Transverse Feedback Systems for Multibunch Beam Diagnostics and Instabilities Suppression

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ICFA MINI-WORKSHOP ON IMPEDANCES AND BEAM INSTABILITIES IN PARTICLE ACCELERATORS
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Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

UNIVERSITA' degli STUDI di ROMA TOR VERGATA

ARIES

ICFA

Agenda

- Basics on bunch-by bunch feedback for lepton storage ring
- Beam diagnostics by using feedback
- New feedback design (for FCC-ee)

Introduction

- Transverse instabilities in storage rings can limit both beam and single bunch currents.
- Vacuum chamber impedance, producing wakefields at the bunch passage, can be source of instabilities for positive and negative charged stored beams and also parasitic e- clouds in the vacuum chamber can give unpleasant or destructive effects for positive charged stored beams.
- Transverse bunch-by-bunch feedback systems are implemented in storage rings as active devices for instability suppression and for state of art beam diagnostics.

- Acknowledgements: This work was supported in part by the European Commission under the HORIZON2020 Integrating Activity project ARIES, grant agreement 730871

Starting with a very simple model of the bunch motion that can be studied for example by using the state space formalism

Bunch-by-bunch feedback systems work in time domain kicking each bunch of particles considered as a simple charged rigid body. The classic harmonic oscillator equation describing small oscillations can be used as a model. For the n-th bunch the formula will be:

$$\ddot{x}_n + 2 d_r \dot{x}_n + \omega_\nu^2 x_n = k * \left(V_n^{fb} - V_n^{wf} \right)$$

- x_n = position displacement in horizontal (or vertical) from the equilibrium orbit
- d_r = natural damping rate
- ω_ν = resonance angular frequency (betatron_fractional_tune*2*π*revolution_frequency)
- k = conversion factor (note that it is not a pure number, it is much more complicate!)
- V^{fb}_n = kick voltage from feedback to bunch n (correction signal applied to bunch n)
- V^{wf}_n = kick voltage from wakefields to bunch n (forcing signal due to vacuum chamber impedance)

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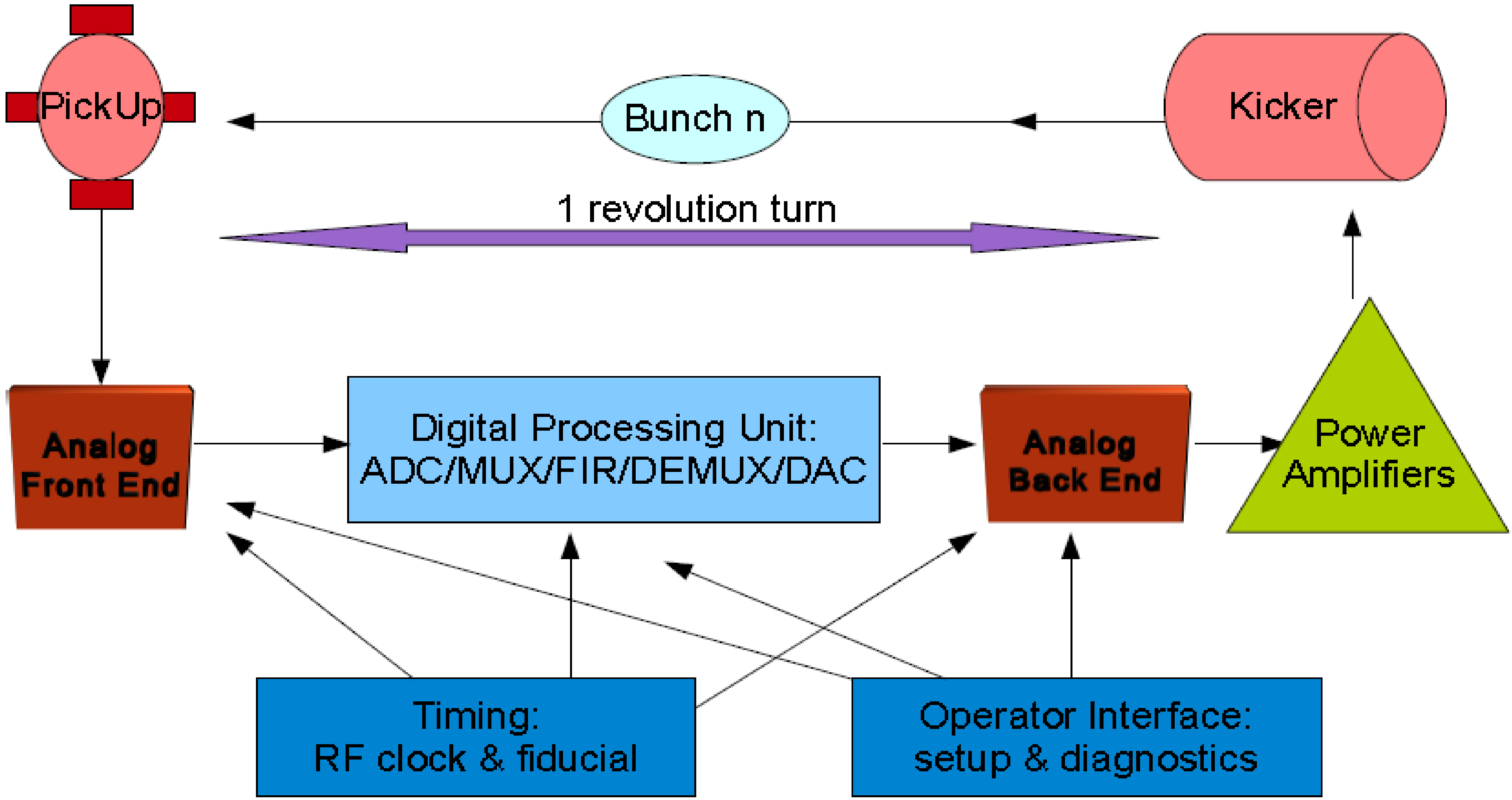
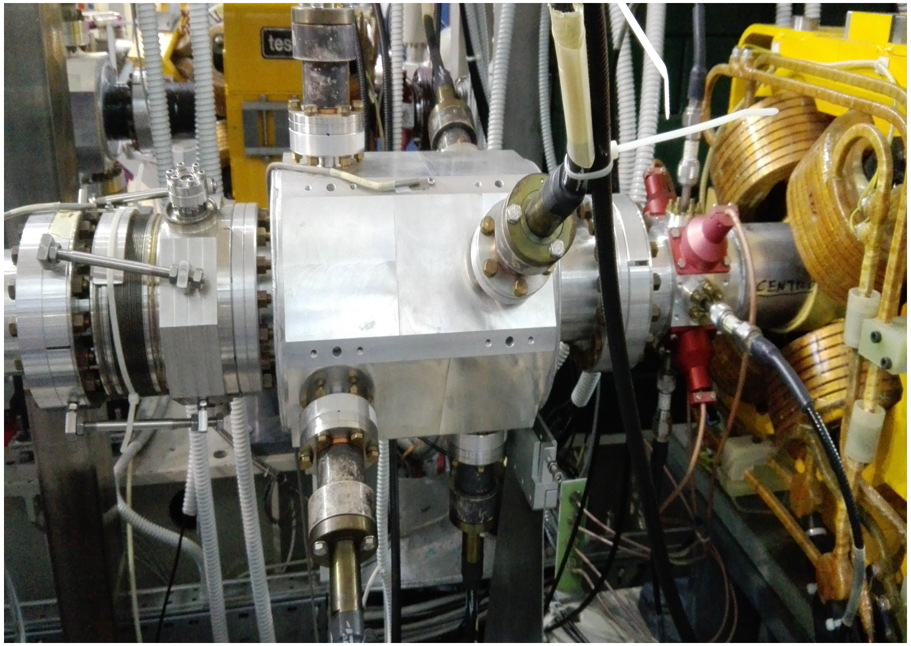
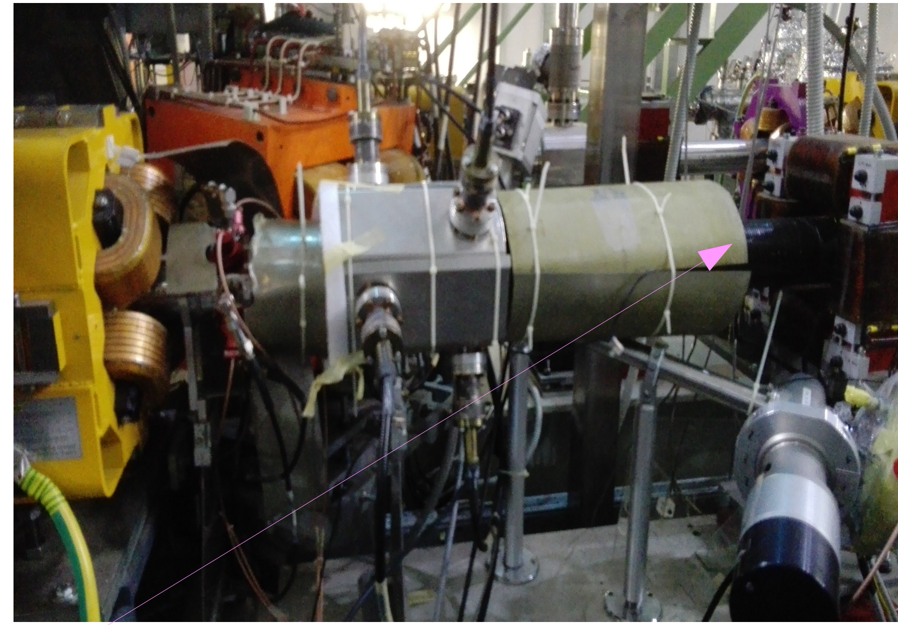
Feedback acts as anti-impedance term !

H/V/L Bunch-by-Bunch Feedback Scheme





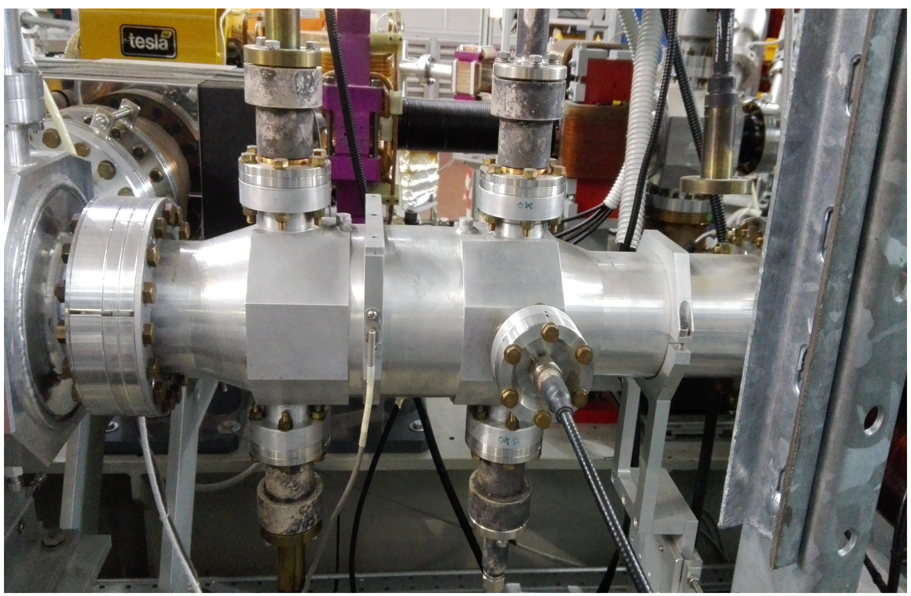
Dafne-type (cavity) longitudinal kickers



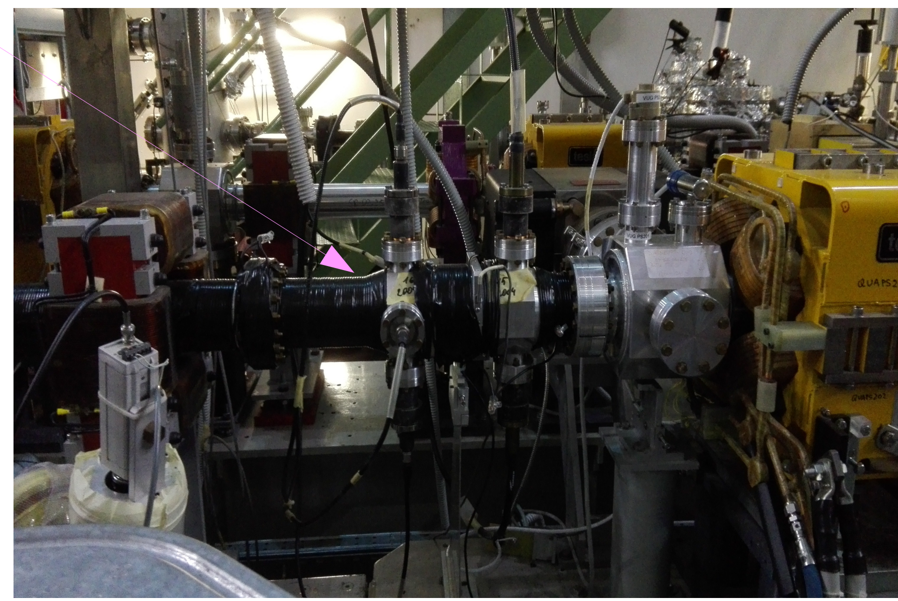
DAFNE e- ring

solenoids

DAFNE e+ ring



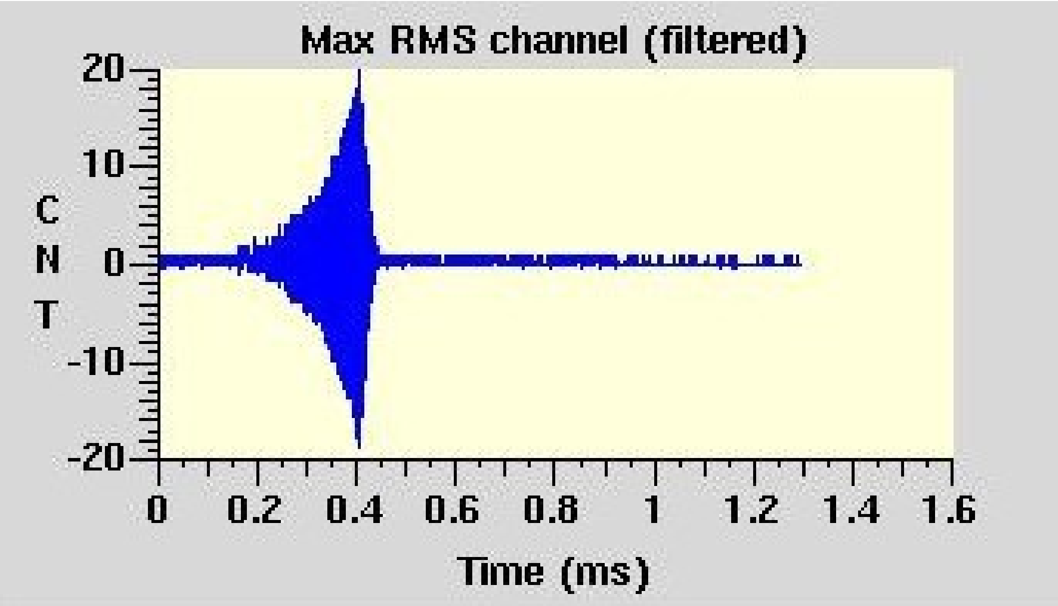
stripline vertical kickers

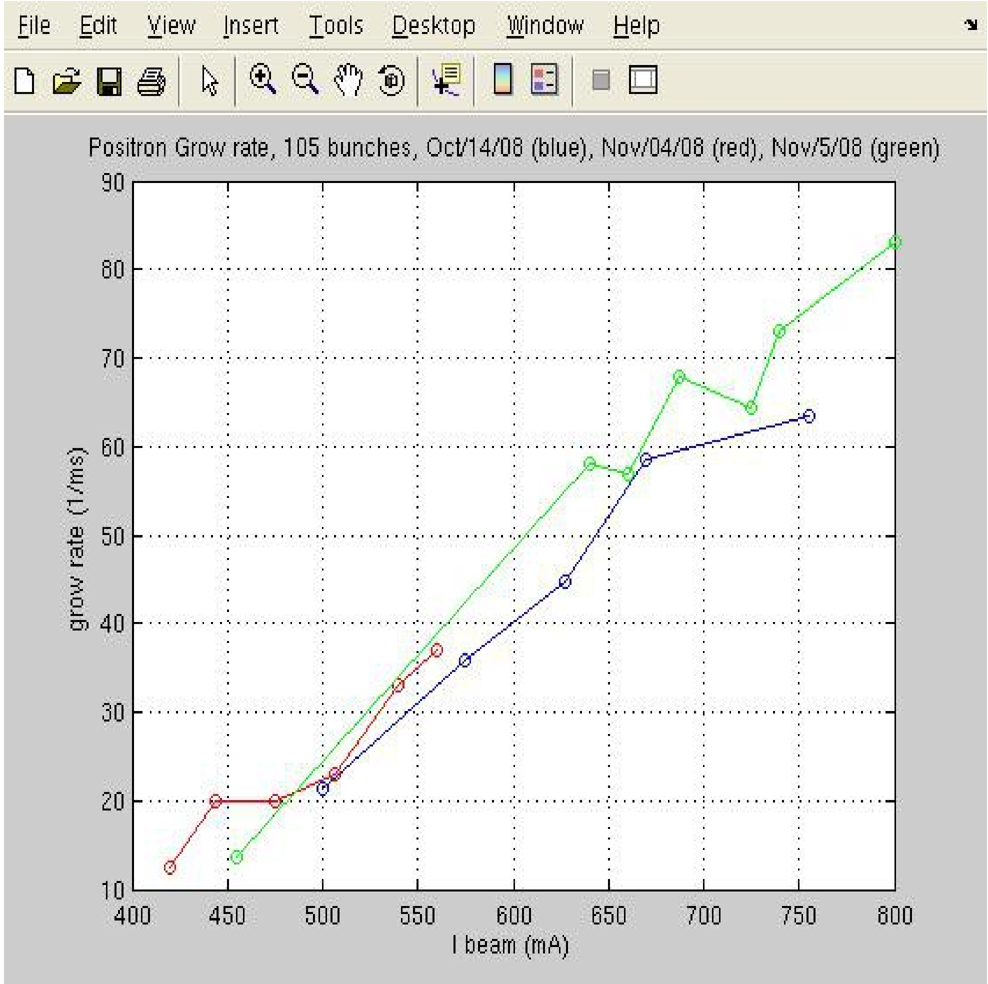


Both kicker types need to be carefully evaluated from the impedance point of view

Beam diagnostics by feedback

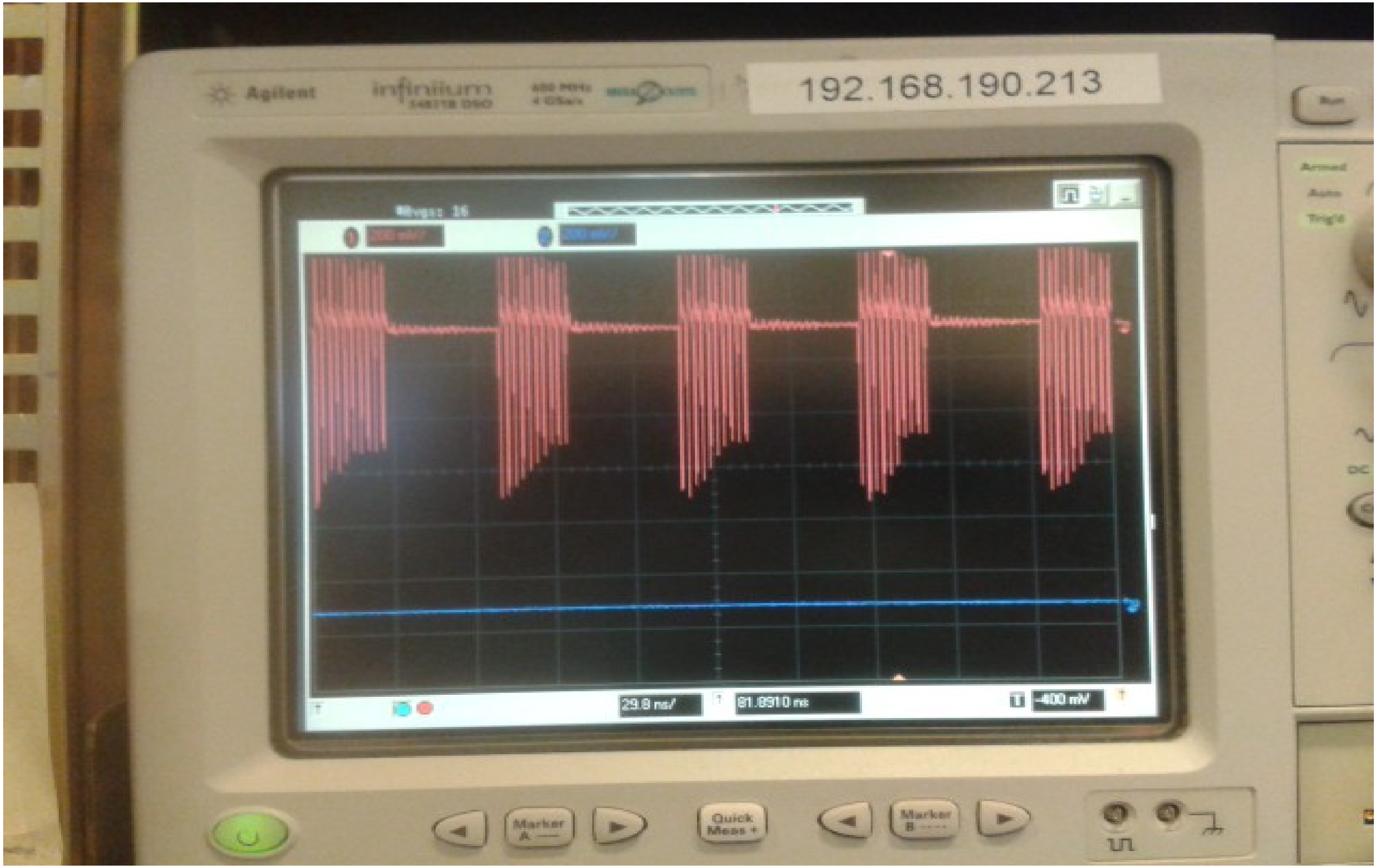
To measure the instability growth rate is necessary to turn off for a short period the feedback.
Below the horizontal oscillation of the DAFNE positron beam with 500mA is shown.
The signal shows the most oscillating bunch of the train. The fb turning off period is 0.4 ms.
The off period has to be chosen in base at the instability growth rate.





In the picture at the right the growth rate measures of the fastest mode are reported. They are made by using the diagnostic capability of the feedback In different dates. They are consistent versus beam current if the ring parameters do not change. The error is small. In the figure the horizontal growth rates versus DAFNE e+ beam current between 400 and 800 mA are plotted.

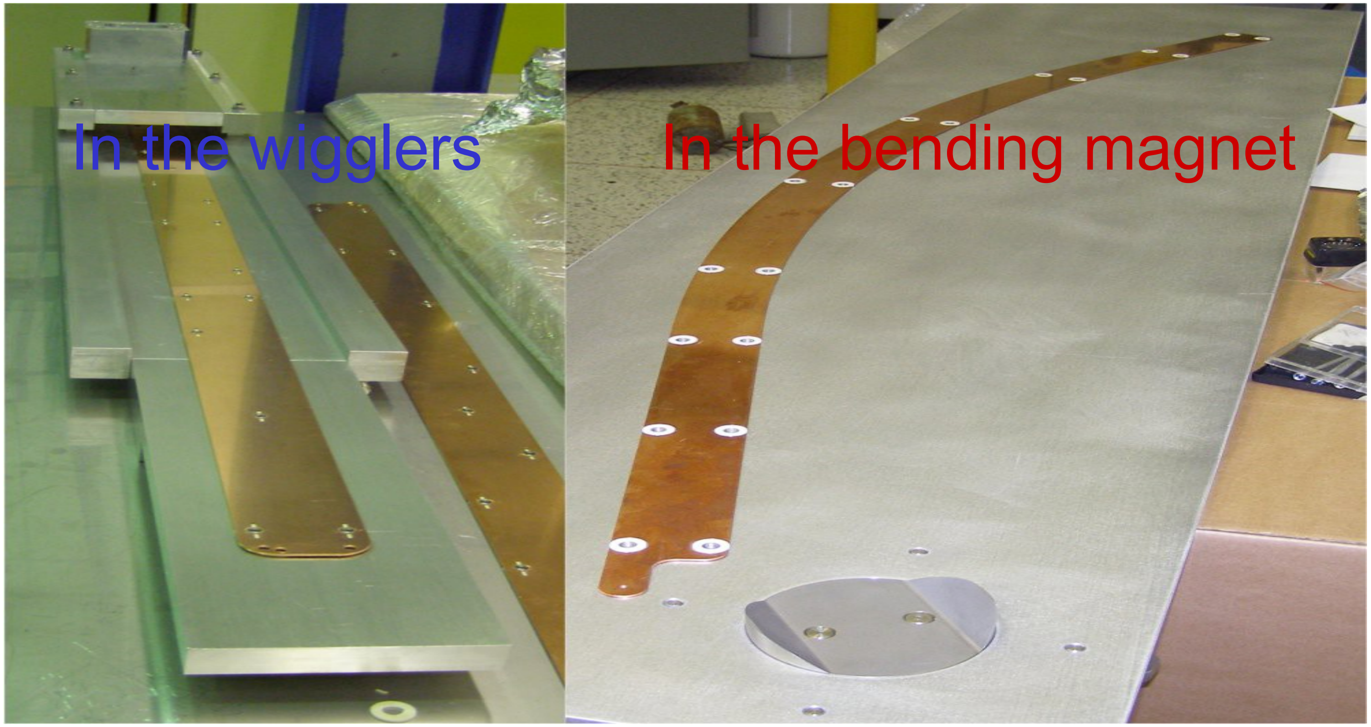
The e- cloud effects in DAFNE are very evident: in the figure below 1A beam current is stored in 50 bunches splitted in 5 trains of 10 bunches followed by gaps. Gaps are necessary to have sufficient cloud decay.
In the tail of each train the bunch current is lower for the e-cloud.

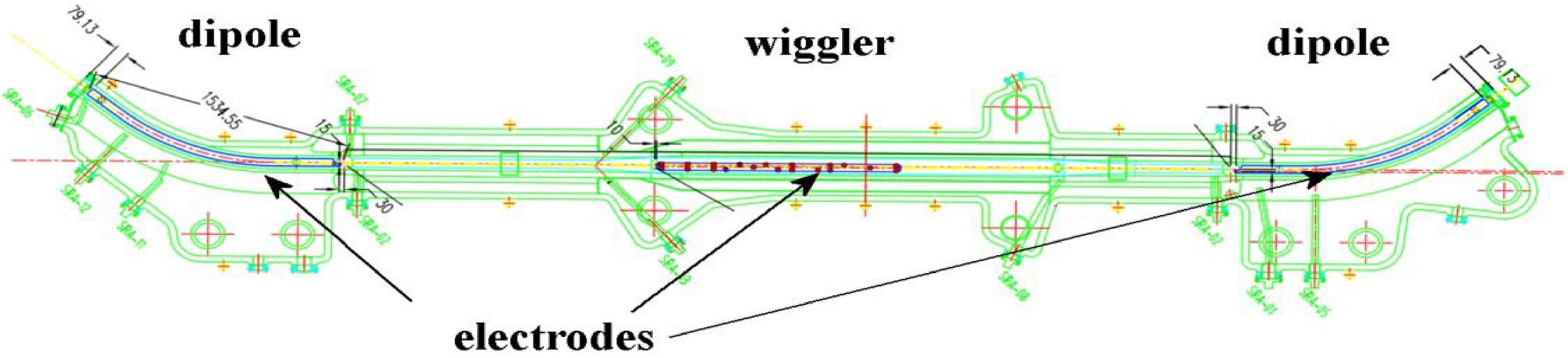


To mitigate instability due to the e- cloud presence, twelve clearing electrodes have been installed in the DAFNE positron ring.

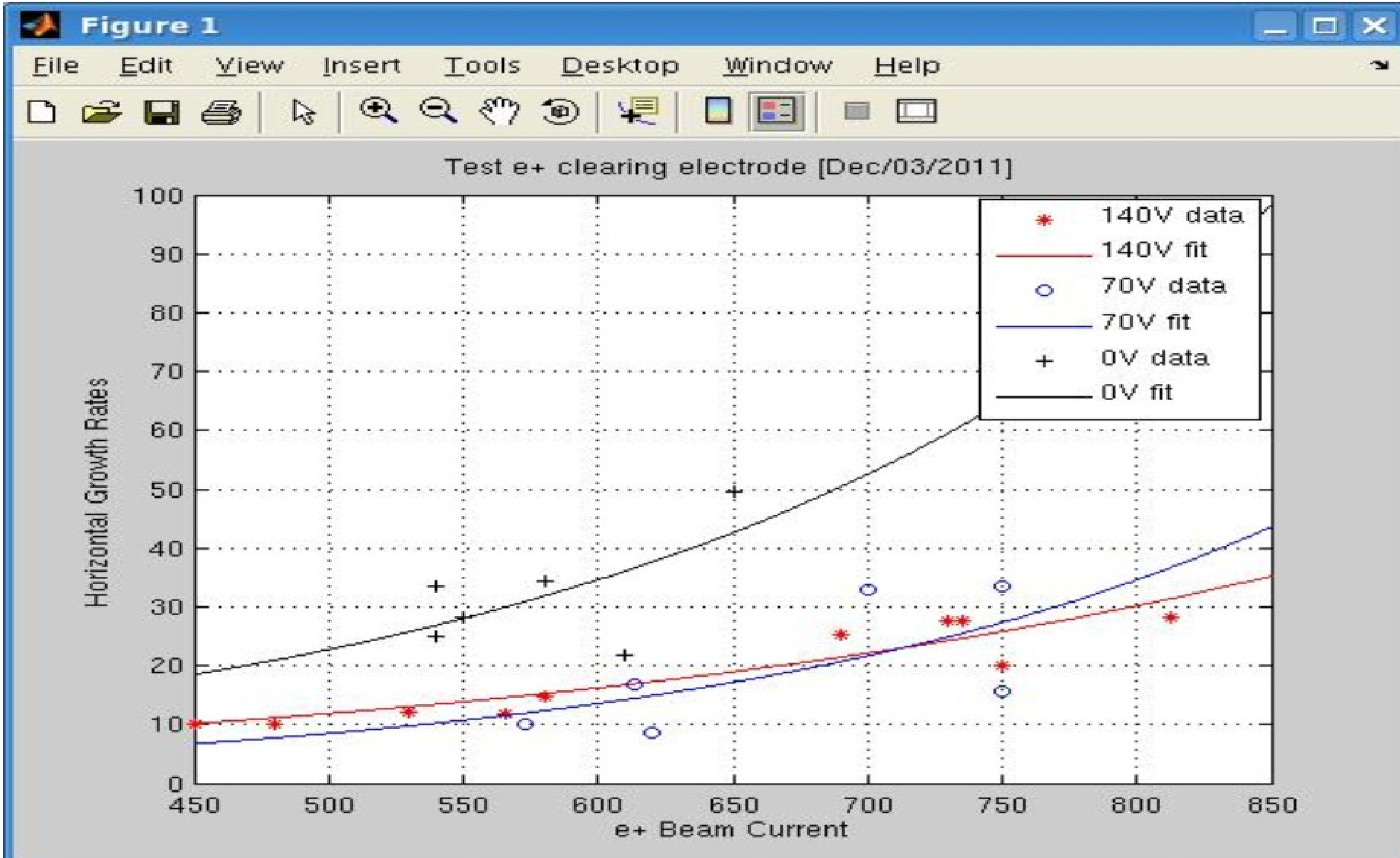
The distance of the electrodes from the beam axis is 8 mm in the wigglers and 25 mm in the bending magnets.

How to evaluate the clearing electrodes ?



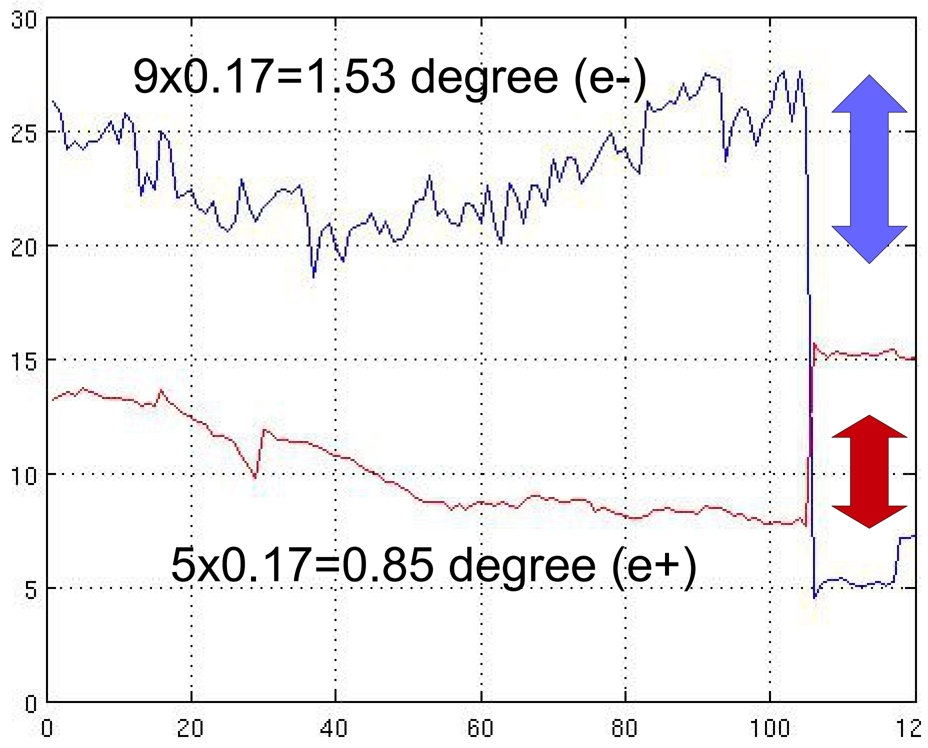


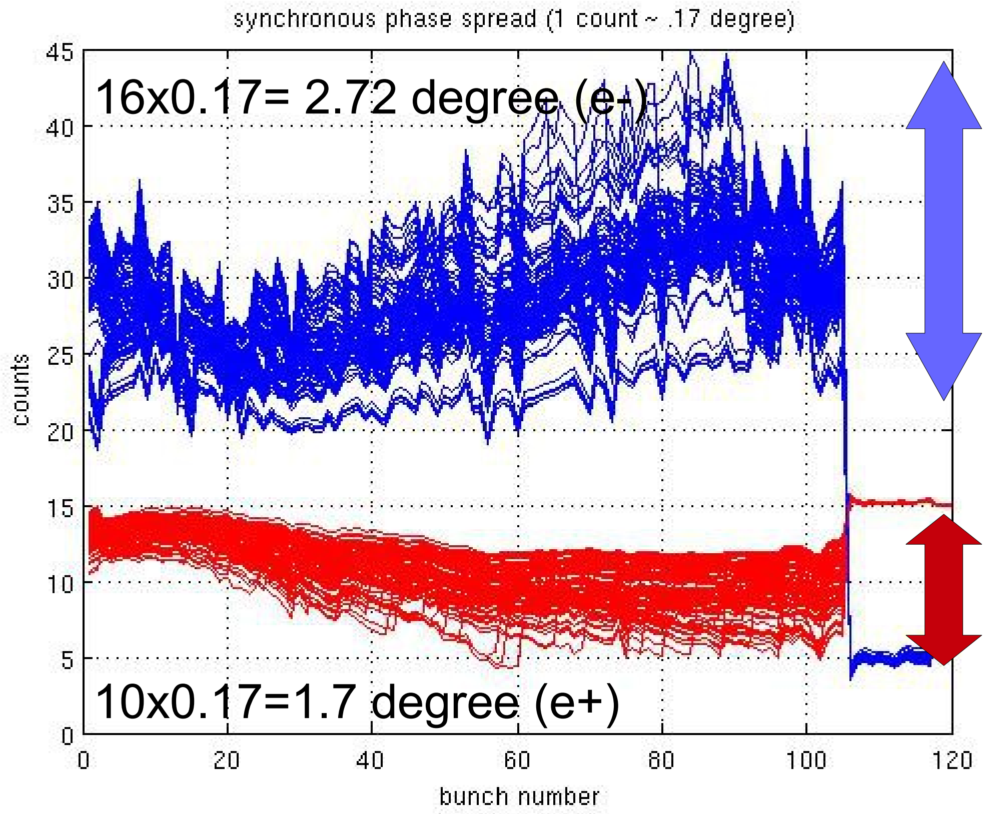
The best way (not the only) to evaluate the clearing electrode performance is by measuring growth rates versus different voltages applied to the electrodes (of course through the feedback system)



Beam diagnostics
that at DAFNE has been
implemented by feedback but that
can be made also by other tools

Synchronous phase spread measurements along the bunch train at DAFNE (beam currents: e- 1.4A, e+ 1A)

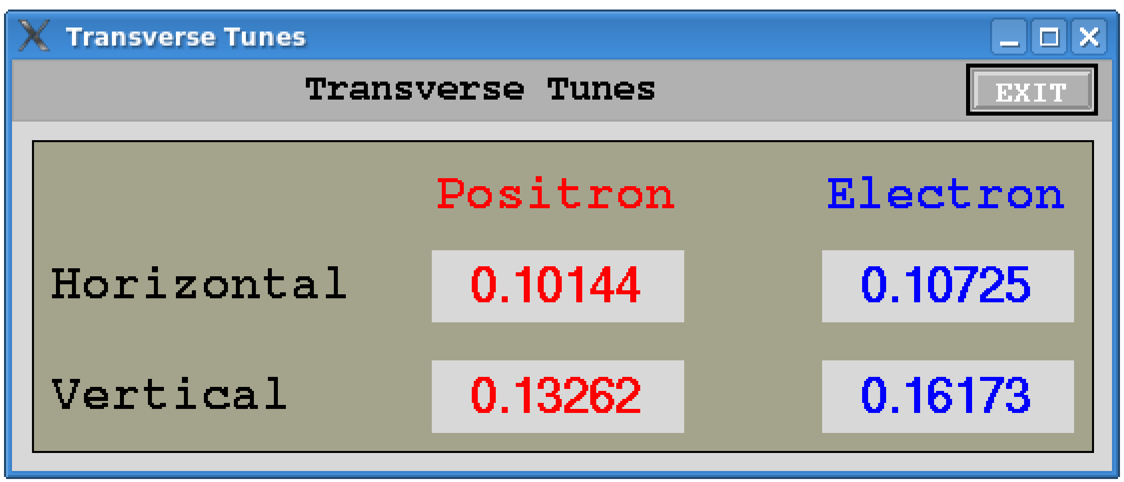




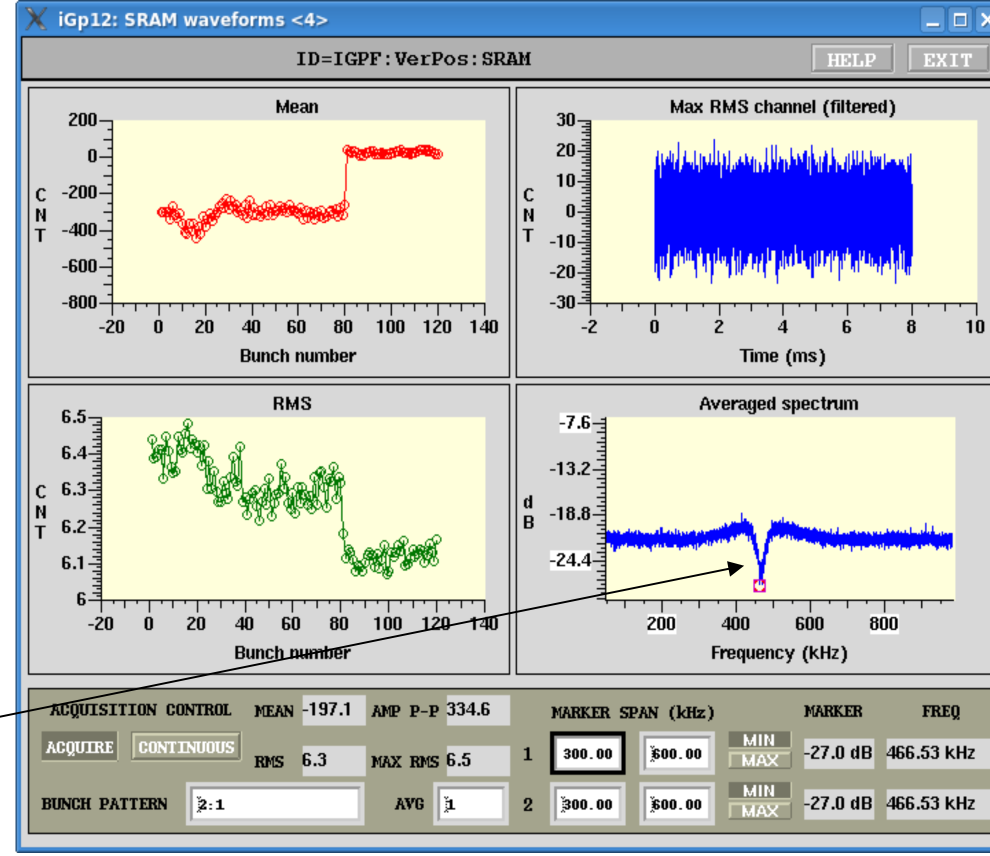
No signal persistence

With signal persistence

By using feedback it is possible to get real time tune measurements (all bunches, below) and bunch-by-bunch tune measurements (following slides)



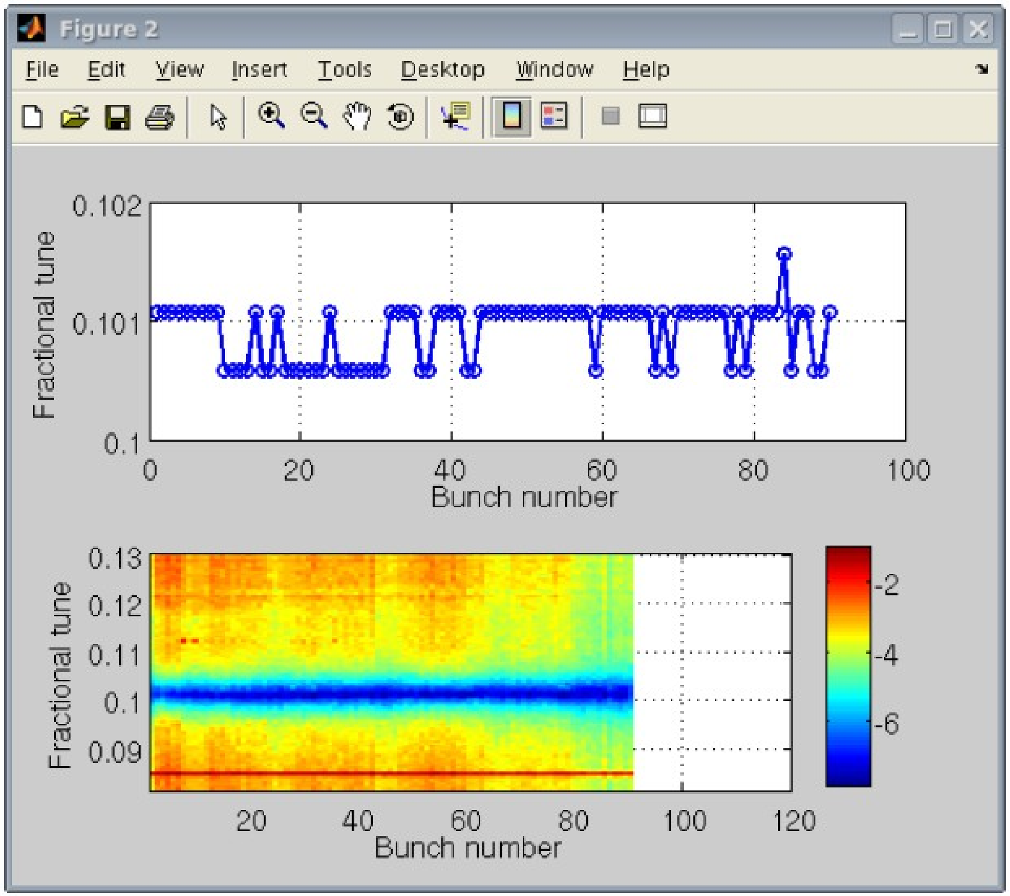
A way for tune measuring that can be used if the feedback itself and the other colliding beam (if any) don't <u>produce tune shift or Landau damping</u>



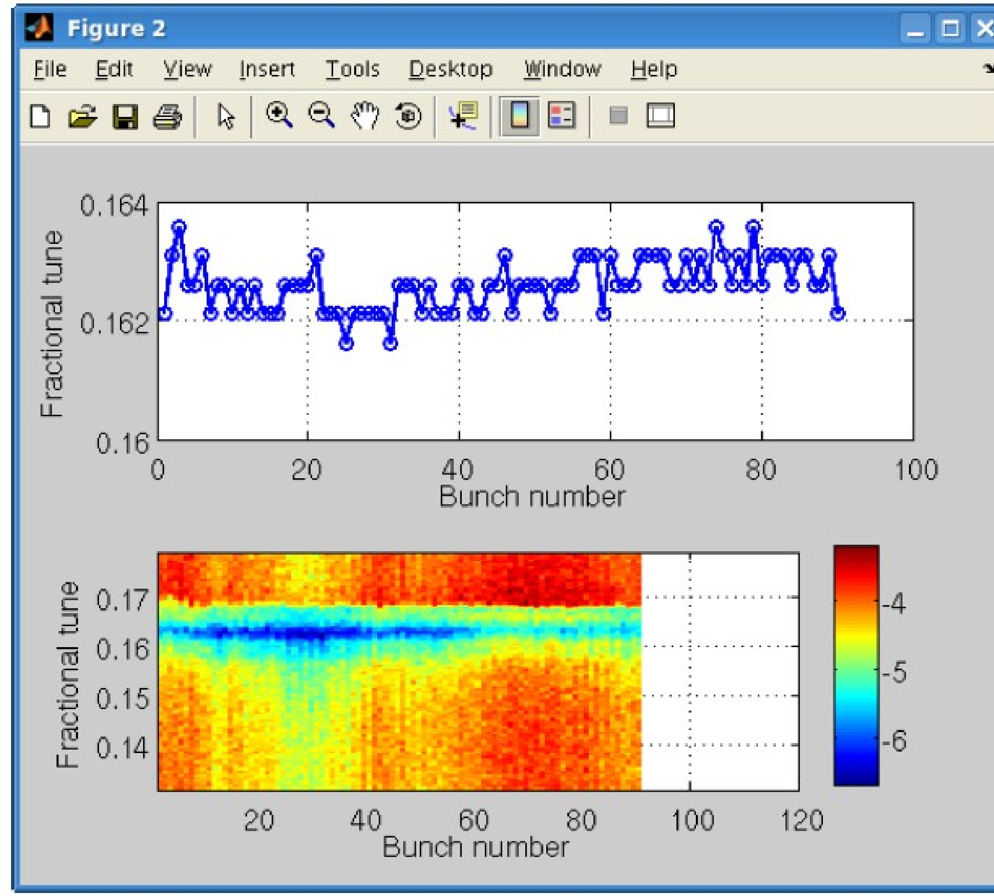
- As it is shown in the picture above, applying a FFT routine to the beam motion recorded by the feedback, it is possible to get a rejection negative peak given by the feedback gain at the frequency where the tune is located and where the S/N ratio is highest
- More feedback gain, more deep the rejection negative peak

Electron beam with 1 Ampere stored in 90 bunches

horizontal tunes



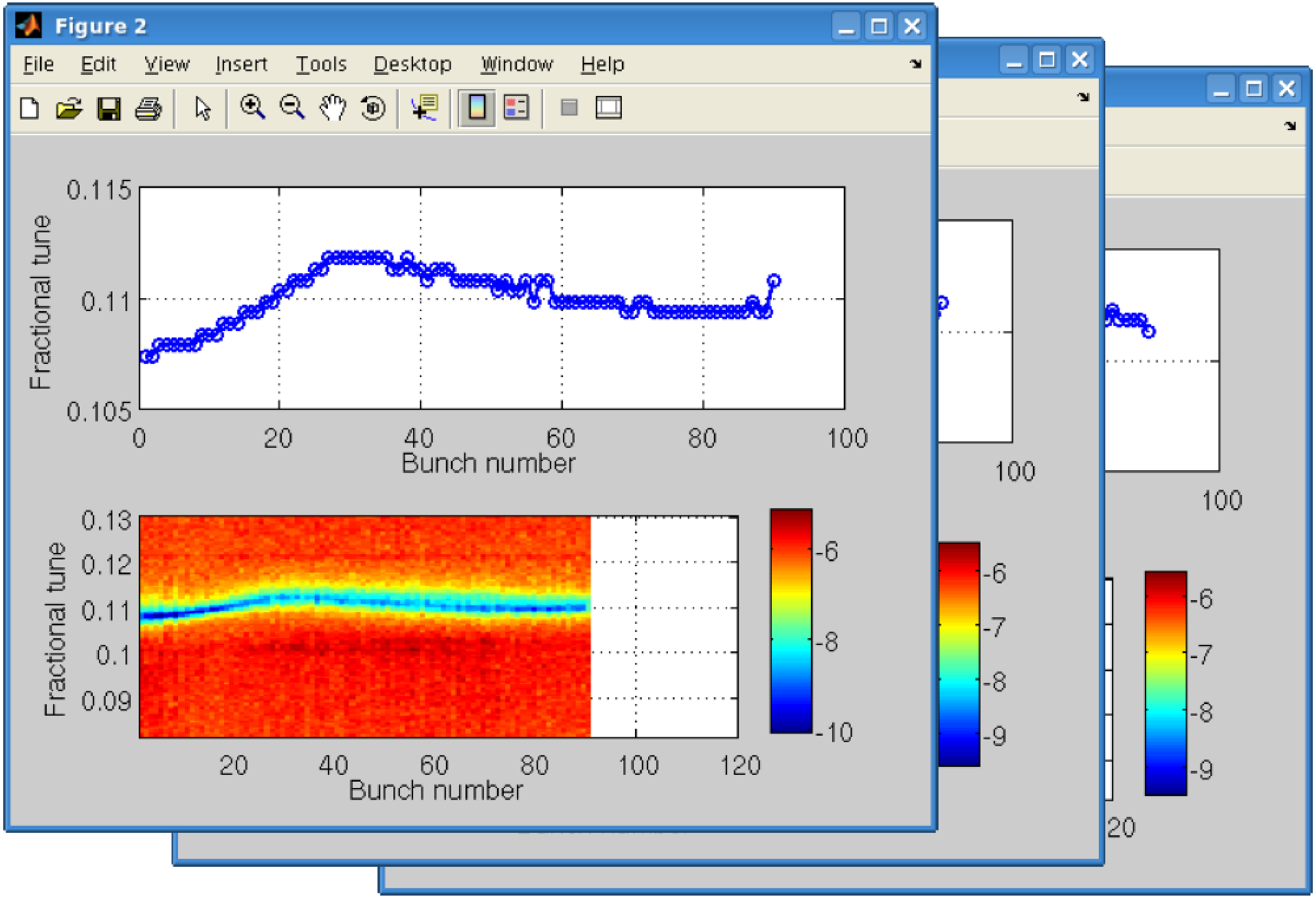
vertical tunes



Bunch-by-bunch tune spread diagnostics made without turning off the feedback

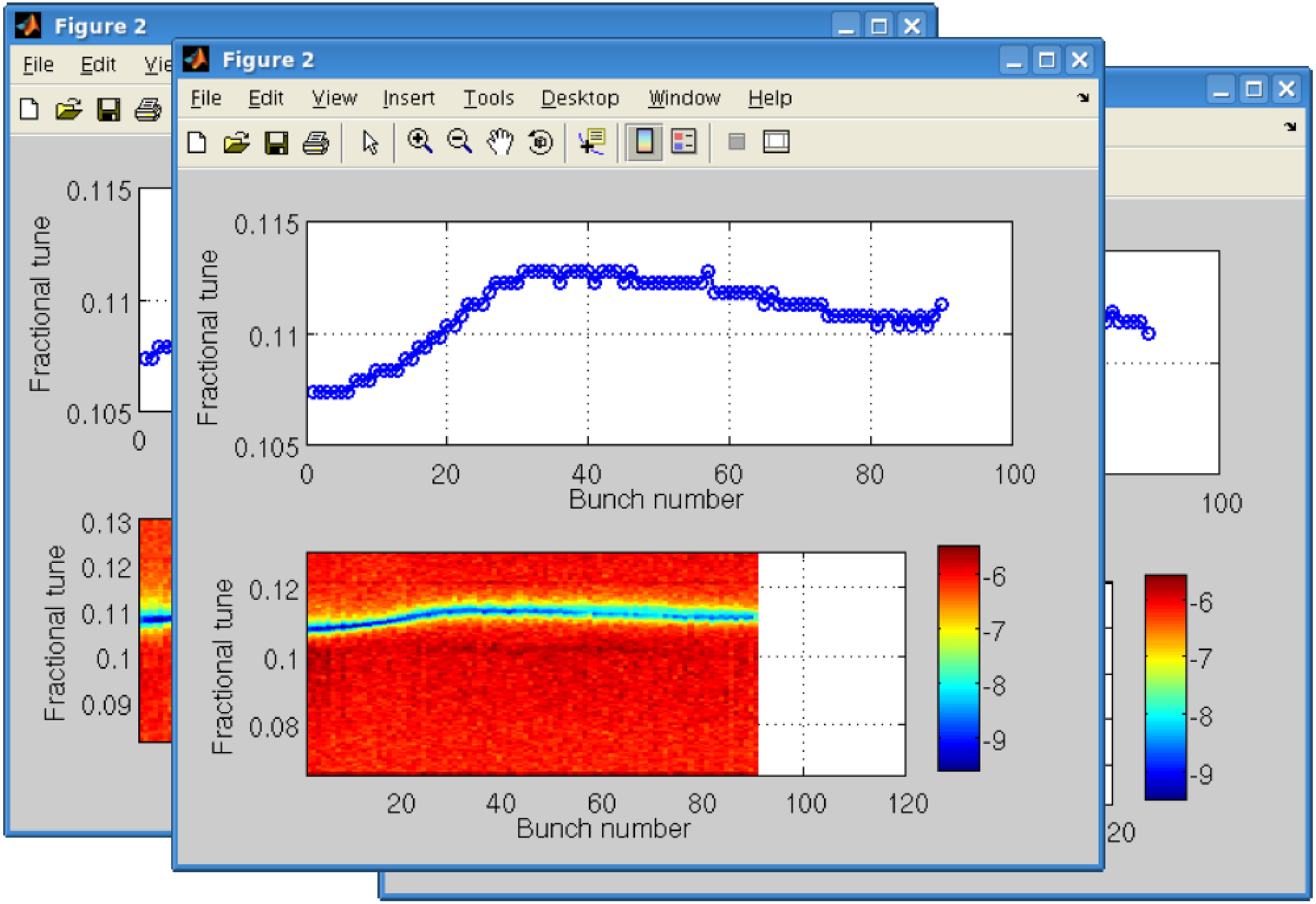
Positron beam with 0.7 Ampere stored in 90 bunches

horizontal tunes with e-cloud clearing electrodes on at full voltage (8 inside bending magnets, 2 inside wiggler magnets)



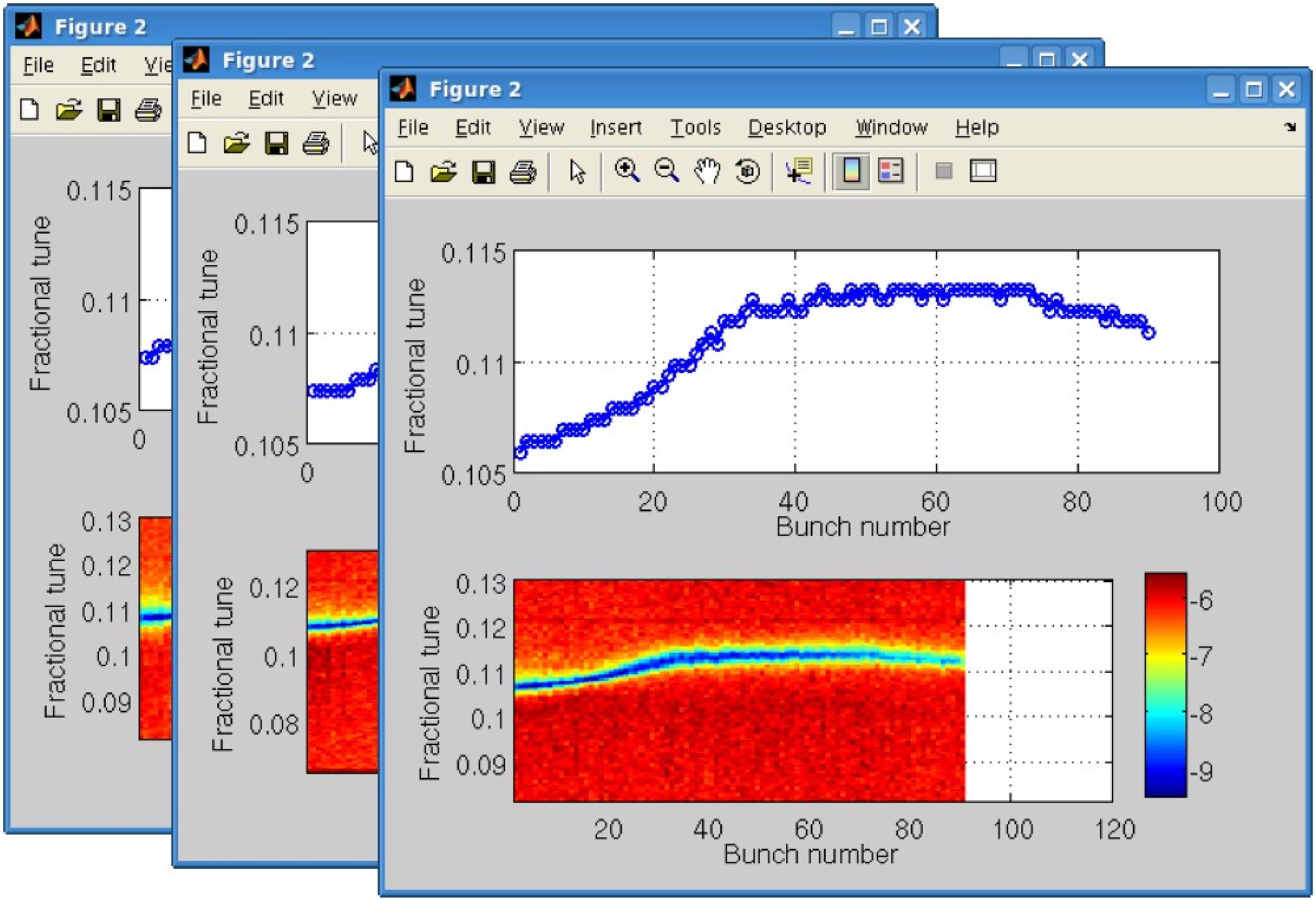
Positron beam with 0.7 Ampere stored in 90 bunches

horizontal tunes with e-cloud clearing electrodes on at full voltage (only the 8 inside bending magnets)



Positron beam with 0.7 Ampere stored in 90 bunches

horizontal tunes with all e-cloud clearing electrodes off



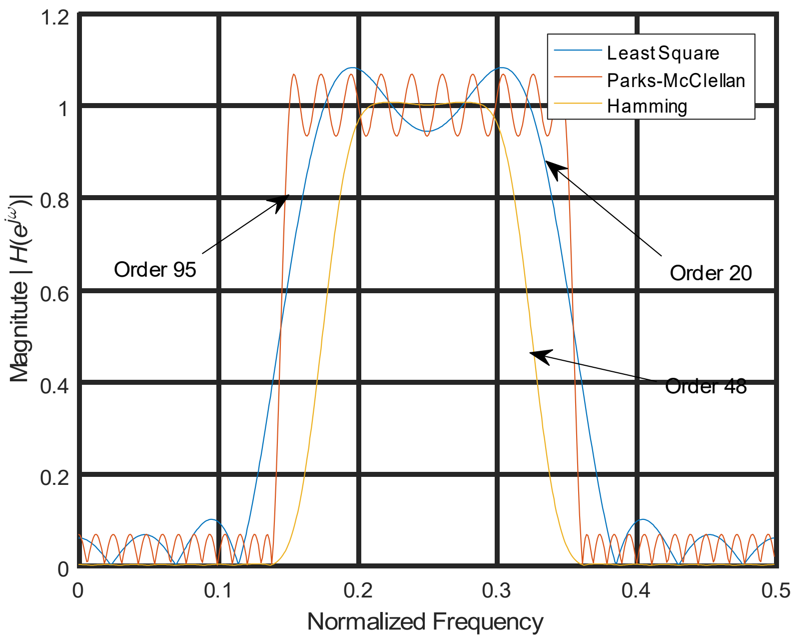
R&D
for FCC-ee feedback

Digital Filter Design & Study

As for linear time invariant filters, choosing a FIR (Finite Impulse Response) or IIR (Infinite Impulse Response) filter depends strictly on characteristics of desired magnitude and phase responses, admissible group delays, sampling time, computational considerations…

A linear phase in the pass-band could be useful in many situations: a FIR system would be preferable in this case.

Figure shows a pass-band FIR design by using different design techniques



Research in progress by S.Caschera (post-doc@LNF)

Computational Intelligence based Optimization Algorithms, as **Genetic Algorithms** able to solve global optimization problems, obtained very interesting results for FIR an IIR filter design too!

Courtesy of E.Belli, FCC week 2017

Transverse coupled bunch instability

- Growth rate for the μ-th mode

$$\frac{1}{\tau_{\mu,\perp}} = -\frac{ecI}{4\pi E Q_\beta}\sum_q Re[Z_\perp(\omega_q)]G_\perp\left(\frac{\sigma_z}{c}\omega'_q\right)=1$$

with

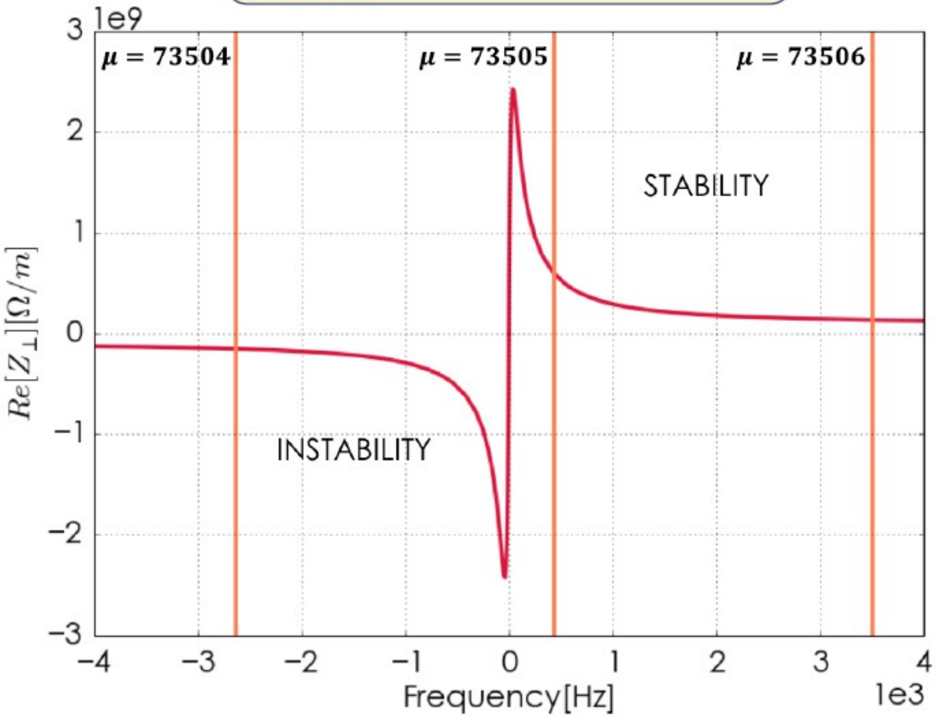
$$\omega_q = (qM + \mu + Q_\beta)\omega_0$$

$$\omega'_q = \omega_q + \xi\frac{\omega_\beta}{\eta}$$

$$Re\,[Z_\perp(\omega)] = sgn(\omega)\frac{C}{2\pi b^3}\sqrt{\frac{2Z_0 c}{\sigma_c|\omega|}}$$

- Negative ω → **unstable** mode with exponential growth
- Positive ω → **stable** mode with damped oscillations
- The most dangerous coupled mode when $\omega_q \approx 0$
  - $\mu = -qM - Q_0 - 1 = 73504$

$$\frac{1}{\tau_{73504}} = 494.8\ s^{-1} \simeq 6\ turns$$



Robust feedback for instability suppression

11

Feedback damping rate limits

- It is an experimental result (tune >0.09) that a bunch-by-bunch feedback in e+/e- collider can damp the instabilities in about 10 revolution turns
- *At very low fractional tune this result should be checked because it could be difficult to compute the correction signal in few turns*
- The damping rate can be achieved by implementing a "standard" feedback system for relatively high beam currents (1-3A) by using a total of 1 or 2 kW power amplifiers.
- The gain limit of this approach is basically limited by the noise in the sytem that comes mainly from pickups and enters in the loop even if filtered
- To mitigate this isuue in the year 2008 at DAFNE we did an experiment by implementing two feedback systems cooperating in the same plane (horizontal e+).
- This was necessary for damping a very strong horizontal mode induced by e-clouds and because we were waiting for a stripline kicker with a better shunt impedance.

- **<u>DAFNE, year 2008</u>**
- **<u>New e+ Transverse Horizontal Feedback</u>**
- The damping times of the two feedback's add up linearly
- Damping time measured:
- ~100 ms-1 (1 FBKs) ➔ fb damps in 30 revolution periods (~10 us)
- ~200 ms-1 (2 FBKs) ➔ fb damps in 15 revolution periods (~ 5 us)
- The power of the H FBK has been doubled

Fast feedbacks for diagnostics and mitigation of e-cloud instability

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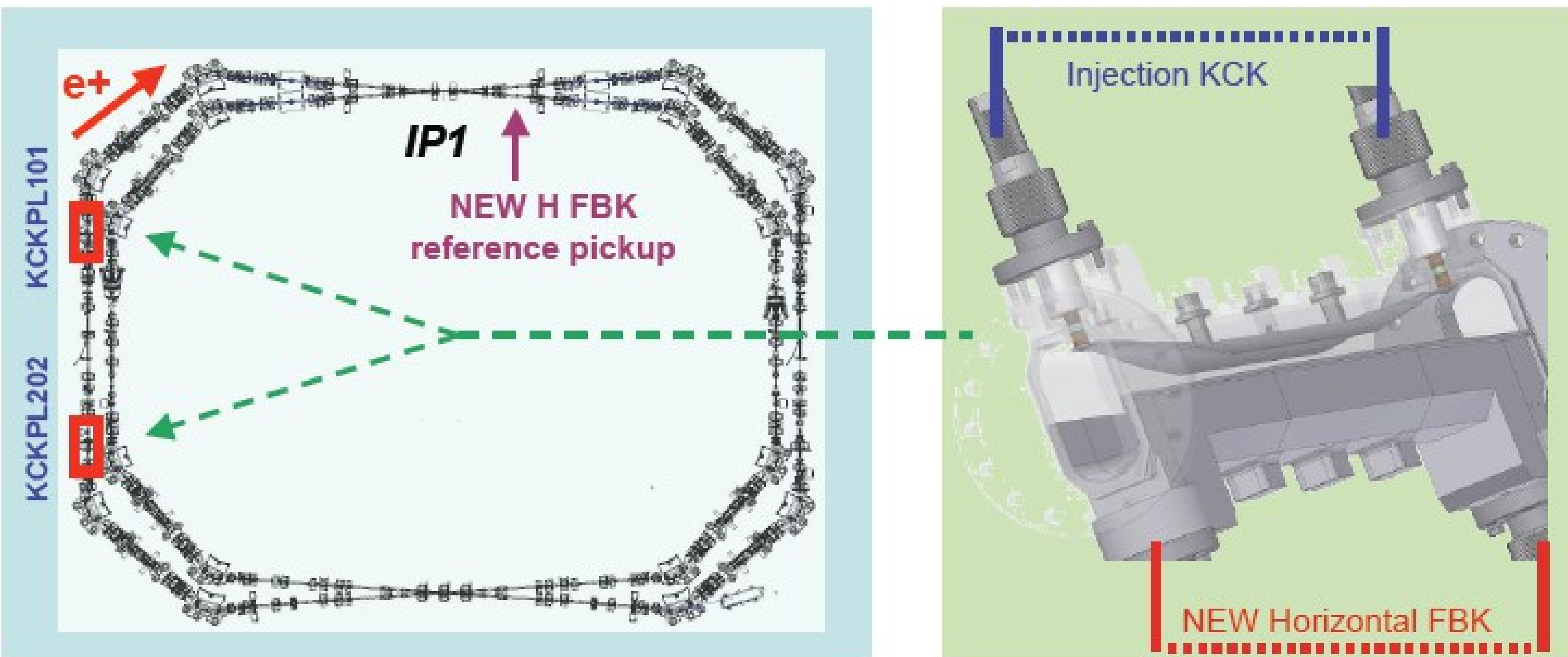
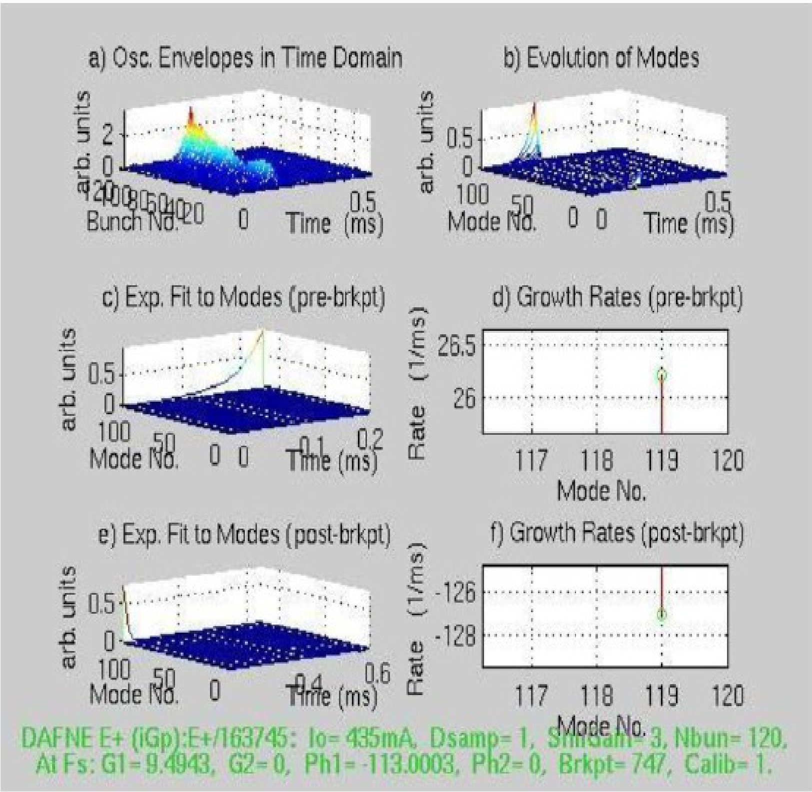
International Linear Collider Workshop 2008
LCWS08 & ILC08
ILC08 Damping Ring session

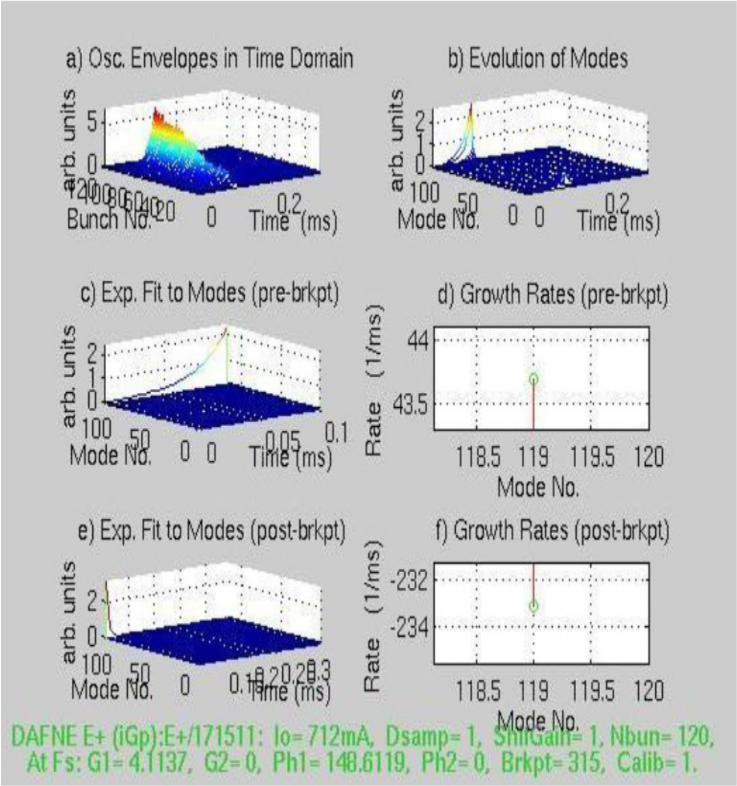
November 16-20, 2008
University of Illinois at Chicago



Single horizontal feedback
I=560mA, mode -1 [=119],
grow=34.5 ms-1, damp=-127 ms-1

Double horizontal feedback:
I=712mA, mode -1 [=119] ,
grow=43.7 (ms-1), damp=-233 (ms-1)





Damping time in 4.3 microsecond i.e. in ~13 revolution turns

International Linear Collider Workshop 2008
LCWS08 & ILC08
ILC08 Damping Ring session

Note: in DAFNE, the mode 119=-1 is the mode of the resistive wall instability

Comment to the 2008 Dafne experiment

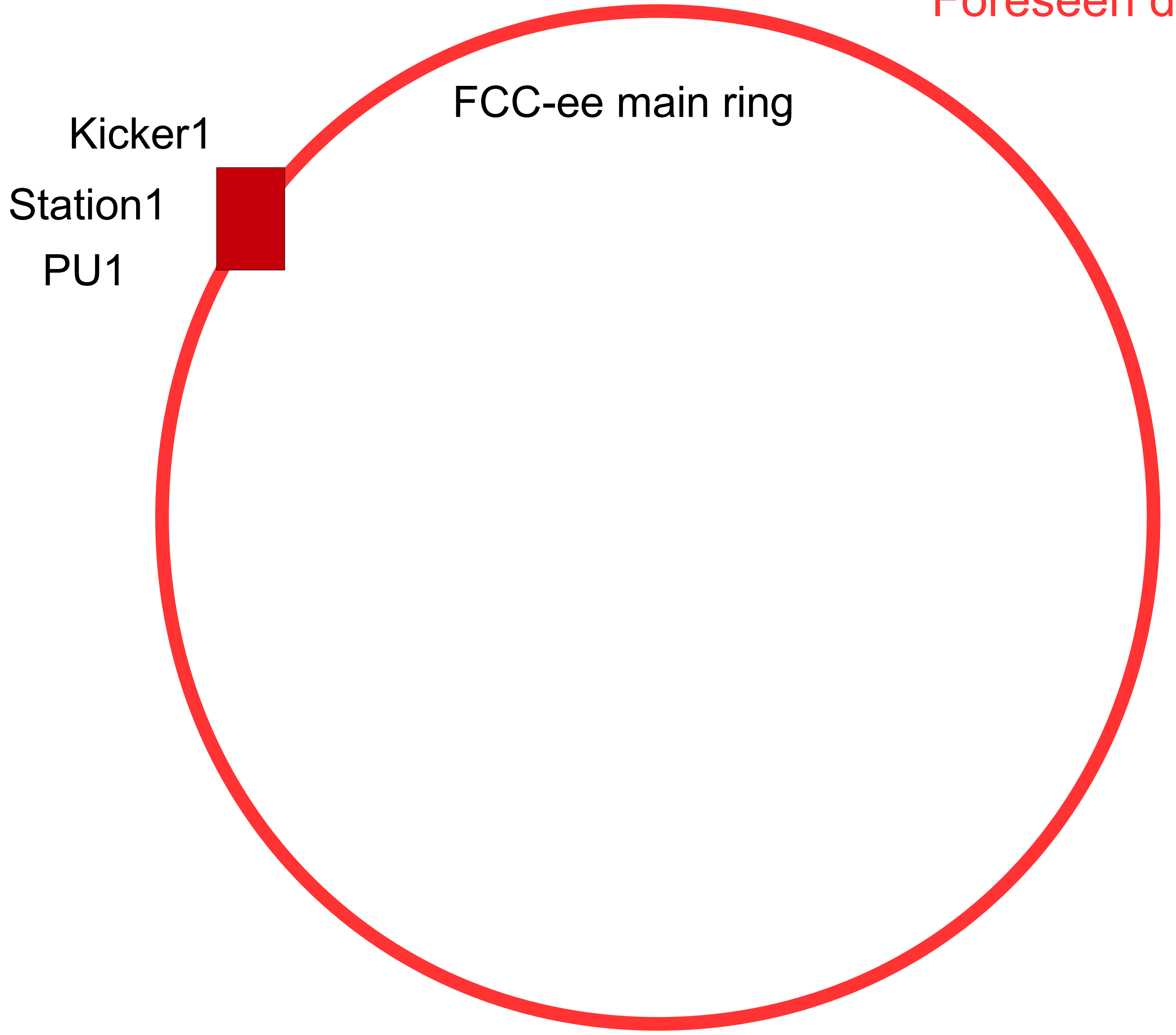
- Two feedback systems in the same ring and damping plane cooperate perfectly without loss of power.
- Having more kickers placed in different parts of the ring asks for a complete duplicate of the feedback system because both timing and phase response would be different.
- *The inverse damping time scales about linearly versus number of feedback systems having the same power.*
- *Note that in the test the fractional tune is 0.10*
- In the previous case we used 2x250W amplifiers for each feedback. After implementing the new kicker with a much better shunt impedance, there was no more need of the second system.

First design proposed for FCC-ee

Feedback based on multiple distributed feedback systems and kickers

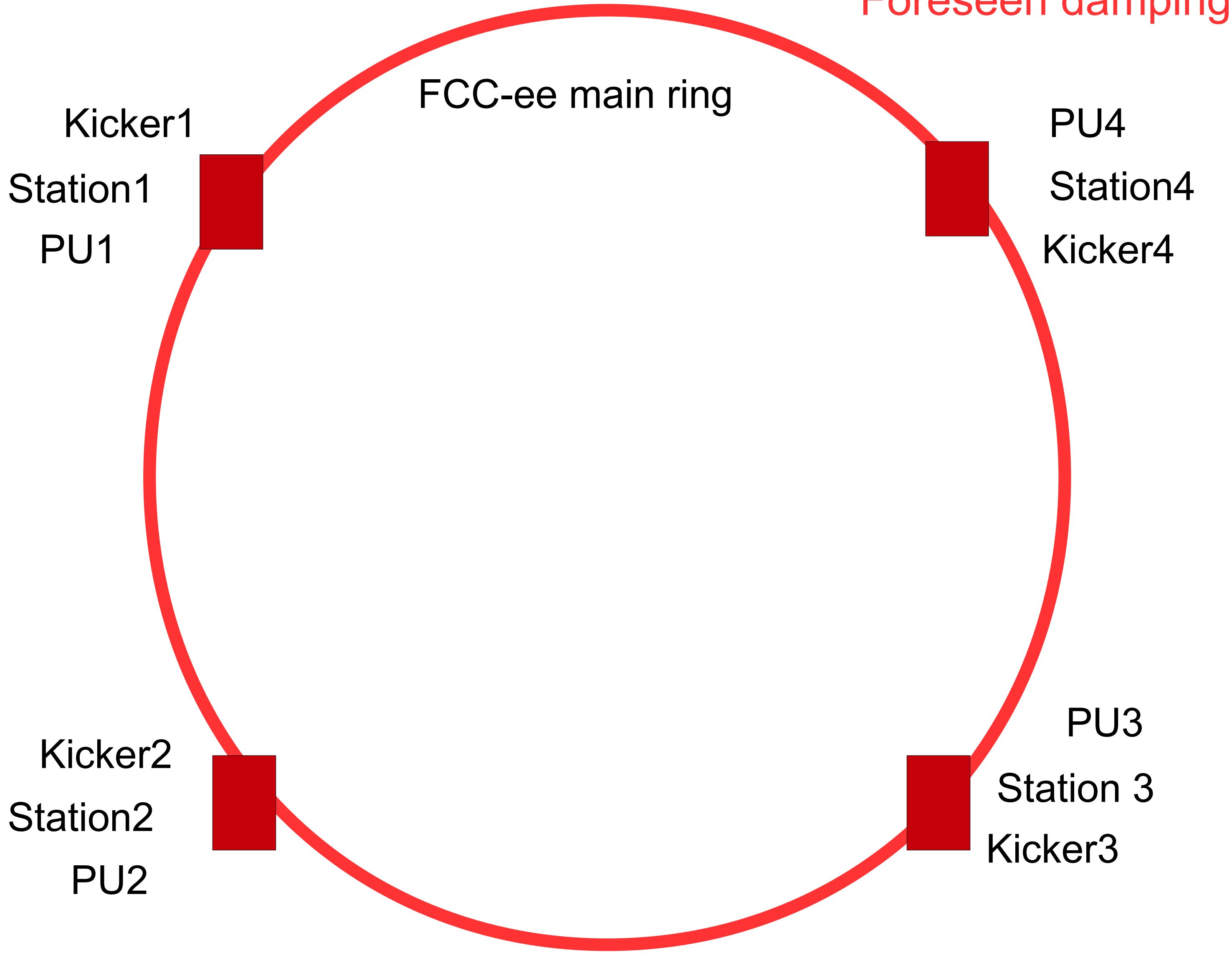
1 Feedback systems (1 stations)

Foreseen damping rate: 10 turns



4 Feedback systems (4 stations)

Foreseen damping rate: 2.5 turns

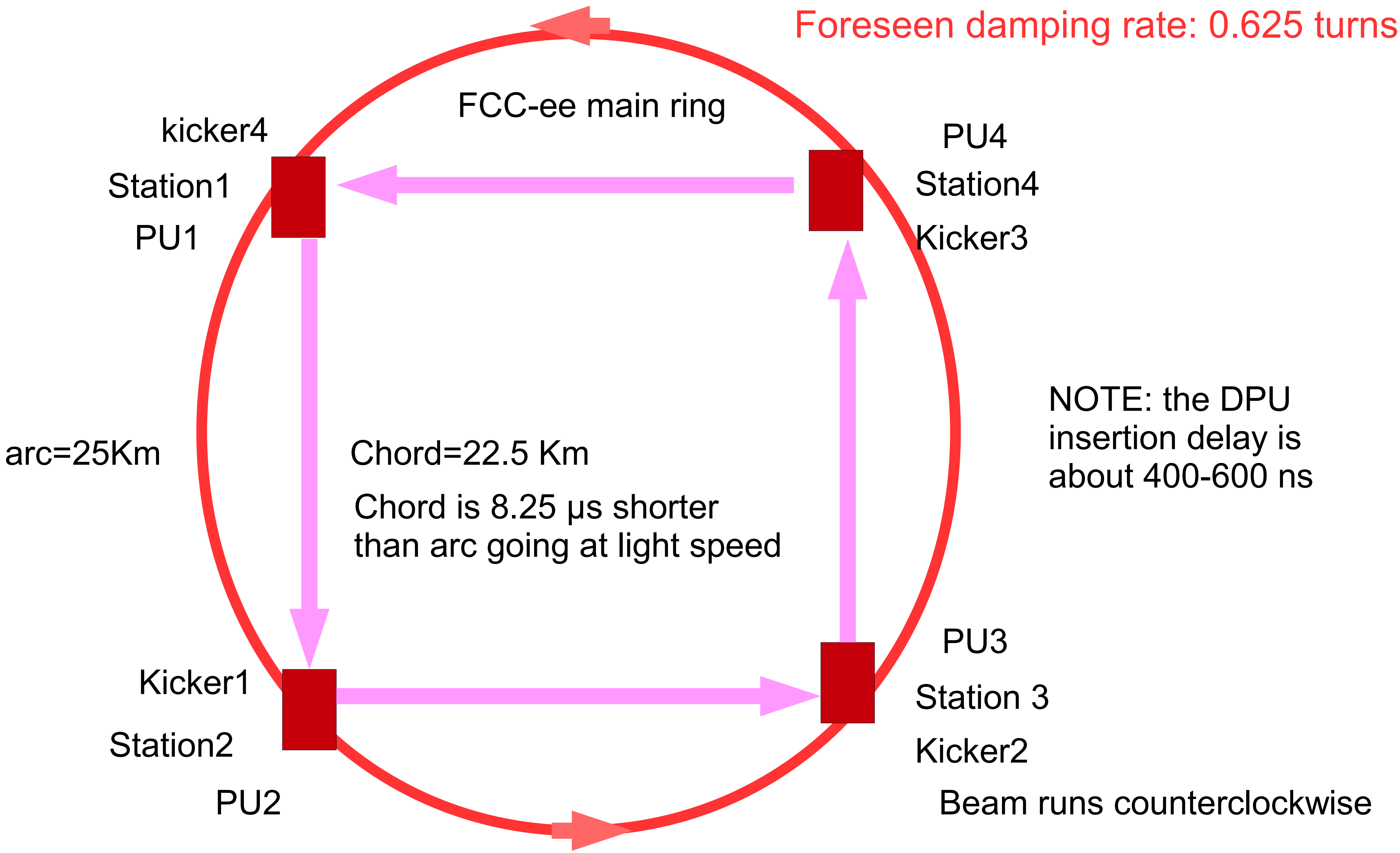


Second and more innovative design:

distributed feedback able to kick quicker than one revolution period

- Looking at the feedback scheme, it is clear that a damping rate faster than 1 turn is not possible because the correction kick is applied after the acquiring of the pickup signal with 1 turn delay.
- However the FCC ring lenght gives a very interesting chance to build "*feeding forward"* systems, producing damping rate even faster than 1 revolution turn. This can be possible applying the correction signal quickly than one revolution period.
- The "*feeding forward*" design will change a bit the usual scheme but not so much. The phase response will be controlled by individual bunch FIR filter inside the DPU in this case too.
- **The implementation would be a big challenge from a technological point of view: it will be necessary to send the correction signal in such a way to arrive to the kicker location before the arrival of the bunch to be corrected.**

4 "*Feeding forward*" systems (4 stations)



How to transmit the correction values at light speed

- <u>This is not a simple task</u>
- In theory the chord lenght could be shorter than 22 Km, but the arc path should be long enough to recover the insertion delay of 400-600 ns plus the cable delays.
- By a laser in air ? ...not easy...
- A second option is to use radiofrequency transmission
- The third idea is to transmit by optical fibers, maybe in blocks of data. In this way the correction signal can be applied to the kicker before the arrival of the bunch that has to be corrected.
- The good point on this last approach is that optical fiber technology has impressive R&D efforts currently ...

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NATURE PHOTONICS | LETTER

日本語要約

Towards high-capacity fibre-optic communications at the speed of light in vacuum

F. Poletti, N. V. Wheeler, M. N. Petrovich, N. Baddela, E. Numkam Fokoua, J. R. Hayes, D. R. Gray, Z. Li, R. Slavík & D. J. Richardson

Affiliations | Contributions | Corresponding author

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Wide-bandwidth signal transmission with low latency is emerging as a key requirement in a number of applications, including the development of future exaflop-scale supercomputers, financial algorithmic trading and cloud computing[1, 2, 3]. Optical fibres provide unsurpassed transmission bandwidth, but light propagates 31% slower in a silica glass fibre than in vacuum, thus compromising latency. Air guidance in hollow-core fibres can reduce fibre latency very significantly. However, state-of-the-art technology cannot achieve the combined values of loss, bandwidth and mode-coupling characteristics required for high-capacity data transmission. Here, we report a fundamentally improved hollow-core photonic-bandgap fibre that provides a record combination of low loss (3.5 dB km^{-1}) and wide bandwidth (160 nm), and use it to transmit 37 × 40 Gbit s^{-1} channels at a 1.54 μs km^{-1} faster speed than in a conventional fibre. This represents the first experimental demonstration of fibre-based wavelength division multiplexed data transmission at close to (99.7%) the speed of light in vacuum.

Year 2013

Transmission by optical fibers at 99.9% of light speed is now possible !!!
R&D are in progress in many laboratory...
Air guidance in hollow core fibres can reduce latency very significantly.

Conclusion

- Feedback systems are extremely useful tools for both beam diagnostics and instabilities suppression in storage rings.
- Transverse instabilities can limit both beam and single bunch currents.
- Source of instabilities are vacuum chamber impedance and (for positive charge stored beams) parasitic e- clouds.
- Transverse bunch-by-bunch feedback systems are implemented in storage rings as active devices for instability suppression and for state of art beam or bunch-by-bunch diagnostics.
- For FCC-ee the feedback systems can be based on the designs developed for other previous e+/e- colliders (PEP-II, KEK, DAFNE, SuperB, SuperKekB).
- By implementing multiple cooperative feedback systems and maintaing the "traditional" design scheme it will be possible to damp up to 1 revolution turn, if necessary.
- Damping in less that 1 revolution turn is possible only changing the usual feedback strategy. An innovative bunch-by-bunch "*feeding forward"* system is proposed.

Acknowledgements

- John Fox for all the ideas developed during the last 3 decades together with his SLAC team: H.Hindi, S.Prabhakar, D.Teytelman, A.Young, J.Olsen, C.Rivetta, J.Cesaratto, T.Mastoridis, and many others
- LNF feedback and kicker team (too many to be reported...)
- ALS 90's feedback team (J.Byrd, W.Barry, J.Corlett, G.Lambertson, ...)
- M. Tobiyama and the KEK feedback team

Thank you for the attention !