Stochastic Cooling for the HESR at FAIR

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COOL 07
Bad Kreuznach, Germany
September 10-14, 2007

- HESR Operation Modes and Beam Parameters
- Stochastic Momentum Cooling Model Predictions
- Experimental Test of Model Predictions at COSY
- Summary and Outlook

Forschungszentrum Jülich
In der Helmholtz-Gemeinschaft

Operation Modes for the HESR

- ***High Resolution Mode (HR)***

  Luminosity $L = 2 \cdot 10^{31}\ cm^{-2}\ s^{-1}$

  Number of Anti-Protons $N = 10^{10}$

  Target Area Density $N_T = 4 \cdot 10^{15}$ atoms/cm^2

  - **momentum range: 1.5 GeV/c up to 9 GeV/c**
  - **desired relative rms-momentum spread: $< 4 \times 10^{-5}$**

- ***High Luminosity Mode (HL)***

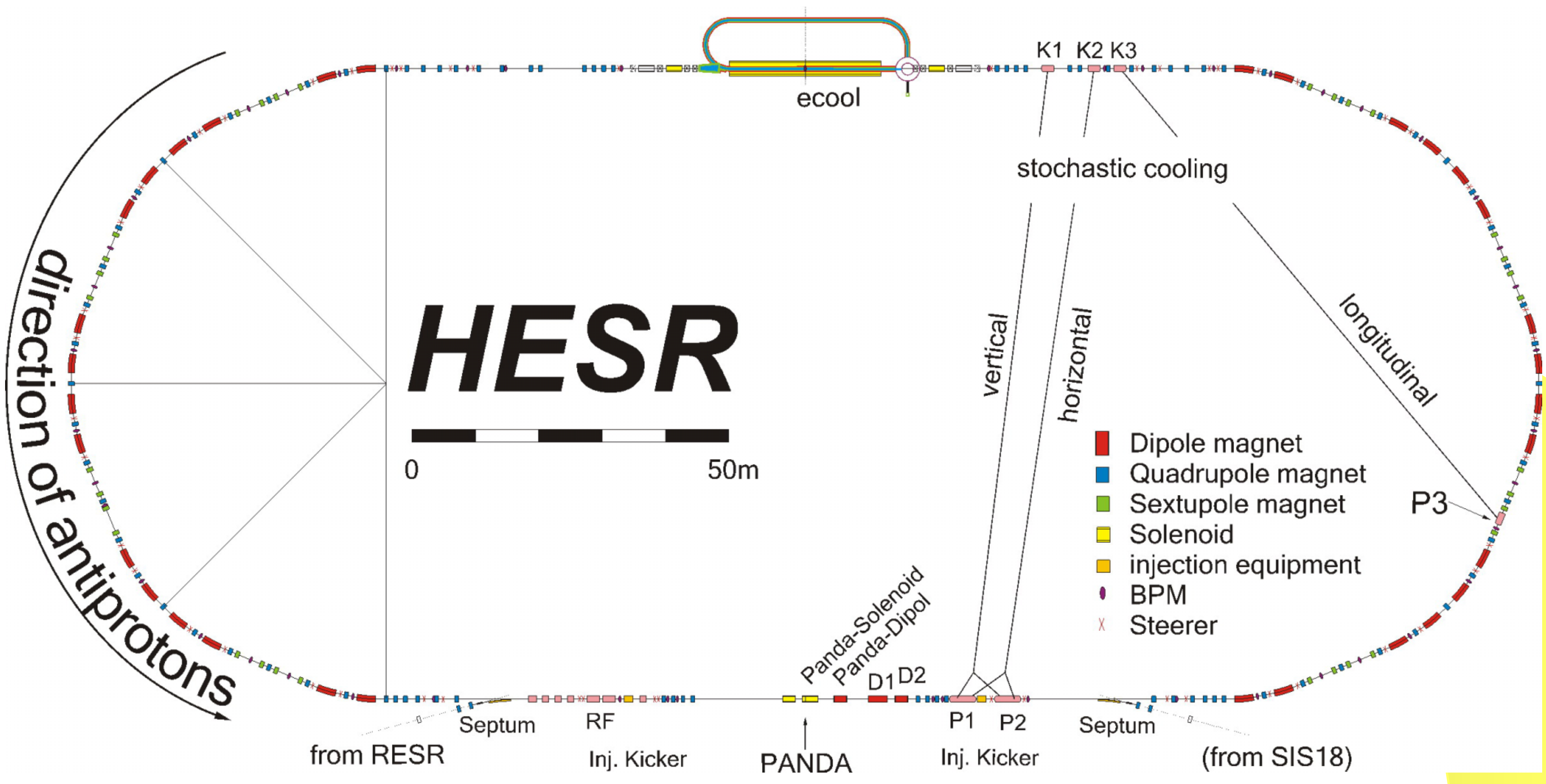
  Luminosity $L = 2 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

  Number of Anti-Protons $N = 10^{11}$

  Target Area Density $N_T = 4 \cdot 10^{15}$ atoms/cm^2

  - **momentum range: 1.5 GeV/c up to 15 GeV/c**
  - **desired relative rms-momentum spread: 1×10^{-4}**
  - **compensate target-beam heating**

Ring Layout and Cooling Signal Paths



Basic HESR Data 1

- Superconducting lattice with γ_{tr} = 6.0 i
- Circumference 574 m (half arc: 155 m, straight 132 m)
- Momentum (energy) range:

  1.5 GeV/c to 15 GeV/c (0.8 GeV to 14 GeV)
- Injection of anti-protons from the RESR at 3.8 GeV/c
- Acceleration rate 0.1 (GeV/c)/s
- Electron cooling up to 8.9 GeV/c
- Stochastic cooling above 3.8 GeV/c

Basic HESR Data 2

- ***The initial beam parameters depend on the particle number N:***

- at T = 3 GeV:

- transverse emittance:

$$\varepsilon_{rms}(N, 3GeV) = \frac{1\,mm\,mrad}{\beta_0\gamma_0}\left(\frac{N}{N_0}\right)^{4/5}$$

- rms-relative momentum spread:

$$\delta_{rms}(N, 3GeV) = \frac{10^{-3}}{\beta_0\gamma_0}\left(\frac{N}{N_0}\right)^{2/5}$$

- acceleration to experiment energy:

$$\varepsilon_{rms} = \frac{\varepsilon_{rms}(N, 3\,GeV)\beta_0\gamma_0}{\beta\gamma}$$

$$\delta_{rms} = \delta_{rms}(N, 3GeV)\cdot\frac{\beta_0\gamma_0}{\beta\gamma}\left[\frac{\eta_0}{\gamma_0}\cdot\frac{\gamma}{\eta}\right]^{1/4}$$

$$N_0 = 3.5\cdot 10^{10}$$

Cooling System Parameters

- Transverse emittance and momentum cooling systems
- Bandwith: (2 – 4) GHz
- New design of pickup and kicker structures with *high sensitivity*:
  - printed loop couplers for transverse cooling
  - ring slot couplers for momentum cooling
  - diameter ≈ 90 mm

➔ POSTER
R. Stassen: THAP13

- Low noise amplifier MITEQ
- Optical Notch Filter for momentum cooling
  - *Advantage: Filter and system delay can be adjusted for optimum cooling conditions with internal target.*
- Filter momentum cooling above T = 3 GeV

The Momentum Cooling Model

Fokker-Planck Equation for the beam distribution $\psi(x,t)$:

$$\frac{\partial}{\partial t}\Psi(x,t) = -\frac{\partial}{\partial x}\left[F(x,t)\Psi(x,t) - D(x,t)\frac{\partial}{\partial x}\Psi(x,t)\right] \quad ^{\star)}$$

- The **hardware components** (PU, KI, amps etc.) and the **Non-Linear Notch Filter** of the cooling system are included and determine:
  - the ***drift term F(x,t)*** (cooling/heating)
  - the ***diffusion term D(x,t)*** (always heating)
- **Lattice properties are included.**
- **Mixing included.**
- ***Beam-target interaction is included.***
- **Numerical solution with initial and boundary condition**

★) D. Möhl, G. Petrucci, L. Thorndahl and S. van der Meer, Phys. Rep. 85(2), 1980

Beam-Target Interaction *)

- ***Restricted Energy Loss Straggling:***

  - mean energy loss ε in the target:

  shift of the momentum distribution towards lower momenta

  - longitudinal emittance growth for a DC beam:

$$\frac{d\delta_{rms}^2}{dt} = f_0 \delta_{loss}^2$$

with the mean square relative momentum deviation per target traversal δ_{loss}^2.

ε and $\delta_{loss}^2 \propto$ target density

*) F. Hinterberger, Beam-Target Interaction and Intrabeam Scattering in the HESR, Jül-4206

Stochastic Cooling and Internal Target 1

- **Additional drift term when target is ON:**

$$f_0 \cdot \varepsilon$$

with *mean energy loss* ε *per turn* (Hinterberger, Prasuhn)

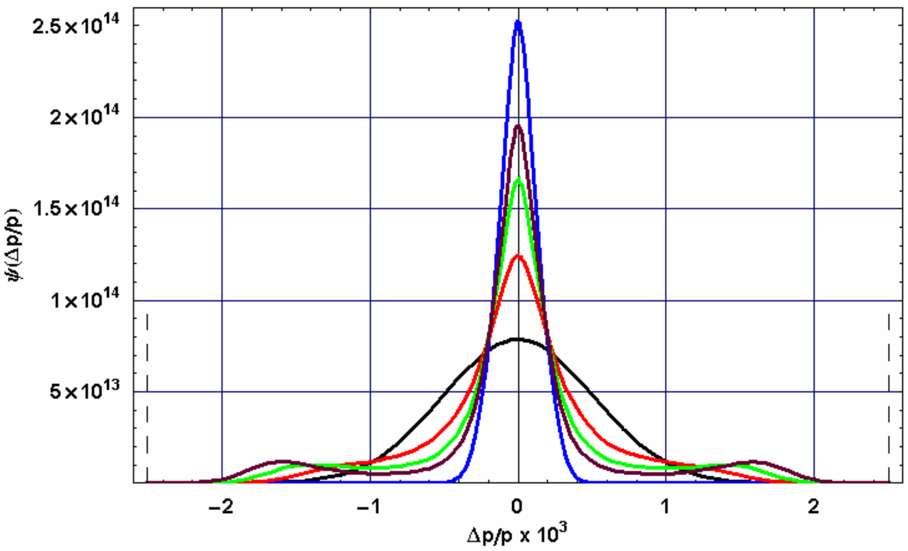
- **Diffusion term:**
  - Sum of amplified and filtered Schottky and thermal noise
  - **With target ON:**

$$D_T = f_0 \cdot \delta_{loss}^2$$

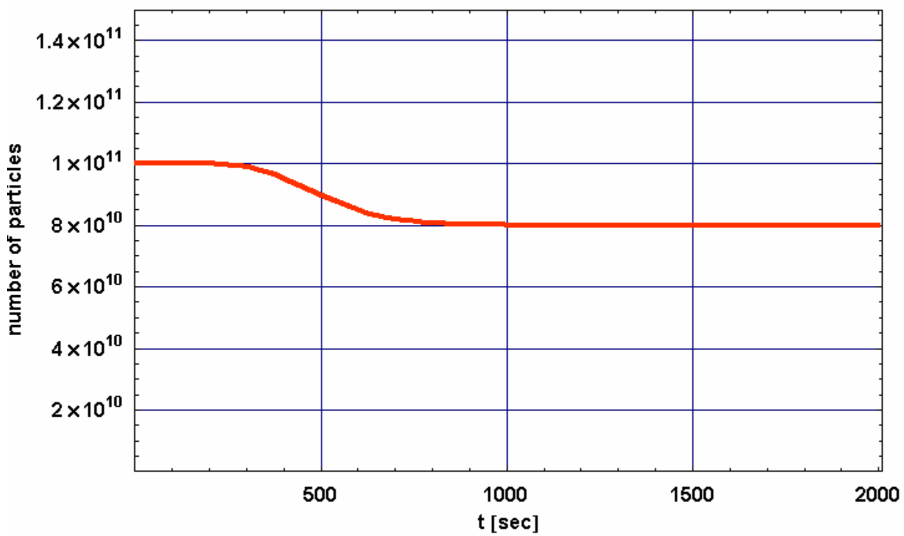
mean square relative momentum deviation per target traversal

Momentum Cooling Predictions for the HESR 1

- ***High Luminosity Mode at T = 3 GeV (worst case)***



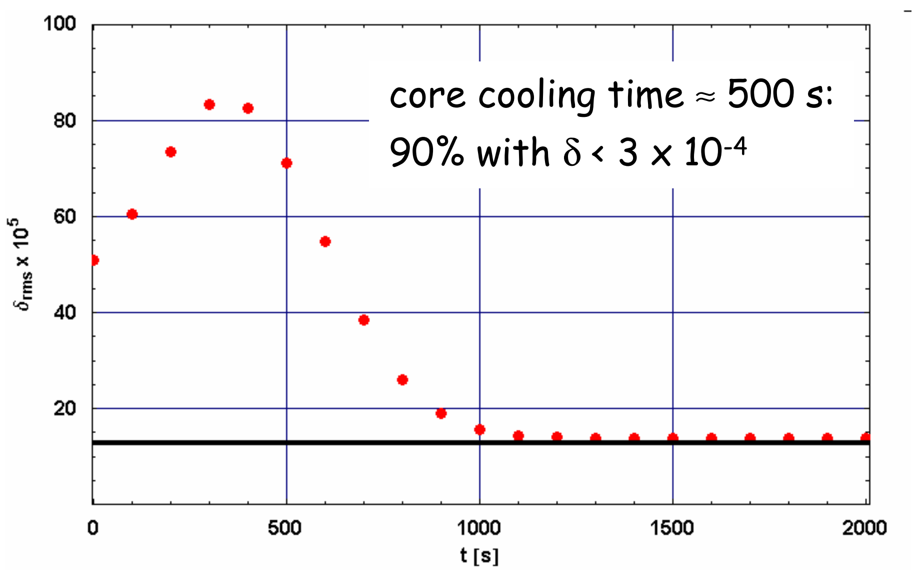
Beam distributions for t = 0s (black), 50s, 100s, 150s, 2000s (blue)

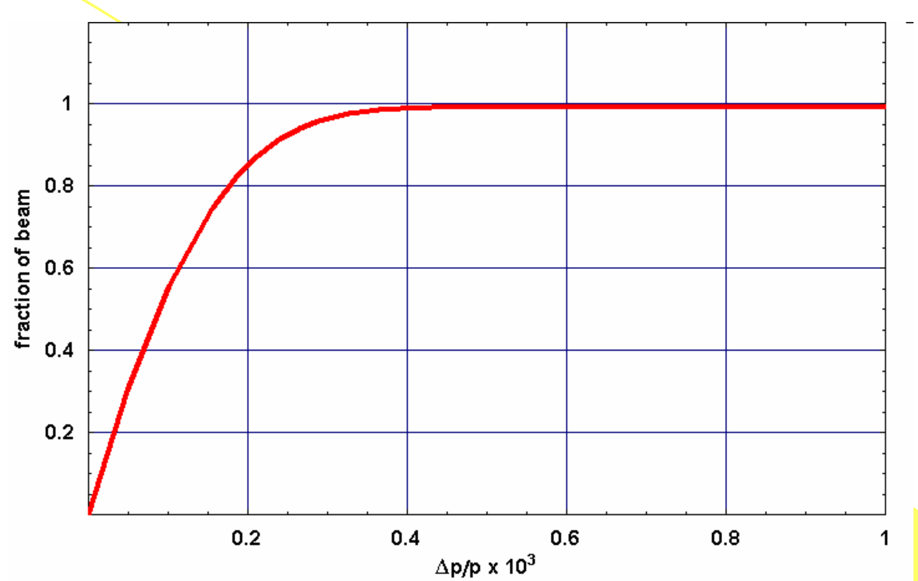


Particle losses 20% due to the undesired mixing from Pu to Ki.

✷ **assumption: mean energy loss is compensated**

Momentum Cooling Predictions for the HESR 2





- Increase in rms-relative momentum spread due to particles which move towards the acceptance limit $\pm 2.5 \cdot 10^{-3}$.
- Final stable momentum spread described by

$$\delta_{eq,rms} = \frac{4}{5}\left(\frac{3}{16}\cdot\frac{N\,f_0^2}{|\eta|Wf_C}\delta_{loss}^2\right)^{1/3}$$

- Fraction of beam particles in the final distribution with a momentum spread less than a given value.

$$\delta_{eq,rms} = 1.3\cdot 10^{-4}$$

95% with less than:

$$2\cdot\delta_{eq,rms} = 2.6\cdot 10^{-4}$$

Stochastic Cooling Predictions for the HESR

- Above $T \approx 4$ GeV no particle losses in the HL-Mode
- No losses in the HR-Mode

HR-Mode:

p [GeV/c]:	**3.8**	**8.9**	**14.9**
rms rel. momentum spread δ_{rms}:	$7 \cdot 10^{-5}$	$6 \cdot 10^{-5}$	$5 \cdot 10^{-5}$
rms transverse emittance ε_{rms} [mm mrad]:	$2 \cdot 10^{-2}$	$7 \cdot 10^{-3}$	$4 \cdot 10^{-3}$
cooling down time [s]:	≈100	≈200	≈250

HL-Mode:

p [GeV/c]:	**3.8**	**8.9**	**14.9**
rms rel. momentum spread δ_{rms}:	$1.3 \cdot 10^{-4}$	$1.2 \cdot 10^{-4}$	$1.0 \cdot 10^{-4}$
rms transverse emittance ε_{rms} [mm mrad]:	$8 \cdot 10^{-2}$	$4 \cdot 10^{-2}$	$2 \cdot 10^{-2}$
cooling down time [s]:	≈500*	≈800	≈1000

* core cooling time

Time of Flight Discrimination Cooling
- TOF Momentum Cooling -

- *How can the low energy tails be cooled?*
- *How can the mean energy loss*
  due to the beam-target interaction be compensated?

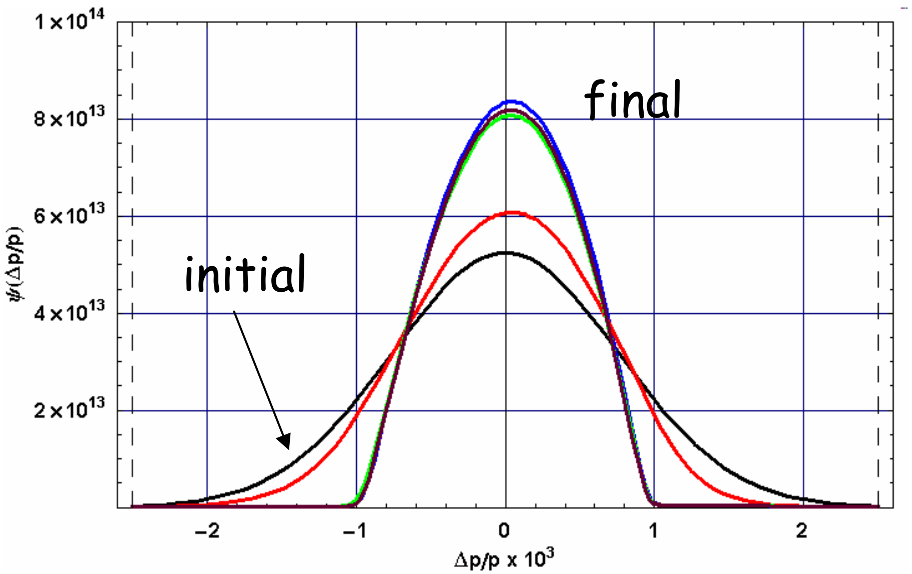
TOF momentum cooling:

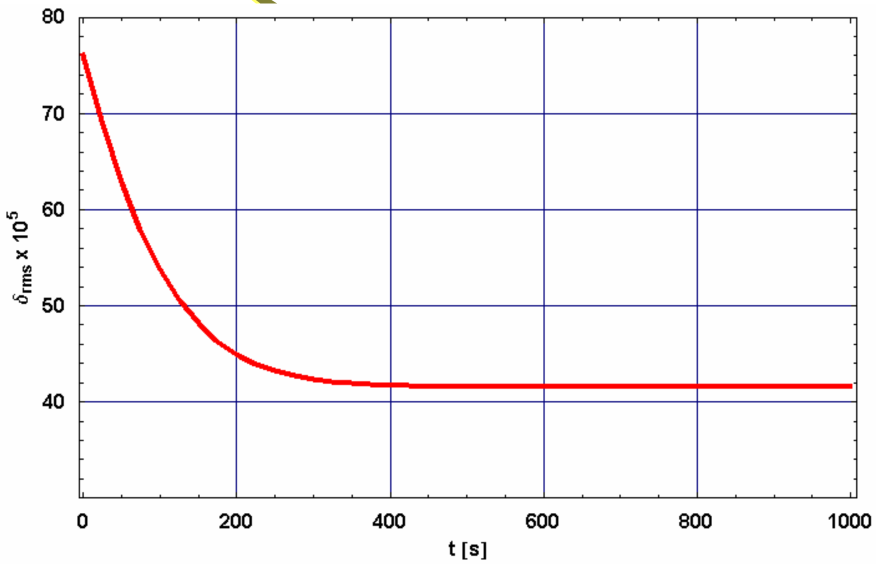
- The notch filter is removed and replaced by a 90 degree broadband phase shifter.
- Low gain and system delay adjusted.
- Method prefers high bandwidth.

TOF Momentum Cooling

Gain and delay adjusted for TOF cooling in the HL-Mode at T = 3 GeV

- Initial momentum spread increased by 50%!





- mean energy loss is compensated
- now low energy tails
- no particle losses

Stochastic Momentum Cooling at COSY with the ANKE Target

- a short overview -

- Beam momentum 3.2 GeV/c
- Number of protons 1×10^{10}
- Frequency slip factor $\eta = -0.1$ ($\gamma > \gamma_{tr}$)

Stochastic Cooling Systems at COSY (present status)

- Stochastic cooling in COSY:
  - Horizontal system: 1.8 – 3.0 GHz
  - Vertical system: 1.0 – 3.0 GHz
  - Longitudinal system: 1.0 – 1.8 GHz
  - Momentum range: 1.5 GeV/c to 3.6 GeV/c

Longitudinal cooling with optical notch filter

Measured Quantities and Procedure

- Longitudinal frequency distributions versus time

- ***1st Step:*** without cooling but with target ON:

  - Determine:

    - mean energy loss $f_0 \cdot \varepsilon$ [eV/s]
    - mean square relative momentum deviation per second δ_{loss}^2
    - target thickness (Bethe-Bloch)

- ***2nd Step:*** cooling ON and target ON (cooling ON and target OFF):

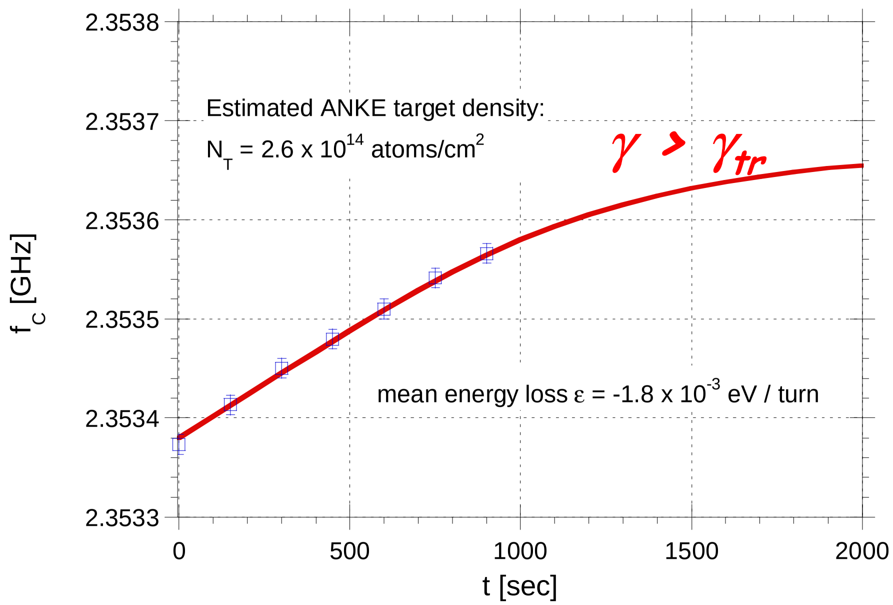
  - Determine:

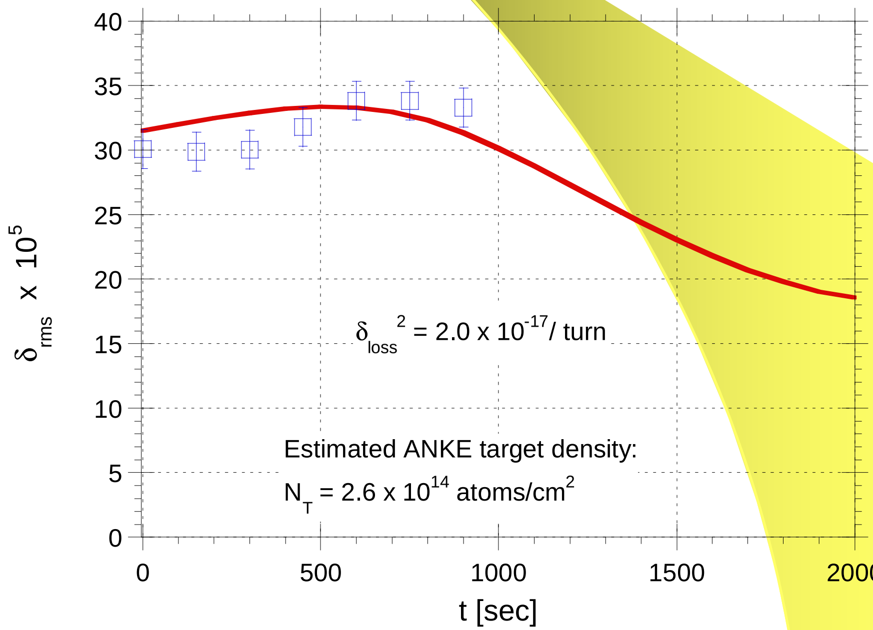
    - beam equilibrium
    - cooling down time
    - vary electronic gain
    - vary electronic delay

1st Step

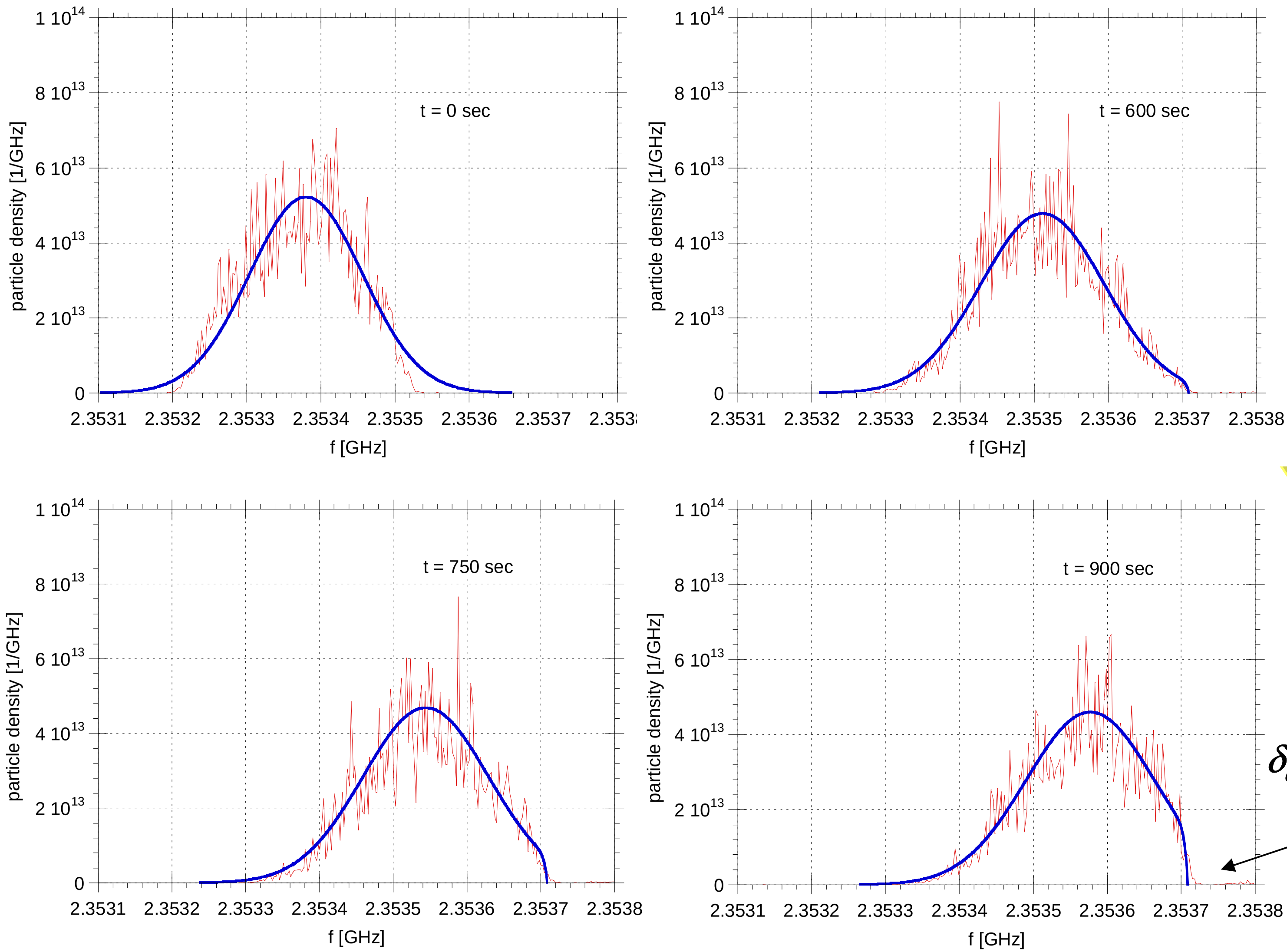
- Experimental investigation of ANKE target-beam interaction

  → target thickness ≈ 3×10^{14} atoms/cm²





1st Step: Target ON, Cooling OFF



Blue:
FPE model

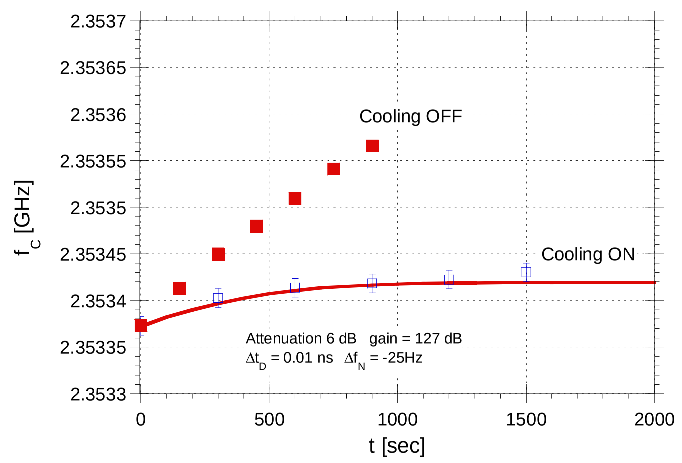
Red:
measured distribution

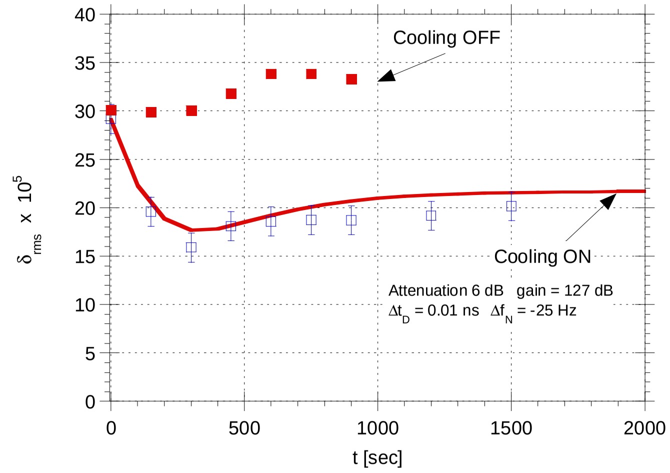
momentum acceptance limit

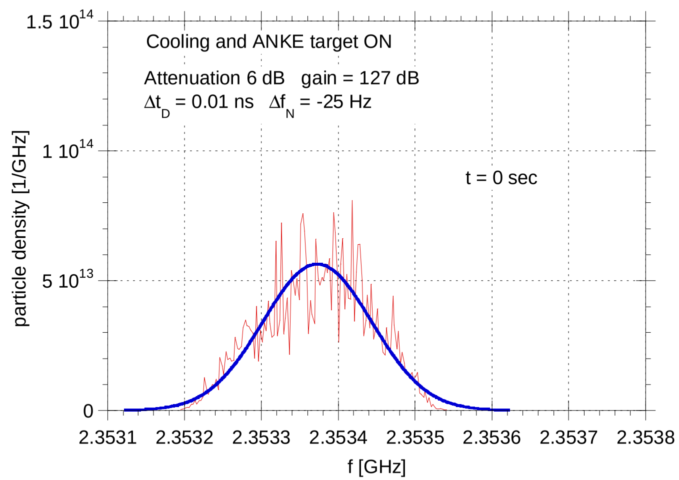
$\delta_{acc} = -1.4 \times 10^{-3}$

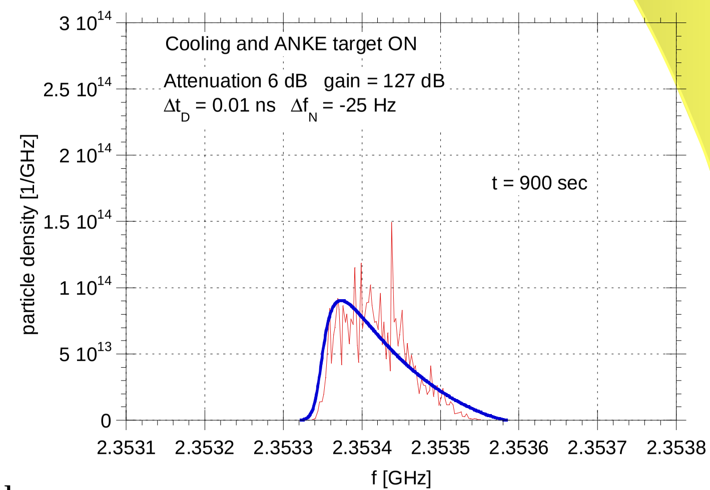
2nd Step

- Longitudinal stochastic filter cooling with target

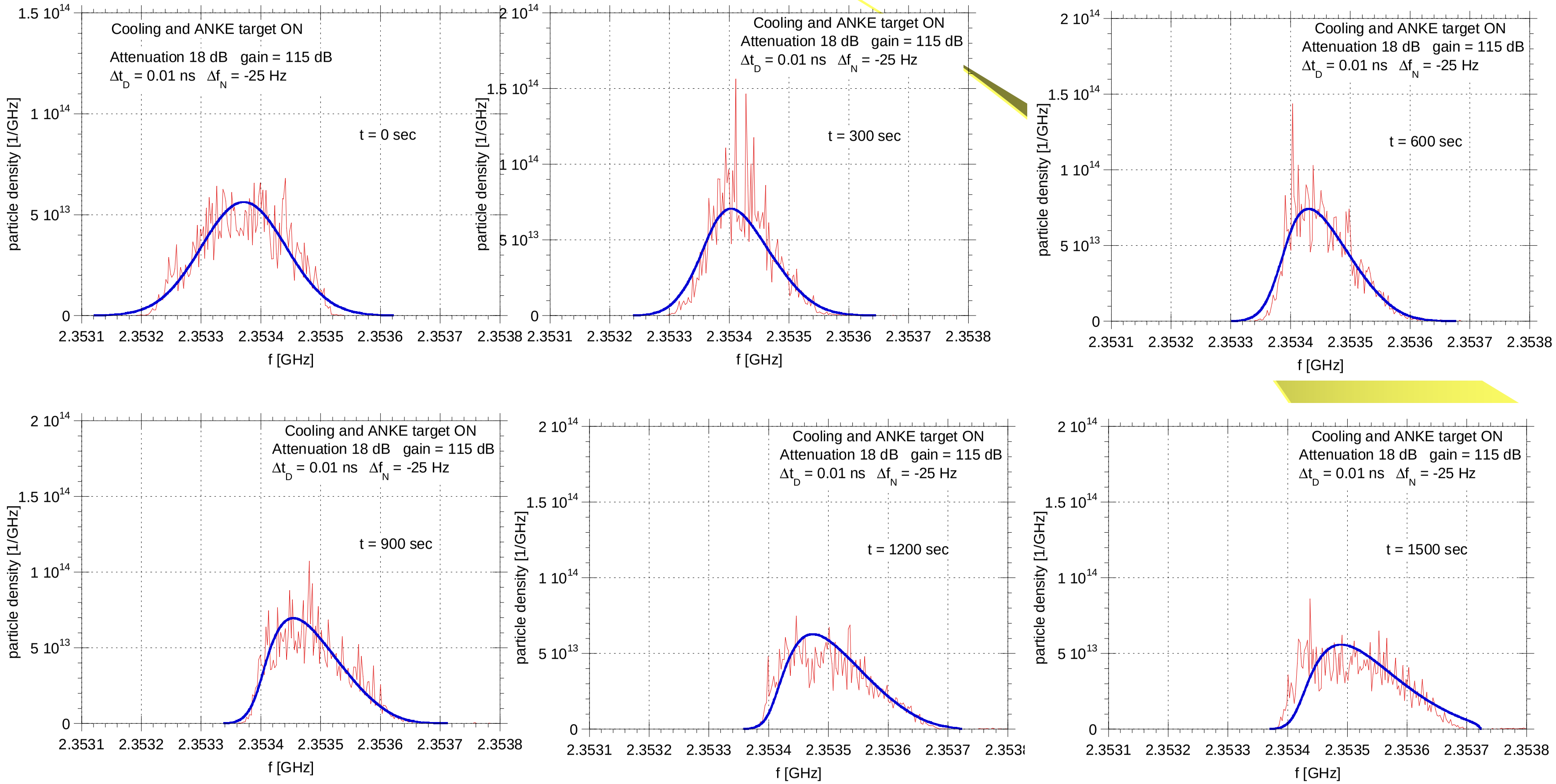








Gain reduced by 12 dB:



Cooling Experiment Summary

- The model receives a remarkable good agreement with the experimental results (not all shown).
- The beam target interaction is well decsribed by the *mean energy loss* ε and the *mean square relative momentum deviation* $(\delta_{loss})^2$ per target traversal.
- The filter cooling method has the advantage of adjusting the filter to (partly) compensate the mean energy loss.

Outlook for HESR, (2-4) GHz system

- Continue investigations of longitudinal stochastic cooling with a non-linear filter <u>and</u> the new HESR PU/Ki structures
- Barrier bucket simulations and verification by experiments at COSY for mean energy loss compensation
- Experiments on a combined application of a barrier bucket rf and longitudinal stochastic cooling at COSY
- TOF cooling simulations (quite promising!) to compensate ***undesired mixing from PU to KI*** and ***mean energy loss***
- Beam experiments with internal Pellet target of WASA
- Include beam feedback in simulations
- Split lattice experiments?

Thank You for Your Attention

Stochastic Cooling and Internal Target 2

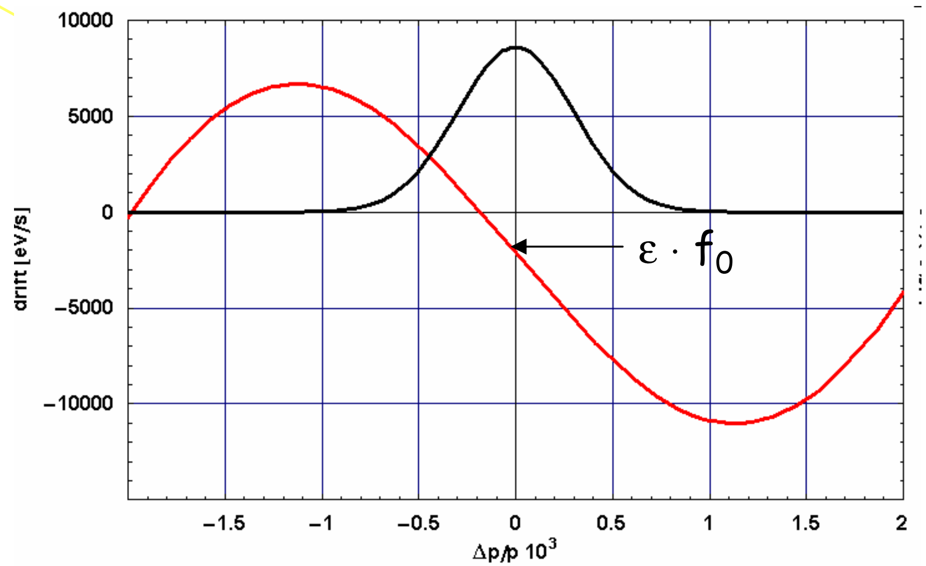
- Drift is shifted towards negative values:

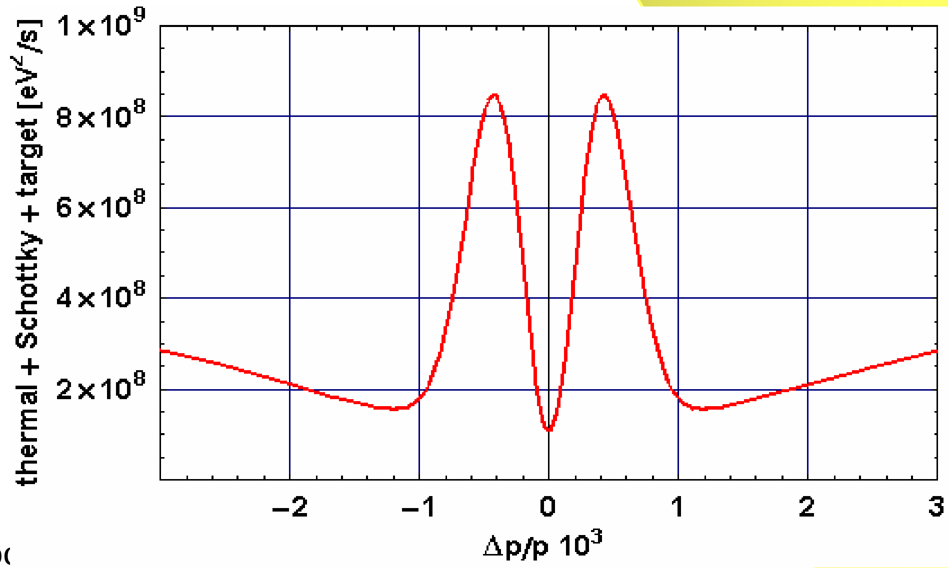
  → reduced cooling force for negative momentum deviations

  → low energy tails

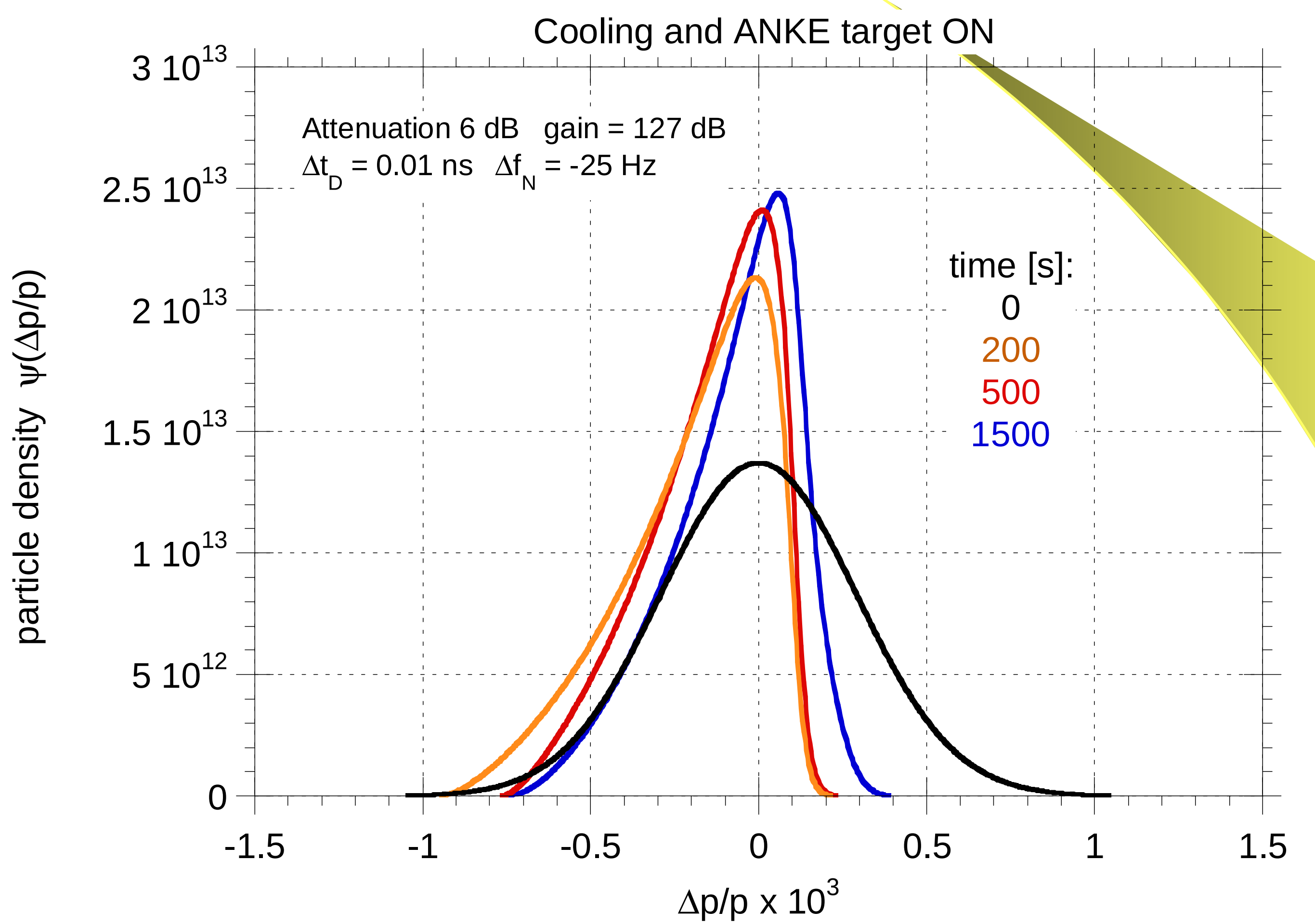
  → particle losses may occur

- Adjust filter center frequency
- Adjust system delay



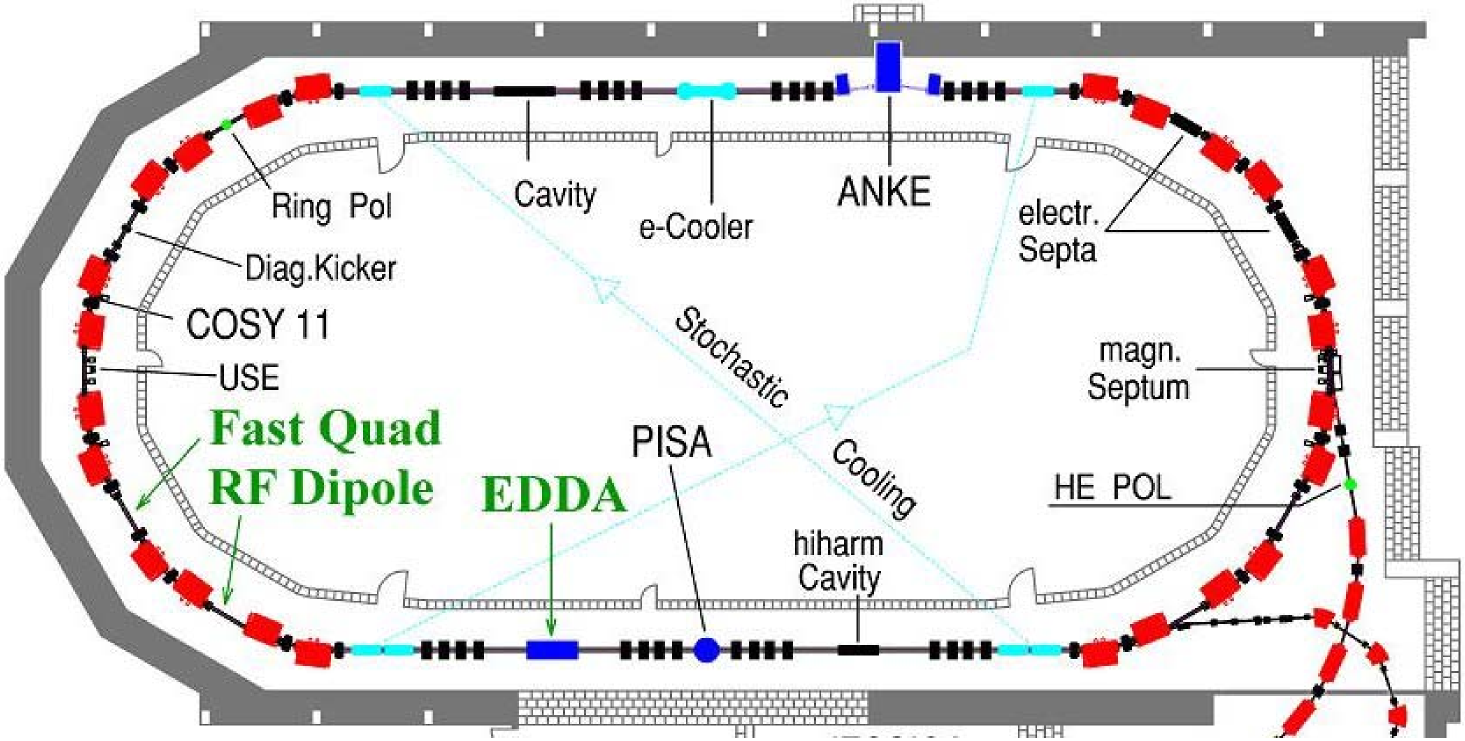


- ***Momentum Distributions***



Stochastic Cooling Systems at COSY (present status)

- Polarized and unpolarized protons and deuterons
- 300 MeV/c < p < 3.7 GeV/c



ring length 184 m

straight section 40 m

revolution frequency $f_0 \approx 1.5$ MHz

(HESR ≈ 0.5 MHz)