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Summary of LHC MD 377: Schottky pick-up

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Abstract

The main objective of this MD was to record Schottky spectra under well-known machine conditions. In summary, 7 set-points for the chromaticity and 8 for the emittance have been established and Schottky spectra have been recorded for each setting. The data will be used to benchmark and develop different fitting algorithms. This note presents the initial attempt of curve-fitting and discusses its shortcomings.

Summary of LHC MD 377: Schottky pick-up

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1 Summary

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2 Introduction

The LHC Schottky monitor can extract beam and machine parameters from incoherent particle motion in a completely non perturbative way. Schottky signals are observed with a transversely sensitive pickup at a frequency range around 4.8 GHz. After downconversion, digitization, FFT-processing and averaging over several minutes, a 22.4 kHz wide spectrum, consisting of 8192 frequency bins is obtained. It shows one revolution harmonic and the characteristic transverse Schottky sidebands. From these it is possible to extract fractional tune, chromaticity, emittance, synchrotron and betatron frequencies by a curve-fitting algorithm. Note, at flat-top energy and under high intensity beam conditions, some of these parameters can not be measured in any other way.

3 Description of the MD

The *MD377* took place from *27 August 2015 03:00 - 27 August 2015 06:00*. The relevant fill numbers are *4275* and *4276*. All measurements have been done with *protons* at injection energy (*450 GeV*). In the first fill, the chromaticity was changed over a wide range by modifying the beam optics, i.e. setting of the sextupole magnets:

3:00 Injection of one nominal bunch of intensity 1.2×10^{11} and one pilot bunch of intensity 2.1×10^{9} for B1 and B2.

3:42 Chromaticity scans (4.1 - 20) with B2V on pilot bunch

4:12 Chromaticity scans (2.4 - 15) with B1H on nominal bunch

4:30 The beams were lost during an attempt of setting the chromaticity to 20.

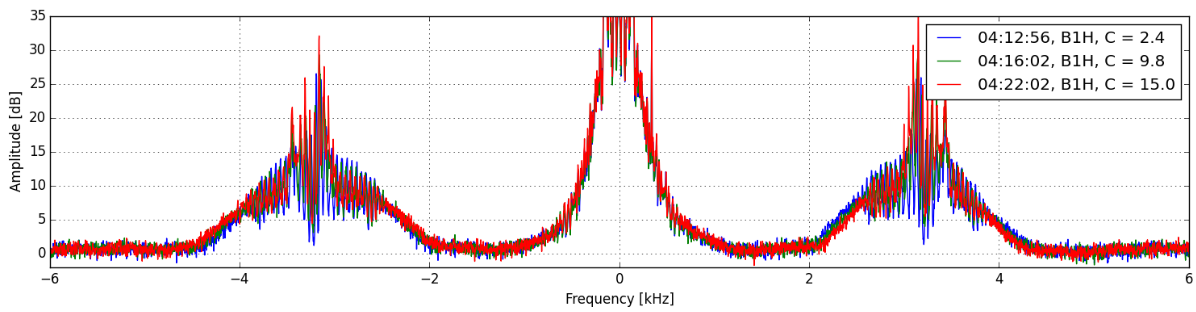

Fig. 1: Typical Schottky spectra for a nominal proton bunch of intensity 1.2×10^{11} at injection energy for different chromaticities (C). The x-axis shows a frequency offset relative to a revolution line close to 4.81 GHz. The y-axis shows amplitude, normalized to the background noise level of the receiving chain. The longitudinal Schottky band as well as the lower and upper transverse Schottky sidebands are clearly visible.

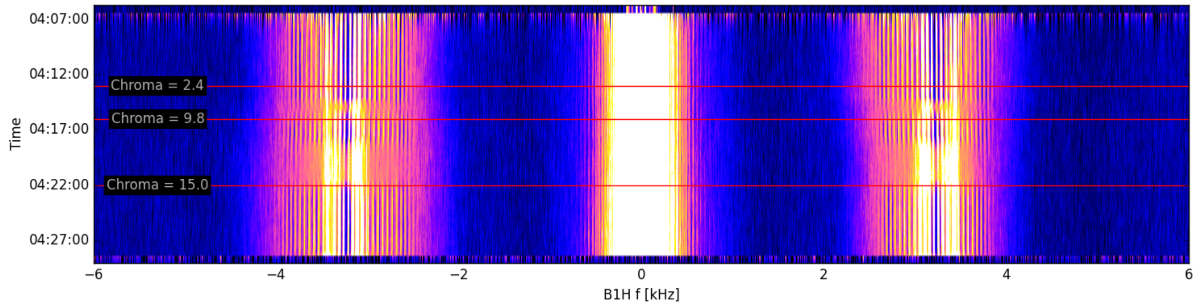

Fig. 2: Spectrogram of the Schottky data over ≈ 30 minutes. The x-axis shows frequency, the y-axis time, and the amplitude values are color coded. The chromaticity has been changed three times. The blurry regions are an artifact of the standard method to measure chromaticity based on modulating the RF cavity frequency.

During the first 30 minutes, the Schottky system was set up and the compensation path was optimized for maximum common mode rejection. Data logging was started at 3:30. Typical Schottky spectra are shown in Fig. 1. The time evolution of the Schottky spectra is shown in a spectrogram plot in Fig. 2. Each chromaticity set-point has been verified with the LHC standard procedure of sweeping the RF frequency and monitoring changes in tune. The RF sweep is visible as a perturbation in the spectrogram plot (Fig. 2), smoothing out the fine-structure (synchrotron lines) within the Schottky sidebands.

In the second fill, emittance was changed over a wide range by using the transverse damper to blow up the beam. Each set-point was verified with wire-scanner measurements.

4:45 A new fill was prepared with 1 pilot and 1 nominal bunch of intensity $1.28\ \times 10^{11}$ (B1) and $1.13\ \times 10^{11}$ (B2).

5:15 Blow up of B1H emittance. 4 set-points from 2 μm rad up to 7.5 μm rad have been established.

5:45 Two more set-points have been established on B2V.

5:56 B2 becomes unstable and the emittance increased to > 20 μm rad.

6:05 Beamdump and end of the MD. B2 intensity has degraded to $3.24\ \times 10^{10}$.

4 The fitting procedure

The beam chromaticity can be extracted from the difference in width of the upper and lower sideband. Plotting the spectra on top of each other, as shown in Fig. 1, does show a slight width-difference for different chromaticities. For a more accurate quantification, the following steps are applied to the raw spectra from the BBQ:

Baseline subtraction The gain of the downmixing chain is slightly frequency dependent, which leads to amplitude ripple in the spectrum of a few dBs. To remove this systematic error, a reference spectrum is acquired without beam (or alternatively, with frontend gating in its Off state). It is subtracted from all subsequent measurements, resulting in a flat baseline.

Linearization the spectra are processed on a linear scale (not dB)

Offset subtraction For each spectrum, the background noise level is subtracted. Noise is measured in two frequency bands, where no beam induced signals are expected. The bands are centered at $f_0 = \pm 5600$ Hz and are $\Delta f = 1400$ Hz wide.

Sideband splitting The upper and lower Schottky sidebands are extracted by fixed frequency windows and processed separately. The center frequency and width are user defined parameters.

Masking of coherent synchrotron sidebands. The N frequency bins with the largest amplitude are masked and not taken into account for the fitting. N is a user defined parameter.

Smoothing A 3rd order Butterworth filter was applied to smooth out incoherent synchrotron lines and other fine structures. The cut-off frequency α is a user defined parameter, specified as a relative value from 0 (maximum smoothing) to 1.0 (no smoothing)

Gaussian curve-fit The gaussian function Eq. 1 is fit to each sideband. The *curve_fit* function of the python package *Scipy* is used to carry out the non-linear least squares fit [1].

Parameter extraction The frequency offset, amplitude and width of the two gaussians are converted to beam and machine parameters.

The gaussian function which is used for the curve-fit of each side-band is

$$y = A \cdot \exp\left[-\frac{(x-\mu)^2}{2\sigma^2}\right], \tag{1}$$

where A is the amplitude, μ is the frequency offset and σ the width of the gaussian. Note that its 'Full Width at Half Maximum' (FWHM) is related to σ by

$$\mathrm{FWHM} = 2\sqrt{2\ln 2}\,\sigma \approx 2.354\,\sigma. \tag{2}$$

After the parameters of the gaussians from the lower and upper sideband (identified by subscript L and H) are known, the fractional tune q is given by:

$$q = \frac{\mu_H - \mu_L}{2 f_{\mathrm{rev}}}, \tag{3}$$

where f_{rev} is the revolution frequency [2–4]. The chromaticity Q' is given by:

$$Q' = \frac{\sigma_L - \sigma_H}{\sigma_L + \sigma_H} \cdot \eta \cdot \frac{f_c}{f_{\mathrm{rev}}}, \tag{4}$$

where $\eta \approx 3.182 \times 10^{-4}$ is the LHC slip factor and $f_c \approx 4.81 \times 10^9$ Hz is the measurement frequency. The emittance ε is given by

$$\varepsilon \propto A_L \cdot \sigma_L + A_H \cdot \sigma_H, \tag{5}$$

where a proportionality factor needs to be taken into account.

5 Results and discussion

For the off-line analysis, the fitting procedure as described in Ch. 4 has been applied to each recorded spectrum and the resulting time-series was compared with the reference measurements.

5.1 Tune

In Fig. 3, the result from the curve-fit has been compared to the LHC Base Band Tune (BBQ) measurement. Note that the measured q value depends only on the distance between the two Schottky sidebands, and hence the smoothing factor α has little influence on the result. Moreover, for tune-values $>$ 0.5 the measurement becomes ambiguous, as it is not possible to distinguish between the local Schottky sidebands and the ones of the adjacent revolution harmonic (q value is offset by 0.5). Due to the moving average filter which is applied to each frequency bin after FFT processing, the time constant of the tune measurement is ≈ 1 minute. This becomes clearly visible during the 3rd RF modulation period starting shortly after 4:18.

It should be mentioned, that the accuracy of the tune might be improved if the fine-structure is taken into account. Instead of measuring the distance between the two smoothed sidebands, the distance between the two largest synchrotron lines is evaluated. This requires an algorithm which identifies the right lines and precisely determines their position in frequency.

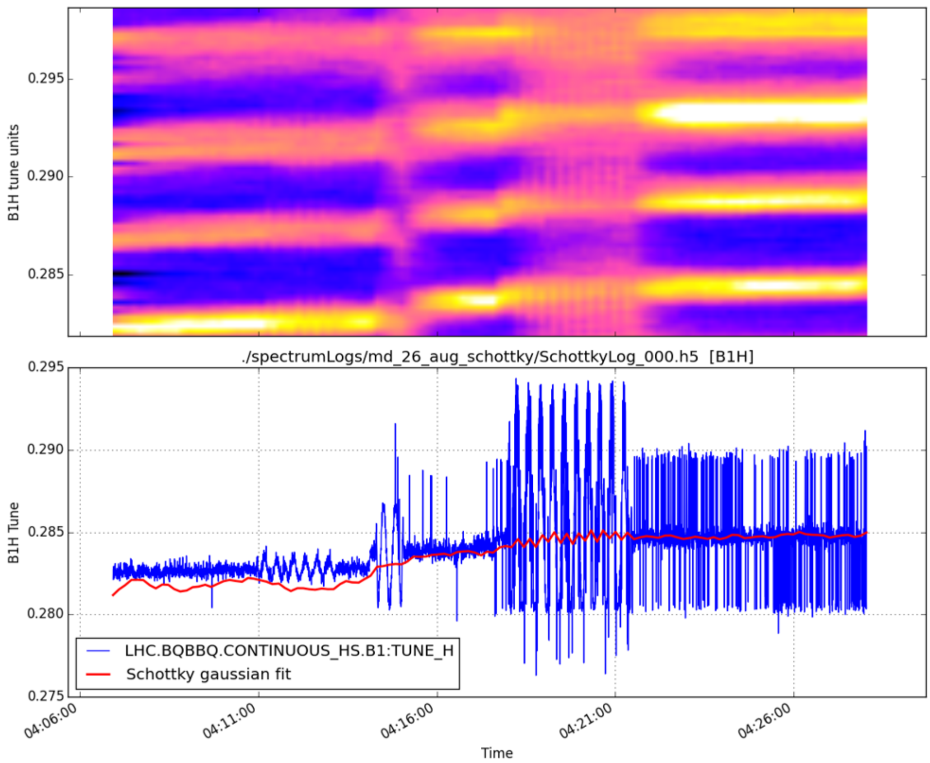

Fig. 3: **Top**: spectrogram plot of the fine structure within a Schottky sideband. The drift of the synchrotron lines indicates a drift of tune. **Bottom**: Result of the curve-fit procedure compared to the reference measurement from the LHC BBQ.

5.2 Chromaticity

The chromaticity measurement depends on the normalized difference in width between the two Schottky sidebands and hence is much more sensitive to the quality of the curve-fit as the tune. The calculation has been carried out for different values of α to show its influence on the chromaticity result. A time series of the resulting chromaticity data is shown in Fig. 4 and the processed data points after smoothing are shown in Fig. 5.

From Fig. 4 it can be seen that the best agreement to the reference measurement (green points) is achieved for $\alpha = 0.004$. Furthermore, Fig. 5 indicates that the post processed data-points match the shape of the Schottky sidebands well under this condition. For smaller values of α the cut-off frequency of the smoothing filter is too low and its output does not follow the original curve shape, resulting in a large error on the calculated chromaticity. For larger values of α (less or no smoothing), the fine structures of the spectrum (synchrotron lines) have a negative effect on the gaussian curve-fit, which also leads to an error in the calculated chromaticity.

5.3 Emittance

The transverse emittance is proportional to the integrated power under the two Schottky sidebands [2–4]. An absolute emittance measurement is difficult as the signal processing chain needs to be calibrated for accurate power measurements on an absolute scale and eventual gain drifts need to be taken into account. Even then, an accurate reference measurement of the emittance is required to determine all calibration factors, including the beam and waveguide coupling coefficients of the pickup. To simplify the analysis, only a brief, relative measurement for three emittance set-points could be performed. For these set-points the emittance values are well-known from wire scanner measurements of the beam profile.

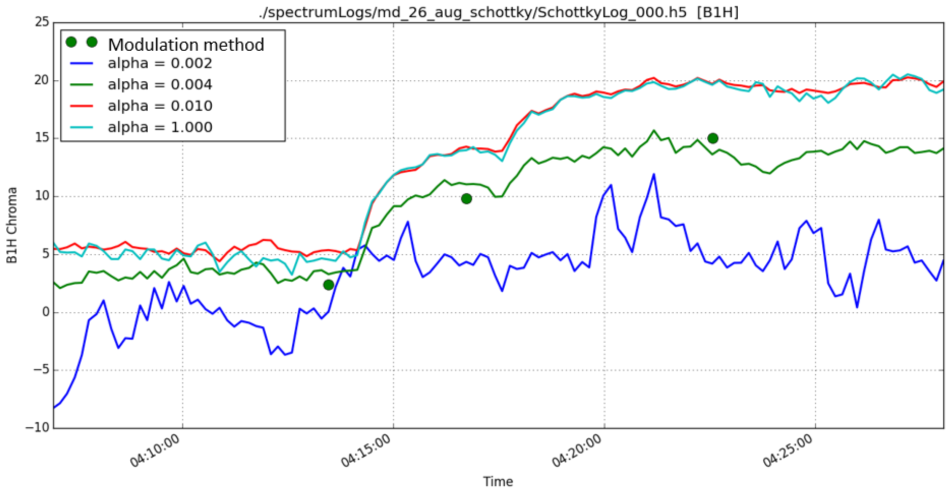

Fig. 4: Result of the chromaticity calculation for different smoothing factors α. The green points indicate the reference measurements.

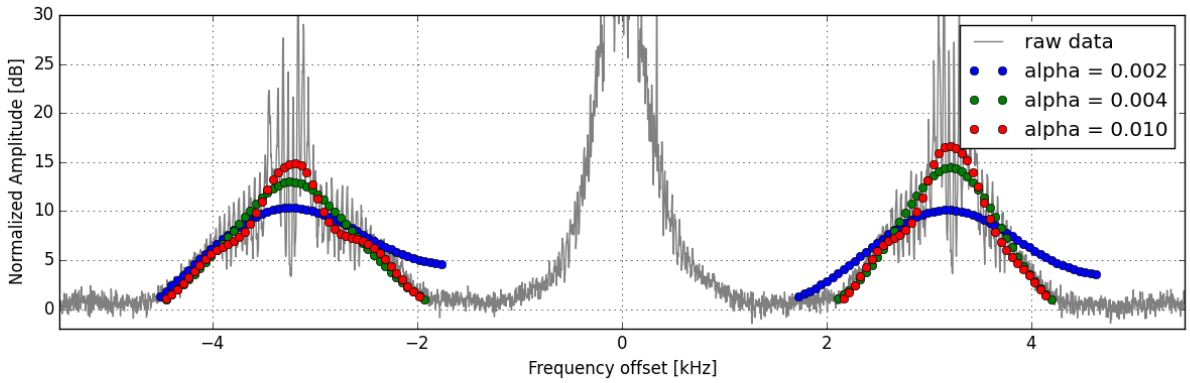

Fig. 5: The effect of the smoothing factor α on the curve-shape. The grey line shows the raw data while the colored dots show the data after all post-processing steps according to Section 4, just before the curve-fit is applied. Note how the low-pass filter can not match the shape of the Schottky sideband if α is too low (blue) while it can not suppress the fine structure if α is too high (red). Both cases lead to a bad fitting result.

Two methods have been tested to extract the emittance. Using the parameters of the curve-fit, the area under the the two Gaussians can be determined by Eq. 5. Note that all proportionality constants have been neglected. The other method is based on a numerical integration of the raw spectral bins within the two sidebands.

A substantial source of errors are the strong peaks in the center of the Schottky sidebands, which originate from synchrotron oscillations (incoherent tune). These peaks do not contribute information about the emittance but have a significant effect on the accuracy for both methods. For that reason, every frequency bin outside of the (arbitrarily defined) linear amplitude range $0.5 \leq \mathrm{ampl} \leq 10$ has been set to zero and was not taken into account for the curve-fitting method.

The results of both methods are summarized in Table 1 and Fig. 6 (right). The latter shows that both methods suffer from a significant uncertainty and that more work is needed before emittance data can be extracted reliably from Schottky spectra for operational measurements. Further investigation with more data points need to be carried out, to test if the linear relationship holds true and to find a way for

Table 1: Emittance curve-fit results, showing measured values and its relative change. 'ε wire-scanner' = reference measurement, 'ε - fit' = from gaussian curve-fit and Eq. 5, 'ε - integrated' = from numerical integration

Time	ε wire-scanner [μm]	ε curve-fit	ε - integrated
5:13	2.0	7154	6459
5:31	4.3	8612	7397
5:38	7.5	8796	7642

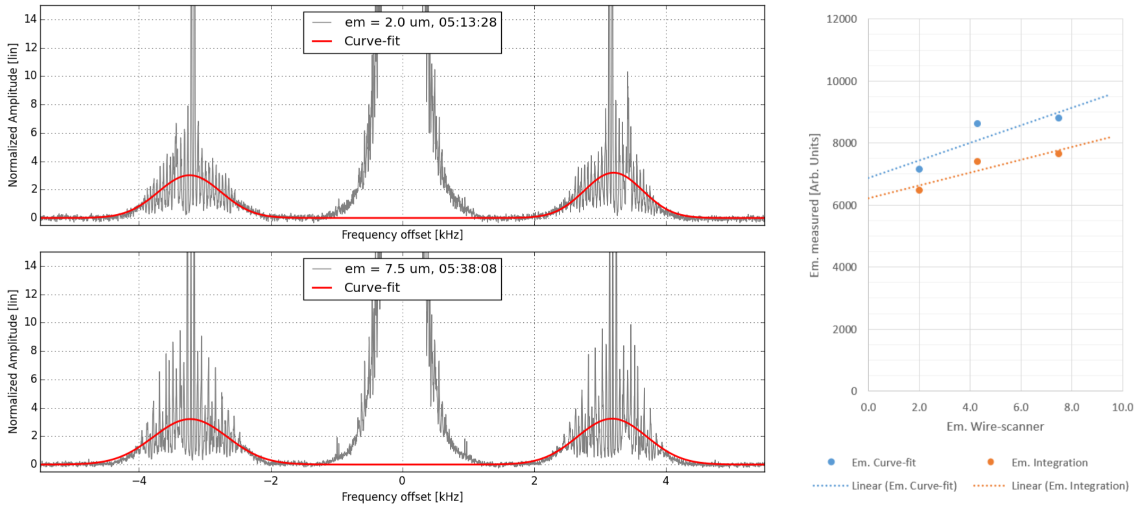

Fig. 6: Left: Raw Schottky spectra for two different emittances and curve-fit result on a linear amplitude scale. Note, the peaks in the center of the Schottky sidebands reaches values up to 100 (+40 dB) in normalized amplitude, and would introduce a substantial error in the curve-fitting. Hence all amplitude values > 10 have been masked. **Right:** Results of the curve-fit and integration method.

reducing the uncertainty.

The Schottky spectra for emittance settings of 2.0 μm rad and 7.5 μm rad are shown in Fig. 6 (left). The two Gaussians from the curve-fit have been overlaid in red. It is noticeable how the lower spectrum with a higher emittance shows a larger spread in amplitude of the individual synchrotron lines. However both data-processing methods do not take this feature into account. One might speculate what kind of information can be extracted from the peak amplitudes (and their statistics) of the synchrotron lines. To investigate this further, the amplitude density function (or histogram) of the two Schottky sidebands has been plotted in Fig. 7. Both histograms show clearly different features, but it is not obvious how to extract the emittance information.

6 Conclusion

The Gaussian curve-fitting method can be used to extract tune and chromaticity, and to some extend also emittance values from the Schottky spectra. However, especially for the latter two, the accuracy of the result depends significantly on the pre-processing of the data. Peaks and outliers in the spectrum which originate from physical beam effects like the incoherent synchrotron sidebands, or which are artifacts of the receiving chain need to be separated and filtered out from the Schottky sidebands. In this case, a simple amplitude threshold was used, which was fine-tuned by hand. Furthermore, the fine-structure (synchrotron lines) within the Schottky spectra do interfere with the Gaussian curve-fitting and have been removed by a smoothing filter. Fitting a more complex model which takes these features into account might lead to more accurate results. A statistical analysis of the amplitude values might also lead to further insights on how to best extract certain parameters.

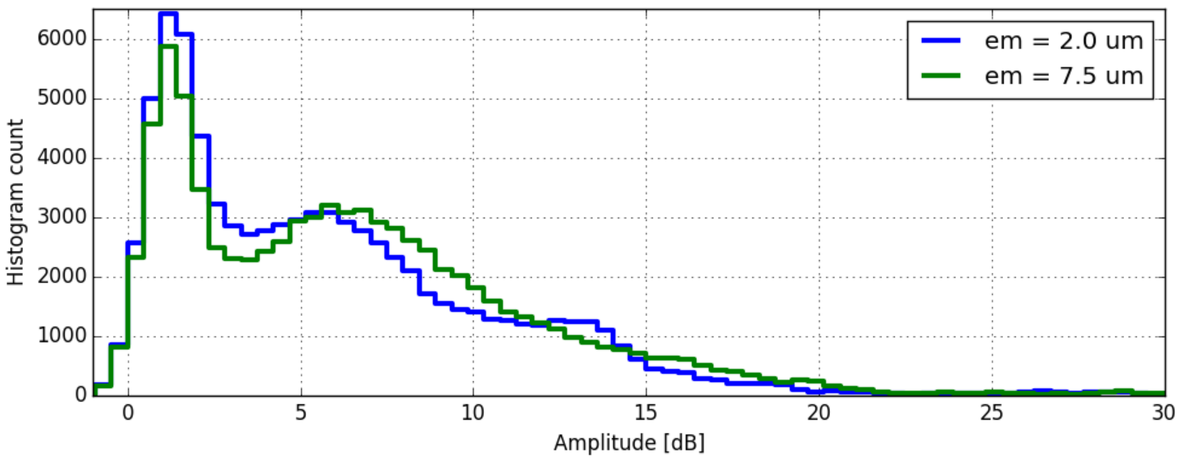

Fig. 7: Statistical distribution (histogram) of the amplitude values (in [dB]) within the Schottky sidebands. There is a significant difference for the two emittance set-points, which relates to the increased variance of the peak amplitudes in Fig. 6.

7 Acknowledgment

The authors would like to express their thanks to R. Jones and F. Caspers for the many fruitful and inspiring discussions.

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