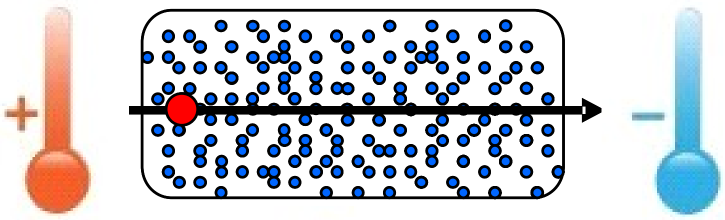
ELECTRON COOLING

M. Freimuth



Quelle: [14]

AGENDA

- INTRODUCTION
- WORKING PRINCIPLE & COMPONENTS
- DIAGNOSTIC & APPLICATION
- CONCLUSION

INTRODUCTION

Space Charge Effekts (SCE)

+

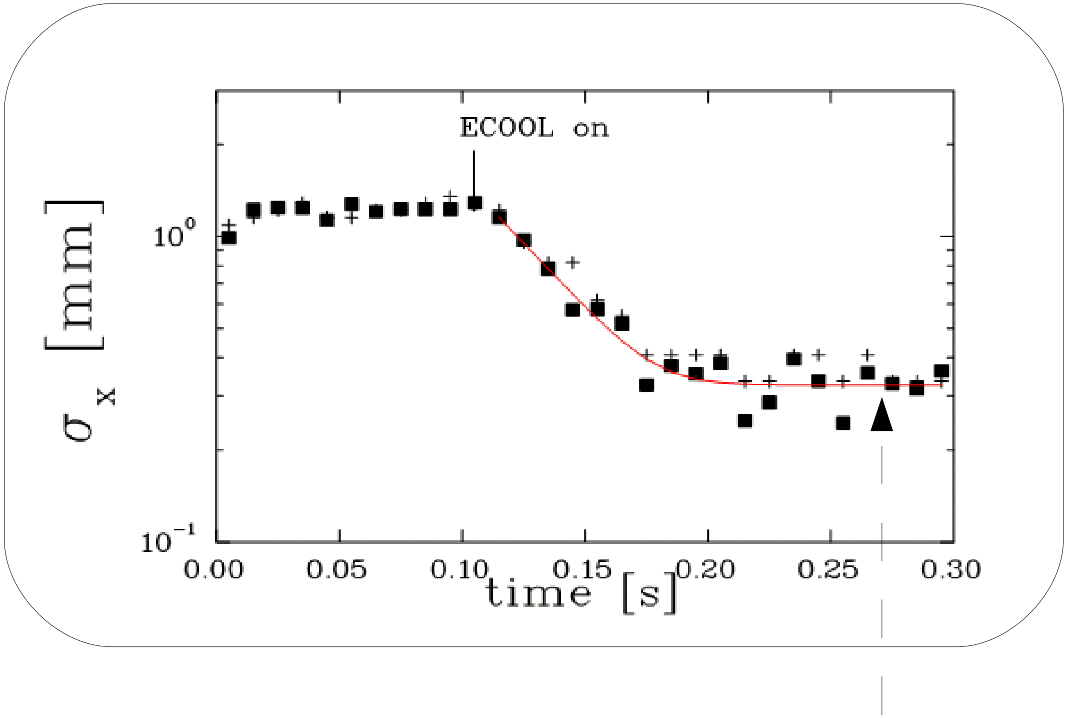
Intra Beam Scattering (IBS) →

+

Residual Gas Scattering (RGS)

=

BEAM LOSSES



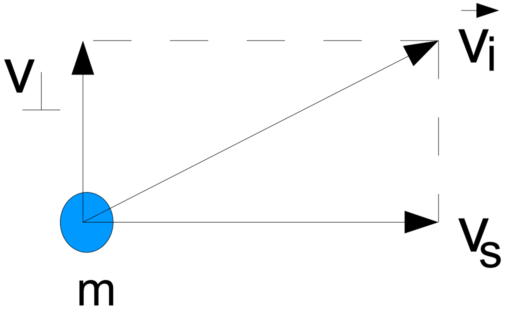
Equilibrium between IBS & e-cooling

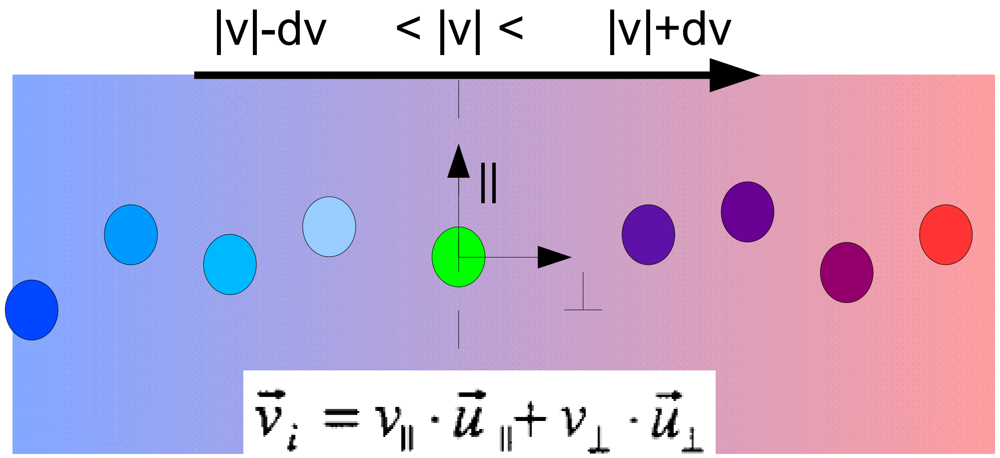
→ luminosity increase
→ increase beam lifetime
→ decrease emittance

Quelle [8]

INTRODUCTION

beam temperature





$$\vec{v}_i = v_\parallel \cdot \vec{u}_\parallel + v_\perp \cdot \vec{u}_\perp$$

thermodynamics

$$E_{kin} = \frac{f}{2} k_B T$$

<->

mechanic

$$E_{kin} = \frac{m}{2} < v^2 >$$

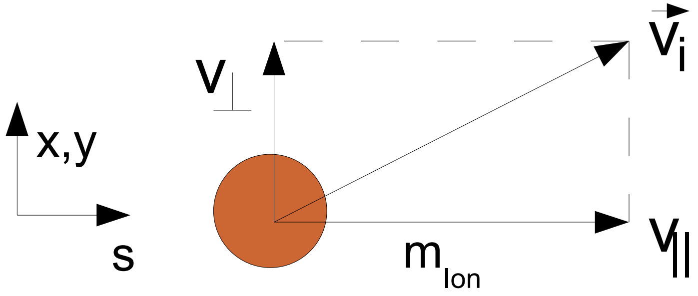
$$k_B T_\perp = m <v_\perp^2>$$

$$k_B T_s = m <v_s^2>$$

Quelle „Physik der Teilchenbeschleuniger und Ionenoptik“, Hinterberger

INTRODUCTION

Ion temperature



$$p_0 = m_i \beta_0 v_i \, *$$

$$\Delta p = m_i(\gamma_0 \Delta v * + v_0 \Delta \gamma)$$

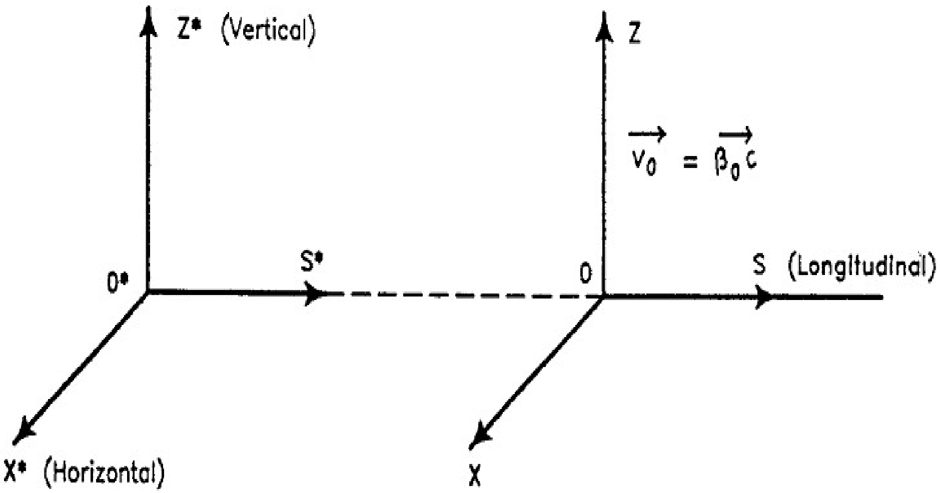
* = LABSYSTEM

longitudinal temperature

$$f \frac{k_B T_\parallel}{2} = \frac{p_0 *^2}{2 \text{ m}}$$

$$k_B T_\parallel = m_i \left(\frac{\Delta p *}{p_0 *} \right)^2 \quad \text{mit } \Delta p* = m_i(v* + dv*)$$

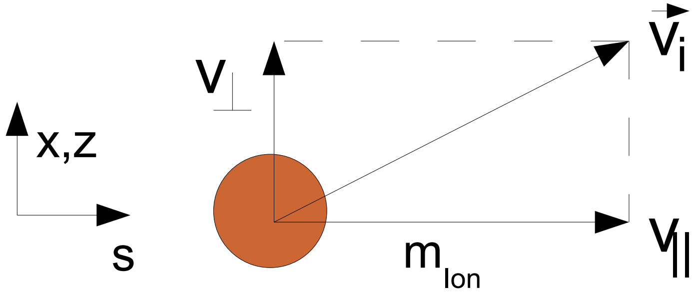
$$k_B T_\parallel = m_i c^2 \beta_0{}^2 \left(\frac{\Delta p}{p_0} \right)^2$$

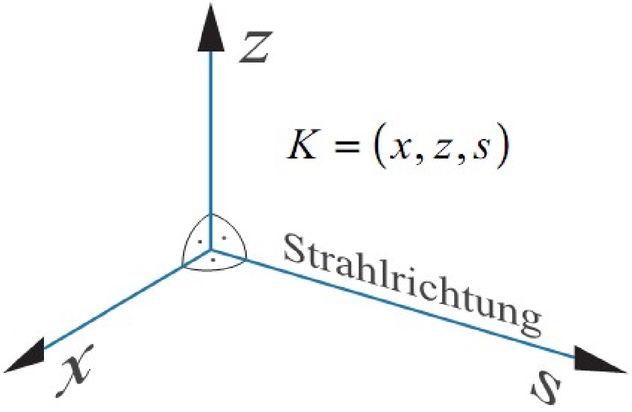


Quelle [3]

INTRODUCTION

Ion temperature





Hill`sche DGL

$$x''(s) + \left(\frac{1}{\rho^2(s)} - k_x(s)\right)x(s) = \frac{1}{\rho(s)}\frac{\Delta p}{p_0}$$

$$z''(s) + k_z(s)z(s) = 0$$

DIPOL
POL

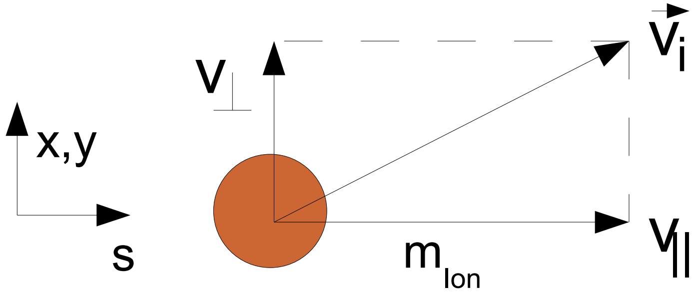
QUADRO
POL

→ assumption: only lineare optic
→ weak focusing

Quelle [3]

INTRODUCTION

Ion temperature



Hill`sche DGL

$$x''(s) + \left(\cancel{\frac{1}{\rho^2(s)}} - k_x(s)\right) x(s) = \frac{1}{\cancel{\rho(s)}} \frac{\Delta p}{p_0}$$

$$x(s) = \sqrt{\varepsilon_\perp \beta_\perp(s)} \cos(\underbrace{\phi_\perp(s) + \phi_{0,\perp}}_{\chi})$$

$$\boxed{x'(s) = \sqrt{\frac{\varepsilon_\perp}{\beta_\perp(s)}} [\cos(\cancel{\chi}) + \sin(\cancel{\chi})]}$$

transersal temperature

$$\frac{f}{\cancel{2}} k_B T_\perp = \frac{m x'^{2}}{\cancel{2}}$$

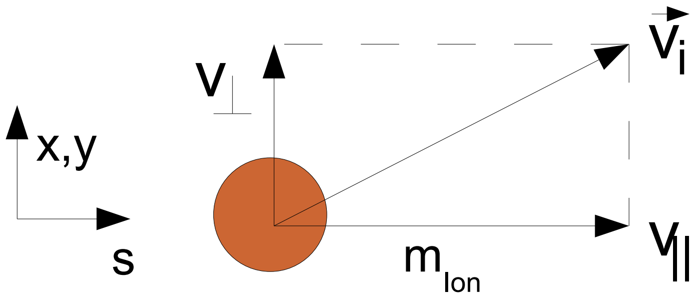
$$k_B T_\perp = m_i (c\gamma\beta_0)^2 \frac{\varepsilon_\perp}{\beta(s)}$$

$$k_B T_\perp = m_i (c\gamma\beta_0)^2 (Q_h + Q_v) \frac{\varepsilon_\perp}{R}$$

Quelle [3]

INTRODUCTION

Ion temperature



longitudinal temperature

$$k_B T_\parallel = m_i c^2 \beta_0^2 \left(\frac{\Delta p}{p_0} \right)^2$$

transversale temperature

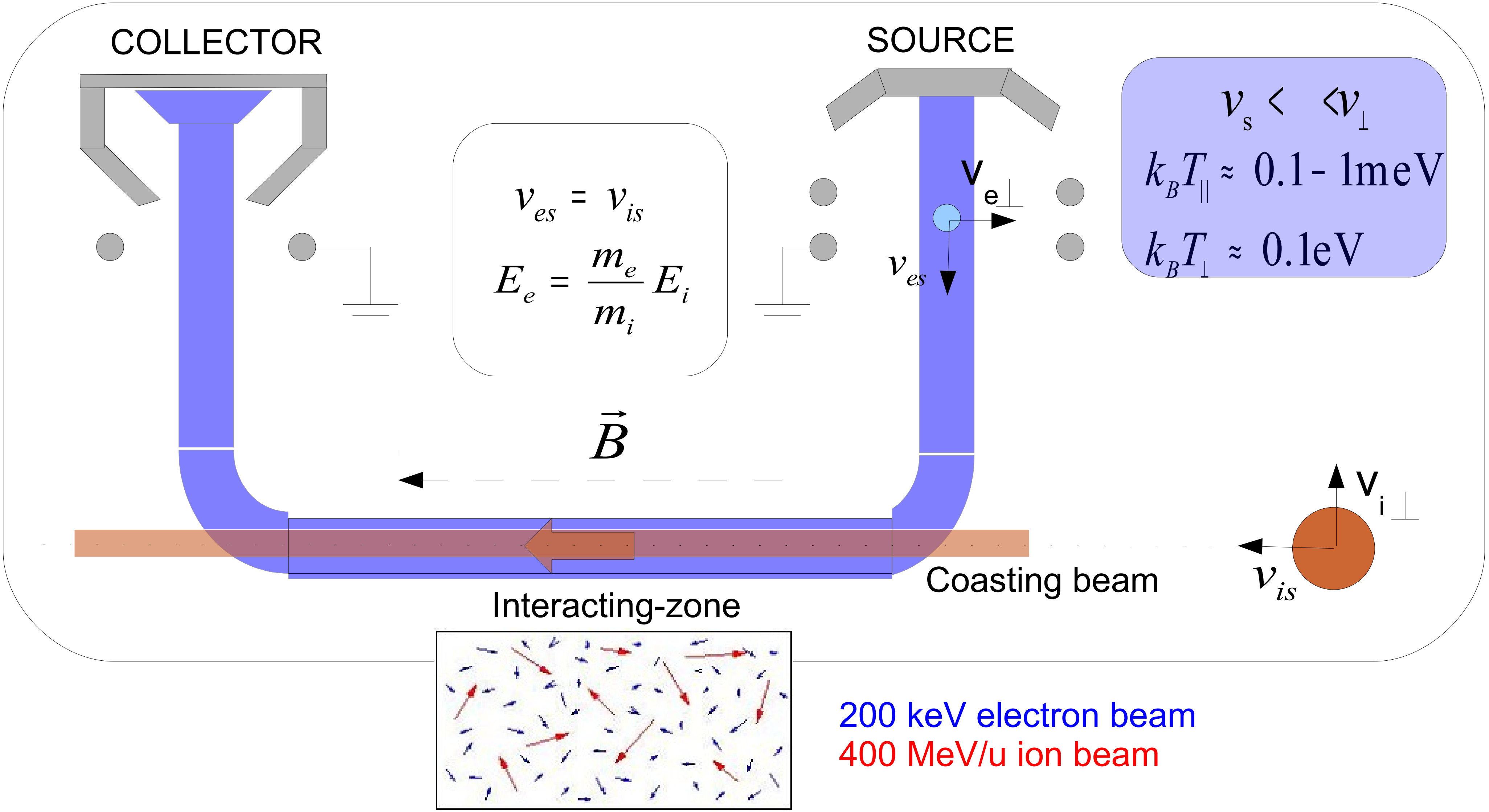
$$k_B T_\perp = m_i c^2 \gamma^2 \beta_0^2 \; (\mathrm{Q_h} + \mathrm{Q_v}) \frac{\varepsilon_\perp}{\mathrm{R}}$$

decrease Δp/p → decrease $T_\parallel$

decrease trans. Emittanz → decrease $T_\perp$

Quelle [3]

WORKING PRINCIPLE



$$v_{es} = v_{is}$$

$$E_e = \frac{m_e}{m_i} E_i$$

$$v_s << v_\perp$$

$$k_B T_\parallel \approx 0.1 - 1\,\mathrm{meV}$$

$$k_B T_\perp \approx 0.1\,\mathrm{eV}$$

200 keV electron beam

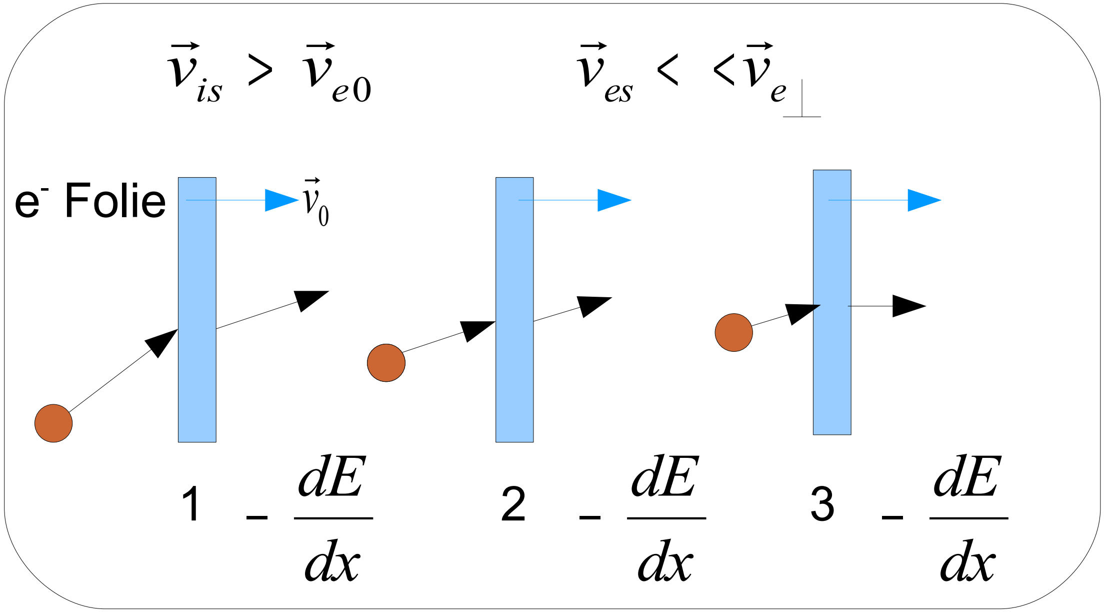
400 MeV/u ion beam

Quelle [7]

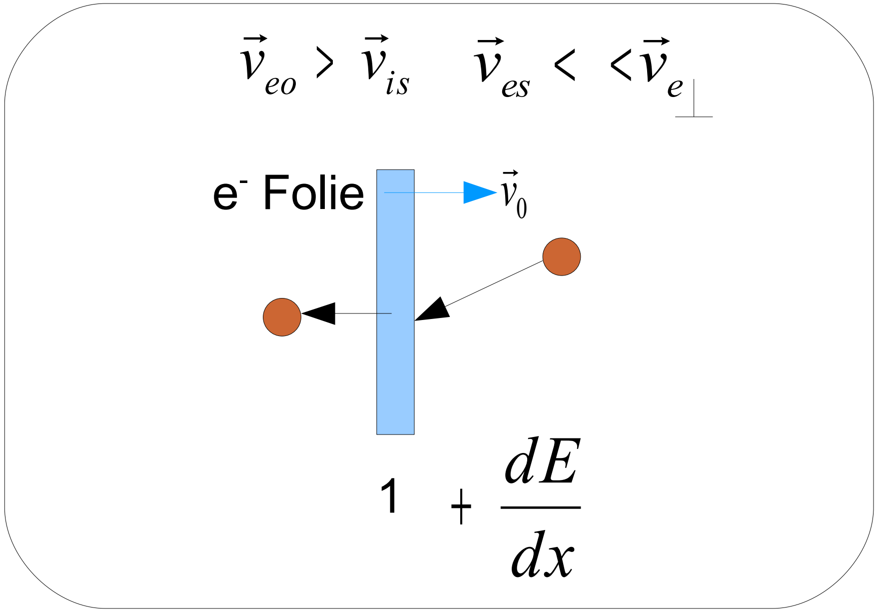
WORKING PRINCIPLE

longitudinal cooling force

$$\vec{v}_{is} > \vec{v}_{e0} \qquad \vec{v}_{es} << \vec{v}_{e\perp}$$



$$\vec{v}_{eo} > \vec{v}_{is} \qquad \vec{v}_{es} << \vec{v}_{e\perp}$$



ENERGY LOSS IN MATTER (Bohr)

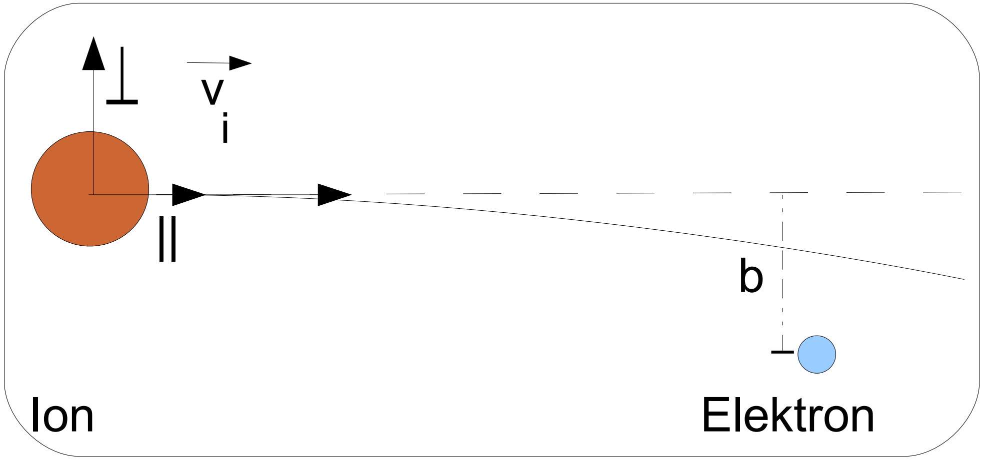
$$-\frac{dE}{dx} \propto \frac{Z^2 n_e}{m_e v_i^2} \alpha_{material}$$

$$F = \frac{dE}{ds}$$

Quelle [7]

WORKING PRINCIPLE

binary collision model



* = beam system v >0

Momentum transfer

$$\Delta p^* \propto \frac{Qe^2}{v_i b}$$

Energy transfer

$$\Delta E_{ele\perp}(b) = \Delta E_{ion\perp}(b) = -\frac{\Delta p_\perp^2(b)}{2m_e}$$

Cooling Force

$$F^* = \frac{\Delta E}{\Delta L} \propto \frac{Q^2 e^4 n_e^*}{v_i^{*3}} Lc$$

Cooling time

$$\tau_c^{*-1} = \frac{F^*}{m_i v_i} \propto \frac{I_e}{L} \frac{Q^2 n_e^* Lc}{m_i m_e v_i^{*3}}$$

$$\frac{dE}{ds_\perp} > > \frac{dE}{ds_\parallel} \qquad \frac{dE}{ds_\parallel} \approx 0$$

$$F^* \rightarrow F_\perp^*$$

Quelle [7]

WORKING PRINCIPLE

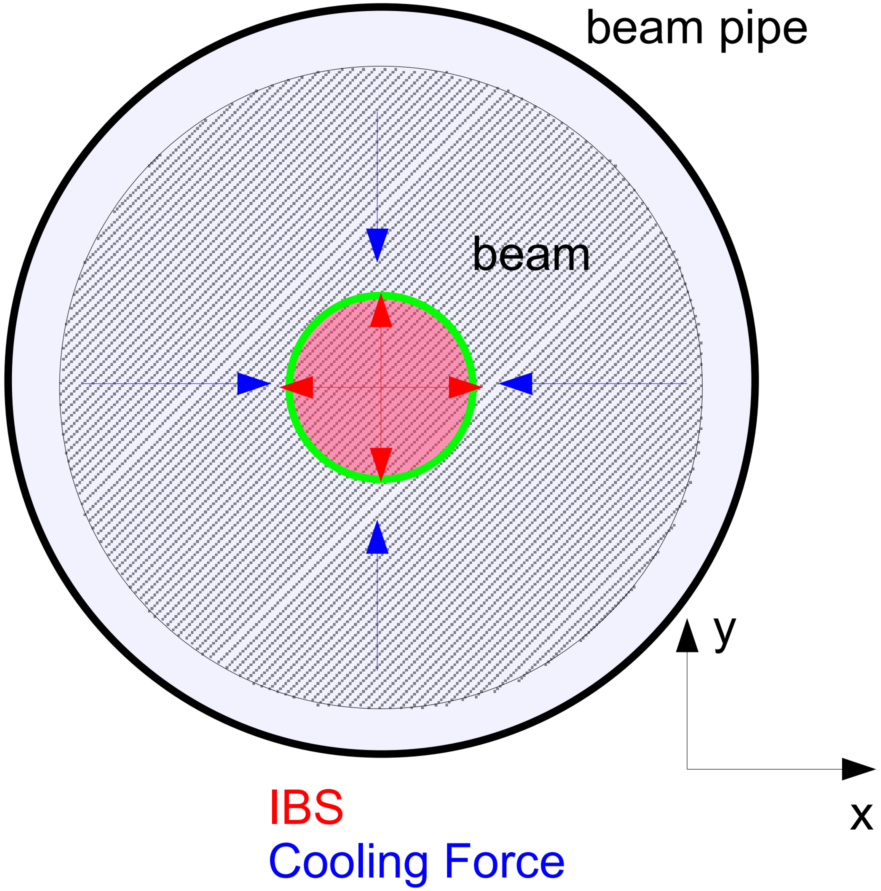
binary collision model

Cooling rate

$$\tau_c^{*-1} = \frac{F^*}{m_i v_i} \propto \frac{I_e}{L}\,\frac{Q^2 n_e^* Lc}{m_i m_e v_i^{*3}}$$

emittance (transversal)

$$\varepsilon_{(x,y,t)} = \varepsilon_{(x,y,t=0)} \exp\left(-\frac{t}{\tau_c}\right)$$



Equilibrium between IBS & e-cooling

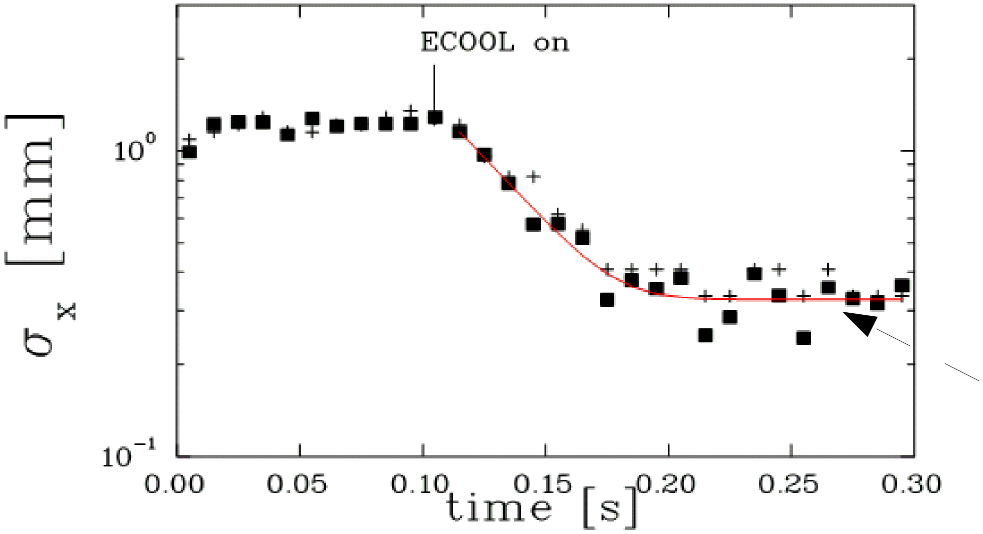
Quelle [7]

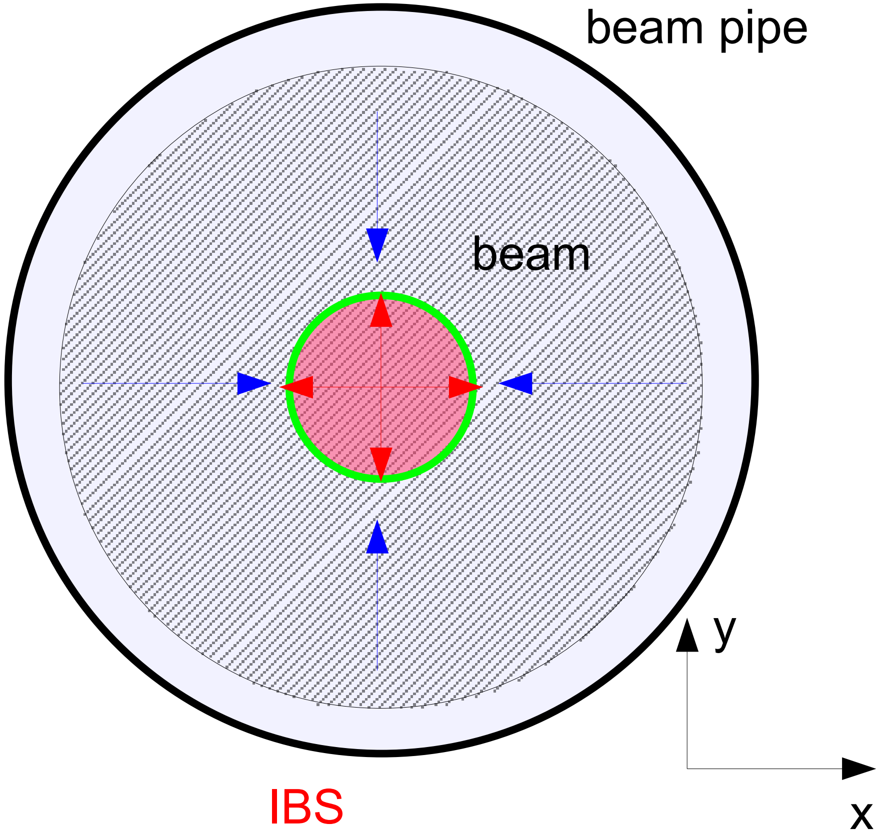
WORKING PRINCIPLE

binary collision model

Cooling rate

$$\tau_c{}^{*-1} = \frac{F^*}{m_i v_i} \propto \frac{I_e}{L} \frac{Q^2 n_e{}^* Lc}{m_i m_e v_i{}^{*3}}$$





IBS

Cooling Force

Equilibrium between IBS & e-cooling

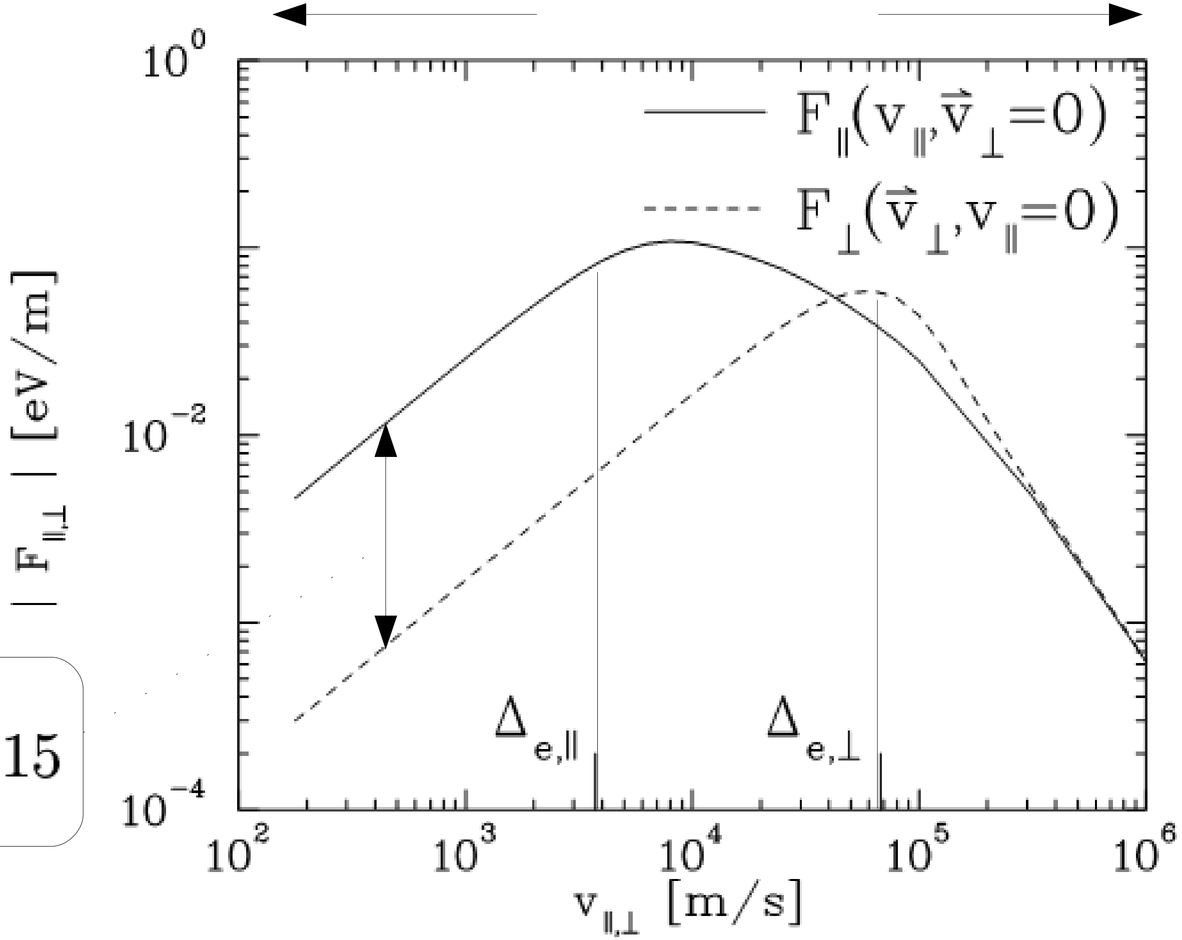
Quelle [7]

WORKING PRINCIPLE

Cooling Force

$F \propto v$

$F \propto v^{-2}$



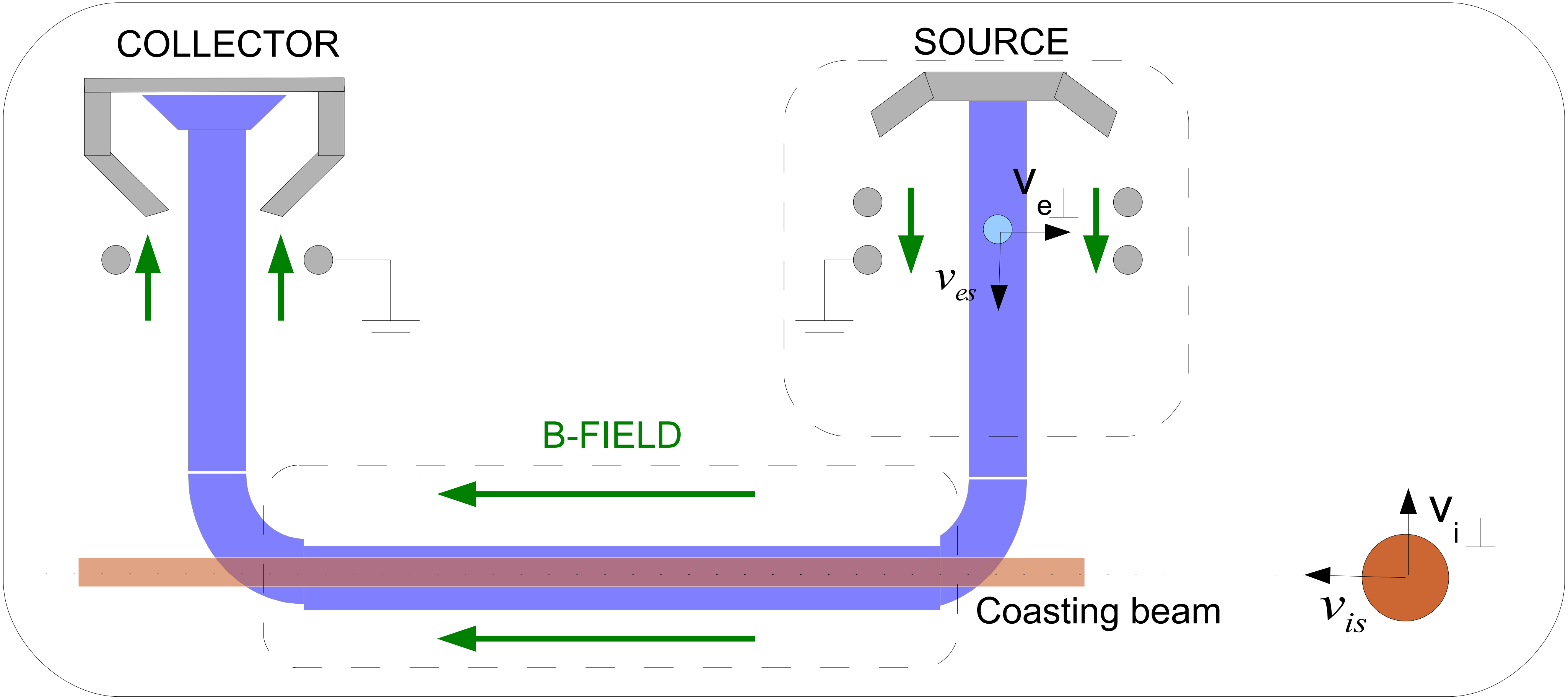
$F \propto Q^{2}$

$$\frac{\alpha_{\|}(v_{\perp}=0)}{\alpha_{\perp}(v_{\|}=0)} \approx 15$$

relative velocity

Quelle [7]

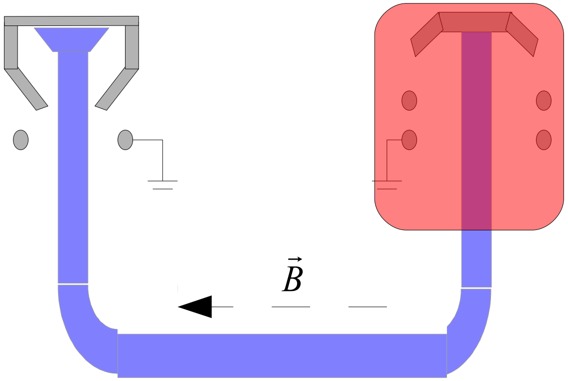
WORKING PRINCIPLE

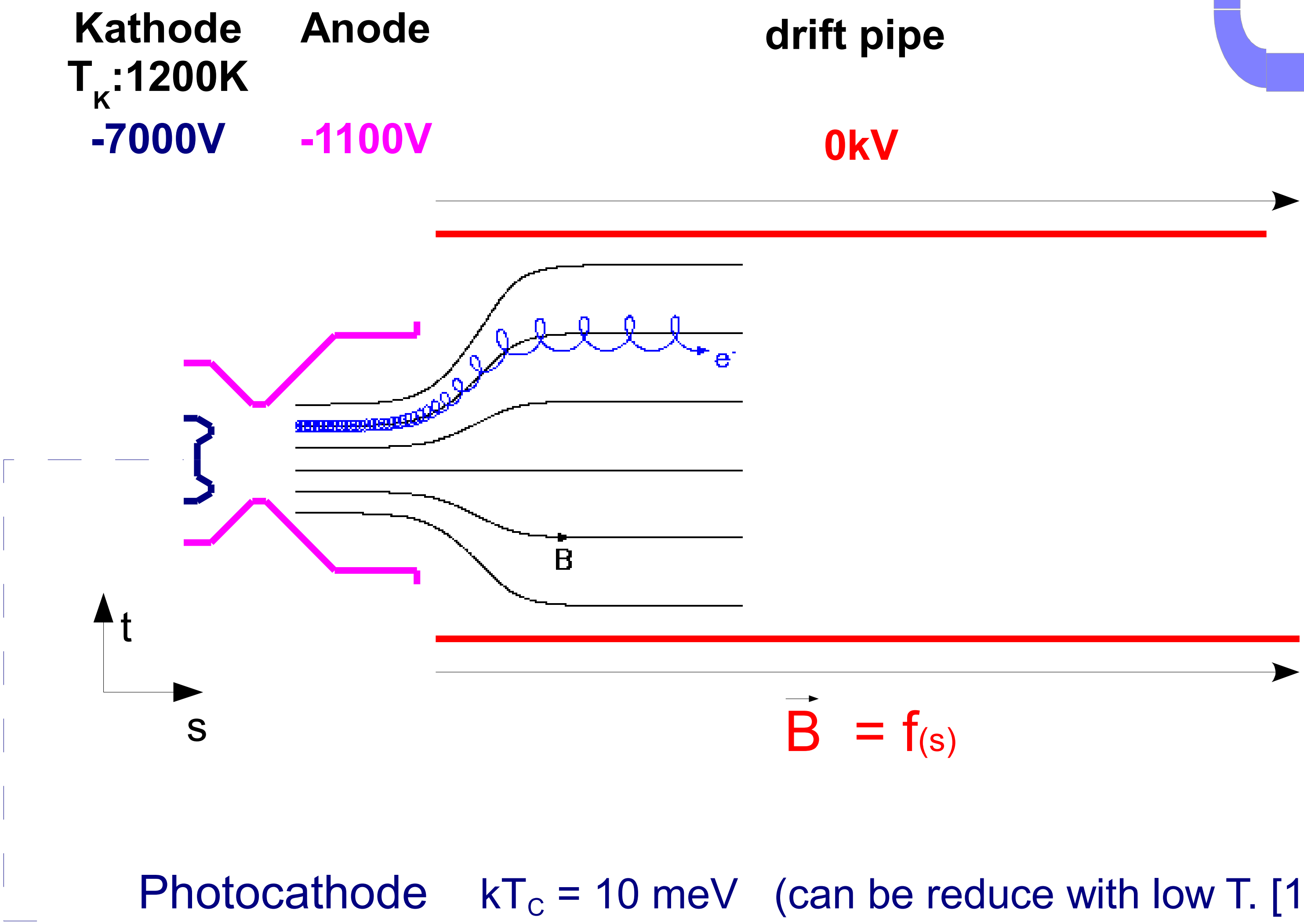


Quelle [7]

WORKING PRINCIPLE

Produce cold electrons





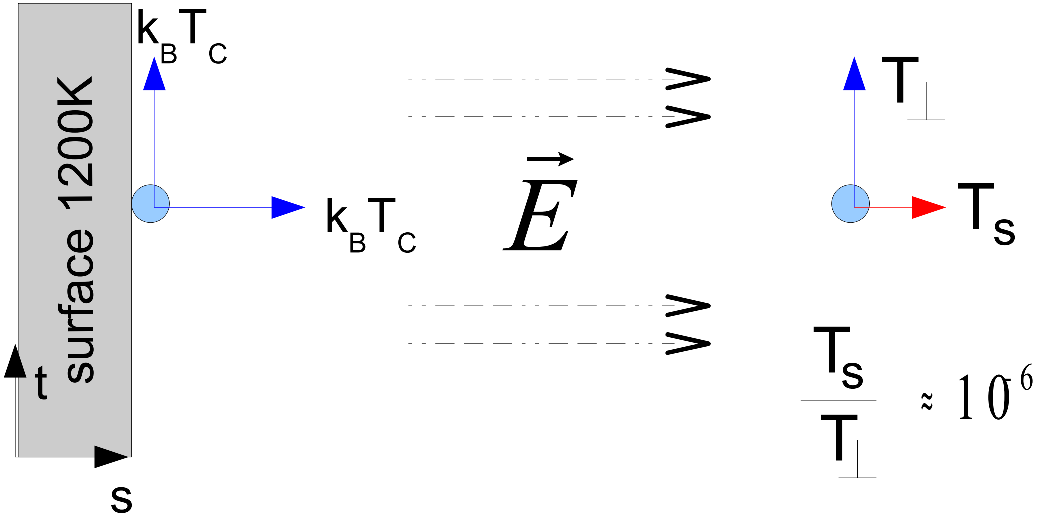
Photocathode kT_C = 10 meV (can be reduce with low T. [14])

Thermocathode kT_C > 100 meV

Quelle [1.2]

WORKING PRINCIPLE

Produce cold electrons & keep them cold



$$\frac{T_s}{T_\perp} \approx 10^6 - 10^7$$

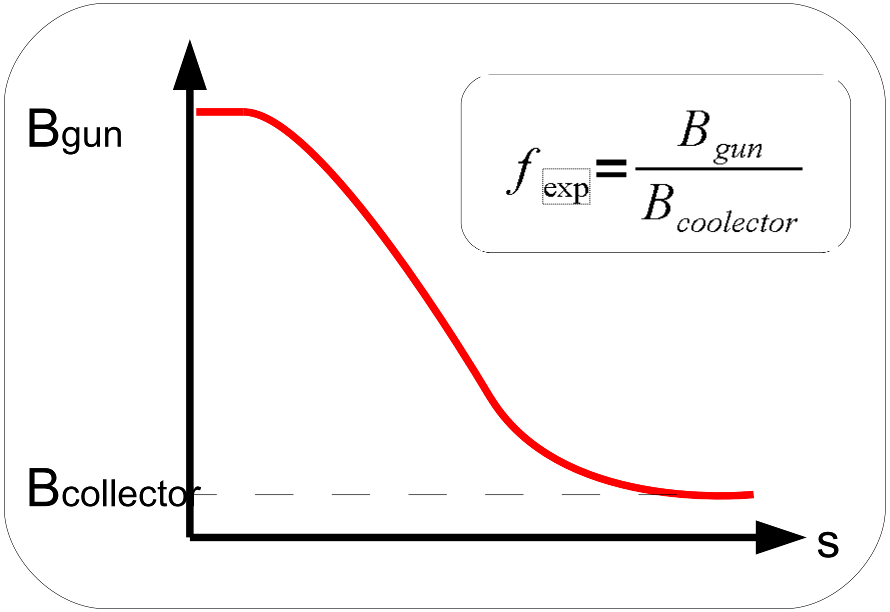
Liouville`sche Theorem

$$\Delta y \Delta p_y = const.$$

$$\varepsilon_{(y)} = \frac{\Delta y \Delta p_y}{p} = \frac{const}{p}$$

Adab. Suspension

This is not a real cooling process!

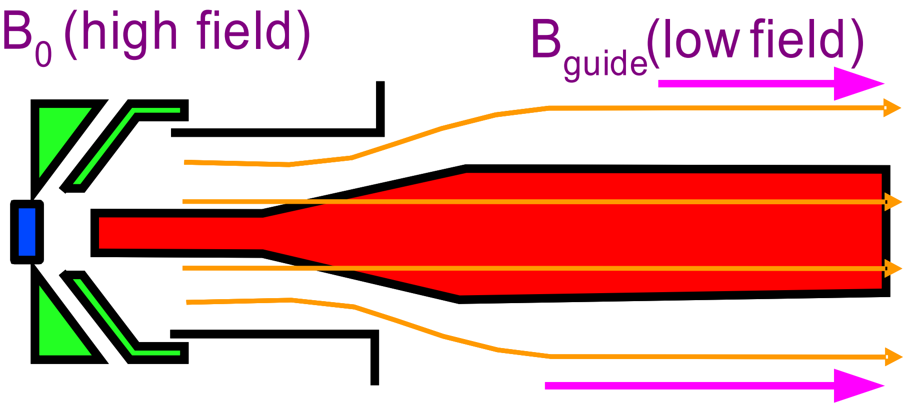


$$f_{exp} = \frac{B_{gun}}{B_{coolector}}$$

$$\frac{E_\perp}{B_s} = const$$

$$r_{cyc}^2 B_s = const$$

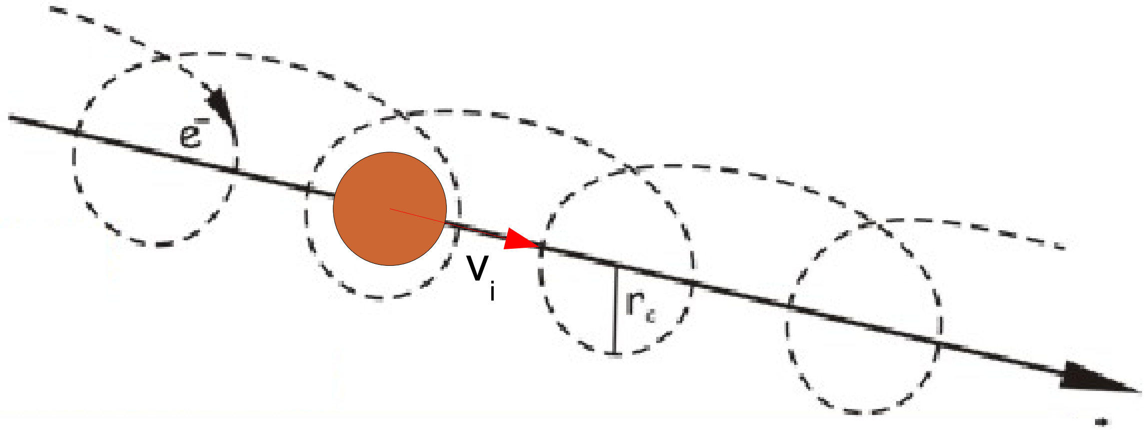
$$T_\perp \propto T_\perp / f_{exp}$$



Quelle [1,2, 14]

WORKING PRINCIPLE

Adiabatic collision

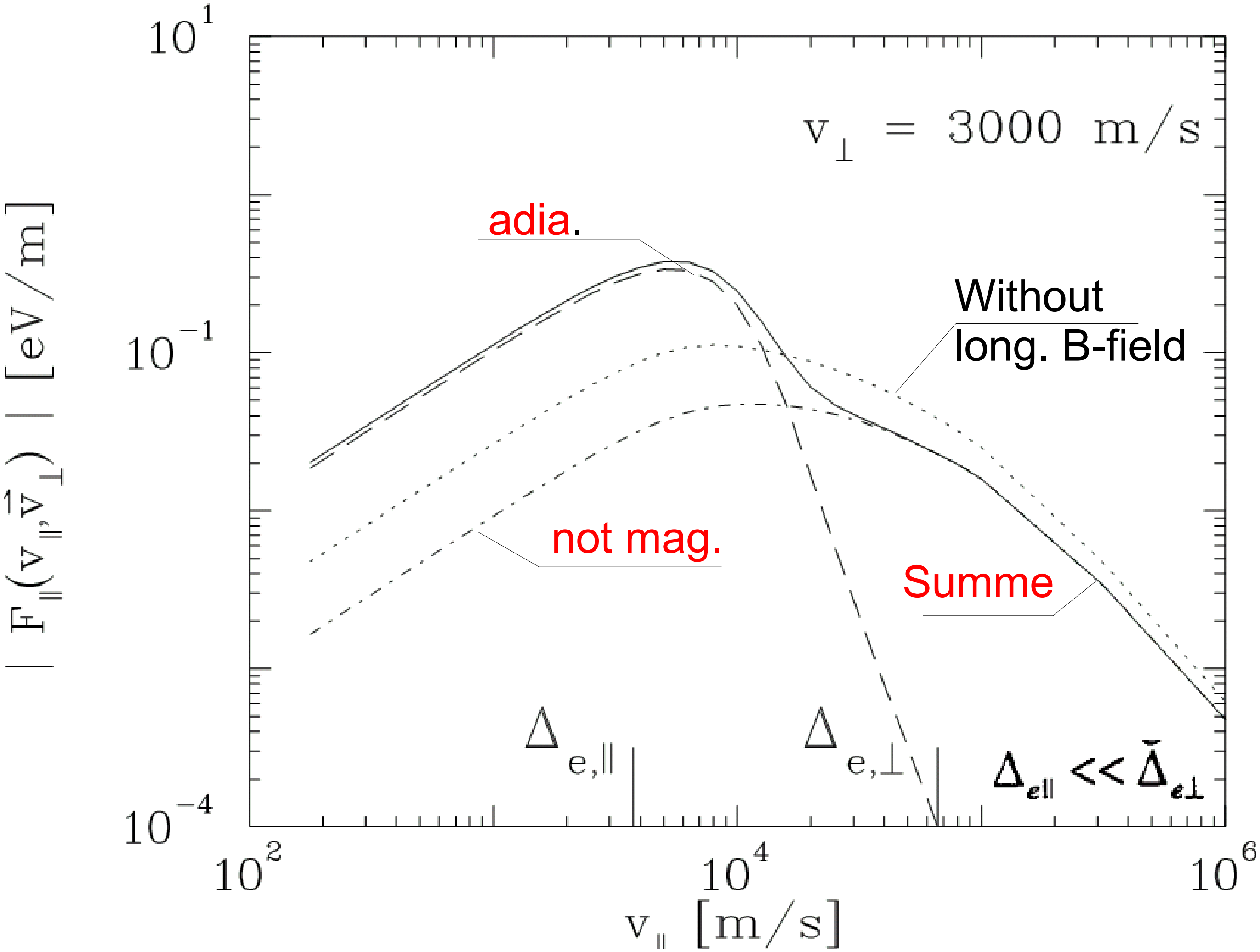


$t_{interact} > t_{cyclotron}$

↓

magnetized cooling

$(T_{eff} = T_{||} << T_T)$



Quelle [1,2, 8]

DIAGNOSTIC & APPLICATION

ESR Elektron Cooler (300 keV)

DIAGNOSTIC

- longitudinal Schottky (GSI)
- Transversal Schottky (GSI)
- Residual Gas Monitor (GSI)
- Beam Transfer Function

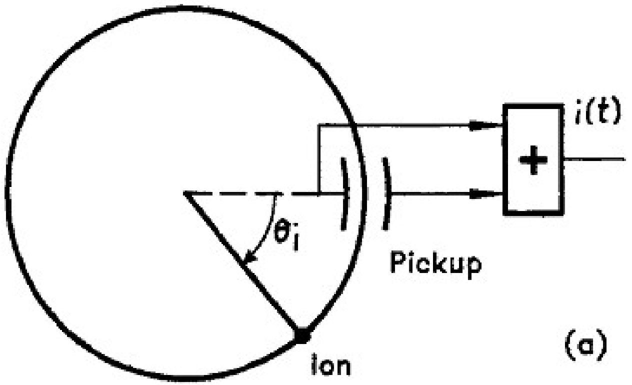
APPLICATION

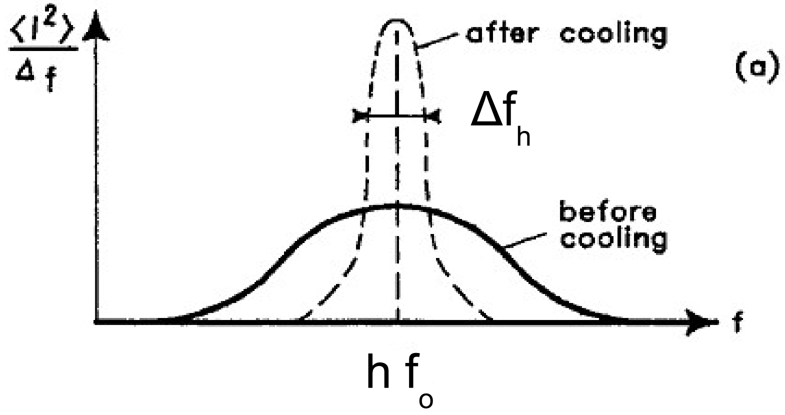
- MASS MEASURMENT OF EXOITC IONS @ ESR
- GSI ESR crystalline beams

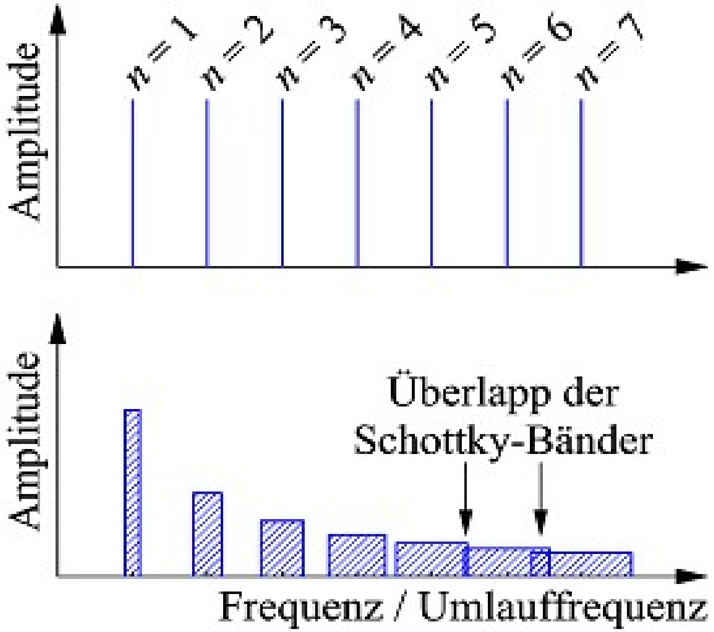
Quelle [7]

DIAGNOSTIC

Long Schottky







$$P(f) \propto \frac{I_{RMS}}{\Delta f}$$

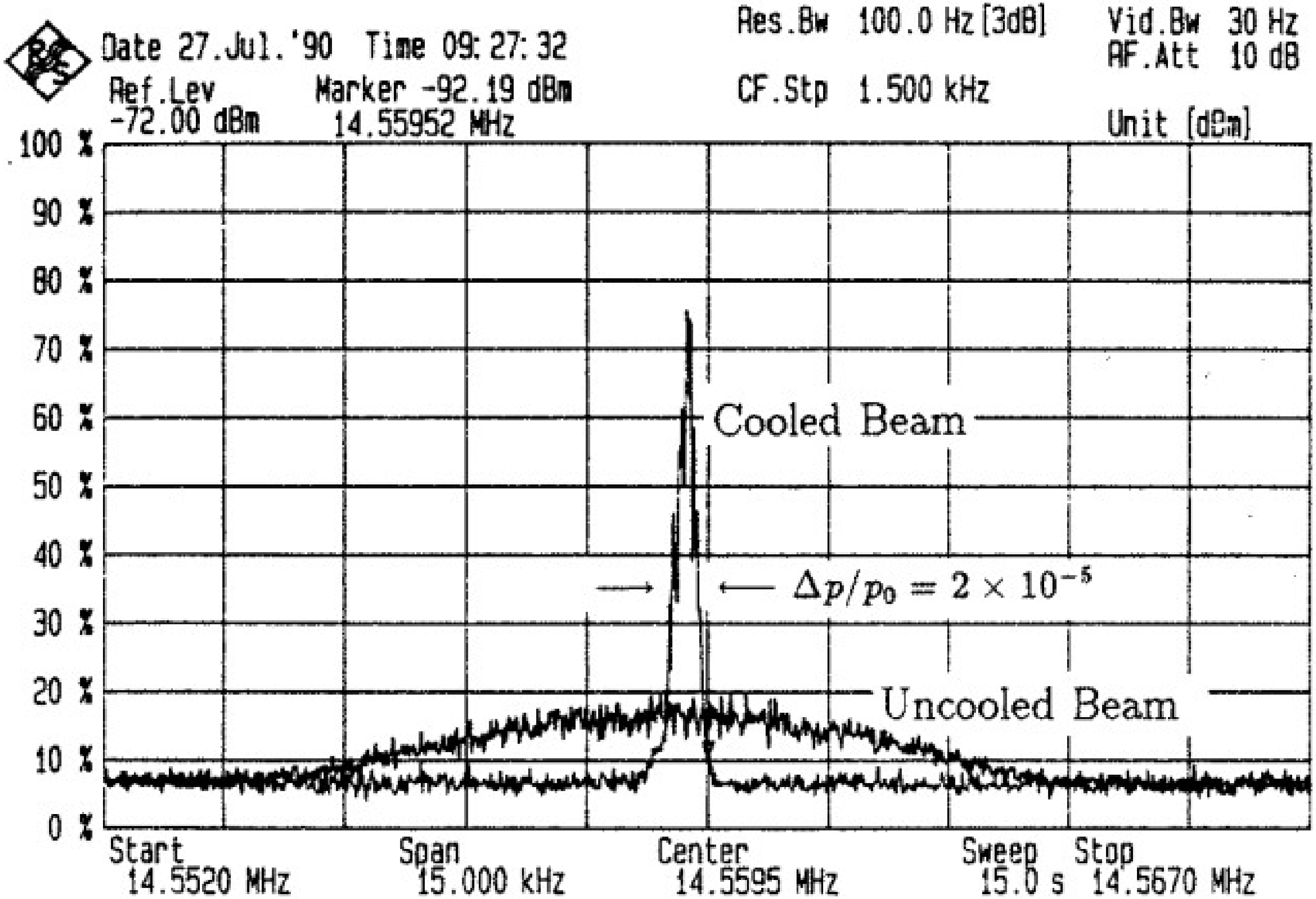
$$\frac{\Delta p}{p_0} = -\frac{1}{\eta}\frac{\Delta f}{h f_0}$$

Quelle [3,5]

DIAGNOSTIC

Long Schottky

coasting beam



Ar^{18+}

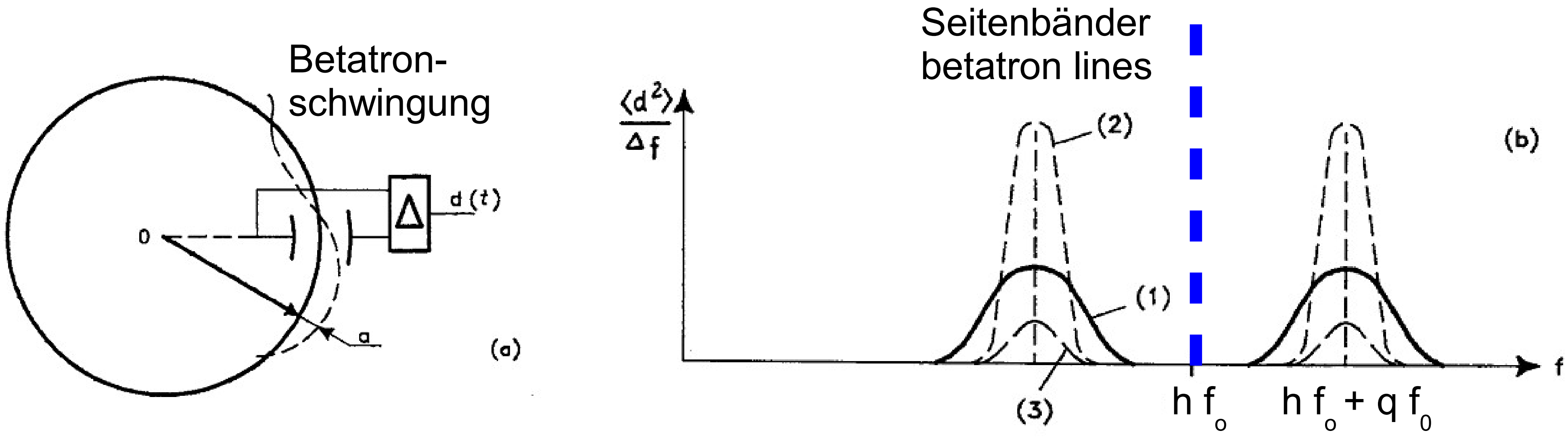
$h = 10th$

GSI Storagering

Quelle [3,5]

DIAGNOSTIC

Transversale Schottkyspektrum (dipol displacement)



Betatron-schwingung

Seitenbänder betatron lines

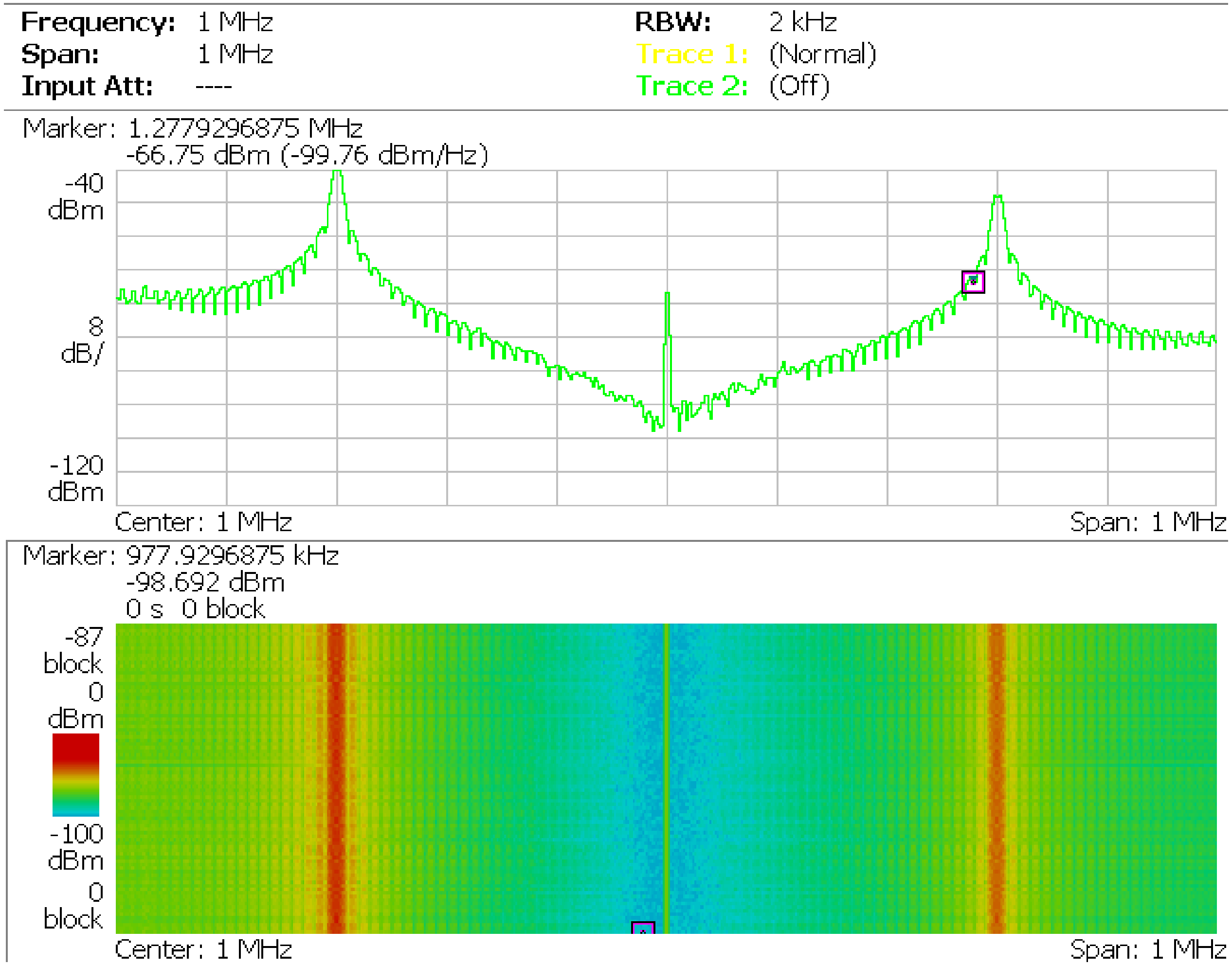
$$\frac{\Delta f}{f_0} = \eta \frac{\Delta p}{p_0} \xrightarrow[\text{freq. spread}]{\text{include betatron}} \frac{\Delta f}{f_0} = \left[(n \pm q)\eta \pm Q_0 \zeta \right] \frac{\Delta p}{p_0}$$

Quelle [3,5,9]

DIAGNOSTIC

Transversale Schottkyspektrum (dipol displacement)

1 MHz carrier frequency
Number of harmonics : 1
q is set to 0.3 with dq of 0.01



Frequency: 1 MHz
Span: 1 MHz
Input Att: ----

RBW: 2 kHz
Trace 1: (Normal)
Trace 2: (Off)

Marker: 1.2779296875 MHz
-66.75 dBm (-99.76 dBm/Hz)

Center: 1 MHz
Span: 1 MHz

Marker: 977.9296875 kHz
-98.692 dBm
0 s 0 block

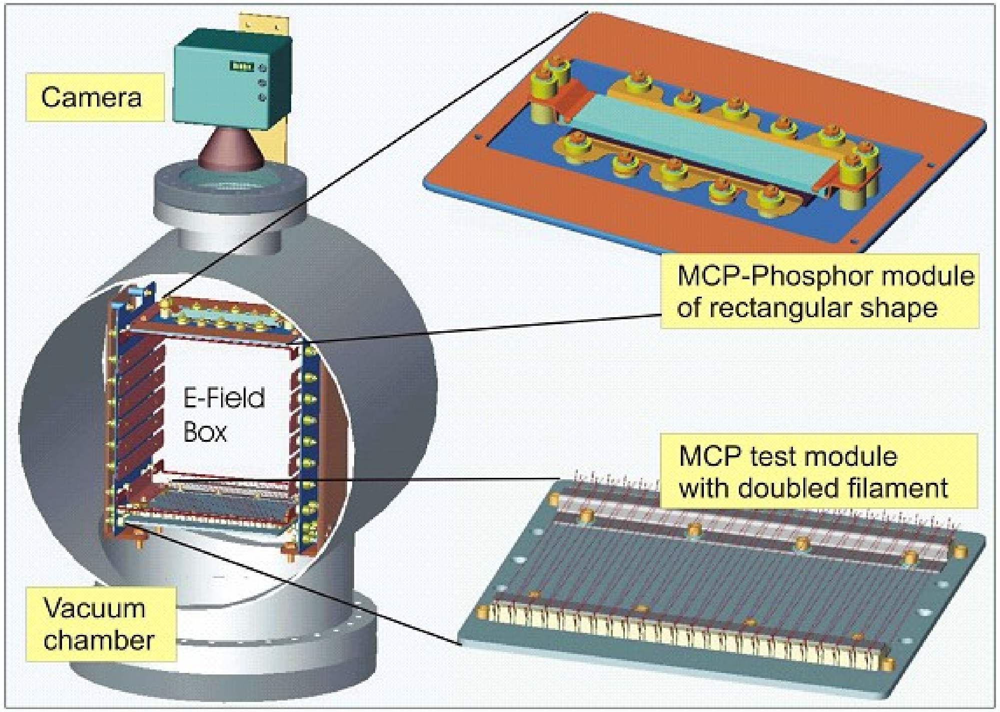
Center: 1 MHz
Span: 1 MHz

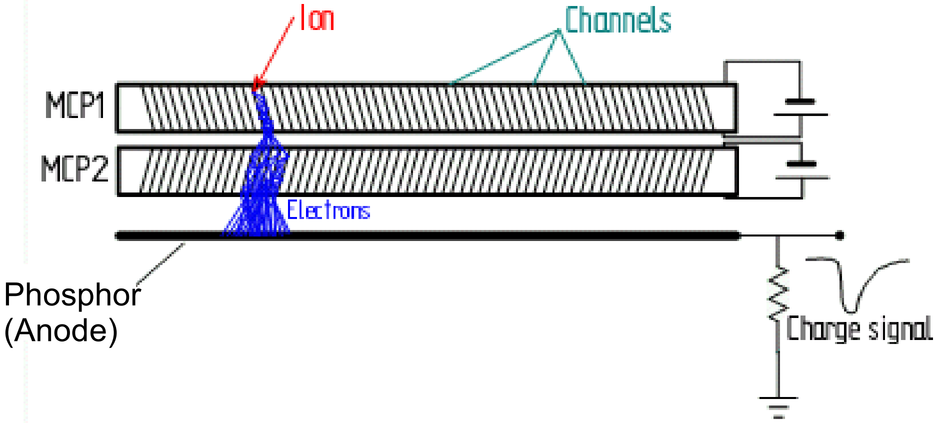
Quelle [3,5,10]

DIAGNOSTIC

Ionization beam profile monitor (IPM)

- Spatial resolution 0.1mm
- 10 profiles /ms



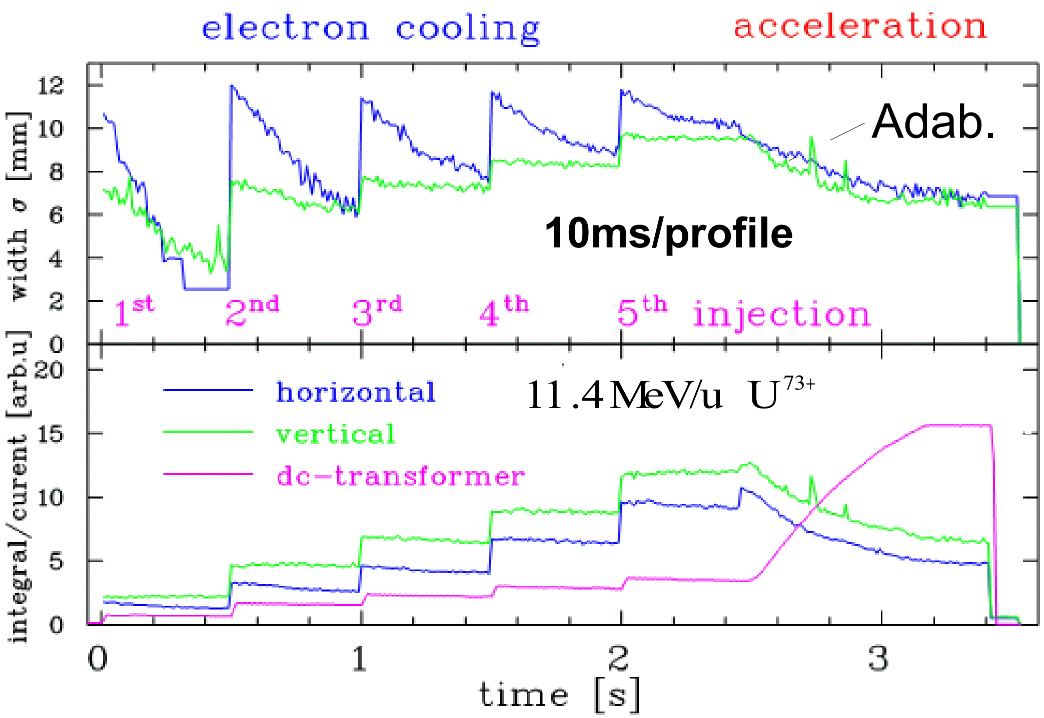


Quelle [6]

DIAGNOSTIC

Ionization beam profile monitor (IPM)

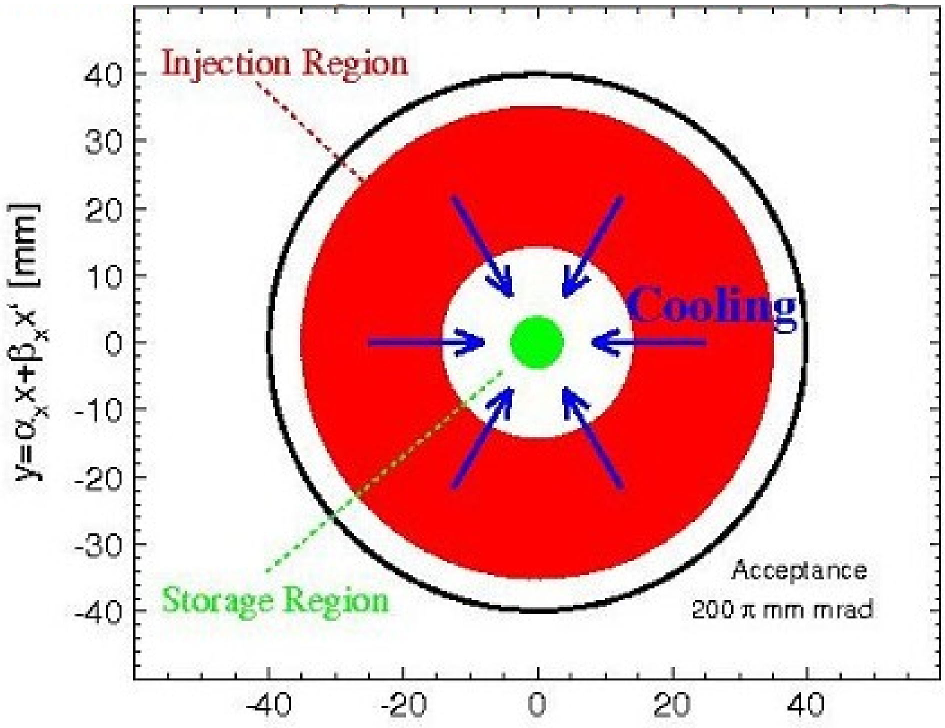
400 MeV/u



Adab.

10ms/profile

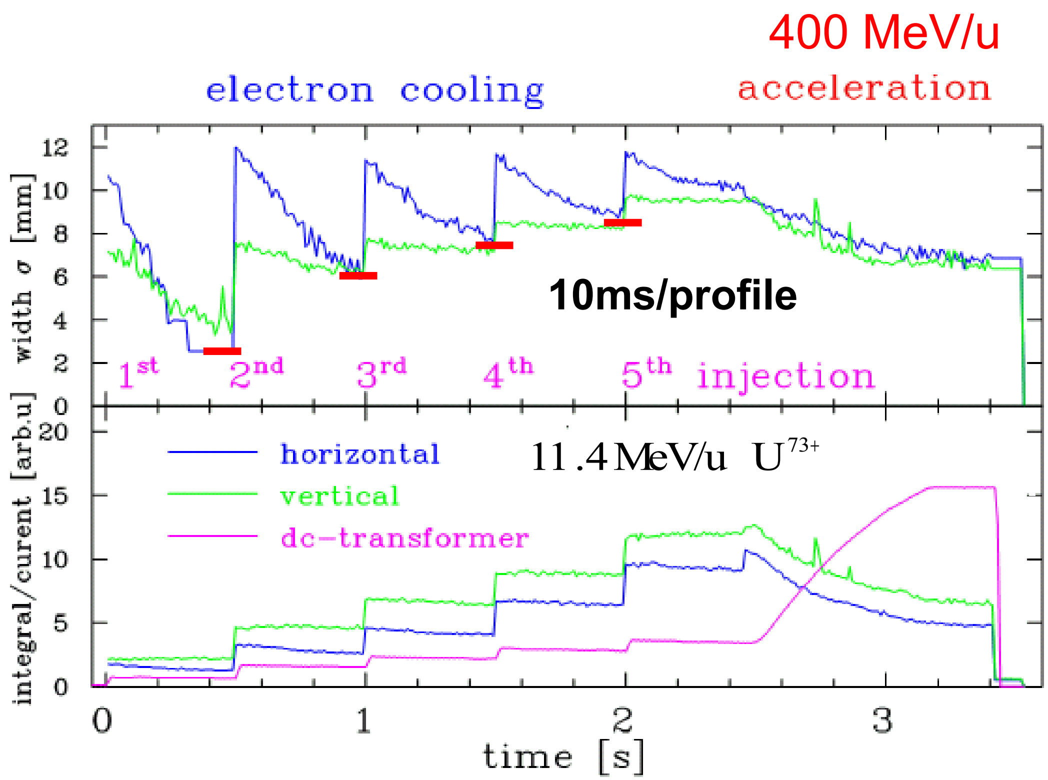
MULTITURN INJECTION

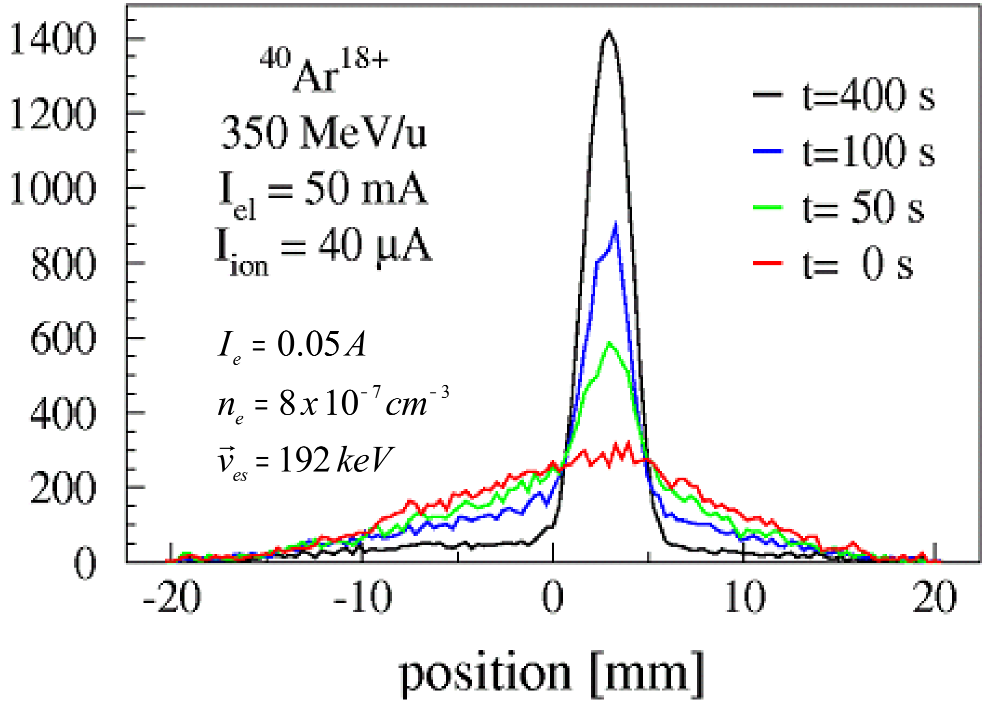


Quelle [6]

DIAGNOSTIC

Ionization beam profile monitor (IPM)



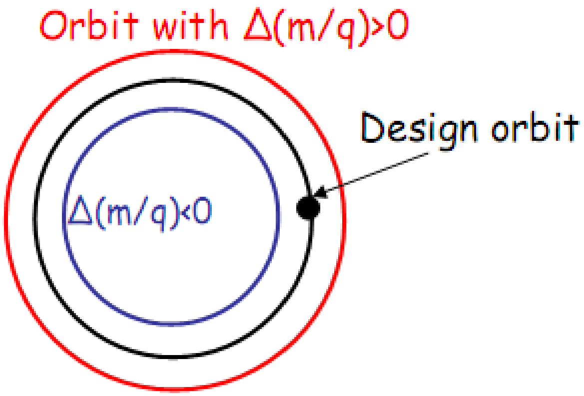


Increase phase space → increase IBS → increase min R_{beam}

Quelle [6]

APPLICATION

MASS MEASURMENT OF EXOITC IONS @ ESR



Bending radius (R)

$$R \propto \frac{p}{QB}$$

Long. Schottky

$$\frac{\Delta f}{f_0} \propto \frac{\Delta R}{R} = \frac{\Delta (m_{ion}/Q)}{m_{ion}/Q}$$

$$\frac{\Delta f}{f_0} = \eta \frac{\Delta p}{p_0}$$

$$\frac{\Delta f}{f_0} = -\alpha_p \frac{\Delta (m_{ion}/Q)}{m_{ion}/Q} \pm \eta \frac{\Delta p}{p}$$

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

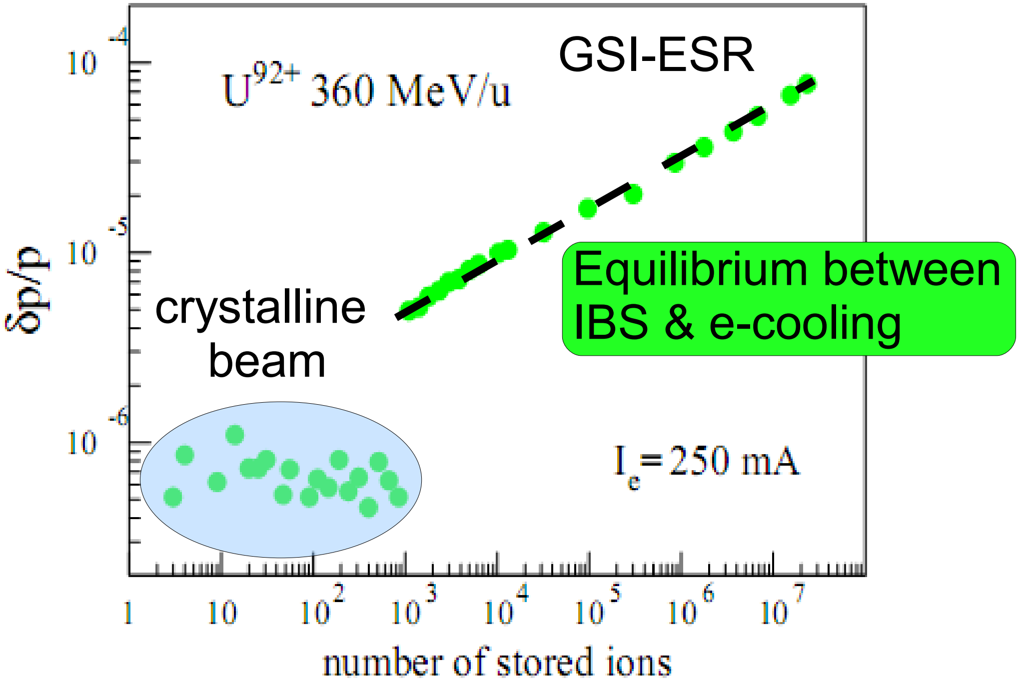
In order to measure m/q with high precision there are two options:

1) make η≈0:
   manipulate quadrupoles strength

2) reduce Δp/p:
   e.g. electron cooling

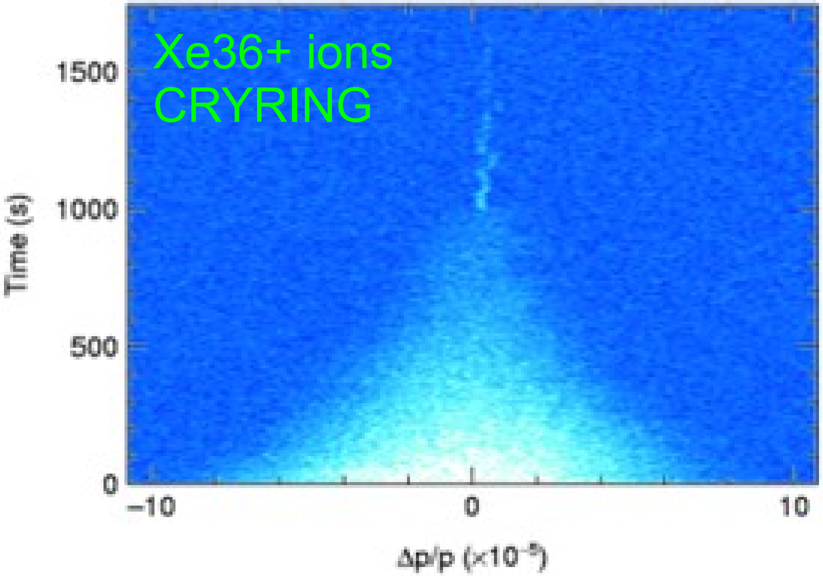
Quelle [13]

APPLICATION



crystalline beam

Equilibrium between IBS & e-cooling



Xe36+ ions
CRYRING

Cooling of ion beams

extreme phase space density

ordered structure
crystalline beam

→ powerful for highly charged ions beams (Q^2)

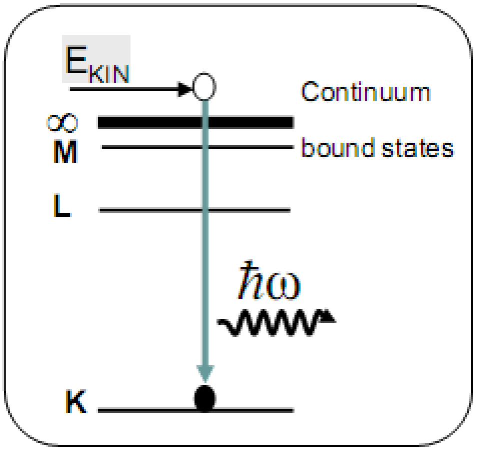
→ limited by the electron temperature

Quelle R.W. Hasse, M. Steck, ORDERED ION BEAMS, EPAC 00
Quelle: Phys. Rev. Lett., 88, 174801 (2002)

ISSUES

TECHNICAL & PHYSICAL ISSUES

- MAGNETIC FIELD IMPERFECTIONS → $kT_{\parallel,\perp}$ ↑
- BEAM MISALIGNMENT
- SPACE CHARGE OF e-BEAM & COMPENSATIONS
- LOSSES BY RECOMBINATION



CONCLUSION

E-cooling is powerful tool

- for multiturn injections
- to decrease the momentum spread & beam emittance
- to increase luminosity & beam life time

- to generate crystalline beams
- to determinate mass/q for exotic ions

LECTURES

[1] UNTERSUCHUNG ZUR ELEKTRONENKÜHLUNG UND REKOMBINATION HOCHGELADENDER IONEN AM SCHWERIONEN SYNCHROTRON SIS, L. Groening, Dissertation 1998.

[2] UNTERSUCHUNG ZUR ELEKTRONENKÜHLUNG HOCHGELADENER SCHWER IONEN,T. Winkler , Dissertation 1996

[3] ELECTRON COOLING, J.Bosser, CAS

[4] Accelerators and ion storage ring TSR, Website MPI für Kernphysik

[5] JUAS Script, P. Forck, Juas 2003

[6] BEAM PROFILE MONITORS BASED ON RESIDUAL GAS INTERACTION, P. Forck, A. Bank, T. Giacomini, A. Peters, EPAC 2006

[7] Beam Cooling, M.Steck, CAS-2009

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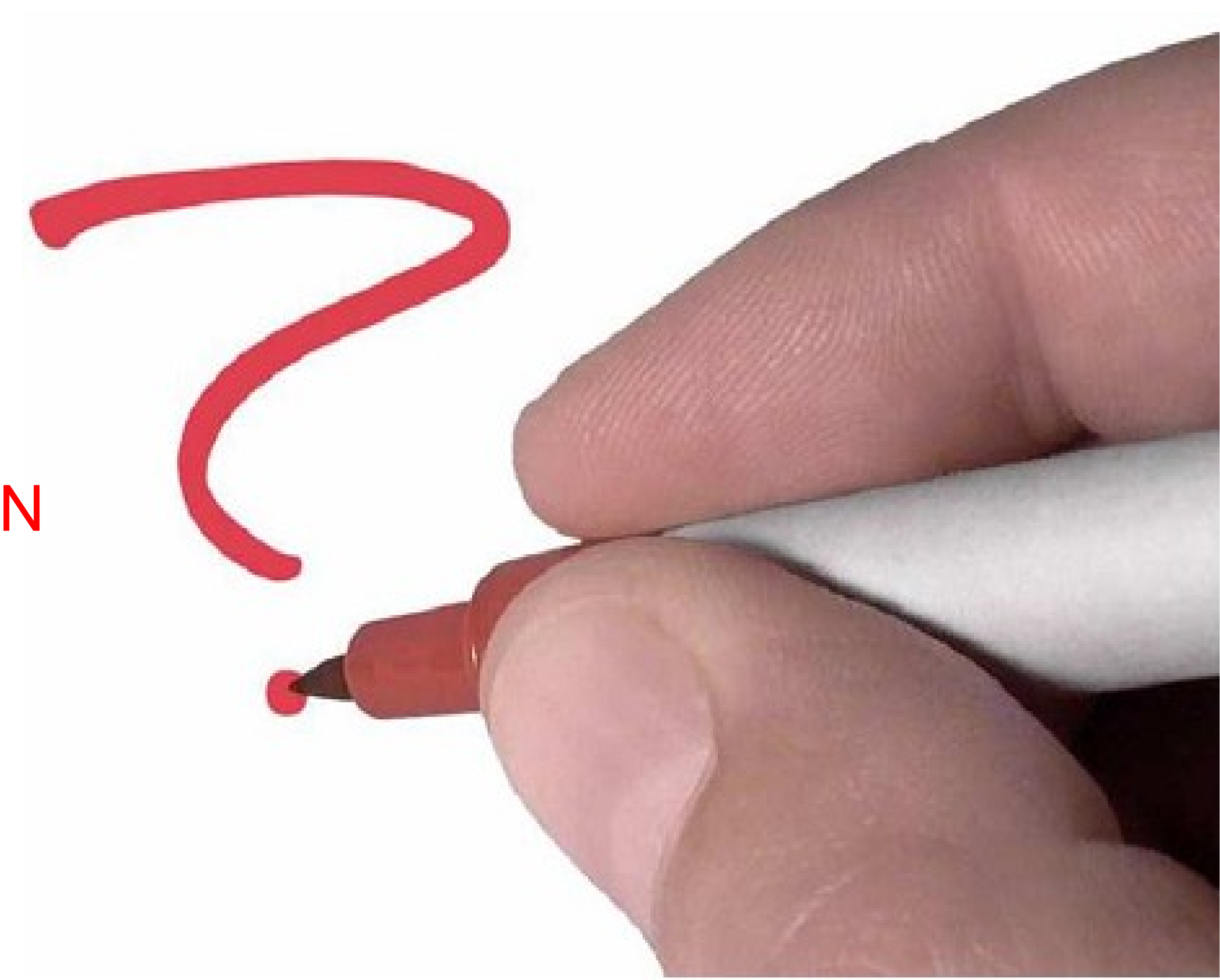
FIN



FRAGEN

THANK YOU FOR YOUR ATTENTION

BACKUP

Produce cold electrons

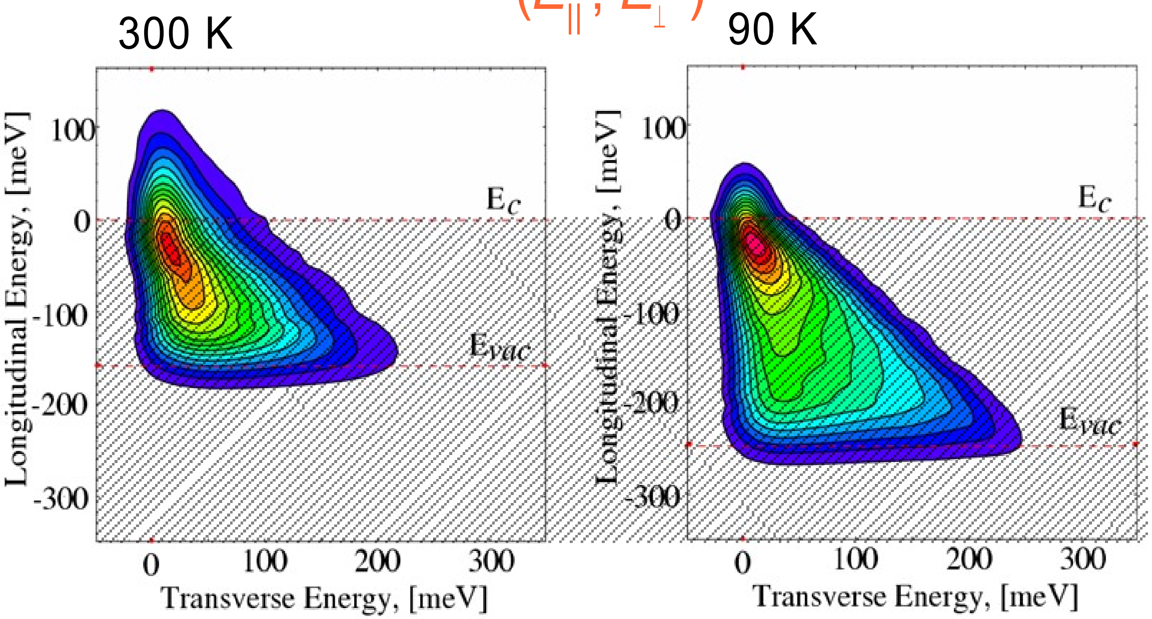
Photocathode $kT_C = 10$ meV

Thermocathode $kT_C > 100$ meV

Energy distributions of photoelectrons

“2D”-measurement

$(E_{||}, E_{\perp})$

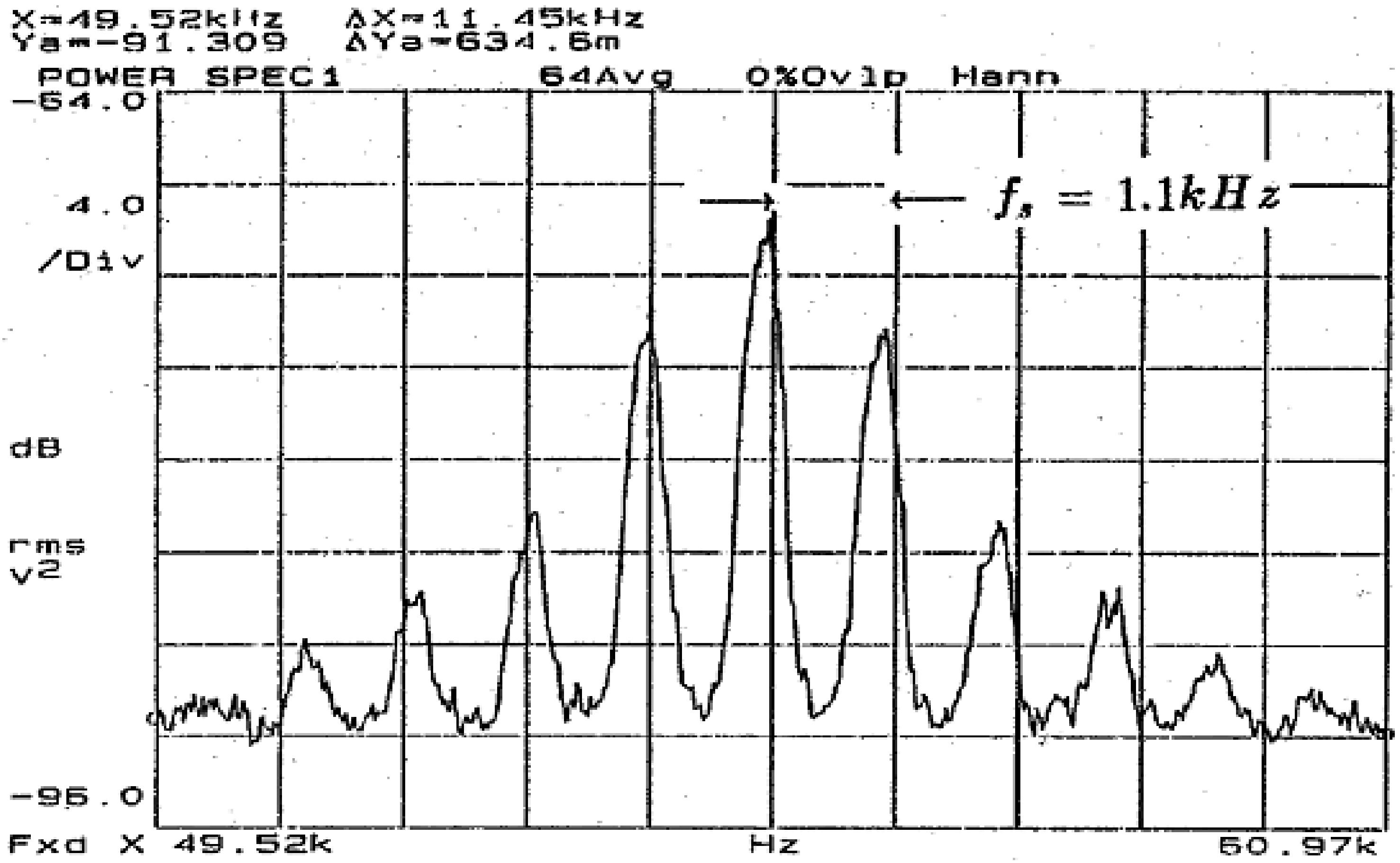


D.A. Orlov et al., APL, 78 (2001) 2721;

BACKUP

Long Schottky

bunched beam

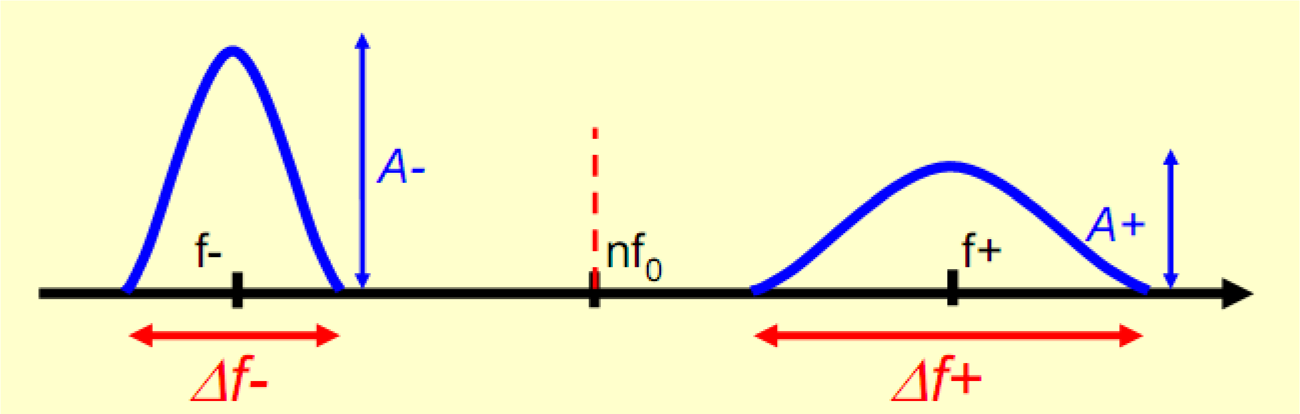


Fluktuation von Stahlteilchen die mit den Synchr..-freq. (fs) oszillieren
→ zusätzliche Seitenbänder

Quelle [3,5]

BACKUP

Transversale Schottkyspektrum
(dipol displacement)



Frequency width of the side bands

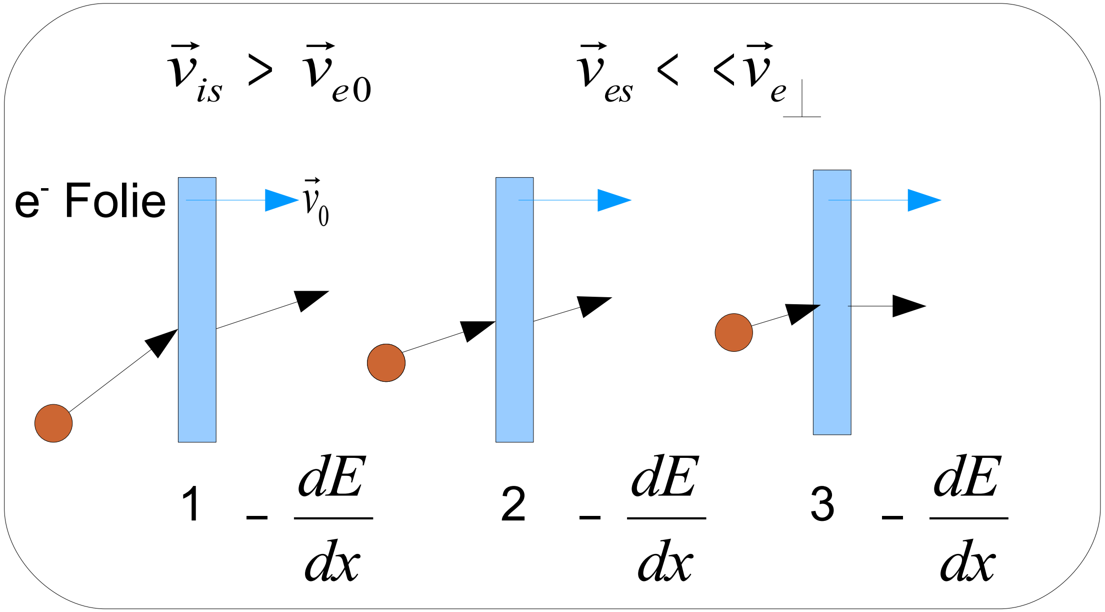
$$\Delta f_{\pm} = (n \pm q) \times df \pm f_0 dq$$

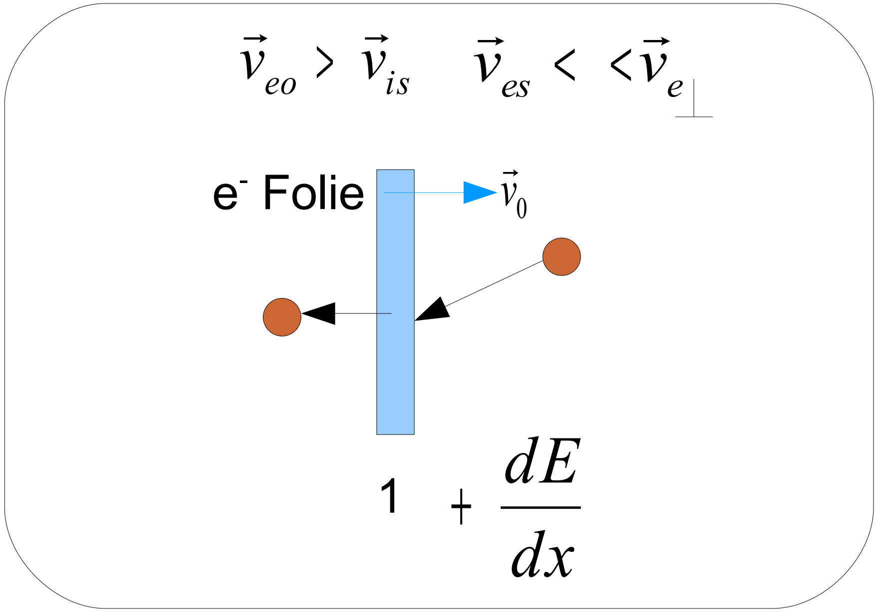
- ungerade Anteil des tunes
- Tune spread
- Chromatisität
- Emittanze

Quelle [3,5,9]

BACKUP

Longitudinal kühlen


$\vec{v}_{is} > \vec{v}_{e0}$ $\quad \vec{v}_{es} << \vec{v}_{e\perp}$


$\vec{v}_{eo} > \vec{v}_{is}$ $\quad \vec{v}_{es} << \vec{v}_{e\perp}$

Energieverlust nach Bohr

$$-\frac{dE}{dx} \propto \frac{Z^2 n_e}{m_e v_i^2} \alpha_{material}$$

↓ Vielfach Streuung

energy straggling

- long. Energy smearing
  → Diffusion (D-konst)
- Energieverlust
  → Kühlung (dE/dx)

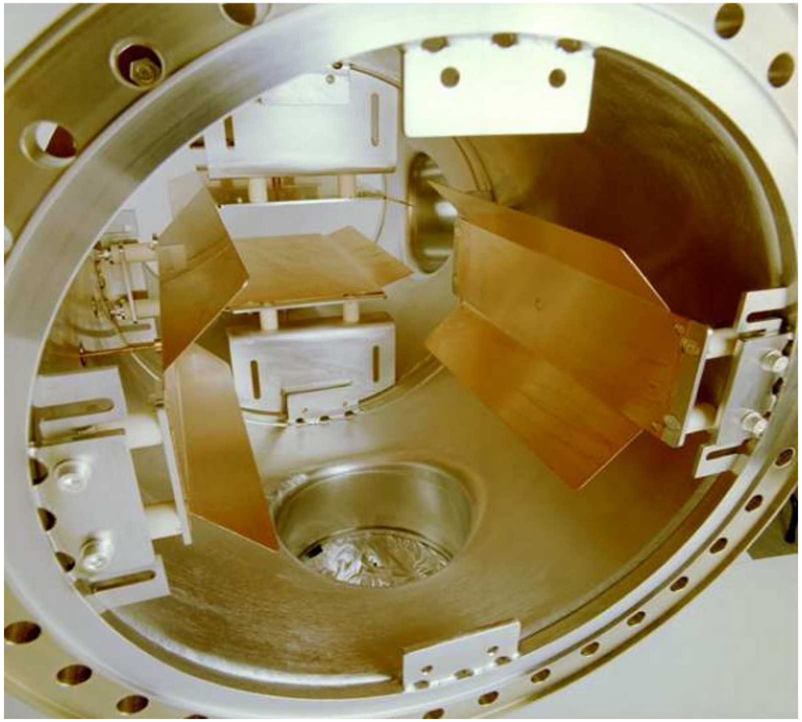
$$D = \frac{d}{dt}(p_i \phi_{rms})$$

$$\frac{dE}{dx} = \frac{1}{m_e} \frac{\partial D}{\partial v_i}$$

Quelle [7]

BACKUP

Schottky



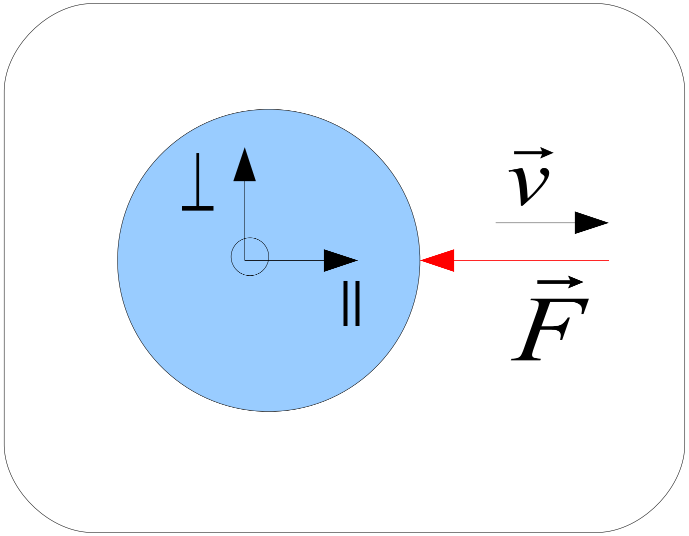
Kapazitve Pick-up
Schottkysonde @ GSI

Wegen Plattenkopplung Messung der Spektren separiert

Quelle [3,5]

BACKUP

Kühlkraft



$$m_i \ddot{s}_\parallel - F_\parallel(\dot{s}_\parallel, \dot{s}_\perp) = 0$$

$$m_i \ddot{s}_\perp - F_\perp(\dot{s}_\parallel, \dot{s}_\perp) + D_\perp s_\perp = 0$$

$$F = \frac{dE}{ds} \longleftrightarrow \begin{array}{l} F_\parallel(\dot{s}_\parallel, \dot{s}_\perp) = -\alpha_\parallel \dot{s}_\parallel \\ F_\perp(\dot{s}_\parallel, \dot{s}_\perp) = -\alpha_\perp \dot{s}_\perp \end{array}$$

Fokker-Planck-Gleichung

$$\frac{\partial \rho_{(\vec{r},\vec{v},t)}}{\partial t} = -\frac{\partial \rho_{(\vec{r},\vec{v},t)}}{\partial v} F + \frac{\partial^2 \rho_{(\vec{r},\vec{v},t)}}{\partial v^2} D$$

$\rho_{(\vec{r},\vec{v},t)}$ = 6 + 1 dim. Verteilungsfunktion der Ionen im Phasenraum

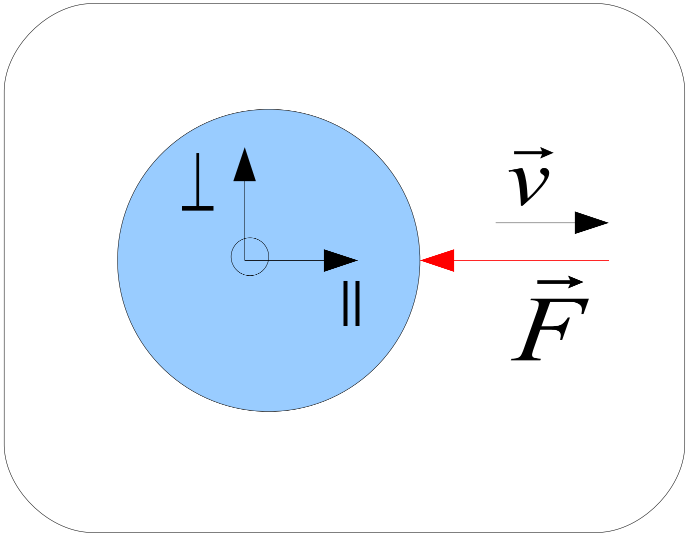
D = Diffusion (→ Aufheizung des Strahls)

F = Kühlkraft

Quelle [3]

BACKUP

Kühlkraft



$$m_i \ddot{s}_{\parallel} - F_{\parallel}(\dot{s}_{\parallel}, \dot{s}_{\perp}) = 0$$

$$m_i \ddot{s}_{\perp} - F_{\perp}(\dot{s}_{\parallel}, \dot{s}_{\perp}) + D_{\perp} s_{\perp} = 0$$

$$F = \frac{dE}{ds} \longleftrightarrow \begin{array}{l} F_{\parallel}(\dot{s}_{\parallel}, \dot{s}_{\perp}) = -\alpha_{\parallel} \dot{s}_{\parallel} \\ F_{\perp}(\dot{s}_{\parallel}, \dot{s}_{\perp}) = -\alpha_{\perp} \dot{s}_{\perp} \end{array}$$

Gleichgewicht

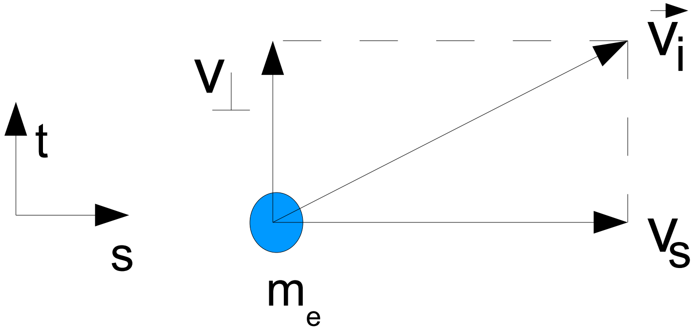
$$\cancelto{=0}{\frac{\partial \rho_{(\vec{r},\vec{v},t)}}{\partial t}} = -\frac{\partial \rho_{(\vec{r},\vec{v},t)}}{\partial v} F + \frac{\partial^2 \rho_{(\vec{r},\vec{v},t)}}{\partial v^2} D$$

→bestimmt bei e-cooling
Emittanz

Quelle [3]

BACKUP

electron temperature



vector decomposition

$$\vec{v}_i = v_\parallel \cdot \vec{u}_\parallel + v_\perp \cdot \vec{u}_\perp$$

thermodynamics

$$E_{kin} = \frac{f}{2} k_B T$$

$\longleftrightarrow$

mechanic

$$E_{kin} = \frac{m}{2} < v^2 >$$

f = 1

$$k_B T_\perp = m < v_\perp^2 >$$

$$k_B T_s = m < v_s^2 >$$

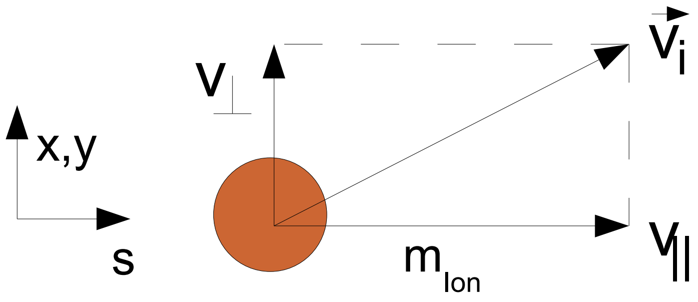
Don‘t confuse: beam energy ↔ beam temperature

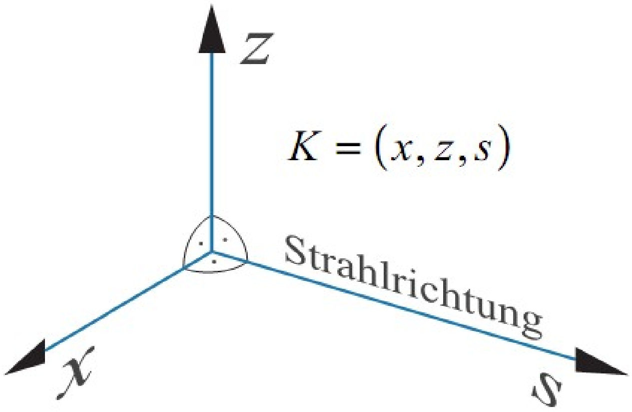
(e.g. a beam of energy 100 GeV can have a temperature of 1 eV)

Quelle [3]

BACKUP

Ionen Temperatur





Hill`sche DGL

$$x''(s) + \left(\cancel{\frac{1}{\rho^2(s)}} - k_x(s) \right) x(s) = \cancel{\frac{1}{\rho(s)}} \frac{\cancel{\Delta} p}{p_0}$$

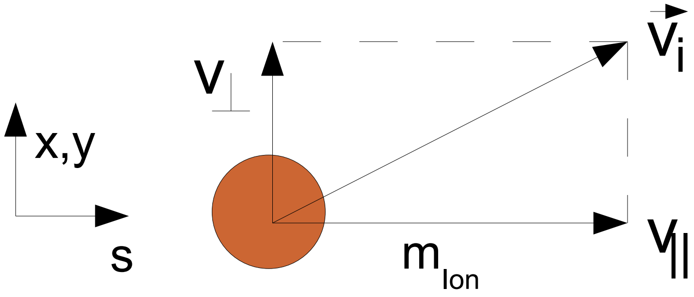
$$z''(s) + k_z(s) z(s) = 0$$

DIPOL → weak focusing
Momentum spread → 0

Quelle [3]

BACKUP

ion temperature



Hill`sche DGL

$$x''(s) + \left(\cancel{\frac{1}{\rho^2(s)}} - k_x(s) \right) x(s) = \cancel{\frac{1}{\rho(s)} \frac{\Delta p}{p_0}}$$

$$x(s) = \sqrt{\varepsilon_\perp \beta_\perp(s)} \cos(\underbrace{\phi_\perp(s) + \phi_{0,\perp}}_{\chi})$$

$$E_{kin(Thermo)} = E_{kin(Mechanik)}$$

Quelle [3]

BACKUP

Cooling rate

Cooling time

$$\tau_c^{*-1} = \frac{F^*}{m_i v_i} \propto \frac{I_e}{L}\frac{Q^2 n_e^* L c}{m_i m_e v_i^{*3}}$$

transversal cooling rate

$$\varepsilon_\perp(t_0 + t) = \varepsilon_\perp(t_0) e^{-\frac{t}{\tau_\perp}}$$

Emittance ↓

cooling rate (longitudinal)

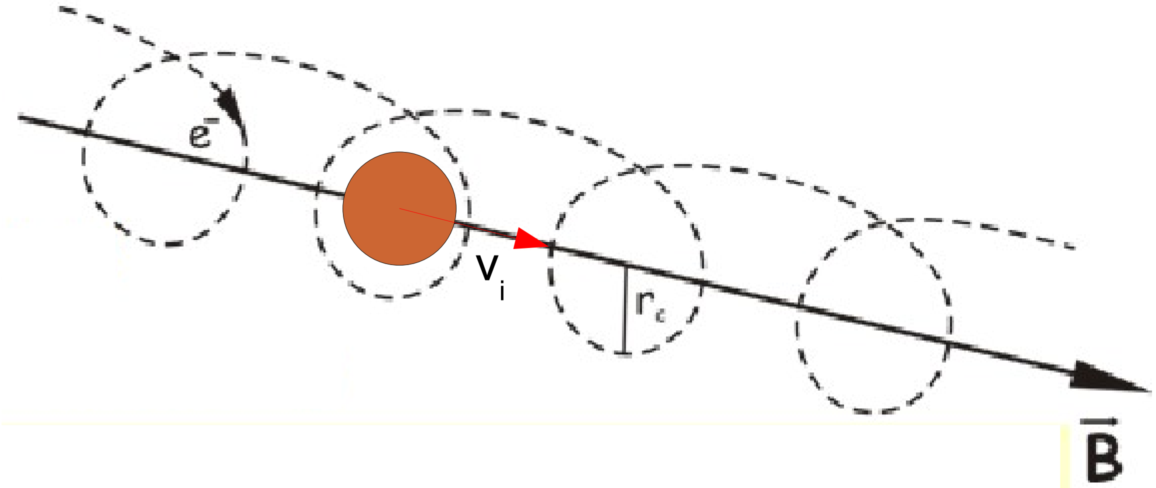
$$\frac{\delta p_\parallel}{p_\parallel}(t_0 + t) = \frac{\delta p_\parallel}{p_\parallel}(t_0) e^{-\frac{t}{\tau_\parallel}}$$

Momentum spread ↓

Quelle [3]

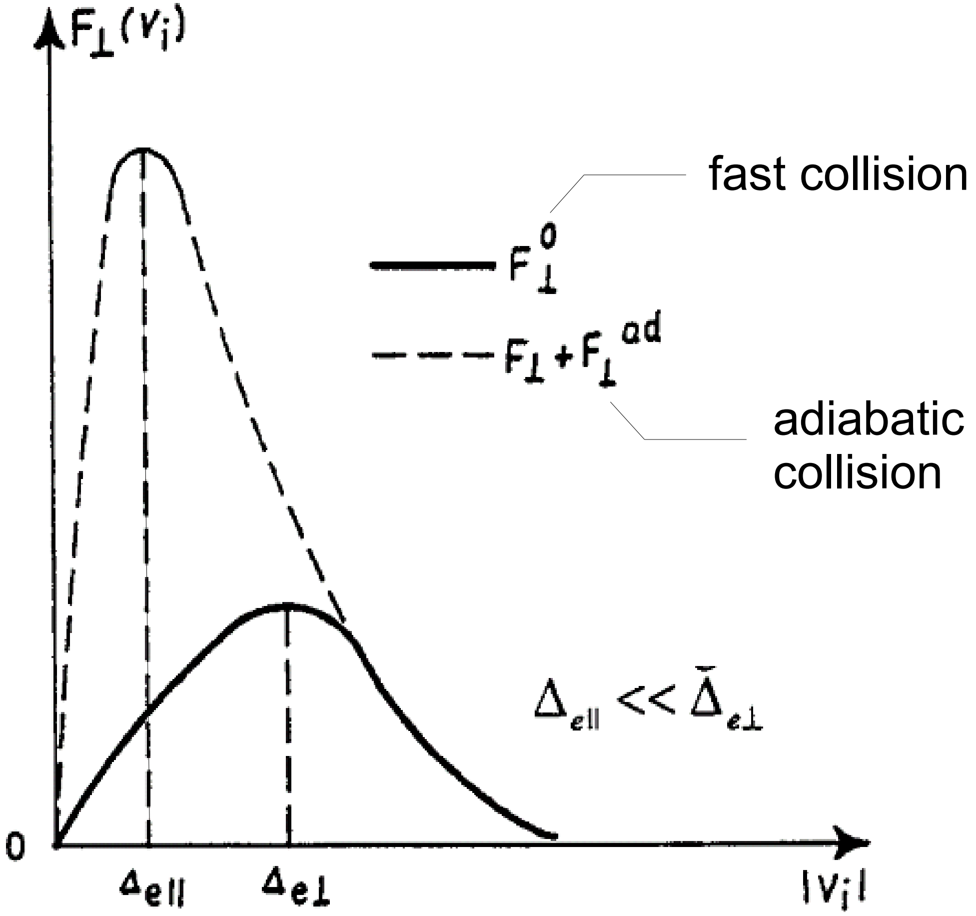
BACKUP

Adiabatic collision



For interaction times long compared to the cyclotron period, the ion does not sense the transversal electron temperature

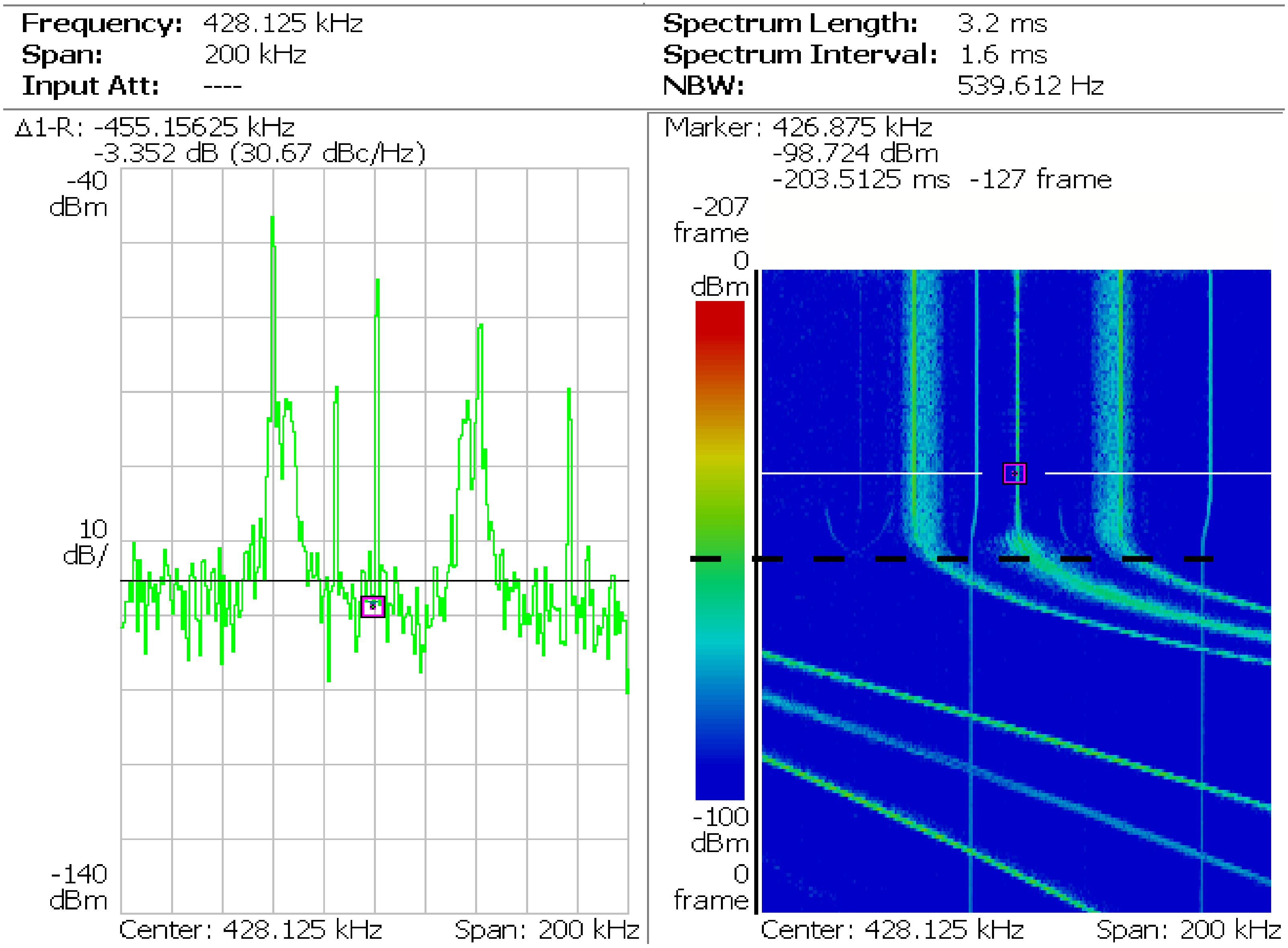
magnetized cooling
$(T_{eff} = T_{||} << T_T)$



Quelle [1,2]

BACKUP

Transversale Schottkyspektrum (dipol displacement)



Frequency: 428.125 kHz
Span: 200 kHz
Input Att: ----

Spectrum Length: 3.2 ms
Spectrum Interval: 1.6 ms
NBW: 539.612 Hz

Δ1-R: -455.15625 kHz
-3.352 dB (30.67 dBc/Hz)

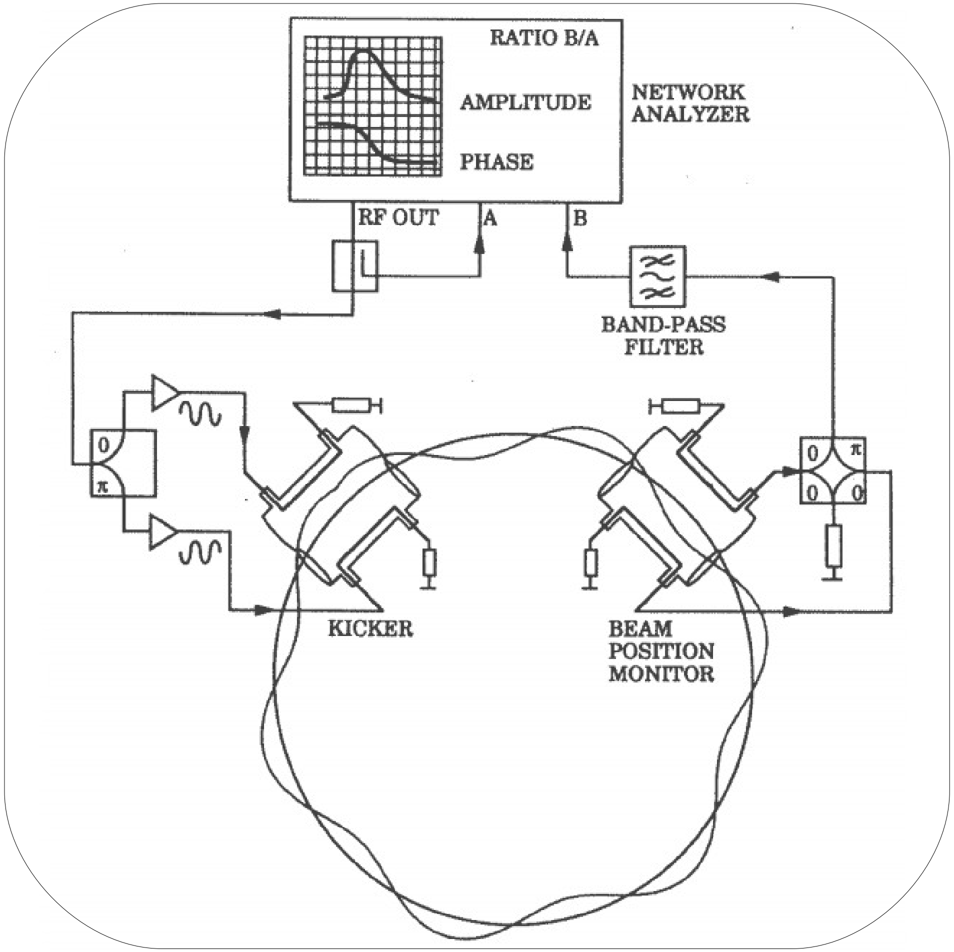
Marker: 426.875 kHz
-98.724 dBm
-203.5125 ms -127 frame

Argon 18+
100 ms cooling
Ramp to 2 GeV in 700 ms

Quelle [3,5]

BACKUP

Beam Transfer Function (BTF)



Übertragungsfunktion ($r_{\parallel}$)
Kicker → Ionenstrahl → Pick up

$$\Re e(r_{\parallel}) \propto \frac{d\rho_0}{df}$$

ρ_0 Normierte Verteilungsfunktion

Annahme : Ionenstrahl hat keine WW
mit seiner Umgebung
→ sonst mit
Koppelimpedanz

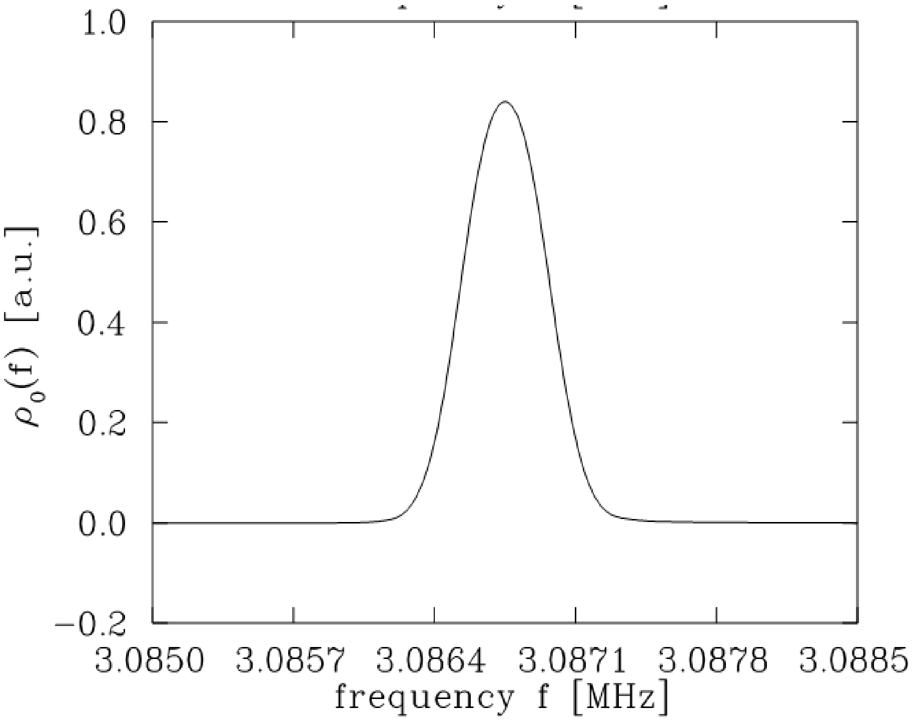
Quelle [5,8]

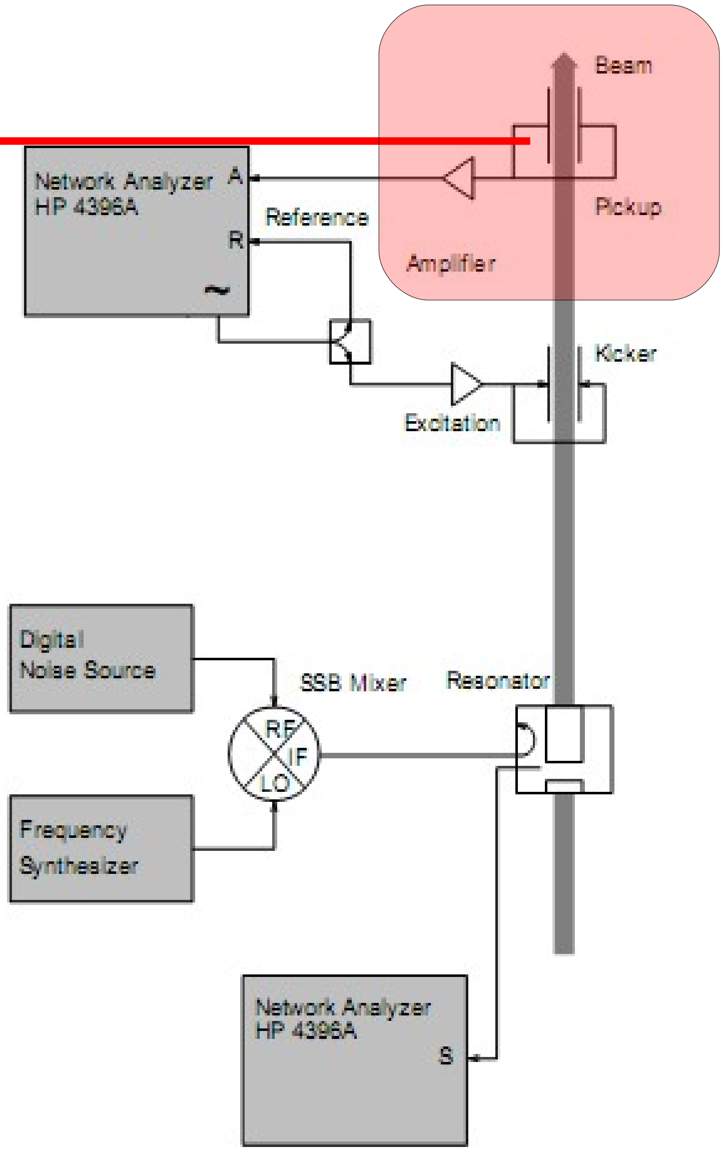
BACKUP

Longitudinale Kühlkraftmessung mit stocha. Heizung

$$\rho_0(f) \propto -\int_{-\infty}^{f} \mathrm{Re}({r_{\parallel}}^{0}(\tilde{f}))\,d\tilde{f}$$

Verteilung des Ionenstrahls





Quelle [5,8]

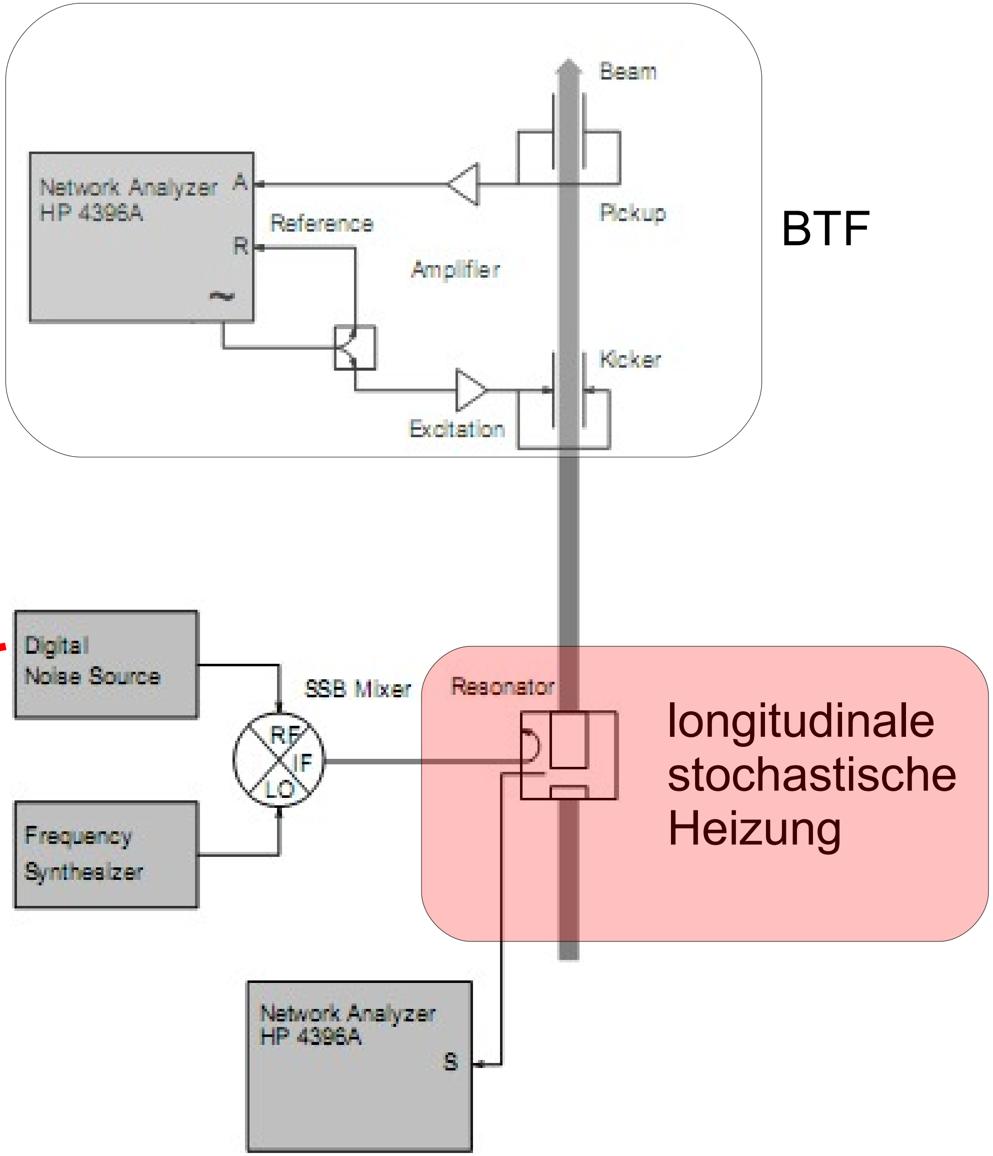
BACKUP

Longitudinale Kühlkraftmessung mit stocha. Heizung

1D Fokker-Planck-Gleichung

$$-\eta_c \frac{F_\parallel(v_\parallel)}{m_i}\rho(v_\parallel) + D\frac{\partial}{\partial v_\parallel}\rho(v_\parallel) = 0$$

$$\eta_c = \text{Resonatorlänge}/\text{Umfang}$$



BTF

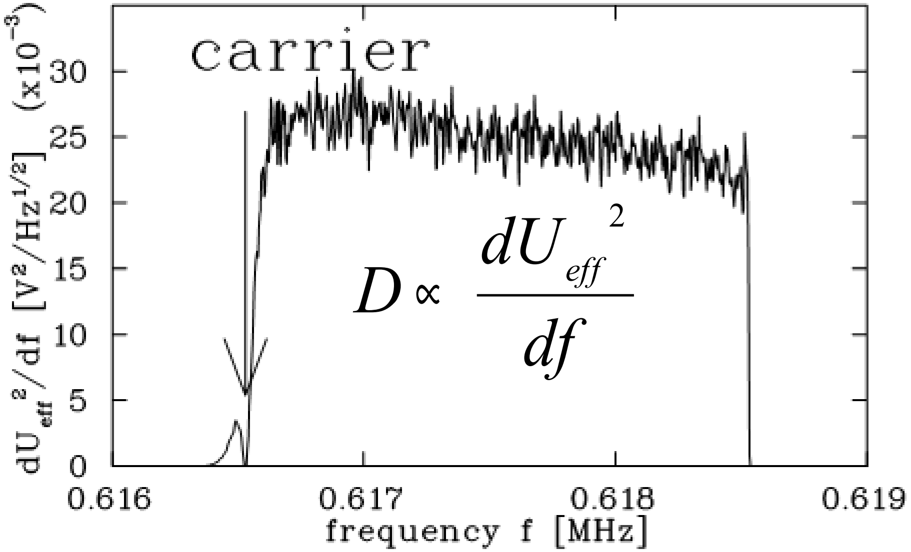
Vorgegebener Diffusionsterm

longitudinale stochastische Heizung

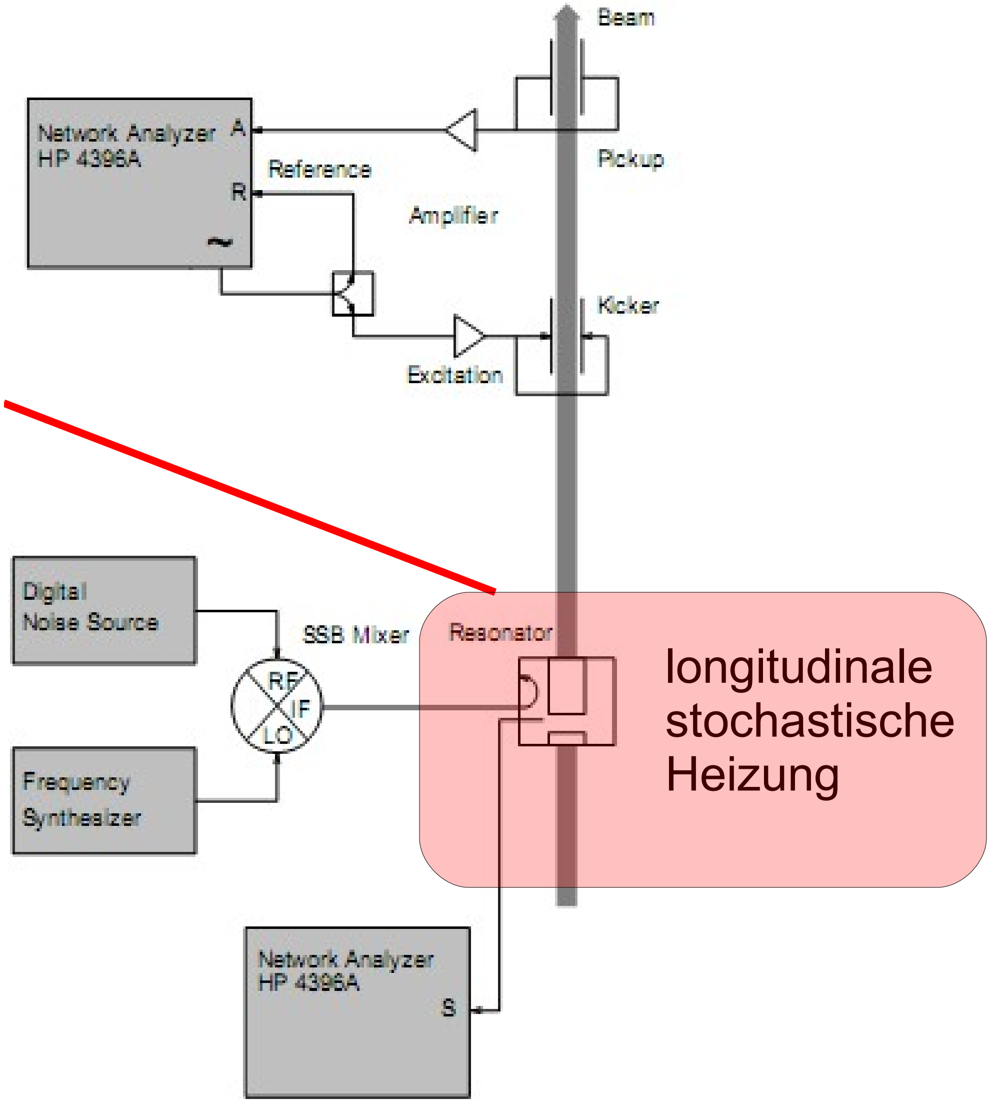
Quelle [5,8]

BACKUP

Longitudinale Kühlkraftmessung mit stocha. Heizung



$$D \propto \frac{dU_{eff}^2}{df}$$



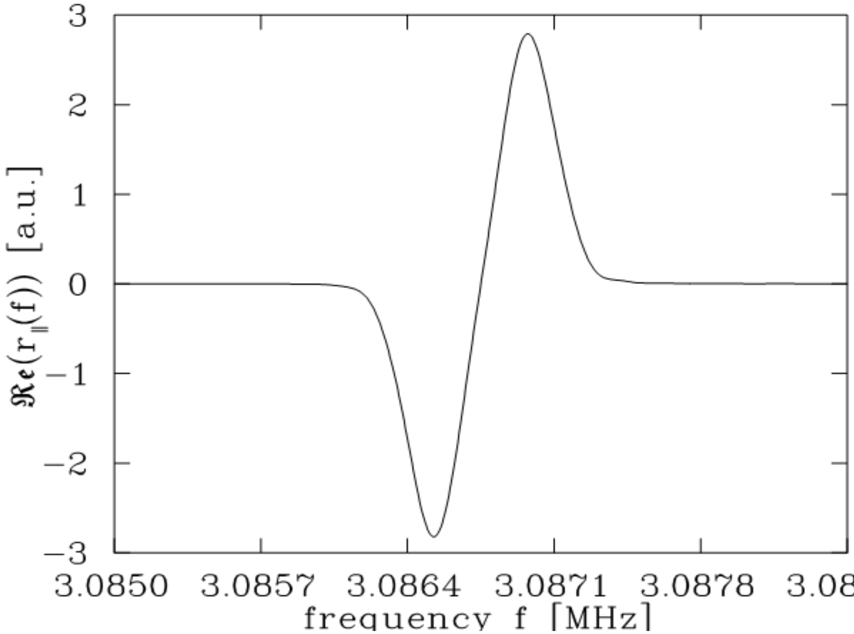
longitudinale stochastische Heizung

Quelle [5,8]

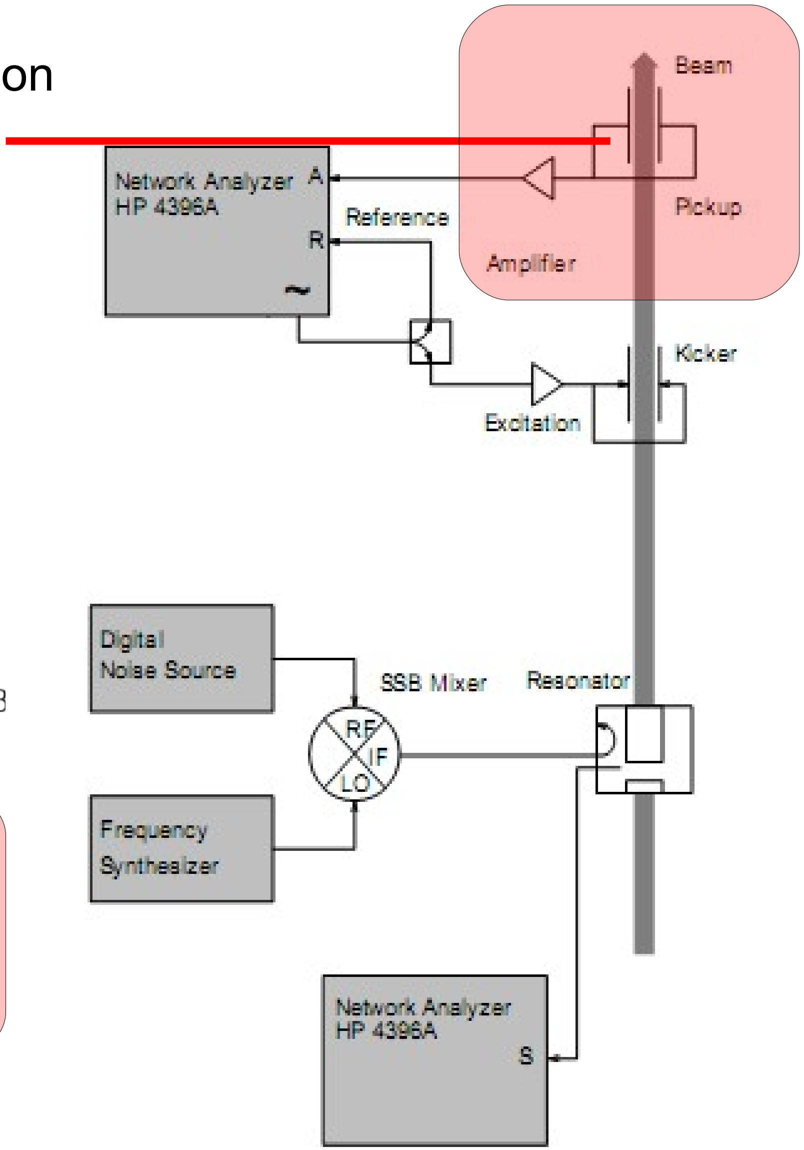
BACKUP

Longitudinale Kühlkraftmessung mit stocha. Heizung

Korregierter Realteil der Transferfunktion



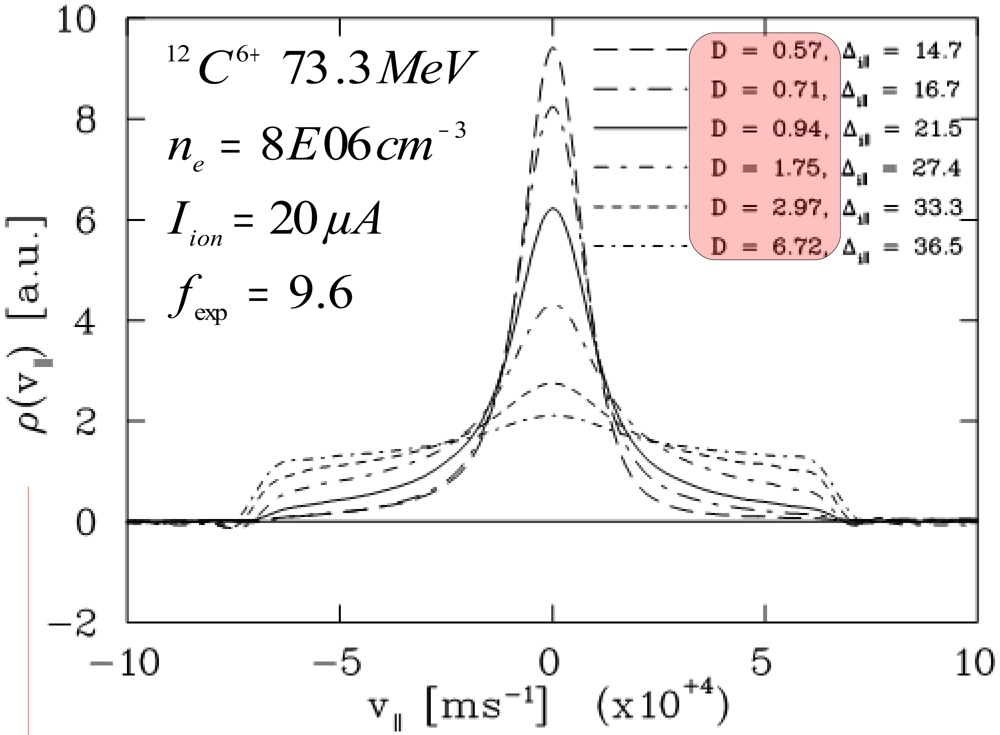
$$\rho_0(f) \propto -\int_{-\infty}^{f} \mathrm{Re}(r_{\|}{}^{0}(\tilde{f}))\,d\tilde{f}$$

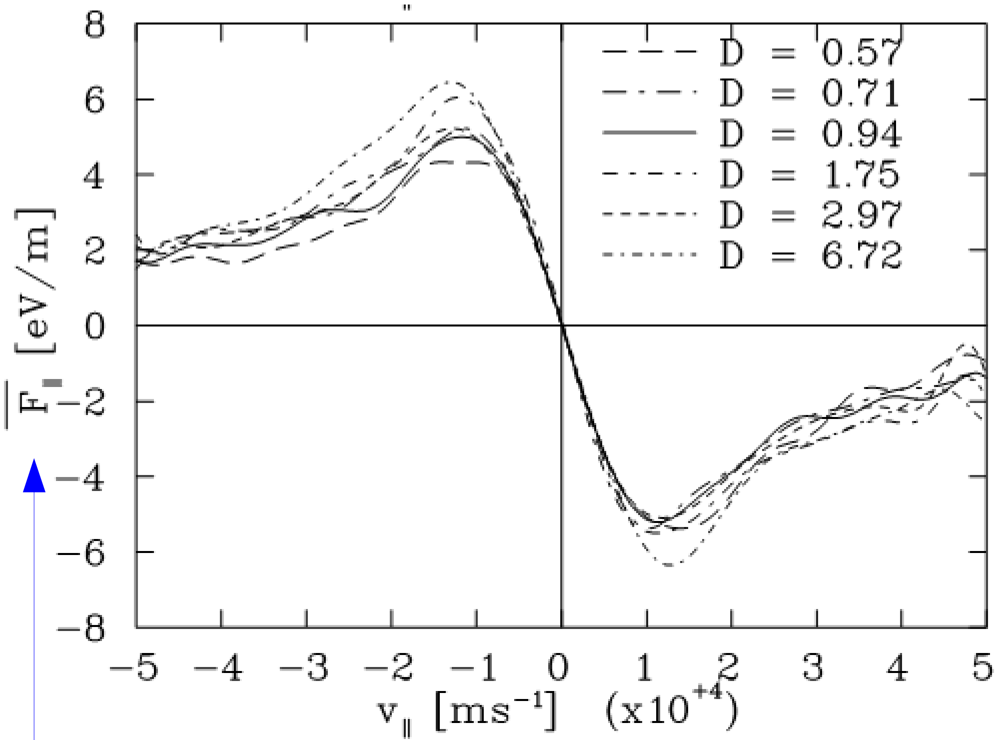


Quelle [5,8]

BACKUP

Measuring the long. cooling force by diffusive heating





$$F_{\parallel} \propto \frac{m_i\, D\, \dfrac{d\rho_{(v)}}{dv}}{\rho_{(v)}}$$

Quelle [4,7,8]