Simulations of stochastic cooling of antiprotons in the collector ring CR

C. Dimopoulou

A. Dolinskii, T. Katayama, D. Möhl, F. Nolden,
C. Peschke, M. Steck, L. Thorndahl

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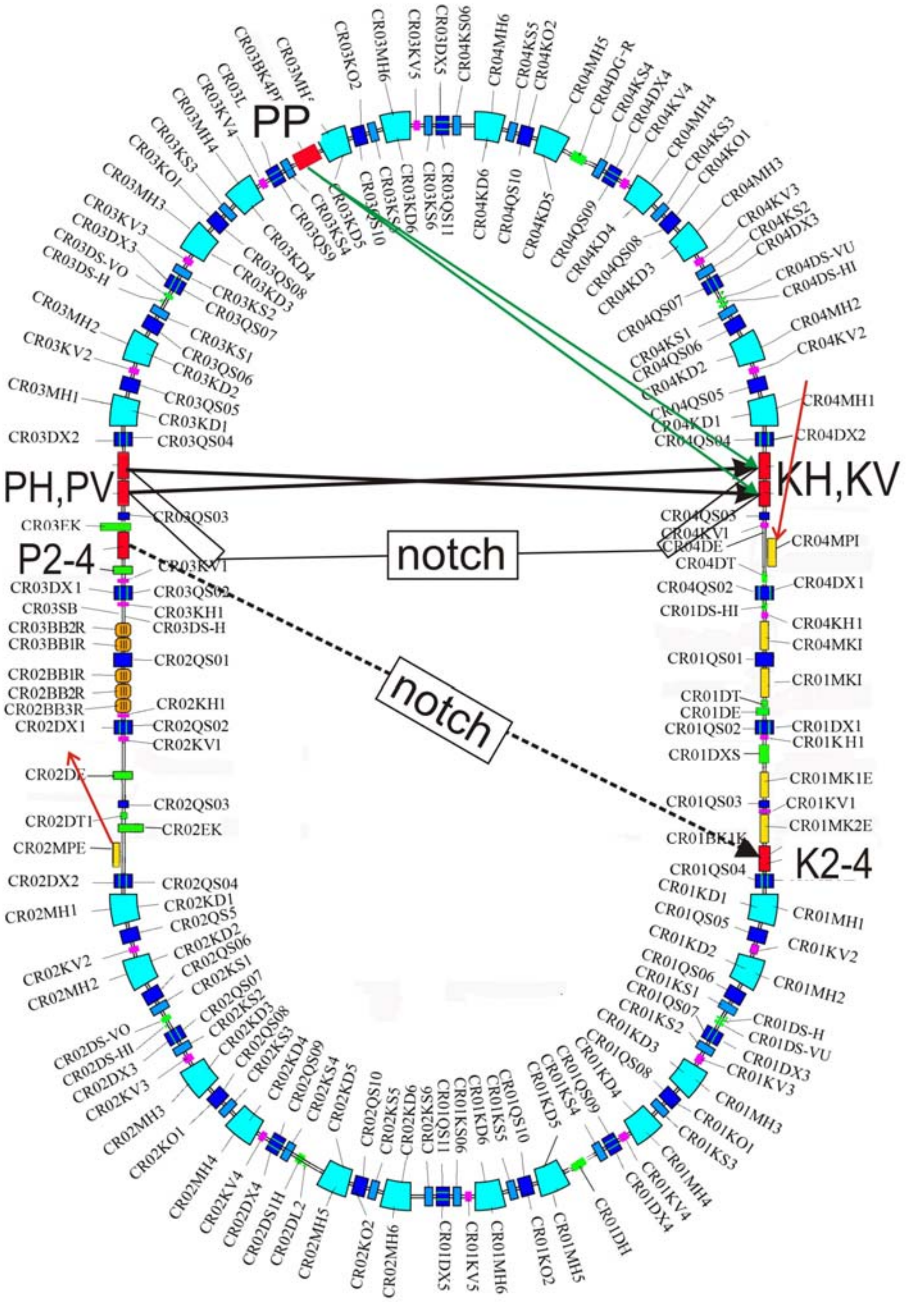
Required performance of CR stochastic cooling

- Short bunch of hot secondary beam from production target into the CR
- After bunch rotation and adiabatic debunching the δp/p is low enough to apply stochastic cooling
- Fast 3D stochastic cooling required to profit from production rate of secondary beams

	Antiprotons **3 GeV, 10^8 ions**		**Rare isotopes** **740 MeV/u, 10^9 ions**	
	δp/p (rms)	$\varepsilon_{h,v}$ (rms) π mm mrad	δp/p (rms)	$\varepsilon_{h,v}$ (rms) π mm mrad
Before cooling	**0.35 %**	**45**	0.2 %	45
After cooling	**0.05 % (*)**	**1.25 (*)**	0.025 %	0.125
Phase space reduction	9×10^3		1×10^6	
Cooling down time	**≤ 9 s**		≤ 1 s	
Cycle time	**10 s**		1.5 s	

(*) 20% lower (if possible) for HESR as accumulator ring (instead of RESR)

Overview of the CR stochastic cooling systems



Systems in frequency band 1-2 GHz				
Pickup	**Kicker**	**pbars**	**RIBs**	**Method**
PH	KH	hor.	hor., final stage	difference PU
PV	KV	vert.	vert., final stage	difference PU
PH+PV	KH+KV	long.	long., final stage	Sum PU + notch filter
PP	KH	-----	hor. + long., first stage	Palmer: difference PU at high D
PP	KV	----	vert., first stage	difference PU
System in frequency band 2-4 GHz (future option)				
P2-4	K2-4	long.	--------	Sum PU + notch filter

Main issue for pbars: increase ratio

$$\frac{\text{Schottky signal}\,(\propto Q^2)}{\text{thermal noise}}$$

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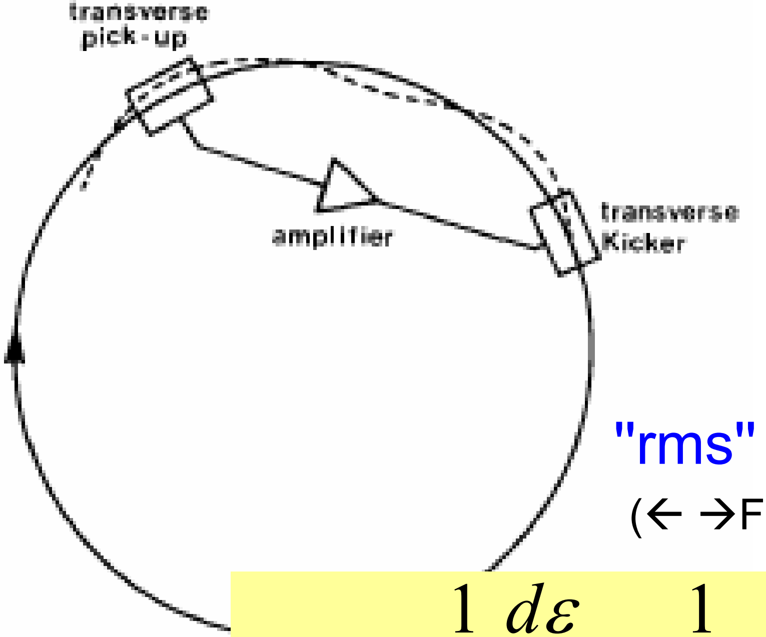
Principle of betatron cooling & basic ingredients



Phase advance PU-K ≈ 90^0

High amplification needed,
electronic gain ~ 10^7 (140 dB)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"rms" theory (analytical model)

(←→Fokker-Planck equation for $\Psi_\perp(J,t) = \partial N/\partial J$)

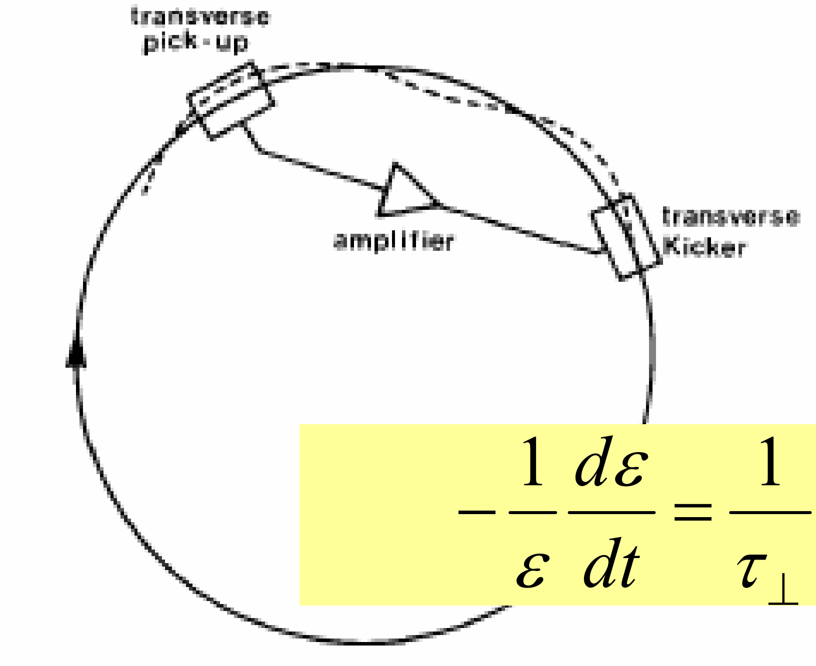
$$-\frac{1}{\varepsilon}\frac{d\varepsilon}{dt} = \frac{1}{\tau_\perp} = \frac{2W}{N}\left[2gB - g^2(M+U)\right]$$

System gain g = PU response x Electronic gain x K response ~ 10^{-2}

Coherent term= cooling force x undesired mixing (PU→K)

Diffusion= heating from Schottky noise (desired mixing (K→PU)) + from thermal noise

Principle of betatron cooling & basic ingredients



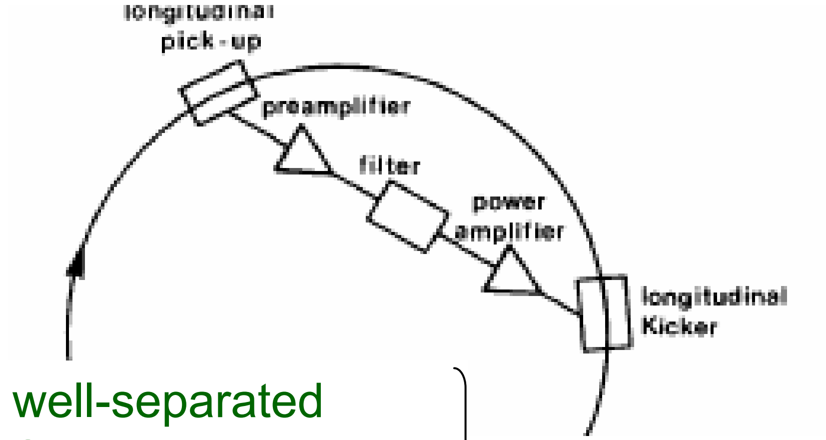
Phase advance PU-K ≈ 90^0

High amplification needed,
electronic gain ~ 10^7 (140 dB)

$$-\frac{1}{\varepsilon}\frac{d\varepsilon}{dt}=\frac{1}{\tau_\perp}=\frac{2W}{N}\left[2gB-g^2(M+U)\right]$$

- Good cooling for overlapping Schottky bands i.e. M=1 and low ratio thermal noise/Schottky signal U
- To cool all the particles within the initial momentum distribution B ≥ 0
- B and M depend in a contradictory way on the spread $\Delta T/T = -\Delta f/f \sim -\eta_{ring/pk}\,\Delta p/p$ of the beam particles, they vary during momentum cooling
- In reality: choose $\eta_{ring/pk}$ for a compromise between B and M

Principle of momentum cooling with notch filter



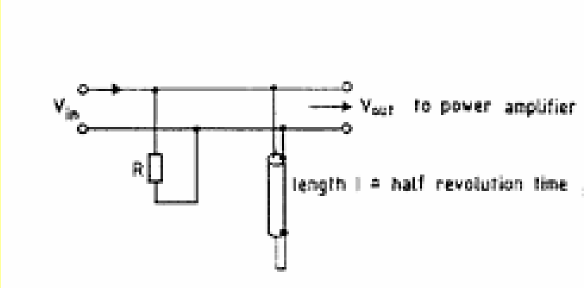
well-separated
Schottky bands M>1
B ≥ 0 for increased
undesired mixing

very small |η|≈1%
i.e. ring almost @ γ_{tr}

Fokker-Planck equation
(solved with CERN code)

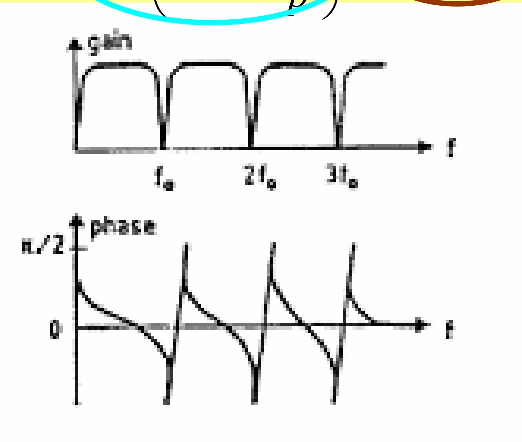
$$\frac{\partial \Psi}{\partial t} = \frac{\partial}{\partial E}\left[-F\Psi + \left(D_s \Psi + D_n\right)\frac{\partial \Psi}{\partial E}\right],$$

$$\Psi(E,t) = \partial N / \partial E$$



The response of the notch filter

$$H_{notch} = \frac{i}{2}\left(1 - e^{-i\,2\pi\, f/f_0}\right) = -\sin\left(\pi\, m\, \eta \frac{\delta p}{p}\right) e^{-i\,\pi\,\pi\,\eta \frac{\delta p}{p}}$$



- ➢provides the cooling force,
- ➢induces extra undesired mixing

Coherent term= cooling force x undesired mixing (PU→K)

System gain G = PU response x Filter response x Electronic gain x K response

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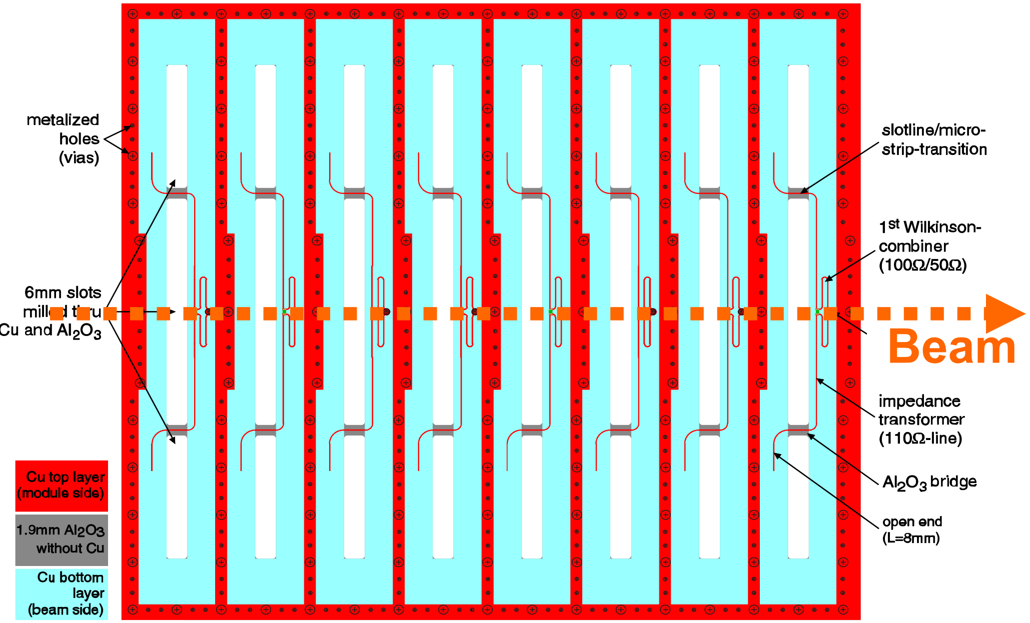
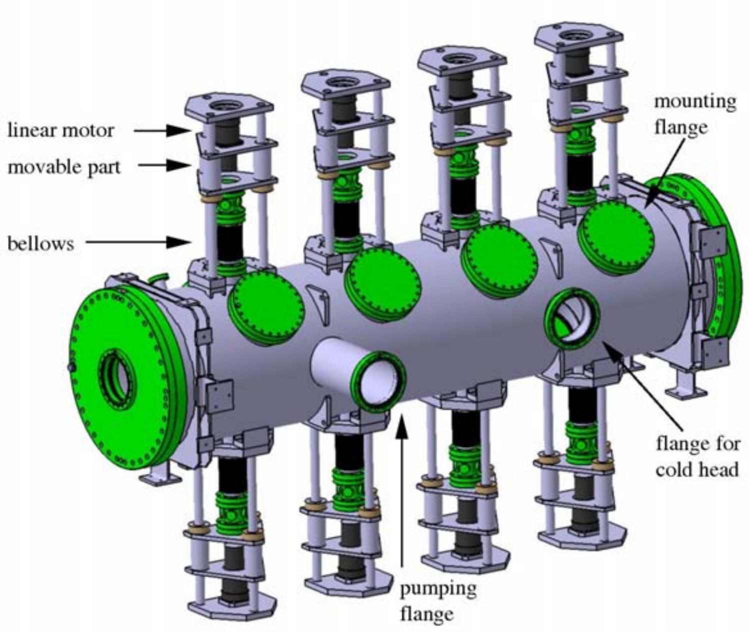
Features and developments for the 1-2 GHz system





- **PU/Kicker tank consists of 2 plates (up+down or left+right) with 64 electrodes/plate PH/KH=PV/KV rotated by 90^0**

- **Plunging of PU electrodes i.e. moving closer to beam during cooling**
- No plunging of KI electrodes

Slotline PU electrodes at 20-30 K
Cryogenic low-noise preamplifiers at 80 K
(open option of preamplifiers in UHV at 20 K)
Kickers at 300 K

} **Effective noise temperature at preamplifier input T_{eff} =73 K**

- **Optical notch filter (< 40 dB deep notches within 1-2 GHz)**

Longitudinal PU/K impedance, sensitivity, PU plunging

circuit convention: $Z_k = \frac{U_{b\,\mathrm{rms}}^2}{P_k}$, $Z_p = \frac{P_p}{I_{b\,\mathrm{rms}}^2}$, $Z_k = 4 \cdot Z_p$

$$\sqrt{Z_k(\mathrm{f},\mathrm{y})} \approx \sqrt{Z_k(\mathrm{f_c})} \cdot S(\mathrm{y}) \cdot S(\mathrm{f})$$

$$\sqrt{Z_p(\mathrm{f},\mathrm{y})} \approx \sqrt{Z_p(\mathrm{f_c})} \cdot S(y) \cdot \mathrm{S(f)}$$

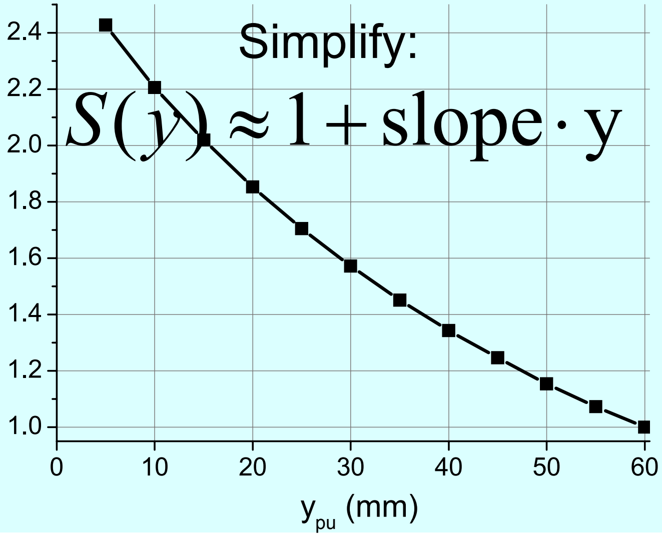
HFSS simulations, absolute values:

$Z_p(\mathrm{f_c}) = 11.25\,\Omega$ at y_{PU}= ±60 mm

$Z_p(\mathrm{f_c}) = 37.75\,\Omega$ at y_{PU}= ±20 mm

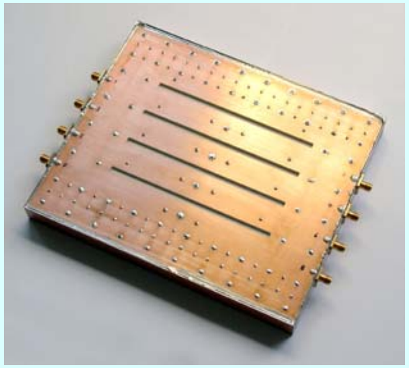
Plunging of PU electrodes:
factor 1.8 in sensitivity (3.4 in Z_p)
from y_{PU}=±60 mm→ ±20 mm

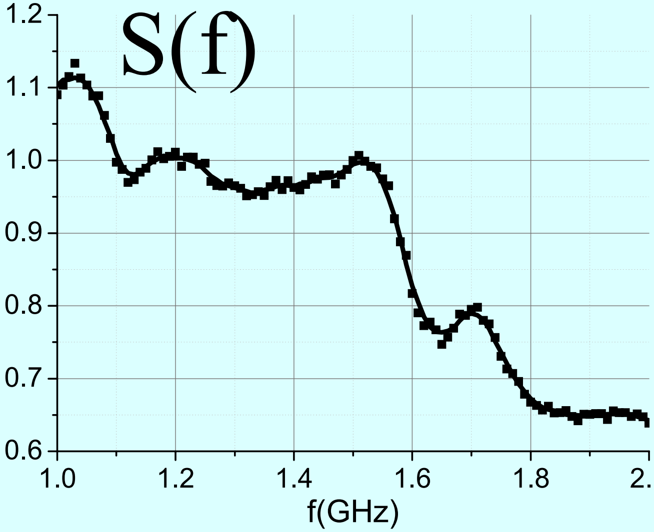
Relative measurements on prototype PU:



Simplify:

$$S(y) \approx 1 + \mathrm{slope} \cdot \mathrm{y}$$





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Input parameters & requirements

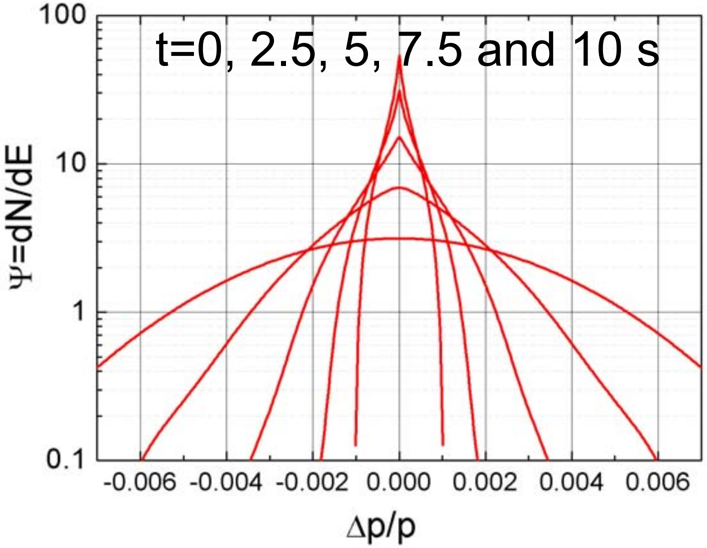
CR Circumference 3 GeV antiprotons	**221.45 m** β=0.9712, γ=4.197, rev. frequency **f_0=1.315 MHz**	
Ring slip factor η, slip factor PU-K η_{pk} Distance PU-K/circumference	**-0.011, -0.033** 0.378	
Beam intensity Initial rms momentum spread Initial rms emittance $\varepsilon_{h,v}$	**10^8** **3.5 10^{-3}, Gaussian/parabolic** **45 π mm mrad**	
System bandwith	**1-2 GHz**	
Number of PU, K (longitudinal cooling) Number of PU, K (transverse cooling)	128, 128 64, 64	
PU, Kicker impedance at midband 1.5 GHz PU/K sensitivity S(y)=1+slope* y PU/K sensitivity vs. frequency S(f)	**no plunging considered, PU electrodes at ± 60 mm** **11.25 Ohm, 45 Ohm** slope= 24.5 m^{-1}	
Effective temperature for thermal noise	**73 K**	
ideal, infinitely deep notch filter + 90^0 phase shifter		
Total installed power at kickers (limited by funding, can be upgraded)	**4.8 kW**	

Goal: Cool longitudinally from σ_p/p= 3.5 10^{-3} → 4 10^{-4} in 9 s

Simultaneous transverse cooling from $\varepsilon_{h,v}$ = 45 → ≈ 1 π mm mrad

Momentum cooling: Cooling force and diffusion

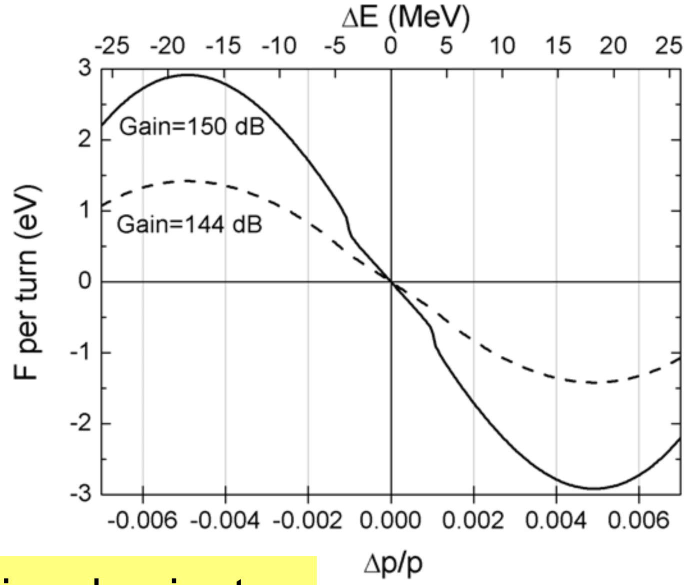
$G_{||}$ = 150 dB ($3.2\ 10^7$); t=10 s

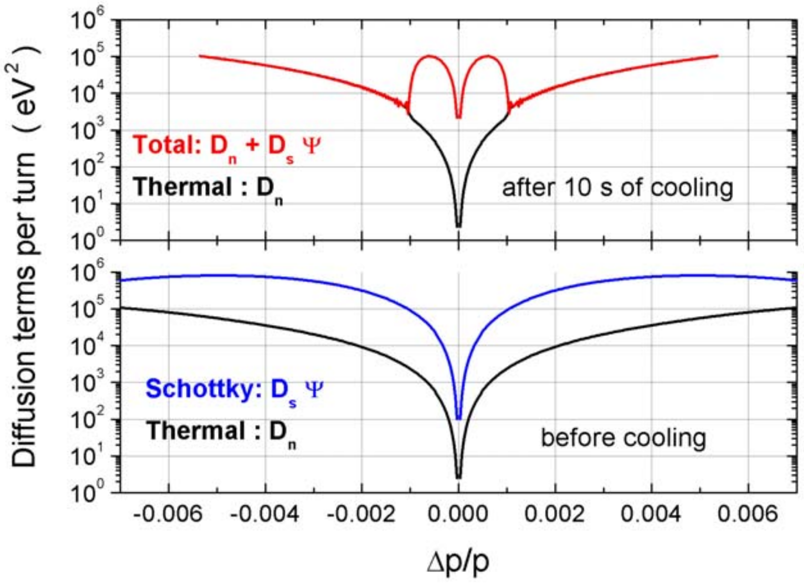


Coherent term:

- linear notch filter response around Δp/p=0 → cooling force
- momentum acceptance of system (undesired mixing ≥ 0) > total initial Δp/p

→ Cooling of all particles





Schottky noise dominates
→ long. cooling time ~ N

Notch filter cuts thermal noise around all harmonics

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Momentum cooling: Feedback by the beam

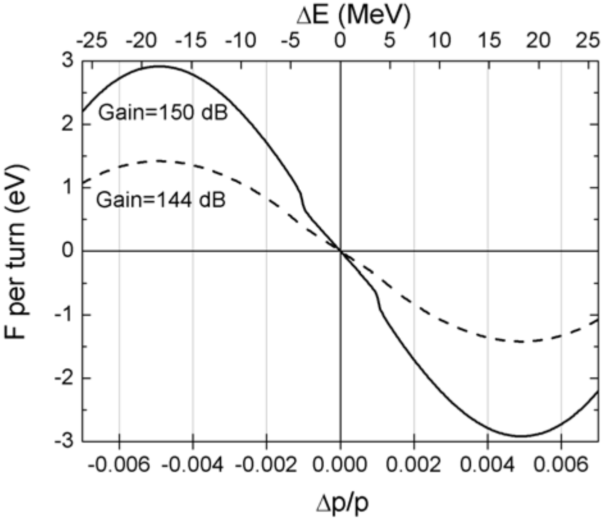
Feedback by the beam included:

$$G(m,E) \rightarrow \frac{G(m,E)}{1-S(m,E,t)}$$

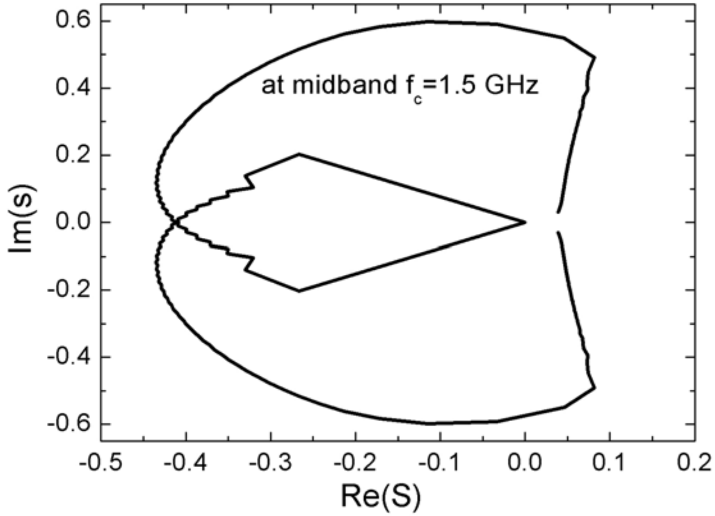
$$S(m,E,t) = \sqrt{n_p\, n_k Z_p(m) Z_k(m)}\; G(m,E) \cdot BTF(m,E,t)$$

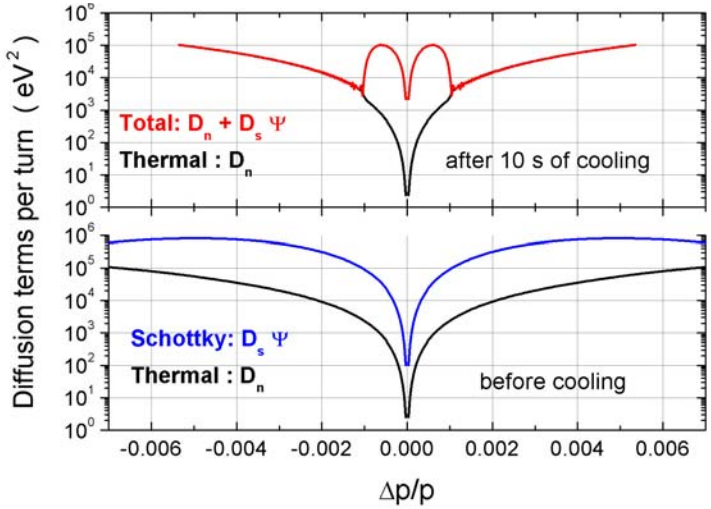
$$B(m,E,t) = -\frac{e f_0^2}{m}\left[\frac{\pi}{|\kappa|}\frac{d\Psi}{dE} + \frac{i}{\kappa}\ {}_{PV}\!\int_{-\infty}^{+\infty} \frac{d\Psi / dE^*}{E^* - E}\, dE^*\right]$$

It deforms the cooling force and suppresses Schottky noise within the distribution, cooling loop is stable (Nyquist plot)



$G_{||}$ = 150 dB (3.2 10^7); t=10 s





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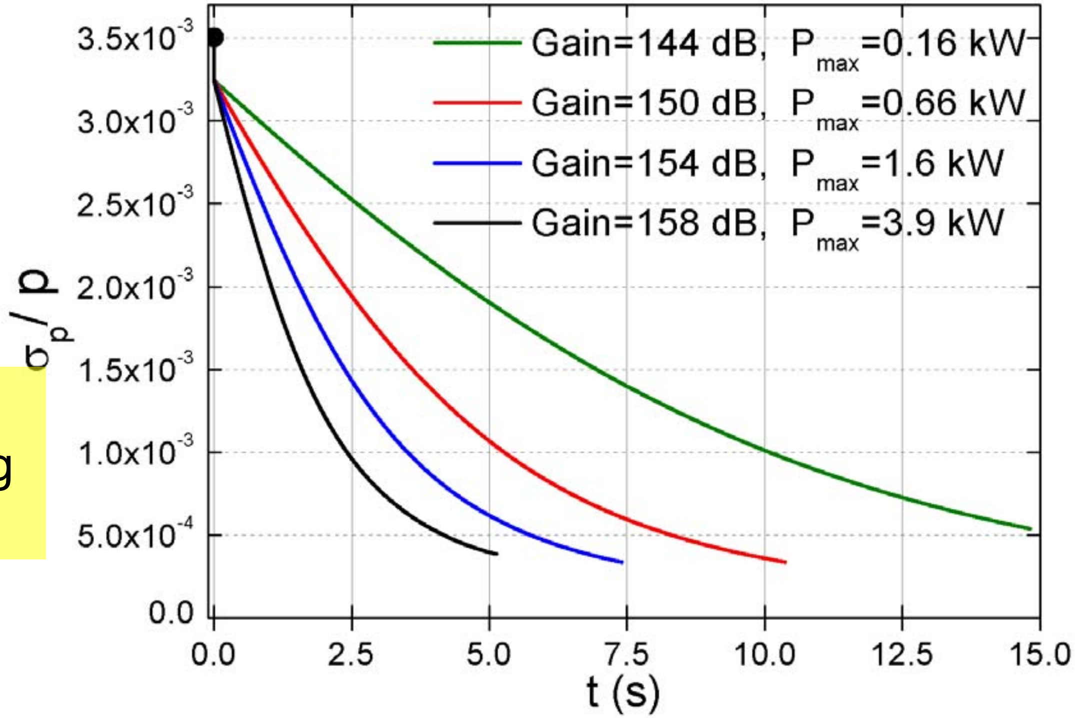
Momentum cooling: Results

Optimization:
For a given signal/noise ratio there is a gain so as to reach the desired σ_p/p in the desired time.
Lower gain leads to lower σ_p/p but cooling takes longer.

→ For ultimate σ_p/p :
increase signal/noise by plunging the PU electrodes during cooling



Total cw power in bandwidth at kicker: $P_{max} = P_s(t=0) + P_n$

Schottky $P_s(t) = \frac{1}{2}(2ef_0)^2 \, n_p \sum_m \sum_E Z_p(m) |G(E,m)|^2 \cdot \Psi(E,t)$, **decreases as σ_p/p shrinks**

filtered thermal $P_n \approx \frac{1}{4} W k T_{eff} \cdot G_{||}{}^2$

Required installed power = 4 P_{max} (to account for signal fluctuations)

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Betatron cooling rate: details

$$-\frac{1}{\varepsilon}\frac{d\varepsilon}{dt}=\frac{1}{\tau_\perp}=\frac{2W}{N}\left[2gB\,|\sin(\mu_{\text{pk}})|-g^2(M+U)\right]$$

$$B(t)\approx\cos\left(2\pi m_c x_{pk}\eta_{pk}\frac{\Delta p}{p}(t)\right)$$

$$M(t)\approx\frac{1}{m_c|\eta|\frac{\Delta p}{p}(t)}$$

Simultaneous notch filter momentum cooling ON

Ansatz from Fokker-Planck results at $G_{\|}=150\,\text{dB}$

$$\frac{\delta p}{p}(t)=\left(\frac{\delta p}{p}\right)_{ini}e^{-\frac{t}{\tau_{long}}}$$

Interplay between betatron & momentum cooling

$$U(t)=\frac{k_B T_{eff}}{Ne^2 f_0\,\beta_p\text{slope}^2 n_p}\left[\frac{f_0}{2W}\sum_{m=-\infty}^{+\infty}\frac{1}{Z_p(m)}\right]\frac{1}{\varepsilon(t)}$$

Optimum gain $g_{opt}(t)=\dfrac{B(t)\,|\sin(\mu_{\text{pk}})|}{M(t)+U(t)}$

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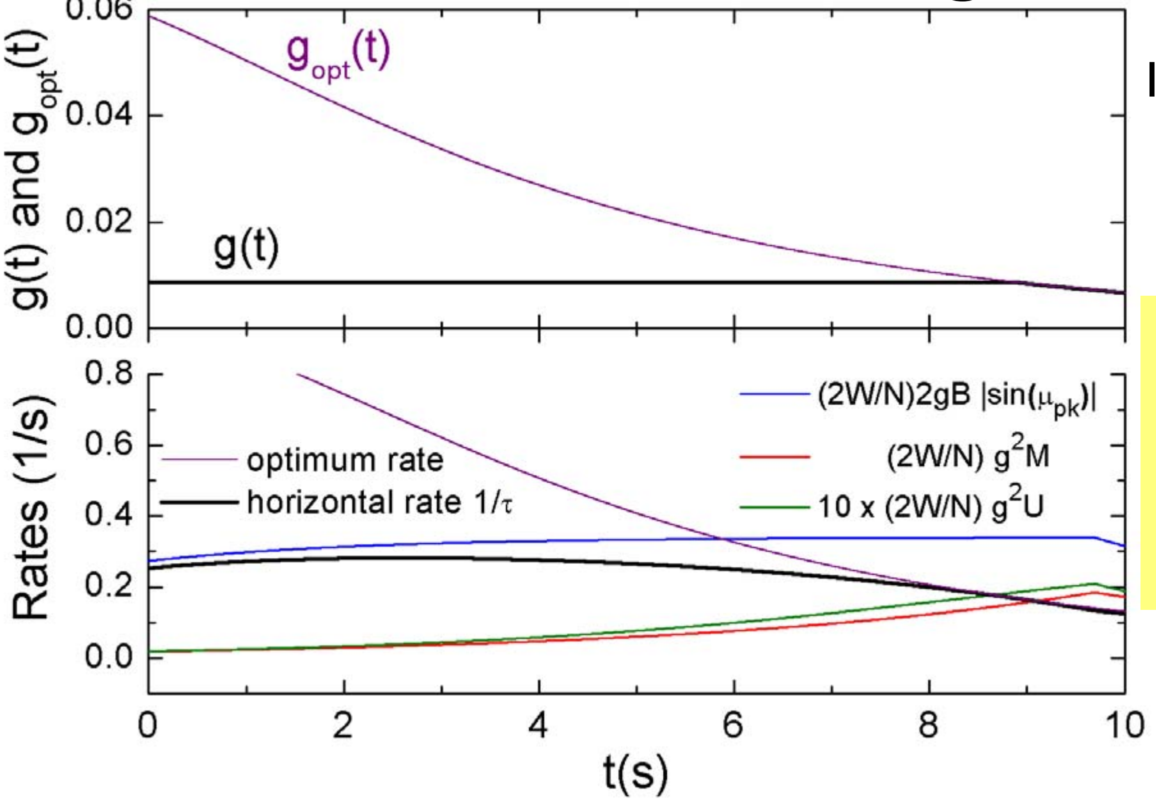
Betatron cooling: First results

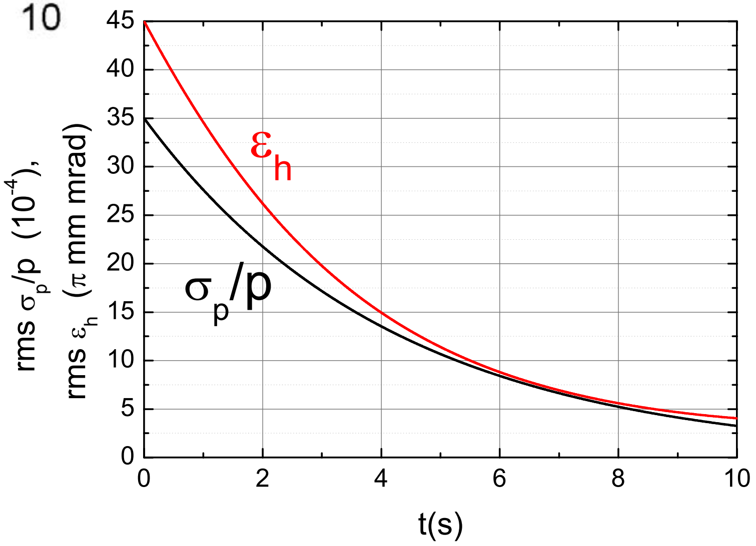


Initially:

$U = 1.2\,,\ \ M = 11$! and grows...

→ M dominates the heating at all t: M~10 U
in principle, need long cooling at very low gain
(plunging helps only at the end)

- ➢ Reached $\varepsilon_h = 4\,\pi$ mm mrad in 9 s
- ➢ Beyond power limits...cw P_{max}= 950 W !
- ➢ For precise treatment,
  feedback by the beam must be included



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Conclusions I

- ➢ Pbar filter momentum cooling from $\sigma_p/p= 3.5\ 10^{-3} \rightarrow 4\ 10^{-4}$ in 9 s is possible in the 1-2 GHz band:

- with a gain around 150 dB ($3.2\ 10^7$),
- required max. installed power ~ 2.6 kW (cw ~0.7 kW),
- assuming unplunged PU electrodes (conservative case), plunging expected to help reaching lower σ_p/p,
- feedback by the beam not negligible but loop stable.

- ➢ The design $\eta=-0.011$ of CR is optimum for both 1-2 and 2-4 GHz bands (undesired mixing)

Conclusions II

- Preliminary results show that betatron cooling is possible

- with separately optimized simultaneous filter momentum cooling (150 dB,~2.6 kW),
- down to $\varepsilon_{rms} \sim 4\ \pi$ mm mrad within 9 s,
- with an electronic gain at midband around 140 dB (10^7),
- with max. required installed power ~ 4 kW (cw ~1 kW) per plane h/v i.e. beyond the foreseen available power,
- assuming unplunged electrodes.

- As expected, betatron cooling suffers from large desired mixing M (required by filter momentum cooling) dominating the diffusion at all t.
  → Way out: slow-down momentum cooling in the beginning

Outlook

- Include feedback by the beam into betatron cooling model

- Time-optimization of momentum and betatron cooling together, distribution of available power accordingly, e.g.,

- Initially, slower filter cooling to help the betatron cooling, then inversely to reach ultimate emittances and momentum spread.
- Apply initially time-of-flight and later notch filter momentum cooling, with simultaneous betatron cooling.

- Include plunging of PU electrodes, expected to reduce diffusion by factors 4-9, especially transversally

- Additional filter momentum cooling in the 2-4 GHz band, study handshake between 2 bands