THE NOVEL OPTICAL NOTCH FILTER FOR STOCHASTIC COOLING AT THE ESR

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Abstract

In the frame of the development for the FAIR facility at GSI, notch filter cooling is essential for the stochastic cooling system of the CR (Collector Ring). A prototype notch filter based on optical components has been developed and assembled. The focus was to achieve sufficient notch depth and low periodicity error of the filter transfer function. The compact optical notch filter was integrated into the ESR stochastic cooling system. Longitudinal cooling of heavy ion beams was successfully demonstrated. The layout of the notch filter and the experimental results are presented.

INTRODUCTION

The principle of a correlation notch filter consists of splitting the input signal into two lines with different electrical lengths. The short line is the direct connection and the long line is the connection with additional delay T. Both branches should have the same attenuation. If the basic propagation delay time of the short line is t_0, for the long one it should be t_0+T. The signals of both lines are subtracted from each other. This ideal notch filter with the transfer function given by equation (1) has zero transmission at all harmonics nf_0 (notches spaced by f_0=1/T in frequency) and maximum transmission at frequencies $(n+1/2)f_0$, n=0,1,...∞. The phase jumps by 180° at each notch.

$$S_{21,ideal} = \frac{S_0}{2}(1-e^{j\omega T}) = -j\,|S_0|\sin\left(\frac{\omega T}{2}\right)e^{j\omega\left(t_0+\frac{T}{2}\right)} \quad (1)$$

$$S_0 = |S_0|\,e^{j\omega t_0}$$

When the notch filter is used for longitudinal stochastic cooling of the ion beam in the storage ring (Thorndahl's method [1]), the delay T (notch distance f_0=1/T) should be exactly equal to the nominal revolution period (frequency) of the beam. Also, ω=2π· n(f-f_0), where f is the revolution frequency of each beam particle. Physically, the notch filter response combined with an additional 90° phase-shift pushes particles with wrong revolution frequency to the nearest notch and does not affect particles with the nominal revolution frequency. The time of flight (TOF) longitudinal cooling method [2] uses only the short line of the filter combined with a -90° phase shift [3]. In practice, the TOF method is applied by opening the long branch of the notch filter (e.g. switching off the lower detector in Fig. 1) and shifting the phase by 180° with respect to the notch filter setting.

The optical notch filter was developed, measured in the lab and then integrated into the ESR stochastic cooling system which operates in the bandwidth 0.9-1.7 GHz and at the nominal ion beam kinetic energy of 400 MeV/u (velocity β=0.71), corresponding to a revolution frequency of 1.96 MHz.

THE OPTICAL NOTCH FILTER

The classic approach is to use a long coaxial cable as delay line. This has different problems. The long cable has large frequency-dependent losses and dispersion. Also, a low-loss cable longer than 100 m is very bulky. In an optical notch filter, an optical fibre is used instead of the coaxial cable. Instead of a baseband signal on a coaxial cable, which has a high relative bandwidth, the signal on an optical fibre is modulated on a 1550 nm (i.e. THz range) carrier. This signal has a small relative bandwidth and, as a result, frequency-dependent losses and dispersion are negligible. Mechanically the optical filter is very compact; the setup presented here was built on a 0.84 m^2 plate.

Components of the Notch Filter

At the input of the notch filter the electrical RF signal is amplitude-modulated on light by a laser modulator (Mitec LBT-10M3G-25-15-M14 FA). The optical output power is measured to be 6.8 dBm. The optical signal is split by a single mode wideband coupler 1x21551 FC APC in two branches. Each output level is 3.5 dBm. The short branch contains a fixed attenuator of 6 dB, type PLK-FA-DW 2 dB connected in series with a 4 dB attenuator. The power level after both attenuators is -3.1 dBm. The short branch determines the propagation delay t_0 (i.e. the electrical length) of the filter. In our case t_0= 5.44 ns.

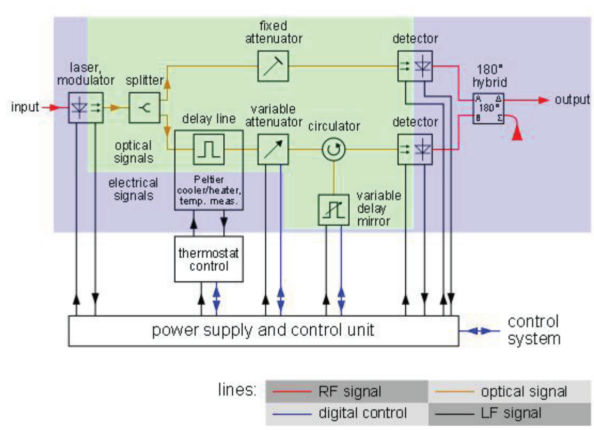

Figure 1: Block diagram of the optical notch filter.

ISBN 978-3-95450-140-3

The long branch contains a fixed delay line (FC/APC 9/125 simplex patch cord) to provide the delay T referring to the short branch. Due to its low attenuation the power level is 3.2 dBm. An attenuator (OZ Optics DD100-MC), variable in the range 0.7-59.7 dB, is integrated in the long branch for fine tuning, so as to match the amplitude between both branches to the same constant value. The variable delay line (circulator GPC-SMS-001-FC/APC-001 and variable delay mirror MDL001, from General Photonics) is used for fine tuning of the notch distance. Its length can be varied up to 1.2 ns, with a resolution of 0.004 ps and reproducibility of ± 0.02 ps. The output power at a delay time of about 600 ps is -0.8 dBm. The insertion loss of the delay line varies slightly versus the chosen delay time. To provide equal power levels at the demodulator inputs the variable attenuator should be set to a value in the vicinity of 2.3dB. Each branch is demodulated to RF signal. Then, the signals are subtracted by a 180° hybrid (ANZAC H 183-4) to provide the notch filter transfer function. The 180° hybrid is a critical component: its non-linear phase behaviour significantly affects the response of the notch filter.

The optical wiring is single mode patch cable FC/APC. To compensate the influence of the ambient temperature to the notch filter frequency stability, the fixed delay line is temperature-stabilized within 0.1 K at 25^0C (according to the data sheets) by a Peltier element and controller. In addition, the filter is mounted on an aluminum plate to provide a heat reservoir. In the CR, the plate will be connected to the water cooling system.

Measurement of the Filter Transfer Function

In practice, within the bandwidth, a real filter has a finite (i.e. non-zero) low transmission (notch depth) at all harmonics nf_0. Because of non-linearity there is also a small deviation f_n-nf_0 between the frequencies f_n at which the transmission minima occur and the harmonics nf_0 (frequency periodicity error). Both effects affect the filter performance and lead to an increase of the equilibrium momentum spread of the cooled beam with respect to the ideal filter case.

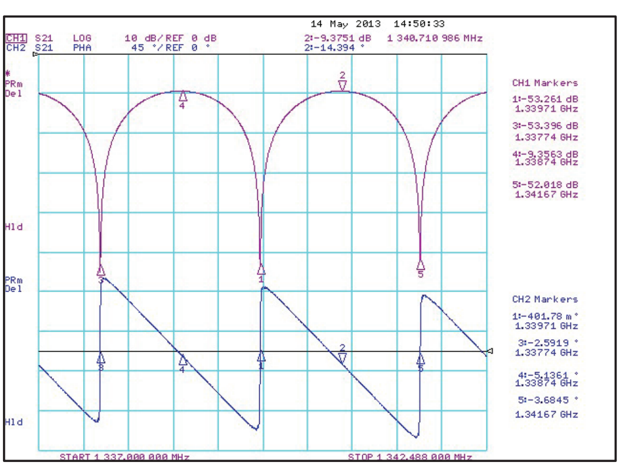

Figure 2: Response of the optical notch filter close to three notches at midband.

We measured the transfer function of the optical notch filter in the pass band 0.9-1.7 GHz according to the ESR requirements. A time delay of 822.2 ps was necessary to setup a notch distance of $f_{0,set}$=1.961719 MHz. The lower and higher harmonic number of $f_{0,set}$ in the bandwidth are n_l=459 and n_2=866, respectively. As an example, the transfer function measured in the vicinity of the midband (1.3 GHz) is shown in Fig. 2. Because of the finite notch depth, the phase jump at each notch was less (164°) than the 180° expected in the ideal case. This response (gain and phase) of the real filter could be reproduced in a simulation by adding an unbalanced attenuation to an ideal notch filter model.

Notch Depth

In Fig. 3 the envelope (solid line) of the measured amplitude $|S_{21}|$ at all in-band minima of the transfer function is displayed. In comparison, the envelope of $|S_{21}|$ at all in-band maxima (dotted line) represents the insertion loss mainly caused by the components in the long branch of the notch filter. It was found to be practically constant close to -8 dB within the whole bandwidth. All in-band notches have a depth lower than -24 dB. A vector network analyser and an automated test setup are used to measure the notch filter transfer function. To reduce the noise impact in the notch center the orthogonal wavelet transformation from the LabVIEW® inbuilt function is used in the measurement to de-noise the vicinity of the notch spot. The minimum then is located by its peak detector function.

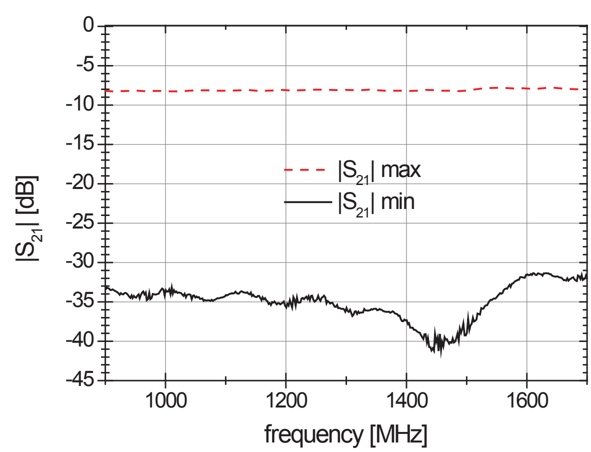

Figure 3: Envelopes of max. and min. $|S_{21}|$ for all notches in the bandwidth 0.9-1.7 GHz.

Periodicity Error

In order to quantify the periodicity error in the band, a linear regression fit was applied to the measured frequencies f_n at which the transmission minima occur (position of notches) for all harmonics n within the bandwidth: $f_n = f(n) = f_0 \cdot n + b = (1.961569\ \text{MHz}) \cdot n - 26\ \text{kHz}$. The slope f_0 represents a mean notch distance within the band. Because of the non-linearity it is slightly different than the setup notch distance $f_{0,set}$ given above. In the storage ring, the beam will be ultimately cooled by the notch filter to the revolution frequency f_0. So,

ISBN 978-3-95450-140-3

optimally, f_0 has to be tuned at the beginning to the nominal revolution frequency of the beam. The ordinate intercept point b expresses the mean periodicity error.

The difference between the measured notch positions f_n of the notch filter transfer function and the ascending linear regression line nf_0 , scaled to the harmonic number n of the notches in the pass band, represents an absolute periodic frequency error Δf (in Hz). A further scaling to the mean notch distance f_0 gives a relative periodicity error α at each harmonic. Both are plotted in Fig. 4.

$$\Delta f = \frac{f_n - n\, f_0}{n} \;; \qquad \alpha = \frac{\Delta f}{f_0}$$

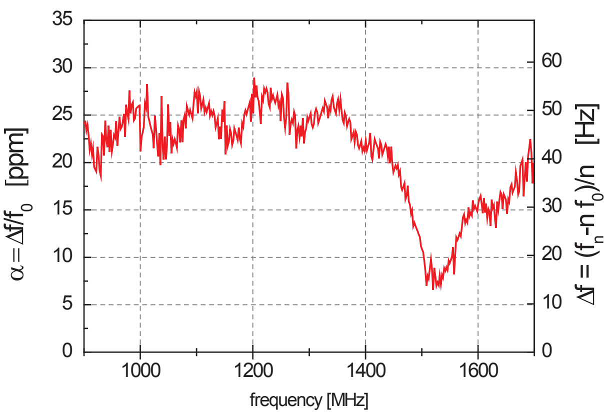

Figure 4: Absolute and relative periodicity error for all notches in the bandwidth 0.9-1.7 GHz.

EXPERIMENTAL RESULTS

In a first run with a Au^{79+} beam, notch filter and TOF cooling have been demonstrated in the ESR using the new optical notch filter setup as explained in the introduction. An example is shown in Fig. 5. Precise settings of (i) the notch distance by changing the position of the variable delay line mirror and of (ii) the optical attenuators were a prerequisite to achieve low equilibrium momentum spread. Then, the two methods have been compared to each other and also to the existing Palmer method.

For an injected beam of $2.6{\cdot}10^6$ ions, for each of the 3 methods the system gain was varied until the lowest equilibrium momentum spread was obtained. For TOF cooling it was a factor of 1.6 lower and for notch filter a factor of 3 lower compared to the Palmer cooling case. As expected [3], since it suppresses both Schottky and thermal noise in the centre of the distribution, the notch filter cools the beam core much more efficiently and ultimately leads to lower momentum spread than the TOF cooling. It is not clear why the Palmer cooling performed worse than the TOF method, which is limited by the high diffusion in the beam core.

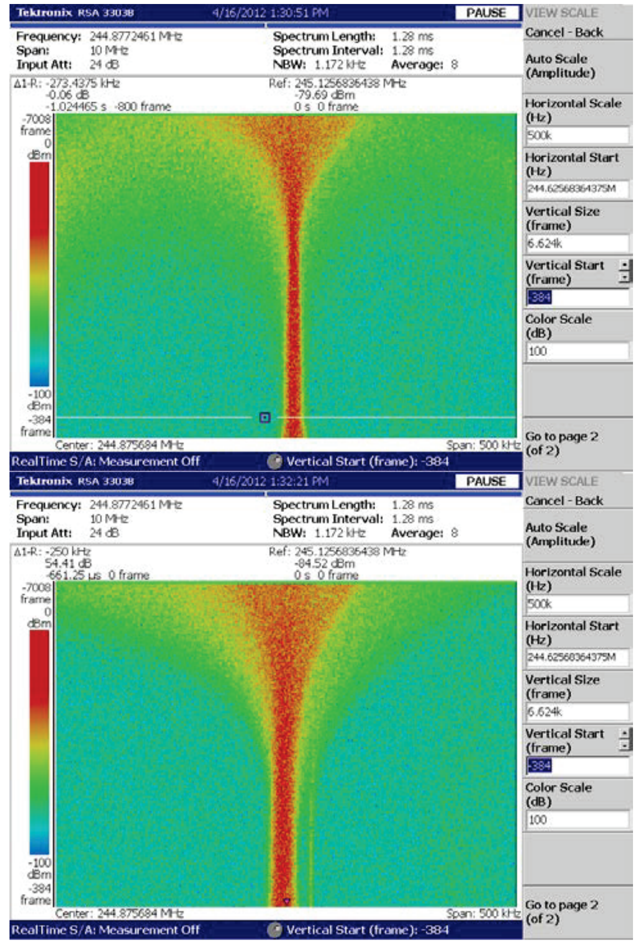

Figure 5: Notch filter (up) and TOF (down) cooling of $4{\cdot}10^6$ Au^{79+} ions at 400 MeV/u, for 8 s after injection, with the same system gain (attenuators setting) in the longitudinal cooling branch. Frequency spectra measured with the resonant Schottky pick-up [4] at about 245 MHz, (124th harmonic), total recording time=9 s.

For the regular ESR lattice with a distance pick-up to kicker equal to half the circumference and momentum slip factor $\eta_{pk}\approx\eta=0.3$, the expected momentum acceptance of the TOF method is 2 times that of the notch filter method. In the latter case, the momentum spread at which the cooling force first changes slope/sign is estimated to be $\pm\, 1.3{\cdot}10^{-3}/\pm\, 2.5{\cdot}10^{-3}$ (see [3, 5] for details), the real acceptance should be in between. Indeed, in the experiment, an injected beam with maximum momentum spread $\pm\, 3.4{\cdot}10^{-3}$ was cooled by the TOF method, whereas it was accepted and cooled by the notch filter only within $\pm\, 1.9{\cdot}10^{-3}$ (the particles at the tails drifted away). The latter result was confirmed as follows: A cold beam at equilibrium was shifted in kinetic energy by changing the electron cooler voltage (a shift of up to 800 V around 220440 V was applied i.e. a δp/p shift of $2.1{\cdot}10^{-3}$) and checked whether it can be cooled by the notch filter back to the initial revolution frequency. This was possible for a shift of $1.1{\cdot}10^{-3}$ but not for $2.1{\cdot}10^{-3}$. Figure 6 illustrates an intermediate case.

ISBN 978-3-95450-140-3

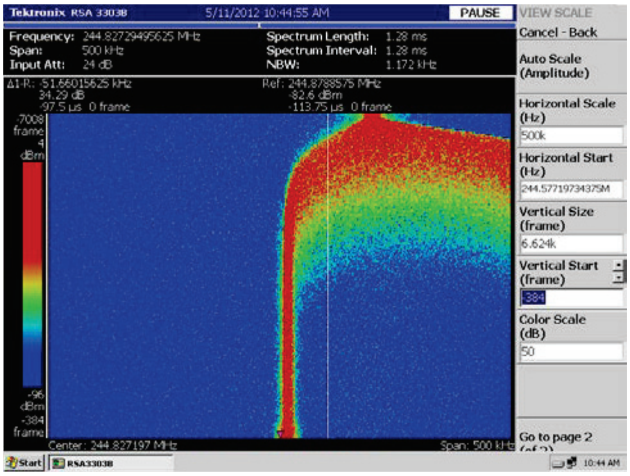

Figure 6: Cooling only within the acceptance of the notch filter, after shifting the beam with the electron cooler by $\delta p/p \approx 1.8 \cdot 10^{-3}$.

In a second run with a $^{58}Ni^{28+}$ beam the cooling performance i.e. cooling down time and equilibrium momentum spread was systematically investigated for different system gains. The 2nd moment σ(t) of the measured frequency (momentum spread) distribution (see Fig. 5) was evaluated and fitted by an exponential decay model with a cooling time constant τ towards an equilibrium value σ_∞ of the momentum spread:

$$\sigma(t) = (\sigma_0 - \sigma_\infty)\exp(-t/\tau) + \sigma_\infty .$$

The injected beam had $\sigma_0 = 2.9 \cdot 10^{-4}$ and $2.6 \cdot 10^{-4}$, for TOF and notch filter cooling, respectively. For $6 \cdot 10^6$ ions, the notch filter yielded ($\sigma_\infty = 2.4 \cdot 10^{-5}$, τ=0.44 s), operating at 16 dB higher gain than the fastest TOF ($\sigma_\infty = 8.1 \cdot 10^{-5}$, τ=1.45 s). For $5 \cdot 10^7$ ions, the notch filter yielded ($\sigma_\infty = 4.1 \cdot 10^{-5}$, τ=0.81 s, Fig. 7), operating at 16 dB higher gain than the fastest TOF method ($\sigma_\infty = 1.1 \cdot 10^{-4}$, τ=2.08 s).

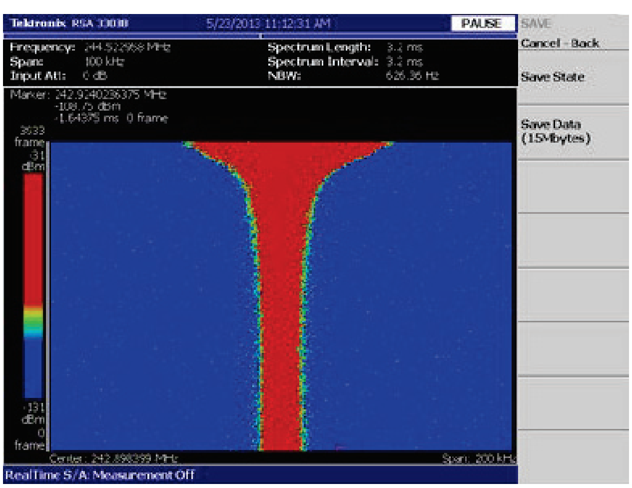

Figure 7: Notch filter cooling of $5 \cdot 10^7$ Ni^{28+} ions at 400 MeV/u, for 12 s after injection.

The results summarized in Table 1 confirm that TOF cooling has to proceed slowly at low gain in order to reach lowest momentum spread.

Table 1: TOF Cooling of $6 \cdot 10^6$ Ions for 12 s

System Gain	τ (s)	σ_∞
G	1.45	$8.1 \cdot 10^{-5}$
G-3 dB	2.09	$7.3 \cdot 10^{-5}$
G-6 dB	4.42	$4.4 \cdot 10^{-5}$
Variable gain: G-1 dB, t=0-3 s G-4 dB, t=3-6 s G-7 dB, t=6-9 s G-10 dB, t=9-12 s	2.20	$5.7 \cdot 10^{-5}$

CONCLUSIONS & OUTLOOK

At present 3 different longitudinal stochastic cooling methods (Palmer, TOF and notch filter cooling) are available at the ESR. All of these are also being developed for the CR. Notch filter cooling in the ESR is very fast and leads to lower final momentum spread compared to the Palmer cooling, i.e. better beam quality for experiments. It is planned to provide fast switching (of the phase-shifter setting) from TOF to notch filter cooling for different ESR operation scenarios, e.g. TOF pre-cooling of the beam tails profiting from the large acceptance, then switching in a second stage to notch filter cooling for ultimate performance.

TOF cooling alone is sufficient for moderate requirements on the final momentum spread or on the cooling time (e.g. lower particle number). Very recently, it was successfully implemented as pre-cooling for fast accumulation of a low-abundant rare isotope $^{56}Ni^{28+}$ beam in the ESR [6].

The experimental results at the ESR confirm that the notch filter method is the choice par excellence for the noise-limited antiproton cooling and for the ultimate cooling-down of rare isotopes in the CR. They give confidence for the CR system design [3,7] and can be used for code benchmarking.

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ISBN 978-3-95450-140-3