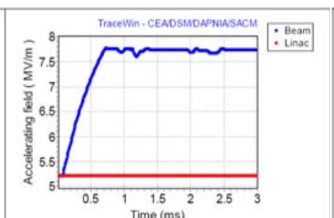


Figure 24 : Field in cavity #2

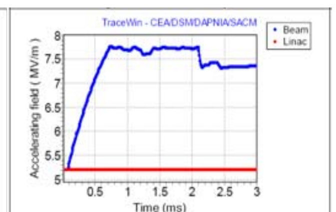


Figure 25 : Field in cavity #3

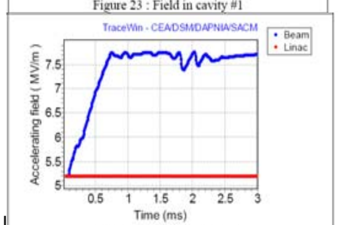


Figure 26 : Field in cavity #4

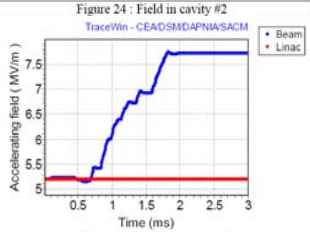


Figure 27 : Field in cavity #5

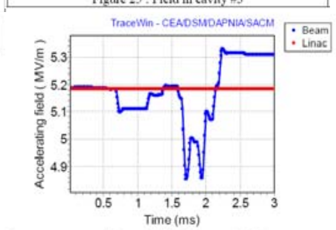
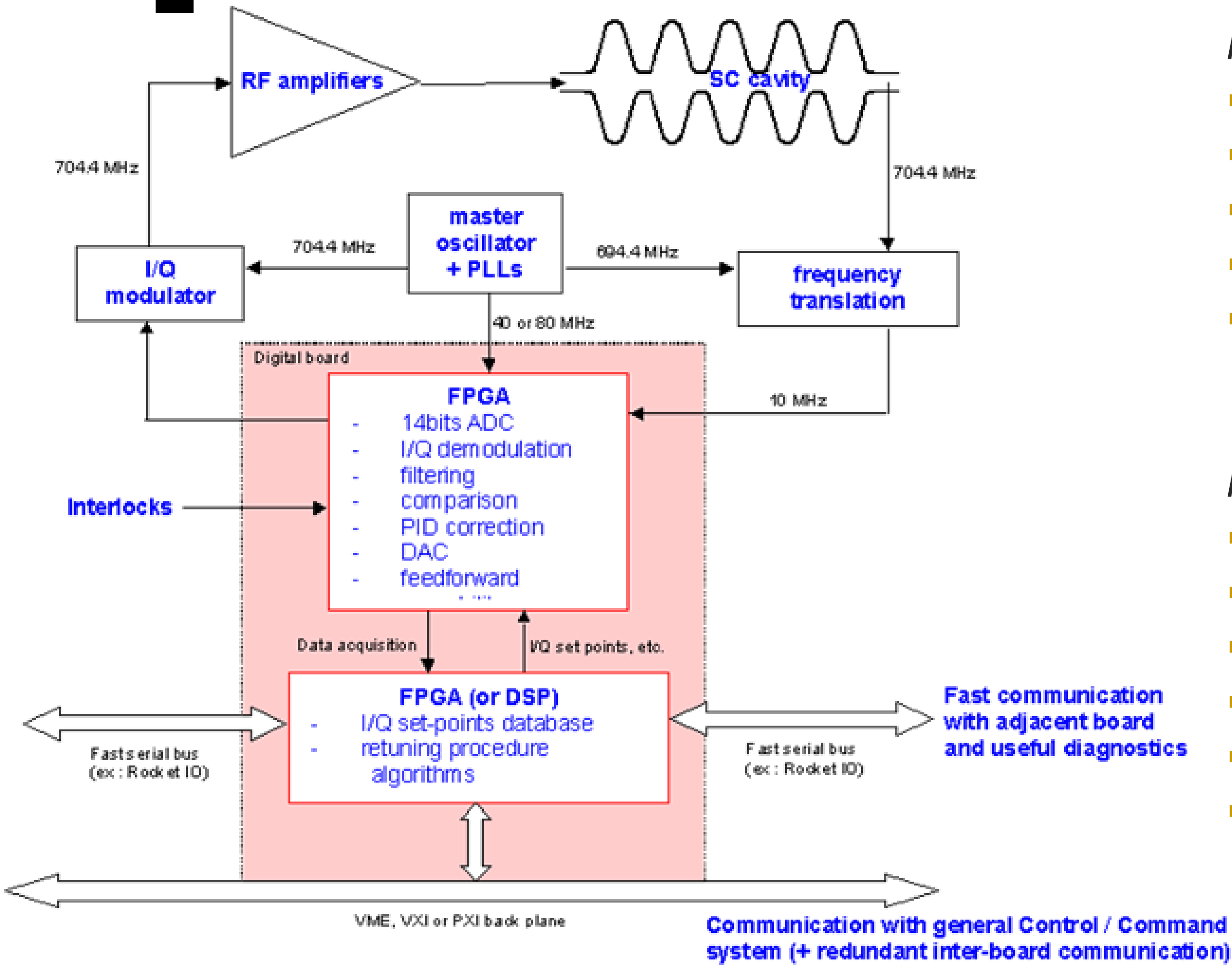


Figure 28 : Field in cavity #6

Recommendations for maximum
detection time = 150 µs
correction step = 150 µs
Above these values beam loss too high

Generic scheme for ADS LLRF digital feedback system



Requirements:

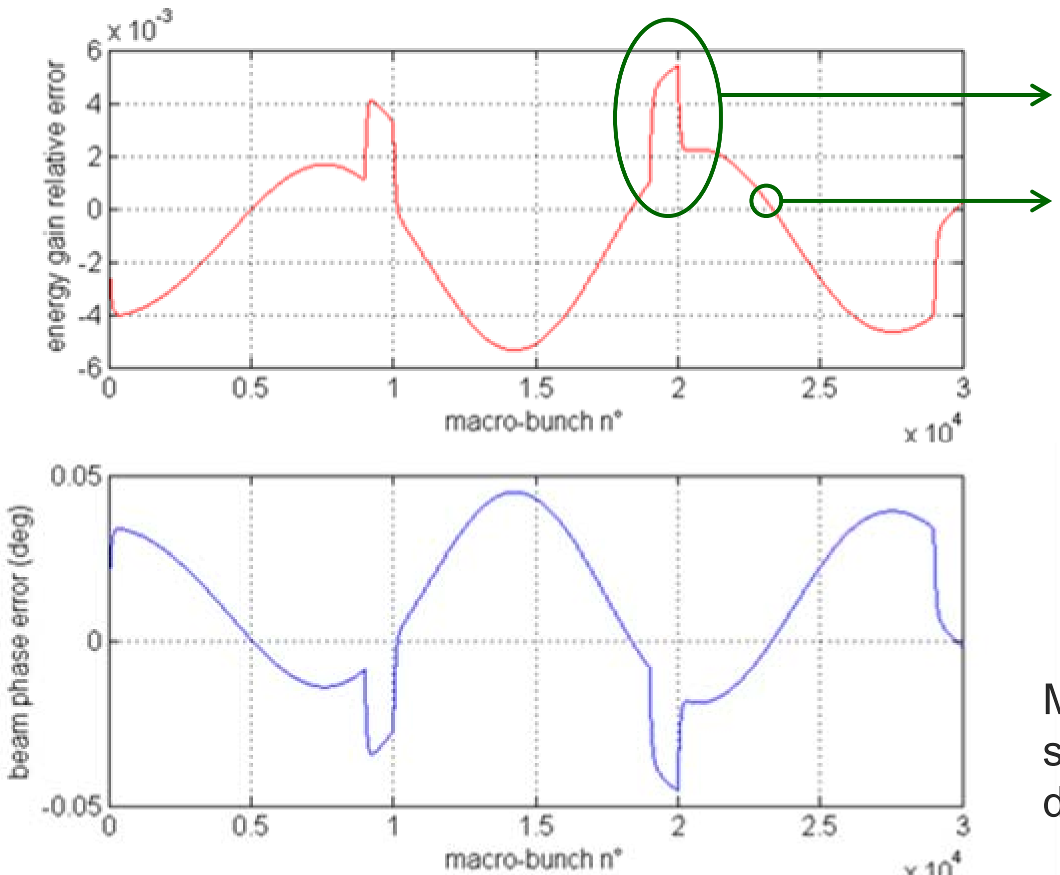
- Field stability: +/- 0.5%
- Phase stability: +/- 0.5°
- Power source budget: +75%
- RF system MTBF > 6000h
- Integration of fast (<1s) failure recovery procedures

RF System features:

- loop delay < 3µs
- loop gain ~100
- 14bits ADC
- 10MHz IF
- FPGA chip
- Fast serial bus for inter-board communication

Simulating LLRF regulation with beam gaps

- Many perturbations may be simulated: beam gap, Lorentz force, microphonics, injection error, etc. (Matlab/Simulink)
- Accelerator is used for reactor criticality measurements => need to have at least 90 µs gaps



gap: 140 µs, 50% current

Microphonics: 50 Hz @ 250 Hz

I/Q feedback loop
gain = 100, delay = 2 µs

⇩

residual energy error = 0.6 %
residual beam phase error = 0.05°

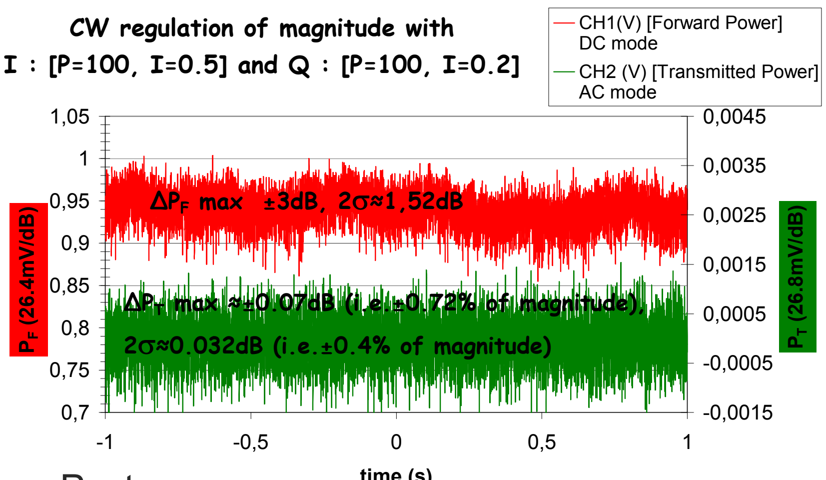
M. Luong, O. Piquet, “RF control system modeling”, EUROTRANS deliverable D 1.3.11

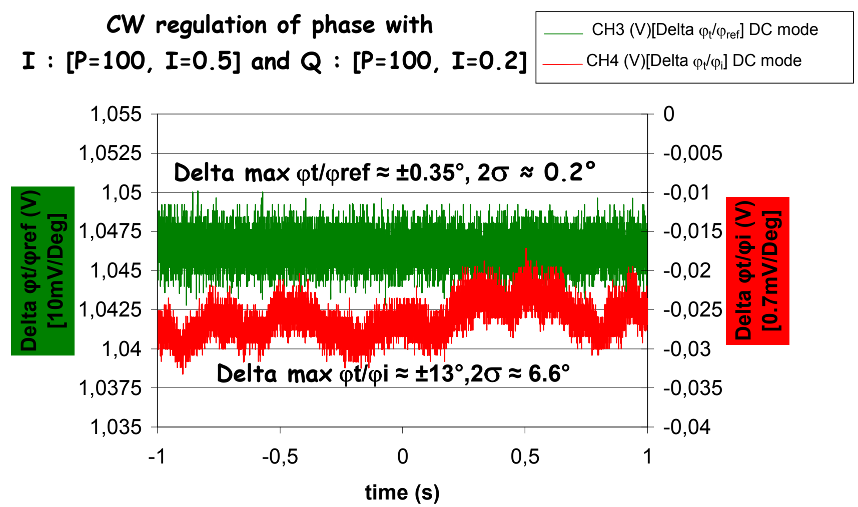
Developing LLRF digital system

LLRF digital system for 352 MHz Spoke cavities

- Stability of the amplitude : 0.1%
- Stability of the phase of the accelerating field : 0.5°
- Response time : less than 10 µs

Tested on β 0.15 cavity with Q_{load} = $6.8 \cdot 10^5$





Posters:

- Tests @ 4.2K of the LLRF Control System for Superconducting SPOKE cavities
- A PXI Format Board for Digital Low Level RF Control of Superconducting Cavities

Summary

- Extremely high reliability requirement of 10 beam trips of over 1 second per year
- Preliminary reliability assessment identified redundancy, derating and **fault tolerance** as strong design criteria for ADS accelerator
- Beam dynamic studies identified two procedures for fault tolerance

Scenario #1 (stopping the beam)	Scenario #2 (on-line)
Implies a ≤ 1 sec beam stop	**No beam stop**
"Relatively fast" fault time detection	"Extremely fast" fault time detection
Lower margins / nb cavities required	Higher margins / nb cavities required
Small pre-defined set-points database	Huge pre-defined set-points database
Fast cold tuner management required	**Classical cold tuner management**

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Thank you for your attention