Stochastic Cooling

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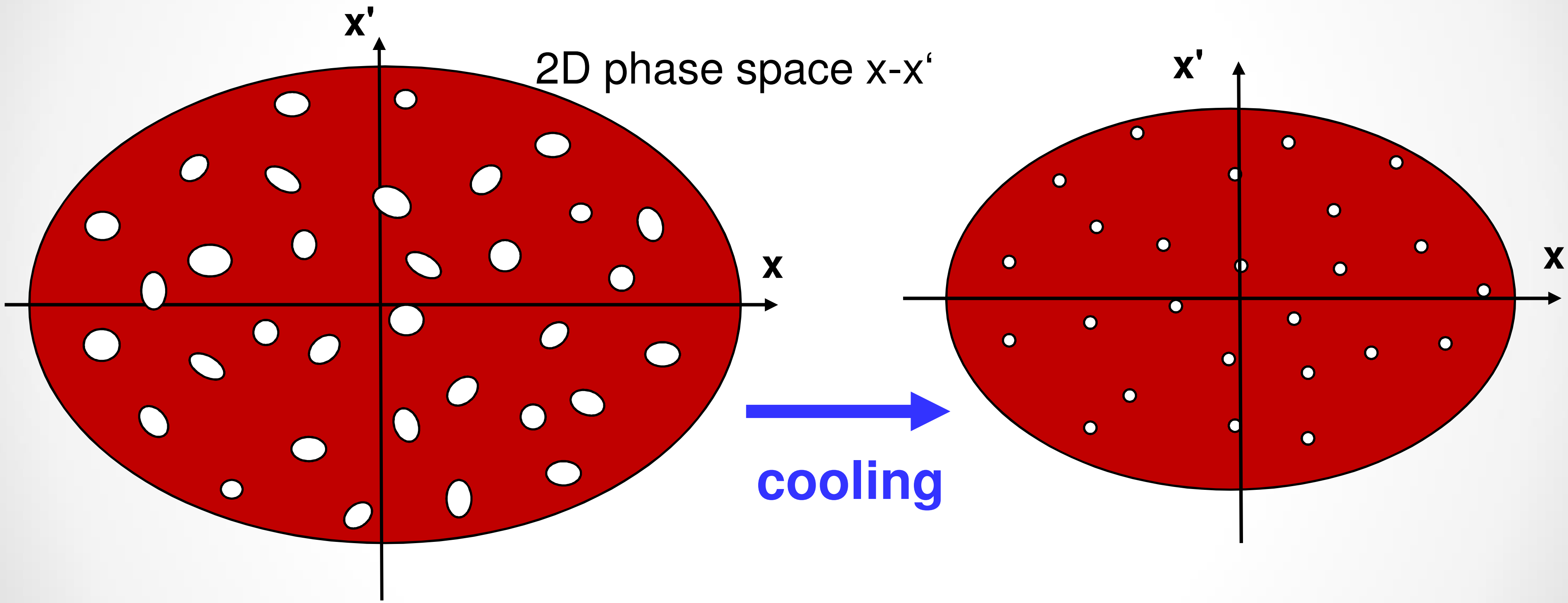
Metalskolen, Slangerup, Denmark,

9 - 21 June 2019

Fluctuations in Phase Space

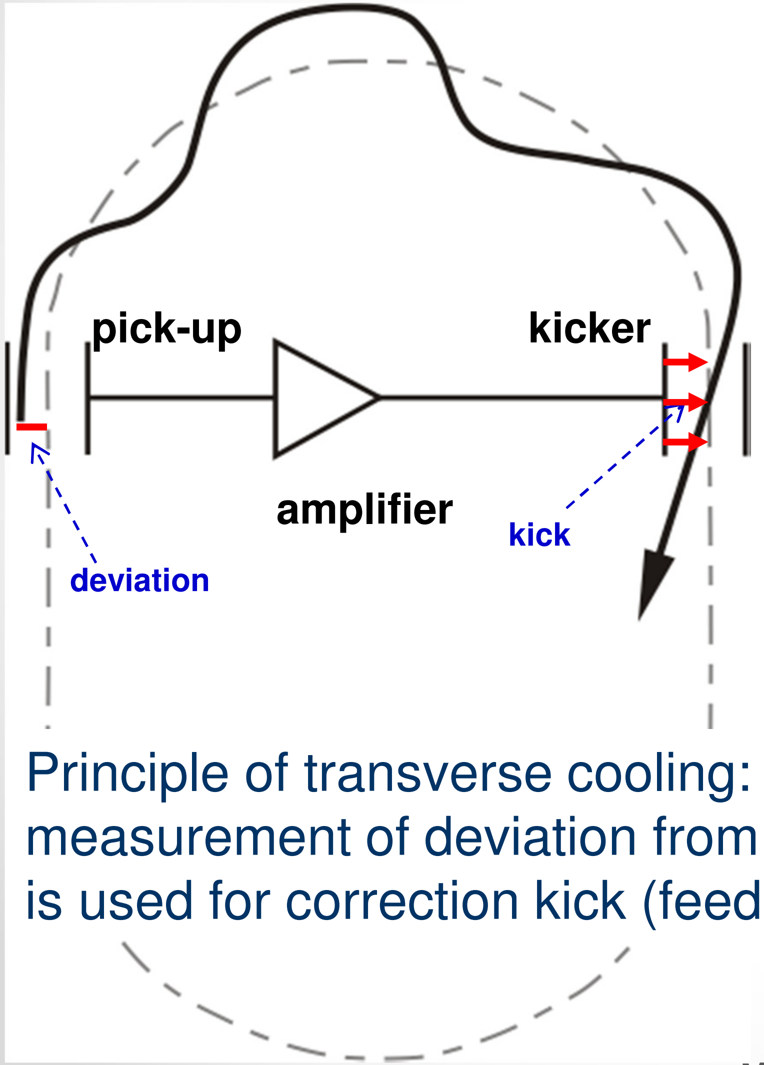
phase space is not homogeneously filled with particles
⇒ fluctuations of local particle density



compression of total phase space volume by reduction of locally empty phase space volume

Stochastic Cooling

First cooling method which was successfully used for beam preparation



S. van der Meer, D. Möhl, L. Thorndahl et al.
(1925 – 2011) (1936-2012)

Conditions:

Betatron motion phase advance (pick-up to kicker): $(n + ½)\ \pi$

Signal travel time = time of flight of particle (between pick-up and kicker)

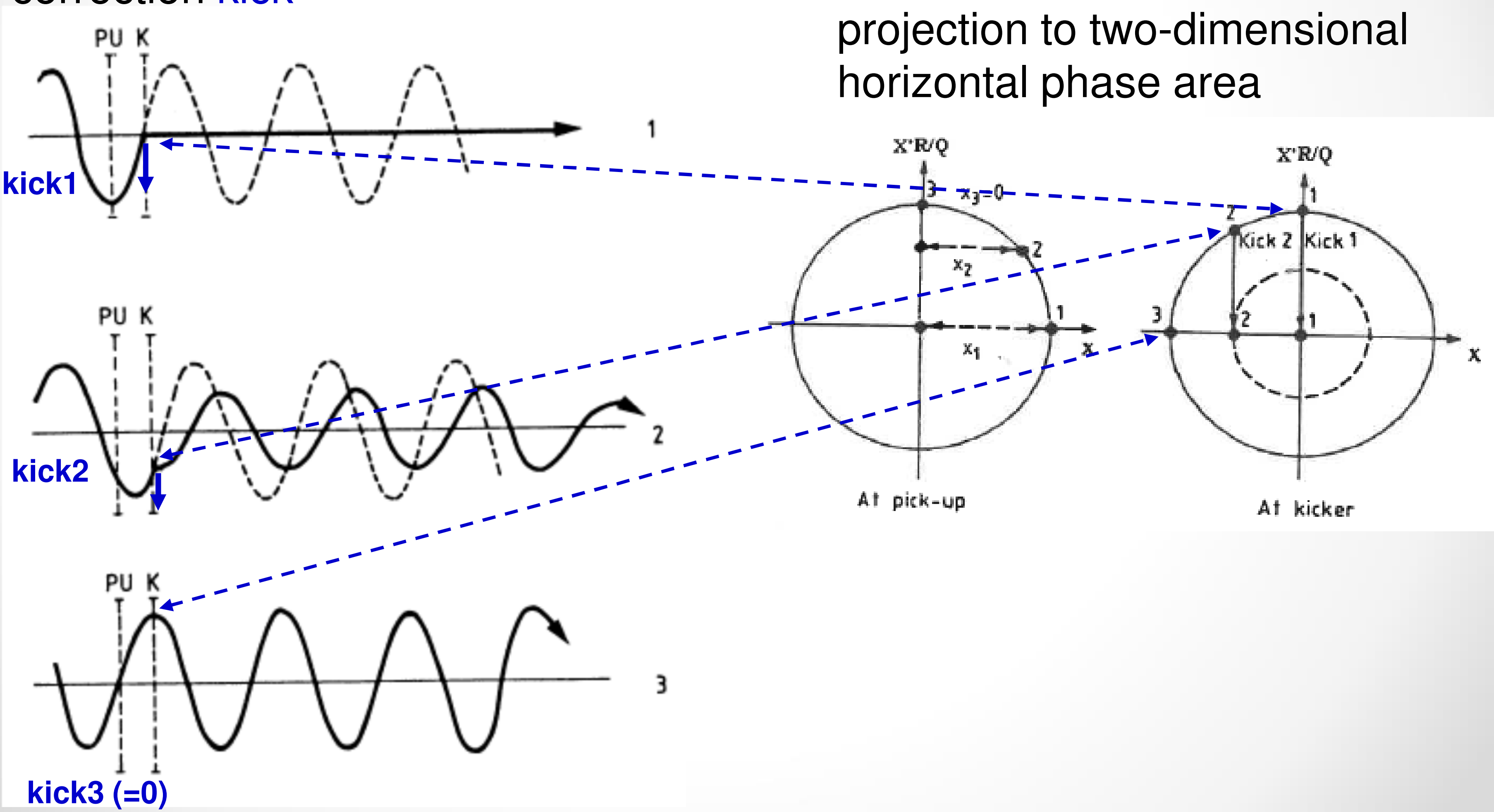
Sampling of sub-ensemble of total beam

Principle of transverse cooling:
measurement of deviation from ideal orbit
is used for correction kick (feedback)

Stochastic Cooling

single particle betatron motion
along storage ring
without (dashed) and with (full)
correction kick

projection to two-dimensional
horizontal phase area

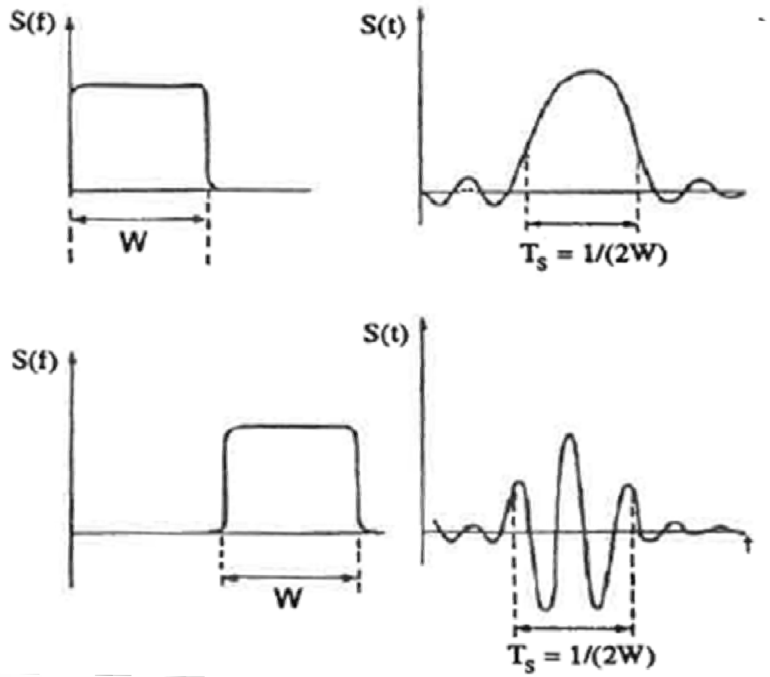


Stochastic Cooling

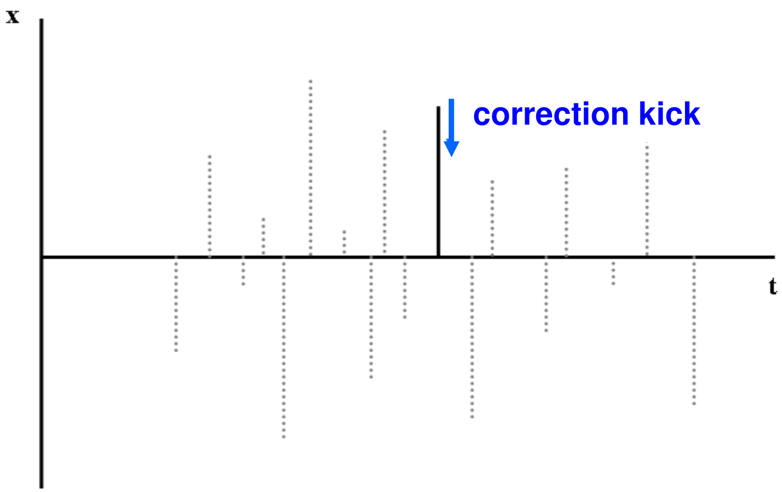
Nyquist theorem: a system with a band-width $\Delta f = W$ in frequency domain can resolve a minimum time duration $\Delta T = (2W)^{-1}$

low pass

band pass



Stochastic Cooling

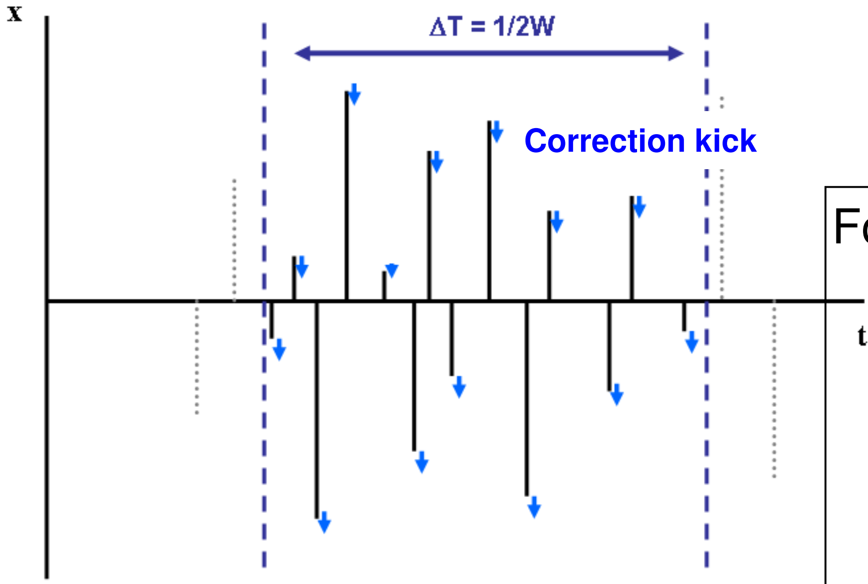


in time domain

correction kick
(unlimited time resolution)

$$-\Delta x = g \times x$$

Nyquist ⇒ the time resolution for a system of bandwidth W is $\Delta T = (2W)^{-1}$



correction kick with bandwidth W

$$-\Delta x = \frac{g}{N_s} \times \sum_{i=1..N_s} x_i \ , \quad N_s = N \frac{\Delta T}{T_0} = \frac{N}{2WT_0}$$

For exponential damping ($x(t) = x(t_0) \times e^{-(t-t_0)/\tau}$):

$$\tau^{-1} = T_0^{-1} \times \frac{\Delta x}{x} = \frac{g2W}{N}, \ if \sum_{i=1..N_s} x_i = x$$

cooling rate

$$\tau^{-1} \leq \frac{2W}{N}, \ if \ g \leq 1$$

Stochastic Cooling

some refinements of cooling rate formula

noise: thermal or electronic noise adds to the beam signal

mixing: change of relative longitudinal position of particles due to momentum spread

cooling rate $$\lambda = \tau^{-1} = \frac{2W}{N}(\underbrace{2g}_{\text{cooling}} - \underbrace{g^2(M+U)}_{\text{heating}})$$

M mixing factor

U noise to signal ratio

maximum of cooling rate

$$\lambda_{max} = \frac{2W}{N}\frac{1}{M+U}$$

$$\frac{d\lambda}{dg} = 0 \Rightarrow g = \frac{1}{M+U}$$

further refinement (wanted ↔ unwanted mixing):

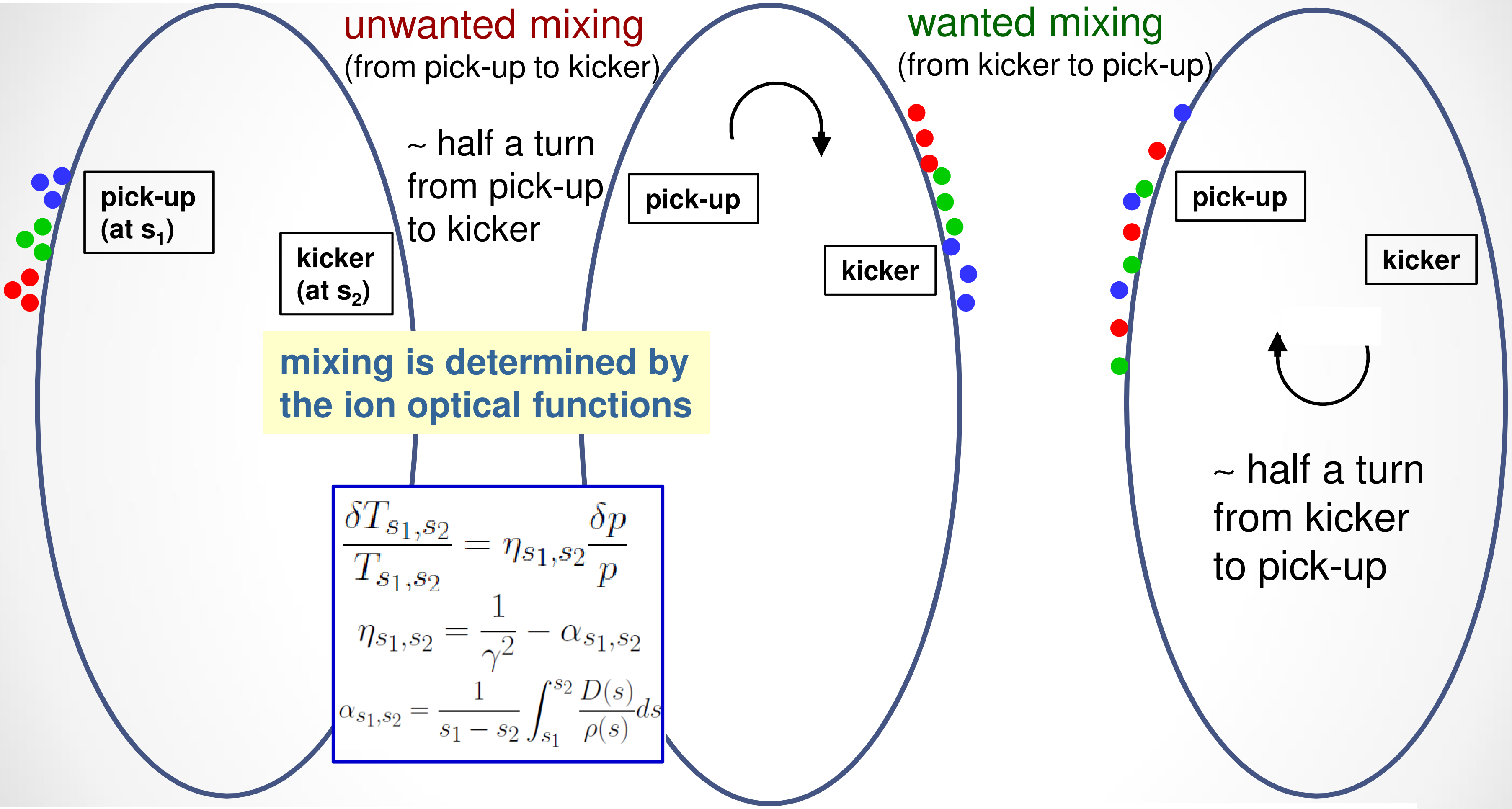
with wanted mixing M (kicker to pick-up)

and unwanted mixing $\tilde{M}$ (pick-up to kicker)

$$\lambda = \tau^{-1} = \frac{2W}{N}(2g(1-\tilde{M}^{-2}) - g^2(M+U))$$

Mixing

$$\lambda = \tau^{-1} = \frac{2W}{N}\left(2g(1-\tilde{M}^{-2}) - g^2(M+U)\right)$$



mixing is determined by the ion optical functions

$$\frac{\delta T_{s_1,s_2}}{T_{s_1,s_2}} = \eta_{s_1,s_2}\frac{\delta p}{p}$$

$$\eta_{s_1,s_2} = \frac{1}{\gamma^2} - \alpha_{s_1,s_2}$$

$$\alpha_{s_1,s_2} = \frac{1}{s_1 - s_2}\int_{s_1}^{s_2}\frac{D(s)}{\rho(s)}ds$$

$$1-\widetilde{M}^{-2} \approx \cos\left[0.5\pi\ \eta_{eff}\ n_{max}(\Delta p/p)_{rms}\right]$$

$\Rightarrow \eta_{eff} \sim 0$

$$M = (2WT\eta(\Delta p/p)_{rms})^{-1}$$

$\Rightarrow \eta_{k\text{-}pu} > 0,\ (T\eta(\Delta p/p_{rms}))^{-1} \sim 1$

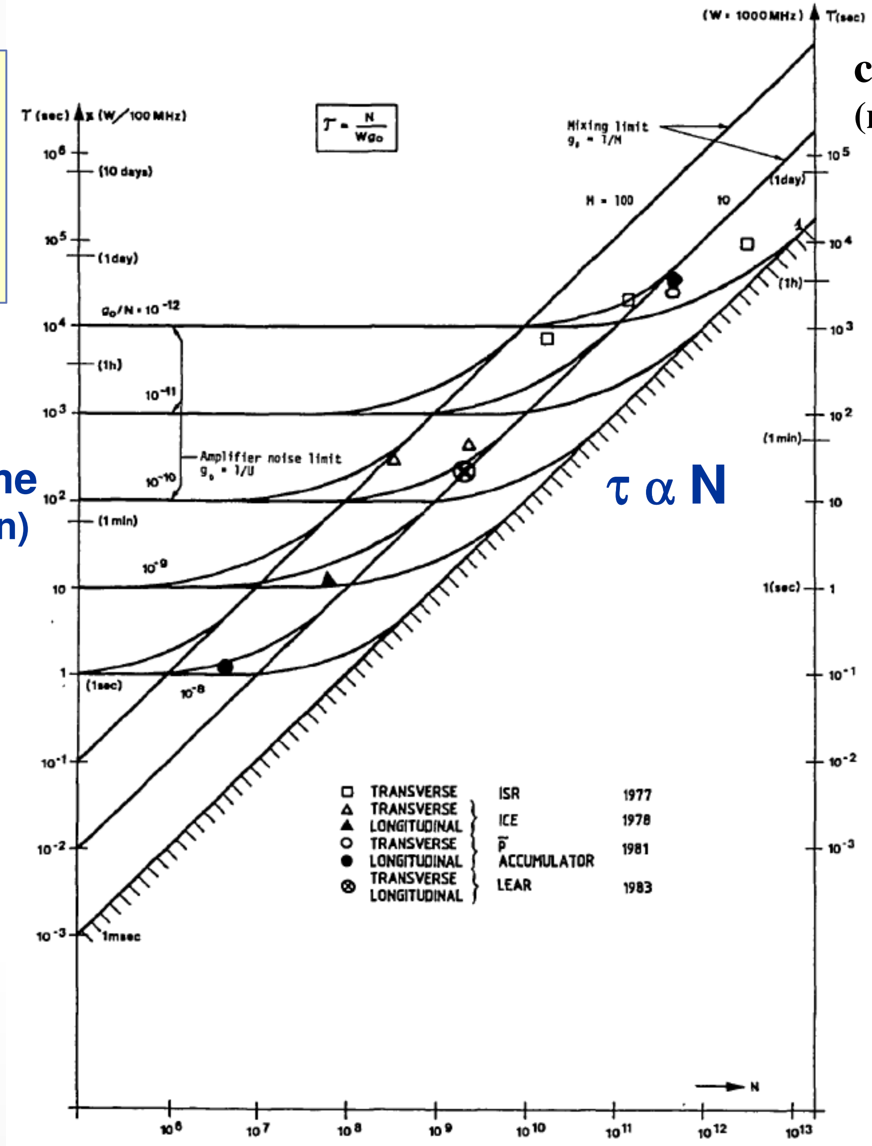
Basic Studies of Stochastic Cooling

summary of initial stochastic cooling studies at CERN with (anti-)protons

cooling time
(normalized to 1 GHz bandwidth)

mixing limit regime

noise limit regime
(depending on gain)



$\tau \propto N$

particle number

Requirements Stochastic Cooling

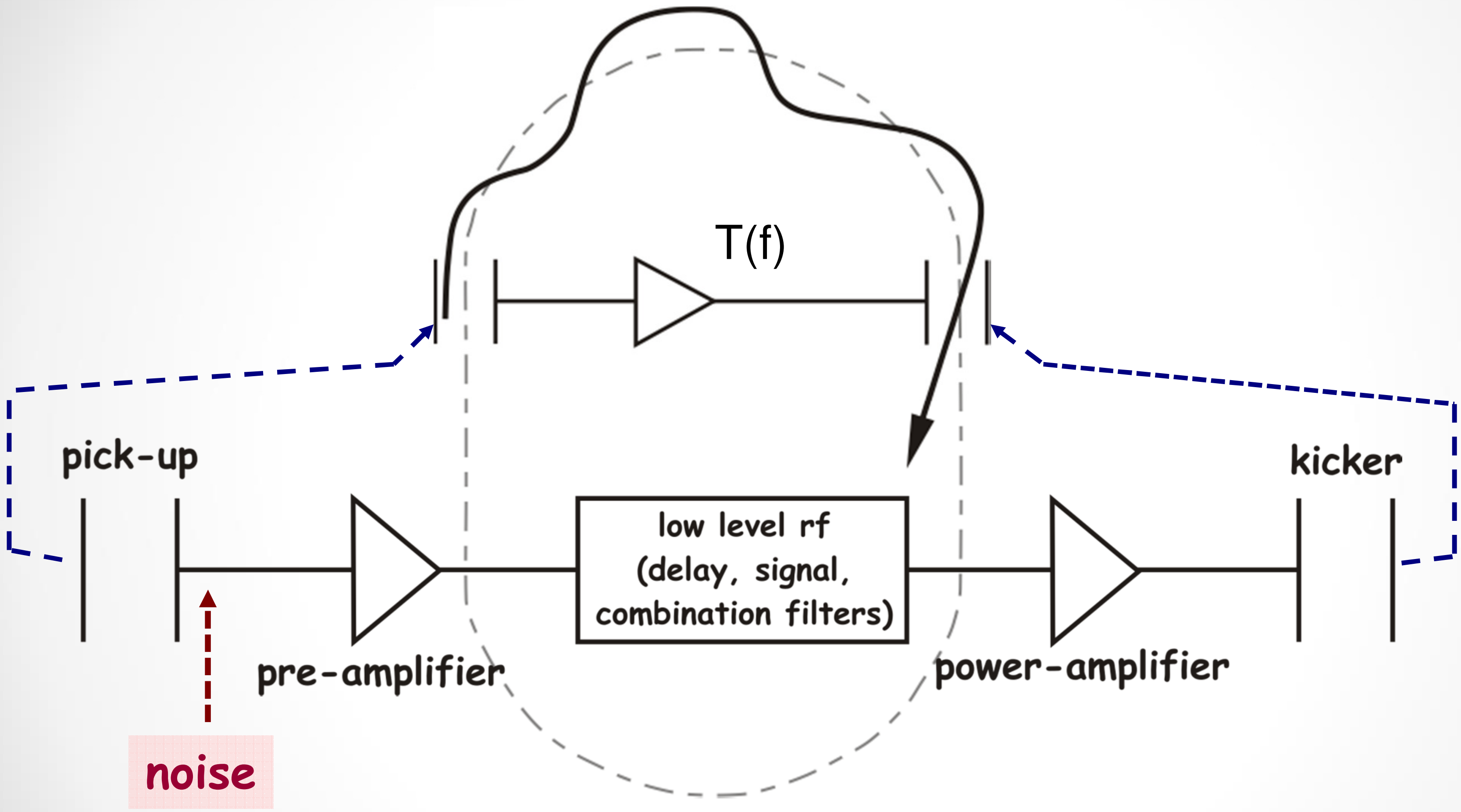
- large bandwidth (typically one octave in the GHz range)
- good transfer function in gain and phase
- high sensitivity (high impedance) of pick-up and kickers
- low electronic noise (cold pick-ups, low noise amplifiers)
- large, but variable gain
- special ion optical properties of the ring

  betatron phase advance between transverse pick-up and kicker

  small momentum slip factor (large wanted and little unwanted mixing)

  for Palmer cooling: large dispersion value at pick-up

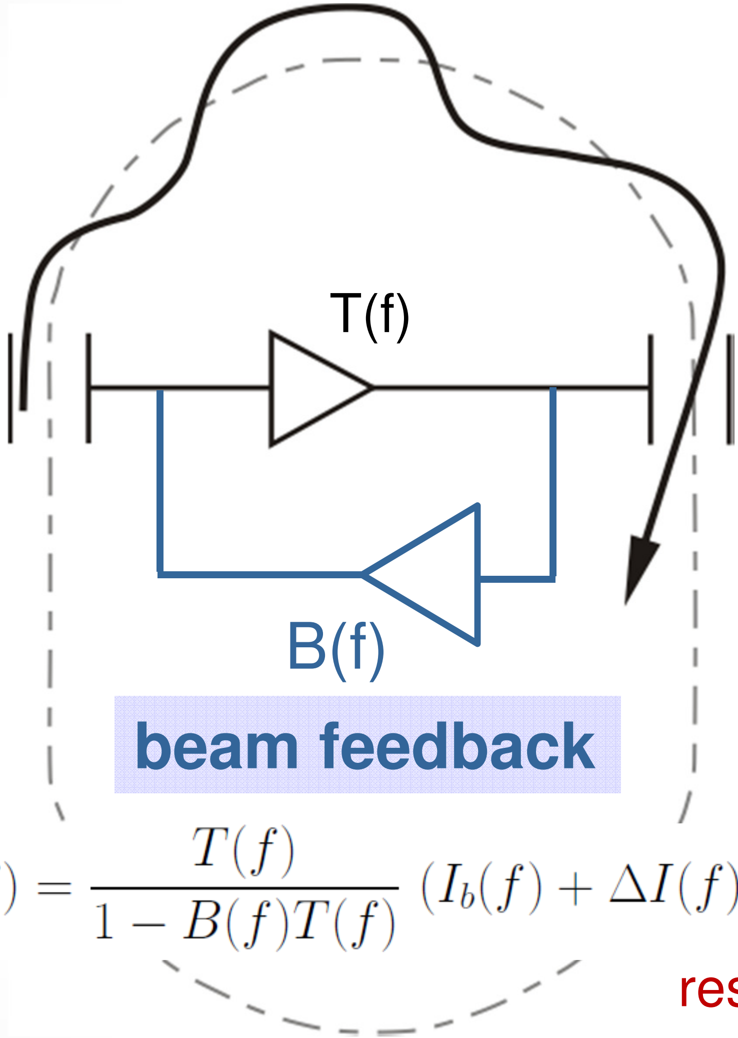
Stochastic Cooling Circuit



energy kick: $\delta E(f) = T(f)\, I_b(f)$

transfer function: $T(f) = Z_{pu} \cdot G_{pu}(f) \cdot H(t_{delay}) \cdot F(f) \cdot G_k(f) \cdot Z_{ki}$

Stochastic Cooling Circuit



kick: $\delta E(f) = \frac{T(f)}{1 - B(f)T(f)} \left(I_b(f) + \Delta I(f)\right)$ $\Delta I(f) = B(f) \cdot \Delta E(f)$

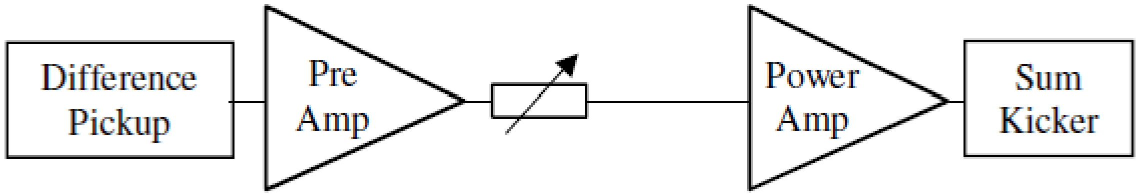
results in shielding and
a reduction of Schottky noise
⇒ reduction of gain

open loop gain: $S(f) = B(f) \cdot T(f)$

Longitudinal Stochastic Cooling

1) Palmer cooling

a pick-up in a dispersive section detects the horizontal position
(sensitivity to the particle longitudinal momentum)



at the kicker the correction signal derived from the position
results in an acceleration/deceleration kick
which counteracts a momentum deviation

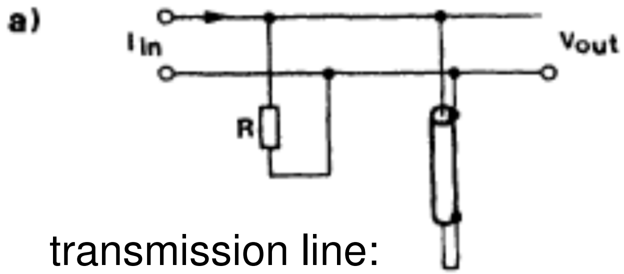
(coupling longitudinal-horizontal degree of freedom can
cause heating $\Rightarrow$ compensation by horizontal cooling system)

Longitudinal Stochastic Cooling

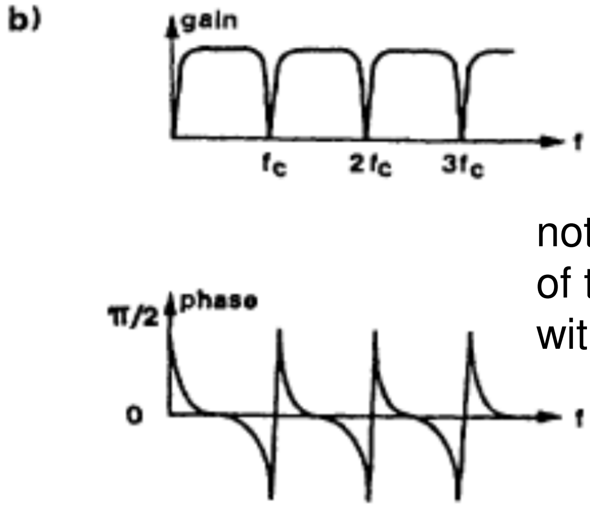
2) Notch filter cooling

filter creates notches at the harmonics of the nominal revolution frequency

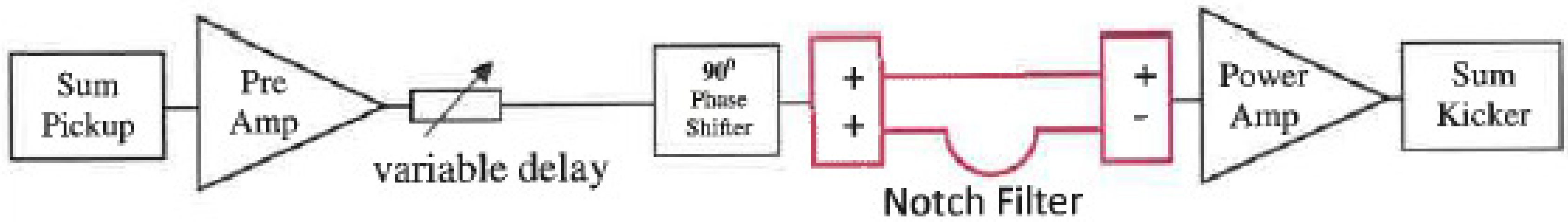
⇒ particles are forced to circulate at the nominal frequency



transmission line:
signal delay by one turn,
short circuit at all harmonics
of the revolution frequency



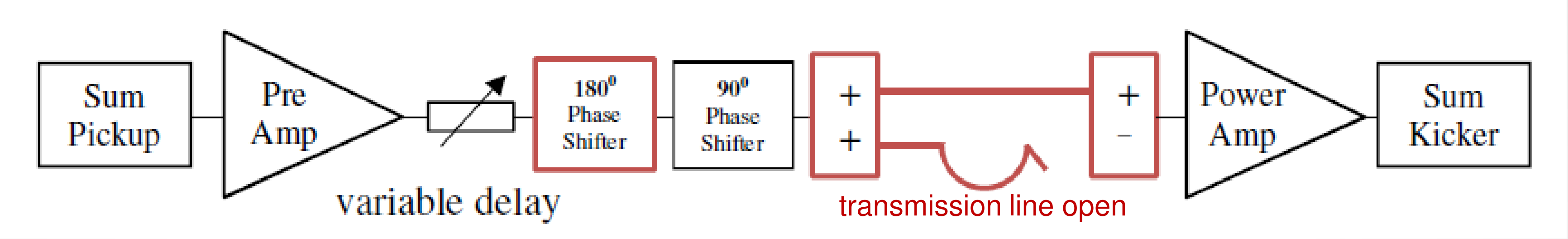
notches at harmonics
of the revolution frequency
with 180º phase jump



Longitudinal Stochastic Cooling

3) **ToF cooling**

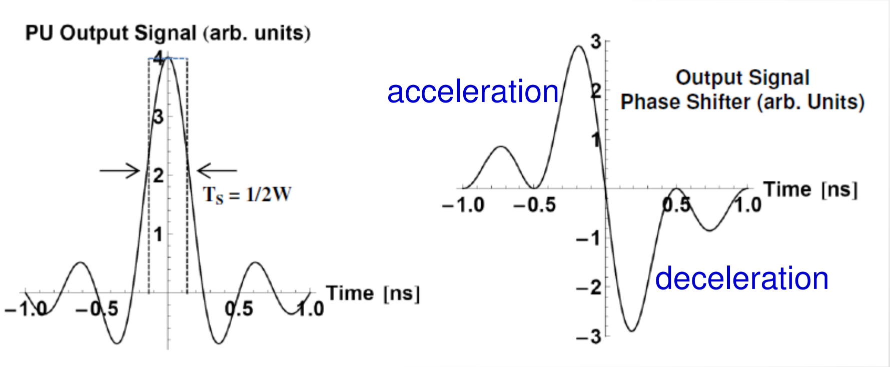
simplified scheme without notches allows efficient pre-cooling



compared to notch filter cooling the delay line is open and

a 90° phase shifter is added

⇒ differentiation of the signal



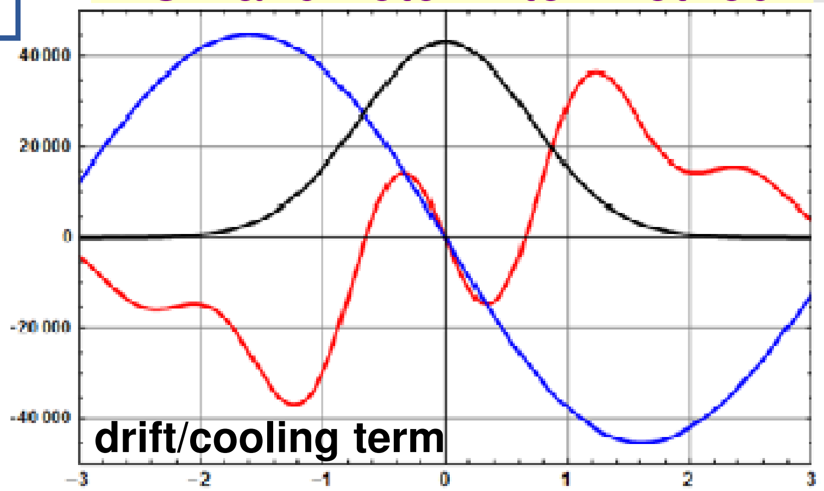
without phase shift

with 90° phase shift

Fokker-Planck Equation

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

longitudinal cooling
TOF and notch filter method



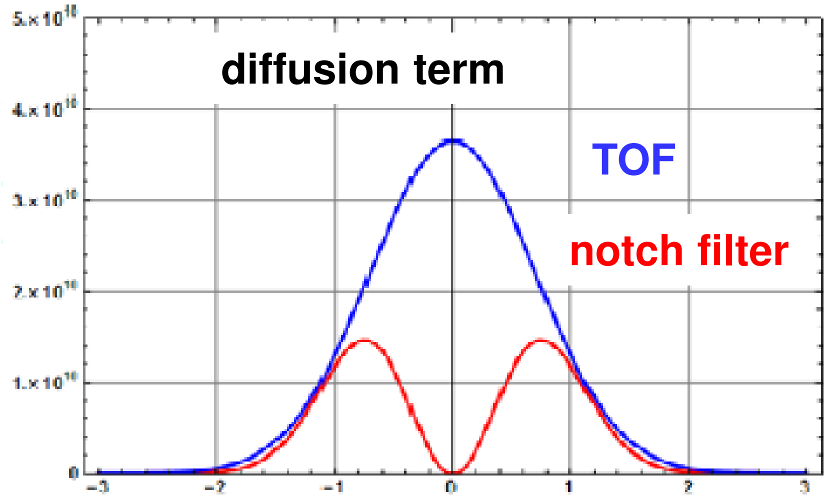
distribution function $\psi(\delta, t)$

coordinate $\delta = x, y, \delta p/p$

cooling term $F(\delta, t) = f_0\ \delta$

diffusion term $D(\delta, t) = \frac{1}{2}\ f_0\ \langle(\delta)^2\rangle$

$\Delta\delta = -g\frac{2W}{Nf_0}\delta \qquad <(\Delta\delta)^2> = g^2\ \delta_n{}^2{}_{rms}$



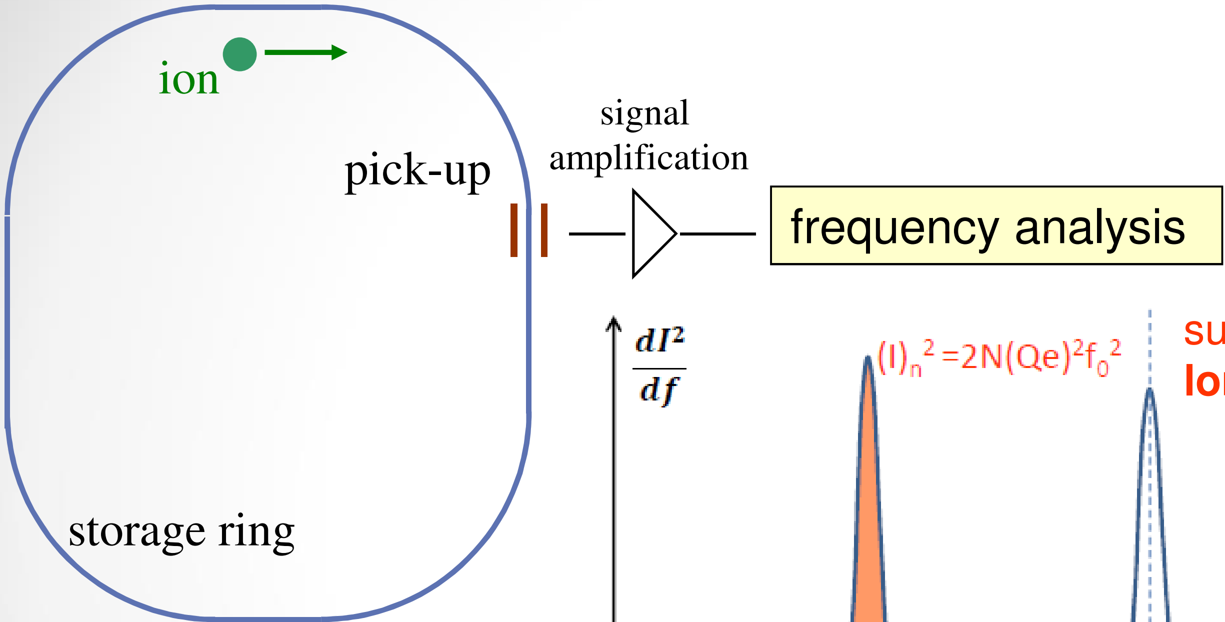
momentum deviation $\delta p/p$ [10^{-3}]

equilibrium distribution ($\frac{\delta\psi}{\delta t}$ =0) is a Gaussian

$$\psi(\delta) = \frac{N}{\sqrt{2\pi}\sigma}\exp[-\delta^2/(2\sigma^2)]$$

$$\sigma = \sqrt{\frac{D}{g}\frac{N}{2W}}$$

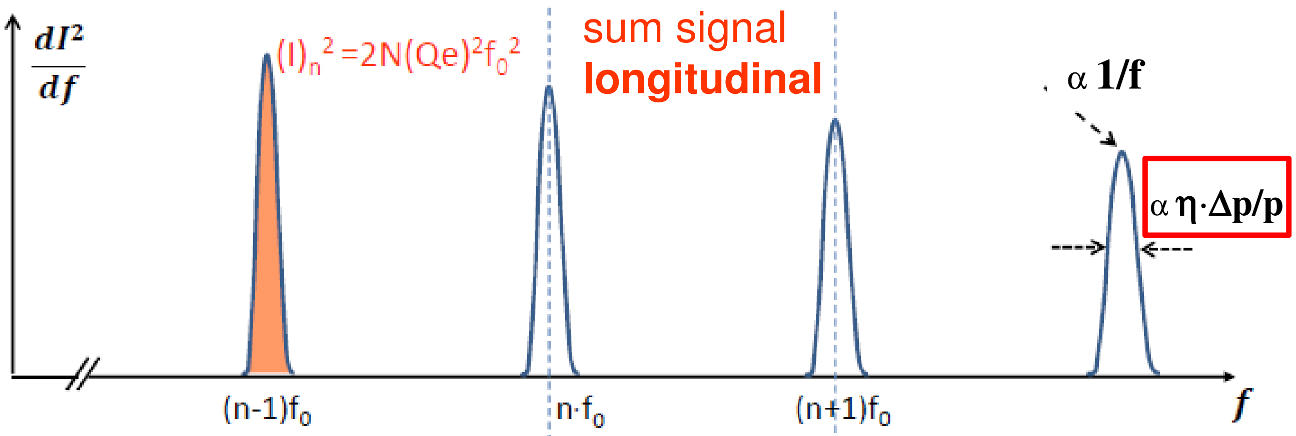
Schottky Diagnostics



momentum slip factor η

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_t^2}$$

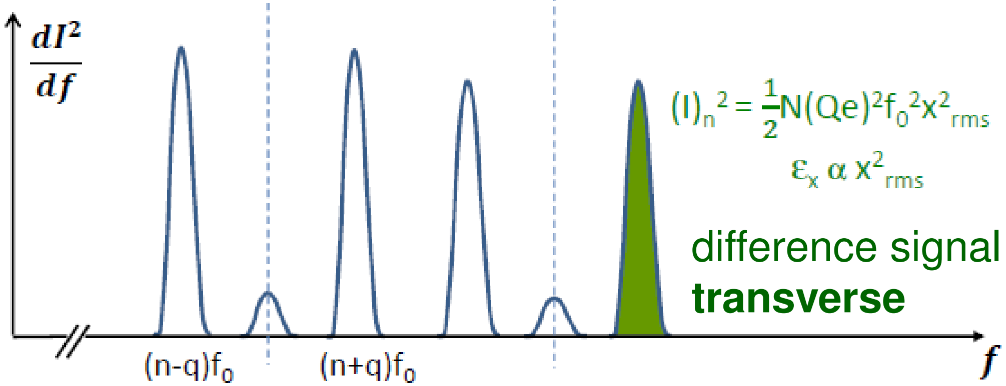
transition energy γ_t



measurement of momentum spread

$$\frac{\Delta p}{p} = \frac{1}{\eta}\frac{\Delta f}{f}$$

N particle number
f_0 revolution frequency
Qe ion charge
n harmonic number
q non-integer tune



measurement of transverse emittance

$$(I)_n^2 \; \alpha \; \varepsilon_x$$

Comparison of Longitudinal Cooling Methods

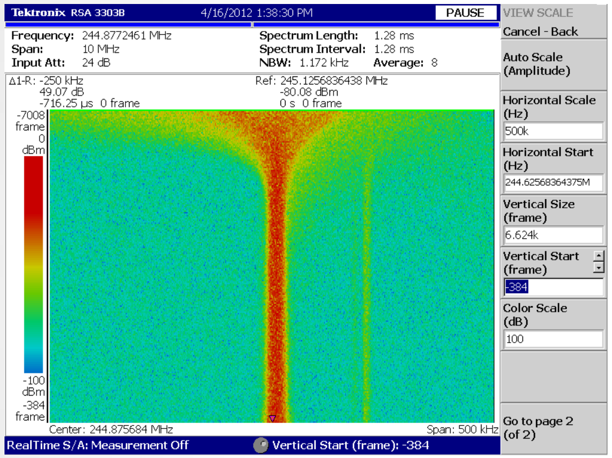
Ar^{18+} 400 MeV/u

longitudinal momentum distribution versus time

measured at the ESR heavy ion storage ring

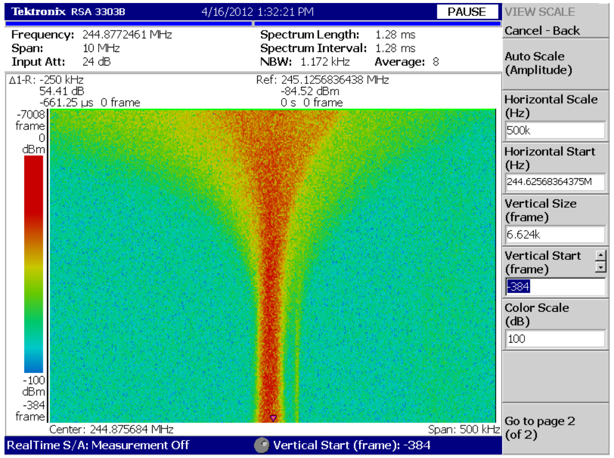
Schottky signal observed at 245 MHz (h=124)

Palmer cooling



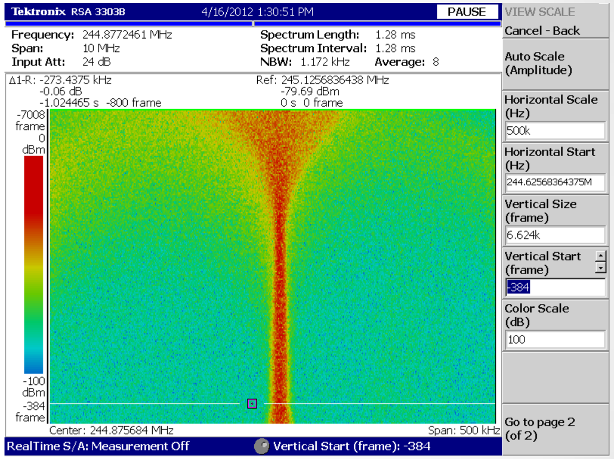
- large momentum capture range
- fast cooling
- good final momentum spread
- drawback: horizontal heating needs to be compensated by horizontal cooling

Time-of-Flight cooling



- large momentum capture range
- slower cooling
- moderate final momentum spread
- simple set-up
- no special lattice requirement

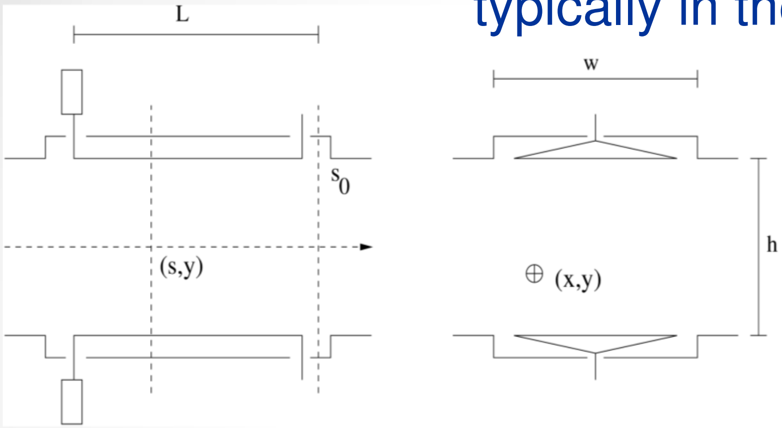
Notch filter cooling



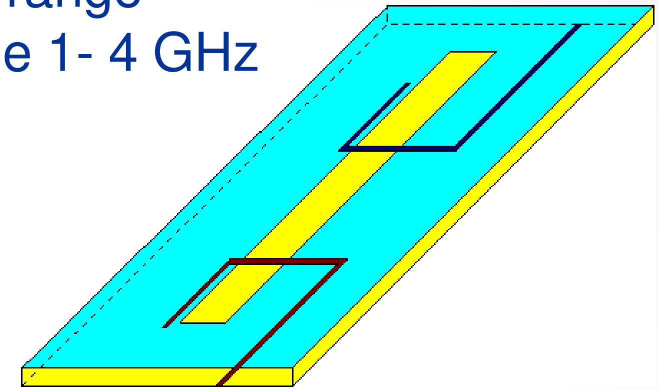
- reduced momentum capture range
- good cooling rate
- smallest final momentum spread
- most elaborate rf hardware
- issue of notch filter stability

Electrode Structures

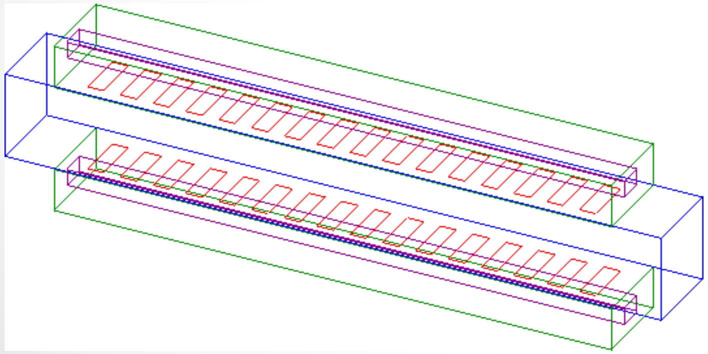
electrode size matched to the frequency range
typically in the range 1- 4 GHz



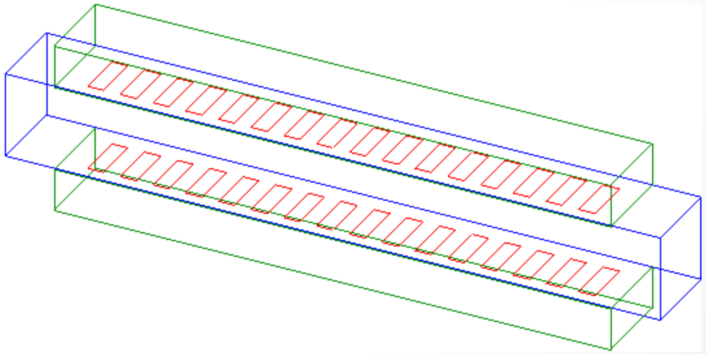
quarter wave pick-up
universal backward coupler



transverse slotline pick-up
transverse microwave slotline
coupled to two microstrip lines



Faltin type structure
travelling wave coaxial waveguide
with slot coupling



slotted waveguide structure
travelling wave rectangular waveguide
with slot coupling

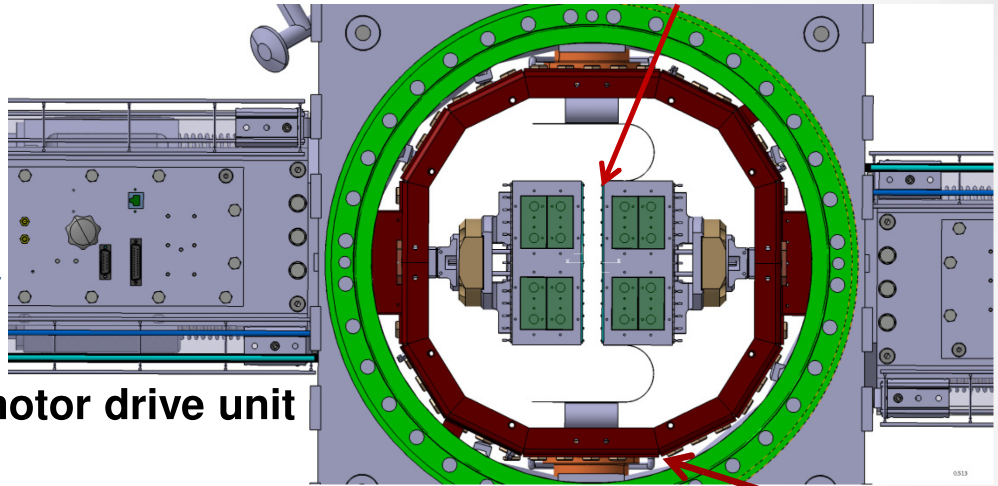
Movable Electrodes

pioneered by the plunging system of CERN AC

more recently developed for:

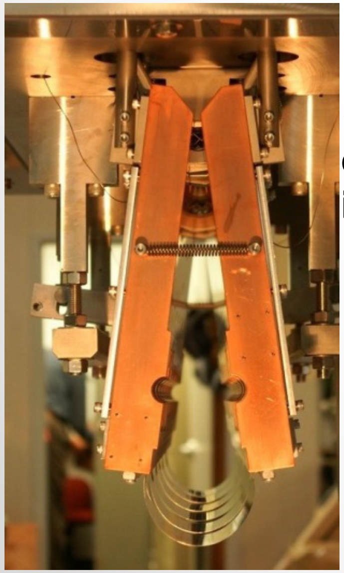
FAIR Collector Ring
stochastic cooling
improvement of sensitivity
repetition time down to 1 s
cooling during motion

electrodes cooled to 30 K



motor drive unit

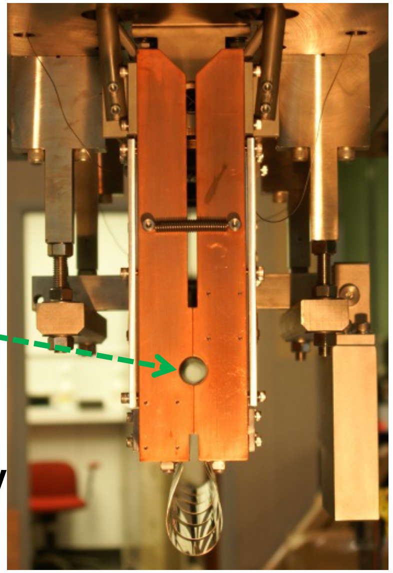
cryogenic shield at 80 K



open position during injection and ramping

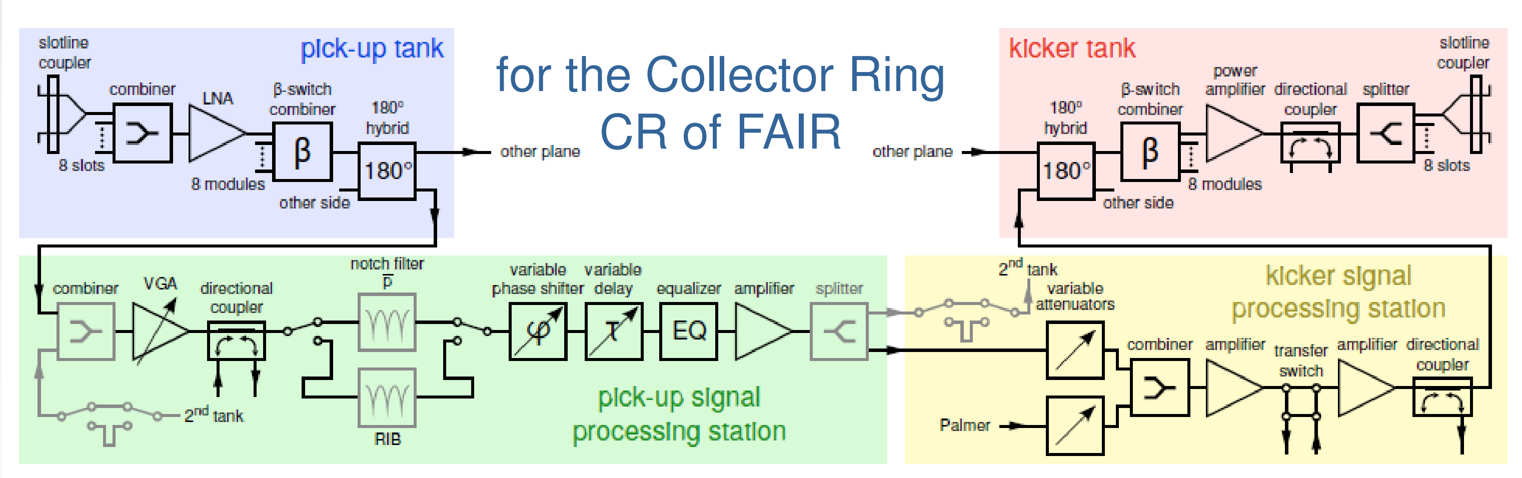
beam opening

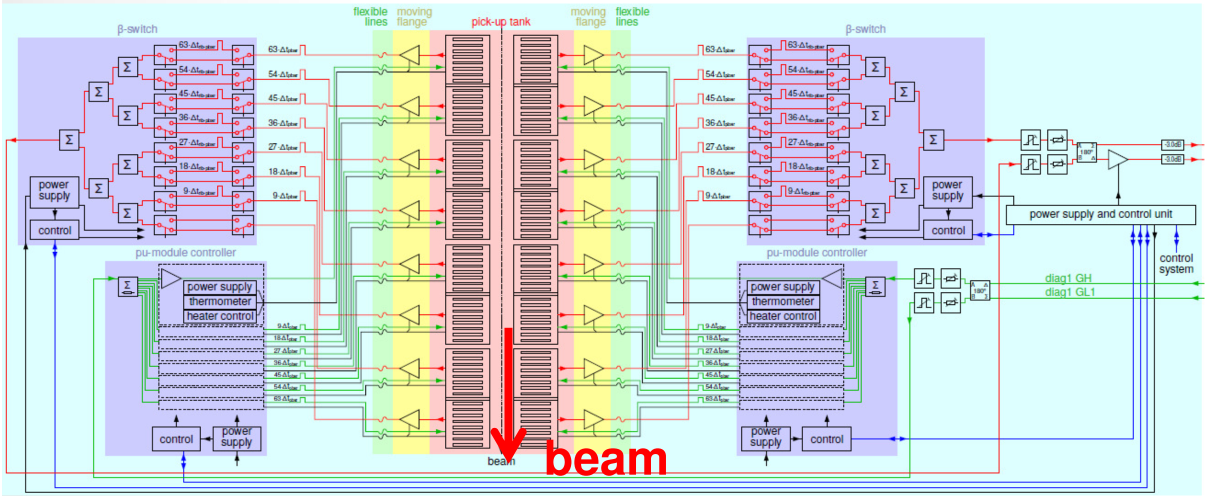
closed for operation at the collision energy



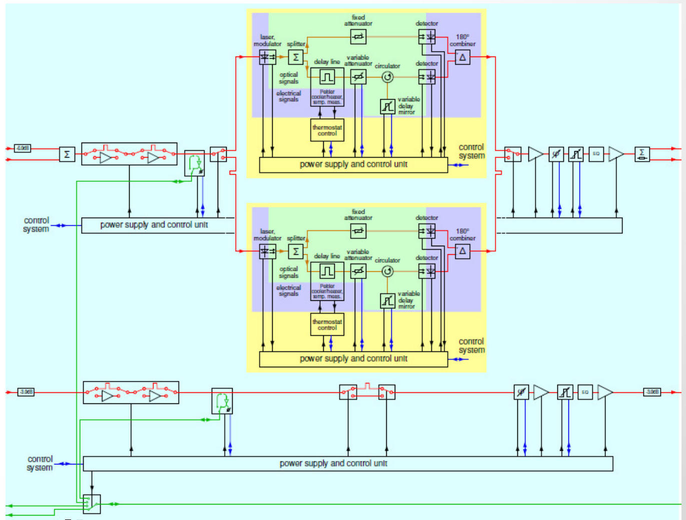
BNL RHIC Collider
operation after acceleration
in the collision mode
repetition time many hours
cooling after acceleration and closing

Stochastic Cooling RF Components





signal processing:
delay, sum/difference, differentiation, filtering



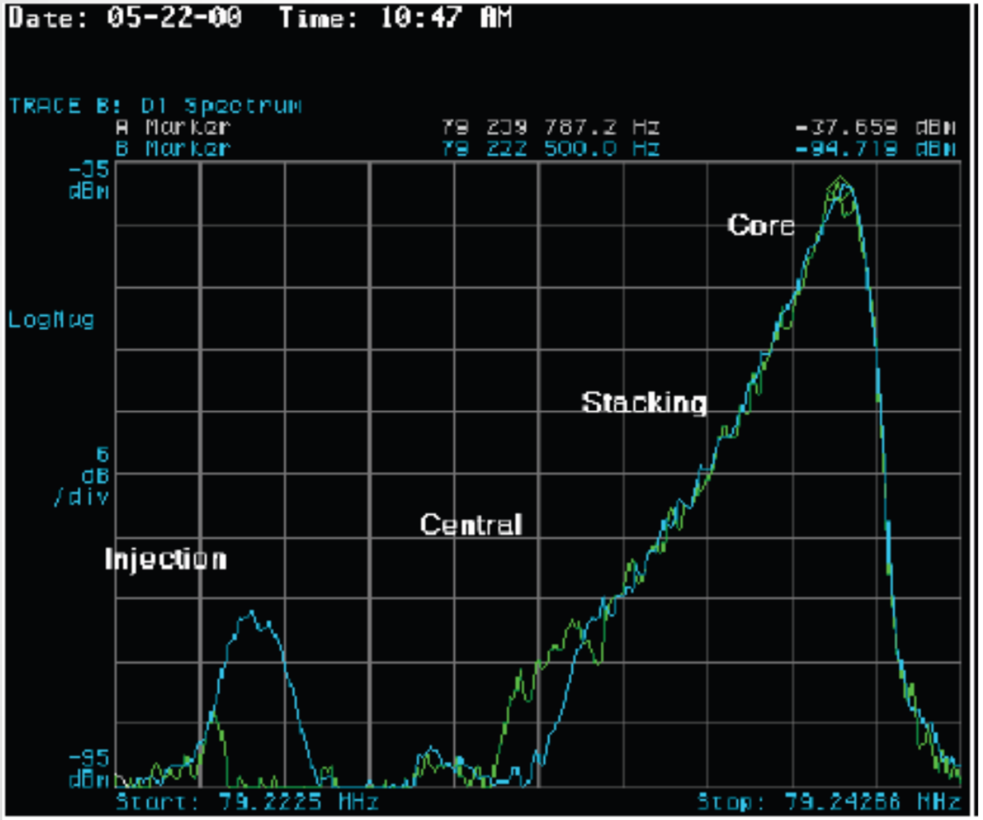
pick-up (kicker) tank

summing of signals from different pick-ups along the beam with matched delay

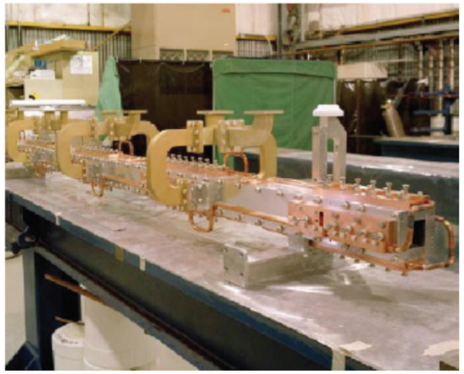
sum/difference of the two sides for longitudinal/transverse cooling

Antiproton Accumulation by Stochastic Cooling

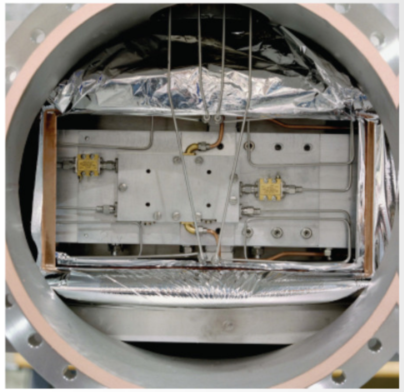
accumulation of 8 GeV antiprotons at accumulator ring, FNAL, shut down 09/2011
a similar facility AC/AA at CERN was operated until 11/1996



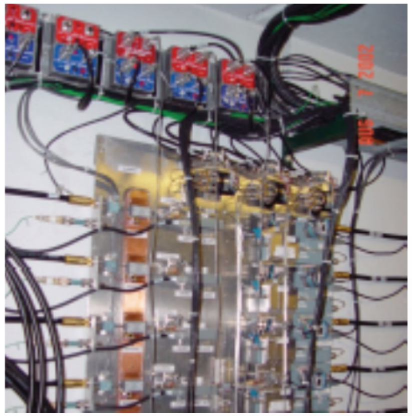
momentum distribution of accumulated antiproton beam



kicker array



cryogenic microwave amplifier

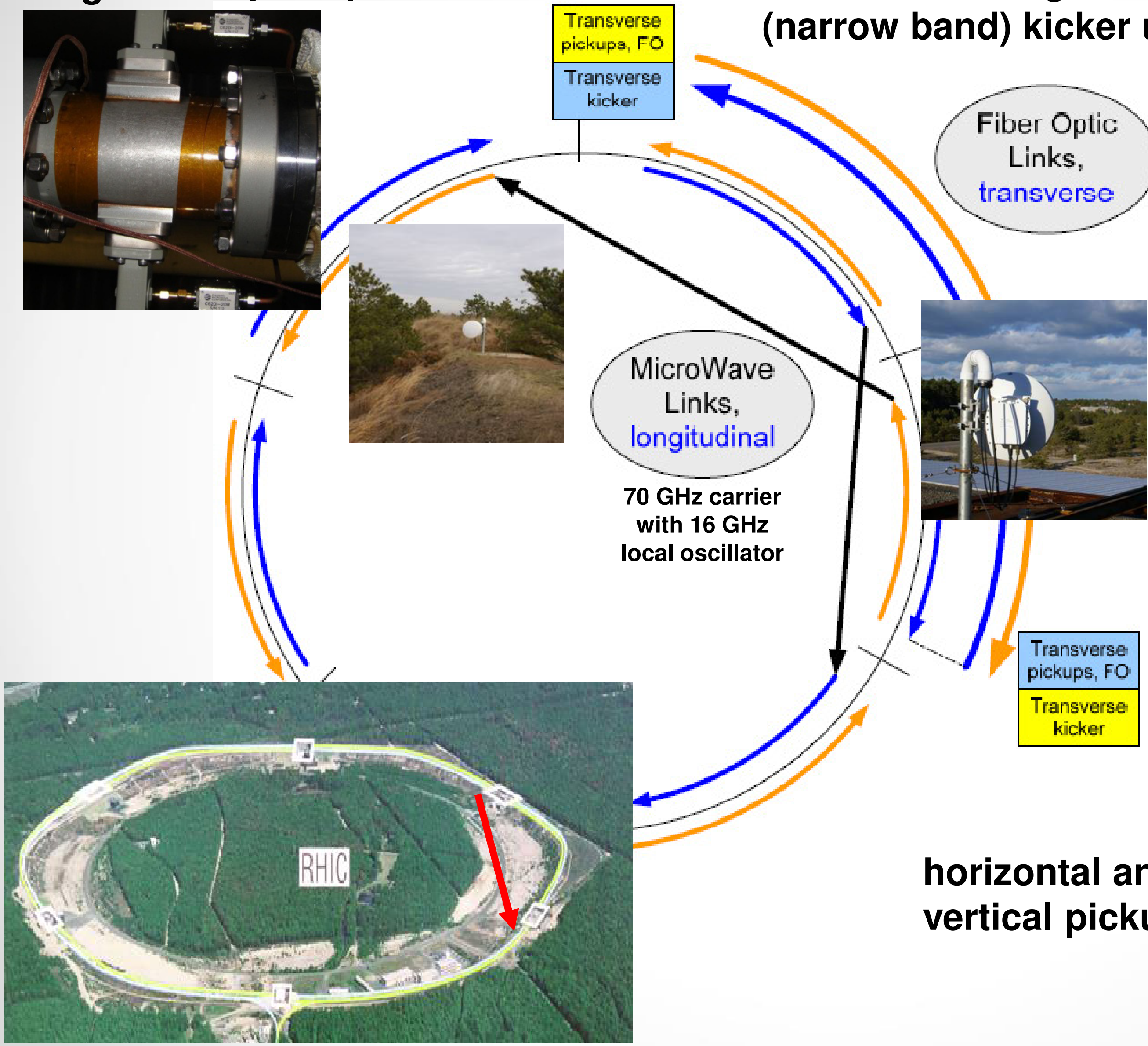


microwave electronics

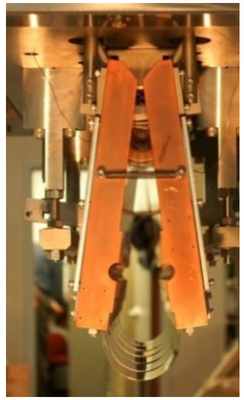
power amplifiers (TWTs)

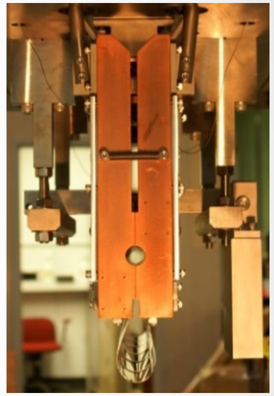
RHIC – 3D stochastic cooling for heavy ions

longitudinal pickup



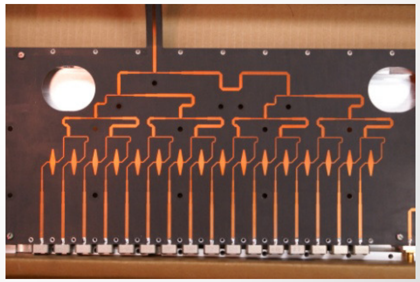
3 tanks with longitudinal (narrow band) kicker units





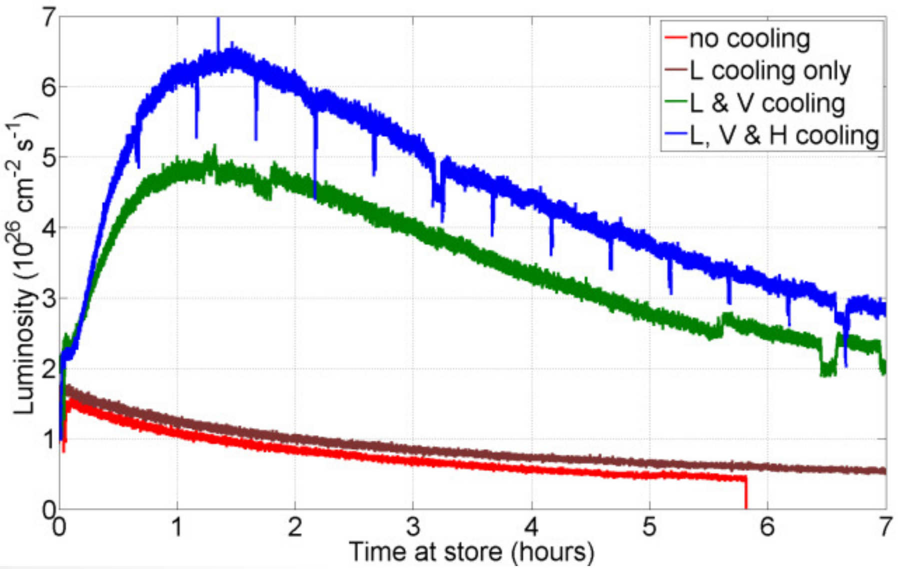
longitudinal kicker open for injection and ramping (left), closed during cooling (right)

horizontal and vertical pickups

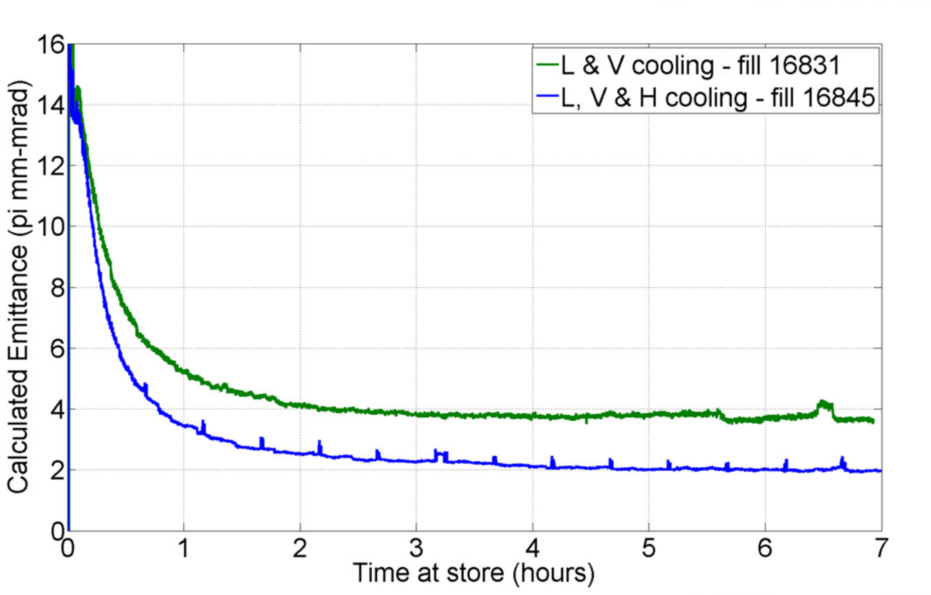


RHIC Luminosity production

luminosity with/without stochastic cooling



beam emittance during store



For Uranium-on-Uranium collisions the cooling increased the integrated luminosity per store by a factor of 5

The transverse emittances were reduced by x 4 with a cooling time of ½ hour

M. Brennan et al.

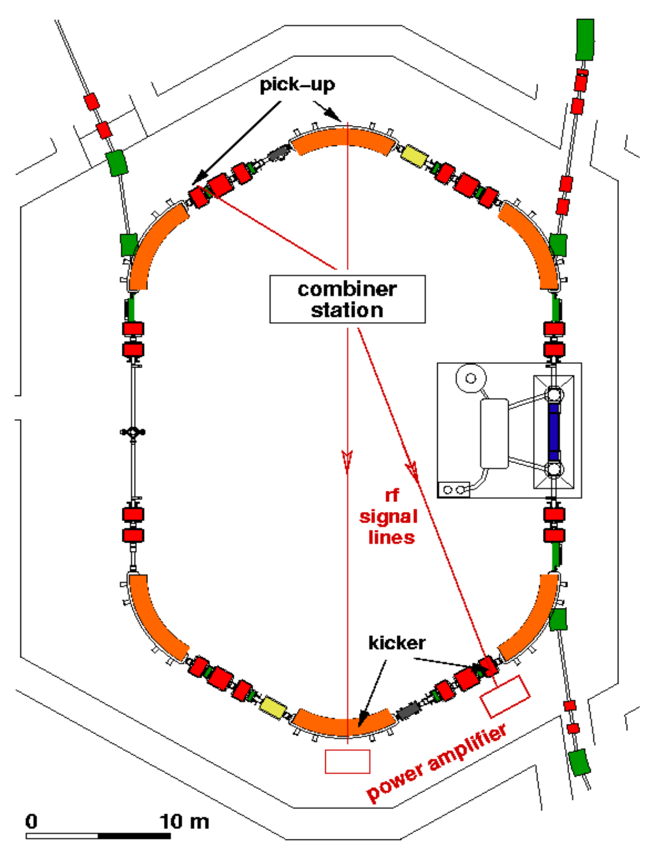
Stochastic Cooling of Rare Isotopes at GSI

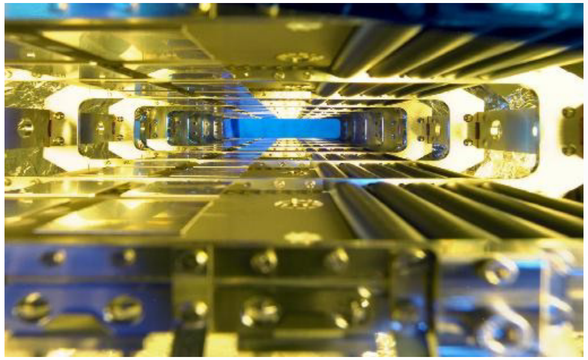
fast pre-cooling of hot rare isotopes

energy 400 (-550) MeV/u
bandwidth 0.8 GHz (range 0.9-1.7 GHz)

$\delta p/p = \pm 0.35\ \% \rightarrow \delta p/p = \pm 0.01\ \%$

$\varepsilon = 10 \times 10^{-6}\ \text{m} \rightarrow \varepsilon = 2 \times 10^{-6}\ \text{m}$





electrodes installed in the ultrahigh vacuum inside magnets

combination of signals from electrodes

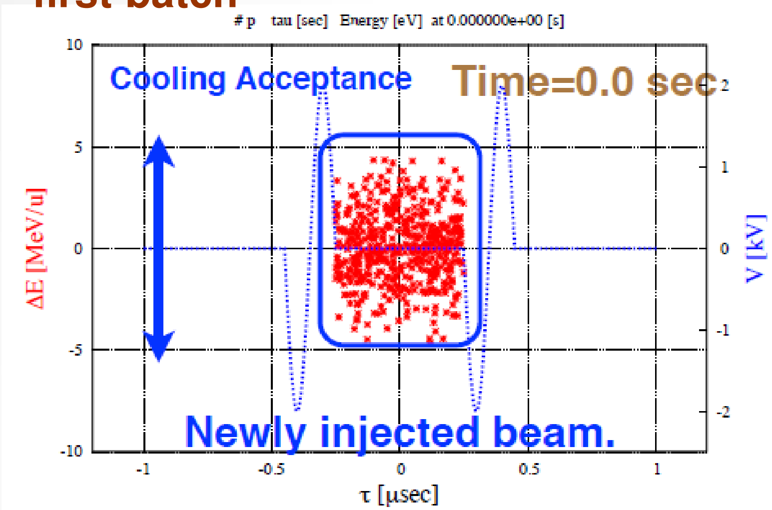
power amplifiers for generation of correction kicks

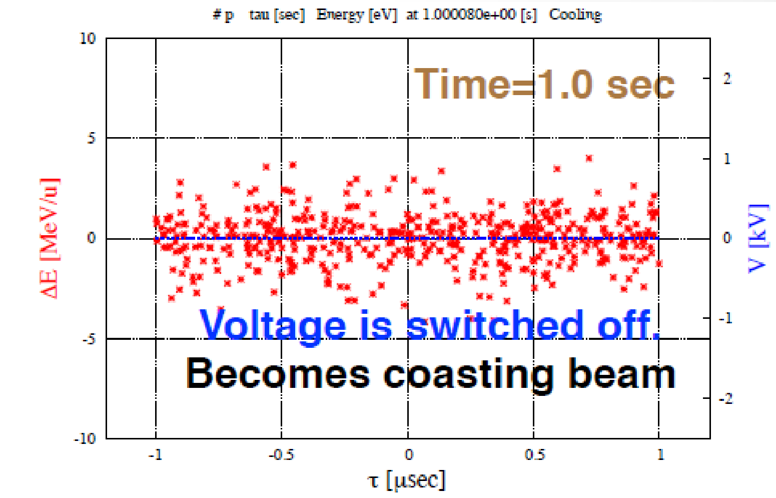
Barrier Bucket Accumulation by Stochastic Cooling

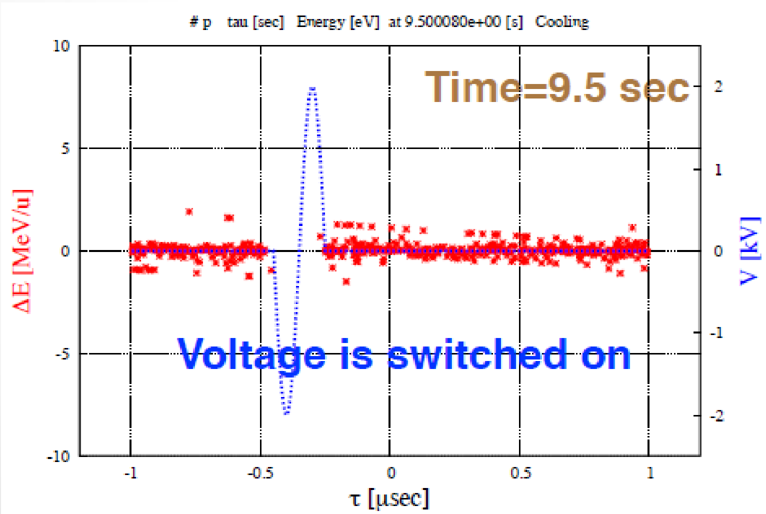
proposed for the accumulation of antiprotons in HESR

a similar method was applied in the Recycler (FNAL)

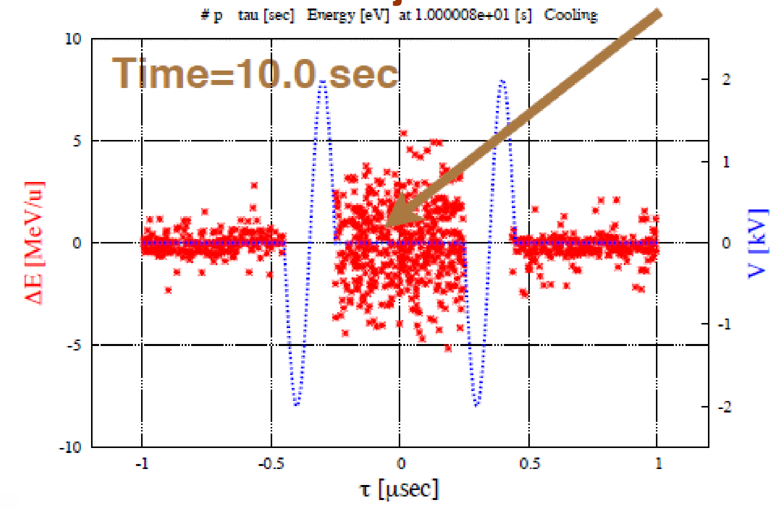
first batch





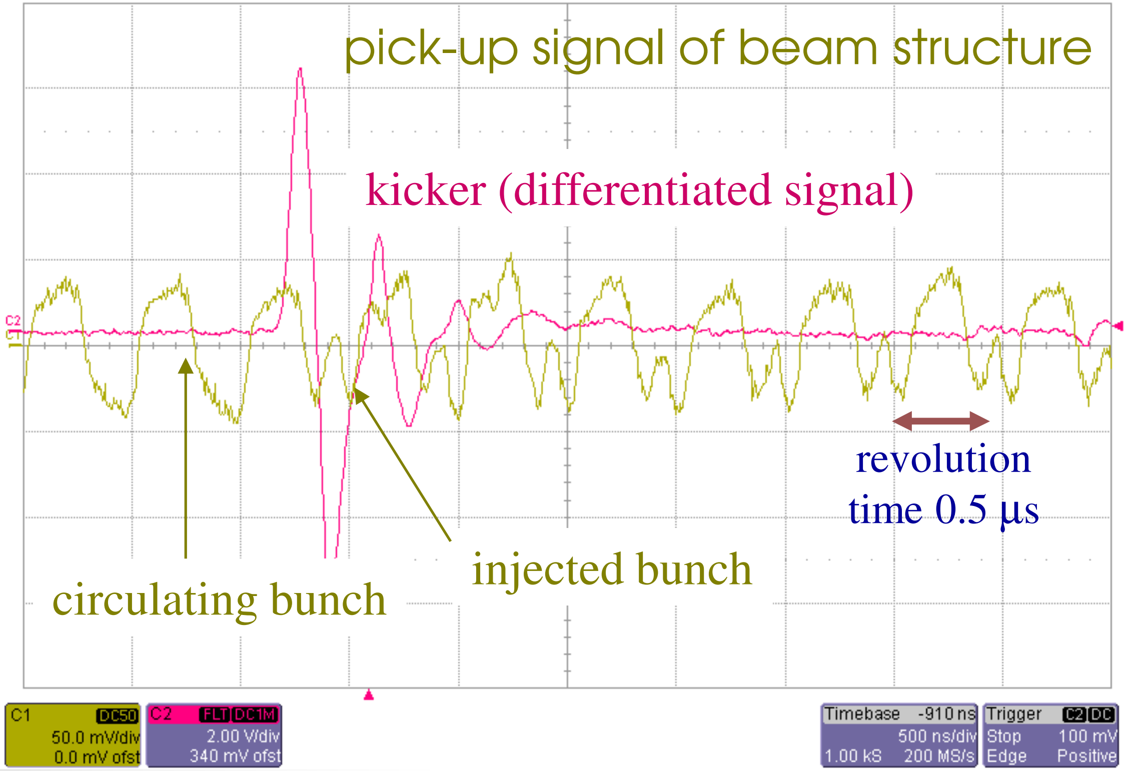


injection of a second batch

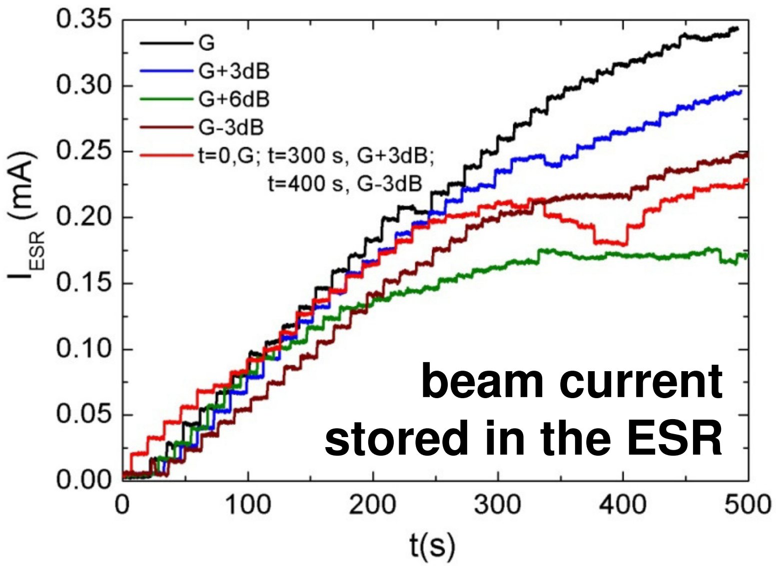


simulation by T. Katayama

Proof of Principle Experiment at ESR
Longitudinal Accumulation with Stochastic Cooling



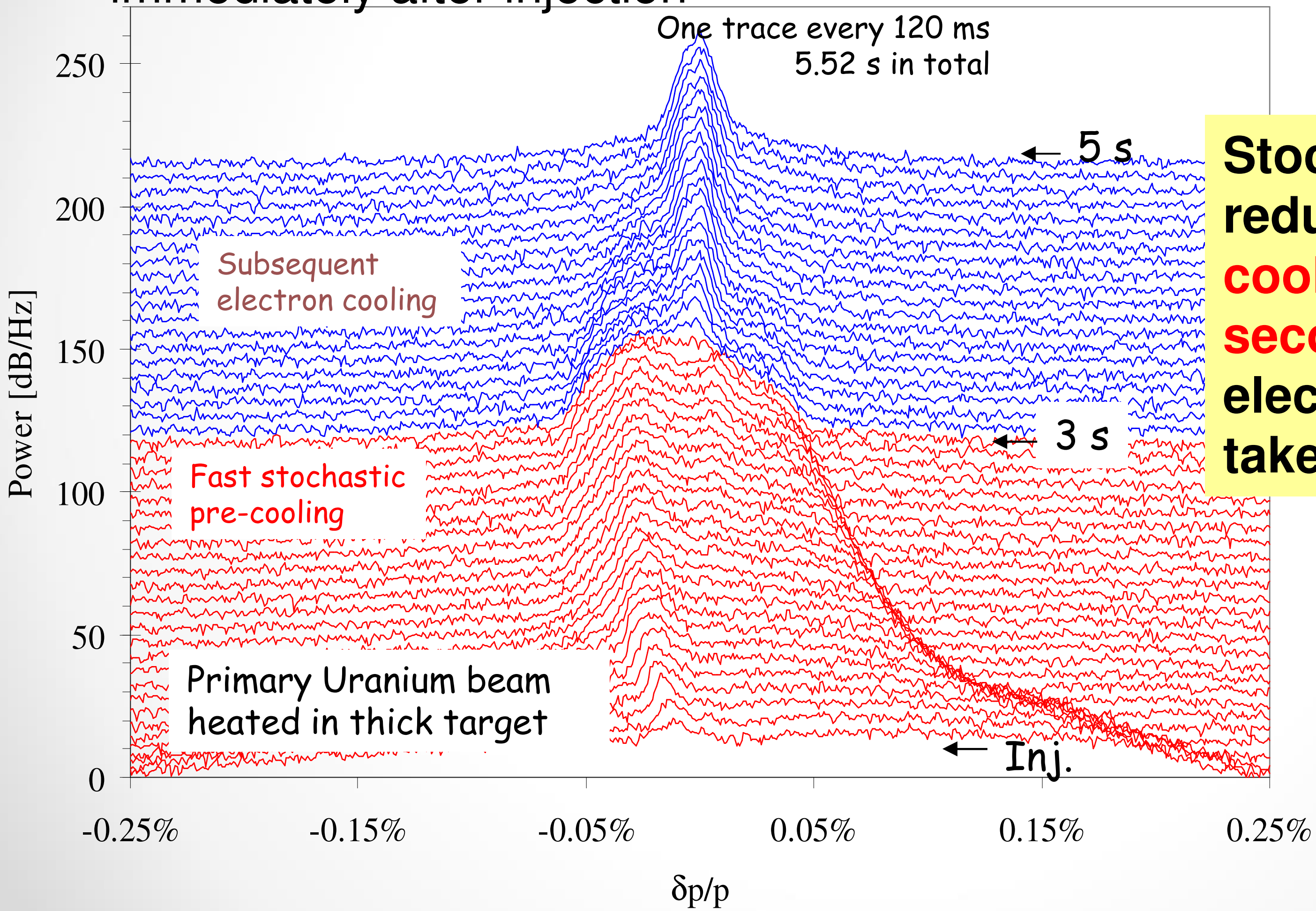
using a single bunch of Ar^{18+} at 400 MeV/u from SIS



at higher intensity and beam density heating can dominate
⇒ mitigate by variation of the system gain in the course of the cooling process

Combination of Stochastic and Electron Cooling

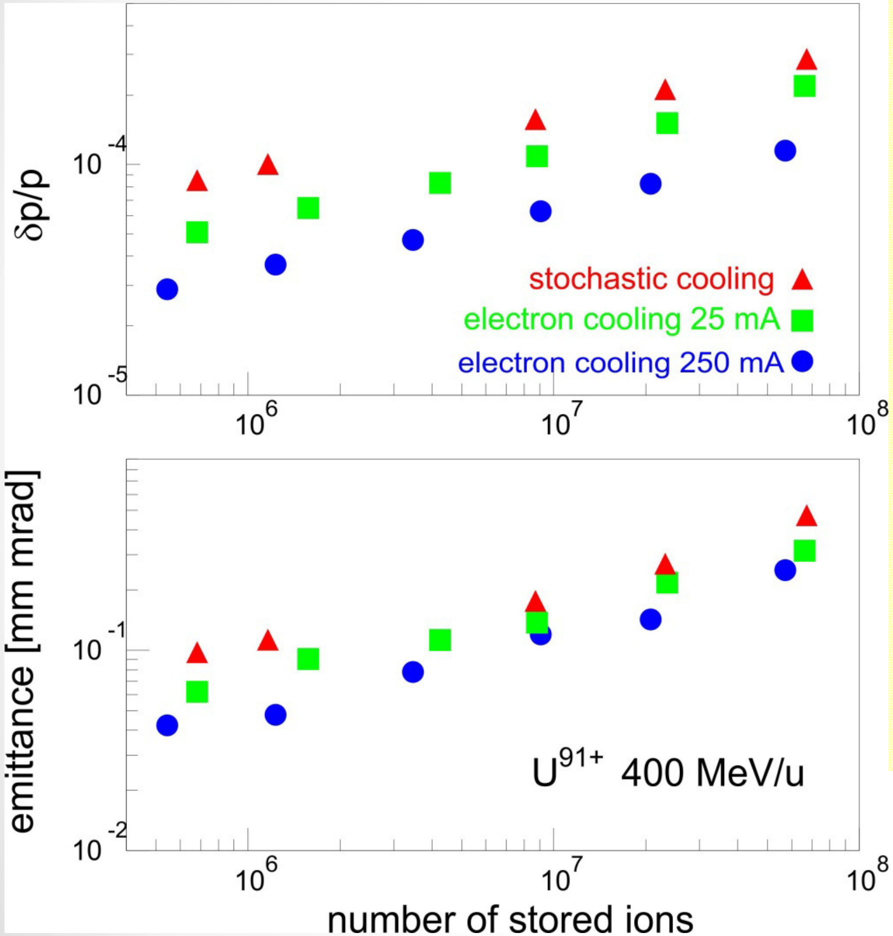
stochastic pre-cooling + **final electron cooling**
immediately after injection



Stochastic pre-cooling reduces the total cooling time to a few seconds, electron cooling only takes 10 - 60 s

lifetime due to nuclear decay of rare isotopes can be seconds or less

Equilibrium Beam Parameters of the Cooled Beam in the ESR



limited by Intrabeam Scattering

Electron cooling results in smaller momentum spread and smaller emittance.

The equilibrium is a balance between the cooling rate and the heating rate by intrabeam scattering.

calculated IBS-heating/cooling rate [s^{-1}]

	longit.	transv.
stoch. cool.	0.9 - 2.2	0.5 - 1.3
el. cool. [25 mA]	2.0 - 6.0	1.4 - 3.3
el. cool. [250 mA]	18 - 58	7 - 10

electron cooling is more powerful in producing cold beams, it provides higher cooling rate for cold beams

Stochastic Cooling Systems

CERN, Geneva, Switzerland
Intersecting Storage Ring (ISR) 1977
Initial Cooling Experiments (ICE) 1978
Antiproton Accumulator (AA) 1981
Low Energy Antiproton Ring (LEAR) 1983
Antiproton Collector (AC) 1987
Antiproton Decelerator (AD) 1999

FNAL, Chicago, USA
Test Ring 1979
Debuncher Ring 1985
Accumulator Ring 1985
Recycler Ring 1997

NAP-M, INP, Novosibirsk, Russia 1979
TARN, Tokyo, Japan 1983
ESR, GSI, Darmstadt, Germany 1997
COSY, FZJ, Jülich, Germany 1997
RHIC, BNL, Brookhaven, USA 2009
CSRe, IMP, Lanzhou, China 2016

decommissioned

in operation

Future Aspects of Stochastic Cooling

increased cooling rate:
- larger bandwidth of cooling system
- dedicated ring lattices

bunched beam cooling:
- increased luminosity in colliders

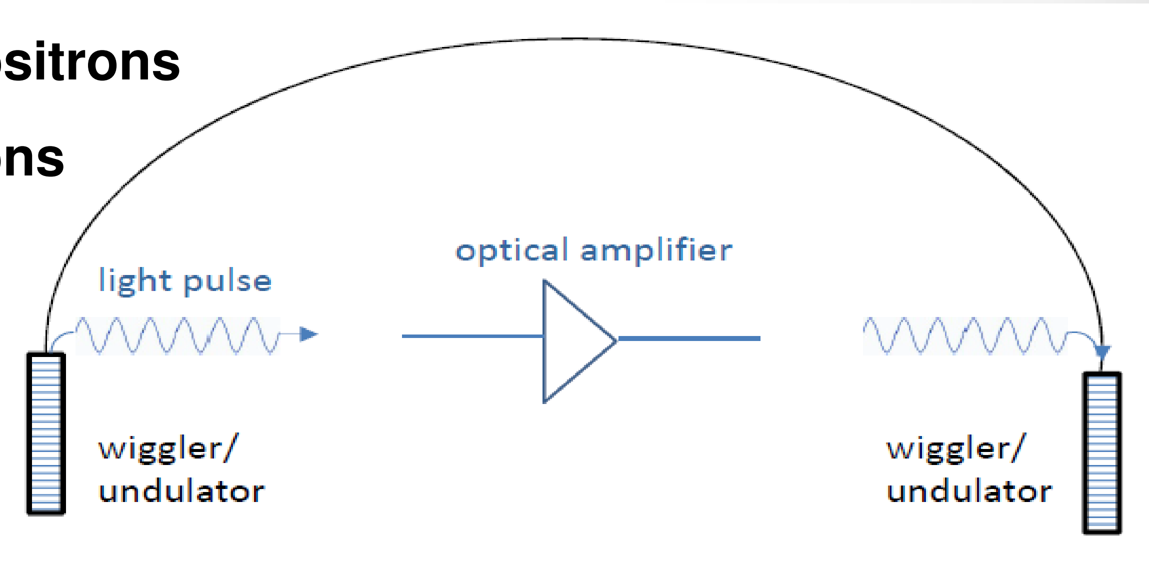
new accumulation schemes employing stochastic cooling

development of technologies
- e.g. optical components
  - new rf components

Optical Stochastic Cooling

applicable to electrons/positrons

or very high energy hadrons

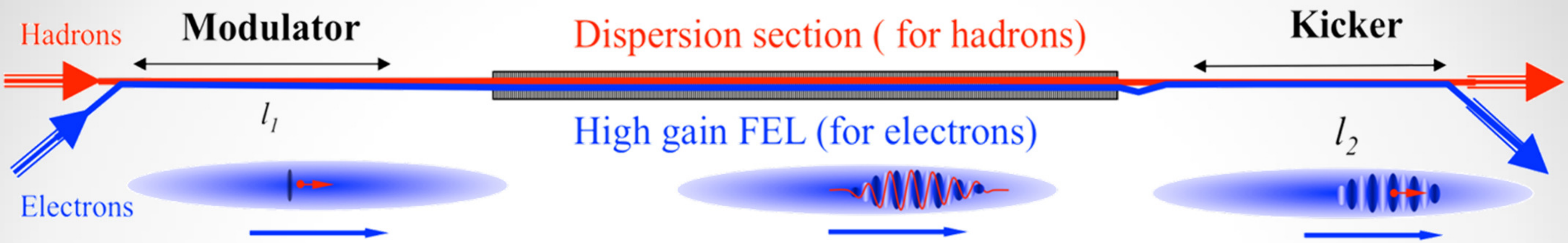


large bandwidth (up to THz) of optical system

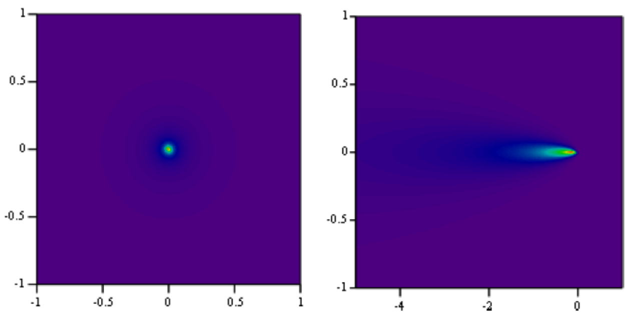
transverse cooling by longitudinal-transverse coupling

accelerator test facility IOTA (Fermilab) is preparing a demonstration of optical stochastic cooling

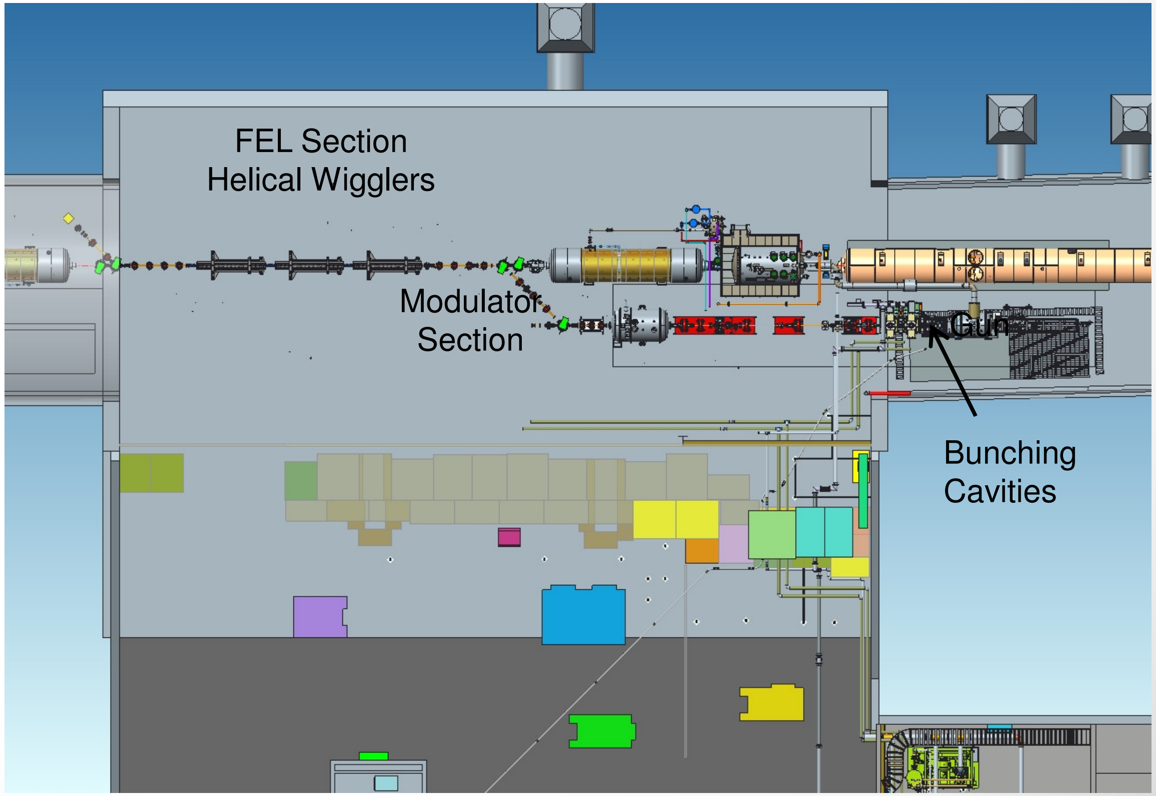
Coherent Electron Cooling



test experiment proposed at RHIC (Brookhaven)



simulations of an ion in the electron plasma



Comparison of Cooling Methods

	Stochastic Cooling	Electron Cooling
Useful for:	low intensity beams	low energy
		all intensities
	hot (secondary) beams	warm beams (pre-cooled)
	high charge	high charge
	full 3D control	bunched beams
Limitations:	high intensity beams	space charge effects
/problems	beam quality limited	recombination losses
	bunched beams	high energy

laser cooling (of incompletely ionized ions)
and ionization cooling (of muons) are quite particular
and not general cooling methods

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