

# EXPERIMENTAL CAVITY COMPENSATION IN SPIRAL2 SC LINAC

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## Abstract

During the years of operation of the GANIL SPIRAL2 SC LINAC (Caen, France), issues affecting amplifiers and cavities have prevented the LINAC operation. To maintain the overall accelerator availability, cavity failure compensation studies have been started for  $D^+$  beam, with nominal energy recover and transmission as main goals.

LINAC setting with one failing cavity is calculated for  $D^+$  beam transported in order to reach 40 MeV and keep losses as low as possible. The method for calculating compensation is discussed, cavity compensation simulations and the associated experimental measurements are presented.

## INTRODUCTION

To ensure high LINAC reliability, a single cavity failure compensation studies were started. To compensate a cavity failure, it is necessary to readjust the phase and voltage of some cavities downstream, and few upstream. Simulations were performed to determine new LINAC settings with one cavity out of order, with the objective of transmitting the different SPIRAL2 beams through the LINAC with minimal losses while maintaining the highest possible beam energy at the LINAC exit. Similar studies were done mainly on cavities with high beta [1–4]. For the SPIRAL2 LINAC [5], there are two families of cavities, with  $\beta = 0.07$  or  $\beta = 0.12$ . This LINAC has been designed to accelerate a large variety of beams, with different  $A/Q$  (from protons  $A/Q = 1$  to heavy ions  $A/Q = 3$ ) [6].

In the nominal case, in SPIRAL2, the  $D^+$  beam has a final energy of 40 MeV [7], and a maximum current of 5 mA. Due to the "low" energy of the particles and the high current, the space charge leads to a more complex cavity compensation. In this framework, it has been decided to study the possibility to operate the SPIRAL2 LINAC with one cavity out of order.

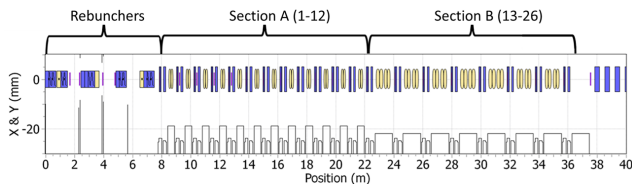


Figure 1: Layout of the SPIRAL2 MEBT and LINAC. Quadrupoles are in blue, cavities and rebunchers in yellow.

The simulations track particles in the MEBT and the LINAC, composed of three rebunchers and 26 cavities. The 12 first cavities ( $\beta = 0.07$ ) compose the section A (1 to 12). The section B ( $\beta = 0.12$ ) is composed of the 14 next cavities (13 to 26) Figure 1.

Simulations are performed using TraceWin [8], with the following parameters for the  $D^+$  beam: initial energy 1.46 MeV, beam current 5 mA at the LINAC entrance,  $\varepsilon_{xx'} = 0.20 \pi$  mm mrad,  $\varepsilon_{yy'} = 0.20 \pi$  mm mrad, and  $\varepsilon_{zz'} = 0.30 \pi$  mm mrad. The nominal energy at the exit of the LINAC is 40 MeV [7]. Calculations are done for a continuous beam with a final beam power of 200 kW. The majority of experiments on SPIRAL2 require  $D^+$  beams, with beam power lower than 2 kW.

## NOMINAL LINAC SETTING

The LINAC parameter settings in 2024, with all 26 cavities operational, are used for an initial simulation. Figure 2 shows the phase and radial particles distribution (MEBT and LINAC) for a  $D^+$  beam.

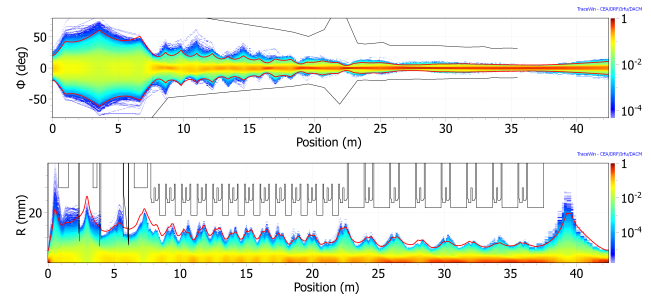


Figure 2: Particles density according to the phase and to the radial position, for the nominal setting (2024).

Beam losses are mainly monitored by BLMs located along the LINAC and the HEBT. Vacuum pressure variation can be also used as a diagnostic [9]. In the case of  $D^+$  beam, only BLMs are used.

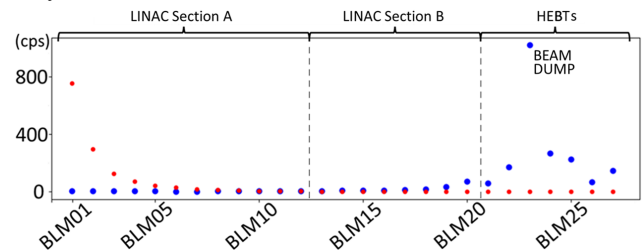


Figure 3: BLMs measurements along the LINAC and the HEBT: for nominal tuning (blue dots) and without beam in the LINAC (red dots). The BLM23 detects back-scatter emissions from beam dump.

Figure 3 shows BLMs measurements along the LINAC. The blue dots correspond to measurement with beam in the LINAC, and in red without beam. BLMs signals will be divided by the final beam power. The signal will be in count per second per watt (cps/W).

## STANDARD COMPENSATION METHOD

Each cavity is defined by its position  $i$  in the LINAC, its synchronous phase  $\varphi_s[i]$ , and  $k_e[i]$  its field divided by 6.5 MV/m. The  $i^{th}$  cavity compensation is done following a "standard" method:

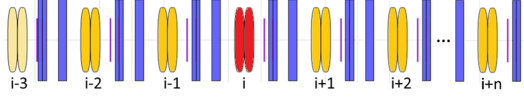


Figure 4: Cavity compensation scheme. The failed cavity is in red. Compensation goes from cavity  $i - 2$  to  $i + n$ .

The phase cavity  $i + 1$  is tuned nearly to rebuncher and its voltage is reduced.  $\varphi_s$  and  $k_e$  of few cavities around the cavity  $i$  are increased as shown in Fig.4). The tunings of  $\varphi_s$  and  $k_e$  are performed by iteration, until convergence towards a setting that meets requirements. The beam transport is optimised by adjusting the quadrupole field. The optimization minimizes the beam size variations between two periods.

## CAVITY COMPENSATION

The study is divided into two stages. The first consists of performing calculations. For every case in which a cavity is out of service, using a  $D^+$  beam, a fault compensation has been identified.

The second part is to validate the results of the simulations on the LINAC. As the time available to carry out the study on the machine is limited, only a few cases involving tunings to a cavity out of service were selected.

### 11<sup>TH</sup> Cavity Compensation

The first case study to have been tested experimentally is the compensation of cavity 11. The cavity is off and detuned to prevent any interaction between the cavity and the beam. Transmission is measured close to  $100 \pm 2\%$ .

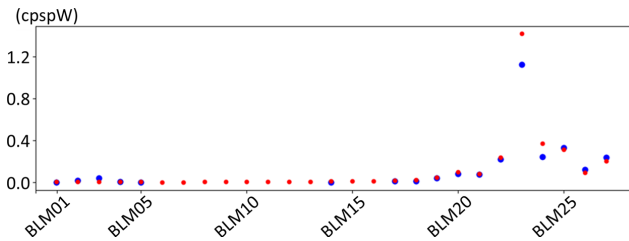


Figure 5: BLM measurements along the LINAC and HEBT: for measurements cavity 11 compensation setting (blue dots), nominal setting (red dots).

The BLM measurements show no increase compared with the nominal case, illustrated by Fig.5. The simulation results and experimental measurements have a good agreement for beam losses and energy at the LINAC exit.

### Early Cavity Compensation in the Linac

Compensation calculations are performed for each cavity in the case for  $D^+$  beam. The cavity compensation complexity decreases as the particle energy increases. In the case of cavity 1 compensation, it is necessary to reduce the

last rebuncher voltage. Cavity 2 is set as rebuncher as every cavity  $i + 1$ . All the cavity compensations calculated for  $D^+$  beam (ending at 40 MeV) were regrouped in order to create a failure compensation repertory.

## CAVITY COMPENSATION FORMULAS

As all reduction field compensations cannot be calculated, empiric formulas are tested. Cavity compensations can be interpreted as adjustments applied to a reference setting. The LINAC setting for the compensation are named  $\varphi_{s,solution}$  and  $k_{e,solution}$ :

$$\begin{aligned}\varphi_{s,solution}[j] &= \varphi_{s,ref}[j] + (\Delta\varphi_s[j]) \\ k_{e,solution}[j] &= k_{eref}[j] (\alpha_{k_e}[j])\end{aligned}\quad (1)$$

where  $\varphi_{s,ref}[j]$  is the synchronous phase of cavity  $j$  for the reference configuration, and  $k_{eref}[j]$  the associated field.  $\Delta\varphi_s[j]$  and  $\alpha_{k_e}[j]$  represent the compensation apply to the cavity  $j$  parameters.

Figure 6 shows the case of cavities 11 and 12 out of order with a transmission of  $100 \pm 0.5\%$  (1.7 kW). The formula gives a good starting point but some minor adjustments in the simulation have been required.

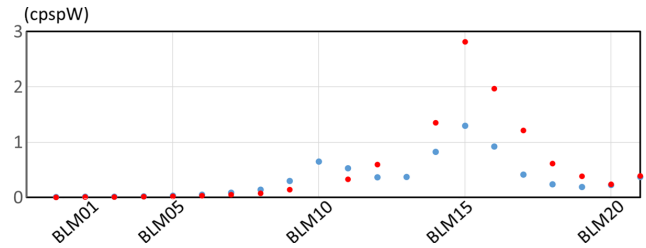


Figure 6: BLM measurements along the LINAC and HEBT: for measurements cavities 11 & 12 compensation setting (blue dots), for measurements cavity 11 compensation setting (red dots).

### Cavity Voltage Reduction

The compensation study focuses cavity out of service. In some cases, a cavity is no longer able to provide the voltage required, although it can still be used, a new LINAC setting is then required. By using both the reference configuration and the configuration with the cavity offline, an interpolation provides a new setting:

$$\varphi_{s,reduced}[j] = \left(\frac{a}{a+b}\right) \varphi_{s,ref}[j] + \left(\frac{b}{a+b}\right) \varphi_{s,off}[j] \quad (2)$$

$$k_{e,reduced}[j] = \left(\frac{a}{a+b}\right) k_{eref}[j] + \left(\frac{b}{a+b}\right) k_{e,off}[j]$$

$ref[j]$  for the reference setting for the cavity  $j$

$off[j]$  for the setting with a cavity Out of Order

$reduced[j]$  for the setting with a maximum voltage reduced on one cavity

and  $a$  and  $b$  two ponderation factors.

This method was tested by simulation for three different cases with  $D^+$  beam, and allowed a shorter optimisation time. (The tested cases were the partial compensation of the cavity 6, of the cavity 8 and of the cavity 12.) For the setting presented below, the cavity 6 voltage is reduced to 1 MV/m (versus 1.95 MV/m for the nominal setting) ( $k_e[6] = (1\text{MV/m})/(6.5\text{MV/m}) = 0.1538$ ).

This method presents a challenge: no phase is defined for an offline cavity. To address this issue, the failed cavity synchronous phase is arbitrarily set to the mean between the adjacent cavities phases. The cavity phase is then adjust to reach expectation. Instead of the 5 to 10 cavities, only 2 need to be adjusted.

$$\varphi_{soff}[6] = \frac{\varphi_{soff}[5] + \varphi_{soff}[7]}{2} = -61.7^\circ \quad (3)$$

The coefficients  $a$  and  $b$  are chosen in order to have:

$$\begin{aligned} k_e[6] &= \left(\frac{a}{a+b}\right)k_{eref}[6] + \left(\frac{b}{a+b}\right)k_{eoff}[6] \\ &= 0.1538 \\ \text{and} \quad a + b &= 1 \end{aligned} \quad (4)$$

$k_{e6off} = 0$  since the cavity is offline. Therefore:

$$\begin{aligned} a &= \left(\frac{k_e[6]}{k_{eref}[6]}\right) = \left(\frac{0.1538}{0.3}\right) \\ a &= 0.5128 \quad \text{and} \quad b = 1 - a = 0.4872 \end{aligned} \quad (5)$$

Using the value of  $a$  and  $b$ , the formulas (eq. 3) are applied to all cavities. As shown by the simulation (Figure 7), the cavities 6 and 7 phases require adjustment.

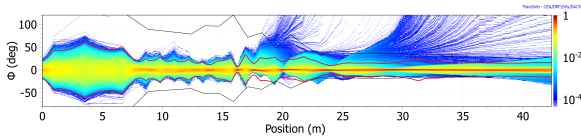


Figure 7: Normalized density of particles regarding the phase. LINAC cavities setting from the calculation.

The LINAC tuning shows longitudinal losses. Regarding the particles phase density, the adjustments are done on the cavities 6 and 7. Both phases are reduced in order to avoid the overbunching effect of the cavities leading to the particle phase distribution. Small oscillations are observed on the phase distribution in section B of the LINAC, but no particle loss occurs (Figure 8).

The  $k_e$  and  $\varphi_s$  values for each setting are displayed in the table 1. The columns "Reference" are for the reference setting, "6 Off" for the cavity 6 compensation, "6 Calcul" for the cavity 6 reduction from calculation, and "Final" for the setting post adjustment.

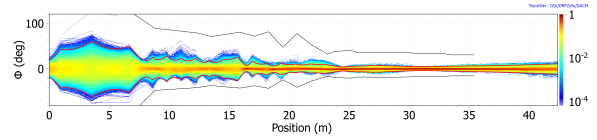


Figure 8: Normalized density of particles regarding the phase. Final setting.

Table 1:  $\varphi_s$  and  $k_e$ . The Values Modified are in Red. The Compensation is in Green

Cav	Reference	6 Off	6 Calcul	Final
$n^\circ$	$k_e$	$\varphi_s$	$k_e$	$\varphi_s$
4	0.23	-39	0.23	-39
5	0.26	-36	0.26	-34
6	0.30	-35	0.0	-62
7	0.48	-32	0.17	-89
8	0.57	-30	0.71	-42
9	0.75	-29	0.32	-53
10	1.00	-25	1.19	-22
11	0.77	-23	0.77	-38
12	1.10	-21	0.90	-32
			$k_e$	$\varphi_s$
			0.23	-39
			0.26	-35
			0.15	-38
			0.33	-40
			0.64	-36
			0.54	-41
			1.09	-24
			0.77	-30
			1.00	-27

## CONCLUSION & PERSPECTIVES

The study on cavity compensation in the case of the SPIRAL2 LINAC demonstrated that it is possible to find tunings for each case of cavity failure, achieving the nominal beam energy and keeping losses under 1 W/m. The settings experimentally tested have shown a good agreements between simulation results and experimental measurements.

Cavity compensation is possible, however each cavity compensation required setting calculations that can take up to several weeks depending on the cavity.

In order to deepen the cavity failure compensation study, calculation compensation formulas were tried on different cases. Formulas calculate a new setting based on already calculated ones. These were tested for two-cavity failure compensations.

In the case of distant compensations, the formulas give setting that match the requirements (nominal energy at the end of the LINAC and losses lower than 1 W/m). In the case of close compensations, with a strong overlap, the output of the formulas need modifications, but remains a good step in the compensation direction.

In addition to the compensation of two cavities at the same time, formulas were also used for cavity voltage reduction. As for the case of compensation overlap, for the voltage reduction, the formulas give a first step that accelerate the calculation. This formulas has shown some encouraging results, and a more advance version may accelerate further the compensation.

Simulations and experimental measurements were carried out with  $D^+$  beam, but the SPIRAL2 LINAC is design to accelerate particles with A/Q going from 1 to 3 (and up to 7 with the injector NEWGAIN). Similar studies must be done for each A/Q family (1, 2, around 3 and around 6).

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