

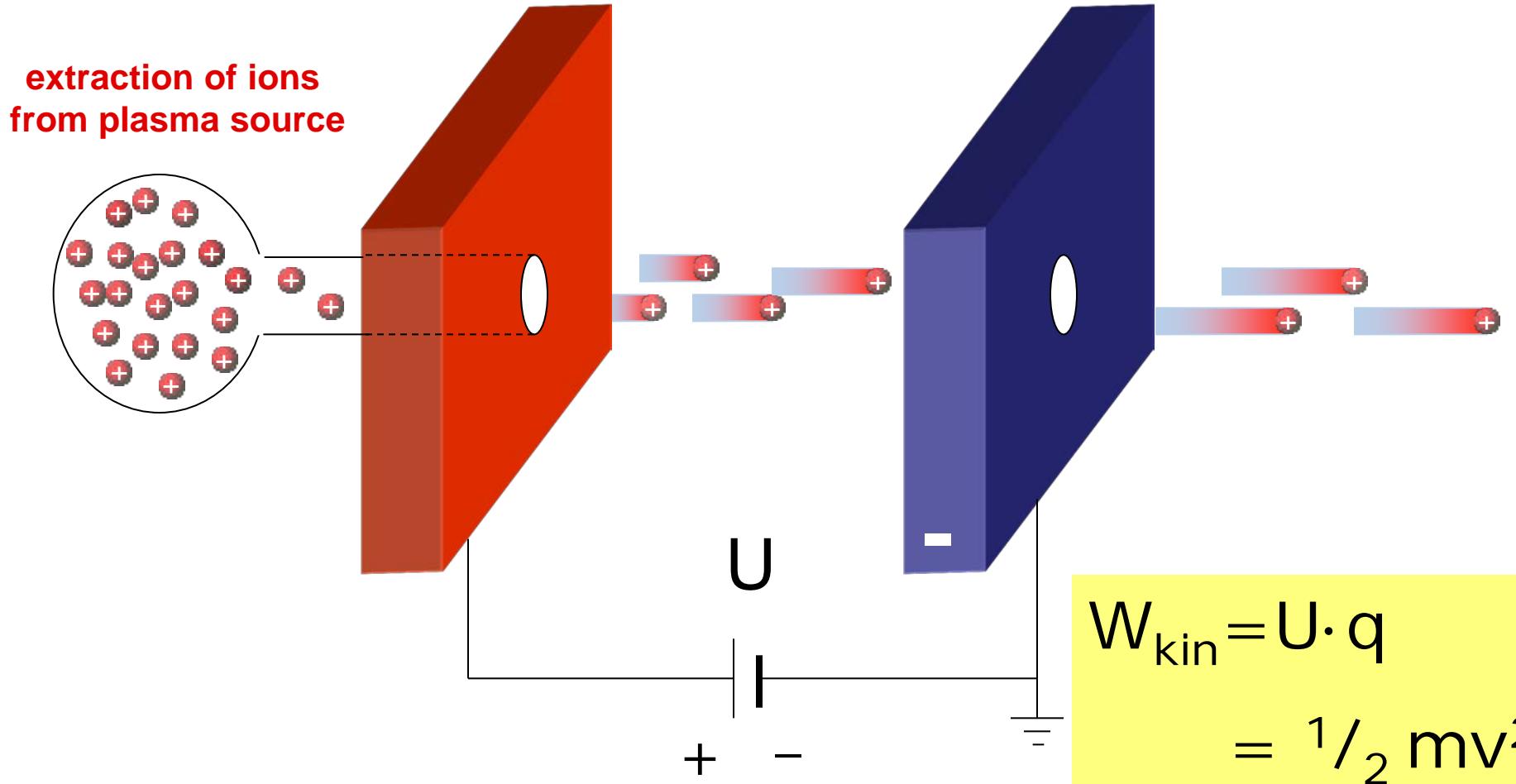
Beam Cooling

Operateurausbildung

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Abteilung SBBC (Beam Cooling)

January 2016

Principle of Acceleration

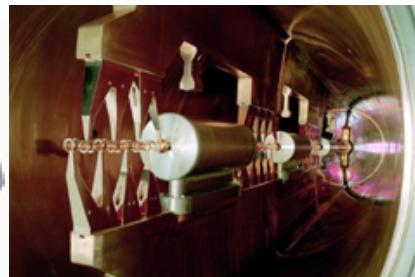


A proton is 1840 times heavier than an electron.
A proton at $W_{\text{kin}}=400 \text{ MeV}$ has the same velocity v
as an electron at $W_{\text{kin}}=220 \text{ keV}$.

The GSI accelerator complex today



ion sources



Unilac



SIS18



All ions from protons to Uranium:

4×10^9 1 GeV/u U^{73+}

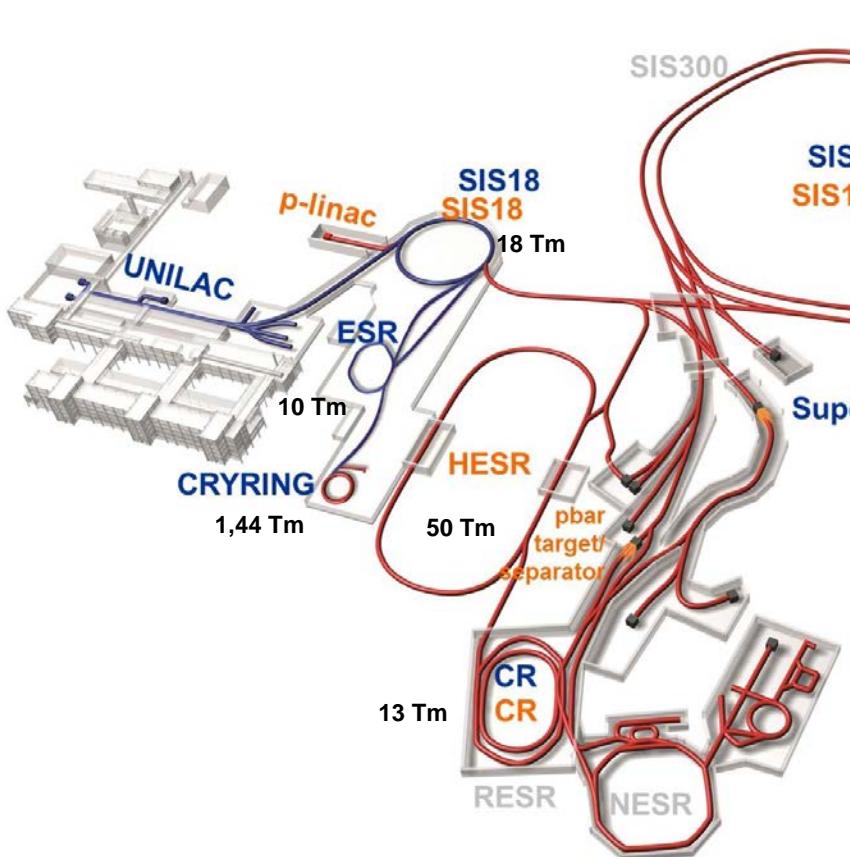
5×10^{10} 1 GeV/u Ar^{40+}

Secondary ion beams (rare isotopes) after FRS

Beams and storage rings with cooling at FAIR

Primary beams = protons & stable heavy ions (from sources)

Secondary beams= antiprotons & Rare isotope beams (RIBs)



SIS18 (ec)

accumulation of **stable ions**

ESR (sc,ec)

accumulation, storage, deceleration,
experiments with **stable ions/RIBs**

CRYRING (ec)

storage, deceleration, experiments with
stable ions/RIBs

Collector Ring CR (sc)

collection, pre-cooling of **antiprotons /RIBs**

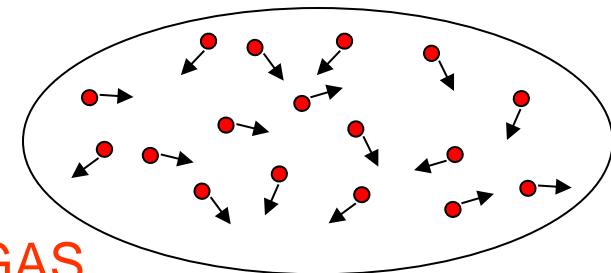
HESR (sc, ec?)

accumulation, storage, experiments with
antiprotons (also stable ions/RIBs)

sc: stochastic cooling

ec: electron cooling

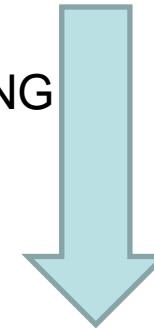
(Secondary) beams: Cool before drinking



HOT GAS

disordered motion of
ions in the beam,
high internal energy

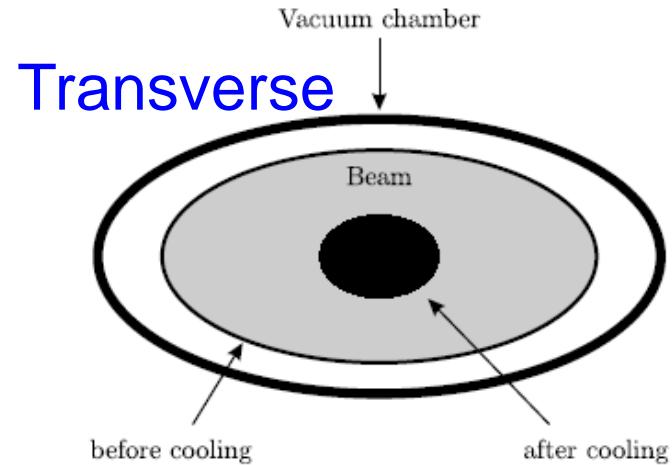
BEAM COOLING
METHOD



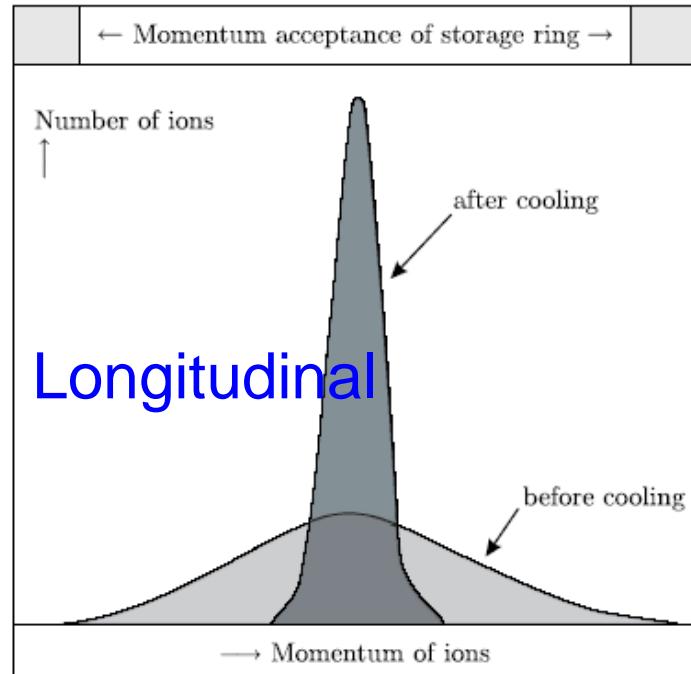
COLD GAS

Ordered motion,
all ions in the beam
fly with the same nominal velocity,
low internal energy

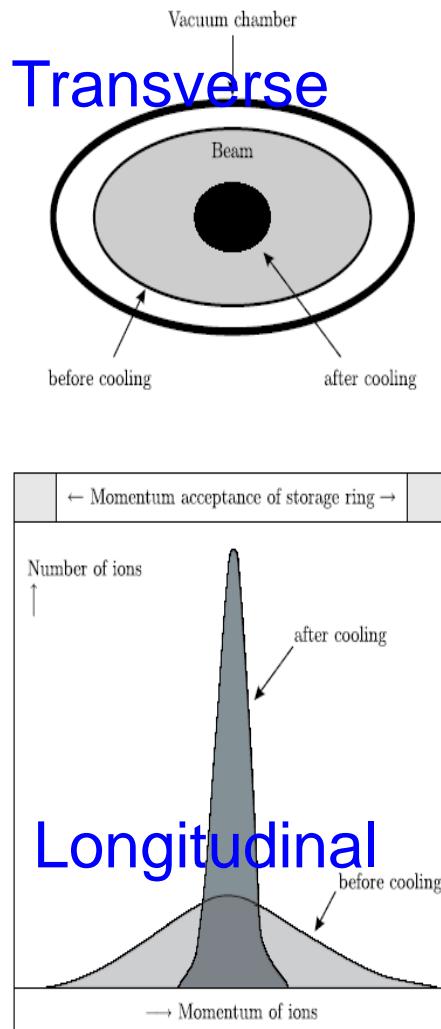
(Secondary) beams: Cool before drinking



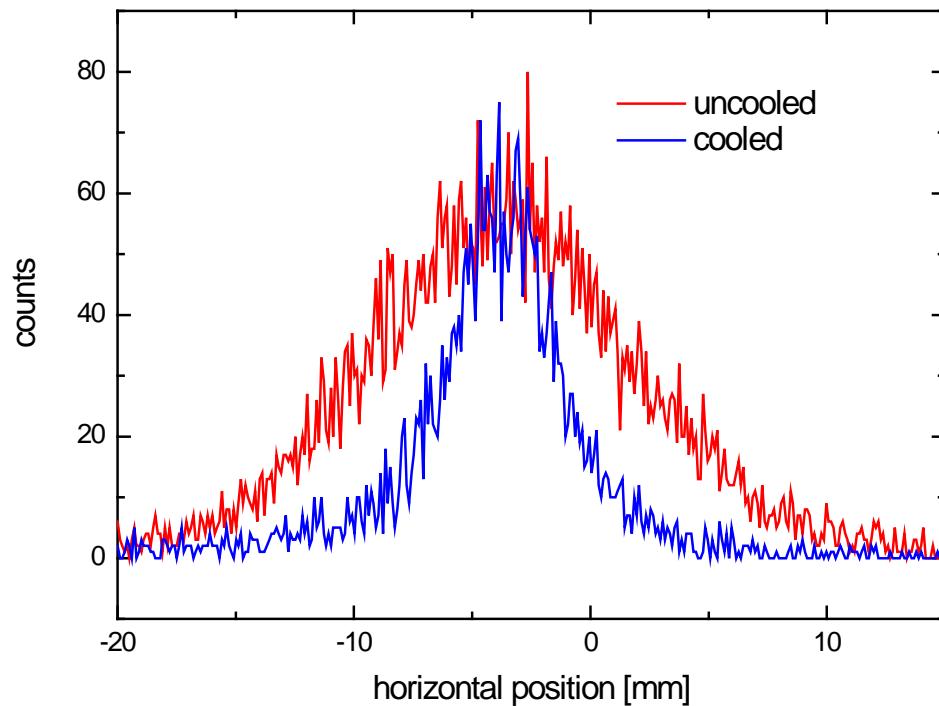
- **accumulation** of antiprotons, radioactive ions, i.e. low-abundant ion species
z.B. Multi(multi)turn Injektion!
- control/compensate beam emittance growth during **deceleration**
- high quality beams for precision experiments
- increase of luminosity in colliders
- counteract beam heating effects in internal targets



Diagnostics for cooling: measured spectra



Rest gas beam profile monitor



Diagnostics for cooling: measured spectra

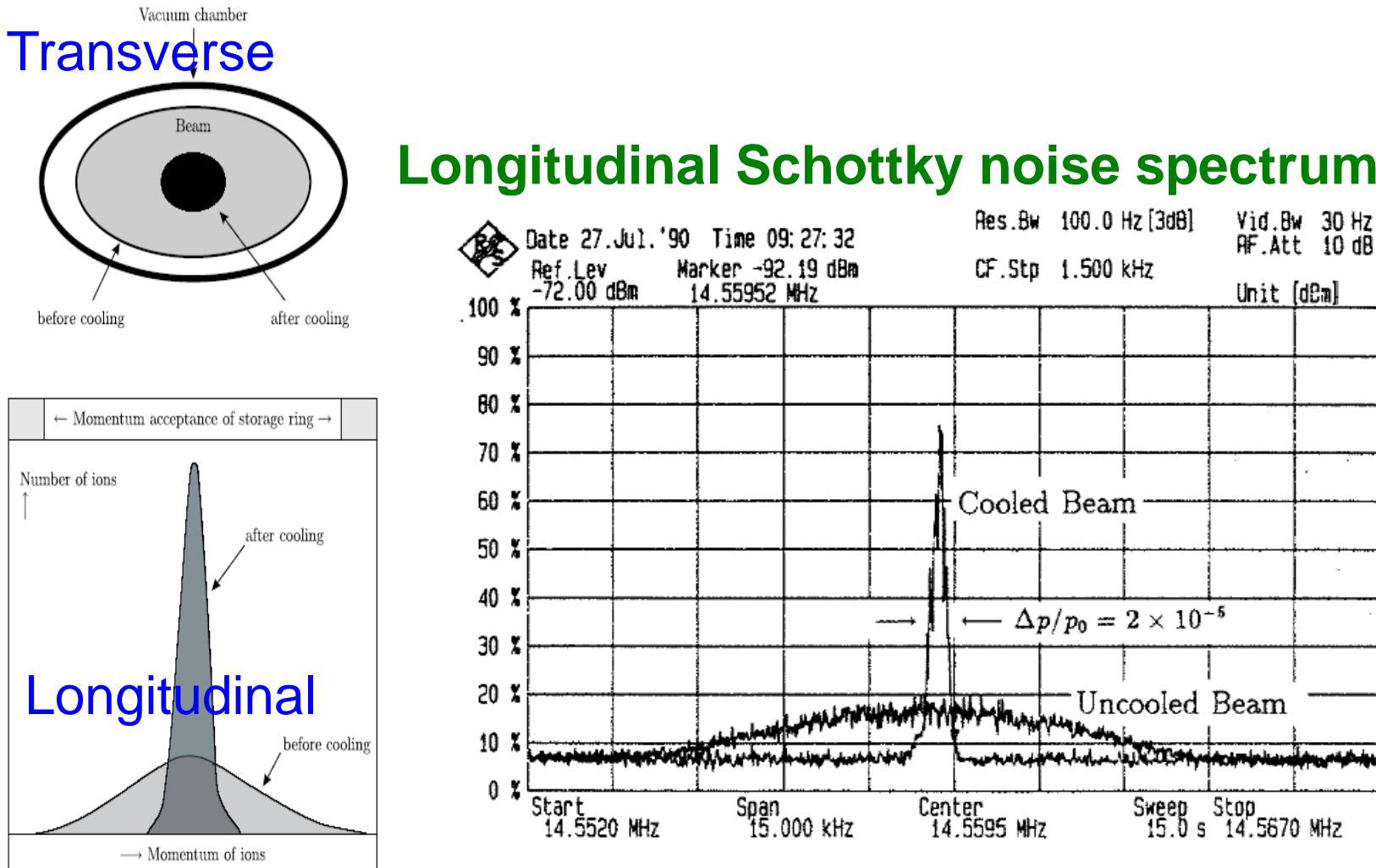
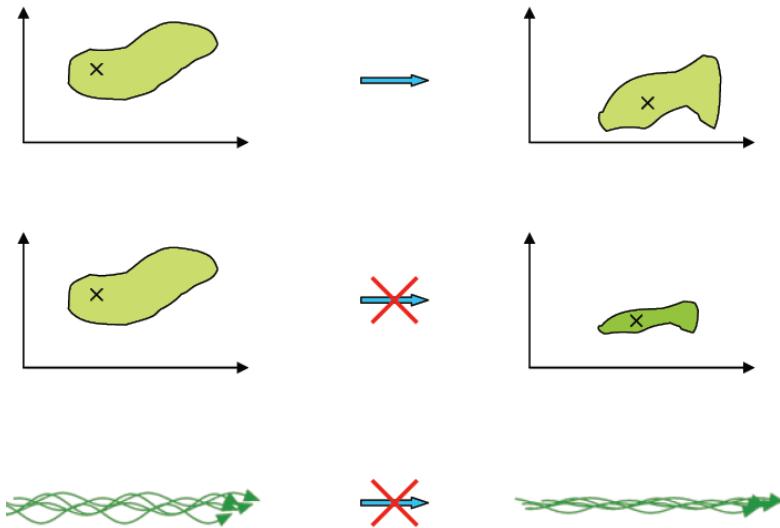


Figure 7.4: Longitudinal Schottky scan at the 10th harmonic of Ar¹⁸⁺ at the GSI storage ring. The broad curve is the frequency spectrum at injection with $\Delta p/p = 1 \cdot 10^{-3}$ and the narrow curve is recorded after electron cooling down to a momentum width of $\Delta p/p = 2 \cdot 10^{-5}$.

Ingenious ideas made cooling possible

A beam in phase space is like an incompressible continuous fluid.

Use of magnets, rf cavities, electromagnetic devices etc. cannot change the phase space volume of the beam.



Then, how do we do it ? Act on single particles

→use EM-forces on finite beam samples: Stochastic cooling



→introduce dissipative forces (friction) to remove internal energy from the beam: Electron cooling



→both very difficult in practice...

Stochastic & electron cooling

- **stochastic cooling** for medium/high energy ions
- **electron cooling** for low/medium energy ions

Stochastic cooling

Simon van der Meer, 1972

Nobel prize, 1984
(shared with C. Rubbia)

The Nobel prize was awarded to **Carlo Rubbia** and **Simon van der Meer** for “their decisive contributions to the large project, which led to the discovery of the field particles W and Z, communicators of the weak interaction”.(quote)
and also from the Laudatio:

Van der Meer made it possible, Rubbia made it happen.

Electron cooling

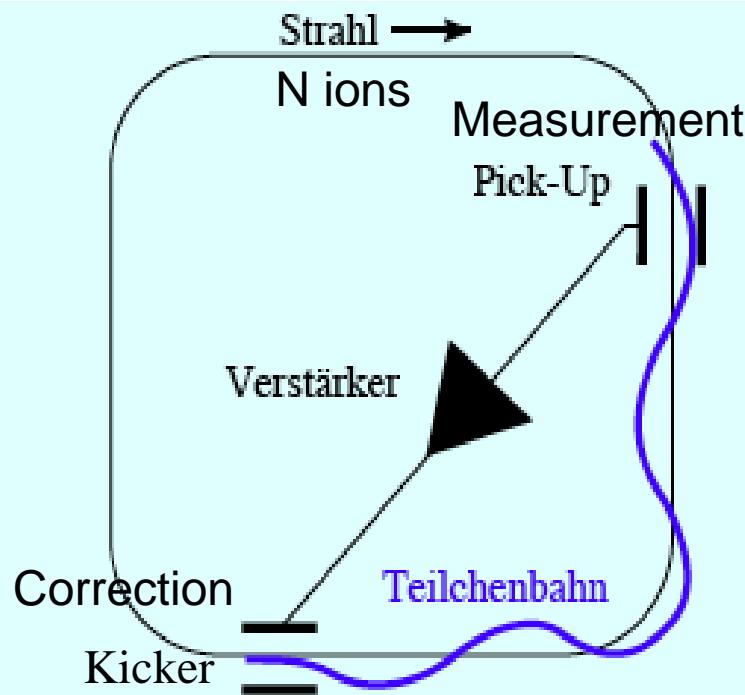
Gersh Budker, 1966



Stochastic cooling: Principle

Abweichungen von der Sollbahn werden mit hoher Zeitauflösung gemessen. Daraus wird ein Korrektursignal abgeleitet, das **noch im selben Umlauf** auf den Strahl angewendet wird. Strahlumlaufzeit (Frequenz) $\sim 1\text{-}2 \mu\text{s}$ (0.5-1 MHz).

Measure in pick-up the deviation of a small beam sample from ideal orbit, amplify this signal and apply it as correction kick to the same beam sample (feedback system)



$$\text{cooling time } \tau \sim \frac{N}{2W}$$

Conditions

- Phase advance PU-K $\approx 90^\circ$
- From PU-K: signal travel time = particle time of flight

High electronic bandwidth W necessary (GHz range-microwaves)

Fast sampling in time = many short beam slices \leftrightarrow high frequency bandwidth

High power amplification needed (~100 dB) at kickers

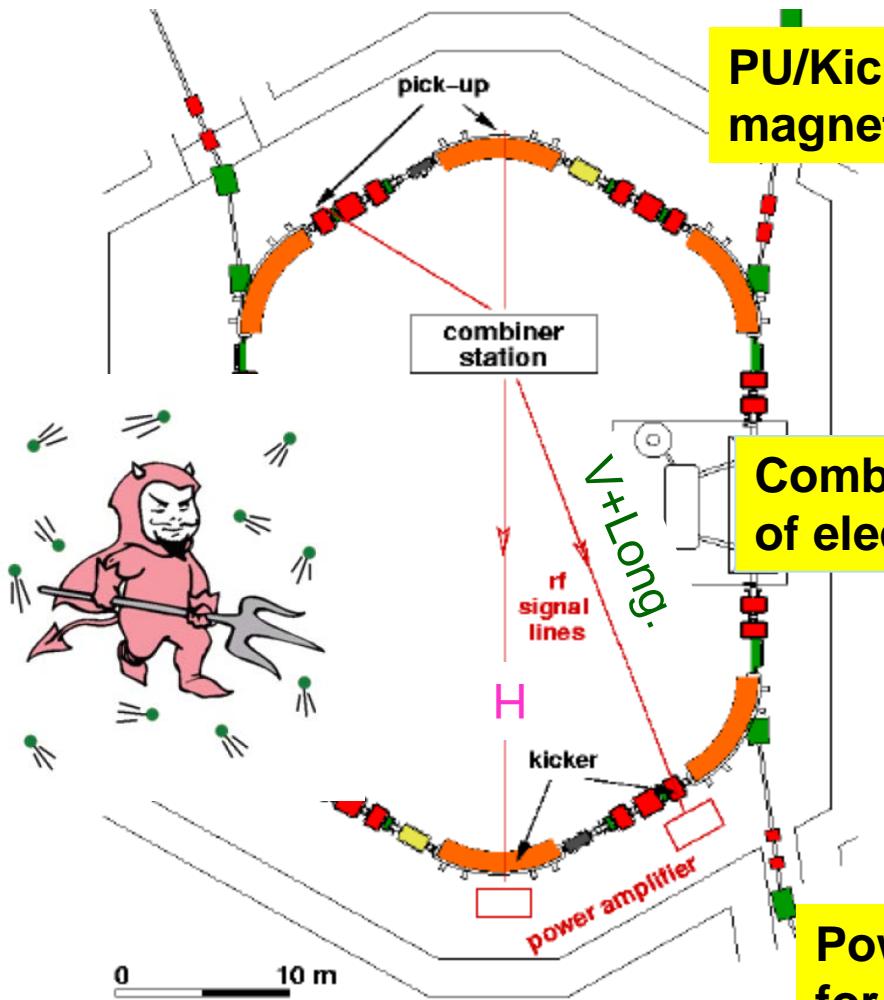
tiny signal at pick-up → realistic voltage for the kick

Stochastic cooling: Practice

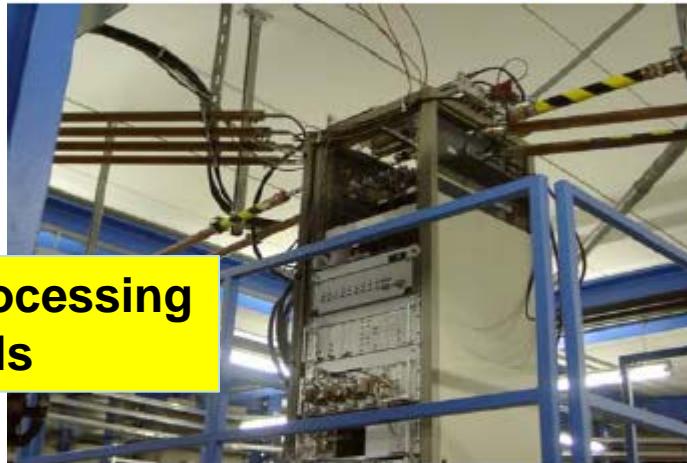
ESR 3D cooling system

bandwidth= 0.9-1.7 GHz

Velocity = $0.71c$ ($-0.79c$) \leftrightarrow 400-(550 MeV/u)



PU/Kicker electrodes inside
magnet vacuum chambers

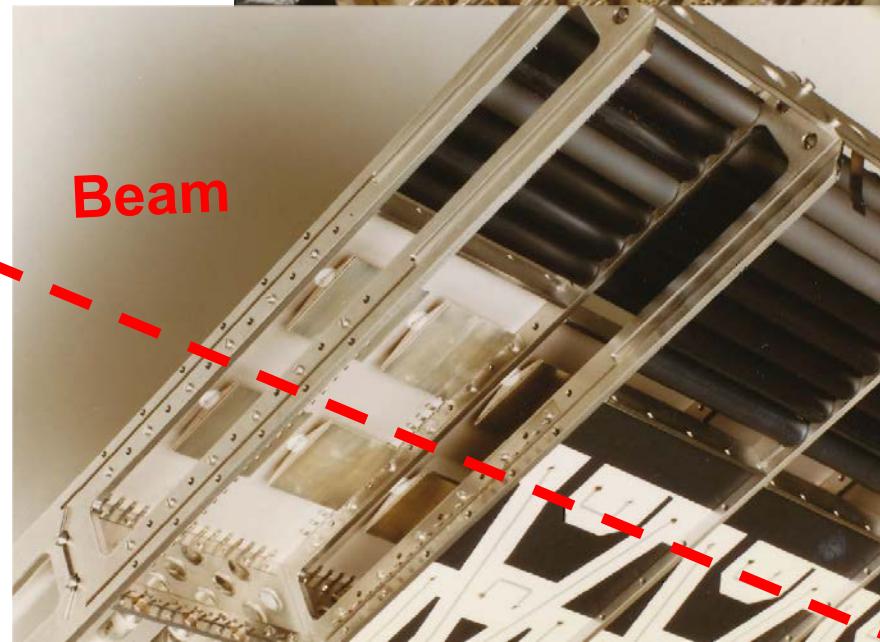
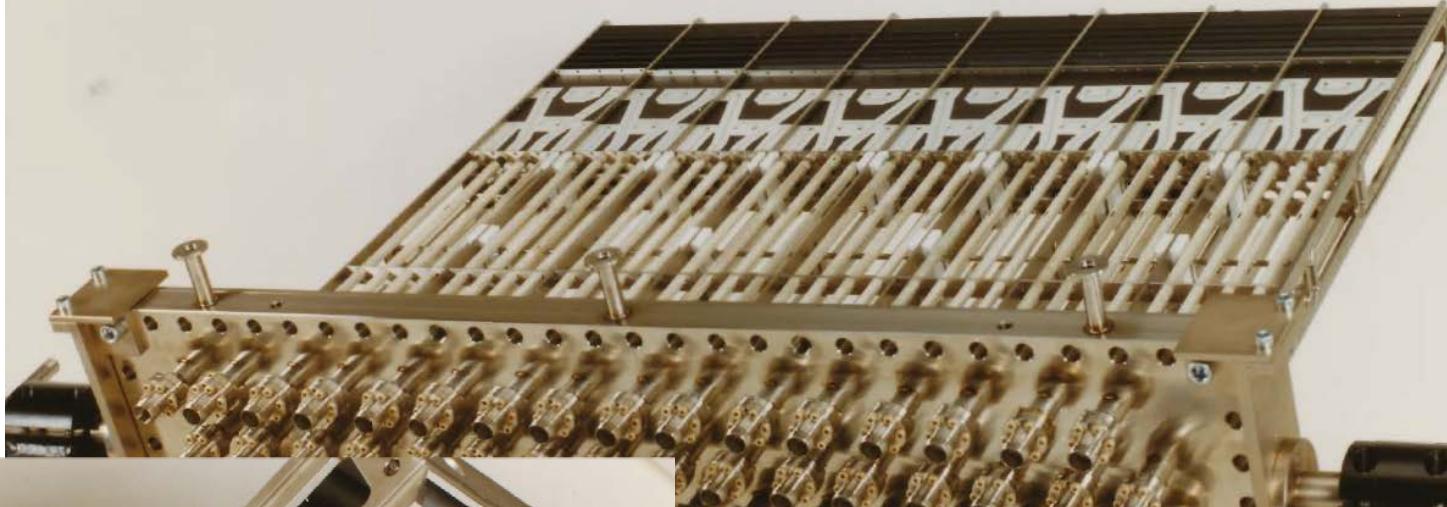


Combination & processing
of electrode signals

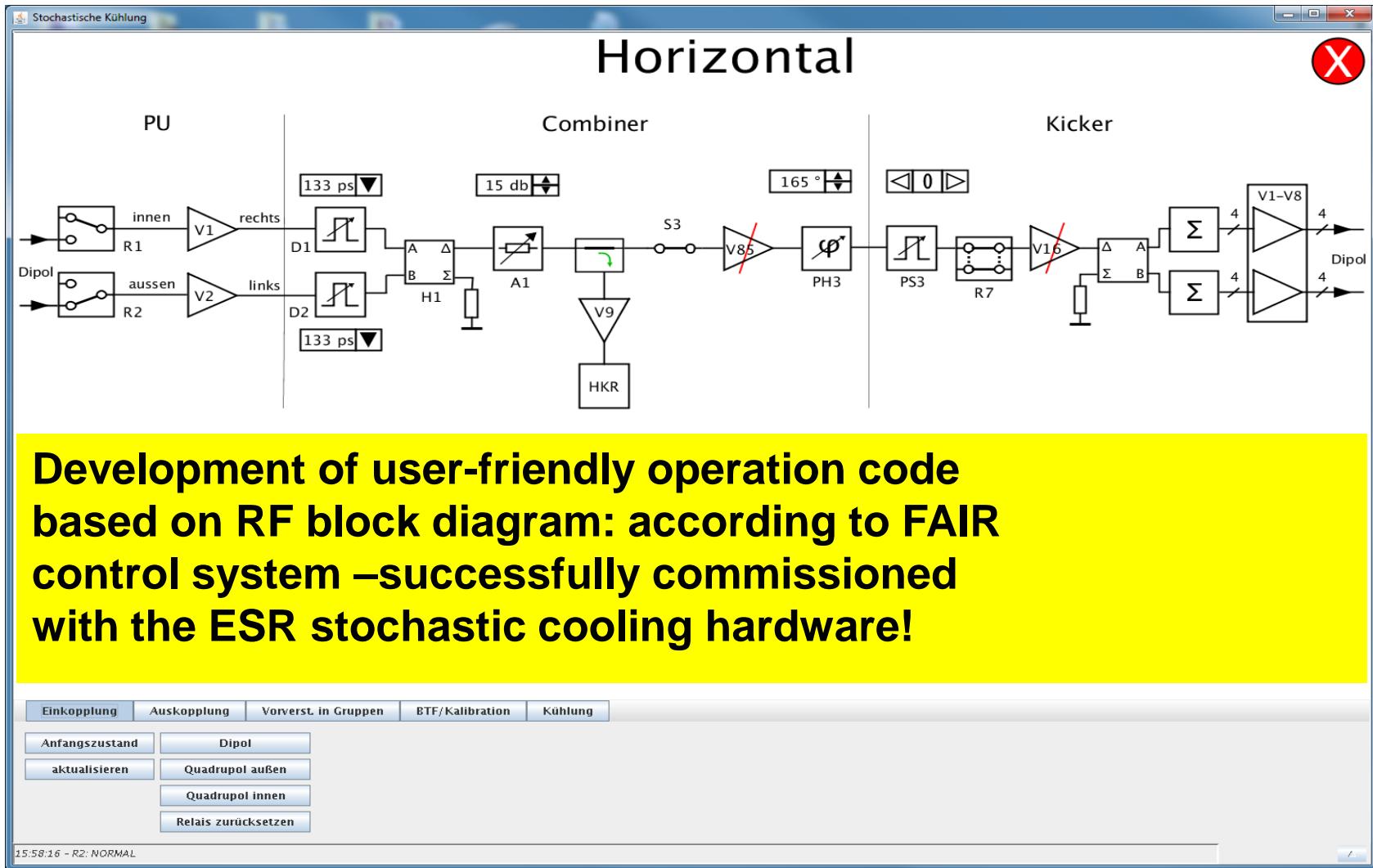


Power amplifiers
for correction kicks

ESR Pickup/Kicker Superelectrodes

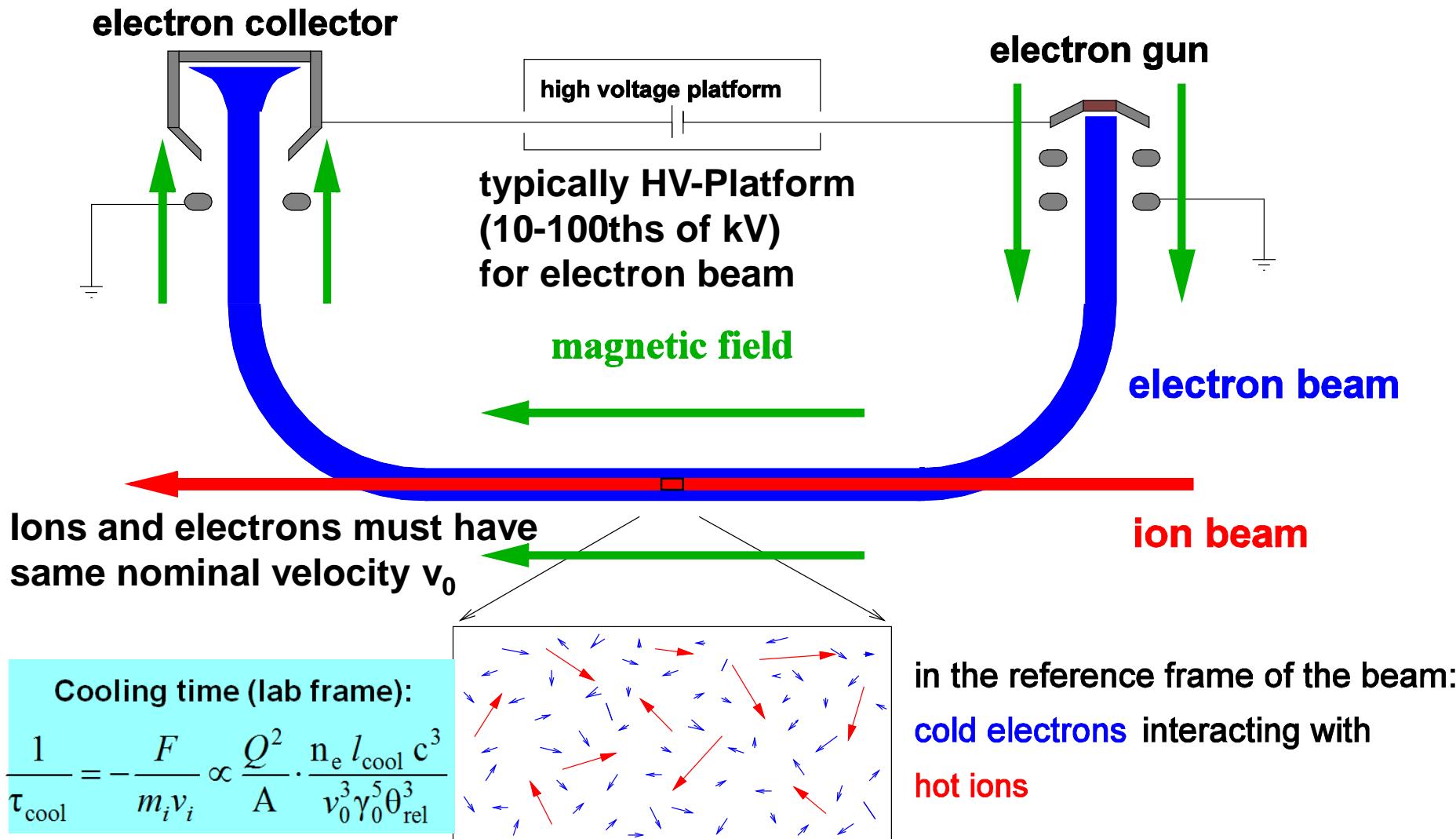


Stochastic cooling: Experten Operating

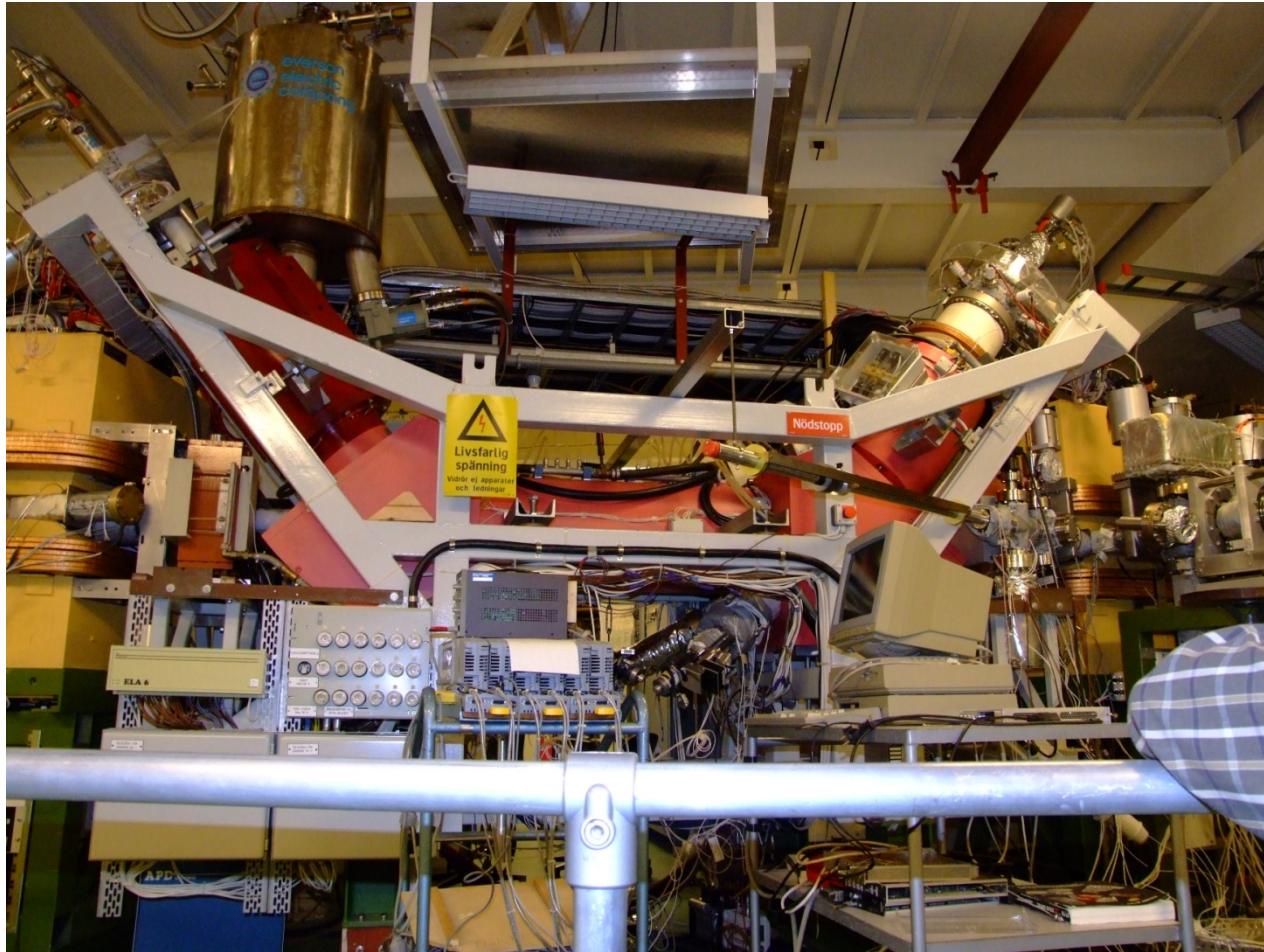


Electron cooling: Principle

Prinzip: Dem **heißen Ionenstrahl** wird ein **kalter Elektronenstrahl** gleicher Geschwindigkeit überlagert. **Abkühlung durch gegenseitige Stöße.**

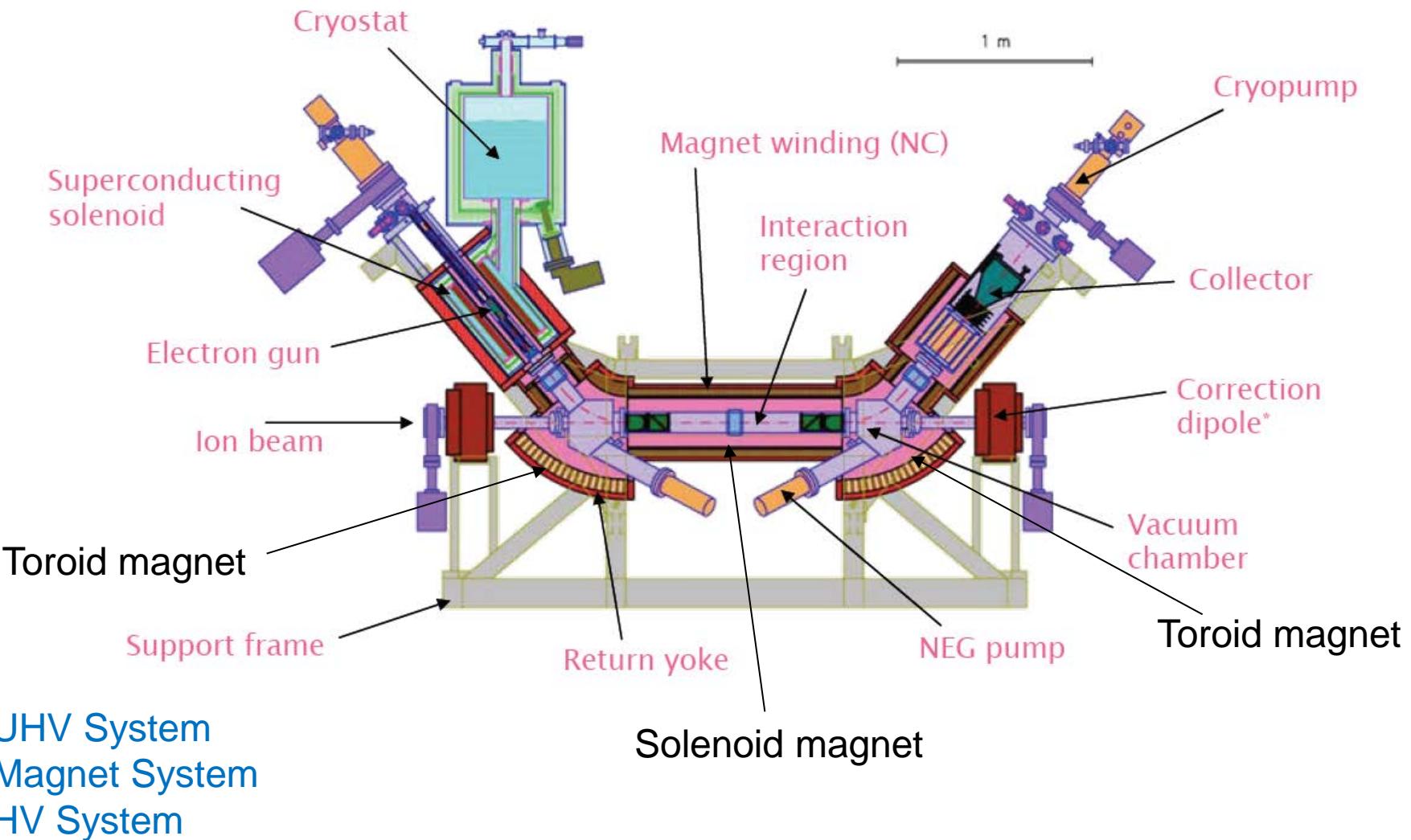


Electron cooling: Practice



CRYRING, Stockholm

Electron cooling: Practice



SISMODI - PARAMETER - EINGABE

S14 U13 TE/ESR 238U 73+ 350.00

iEnergie [MeV] : 11.203 eEnergie [MeV]
 iB-Rho [Tm] : 1.5759 eB-Rho [Tr]
 iFrequenz [kHz] : 850.515 eFrequenz [kHz]
 i[Teilchen/μA] : 0.402E+06
 iQH : 4.29 eQH
 iQU : 3.23 eQU
 iRad.Pos. [mm] : 0.0 eRad.Pos. [mm]
 IstFrequ. [kHz] : 850.515
 Bump.Flank[μs] : 200.0
 Bump.Ampl [mm] : 77.0
 BpTacho [mm/μs] : 0.385
 Chop.Verz. [μs] : 30.0
 ChopFenst. [μs] : 60.0
 BpWeglänge [mm] : 23.1
 dU-Ready : 10020
 dTK7BC1L [mrad] : 0.0
 dTK7MU5 [mrad] : 0.0
 ds12MU3I [mrad] : 1.8
 ds12ME1I [mrad] : -0.5

AnzInjekt. : 3
 e-Kühler 0/1 : 1
 MMIKühlZ. [ms] : 300.0
 Kühler dp/p : 1.35
 Kühlerf.Inj. : 600.0
 Kühlerstrom[A] : 0.3
 KüBumpX [mm] : 0.0
 KüBumpX' [mrad] : 0.0
 KüBumpY [mm] : 0.0
 KüBumpY' [mrad] : 0.0

Kickw. [mrad]
 Kickstart [°]
 HF-Trigg:1|2
 ESR-Synch.:0
 Synch-Zeit[μs].

S14 U13 TE/ESR 12C 5+ 400.00 schnell_1H1	2 HF-Kavi	Normal
iEnergie [MeV] : 11.498 eEnergie [MeV] : 400.0	eB-Rho [Tm] : 0.97915 eB-Rho [Tr] : 6.34545	Profilgit.Trig Inj.
iFrequenz [kHz] : 861.5 eFrequenz [kHz] : 3953.781	Zyklus-Zeit [s] : 4.281	Wartezeit [ms] : 0.0
i[Teilchen/μA] : 0.483E+07	iQH : 4.3 eQH : 4.29	U-Injektion [kU] : 0.0
iQU : 3.26 eQU : 3.26	iRad.Pos. [mm] : -2.0 eRad.Pos. [mm] : 0.0	U-RampA [kU] : 9.0
IstFrequ. [kHz] : 861.5	Bump.Flank[μs] : 200.0 SpillZeit [μs] : 100.0	U-RampE [kU] : 20.0
Bump.Flank[μs] : 200.0	Bump.Ampl [mm] : 70.0	U-Flattop [kU] : 20.0
Bump.Ampl [mm] : 77.0	BpTacho [mm/μs] : 0.35	t-Ramp [ms] : 64.0
BpTacho [mm/μs] : 0.385	Chop.Verz. [μs] : 30.0	extr.Bunche 1 2 : 1
Chop.Verz. [μs] : 30.0	ChopFenst. [μs] : 160.0	B-Punkt [T/s] : 1.30831
ChopFenst. [μs] : 60.0	BpWeglänge [mm] : 56.0	Taupunkt [ms] : 0.0
BpWeglänge [mm] : 23.1	dU-Ready : 10030	BunchRot [μs] : 400.0
dU-Ready : 10020	dTK7BC1L [mrad] : 0.0	Bypass [mrad] : 4.5
dTK7BC1L [mrad] : 0.0	dTK7MU5 [mrad] : 0.0	
dTK7MU5 [mrad] : 0.0	ds12MU3I [mrad] : 3.5	
ds12MU3I [mrad] : 1.8	ds12ME1I [mrad] : 1.0	
ds12ME1I [mrad] : -0.5		

AnzInjekt. : 3
 e-Kühler 0/1 : 1
 MMIKühlZ. [ms] : 800.0
 Kühler dp/p : 1.25
 Kühlerf.Inj. : 600.0
 Kühlerstrom[A] : 0.3
 KüBumpX [mm] : 0.0
 KüBumpX' [mrad] : 0.0
 KüBumpY [mm] : 0.0
 KüBumpY' [mrad] : 0.0

Kickw. [mrad] : 8.0
 Kickstart [°] : 76.5
 HF-Trigg:1|2|3 : 3
 ESR-Synch.:0|1 : 0
 Synch-Zeit[μs] : 0

an Geraete InitWerte alter Zustand BF aktualis

SAVE
 RESTORE
 SOLL_SOLL
 COPY
 EXIT

an Geraete

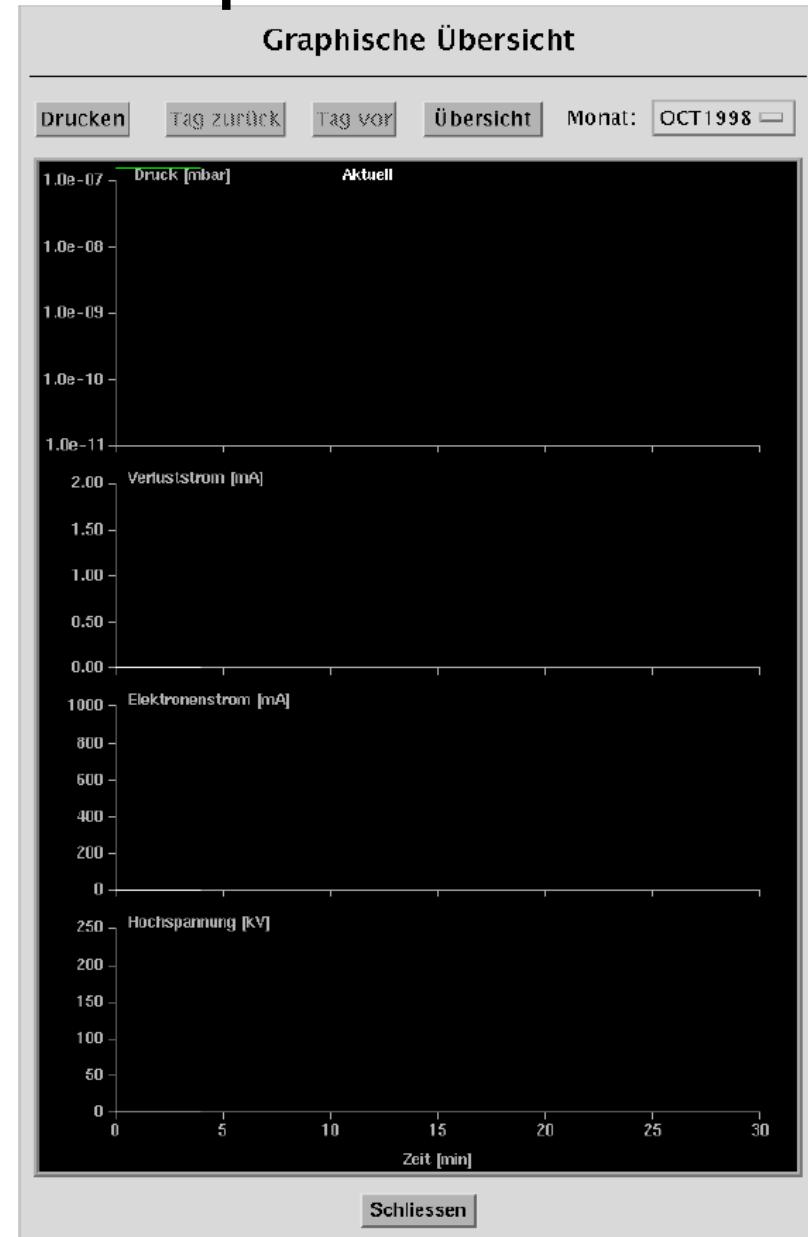
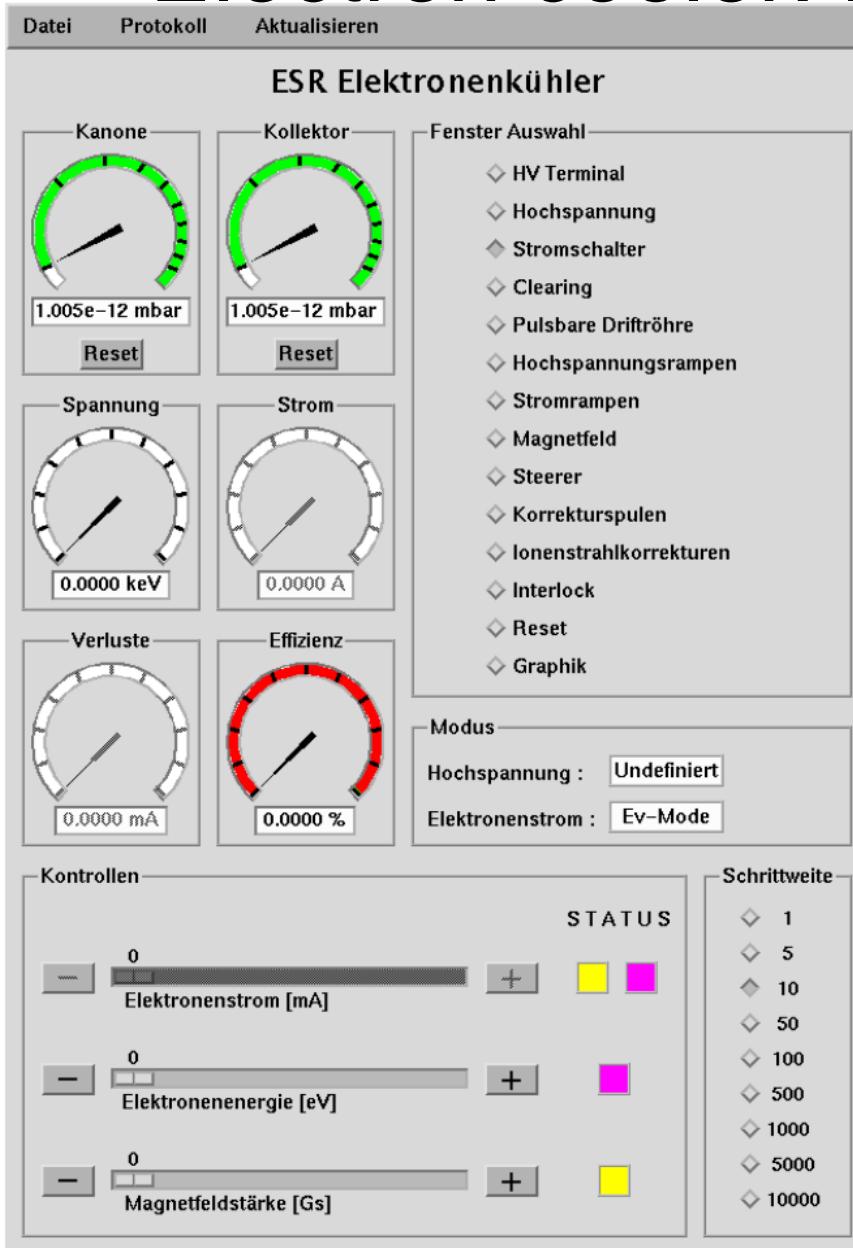
InitWerte

alter Zustand

BF aktualis

INIT
 SAVE
 RESTORE
 SOLL_SOLL
 COPY
 EXIT

Electron cooler: basic operation



Electron cooler: basic operation I

Cooler einstellen

Vakuum Druckanzeige Gun/Collector OK
Kühlwasser Gun/Collector OK

Kathodenheizung AN

Elektronen HV Beschleunigerspannung = Ground – Kathodenspannung (negativ) AN

wird vom MODI gesetzt $U_e [kV] = \left(\frac{1}{1840}\right) \cdot 1000 \cdot E_{ion} \left[\frac{MeV}{u}\right]$

1. Ansatz für Ionenstrahl und Elektronen gleicher Geschwindigkeit v_0

Cooler Magnetfeld (Stromversorgung Cooler Magnete) AN

HV-Netzgeräte Kollektor Anode, Kollektor Suppressor, Kollektor AN

Elektronenstrom (bestimmt durch die HV Anodenspannung
gemessen am Kollektor HV Netzgerät) AN

-> HV Netzgerät Anode = mehrere Hardware Interlocks
(HV Beschleunigerspannung, Vakuum, Kühlwasser Kollektor)

Was passiert wenn Elektronen an die Wand gehen z.B. Ausfall Magnetstromversorgung?
1. le Verlust → Strombegrenzung HV Netzgerät Beschleunigerspannung → AUS
dann Interlock → Anode AUS d.h. keine Elektronen mehr...
2. Vakuumdruck schlechter, Vakuum Interlock → Anode AUS d.h. keine Elektronen mehr...

Electron cooler: basic operation II

Cooler + Ionenstrahl einstellen

Ionenstrahlbahnstörung (wegen Toroid Kicks im Cooler)

$$\theta_x \sim \int_{toroids} \frac{\mathbf{B}_{cooler} \cdot d\mathbf{s}}{(B\rho)_{ion}}$$

z.B: SIS18 1.5 Tm Strahl
 $\theta_x \sim 13 mrad$

Bahnkorrektur (Kühlerbump) Schema
mit 2 Cooler KX Steerern + 2 (4) benachbarten Ring KX Steerern.

muss je nach Cooler-B Feld und Ionenstrahlsteifigkeit angepasst werden!

Electron cooler: basic operation III

Kühlung Optimieren

Fein Anpassung δU_e um den gesetzten U_e : Cooler AN, Ionenstrahlsignal im Schottky

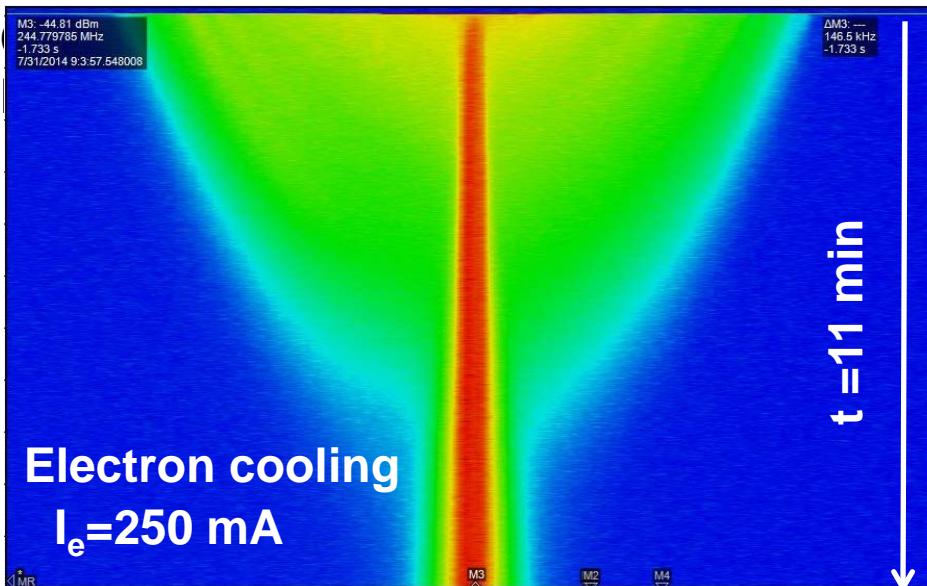
- absolutes feintuning U_e Elektronenenergie (HV Spannung) Knopf ESR

- Relatives feintuning $\frac{\delta p}{p}$ Knopf (SIS)

→ Ionenstrahlen und Elektronen gleicher Geschwindigkeit → effiziente Kühlung

Kühlzeit (wie lange sollte die Coolingwirkung = der Elektronenstrom AN sein ?)
~10-100 ms für U92+, ~sec für C6+, ~Minuten für Protonen

ESR protons at 400 MeV



Cooling time (lab frame):

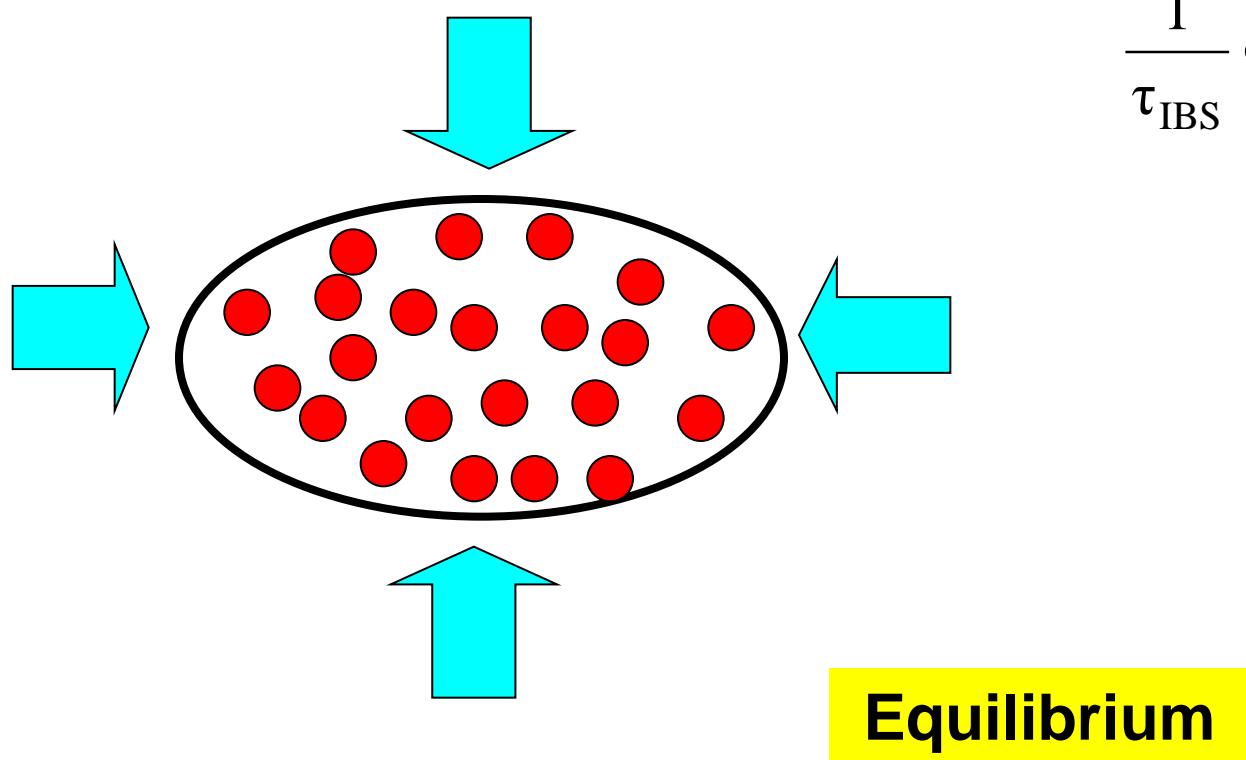
$$\frac{1}{\tau_{\text{cool}}} = - \frac{F}{m_i v_i} \propto \frac{Q^2}{A} \cdot \frac{n_e l_{\text{cool}} c^3}{v_0^3 \gamma_0^5 \theta_{\text{rel}}^3}$$

Cooler AN, Ionenstrahlsignal im Schottky:
Keine Änderung → Strahl gekühlt

Equilibrium

Can cooling go on forever ?

The intrabeam scattering (IBS) is the multiple Coulomb scattering of charged particles in the beam →heating



$$\frac{1}{\tau_{\text{IBS}}} \propto \frac{Q^4}{A^2} \cdot \frac{N_i c^3}{v_0^3 \gamma_0^4 \epsilon_x \epsilon_y (\Delta p/p)}$$

$$\frac{1}{\tau_{\text{cool}}} = \frac{1}{\tau_{\text{IBS}}}$$

Typical operation parameters SIS18/ESR/CRYRING electron coolers

cool. section length/circumference = 2%

SIS18 (216 m)

e- accelerating voltage (HV)	up to 7 kV
e- current	0-1 A
cathode diameter	1 inch
guiding magnetic field (expansion) gun 0.18 T → cooling section 0.06 T	

fixed-energy operation
at injection from TK

11.4 MeV/u Ionen
→ 6.3 kV Cooler accelerating HV

ESR (108 m)

e- accelerating HV	2-220 kV (± 1 V)
e- current	0-1 A
cathode diameter	2 inch
guiding magnetic field (no expansion)	0.02-0.1 T

Fixed energy or
ramped-energy operation
e.g. deceleration of ion beam
Ramped cycle:

Cooler accelerating HV

+

Cooler magnetic field

+

Cooler electron current

CRYRING (54 m)

(Sweden)	
e- accelerating HV	up to 6 kV
e- current	up to 0.15 A
cathode diameter	0.16 inch
guiding magnetic field (expansion) gun 3 T → cooling section 0.03 T	

Event mode,
complex operation MODI+Cooler

Electron Coolers at GSI



Hands-on engineering tasks & developments:

- electric and electronic engineering
- High voltage, high current power supplies
- RF, microwave techniques
- Ultra-high vacuum
- Mechanics, precision machining
- Control interfaces/software

In preparation for CRYRING (2016):

new Ecooler application program compatible with LSA Ring Modelling
can be generically adapted later to ESR and SIS18 coolers (within new LSA-based operation)

Comparison of cooling methods

	Stochastic Cooling	Electron Cooling
Ion species	All	ions
Favored beam velocity	High	Low/medium $(\beta_0 \gamma_0 \leq 1)$
Beam intensity	Low	Any
Cooling time	$N \cdot 10^{-8} s$ $N \geq 10^8$	$1 - 10^{-2} s$
Favored beam temperature	high	low

Thank you for your attention!