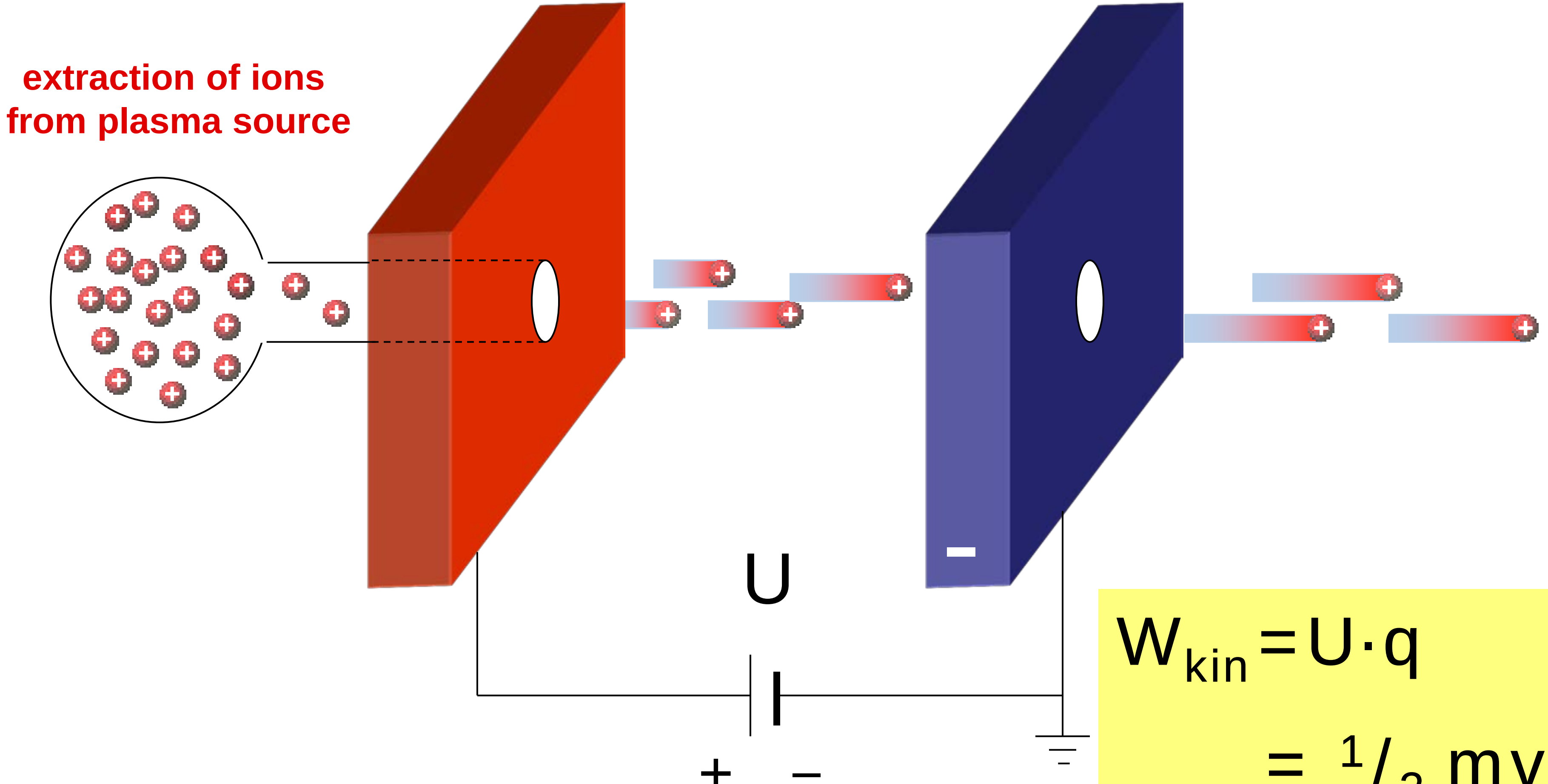
Electron Cooling @ GSI/FAIR

Operateurausbildung

C. Dimopoulou (Abteilung Strahlkühlung BCO)

September 2017

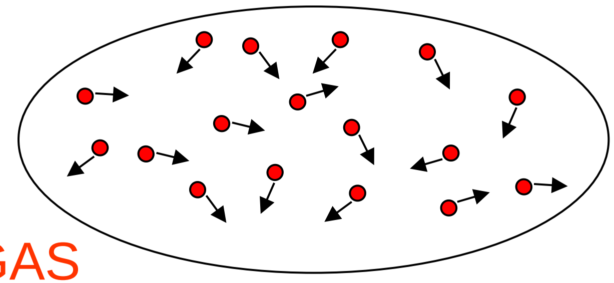
Principle of Acceleration



$$W_{kin} = U \cdot q$$
$$= {}^{1}/_{2}\, mv^2$$

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

Stored beams: Cool before using!



HOT GAS

disordered motion of
ions in the beam,
high internal energy

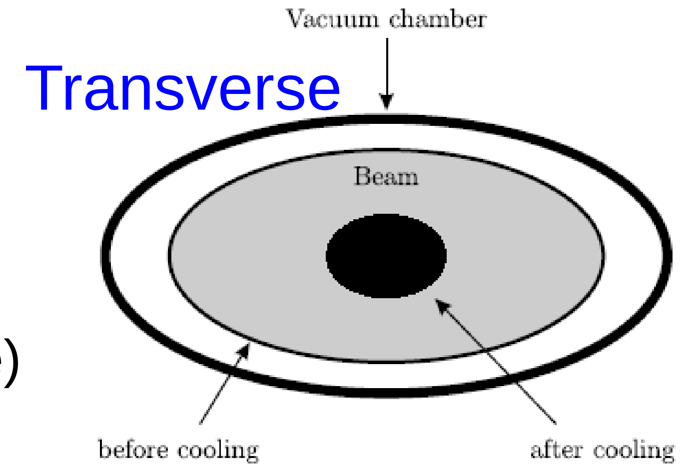
BEAM COOLING
METHOD

COLD GAS

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

Applications & benefits of Beam Cooling

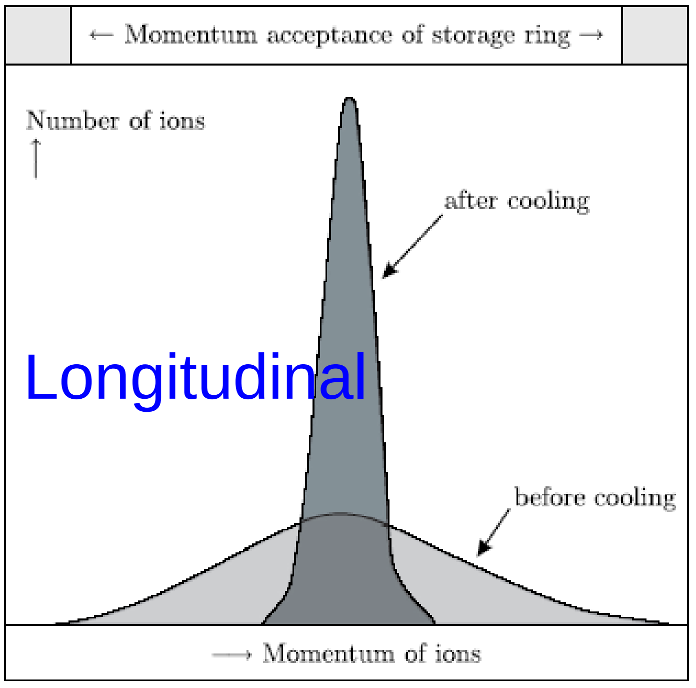
- Secondary beams from production targets
  (antiprotons, rare isotopes)
- Improved beam quality
  - Precision experiments
    (good energy definition, small beam size)
  - Luminosity increase in colliders



- Counteract beam heating effects
  - Experiments with internal target
  - Colliding beams

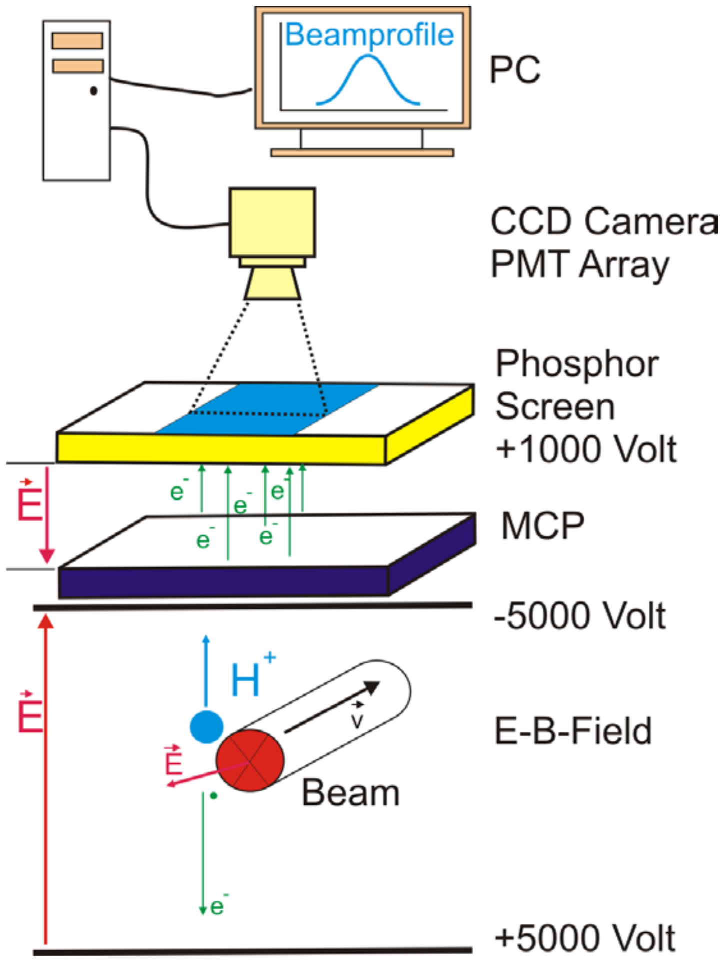
- Decelerated beams:
  Compensate beam emittance growth

- Intensity increase by accumulation
  - Weak beams or low-abundant species from source
    z.B. Multiturn Injektion!

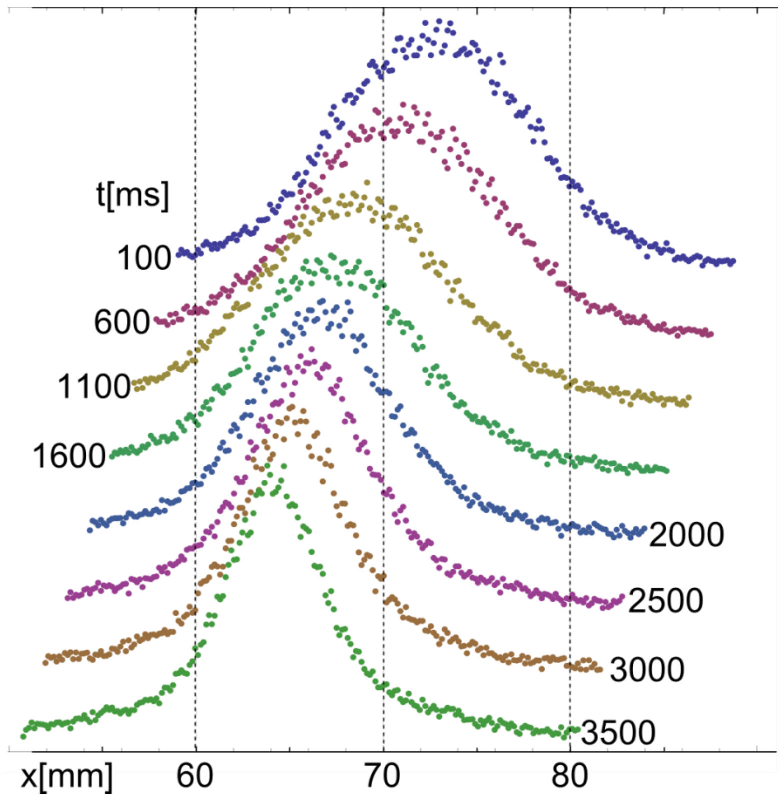


Non-destructive diagnostics: transverse

Profile of transverse distribution from ionization of residual gas

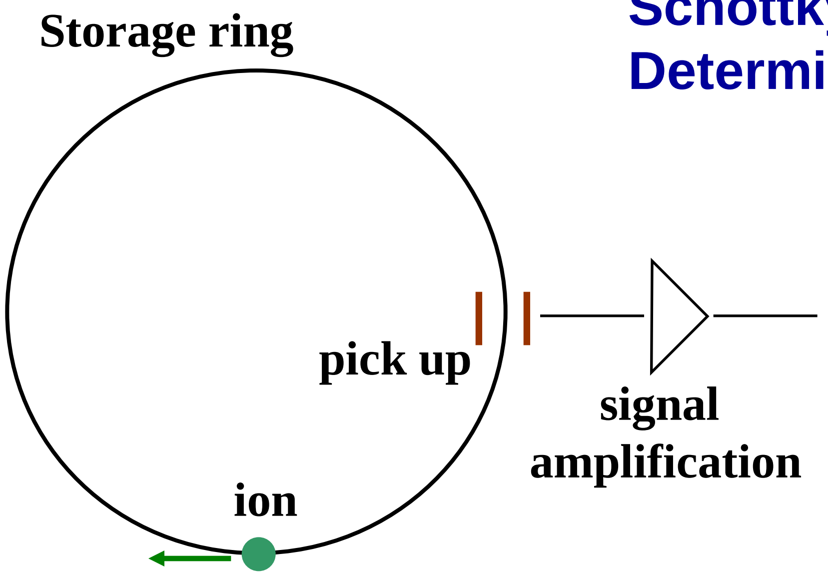


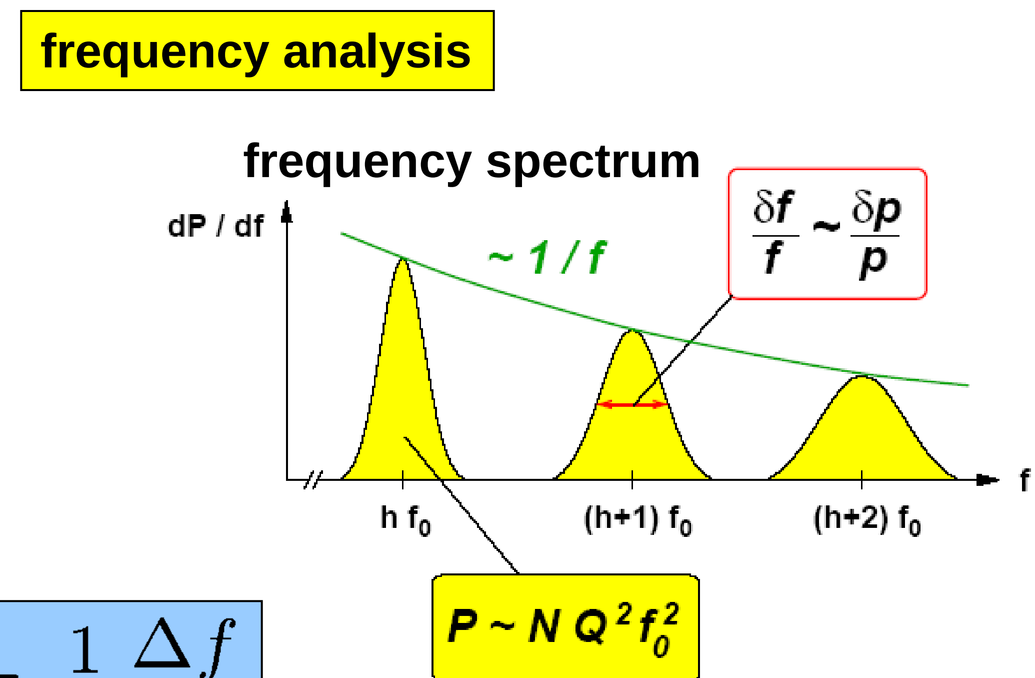
transverse cooling of the beam after injection into ESR



Non-destructive diagnostics: longitudinal

Schottky noise longitudinal diagnostics
Determination of momentum spread





momentum compaction factor η

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

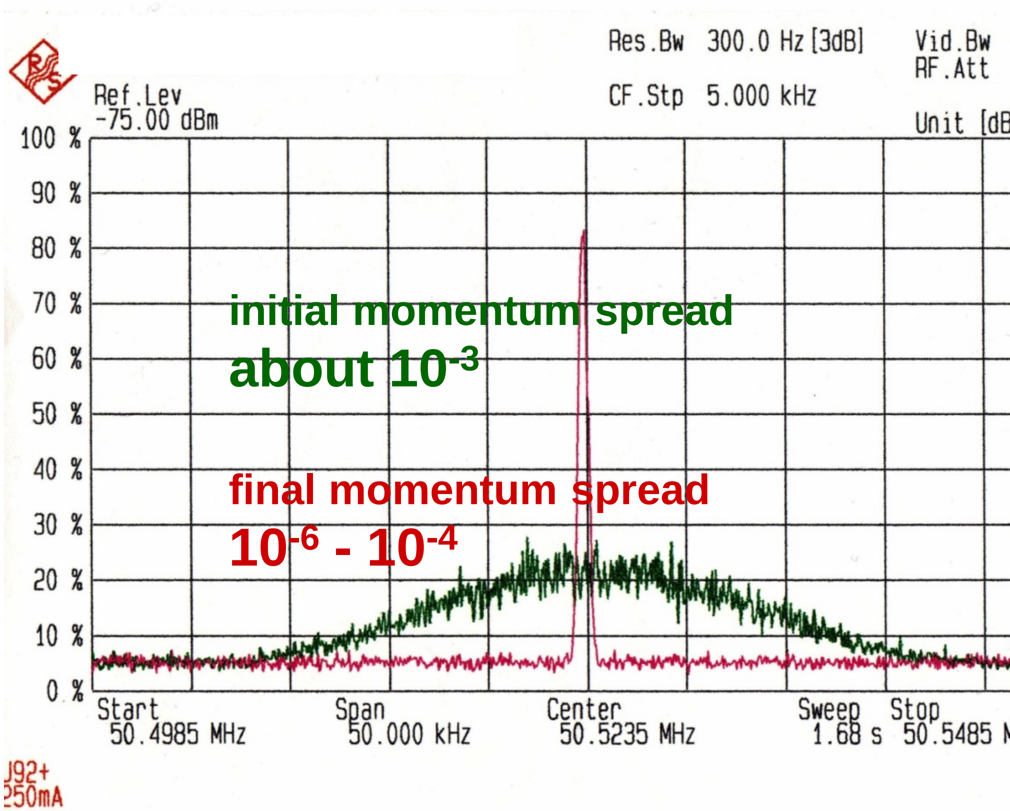
transition energy γ_t

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

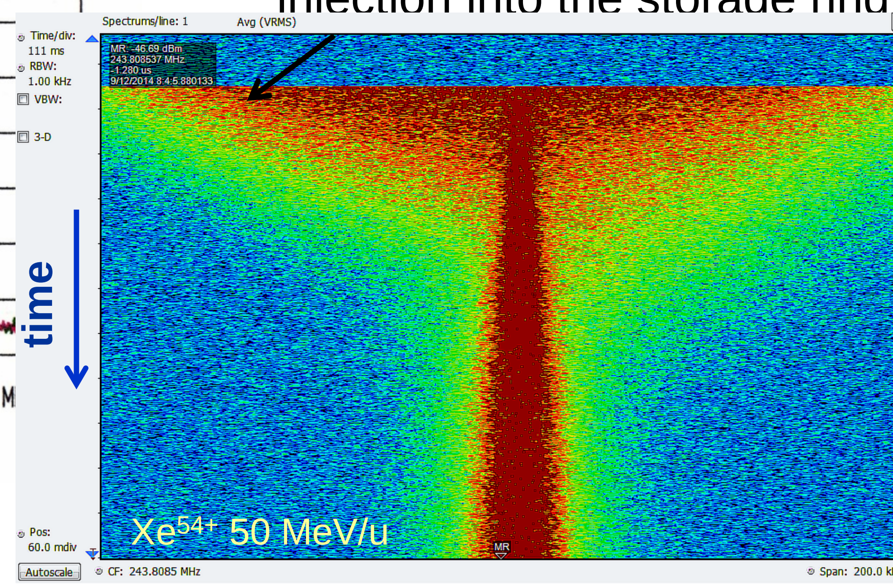
Measured Schottky noise spectra I

U^{92+} at 300 MeV/u before and after electron cooling (I = 0.25 A)

longitudinal (momentum) cooling



injection into the storage ring

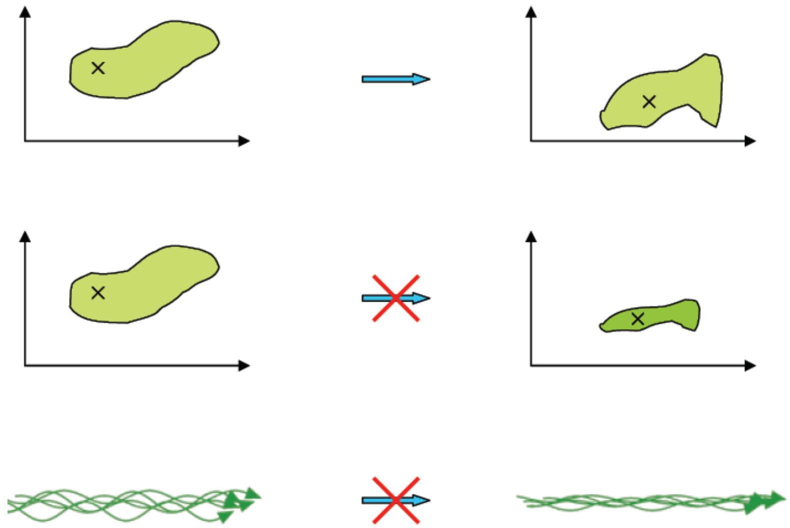


$\delta f/f \sim \delta p/p$

Ingenious ideas made cooling possible

A beam in phase space space is like an incompressible <u>continuous</u> fluid.

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

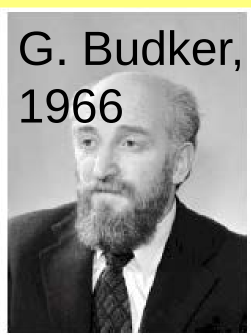


Then, how do we do it ? Act on single particles

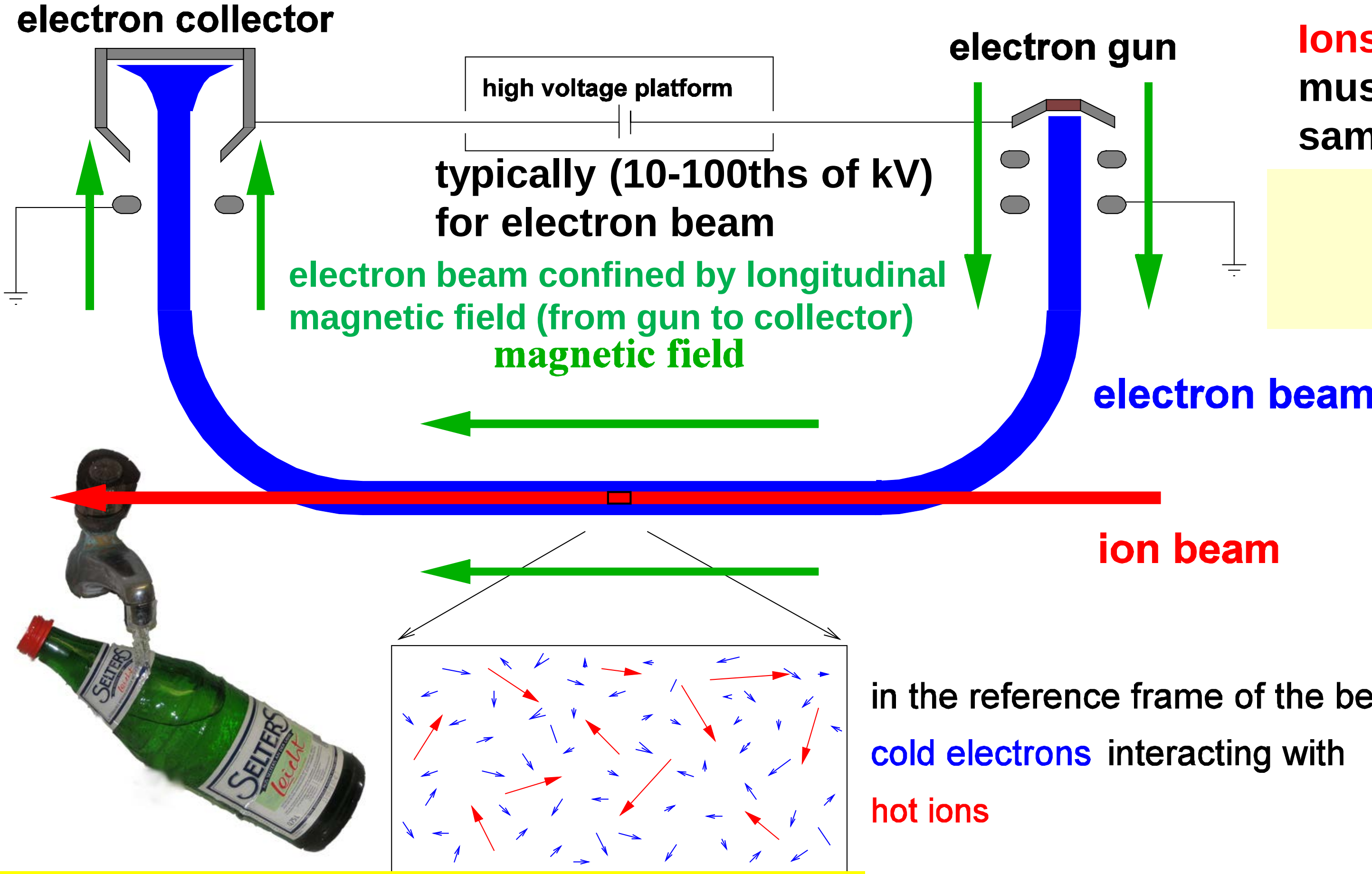
→use EM-forces on beam samples: stochastic cooling

→introduce friction to remove internal energy from the beam: Electron cooling

→both very difficult in practice...



Electron cooling: principle



Ions and electrons must have same nominal velocity v_0

$$v_0 = v_{e\parallel} = v_{i\parallel}$$

$$E_e = m_e / M_i \cdot E_i$$

e.g.: 220 keV electrons cool 400 MeV protons

in the reference frame of the beam:

cold electrons interacting with

hot ions

electron temperature

$kT_\perp \approx 0.1$ eV (1100 K)

$kT_\parallel \approx 0.1 - 1$ meV

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

momentum transfer by Coulomb collisions

cooling force results from energy loss in the co-moving gas of free electrons

Cooling time (lab frame):

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

But, electrons and positive ions recombine !?

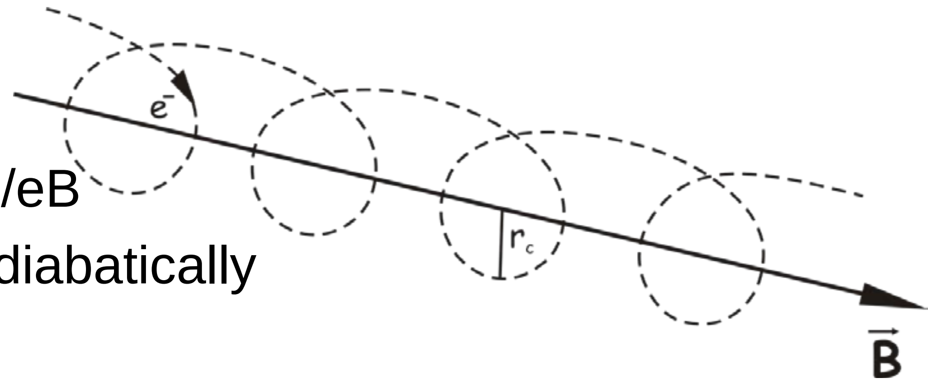
Electron motion in guiding longitudinal magnetic field

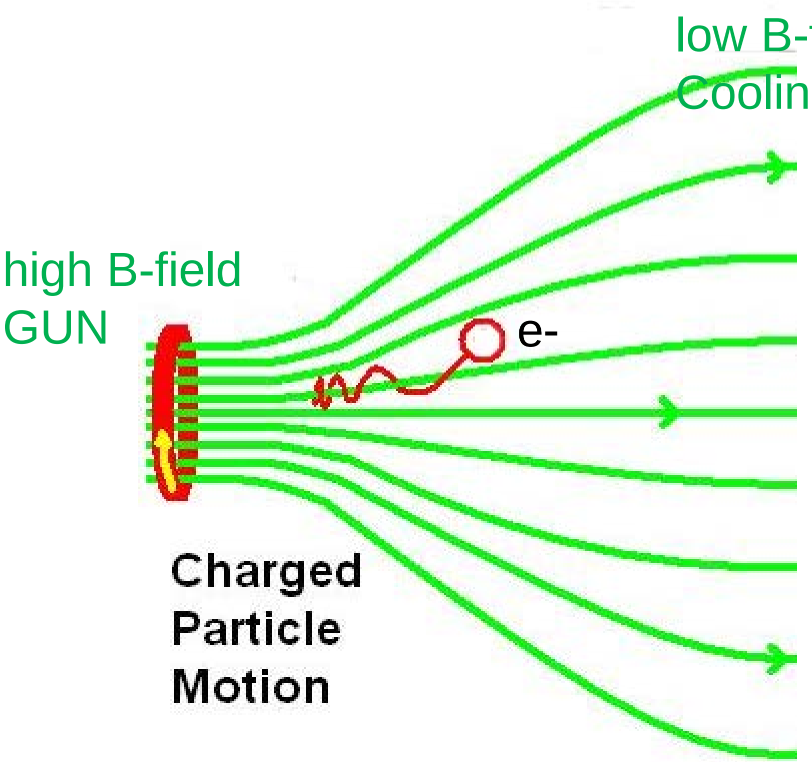
single particle cyclotron motion

cyclotron frequency $\omega_c = eB/\gamma_0 m_e$

cyclotron radius $r_c = v_\perp/\omega_c = (kT_\perp m_e)^{1/2}\,\gamma_0/eB$

electrons follow the magnetic field line adiabatically





Option: adiabatic magnetic expansion

B·(electron beam radius)² =invariant;

transverse electron temperature/B=invariant.

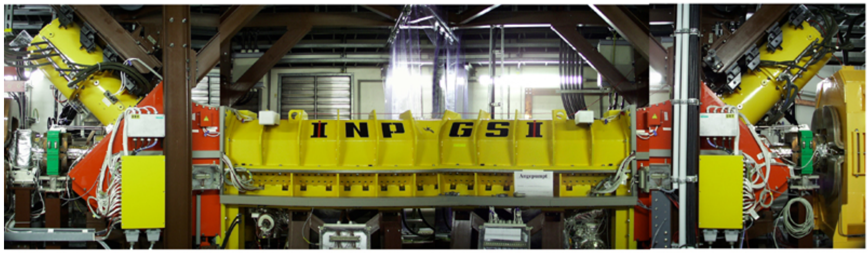
B-field:	**gun 3 T**	**→ cool section 0.03 T**
e-beam diameter :	**4 mm →**	**40 mm**

Electron Coolers at GSI

cool. section length/circumference = 2%

SIS18 (216 m)
e- accelerating voltage (HV) up to 7kV
e- current 0-1 A
cathode diameter 1 inch
guiding magnetic field (expansion)
gun 0.18 T→ cooling section 0.06 T

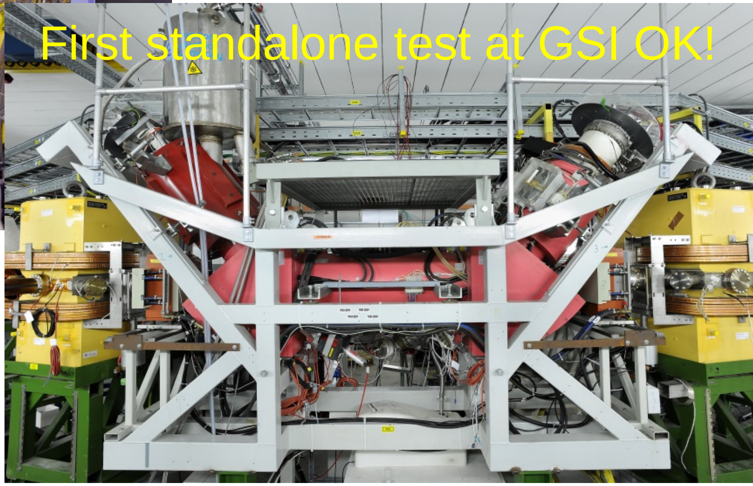
Cooling at Injection Energy of Synchrotron
Accumulation in transverse phase space
By Multiple Multiturn Injection (MMTI)



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

Cooling for Internal Experiments
Cooling of decelerated beams
ESR: also accumulation

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



Responsibility of GSI Beam Cooling Department

Electron Coolers at GSI
Typical operation parameters

SIS18 (216 m)
e- accelerating voltage (HV) up to 7kV
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

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

Fixed energy (DC) or
ramped-energy operation
e.g. deceleration of ion beam
Multiplexed (ramped) cycle:
Cooler accelerating HV (scalar)
+
Cooler magnetic field (FG ramp)
+
Cooler electron current (scalar)

Event mode,
complex operation LSA/MODI+Cooler

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 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 AN

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

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

Was passiert wenn Elektronen an die Wand gehen z.B. Ausfall Magnetstromversorgung?
1. I_e 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)

$$\theta_x \sim \int_{toroids} \frac{B_{cooler} \cdot ds}{(B\rho)_{ion}}$$

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

Bahnkorrektur (Kühlerbump) Schema

ESR,SIS18
mit 2 Cooler KX Steerern + 2 (4) benachbarten Ring KX Steerern.

CRYRING
mit 2 Cooler KH Steerern + 2 benachbarten Backlegs KD Steerern (in Dipolen).

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

Electron cooler: basic operation III
Kühlung Optimieren

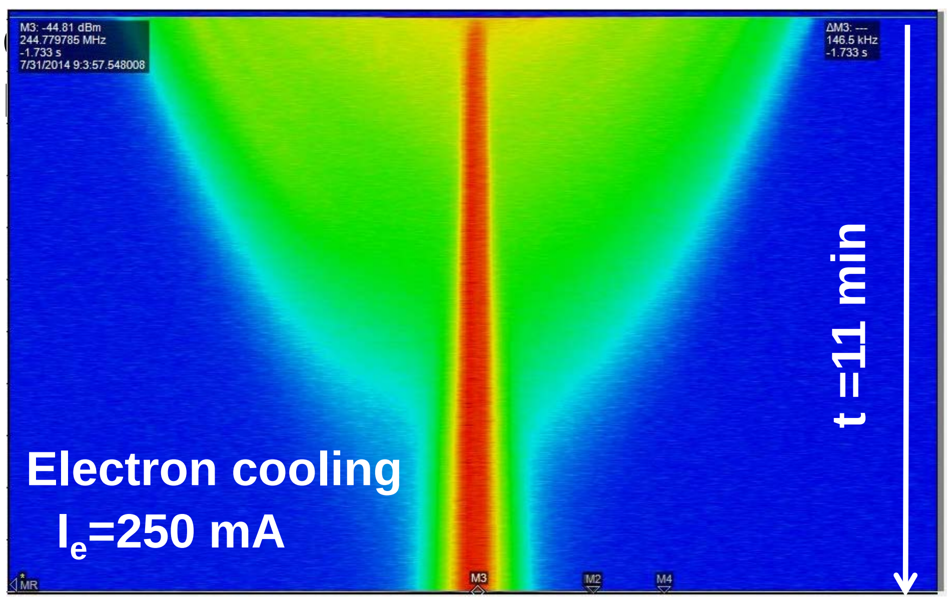
Fein Anpassung δU_e um den gesetzten U_e : Cooler AN, Ionenstrahlsignal im Schottky

- 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):

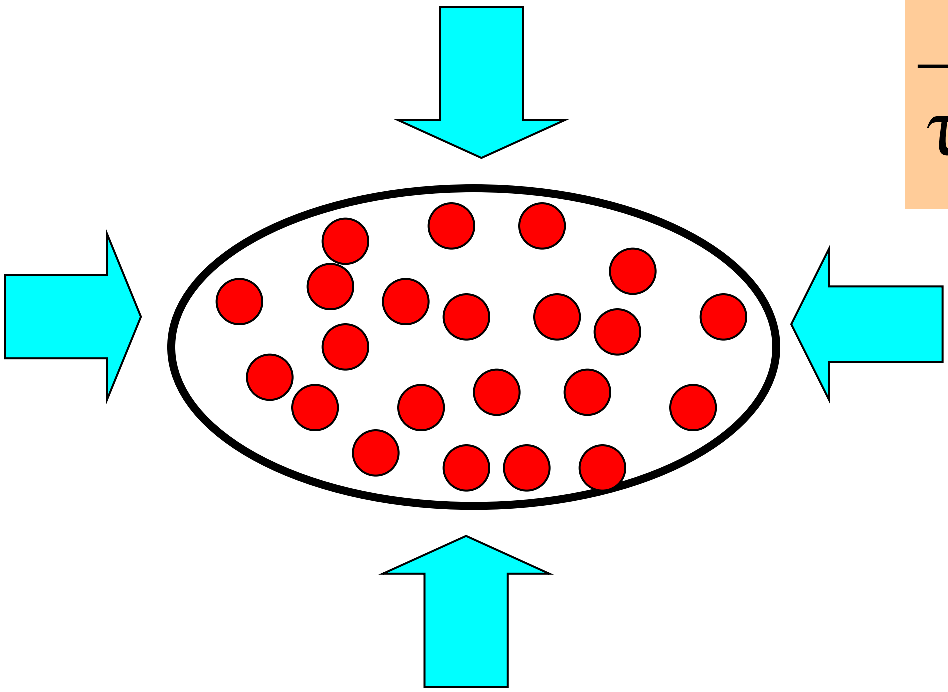
$$\frac{1}{\tau_{cool}} = -\frac{F}{m_i v_i} \propto \frac{Q^2}{A} \cdot \frac{n_e\, l_{cool}\, c^3}{v_0^3 \gamma_0^5 \theta_{rel}^3}$$

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

Equilibrium

Can cooling go on forever ?

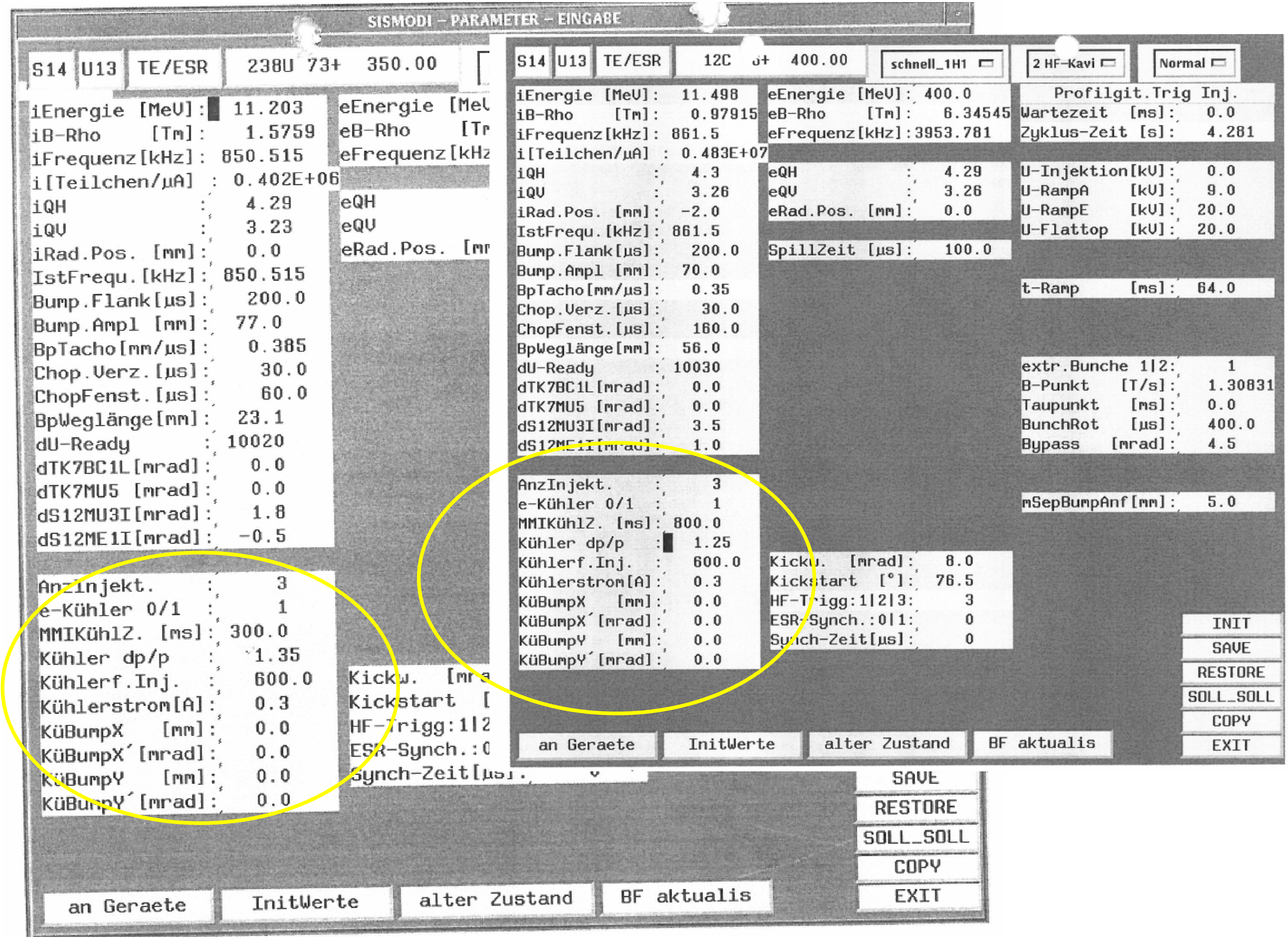
The intrabeam scattering (IBS) is the multiple Coulomb scattering of charged particles in the beam



$$\frac{1}{\tau_{IBS}} \propto \frac{Q^4}{A^2} \cdot \frac{N_i\, c^3}{v_0^3 \gamma_0^4 \varepsilon_x \varepsilon_y \left(\Delta p/p\right)}$$

$$\frac{1}{\tau_{cool}} \propto \frac{Q^2}{A} \cdot \frac{n_e\, l_{cool}\, c^3}{v_0^3 \gamma_0^5 \theta_{rel}^3}$$

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


SISMODI – PARAMETER – EINGABE
S14 U13 TE/ESR 238U 73+ 350.00
iEnergie [MeV]: 11.203
iB-Rho [Tm]: 1.5759
iFrequenz[kHz]: 850.515
i[Teilchen/µA] : 0.402E+06
iQH : 4.29
iQV : 3.23
iRad.Pos. [mm]: 0.0
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
eEnergie [MeV
eB-Rho [Tm
eFrequenz[kHz
eQH
eQV
eRad.Pos. [mm
Kickw. [mra
Kickstart [
HF-Trigg:1|2
ESR-Synch.:0
Synch-Zeit[µs]:
SAVE
RESTORE
SOLL_SOLL
COPY
EXIT
an Geraete
InitWerte
alter Zustand
BF aktualis
S14 U13 TE/ESR 12C 6+ 400.00
schnell_1H1
2 HF-Kavi
Normal
iEnergie [MeV]: 11.498
iB-Rho [Tm]: 0.97915
iFrequenz[kHz]: 861.5
i[Teilchen/µA] : 0.483E+07
iQH : 4.3
iQV : 3.26
iRad.Pos. [mm]: -2.0
IstFrequ.[kHz]: 861.5
Bump.Flank[µs]: 200.0
Bump.Ampl [mm]: 70.0
BpTacho[mm/µs]: 0.35
Chop.Verz.[µs]: 30.0
ChopFenst.[µs]: 160.0
BpWeglänge[mm]: 56.0
dU-Ready : 10030
dTK7BC1L[mrad]: 0.0
dTK7MU5 [mrad]: 0.0
dS12MU3I[mrad]: 3.5
dS12ME1I[mrad]: 1.0
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
eEnergie [MeV]: 400.0
eB-Rho [Tm]: 6.34545
eFrequenz[kHz]:3953.781
eQH : 4.29
eQV : 3.26
eRad.Pos. [mm]: 0.0
SpillZeit [µs]: 100.0
Kickw. [mrad]: 8.0
Kickstart [°]: 76.5
HF-Trigg:1|2|3: 3
ESR-Synch.:0|1: 0
Synch-Zeit[µs]: 0
Profilgit.Trig Inj.
Wartezeit [ms]: 0.0
Zyklus-Zeit [s]: 4.281
U-Injektion[kV]: 0.0
U-RampA [kV]: 9.0
U-RampE [kV]: 20.0
U-Flattop [kV]: 20.0
t-Ramp [ms]: 64.0
extr.Bunche 1|2: 1
B-Punkt [T/s]: 1.30831
Taupunkt [ms]: 0.0
BunchRot [µs]: 400.0
Bypass [mrad]: 4.5
mSepBumpAnf[mm]: 5.0
INIT
SAVE
RESTORE
SOLL_SOLL
COPY
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an Geraete
InitWerte
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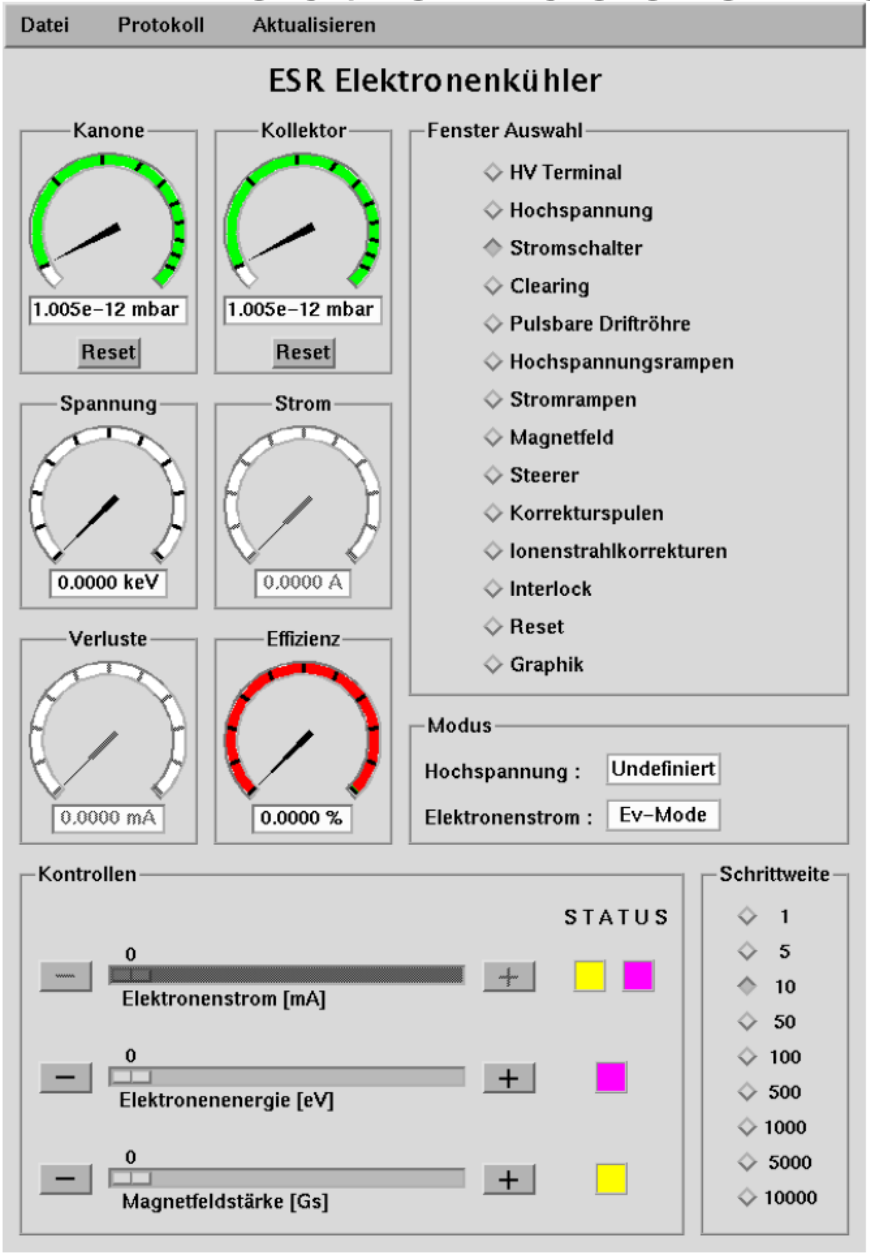
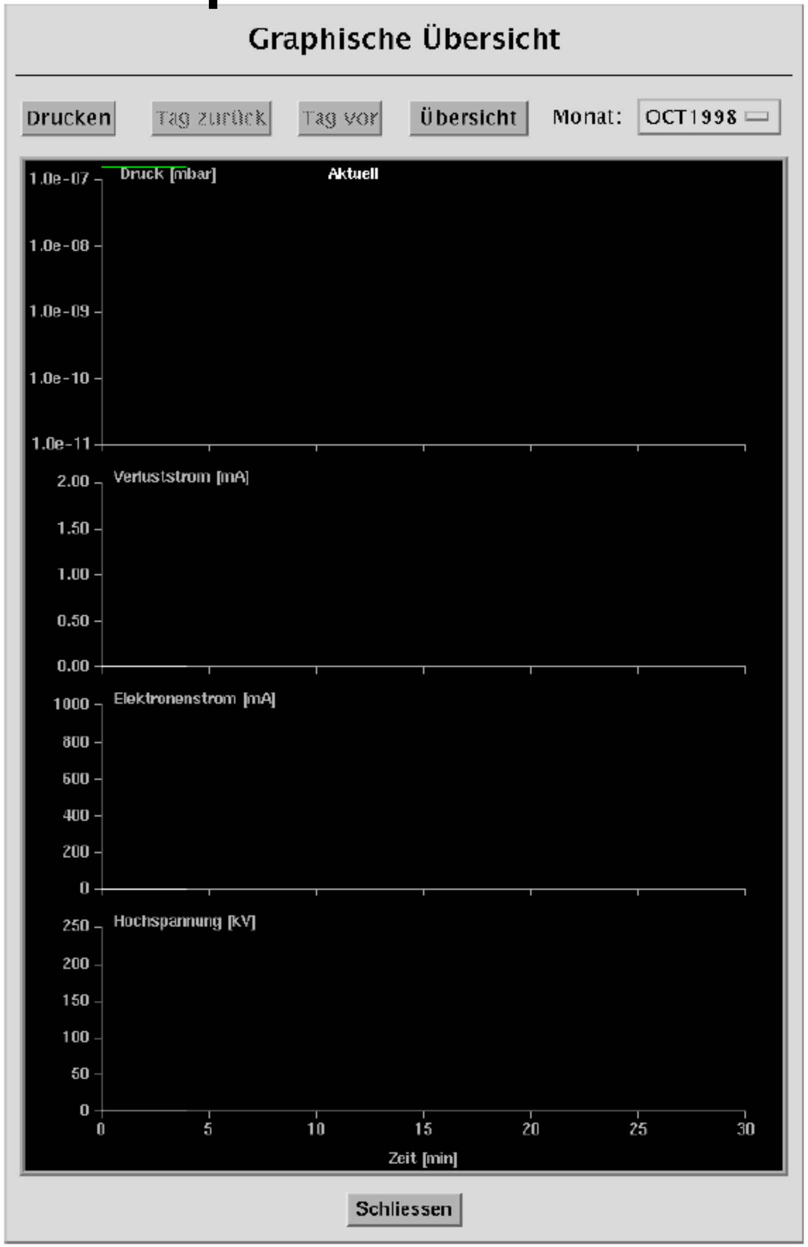
BF aktualis

Electron cooler: basic operation

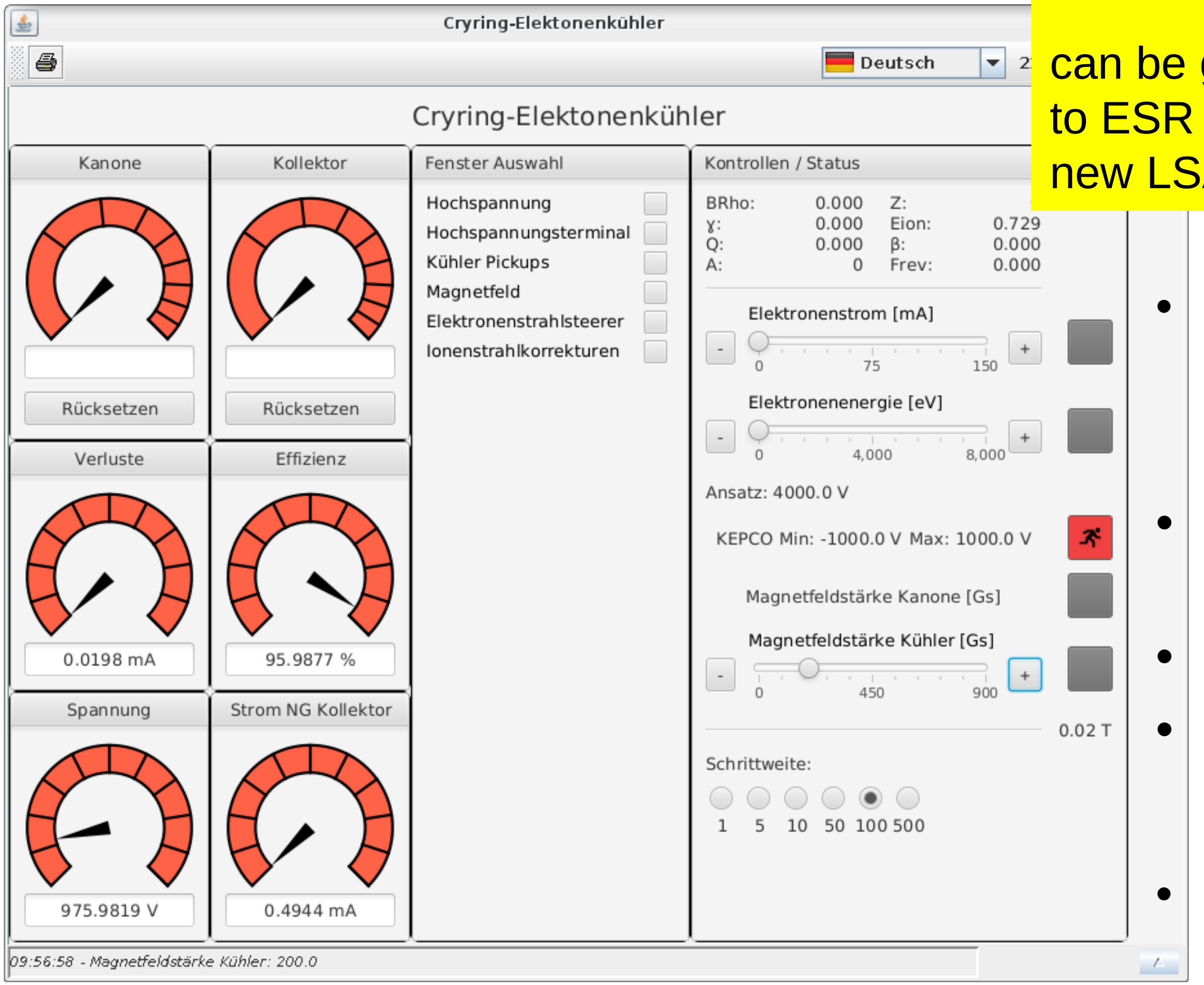




Cryring Cooler application program

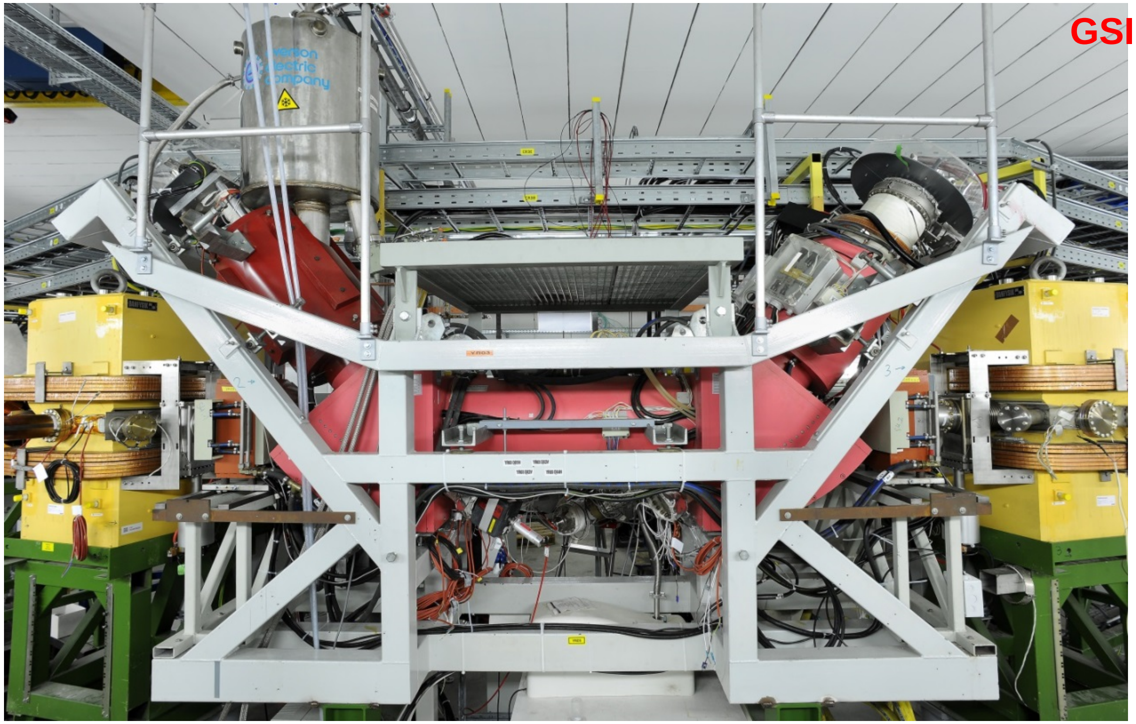
CRYRING: new APP
compatible with LSA Ring Modelling

can be generically adapted later to ESR and SIS18 coolers (within new LSA-based operation)



- **hierachy (formulae, curves, parameters) is set-up in LSA**
- **settings/readout via LSA**
- **& pattern under test.**
- **--direct communication via FESA OK.**
- **application via LSA tested for HV-supplies and steerer magnet supplies**

CRYRING Electron Cooler

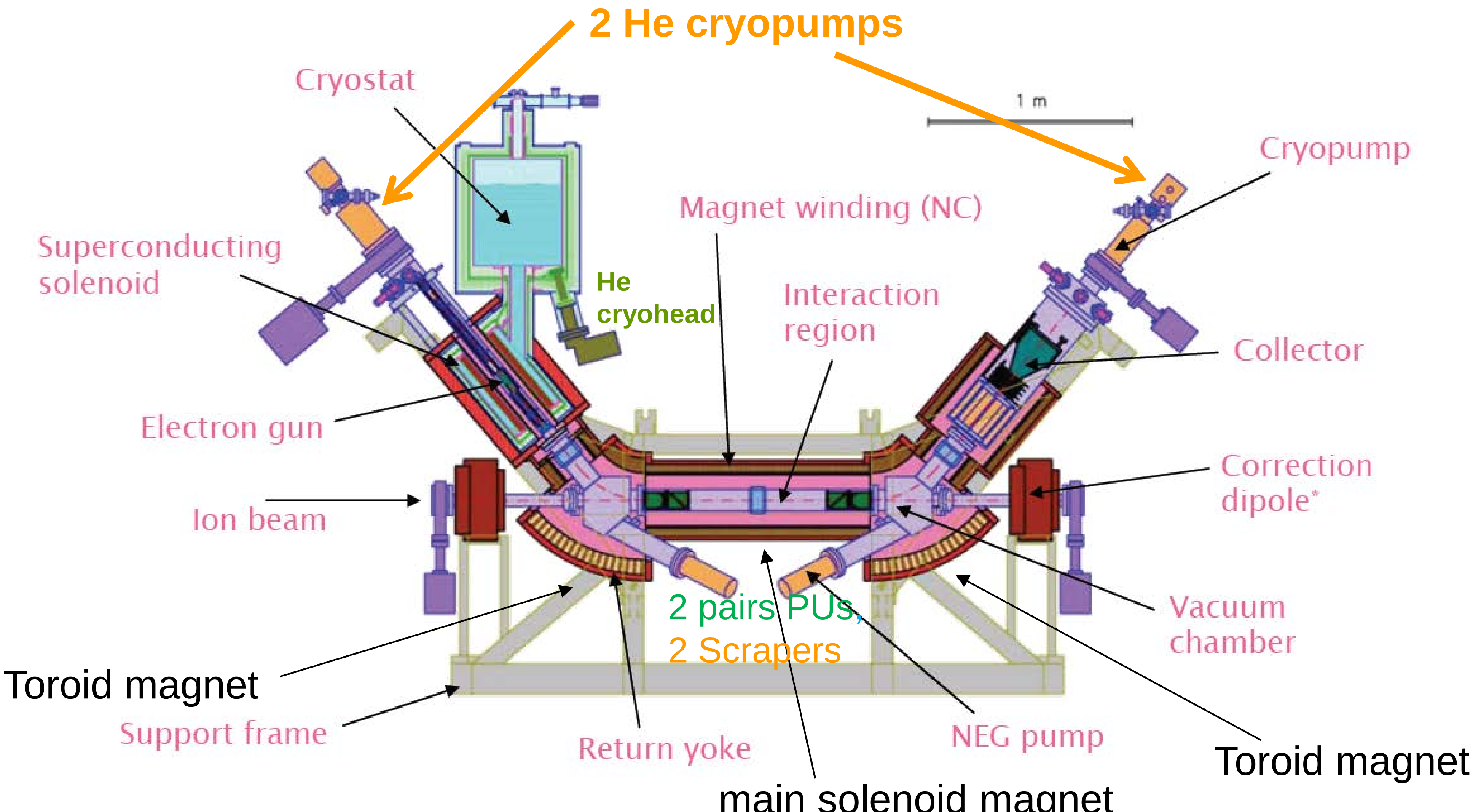


Christina Dimopoulou

on behalf of the Beam Cooling team and collaborators from other departments

(e.g. DEC, CSVS, CSCY, LOEP, CSCO, CSTI, LOBI...)

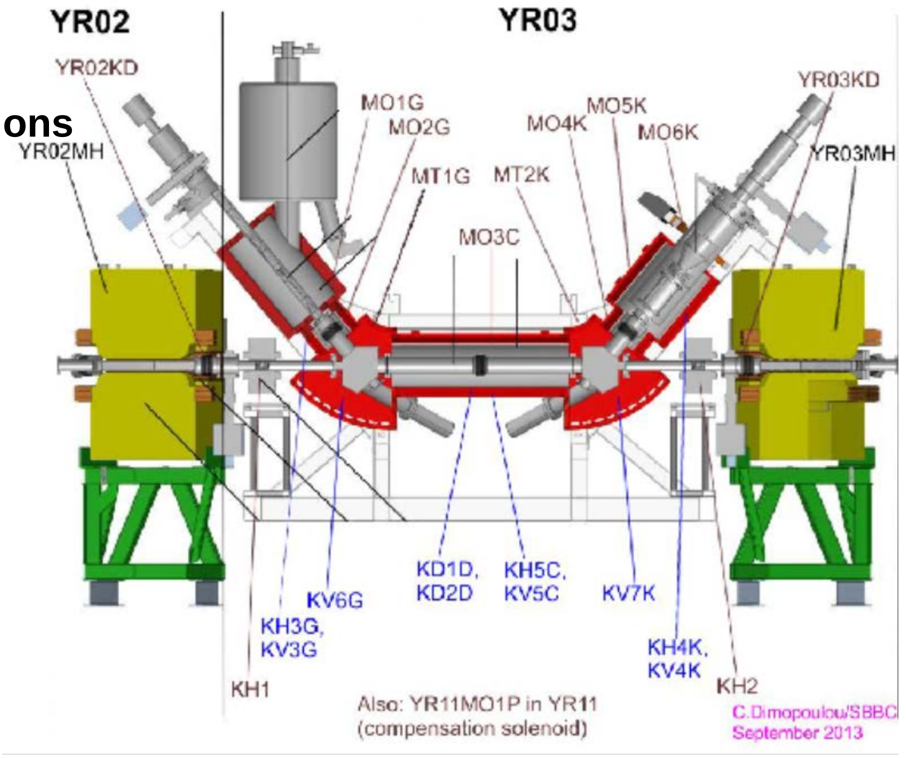
Overview



UHV System (incl. NEG, cryopumps, bakeout)
Magnet System
HV System

Main components & novelties

- **10 normal conducting magnets in series (all except gun)**
- **correction coils in main solenoid and toroids**
- **e⁻ steerers in gun, main solenoid, collector sections**
- **3 He cryohead/cryopumps, 2 compressors**
- **HV facility: 10 power supplies, interlocks**



New i.e. @ GSI

- **Helium supply for the SC gun magnet**
- collector HV power supply -> better e^- current resolution (16-bit for 0-200 mÁ)
- bakeable RF cables at pickups (BPMs)
- KEPCO for fast (multiple ~10µs ramps) cooler HV-steps (-1000 V...+1000 V) for experiments
- precision HV-divider for experiments

Status August 2017-Hardware

- **superconducting magnet tested in persistent mode: 3T reached**
  →no transport damage ☺

- **assembly gun with new cathode, moderate bake-out of cooler**

- **electrons successfully guided from gun to collector**
  →Demonstrated basic function of cooler hardware and its HV facility with electron beam i.e. no show-stopper inside.

- **cathode exchanged, bake-out finished.**
- **cryopumps gun/collector ON; Cooler Pressure ~$2 \cdot 10^{-10}$ mbar.**

- **sustainable Helium supply for SC magnet → by end of September**
- **hardware protection interlocks under preparation/test**

Next steps

- **October 2017 (after beam time): systematic standalone (electron beam only) commissioning by cooler experts**

  ---with the application program via LSA

  --- cooler controls run in DC mode

  → gather/confirm operation parameters, debug controls, edit cooler manual.

- **Set-up cooler with stored ion beam, implement into controls the ion orbit correction (compensation of cooler toroid kicks)**

$$\theta_x \sim \int_{toroids} \frac{B_{cooler} \cdot ds}{(B\rho)_{ion}}$$

- **Q4/2017: change cooler controls to multiplexed mode (scalar and ramped)**

  ----followed by standalone testing/debugging with LSA pattern & ramps

- **demonstrate cooling of *<u>stored ion beam</u>***

  provided CRYRING *control system and appropriate beam diagnostics* are *fully operational* ☺