The MYRRHA Superconducting linac - Fault-tolerant design and developments

Frédéric Bouly

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Technology and Components of Accelerator-Driven Systems (TCADS-4) Workshop

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MYRRHA linac Goals

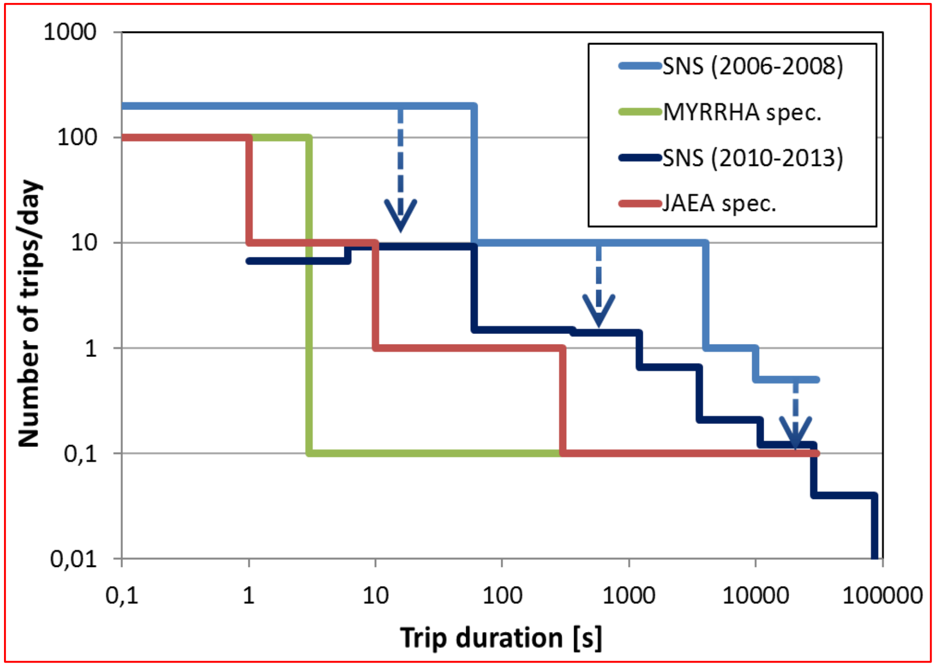
- Design to follow the construction Phase approach :
  - MINERVA (Phase 1) : 100 MeV
  - MYRRHA: 600 MeV

High power proton beam (up to 2.4 MW)

	MYRRHA	MINERVA
Proton energy	600 MeV	100 MeV
Peak beam current	0.1 to 4.0 mA	
Repetition Rate	1 to 250 Hz	
Beam duty cycle	2.10^{-4} to 1	2.10^{-4} to 0.125 (on PTF) 2.10^{-4} to 0.875 (on FPBD)
Beam power stability	< ± 2% on a time scale of 100 ms	
Beam current stability		< ± 2% over macropulse duration (To be confirmed)
Beam footprint on reactor window / or PTF	Circular Ø 85 mm	To be specified
Beam footprint stability	< ± 10% on a time scale of 1 s	
# of allowed beam trips on reactor longer than 3 sec	10 maximum per 3-month operation period	
# 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	

MYRRHA and MINERVA main proton beam specifications

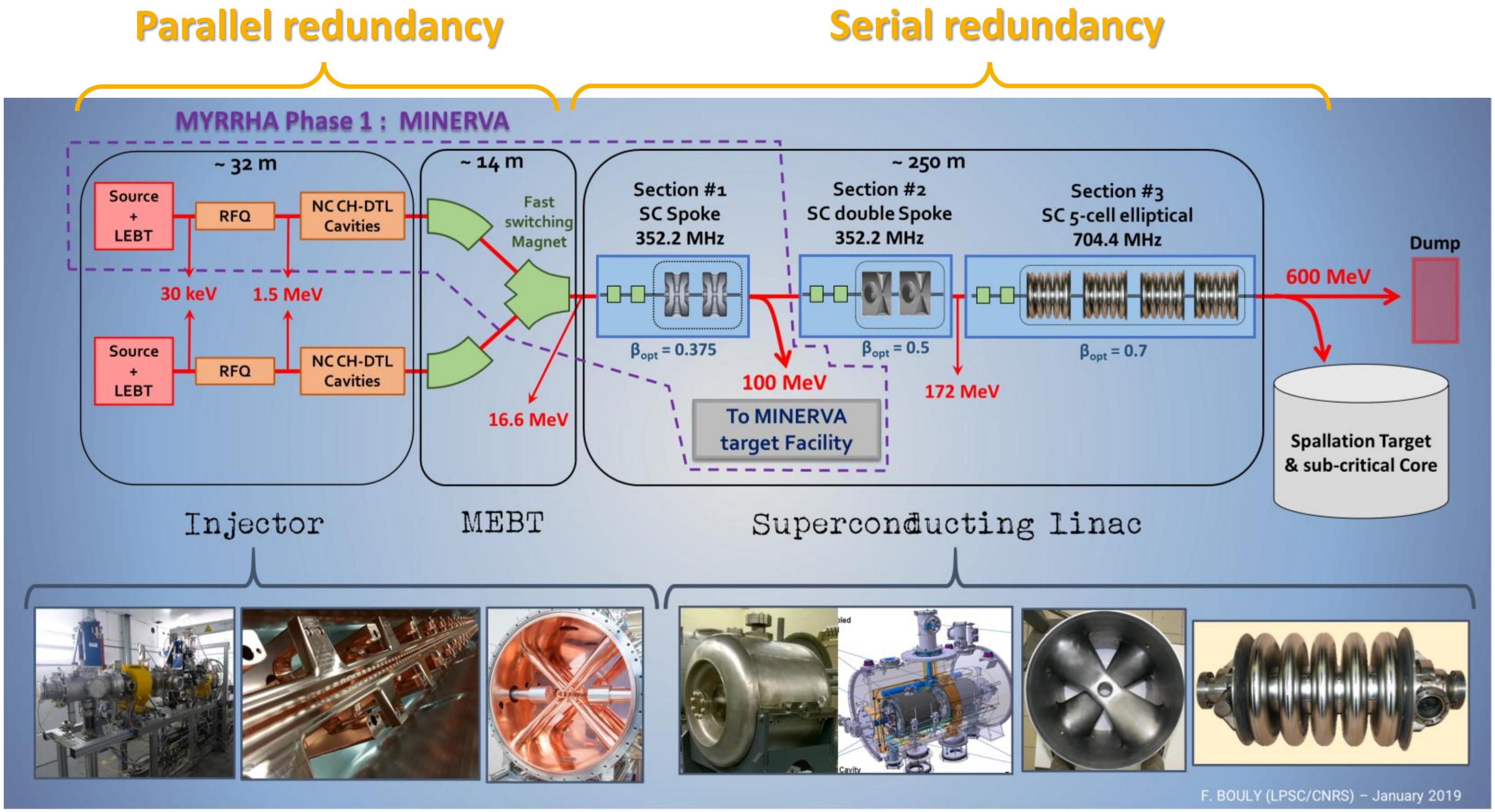
Extreme reliability



D. Vandeplassche et al., "Accelerator Driven Systems", Proc. IPAC 2012, New Orleans Louisiana, USA, 2012

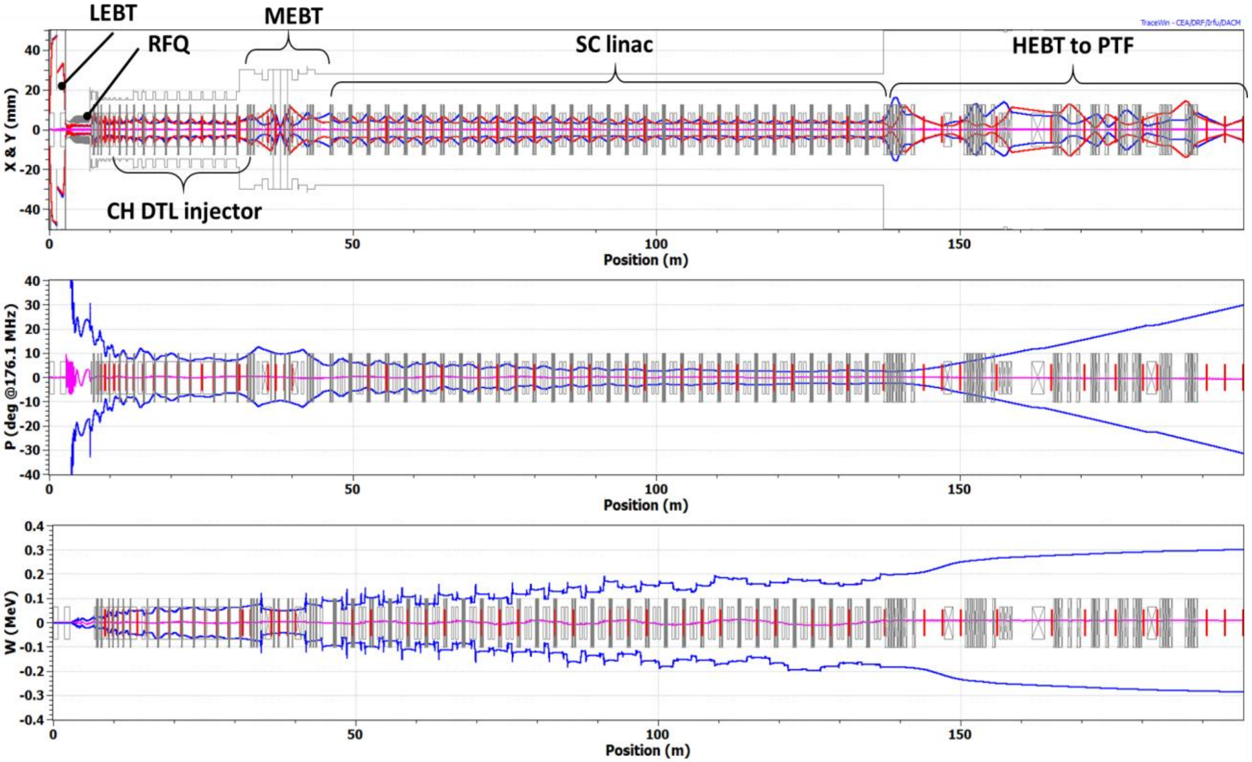
A. Bargallo, "ESS reliability and availability approach", ARW 2015, Knoxville, Tennessee

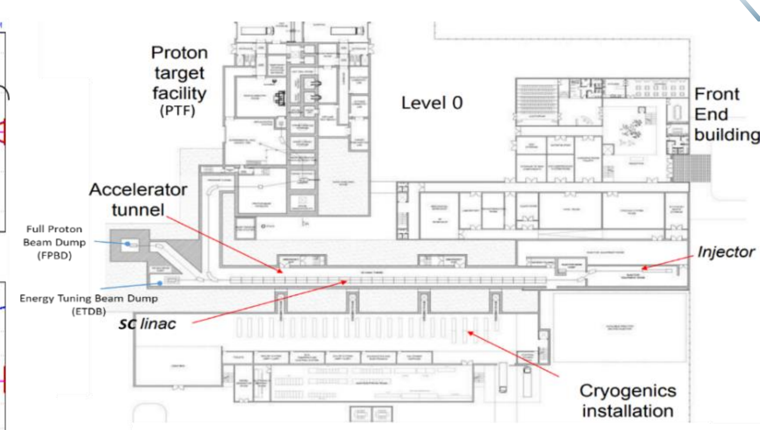
Linac layout



- Reliability guidelines for the ADS accelerator design:
  - **Robust design** i.e. robust optics, simplicity, low thermal stress, operation margins…
  - **Reparability** (on-line where possible) and efficient maintenance schemes
  - **Redundancy** (serial where possible, or parallel) to be able **to tolerate/mitigate failures**

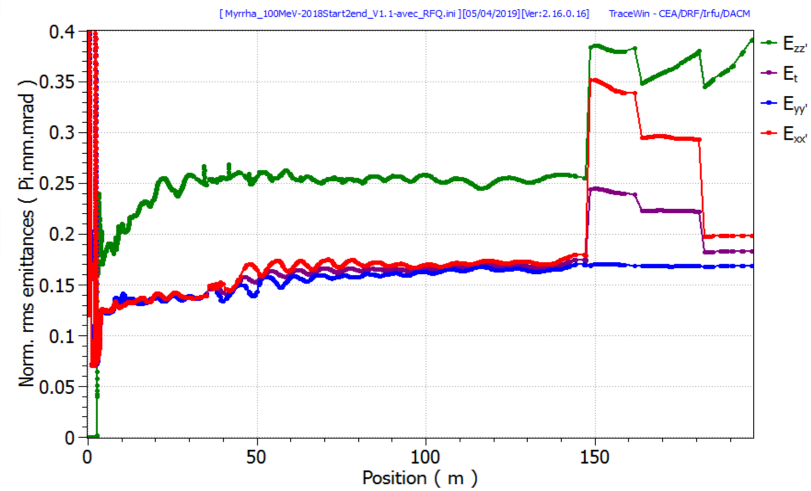
MINERVA Start-to-End Design





[See previous presentation](#)
D. Vandeplassche: *MYRRHA Phase 1 accelerator: design and integrated prototyping*

[LEBT recommissioning See next presentation](#)
M. Debongnie : *MYRRHA LEBT recommissioning and high speed modelling with Neural Networks*



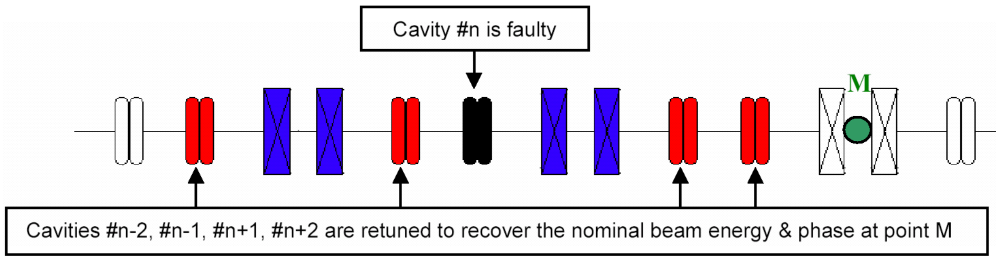
Normalized RMS emittance evolutions through the MINERVA linac

SC Linac design : Evolution & Fault Compensation

- Lesson learned from previous R&D (FP6, FP7) and improvements
  - Previous design : section #1: spoke– section #2: 5-cell elliptical (β 0.51) – section #3: 5-cell elliptical (β 0.7)

1. Increase the longitudinal acceptance, minimise longitudinal losses risks
   → **Decrease the RF synchronous phase of 1st cavity + minimize emittance growth in the MEBT particularly (New design)**
2. Section #2 : 5-Cell elliptical cavities too sensitive to mechanical perturbations for CW operation
   → **Use double Spoke cavity : ESS design**
3. Improve longitudinal matching at the entrance of the high beta elliptic section
   → **Ensure phase advance continuity**

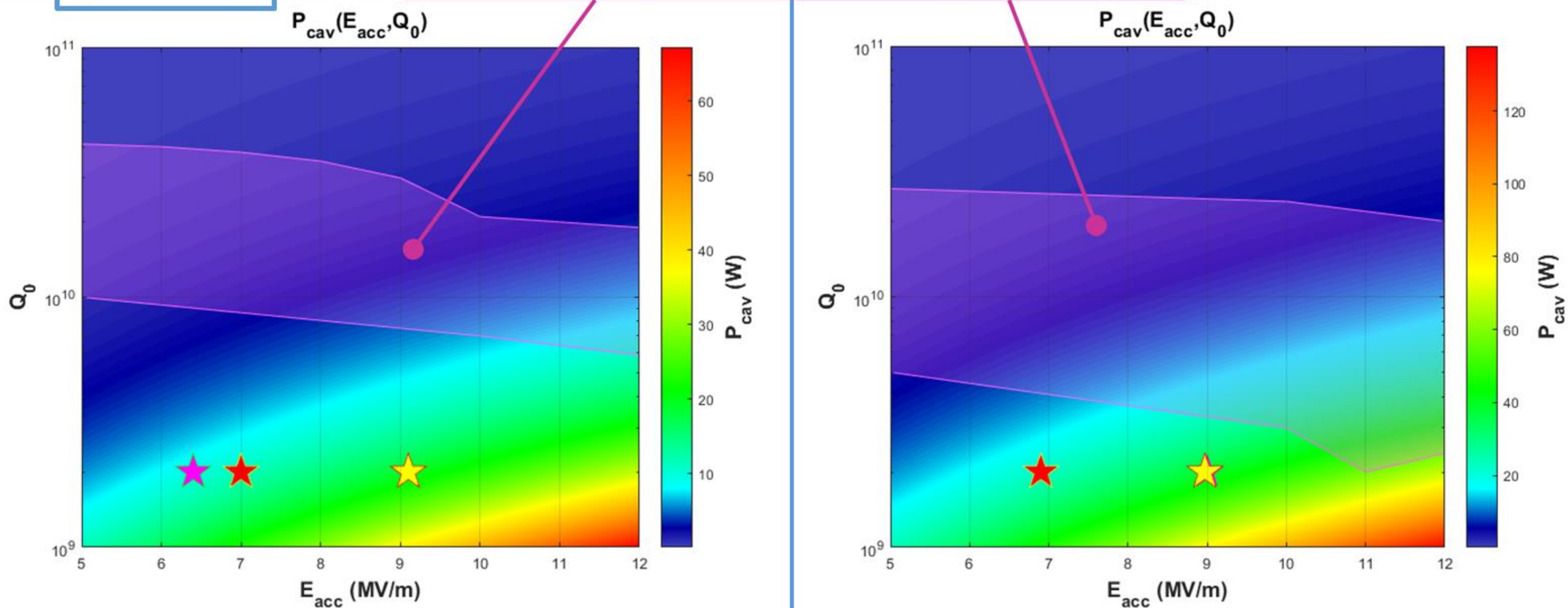
- Enable Fault Compensation
  - Independently-powered cavities w. moderate E_{acc} (**30% margins**) to ensure a fault-tolerant capability



Baseline (to be performed in less than 3sec):
1. The RF fault is detected (or anticipated) via suited dedicated diagnostics and interlocks, and a fast beam shut-down is triggered.
2. The new correcting field and phase set-points (calculated from model and Stored in a data base) are updated.
3. The failed cavity is quickly detuned to avoid the beam loading effect.
4. Once steady-state is reached, beam re-injection is triggered.

Cavity Accelerating Gradient

Operating zone from Vertical tests Results
[Ref] : D. Longuevergne, SLHiPP-7 workshop
https://indico.esss.lu.se/event/800/timetable/#20170608



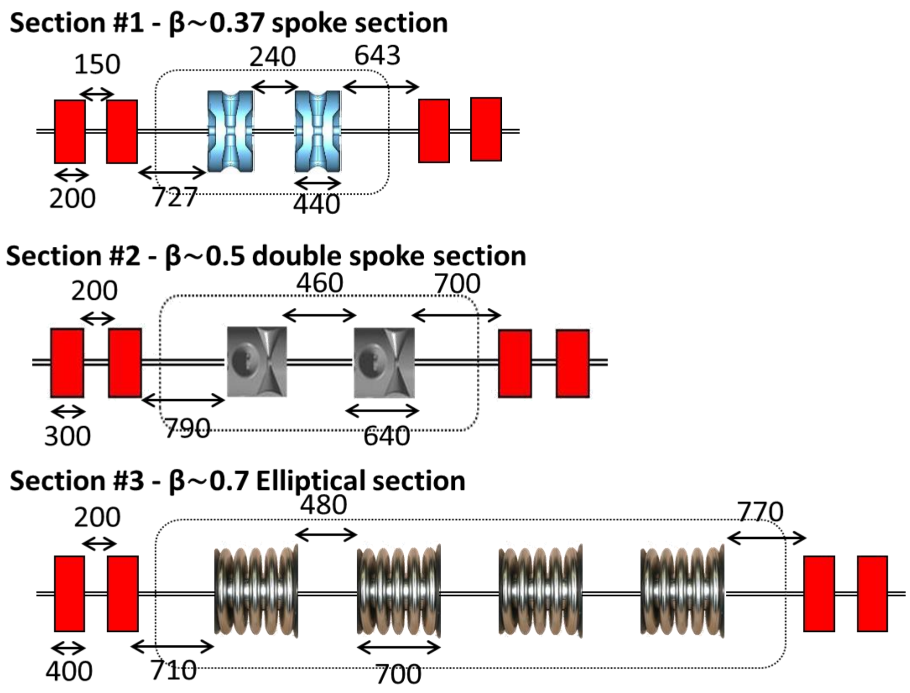
Single Spoke: β_{opt} = 0.375

Double Spoke: β_{opt} = 0.5 (ESS Type)

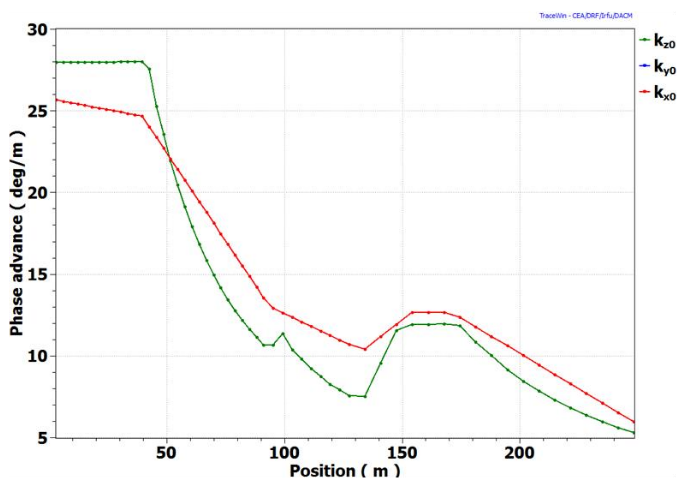
Architecture - Reference solution

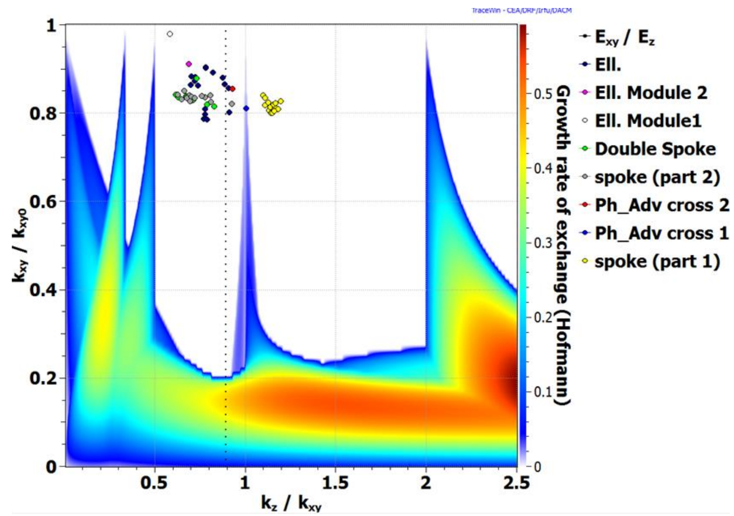
Section #	#1	#2	#3
E_{input} (MeV)	16.6	101.4	172.3
E_{output} (MeV)	101.4	172.3	601.6
Focusing type	Normal conducting quadrupole doublets		
Cavity technology	Single Spoke	Double Spoke	Elliptical
Cavity frequency (MHz)	352.2		704.4
Cavity optimal β	0.375	0.495	0.705
Nb. of cav. / cryomodule	2	2	4
Total nb of cavity	60	18	72
Nb. of cells / cavity	2	3	5
B_{pk}/E_{acc}* (mT/MV/m)	7.3	8.75	4.6
E_{pk}/E_{acc}*	4.3	4.4	2.5
R/Q** (ohms)	217	427	315
Nominal E_{acc} (MV/m) *	7.0	6.8	11.0
Max. E_{acc} (MV/m) *	9.1	9.0	14.3
Synchronous phase (deg)	-45 to -15		-35 to -15
4 mA beam load / cav (kW)	1.1 to 8.4	8.2 to 16.4	2.9 to 31.9
Q_L	1.5 10^6	2.1 10^6	6.9 10^6
Nominal Qpole grad. (T/m)	5.1 to 7.9	3.8 to 4.3	4.4 to 6.0
Section length (m)	91.2	36.3	121.0

*E_{acc} *is given at* β_{opt} *normalised to* L_{acc} = Ngap.β.λ/2
**R/Q is given at β_{opt} with the "linac" definition

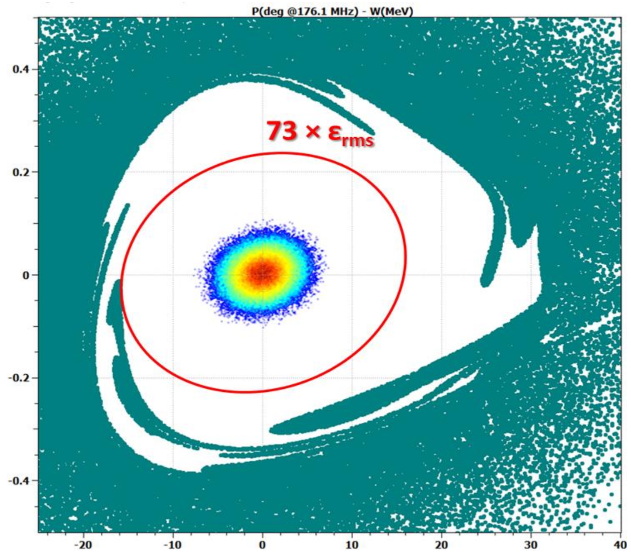


Linac tuning

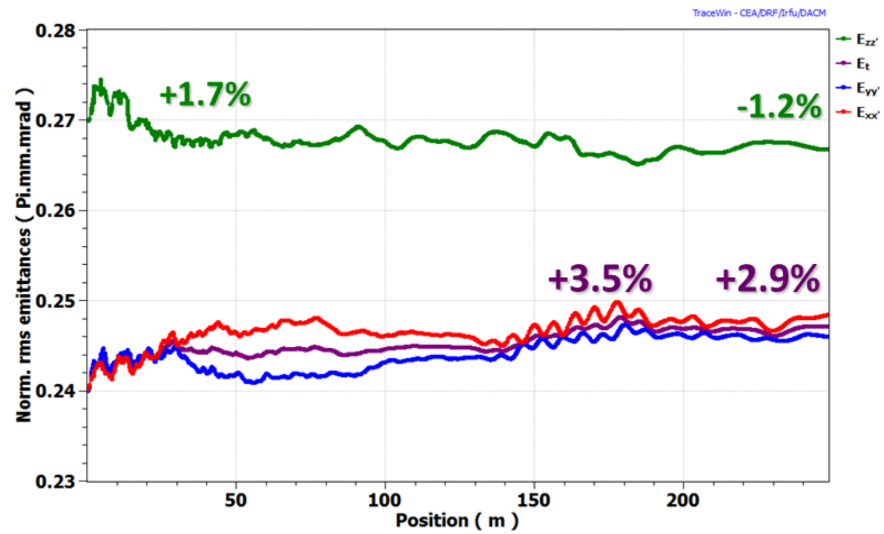




Zero-current phase advance (per meter) law and tuning set-points in the Hofmann diagram (after section matching).



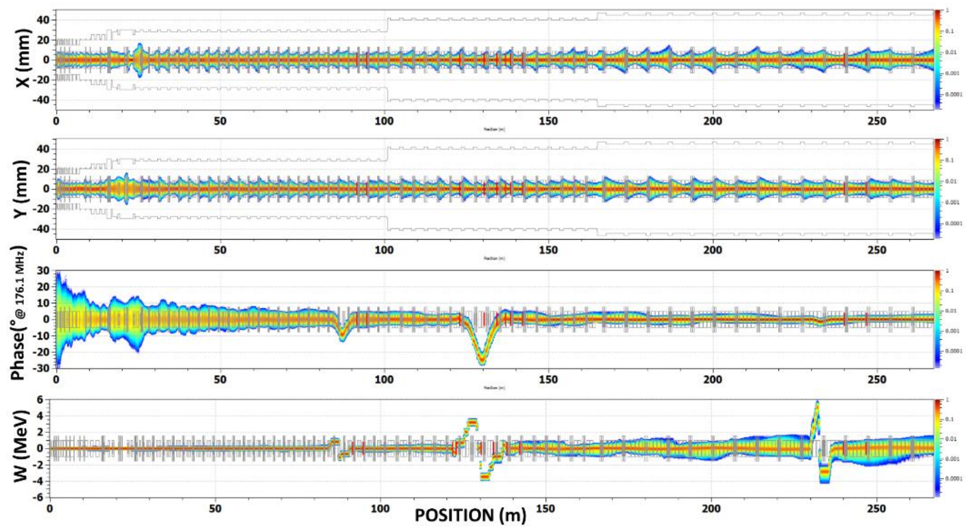
Longitudinal acceptance (white area of the plot) and considered 16.6 MeV input beam distribution.



Evolution of the RMS normalised emittances along the linac.

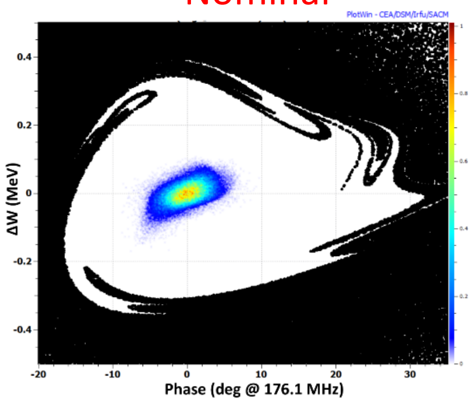
Fault recovery : beam dynamics feasibility

- Beam dynamics already studied with different scenarios and multiple failures
  - Example with multiple failures :
    - Section #1: 1 Spoke cavity
    - Section #2: 1 Cryomodule (i.e. 2 cavities)
    - Section #1: 1 elliptical cavity

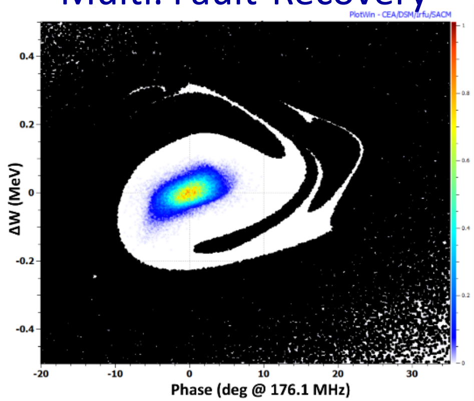


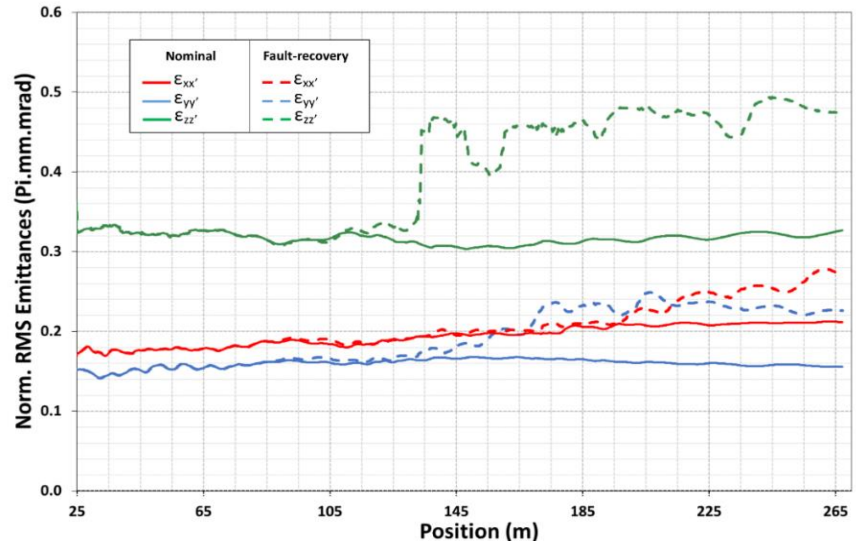
- Feasibility of beam retuning have been assessed
- Losses (> 1W/m) can occur when tested on a non perfect machine (statistic errors analysis)
- Fault compensation may induce emittance growth and longitudinal acceptance decrease

Nominal



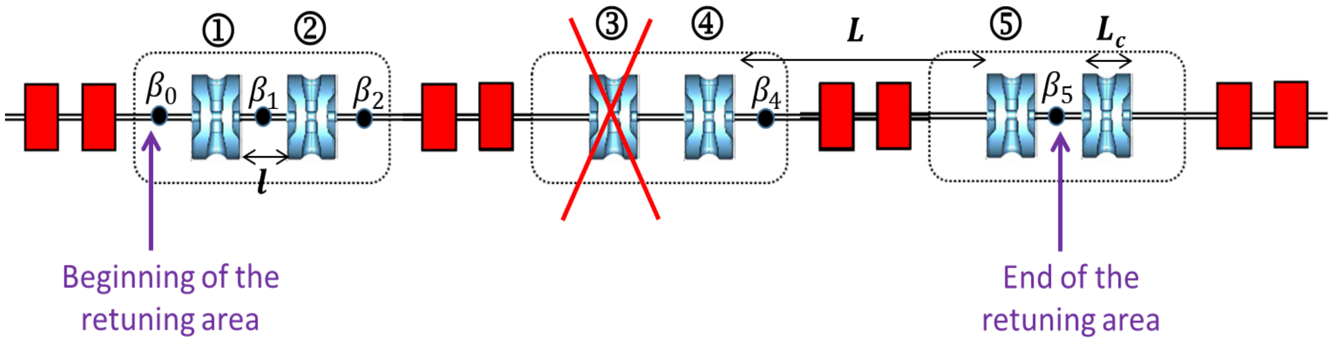
Multi. Fault-Recovery





Method development for retuning

- Goal develop an algorithm to be able to quickly pre-calculate any cavity failure case and find optimisation to be less aggressive on the beam.
- Example with the compensation of one failed cavity



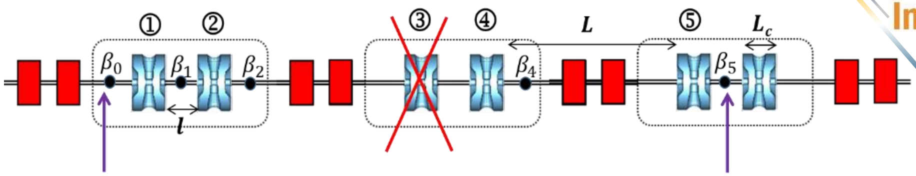
- Based on several criterions

- **1st criterion**: recover the same transfer matrix (longitudinal plane) of the retuned area than in nominal condition
  - In this case 4 non-linear equations, 4 unknowns (k_i)
  - Find the best compromise on k_i *: solve nonlinear least-squares problem.*

$$\begin{bmatrix} \delta\phi \\ \delta\phi' \end{bmatrix}_{OUT} = \begin{bmatrix} Cos(k.L_c) & \frac{1}{k} Sin(k.L_c) \\ -k\ Sin(k.L_c) & Cos(k.L_c) \end{bmatrix}_{Cavity} \cdot \begin{bmatrix} \delta\phi \\ \delta\phi' \end{bmatrix}_{IN}$$

$$k = \sqrt{\frac{\omega_{RF}}{m_0\, c^3\, \beta^3 \gamma^3}\ q\ Eacc\ \sin(\phi_S)}$$

Method development for retuning



- **2nd criterion**: the total Energy gain should remain the same than in the nominal case

$$\Delta W_1 + \Delta W_2 + \Delta W_3 + \Delta W_4 + \Delta W_5 = \Delta W_{Tot} = \Delta W_1^R + \Delta W_2^R + \Delta W_3^R + \Delta W_4^R$$

Energy gain per cavity: $\Delta W = q\, V_c\, Cos(\phi_s)$

- **3rd criterion**: the time of flight should remain the same than in the nominal case
  - Assumption on the cavity time of flight: $T_i = \frac{L_c}{\frac{(\beta_{i-1} + \beta_i).c}{2}}$

$$c.T_{Tot} = \frac{l}{\beta_1^R} + \frac{L}{\beta_4^R} + \frac{(L + L_C + l)}{\beta_2^R} + 2\, L_C \left[\frac{1}{\beta_0 + \beta_1^R} + \frac{1}{\beta_1^R + \beta_2^R} + \frac{1}{\beta_2^R + \beta_4^R} + \frac{1}{\beta_4^R + \beta_5}\right]$$

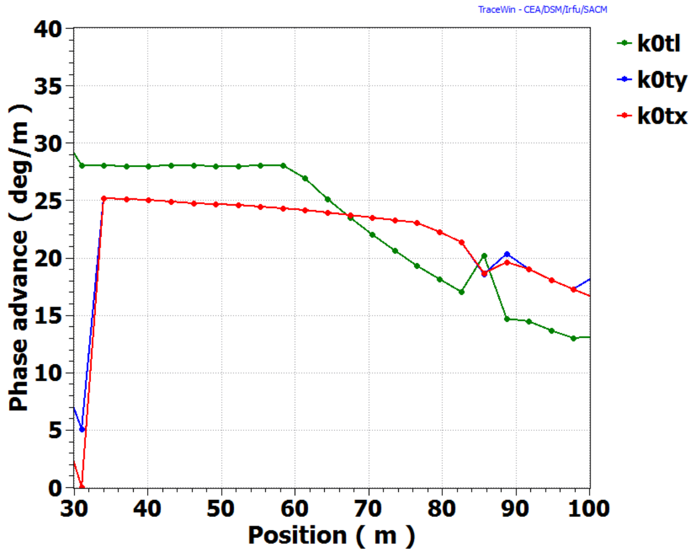
- **Problem can be solved by optimization of β_i and k_i**

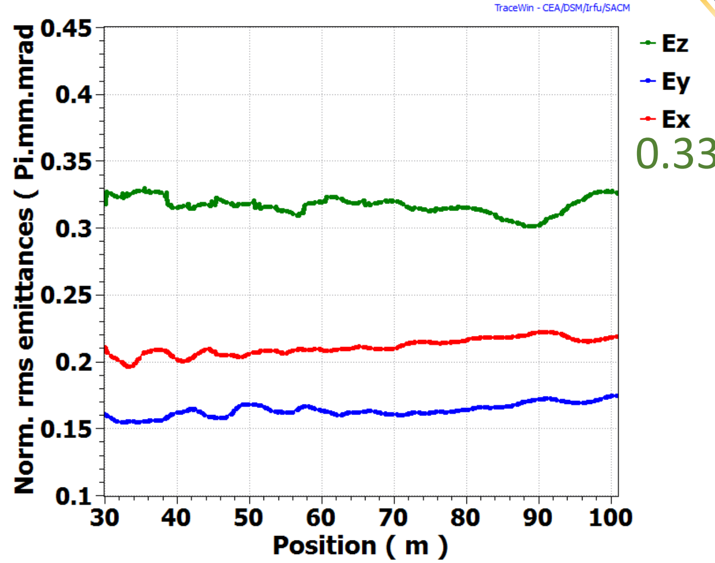
➢ (ΔW_i ,k_i) → (E_{acc}, ϕ_s) → (Amplitude increase, $\Delta\varphi_{RF}$)

➢ The solution with the simplified model is injected into the TraceWin model (that includes field maps) for fine (adjustments) tuning of the solutions

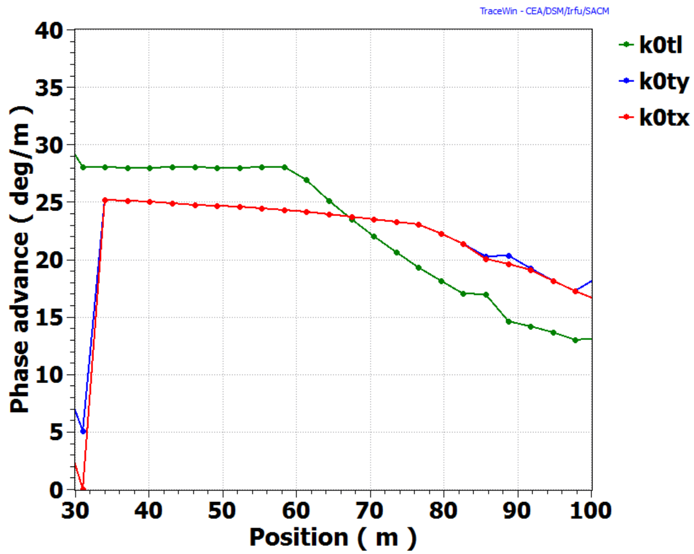
Example : failure compensation of a Spoke

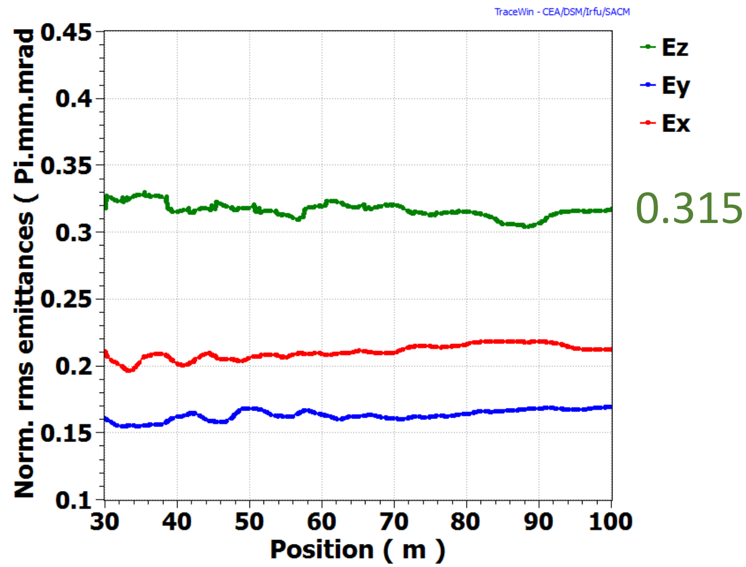
Set points calculation with Tracewin code





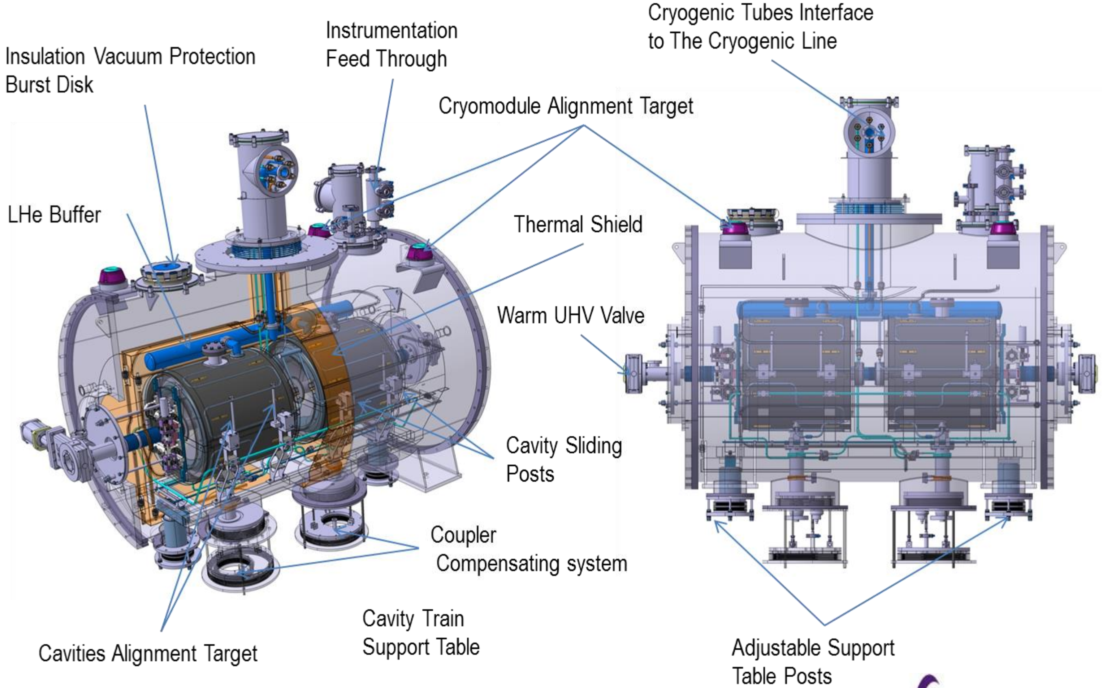
Set points with dedicated algorithm (theoretical model)

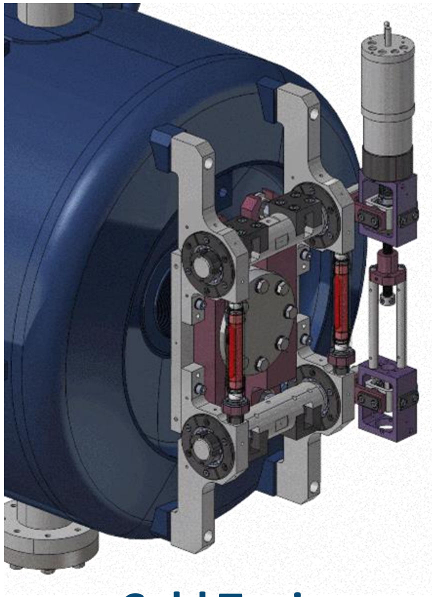




Fast failure compensation feasibility

- Technological feasibility of fast retuning to be assessed experimentally
  - Spoke cryomodule development

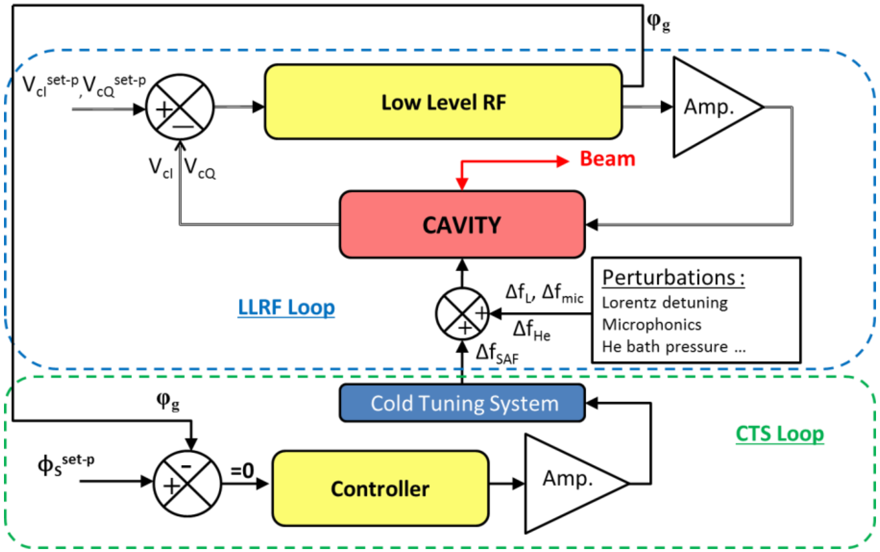




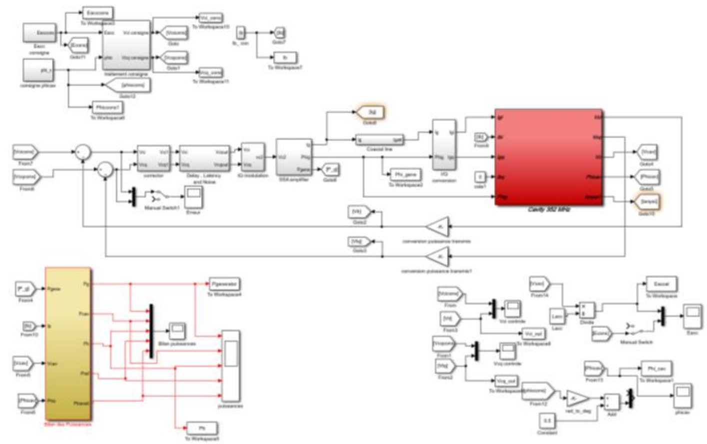
Cold Tuning System

Cavity and control loops model

- A model to study the technological feasibility of retuning procedures and to set the requirements on the cavity control loops, the tuning systems.



- Matlab Simulink Model



- Parameters

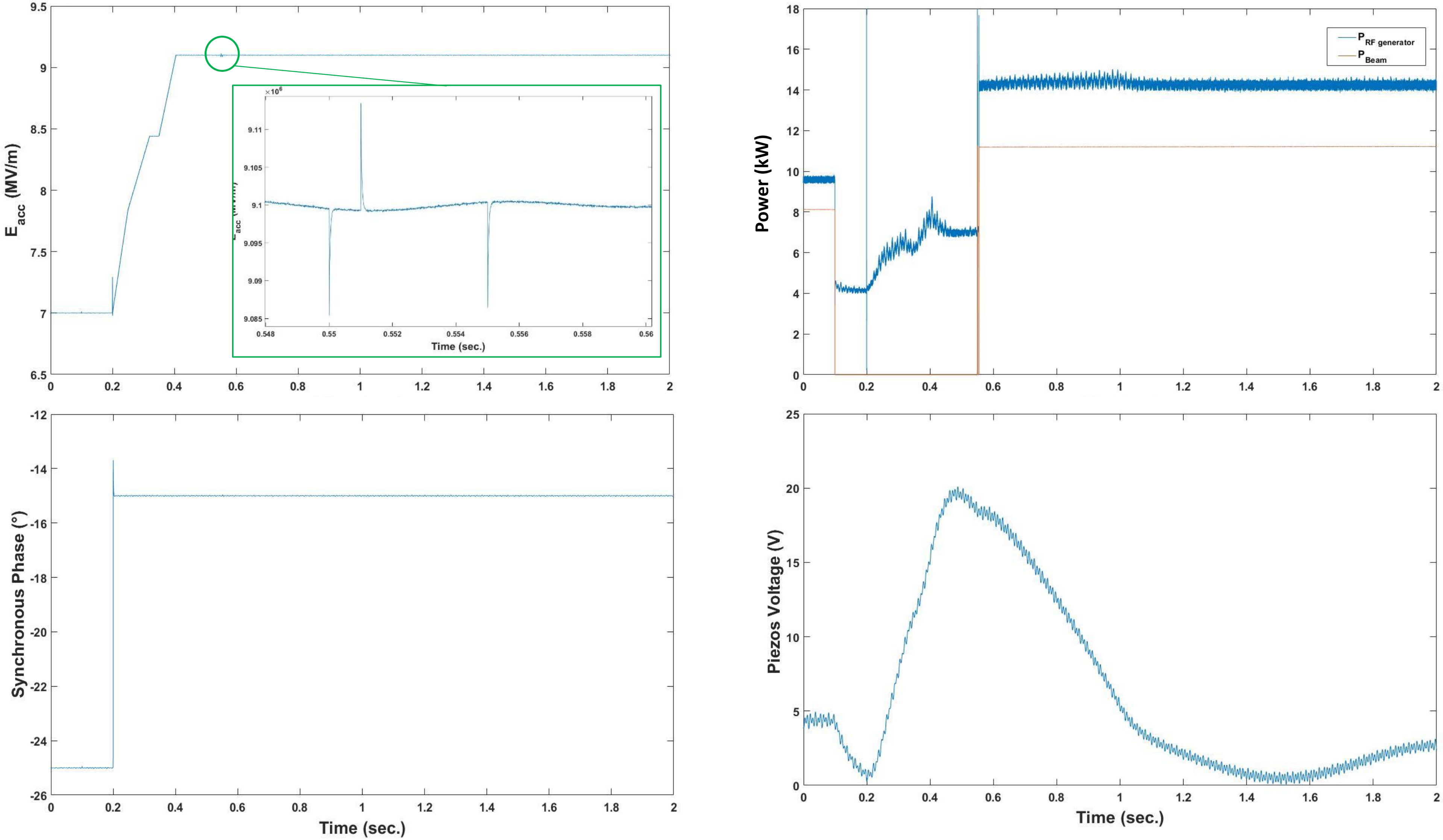
Param.	value
r/Q (@ β_{opt})	217
Q_L	1.5 10^6
$E_{acc\ nomi}$	7.0 MV/m
$E_{acc\ retuning\ (+30\ \%)}$	9.1 MV/m
P_{max} Ampli RF	18 kW
I_b	4 mA

- Accuracy requirement for beam stability

$$\frac{\Delta V_{cav}}{V_{cav}} < 0.5\ \% \qquad \Delta\phi_S < 0.5°$$

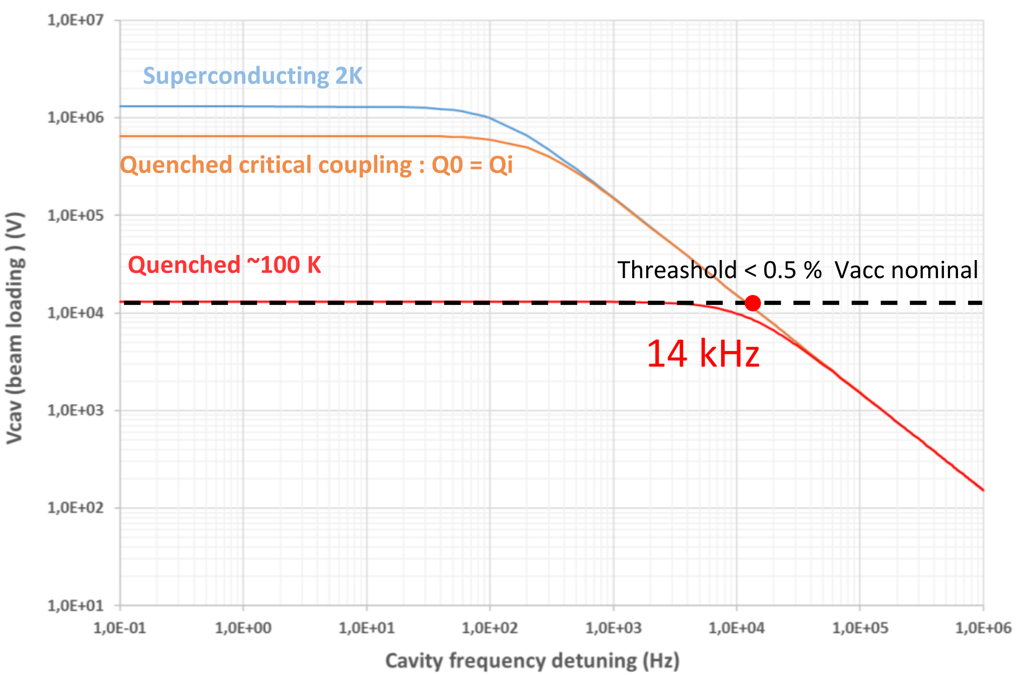
- I. Martin-Hoyo, F. Bouly et al., "Optimized Adaptive Control for the MYRRHA Linear Accelerator: Control System Design for a Superconducting Cavity in a Particle Accelerator" ,in IEEE Control Systems Magazine, vol. 38, no. 2, pp. 44-79, April 2018.
- F. Bouly, Phd Thesis, 2011
- *M. Dominiczak et al., SRF'19, Dresden, Germany, paper TUP002.*

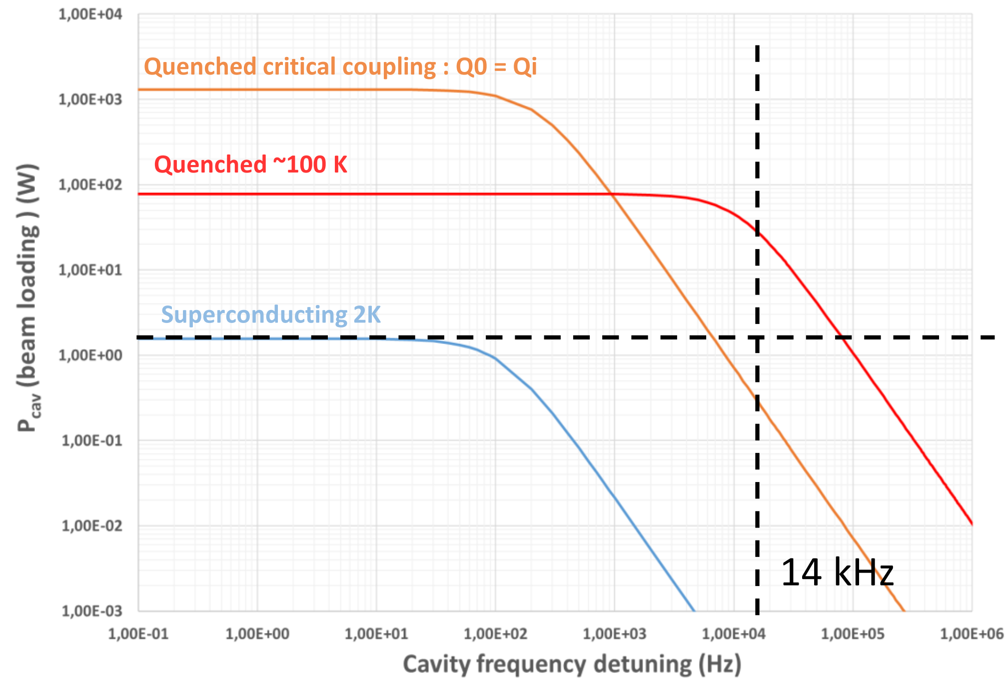
Failure compensation – Fast cavity retuning



Failed cavity – Fast detuning

- A failed cavity can perturb the beam : **it has to be detune**





<u>Goal</u> :

14 kHz detuning in 1 seconde

Total detuning capacity : > 100 kHz

Conclusions

- MINERVA linac design
  - next steps :
    - Detailed definition of beam modes (peak curent, duty cycle) : from commissioning to operation
    - Detailed definition of required beam diagnostics
    - Update with mechanical engineering design & construction
    - Upgrade HEBT design according to target & dump buildings/ experiments needs.

- Fault recovery procedures
  - Fast recovery procedures to be tested on Spoke cryomodule prototype
  - Algorithm for cavity set point calculation under developments (machine learning technics to be explored)
  - Study to be carried out in close relation with reliability model development : evaluate the number of failure to be expected

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