TRANSIENT BEAM RESPONSE IN SYNCHROTRONS WITH A DIGITAL TRANSVERSE FEEDBACK SYSTEM

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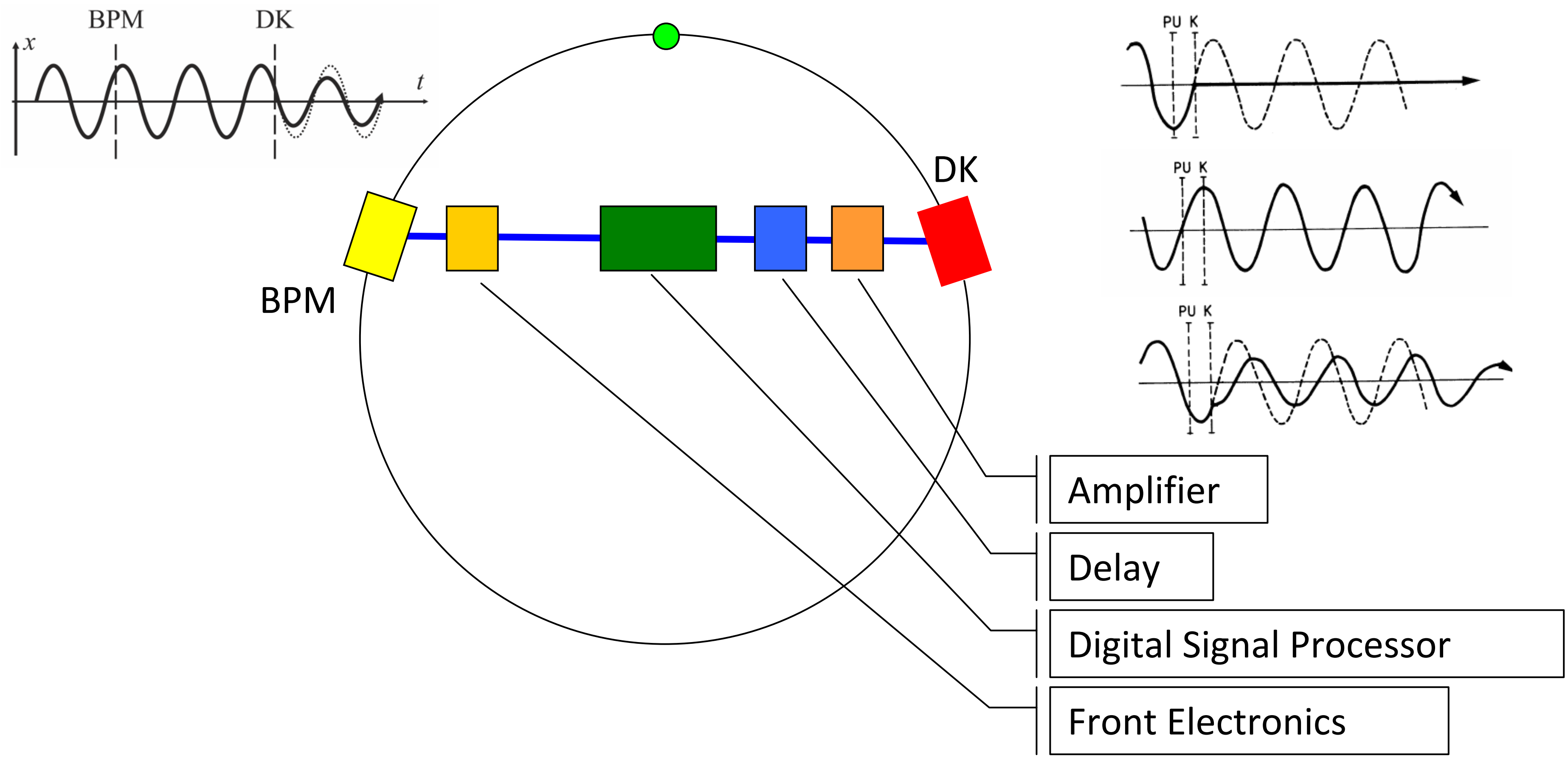
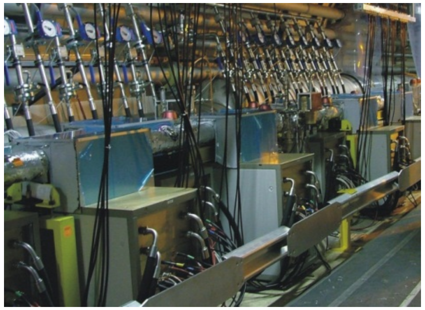
Transverse Feedback System in Synchrotrons

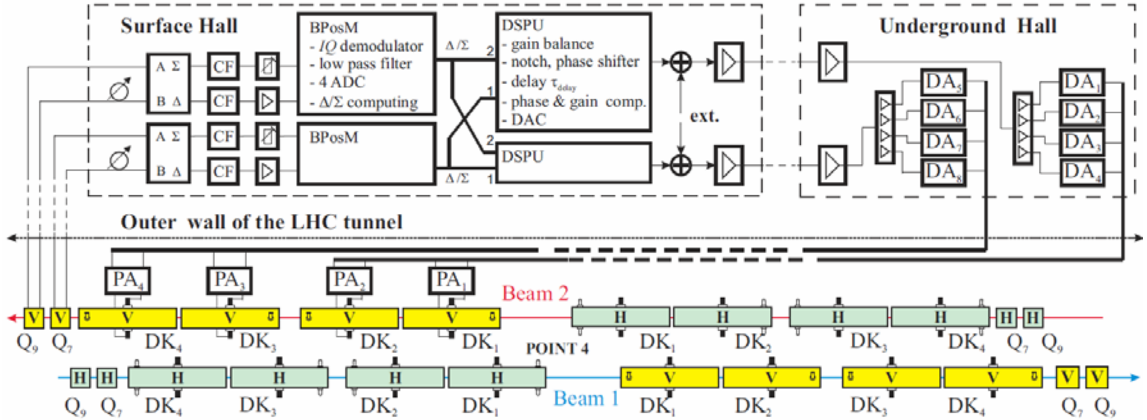


$$g = \frac{\langle \Delta x'[n,\, s_{\rm K}] \rangle \sqrt{\hat{\beta}_{\rm P} \hat{\beta}_{\rm K}}}{\langle x[n,\, s_{\rm P}] \rangle} = \frac{2\,T_{\rm rev}}{\tau_{\rm d}}\bigg|_{\rm opt}$$

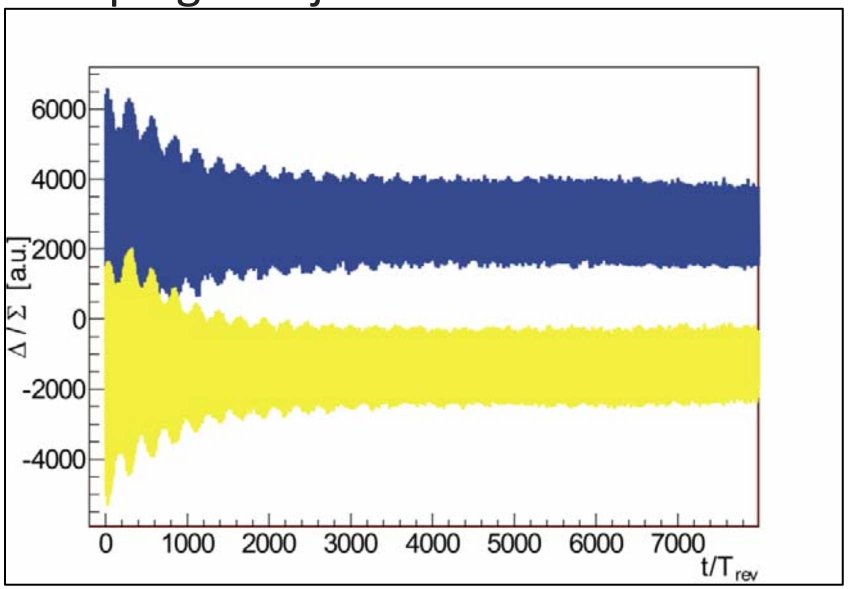
$$\text{LHC Damper:} \quad g = 0.05 \;\rightarrow\; \tau_{\rm d} = 40\,T_{\rm rev}$$

LHC Damper (CERN, JINR)

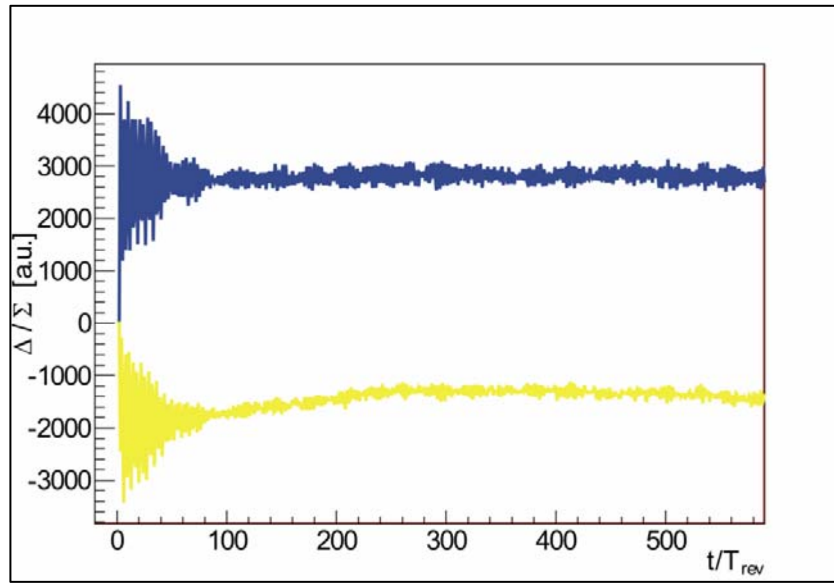




Single Bunch Operation:
Damping of Injection Errors



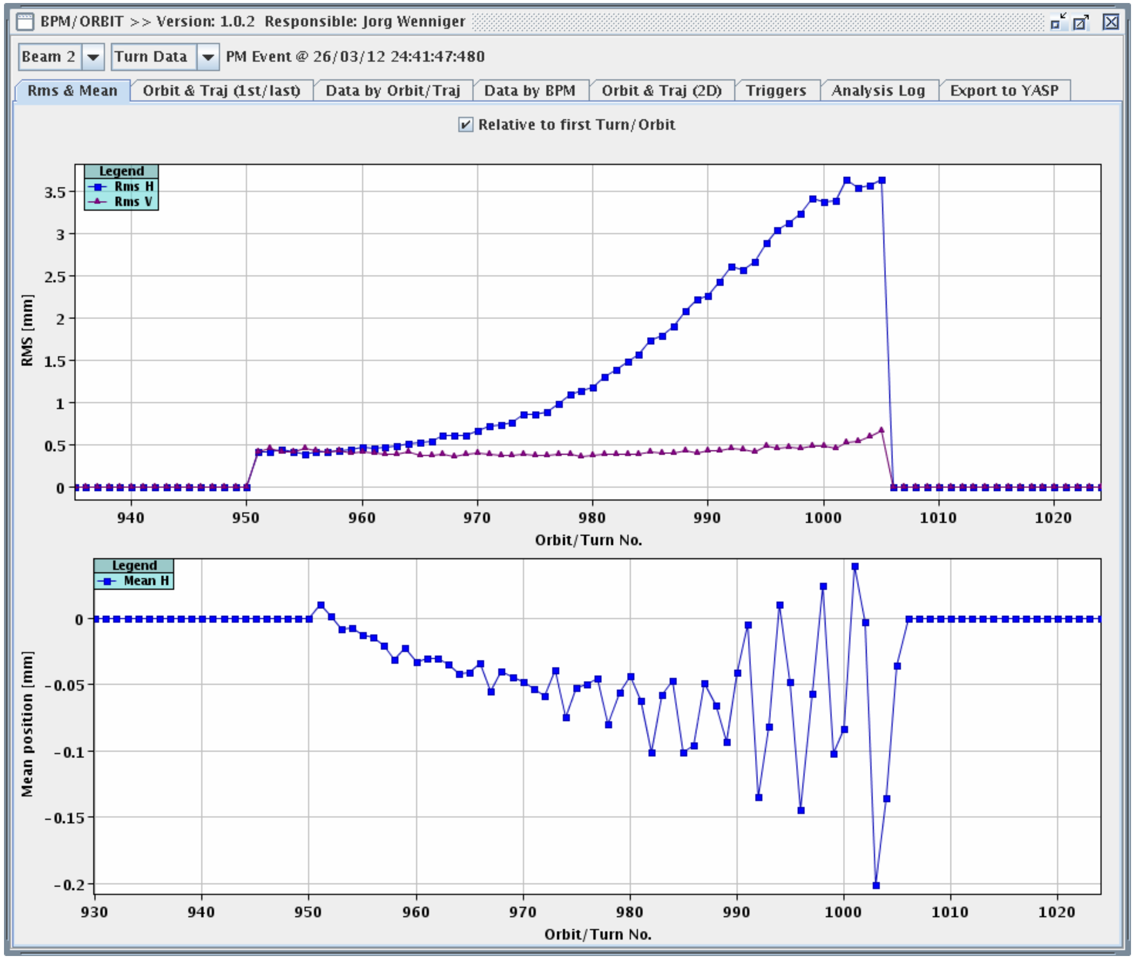
Damper OFF



Damper ON

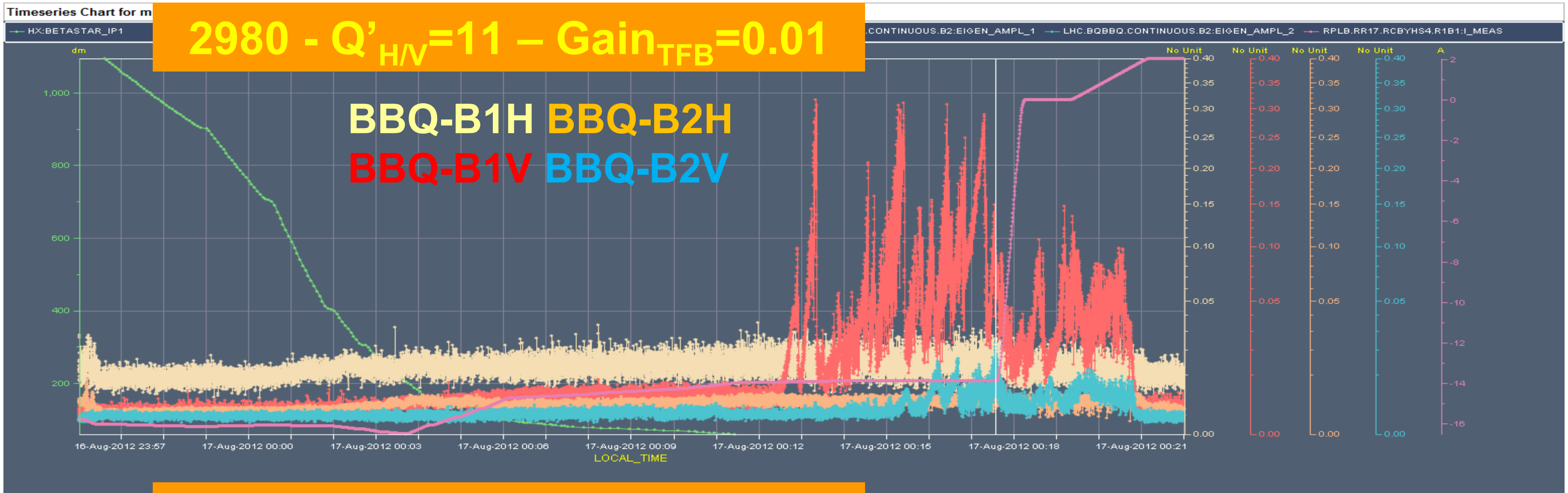
V.Zhabitsky, W.Höfle et al. RuPAC 2010

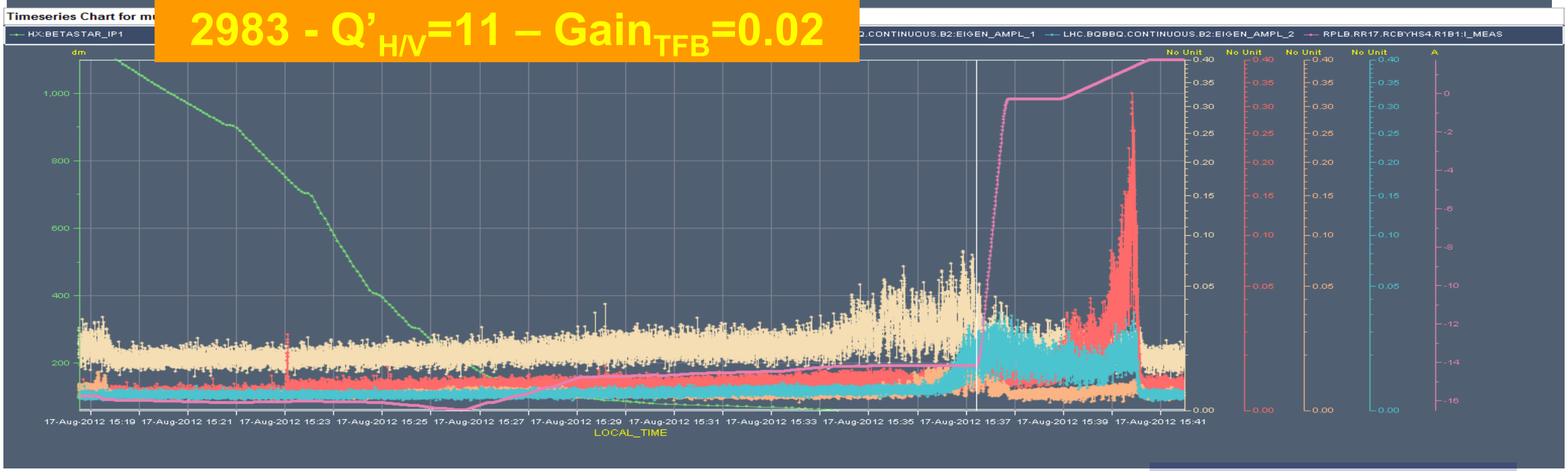
- 24:00 – 01:00 ADT fast losses test – one pilot at 450 GeV
- Achieved very fast losses (could be used for UFO studies)



J. Uythoven, E.B. Holzer (CERN)

Instabilities

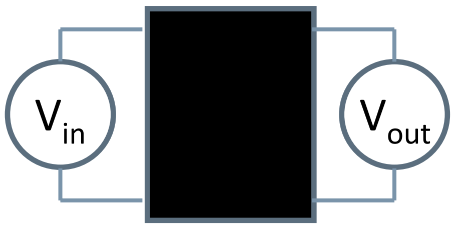


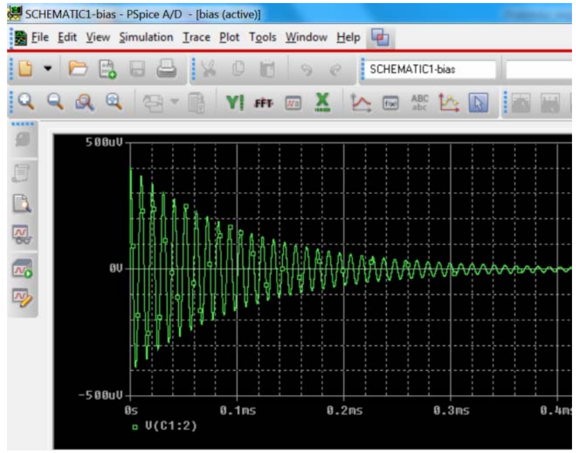


G. Arduini (CERN)

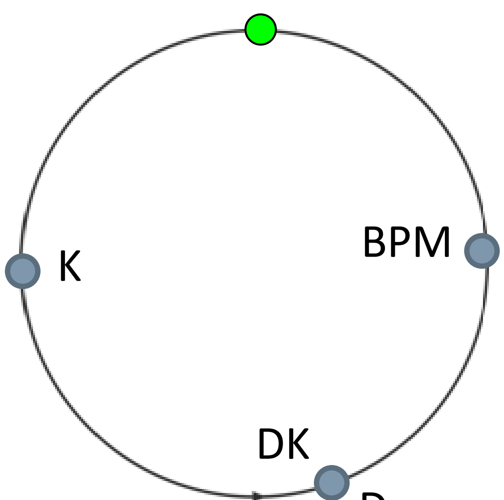
Response to impulse

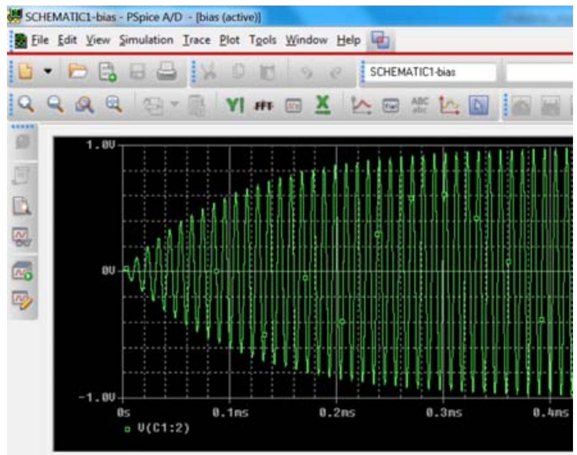
Radio technical device

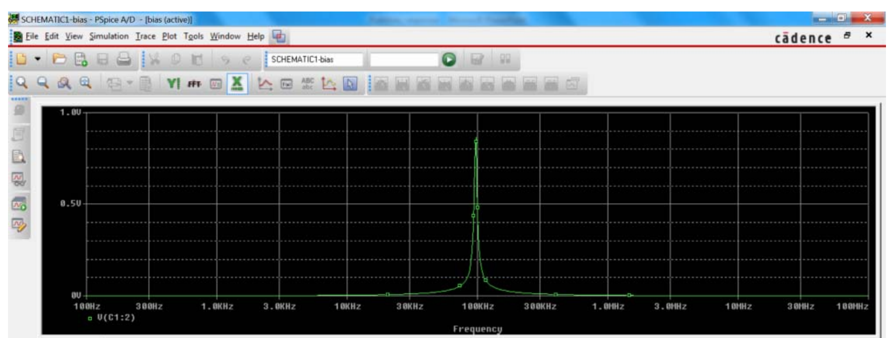




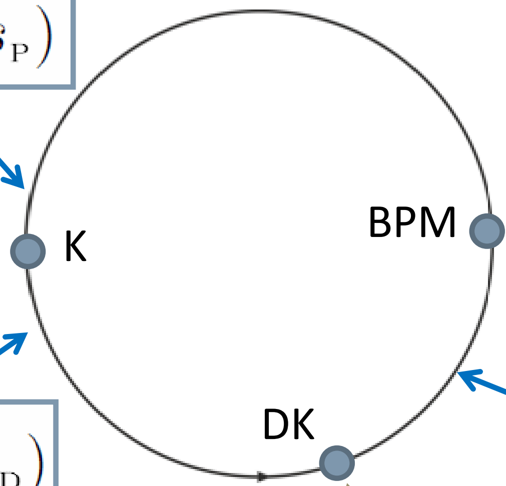
Synchrotrons







$$\widehat{M}(s_{\mathrm{D}}|s_{\mathrm{P}})$$



$$\widehat{X}[n, s_{\mathrm{P}}] = \begin{pmatrix} x[n, s_{\mathrm{P}}] \\ x'[n, s_{\mathrm{P}}] \end{pmatrix}$$

$$\widehat{M}(s_{\mathrm{K}}|s_{\mathrm{D}})$$

$$\widehat{M}(s_{\mathrm{P}} + C|s_{\mathrm{K}})$$

$$\widehat{E} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

$$\widehat{X}[n, s_{\mathrm{K}}] = M(s_{\mathrm{K}}|s_{\mathrm{D}})\widehat{M}(s_{\mathrm{D}}|s_{\mathrm{P}})\widehat{X}[n, s] + \Delta x'[n, s_{\mathrm{K}}]\,\widehat{E} + \Delta x'_{\mathrm{D}}[n]\,\widehat{M}(s_{\mathrm{K}}|s_{\mathrm{D}})\widehat{E}$$

$$\widehat{X}[n, s_{\mathrm{P}} + C] = \widehat{M}(s_{\mathrm{P}} + C|s_{\mathrm{K}})\widehat{X}[n, s_{\mathrm{K}}]$$

$$\widehat{X}[n+1, s] \equiv \widehat{X}[n, s + C] = \widehat{M}(s)\widehat{X}[n, s] + \Delta x'[n, s_{\mathrm{K}}]\,\widehat{M}_{\mathrm{K}}\widehat{E} + \Delta x'_{\mathrm{D}}[n]\,\widehat{M}_{\mathrm{D}}\widehat{E}$$

$$\widehat{M}(s_{\mathrm{P}}) \equiv \widehat{M}(s_{\mathrm{P}} + C|s_{\mathrm{P}}),\;\; \widehat{M}_{\mathrm{K}} \equiv \widehat{M}(s_{\mathrm{P}} + C|s_{\mathrm{K}}),\; \widehat{M}_{\mathrm{D}} \equiv \widehat{M}(s_{\mathrm{P}} + C|s_{\mathrm{D}})\,.$$

$$\widehat{X}[n+1,s] \equiv \widehat{X}[n,s+C] = \widehat{M}(s)\widehat{X}[n,s] + \Delta x'[n,s_{\mathrm{K}}]\,\widehat{M}_{\mathrm{K}}\widehat{E} + \Delta x'_{\mathrm{D}}[n]\,\widehat{M}_{\mathrm{D}}\widehat{E}$$

Damper kicker:

$$\Delta x'[n,s_{\mathrm{K}}] = S_{\mathrm{K}}\,V_{\mathrm{out}}[n] = S_{\mathrm{K}}\,\mathrm{K}_{\mathrm{out}}\,\mathrm{K}_{\mathrm{in}}\sum_{m=0}^{N_{\mathrm{F}}} h[m]\,V_{\mathrm{in}}[n-\hat{q}-m]\,u[n-\hat{q}-m]$$

$$\tau_{\mathrm{delay}} = \tau_{\mathrm{PK}} + \hat{q}\,T_{\mathrm{rev}}$$

$$V_{\mathrm{in}}[n] = (x[n,s_{\mathrm{P}}] + \delta x_{\mathrm{P}})\,S_{\mathrm{P}}\,u[n]$$

Driving force:

$$\Delta x'_{\mathrm{D}}[n]\sqrt{\hat{\beta}_{\mathrm{D}}\hat{\beta}_{\mathrm{P}}} \equiv V_{\mathrm{D}} = a_{\mathrm{D}}\,\delta[n-n_{\mathrm{D}}]$$

$$V_{\mathrm{D}} = a_{\mathrm{D}}\sin\left(2\pi(n-n_{\mathrm{D}})Q_{\mathrm{D}} + \phi_{\mathrm{D}}\right)\left(u[n-n_{\mathrm{D}}] - u[n-n_{\mathrm{D}}-N_{\mathrm{D}}]\right)$$

$$\mathbf{y}(z) = \mathcal{Z}\{y[n]\} \equiv \sum_{n=0}^{\infty} y[n]\,z^{-n}\,, \qquad y[n] = 0 \quad \forall n < 0,$$

$$y[n] = \mathcal{Z}^{-1}\{\mathbf{y}(z)\} \equiv \frac{1}{2\pi \mathrm{j}}\oint_{\Gamma} \mathbf{y}(z)\,z^{-1}dz = \sum_{k} \mathrm{Res}\left[\mathbf{y}(z)\,z^{n-1};\; z_k\right]$$

$$\widehat{\mathbf{X}}(z,s) = \frac{z\widehat{I} - \widehat{\mathbf{M}}^{-1}\det\widehat{\mathbf{M}}}{\det\left(z\widehat{I} - \widehat{\mathbf{M}}\right)}\left(\mathcal{Z}\{\Delta x'_{\scriptscriptstyle D}[n]\}\,\widehat{M}_{\scriptscriptstyle D}\widehat{E} + z\widehat{X}[0,s] + \frac{g\,z^{-\hat{q}}\,\mathbf{K}(z)\,\delta x_{\scriptscriptstyle P}}{(1-z^{-1})(\hat{\beta}_{\scriptscriptstyle K}\hat{\beta}_{\scriptscriptstyle P})^{1/2}\mathrm{K}_0}\,\widehat{M}_{\scriptscriptstyle K}\widehat{E}\right)$$

$$\mathbf{K}(z) = \mathbf{K}_{\mathrm{out}}H(z)\mathbf{K}_{\mathrm{in}}$$

$$H(z) = \mathcal{Z}\{h[n]\}$$

$$g = (\hat{\beta}_{\scriptscriptstyle K}\hat{\beta}_{\scriptscriptstyle P})^{1/2}\,\mathrm{K}_0 S_{\scriptscriptstyle K} S_{\scriptscriptstyle P}$$

It can be done if $|z_k| < 1$ and

$$\lim_{n\to\infty}\widehat{X}[n,s] = \lim_{z\to 1}(z-1)\,\widehat{\mathbf{X}}(z,s) = 0.$$

Consequently $\mathbf{K}(z=1) = 0.$

$$H_{\scriptscriptstyle NF}(z) = (1 - z^{-1}).$$

$$\widehat{\mathbf{M}} \equiv \widehat{\mathbf{M}}(z,s) = \widehat{M}(s) + \frac{g\,z^{-\hat{q}}\,\mathbf{K}(z)}{(\hat{\beta}_{\scriptscriptstyle K}\hat{\beta}_{\scriptscriptstyle P})^{1/2}\,\mathrm{K}_0}\,\widehat{M}_{\scriptscriptstyle K}\,\widehat{T}\,\widehat{M}(s_{\scriptscriptstyle P}|s), \qquad \widehat{T} \equiv \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$z_k^2 - \left(2\cos(2\pi Q) + \frac{g\,z_k^{-\hat{q}}\,\mathbf{K}(z_k)}{\mathrm{K}_0}\,\sin(2\pi Q - \psi_{\mathrm{PK}})\right) z_k + 1 - \frac{g\,z_k^{-\hat{q}}\,\mathbf{K}(z_k)}{\mathrm{K}_0}\,\sin\psi_{\mathrm{PK}} = 0$$

$$g = 0 \quad \Rightarrow \quad z_{1,2}^{(0)} = \exp(\pm \mathrm{j}\,2\pi Q)$$

TFS: Damping Parameters

$$x[n, s_{\text{K}}] = \sum_k A_k \sqrt{\hat{\beta}_{\text{K}}}\, \mathrm{e}^{-n\alpha_k + \mathrm{j}\,(2\pi n\{Q_k\} + \Phi_k)}$$

$$\alpha_k \equiv -\ln|z_k| = \frac{T_{\text{rev}}}{\tau_k}, \qquad \{Q_k\} = \frac{1}{2\pi}\arg z_k$$

If $g \ll 1$ and $\mathbf{K}_{\text{in}}(\omega)\mathbf{K}_{\text{out}}(\omega)$ depends weakly on frequency then:

$$\alpha_m = \frac{g\,|\mathbf{K}(\omega_m)|}{2\mathrm{K}_0}\sin\Psi_{\text{PK}}\,, \qquad \omega_m = 2\pi(Q+m)f_{\text{rev}}$$

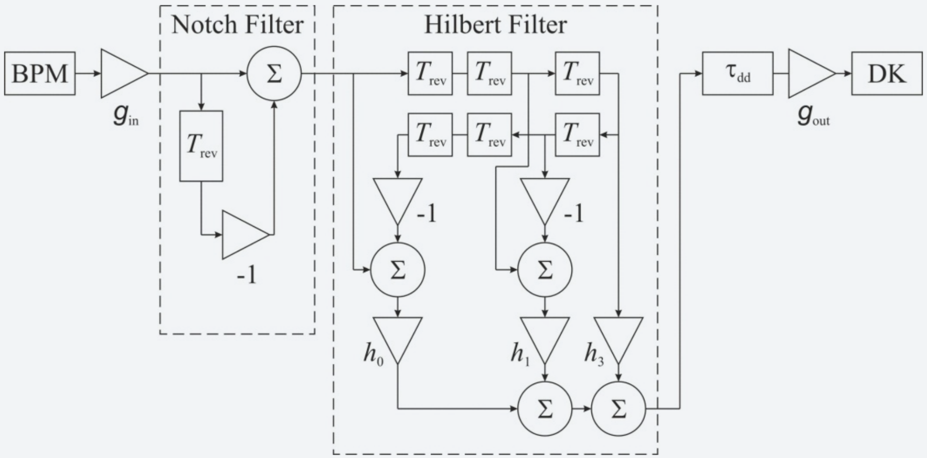
$$\{Q_m\} = \{Q\} - \frac{g\,|\mathbf{K}(\omega_m)|}{4\pi\mathrm{K}_0}\cos\Psi_{\text{PK}}\,, \qquad -0.5 < \{Q\} \leqslant 0.5.$$

$$\Psi_{\text{PK}} = \psi_{\text{PK}} + 2\pi\hat{q}\,Q - \arg\mathbf{K}(\omega_m)\,,$$

$$\mathbf{K}(\omega_m) = \mathbf{K}_{\text{in}}(\omega_m)\,\mathbf{K}_{\text{out}}(\omega_m)\,H\big(z = \mathrm{e}^{\mathrm{j}\,2\pi Q}\big)\,,$$

$$|\mathrm{K}_0| = |\mathbf{K}(\omega_{\min})|, \qquad \mathrm{K}_0 \sin\Psi_{\text{PK}}(\omega_{\min}) > 0,$$

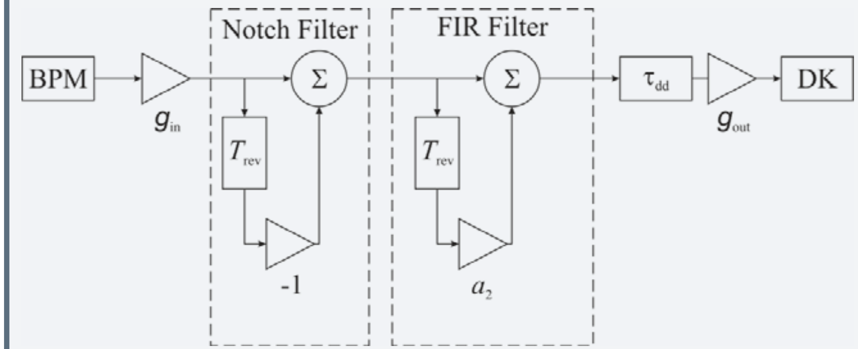
TFS with Notch and Hilbert Filters



$$H_1(z) \equiv H_{\rm N}(z)\, H_{\rm HF}(z) = \left(1 - z^{-1}\right)\left(h_0 z^{-3} + h_1 z^{-2}(1 - z^{-2}) + h_3(1 - z^{-6})\right)$$

$$h_0 = \cos(\Delta\varphi)\,, \quad h_1 = \frac{2}{\pi}\sin(\Delta\varphi)\,, \quad h_3 = \frac{2}{3\pi}\sin(\Delta\varphi)$$

TFS with Notch and FIR-1 Filters



$$H_2(z) \equiv H_{\rm N}(z)\, H_{\rm FIR}(z) = \left(1 - z^{-1}\right)\left(1 + a_2 z^{-1}\right)$$

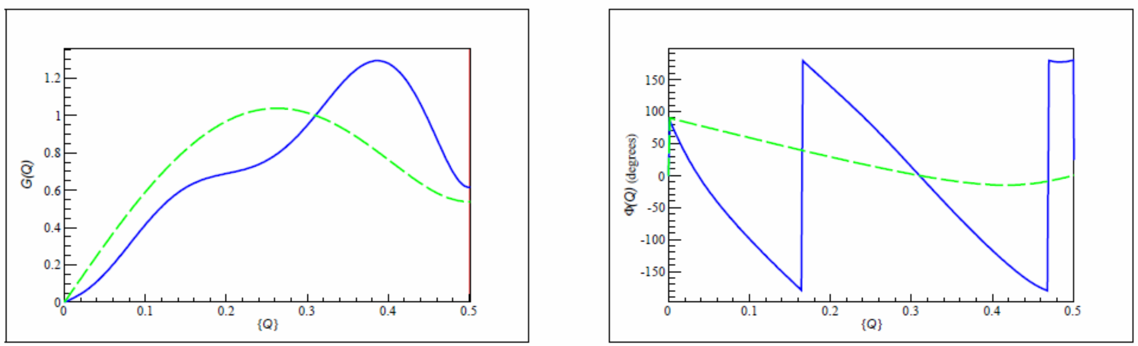
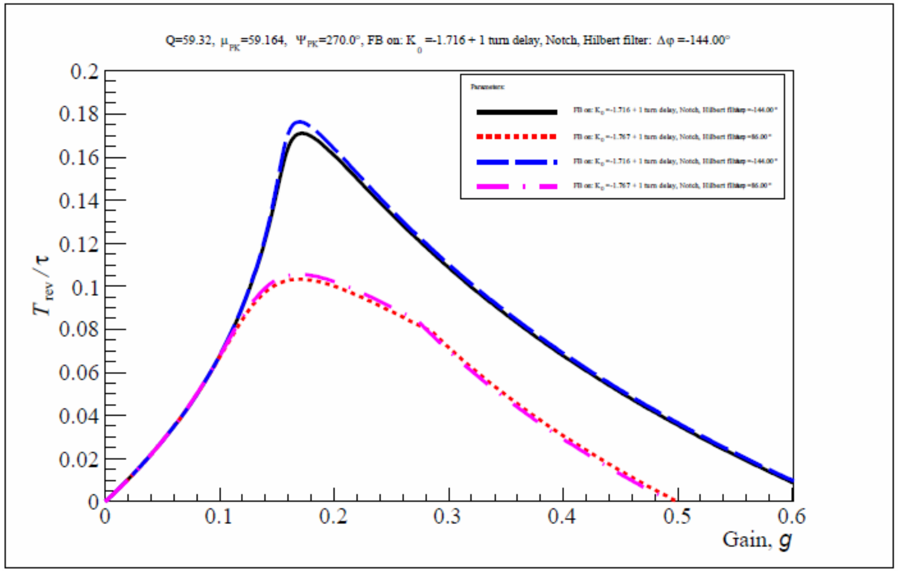
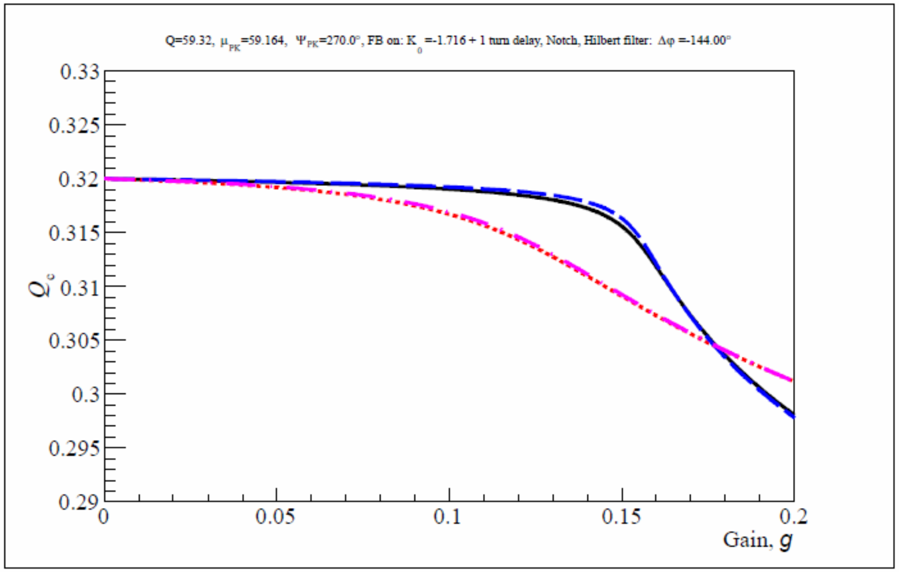
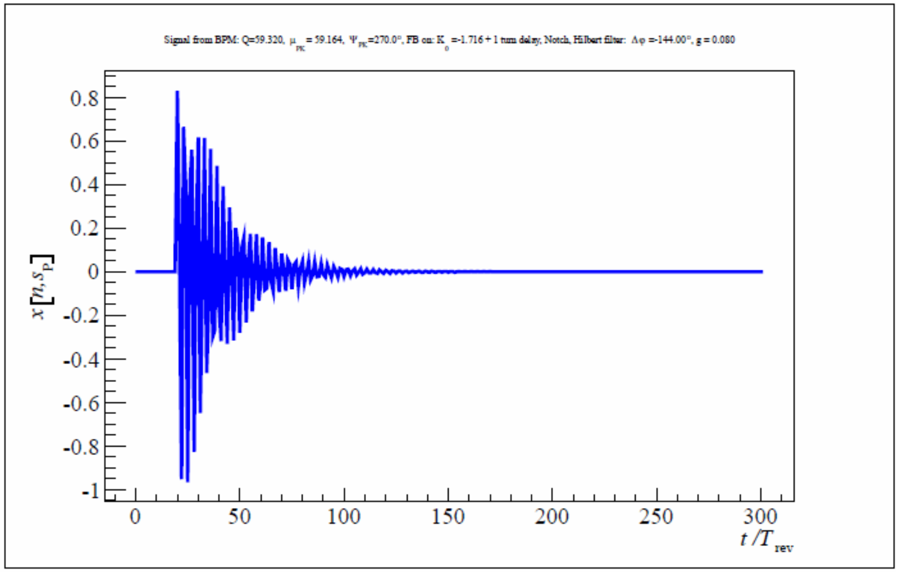


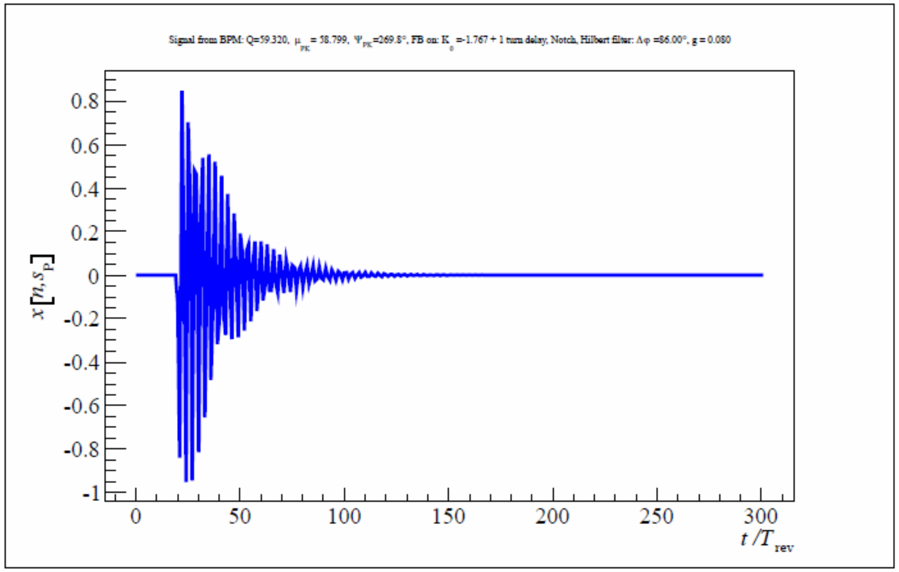
Figure 2: The magnitude $G(Q)$ and phase response $\Phi(Q)$ graphics for the notch and Hilbert filters (solid curve) and for the notch filter and the FIR filter of the first order (dashed curve)

TFS & Beam response to δ-kick









TFS & Beam response on δ-kick

W. Höfle et al.
CERN ATS/Note/2011/131
2011-12-12

Beam	Plane	Gain setting (dB)	Damping time [turns]					
			Q7+	Q7−	Q9+	Q9−	ave	StDev
1	hor.	-49	1188	729	1247	1172	1084	239
1	hor.	-43	1096	613	969	1066	936	222
1	hor.	-37	884	564	476	873	699	210
1	hor.	-31	370	383	902	414	517	257
1	hor.	-25	692	278	594	288	463	212
1	hor.	-19	294	203	280	200	244	50
1	hor.	-13	214	290	214	285	251	42
1	hor.	-7	83	89	78	89	85	5
1	hor.	-1	43	39	36	44	41	5
1	vert.	-49	887	800	1049	999	934	112
1	vert.	-25	558	496	592	594	560	46
1	vert.	-19	460	408	499	467	458	38
1	vert.	-13	301	165	341	317	281	79
1	vert.	-7	86	89	–	–	88	2
1	vert.	-1	47	39	48	–	44	5
2	hor.	-49	1735	1758	1828	1677	1750	62
2	hor.	-25	398	422	395	419	408	14
2	hor.	-19	251	328	574	314	367	142
2	hor.	-13	224	188	400	238	262	94
2	hor.	-7	89	83	87	91	87	4
2	hor.	-1	45	41	31	56	43	10
2	vert.	-49	405	360	917	1224	726	417
2	vert.	-25	347	363	484	411	401	62
2	vert.	-19	172	243	295	170	220	60
2	vert.	-13	70	90	77	96	83	12
2	vert.	-7	43	42	46	46	44	2
2	vert.	-1	22	20	20	20	20	1

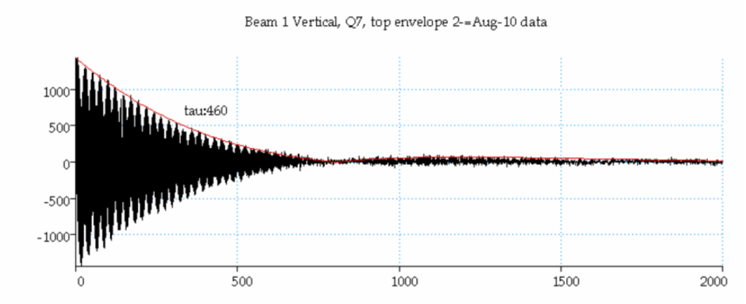
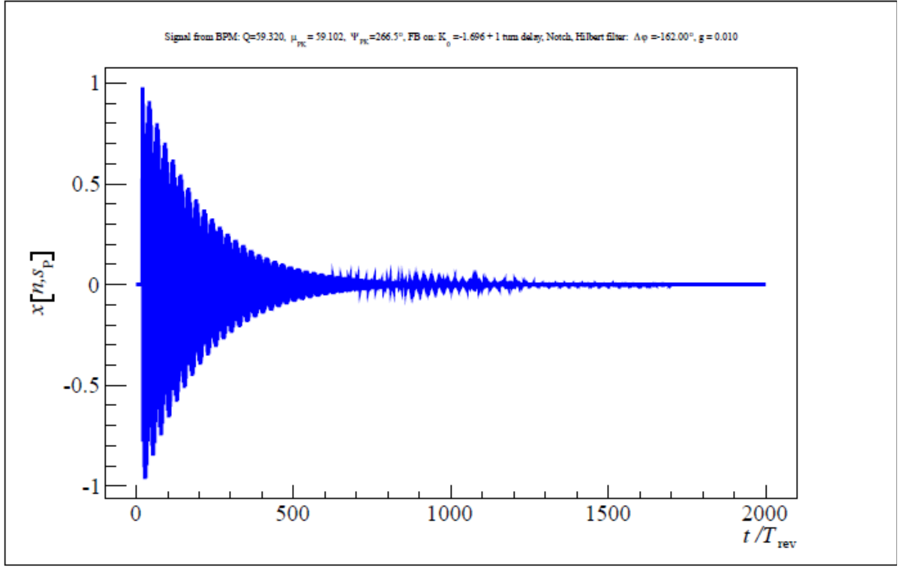
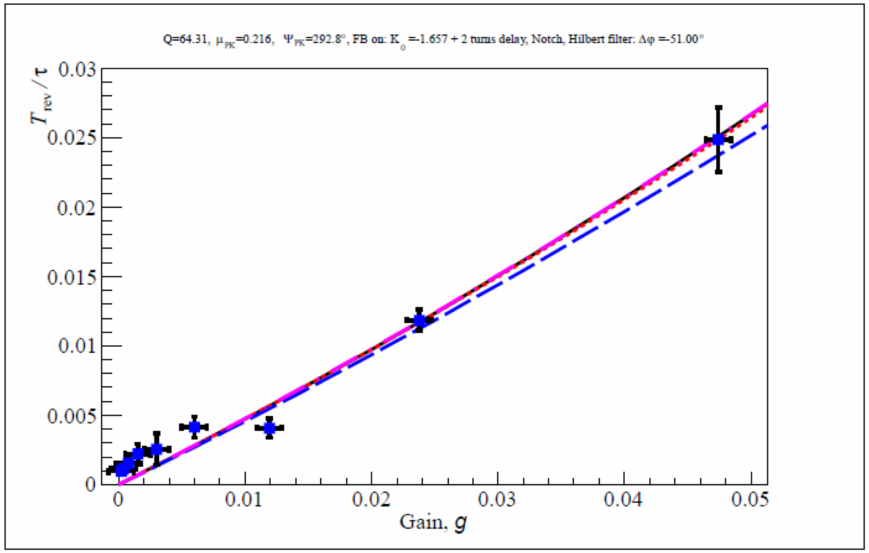
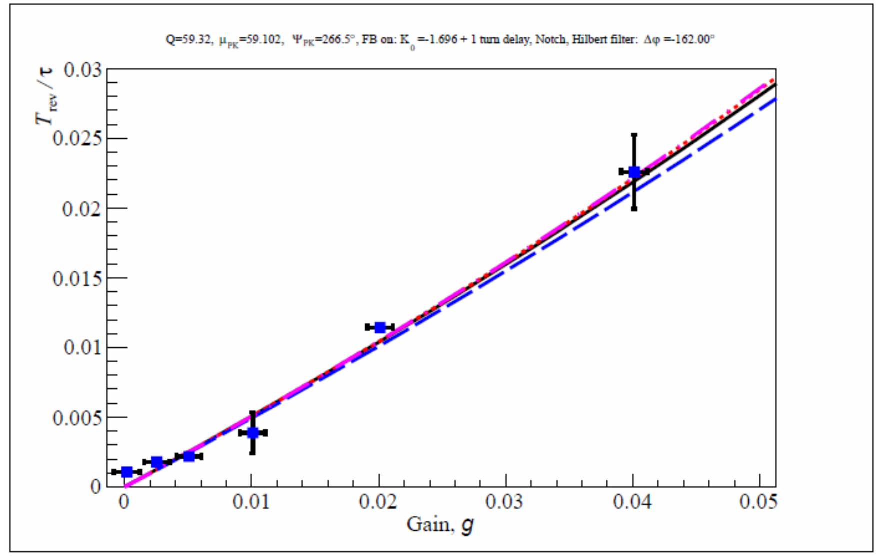


Figure 1.2: Envelope fit example for Beam 1, Q7 data, -19 dB gain setting.

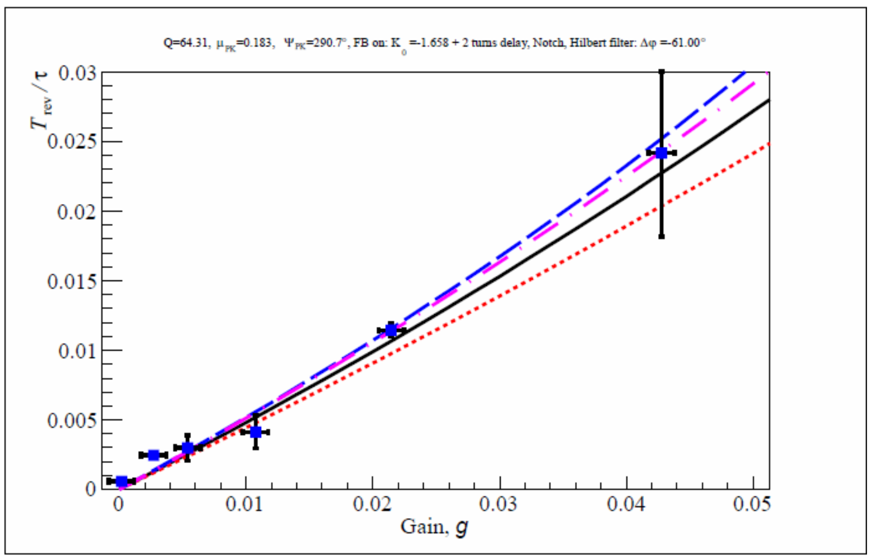




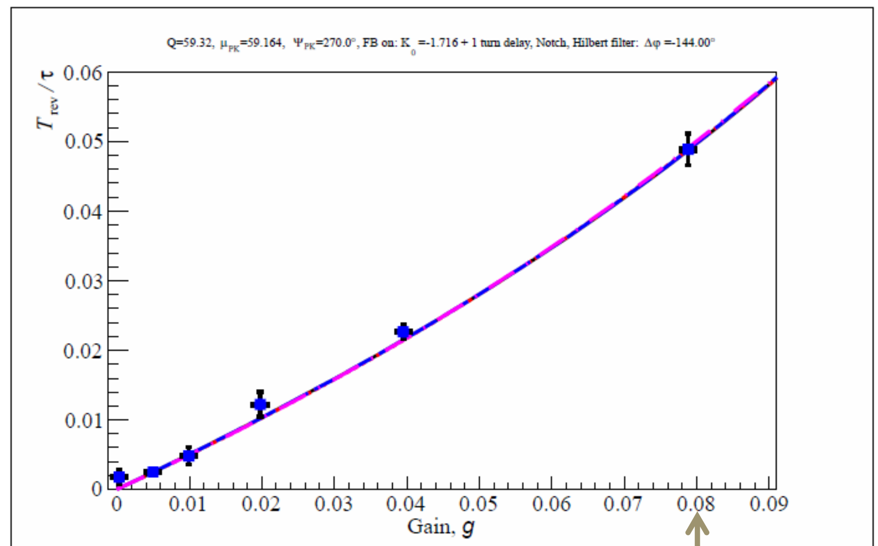
Beam 1, hor.



Beam 1, ver.



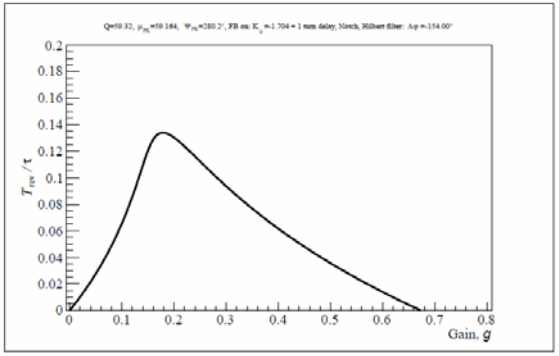
Beam 2, hor.



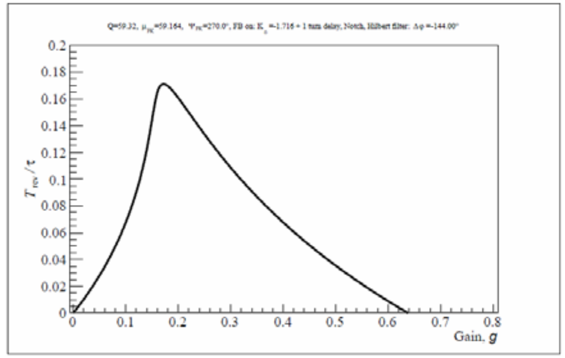
Beam 2, ver.

$a_{\max} < 0.15$ mm; $\Delta x' < 0.24\,\mu$rad; $E = 3.5$ TeV

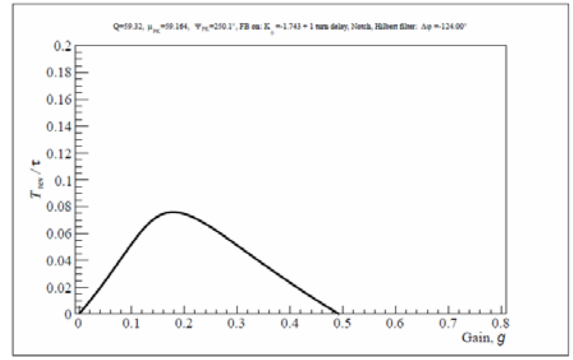
TFS: variation of parameters



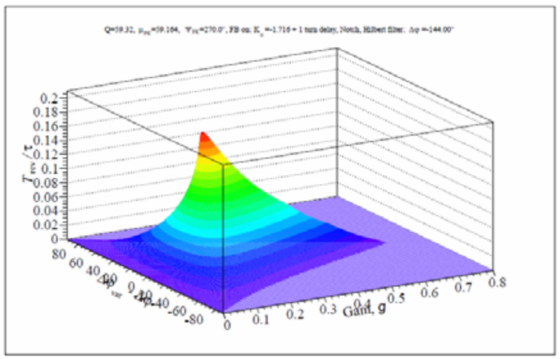
$$\Delta\varphi_{\mathrm{var}} = \Delta\varphi_{\mathrm{opt}} - 10$$

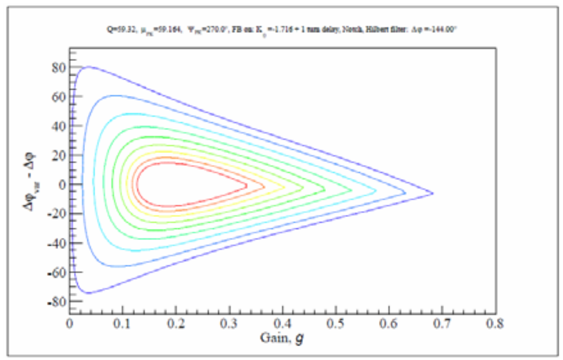


$$\Delta\varphi = \Delta\varphi_{\mathrm{opt}}$$



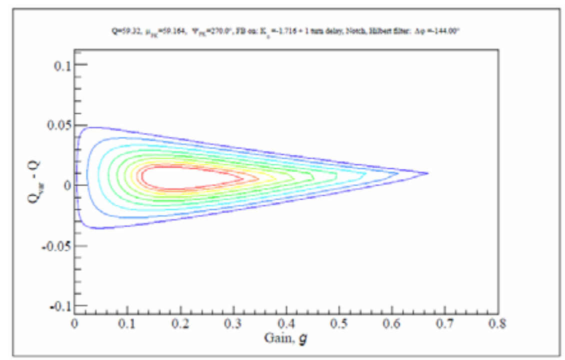
$$\Delta\varphi_{\mathrm{var}} = \Delta\varphi_{\mathrm{opt}} + 20$$





$$T_{\mathrm{rev}}/\tau \equiv \alpha(g, \Delta\varphi_{\mathrm{var}} - \Delta\varphi) = \alpha_n;$$

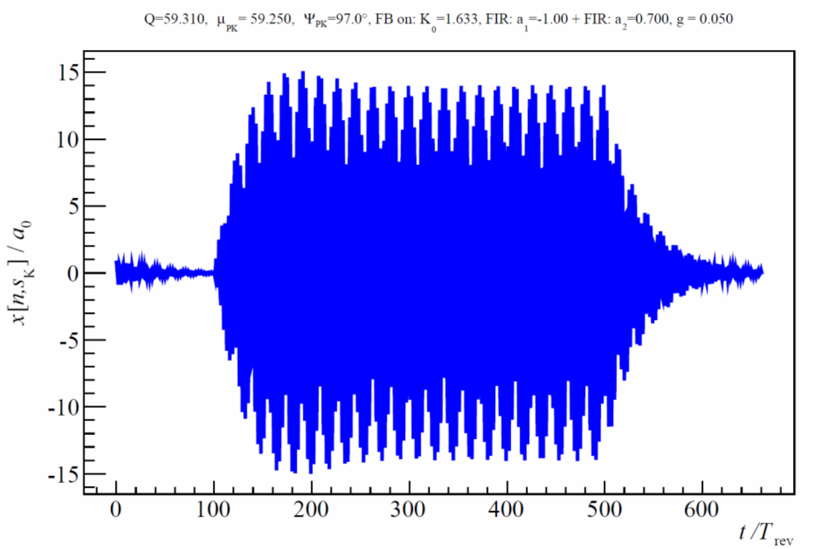
$$\alpha_0 = 0.002, \quad \alpha_n = n_c/80, \qquad 1 \le n_c \le 8$$

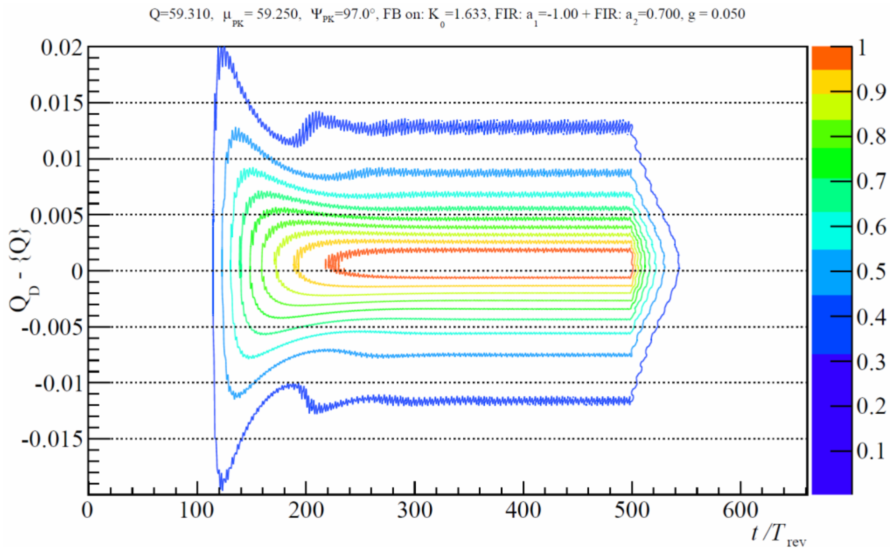


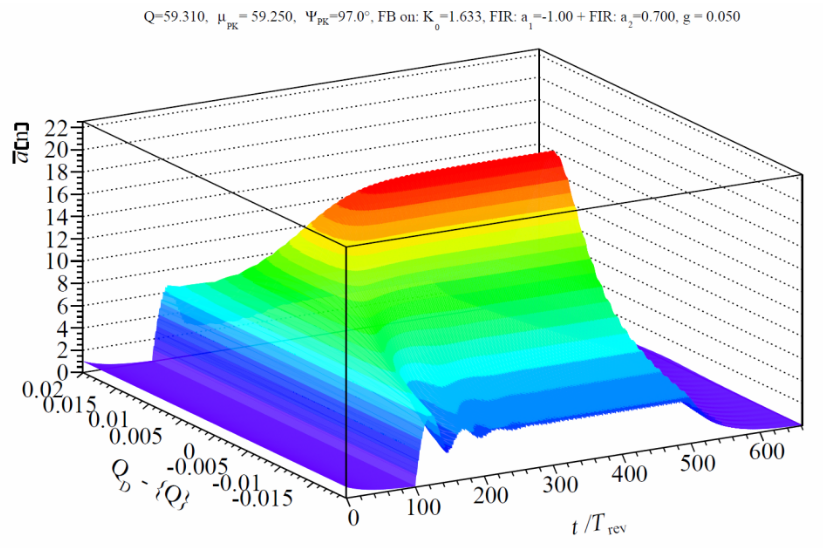
$$T_{\mathrm{rev}}/\tau \equiv \alpha(g, Q - Q_0) = \alpha_n;$$

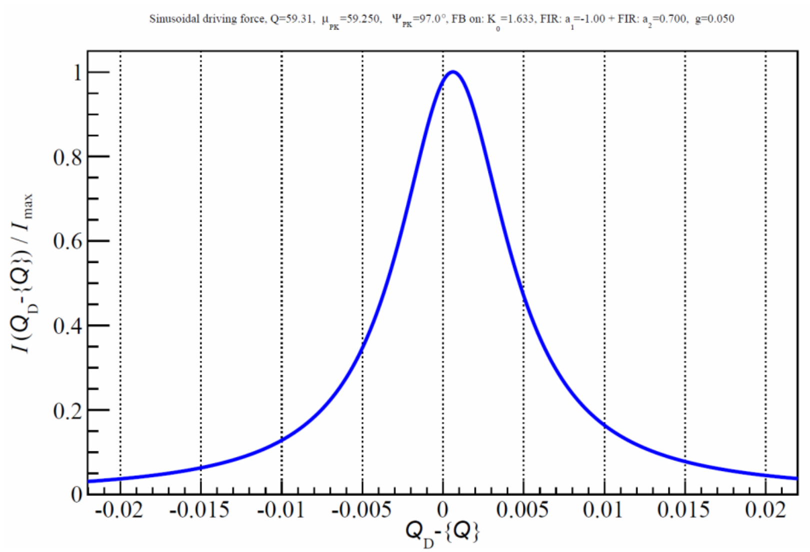
TFS & Sinusoidal driving force

Isolines: $a(\, t/T_{rev}\, ,\; Q_D\text{-}\{Q\}\,) \;=\; a_n$









TFS: Resonance Curve

$$\frac{I(Q_{\rm D})}{I_{\max}} = \frac{1}{I_{\max}} \left| \det \left(z_{\rm D} \widehat{I} - \widehat{\mathbf{M}}(z_{\rm D}) \right) \right|^{-2} ,$$

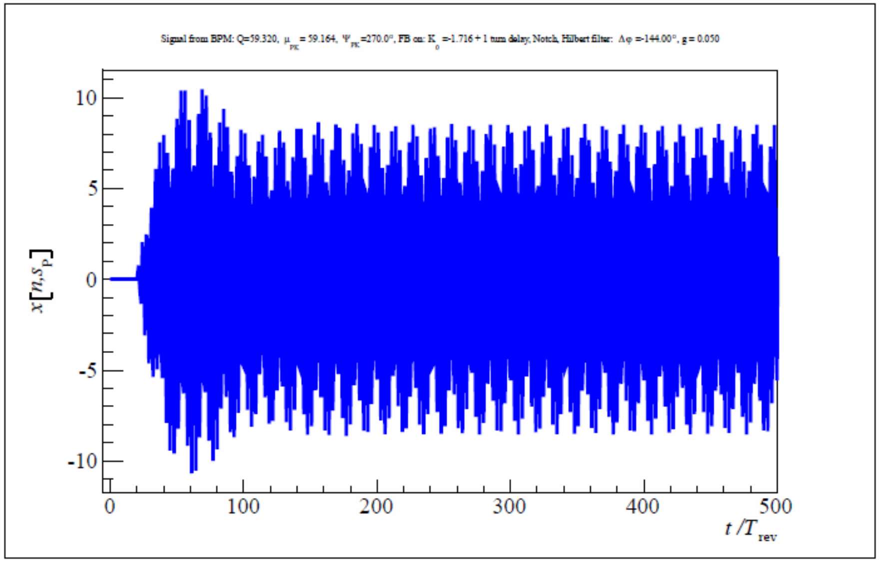
$$z_{\rm D} = \exp(\mathrm{j}\, 2\pi \{Q_{\rm D}\}), \quad I_{\max} = I\left(Q_{\rm D}^{(\max)}\right) .$$

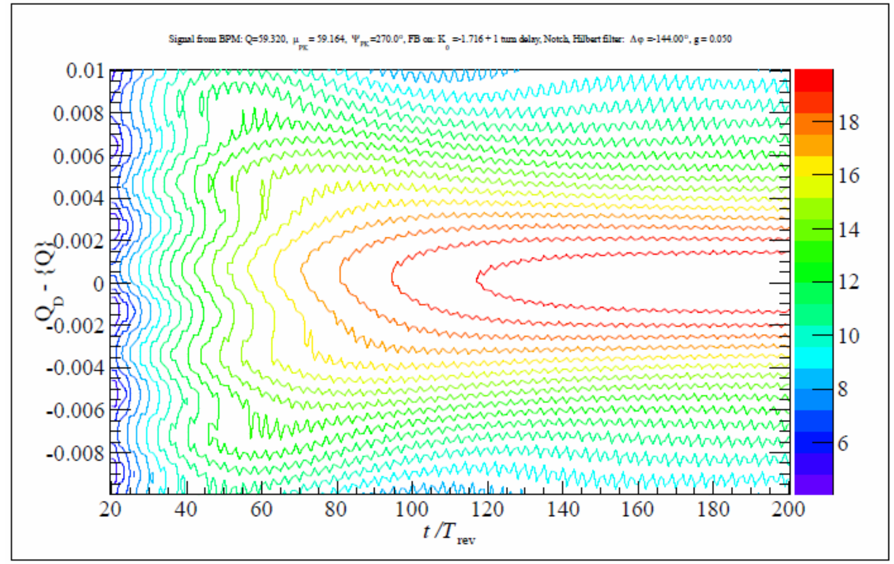
If g « 1:

$$\frac{I(Q_{\rm D})}{I_{\max}} = \frac{\alpha_m^2}{4\pi^2(\{Q_{\rm D}\} - \{Q_m\})^2 + \alpha_m^2} .$$

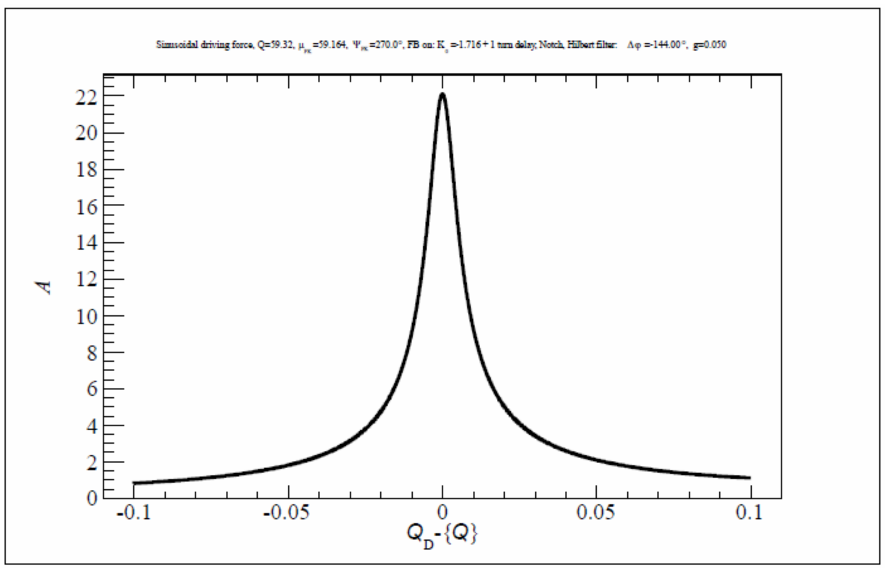
$$\{Q_{\rm D}^{(\max)}\} = \{Q_m\} = \{Q\} - \frac{g\,|\mathbf{K}(\omega_m)|}{4\pi \mathrm{K}_0} \cos \Psi_{\rm PK} .$$

TFS & Sinusoidal driving force





$a(\ t/T_{\text{rev}}\ ,\ Q_{\text{D}}\text{-}\{Q\}\ )\ =\ a_{\text{n}}$

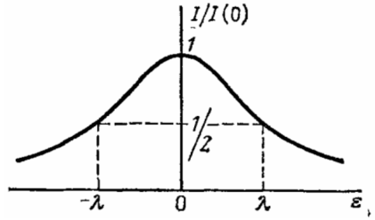


Resonance

$$\ddot{x} + 2\lambda\, x + \omega^2 x = \frac{f_{\rm D}}{m}\cos(\omega_{\rm D} t)$$

Intensity of oscillations:

$$I(\epsilon = \omega_{\rm D} - \omega) \propto \frac{\lambda^2}{\epsilon^2 + \lambda^2}$$

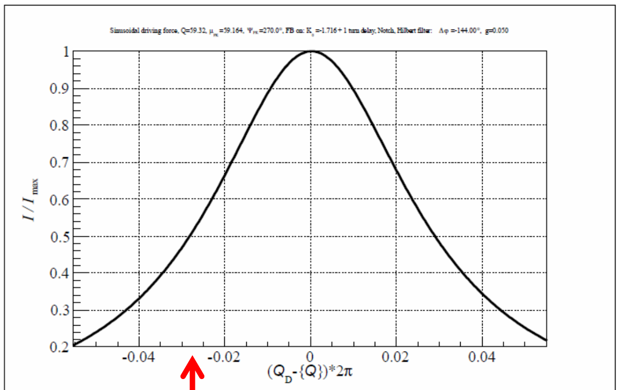


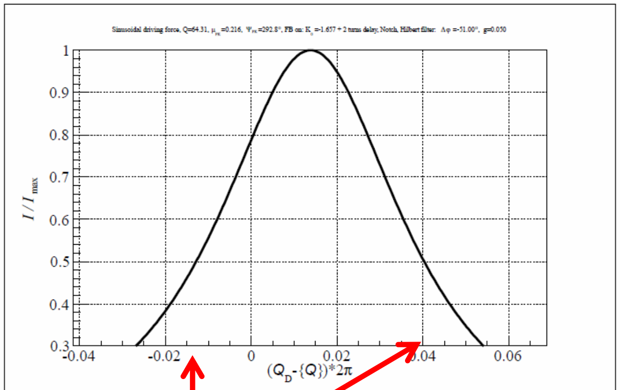
Synchrotrons:

$$\omega_m = Q_m\, \omega_{\rm rev} = 2\pi Q_m / T_{\rm rev}; \qquad \alpha_m = \lambda\, T_{\rm rev}$$

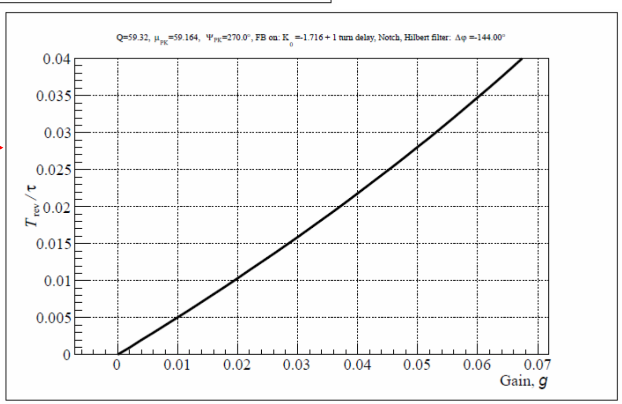
$$I(Q_{\rm D}) \propto \frac{\alpha_m^2}{4\pi^2(\{Q_{\rm D}\} - \{Q_m\})^2 + \alpha_m^2}$$

$$\{Q_m\} = \{Q\} - \frac{g\,|\mathbf{K}(\omega_m)|}{4\pi \mathrm{K}_0}\cos\Psi_{\rm PK}$$

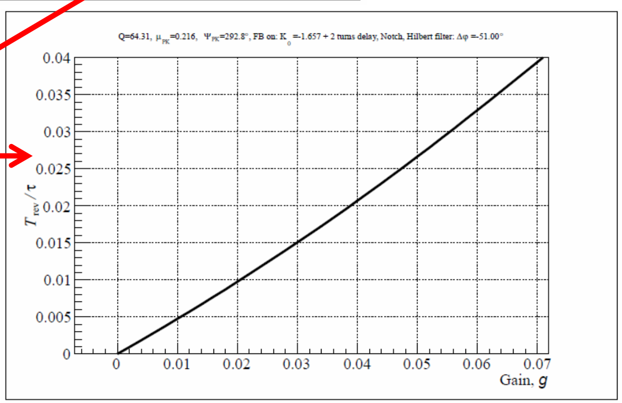




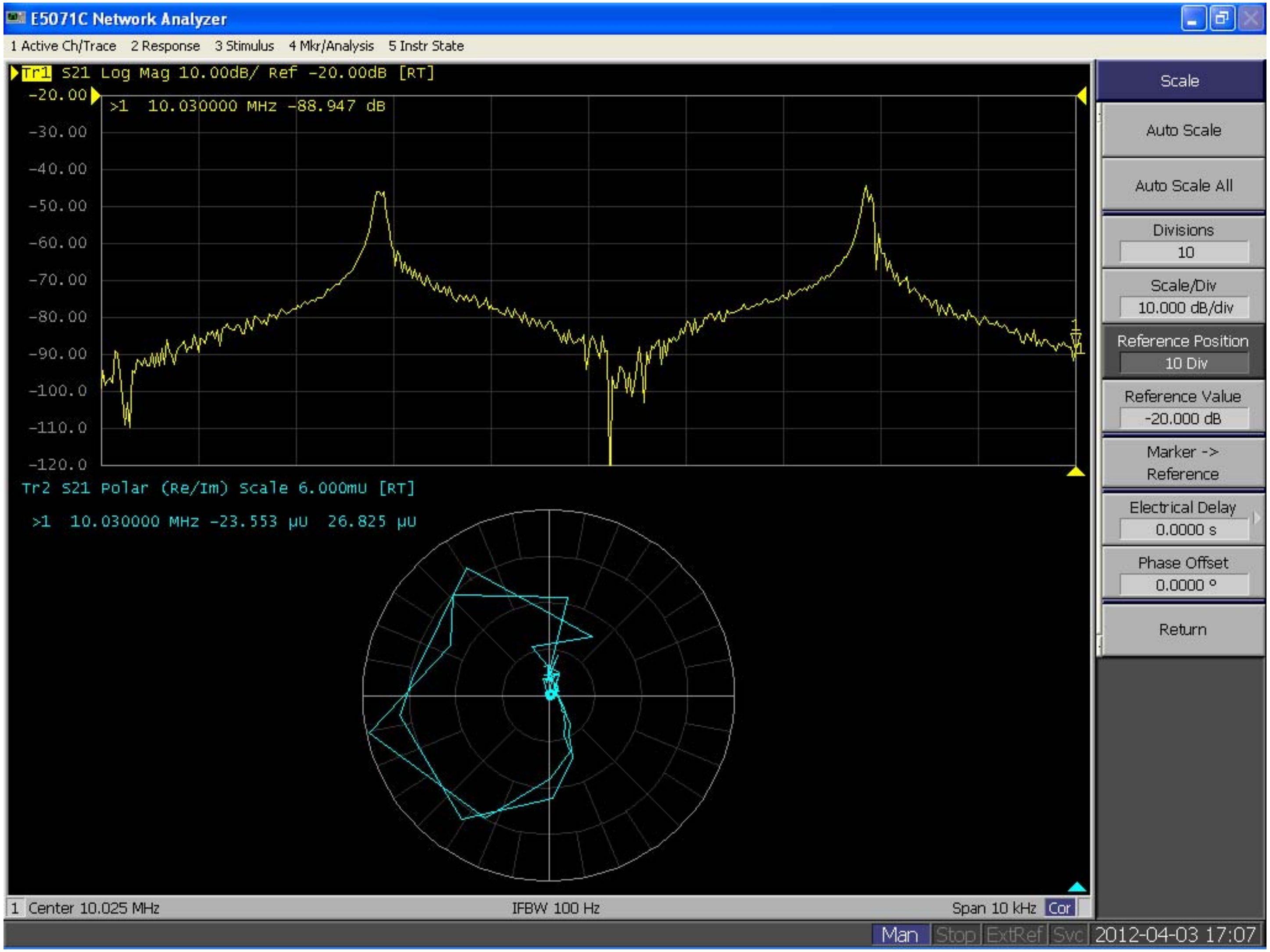
α=0.028



α=0.027



LHC Damper



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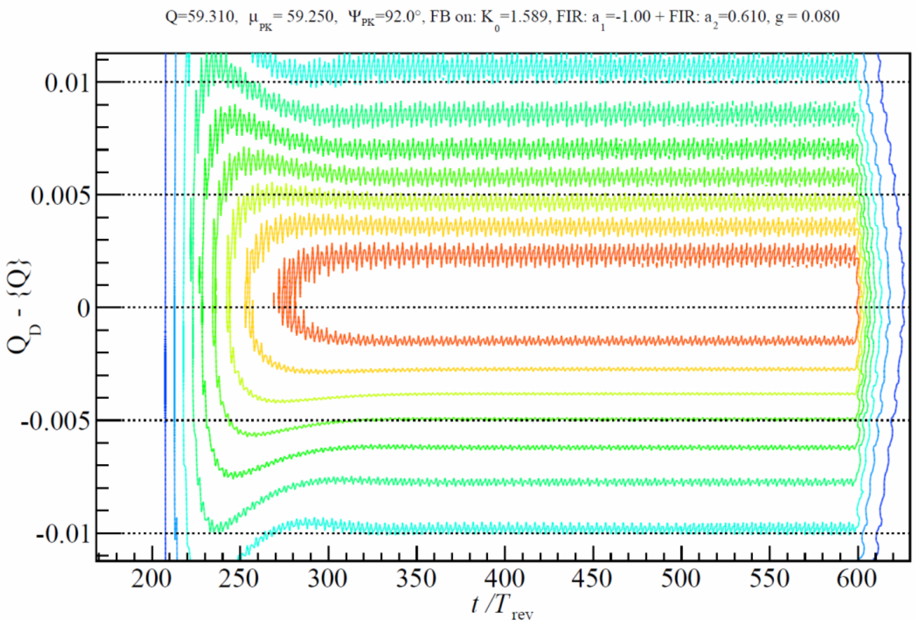
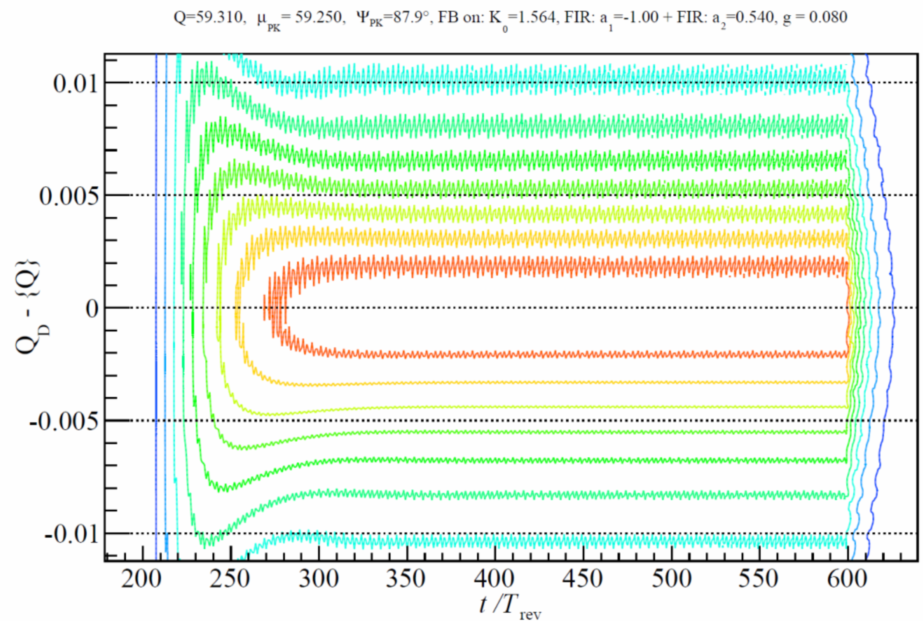
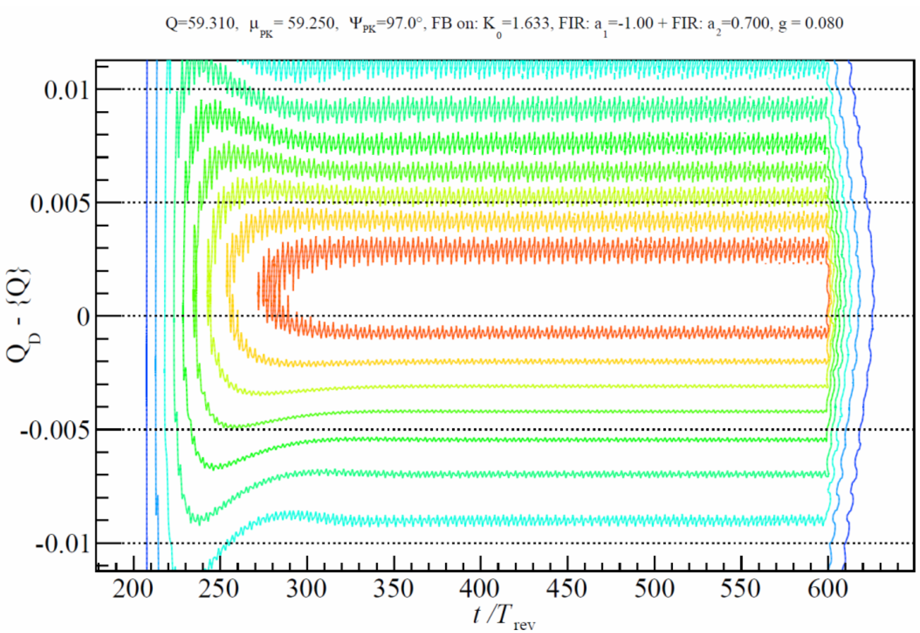
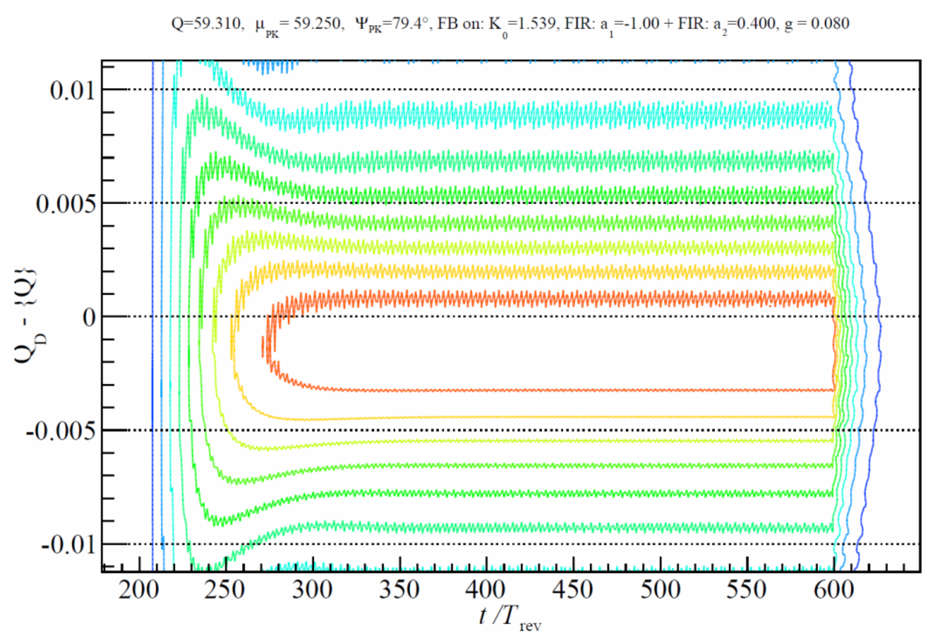
TFS & Sinusoidal driving force

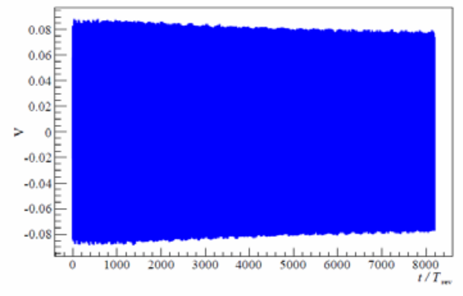


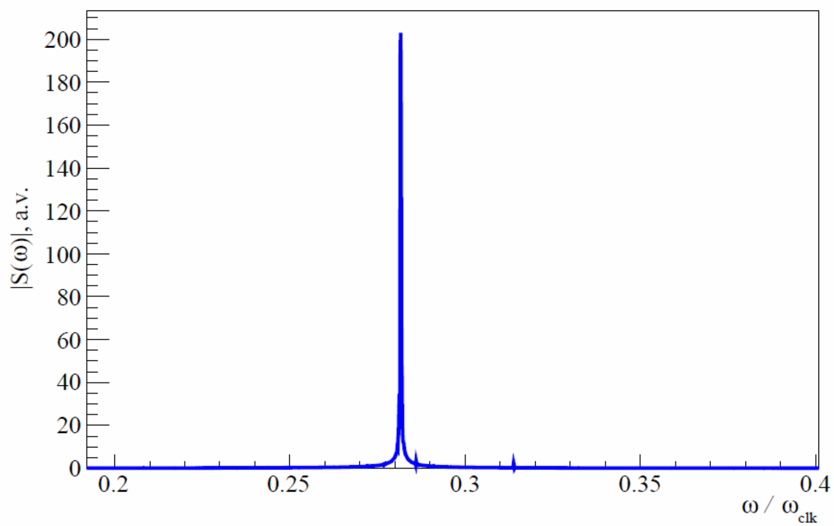




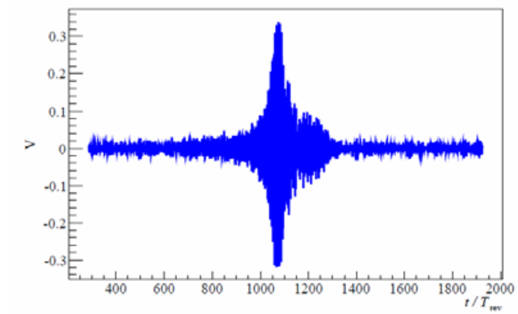


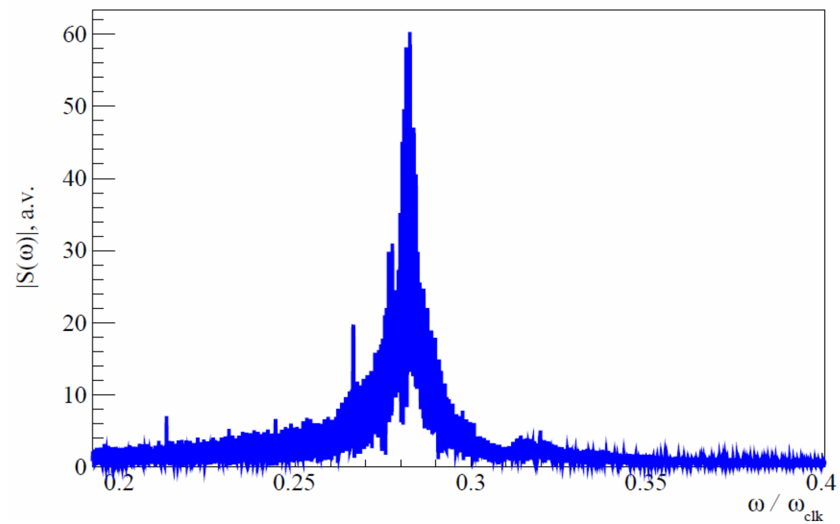
Base-Band Q (BBQ) Measurements at the LHC





Damper OFF (oscillations after injection)





Damper ON (chirp excitation)

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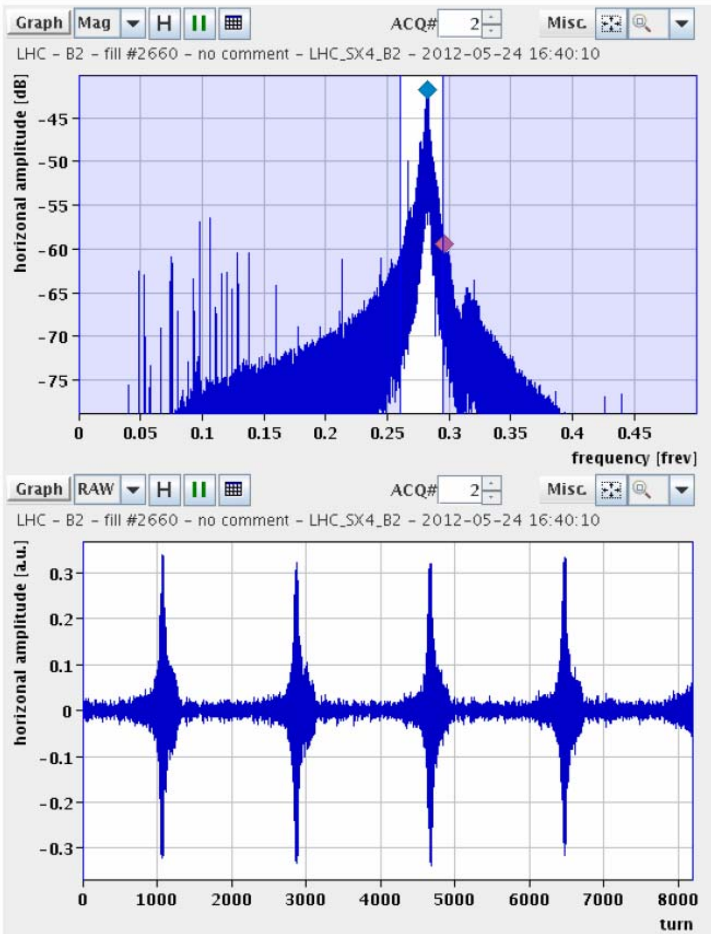
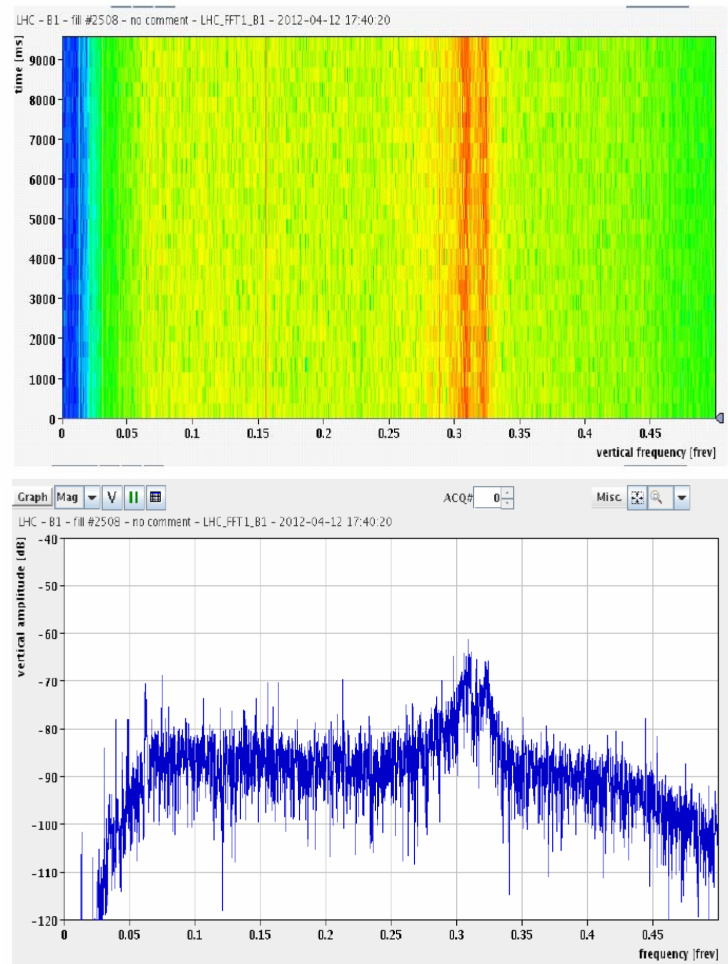
Base-Band Q (BBQ) Measurements at the LHC



Damper ON (chirp excitation)



Q-map (top) and Q-line (bottom) from BBQ Display

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CONTROLLED TRANSVERSE BLOW-UP OF HIGH-ENERGY PROTON BEAMS FOR APERTURE MEASUREMENTS AND LOSS MAPS

W. Hofle *, R. Assmann, S. Redaelli, R. Schmidt, D. Valuch, D. Wollmann, M. Zerlauth,
CERN, Geneva, Switzerland

Proceedings of IPAC2012, New Orleans, Louisiana, USA. Pp.4059-4061

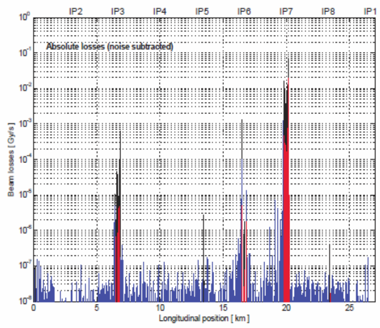


Figure 4: Loss maps obtained with the damper blow-up method with one nominal bunch in the LHC (blue: cold part of LHC, red and black: warm part).

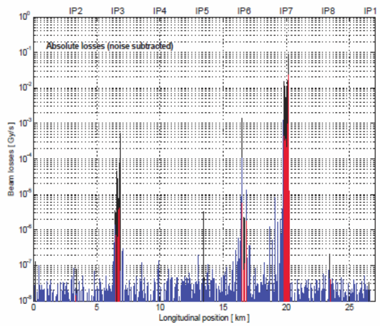
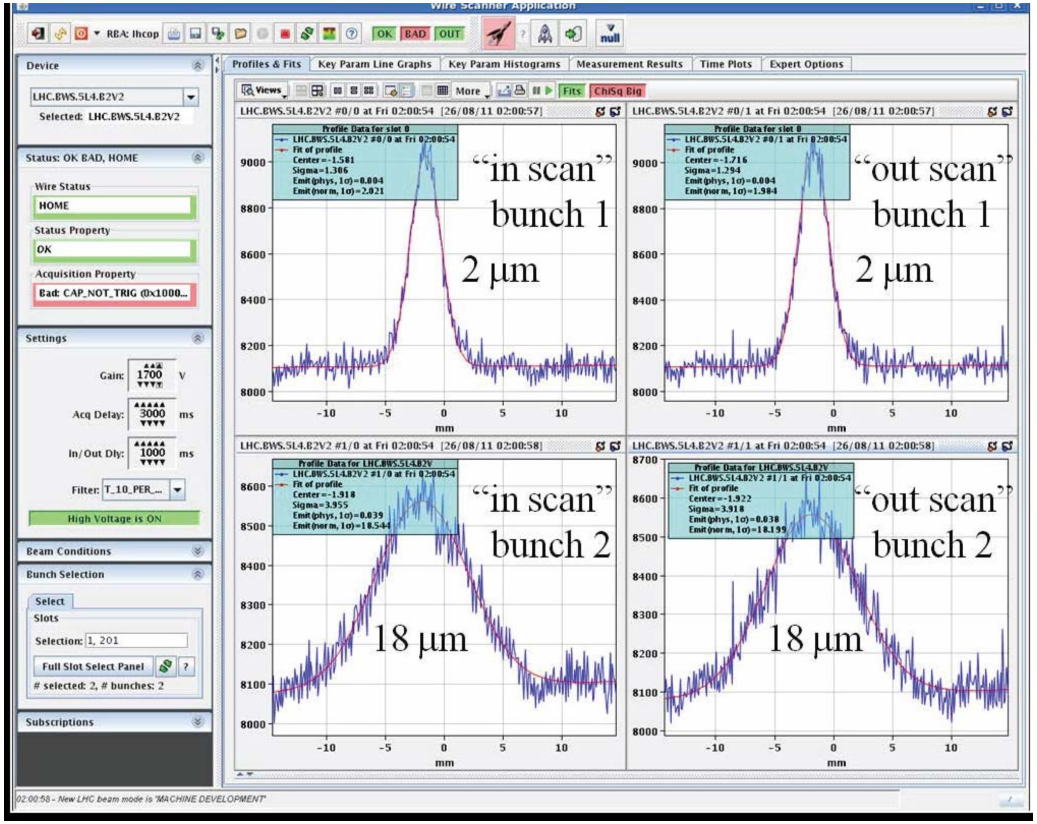


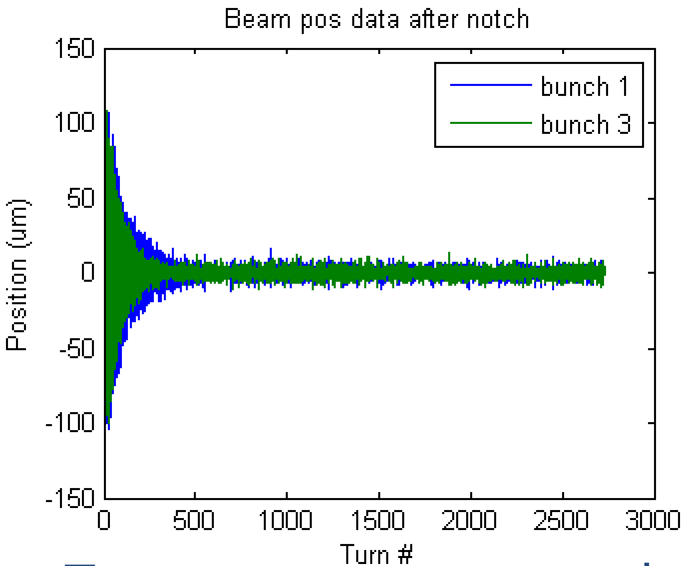
Figure 5: Loss maps obtained by crossing the third-order resonance with one nominal bunch in the LHC (blue: cold part of LHC, red and black: warm part).

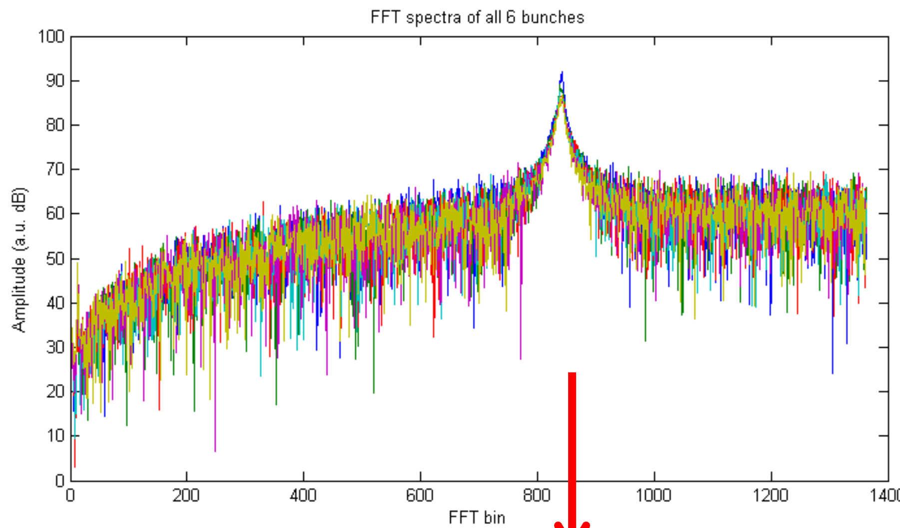
One can get the aperture in one single measurement taking 1-2 minutes only.

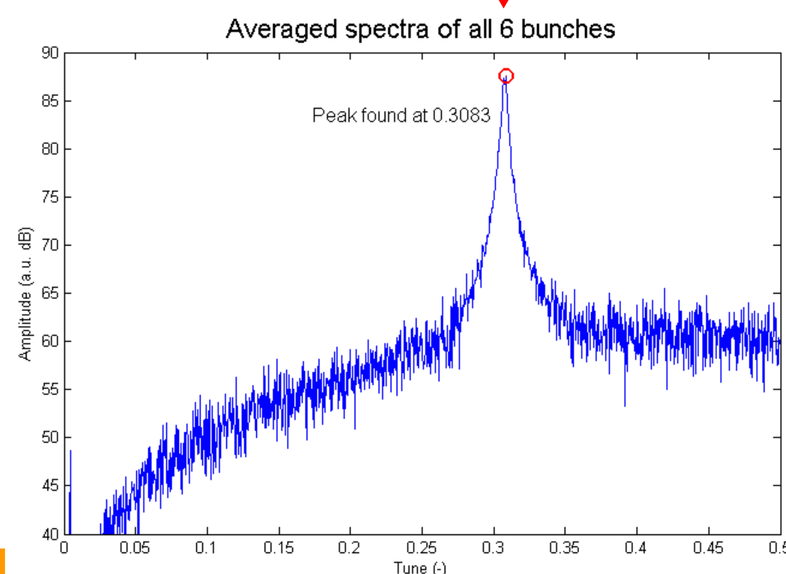


Profiles measured with the wire scanners after a blow-up targeted to bunch 2: blow-up to aperture limit of this bunch; bunch 1 emittance unchanged.

Wednesday: ADT tune measurement test







- Test tune measurement by selective excitation of 6 bunches.
- FFT of data for each observed bunch, average the spectra, find the peak
- Very successful test. Validation during a ramp required (including emittance blow-up measurement) + operational implementation

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Conclusion

Measurements of a beam response to the δ-impulse are the effective approach to tune the transverse feedback system in the damping mode of coherent betatron oscillations of the bunch.

Observation of a beam response to the harmonic impulse can be a good instrument for selective measurements of circulated bunches because of the dedicated resonance behavior of the detected signal in synchrotrons with a digital transverse feedback system.

Thank you for your attention!