

## DISCHARGE MEASUREMENTS AT LA RANCE TIDAL POWER PLANT USING CURRENT METERS METHOD

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### ABSTRACT

La Rance was the first tidal power plant worldwide with a capacity of 240 MW supplied by 24 bulb units working in both flow directions. Many tests had been undertaken in laboratory and on the prototype of Saint-Malo, but no real commissioning tests had been carried out until now. Measuring discharge at La Rance is indeed complex because of a very low and changing head from 2 m to 11 m depending on the tides, large gate bays of 8.7 m on 8.8 m, and high flow rate variations from 75 m<sup>3</sup>/s to 280 m<sup>3</sup>/s. It was decided to use current meters on a moving frame in the bulkhead slot for flow rate measurement. Further challenge was to maintain an almost constant head of 4 m during data acquisition. Full exploration of the velocity field was completed in both directions in 6 vertical positions. Additionally cam tests were performed, using index measurement with the frame in the middle position.

### INTRODUCTION

The Rance Tidal Power Station is the world's first tidal power plant and also the world's second biggest tidal power plant (recently the second, but the first for a long time). The facility is located on the estuary of the Rance River, in Brittany, France, near the town of Saint-Malo. It was commissioned in 1966. With a peak rating of 240 MW, generated by its 24 bulb turbines, it supplies an annual output of approximately 540 GWh. Thus La Rance was the first power plant to produce massive energy from tidal power.

In the 50s and 60s, many of studies were carried out and model turbines were tested before the initiation of the construction of the power plant to ensure the best efficiency design for these new generation bulbs. In particular a model turbine was built on site in Saint-Malo on which performance tests were performed. But until now, no efficiency tests have ever been carried out on La Rance units.

Cam tests for high head were realized in 1999 and potential efficiency gains at low head were identified. The classical method for index flow measurement is not possible at La Rance because no pressure taps are available for differential pressure measurements. In 1999, field tests were carried out by exploring the index flow rate with one current meter and one Pitot tube.

Based on the previous experience, it was decided in 2013 to realize an absolute discharge measurement. Among all discharge measurement methods, the only IEC Standard 60041 code approved method for very short intakes is with current meters. However, a special structure was necessary to measure high velocities in a large intake in both flow directions.

This paper presents the important details of the performance tests and evaluation carried out by etaeval and EDF-DTG teams on unit C11 in LA RANCE for a 4-meter head. Special attention was given to the design of the frame and the absolute and relative discharge measurement.

## 1 TIDAL POWER PLANT'S OPERATION CYCLE

La Rance estuary has among the highest tides in the world: 8.2 meter on average with a 13.5 meter peak. A dam was built in the estuary, creating a reservoir. Operating in both directions, the dam creates a difference of water levels inducing a flow, which can pass through the turbines twice a tide (during the incoming and outgoing tidal flows). An orifice mode is also available for low head while not producing electricity.

A brief description of the scheme is given, explaining “one-way” and “two-way” tide cycle utilization.

### 1.1 « Simple effect » – ebb generation

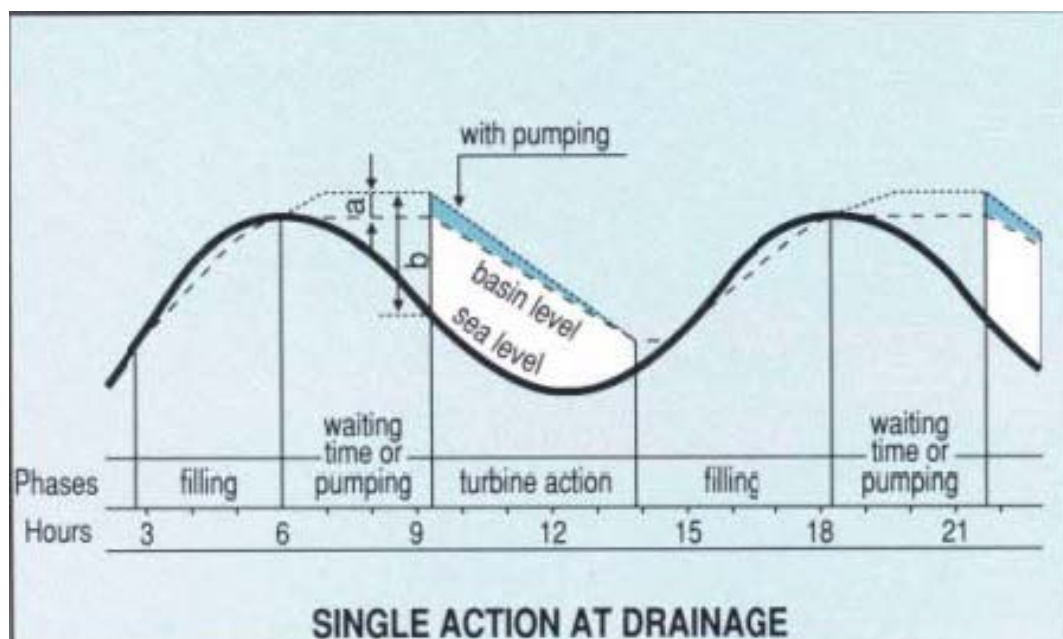


Figure 1 – Ebb generation

In this cycle, water flows through the turbine from the basin to the sea, see Figure 3. The maximum flow rate for each 10 MW unit is about 260 m<sup>3</sup>/s for a head of 4 m in direct turbine mode.

## 1.2 « Double effect » – ebb and flood generation

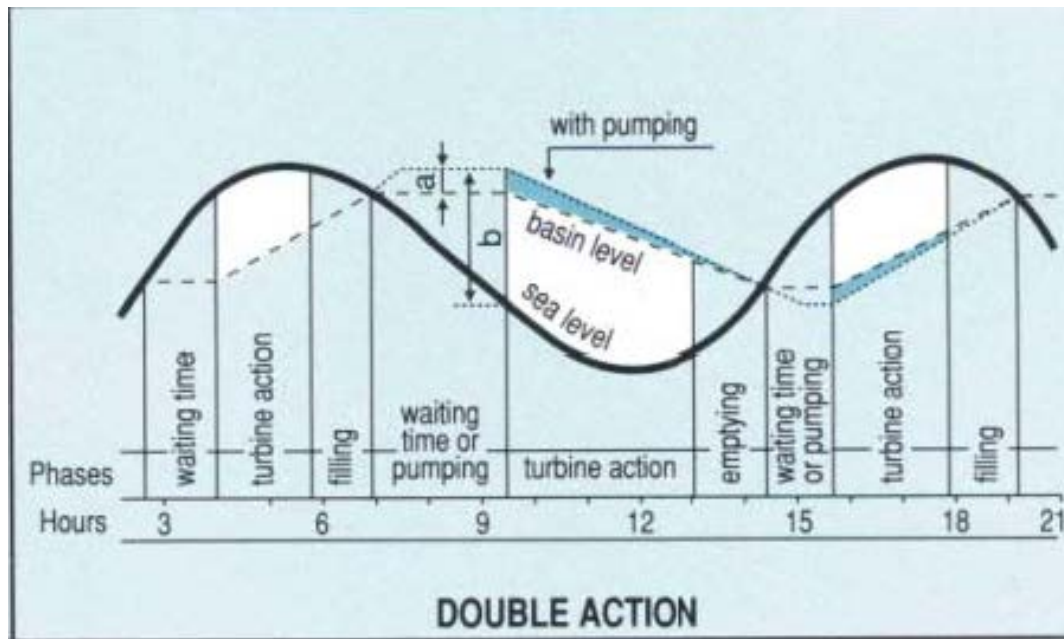


Figure 2 – Flood and Ebb generation

In this cycle, flow passes the turbine from the basin to the sea and from the sea to the basin. The maximum flow rate is about  $220 \text{ m}^3/\text{s}$  for a head of 4 m in reverse turbine mode and  $280 \text{ m}^3/\text{s}$  in reverse orifice mode.

Ebb generation (direct turbine mode) covers 60 % of operations. Flood generation (reverse turbine mode) covers 2 to 6 % and direct pumping 15 to 20 %. The remaining time, water flows freely through turbine orifices.

In order to have a constant head of 4 m during field tests, it was necessary to adjust the production program to maintain equal level variation in basin and sea. That was only possible during a two hour period, so that two consecutive tidal cycles were necessary to perform the entire field tests.

## 2 DESCRIPTION OF THE MEASUREMENT CAMPAIGN

The measurements included absolute measurements in turbine (flow direction from basin side to sea side) and in orifice modes (flow direction from sea side to basin side). Additionally, index measurements (cam tests) were performed in turbine mode. EDF-DTG performed measurements of generator power, of head, guide vane position and turbine blade position, while etaeval was carrying out the velocity measurements with current meters. With all the acquired data turbine efficiencies could be evaluated.

For the absolute discharge measurements in turbine and orifice mode, six positions (elevations) with the current meter frame and accordingly 24 measuring points each were measured, see Figure 4, resulting in a total of 112 velocity data. For the index measurements one position in the middle of the measuring section was selected to speed up the measurements. Thus the index flow was based on 24 measuring points. This index data could be attributed to an absolute flow rate, thanks to the previously performed full tests in the entire cross section.

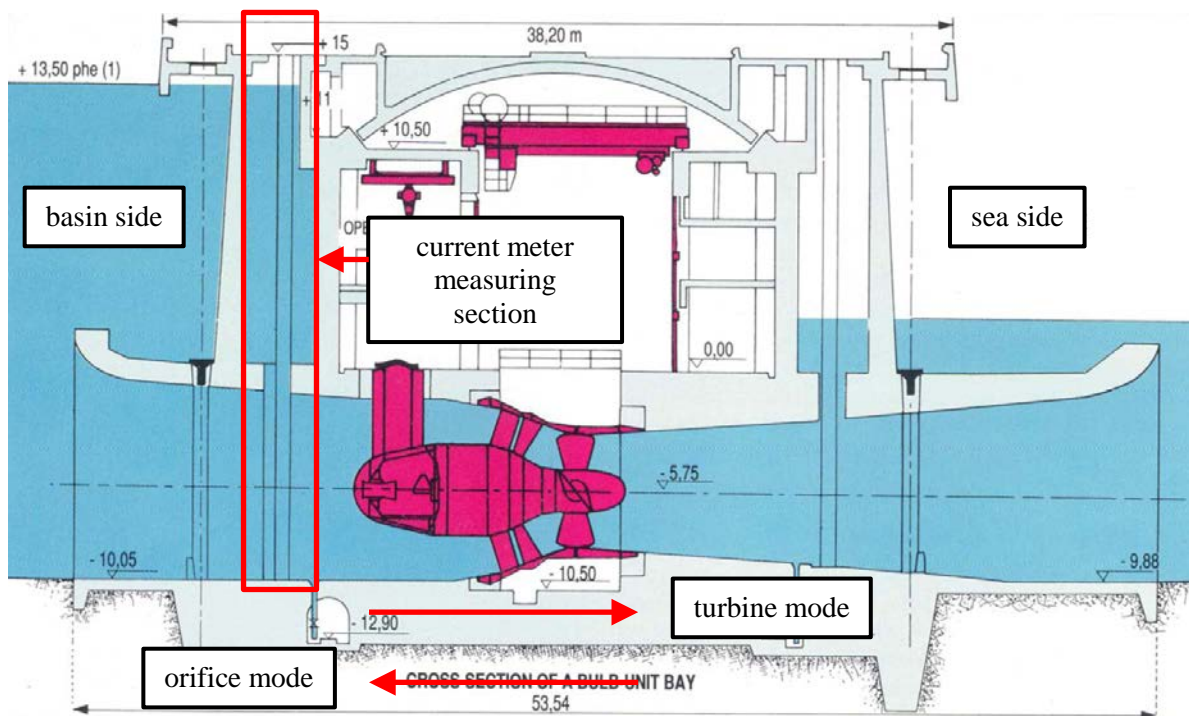


Figure 3 – Cross section through turbine water way of the Tidal Power Plant La Rance

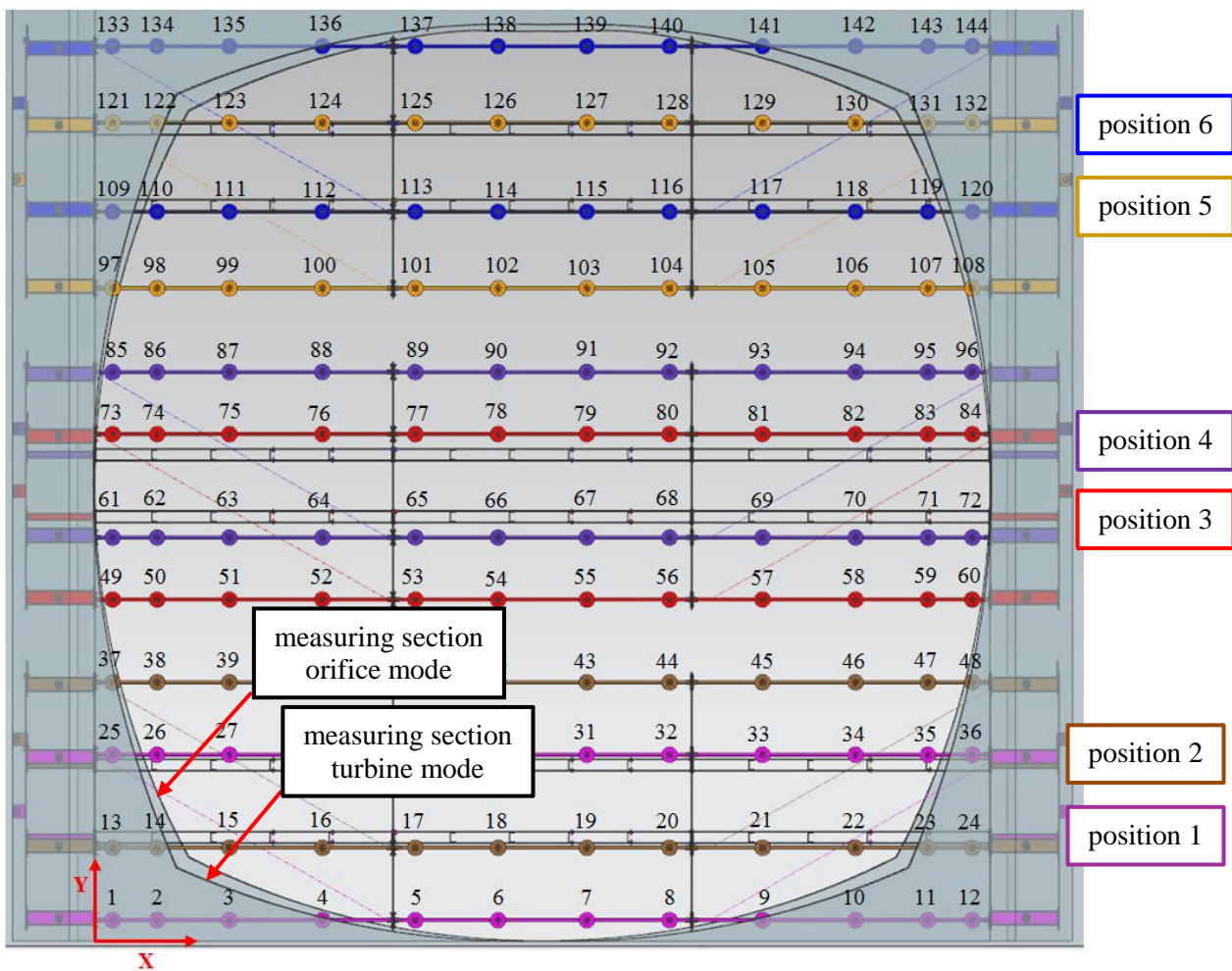


Figure 4 – Cross section at current meter section of the Tidal Power Plant La Rance

### 3 DESIGN OF THE CURRENT METER FRAME

The design of the frame for the current meter flow measurements includes essentially two different parts. The first part (marked in red in Figure 5) is a steel frame comprising the two boxes with mounted wheels, which are sliding in the bulk head slots. The central beam is designed for low drag forces and high mechanical resistance. It is fixed to the side boxes and the middle plates. The central beam is the core of the frame because it takes all forces of all parts exposed to the flow. The middle plates are the support of current meter profiles. Two steel cables provide additional stiffness in vertical direction and add damping to the frame.

The second part includes the current meter profiles manufactured in aluminum, which are mounted on the base construction with profile shoes. 12 Ott component current meters are mounted on each of the two horizontal measurement lines. For the change of the flow direction the profiles including the profile shoes and the current meters can be rotated by 180 degrees without disassembling the frame completely.

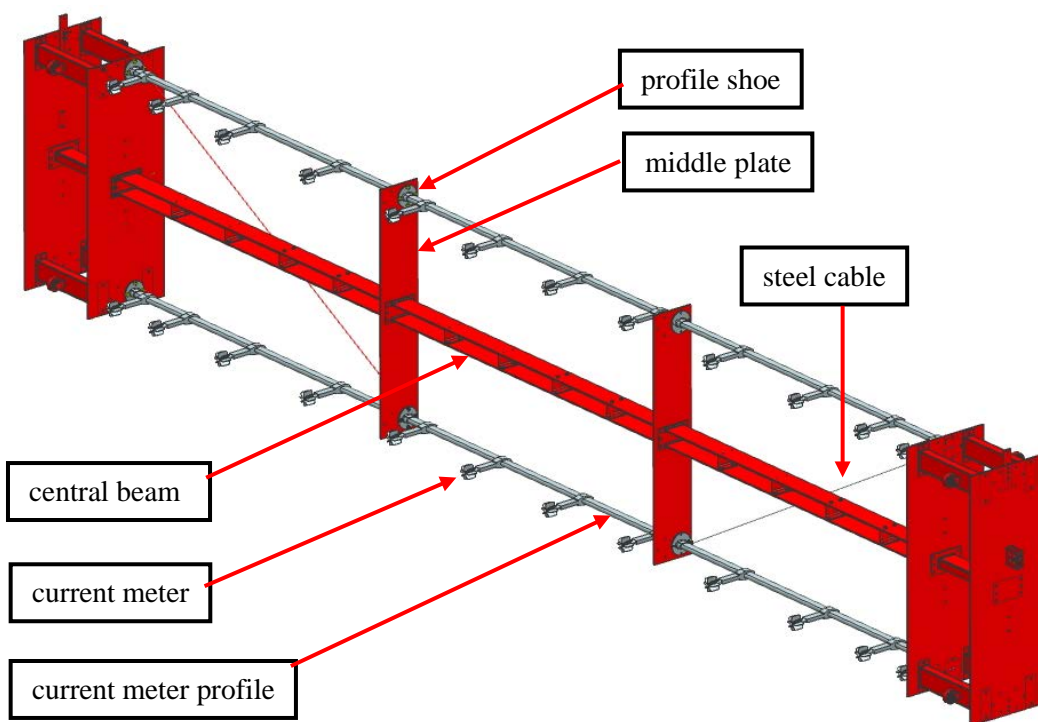


Figure 5 – Current meter frame for HPP La Rance

Before manufacturing the frame, a calculation for the static and dynamic loading was carried out. The static loading encompasses the weight of the elements and the fluid forces. The dynamic loading stems from the turbulence and vortex shedding behind upstream elements of the structure and eventually from pressure pulsations induced by the blade passing frequency of the machine. The most important element was to ensure that none of the mechanical eigenmodes of the structure might be excited.

The following frequencies were taken into account:

- Kármán vortex streets with the corresponding Strouhal numbers
- Blade passing frequency of the turbine
- Eigenfrequencies of the current meter profiles and the frame

The eigenfrequency of the current meter profile is far below the excitation frequencies of the Kármán vortex street and consequently no resonance had to be expected. Also, since the

eigenfrequency of the current meter profile is considerably higher than the blade passing frequency no resonance will occur. A possible excitation during starts or shut down at the low flow velocities was not considered as problematic.

#### 4 RESULTS OF CURRENT METER MEASUREMENTS

The absolute flow rates were calculated by integrating the differences between CFD-simulated velocities and the measured point velocities. The advantage of such integration of the velocity differences is that the near wall zones are correctly described in CFD and extrapolation (normal procedure according to ISO 3345:2008) becomes needless. The CFD simulations were performed for the exact geometry of the measuring sections and fulfill the law of conservation of mass. The mean velocity is then determined by dividing the flow rate through the area (which was slightly different for turbine and pump mode as can be seen from the contour of the measuring section in Figure 4).

The index velocity results from the cubic integration of the 24 measuring points in the middle position divided by the width. The factor listed in the table 1 and 2 is defined as follows:

$$\text{Factor} = \text{Discharge divided by the index velocity} \quad (1)$$

Table 1: Results for the absolute turbine mode discharge measurements

Measurement point	Index velocity	Mean velocity	Area	Discharge	Factor	
	[m/s]	[m/s]	[m <sup>2</sup> ]	[m <sup>3</sup> /s]	[m <sup>2</sup> ]	
ab_tm_1	3.197	3.175	67.104	213.054	66.650	
ab_tm_2	2.175	2.154	67.104	144.574	66.471	
ab_tm_3	2.173	2.158	67.104	144.825	66.641	
					66.588	Mean factor

Table 2: Results for the absolute orifice mode discharge measurements

Measurement point	Index velocity	Mean velocity	Area	Discharge	Factor	
	[m/s]	[m/s]	[m <sup>2</sup> ]	[m <sup>3</sup> /s]	[m <sup>2</sup> ]	
ab_oi_1	2.253	2.971	66.538	197.710	87.758	
ab_oi_2	2.073	2.738	66.538	182.199	87.913	
					87.835	Mean factor

Although the discharge in turbine mode varies by approximately 32 % (see Table 1, from 213.05 m<sup>3</sup>/s to 144.70 m<sup>3</sup>/s) the ratio between the discharge and the index velocity (factor) remains almost constant. This indicates that the velocity distribution is self-similar over a wide operating range, as demonstrated with an example in Figure 4. On the basis of this finding the index velocities could be scaled to an absolute flow rate.

Although the velocity distribution in orifice mode is very non-uniform due to the wake flow downstream of the bulb and the swirling flow behind the machine, the described ratio appears also to be constant in the orifice mode for the tested operating range, see Table 2.

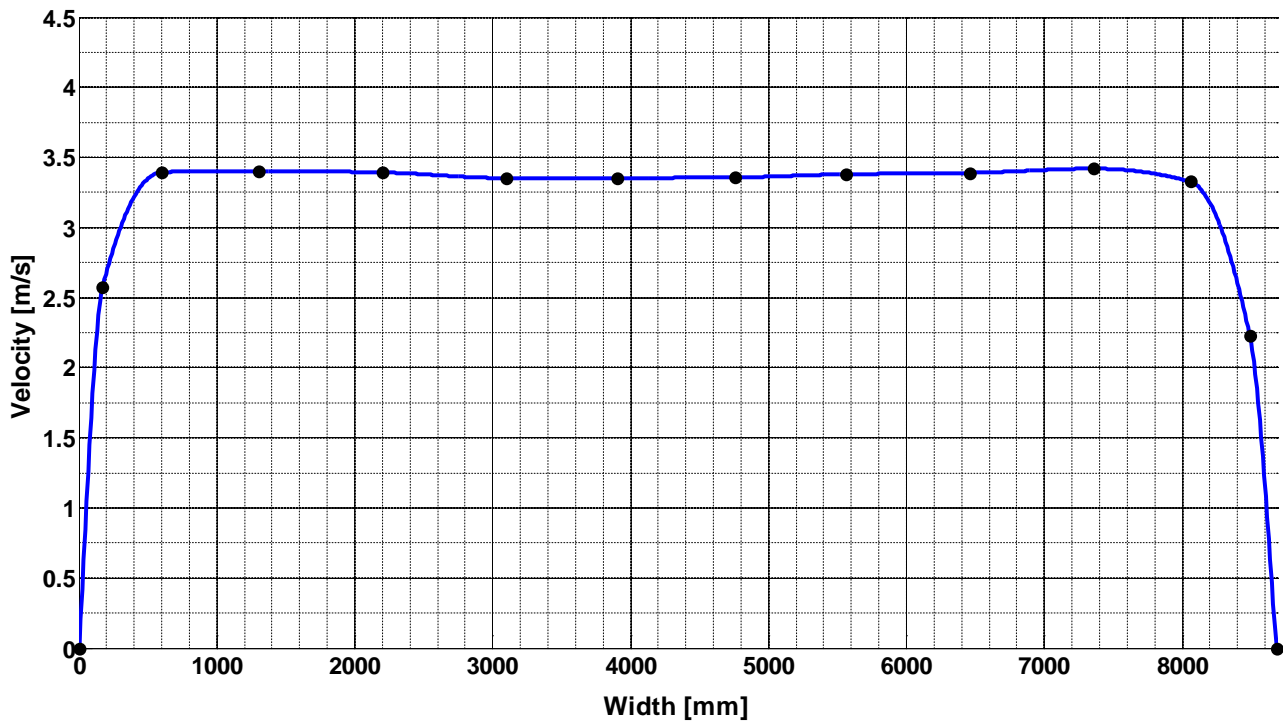


Figure 6 – Typical velocity distribution in turbine mode for index efficiency measurements

Thus the index velocity can be used to calculate an absolute discharge for the index measurements (cam tests) using the above-defined mean factor. Therefore, an absolute efficiency can be calculated for the index measurements, as well.

With the chosen methodology of integration supported by CFD a calculated relative measurement uncertainty of 0.92 % for the discharge in the turbine mode was estimated. Due to the presence of the wake effect and of swirling flow in the orifice mode, the calculated relative measurement uncertainty of the discharge became 1.82 %. The repeatability of the discharge measurements showed to be excellent and lay in the order of 0.1 %.

## 5 RESULTS OF CAM TESTS

To obtain optimum performance from double regulated bulb turbines, the proper guide vane to runner blade relationship has to be adjusted. Such an optimization, also called cam tests, consists in determining the optimum dependence between the opening angles of the guide vane and of the runner blades so that the unit is operating at maximum efficiency for a given head and discharge.

In first step propeller curves were measured by fixing the runner blades angles and changing the guide vane position. Such curves were determined for 7 different runner blade angles. The envelope around the measured propeller curves allows assigning to each runner blade angle the optimum guide vane opening.

The net head was calculated from the difference of the sea and reservoir levels, which were measured in bulkhead grooves and from the difference of the kinetic energy at the inlet and outlet of the turbine.

For each operating point the following parameters were measured:

- Guide vane opening (in percent of total opening) with an accuracy of 1%;
- Runner blade inclination (in percent of total opening) with an accuracy of 1%;
- Sea level at bulkhead groove with an accuracy of 2 cm;
- Basin level at bulkhead groove with an accuracy of 2 cm;

- Electrical power with an accuracy of 1.1%;
- Flow rate with current meters with an accuracy of 0.92 % in turbine mode.

Figure 7 depicts the configuration of measuring equipment for cam tests.

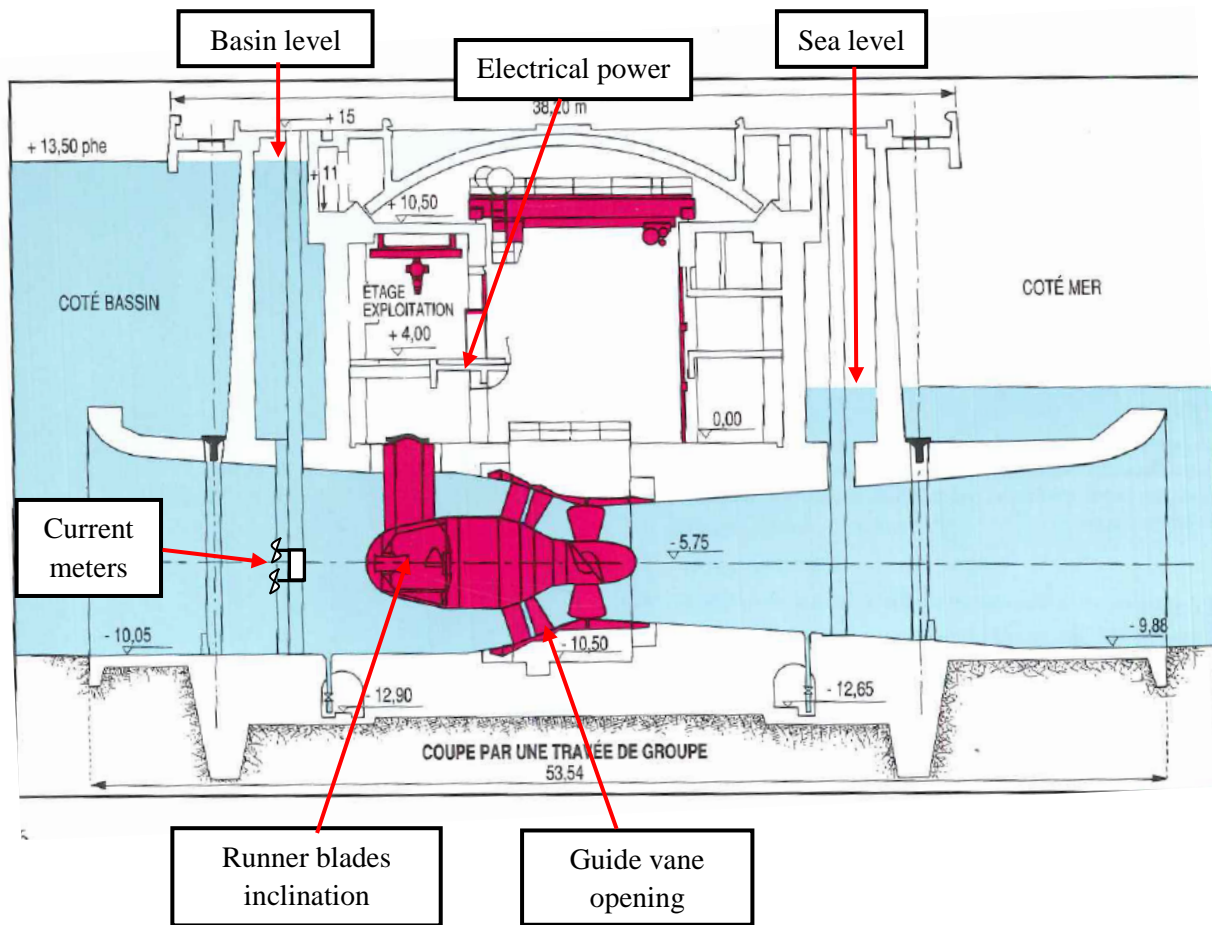


Figure 7 – Unit's instrumentation for cam tests

For cam tests, it is sufficient to measure not the absolute but the index flow rate. Such index flow rate measurements can be performed with an appropriate differential pressure measurement. Unfortunately, La Rance is not equipped with such pressure taps. A first idea was to replace the cathodic protection probes by pressure taps, as shown in Figure 8. However, the low pressure section was too close to the runner and no relevant differential pressure acquisition was possible. Finally, it was decided to use the current meters method.

The duration of the tides was too short to measure absolute discharge for each of the approximately 100 operating points with current meters. One absolute discharge measurement requires indeed about 20-30 minutes, while only 2 hours are available for the measurement with a constant head. As consequence it was decided to measure for the cam tests only with 24 current meters in the mid position.

As mentioned above, a special production program allowed keeping a constant gross head for the entire HPP from the lock sensor. The gross head for HPP remained at about 4.5 m except for some acquisitions for which head reached 4.17 m (see Figure 9).

The basin level is not flat from bank to bank. Gross head was also measured for group C (C9-C10-C11-C12 units). The head was 4.4 m on average with a fluctuation of about  $\pm 0.2$  m (4.5 %).



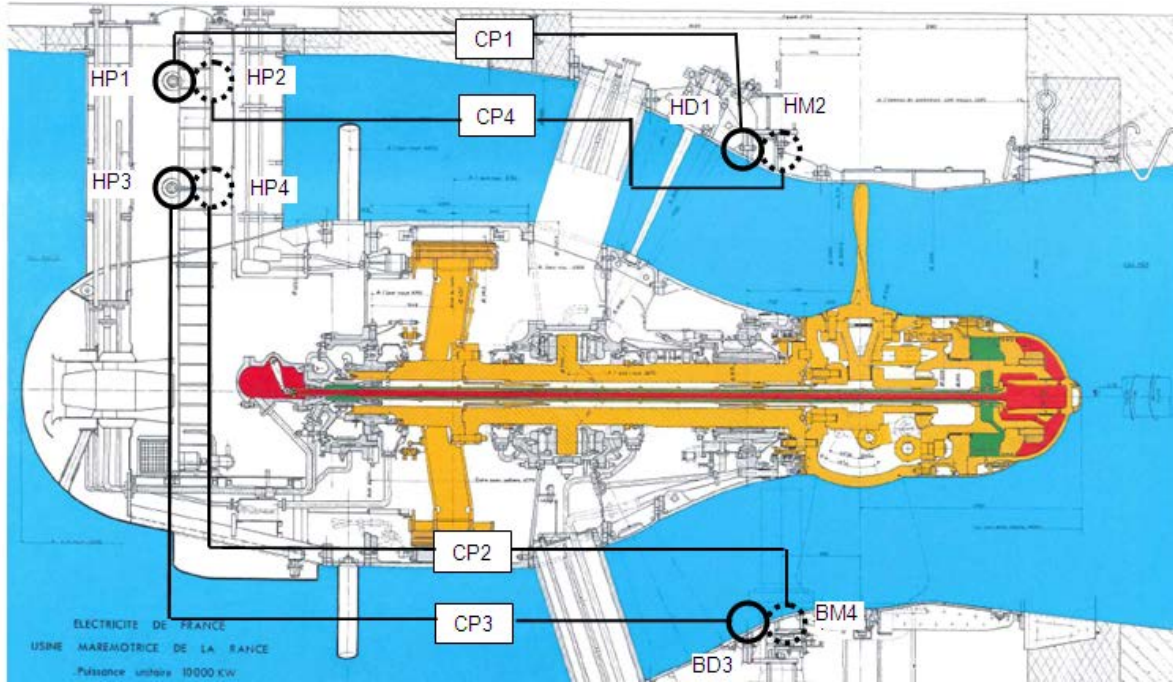


Figure 8 – Pressure tap location for index measurements (unsuccessful solution)

Net head fluctuated between 3.25 and 4.32 m (see Figure 10). However, for each propeller curve measurement, net head difference between the existing cam point and optimum point did not exceed  $\pm 0.12$  m (3.4%) (see Table 3).

Table 3: Net head variation between optimum and on-cam point

On existing cam point	Net head (m)	Optimum point	Net head (m)	Difference (%)
H1c	3.96	H1-4	4.06	2.5%
H2c	4.32	H2-3r	4.30	-0.5%
H3c	4.11	H3-2	4.12	0.2%
H4c	3.88	H4-3	3.83	-1.3%
H7c	3.76	H7-2	3.86	2.6%
H8c	3.82	H8-3	3.76	-1.6%
H9c	3.66	H9-2	3.54	-3.4%

All results are computed for the net head using equations (1) and (2):

$$Q_{4m} = Q \cdot \left( \frac{H_{4m}}{H} \right)^{1/2} \quad (1)$$

$$P_{out4m} = P_{out} \cdot \left( \frac{H_{4m}}{H} \right)^{3/2} \quad (2)$$

Where  $Q$  is the absolute discharge ( $\text{m}^3/\text{s}$ ),  $P_{out}$  the electrical power (MW) and  $H$  the net head (m).

Cam curves for a 4-meter net head are presented in Figure 11.

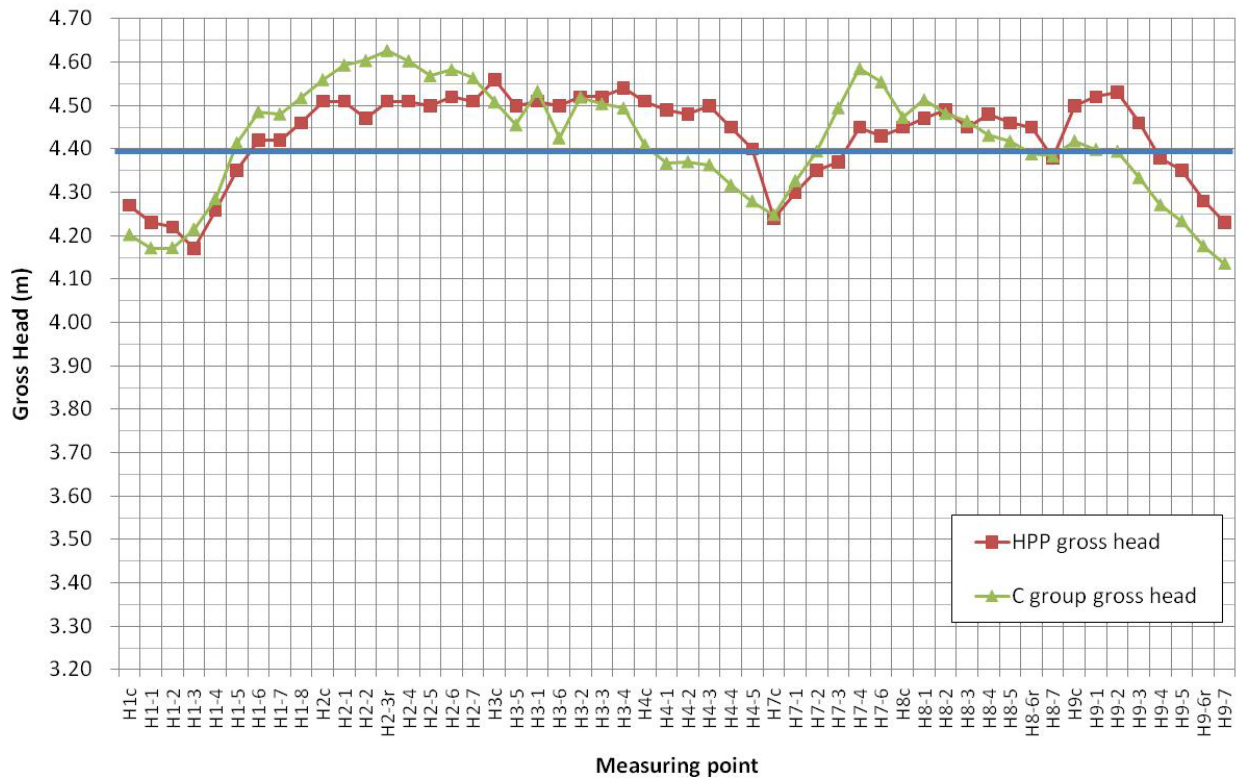


Figure 9 – Gross head evolution

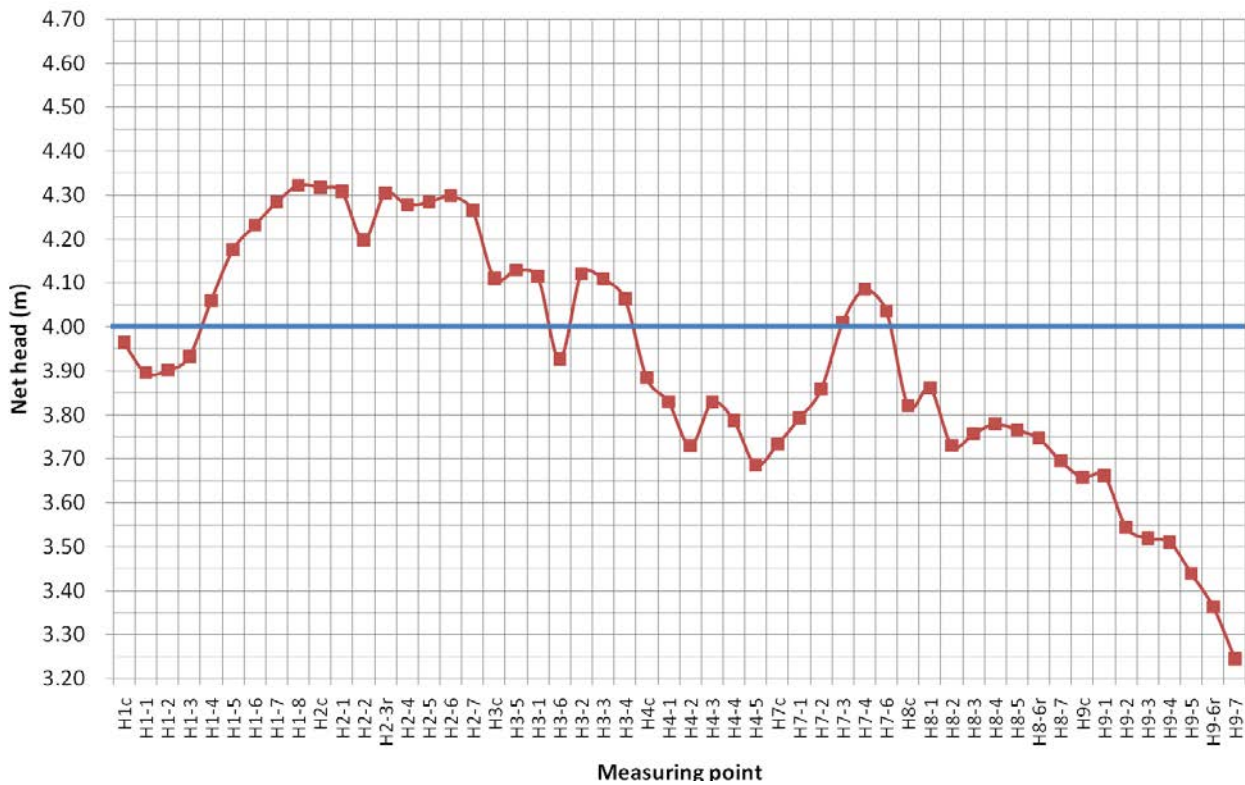


Figure 10 – Net head evolution

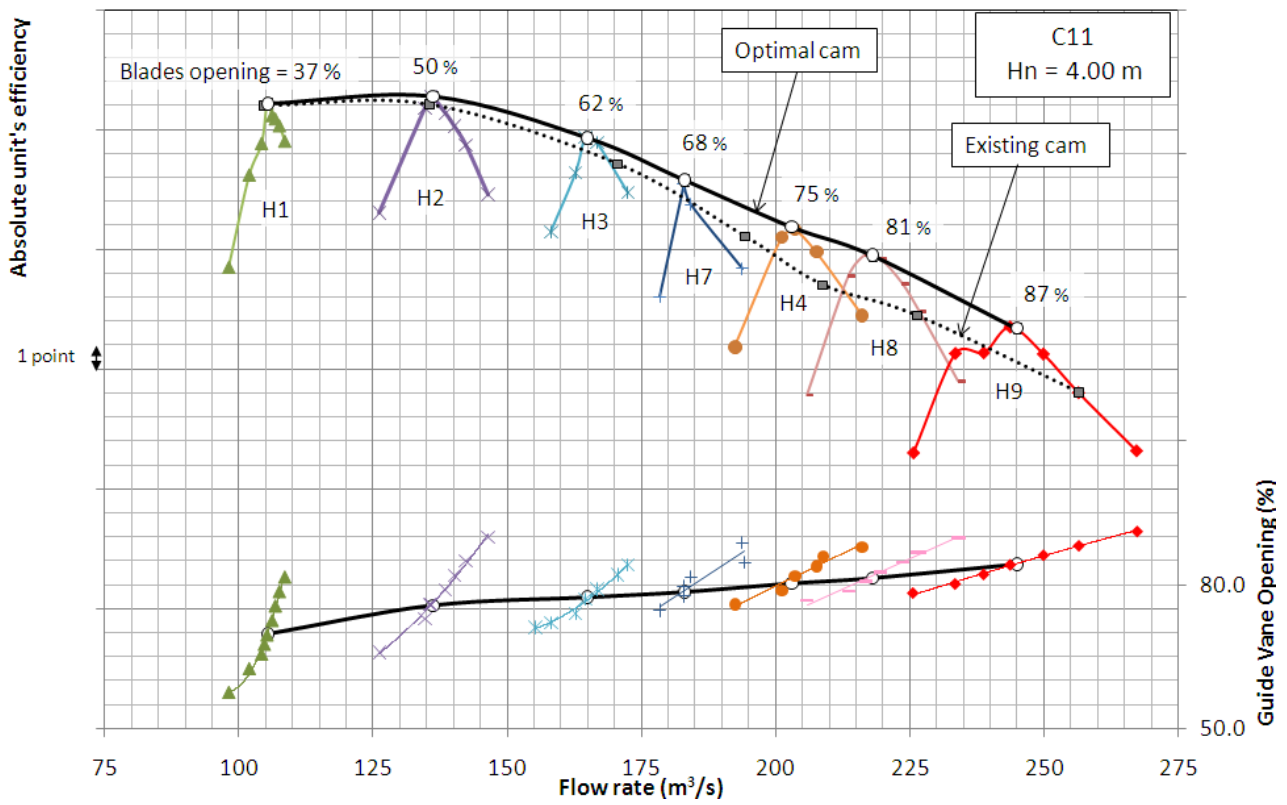


Figure 11 – Efficiency for broke-off cam combination (propeller curves) with the envelope curve defining optimum values

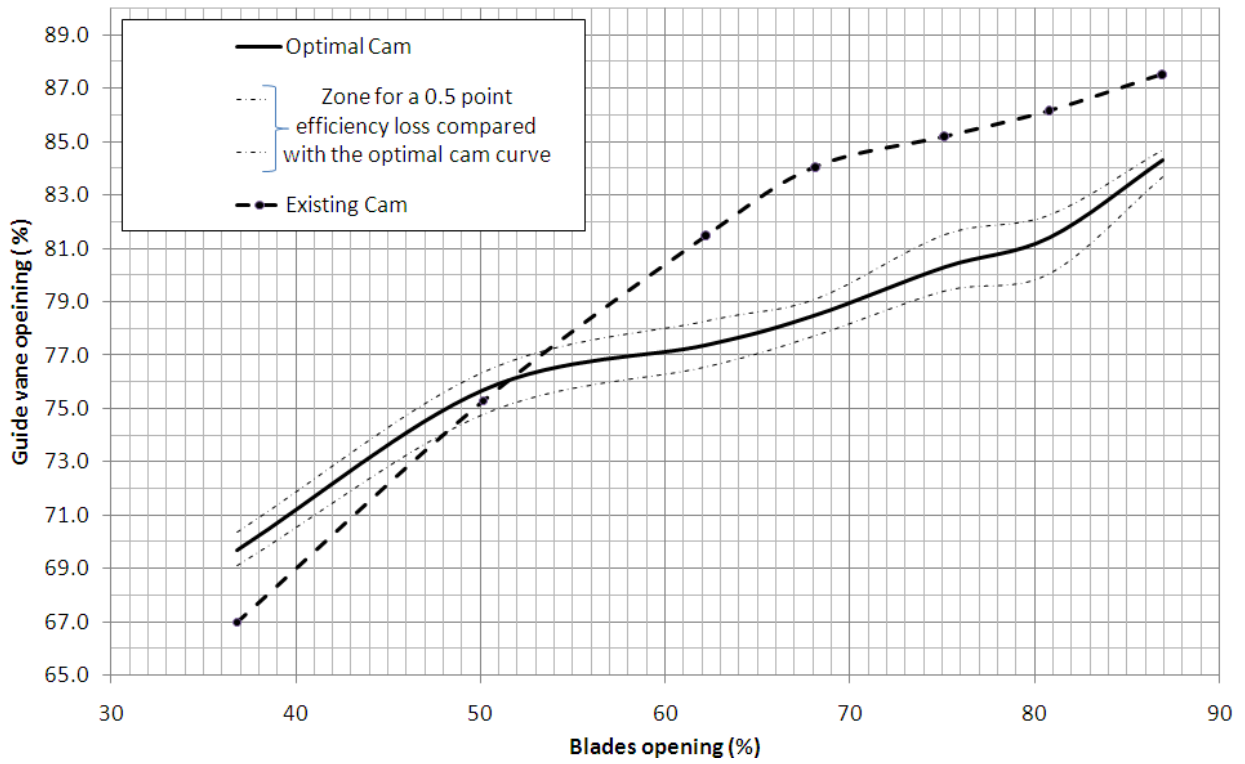


Figure 12 – Existing and optimum cam combination

For index measurement, uncertainty is derived from random uncertainty only. The systematic uncertainty can be assumed to be constant for flow rate variations. The random uncertainty of the flow rate was determined to be 0.33 %. It is the mean standard deviation of several acquisitions at the same point.

Figure 11 shows that efficiency could be increased by up to 2 percent with the optimized cam relation for the head conditions of the field tests. This is achieved by a 0 to 6 % smaller guide vane opening compared to the existing cam (Figure 12).

## 6 CONCLUSION

La Rance Tidal Power Plant is a complex place for flow rate measurement as the head keeps changing and the intake is very short. Measuring a relative flow rate was not possible because no such pressure taps for index measurements were considered during the construction of the power plant. New pressure taps were installed at the positions of the existing cathodic protection system, but differential pressures were too small and no accurate relationship between the differential pressure and relative flow rate could be obtained.

A special movable structure was then designed to fix 24 current meters and to explore the basin-side bulkhead cross section in the two directions of flow. The absolute flow rates are calculated by integrating the differences between CFD-simulated velocities and the measured point velocities to reduce the integration error. Good results have been achieved in this way with an estimated uncertainty of 0.92 % in direct turbine mode and 1.82 % in reverse mode.

With this structure, cam tests could also be performed by measuring velocities in the mid position of the bulk head cross section with 24 current meters. Discharge has then been calculated using a factor between index velocity and absolute flow rate. Only two consecutive tides and a duration of 4 hours were needed to complete cam tests for one head.

Results show that turbine efficiency could be improved for high flow rates by about 2 percent with a better relation of guide vane and runner blades openings. This finding enables the power plant operator now to optimize the production of the tested and all the other 23 units.

## REFERENCES

- [1] Standard IEC 60041. *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump turbine*. IEC, 3<sup>rd</sup> edition, 1991.
- [2] EDF-DTG, A. Reymond. *LA RANCE – Groupe n°E19 – Détermination de la conjugaison optimale sous 5,80 m et 7,50 m*, 1999.