JÜLICH FORSCHUNGSZENTRUM

Stochastic Cooling System for HESR - theoretical and simulation studies -

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Outline

- Modes of operation HESR
- Basic machine and beam parameters of HESR
- Momentum cooling models
- Comparison of momentum cooling techniques for HESR
  - Filter momentum cooling
  - Filterless (TOF) cooling

The High Energy Storage Ring HESR

- in the Modularized Start Version of FAIR (MSV) -

- ***Antiproton Beam Mode***
  - Accumulation and Acceleration
  - Internal Target Experiments with High Momentum Resolution
  - Stochastic Momentum Cooling Assisted by BB
- ***Heavy Ion Mode***
  - Acceleration and Internal Target Experiments

Basic Machine and Beam Parameters of HESR

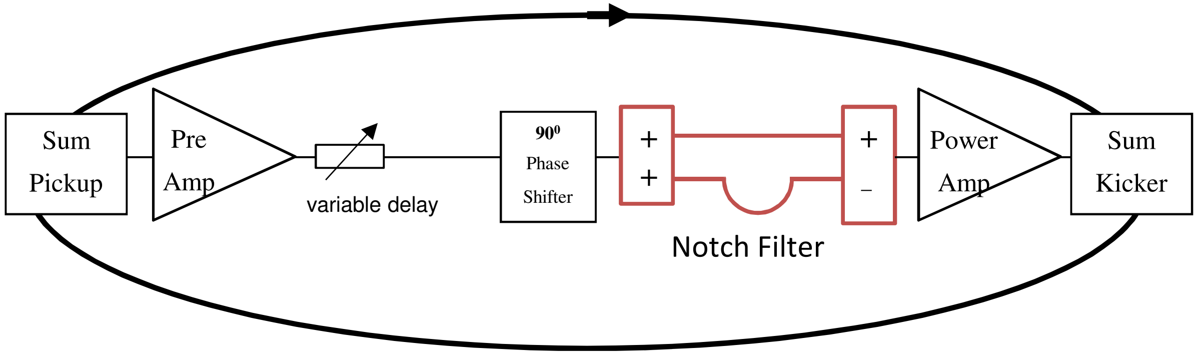
- Ring circumference 575 m, two long straight section 132 m each
- Magnetic rigidity 5 Tm $\leq B\rho \leq$ 50 Tm
- Dipole field 0.17 T $\leq B \leq$ 1.7 T
- Max. dipole ramp rate 25 mT/s
- Transition gamma 6 – 25
- Transverse acceptance 16 mm mrad @ $\gamma_{tr} = 6.23$
- Momentum acceptance $\pm\, 3 \cdot 10^{-3}$
  - Antiprotons: kinetic energy 830 MeV to 14081 MeV
    injection 3 GeV
  - Ions (bare uranium): 165 MeV/u to 4940 MeV/u
    injection 740 MeV/u

Momentum Cooling Models

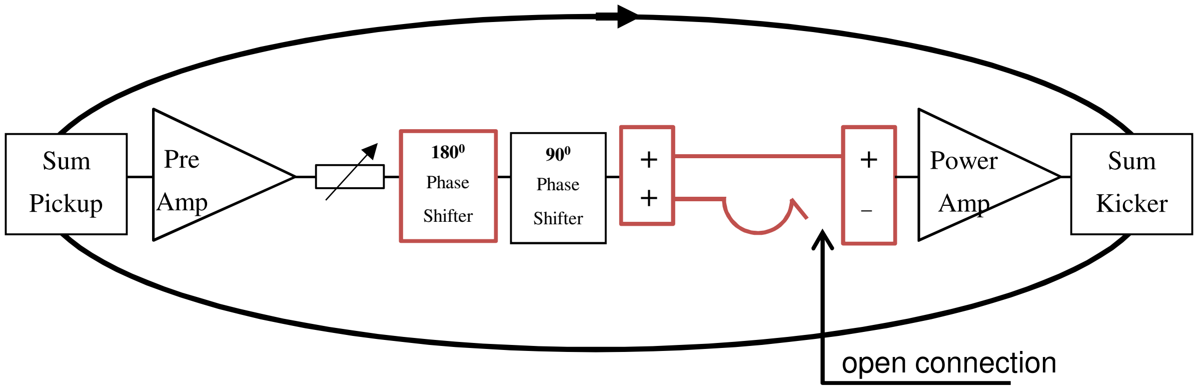
- **Fokker-Planck Equation for Momentum Cooling**
  - includes beam-target interaction
  - Intrabeam scattering IBS
- **Particle Tracking Momentum Cooling (bunched beam cooling)**
  - includes synchrotron motion due to em-fields of cavities
  - Includes beam-target interaction
  - IBS
- **SystemTransfer Function includes models of system components**
  - Filter Cooling
  - Filterless Cooling ≡ Time-Of-Flight (TOF) Cooling
  - (Palmer method)
- Beam feedback included, Open loop gain simulation

Cooling Methods

- ***Filter cooling:*** $\eta_{PK} \approx 0$



- ***TOF cooling:*** $\eta_{PK} \neq 0$



- ***Filter Cooling:***

Notch Filter discriminates between particles with different momenta.
Optimum:
no mixing from PU to Ki

- ***TOF Cooling:***

Uses mixing from PU to Ki to discriminate between particles with different momenta.

Drift and Diffusion Terms

Fokker-Planck Equation

$$\frac{\partial}{\partial t}\Psi(\delta,t) = -\frac{\partial}{\partial \delta}\left[F(\delta,t)\Psi(\delta,t) - D(\delta,t)\frac{\partial}{\partial \delta}\Psi(\delta,t) \right]$$

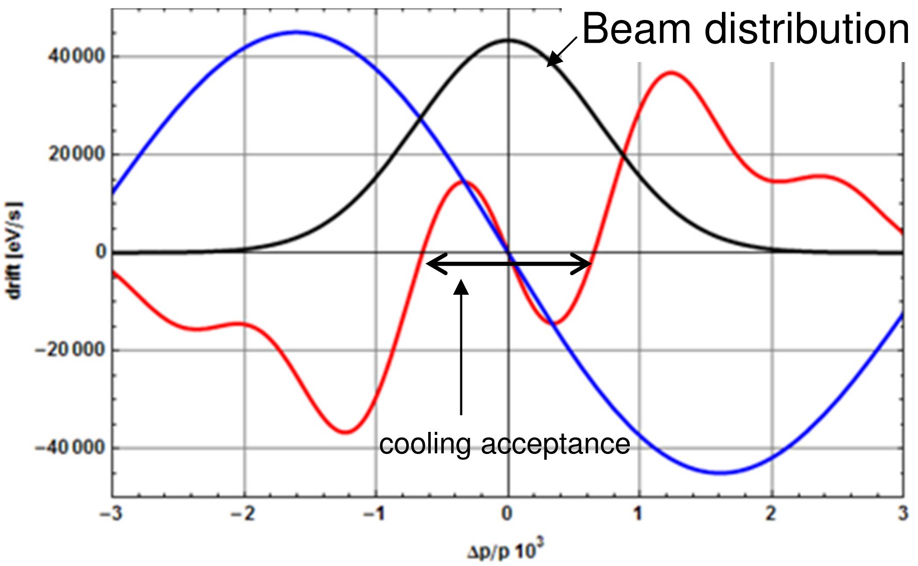
Bandwidth (2 - 4) GHz
Gain G_A = 100 dB
Equal additional delay

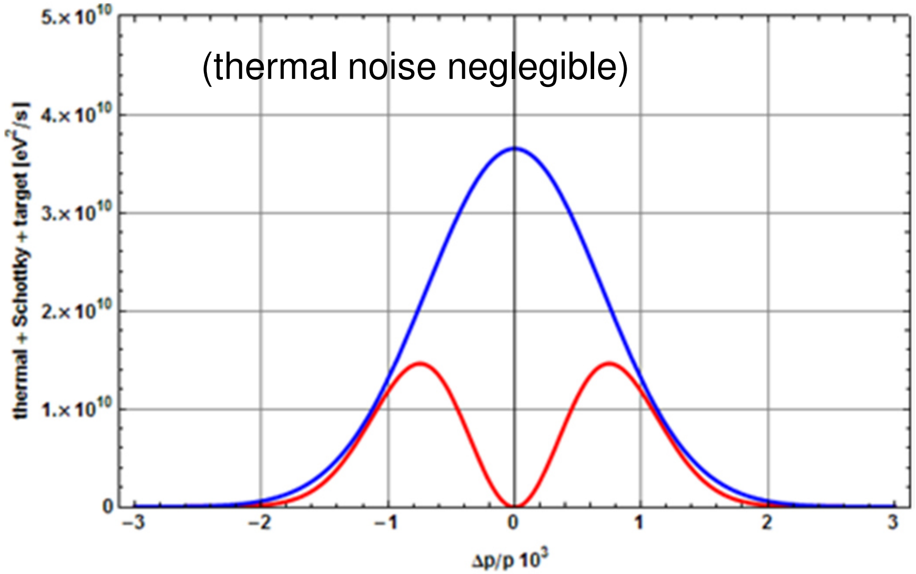
$$F(\delta,t) = h(\delta)\cdot G_A \cdot f_0 \cdot \delta$$

Filter: $D_{Schottky}(\delta,t) \propto G_A^2 \cdot \Psi(\delta,t)\cdot \delta^2$

TOF: $D_{Schottky}(\delta,t) \propto G_A^2 \cdot \Psi(\delta,t)$

TOF cooling: large cooling acceptance





shown at the beginning of cooling process

TOF
Filter
cooling

Comparison TOF and Filter Cooling

TOF *)

- mixing from PU to Ki necessary
- large cooling acceptance
- large bandwidth possible
- large Schottky noise heating terms require small gain
- beam equilibrium larger
- Sensitive to loop instabilities

Filter **)

- mixing from PU to Ki unwanted
- restriction in:
  bandwidth
  cooling acceptance
- filter suppresses Schottky particle and thermal noise
- small beam equilibrium

*) W. Kells, “Filterless Fast Momentum Cooling”, 11th Int. Conf. On High-Energy Accelerators, Geneva, July 7-11, 1980

**) D. Möhl et al., “Physics and Technique of Stochastic Cooling”, Phys. Rep. 85(2), 1980

Beam Feedback

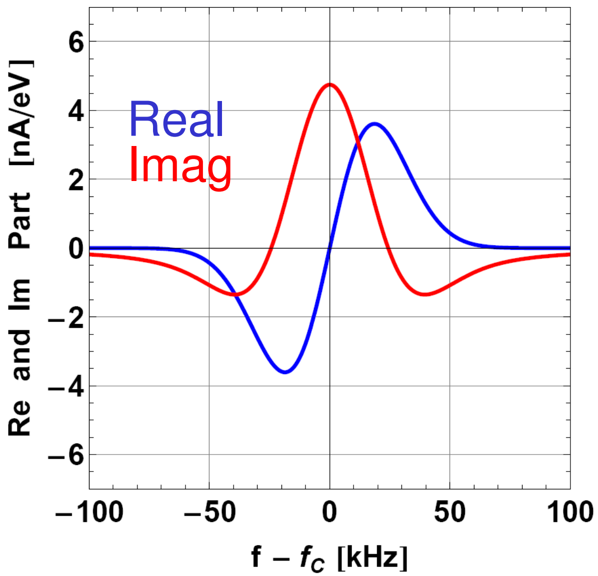
$$F(\omega) \propto Re(T(\omega)) \rightarrow Re\left(\frac{T(\omega)}{1-S(\omega)}\right)$$

$$D_{th}(\omega) \propto |T(\omega)|^2 \rightarrow \frac{D_{th}(\omega)}{|1-S(\omega)|^2}$$

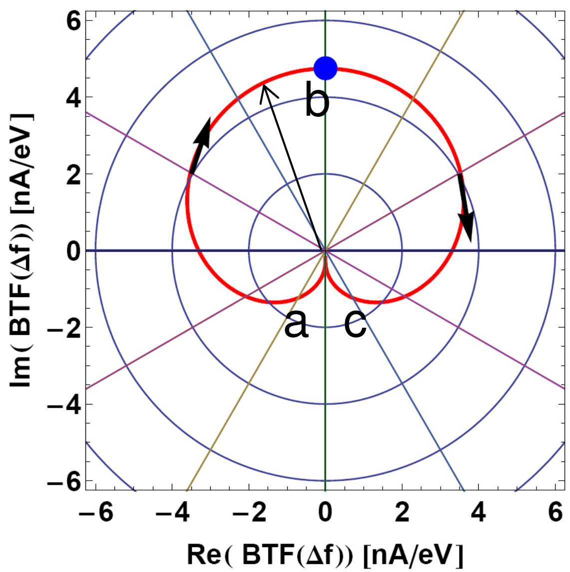
$$D_S(\omega) \propto |T(\omega)|^2 \rightarrow \frac{D_S(\omega)}{|1-S(\omega)|^2}$$

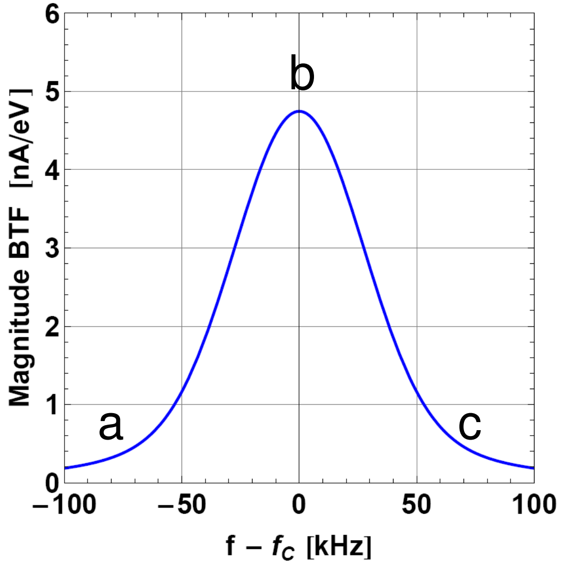
- **Open loop gain** ***S(ω)*** = BTF ***B(ω)*** x System ***T(ω)***
  S is a dimensionless quantity
- System transfer function: *T(ω)*
  - Includes models of PU and KI response, amplifiers, filters, phase shifter
- Closed loop gain $T_C(\omega) = \dfrac{T(\omega)}{1-S(\omega)}$
- Feedback loop stability: **critical point S = (1, j0)**

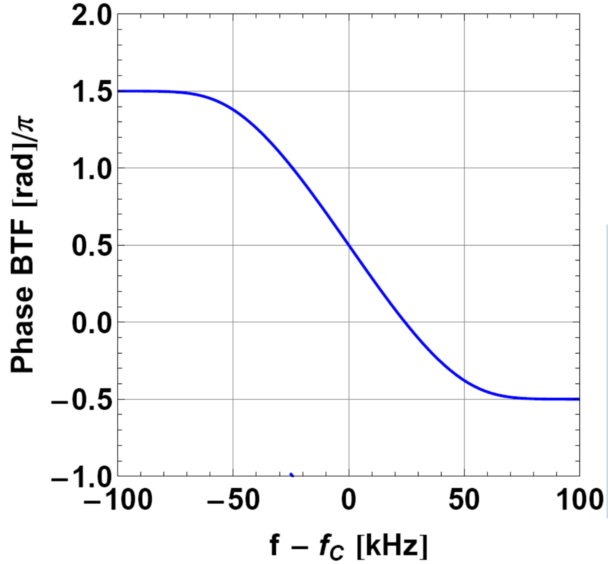
Beam Transfer Function (BTF) Simulation



Nyquist Plot:







- The BTF describes the current modulation ΔI observed at the PU due to the energy change ΔE induced by the KI
- Nyquist plot: Radius of the loop
  - $\propto 1/(\Delta p/p)$
  - $\propto 1/\eta$
  - $\propto N$
  - $\propto 1/n$

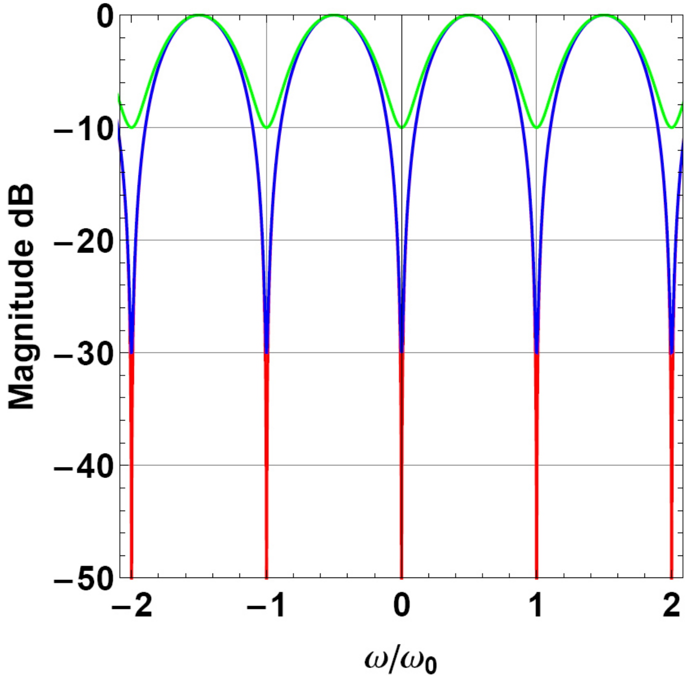
Example for HESR 3.8 GeV/c:

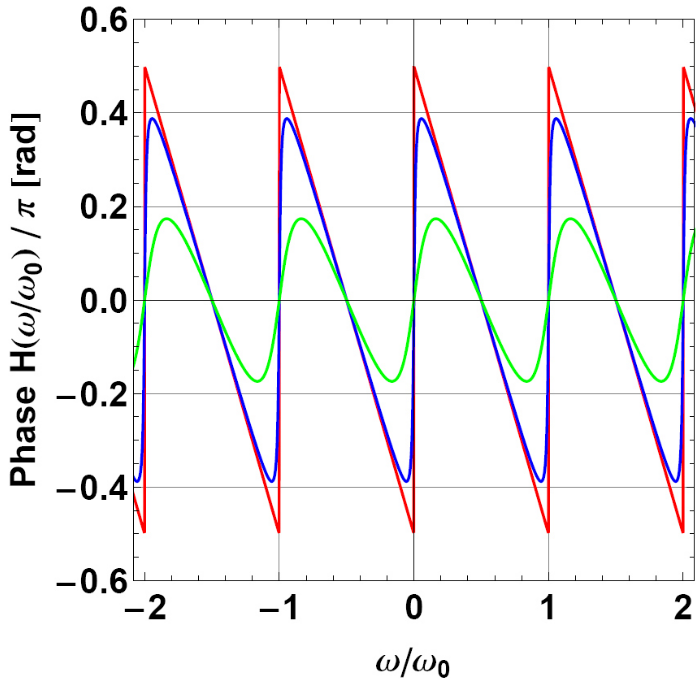
N = 10^{10} antiprotons
η = 0.03 ($\gamma < \gamma_{tr}$)
$\delta_{rms} = 2 \cdot 10^{-4}$
Harmonic number n = 5927

Notch Filter Response

$$H(\omega) = \frac{1}{1+a}\left\{1 - a \cdot e^{-i2\pi\omega/\omega_0}\right\}$$

$$0 \le a \le 1$$





- Notch depth: $D_{dB} = 20\log\frac{1-a}{1+a}$

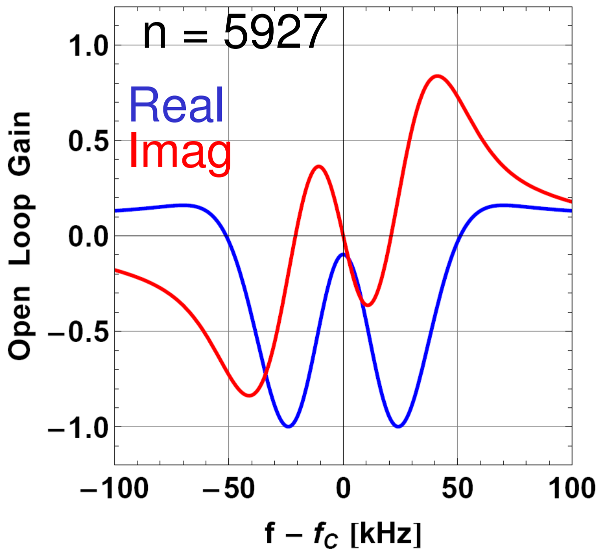
Red: infinite notch depth
Blue: -30 dB
Green: -10 dB

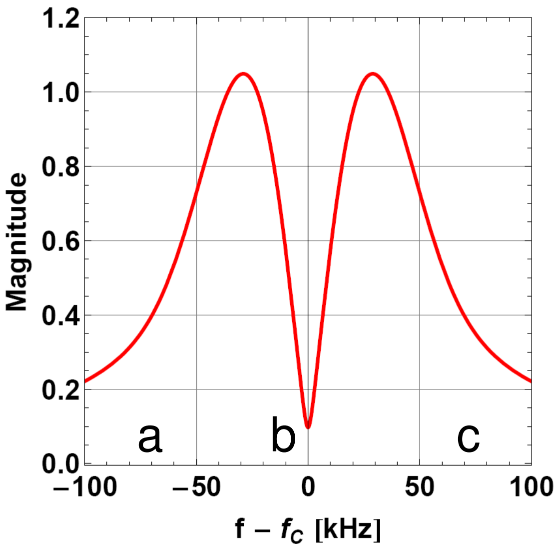
Open Loop Gain Filter Cooling

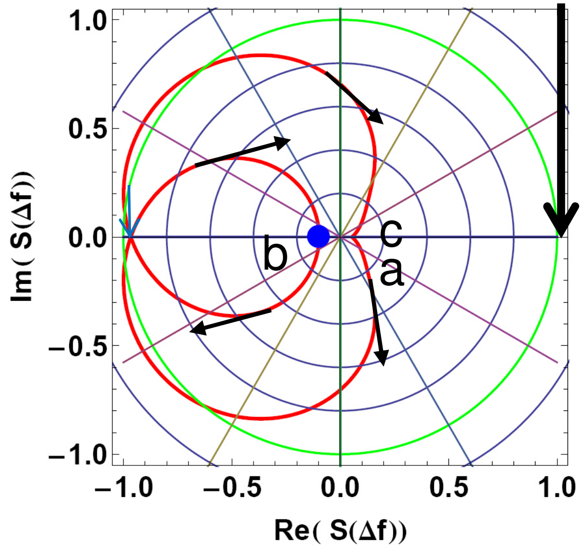
Example HESR

- Delay adjusted to the reference particle travelling time from PU to KI
- Any phase error will be visible as a rotation and deformation of the Nyquist diagram

critical point (1,0j)





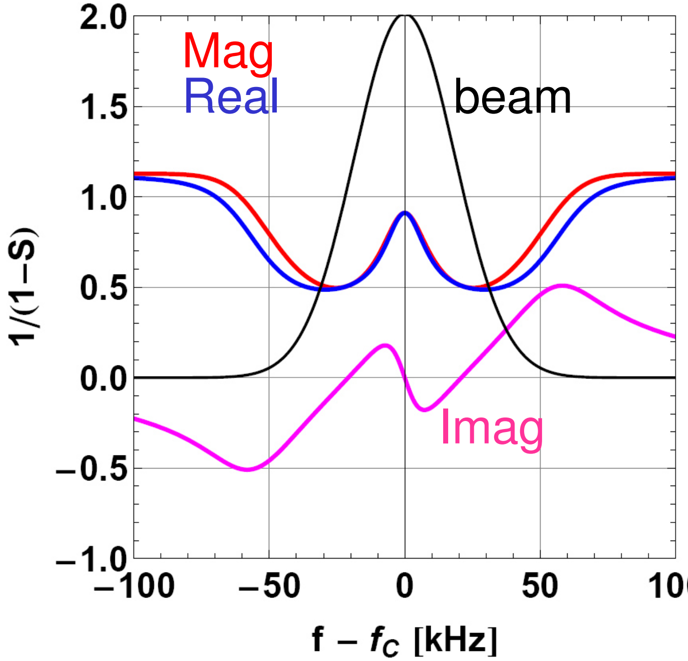


- Optimal gain and phase 180^0 for filter cooling: S = -1 (not over the whole bandwidth possible)
- **Loop unstable if |S(ω)| = 1 and arg(S(ω) = 0^0**
- Gain 122 dB notch depth -40 dB

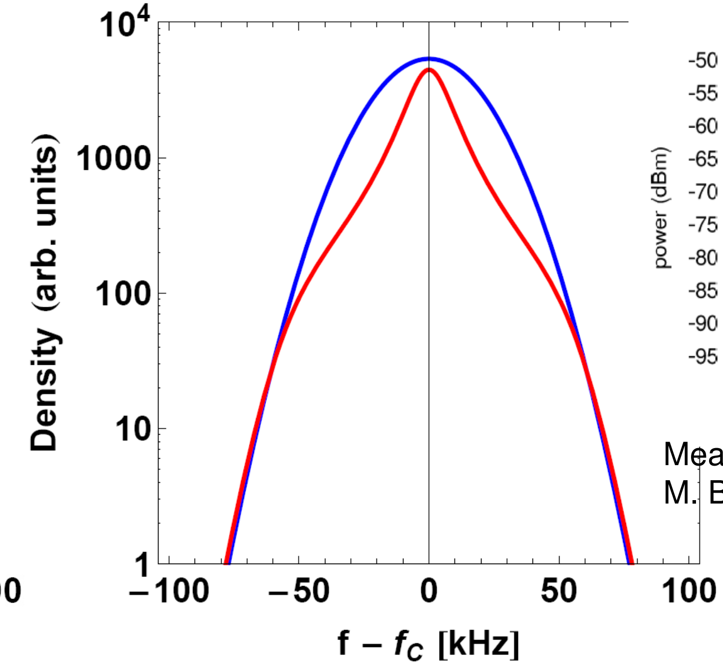
Arrows:
direction of increasing frequency:
a $\rightarrow$ b $\rightarrow$ c

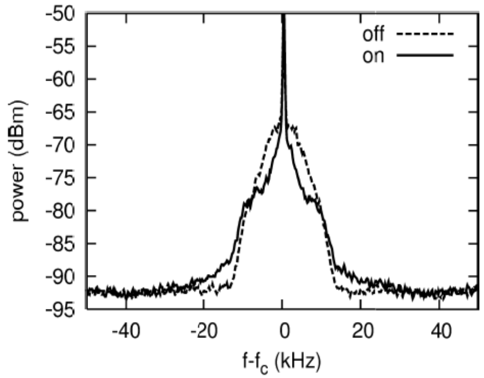
Signal Suppression Filter Cooling

Example HESR n = 5927



Beam distribution:
Cooling loop open and closed





Measurement*):
M. Blaskiewicz and J. M. Brennan

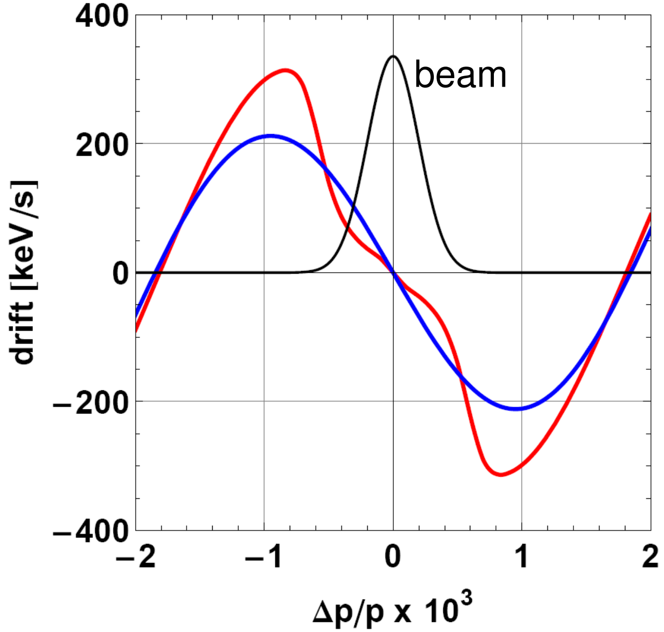
- For optimal gain and phase 180^0: S = -1
- Not possible over the whole bandwidth for constant electronic gain
- Measurement signal suppression: see RHIC*)

*) M. Blaskiewicz and J. M. Brennan, Phys. Rev. ST Accel. Beam 10, 061001 (2007).

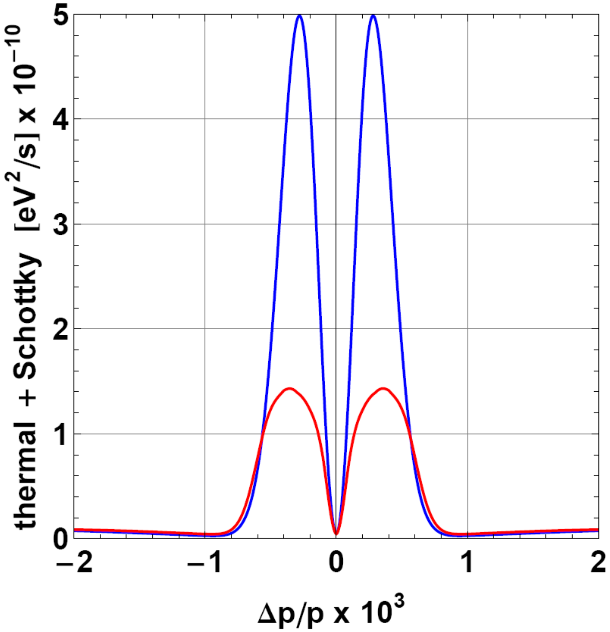
Drift and Diffusion Term Filter Cooling Including Beam Feedback

Blue curves: without beam feedback

Drift:



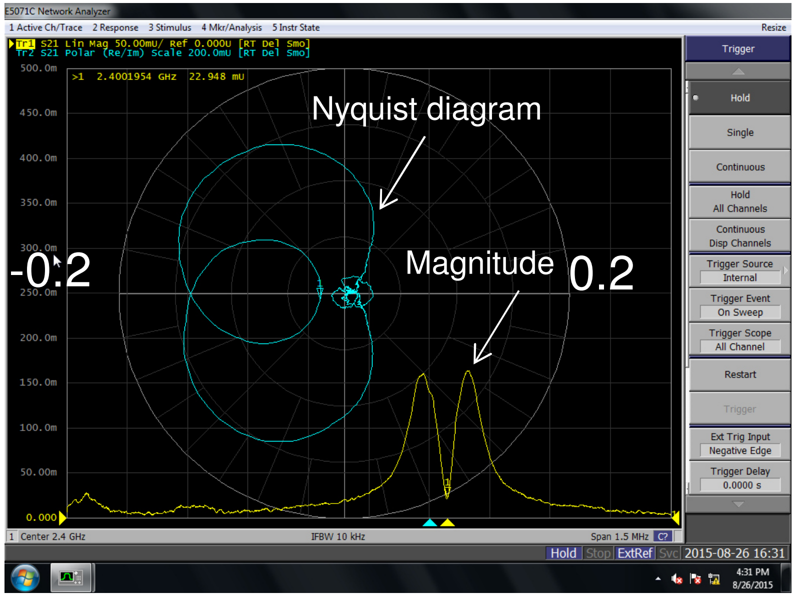
Diffusion:

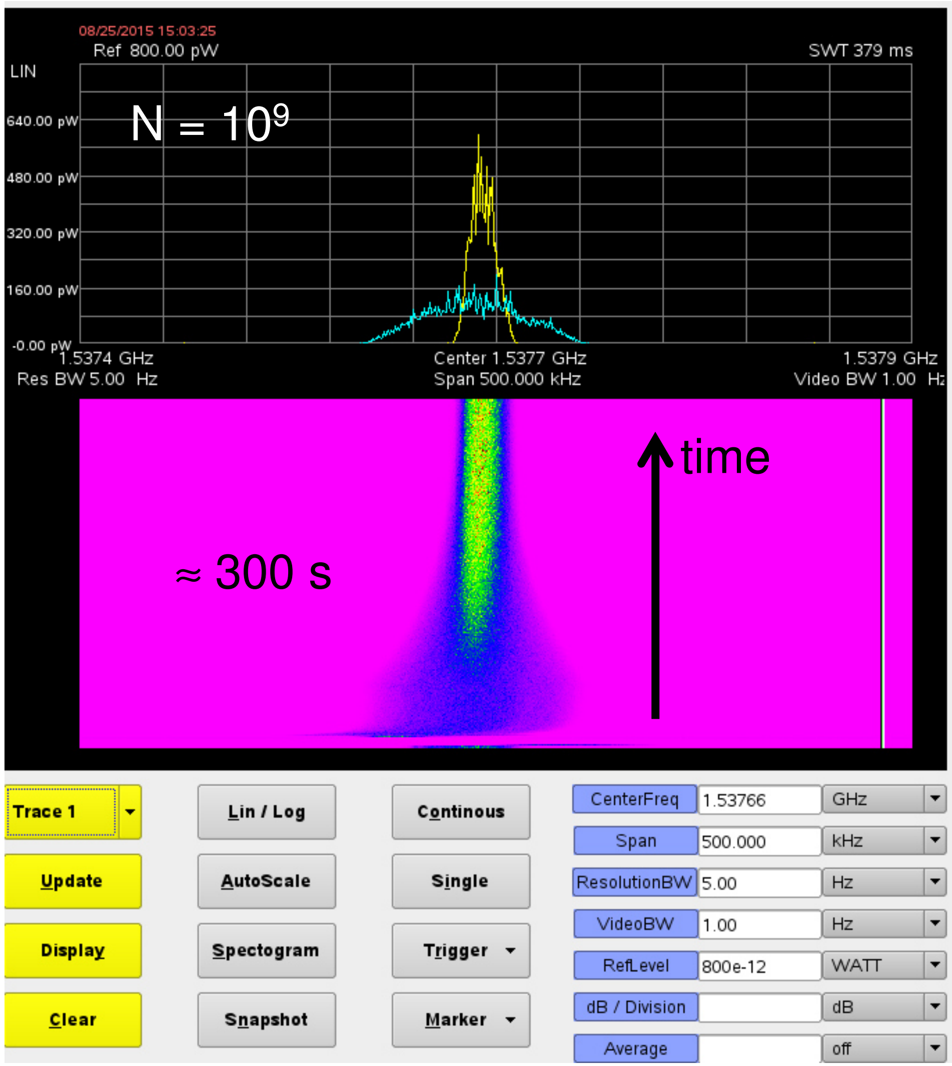


- Cooling force slightly reduced in the tails of the beam
- But: Thermal and Schottky particle noise suppressed

Open Loop Measurement Filter Cooling at COSY

Nyquist Plot (blue curve):

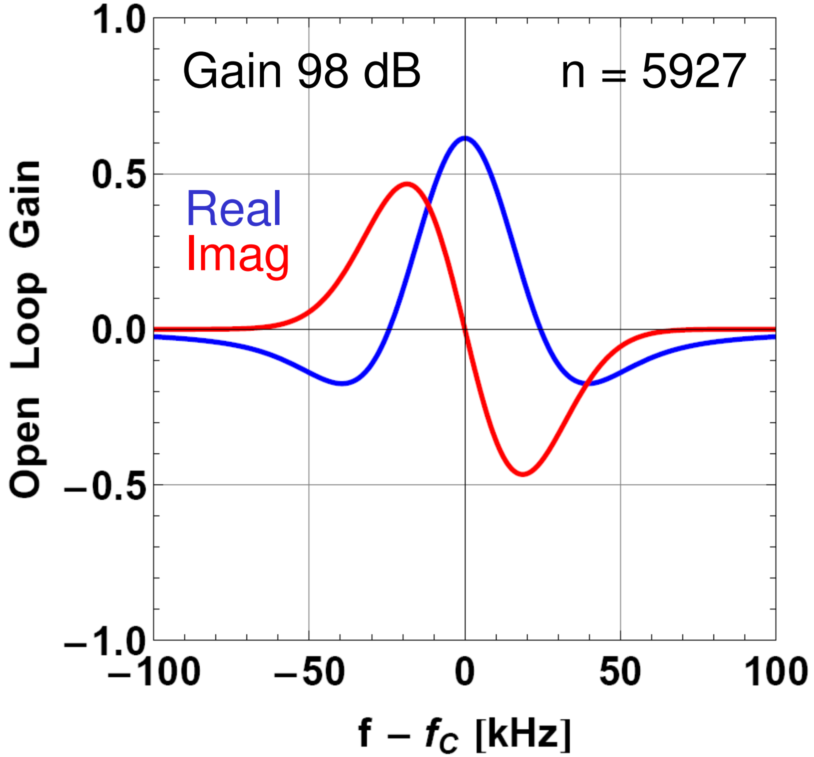


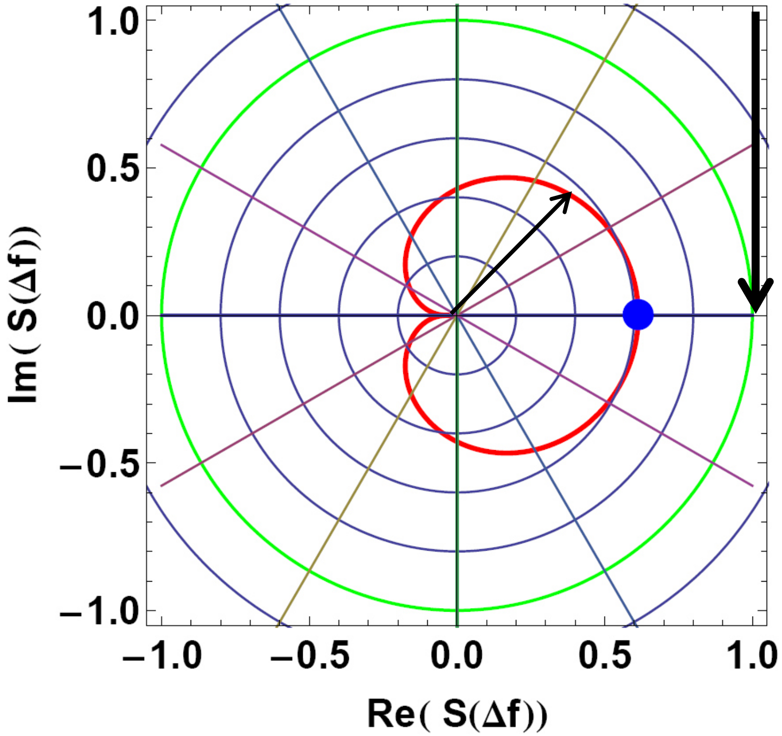


- Filter cooling at 2.425 GeV/c
- (1.8 – 3) GHz
- System unstable if open loop gain encircles point (1,j0)

Completely different: Open Loop Gain TOF Cooling

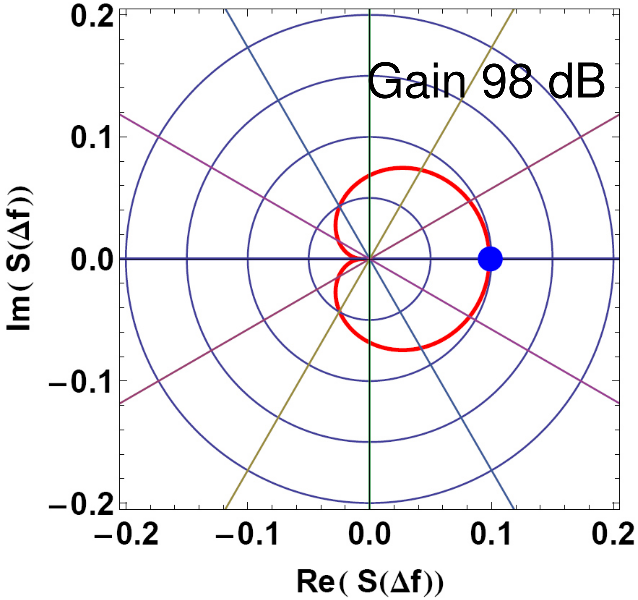
critical point (1,0j)



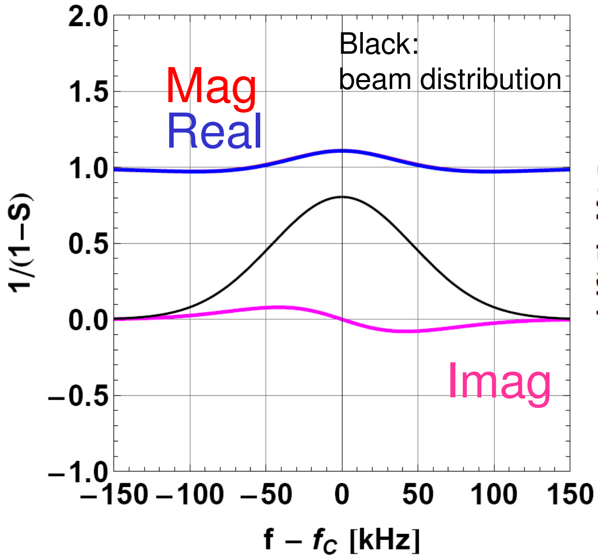


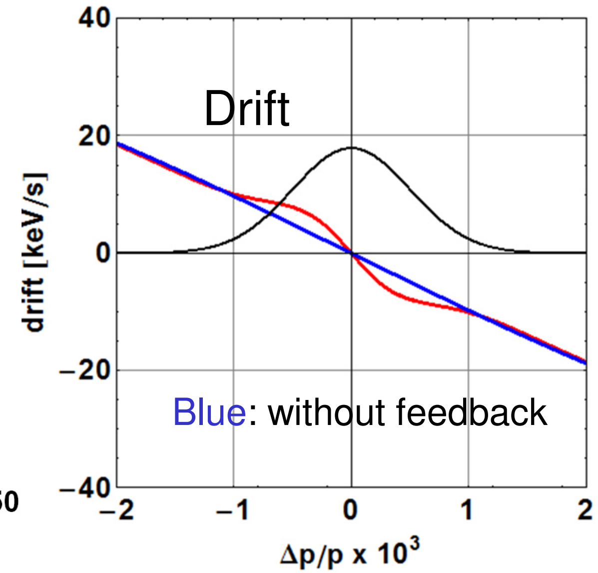
- **Phase** for cooling in the center of the distribution **zero degree**
- During cooling loop may become unstable (blue point moves to critical point!)

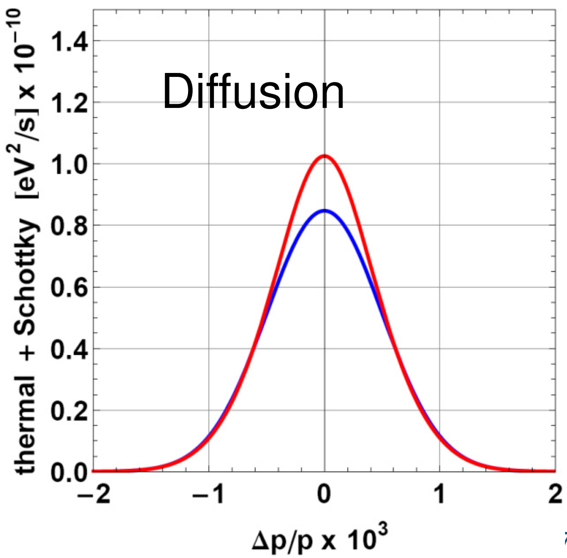
TOF Cooling (3)



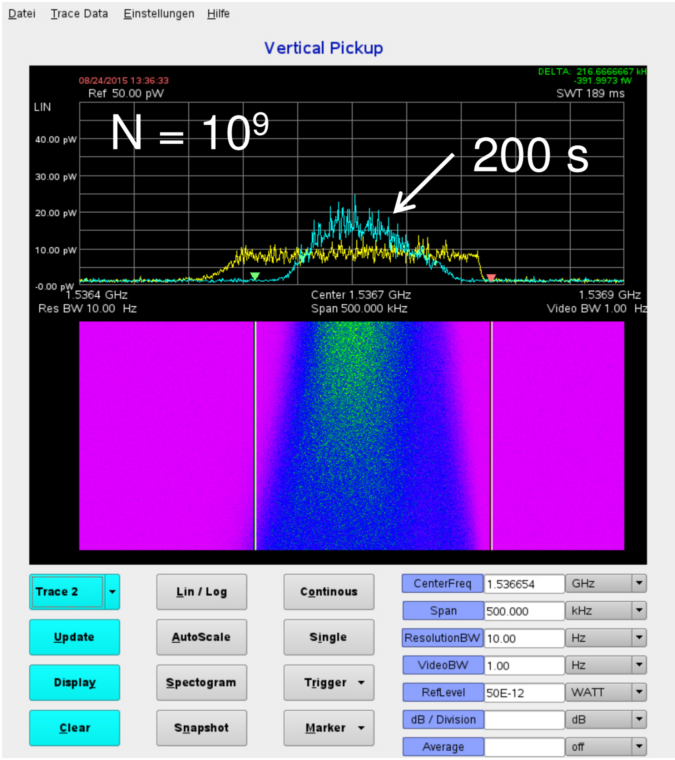
- Initial rel. momentum spread increased to $5 \cdot 10^{-4}$
- Gain unchanged 98 dB
- Larger stability margin
- Almost no effect on drift term
- ***TOF cooling works best with large initial momentum spread***

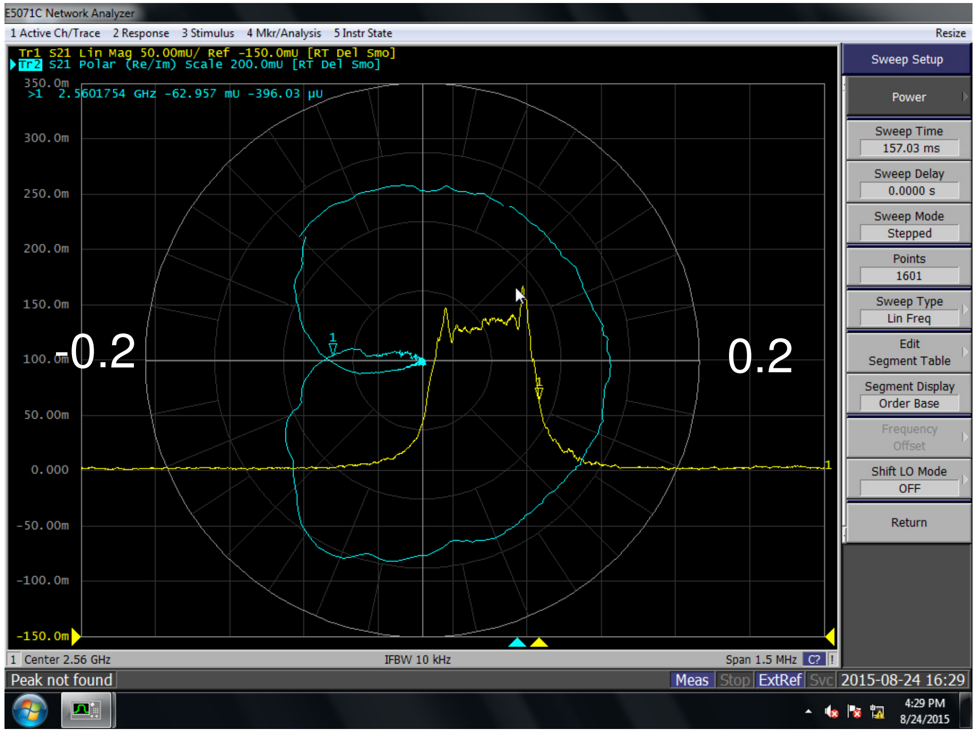






TOF Proton Cooling at 2.6 GeV/c



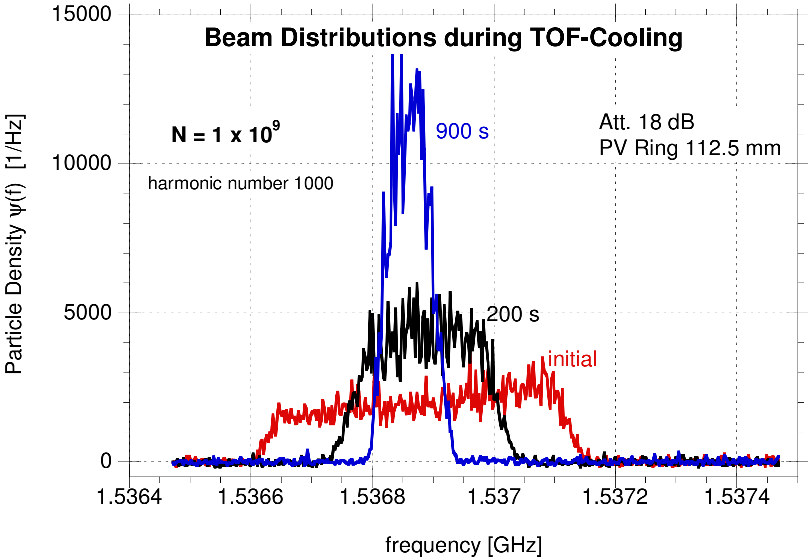


Nyquist diagram **before** shaping and cooling
Open loop phase adjusted

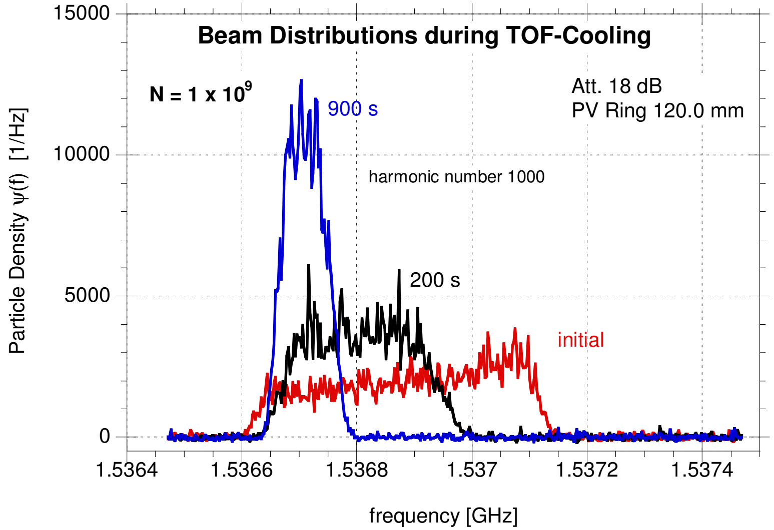
- The beam is initially heated to increase the rel. momentum spread to $1 \cdot 10^{-3}$
- The loop is stable, Re(S) < 1

TOF Proton Cooling at 2.6 GeV/c ($\gamma > \gamma_{tr}$)

Delay: adjusted

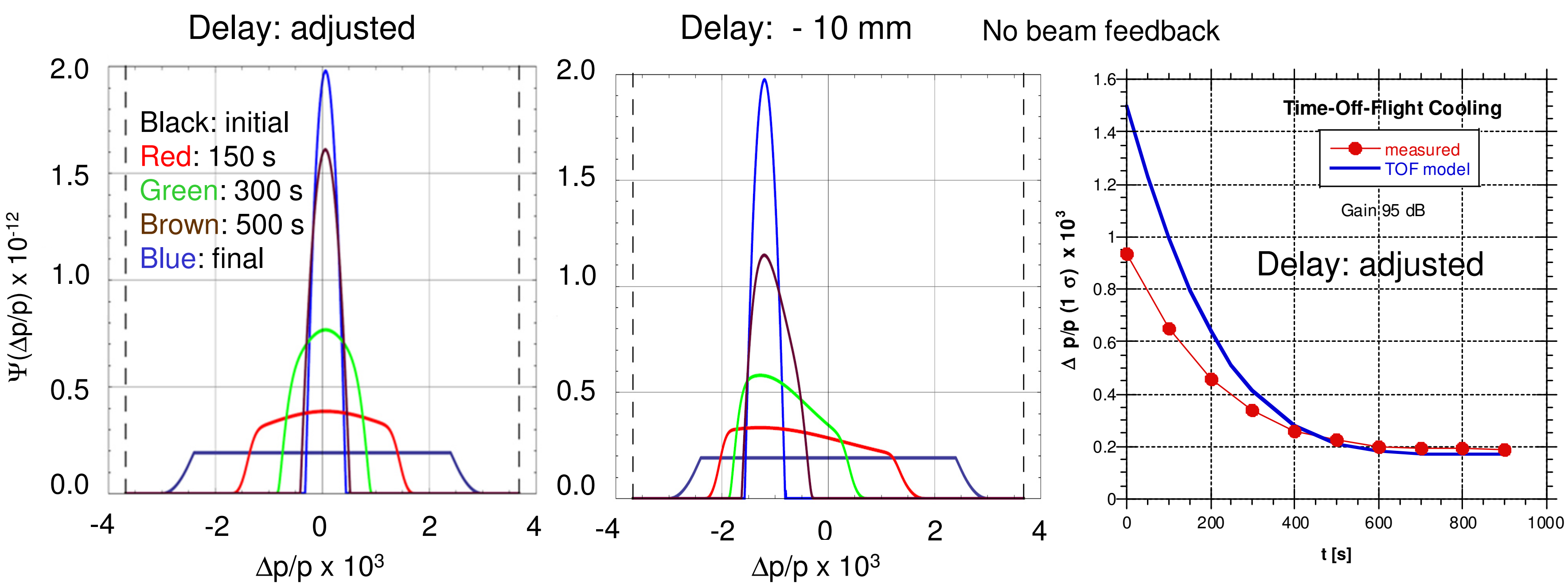


Delay: + 7.5 mm



- Initial momentum spread heated to $\Delta p/p \approx 1 \cdot 10^{-3}$ (rms)
- Center frequency moves towards an equilibrium value during cooling that depends on the delay setting

Simulation Results for TOF Cooling at COSY



- Beam equilibrium independent from initial value
- Model predicts the same equilibrium value as measured

Summary of TOF Cooling (1)

- TOF cooling is available if Filter cooling is already installed
- No additional costs
- TOF cooling works best when momentum spread is large
  - Momentum cooling acceptance is larger than for Filter cooling
- Pre-cooling with TOF and then switching to Filter cooling is easily established without particle losses.
- TOF cooling technique is essential in the HESR when the initial momentum spread is large.

Summary of TOF Cooling (2)

- The filterless momentum cooling technique (TOF cooling) has been invented by W. Kells (Fermilab) 1980 in time domain*).
- The TOF cooling technique has been experimentally verified for the first time at COSY**).
- A mathematical description of TOF cooling is formulated in frequency domain and the results are compared with the filter method***).

*) W. Kells, "Filterless Fast Momentum Cooling", 11th Int. Conf. On High-Energy Accelerators, Geneva, July 7-11, 1980

W. Kells, "A New Approach to Stochastic Momentum Cooling", Fermilab TM-942, January 1980

**) F. Caspers and D. Möhl, "History of stochastic beam cooling and its application in many different projects", Eur.Phys.J. H36 (2012) 601-632

***) H. Stockhorst, T. Katayama and R. Maier, "Beam Cooling at COSY and HESR - Theory and Simulation", to be published

Heavy Ion Mode

- Injection of a $^{238}U^{92+}$ beam from CR into HESR
  - Beam preparation at 740 MeV/u
  - Mean energy loss compensation with Barrier Bucket (BB) cavity
  - ***TOF*** Stochastic cooling with internal hydrogen target

- Injection of a $^{238}U^{92+}$ beam from CR into HESR
  - Capture and acceleration to 4.5 GeV/u
  - Beam preparation at 4.5 GeV/u
  - ***Filter*** Stochastic cooling with internal hydrogen target and BB operation

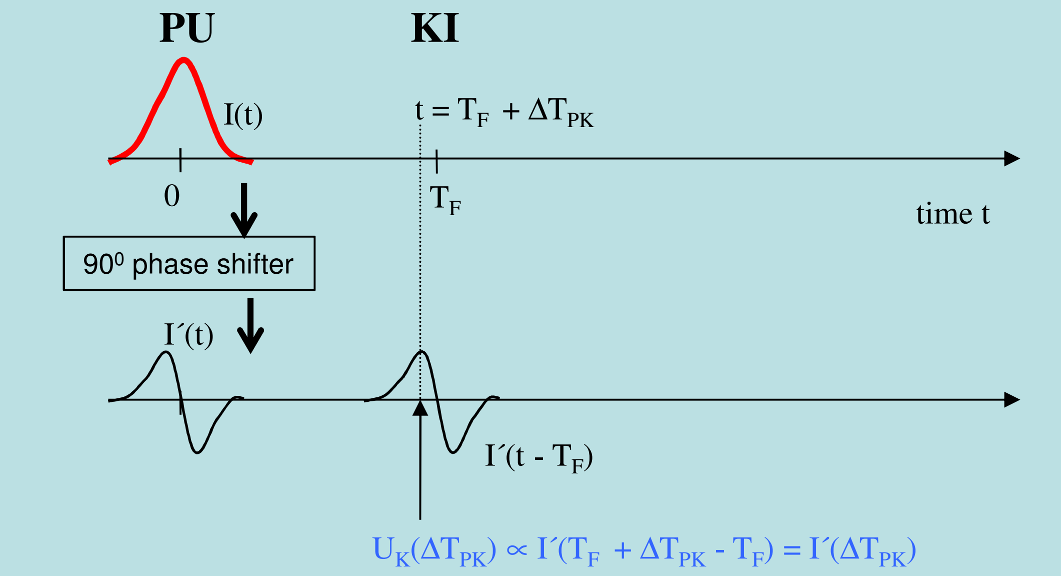
Target thickness: $N_T = 4 \cdot 10^{15}$ cm^{-2}

Thank you for your attention

Time-Of-Flight (TOF) Momentum Cooling ($\eta_{PK} \neq 0$)

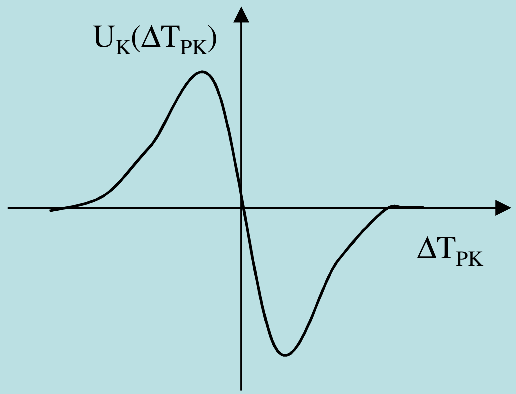
Simplified illustration:

Delay adjusted for reference particle



Coherent kick voltage: $U_K(\Delta T_{PK}) \propto I'(\Delta T_{PK})$

Coherent kicker voltage:



- cooling for $\eta_{PK} < 0$ $(\gamma > \gamma_{tr})$
- for $\eta_{PK} > 0$ $(\gamma < \gamma_{tr})$: reverse amplifier gain

- For $\gamma < \gamma_{tr}$ additional phase shift 180^0 necessary: total system 270^0 or **-90^0**

Beam Transfer Function (BTF)

$$B(\Omega)=\frac{\Delta I(\Omega)}{Ze/A\cdot U(\Omega)}=\frac{\textit{current modulation at the PU}}{\textit{energy change at the KI}}$$

- Well separated revolution bands at harmonic n:

$$B(\Omega)=-N\frac{Ze}{2}\left(\frac{\kappa\omega_0}{2\pi E}\right)\frac{\omega_0^2}{|n|}e^{i\Omega T_F}\left\{\underbrace{\frac{\partial}{\partial\omega}\Psi_0\left(\frac{\Omega}{n}\right)}_{\text{Real part: asymmetric}}-\underbrace{sign(n)\frac{i}{\pi}P\int\frac{\frac{\partial}{\partial\omega}\Psi_0(\omega)}{\Omega/n-\omega}d\omega}_{\text{Imaginary part: symmetric}}\right\}$$

- Sign of the BTF different for $\gamma < \gamma_{tr}$ or $\gamma > \gamma_{tr}$ $\rightarrow$ $\kappa=\eta/\beta^2$, $\eta=1/\gamma^2-1/\gamma_{tr}^2$

Particle frequency distribution: $\int\Psi_0(\omega)d\omega=1$

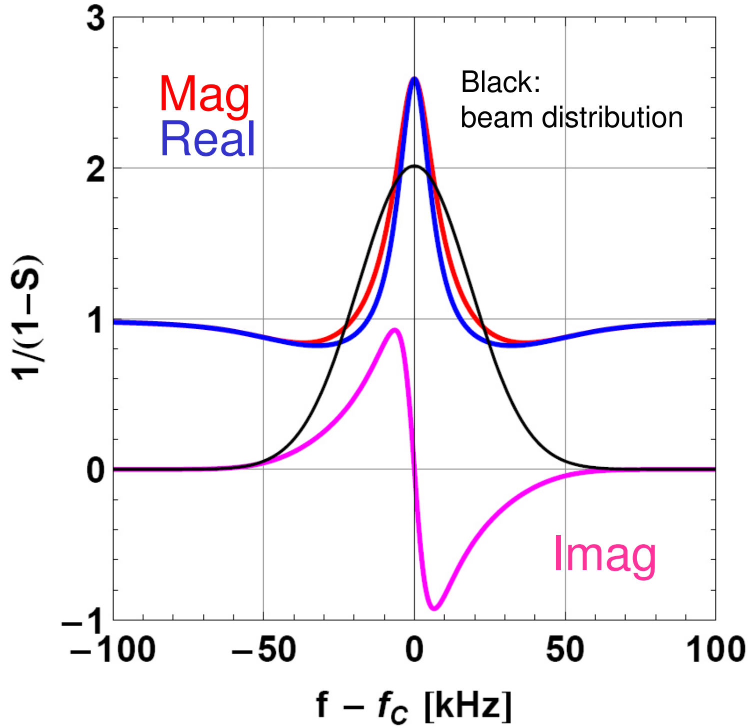
E: Total beam energy per nucleon, N: particle number
Ze: ion charge T_F: particle transit time PU to KI
ω_0: nominal angular revolution frequency

$$\kappa=\eta/\beta^2$$

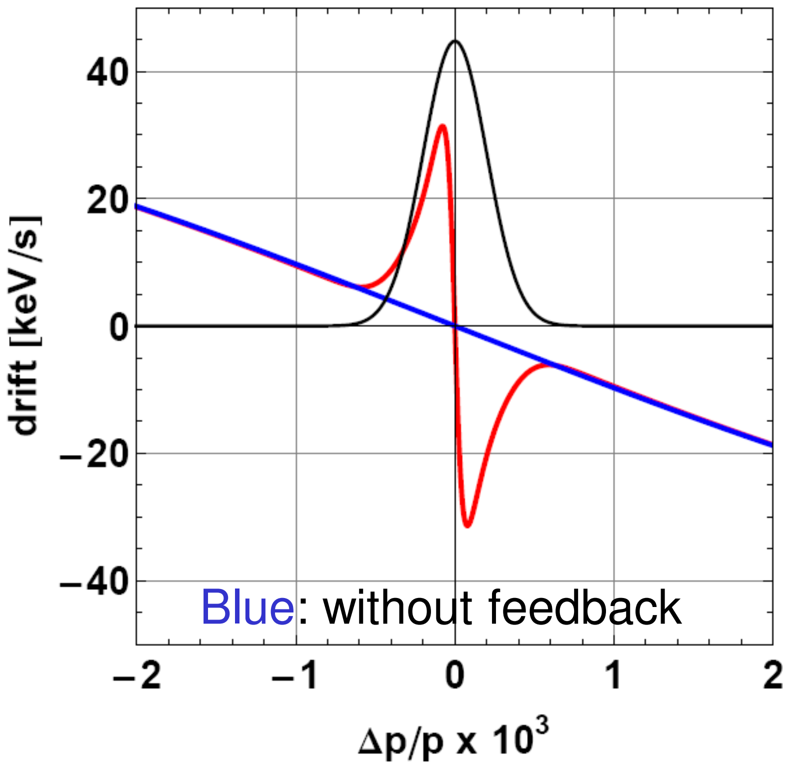
$$\eta=1/\gamma^2-1/\gamma_{tr}^2$$

TOF Cooling (2)

Signal Enhancement:



Drift:



- Loop close to instability
- Drift terms strongly enhanced with feedback