STATUS REPORT ON THE FRENCH HIGH-INTENSITY PROTON INJECTOR PROJECT AT SACLAY (IPHI)

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Abstract

The construction of IPHI (High Power Proton Accelerator) is in its final step of installation. The high intensity light ion source (SILHI) has been built first to produce regularly CW high intensity (over 100 mA) proton beams. The low energy front end of IPHI is based on a 352 MHz, 6 m long Radiofrequency Quadrupole (RFQ) cavity. The RFQ will accelerate beam up to 100 mA with energy up to 3 MeV. A diagnostics line has been built to measure all the main characteristics of the beam at the RFQ output. In this paper we will present the status for the main components of the injector, in particularly the RF power facility, the RFQ fabrication, and the RF tuning.

STATUS OF THE INSTALLATION

Source and Diagnostics Line

The ECR source (2.45GHz, 100keV) is for some years producing routinely beam currents of 130 mA. The beam is used to optimize diagnostics for high energy and to develop new non interceptive diagnostics [1]. The beam diagnostics will allow the characterization of the beam accelerated by the RFQ. The diagnostics line is completely assembly and in vacuum. Every diagnostics were tested and operational.

RF Power Facility

The RFQ will be now powered through four RF ports (instead of three in the previous design). This power is provided by two equally loaded 1100kW klystrons. The two klystrons (1100 kW) have been conditioned (CW operation with matched water cooled load). The conditioning duration was two hours for High Voltage only and one day for Radiofrequency.

The four RF windows have been conditioned by pair in standing wave operation (full reflection) at a maximum 550kW 300µs square pulse (10Hz rep. rate) and 250kW CW direct power, the reflected power being dissipated into the circulator load.

RFQ

The IPHI RFQ, 4-vane RFQ, made up of 6, one-meter module assembled in three coupled segments by two coupling plates. Each module is machined in four parts (the vanes) which are brazed together. The final precision (10µm) required is close to the limit of what is possible to manufacture using the technology available today with machining and brazing. After different tests, the brazing in vertical position and in one step was chosen.

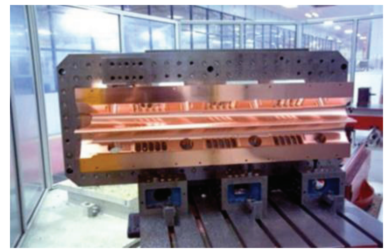

Figure 1 : Final machining of one RFQ's major vane

The method defined is: deep drilling for cooling channels (1 m long with a maximum deviation about 0.4 mm), rough machining (residual skin: 1 mm), annealing, semi-final machining (residual skin: 0.2 mm), RF control, final machining (Fig. 1), cleaning (chemical polishing), assembling, RF checking, brazing, RF control and vacuum test.

The brazing temperature is about 800°C. The required time for brazing is about 36 hours which include warming and cooling time. The RFQ ready for brazing inside the furnace is shown in Figure 2.

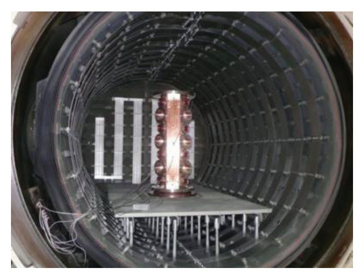

Figure 2: The RFQ in vertical position in the furnace

RF Control of RFQ Modules

RF properties of RFQ modules are carefully controlled after each fabrication step (assembly, 1st braze, etc.). Inter-vane voltages are deduced from bead-pull measurements, and the RFQ 4-wire transmission line model is used to estimate departure of electrical parameters from theoretical values. There are 10 such parameters: 4 parallel inductances, 4 parallel capacitances and 2 diagonal capacitances. However voltage and voltage-slope (the analogue of current for a transmission line) carried by a 4-wire system are dim. 3 vectors (one quadrupole component "Q" and two dipole components "S" and "T"), hence only three parameters may be estimated. Observing that voltage perturbations result primarily from axial region misalignments hence from capacitance errors, and using first-order perturbation analysis, these three parameters are $C_{QQ} = (C_1+C_2+C_3+C_4)/4$, $C_{SQ} = (C_1–C_3)/2$ and $C_{TQ} = (C_4–C_2)/2$ (where the

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C_i's are inter-vane parallel capacitances). The method is able to discriminate a few 10^{-3} relative errors (Fig. 4).

RF TUNING

Strategy of Tuning

Electrical parameters of end-circuits and coupling-circuits must ensure that the desired voltage profile may be obtained at the end of slug tuning process [2]. Desired values of Q-related coefficients are deduced from accelerating voltage profile V(z). End-circuits should satisfy $(s_{end1})_{QQ} = -(\partial_z V)/V|_{end1}$, $(s_{end2}) = -(\partial_z V)/V|_{end2}$. Each coupling-circuit #i (i = 1, 2) should satisfy tuning condition $(s_{cci})_{\Sigma\Sigma} = (\partial_z V)/V|_{cci}$, matching condition $(s_{cci})_{\Delta\Sigma} = 0$, and coupling capacitance requirement C_c = 1.1 pF (minimizing sensitivity to quadrupole-like perturbations). Q-related coefficients are tuned upon adjusting thicknesses of input plate (e_{end1}), thicknesses on either side of coupling plates (e_{cc1-}, e_{cc1+}, e_{cc2-}, e_{cc2+}), and length of quadrupole rods located on output plate (e_{end2}). Coupling capacitances are determined by gaps separating facing electrodes on either side of coupling-circuits, and cannot be adjusted in significant amounts without compromising beam dynamics.

S/T-related coefficients are determined in order to minimize sensitivity of RFQ voltage to dipole-like perturbations; they are tuned by adjusting lengths L_{end1}, L_{cc1-}, L_{cc1+}, L_{cc2-}, L_{cc2+}, L_{end2} of so-called dipole rods, located on end plates and on either side of coupling plates. The tuning process aims at fitting dipole modes frequencies directly, thus avoiding to consider the complicated variations of boundary conditions vs. dipole rod lengths [3].

Tuning Operations

All the modules are presently brazed and they are assembled to do the tuning (Fig. 3). Tuning operations are detailed in Table 1. Dipole rods modify dipole eigen-frequencies only, while quadrupole devices modify both dipole and quadrupole eigen-frequencies: tuning starts with quadrupole devices (using excitations set method [2]), and proceeds with dipole rods (using spectrum analysis). The excitations set method needs the structure under analysis to be stable, and dipole rods pre-tuning is required. Note that dipole spectrum and quadrupole devices tuning are carefully checked every time a new configuration of segments SG1, SG2, SG3 is assembled.

Figure 3: Modules assembled for tuning

Table 1: Tuning Operations

configuration	operations	method
SG1	dipole rods pre-tuning	spectrum analysis
SG1	end #1 plate tuning	excitations set
SG2	dipole rods pre-tuning	spectrum analysis
SG1-SG2	dipole rods pre-tuning	spectrum analysis
SG1-SG2	coupling plate #1 tuning	excitations set
SG3	dipole rods pre-tuning	spectrum analysis
SG3	end #2 plate tuning	excitations set
SG2-SG3	dipole rods pre-tuning	spectrum analysis
SG2-SG3	coupling plate #2 tuning	excitations set
SG3	dipole rods tuning	spectrum analysis
SG2	dipole rods tuning	spectrum analysis
SG2-SG3	dipole rods tuning	spectrum analysis
SG2-SG3	end #2, coupling #2 check	excitations set
SG1	dipole rods tuning	spectrum analysis
SG1-SG2	dipole rods tuning	spectrum analysis
SG1-SG2	end #1, coupling #1 check	excitations set
SG1-SG2-SG3	dipole rods tuning	spectrum analysis
SG1-SG2-SG3	local modes check	spectrum analysis
SG1-SG2-SG3	slug tuning check	tuning loop

Tuning Report

Tuned devices dimensions and values of Q-related coefficients are reported in Tables 2 and 3 respectively. General accuracy is a few 10^{-2} V/m/V. Coupling capacitances are found to be smaller than expected: stability analysis has been updated accordingly. Sensitivity to quadrupole-like perturbations will be about two time higher than expected (while remaining 1.4 time smaller than for an un-segmented structure).

Table 2: Tuned Devices Dimensions (in mm)

	end1	cc1–	cc1+	cc2–	cc1+	end2
quad. devices	20.00	11.61	6.76	10.12	6.77	41.4
dipole rods	145	150	150	151	140	102

Table 3: Tuned Values of Q-Related Coefficients

		required	achieved		
end1	s_{QQ}	0	$-5.46\ 10^{-3}$	($\sigma = 1.55\ 10^{-2}$)	V/m/V
cc1	$s_{\Sigma\Sigma}$	$+7.91\ 10^{-2}$	$+7.33\ 10^{-2}$		V/m/V
	$s_{\Delta\Sigma}$	0	$+9.29\ 10^{-3}$		V/m/V
	C_c	1.10	0.706	(±0.05)	pF
cc2	$s_{\Sigma\Sigma}$	$+1.304\ 10^{-1}$	$+1.07\ 10^{-1}$		V/m/V
	$s_{\Delta\Sigma}$	0	$+1.82\ 10^{-2}$		V/m/V
	C_c	1.10	0.934	(±0.05)	pF
end2	s_{QQ}	$+2.11\ 10^{-2}$	$+4.48\ 10^{-2}$	($\sigma = 1.24\ 10^{-2}$)	V/m/V

Table 4: Slug Tuning Test Summary

step	tu. pos. (mm)		freq. (MHz)	Q (%)	S (%)	T (%)
0	–4.80	+8.80	350.524 9	84.40	13.03	6.28
1	–1.57	+9.23	351.385 4	12.61	6.04	3.56
2	–0.53	+9.90	351.885 4	8.91	1.78	1.91
3	–0.69	+10.20	352.072 1	3.27	1.10	0.93

This RFQ is tuned to 3% voltage accuracy in 3 steps, with slug tuner positions between –4.8 and +10.2 mm (Table 4, Fig. 5 and 6); additional steps would of course improve accuracy, to the expense of somewhat larger tuner positions.

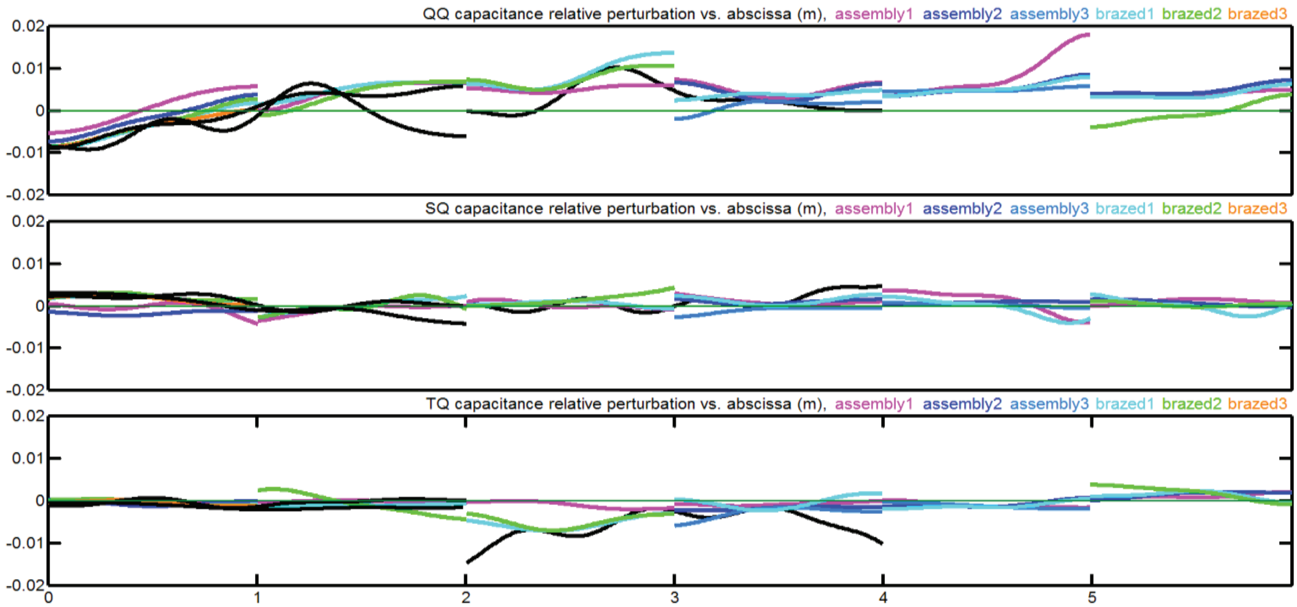

Figure 4: Capacitance relative errors vs. abscissa along RFQ and fabrication step (color code). Black traces apply to segments SG1 and SG2. The wavy shape of curves is due to limited bandwidth of analysis.

Quadrupole and dipole modes frequencies and quadratic frequency shifts (QFS) are reported in Table 5. QFS are seen to be virtually independent of accelerating mode frequency, as expected. QFS of modes closer to accelerating Q_{0+0+0} mode, which have larger impact on stability, are seen to be in good agreement with expected values.

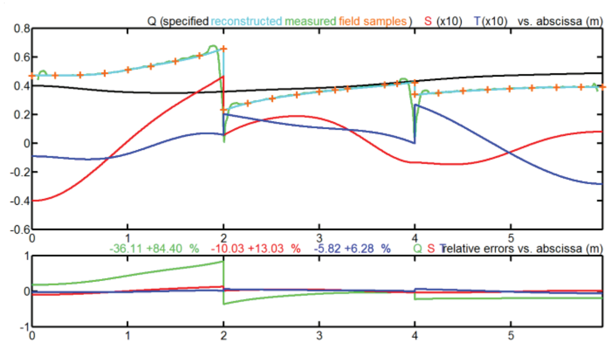

Figure 5: Voltage and voltage error at tuning step 0.

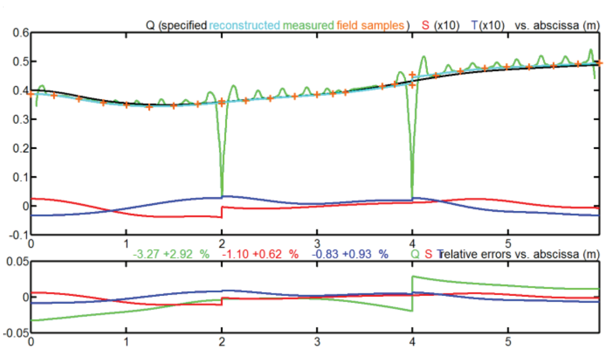

Figure 6: Voltage and voltage error at tuning step 3.

Table 5: Quadrupole and Dipole Modes Frequencies and QFS (Between Brackets). All Values in MHz

mode	model	step0	step2
Q 0–0–0	[–21.03]	347.55 [–22.7]	349.10 [–22.2]
Q 0–1–0	[–27.57]	349.30 [–29.0]	350.60 [–30.2]
Q 0+0+0	[0.00]	350.50 [0.0]	351.90 [0.0]
Q 1–1–1	[+55.07]	354.35 [+52.1]	not observed
Q 1+1–1	[+34.42]	357.25 [+34.6]	358.10 [+33.2]
Q 1+1+1	[+25.18]	358.25 [+24.7]	359.65 [+24.8]
mode	**model**	**step0**	**step2**
D 1–1–1	[–78.49]	342.00 [–76.7]	343.20 [–77.8]
D 1+0+1	[–59.69]	345.75 [–57.5]	346.50 [–61.4]
D 1+1+1	[–46.06]	347.60 [–45.0]	348.60 [–48.1]
Q 0+0+0	[0.00]	350.50 [0.0]	351.90 [0.0]
D 2–2–2	[+102.74]	361.40 [+88.1]	362.65 [+87.6]
D 2+2–2	[+116.40]	366.35 [+106.6]	367.05 [+104.4]
D 2+2+2	[+122.93]	368.50 [+113.8]	not observed

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