# Last developments and compensation strategies of cavity failures in superconducting linacs

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Journées Accélérateurs SFP, October 6$^{th}$, 2023

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# Presentation outline

Context of the study

Development of LightWin

Usage of LightWin on ADS linacs

Conclusions

# Context of the study

# Fundamental to avoid beam losses in modern hadron accelerators

- Hadron accelerators go towards increasing mean beam power.
- High power ⇒ impact of beam losses on accelerator structure.
- Very stringent availability requirements.

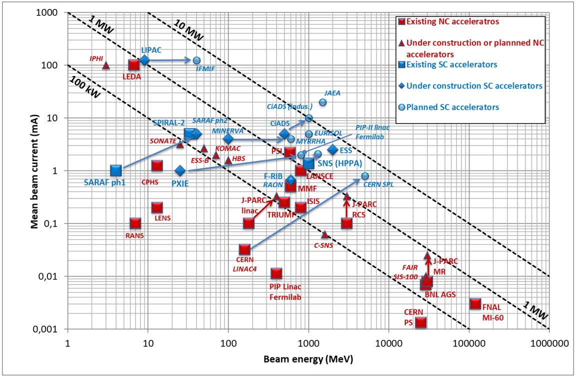



**Figure 1:** Panorama of the hadron accelerators (existing, projects). Courtesy of F. Bouly.

# ADS have particularly stringent availability requirements

- Accelerator-Driven Systems (ADS): sub-critical nuclear reactor driven by proton accelerator.
- Avoiding prolonged beam trips is even more important:
    - thermal constraints on the reactor structure;
    - long restart procedures.

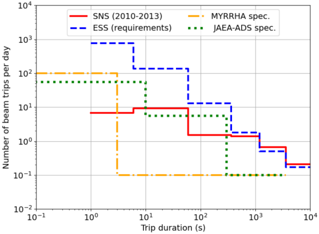



**Figure 2:** Daily max number of fault per fault duration for several proton accelerators. Data from Yee-Rendon 2022.

$\Rightarrow$ MYRRHA-ADS: max 10 beam interruptions longer than 3 s per 3 month operating cycle.

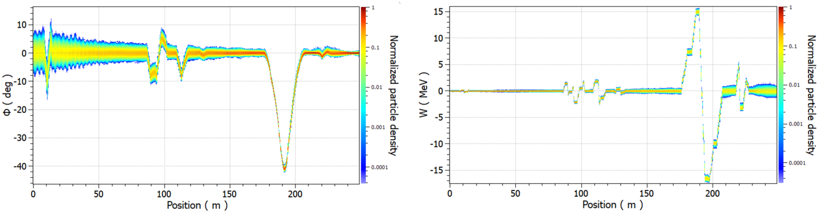

Yee-Rendon (2022), "Overview of ADS Projects in the World"

Biarrotte et al. (2008), "Dynamic compensation of an rf cavity failure in a superconducting linac"

Bouly et al. (2014), "Fault tolerance and consequences in the MYRRHA superconducting LINAC"

# Cavity failure compensation to limit beam interruptions

- Retune cavities to compensate for a failed one.




(a) Absolute phase. (b) Kinetic energy.

**Figure 3:** Compensation in the MYRRHA-ADS. Particle densities of the retuned linac, w.r.t. nominal linac. Courtesy of F. Bouly.

- In ADS, facilitated by specific design:
  - linac is very acceptant, cavities are derated (MYRRHA: $E_{\mathrm{acc}} + 30\,\%$).
- Create a database to link a failure to the associated compensation settings.

Bouly (2020), "MYRRHA Superconducting linac and Fault Tolerance Concept"

# Development of LightWin

# Motivations for an automatic compensation tool

- Classic workflow to find compensation settings (*e.g.* with TraceWin).
  1. ($\approx$ min) Manually set up compensation process.
  2. ($\approx$ s to h) Run optimisation process.

     $\rightarrow$ Incompatible with ADS requirements.
- Envisioned workflow: generate a database with dedicated tool LightWin.
  1. ($<$ ms) Take settings from database.
  2. That's all.
- NB: applying the new settings in a short amount of time is also an important problematics.

Bouly (2011), "Etude d'un module accélérateur supraconducteur et de ses systèmes de régulation pour le projet MYRRHA"

# LightWin has a modular code structure

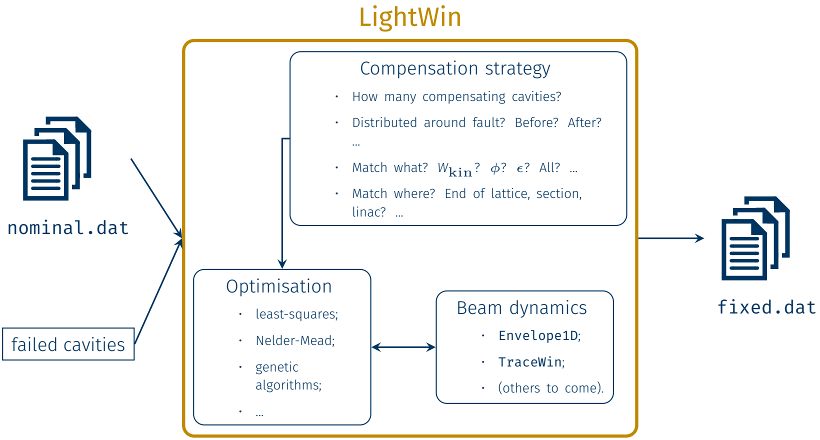



**Figure 4:** Structure of the LightWin code.

# Usage of LightWin on ADS linacs

- Beam dynamics:
  - Relatively high energies ($\approx$ 10 MeV $\rightarrow$ 1 GeV), protons.
  - Can study only longitudinal dynamics, envelope.
    - $\rightarrow$ Faster `Envelope1D` beam dynamics tool.
- Compensation strategy:
  - Local compensation (cavities in green remain untouched).
  - For each failed cavity, compensate with 1 lattice before, 1 after.


**Figure 5:** Illustration of the compensation strategy. Red: failed. Orange: compensating. Green: nominal.

# Optimisation problem

10 variables (2 per compensating cavity):

- Amplitude $k_e$,
- Phase $\phi_0$.

10 constraints (2 per compensating cavity):

- $-90° < \phi_s$,
- $\phi_s < 0°$.

3 objectives:

- $\Delta W_{\mathrm{kin}}$,
- $\Delta \phi_{\mathrm{abs}}$,
- $M$.

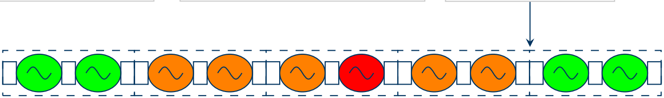


**Figure 6:** Parametrization of the optimisation problem. Red: failed ($k_e = 0$). Orange: compensating. Green: nominal.

- Difference of kinetic energy: $\Delta W_{\mathrm{kin}} = |W_{\mathrm{kin}}^{\mathrm{nominal}} - W_{\mathrm{kin}}^{\mathrm{fix}}|$
- Difference of absolute phases: $\Delta \phi_{\mathrm{abs}} = |\phi_{\mathrm{abs}}^{\mathrm{nominal}} - \phi_{\mathrm{abs}}^{\mathrm{fix}}|$
- Mismatch factor: $M = \sqrt{\frac{1}{2}\left(R + \sqrt{R^2 - 4}\right)} - 1$
- $R = \beta\gamma' + \beta'\gamma - 2\alpha\alpha'$

# MYRRHA-ADS study presented @ LINAC2022

- 10 faults distributed along MYRRHA-ADS linac.

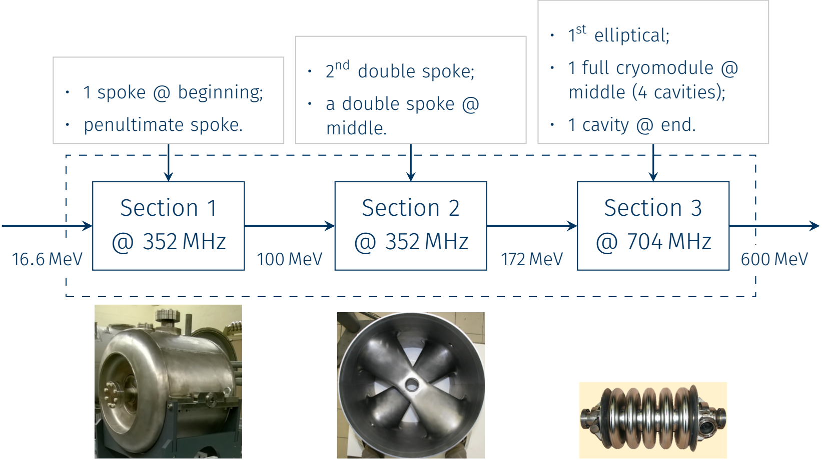



**Figure 7:** Structure of the MYRRHA-ADS with the faults that we studied. Beam current 4 mA.

Plaçais et al. (2022), "Cavity Failure Compensation Strategies in Superconducting Linacs"

# Cavity parameters on a multi-fault scenario on MYRRHA

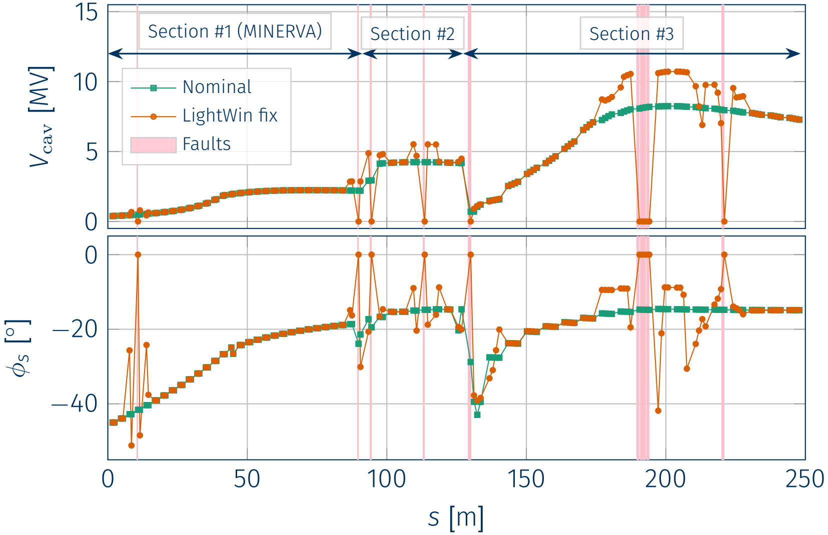
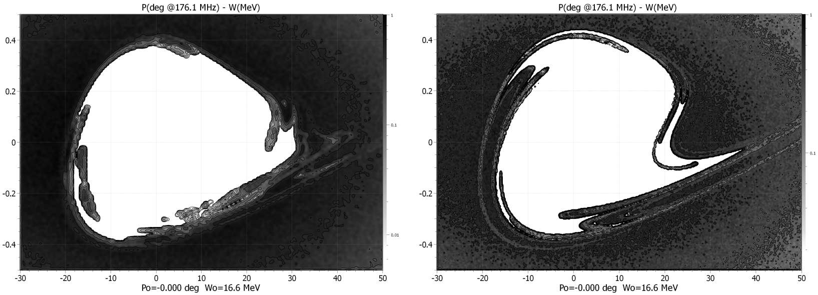



**Figure 8:** Accelerating voltage and synchronous phase of MYRRHA-ADS, in nominal and fixed cases.

# Acceptance is reduced in this case




(a) Nominal case (no fault).

(b) With LightWin compensation settings.

**Figure 9:** Acceptance of the MYRRHA-ADS calculated with TraceWin.

- Retrieve nominal energy at the end of the linac.
- No beam losses.
- But reduction of acceptance.
  - → Possible to find better settings?

# JAEA-ADS systematic study presented @ IPAC2023

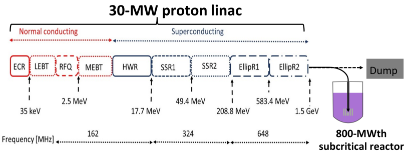



**Figure 10:** Schematics of the JAEA-ADS.

Study of last section:

- 940 MeV to 1500 MeV;
- 5-cell elliptical cavities;
- 648 MHz;
- five cavities per cryomodule.

- Simpler scenarios:
  - a single error at the time;
  - single cavity & cryomodule failures;
  - systematic study of all errors in this section (database);
- Comparison w/ settings found during previous TraceWin study Yee-Rendon 2022.
- *k*-out-of-*n*: a failure is compensated with 5 neighboring cavities.

Plaçais et al. (2023), "Development of a Tool for Cavity Failure Compensation in Superconducting Linacs: Progress and Comparative Study"
Yee-Rendon et al. (2022), "Beam dynamics studies for fast beam trip recovery of the Japan Atomic Energy Agency accelerator-driven subcritical system"

# Beam parameters @ linac exit similar LightWin/BYR study

**Table 1:** Longitudinal beam optics performance for this study (transverse optics in appendix). TraceWin results are taken from Yee-Rendon 2022. Outlined results = TraceWin optics are better.

| | $\Delta\varepsilon/\varepsilon_0$ [%] | | $M$ | |
|---|---|---|---|---|
| Faulty cavity | LightWin | TraceWin | LightWin | TraceWin |
| 257 | −1.11 | 1.52 | 0.10 | 0.09 |
| 258 | −0.27 | 1.02 | 0.02 | 0.09 |
| 289 | −0.10 | 0.13 | 0.00 | 0.04 |
| 290 | 0.10 | 0.25 | 0.01 | 0.08 |
| 291 | −0.03 | 0.13 | 0.03 | 0.09 |
| 292 | 0.10 | 0.25 | 0.02 | 0.09 |
| 293 | 0.17 | 0.25 | 0.02 | 0.09 |
| 289–293 | −0.29 | −1.27 | 0.35 | 0.06 |

Yee-Rendon et al. (2022), “Beam dynamics studies for fast beam trip recovery of the Japan Atomic Energy Agency accelerator-driven subcritical system”

# Conclusions

# Future developments for LightWin

- Developed LightWin.
  - Automatic tool for compensation of cavity failures.
  - Usage validated on ADS.
- And now?
  - Systematic study on MINERVA (first section of MYRRHA).
  - Started working with SPIRAL2 linac.
    - Global compensation.
  - New beam dynamics tools (B. Yee-Rendon, J.-M. Lagniel).
  - Publish code open-source.

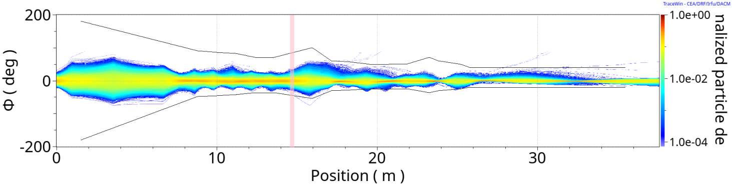



**Figure 11:** Evolution of $\phi_{\mathrm{abs}}$ density in SPIRAL2 linac. Cavity #6 failure, compensated. 900 µA $^{4}He^{2+}$ 63.87 MeV 2 kW. Courtesy G. Normand.

Orduz (2023), “Première année d’exploitation de SPIRAL2”

# References

[1] Bruce Yee-Rendon. **“Overview of ADS Projects in the World”.** In: *Proceedings of LINAC2022*. Liverpool, United Kingdom: JACoW Publishing, Geneva, Switzerland, 2022 (cit. on p. 5).

[2] Jean-Luc Biarrotte and Didier Uriot. **“Dynamic compensation of an rf cavity failure in a superconducting linac”.** In: *Physical Review Special Topics - Accelerators and Beams* 11.7 (July 2008), p. 072803 (cit. on p. 5).

[3] Frédéric Bouly, Jean-Luc Biarrotte, and Didier Uriot. **“Fault tolerance and consequences in the MYRRHA superconducting LINAC”.** In: *Proc. 27th Linear Accelerator Conf. (LINAC14)*. Geneva, Switzerland: JACoW Publishing, Geneva, Switzerland, 2014 (cit. on p. 5).

[4] Frédéric Bouly. **“MYRRHA Superconducting linac and Fault Tolerance Concept”.** In: *Proc. 30th Linear Accelerator Conf. (LINAC20)*. Virtual Conference: JACOW Publishing, Geneva, Switzerland, 2020 (cit. on p. 6).

[5] Frédéric Bouly. **“Etude d’un module accélérateur supraconducteur et de ses systèmes de régulation pour le**

**projet MYRRHA".** PhD thesis. Paris, France: Université Paris-Sud XI, Nov. 2011 (cit. on p. 8).

[6] Adrien Plaçais and Frédéric Bouly. **"Cavity Failure Compensation Strategies in Superconducting Linacs".** In: *Proceedings of LINAC2022*. Ed. by Peter McIntosh et al. Liverpool, United Kingdom: JACoW Publishing, Geneva, Switzerland, 2022, pp. 552–555 (cit. on pp. 13, 27).

[7] Adrien Plaçais, Frédéric Bouly, and Bruce Yee-Rendon. **"Development of a Tool for Cavity Failure Compensation in Superconducting Linacs: Progress and Comparative Study".** In: *Proc. 14th Int. Particle Acc. Conf. (IPAC'23)*. Venice, Italy: JACoW Publishing, Geneva, Switzerland, 2023 (cit. on p. 16).

[8] Bruce Yee-Rendon et al. **"Beam dynamics studies for fast beam trip recovery of the Japan Atomic Energy Agency accelerator-driven subcritical system".** In: *Physical Review Accelerators and Beams* 25.8 (Aug. 2022), p. 080101 (cit. on pp. 16, 17).

[9] Angie Orduz. **“Première année d’exploitation de SPIRAL2”.** In: *Journées Accélérateurs 2023 de la SFP*. Roscoff, France, 2023 (cit. on p. 19).

# Overview of some proton linac accelerator characteristics

Table 2: Linac specifications of some multi-MW proton accelerators.

| Linac | Energy [MeV] | Current [mA] | Power [MW] |
|---|---|---|---|
| ESS | $3.6 \rightarrow 2000$ | 62.5 | 5 (4 %) |
| CiADS | $2.5 \rightarrow 500$ | 5 | 2.5 (CW) |
| JAEA-ADS | $2.5 \rightarrow 1500$ | 20 | 30 (CW) |
| MYRRHA-ADS | $16.6 \rightarrow 600$ | 4 | 2.4 (CW) |

# Optimisation algorithm tries to find the global minimum

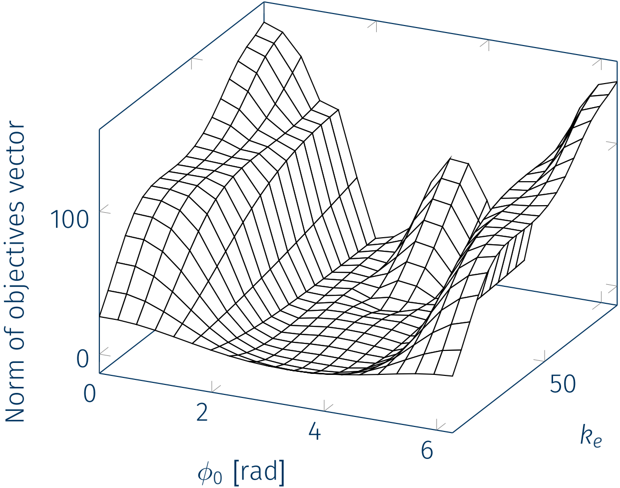



**Figure 12:** Objective value against two variables in a simplified problem: only one compensating cavity to allow visualisation. The amplitude $k_e$ required to reach optimum is unrealistically high.

# Transverse and longitudinal beam optics in JAEA study

Table 1: Beam optics performance for this study. “LW” stands for LightWin and “TW” for TraceWin. TraceWin results are taken from Ref. [6]. We outlined in red the beam optics that were better with TraceWin than with LightWin.

| | $\Delta\varepsilon/\varepsilon_0$ [%] | | | | M | | | |
|---|---|---|---|---|---|---|---|---|
| | Transverse | | Longitudinal | | Transverse | | Longitudinal | |
| Faulty cavity | LW | TW | LW | TW | LW | TW | LW | TW |
| 257 | 0.42 | 1.07 | −1.11 | 1.52 | 0.03 | 0.02 | 0.10 | 0.09 |
| 258 | 0.11 | 0.88 | −0.27 | 1.02 | 0.01 | 0.01 | 0.02 | 0.09 |
| 289 | −0.01 | 0.09 | −0.10 | 0.13 | 0.00 | 0.01 | 0.00 | 0.04 |
| 290 | −0.06 | −0.17 | 0.10 | 0.25 | 0.00 | 0.03 | 0.01 | 0.08 |
| 291 | 0.12 | 0.04 | −0.03 | 0.13 | 0.01 | 0.03 | 0.03 | 0.09 |
| 292 | −0.09 | 0.04 | 0.10 | 0.25 | 0.01 | 0.03 | 0.02 | 0.09 |
| 293 | −0.02 | 0.21 | 0.17 | 0.25 | 0.01 | 0.03 | 0.02 | 0.09 |
| 289–293 | 0.18 | 1.78 | −0.29 | −1.27 | 0.13 | 0.02 | 0.35 | 0.06 |

**Figure 13:** Table taken from Placais 2022.

Plaçais et al. (2022), “Cavity Failure Compensation Strategies in Superconducting Linacs”