Iterative learning control

(Study of work by Christian Schmidt and others)

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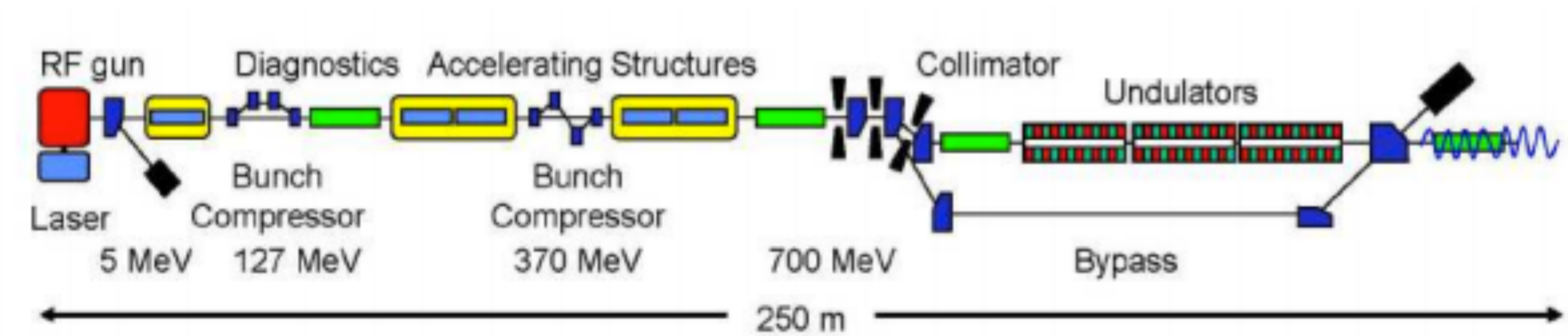
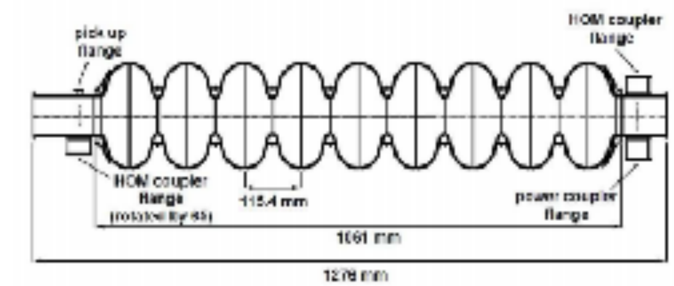
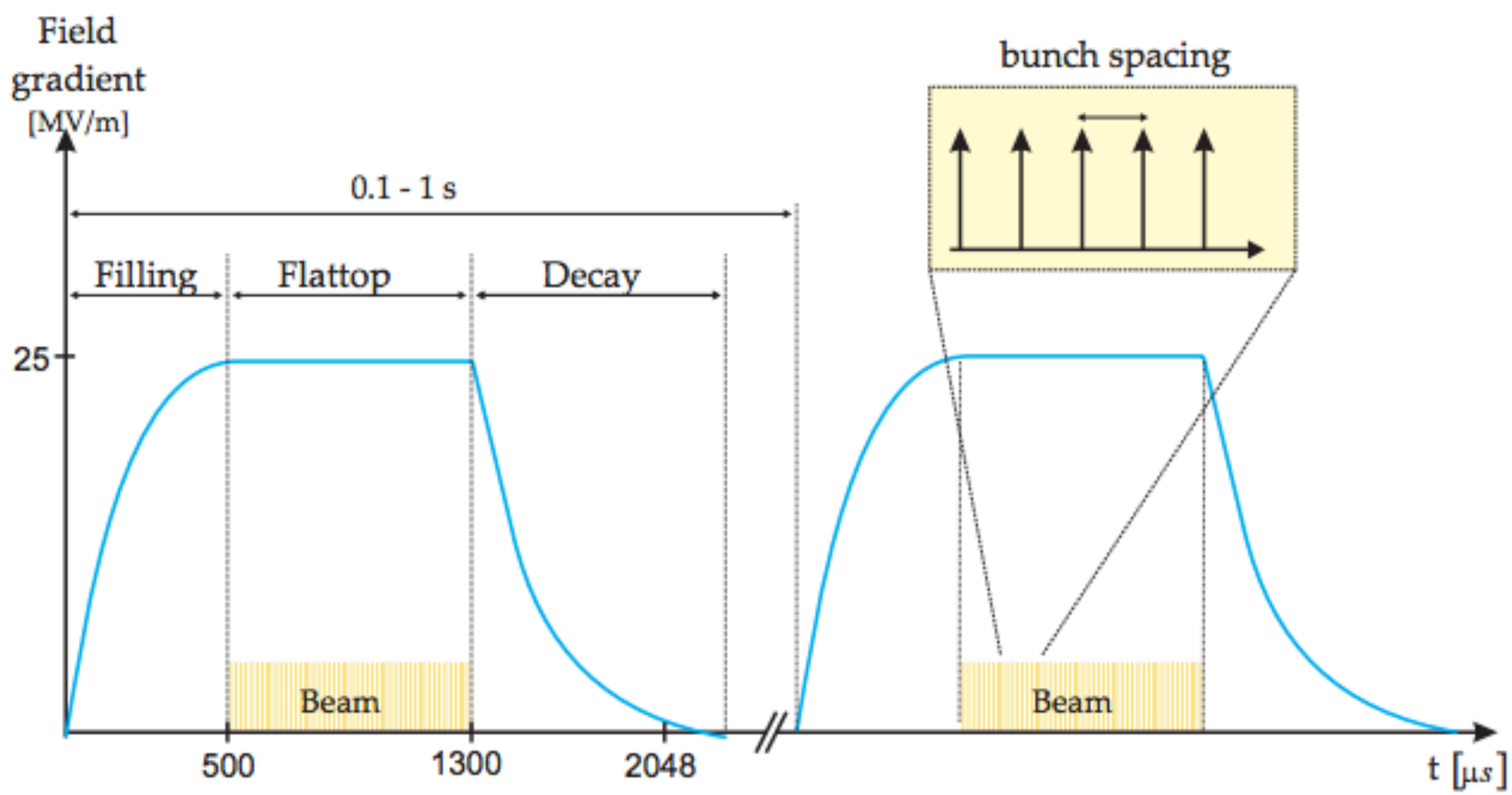
Free Electron Laser in Hamburg (FLASH) at DESY

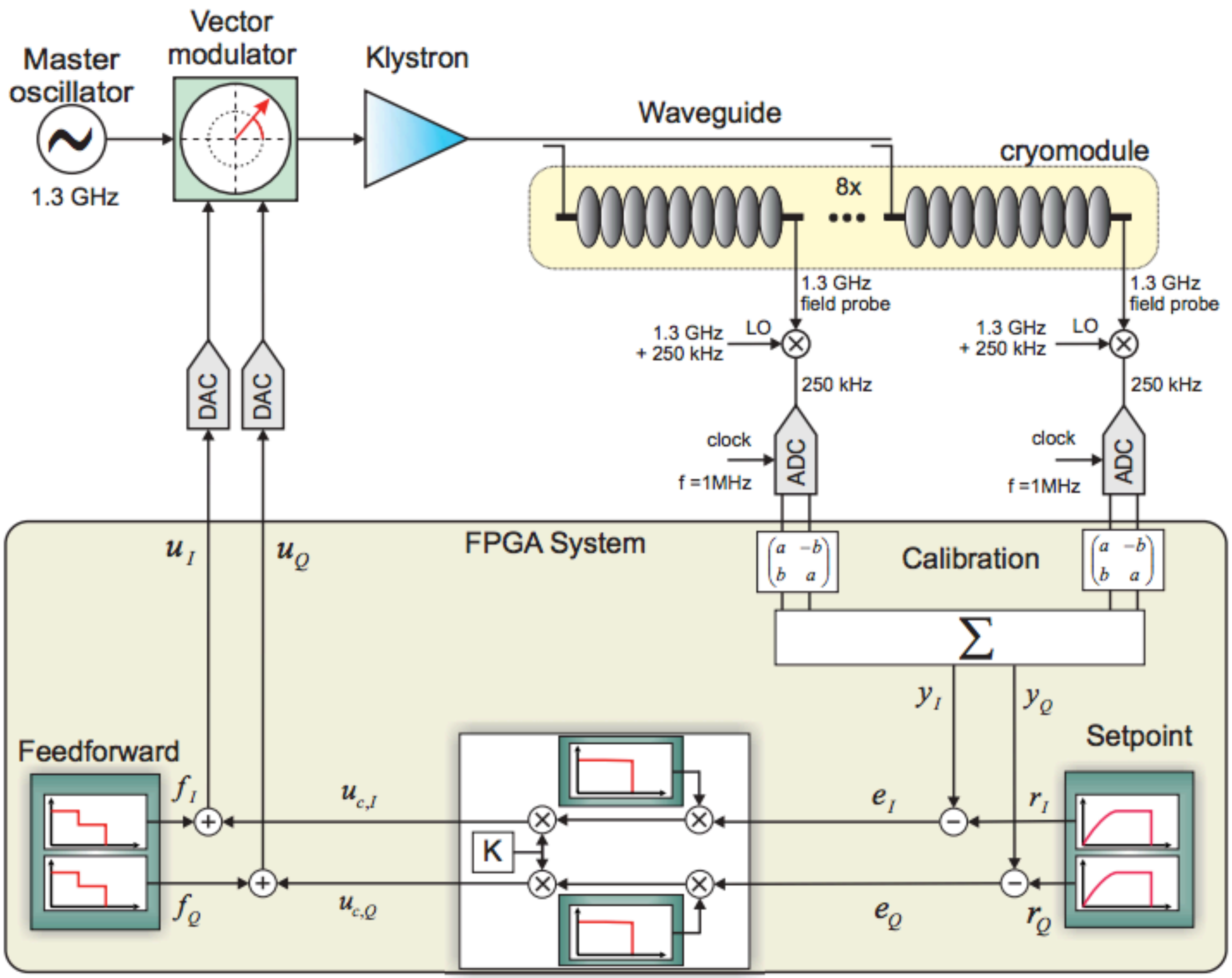




- pulsed RF Operation due to the thermal losses

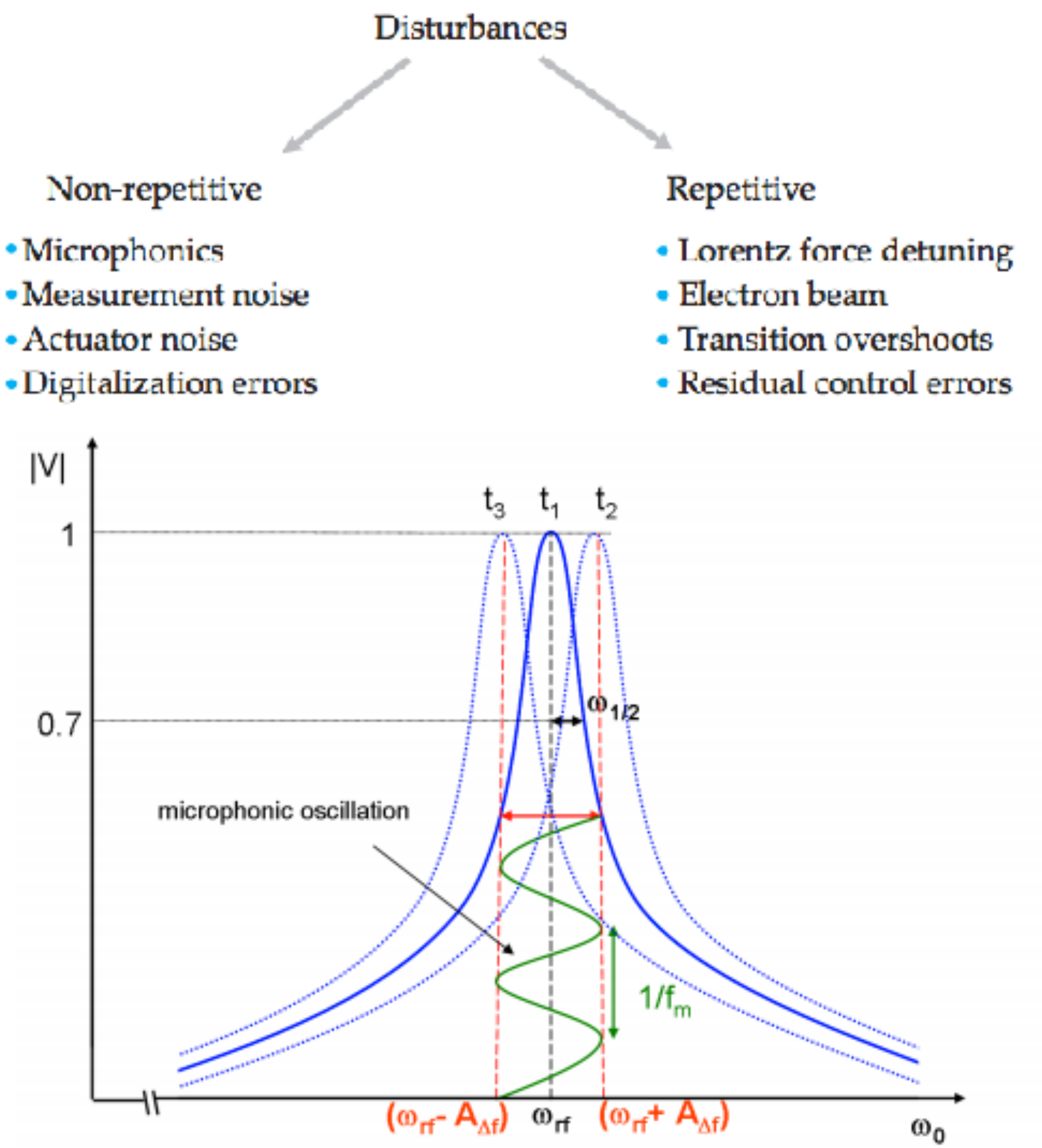


FLASH LLRF



Master oscillator
1.3 GHz
Vector modulator
Klystron
Waveguide
cryomodule
8x
1.3 GHz field probe
1.3 GHz field probe
1.3 GHz + 250 kHz
LO
250 kHz
1.3 GHz + 250 kHz
LO
250 kHz
clock
f =1MHz
ADC
clock
f =1MHz
ADC
DAC
DAC
FPGA System
Calibration
u_I
u_Q
y_I
y_Q
Setpoint
Feedforward
f_I
f_Q
$u_{c,I}$
$u_{c,Q}$
K
e_I
e_Q
r_I
r_Q

Disturbances - microphonic



- typically in a range up to a few hundred hertz, which in pulsed operation appears as fluctuations from pulse-to-pulse.

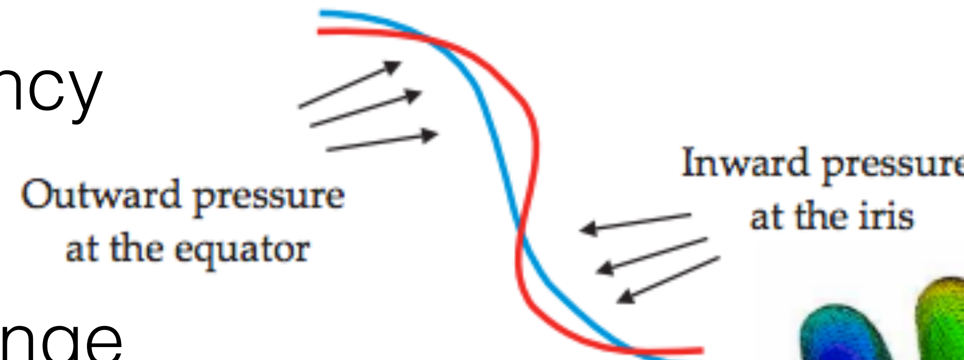
  The amplitude or resonance frequency change for FLASH type of cavities is typically $\sigma A\Delta\ f \approx 6$ Hz

- Can use (mechanical) feedback loop to compensate

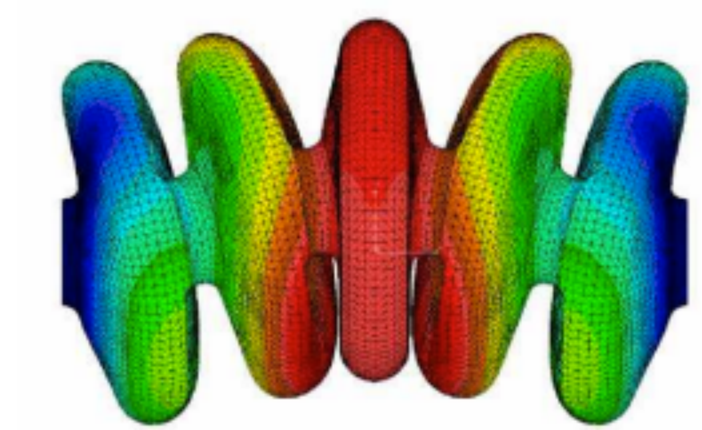
Disturbances - Lorentz force detuning

- stronger resonance frequency deviation
- If the RF field does not change from pulse-to-pulse, the deformations will show almost the same behavior
- For the pulsed operation mode only the transient response is measurable
(Deformations are disappeared before the next pulse starts, so the effect is repeated with the next pulse)

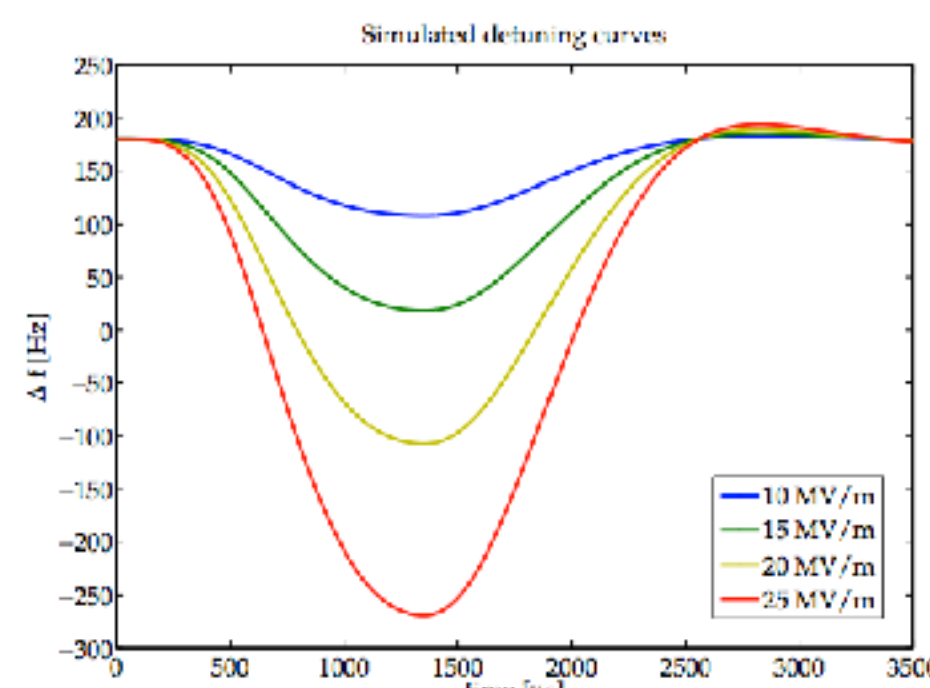
$$\Delta\ddot{\omega}(t) + \frac{1}{\tau_m}\Delta\dot{\omega}(t) + \omega_m^2\Delta\omega(t) = \omega_m^2\Delta\omega_T - 2\pi K\omega_m^2 \cdot E_{acc}^2(t)$$



(a) pressure directions



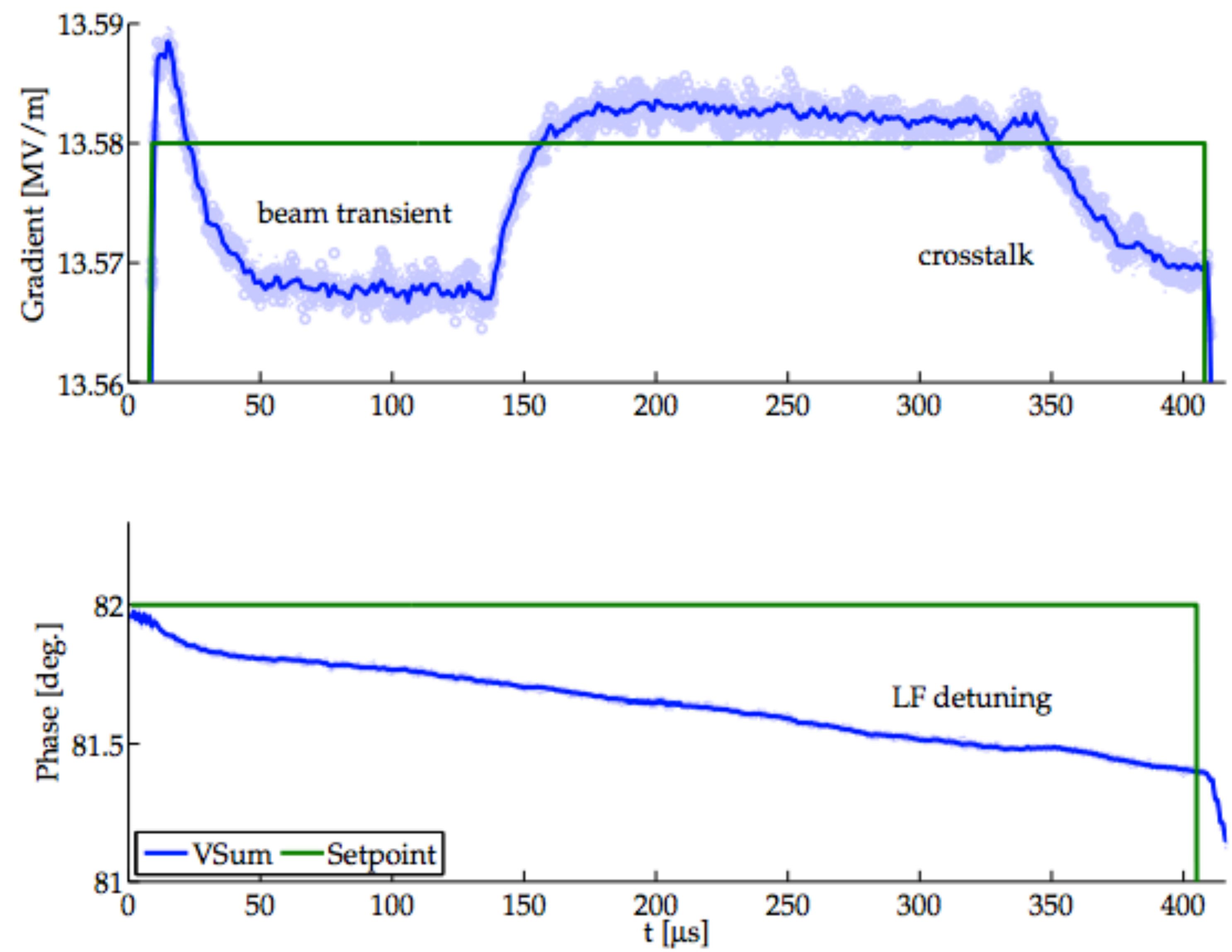
(b) deformation simulation



Disturbances - beam loading

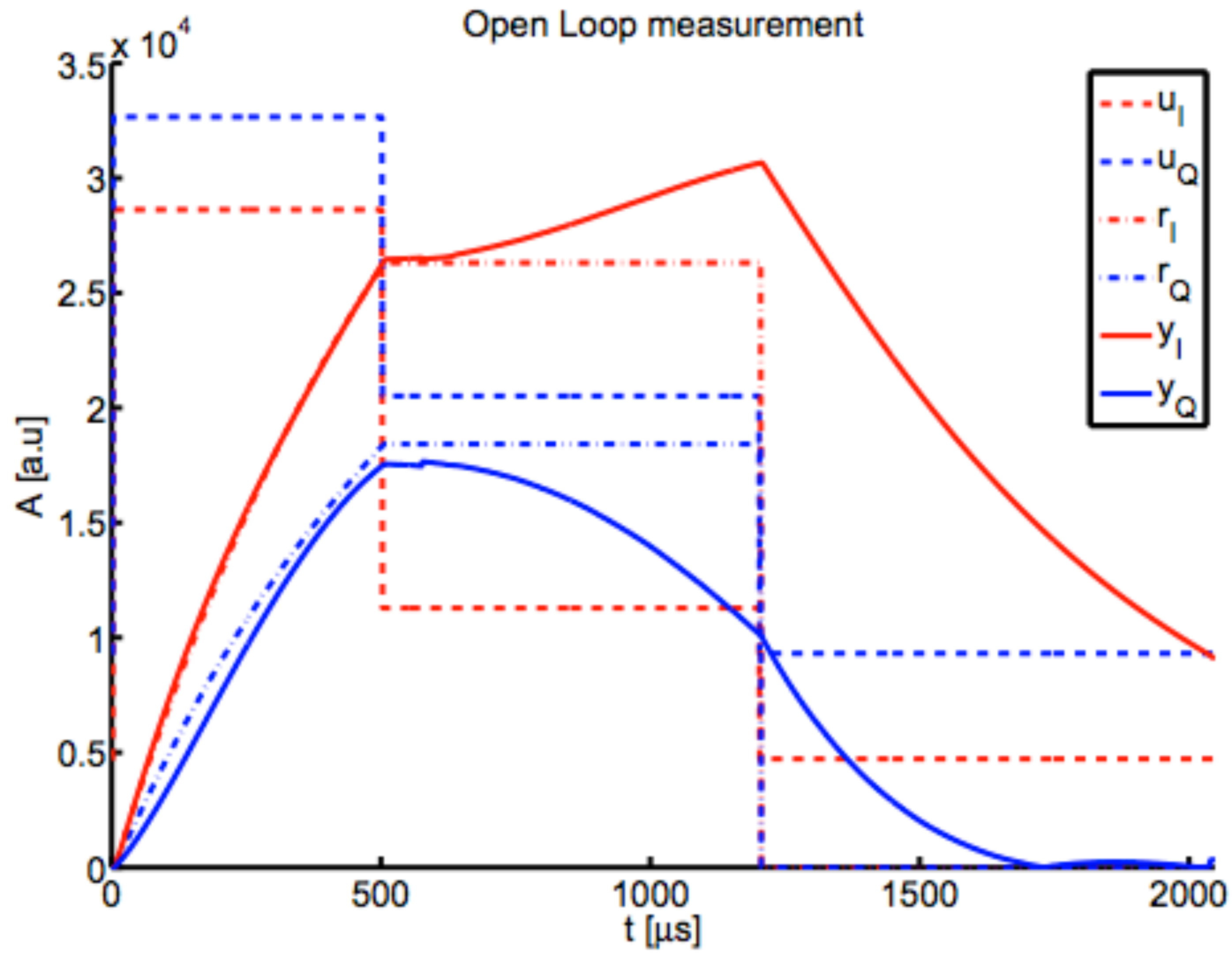
- repetitive disturbance source, therefore predictable (if operation state remains)

- Shown with proportional feedback loop closed



RF open-loop response and feedback control

- Proportional gain controller has limit gain due to measurement noise and HOM (8/9 pi mode)
- Phase lag due to digitalization
- Tradeoff between in-pulse and pulse-to-pulse errors
- Out of scope - designing a MIMO feedback controller via generalized plant and weighting filter with HIFOO - see [1]

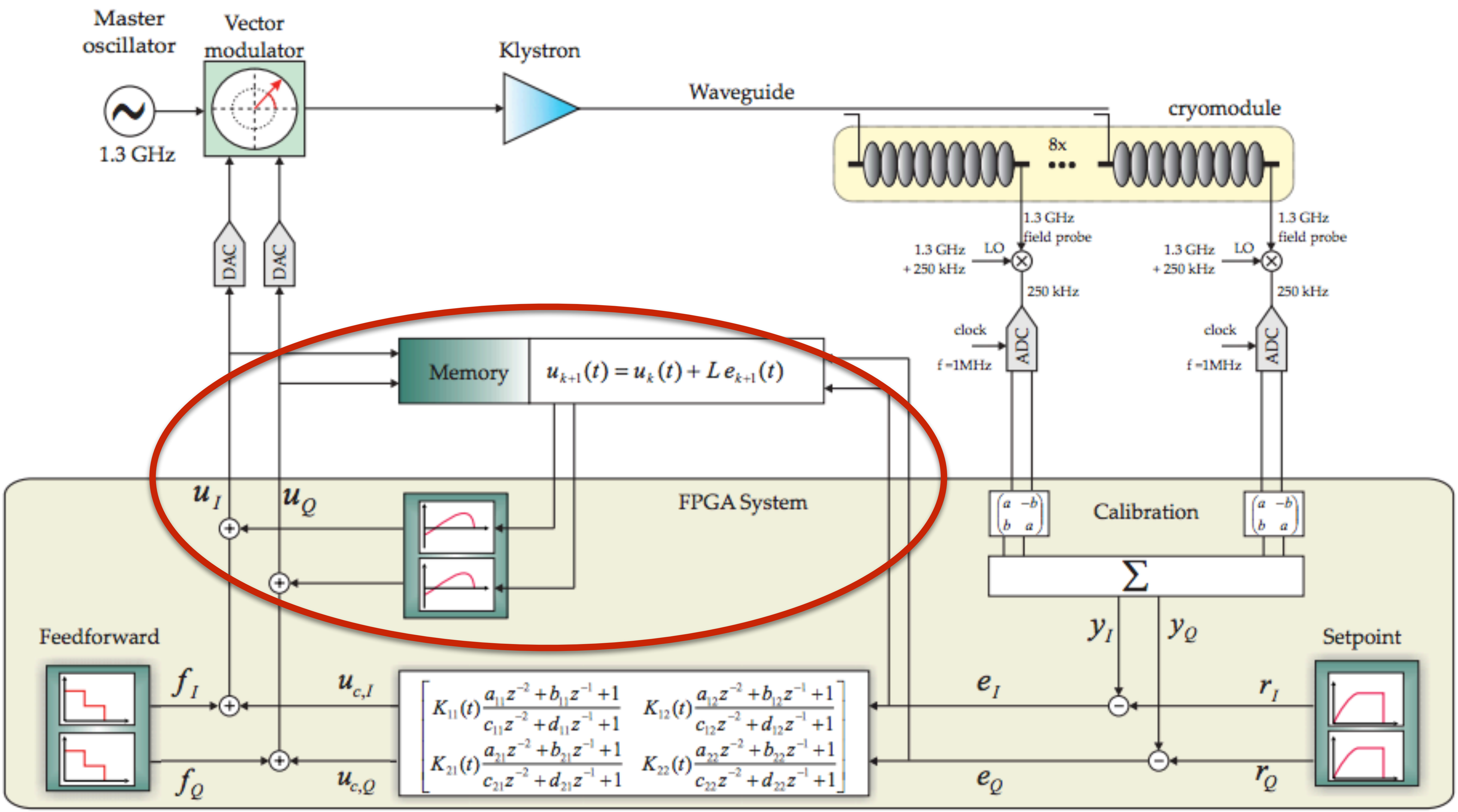


Feedforward control

- Residual field errors due to the low BW of the feedback loop and limitations on the gain
- Predictable disturbance - can compensate with RF modulation
- How to calculate? Constant during operation? Optimal?

  Iterative learning control - take information from previous trials to optimize the control inputs on the next trial

FLASH LLRF - NOILC Feed forward



Norm-optimal iterative learning control

- General iterative control - $u_{k+1}(t) = Q(u_k(t) + L e_k(t))$
  to ensure some error metric $\|e_k\| \to 0 \text{ as } k \to \infty, k \in \mathbb{N}$

- Given a system
$$\begin{aligned} x(t+1) &= A\,x(t) + B\,u(t) \; ; \\ y(t) &= C\,x(t) \end{aligned}$$

- NOILC - optimize u_{k+1} iteratively

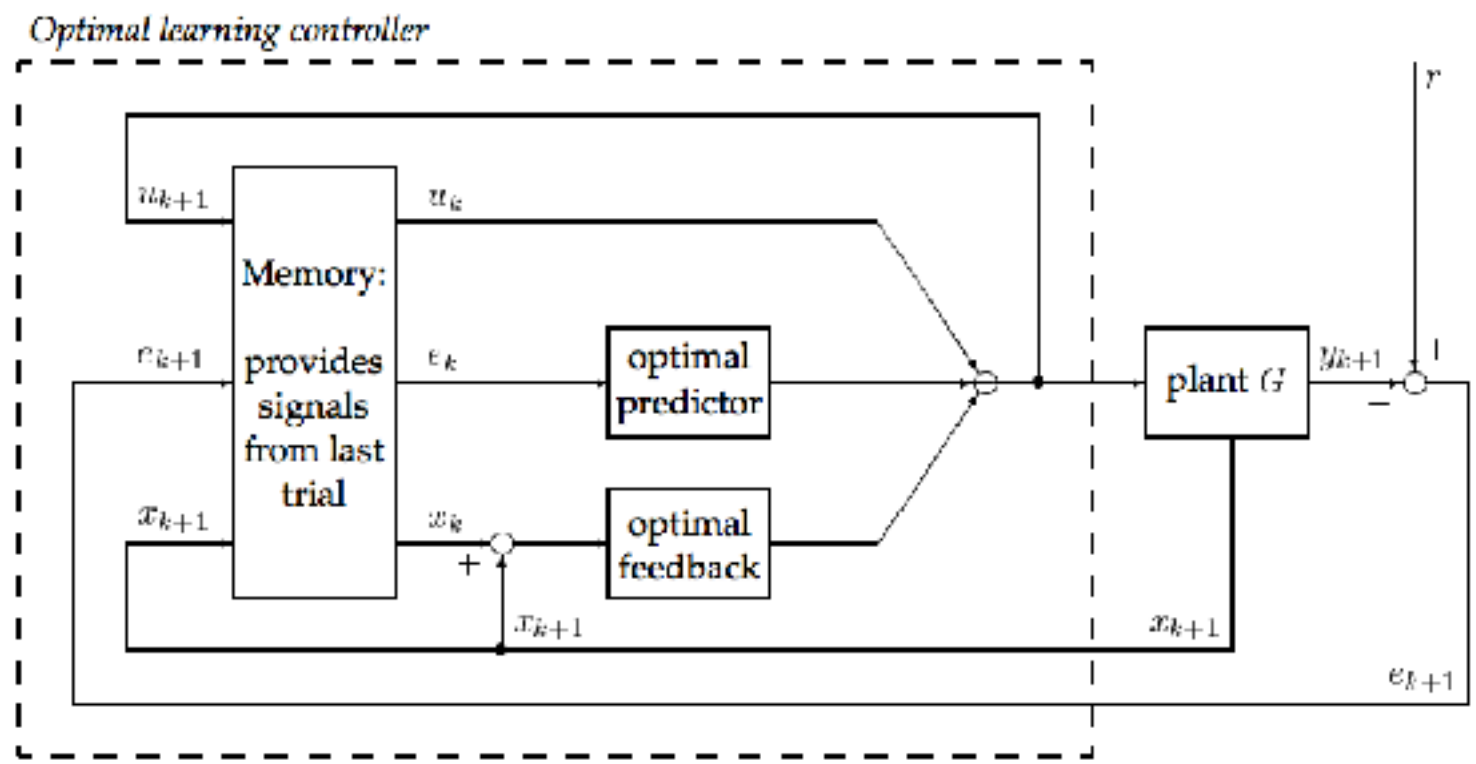
$$u_{k+1} = \arg\min_{u_{k+1}} \{ J_{k+1}(u_{k+1}) : \quad e_{k+1} = r - y_{k+1}, \quad y_{k+1} = G u_{k+1} \}$$

per selected performance index

$$J_{k+1} = \sum_{t=1}^{N} [r(t) - y_{k+1}(t)]^T Q(t) [r(t) - y_{k+1}(t)] + \sum_{t=0}^{N-1} [u_{k+1}(t) - u_k(t)]^T P(t) [u_{k+1}(t) - u_k(t)]$$

NOILC - solution

- Problem stated has a solution [2]:



- Matrix gain

$$K(t) = A^T K(t+1)A + C^T Q(t+1)C - A^T K(t+1)B(B^T K(t+1)B + R(t+1))^{-1} B^T K(t+1)A$$

- Predictive component

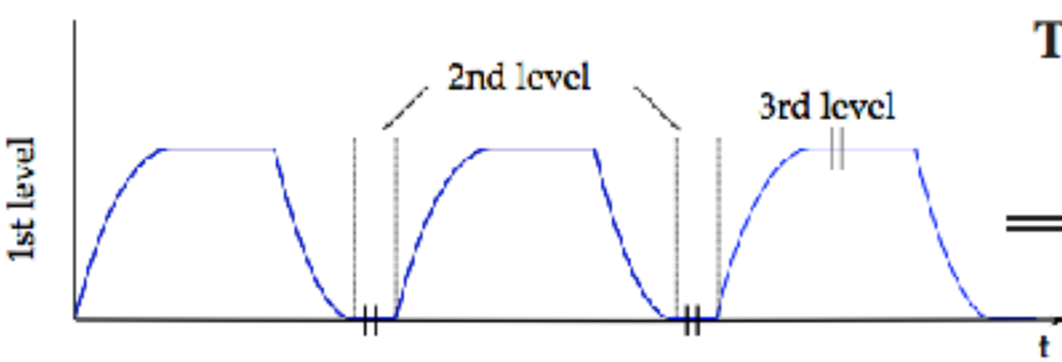
$$\xi_{k+1}(t) = (I + K(t)BR^{-1}(t)B^T)^{-1}(A^T \xi_{k+1}(t+1) + C^T Q(t)e_k(t)) \ ; \quad \xi_{k+1}(N) = 0$$

- Input update

$$u_{k+1}(t) = u_k(t) - (B^T K(t)B + R(t))^{-1} B^T K(t)A[x_{k+1}(t) - x_k(t)] + R^{-1}(t)B^T \xi_{k+1}(t)$$

Implementation note - F-NOILC

- Extensive calculations to update input values.
- Can rearrange for pre-calculation of a lot of terms in advance and minimize real-time calculations
- Note - need to recalculate with model changes (if any)
- See for ex. [3]



First level (before operation):

$$
\begin{aligned}
K(t) = {} & A^T K(t+1)A + C^T W_1(t+1)C \\
& -[A^T K(t+1)B \cdot \{B^T K(t+1)B + W_2(t+1)\}^{-1} \\
& \cdot B^T K(t+1)A] \quad ; \quad K(N) = 0
\end{aligned}
$$

$$
\begin{aligned}
\alpha(t) = {} & \{I + K(t)BW_2^{-1}(t)B^T\}^{-1} \\
\beta(t) = {} & \alpha(t)A^T \\
\gamma(t) = {} & \alpha(t)C^T W_1(t+1)
\end{aligned}
$$

$$
\begin{aligned}
\omega(t) = {} & W_2^{-1}(t)B^T \\
\lambda(t) = {} & (B^T K(t)B + W_2(t))^{-1} B^T K(t)A
\end{aligned}
$$

Second level (between trials):

$$
\xi_{k+1}(t) = \beta(t)\xi_{k+1}(t+1) + \gamma(t)e_k(t+1) \quad ; \quad \xi_{k+1}(N) = 0
$$

Third level (between each sample interval):

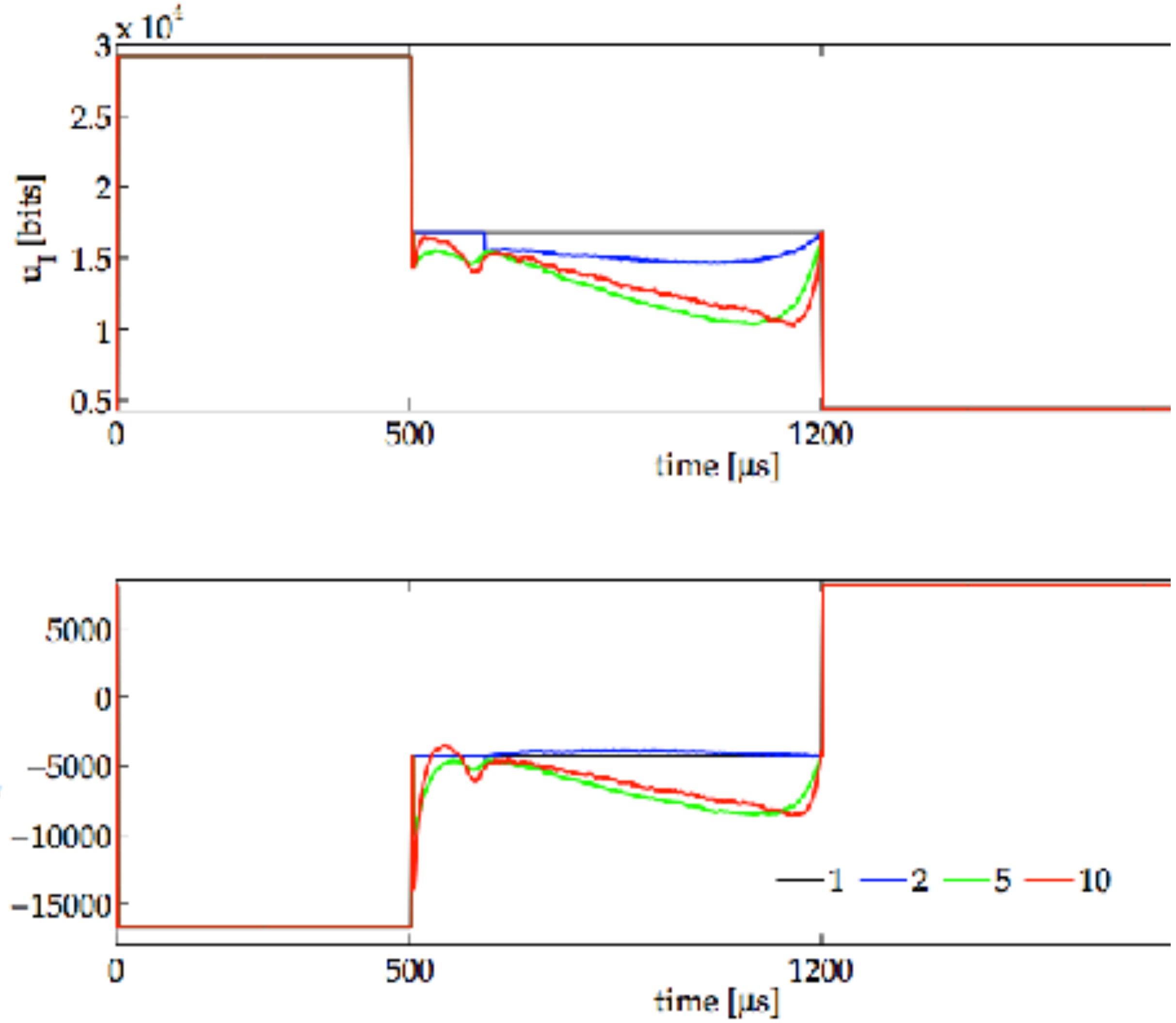
$$
u_{k+1}(t) = u_k(t) - \lambda(t)\{x_{k+1}(t) - x_k(t)\} + \omega(t)\xi_{k+1}(t)
$$

Out of scope - system identification

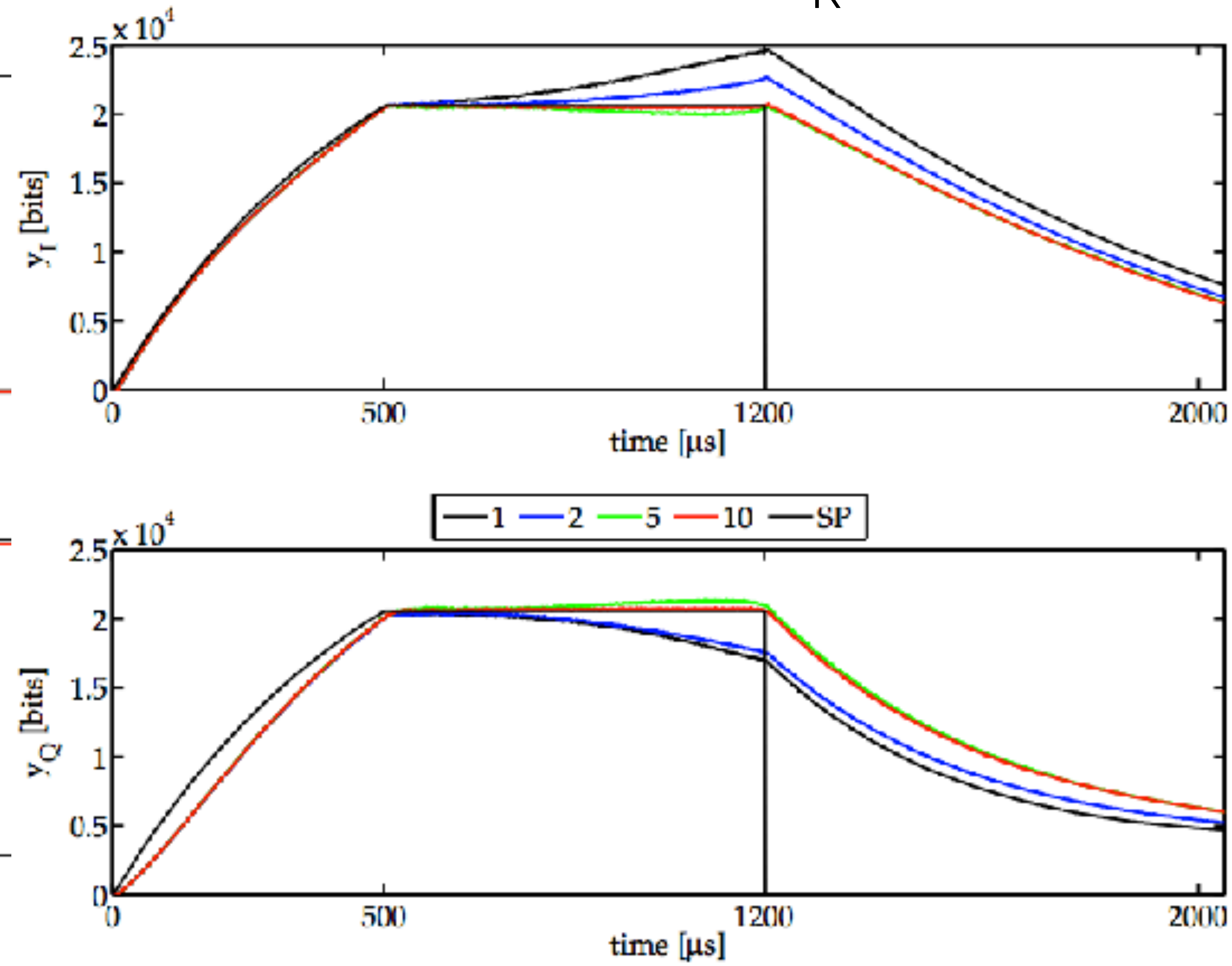
- Requires A, B, C, D…
- Black-box model for system identification
- Model validation

Experimental results - open-loop ILC (no beam, LFD only)

System input $u_k(t)$

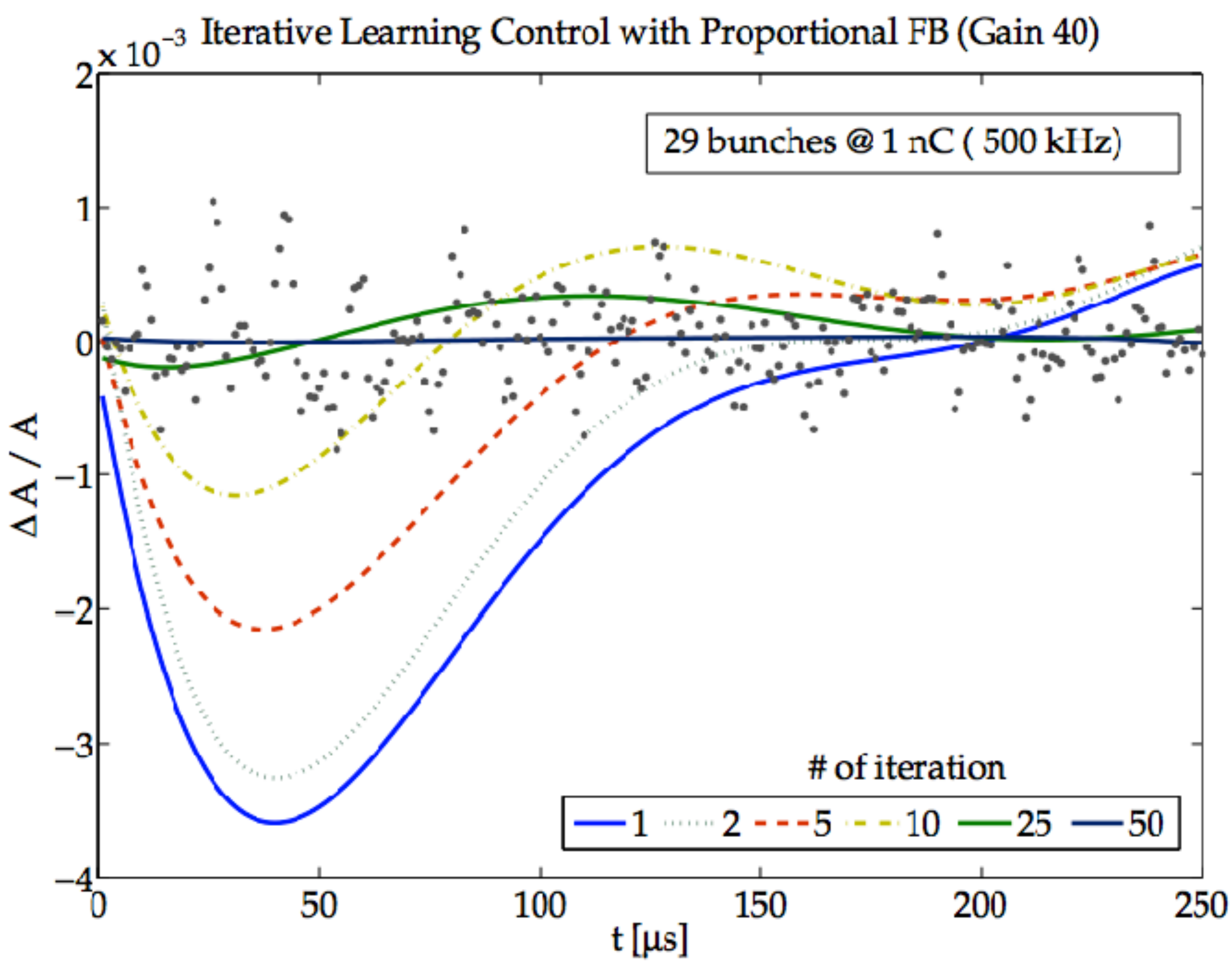


System output $y_k(t)$

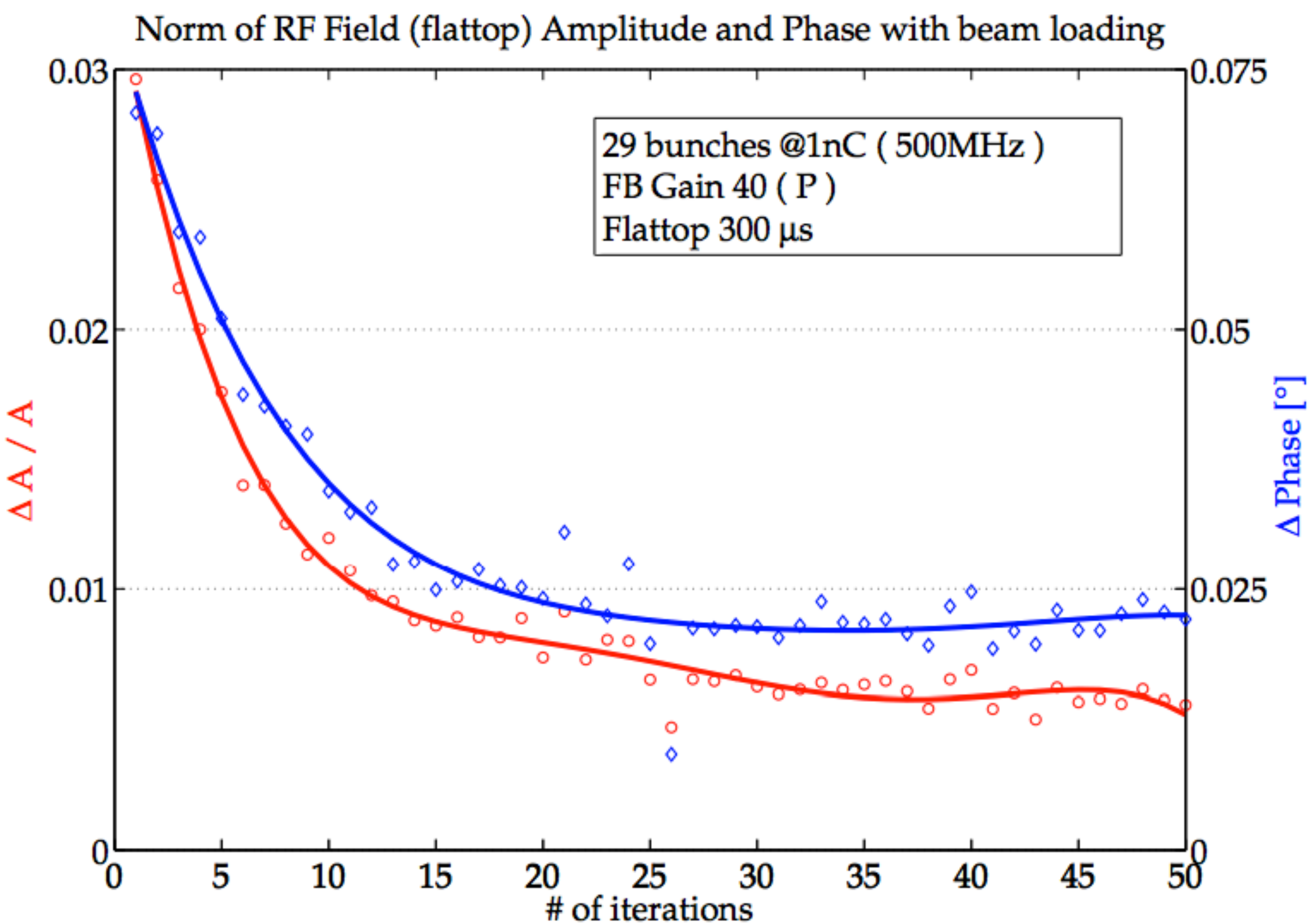


Experimental results - closed-loop ILC (P controller)

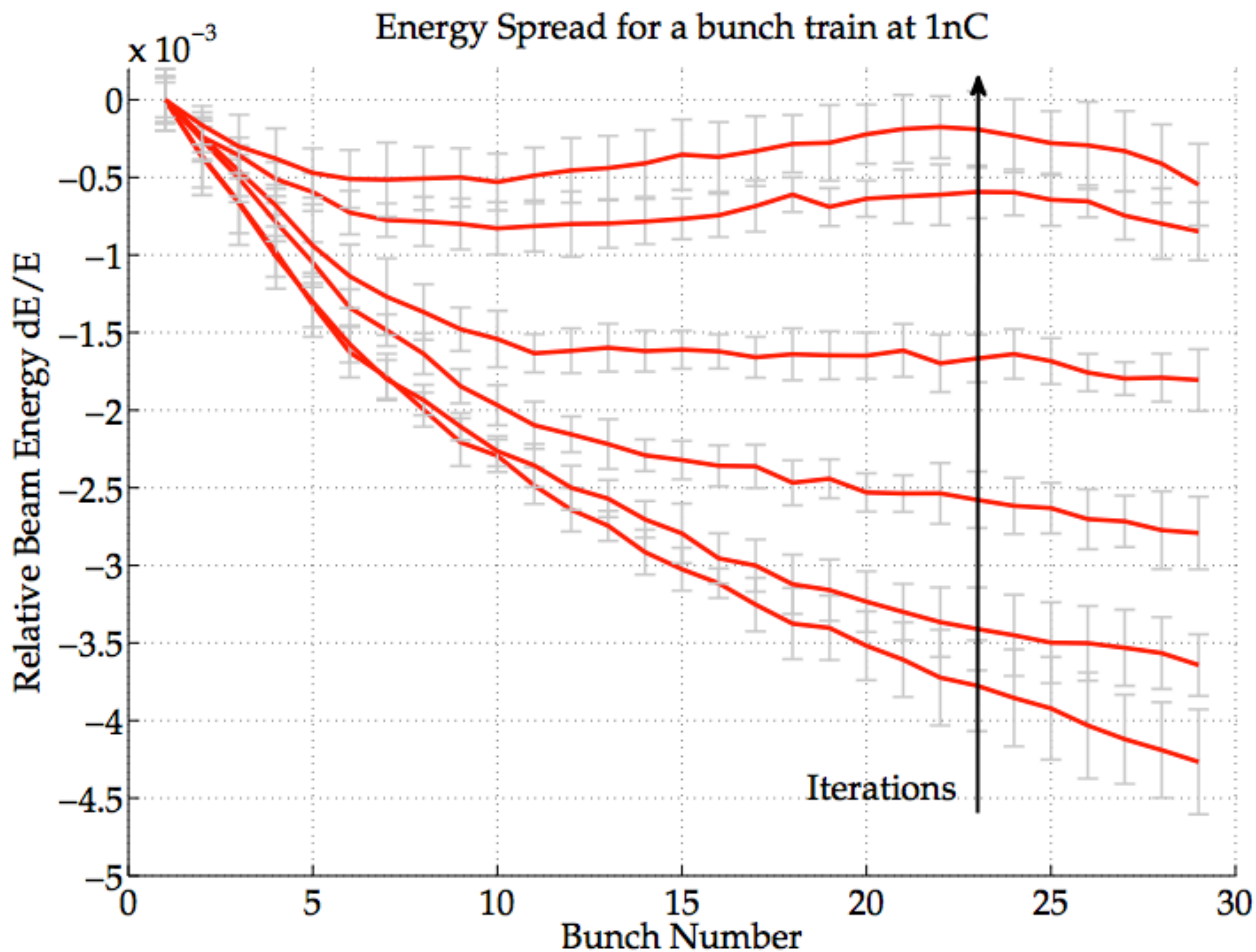
- Fitted curves of RF field amplitude changes due to feedforward adaptation
- Dots represent the measurement points after 50 iterations showing that only **non repetitive fluctuations are left over**



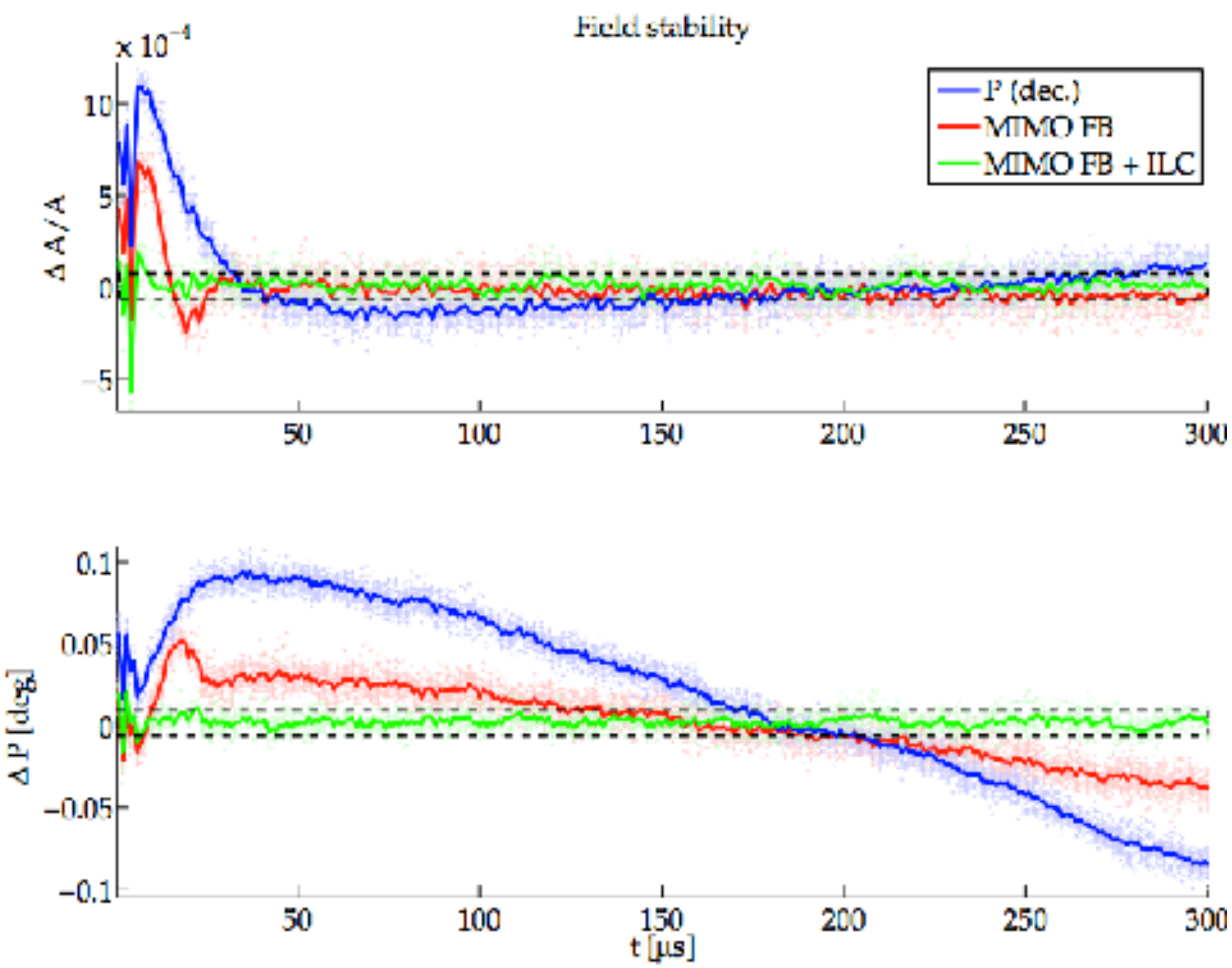
Experimental results - ILC convergence (P controller)

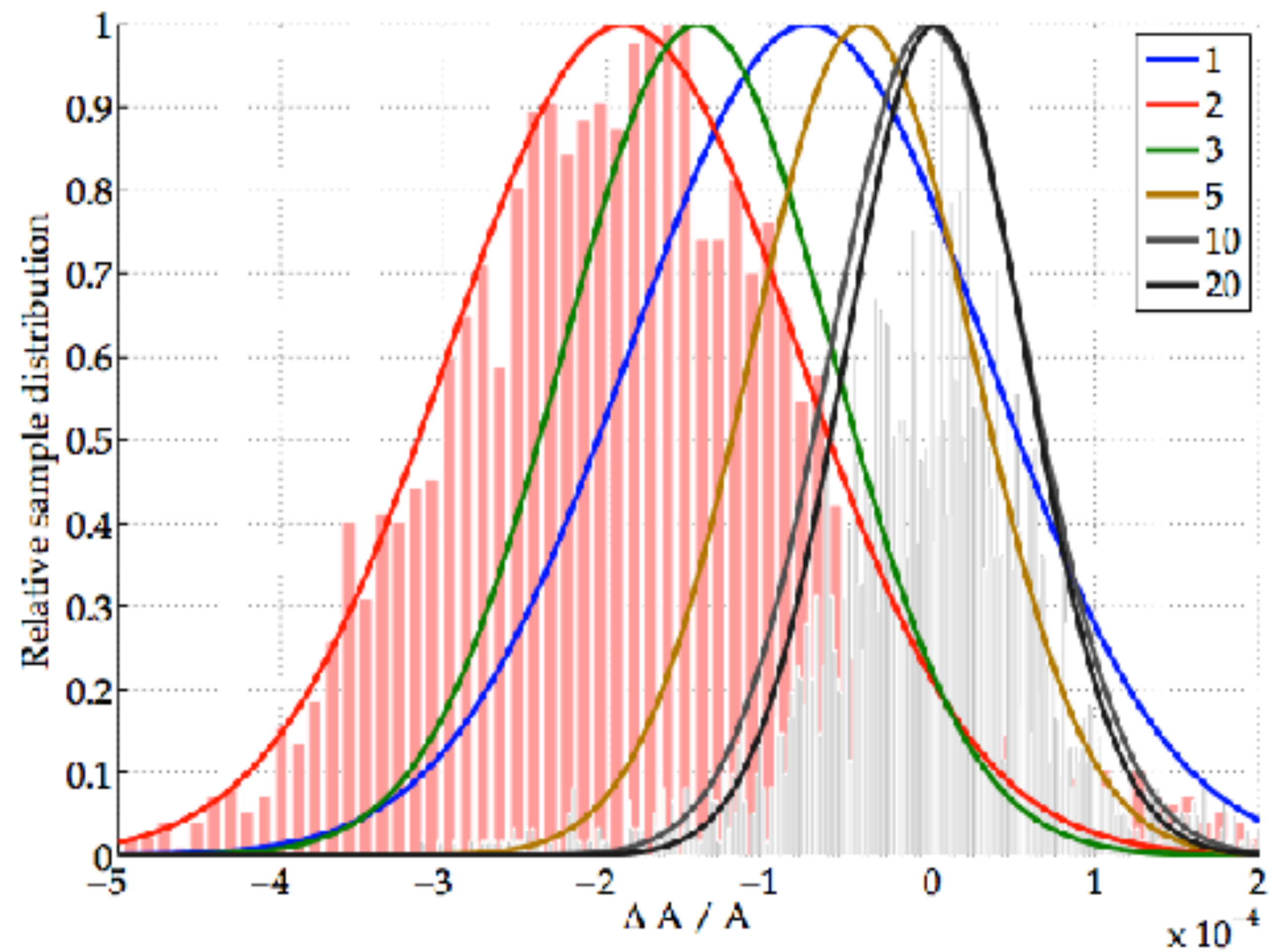


Experimental results - pulse train energy spread (P controller)



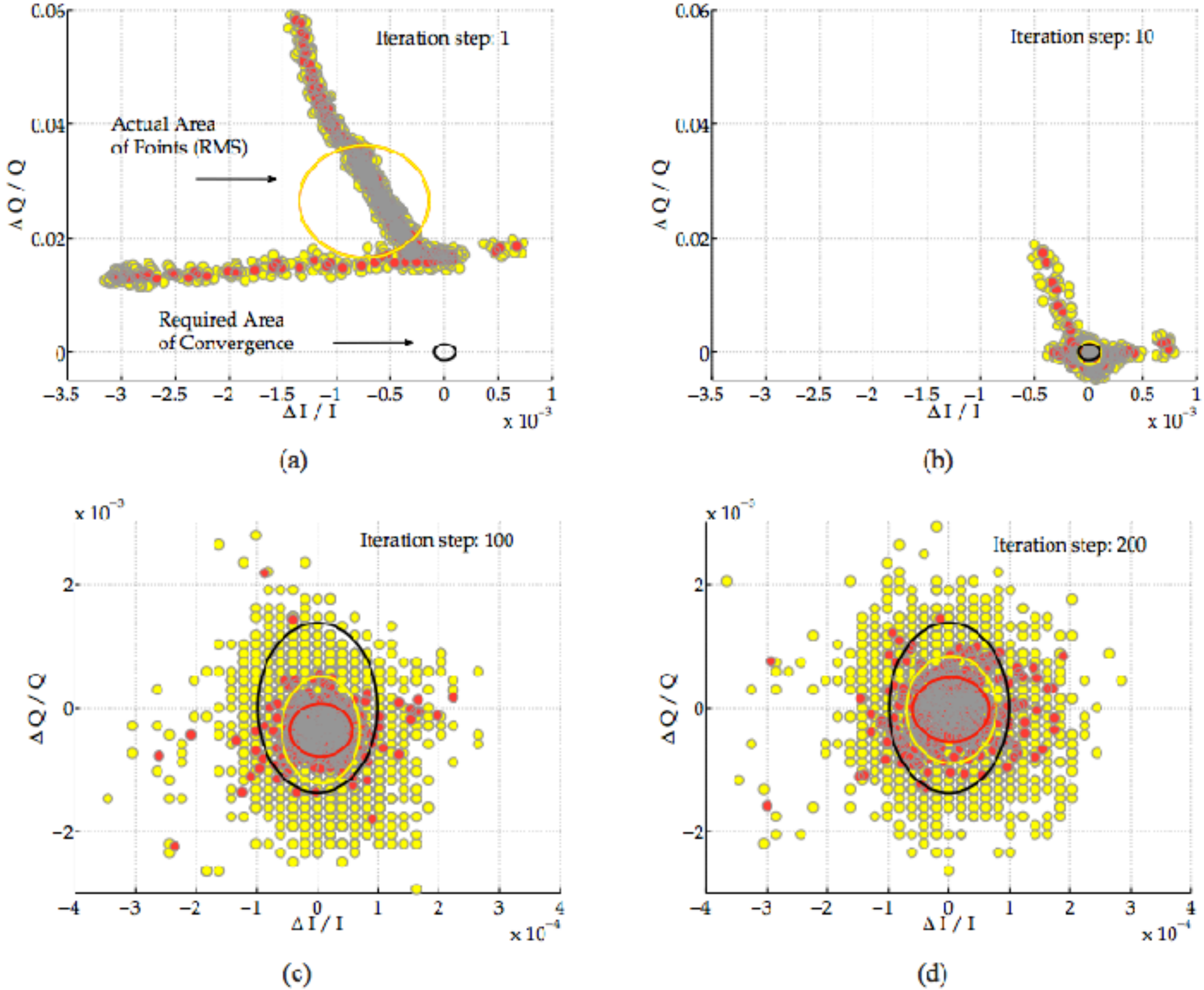
ILC and MIMO controller





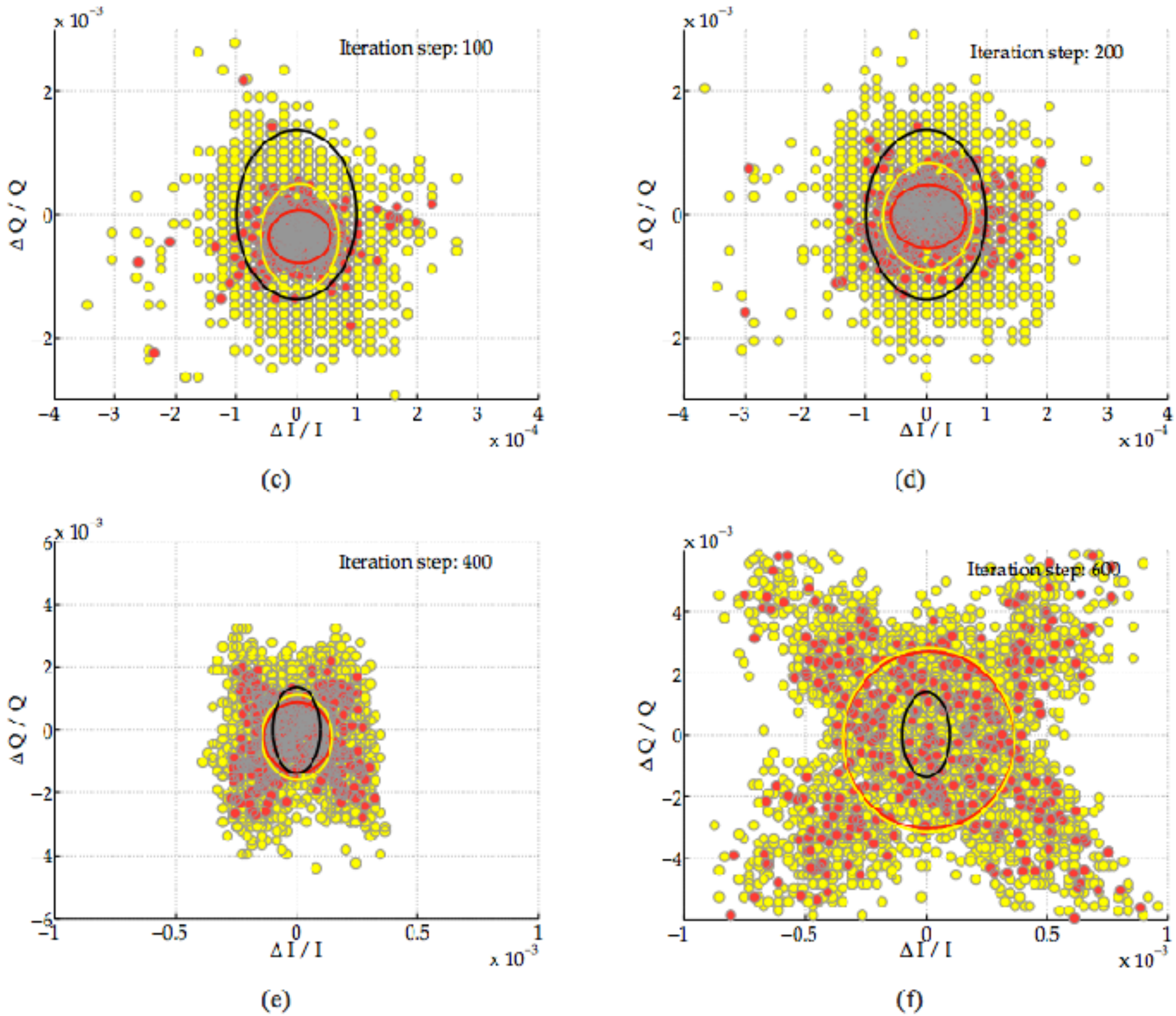
ILC long term adaptation

- I/Q domain
- yellow dot - data point
- red dot - 5 sample average
- yellow/red ovals - rms error
- black oval - system requirement
- System converges nicely.
  what happen next as iteration number increase?



ILC long term adaptation (cont.)

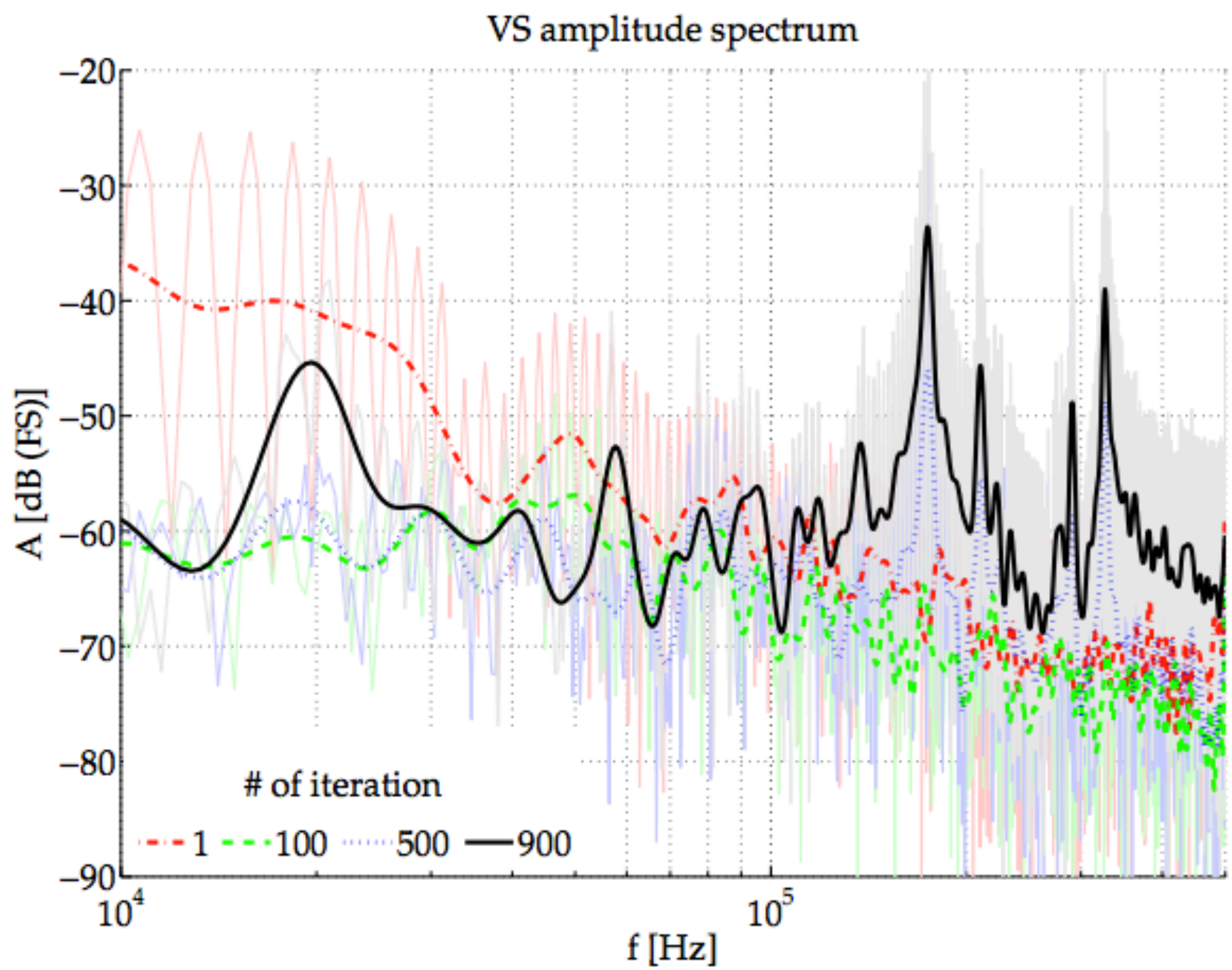
- ILC induced oscillations
- What can caused this?



ILC - implications of model limitation

- Spectrum analysis of vector sum shows that as iterations increase, peaks occur at frequencies consistent with 8/9pi mode of the cavity

- Limitation of the system model used for ILC derivation



References

Following references were used in this presentation for strictly educational purpose:

[1] C. Schmidt (2010): *RF System Modeling and Controller Design for the European XFEL* (Doctoral thesis)

[2] N. Amann, D.H. Owens, E. Rogers: *Iterative learning control for discrete-time systems with exponential rate of convergence*, IEE Proc. Control Theory Appl., vol. 143, no. 2, pp. 217224, 1996.

[3] J.D. Ratcliffe, P.L. Lewin, E. Rogers, J.J. Htnen, D.H. Owens: *Norm-Optimal Iterative Learning Control Applied to Gantry Robots for Automation Applications*, IEEE Transactions on Robotics, Vol. 22,No. 6, 2006