

CHECHIA cavity driving with FPGA controller

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ABSTRACT

The initial control of the superconductive cavity has recently been performed by applying the FPGA (Field Programmable Gate Array) technology system in DESY Hamburg. This first experiment turned attention to the general recognition of the cavity features and projected control methods. The electrical model of the cavity is taken as a consideration origin. The calibration of the signal channel is considered as a key preparation for an efficient cavity driving. The cavity parameters identification is confirmed as a proper approach for the required performance: driving on resonance during *filling* and field stabilization during *flattop* time with reasonable power consumption. The feed-forward and feedback modes were applied successfully for the CHECHIA cavity driving. Representative results of experiments are presented for different levels of the cavity field gradient.



Keywords: Super conducting cavity control, CHECHIA driving, FPGA, system identification, LLRF controls, TESLA, SIMCON, VUV FEL.

1. INTRODUCTION

The LLRF – Low Level Radio Frequency TESLA cavity control system is still under development in order to regulate accelerating fields of the resonators [1] (figure 1). The control section, powered by one klystron, may consist of many cavities. The fast amplitude and phase control of the cavity field is accomplished by modulation of the signal driving the klystron from the *vector modulator*. The cavities are driven with pulses of 1.3 ms duration and average accelerating gradients of 25 MV/m. The cavity RF signal is *down-converted* to an intermediate frequency of 250 KHz preserving the amplitude and phase information. The ADC and DAC converters link the analog and digital parts of the system. The digital signal processing is realized in FPGA system for the field vector detection (I/Q Detector), calibration and filtering. The control feedback system regulates the vector sum of pulsed accelerating fields in multiple cavities. The FPGA based controller stabilizes the detected real (in-phase) and imaginary (quadrature) components of the incident wave according to the desired set point. Additionally, the adaptive feed-forward is applied to improve the compensation of repetitive perturbations induced by the beam loading and by the dynamic Lorentz force detuning. The control block applies the value of the cavity parameters estimated in the identification system and generates the required data for the FPGA based controller.

A comprehensive system modeling was developed for the investigation of the optimal control method for the cavity [2],[3],[4]. The design of a fast and efficient digital controller is a challenging task and it is an important contribution to the optimization of a linear accelerator [5].

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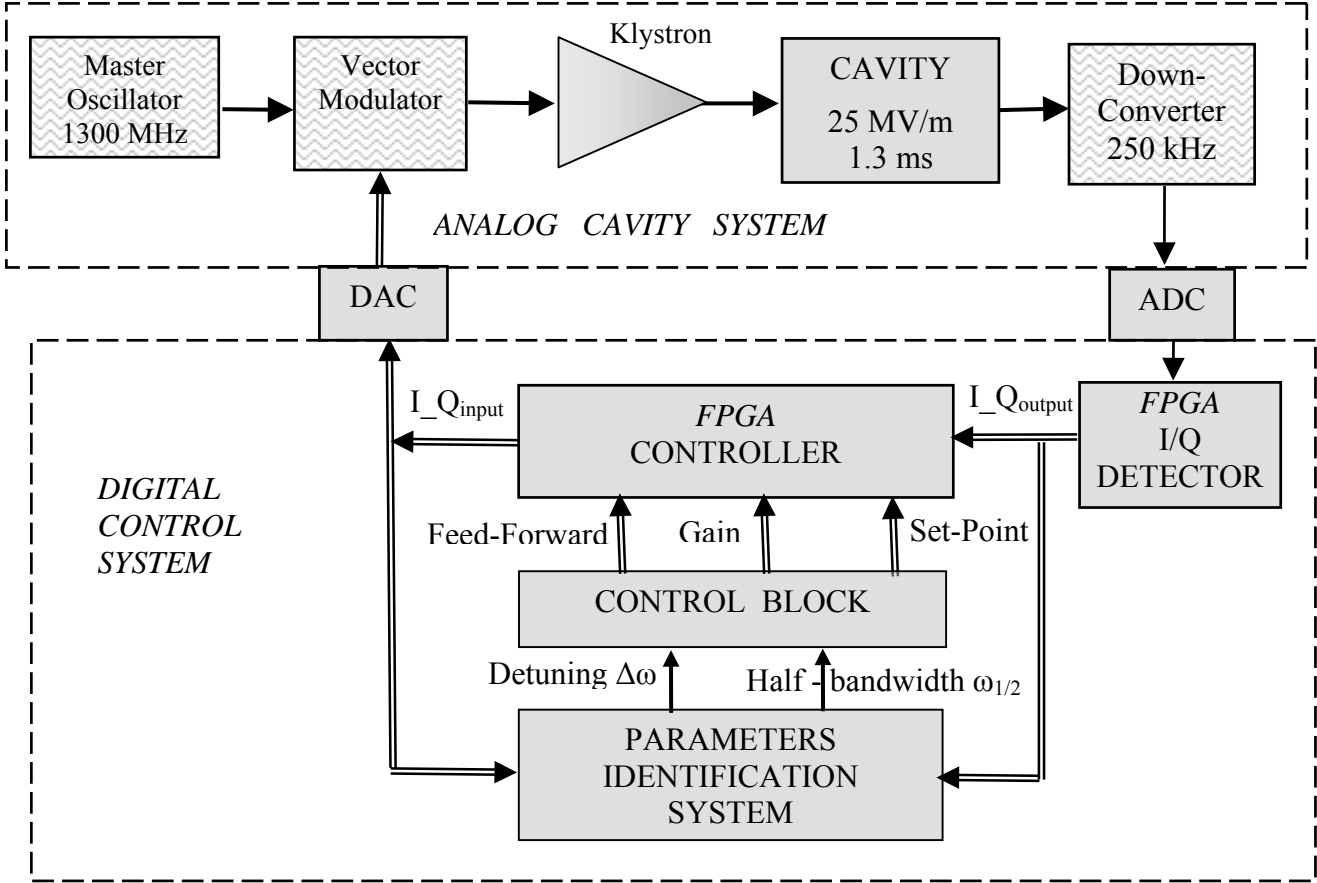


Fig 1. Functional block diagram of LLRF cavity control system (for one cavity)

2. CALIBRATION PROCEDURE FOR CAVITY ENVIRONMENT CHANNEL

The electrical discrete model of the cavity is based on the difference equation for the *complex envelope* \mathbf{v} , driven with the input signal samples: \mathbf{u} for the generator and \mathbf{u}_b for the beam loading. The recursive equation of the cavity model with sampling interval of T is expressed by the complex normalized form for a step k :

$$\mathbf{v}_k = \mathbf{E}_{k-1} \cdot \mathbf{v}_{k-1} + \mathbf{u}_{k-1} - (\mathbf{u}_b)_{k-1} \quad (1)$$

where the system factor is $\mathbf{E} = (1 - \omega_{1/2} \cdot T) + i\Delta\omega \cdot T$ with parameters:

the cavity half-bandwidth = $\omega_{1/2}$ and cavity detuning = $\Delta\omega$.

In the real operational condition the cavity input and output signals are not available directly for the control purpose (fig. 1). The static and linear characteristic of the cavity environment is described in the complex domain by the output distortion factor \mathbf{C} , input distortion factor \mathbf{D} and input offset phasor \mathbf{u}_0 . An efficient cavity control requires a comprehensive correction of the signal channel. Consequently, the complementary components are implemented within the controller area: output calibrator \mathbf{C}' , input calibrator \mathbf{D}' and input offset compensator \mathbf{u}'_0 .

The resultant, external discrete model of the cavity, seen internally by the controller, with the substituted envelope $\mathbf{v}' = \mathbf{C}\mathbf{C}' \cdot \mathbf{v}$, driven with the input phasor \mathbf{u}' , is expressed by the complex form for a step k :

$$\mathbf{v}'_k = \mathbf{E}_{k-1} \cdot \mathbf{v}'_{k-1} + \mathbf{C} \cdot \mathbf{C}' \cdot \mathbf{D} \cdot [\mathbf{u}_0 + \mathbf{D}' \cdot (\mathbf{u}'_{k-1} + \mathbf{u}'_0)] - \mathbf{C} \cdot \mathbf{C}' \cdot (\mathbf{u}_b)_{k-1}. \quad (2)$$

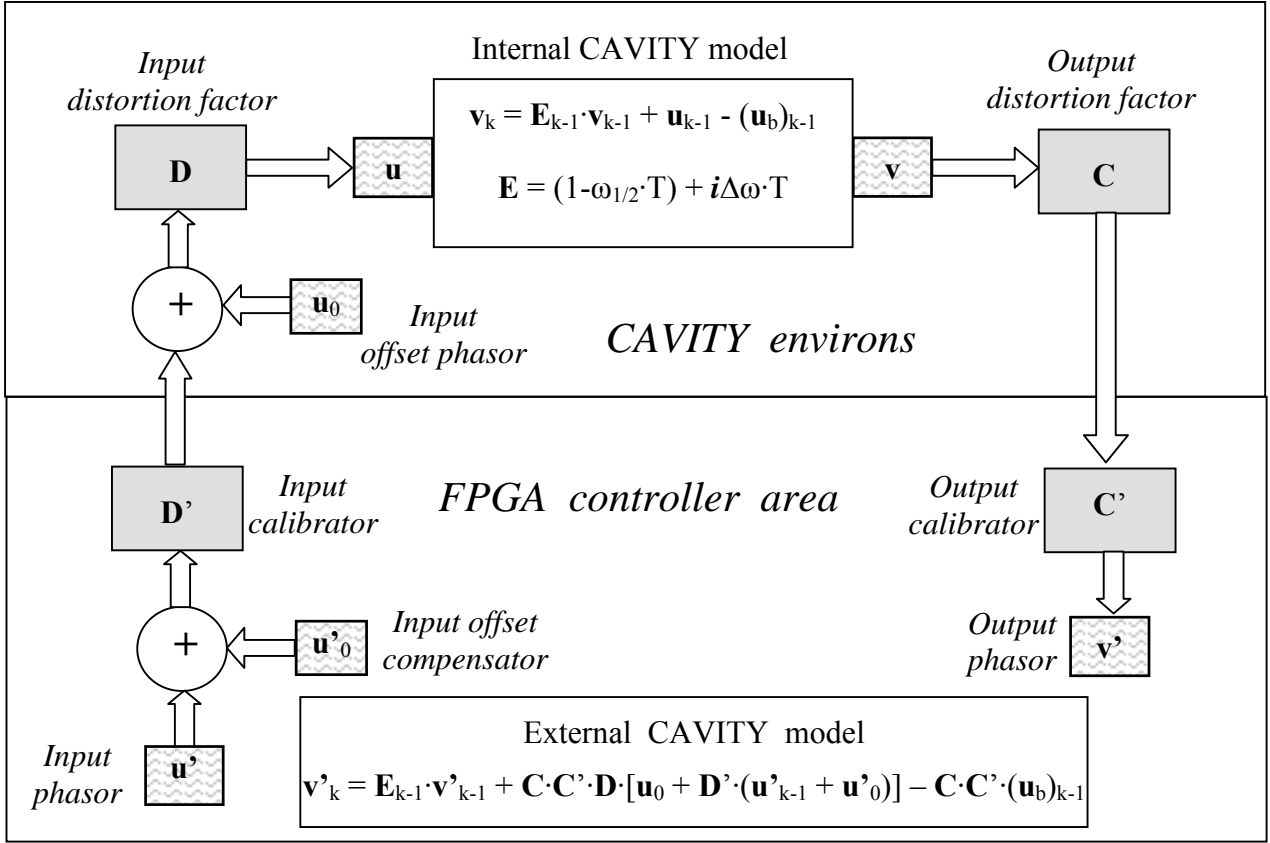


Figure 2. Algebraic model of cavity environment system

The calibration procedure is carried out experimentally applying the feed-forward driving in the following steps.

1. Initial calibration for the signal of the intermediate frequency 250 kHz is performed as follows:
 - signal scaling to match the range of the FPGA registers
 - signal level shifting to compensate the *down-converter* offset.

2. Output scaling

The required scaling factor $|C'| = 1/|C|$ is determined, so the detected value $|v'|$ corresponds to the real cavity gradient taken from *DOOCS* indicator (*Distributed Object Oriented Control System*).

3. Input offset compensation

The required input offset compensator value $u'_0 = -(D')^{-1} \cdot u_0$ is determined, so to minimize the output signal of the *vector-modulator* (equivalent to the condition: $u \approx 0$). The linear driving with feed-forward table is applied covering the proper range of only the real (I) and then imaginary (Q) components.

4. Loop phase calibration

The required phase value $\arg(C' \cdot D') = -\arg(C \cdot D)$ is determined, so the input phase $\arg(u')$ equals the output phase $\arg(v')$ in the resonance condition.

The desired output phase calibration, so $\arg(C') = -\arg(C)$, requires beam transient procedure. The output phase calibration has not been performed.

5. Loop scaling

The required scaling component $|D'| = 1/|D|$ is determined, so the detected value $|v'|$ corresponds to the output of the cavity MATLAB model driven in the same condition with the input phasor u' and the parameter factor E .

Actually, due to circuit nonlinearities the input scaling factor $F = |D' \cdot D|$ is no stationary during a pulse.

Consequently, the reduced cavity model seen internally by the controller is expressed, after calibration procedure:

$$v'_k = E_{k-1} \cdot v'_{k-1} + F_{k-1} \cdot u'_{k-1} - (u'_b)_{k-1} \quad \text{for} \quad u'_b = CC' \cdot u_b. \quad (3)$$

3. CAVITY PARAMETERS IDENTIFICATION

The cavity parameters identification is an essential task for the comprehensive control algorithm [2]. The feed-forward, as a direct control, can well support the feed-back mode according to the recognized model of the process. The cavity discrete model (1) can be expanded to the scalar equations without the beam, applying the real (v_r , u_r) and imaginary (v_i , u_i) components of the envelope \mathbf{v} and \mathbf{u} respectively, for step k as follows:

$$(v_r)_k - (v_r)_{k-1} = (\Delta v_r)_k = -T \cdot \Delta \omega_{k-1} \cdot (v_i)_{k-1} - T \cdot \omega_{1/2} \cdot (v_r)_{k-1} + F_{k-1} \cdot (u_r)_{k-1} \quad (4)$$

$$(v_i)_k - (v_i)_{k-1} = (\Delta v_i)_k = T \cdot \Delta \omega_{k-1} \cdot (v_r)_{k-1} - T \cdot \omega_{1/2} \cdot (v_i)_{k-1} + F_{k-1} \cdot (u_i)_{k-1} \quad (5)$$

The cavity half-bandwidth $\omega_{1/2}$ is supposed as a constant value. The time varying parameters of the cavity - detuning $\Delta \omega$ and scaling factor F are estimated by a series of base functions: polynomial or cubic *B-spline* functions.

Let us assume a *step-varying* cavity detuning $\Delta \omega_k$ as a L-order discrete series for successive steps k (linear combination of base functions), as follows:

$$\Delta \omega_k = \mathbf{w}_k * \mathbf{x} \quad (6)$$

where, the column vector \mathbf{x} contains L unknown series coefficients, and the row vector \mathbf{w}_k describes the given L-order series structure of the *step-varying* detuning model. An analogous decomposition is considered for the scaling factor F_k with a vector \mathbf{y} of unknown series coefficients. Consequently, the non stationary parameters in equations (4) and (5) are substituted by their linear decomposition. For a measurement range of N steps, the cavity model without beam consists of 2N equations expressed by the matrix form, as follows:

$$\Delta \mathbf{V} = \mathbf{X} * \mathbf{x} + \mathbf{V} \cdot \omega_{1/2} + \mathbf{Y} * \mathbf{y} = [\mathbf{X}, \mathbf{V}, \mathbf{Y}] * [\mathbf{x}; \omega_{1/2}; \mathbf{y}] = \mathbf{Z} * \mathbf{z} \quad (7)$$

where,

$\Delta \mathbf{V}$ – total output difference vector,

\mathbf{V} – total output vector,

\mathbf{X} – structure matrix of the model part related to the detuning,

\mathbf{Y} – structure matrix of the model part related to the scaling factor,

$\mathbf{Z} = [\mathbf{X}, \mathbf{V}, \mathbf{Y}]$ – total structure matrix,

$\mathbf{z} = [\mathbf{x}; \omega_{1/2}; \mathbf{y}]$ – resultant column vector of unknown coefficients.

The vector \mathbf{z} can be effectively estimated, in a noisy condition, with the over-determined matrix equation created for a long enough range of N steps. Multiplying two sides of the above equation by matrix transposition \mathbf{Z}^T , the solution for the vector \mathbf{z} is given by:

$$\mathbf{z} = (\mathbf{Z}^T * \mathbf{Z})^{-1} * \mathbf{Z}^T * \Delta \mathbf{V} \quad (8)$$

It is a unique and optimal solution, according to the *least square* (LS) method for the measured data of the vector $\Delta \mathbf{V}$ and the structure matrix \mathbf{Z} .

The comprehensive algorithm of the cavity parameters identification was implemented in the Matlab system with several possible variants of its application.

4. CHECHIA CAVITY CONTROL

4.1. Feed-forward driving

The CHECHIA cavity testing has been carried out according to the scheme of figure 2. The control data generated by Matlab system is loaded to the part of the internal FPGA memory as a feed-forward (FF) table driving the CHECHIA cavity. The output data of the cavity is acquired to another area of the memory during a pulse operation of the controller. Subsequently, the input and output data are conveyed to the Matlab system for the parameters identification processing between the pulses. For the comparison, the Matlab cavity model is driven in the same condition: with the same FF table applying the estimated CHECHIA parameters – half-bandwidth, detuning vector and no stationary scaling factor.

The cavity control was performed for different *flattop* levels of the field gradient within the range of $v_0 = 10 \div 30$ MV with the preferred phase $\varphi_0 = 0$. Due to potential circuit nonlinearities, the calibration procedure was accomplished for each desired *flattop* level.

The required input phasor \mathbf{u} (for the feed-forward table) is calculated for each desired output phasor \mathbf{v} according to the cavity electrical model (1) without the beam for the supposed values of the cavity parameters.

The required amplitude $|\mathbf{u}| = 2v_0 \cdot T \cdot \omega_{1/2}$ and time varying phase $\varphi_k = \varphi_{k-1} + T \cdot \Delta \omega_{k-1}$ of the input envelope is estimated in order to drive the cavity in the resonance condition during the *filling* time.

The envelope of the cavity voltage is stable during the flattop operation and the solution of the equation (1) for a steady state is as follows:

$$\mathbf{u} = v_0 \cdot \exp(i\varphi_0) \cdot (\omega_{1/2} - i\Delta\omega) \cdot T \quad (9)$$

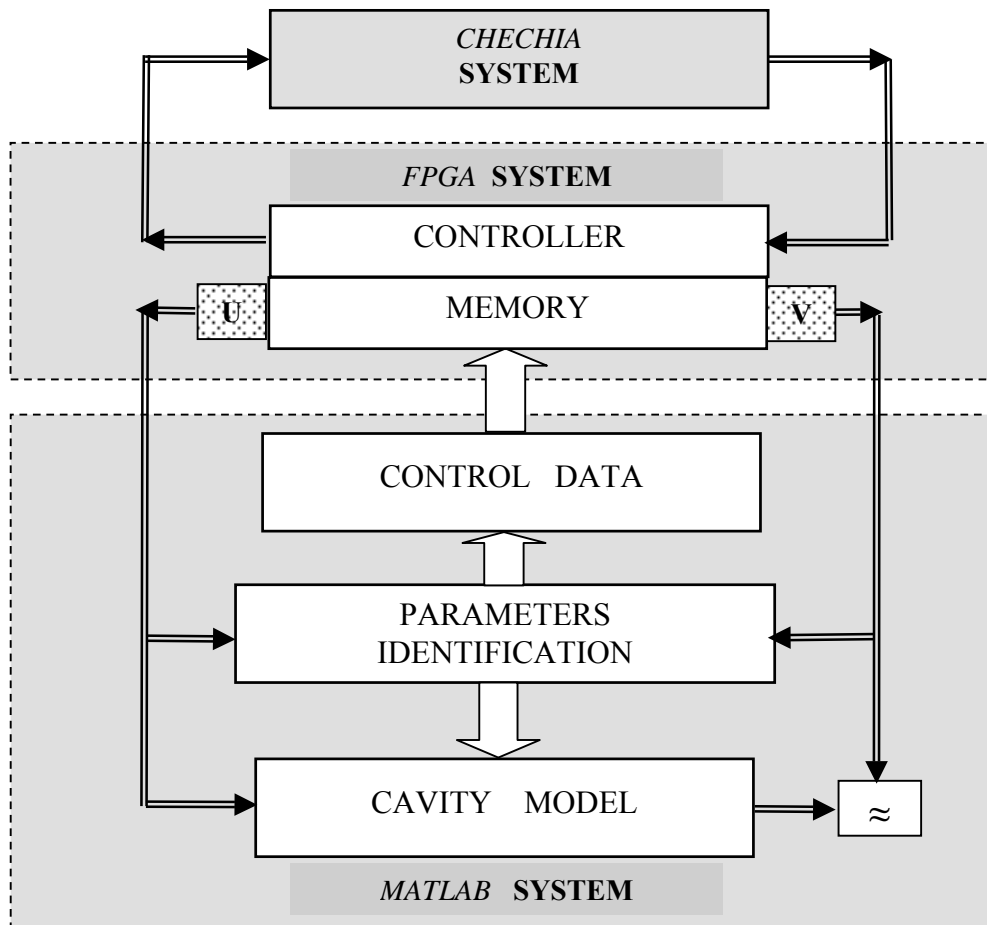


Figure 3. Functional diagram of testing system for CHECHIA cavity driven with FPGA controller supported by MATLAB system

The control algorithm can use the estimated real cavity parameters to generate an improved feed-forward table for a next pulse, assuming repeatable condition for succeeding pulses.

Unfortunately, due to a loose mechanical assembly of the CHECHIA cavity tuner, an unstable condition caused a variation of the predetuning value within the range of *ca.* 200 Hz for different pulses (*micro-phonics* effect). So, the iterative feed-forward control algorithm could not be employed.

Nevertheless, the simple vector of cavity detuning has been supposed for the given *flattop* level as the expected average one. Additionally, the *Master Oscillator* frequency has been tuned to the supposed cavity detuning vector, so to optimize the klystron power distribution during the flattop level. The method of successive approximation applying the estimated cavity detuning was carried out. The broken line with different slopes for *filling* and *flattop* was taken as the supposed cavity detuning curve for the control purpose.

The input and output data are acquired for several random pulses for the given feed-forward table related to the desired *flattop* level. The results of experiments are presented in the figures 4 - 6 for 10, 20, 25 MV respectively.

The next experiments would try to verify the Matlab cavity model and reliability of the identification algorithm. The data readouts were repeated for many random pulses. Some better examples are selected, so the supposed detuning vector matches closer to the estimated curve. The CHECHIA cavity and Matlab model responses are compared, while driven in the same condition. The results of experiments are presented in the figures 7 - 11 for 10, 15, 20, 25, 30 MV respectively. A quite good agreement for the envelopes of CHECHIA cavity and

MATLAB model is observed in all cases, and two curves are hardly distinguishable in that scale. The Matlab model of the cavity was confirmed using the CHECHIA setup. The cavity parameters identification was verified for the control purpose. The proposed algorithm yields a reliable smooth line of estimated detuning which is very useful for the control system purpose.

4.2. Feed-forward with Feedback driving

The required data for the set point table are calculated according to the cavity electrical model (1) for the supposed values of the cavity parameters. The amplitude $|v| = 2v_0(1 - \exp(-\omega_{1/2} \cdot kT))$ and time varying phase $\varphi_k = \varphi_{k-1} + T \cdot \Delta\omega_{k-1}$ are estimated in order to drive the cavity in the resonance condition during *filling* time. The complex envelope equals $v_0 \cdot \exp(i\varphi_0)$ and is stable during the *flattop* operation for the set point table.

The test of the feed-forward cavity driving was repeated and the feedback loop was closed starting with a small value of a loop gain. No filter has been applied. A loop gain was gradually increased to the possible maximum value for a stable condition. The loop gain of ~ 250 and ~ 150 was achieved for the *flattop* cavity gradient of 10 MV and 20 MV respectively. The results of experiments with loop gain of 100 are presented in the figures 12 - 14 for 10, 20, 25 MV respectively. The *flattop* area for the amplitude and phase curves is zoomed in figure 15.

5. CONCLUSION

The initial tests, applying the FPGA based controller, have been carried out with the TESLA type superconductive cavity in DESY. The CHECHIA cavity was successfully driven by feed-forward and feedback mode. The calibration procedure is presented as an essential approach to the efficient control of the cavity. The parameters identification algorithm, according to the algebraic model of the superconductive cavity is proposed for the control system development. The over-determined matrix equation for the input-output relation is considered with the least squares solution for the unknown parameters. The polynomial approximation or cubic *B-spline* functions are applied for the cavity parameters estimation. The electrical model of the cavity has been confirmed using the CHECHIA cavity set-up. The algorithm of the cavity parameters identification is verified as the useful tool for the cavity detuning recognition.

6. REFERENCES

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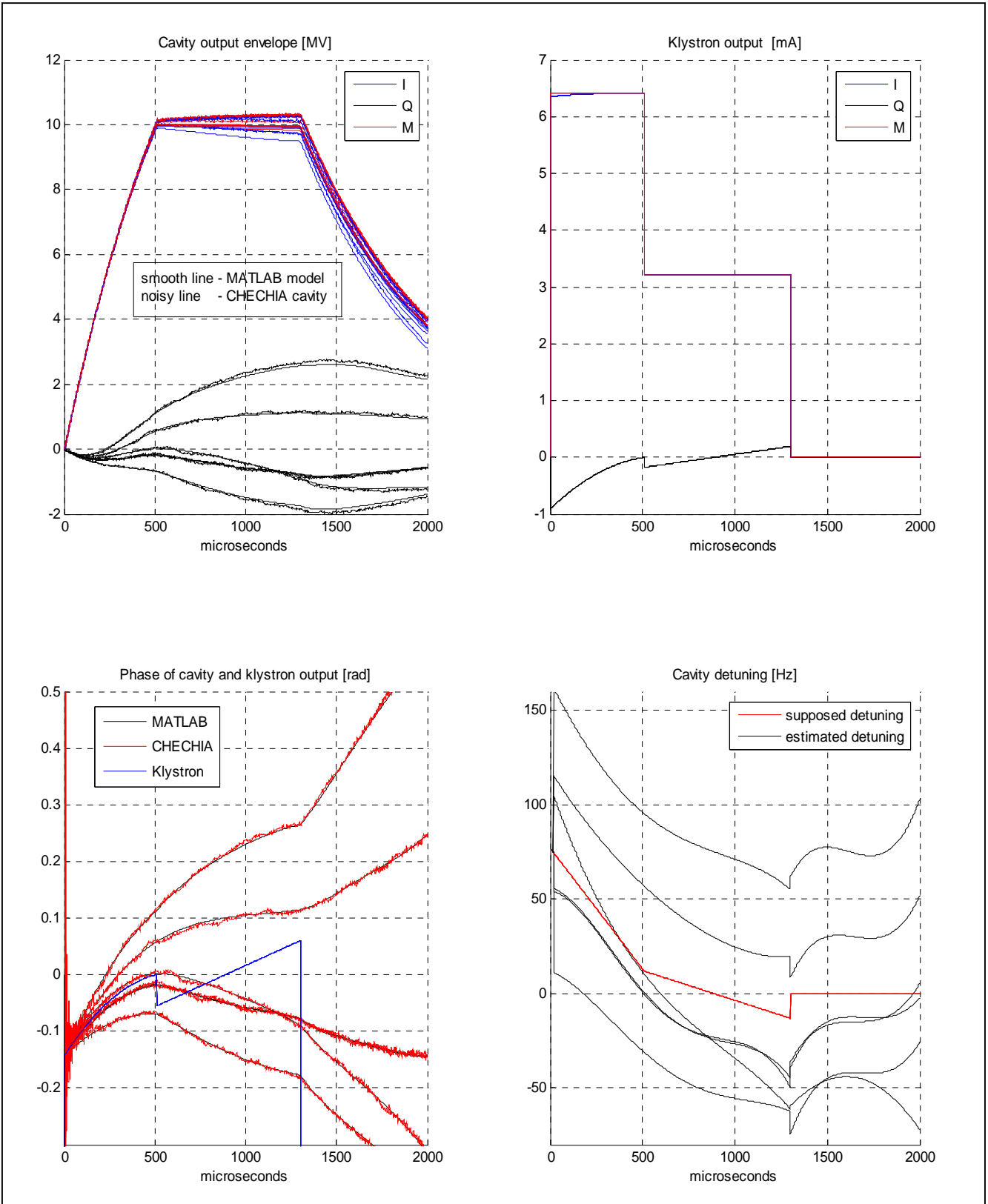


Figure 4. Feed-forward cavity driving: series of random readouts for 10 MV *flattop* level.

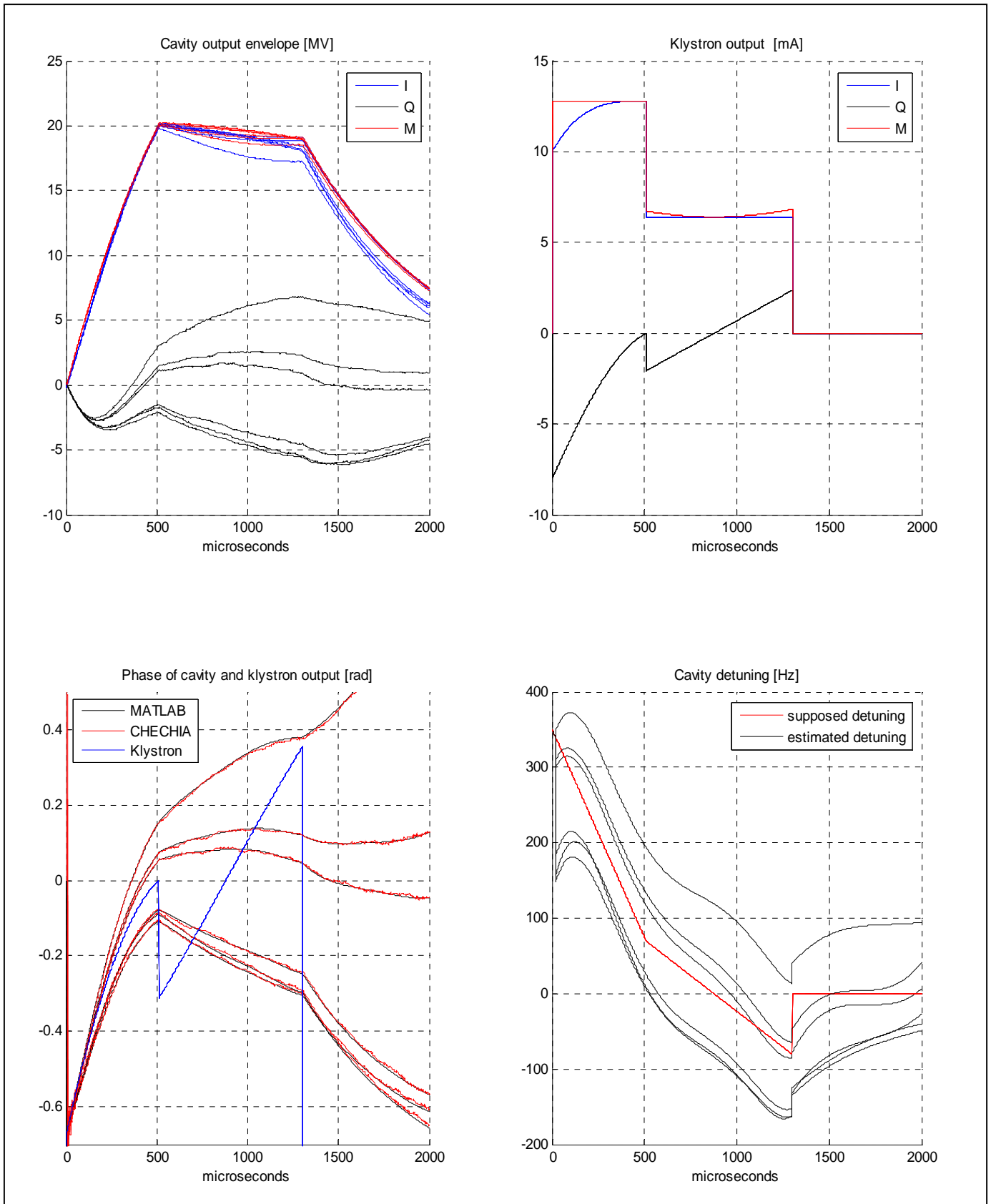


Figure 5 Feed-forward cavity driving: series of random readouts for 20 MV *flattop* level.

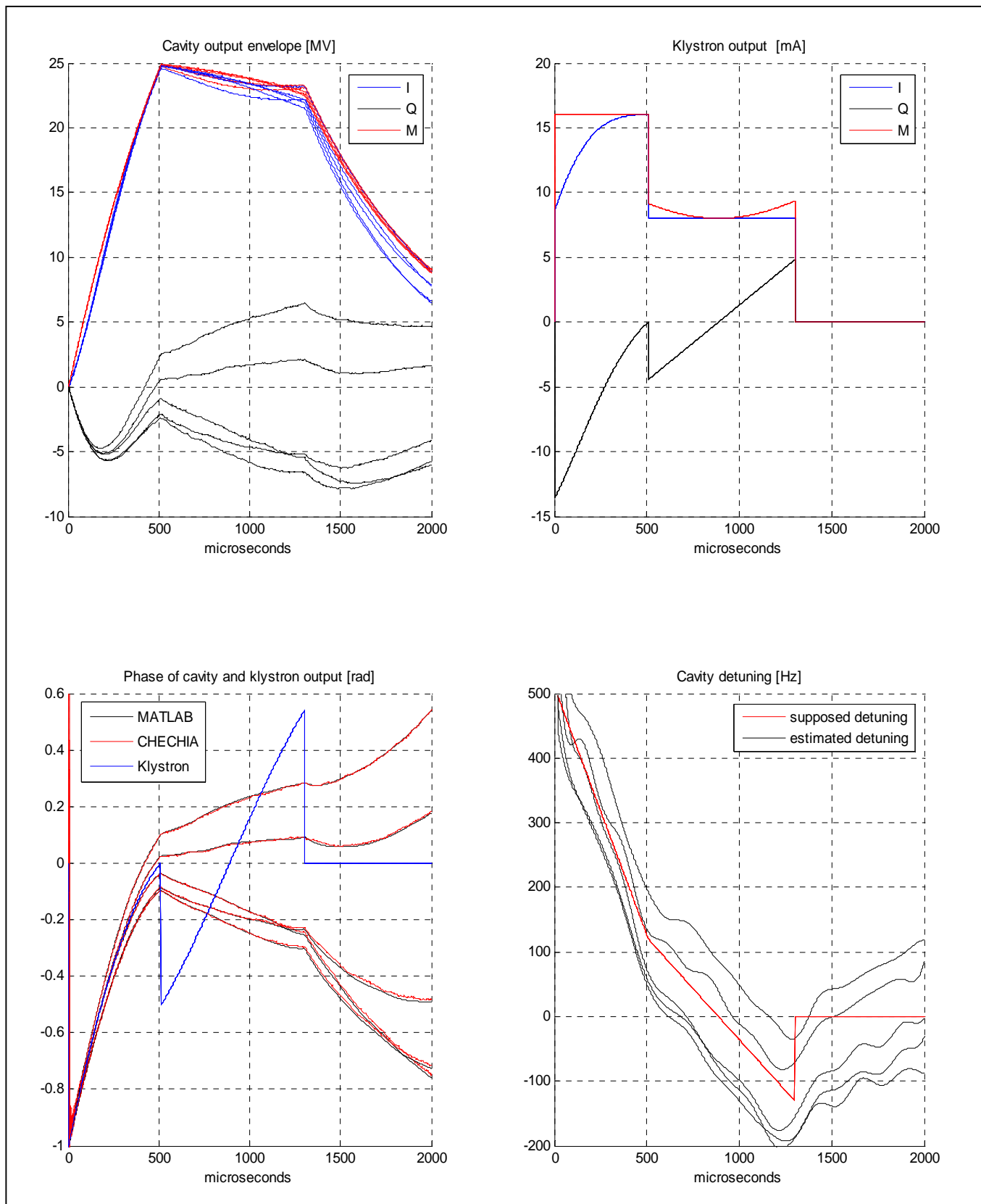


Figure 6. Feed-forward cavity driving: series of random readouts for 25 MV *flattop* level.

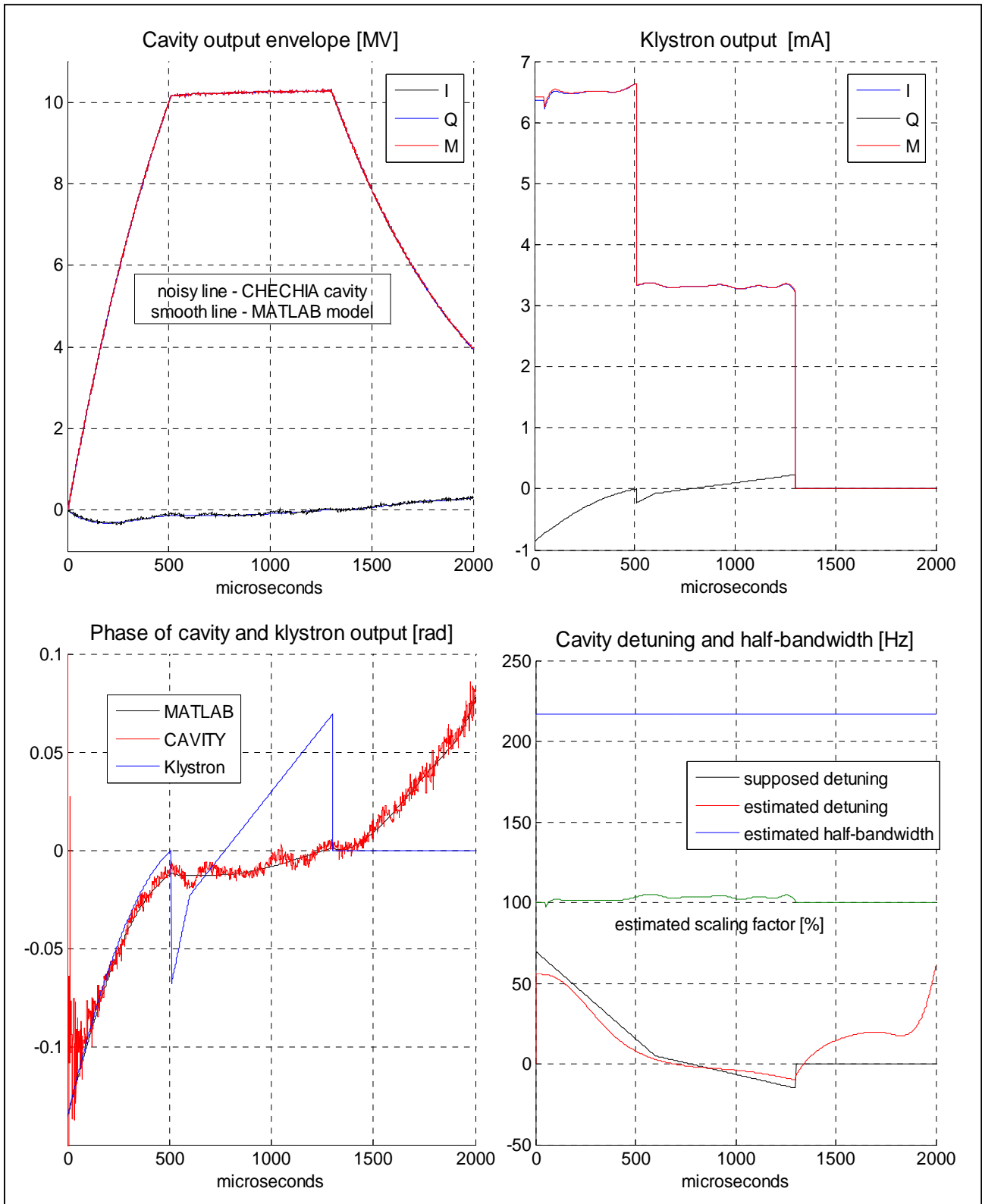


Figure 7. Feed-forward cavity driving: selected readout for 10 MV *flattop* level

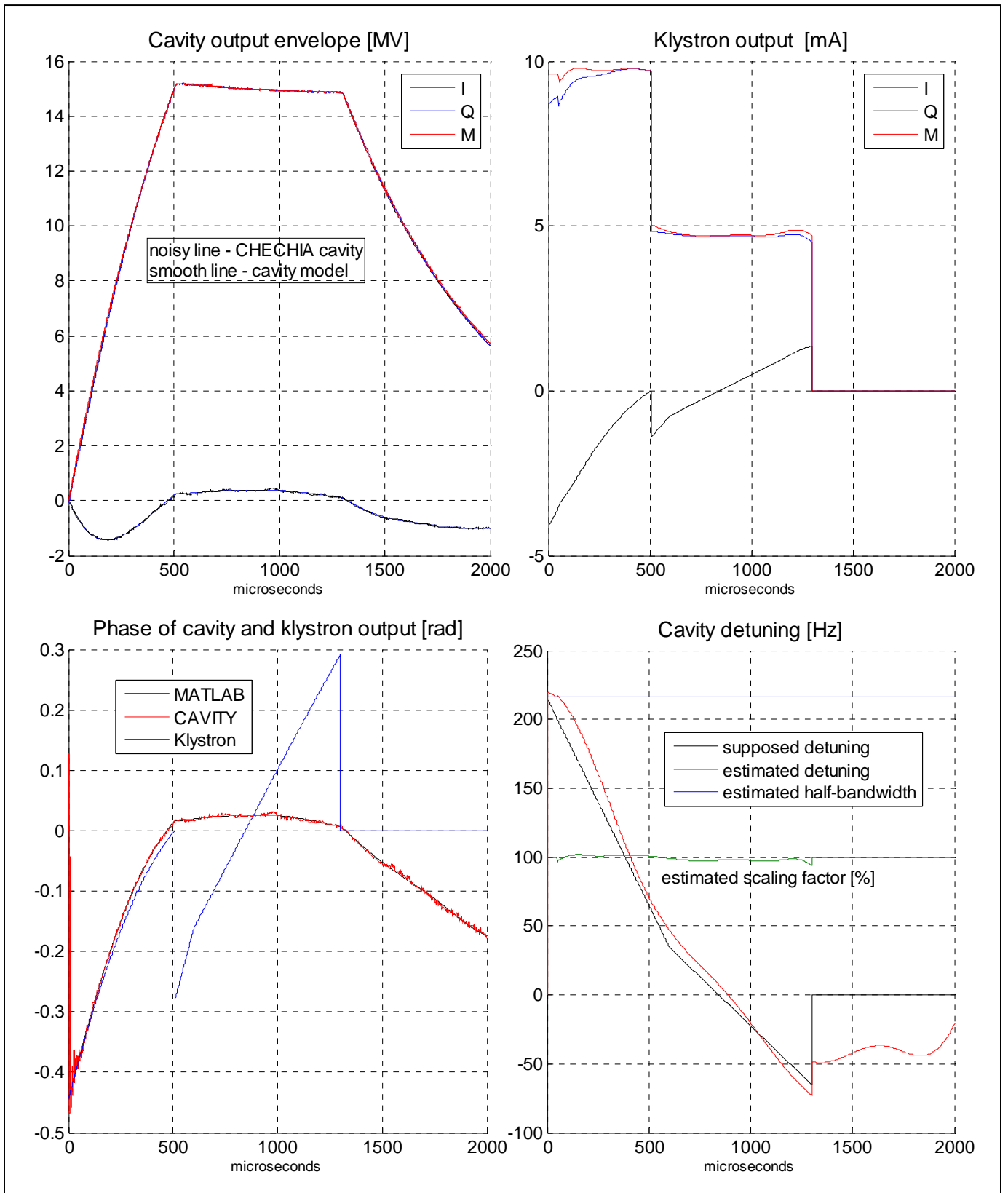


Figure 8. Feed-forward cavity driving: selected readout for 15 MV *flattop* level.

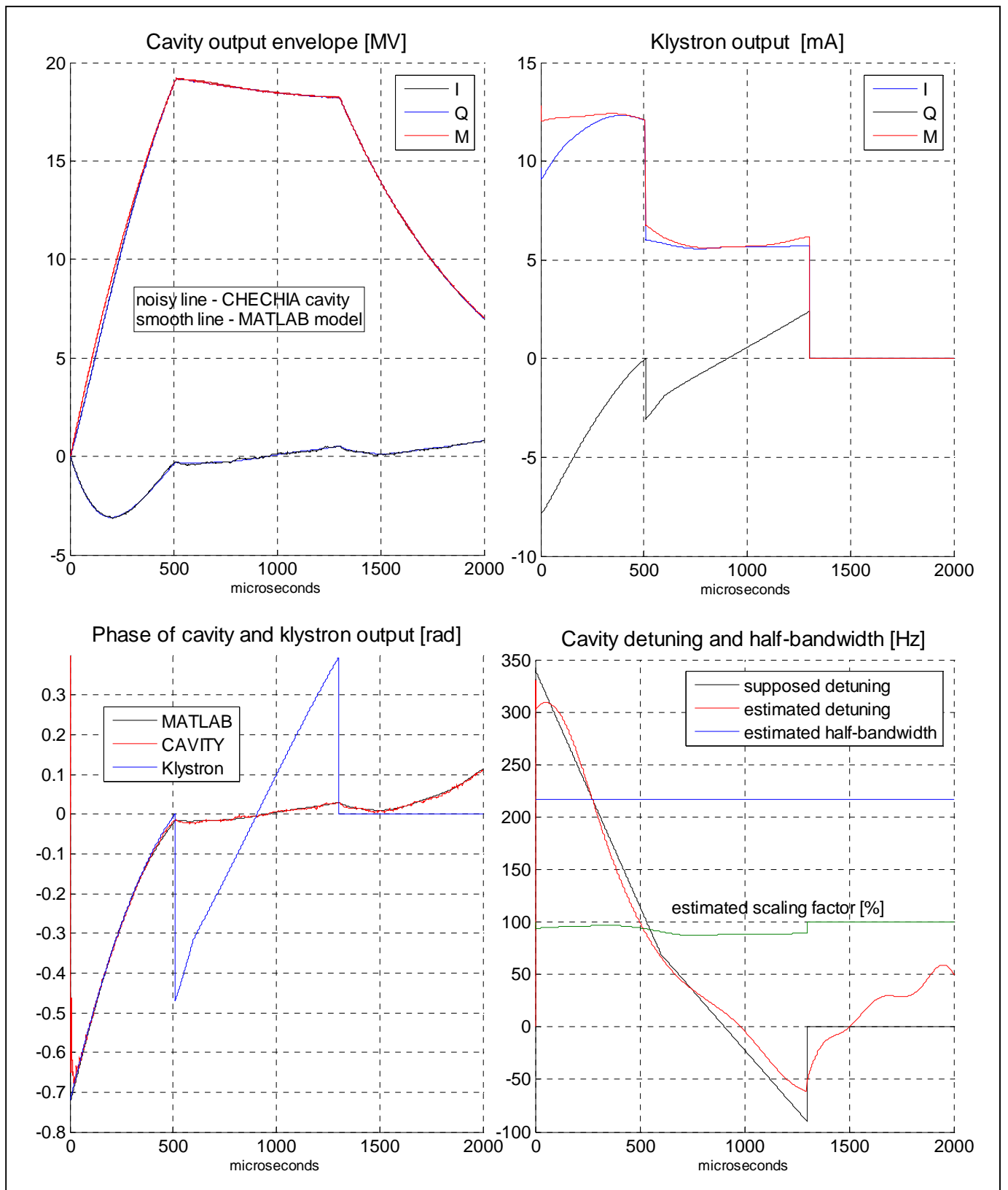


Figure 9. Feed-forward cavity driving: selected readout for ~20 MV *flattop* level.

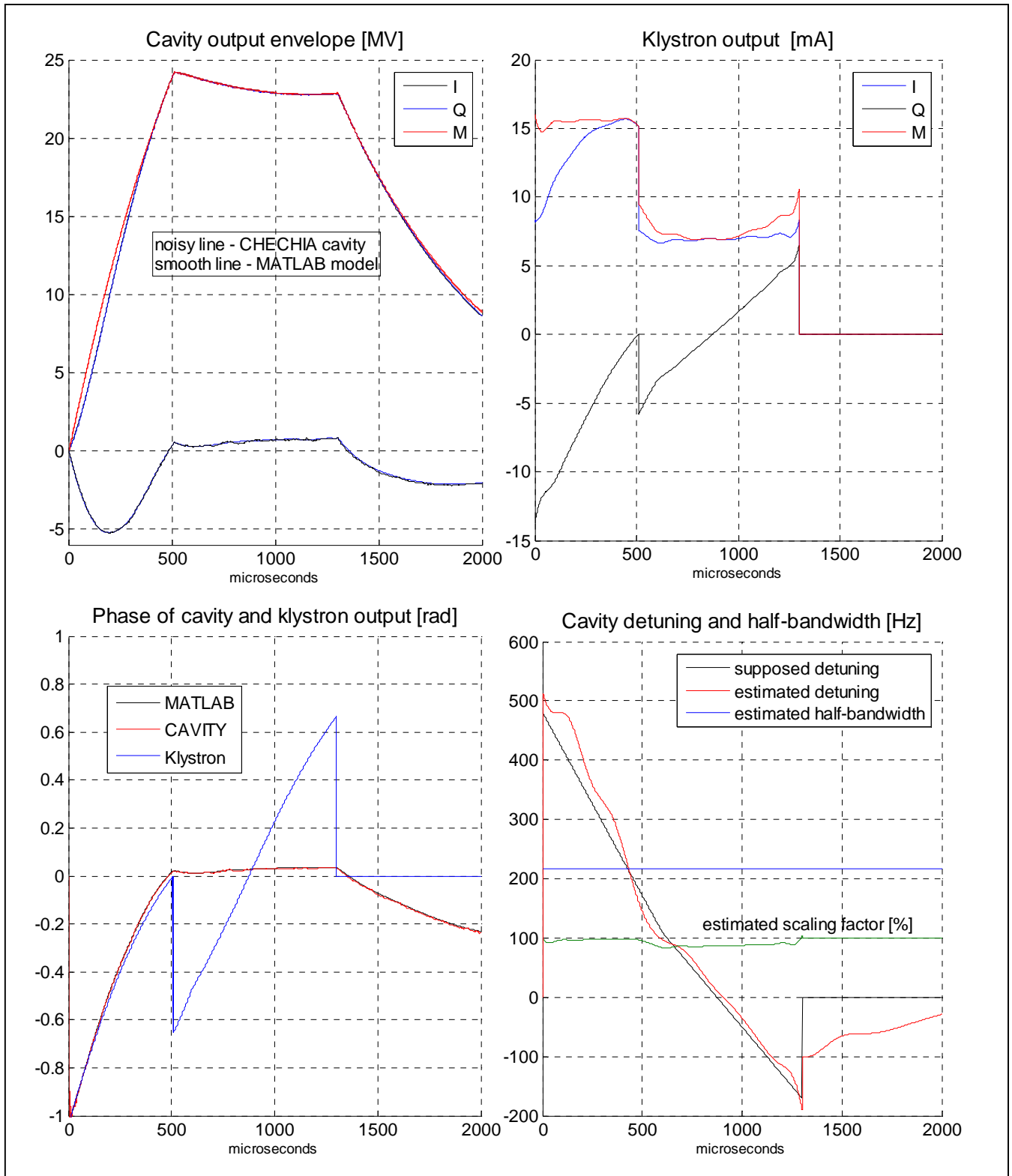


Figure 10. Feed-forward cavity driving: selected readout for ~25 MV *flattop* level.

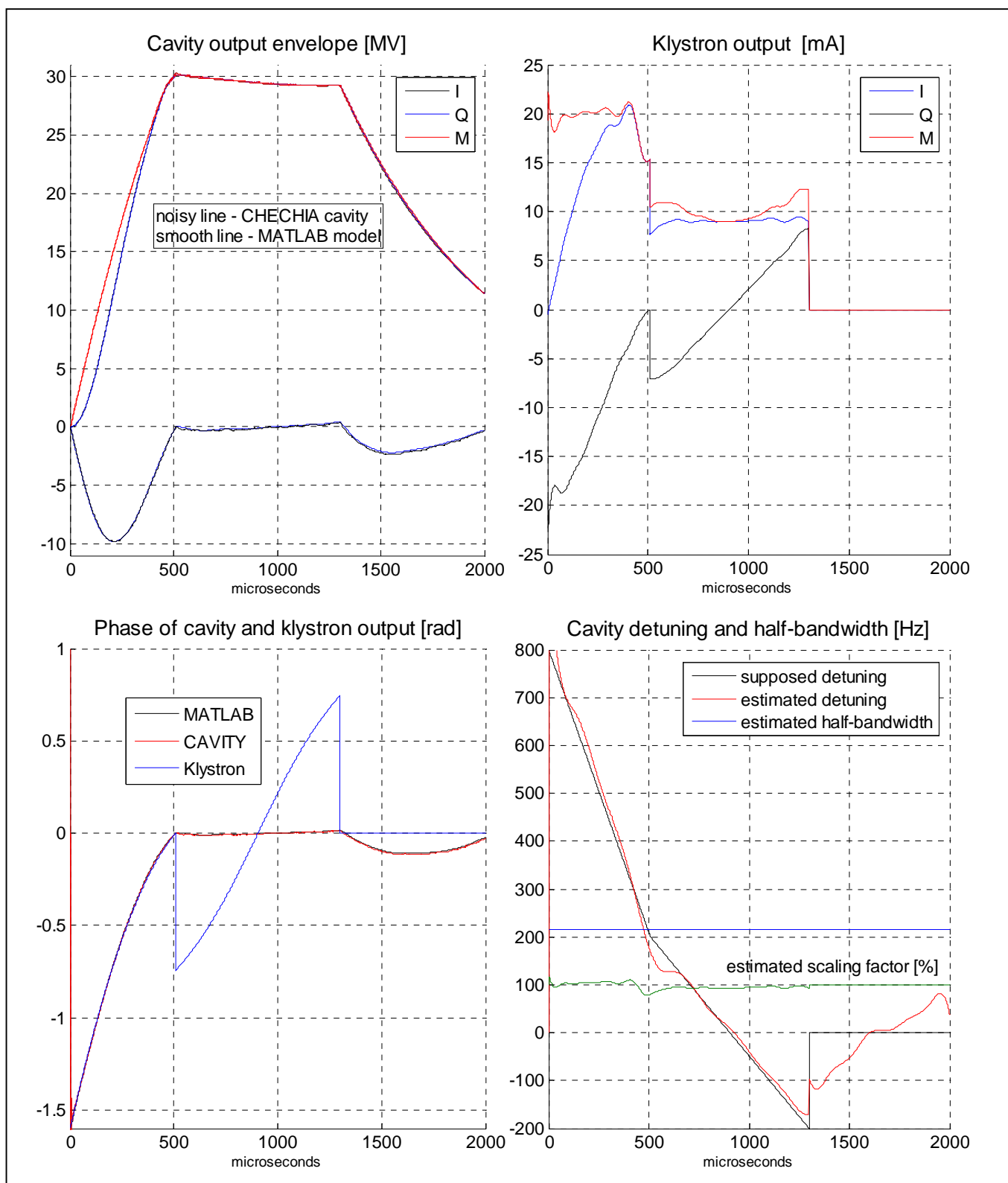


Figure 11. Feed-forward cavity driving: selected readout for 30 MV *flattop* level.

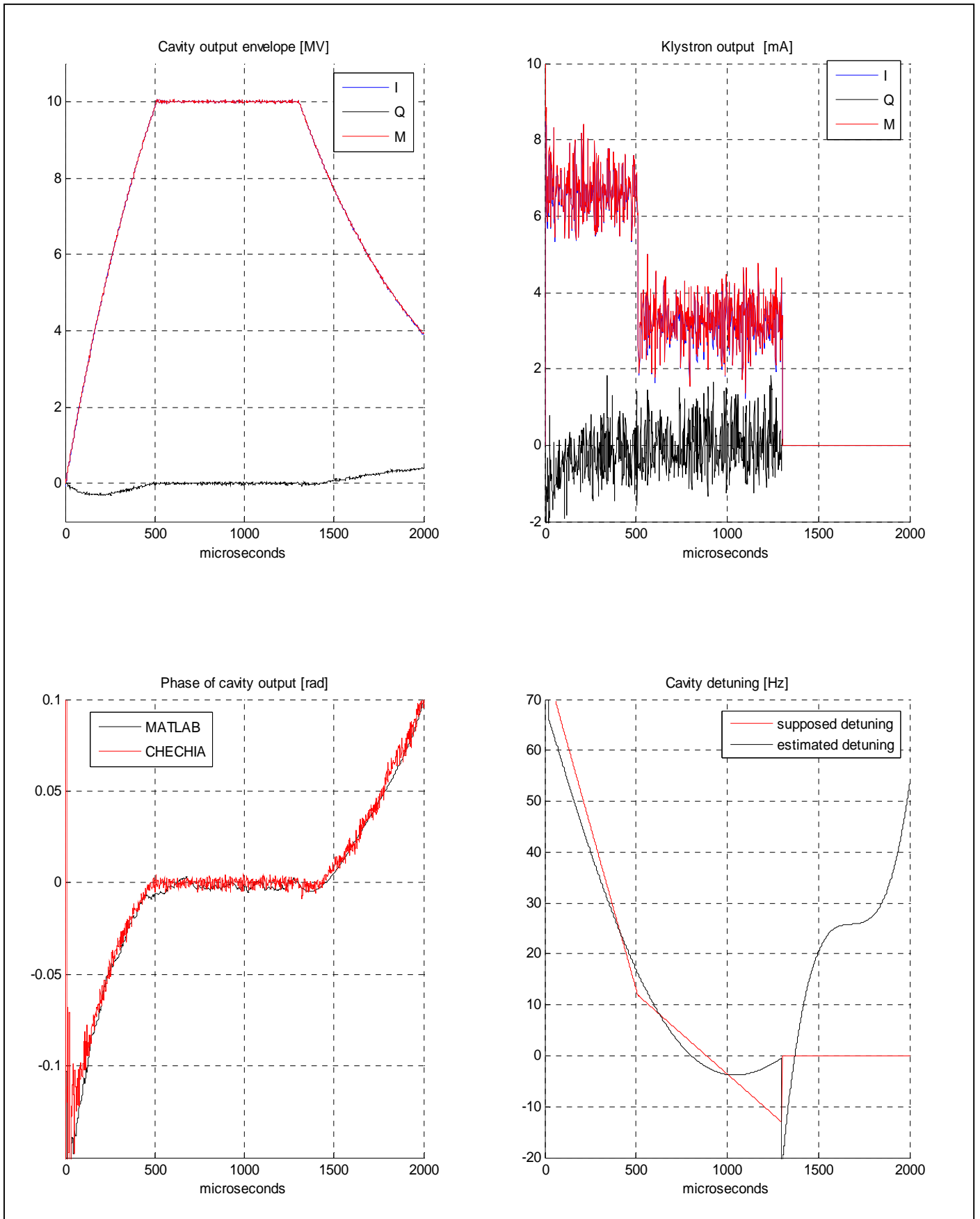


Figure 12. Feed-forward with feedback cavity driving (gain = 100): selected readout for 10 MV *flattop* level.

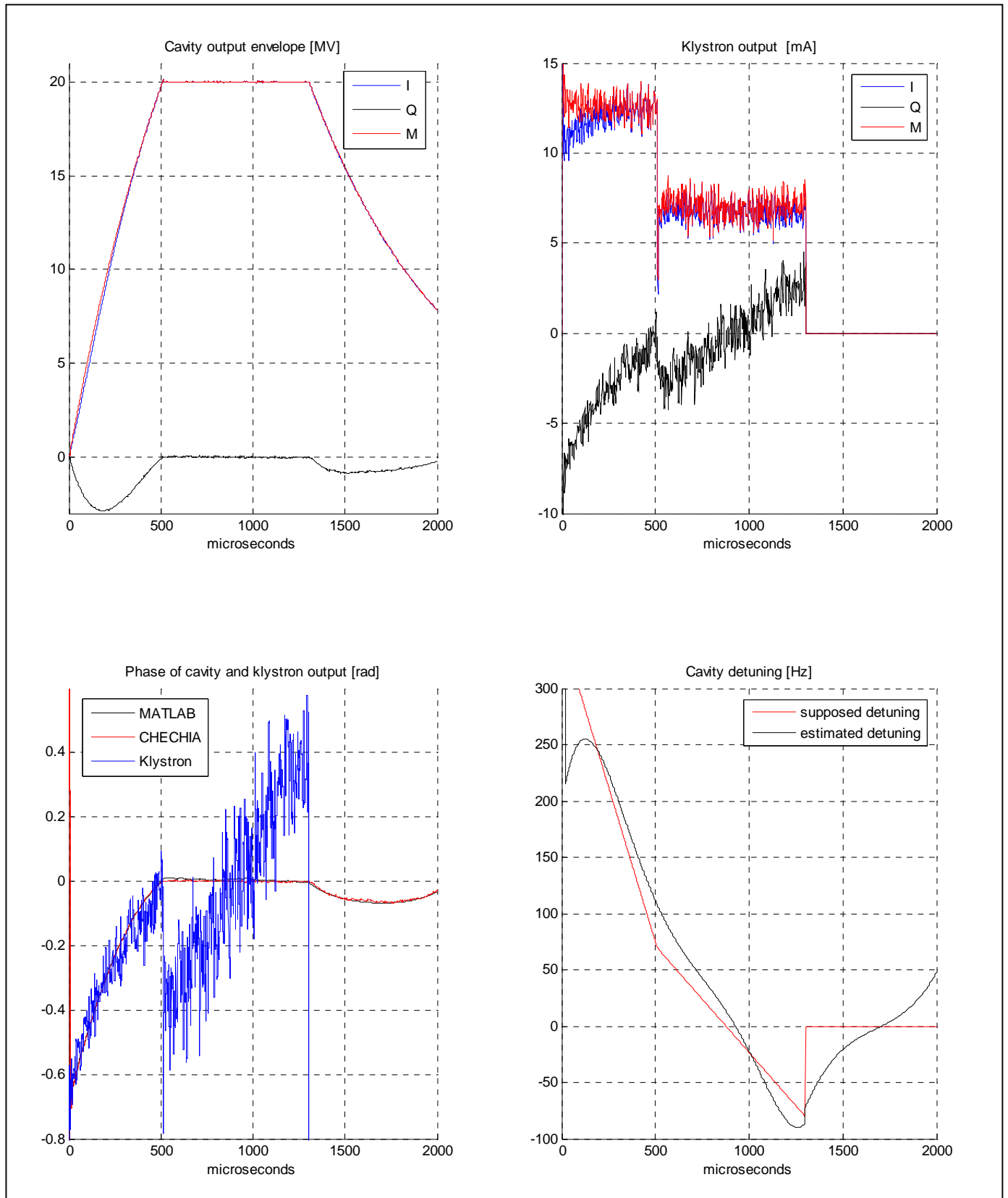


Figure 13. Feed-forward with feedback cavity driving (gain = 100): selected readout for 20 MV *flattop* level

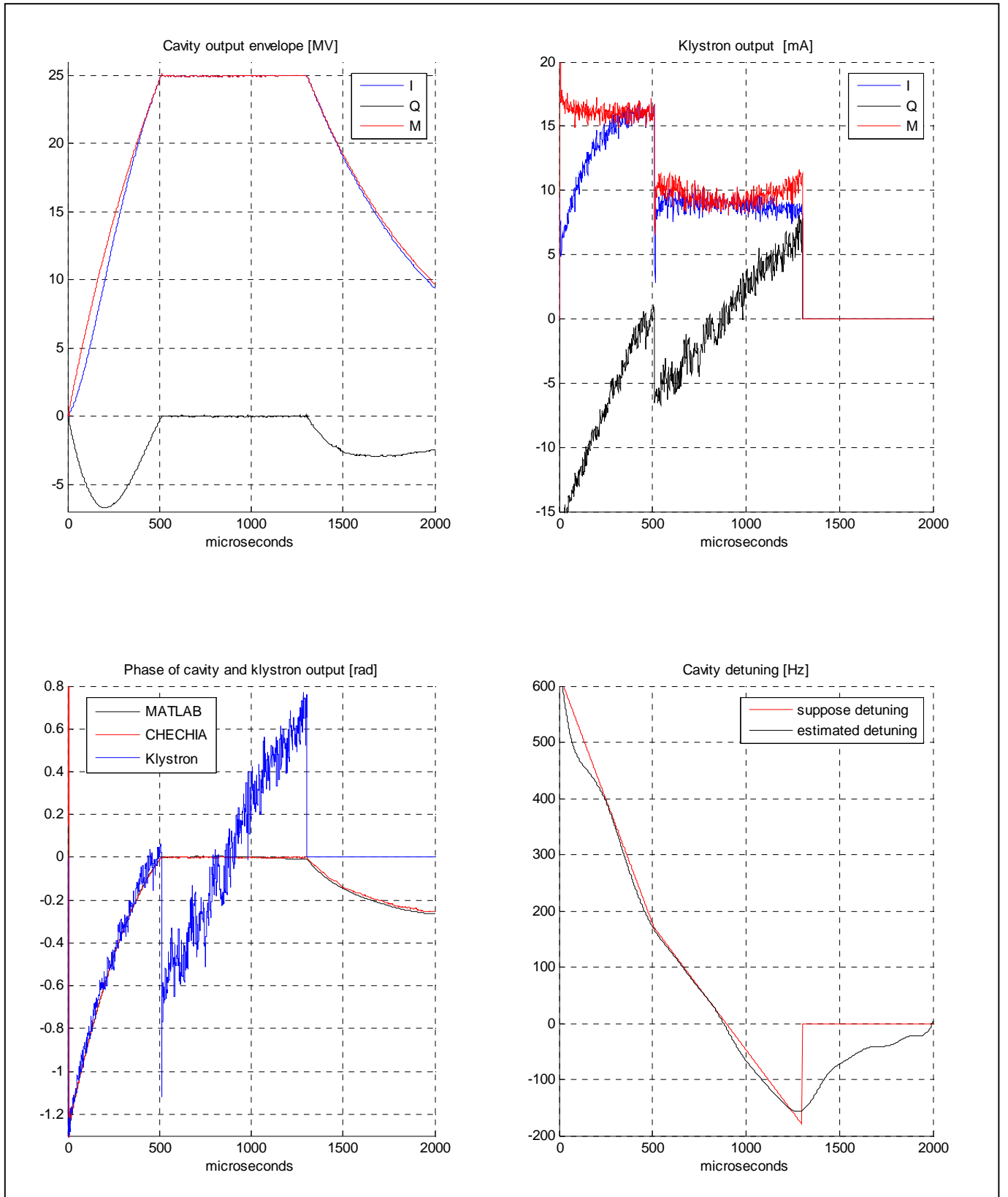


Figure 14. Feed-forward with feedback cavity driving (gain = 100): selected readout for 25 MV *flatop* level

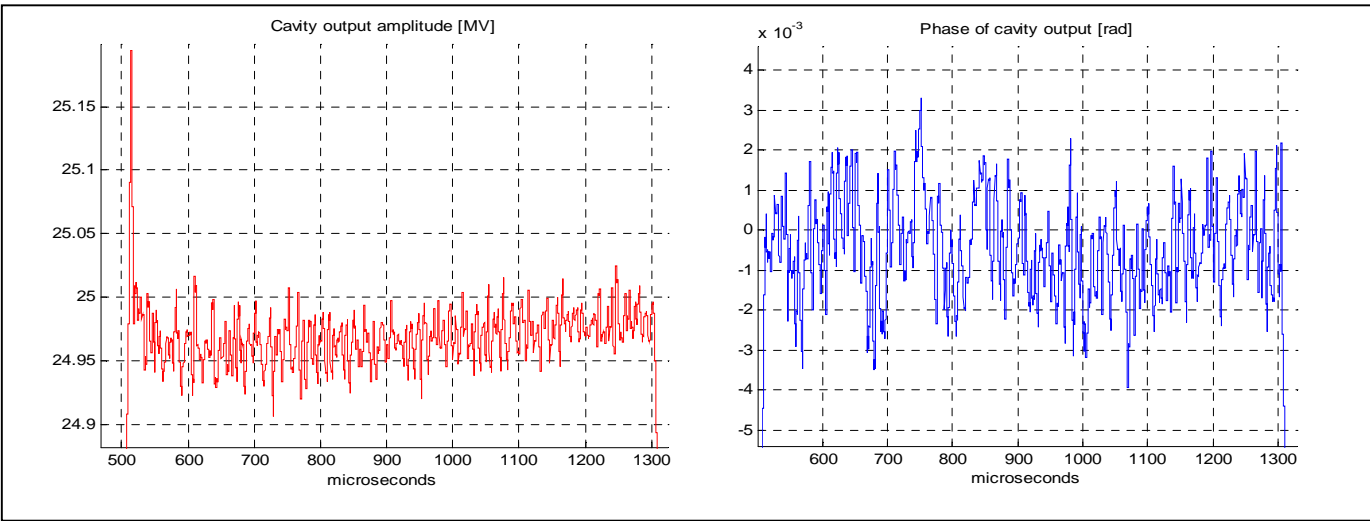
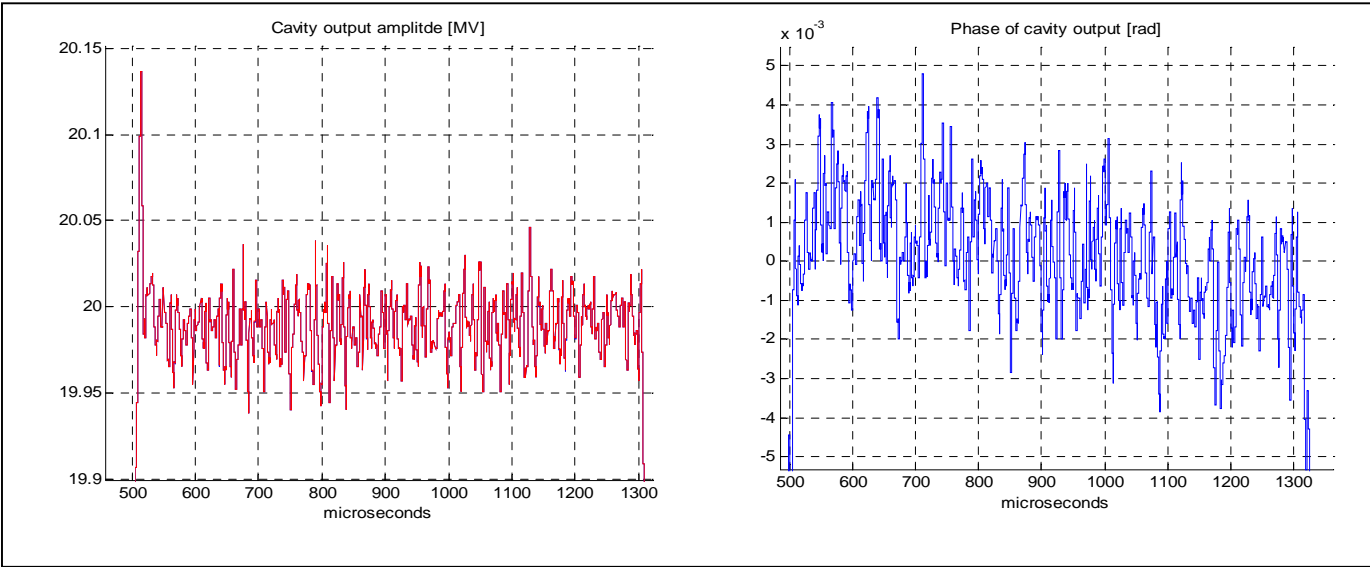
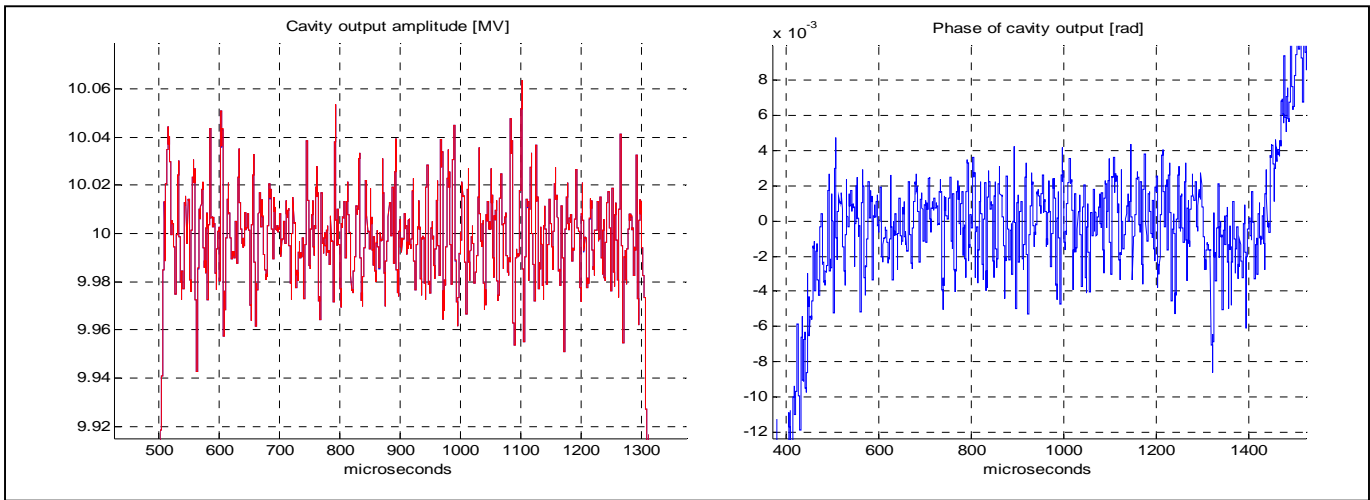


Figure 15. Feed-forward with feedback cavity driving (gain = 100): selected readouts for 10, 20, 25 MV flattop level –zoomed outlook for amplitude and phase curves