Cooling Scenario for the HESR

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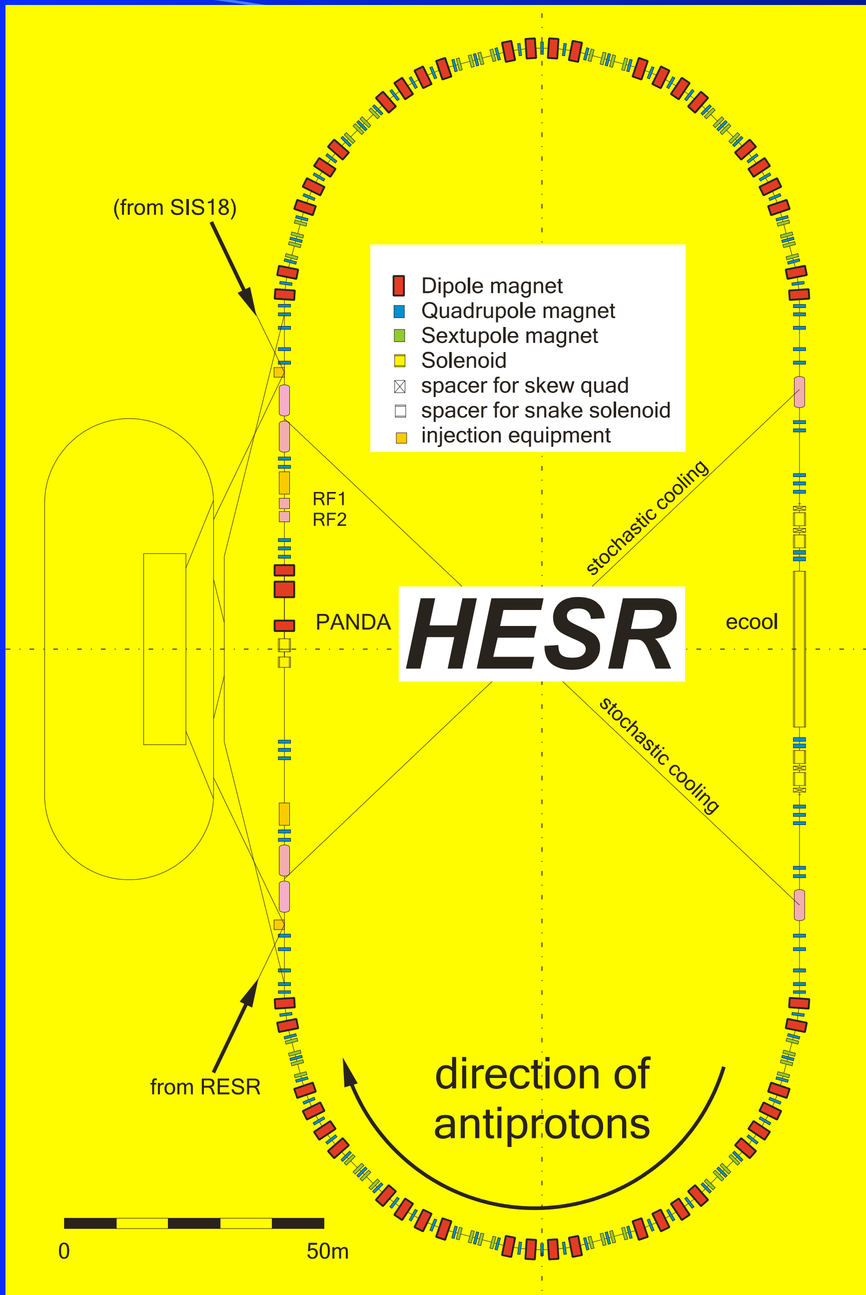
COOL 05, Eagle Ridge, Galena, IL USA
September 18th to 23th, 2005

- HESR Layout
- Electron Cooling at Momenta p ≤ 8.9 GeV/c
  for the High Resolution Mode
- Small Angle and Energy Scattering
- Stochastic Cooling with Internal Target
  for p ≥ 3.9 GeV/c in the High Luminosity Mode



HESR Layout

Basic Parameters:

- Circumference: 574 m
- Arc Length: 155 m
- Straight Section: 132 m

- Ions:
  - anti-protons
  - protons

- Momentum Range:

  1.5 GeV/c – 15 GeV/c

- anti-proton injection

  at 3.9 GeV/c from RESR

Scenario High Resolution Mode

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

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

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

*

rms-relative momentum spread ≈ 1 x 10^{-5}
required up to 8.9 GeV/c

- **The beam is injected into HESR at T = 3 GeV**
- **Electron Pre-Cooling**
- **Acceleration to the Desired Energy**
- **Electron Cooling and Target ON**

Cooling Models
Simulation with BETACOOL

Electron Cooling

- Model Beam Option
- Semi Empirical Formula by V.V. Parkhomchuk

Stochastic Cooling

- rms-Beam Option
- Transverse Cooling: Model by B. Autin
- Longitudinal Filter Cooling: T. Katayama and N. Tokuda (and H.St.)

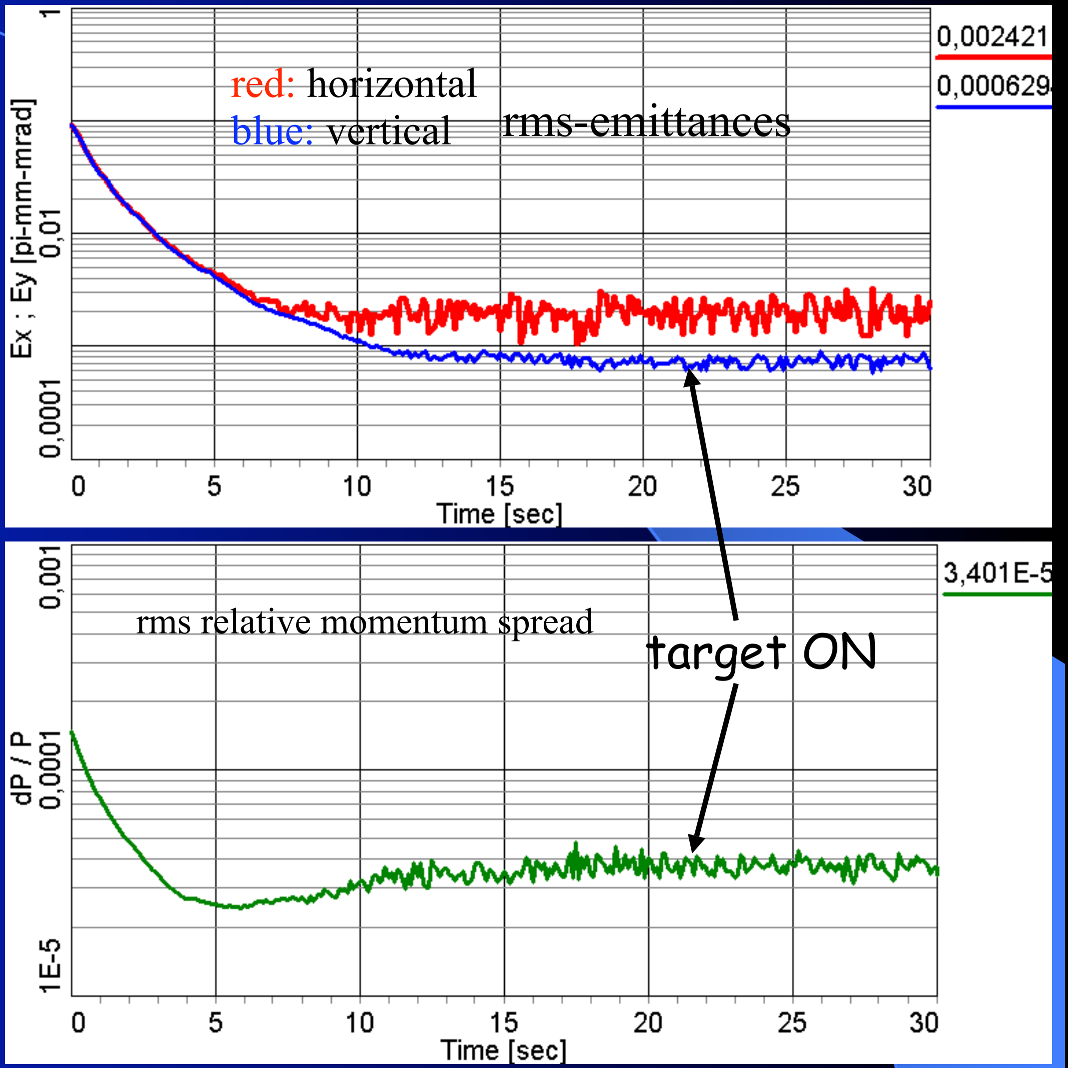
- HESR Lattice with γ_{tr} = 6.5i
- Intra Beam Scattering (IBS): Martini Model

Electron Cooler Parameters

Beta function at cooler (H/V):	100	m
Cooling section length:	30	m
Electron beam radius:	5	mm
Electron beam current:	1	A
Electron beam density:	2.7×10^{8}	cm^{-3}
Magnetic field in cooler:	0.2	T
Field homogeneity:	1×10^{-5}	
Transverse electron temperature:	0.1	eV

Electron Cooling at T = 3 GeV

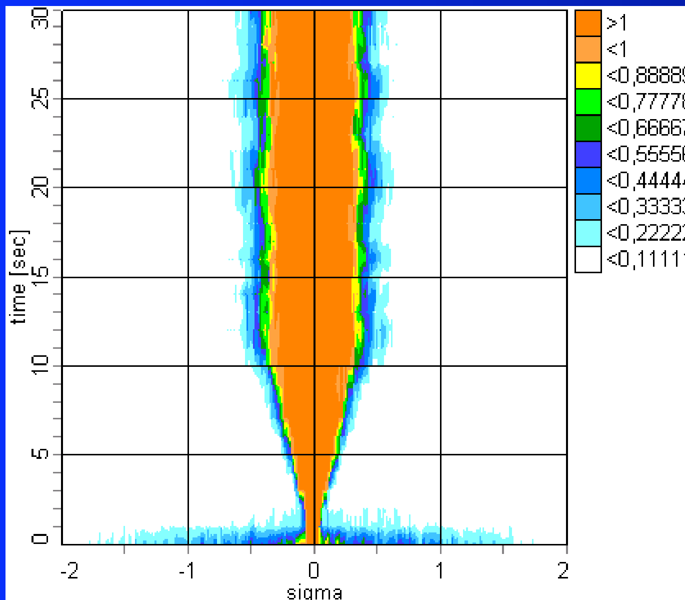
Number of antiprotons:	10^{10}	
Initial rms emittance (H/V):	0.092	mm mrad
Initial rms relative momentum spread:	1.5×10^{-4}	
rms-beam radius at cooler:	3	mm
Revolution frequency:	507.25	kHz
Kinematic beta:	0.97	
Kinematic gamma:	4.197	
Frequency slip factor:	0.08	
Luminosity:	2×10^{31}	$cm^{-2}\ s^{-1}$

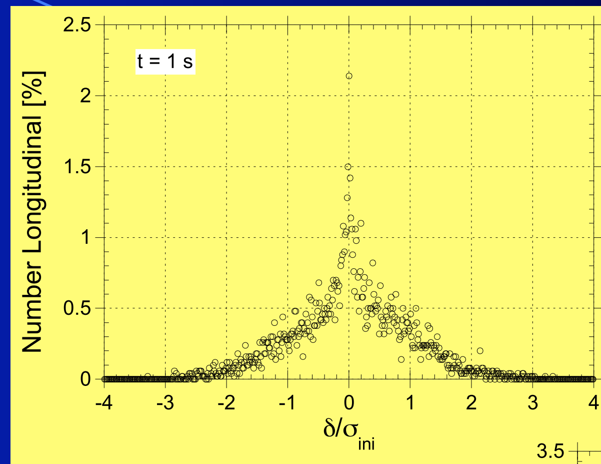


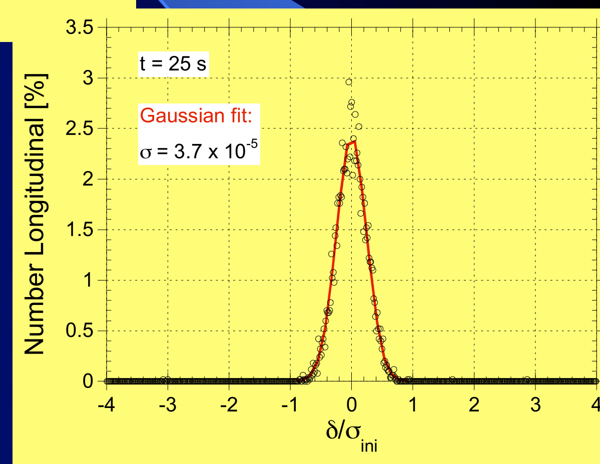
- The equilibrium is determined by IBS
- The target is switched on at about 22 s. No influence

- **Final relative rms-momentum spread: 3.4×10^{-5}**

Time Evolution of the Momentum Distribution @ 3 GeV





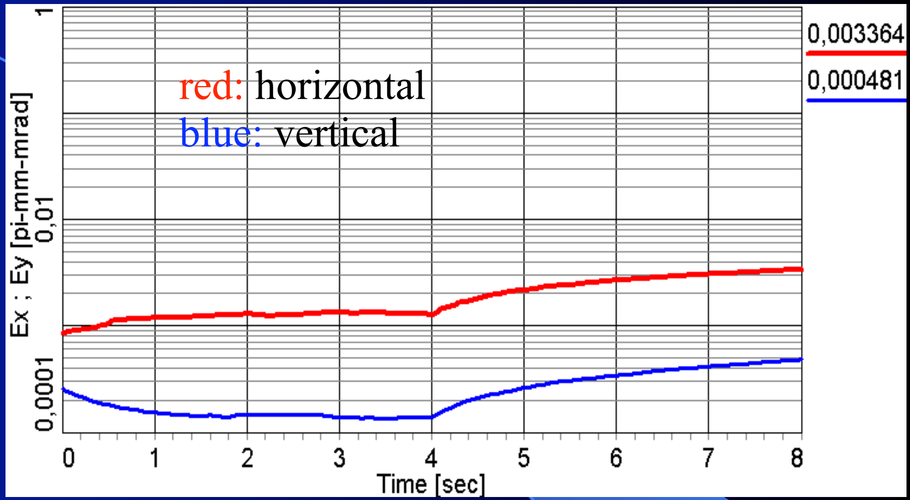


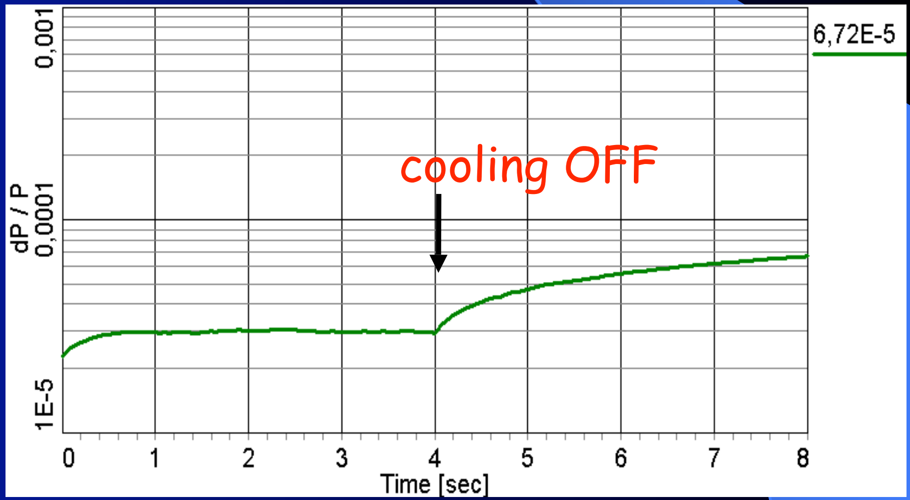
beam distribution

- Initially: dense core and long tails
- At equilibrium: Gaussian distribution

Electron Cooling at 8 GeV

Number of antiprotons:	10^{10}	
Initial rms emittance (H):	0.000861	mm mrad
Initial rms emittance (V):	0.000258	mm mrad
Initial rms relative momentum spread:	2.28×10^{-5}	
Rms-beam radius at cooler (H):	0.3	mm
Rms-beam radius at cooler (V):	0.2	mm
Revolution frequency:	519.40	kHz
Kinematic beta:	0.994	
Kinematic gamma:	9.526	
Frequency slip factor:	0.035	
Luminosity:	2×10^{31}	$cm^{-2}\ s^{-1}$





- Electron cooling and target ON
- Equilibrium dominated by IBS
- **rms-momentum spread with target and IBS : 3.0×10^{-5}**

Resume

In the HESR Synchrotron Mode:

- The High Resolution Mode with $\delta_{rms} \approx 3.0 \times 10^{-5}$ up to T ≈ 8 GeV seems possible with electron cooling.

But

- No phase space distortion during acceleration has been assumed.
- No phase space increase during injection

Scenario High Luminosity Mode

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

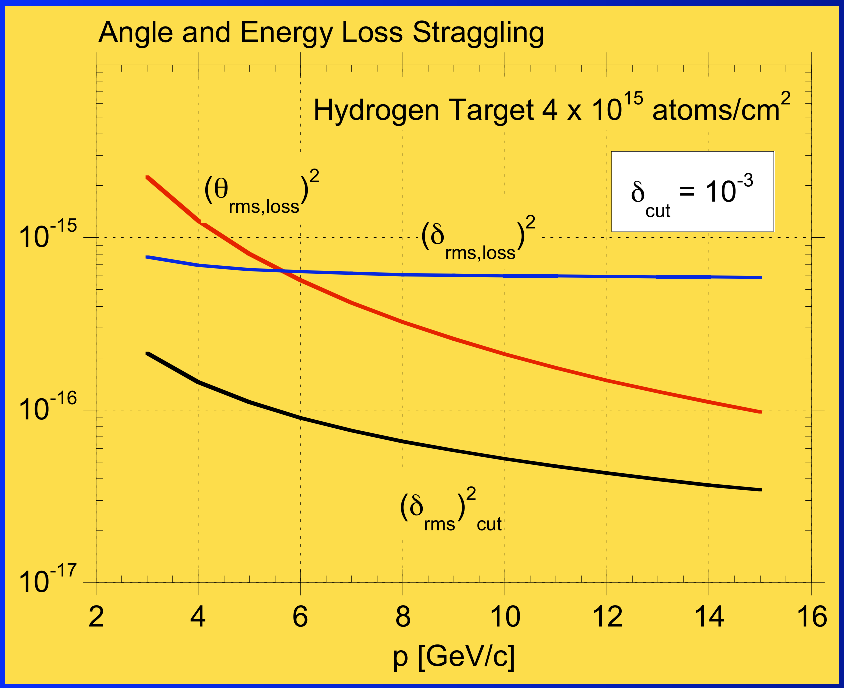
- **The beam is injected at 3.9 GeV/c**
- **Required in the whole momentum range**
  - **Acceleration to the desired momentum**
  - **Stochastic Cooling**

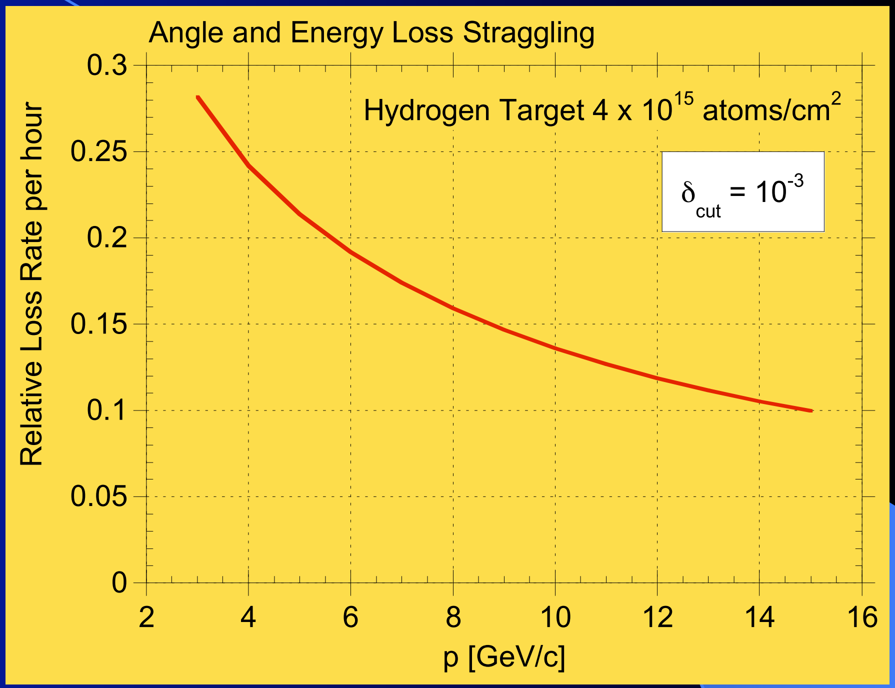
    to compensate target-beam heating

Small Angle and Energy Loss Straggling

for the High Luminosity Mode

F. Hinterberger, INTAS Workshop, 3.6.05, GSI

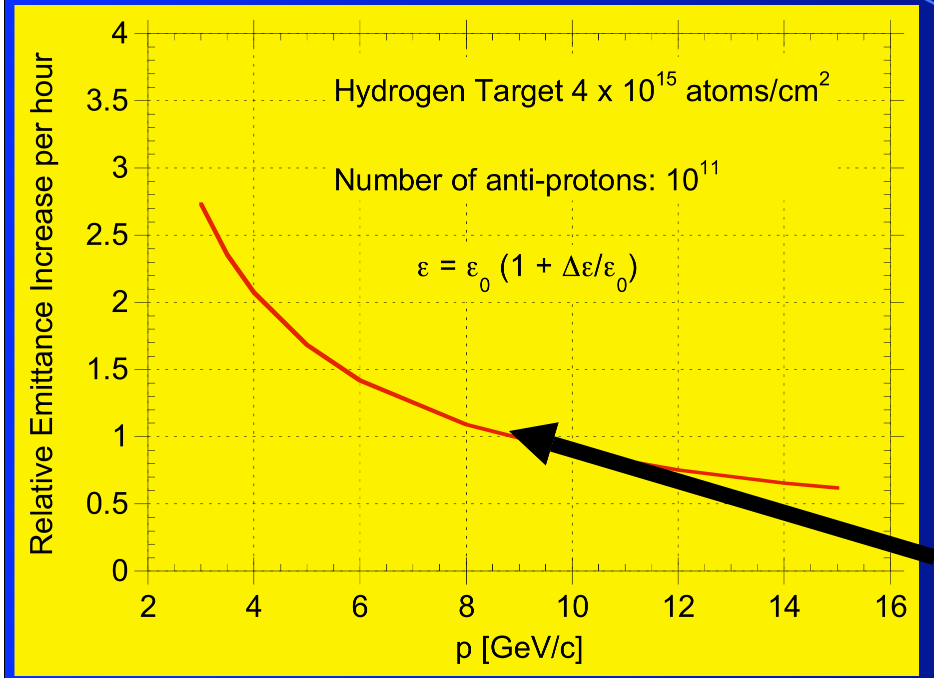




- Introduce scrapers to limit the maximum relative momentum deviation by $\delta_{Cut} = 10^{-3}$ will decrease the squared rms deviation per target traversal by more than one magnitude above T = 8 GeV.

- The relative particle loss rate is less than 15 %/h above T = 8 GeV.

Small Angle and Energy Loss Straggling



$$\left(\frac{d\varepsilon}{dt}\right)_T = \frac{f_0}{2}\beta_T\theta^2_{rms,loss}$$

small angle scattering is less important above T = 8 GeV.

the maximum emittance increase is about a factor of two over one hour at T = 8 GeV.

- Dominant process: Increase in momentum spread above 8 GeV

$$\left(\frac{d\delta^2_{rms}}{dt}\right)_T = f_0\delta^2_{rms,loss}$$ (DC-beam)

Scenario High Luminosity Mode

- Transverse stochastic cooling seems to be only necessary below 8.9 GeV/c.
- Longitudinal stochastic cooling is necessary in the whole range.

Longitudinal Equilibrium with Stochastic Cooling and Target

Longitudinal filter cooling for a Gaussian distribution obeys the differential equation

$$\frac{d\delta_{rms}^2}{dt} = -\frac{2}{\tau}\delta_{rms}^2 + \frac{3}{4\sqrt{\pi}} B \cdot N \cdot \delta_{rms} + \left(\frac{d\delta_{rms}^2}{dt}\right)_T$$

Schottky noise heating

$$\left(\frac{d\delta_{rms}^2}{dt}\right)_T = f_0 \delta_{rms,loss}^2$$

N: particle number, n_P,n_K: number of PU, KI loops, W: bandwidth, f_C: center frequency, G_A: electronic gain, $2/\tau$: cooling rate

Longitudinal Equilibrium with Stochastic Cooling and Target

equilibrium relative rms-momentum spread:

$$\delta_{rms,EQ} = \frac{3}{16\sqrt{\pi}} B \times N \times \tau + \frac{1}{2}\sqrt{\left(\frac{3}{16\sqrt{\pi}} B \times N \times \tau\right)^2 + 2\tau \times \left(\frac{d\delta_{rms}^2}{dt}\right)_T}$$

with contribution from

Schottky noise equilibrium:

$$\delta_{rms,S} \propto B \cdot N \cdot \tau \propto N \cdot \sqrt{n_p n_K G_A}$$

Target equilibrium:

$$\delta_{rms,T} \propto \tau \propto \frac{1}{W f_C} \cdot \frac{1}{\sqrt{n_P n_K G_A}}$$

N: particle number, n_P,n_K: number of PU, KI loops, W: bandwidth, f_C: center frequency, G_A: electronic gain, $2/\tau$: cooling rate

Longitudinal Equilibrium with Stochastic Cooling and Target

- For a given bandwidth W and center frequency f_C of the cooling system as well as particle number N the minimal equilibrium value is attained for a certain value of the product $(n_P\, n_K)^{1/2}\; G_A$.

- The number of pickup loops n_P, the number of kicker loops n_K and the electronic gain G_A can be chosen to optimize the signal-to-noise ratio at the pickup output and to keep the electronic power in reasonable limits.

- The only way to reduce the equilibrium value (and cooling down time) for a given particle number N is to increase the bandwith W and the center frequency f_C.

(2 – 4) GHz System

- Quarter wave loop pairs for pickup and kicker: #64
- Electrode length and width: 2.5 cm
- Gap height: 2.6 cm
- Pickup/kicker length ≈ 3 m
- Beta function at pickup and kicker: 75 m
- Impedance: 50 Ohms
- Cooled structures and eq. amplifier temperature (both 80 K)

Longitudinal cooling: Optical notch filter

Transverse cooling: Pickup/kicker in difference mode

Low electronic power < 200 W

Below T = 3 GeV longitudinal band overlap

Longitudinal Stochastic Cooling Performance for Different Momenta in the HL mode

Transverse
and Longitudinal Cooling

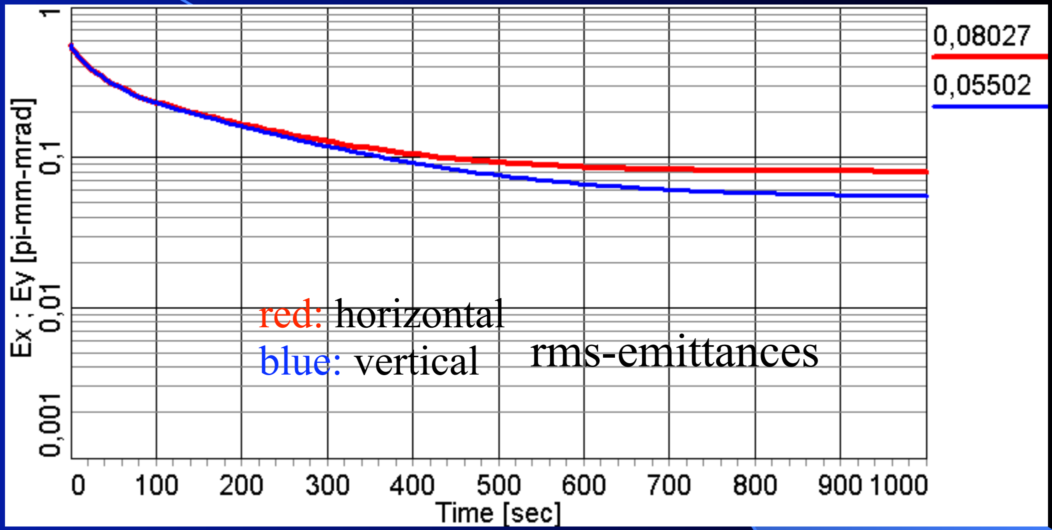
Including IBS+Target

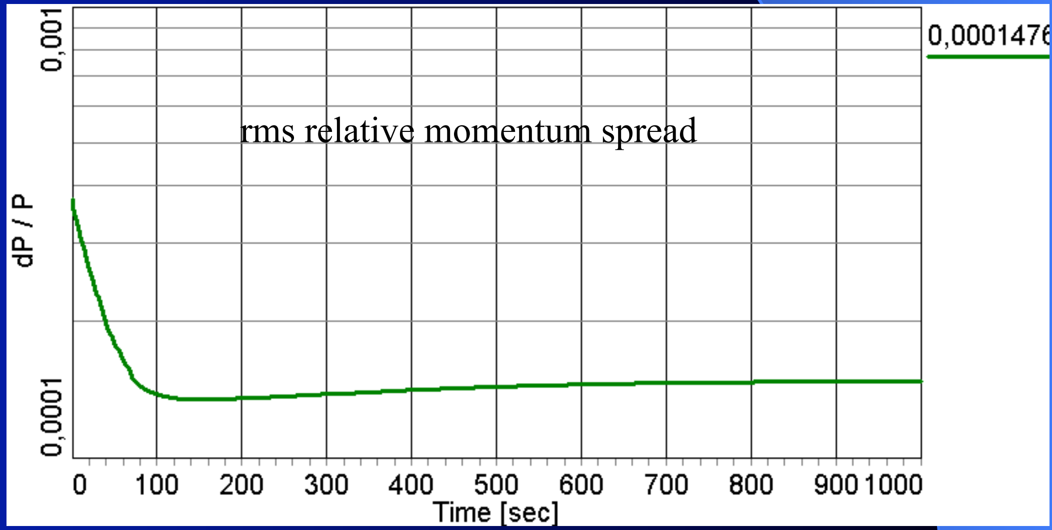
p = 3.9 GeV/c

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

$N = 10^{11}$

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





Longitudinal Stochastic Cooling Performance for Different Momenta in the HL mode

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

$N = 10^{11}$

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

		3.9 GeV/c	8.9 GeV/c	14.9 GeV/c
$\delta_{Cut} = \infty$	$\delta_{rms,Ini} \times 10^4$:	3.8	2.5	1.8
	$\delta_{rms,eq} \times 10^4$:	1.3	1.6	1.8
	t_{eq} [s]:	≈ 150	≈ 150	-
	$\sqrt{n_P n_K} G_A$:	0.64×10^7	2.0×10^7	3.6×10^7
	dB:	136	146	151
$\delta_{Cut} = 2 \times 10^{-3}$	$\delta_{rms,eq} \times 10^4$:	1.0	0.94	0.9
	t_{eq} [s]:	≈ 250	≈ 400	≈ 500
	$\sqrt{n_P n_K} G_A$:	0.36×10^7	0.9×10^7	1×10^7
	dB:	131	139	140

above 8.9 GeV/c only longitudinal cooling

$$dB = 20 Log_{10}(\sqrt{n_P n_K} G_A)$$

Stochastic Cooling Performance for Different Momenta

- For all energies above T = 3 GeV almost the same equilibrium relative momentum spread values are attained.
- Target heating can be compensated.
- As compared to electron cooling: IBS plays (almost) no role if the beam is only longitudinally cooled.
- If the momentum aperture is limited to $\delta_{Cut} = 2 \cdot 10^{-3}$ the rms relative momentum spread can be cooled down by more than a factor of two.

Thank You for Your Attention

References

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  according to a private communication with Tokuda the noise contributions have been recalculated by H.St.
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