# COMMISSIONING AND RESULTS OF SPIRAL2 BPMS

C. Jamet†, P. Legallois GANIL, Caen, France

email:jamet@ganil.fr

*Construction of a new accelerator is always an opportunity to face challenges and make new developments. The BPM diagnostics installed in the SPIRAL2 linac and the associated instrumentation are part of these developments. BPM instrumentations are, of course, used to measure positions and phases of ion beams but also transverse shapes, called ellipticity, as well as the beam velocity.*

*Specifications involve knowing and calculating the sensitivities in position and in ellipticity as a function of the beam velocities. These impose small amplitude differences between channels, which require precise calibration of electronics. This paper describes the modelling and analysis of the BPM behaviour according to the beam velocity, the technical solutions, modifications and improvements. An analysis of the results and evolutions in progress are also presented.*

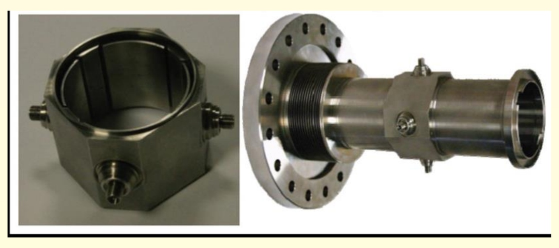
## INTRODUCTION

The SPIRAL2 accelerator is a new facility built on the GANIL site at Caen in France. A high power CW superconducting linac produces up to 5 mA beams with a maximum energy of 33 MeV for protons and 20 MeV/A for deuterons.

BPMs are installed inside quadrupoles in the warm sections of the linac between cryomodules. BPMs are composed of 4 squared electrodes with a radius of 24 mm, a length of 39 mm and an electrode angle of 60°.

BPM Specifications

| Parameter | Resolution | Range |
|---|---|---|
| Position | +/- 150µm | +/-20 mm |
| Phase | +/-0.5 deg. | +/-180 deg. |
| Ellipticity | +/-20 % or +/- 1.2 mm² | |



## BPM MODEL

At low velocities, sensitivities in position and ellipticity are function of the beam beta and the harmonic. One objective was to find a formula to calculate the ellipticity sensitivity correction.

The wall current density iω, at frequency ω/2pi, induced by a pencil beam on the conducting cylindrical tube is given by the equation:

$$i_w(n\omega_0, r, \theta, \phi_w) = \frac{A_n\langle I_b\rangle}{\pi a}\left[\frac{I_0(gr)}{I_0(ga)} + 2\sum_{m=1}^{\infty}\frac{I_m(gr)}{I_m(ga)}cos\big(m(\phi_w - \theta)\big)\right]$$

- r the beam radius
- ϕω the position angle on the cylindrical tube
- Im() the modified Bessel function of order m
- a the radius of the tube
- θ the beam angle
- λ the wave length
- γ the Lorentz factor
- ω the pulsation

With $g = \frac{n\omega_0}{\beta\gamma c} = \frac{n\omega_0\sqrt{1-\beta^2}}{\beta c}$

With a Gaussian shape for the bunch longitudinal distribution, the instantaneous beam current is:

$$I_b(t) = \frac{\langle I_b\rangle}{\sqrt{2\pi}\sigma_{tp}}e^{-\frac{(t)^2}{2\sigma_{tp}^2}}$$

- $<I_b>$ the average beam intensity
- σtp the RMS length in time of the beam pulse

Wall current equations are simplified by taking only the Bessel coefficients of order 2 with gr << 1.

$$I_{w(R,L,U,D)} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\frac{1}{\sigma_x\sqrt{2\pi}}\frac{1}{\sigma_y\sqrt{2\pi}}I_{w(r,l,u,d)}(x, y, X_0, Y_0)e^{\frac{-x^2}{2\sigma_x^2}}e^{\frac{-y^2}{2\sigma_y^2}}dxdy$$

$$I_{wR,L} = \frac{A_n\langle I_b\rangle}{\pi}\left[\frac{\phi_0}{I_0(ga)} \pm \frac{2g}{I_1(ga)}sin(\frac{\phi_0}{2})X_0 + \frac{g^2 sin(\phi_0)}{4I_2(ga)}\left((X_0^2 - Y_0^2) + (\sigma_x^2 - \sigma_y^2)\right)\right]$$

$$I_{wU,D} = \frac{A_n\langle I_b\rangle}{\pi}\left[\frac{\phi_0}{I_0(ga)} \pm \frac{2g}{I_1(ga)}sin(\frac{\phi_0}{2})Y_0 - \frac{g^2 sin(\phi_0)}{4I_2(ga)}\left((X_0^2 - Y_0^2) + (\sigma_x^2 - \sigma_y^2)\right)\right]$$

- $A_n$ the Fourier component amplitudes
- $\phi_0$ the electrode angular width
- $\phi_0$ the angle of electrodes (radian)
- $X_0$, $Y_0$ the horizontal and vertical positions (mm)
- $\sigma_x$ ,$\sigma_y$ The horizontal and vertical RMS sizes (mm)
- $I_0$, $I_1$, $I_2$: Modified Bessel functions of order 0,1,2

The positions and ellipticity are defined taking into account the sensibility corrections.

$$X = \frac{K}{1+G}\frac{(I_{wR} - I_{wL})}{(I_{wR} + I_{wL} + I_{wU} + I_{wD})} \qquad Y = \frac{K}{1+G}\frac{(I_{wU} - I_{wD})}{(I_{wR} + I_{wL} + I_{wU} + I_{wD})}$$

K, the position sensitivity, is function of the mechanical dimensions.

- $\phi_0$ the angle of electrodes (radian)
- a the radius of the tube

$$K = \frac{\phi_0 a}{2sin(\frac{\phi_0}{2})}$$

Ellipticity is :

$$Ell = (\sigma_x^2 - \sigma_y^2) = \frac{S}{1+G_E}\frac{(I_{wR} + I_{wL}) - (I_{wU} + I_{wD})}{I_{wR} + I_{wL} + I_{wU} + I_{wD}} - (X_0^2 - Y_0^2)$$

S, the ellipticity sensitivity, is: $S = \frac{a^2\phi_0}{2sin(\phi_0)}$

For SPIRAL2 BPMs, K = 25.1 mm, S = 348 mm²

For gr << 1, the simplified equations of G and $G_E$ the correction coefficients are:

$$1+G \approx \frac{I_0(ga)}{I_1(ga)}\frac{ga}{2} \qquad (1+G_E) \approx \frac{I_0(ga)(ga)^2}{8I_2(ga)}$$

Values of the corrected sensitivities in function of different beta are shown on the Table:

| beta | Kh1 (mm) | Kh2 (mm) | Sh1 (mm²) | Sh2 (mm²) |
|---|---|---|---|---|
| 0.04 | 21.8 | 16.6 | 290 | 194 |
| 0.08 | 24.2 | 22 | 331 | 290 |
| 0.12 | 24.7 | 23.6 | 341 | 320 |
| 0.26 | 25.0 | 24.8 | 347 | 342 |

From the wall current, the wall density charges are calculated at a given ω.

$$Q_{elec}(t) = \beta c\lambda \otimes \mathcal{H}(t) \qquad \tilde{Q}_{elec}(f) = \beta c\tilde{\lambda} \times \tilde{\mathcal{H}}(f)$$

The h1 and h2 vector sum of electrode amplitudes are obtained from the Fourier Transform.

$$V_{VS-h1_{eff}} = \frac{4\sqrt{2}}{3}|Z_{RC_{h1}}|sin(\pi\frac{L_{elec}}{L_{acc}})\frac{\langle I_b\rangle}{I_0(g_{h1}a)}e^{-2\pi^2\sigma_{tp}^2F_{acc}^2} \qquad |Z_{RC_{h1}}| = \frac{R}{\sqrt{1+(2\pi F_{acc}RC)^2}}$$

$$V_{VS-h2_{eff}} = \frac{4\sqrt{2}}{3}|Z_{RC_{h2}}|sin(2\pi\frac{L_{elec}}{L_{acc}})\frac{\langle I_b\rangle}{I_0(g_{h2}a)}e^{-8\pi^2\sigma_{tp}^2F_{acc}^2} \qquad |Z_{RC_{h2}}| = \frac{R}{\sqrt{1+(4\pi F_{acc}RC)^2}}$$

The bunch length is calculated from the ratio of h1 and h2 vector-sum amplitudes.

$$\sigma_{tp} = \frac{1}{\sqrt{6}\pi F_{acc}}\sqrt{ln\left[2\frac{|Z_{RC_{h2}}|}{|Z_{RC_{h1}}|}cos(\pi\frac{L_{elec}}{L_{acc}})\frac{I_0(g_{h1}a)}{I_0(g_{h2}a)}(\frac{V_{VS-h1_{eff}}}{V_{VS-h2_{eff}}})\right]}$$

## LINAC CAVITY TUNING

The ß values in the linac are from 0.04 up to 0.26 for the 33 MeV proton beam.

The cavity tuning step consists to :

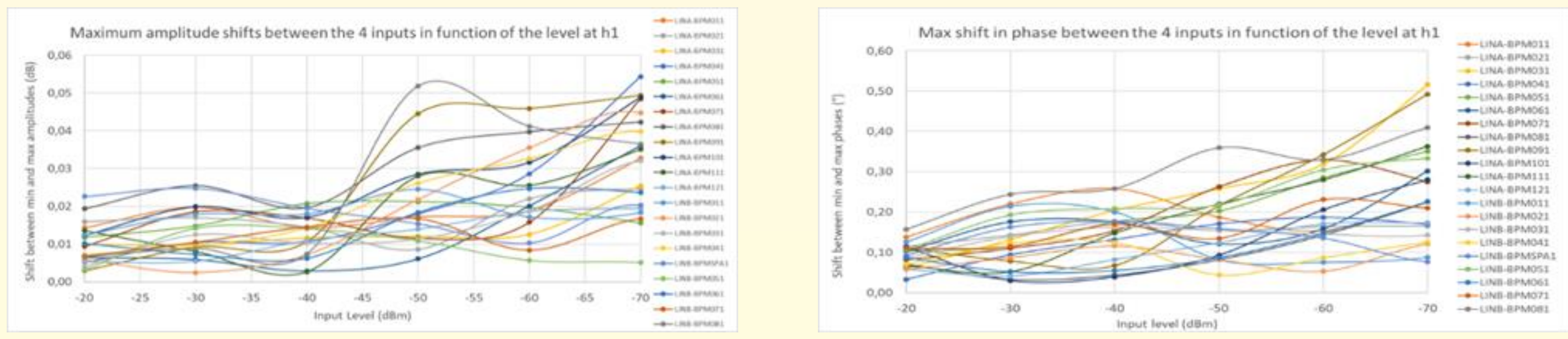
- tune the phase and amplitude of the cavities one by one at low beam power, the downstream cavities being detuned to avoid beam energy changes. Three BPM phase measurements, one before and two after the cavity to tune, allow to measure the beam velocity.
- match the beam to the linac with quadrupole tunings in the MEBT by an iterative process. The matching method uses the ellipticity values given by the BPMs.
- gradually increase the beam power while monitoring beam losses.

## CALIBRATION

In order to obtain the required resolutions, 2 solutions were implemented in the electronic process, a very precise calibration and stabilizations of the 4 gains and phases.

- The calibration is used to correct the gain and phase deviations of signals and offset tone on the 4 channels at h1 and h2.
- Gain and phase stabilizations were designed to correct gain and phase deviations over the entire operating range.

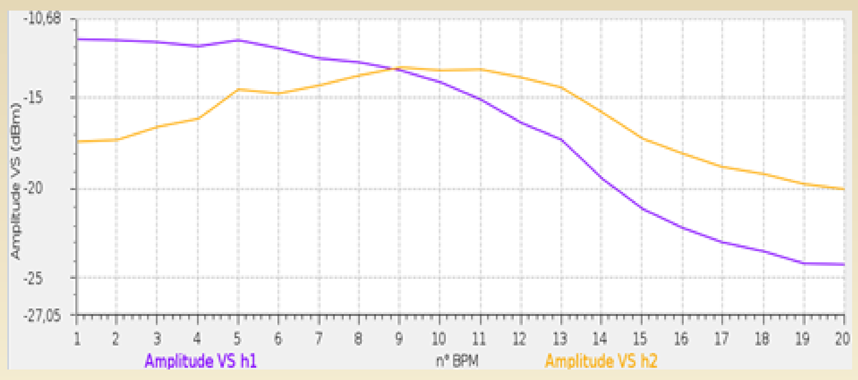
After the calibration, tests are carried out with a generator to verify the results.




Maximum amplitude shifts and phase shifts between the 4 channels

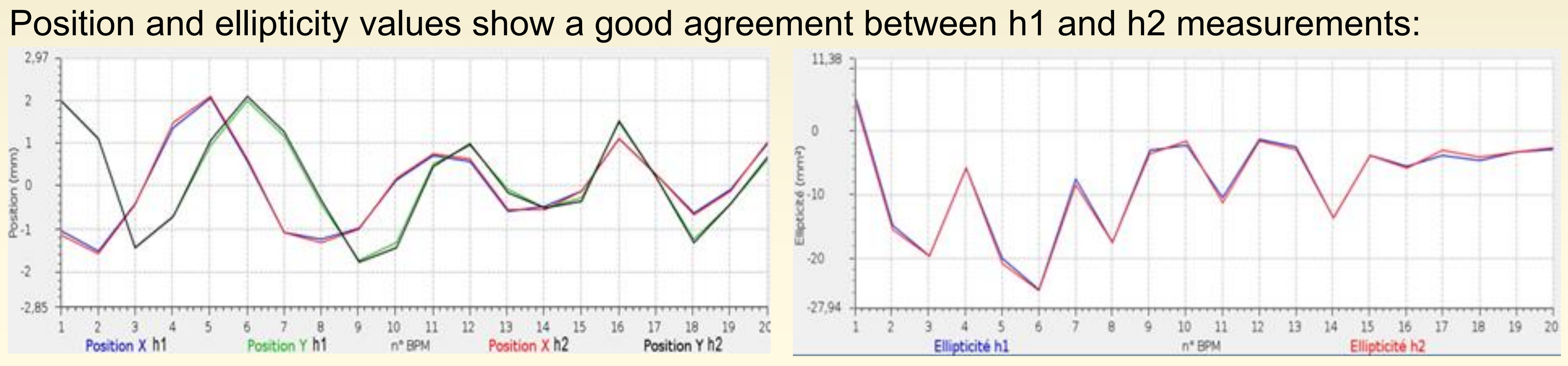
## RESULTS WITH BEAMS

In 2020, a 4.15 mA proton beam at 33 MeV, generated the BPM signals.



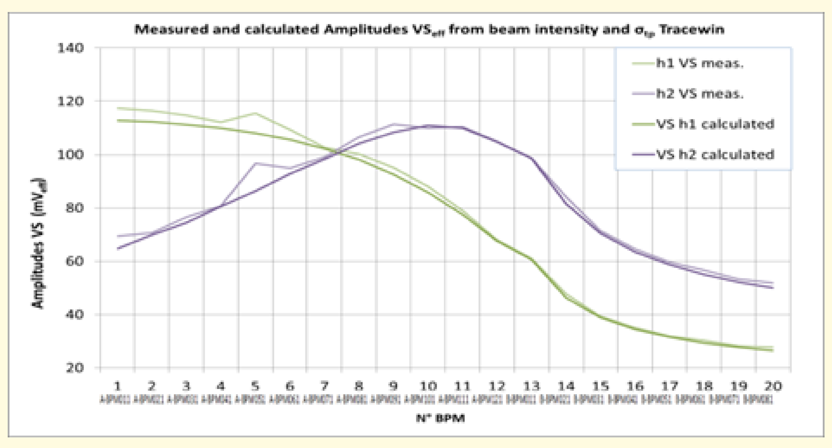
The h1 amplitudes (purple curve) gradually decrease when the velocity increase. The h2 amplitudes (orange curve) reach a maximum for a beta around.

Position and ellipticity values show a good agreement between h1 and h2 measurements:



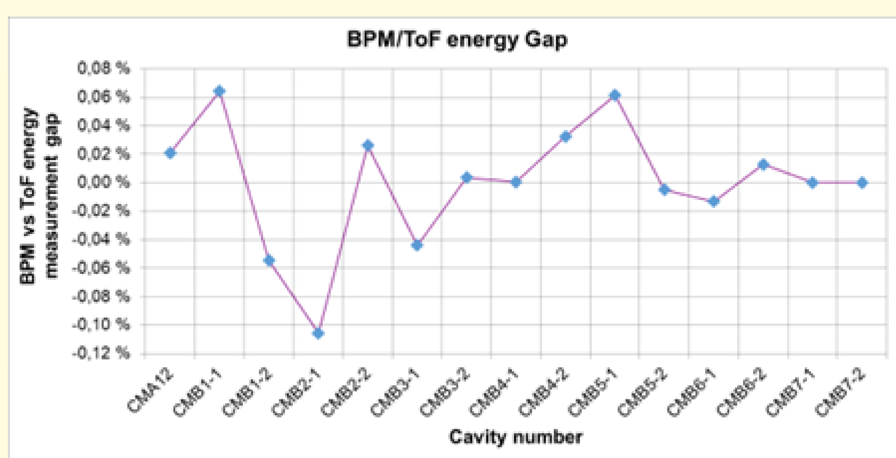
h1 and h2 positions and ellipticities from the 20 BPMs

Amplitude calculations taking the measured beam intensity with an ACCT and the bunch lengths given by the TraceWin code are compared with the measured h1 and h2 amplitudes.



The calculated and measured curves are close and validate the VS amplitude equations.

In July 2021, with a helium beam at 40 MeV, beam energies were measured using the Time of Flight monitor (ToF) located at the linac exit to check the BPM measurements.




The figure shows that from cavity 12 the energy differences are relatively small.

Energy differences between BPMs and ToF

## CONCLUSION

After various optimizations, the BPM systems meet the requirements and allow an optimal setting of the linac. The position and ellipticity sensitivities are calculated and applied for each new beam according to the theoretical velocity parameters. The calibration and stabilization systems allow to obtain a very good precision, big thanks to the BARC team which conceived and provided these systems. The next actions concern the development of a "Post-Mortem" system of data storage with an acquisition rate of 10 µs, an improvement of the bunch length measurements, an automation of the calibrations and an increase of the sensitivity towards the very low levels.