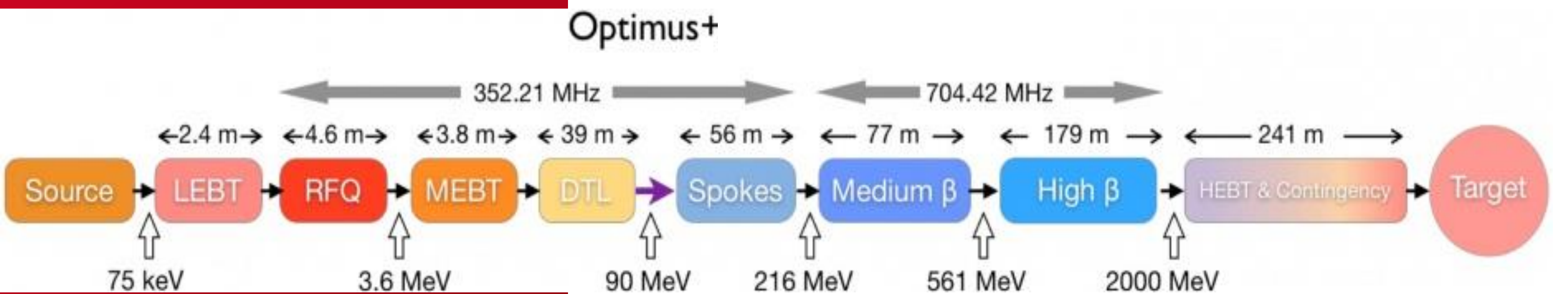
DE LA RECHERCHE À L'INDUSTRIE

THE RFQ COOLING CIRCUIT



TAC-15 | M. Desmons

5-7 APR. 2017

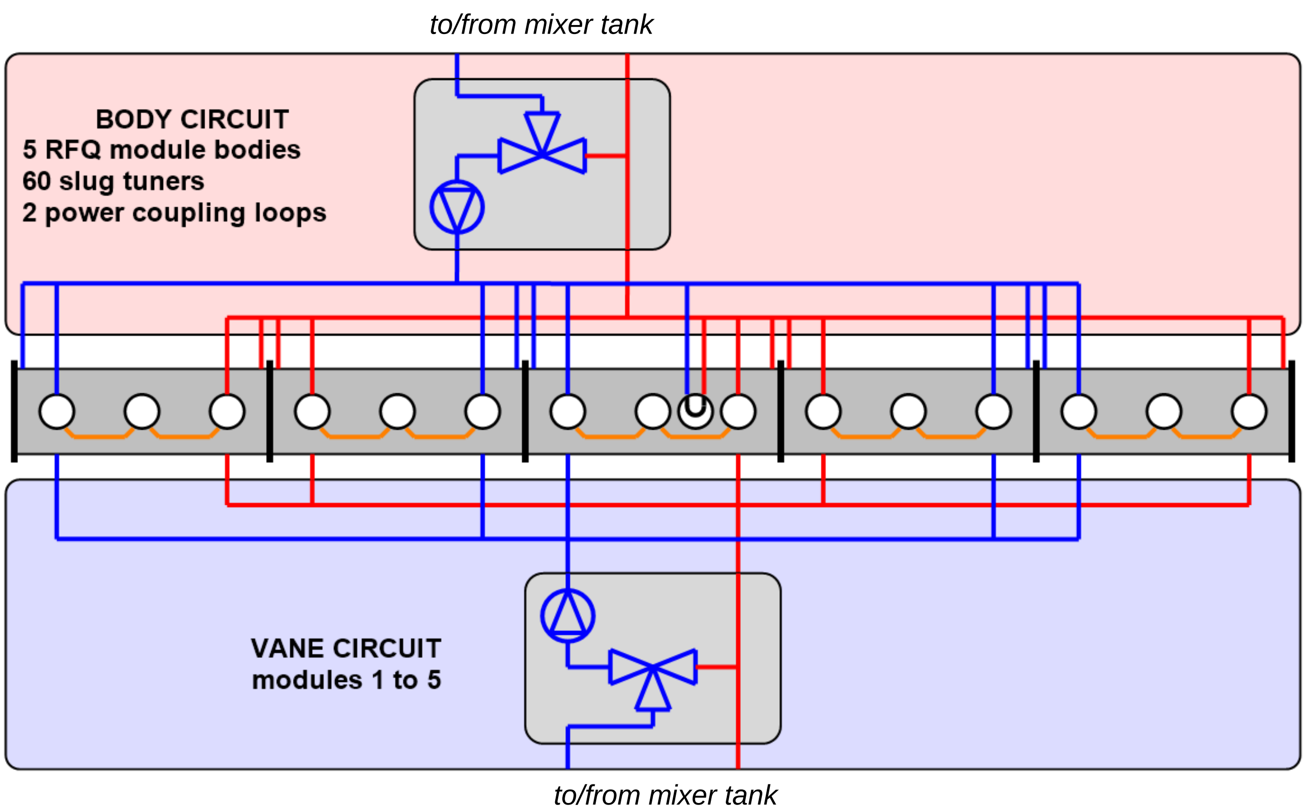
www.cea.fr

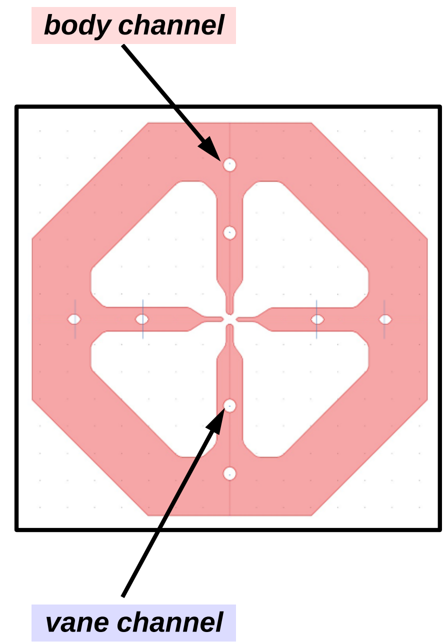
A SIMPLE COOLING CIRCUIT

The RFQ is the primary source of heat

3-way valves are used to mix hot water from the RFQ with cold water from tank, in order to achieve the desired temperature

The pump is a secondary source of heat





CONTENTS

What we have done:

- **RFQ power budget update**
- **RFQ steady state assessment**
- **triple body circuit proposal, in relation with voltage monitoring**
- **cooling dynamics analysis, using multiphysics**

RFQ POWER BUDGET UPDATE

Duty cycle = 5% - Stored energy = 2.52 J - Beam power = 240 kW - Roughness loss (~100 kW) not included
Values in watts

Tuners at nominal positions P_{Cu} = 37.7 kW Q_0 = 7 388 Q_L = 3 187

	Vane circuit	Body circuit						RFQ total	CW total
		2D Body	Ends	Vac ports	Tuner bores	Tuners	Total		
1	1 788.7	1 891.1	115.0	497.5	53.8	568.5	3 125.9	4 913.6	98 272.8
2	2 557.7	2 604.4		690.6	89.9	799.5	4 184.4	6 742.1	134 841.6
3	3 051.4	3 170.2		831.3	100.7	955.5	5 057.7	8 109.1	162 182.0
4	3 325.1	3 571.0		897.6	92.0	1 030.1	5 590.7	8 915.8	178.316.4
5	3 262.2	3 576.8	175.0	918.2	80.3	1 051.1	5 801.4	9 063.5	181 270.4
	13 984.1	19 355.4				4 404.7	23 760.1	37 744.2	754 883.2

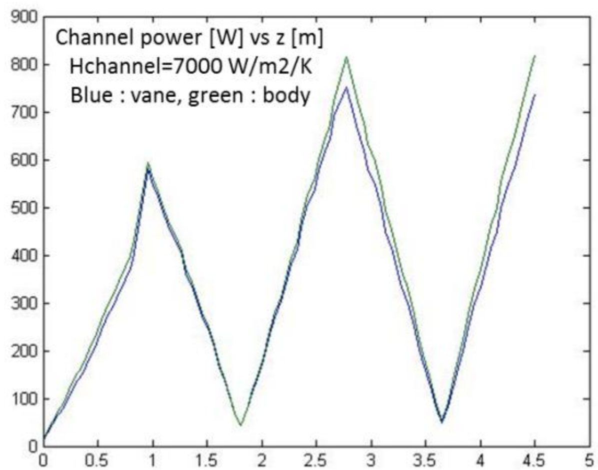
Tuners at max. position (+26 mm) P_{Cu} = 48.5 kW Q_0 = 5 755 Q_L = 2 560

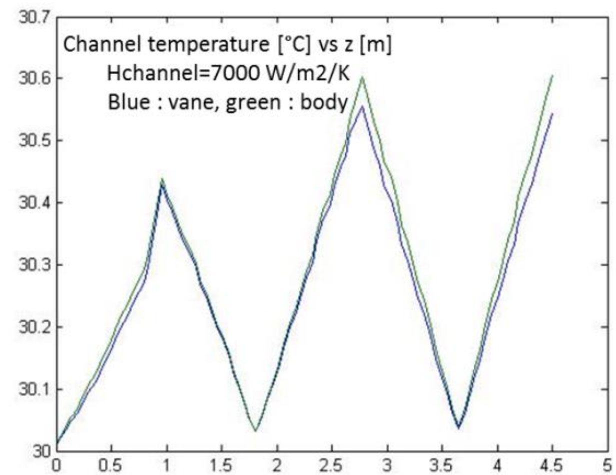
	Vane circuit	Body circuit						RFQ total	CW total
		2D Body	Ends	Vac ports	Tuner bores	Tuners	Total		
1	1 788.7	1 891.1	115.0	497.5	742.8	1 262.9	4 509.3	6 297.0	125 940.8
2	2 557.7	2 604.4		690.6	1216.9	1 849.1	6 361.0	8 918.7	178 373.6
3	3 051.4	3 170.2		831.3	1 364.8	2 165.4	7 531.7	10 583.1	211 662.0
4	3 325.1	3 571.0		897.6	1 276.3	2 241.5	7 986.4	11 311.5	226 230.4
5	3 262.2	3 576.8	175.0	918.2	1 164.5	2 244.9	8 079.4	11 341.5	226 830.4
	13 984.1	24 704.0				9 763.8	34 467.8	48 451.9	969 037.2

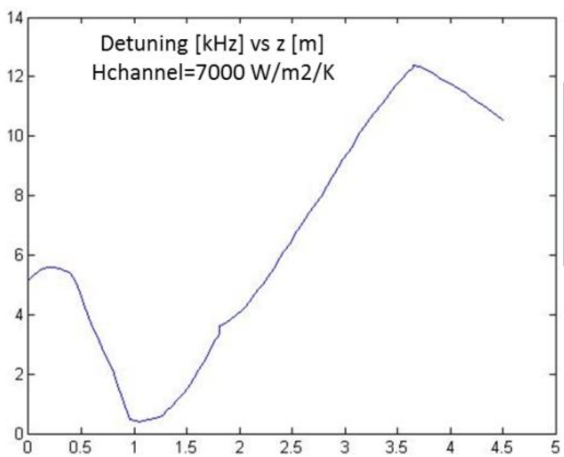
(RFQ radiofrequency design-CEA-ESS-RFQ-RP-0002A : 999 kW)

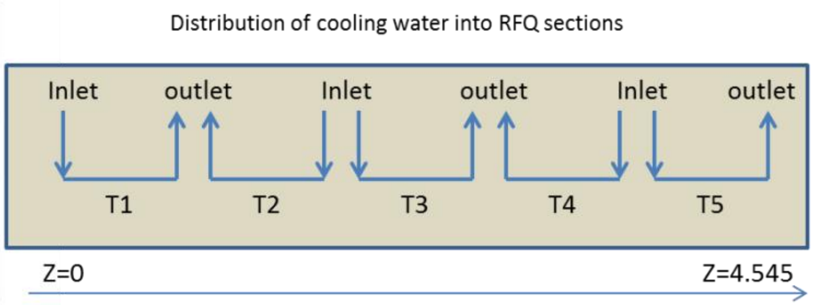
RFQ STEADY STATE - NOMINAL TEMPERATURES
$T_{in\ Body} = 30°C$ $T_{in\ Vane} = 30°C$

2D calculations (vacuum ports and tuners not included)
Alternation of water flow from one module to the next minimizes the detuning (< 12 kHz)
Resulting voltage error < 0.6%



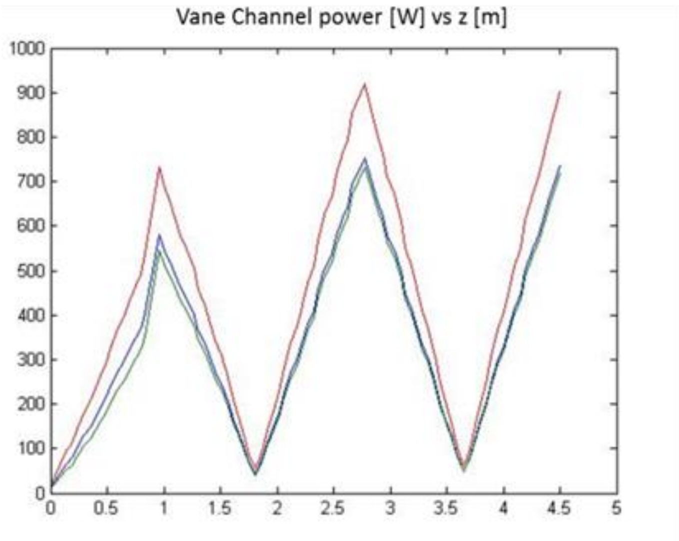


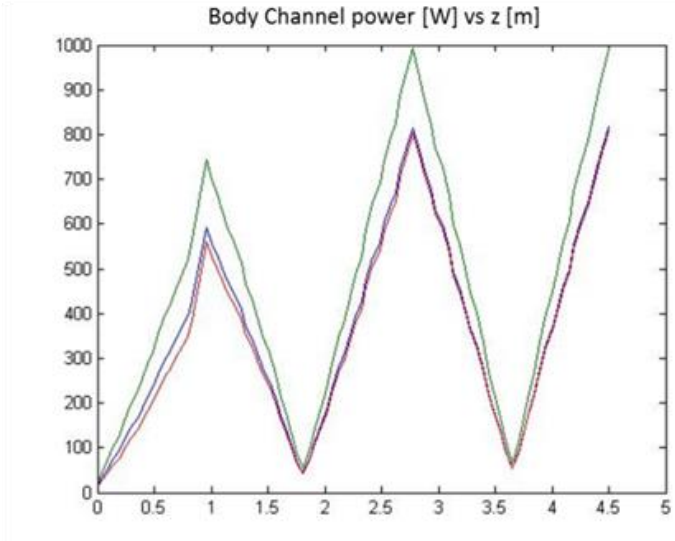




RFQ STEADY STATE

$\Delta T_{\text{in Body}} = +1$ K $\quad \Delta T_{\text{in Vane}} = +1$ K

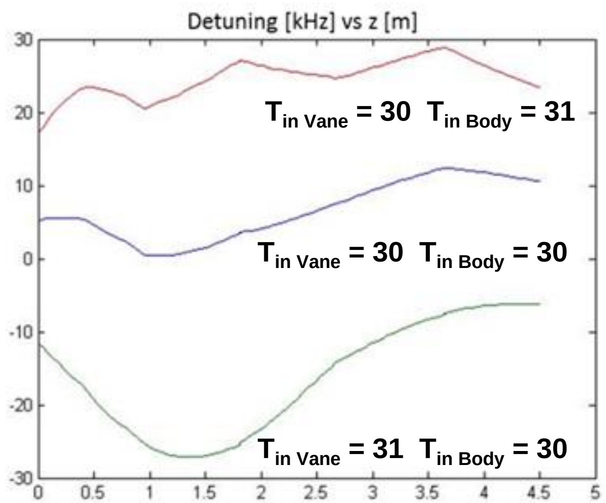




Mean detuning sensitivities

$$\frac{df}{dT_{\text{in Vane}}} \cong -20\ \text{kHz/K}$$

$$\frac{df}{dT_{\text{in Body}}} \cong +14\ \text{kHz/K}$$



Vane → Body and Body → Vane channels power crosstalk

$$P_{\text{cross Body}} \cong 26.8\,(T_{\text{in Vane}} - T_{\text{in Body}})\ \text{kW}$$

$$P_{\text{cross Vane}} \cong 26.8\,(T_{\text{in Body}} - T_{\text{in Vane}})\ \text{kW}$$

CORRECTION OF VOLTAGE ERRORS USING RFQ MODULE TEMPERATURES

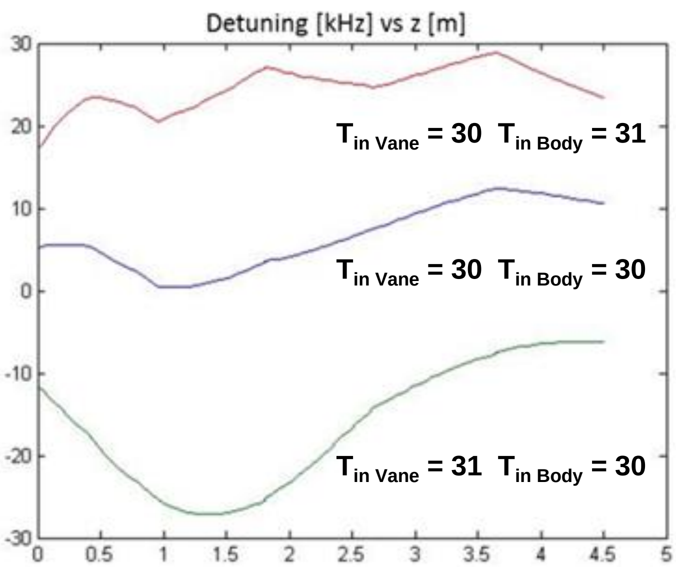
Two possible scenarii (which are equivalent in steady state) are available:

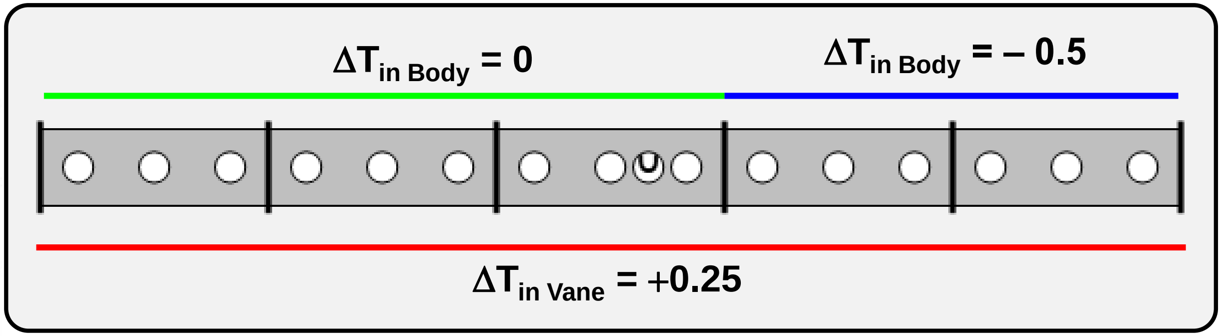
(1) modify the inlet temperatures of : Body Circuit in modules 4 and 5 to center detuning about 5 kHz
: Vane Circuit in all modules to nullify detuning;

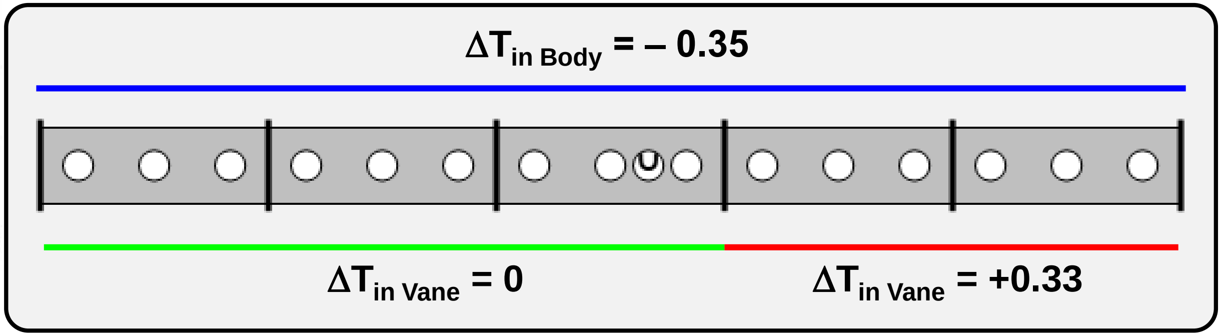
(2) modify the inlet temperatures of : Vane Circuit in modules 4 and 5 to center detuning about 5 kHz
Body Circuit in all modules to nullify detuning.

Use monitoring pickups to check voltage error vs. z.

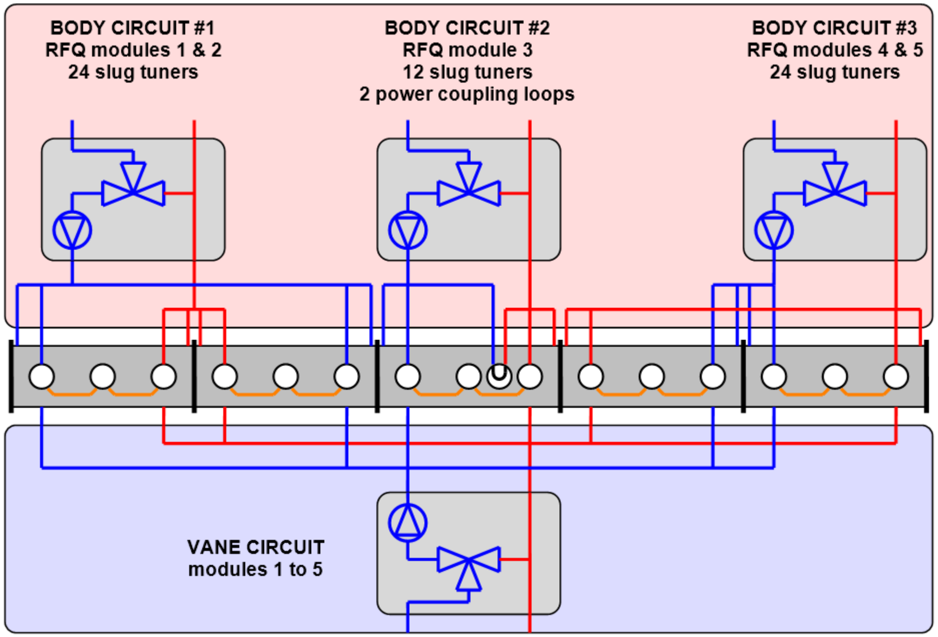
Linac4 tests have demonstrated an excellent agreement with theoretical predictions.







TRIPLE BODY CIRCUIT PROPOSAL



Tuners at nominal positions

	Vane circuit	Body circuits		
		Modules 1 & 2	Module 3	Modules 4 & 5
Collected power (W)	13 984	7 310	5 058	11 392
Water flow (liter/min)	400	288	144	288
Temperature increase (K)	0.502	0.364	0.504	0.568

Tuners at max position

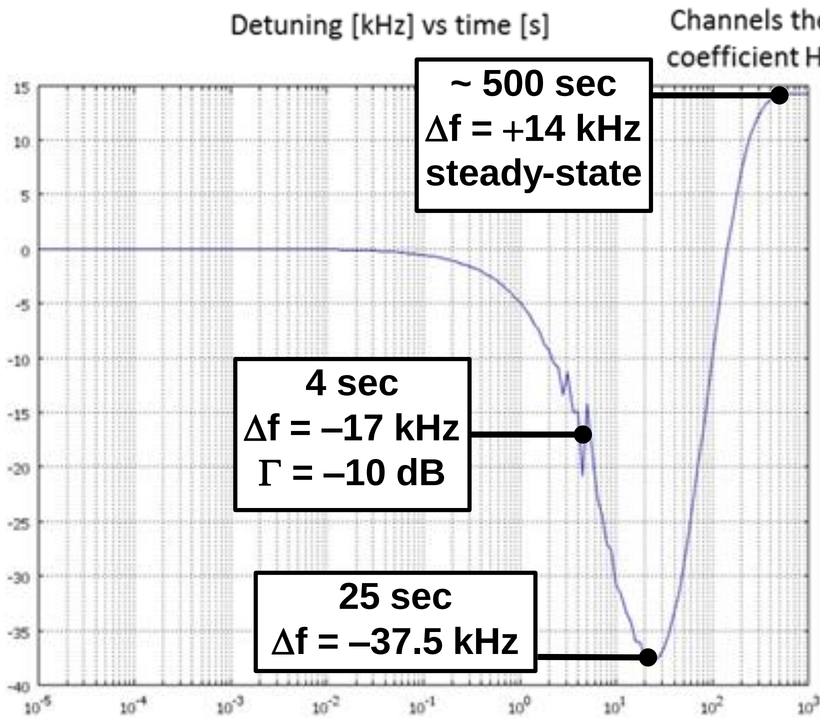
	Vane circuit	Body circuits		
		Modules 1 & 2	Module 3	Modules 4 & 5
Collected power (W)	13 984	10 870	7 532	16 066
Water flow (liter/min)	400	288	144	288
Temperature increase (K)	0.502	0.542	0.751	0.801

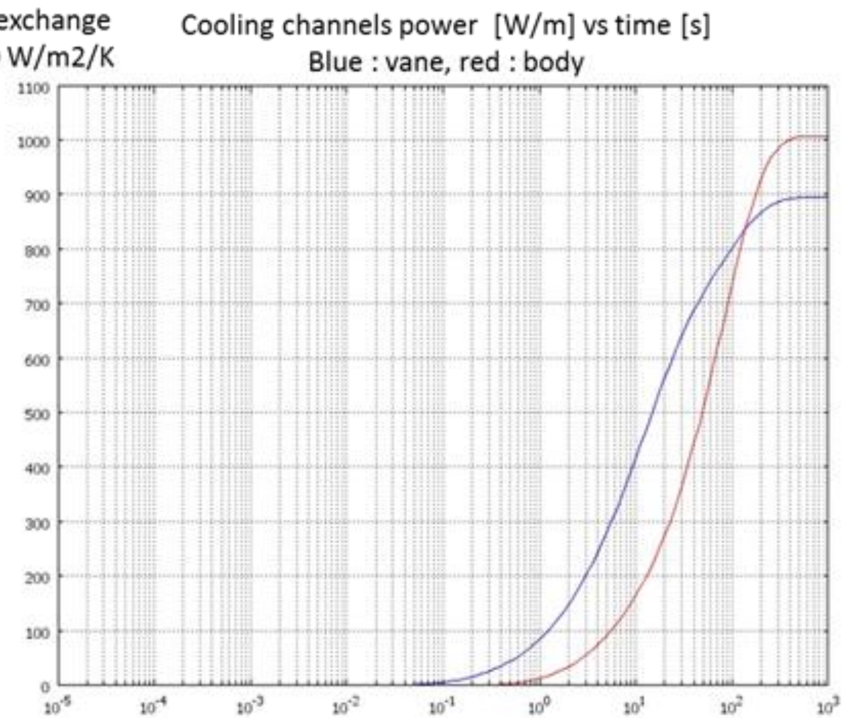
TRANSIENT RF OPERATION

Obtain the RFQ time constants needed to tune the loop parameters
2D calculation in one cross-section at the end of the RFQ (vacuum ports and tuners not included)

(I) RF power step $T_{in\ Body} = 30°C$ $T_{in\ Vane} = 30°C$

Channels thermal exchange coefficient H=7000 W/m2/K





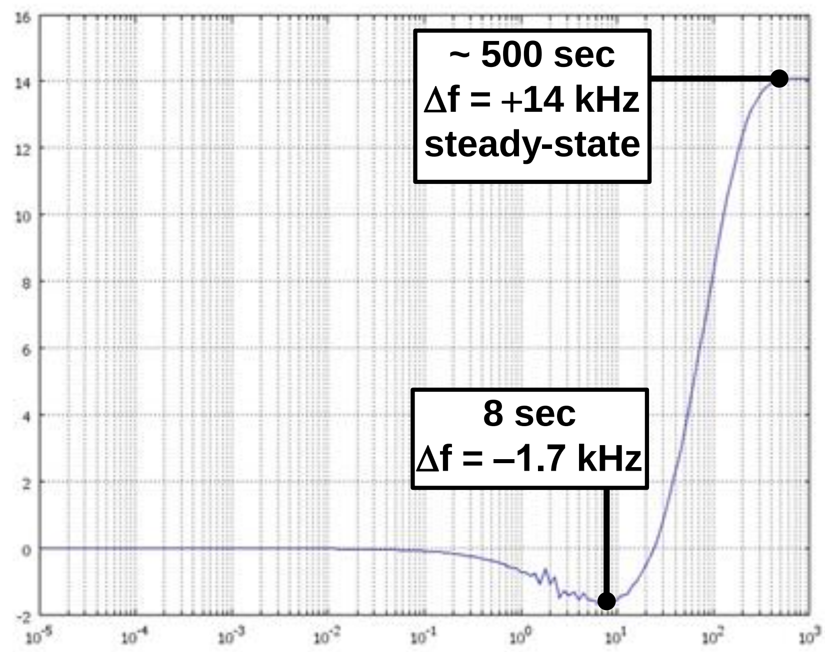
"vane detuning faster and larger than body detuning"

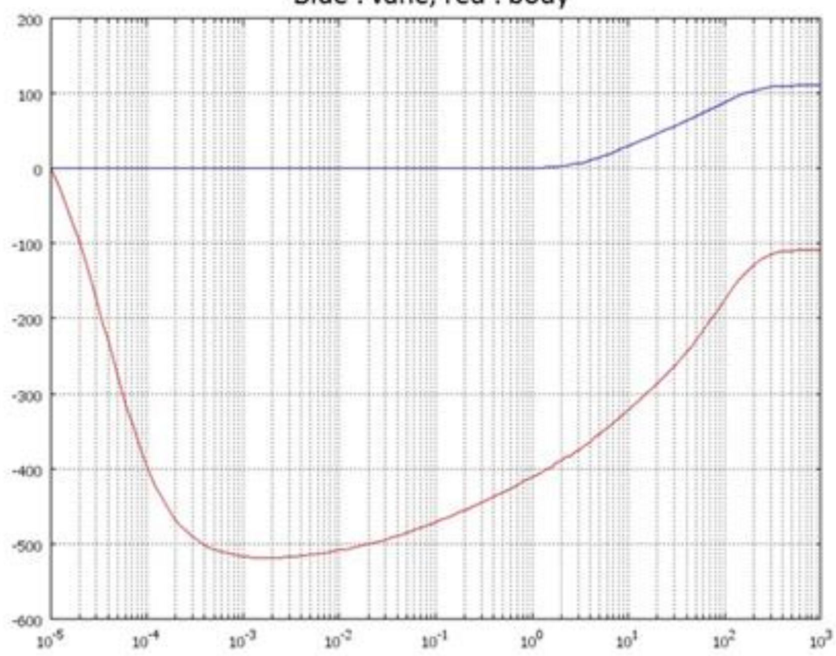
(II) no RF power $T_{in\ Body}$ = +1 K step $T_{in\ Vane}$ = 30°C

Detuning [kHz] vs time [s]

Channels thermal exchange coefficient H=7000 W/m2/K

Cooling channels power [W/m] vs time [s]
Blue : vane, red : body

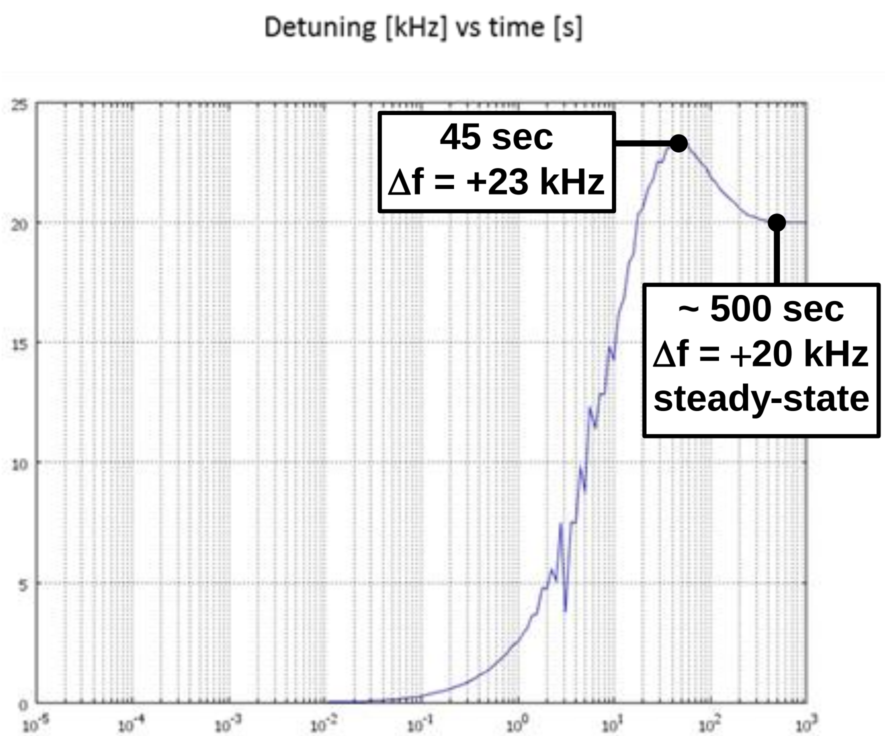


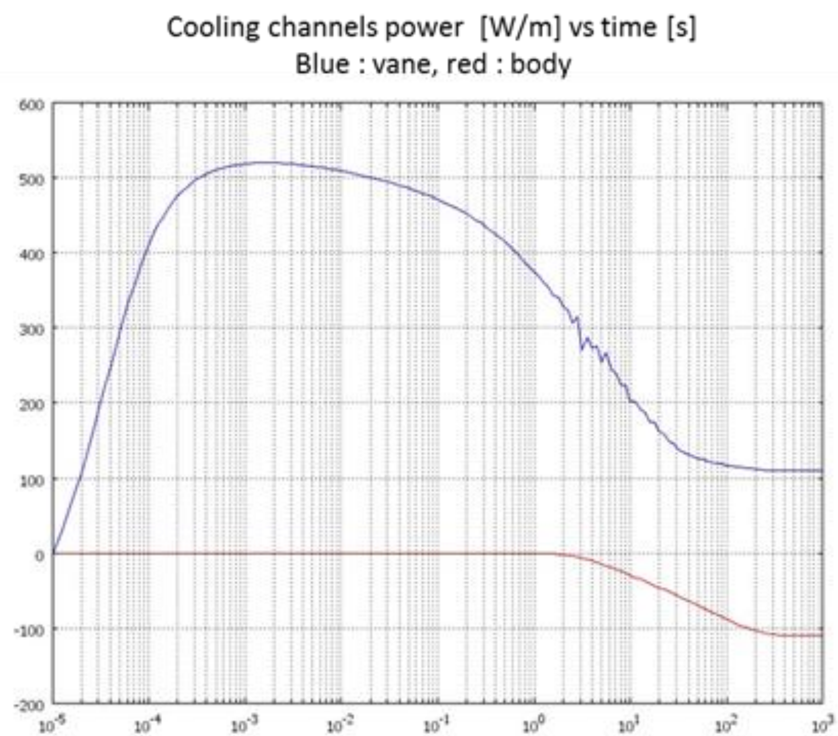


the heat flux increase is first absorbed in copper, hence the negative initial slope

TRANSIENT RF OPERATION

(III) no RF power **$T_{in\ Body}$ = 30°C** **$T_{in\ Vane}$ = –1 K step**





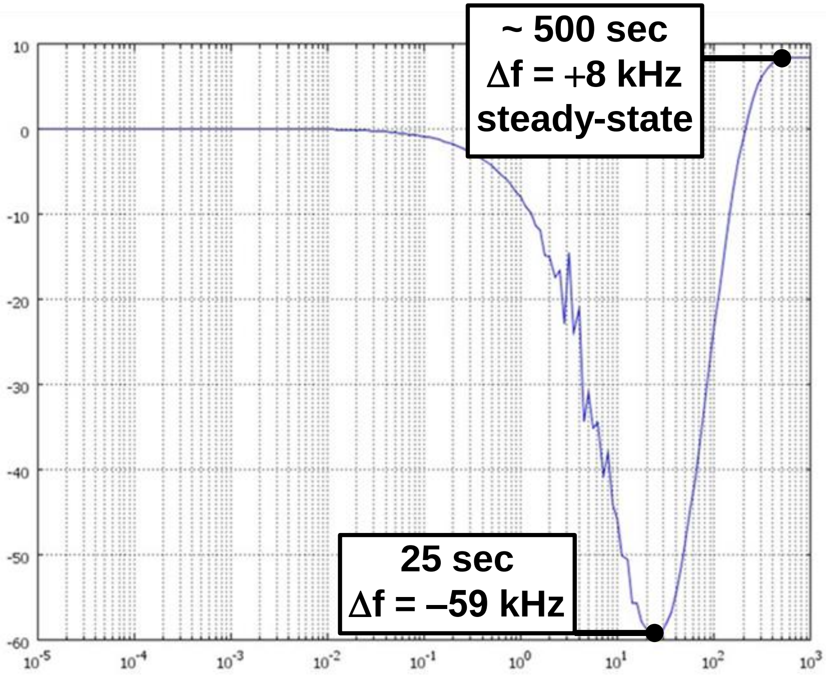
the heat flux from copper warms up the vane, hence the positive initial slope

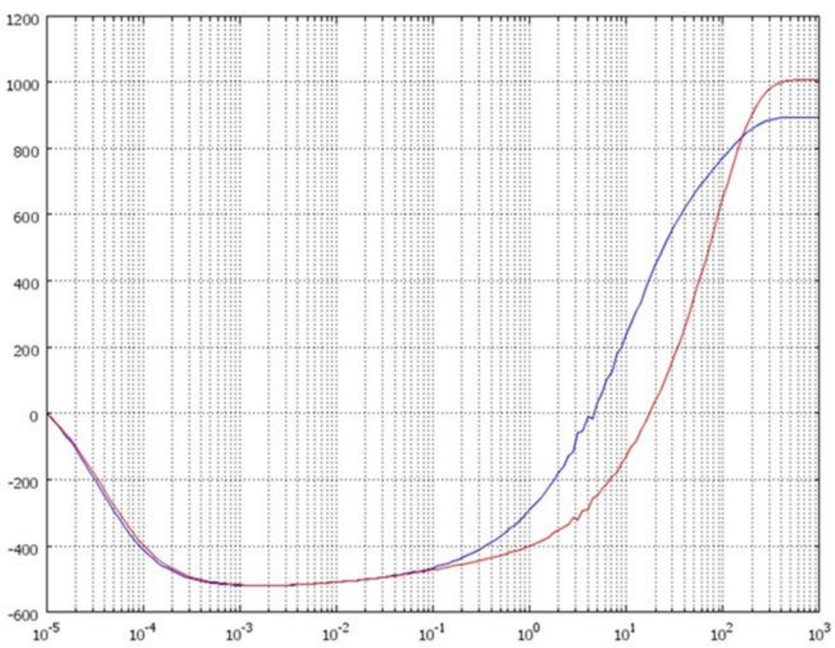
(IV) RF power step $T_{in\ Body}$ = +1 K step $T_{in\ Vane}$ = +1 K step

Detuning [kHz] vs time [s]

Channels thermal exchange coefficient H=7000 W/m2/K

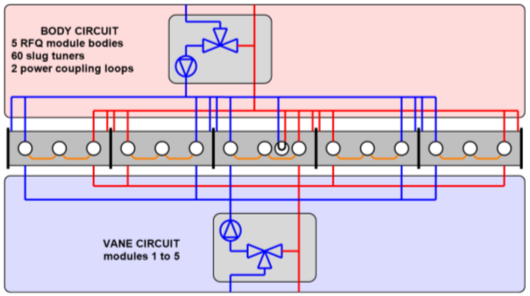
Cooling channels power [W/m] vs time [s]
Blue : vane, red : body





the transient solution (IV) is the exact linear combination of the three individual single-step solutions (I), (II) and (III)

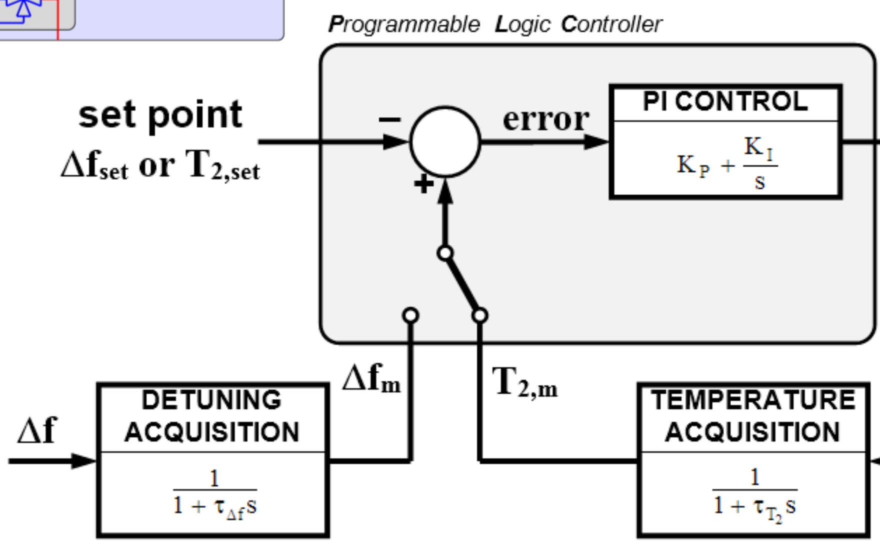
DYNAMIC SIMULATION SETUP

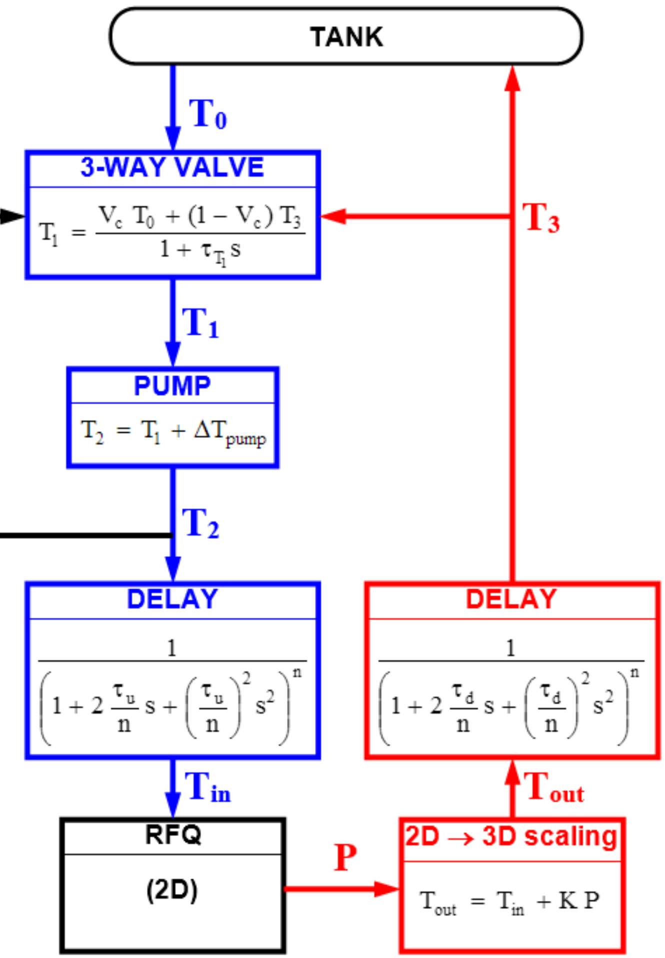


Identical setups for the Vane and Body circuits

Full time-simulation using Comsol ODE solver

Regulation of detuning (Δf) or temperature (T_2)





2D calculation of collected power P in one cross-section at the end of the RFQ

3D outlet temperature is calculated with proper scaling derived from steady-state 2D and 3D results:

K_{Body} = 0.565 K/kW, K_{Vane} = 0.564 K/kW

DYNAMIC SIMULATION PARAMETERS

System parameters

	Vane Circuit	Body Circuit	
T_0 (°C)	28	28	Water tank temperature
ΔT_{pump} (K)	0.2	0.2	Water pump temperature step
τ_{T_1} (s)	10	10	3-way valve time constant
τ_{T_2} (s)	10	10	Temperature acquisition time constant
$\tau_{\Delta f}$ (s)	2	2	Detuning acquisition time constant
τ_u (s)	0 / 30	0 / 30	Upstream delay (from pump to RFQ)
τ_d (s)	0 / 30	0 / 30	Downstream delay (from RFQ to pump)
τ (s)	0 / 60	0 / 60	Total delay ($\tau = \tau_u + \tau_d$)
n	10	10	Number of 2nd order ODE for delay simulation
K (K/kW)	0.564	0.565	Ratio of water temperature increase to collected power

Feedback loop parameters

	Vane Circuit	Body Circuit	
$T_{2,set}$ (°C)	30	30	Set point for temperature regulation
Δf_{set} (kHz)	0	0	Set point for frequency regulation
K_P	0.01	0.01	Proportional coefficient for temperature regulation
$1/K_I$ (s)	1 000	1 000	Reciprocal of integration coefficient for temperature regulation

GENERAL PRINCIPLES USED IN SIMULATIONS

1. choose the Body or the Vane Circuit for frequency regulation

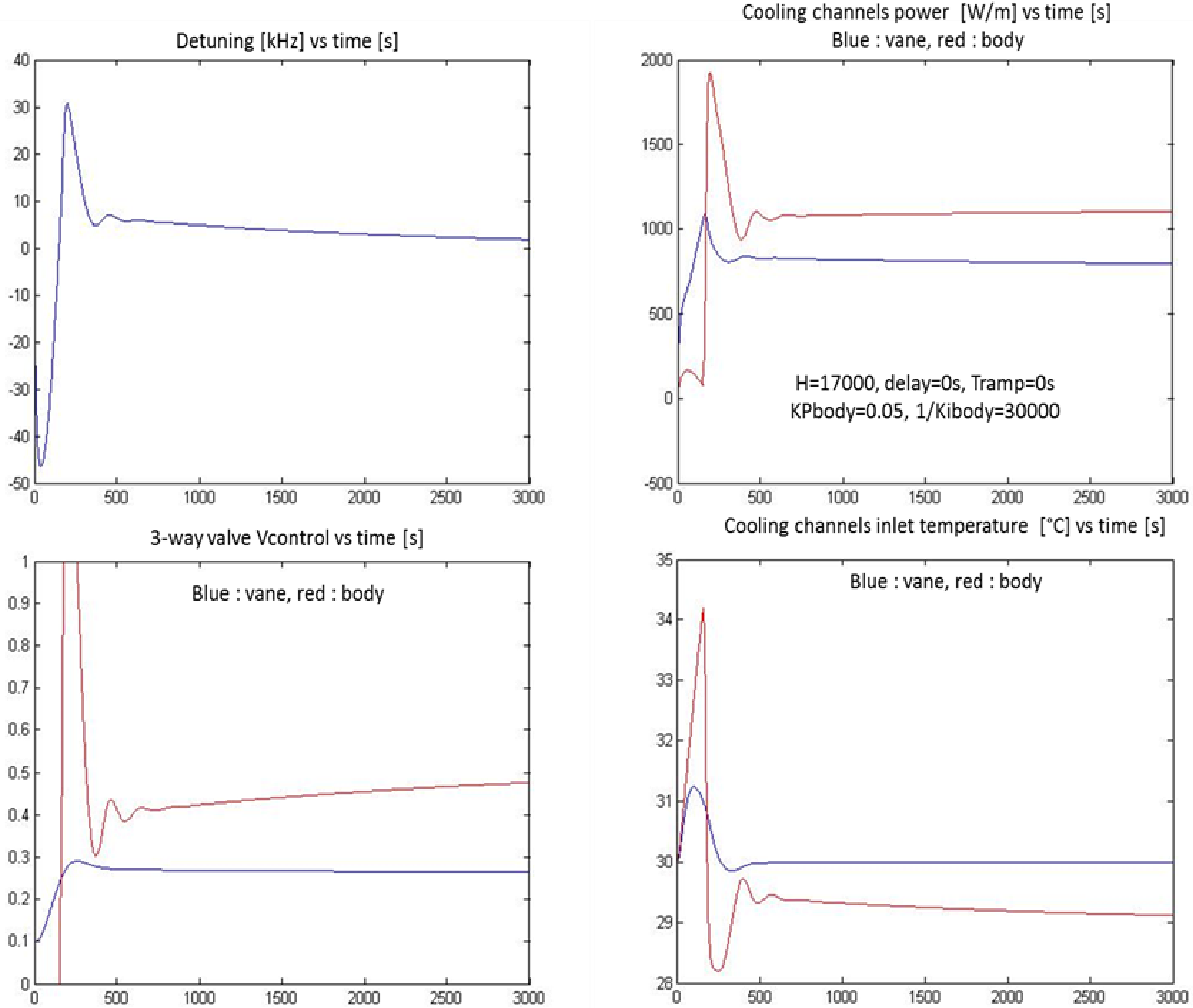
2. set to zero both delay ($\tau = 0$) and RF power ramp time ($T_{ramp} = 0$)
   $\rightarrow$ choose K_P and $1/K_I$ to avoid saturation and achieve stability

3. set delay $\tau \neq 0$, keep RF power ramp time at zero ($T_{ramp} = 0$)
   $\rightarrow$ adjust $1/K_I$ to achieve stability

4. keep delay $\tau \neq 0$
   $\rightarrow$ adjust T_{ramp} to maintain detuning within ±17 kHz to achieve $\Gamma < -10$ dB

FREQUENCY REGULATION WITH $T_{in\ Body}$

$\tau = 0$ s $T_{ramp} = 0$ s $K_{P\ Body} = 0.05$ $1/K_{I\ Body} = 30\ 000$ s



(1) Beginning of pulse - negative detuning:
the valve remains fully open (feedback saturation) until water has been warmed enough by the RFQ : +4°C in 200s;

(2) then the detuning goes positive:
the valve remains fully closed (saturation again) until water has cooled enough down; this needs another 200 s.

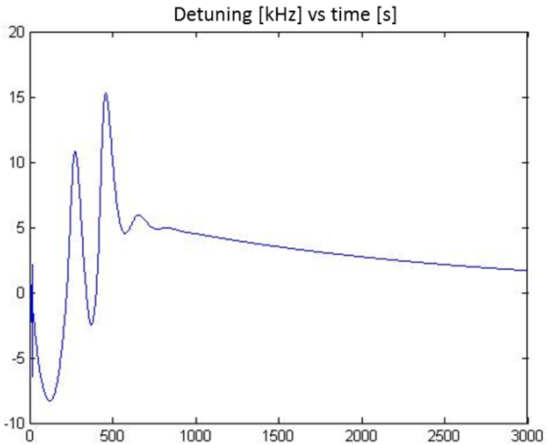
Peak detuning is –46 kHz.

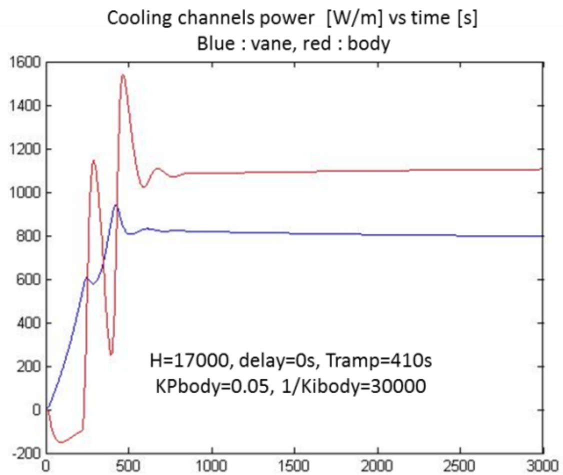
The very large $1/K_I$ needed for stability leads to a very narrow loop bandwidth.

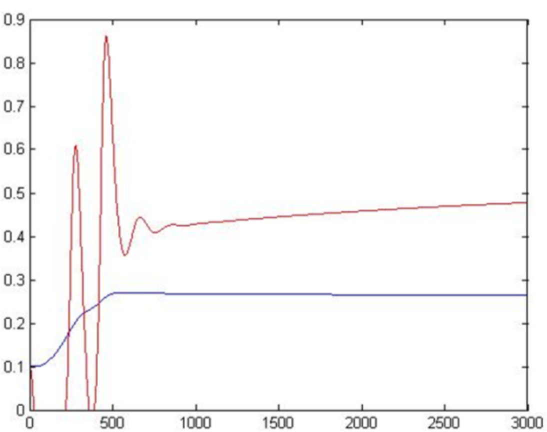
This scenario is quite ineffective to compensate even slow variations of RFQ detuning.

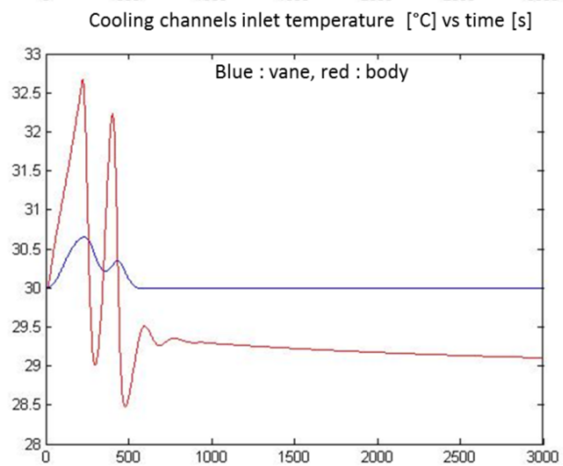
FREQUENCY REGULATION WITH $T_{in\ Body}$

τ = 0 s	T_{ramp} = 410 s	$K_{P\ Body}$ = 0.05	$1/K_{I\ Body}$ = 30 000 s









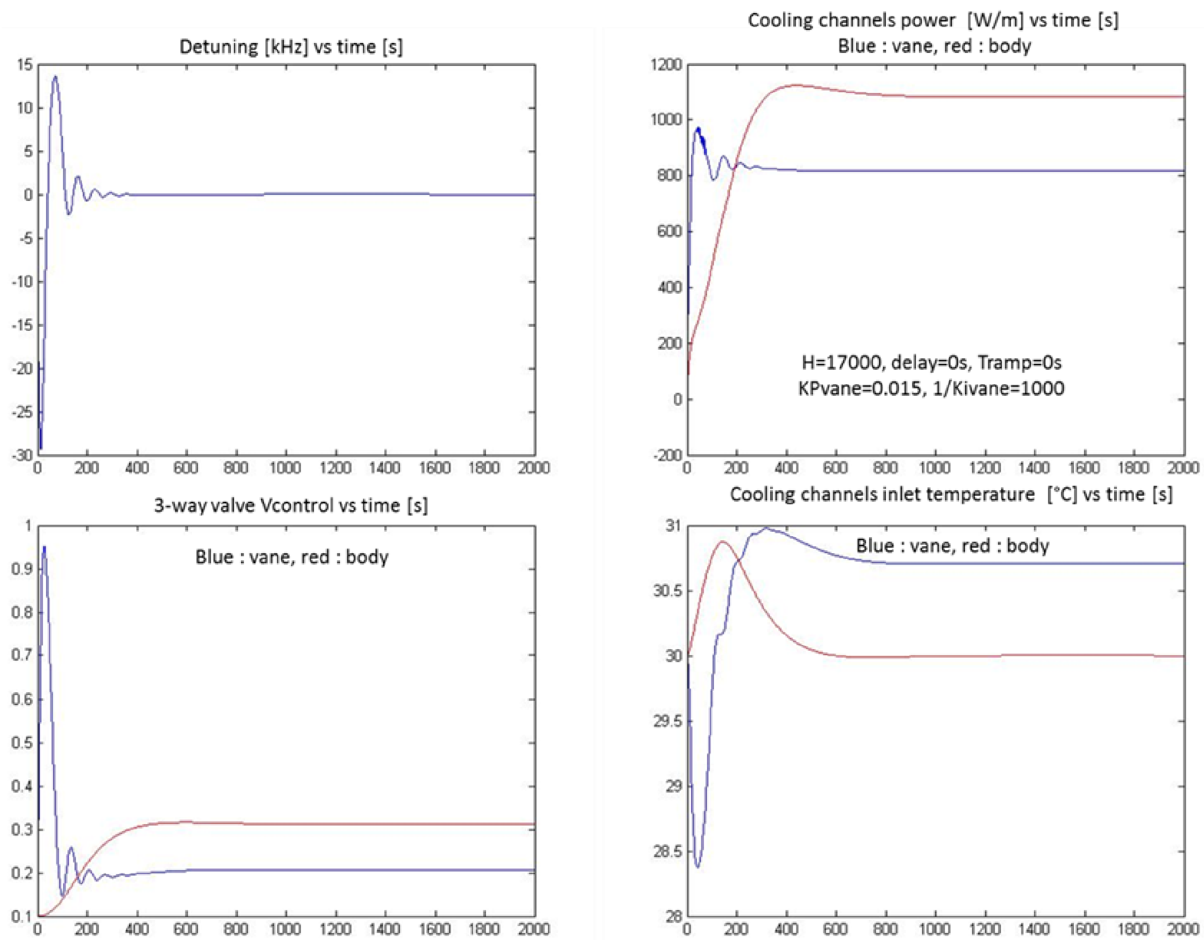
An RF power ramp longer than 400 s is needed to maintain detuning smaller than 17 kHz (Γ = -10 dB).

Saturation is still present during the first 200 s and about 400 s.

A much longer ramp would be needed to avoid saturation.

FREQUENCY REGULATION WITH $T_{in\ Vane}$

τ = 0 s	T_{ramp} = 0 s	$K_{P\ Vane}$ = 0.015	$1/K_{I\ Vane}$ = 1 000 s



Stability is achieved with K_P = 0.015.

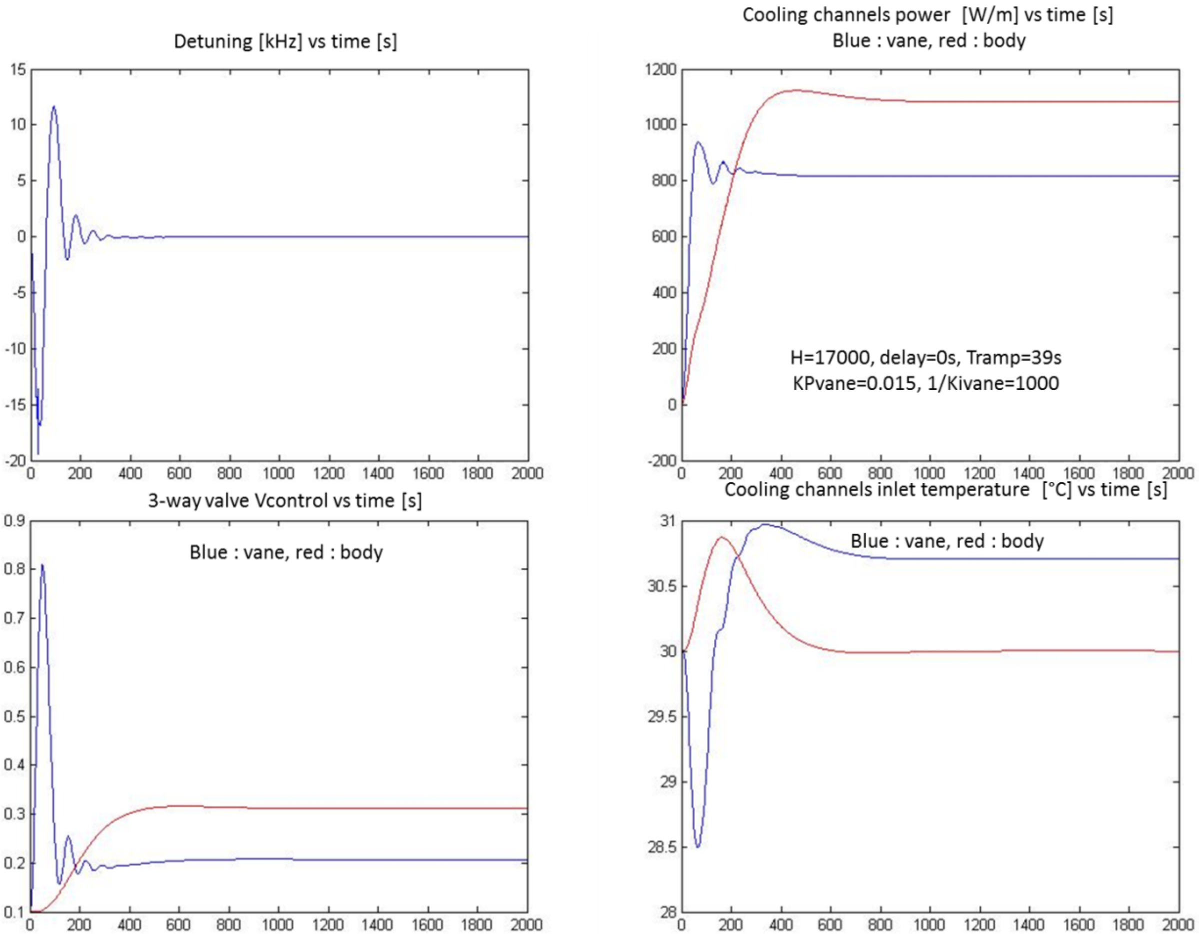
$1/K_I$ is 30 times smaller than when using $T_{in\ Body}$ for frequency regulation: the feedback bandwidth is 30 times larger.

Peak detuning is –29 kHz.

The cold water needed to cool the vanes already exists, and it takes 26 s to maintain the detuning within the ±17 kHz range (100 s within ±2 kHz).

FREQUENCY REGULATION WITH $T_{in\ Vane}$

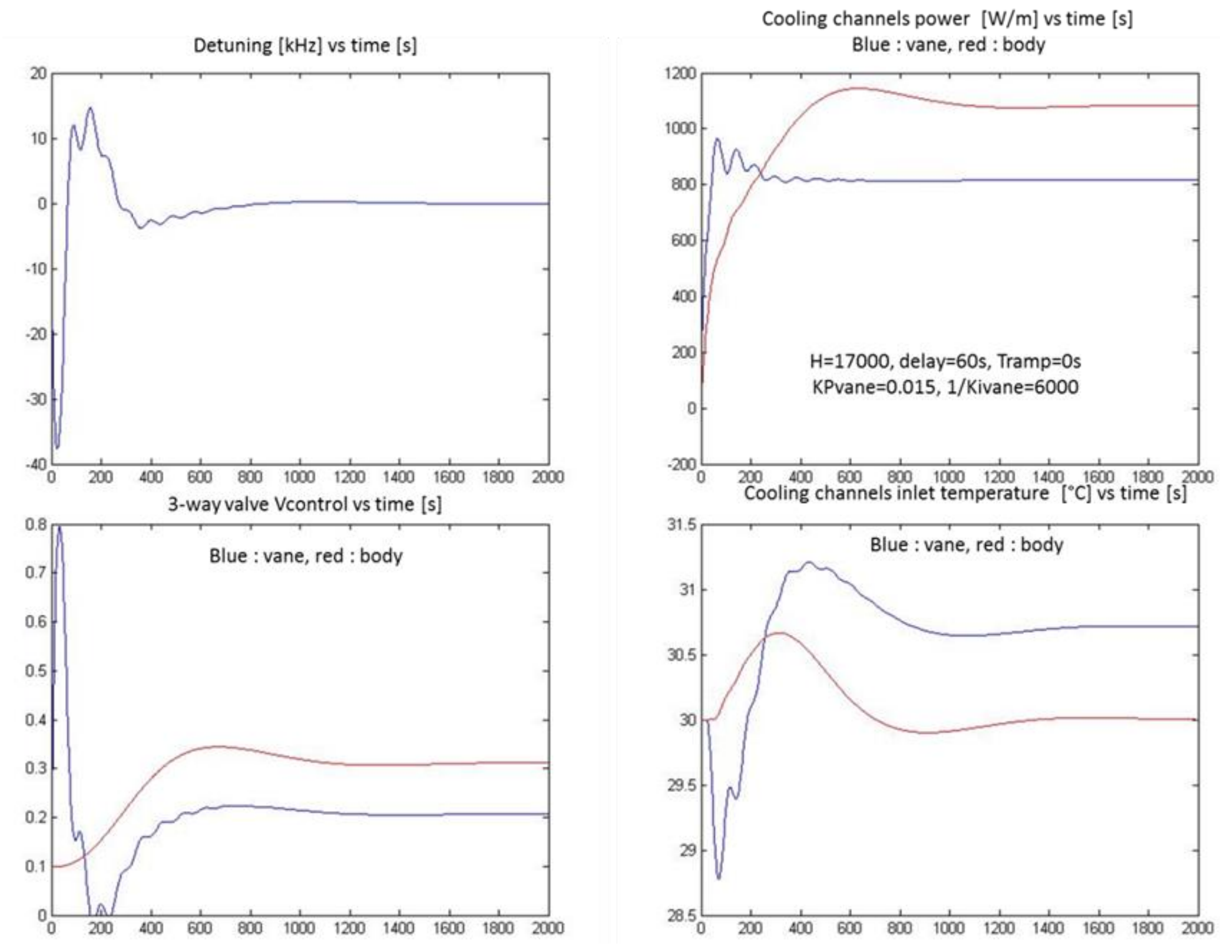
$\tau = 0$ s	$T_{ramp} = 39$ s	$K_{P\ Vane} = 0.015$	$1/K_{I\ Vane} = 1\ 000$ s



An RF power ramp longer than 39 s is needed to maintain detuning smaller than 17 kHz (Γ < -10 dB).

FREQUENCY REGULATION WITH $T_{in\ Vane}$

τ = 60 s	T_{ramp} = 0 s	$K_{P\ Vane}$ = 0.015	$1/K_{I\ Vane}$ = 6 000 s



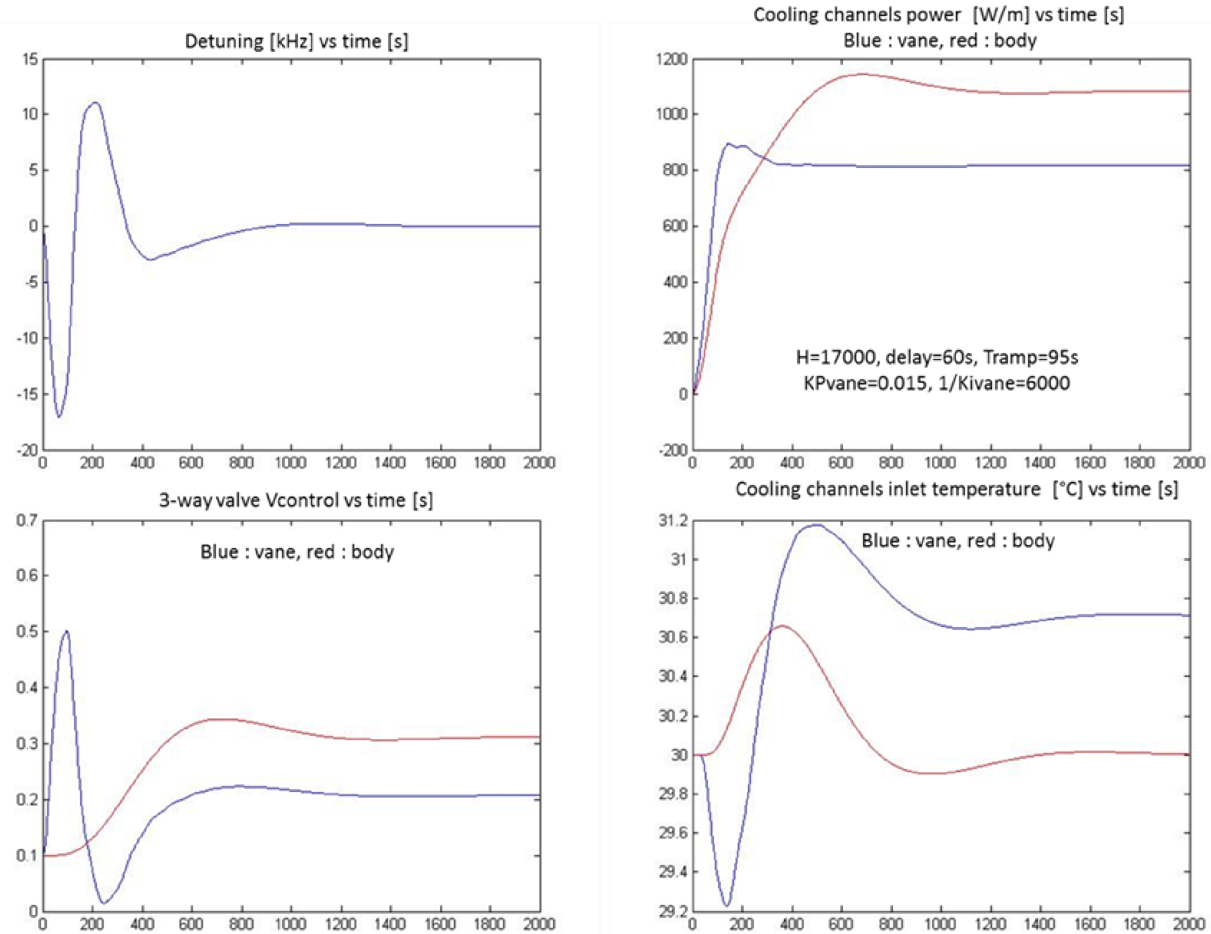
Integration time has to be increased to 6 000 s to achieve stable operation.

Peak detuning is –38 kHz.

The vane feedback loop is saturated from 150 s to 250 s after the beginning of the RF pulse.

FREQUENCY REGULATION WITH $T_{in\ Vane}$

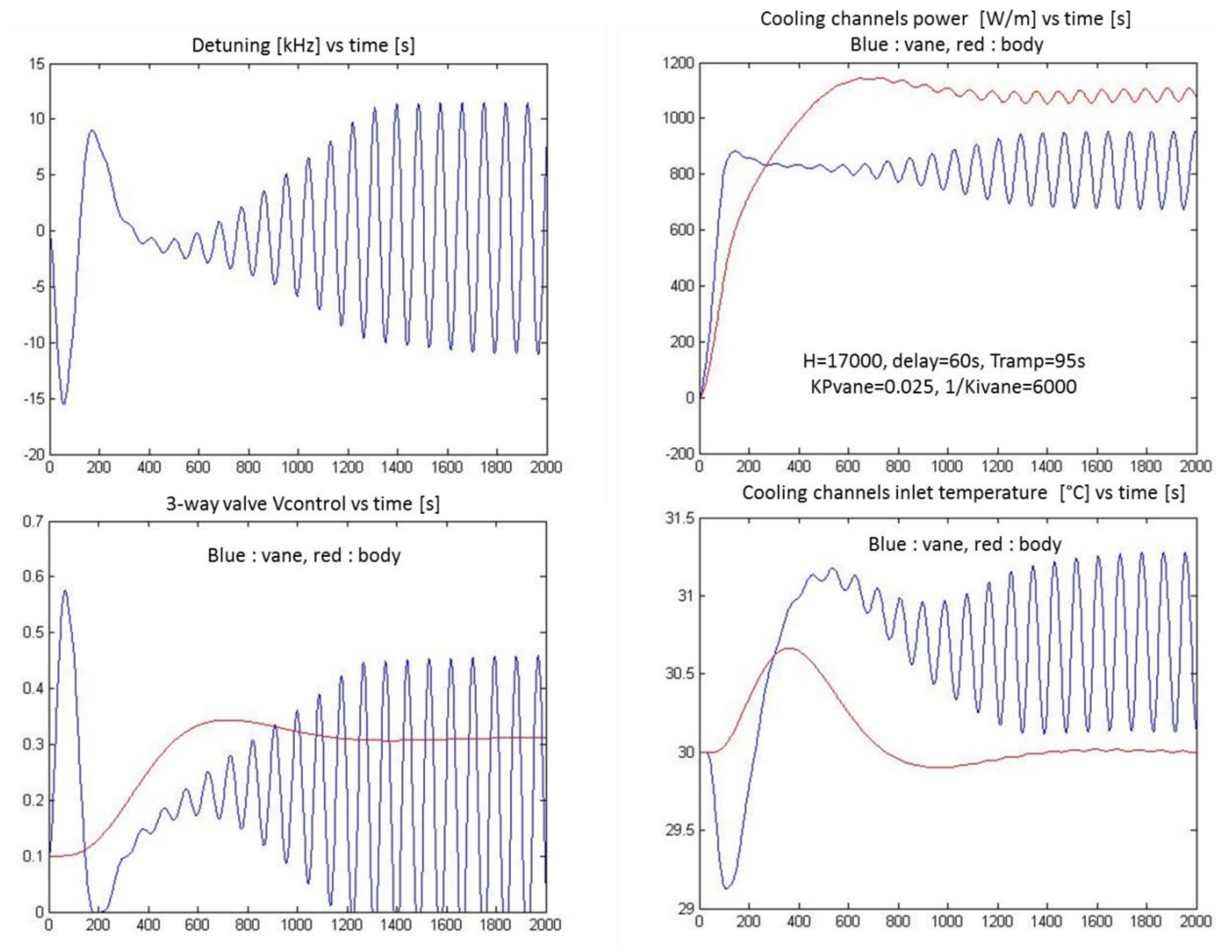
τ = 60 s	T_{ramp} = 95 s	$K_{P\ Vane}$ = 0.015	$1/K_{I\ Vane}$ = 6 000 s



A ramp longer than 95 s is needed to maintain detuning smaller than 17 kHz (Γ < -10 dB).

FREQUENCY REGULATION WITH $T_{in\ Vane}$

τ = 60 s	T_{ramp} = 95 s	$K_{P\ Vane}$ = 0.025	$1/K_{I\ Vane}$ = 6 000 s



The simulation shows the start of an instability with K_P = 0.025.

The amplitude of the oscillation is limited to 11 kHz thanks to the saturation of the 3-way valve drive.

This would be acceptable for RF since the detuning remains within the ±17 kHz range (Γ < -10 dB).

However this situation should be avoided to preserve the valve lifetime and to prevent alternating thermal stresses of the RFQ !

SUMMARY OF SIMULATIONS

Frequency regulation using Body Circuit inlet temperature is much too slow.

Frequency regulation using Vane Circuit inlet temperature may be tuned as follows:

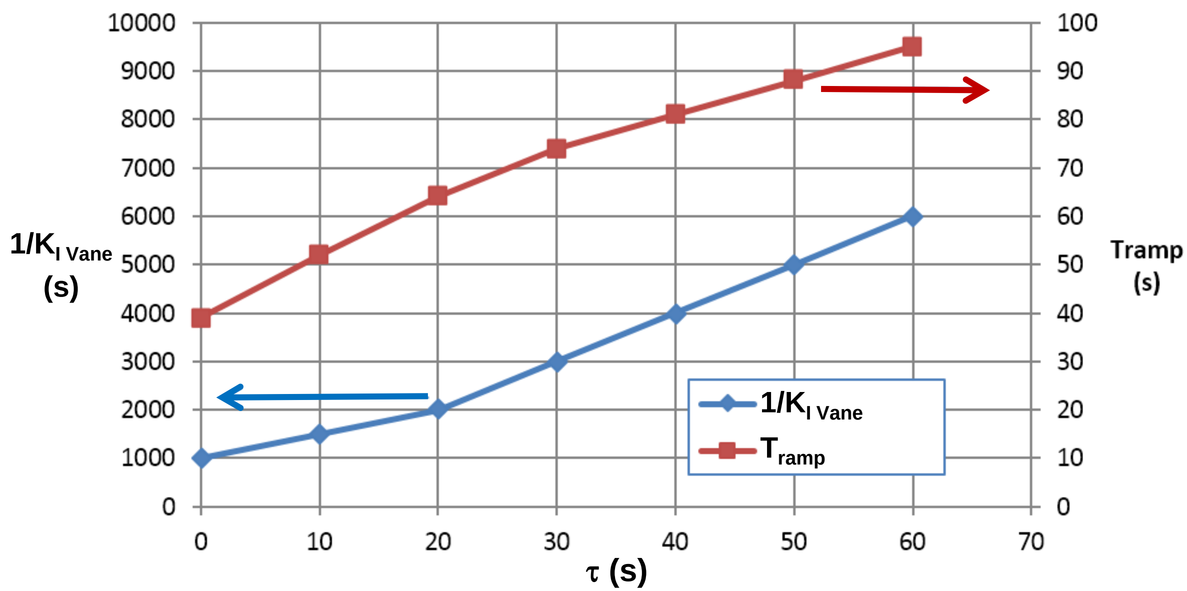
→ K_P = 0.015 to achieve stability

→ integration time $1/K_I$ large enough to achieve stability, depending on delay

→ RF power ramp long enough to maintain detuning in the ±17 kHz range, depending on delay

SUMMARY OF SIMULATIONS

Temperature regulation : $T_{2\ Vane\ set}$ = 30°C		Frequency regulation : $\Delta f_{set} = 0$
$K_{P\ Body} = 0.01$	$1/K_{I\ Body}$ = 1 000s	$K_{P\ Vane} = 0.015$



Linear formulas, valid for $\tau > 20$s

$1/K_{I\ Vane} = 100\ \tau$ (s)

$T_{ramp} = 55 + 2\ \tau / 3$ (s)

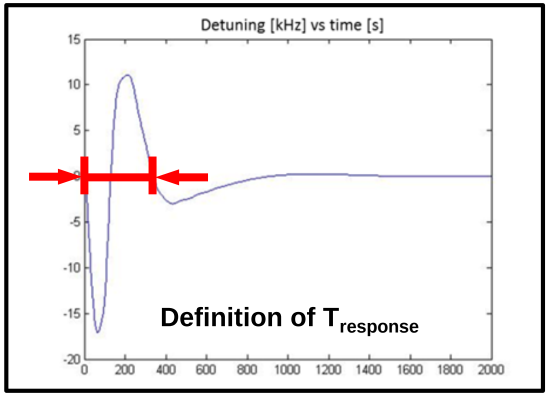
$T_{response} = 130 + 3.5\ \tau$ (s)

Example :

75 m long upstream + downstream circuit,

1.5 m/s water flow velocity

$\tau = 50$ s $T_{ramp} = 90$ s $T_{response} = 305$ s



CONCLUSIONS

Frequency regulation must use the Vane Circuit inlet temperature

A stable loop operation may be obtained with valve-to-RFQ roundtrip delays ranging from 0 to more than 60 s; the valve-to-RFQ distance may be freely chosen

A triple Body Circuit, while not mandatory, would help to correct the voltage profile

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