Single bunch transverse intensity limitations in the SPS

- **1.15x10^{11} nominal and ultimately 1.7x10^{11} protons/bunch required for LHC injection - at the limit of SPS stability at injection energy 26 GeV**

- **SPS impedance reduction campaign, followed by measurements**

- **Coherent tune shift and growth/decay measurements**
  Higher order head/tail modes

Acknowledgement:

measurements with G. Rumolo (+model head-tail), F. Zimmermann, E. Vogel, G. Arduini, M. Zorzano, Koschik, Papaphilippou

RF-group: T. Bohl, P. Baudrenghien, T. Linnecar, E. Shaposhnikova   OP : J. Wenninger

discussions, theory: B. Zotter, J. Gareyte, L. Vos, E. Metral (-> talk later)

Introduction / Overview

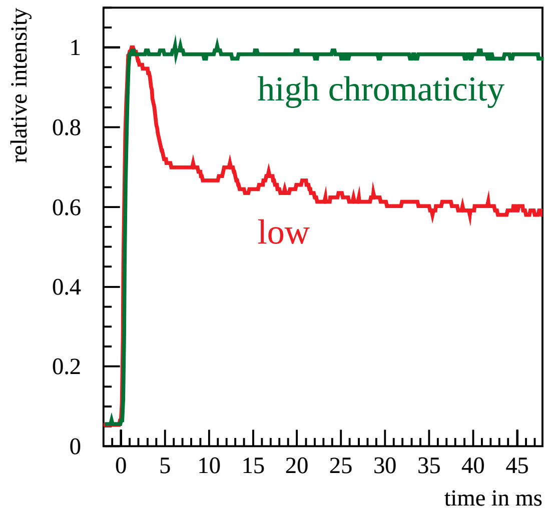
- There has been a substantial effort to reduce the SPS impedance as injector for the LHC with shielding of 1200 bellows and pumping ports, 20% in 1999/2000 and rest in 2000/2001 shutdown — Collier et al. EPAC'02
  - The improvement was followed and nicely confirmed by longitudinal and transverse measurements. A factor of about 2.5 decrease in Im Z/n was seen in the longitudinal plane — T. Bohl et al. EPAC'02

  and about a 40 % improvement in the transverse plane — H.Burkhardt et al. EPAC'02

- 2002/2003 5 extraction kickers (MKE, extraction into TI 8 -> LHC) installed nearly cancelling the improvement in the transverse plane

  a fast (~ 4 ms or 1/2 synch.period) transverse single bunch instability is observed for the first time in the SPS on protons

  see also E. Métral, this session



H.Burkhardt et al. EPAC'04

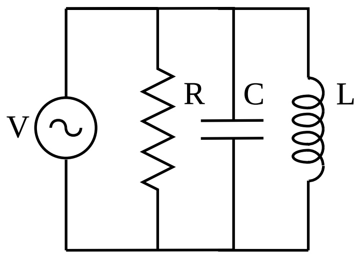
- 2005/2006 4 extraction kickers scheduled for installation (extraction into TI 2 -> LHC) potentially limiting the single bunch intensity in the SPS to about nominal ($1.15\ 10^{10}$) below ultimate ($1.7\ 10^{10}$)

Wake, Impedance (illustrated with broad band model)

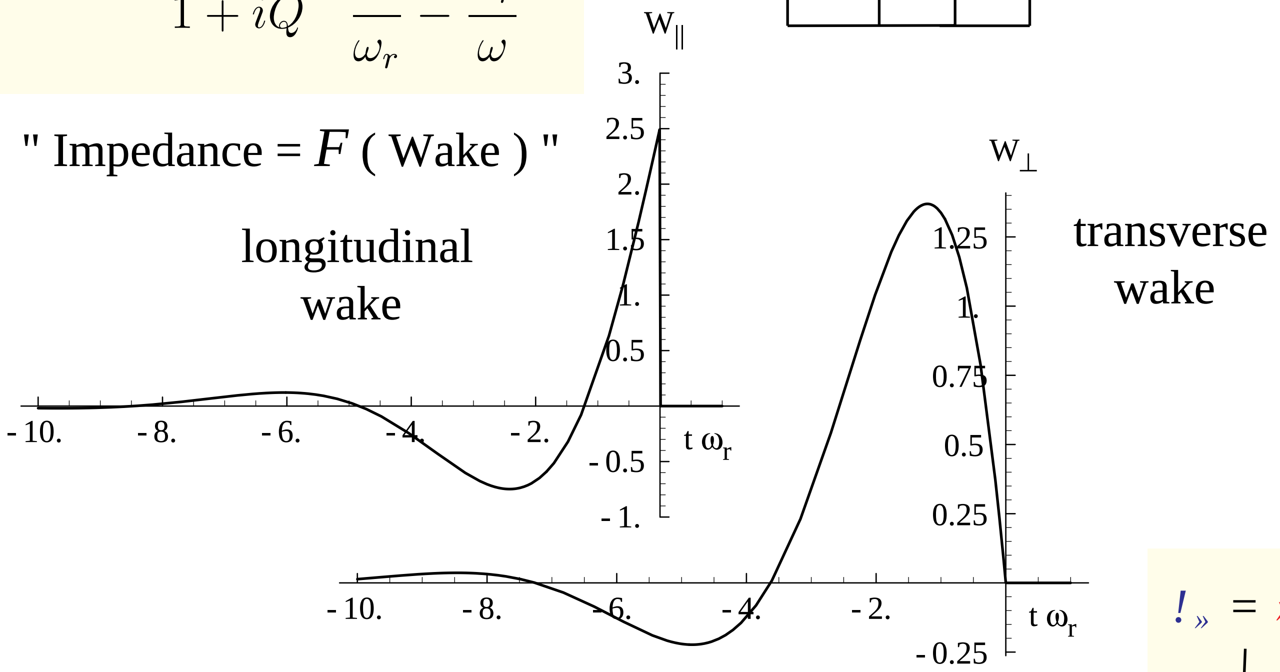
Sacherer, Hofmann, Zotter et al. CERN 77-13 ..

$$Z_{\parallel} = \frac{R}{1 + iQ\left(\dfrac{\omega}{\omega_r} - \dfrac{\omega_r}{\omega}\right)}$$

$$Z_{\perp} = \frac{\omega_r}{\omega}\,\frac{R_{\perp}}{1 + iQ\left(\dfrac{\omega}{\omega_r} - \dfrac{\omega_r}{\omega}\right)}$$



" Impedance = F (Wake) "



! » = » !− / '

transverse wake:
complex freq. shift

Δ!− = N e c / (4p¼ !− (E=e) T₀ ¾t) i(Z?)eff

effect on (transverse) β-oscillations $e^{i\,\omega_\beta\, t}$

(real coherent) tune shift with intensity N from Im $Z_\perp$

(imag. tune shift) growth ($\xi/\eta < 0$) or decay ($\xi/\eta > 0$) from Re $Z_\perp$

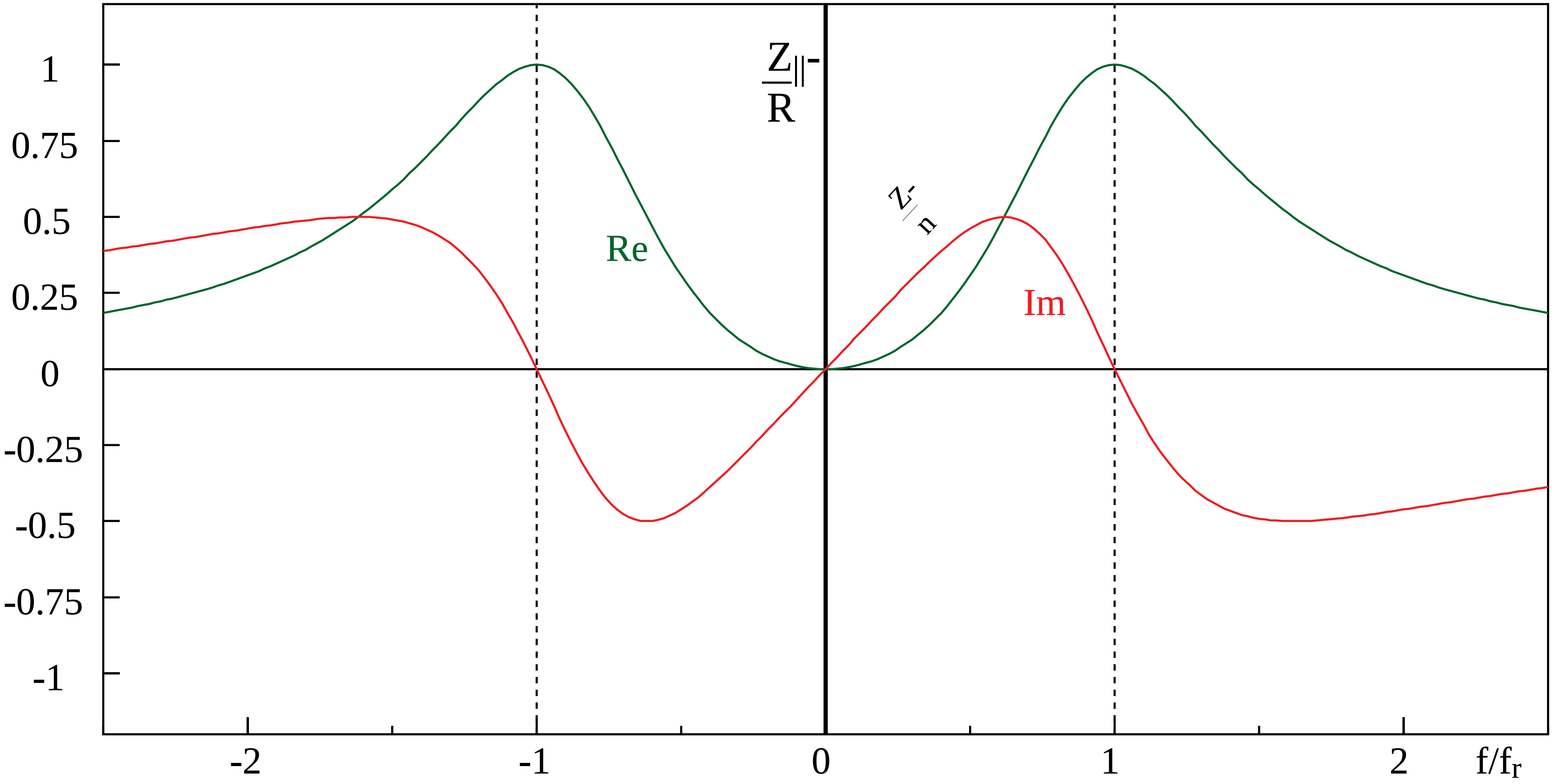
effective transverse imped. $(Z_\perp)_{\text{eff}}(\omega_\xi) = \int_{-\infty}^{\infty} Z_1^{\perp}(\omega)\, h_m(\omega - \omega_\xi)\, dw$

Gaussian bunch spectrum (0 mode) $h_0(\omega) = \dfrac{\sigma_t}{\sqrt{\pi}}\, e^{-(\omega\sigma_t)^2}$

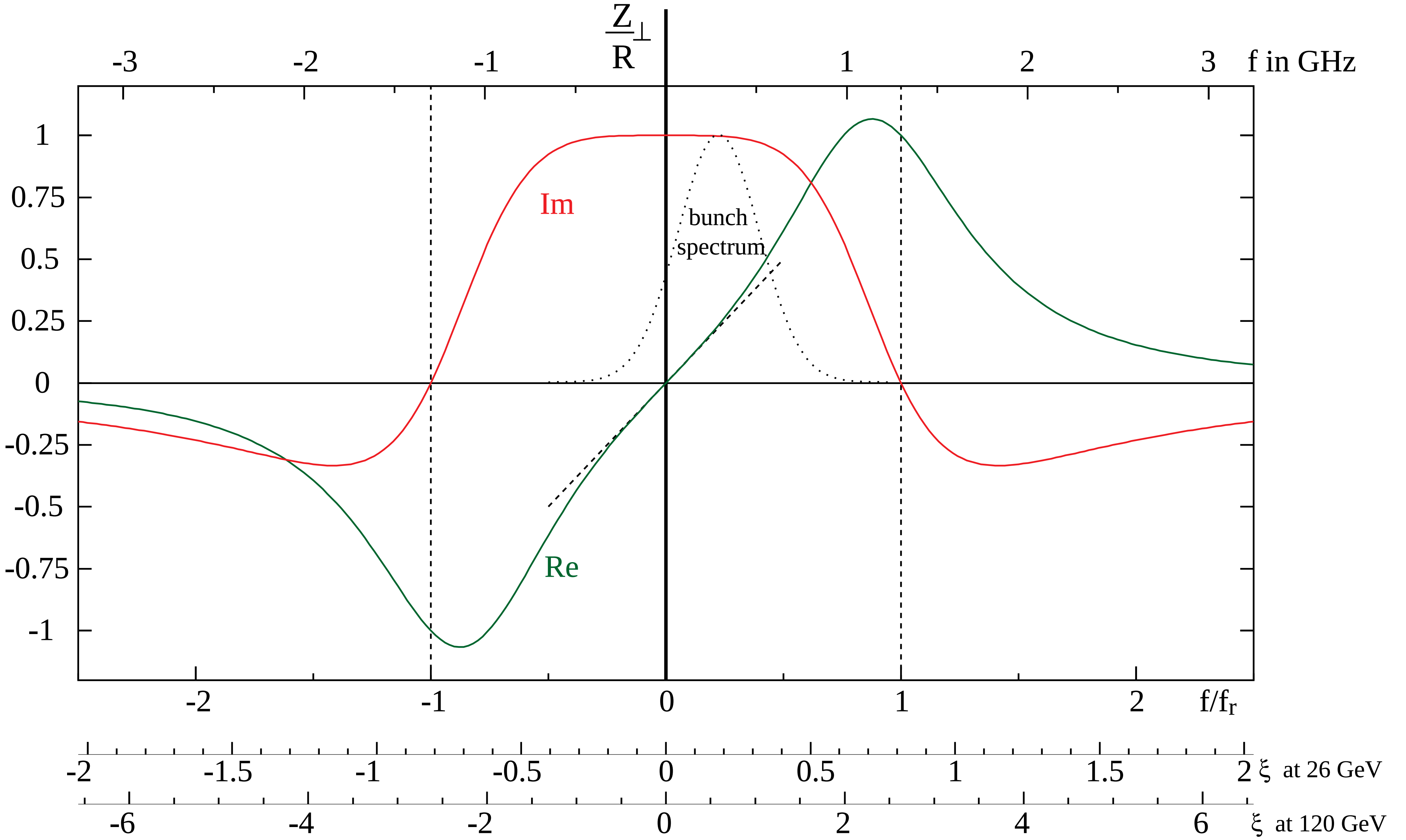
$\omega_\beta = 2\pi\, Q\, f_{\text{rev}}$ SPS $Q_{x,y} \approx 26.6$ $\alpha_c = 1.856 \times 10^{-3}$ chromaticity $\xi = Q'/Q = \frac{\Delta Q}{Q} / \frac{\Delta p}{p}$

$p = 26\,\text{GeV}/c$ $E = 26.0169\,\text{GeV}$ $\gamma = 27.7286$ phase slip factor $\eta = \alpha_c - 1/\gamma^2 = 5.55164 \times 10^{-4}$

typical (broad band Q=1) longitudinal Impedance



typical (broad band Q=1) transverse Impedance, with f_r = 1.3 GHz and ξ of the SPS



Transverse impedance measurements, single bunch

• inject a low emittance single bunch from the PS into the SPS (26 GeV), match capture (~.8 MV)
optionally ramp RF to ~ 2 MV to obtain shorter bunches and more sensitivity for coh. tune shift meas
well adjusted machine : linear (detuning minimized using small octupole corr.), small chromaticity,
well corrected closed orbit. As much as possible same conditions every year.

Vary the intensity by scraping (in steps every ~ 10 SPS pulses) in the vertical plane and record:

• coherent motion - centre of gravity motion over typically 213 = 8192 consecutive turns (0.18 sec)
"tune meter"
following an initial kick of ~ 1 mm in case of tune / damping measurements (chromaticity > 0)
following a jump to negative chromaticity in case of growth rate measurements

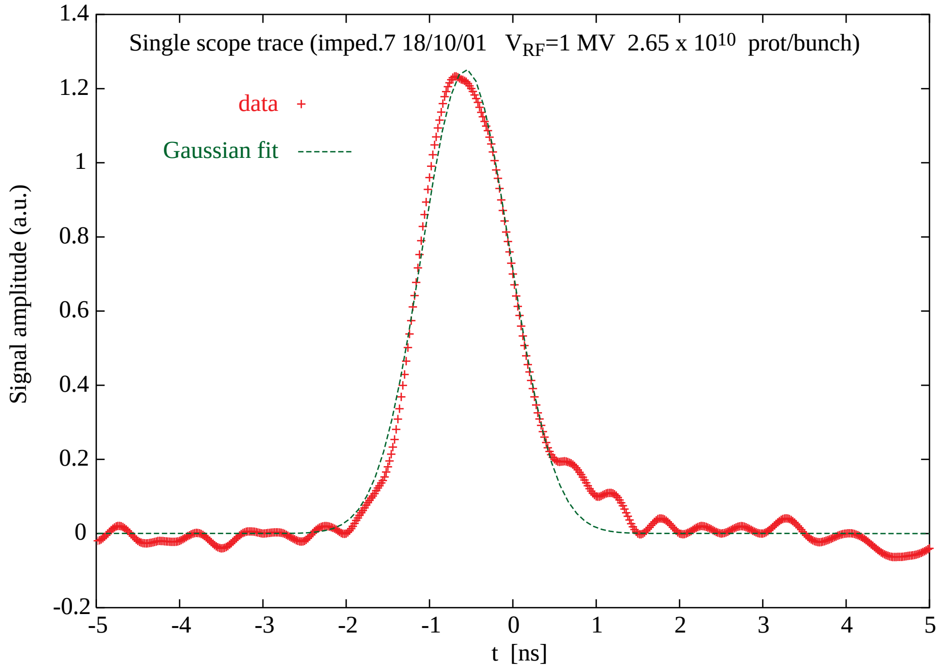
• intensity (number of protons) during the tune measurement

• longitudinal bunch profile over many turns during the tune measurement,
generally fits to Gaussian to extract the average bunch length

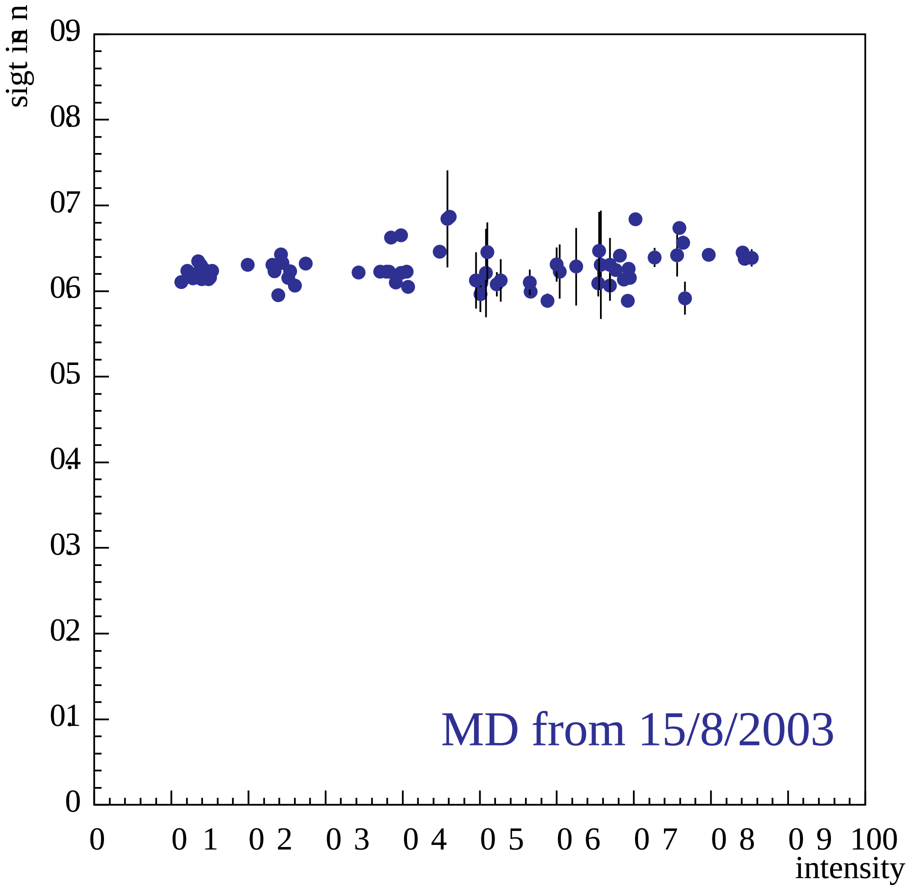
• transverse beam sizes
(for completeness to allow to evaluate potential second order effects, space charge)

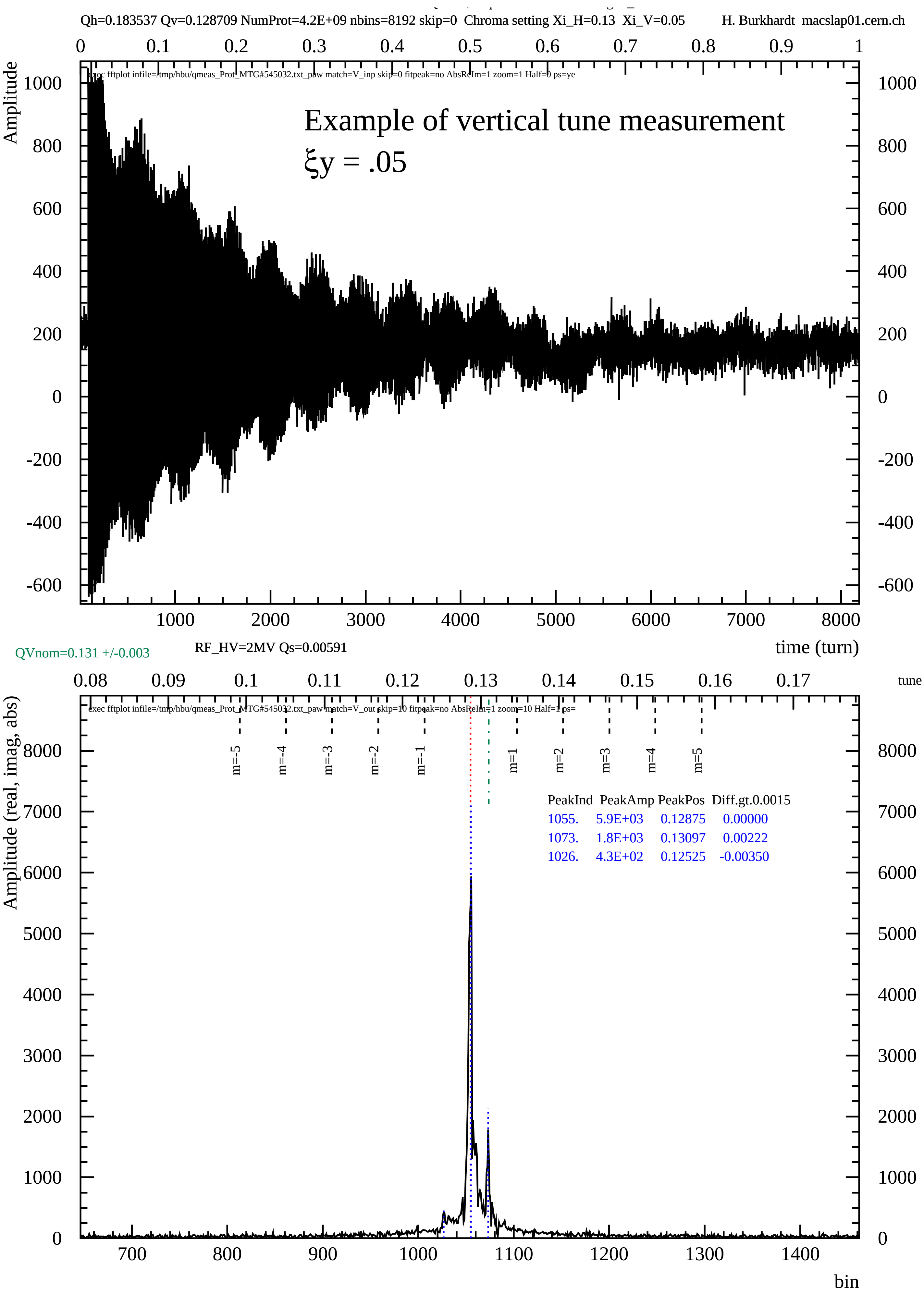
Bunch shape measurements with a Gaussian fit

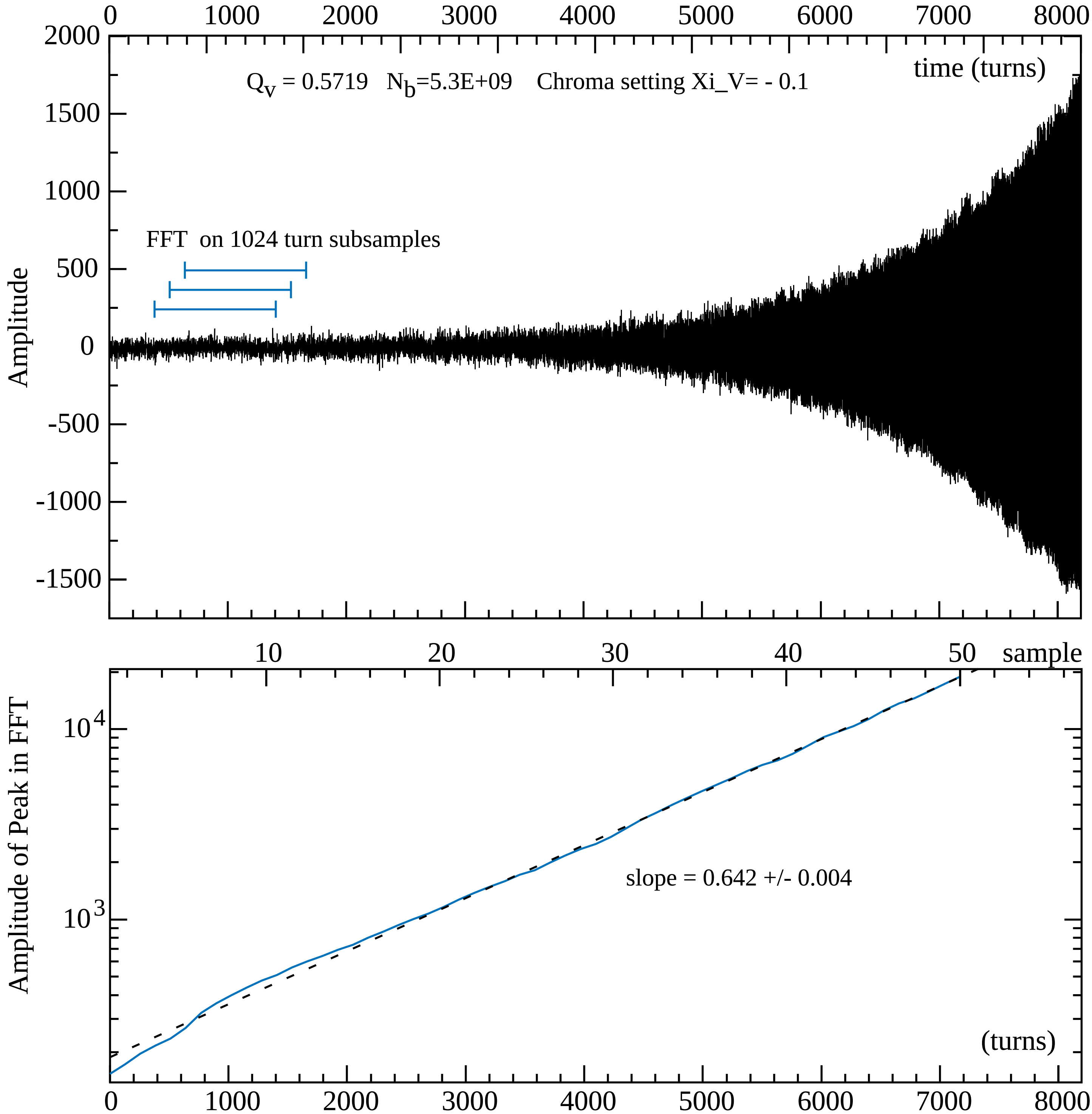
example of a single trace



average fitted bunch length
as function of intensity

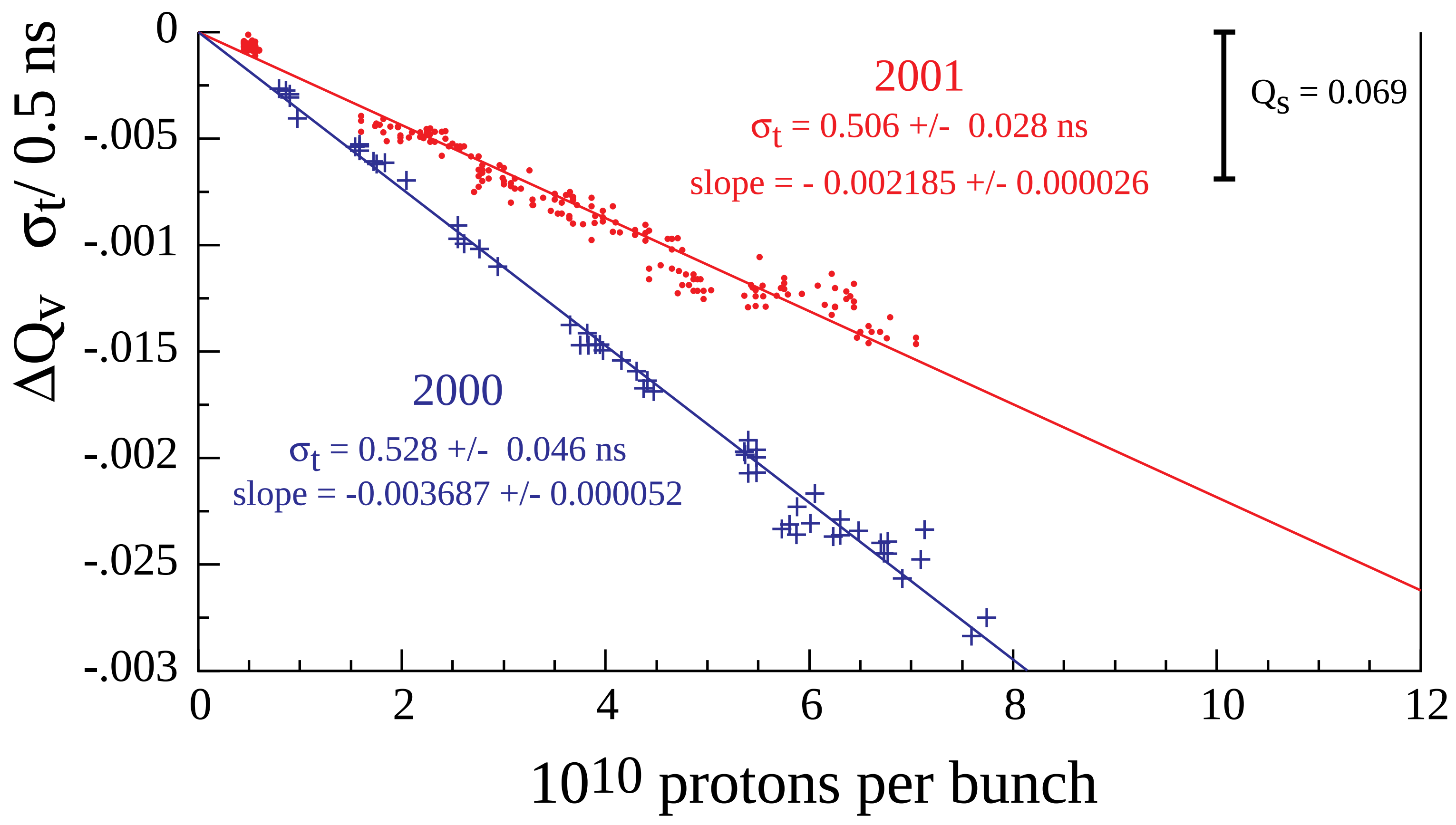



Qh=0.183537 Qv=0.128709 NumProt=4.2E+09 nbins=8192 skip=0 Chroma setting Xi_H=0.13 Xi_V=0.05
H. Burkhardt macslap01.cern.ch
Example of vertical tune measurement
ξy = .05
Amplitude
time (turn)
QVnom=0.131 +/-0.003
RF_HV=2MV Qs=0.00591
tune
Amplitude (real, imag, abs)
m=-5
m=-4
m=-3
m=-2
m=-1
m=1
m=2
m=3
m=4
m=5
PeakInd PeakAmp PeakPos Diff.gt.0.0015
1055. 5.9E+03 0.12875 0.00000
1073. 1.8E+03 0.13097 0.00222
1026. 4.3E+02 0.12525 -0.00350
bin



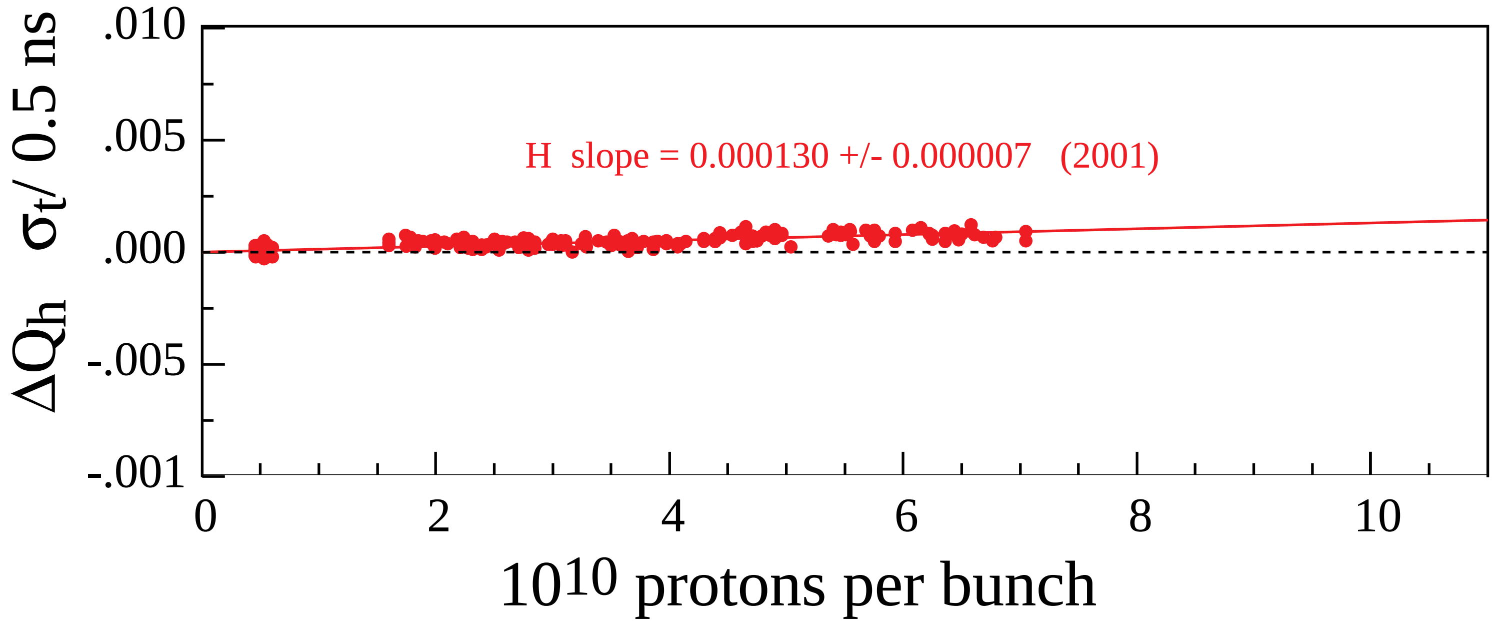
Growth/decay determination. The vertical chromaticity was set slightly negative at the start of the measurement. Vertical turn to turn amplitudes recorded with the tune meter on successive turns are shown on the top and the height of the tune peak of sub-samples is displayed with logarithmic y-scale in the bottom of the picture. The time constant τ of the exponential growth rate is obtained from the slope of the straight dashed line.

Comparison 2001 / 2002 before and after the main changes for the impedasnce reduction



Comparison of measured coherent tune shifts (normalized to bunch length) with intensity in the vertical plane in the years 2000 (before)
and 2001 (after the major part of the impedance reduction program)

The visible coherent tune shift in the horizontal plane with current is very small and positive. This is due to the flat SPS chamber geometry which results in quadrupole wake fields which add up in the vertical plane and cancel in the horizontal plane and a small additional component from longer range resistive wall impedance.

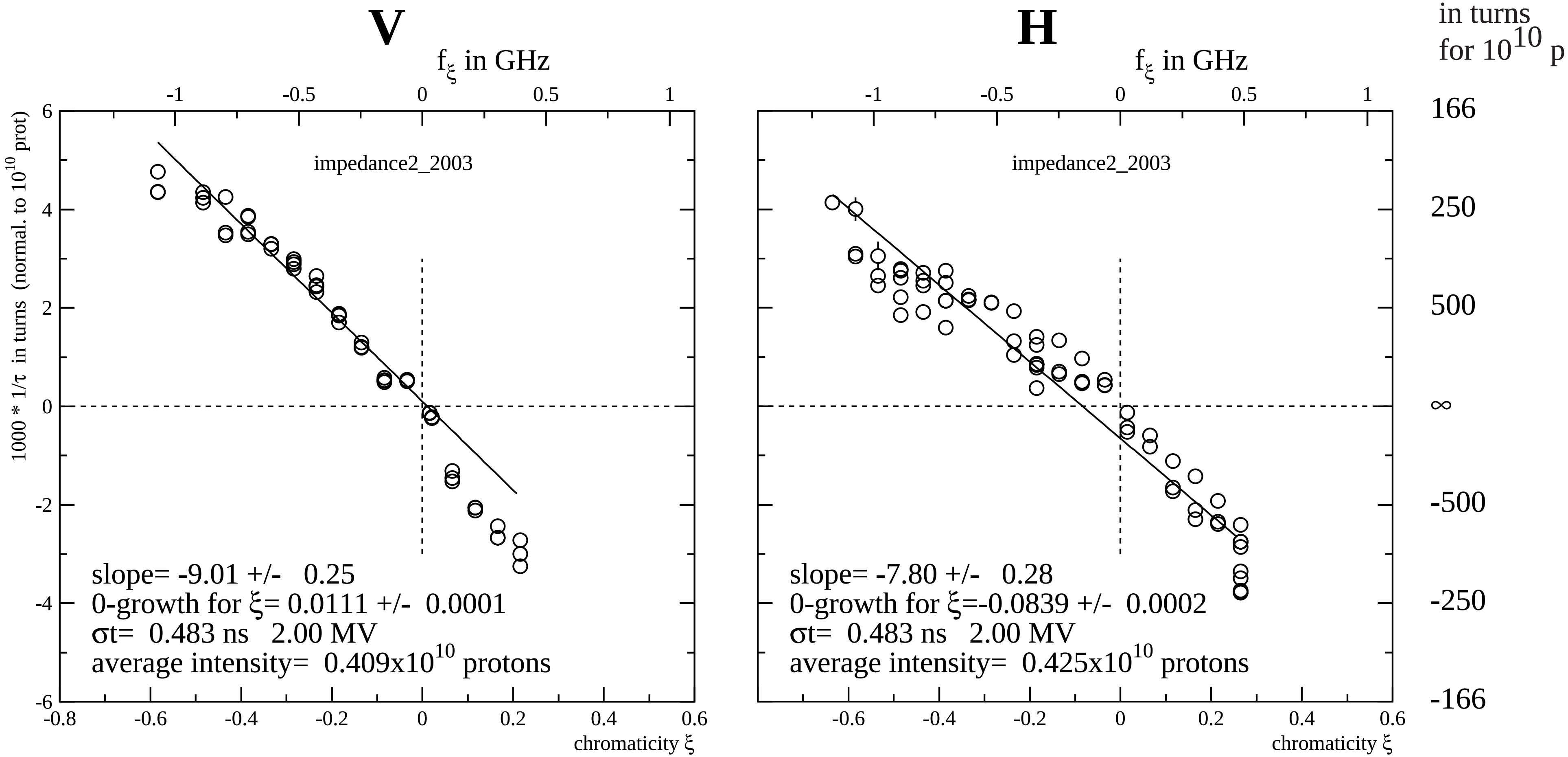


see also:

IMPEDANCES: MEASUREMENTS AND CALCULATIONS FOR NON-SYMMETRIC STRUCTURES
J. Gareyte, EPAC 2002 and
Coherent tune shifts measured with few bunches in the SPS and comparison with resistive wall theory
H. Burkhardt, A. Koschik, G. Rumolo, F. Zimmermann, B. Zotter ; PAC 2003

Growth/Decay Zt (f)

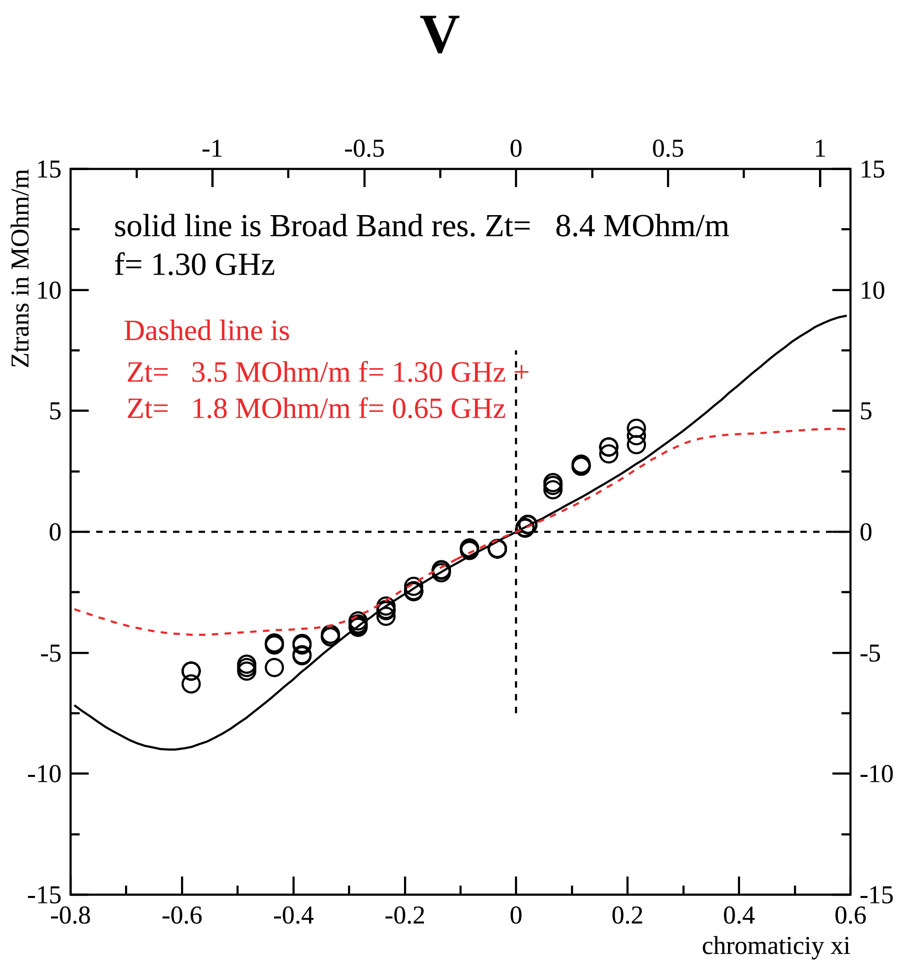
Growth/decay measurements determine Re Z_t as function of the chromatic frequency
$f_\xi = \xi f_\beta / \eta$ For the SPS at 26 GeV roughly $f_\xi = \xi \times 2$ GHz

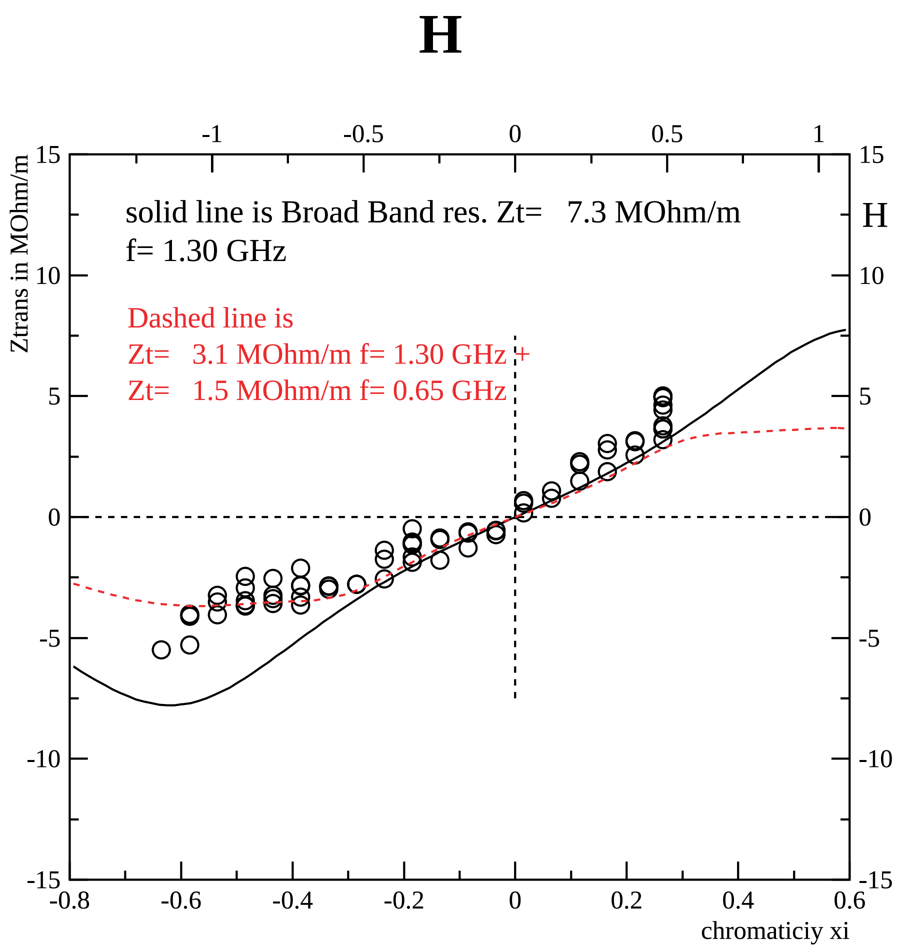


Note that the growth can be very fast. For $\xi = -.5$ and 10^{10} protons or 10% of nominal
we have $1 / \tau = 250$ turns. The length of a synchrotron period for 2 MV RF voltage is 169 turns.

Now in terms of Re Zt (f) (mainly normalise to bunch length, flip sign)

a broad band (Q=1) Oscillator with f_r = 1.3 GHz fits quite well, both in V and H
the sum of two broad band oscillators 1.3 GHz + 0.65 GHz appears to fit even better





Results in terms of (effective) Impedance

Directly using formula quoted on page 3 no flat chamber correction
Uncertainty about ± 10 - 20 % for comparisons between years with measurements taken under similar conditions.

Absolute uncertainty relevant for comparison with simulation is larger
(non-perfectly Gaussian longitudinal, some uncaptured beam..)
~ 30 % for Im Z and of order factor 2 for Re Z (growth / decay)

Re Z_{eff} is for broad band impedance Q = 1 f_r = 1.3 GHz

Im Z_{eff} in MOhm/m

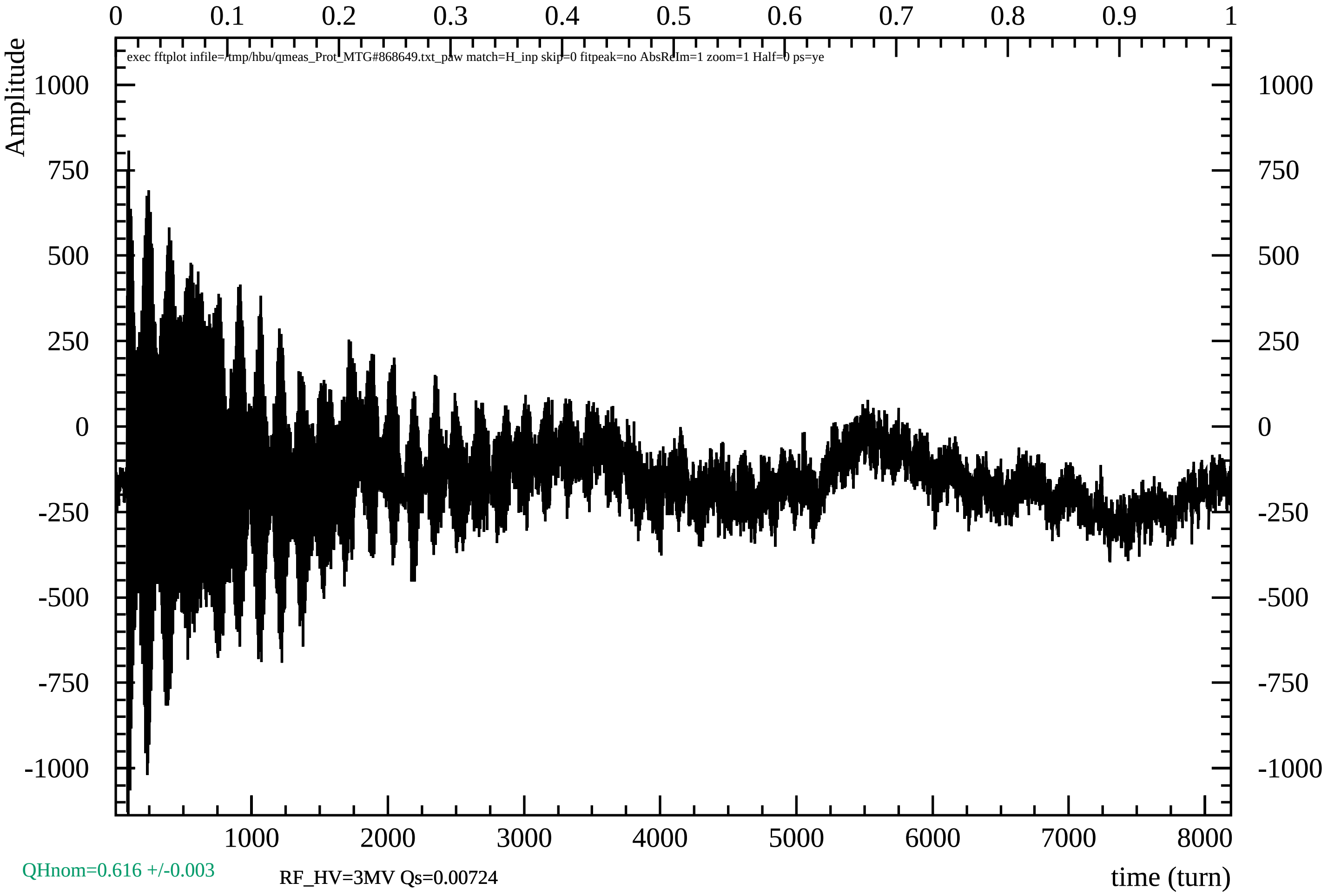
	Horiz.	Vertical
2000	- 1 ± 2	~ 30
2001	-0.5 ± 0.5	18
2002	- " -	15
2003	- " -	24

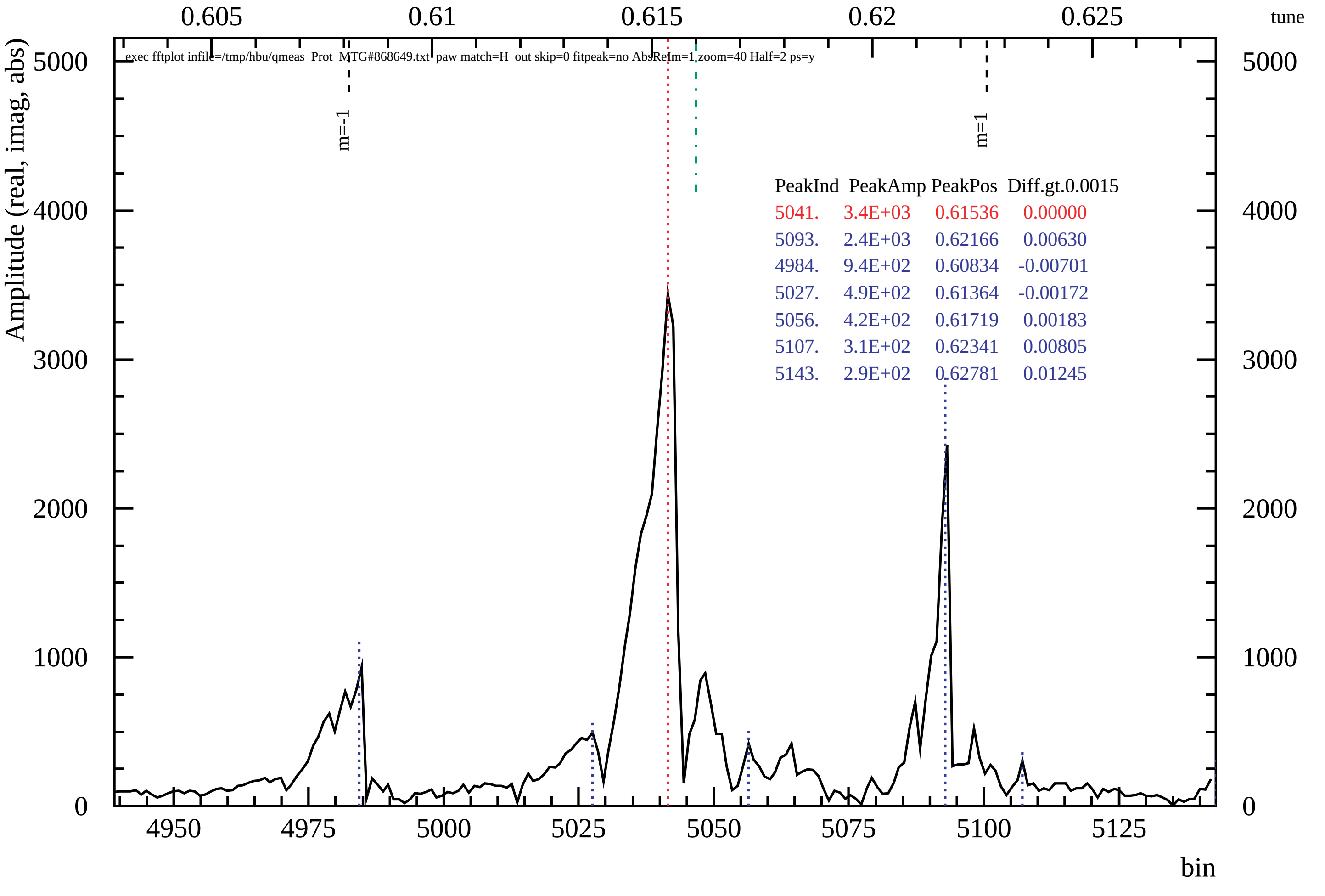
Re Z_{eff} in MOhm/m

	Horiz.	Vertical
2000		
2001	5	9
2002		
2003	7	10

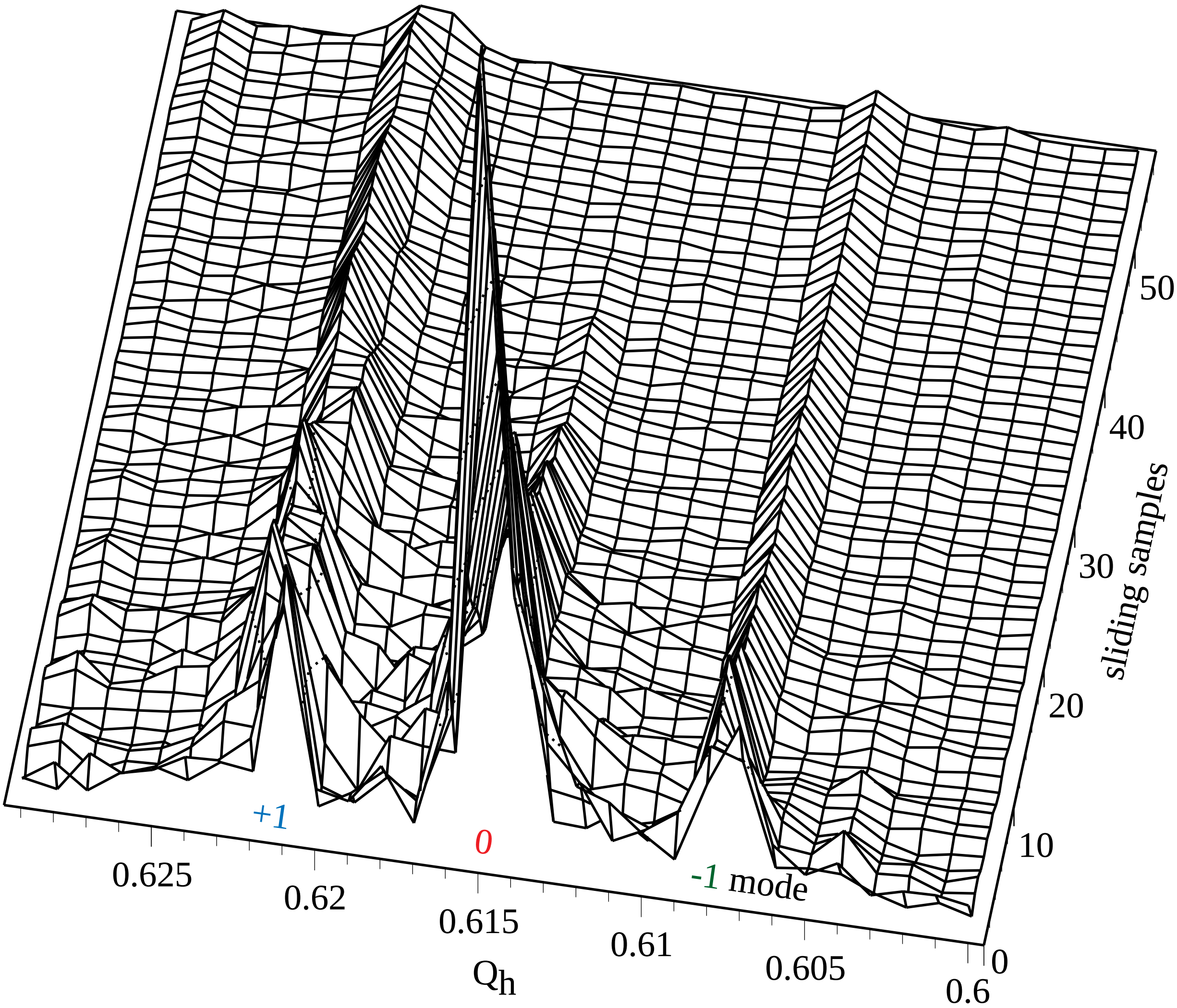
Higher order head-tail modes

ξ_x =+0.4   3 modes clearly visible





The higher order modes appear still to be damped, but much less than the 0-mode



another view of the same data

owType=Rect cleanup=0 Half=2 ps=no
exec fft#MountainRange plane=H Qmin=.60 Qmax=.65 logy=no plotcommand=contour 123 50 3 hmin=0 project=0 te
8192 1024 128 .616 .003 .572 .003 120. 120. 1.e10 1

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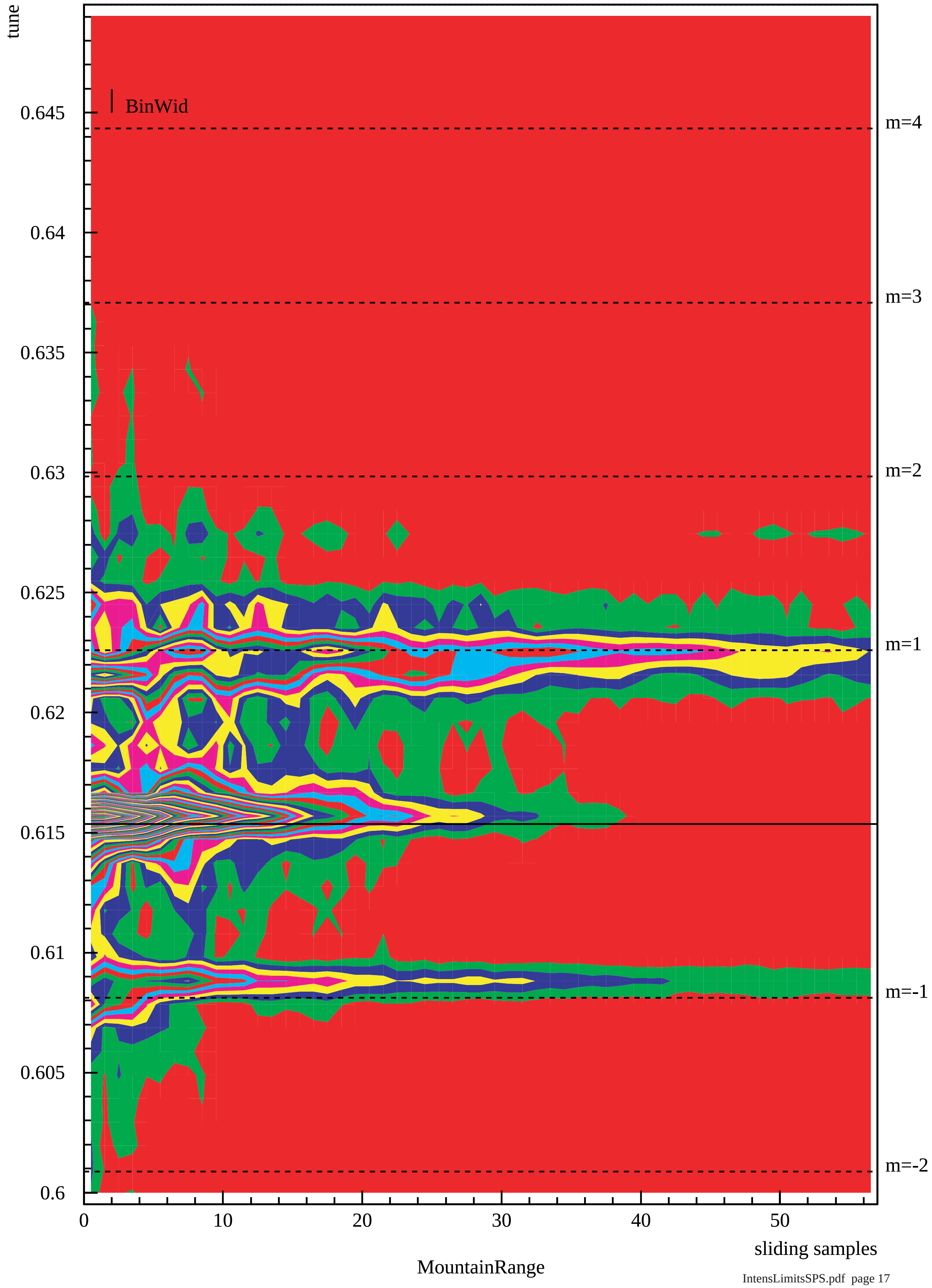
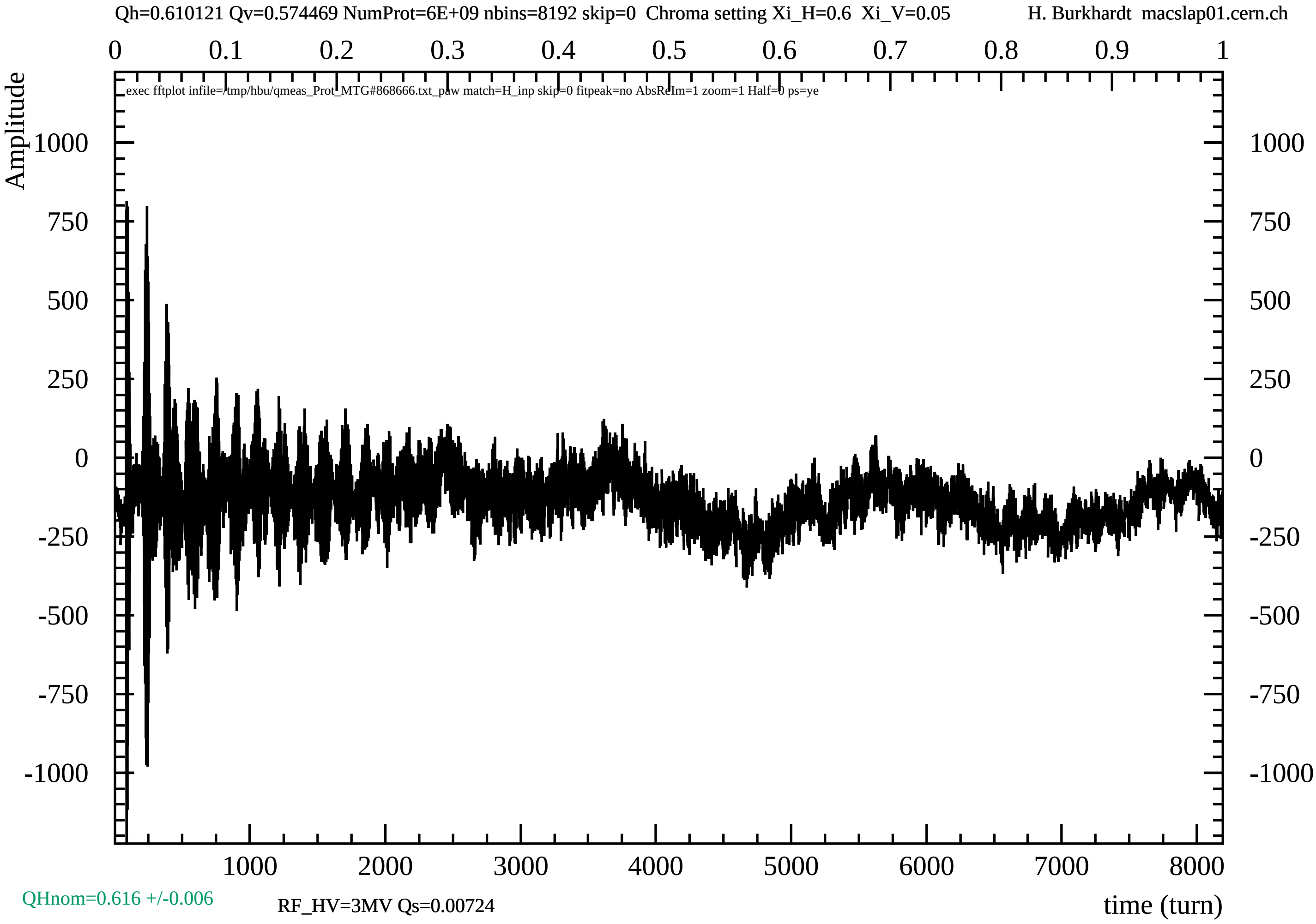
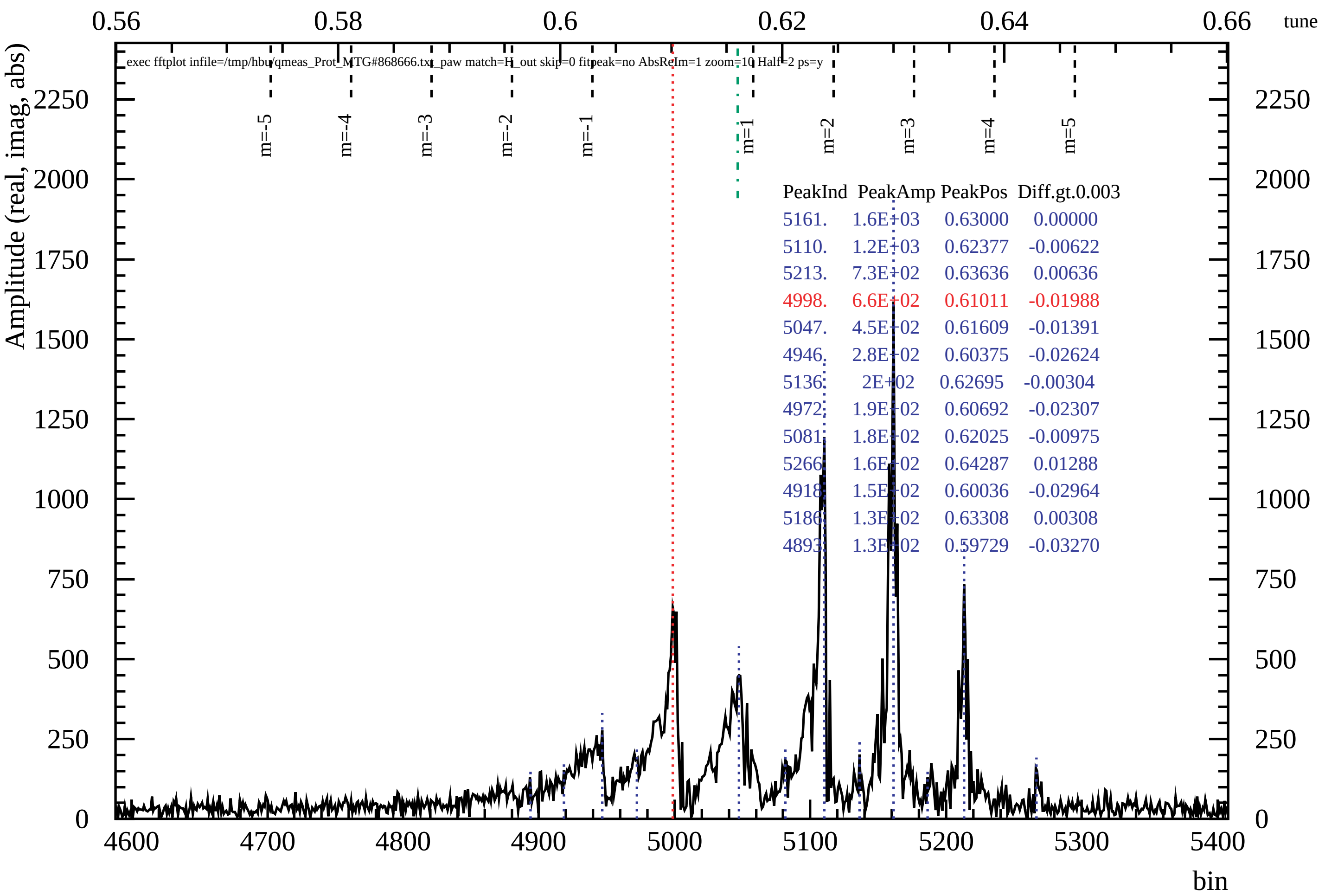


at high chromaticity (here ξ_X =+.6) many modes become visible





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8192 1024 128 .616 .003 .572 .003 120. 120. 1.e10 1

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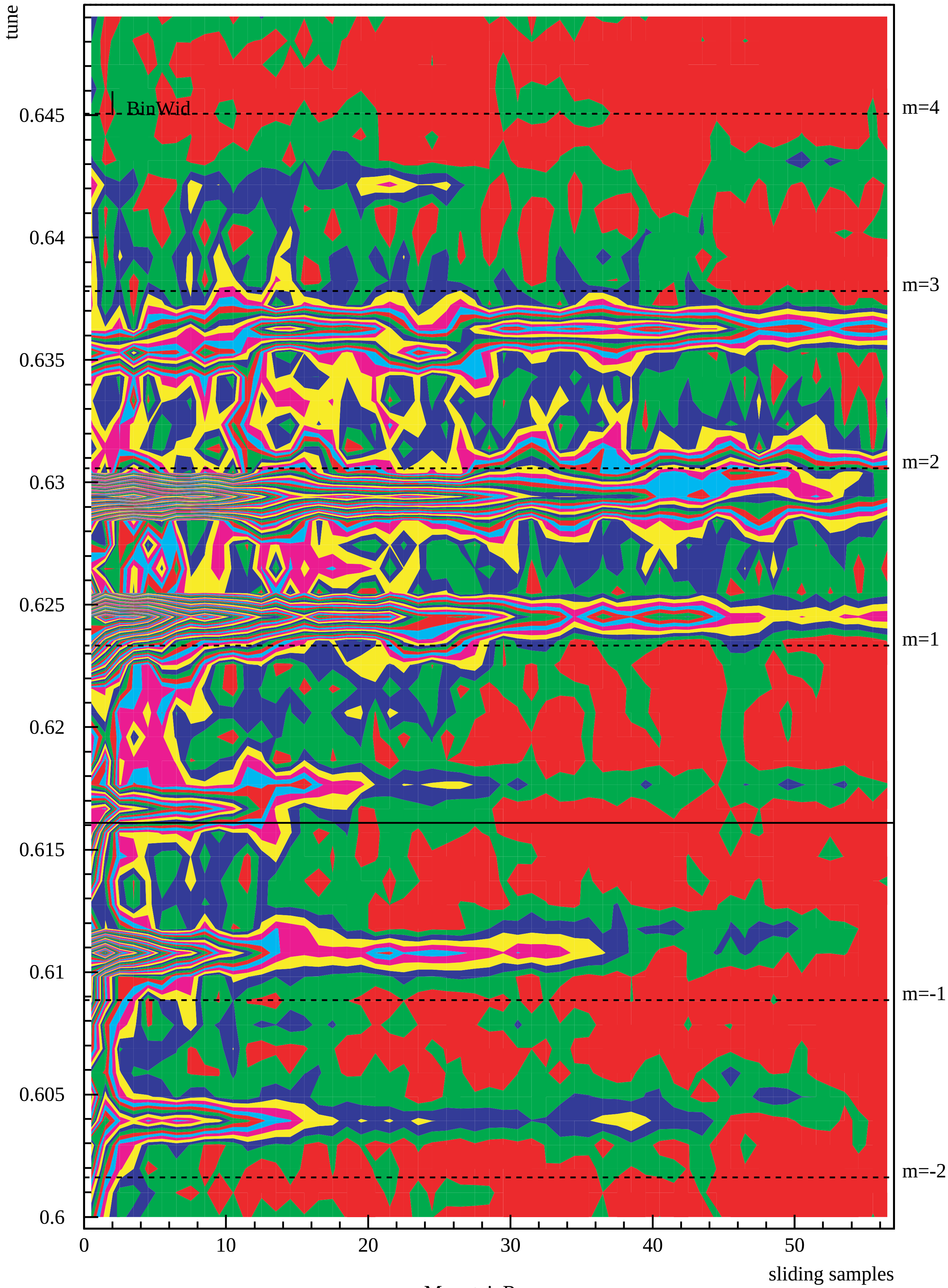


MountainRange

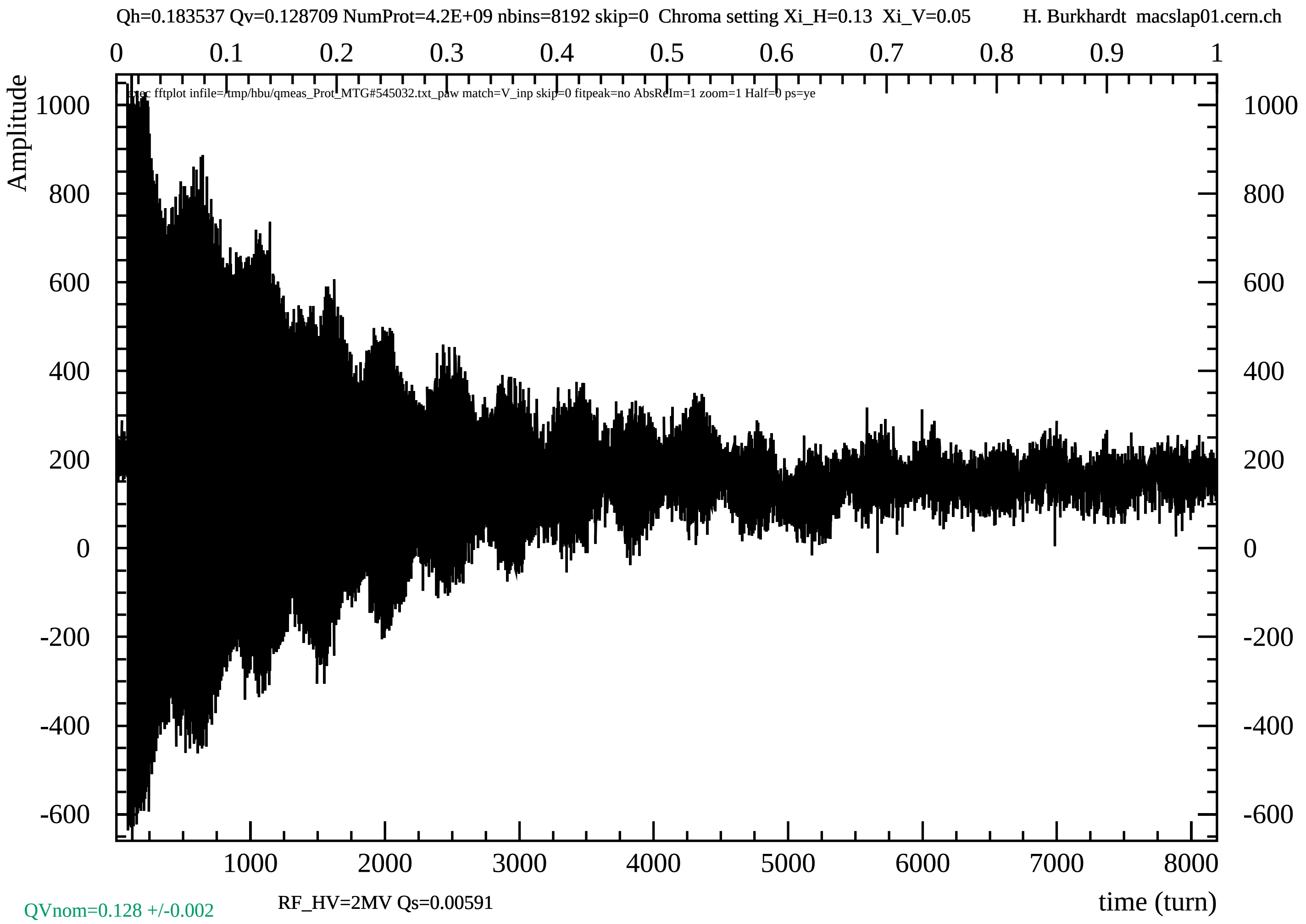
Conclusion

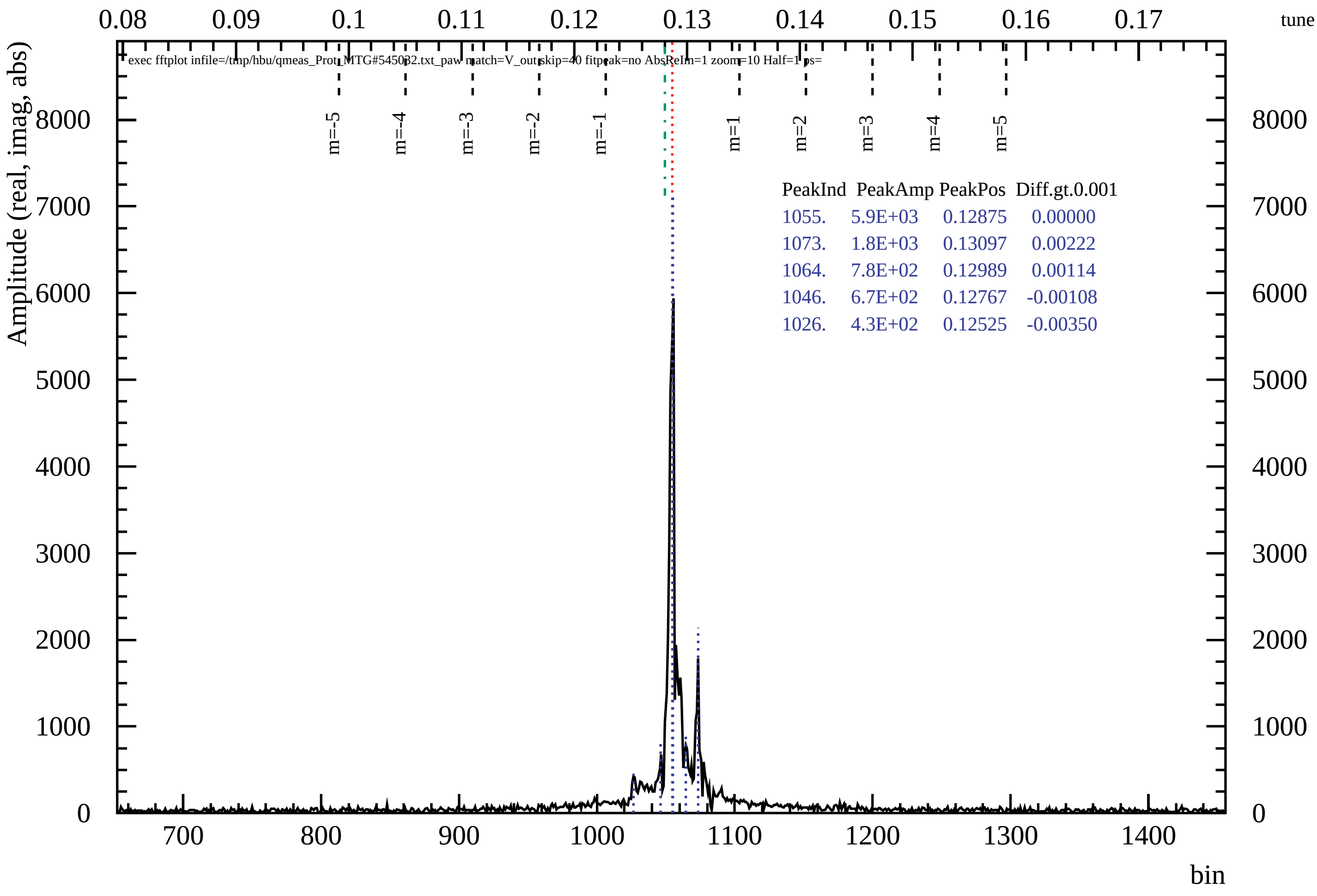
- The major efforts to reduce the SPS impedance were very successful for the longitudinal impedance and still clearly visible in the transverse plane.
- The installation of the first of two sets of extraction elements already nearly cancelled this improvement in the transverse impedance.
- A fast transverse instability is now observed at about nominal intensity and 50 % reduced longitudinal emittance

- The second half of extraction elements is scheduled for installation in the 2005 / 2006 shutdown.

  It will be very important to continue to monitor the transverse impedance and to check that nominal LHC intensities do not yet suffer from the fast transverse instability

- A further effort to reduce the SPS impedance, this time with emphasis on the transverse plane (with new or modified extraction kickers, ...) should be be launched to be able to increase towards the ultimate $1.7\ 10^{11}$ intensities we have also observations of modes space by less than Qs, mainly visible in V, here $\xi_y = .05$





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8192 1024 64 .185 .002 .129 .002 200. 100. 1.e10 1 0 -0.0018 -.010 -.011

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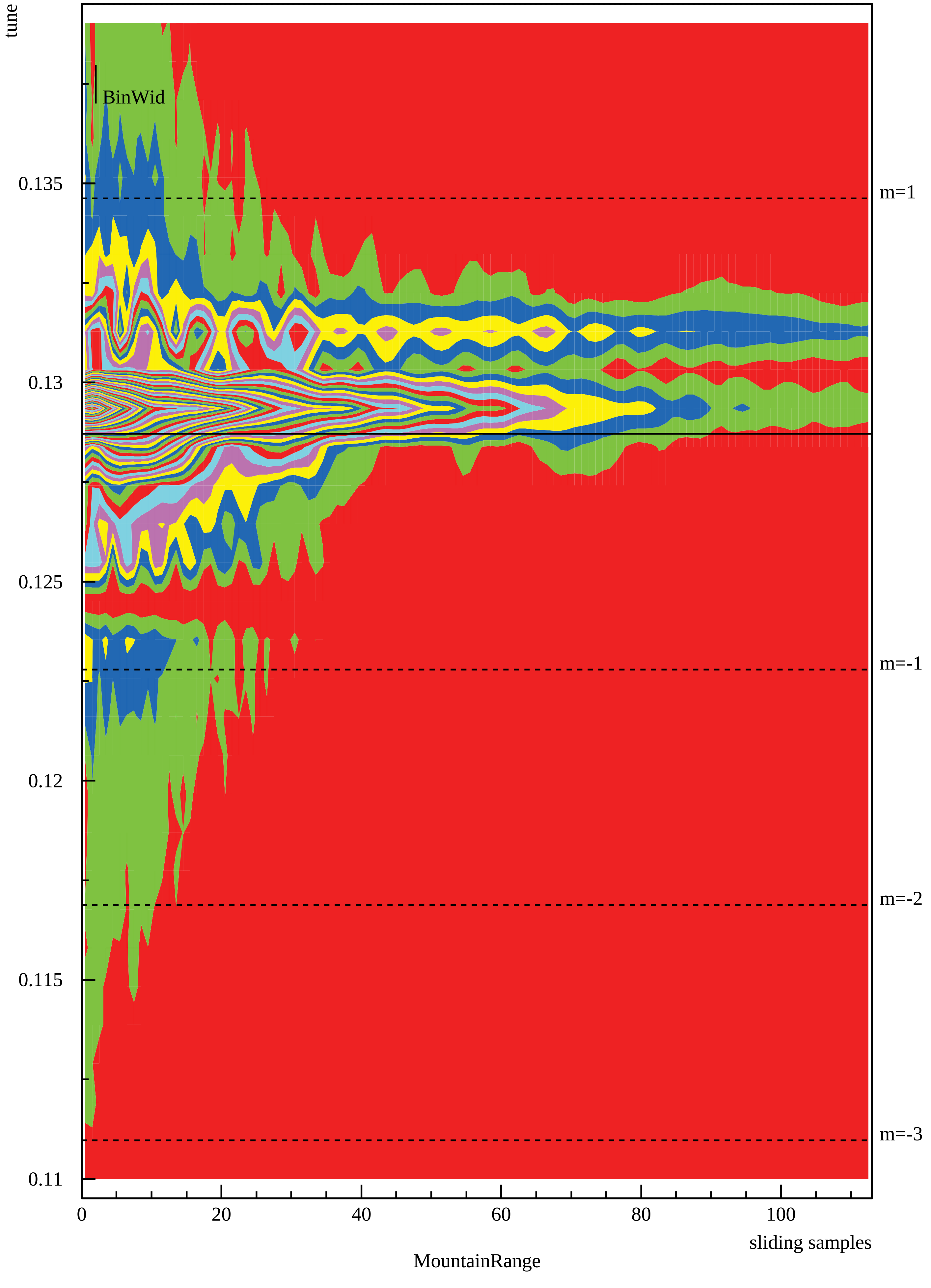
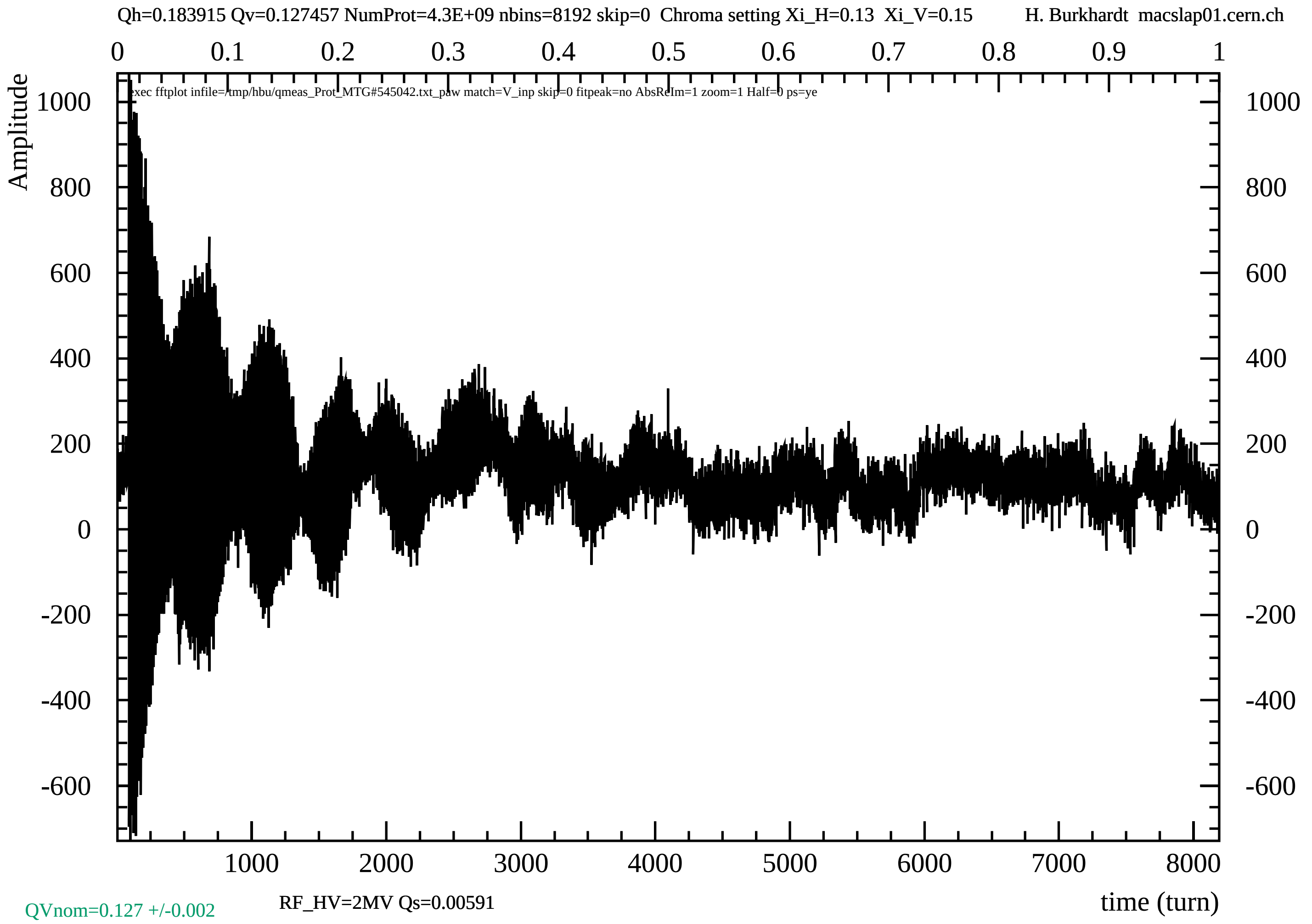


$\xi_y = .15$


Qh=0.183915 Qv=0.127457 NumProt=4.3E+09 nbins=8192 skip=0 Chroma setting Xi_H=0.13 Xi_V=0.15
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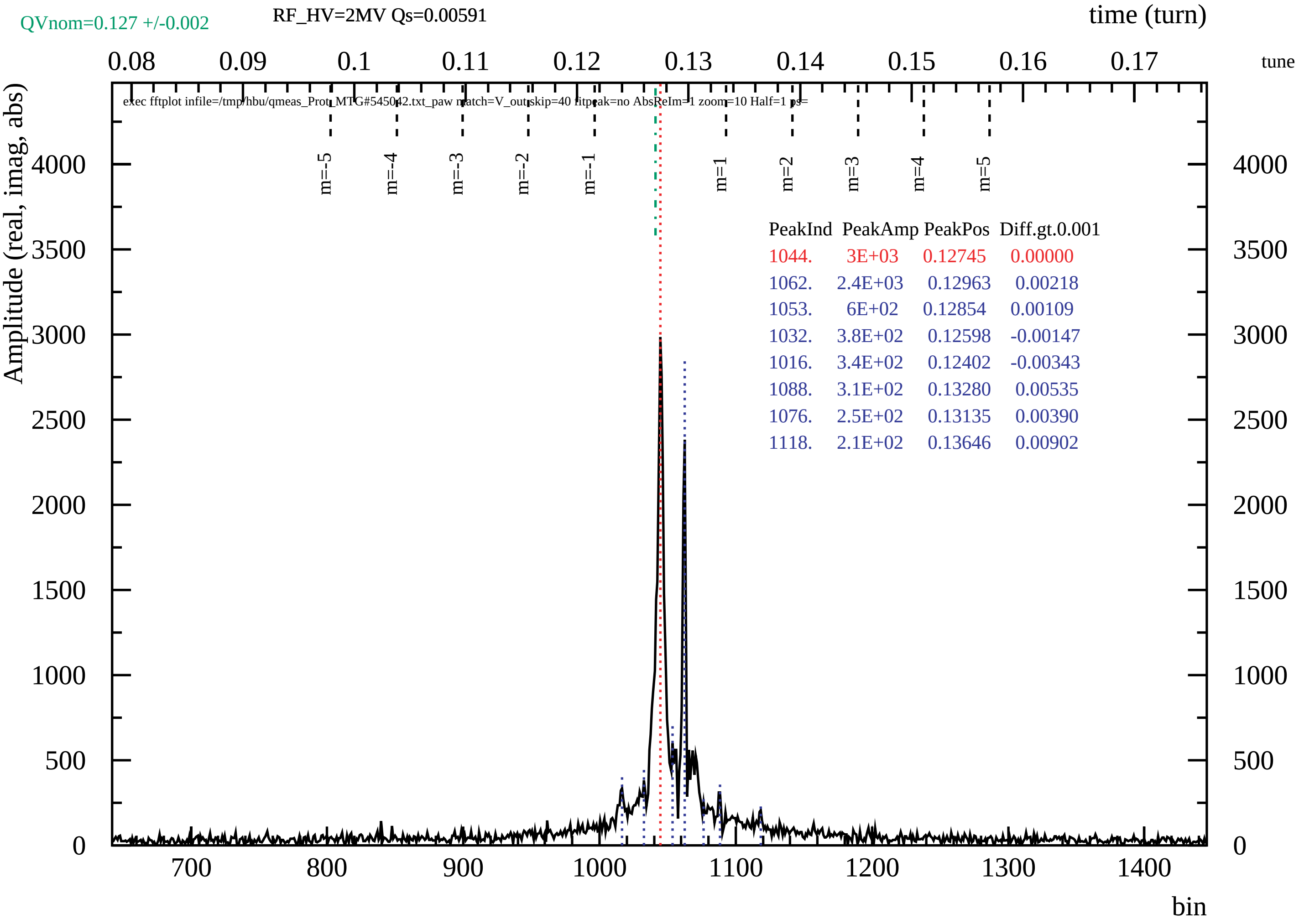
Amplitude
time (turn)


QVnom=0.127 +/-0.002
RF_HV=2MV Qs=0.00591
tune
Amplitude (real, imag, abs)
m=-5
m=-4
m=-3
m=-2
m=-1
m=1
m=2
m=3
m=4
m=5
PeakInd PeakAmp PeakPos Diff.gt.0.001
1044. 3E+03 0.12745 0.00000
1062. 2.4E+03 0.12963 0.00218
1053. 6E+02 0.12854 0.00109
1032. 3.8E+02 0.12598 -0.00147
1016. 3.4E+02 0.12402 -0.00343
1088. 3.1E+02 0.13280 0.00535
1076. 2.5E+02 0.13135 0.00390
1118. 2.1E+02 0.13646 0.00902
bin

dowType=Rect cleanup=0 Half=1 ps=yes
exec fft#MountainRange plane=V Qmin=.11 Qmax=.14 logy=no plotcommand=contour 123 50 3 hmin=0 project=0 te

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8192 1024 64 .185 .002 .129 .002 200. 100. 1.e10 1 0 -0.0018 -.010 -.011