European Commission

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION

HORIZON 2020

Myrte MYRRHA Research and Transmutation Endeavour

Proton Linacs as ADS Drivers

EUCARD2 Workshop

Status of Accelerator Driven Systems Research and Technology Development

cnrs IN2P3 Les deux infinis

LPSC Grenoble Laboratoire de Physique Subatomique et de Cosmologie

EuCARD²

Meyrin (CERN), Wednesday 8 February 2017

F. Bouly (CNRS/IN2P3/LPSC)

1. **Requirements & Issues for ADS accelerators**
2. Linacs & RF Superconductivity
3. Reliability & Performance optimisation
4. Summary – Final Remarks

Basics concepts – Order of Magnitude

- A subcritical system needs an external source of neutrons to operate
  - Spallation neutrons produced by an proton accelerator

- First approximation : Thermal Power of an ADS
  - Depends on the spallation target and the proton beam properties (Energy & current)

$$P_{th}(MW_{th}) = E_f\,(MeV).I(A).\frac{\varphi^*.k_{eff}}{1-k_{eff}}.\frac{\zeta_{spal}}{\nu}$$

P_{th}: Thermal power of the reactor
E_f : Energy generated per fission (~200 MeV)
ν : Neutrons emitted per fission (~2.5)
I : Proton beam current
k_{eff} : Effective neutron multiplication factor
φ^*: Source importance (~1.5) – characterise the efficiency of the external neutrons and thus the coupling quality (Source/Reactor).
ζ_{spal} : Spallation target neutron yield per incident proton (~30, for a 1 GeV proton on LBE target)

- OM : Minimum required proton beam current

  - **MYRRHA** (P_{th} = 100 MW_{th} , k_{eff} = 0.95, Ep = 600 MeV)
    ⇒ I_{beam} = 2.4 mA
  - **C-ADS** (P_{th} = 1.0 GW_{th} , k_{eff} = 0.97, Ep = 1.2 GeV)
    ⇒ I_{beam} = 8.6 mA

Accelerator requirements

1- High Power accelerator

- Multi-MegaWatt class accelerator .

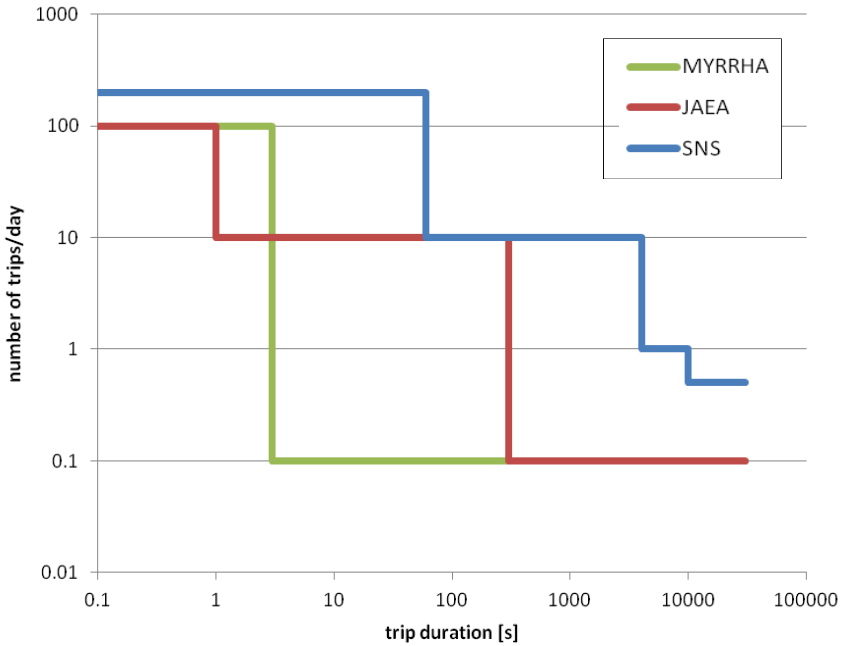
  Beam Power : *Demonstrator ~2.5 MW . Industrial Application ~30 MW*

- Need to provide a (or almost) continuous wave beam (CW)

  high duty factor ~ 95 %, with holes for sub-criticality monitoring

2- Operate with a very high level of reliability

- To limit thermal stress & fatigue on the target window, reactor structures & fuel assemblies
- To ensure a 80% availability – given the foreseen reactor start-up procedures after SCRAMs



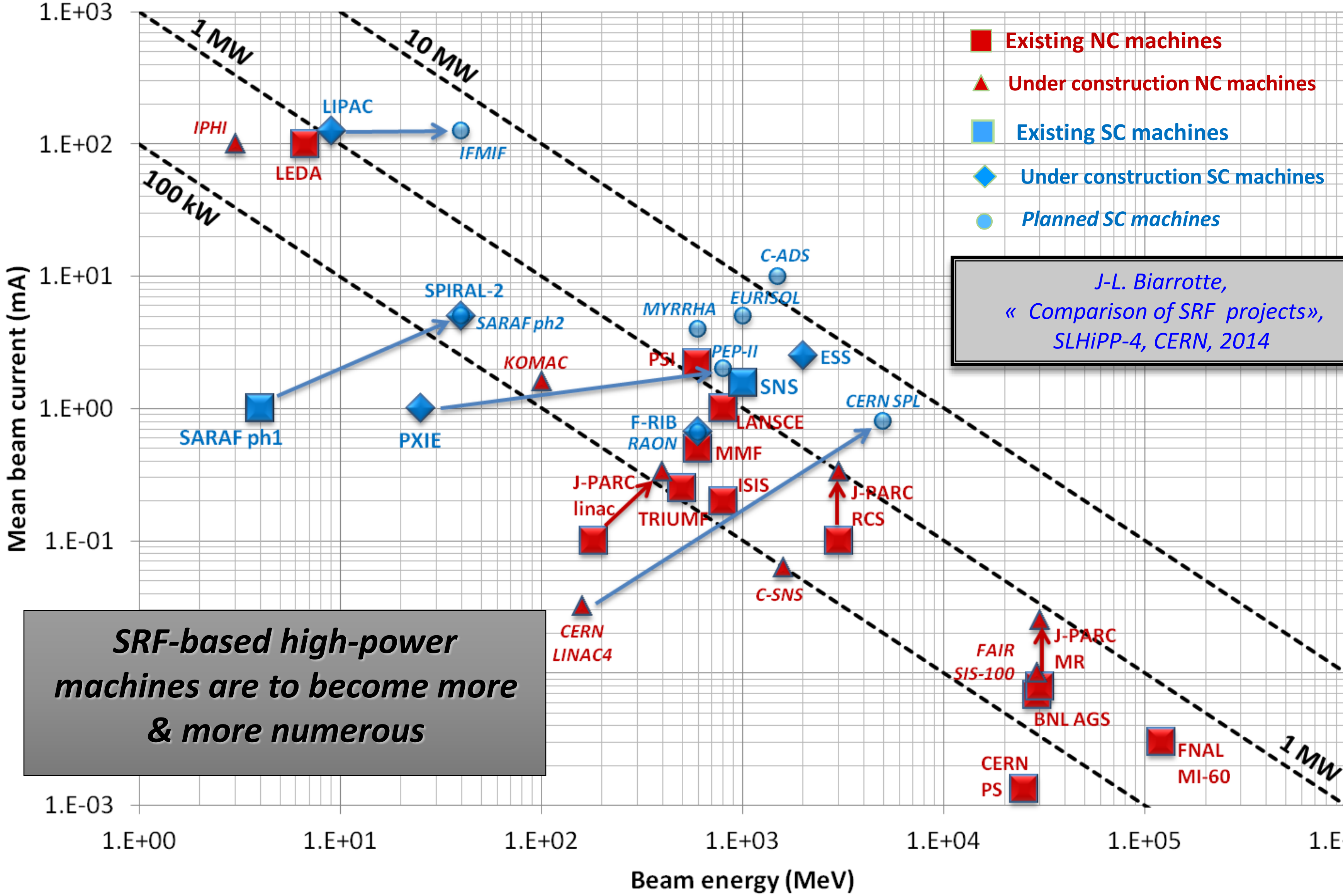
- MYRRHA specifications based on the PHENIX reactor operation analysis
- Above current HPPA accelerator performance (PSI cycl. or SNS linac)

  -> SNS data from 2006-2008 period : COMMISSIONING

- Japan Atomic Energy Agency specifications for an Industrial ADS are based on simulations

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

High power beams around the World



J-L. Biarrotte,
« Comparison of SRF projects»,
SLHiPP-4, CERN, 2014

SRF-based high-power machines are to become more & more numerous

Non exhaustive plot !

OUTLINE

1 Requirements & Issues for ADS accelerators

2 **Linacs & RF Superconductivity**

3 Reliability & Performance optimisation

4 Summary – Final Remarks

Normal Conducting & Superconducting

- The accelerating Technology (cavities) choice consists in finding the best compromise to optimise :
  - Compacity of linac "footprint" : tunnel construction cost

  -> one key point is the achievable accelerating gradients which also depends on the beam dynamics

  - Reliability & Operational flexibility for implementation of fault tolerance and compensation scheme
  - The operating cost :

  -> Improve electrical efficiency = acceleration efficiency (also impacts the construction cost)

- Basic definition of acceleration efficiency for a cavity :

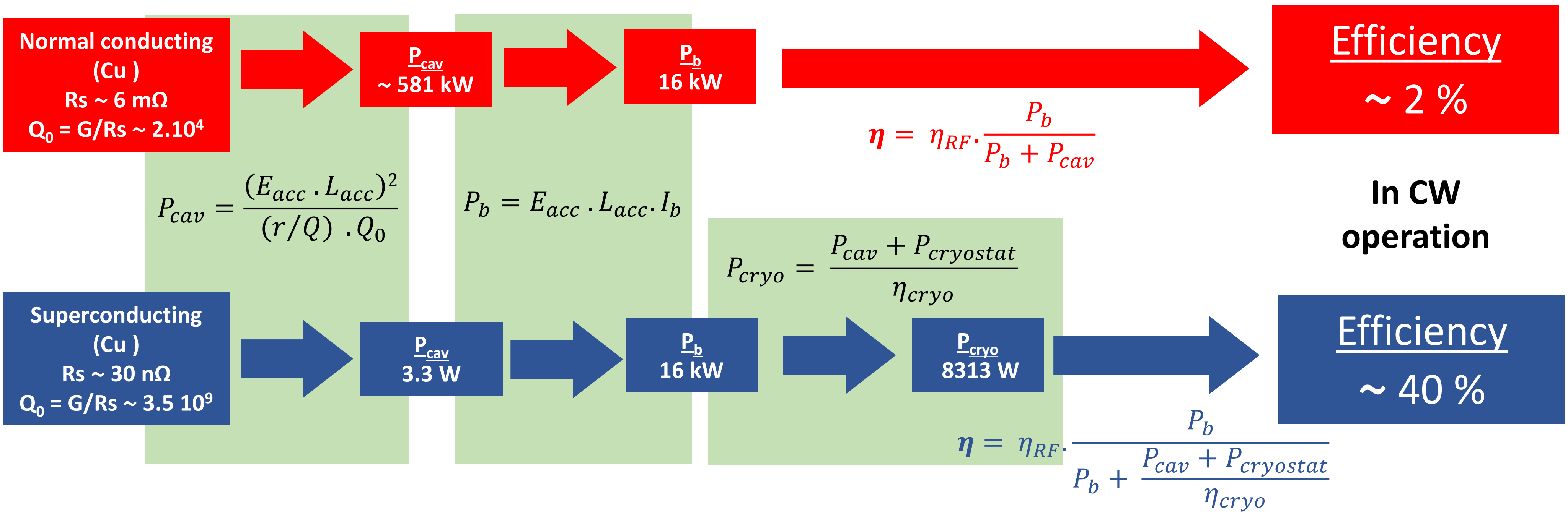
$$\boldsymbol{\eta} = \eta_{RF} \cdot \frac{P_b}{P_b + \dfrac{P_{cav} + P_{cryostat}}{\eta_{cryo}}}$$

P_b: Power delivered to the beam
P_{cav}: Power consumption of the cavity
$P_{cryostat}$: inherent static losses of a cryomodule ***– chosen value : ~ 10 W***
η_{RF}: RF power supply efficiency : ~ 60 %
η_{cryo}: Cryogenic efficiency (Carnot cycle + cryo. plants efficiency)

$$\boldsymbol{\eta_{cryo}} = \eta_{carnot} \cdot \eta_{plant} = \frac{2K}{300K - 2K} * 0.25 \approx \mathbf{0.16\%}$$

Normal Conducting & Superconducting

- Example with a cavity which accelerates a **CW 10 mA** proton beam @ β=0.37 (~70 MeV) :
  - **E_{acc} = 5 MV/m**
  - Spec. based on the MYRRHA Spoke cavity : (r/Q) = 220 Ω, G=110 Ω, L_{acc} = 0.32 m



Duty Cycle Importance

- Example with a cavity which accelerates proton beam **@ β=0.37 (~70 MeV)** :
  - **E_{acc} = 5 MV/m**
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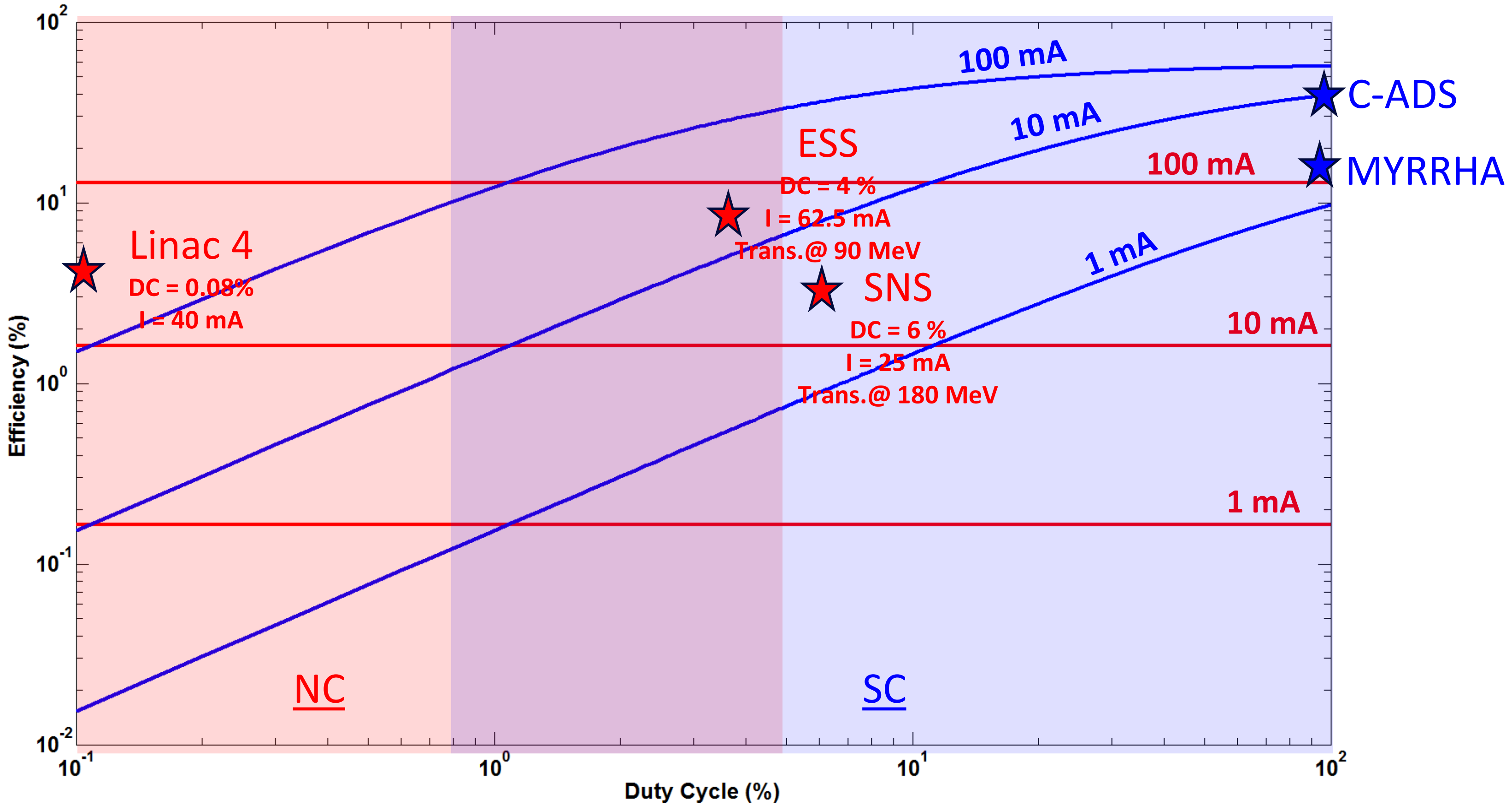
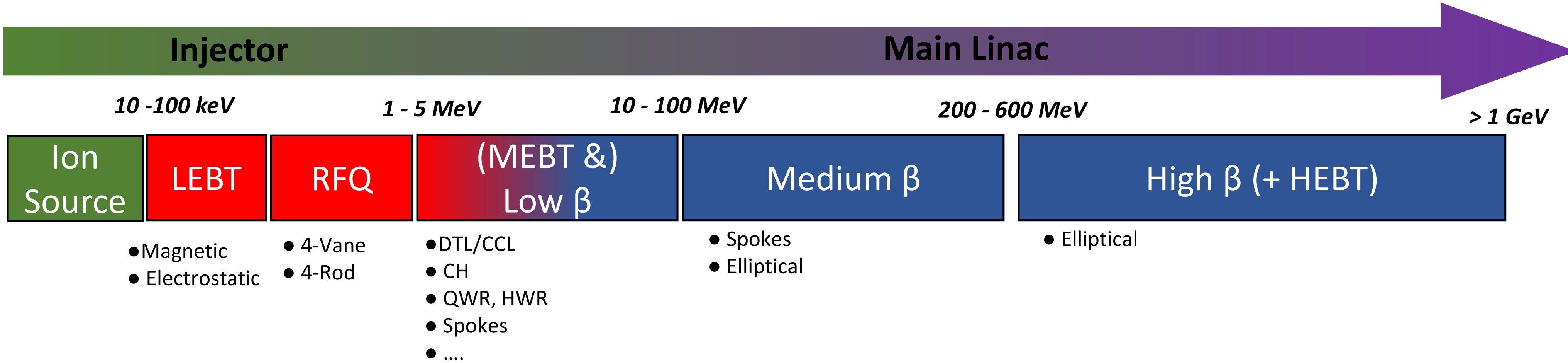


Generic topology for High Power Linacs

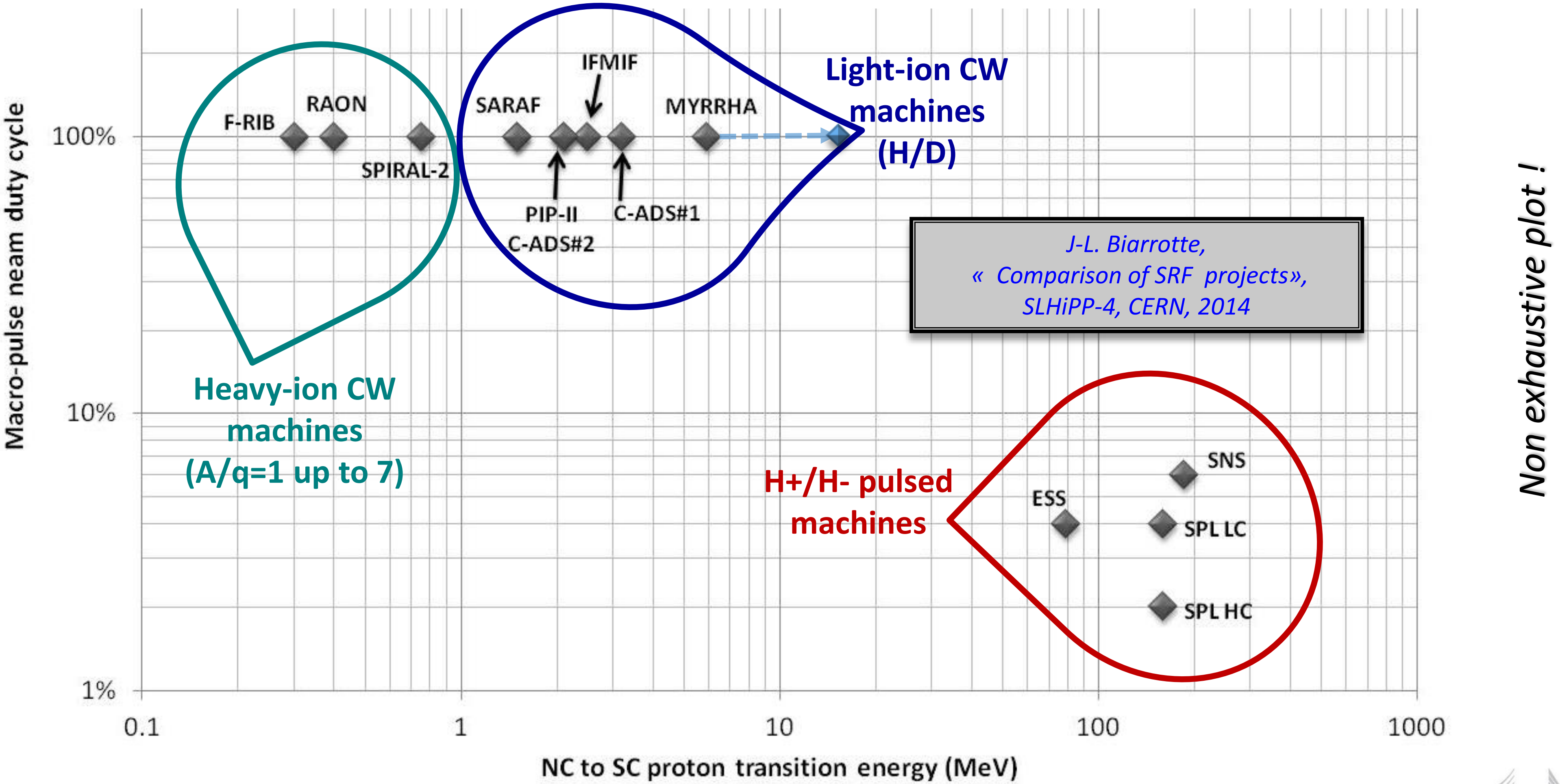


- Building on past experience from APT/ATW (1990-2001) and SNS
- Uses superconducting RF accelerating structures
- Allows pulsed & CW operation
- Requires high beam current stability (better than 1%)
- < 1 W/m beam loss
- Low incidence and duration of beam trips
- High availability during scheduled operations (>90%)

Robert Garnett
"Design Features of Modern High-Power Proton Linacs",
TCADS-3,
Mito, Japan, Sept 2016

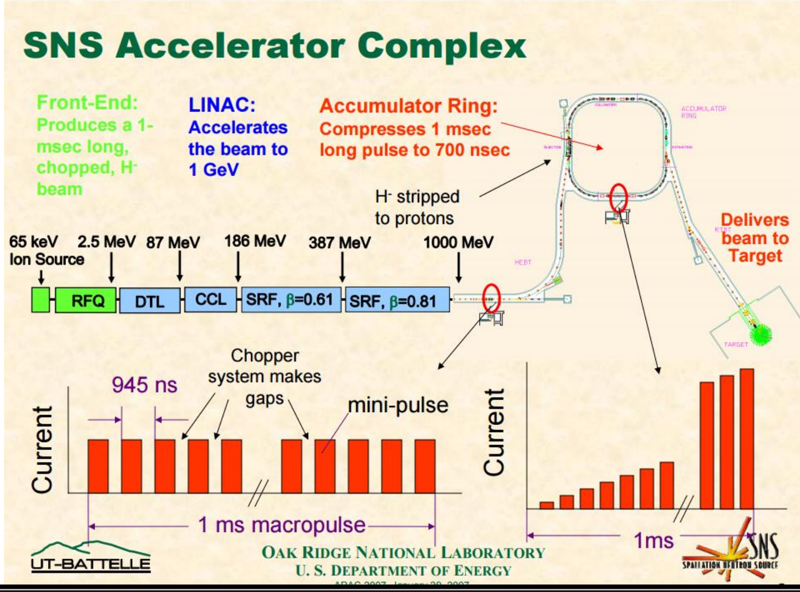
NC to SC Transition

- **NC/SC transition** ideally minimizes overall power consumption ~ DC*(P_{cav}+P_{beam}) + P_{cryo}
- **For CW operation**, "SRF As Low As Reasonable Achievable" (i.e. down to the RFQ) has become the worldwide rule

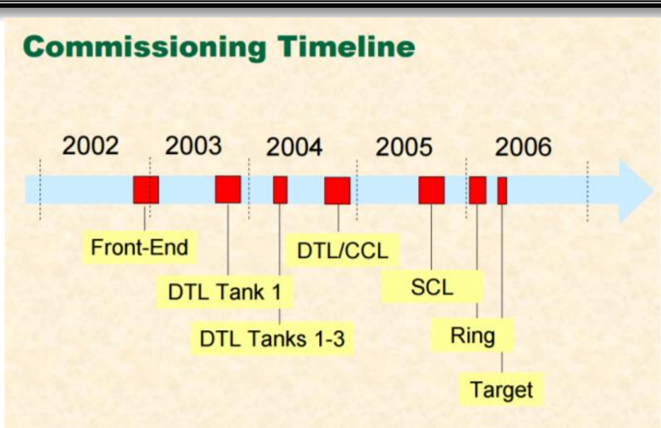


SNS : The High Power Linac reference

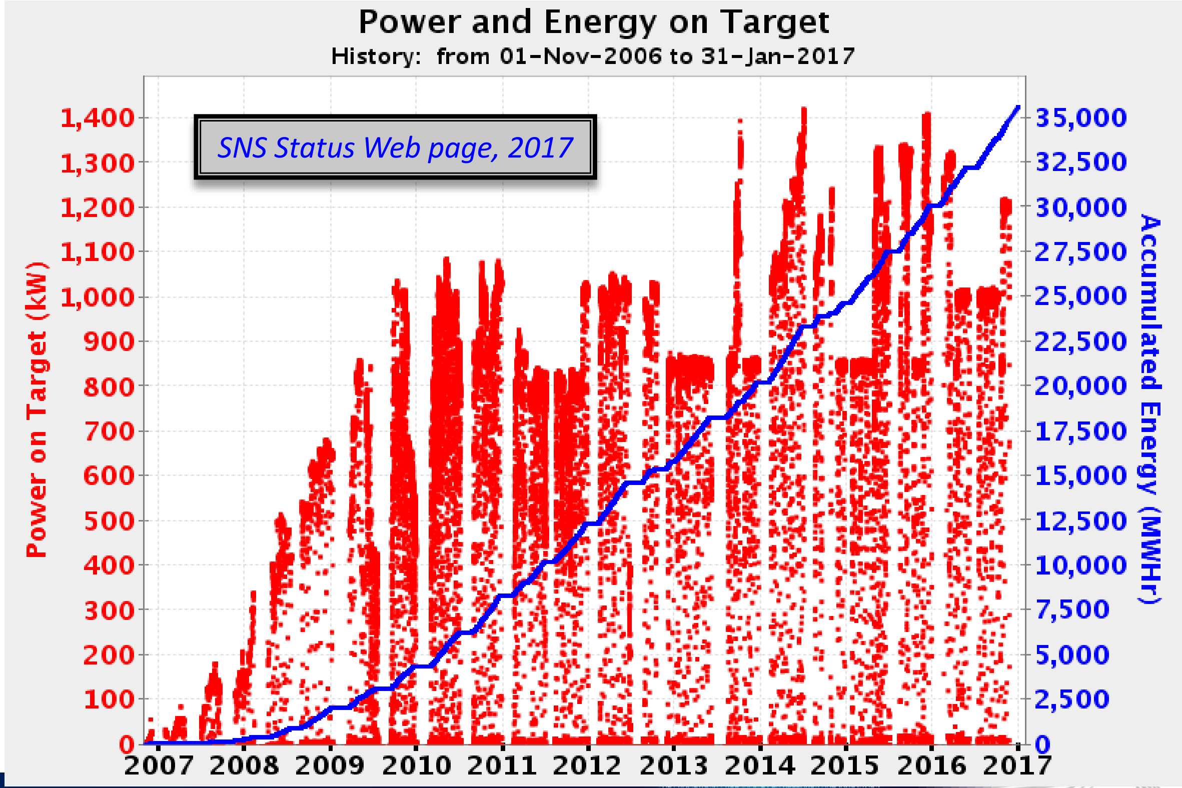
- **SNS = the first high-energy SRF linac for protons/H$^-$**
  + the first MW-class one (pulsed but at relatively high Duty Cycle : 6%)



M. Plum, "Commissioning Experience of SNS, APAC07, 2007



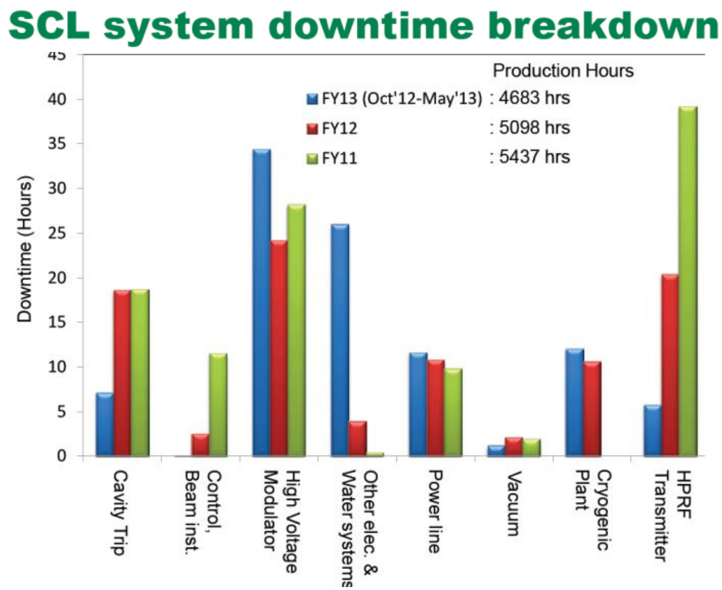
- Availability >90%
- 3 years to ramp the beam power up to 1 MW
- 3 MW upgrade plan (PUP)
- Replacement of some NC sections by SRF is considered

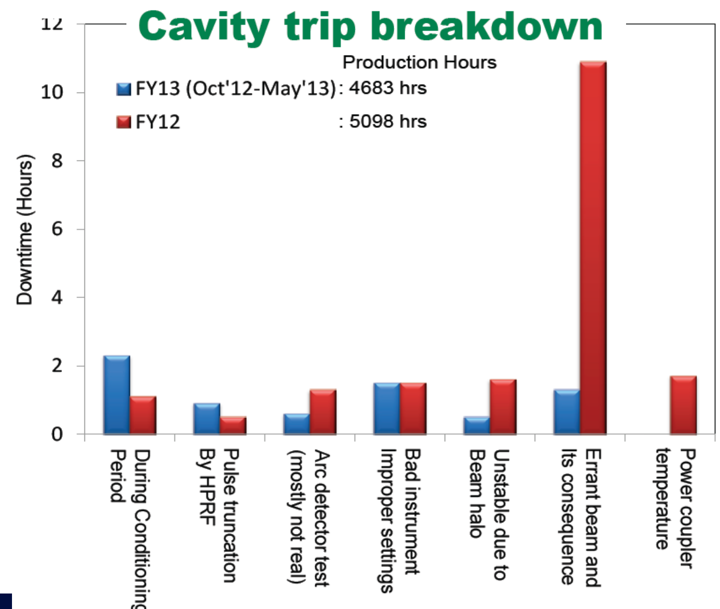


SNS experience feedback

- **Beam losses & SC linac activation**
  - Activation is well contained in the SNS, but unpredicted beam losses have been observed
  - Losses recently explained by intra-beam stripping
  - **Use H+ instead of H- if possible !!** (losses /30)

- **SC linac has proven to be substantially more reliable than the NC linac** despite the high number of RF stations & the complexity of cryogenics
  - Less than 1 trip of the SC linac per day
  - Trips dominated by RF systems
  - Trips due to cavities are mainly due to errant beam hitting cavity surface (BLM trips from discharge/arcing in warm linac)
  - Cavity degradation is observed (usually recovered by thermal cycling)
  - Multiple cryomodule repairs in house (coupler window leaks, He & vacuum leaks, tuner failures, HOM couplers…)





OUTLINE

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Reliability Requirements

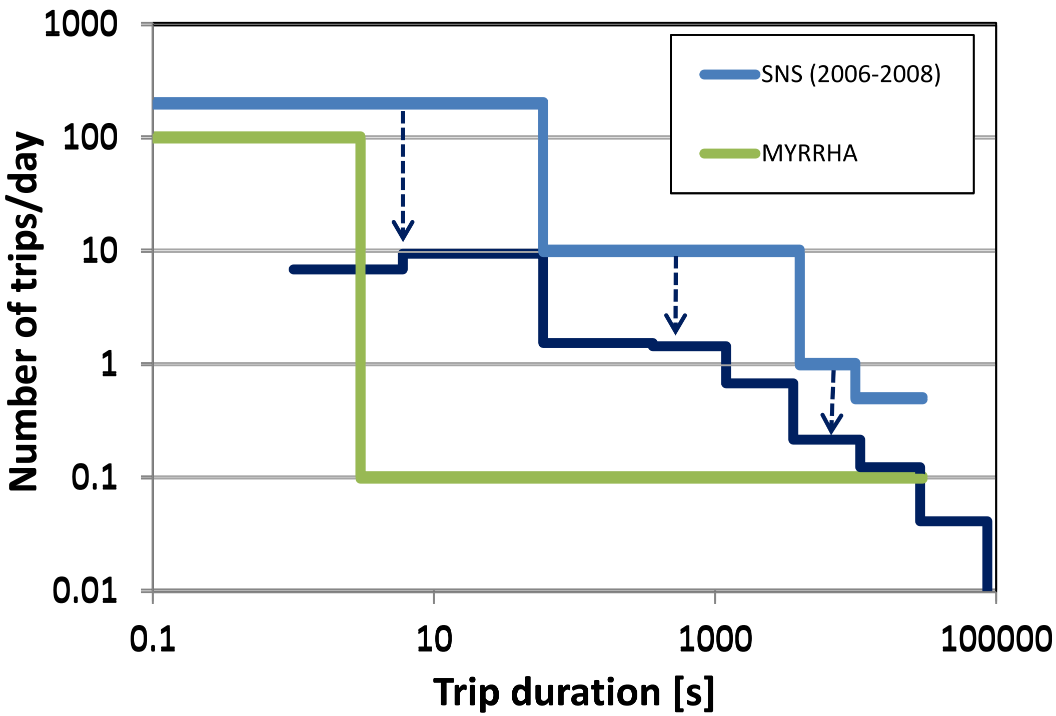
- The case of **MYRRHA** : **Beam trips longer than 3 sec** must be very rare: <10 beam trips per 3-month operation period (i.e. MTBF > 250h)

  -> Derived from the PHENIX reactor operation analysis

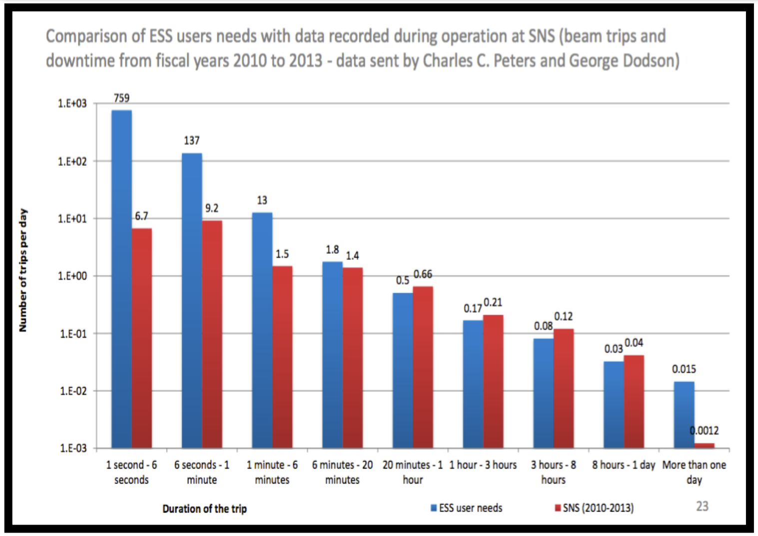
➢ To minimise Thermal stress & fatigue on the target window, reactor structures & fuel assemblies

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

- Improvements through the commissioning and the machine operation



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



Reliability guidelines

In any case, reliability guidelines are needed for an ADS accelerator design:

- **Robust design** :

➢ Robust beam optics : avoid beam resonance, focussing current- independent, large acceptance, minimise halo formation (hard to predict),…

➢ Make it simple (as possible)

➢ Low thermal & mechanical stress, operation margin

➢ Careful choice of ancillary system : pumps, cooling systems, etc..

- **Reparability**

➢ On-line where possible

➢ Efficient maintenance scheme (MYRRHA : 1 month maintenance vs. 3 month operation)

- **Redundancy**

➢ **Serial** where possible, or **parallel** even for ancillary systems

➢ **Failures** can be tolerated but must be **mitigated** to guaranty a **high Fault Tolerance**

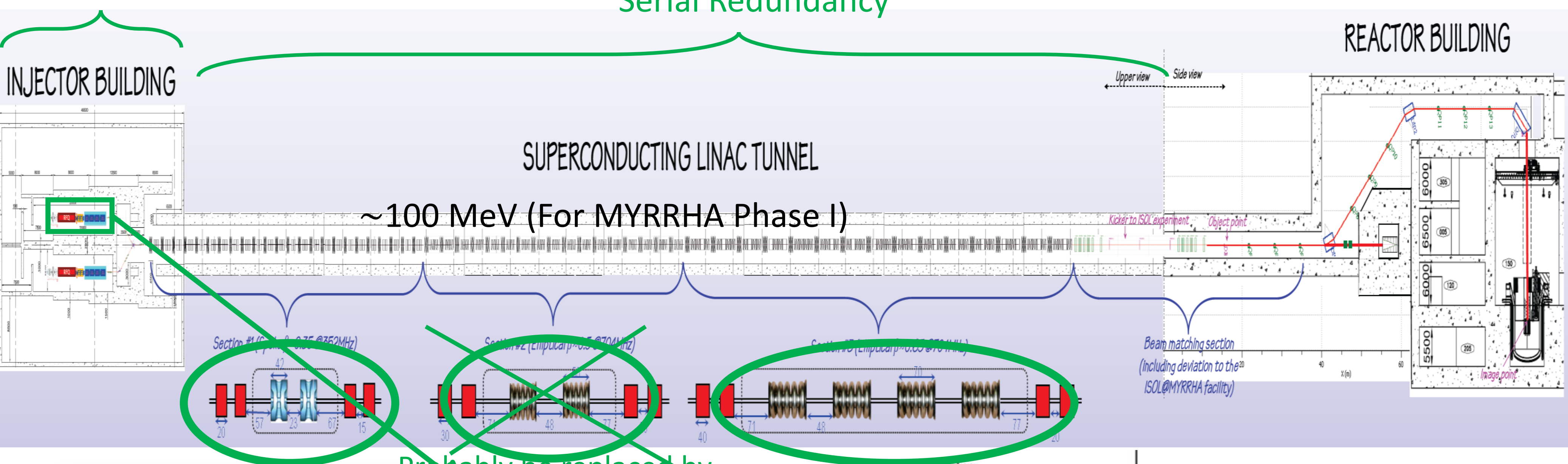
➢ **Fault compensation scheme** : Introduced during design studies of the MYRRHA accelerator (PDS-XADS, EUROTRANS FP7 projects)

J.-L. Biarrotte, D. Uriot, "Dynamic compensation of an RF cavity failure in a superconducting linac", Physical Review ST: A&B, 2007

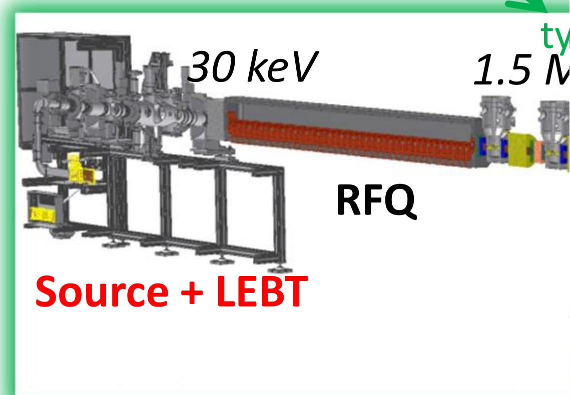
Layout of the MYRRHA Linac

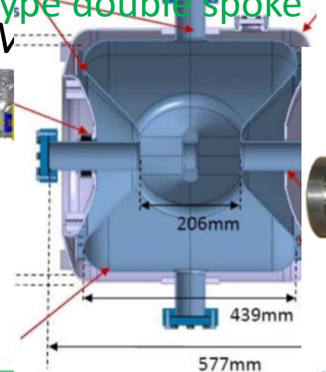
Parallel Redundancy

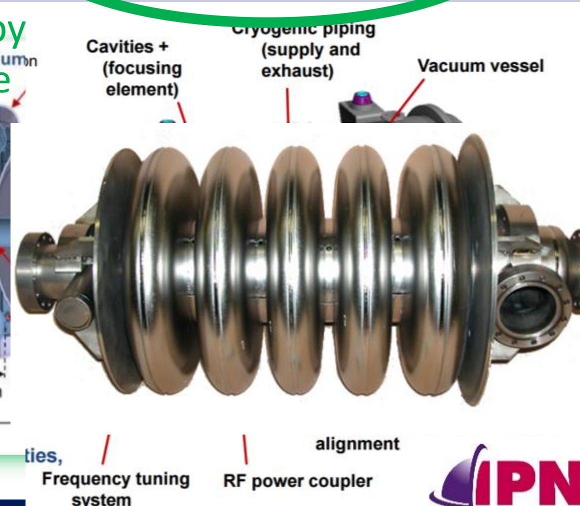
Serial Redundancy



Probably be replaced by type double spoke







ESS Type double Spoke

Single Spoke

5-cell elliptical

$\beta_{opt} = 0.37$

$\beta_{opt} \sim 0.5$

$\beta_{opt} = 0.65$

Freq. = 352.2 MHz

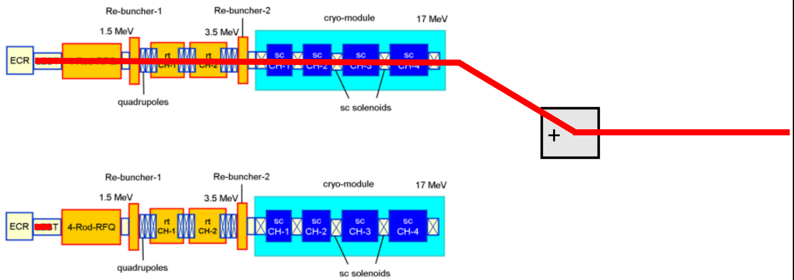
Freq. = 352.2 MHz

Freq. = 704.4 MHz

Injector Fault compensation strategy : Parallel Redundancy

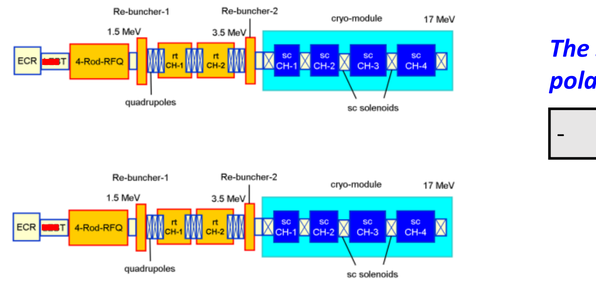
❶ Initial configuration

Operational injector 1: RF + PS + beam ON



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

❸ The failure is localised in injector

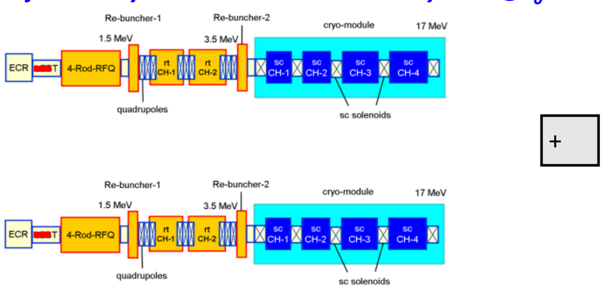


The switching magnet polarity is changed (~1s)

Need for an efficient fault diagnostic system !

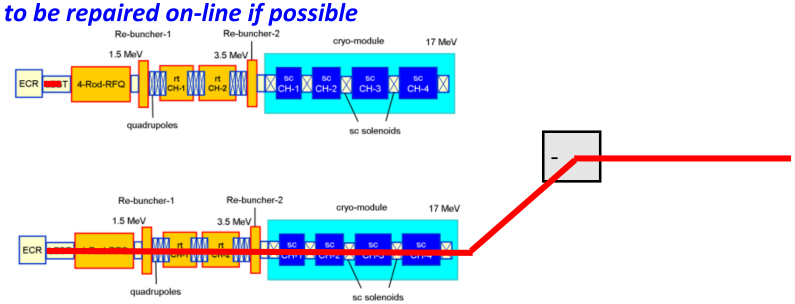
❷ A failure is detected anywhere

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)

SC linac Fault compensation : Serial Redundancy

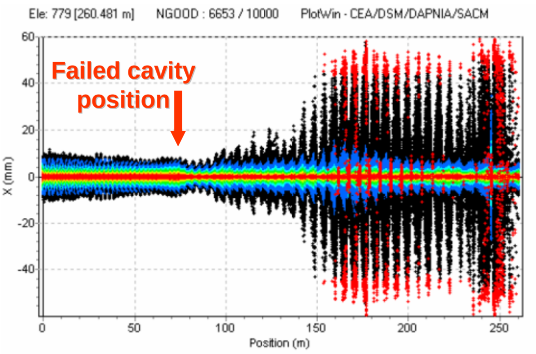


Figure 12 : Transverse beam distribution at 220 µs, in red are plotted the losses

❶ A failure is detected anywhere

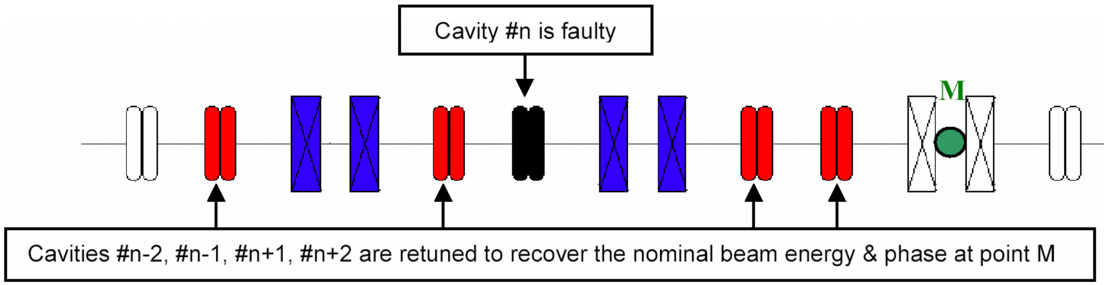
→ Beam is stopped by the MPS in injector at t_0

❷ The fault is localised in a SC cavity RF loop

→ Need for an efficient fault diagnostic system

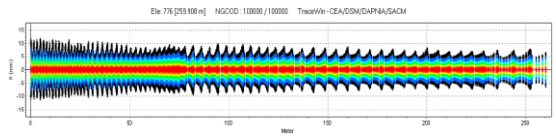
❸ New V/ϕ set-points are updated in cavities (cryomodule) adjacent to the failed one

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



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

→ Using the Cold Tuning System

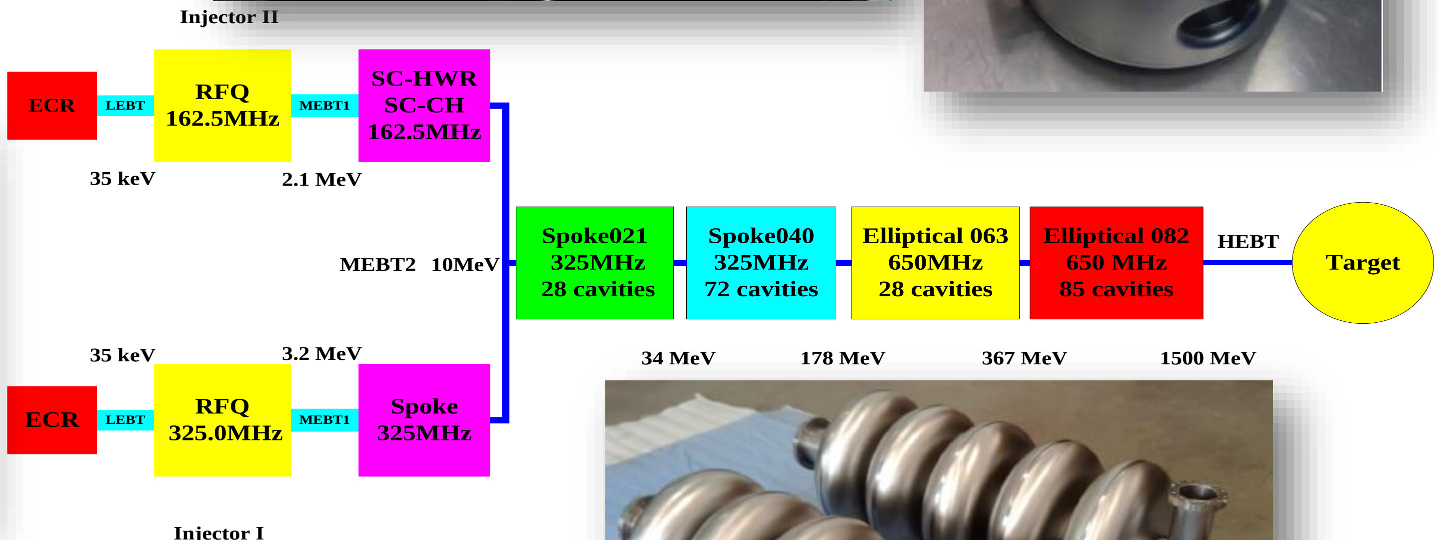


❺ Once steady state is reached, beam is resumed at $t_1 < t_0 + 3sec$

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

China-ADS Accelerator

- Same reliability-oriented concepts as MYRRHA
- Ambitious ADS program
  - ➢ Injectors by 2015
  - ➢ 1 GeV by 2022
  - ➢ 15 MW ADS by 2032



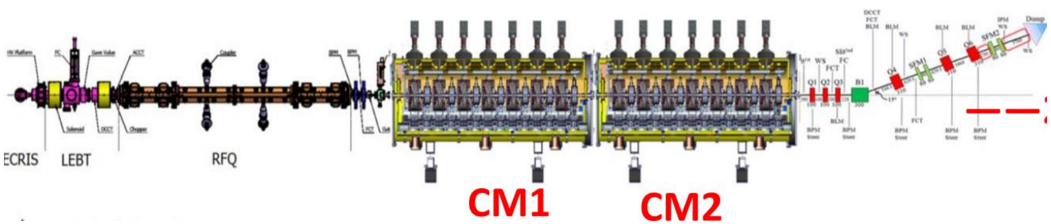
- **2 different injector designs**

➢Injector I @ Institute of High Energy Physics (IHEP), Beijing

➢Injector II @ Institute of Modern Physics (IMP), Lanzhou

C-ADS injectors

- **Injector I** : 4 vanne RFQ + Spoke @ 325 MHz



➢ "Successfully commissioned up to **10.1MeV** at a **pulse beam current of 10.03mA** with fourteen low-beta SC spoke cavities on **June 17th, 2016"**.

➢ **Jan. 2017 : CW 2.1 mA at 10 MeV**


CERN Courier September 2016

News

ACCELERATOR PHYSICS

Chinese accelerator passes milestone

Physicists in China have passed an important milestone towards an accelerator-driven sub-critical (ADS) system, a novel accelerator design for advanced energy and other technologies. On 2 July, teams working on "Injector I" at the Chinese Academy of Sciences' Institute of High Energy Physics (IHEP) in Beijing succeeded in accelerating a proton beam to an energy of 10.11 MeV with a peak beam current of 10.5 mA in pulse mode. "This is a major breakthrough for the ADS Injector I after five years of hard work by scientists from the Institute of High Energy Physics, and marks a new step for high-current proton-linear-accelerator technology worldwide," explains IHEP deputy-director Weimin Pan.

... the past 10 years has seen the development of various combined ADS systems aiming at different applications – including ...

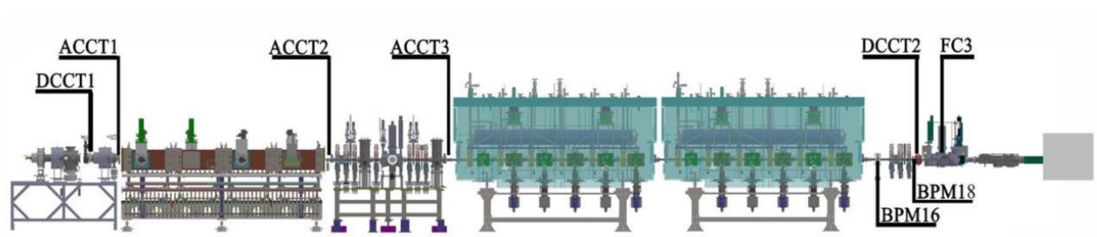
... resonance (ECR) ion source, a 325 MHz radio-frequency quadrupole accelerator, a superconducting linac containing ...

... of 7 MV m^{-1} and beam transmission through the superconducting linac was 100%. "This is an important focus of ...

Lin Bian et al., "2K-Superfluid He Cryogenic System for ADS Injector I in China", TCADS3, Mito, Japan, 2016

W. Zhan., "Recent ADS/ADANES Activities in China", This workshop, 2017

- **Injector II** : 4 vane RFQ + HWR @ 325 MHz



➢ Successfully commissioned in **December 2016 :**

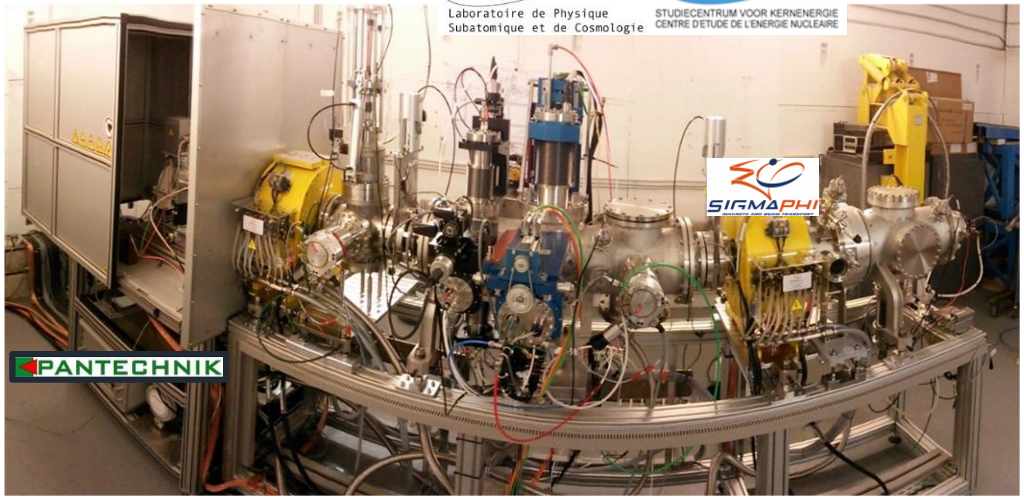
Pulsed : **10.1 MeV** with peak current at **11.7 mA**

CW : **10.1 MeV** and **I = 1.17 mA**

Courtesy of Hongwei Zhao

MYRRHA injector

- Source +LEBT



➢ *Compact Magnetic solution : ~ 3 meters long – 2 sol.*

- No 'clean' ions separation to ensure a direct proton current monitoring
- Less elements to tune
- Simple design
- Minimise the number of electrostatic elements
- Minimise Space Charge Compensation transients

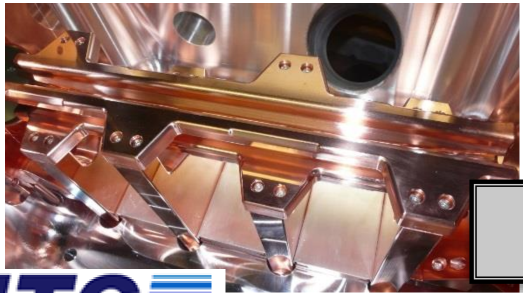
➢ Dedicated Beam physics program

F. Bouly et al., "The Low Energy Beam Transfer Line of the MYRRHA Accelerator", TCADS3, Mito, Japan, 2016

- RFQ + CH-DTL cavities

➢ *4-Rod @ 176.1 MHz : cooling optimised by prototyping (*P_{th}**=116 kW/m***)*

- Simpler to tune, easy maintenance & cheaper than 4-Vane

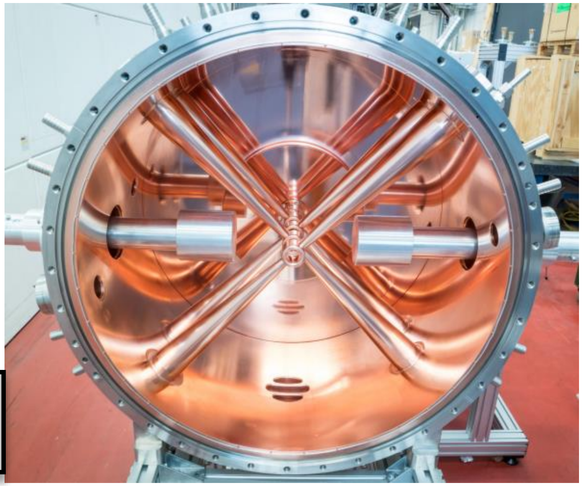


GOETHE UNIVERSITÄT FRANKFURT AM MAIN

IAP Institut für Angewandte Physik

H. Podlech et al., "The Proton Linac for the MYRRHA ADS", TCADS3, Mito, Japan, 2016

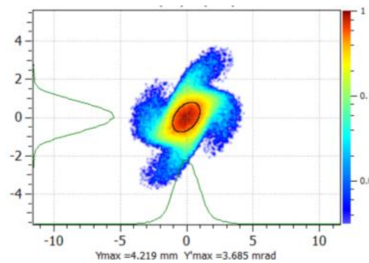
➢ RT *CH-DTL 176.1 MHz*



Importance of the beam physics

- Limit uncontrolled beam losses to less than 1 W/m to reduce radioactivation for hands-on maintainability and high availability.
- Design with margins (on E_{acc}) : for failures mitigations
- Minimise beam halo/emittance growth : space charges, instabilities, resonances, mismatch …

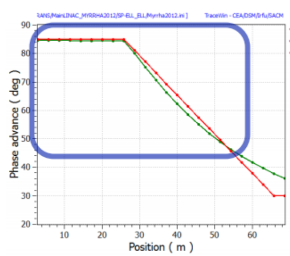
- Guidelines for transverse beam dynamics design
  - **1. Keep phase advance at zero-current σ_{T0} < 90° / lattice**

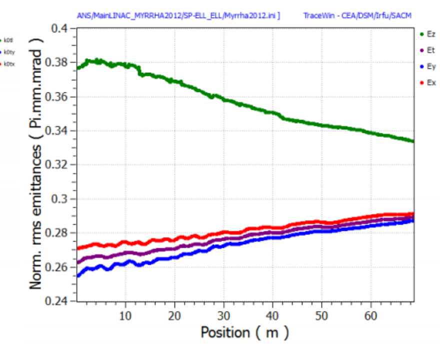


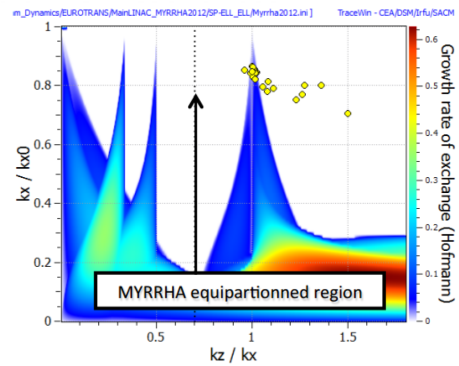
  - **2. Keep σ_T > 70%σ_L to stay away from the dangerous parametric resonance ($\sigma_T = \sigma_L/2$) & avoid emittance exchange between the transverse and the longitudinal planes and thus space charge driven resonances**

Ex:

σ_{T0} ~ σ_{L0}
I = 4mA







T. P. Wangler, K. R. Crandall, R. Ryne, and T. S. Wang, "Particle-Core Model for Transverse Dynamics of Beam Halo", Physical Review Special Topics - Accelerators and Beams, Vol. 1, 084201 (1998)

J.-L. Biarrotte, " Design of the MYRRHA superconducting linac & beam delivery", SLHipp2, Catana, Italy, 2012

Longitudinal Beam dynamics

- Guidelines for Longitudinal beam dynamics beam dynamics design
  - **1. Keep phase advance at zero-current σ_{L0} < 90° / lattice**

  → GOAL = avoid space charge driven parametric resonances & instabilities in mismatched conditions

  → Implies limitations on E_{acc}

  - **2. Continuity of the phase advance per meter (< 2°/m) : adiabatic transitions**

  → GOAL = minimise the potential for mismatch and ensure a current independent lattice

  → Implies especially limitations on E_{acc} at the frequency jump/transition between family sections

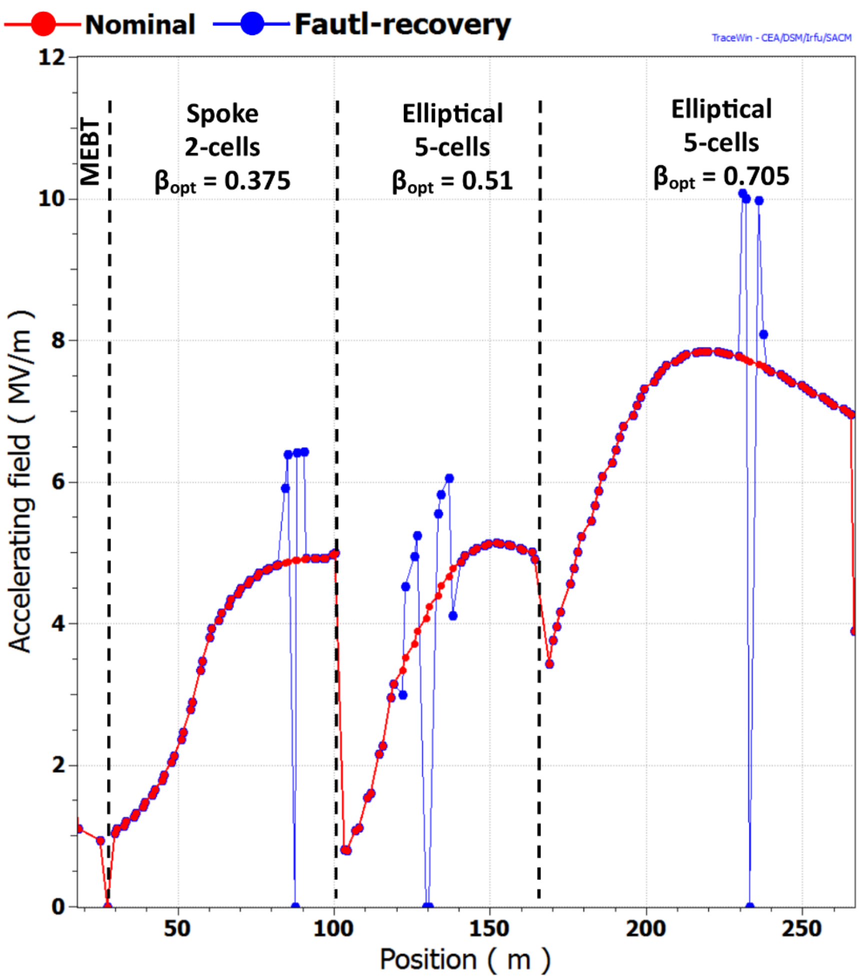
  - **3. Provide high longitudinal acceptance**

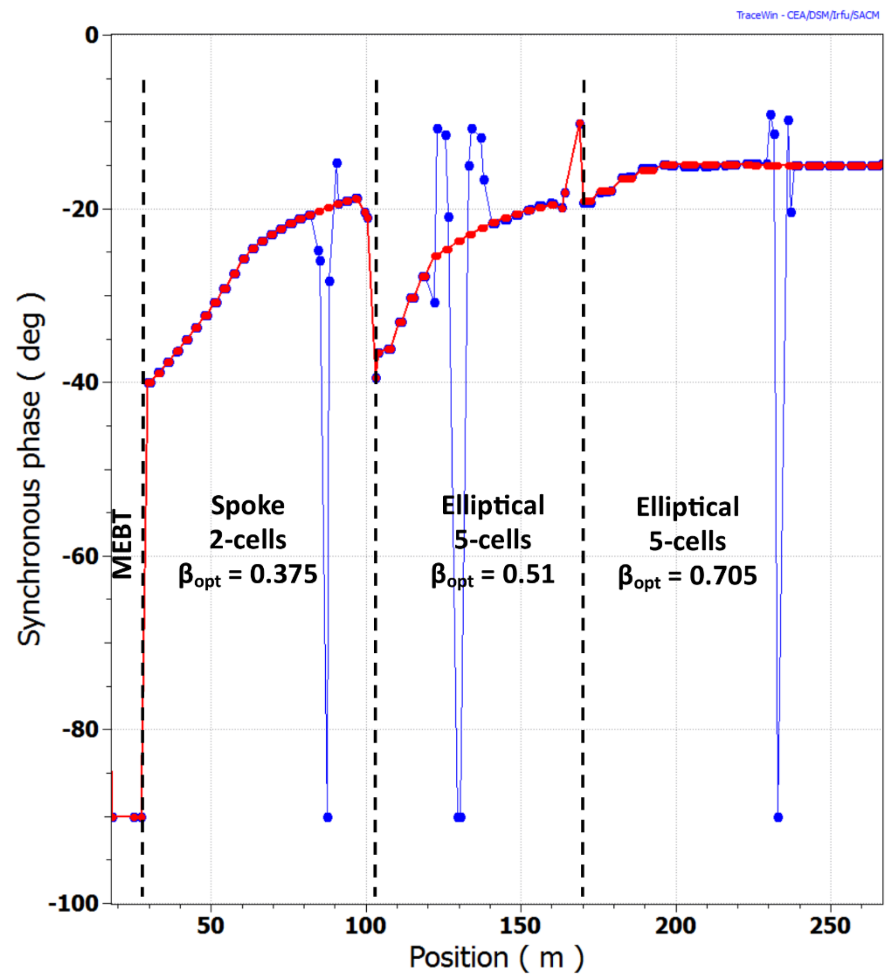
  → GOAL = avoid longitudinal beam losses & easily accept fault conditions

  → Implies low enough synchronous phases (ϕ_s= -40° at input, keep ϕ_s< -15°) & to keep constant phase acceptance through the linac; especially at the frequency jump

- Ex : MYRRHA linac design error studies with fault-compensations

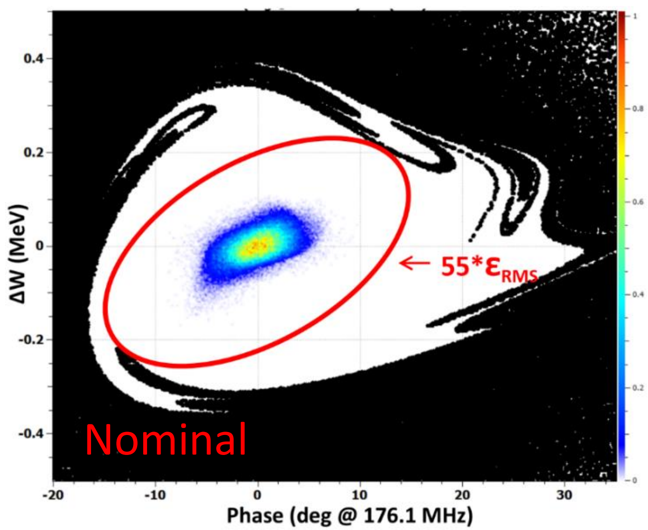
Fault compensation in MYRRHA - Example

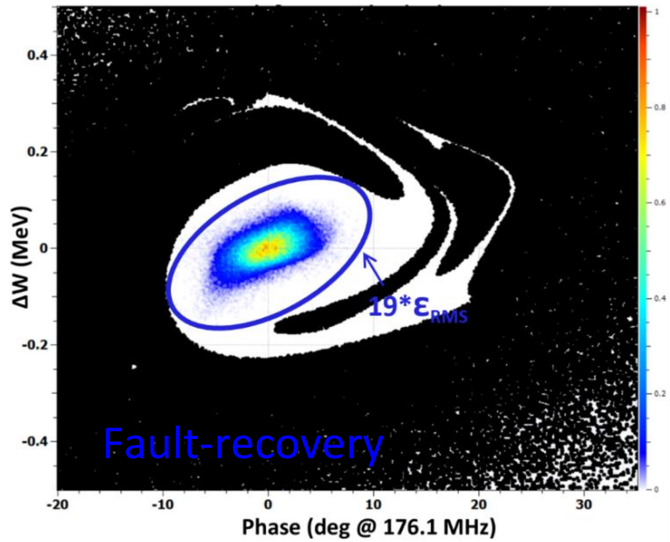




Fault compensation & Beam Dynamics

- Longitudinal acceptance

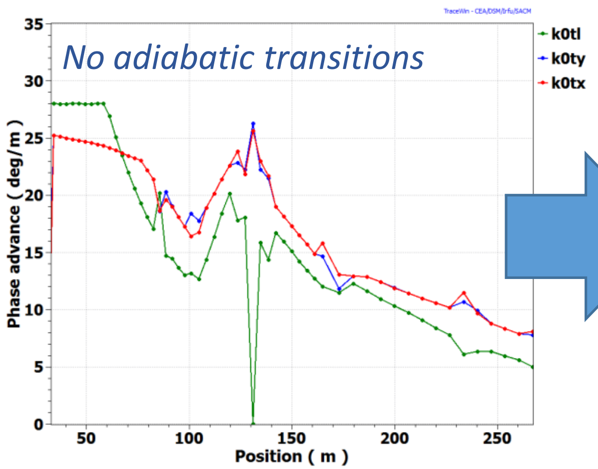


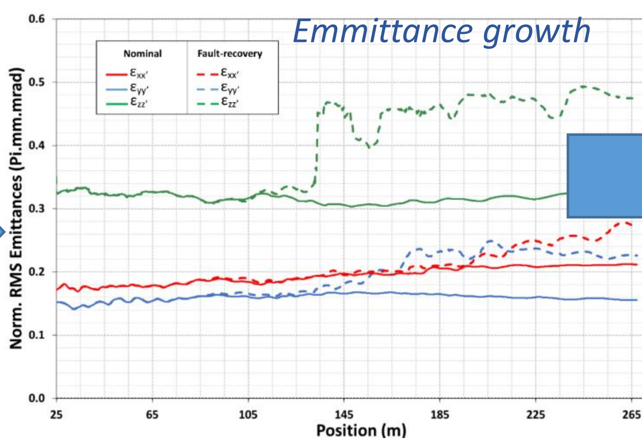


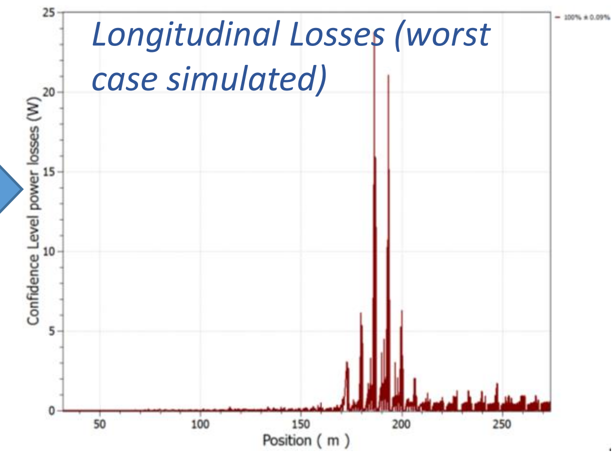
F. Bouly et al., " Fault tolerance and consequences in the MYRRHA SC linac", Linac14, Geneva, Switz., 2014

D. Uriot, J.-L. Biarrotte et al., " MAX project Del. 1.4, 2015

- Error studies shows that the losses may reach the acceptable limit of 1 W/m







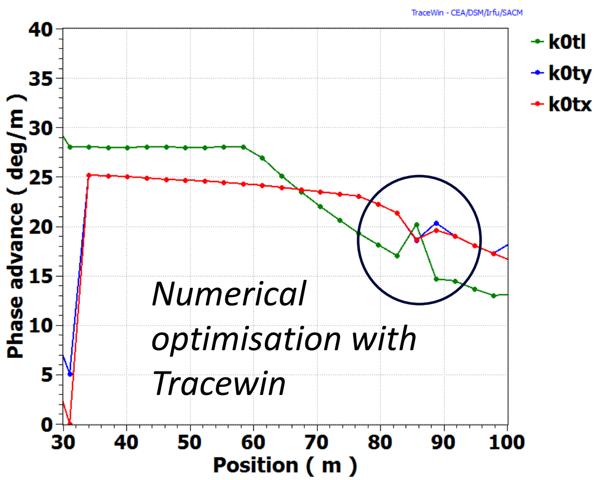
Fault compensation in MYRRHA - Example

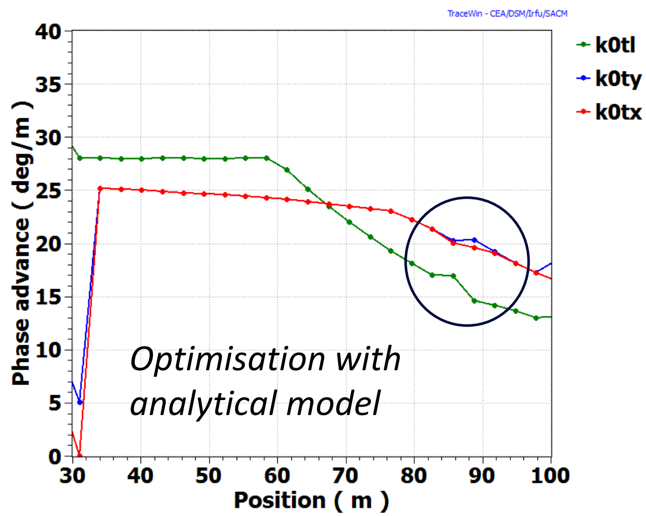
- Studies for MYRRHA : development of a retuning algorithm based on a an analytical model + improvement of the nominal longitudinal acceptance.

$$M_{\Delta\phi}=\begin{bmatrix} \mathrm{Cos}(k.Lc) & \frac{1}{k}\,\mathrm{Sin}(k.Lc) \\ -\,k\ \mathrm{Sin}(k.Lc) & \mathrm{Cos}(k.Lc) \end{bmatrix}_{\text{cavity}}$$

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

k : synchrotron phase advance per length unit





- This method is based on the use of a virtual accelerator
  - ➢ A model of the accelerator which "fits"/ well describes the beam dynamics and the running machine
  - ➢ Must be adjusted during the machine commissioning and operation

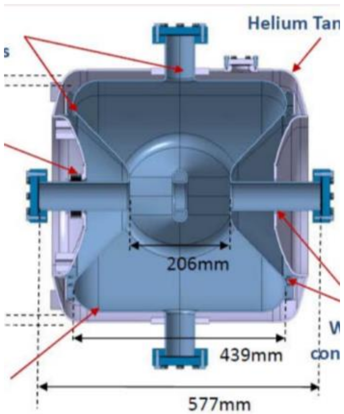
- **The fault compensation method has an impact on the Technological R&D**

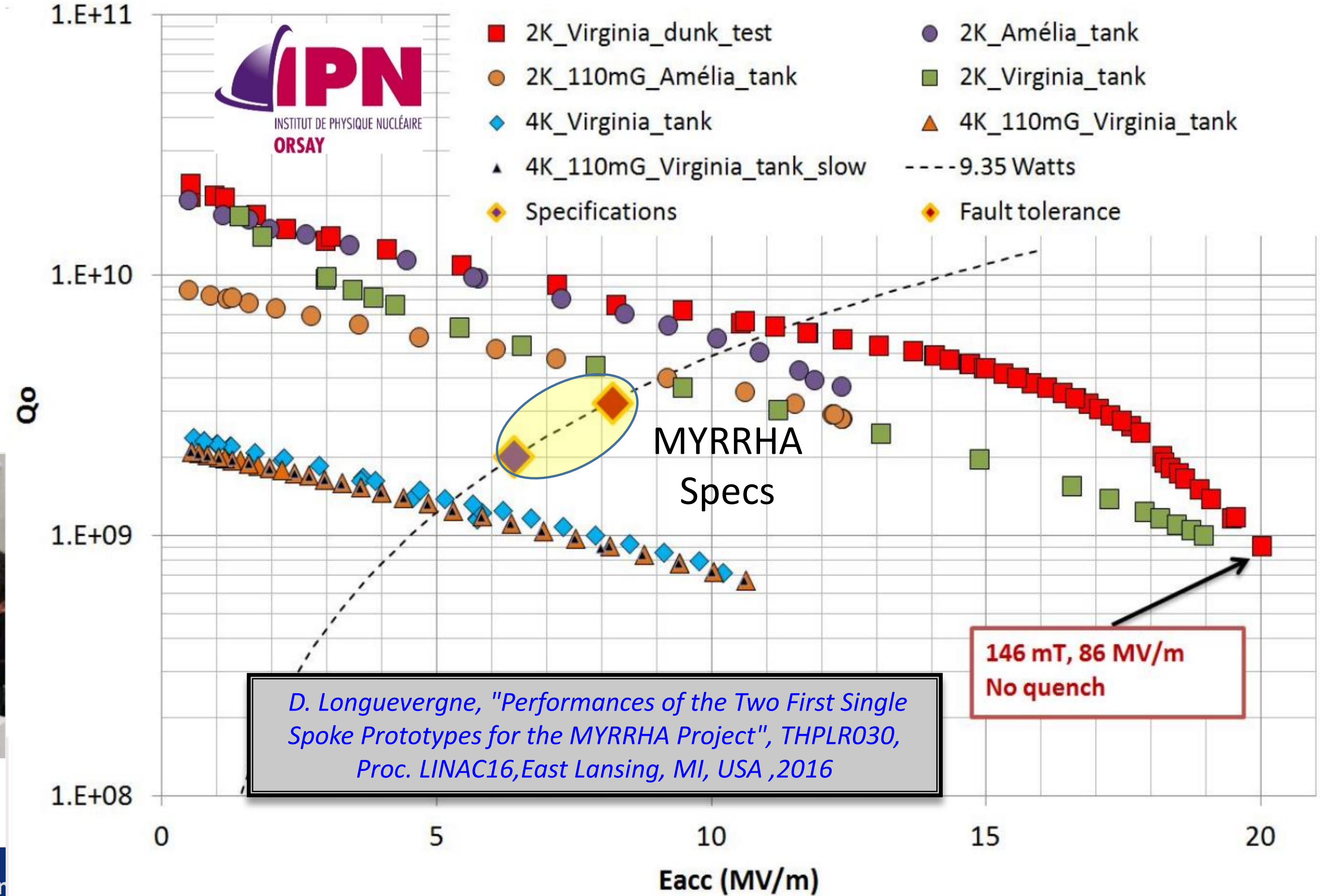
Design constraint #1 : Cavity performances

- Need for margins & flexibility

➢ Achievable gradients are mainly limited by heating by electron activity at high duty factor (field emission & multipacting)

- MYRRHA Spoke cavity @ β 0.37





Design constrains #2 & #3 : SC cavity ancillaries device

- **The maximal power given by the power coupler to the cavity is a clear limit** for linac designers, especially for pulsed high-current machines

  SNS design limit: 550kW peak (48kW average), tested up to 2MW in test stand

  ESS design limit: 1.1MW peak (about 100kW average)

- **Most of the high-power couplers design are very similar**

  Scaled from the original KEK 508 MHz coupler

  Coaxial, single warm window, fixed coupling

ESS

MYRRHA

SNS

- **Frequency tuning system**

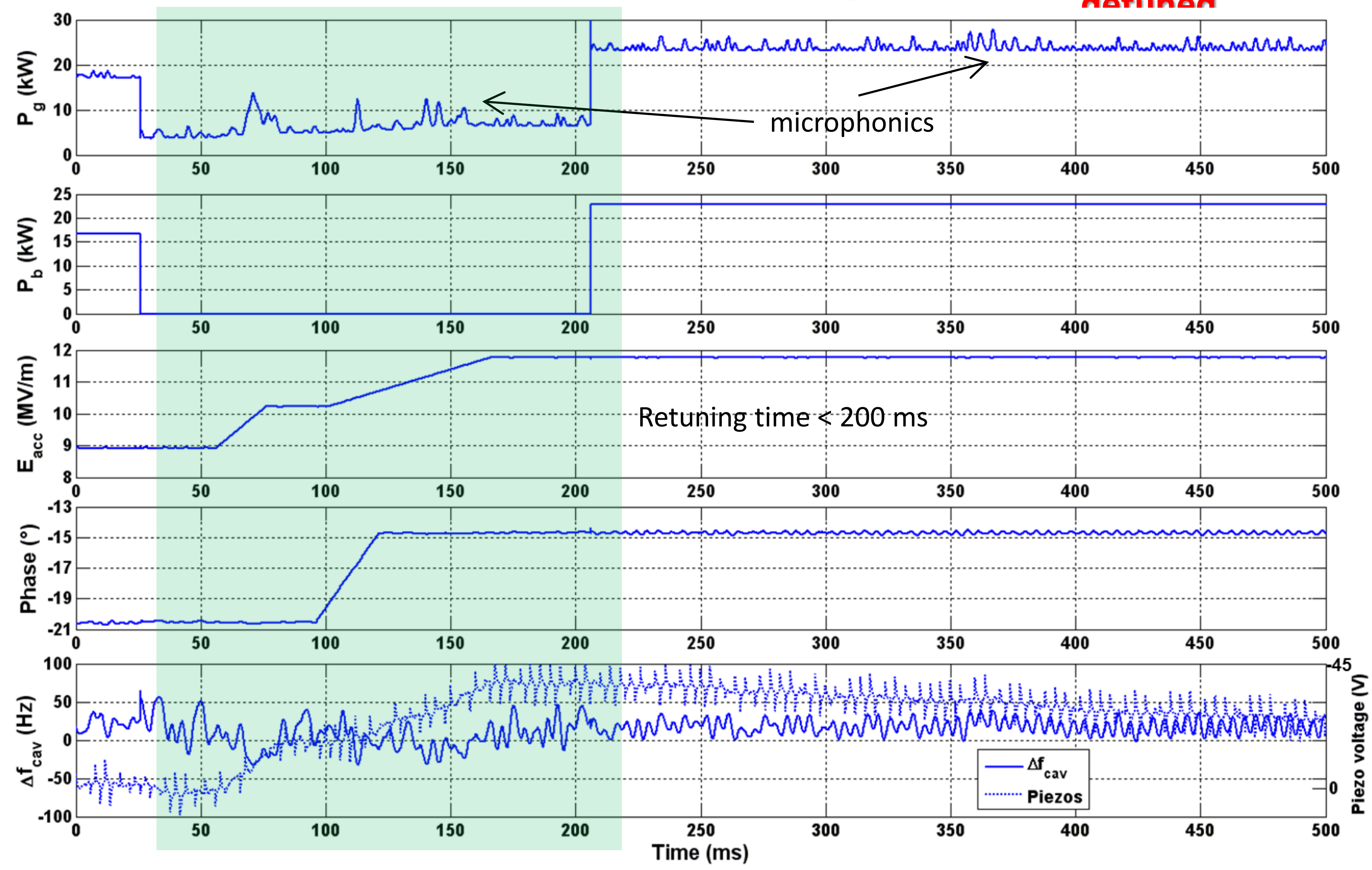
  - Most of the slow mechanical tuners are based on the CEA Saclay design
  - **Active detuning with piezo actuators are a necessity for ESS and SPL**, due to higher gradients and therefore higher Lorentz dynamic detunings
  - **A necessity (mandatory) for ADS drivers** : keep the power margins (affected by microphonics) and to apply the fault-compensation method

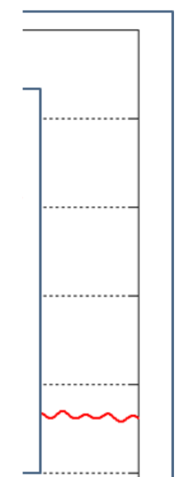
Cavity Control System & Fault Recovery

- Cavity control system : Model & Simulation

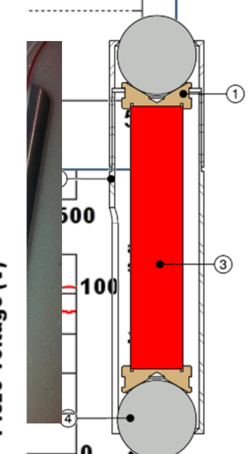
Failed cavity has to be detuned

Compensation Cavity





MYRRHA



Pre-load system

Other Design constraints

- **Cryomodules & Cryogenic systems**
  - Mostly from CEBAF-like or DESY-style concepts (elliptical cavity)
  - Innovative solutions are developed (spoke cavities)
  - **For CW machines** -> the main concern is to **minimise dynamic heat loads** and therefore **maximise Q_o**
- **RF power supply**
  - For **CW machines**, **solid state** development is the solution : modularity, no modulator, still need to be tested
- **Global control system**
  - Need a smart and efficient control system for failure detection and fast diagnosis
  - Avoid "false failures"
  - Such system will always evolve, especially during the **commissioning** …
- **Ancillary system (Vacuum, Cooling, Mechanics, Electronics….)**
  - **RAMS** (Reliability, Availability, Maintainability & Safety) is mandatory before construction
  - Availability studies are fundamental to assess the expected availability of a Linac, the week points and the efficiency of redundancy.
  - The analysis carried out on existing/operating machines are fundamental to validate & improve the actual reliability models : i.e. Linac4 @ CERN

A. Apollonio,, "Availability Studies for LINAC4 and Machine Protection requirements for Commissioning", Proc. IPAC2014, Dresden, Germany, 2014

1. Requirements & Issues for ADS accelerators
2. Linacs & RF Superconductivity
3. Reliability & Performance optimisation
4. **Summary – Final Remarks**

Summary/ Final remarks

● **High-power hadron accelerators have been made feasible thanks to Superconducting RF**

➢ Mature technology (thanks to projects/collab. : APT/ATW/SNS & TTF/ILC/XFEL)

● **CW SRF Linacs adapted for ADS demo. & full-scale plants : high potential regarding reliability and power upgrade capability.**

➢ No intrinsic current limit (Ex: IFMIF project 125 mA CW)

➢ Redundancy is possible for "on-line" failure compensation

➢ Cost optimisation (not compact)

● **Main challenges**

➢ Beam physics : Robust models at medium and high beta but the core-halo models can be improved as well as at very low energy (source, LEBT, low beta – Space Charge dominated)

➢ SRF cavities : High gradients and especially high Q_0 for CW machines (surface treatment Research)

➢ Demonstration of SRF injectors is required & on going : SPIRAL2, IFMIF, C-ADS

➢ Tuning systems : Piezo-actuators for tuners become a necessity - reliability has to be improved

➢ Fast switching magnets R&D is necessary

➢ Efficient Global Control system & Fault compensation procedure

-> **Commissioning phase is essential for reliability improvements (ref: SNS) + Human factor**

● **Strong potential for Synergies in between HPPL**

➢ Potential for common cavity (HWE/Spoke) and/or cryomodule designs (e.g. ESS/MYRRHA spokes)

➢ Potential for a common/worldwide high-power coupler design

➢ Solid-state amplifiers developments (at high freq.) has to be supported by the community

➢ ADS R&D to improve reliability can be a potential benefit to all future projects

THANK YOU !