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Further Results and Evaluation of Electron Cooling Experiments at LEAR

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Abstract

First electron cooling experiments were performed with 10^7 to 2×10^9 stored antiprotons of 50, 21 and 6 MeV at the Low Energy Antiproton Ring (LEAR) at CERN. Most effort was put into the study of the longitudinal cooling. Schottky pick-up signals were used to measure the equilibrium momentum spread and the longitudinal cooling time. From the equilibrium between stochastic heating and electron cooling the longitudinal friction force in the low 10^3 m/s relative velocity range could be deduced. This method was used also to increase the cooling force by improving the alignment between the antiproton and the electron beam. Some of the experimental data are compared with results of a simulation program for electron cooling (SPEC).

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1. Introduction

Electron cooling proposed in 1966 by Budker [1] is a new possibility to reduce the phase space of a stored ion beam very fast. In the seventies the principle was successfully tested with proton beams at the NAP-M ring at Novosibirsk [2], at Fermilab [3] and at the ICE (Initial Cooling Experiment) ring at CERN [4]. These electron cooling experiments have demonstrated the large possibilities of this method for experiments with stored and cooled ions. Therefore it was decided to build an electron cooling device for LEAR. The very low emittances and momentum spreads achieved by fast cooling would offer new possibilities for experiments with antiprotons at LEAR [5], e.g. the operation of an internal target at low $\overline{p}$ energies [6]. Furtheron the deceleration of $\overline{p}$ beams down to very low energies, possibly a few MeV, in much shorter times than with stochastic cooling, is facilitated.

The electron cooling device for LEAR [7] was developped by a collaboration between the Kernforschungszentrum Karlsruhe and CERN and installed in LEAR in 1987. Initial cooling experiments with proton beams [8] were successfully performed in October/November 1987 and in March 1988. First experiments with antiprotons were done March 1989. The aim was to prove the applicability of electron cooling for antiprotons and to bring electron cooling a step further to routine operation at LEAR. During this run a new method was tested to measure the longitudinal friction force at very low relative velocities.

2. Experimental set-up and equipment

The electron cooling experiments were performed with antiprotons of 308.6, 200 and 105 MeV/c (49.45, 21.08 and 5.86 MeV respectively). About once a hour a few 10^9 $\overline{p}$ were transfered from the AA (Antiproton Accumulator) and injected in LEAR with a momentum of 609 MeV/c. Before deceleration to the experimental energies (see later) the $\overline{p}$ beam was stochastically cooled for 10 to 15 minutes at the injection energy (180 MeV) because electron cooling was not designed for this high energy.

For the experiments the standard $\overline{p}$-beam diagnostic equipment of LEAR was used. The number of stored $\overline{p}$ was measured by a beam current transformer (BCT) and the orbit was determined by electrostatic position pick-ups. The longitudinal and vertical Schottky noise was analysed by a fast spectrum analyser in order to deduce the momentum spread and the emittance of the $\overline{p}$ beam. The latter was also determined by scraper measurements. The stochastic cooling system of LEAR could be used for a specific beam preparation and as a diagnostic element. By putting RF noise on a longitudinal gap ('stochastic heating') a cold beam was heated in the longitudinal phase space up to a specific momentum spread corresponding to the bandwidth of the heating noise. The balance between the constant stochastic heating and the electron cooling produced an equilibrium distribution whose shape reflected the cooling (friction) force dependence on relative velocity (see section 3.).

The electron cooler was installed in straight section SL3. Electrons emitted from a thermionic cathode at about 1000 K were accelerated to the same velocity as the antiprotons by an electrostatic gun (perveance: 0.56 μP) with 4 anodes. This electron beam (5 cm in diameter) was merged with the $\overline{p}$ beam over an effective cooling length of 1.5 m and thereafter recollected in a collector. The electron beam was embedded in a solenoidal (and toroidal) magnetic field from the gun to the collector to counteract space charge effects. There existed several correction coils for fine tuning of the electron beam direction and displacement in the cooling region. The main parameters of LEAR and the electron cooler during the cooling experiments are listed in table 1. Both are described in more detail in references [7] and [9].

The LEAR machine was controlled through its normal operating system, whereas the electron cooler was mainly operated by its own control system, except during deceleration which was normally done in the following manner. A time signal was sent to the ring magnets to ramp the currents of all magnets synchronously down to several flat tops (beam energies at which the cooling experiments were performed). At each flat top beam cooling was applied in order to reduce the phase space of the beam (emittance and momentum spread) before decelerating further down.

Because the toroid magnetic field of the electron cooler (which scales with momentum) displaces the orbit of the stored $\overline{p}$, this parameter of the cooler was included in the deceleration cycle. At each flat top the necessary orbit and tune adjustments were done. It was therefore decided to use the electron cooler in a 'pulsed' mode, which means that the magnetic field of the cooler was synchronized with the LEAR cycle, while the electron acceleration voltage was swiched off and the correction coils were set by the electron cooler control system as soon as the cooler magnet changed the value. For beam cooling at the flat tops electron cooling was used now instead of stochastic cooling (except for the injection energy). For that purpose the accelaration voltage was ramped to the operational value in about 120 ms and was kept on for 6 sec. In this manner we were able to decelerate to 6 MeV saving some 15 minutes in cooling time. At each flat top cooling experiments were performed of which some results are presented here.

3. Measurements and results

One aim of these measurements was to demonstrate that electron cooling works in practice for antiprotons as well as for protons and that it can be fully included in the normal operation of LEAR down to energies as low as a few MeV. (Cooling of protons and antiprotons was expected to be similar.) Therefore much effort was put into the smooth deceleration of the $\overline{p}$ beam and in the achievement of stable conditions for electron cooling at each flat top of the LEAR cycle. A second, more physical, aim was to test a new method of friction force measurement and to make a comparison of the friction forces between protons and antiprotons. Owing to the fact that the diagnostic equipment of LEAR is more sensitive in the longitudinal phase space of the beam we resticted ourselves to the case of quantitative longitudinal cooling measurements.

3.1. Equilibrium momentum spread

The longitudinal Schottky noise spectra for cooled $\bar{p}$ beams (Fig. 1) were recorded at the 35th harmonic of the revolution frequency for various stored currents which were measured by the BCT. The shape of the measured spectra differed from the usual Gaussian shape and showed a structure with two peaks whose distance increases with the number of stored $\bar{p}$. A similar behaviour was first observed with protons at the cooling test ring NAP-M at Novosibirsk [11] and recently in the first cooling experiments at LEAR [8]. This structure was explained [12] by the occurance of density waves travelling in and against the direction of the beam with a characteristic frequency f_c (which is half the peak distance). The collective phenomena set in when the longitudinal temperature of the beam ($T_{\parallel} = Mc^2 \beta^2 (\Delta p/p)^2$) become comparable to the interparticle Coulomb energy. The characteristic frequency f_c is given by

$$\frac{f_c}{nf_o} = e\sqrt{\frac{\eta N_{\bar{p}}}{pC}\,\frac{\mathrm{Im}(Z_n)}{n}} \;, \qquad (1)$$

where Z_n is the longitudinal impedance of the machine at the nth harmonic of the revolution frequency f_o, C the ring circumference, and $\eta = 1 - \beta^2 + 1/\gamma_t^2$ a ring parameter ($\gamma_t Mc^2$ being the transition energy). The shape of the frequency spectrum can by calculated for a Gaussian distribution of the particle momenta [8]. This functional behaviour can be used for a fit of the experimental spectra. Amongst five fit parameter the r.m.s. momentum spread and the imaginary part of the longitudinal impedance can be deduced. The momentum spread is plotted in Fig. 2 together with other data obtained in cooling experiments with protons at LEAR and at NAP-M. For low antiproton numbers the BCT reading was inaccurate and eq. (1) was used to determine $N_{\bar{p}}$ assuming a constant impedance. For antiprotons larger equilibrium momentum widths as for protons were measured which, however, may be explained by a more noisy electron acceleration voltage (up to 50 V peak-to-peak oscillations), and hence a worse cooling, in these experiments as compared to previous ones.

Calculations were done with a simulation code [10] for electron cooling (SPEC) which uses the best-known friction force and which also includes beam blow-up by residual gas scattering and by intrabeam scattering in order to compare the systematically measured dependence of the equilibrium momentum spread on the number of stored particles with a theoretical model. The result of these calculations using realistic values for all relevant parameters of the cooler and the LEAR ring is also shown in Fig. 2. The slope coincides well with the experimental one.

3.2. Longitudinal cooling times

Measurements of the longitudinal cooling time were done with antiprotons of 50 and 21 MeV for only one momentum spread. Radiofrequency (RF) noise at the 11th and 17th harmonic of the revolution frequency, respectively, with a bandwith of 10 kHz was put on a longitudinal gap which blew up the beam to a momentum spread of about 10^{-3}. After swiching on electron cooling the increase of the Schottky noise around the revolution frequency was recorded (Fig. 3). The cooling time was measured after aligning the $\bar{p}$ and the electron beam (see section 3.3) and resulted in a total cooling time of 1.2 sec which is compared with different SPEC calculations in Fig. 3. Because the resolution bandwith of the spectrum analyser was 10% of the initial momentum spread, the experimental data were normalized to 10 and 100 before and after cooling, respectively. With optimized parameters a much faster cooling (0.6 sec) should happen (dash-dotted line) according to the simulation. The experimental cooling time can be reproduced by the calculations assuming a reduced cooling efficiency by increasing either the electron acceleration voltage noise or the emittance of the $\overline{p}$ beam.

At 21 MeV there was no time to optimize the cooling (e.g. the beam alignment) so a rather long cooling time of 2.2 sec was measured in contrast to the expected near constancy of the cooling time. In the former cooling experiments with protons [8], however, times less than 0.1 sec were measured for a comparable momentum spread.

Further SPEC calculations were performed with varying initial momentum spreads up to a few 10^{-2}. A scaling of the e-folding cooling time like $(\Delta p/p)^{5/2}$ was found in contrast to the scaling with the 3rd power predicted by the simple scaling law neglecting the magnetic confinement of the electrons.

3.3. *Longitudinal friction force*

The measurement of the longitudinal friction force is usually done by stepping away the electron acceleration voltage by a certain amount. The time it takes to accelerate (or decelerate) the stored beam to the new energy determines directly the friction force. This dynamical method is, however, difficult for small energy steps. In order to determine the friction force at low relative velocities, a new static method was firstly applicated. It comprises the analysis of the distribution in equilibrium between a constant stochastic heating power and electron cooling.

The measurement was executed in the following way (see Fig. 4). First the injected beam was cooled (dotted line). Then RF noise with a bandwidth of 10 kHz and a power of 5 μW/Hz was injected at 13.126 MHz on a RF gap, which produces a broad distribution of revolution frequencies (dash-dotted line). The power of this stochastic heating was varied by changing the attenuation of the noise. Thereafter electron cooling was switched on and the balance between the heating and the cooling processes produced a new equilibrium distribution (solid line) whose width increases with noise power. Further a dependence on the alignment and displacement of the electron and the antiproton beam was found. The measurement of the equilibria proved to be a good diagnostic element for fine adjustment of the two beams which was done by changing the fields of the correction coils of the cooler.

In order to obtain the velocity dependence of the friction force F(v) from the equilibrium distribution ρ(v), one has to solve the one dimensional Fokker-Planck equation for a frequency independent diffusion constant D:

$$\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial v} \left(-F(v)\, \rho(v) + D \frac{\partial \rho}{\partial v} \right) \qquad (2)$$

In the equilibrium case $\partial\rho/\partial t = 0$, the shape of the friction force is determined by the normalized slope of the distribution function:

$$F(v) = D \frac{\partial\rho/\partial v}{\rho(v)} \tag{3}$$

The absolute value, however, is proportional to the diffusion constant D which has to be known for the specific heating used in the experiments. The diffusion constant was determined in a direct way similar to the measurement of the longitudinal cooling time (Fig. 3). The time development of the Schottky noise power around the revolution frequency f_0 (Fig. 5) was recorded and compared with the theoretical behaviour which again is described by the Fokker-Planck equation (2). Assuming a δ-like initial distribution the solution of eq. (2) with $F(v) = 0$ gives a Gaussian shaped distribution whose width increases with time proportional to D:

$$\rho(f,t) = \frac{N}{\sqrt{4\pi Dt}} \exp\left(-\frac{(f-f_0)^2}{4Dt}\right) \tag{4}$$

(N being a normalization constant). By fitting the experimental peak power decay with eq. (4), or more accurately with the integral of eq. (4) over the bandwidth Δf, the diffusion constant D was obtained. For a heating power of 5 μW/Hz with an attenuation of 40 dB D was 4.36 kHz^2/s Analysing the theory in more detail we recognized that the determination of D is very sensitive to the correct center frequency of the time spectrum and to the resolution bandwidth Δf which is chosen best as the width of the cold beam. In our measurement we did not take particular care of this, so we estimate the accuracy of D to be of the order of 20 - 40%.

In Fig. 6 the result of two friction force measurements with 50 MeV $\bar{p}$ is shown, one with aligned beams and one with misaligned beams (angle about 1 mrad). The friction force could be measured for relative velocities less than 10^4 m/s and the position of the maximal force was found in the case of aligned beams. As a consequence of the alignment the cooling improved, clearly indicated by the stronger friction force whose maximum is at much lower relative velocities. The lines drawn in Fig. 6 show the dispersion-like shape of the friction force as predicted by theory. It can be approximated by the function

$$F(v) = F_0 \frac{3v}{|v|^3 + 2\Delta^3}, \tag{5}$$

where Δ in our case is the longitudinal velocity spread of the electron beam. The measured value of 1.5×10^4 m/s leads together with the former measured [8] transverse temperature of 0.25 eV to a flattening factor of the velocity distribution of the electron beam of 20.

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TABLES:

Antiproton-beam energy	49.45	21.08	5.86	MeV
Electron-beam energy (at axis)	26.93	11.48	3.19	keV
Electron current	2.5	0.70	0.088	A
Solenoid field	455	300	145	Gauß
Ring circumference	78.54	78.54	78.54	m
Hor. and vert. focussing function	1.9 , 5.3	1.9 , 5.3	1.9 , 5.3	m
Momentum dispersion (at the cooler)	3.6	3.6	3.6	m
Number of stored antiprotons	10^7 to 2×10^9	10^7 to 2×10^9	10^7 to 2×10^9	
Initial emittance (95% of part.)	20	20	20	π mm mrad
Initial momentum spread (95% of part.)	2×10^{-3}	2×10^{-3}	2×10^{-3}	
Typical vacuum (ring average)	3×10^{-12}	3×10^{-12}	3×10^{-12}	Torr

Table 1. Main parameters for electron cooling in LEAR

FIGURE CAPTIONS:

Fig. 1: Longitudinal Schottky spectra for 1.4×10^8, 5.0×10^8 and 1.2×10^8 $\bar{p}$ of 50 MeV measured around the 35th harmonic of the revolution frequency. The dashed lines are fits of the spectra.

Fig. 2: Equilibrium momentum widths for cooled protons (full circles) and antiprotons (open circles) at LEAR and at NAP-M (full squares). For the LEAR proton data the dependence on the number of stored particles is compared with the results of the simulation code SPEC (dashed line).

Fig. 3: The time development of the Schottky noise power around the 35th harmonic of the revolution frequency is recorded for the cooling of a stochastic heated (10 kHz noise width at 13.126 MHz) $\bar{p}$ beam of 50 MeV (crosses). It is compared with different SPEC calculations: a) for optimal cooling (dash-dotted line) b) with 25 V acceleration voltage noise (dashed line) and c) for a $\bar{p}$ beam with a horizontal and vertical emittance of 2.5 π mm mrad (solid line).

Fig. 4: The principle of a new method for measuring the longitudinal friction force at low relative velocities is explained. A cooled beam (dotted line) is stochastically heated to a broad distribution (dash-dotted line). Switching on electron cooling a new equilibrium distribution (solid line) is reached, whose shape reflects the dependence of the friction force on relative velocity (eq. (3)).

Fig. 5: The stochastic heating (5 μW/Hz, 40 dB attenuation) of a cold $\bar{p}$ beam results in a decrease of the Schottky signal power around the revolution frequency (crosses). A fit of this time development (solid line) gives the diffusion constant D for this specific heating (eq. (4)).

Fig. 6: The longitudinal friction force for 50 MeV $\bar{p}$ is shown as a function of the relative velocity for well-aligned beams (full triangles, solid line) and for misaligned beams (open triangles, dashed line). The increase of the maximal friction force and the shift to lower relative velocities for the better aligned beams can be seen clearly. The lines show the theoretical dispersion-like behaviour of the friction force (eq. (5)).

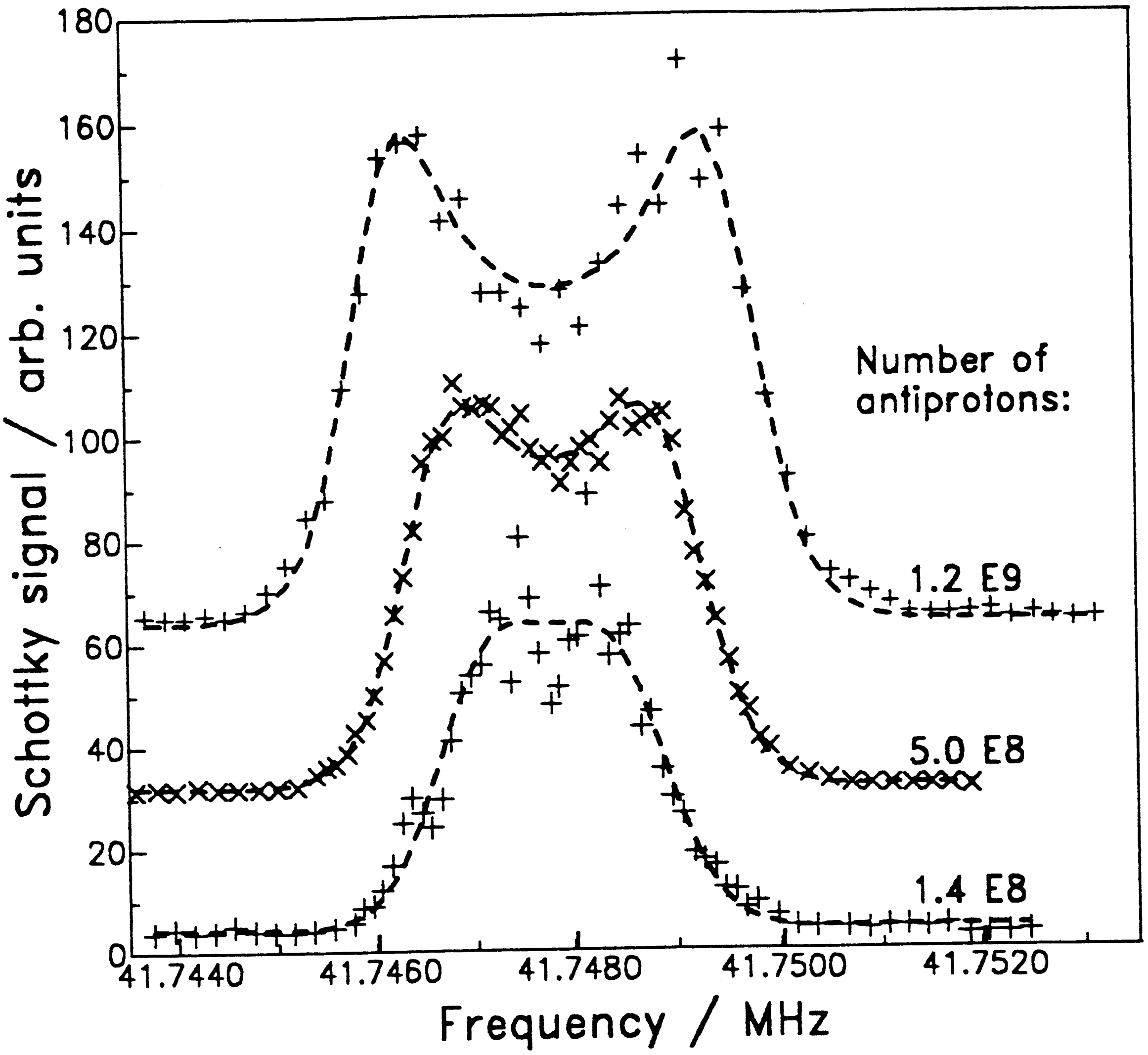
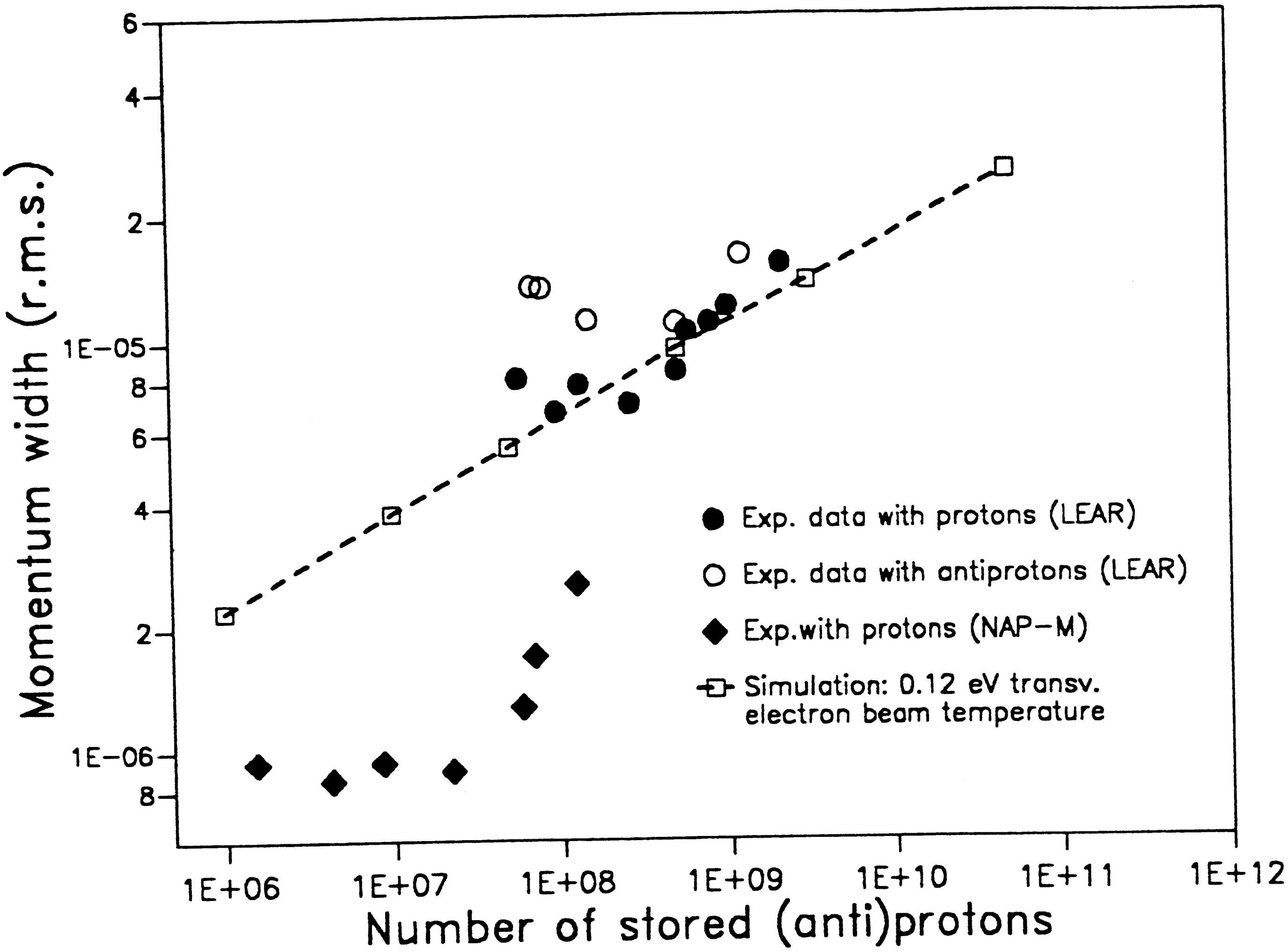

180
160
140
120
100
80
60
40
20
0
41.7440
41.7460
41.7480
41.7500
41.7520
Frequency / MHz
Schottky signal / arb. units
Number of antiprotons:
1.2 E9
5.0 E8
1.4 E8

Fig. 1



Momentum width (r.m.s.)
6
4
2
1E-05
8
6
4
2
1E-06
8
1E+06
1E+07
1E+08
1E+09
1E+10
1E+11
1E+12
Number of stored (anti)protons
Exp. data with protons (LEAR)
Exp. data with antiprotons (LEAR)
Exp.with protons (NAP-M)
Simulation: 0.12 eV transv.
electron beam temperature

Fig. 2

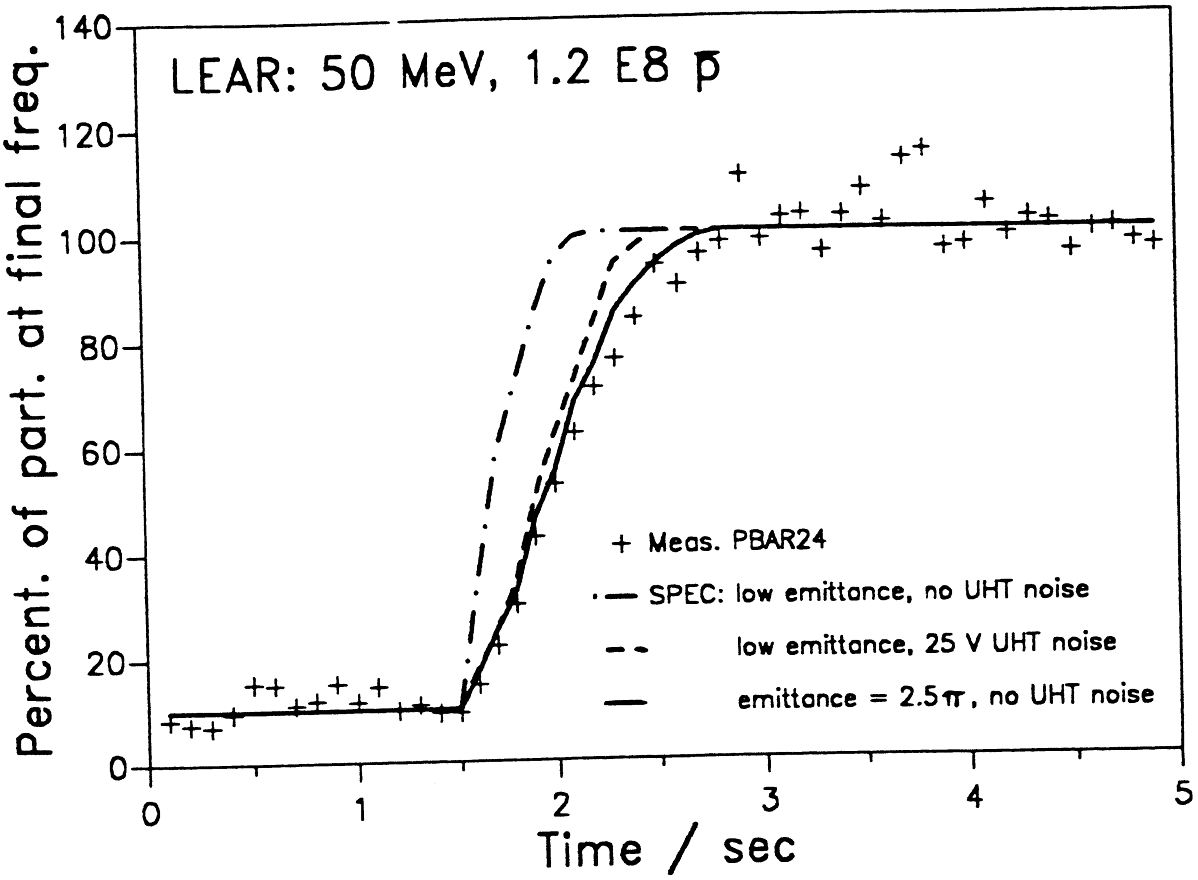
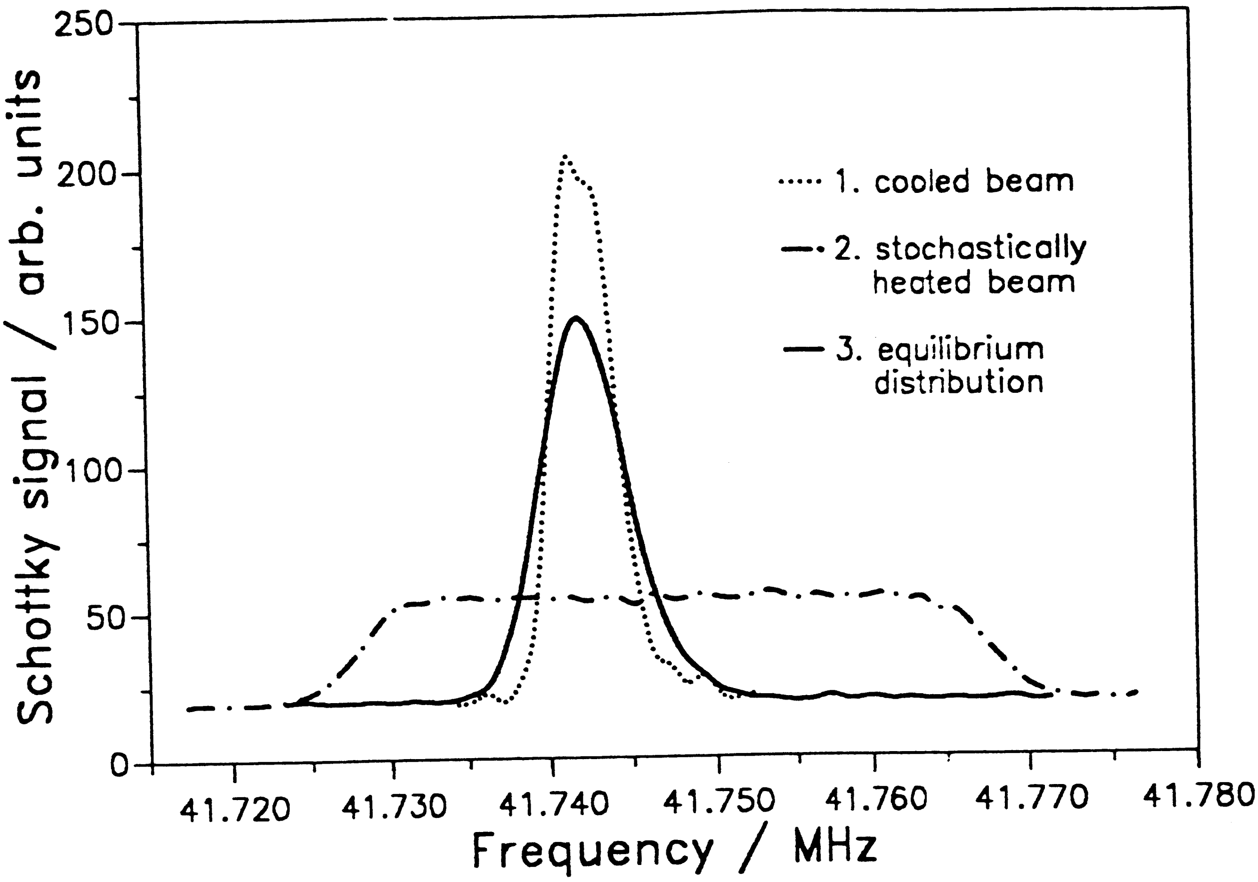

LEAR: 50 MeV, 1.2 E8 p̄
Percent. of part. at final freq.
140
120
100
80
60
40
20
0
0
1
2
3
4
5
Time / sec
+ Meas. PBAR24
SPEC: low emittance, no UHT noise
low emittance, 25 V UHT noise
emittance = 2.5π, no UHT noise

Fig. 3



Schottky signal / arb. units
250
200
150
100
50
0
1. cooled beam
2. stochastically heated beam
3. equilibrium distribution
41.720
41.730
41.740
41.750
41.760
41.770
41.780
Frequency / MHz

Fig. 4

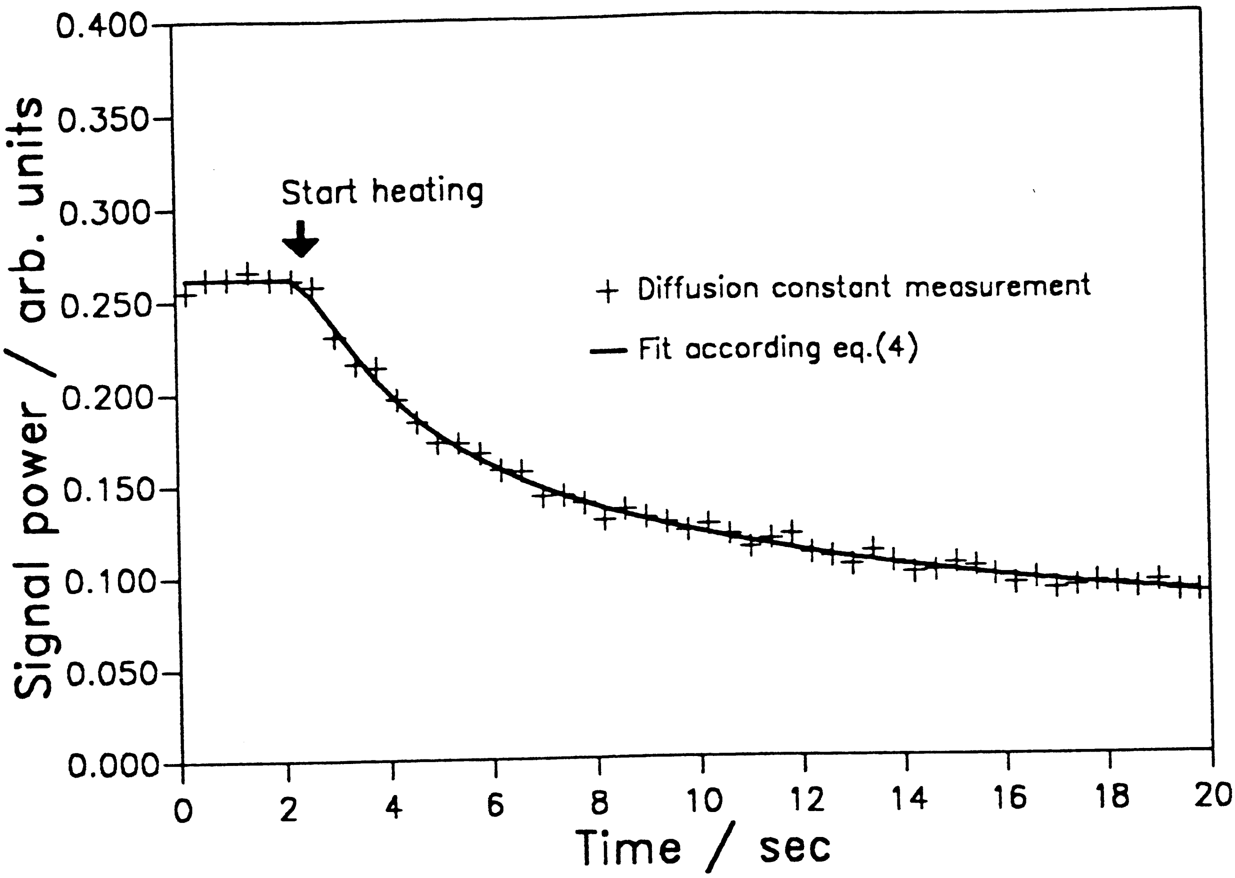

0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
0.000
Signal power / arb. units
Start heating
+ Diffusion constant measurement
— Fit according eq.(4)
0
2
4
6
8
10
12
14
16
18
20
Time / sec

Fig. 5

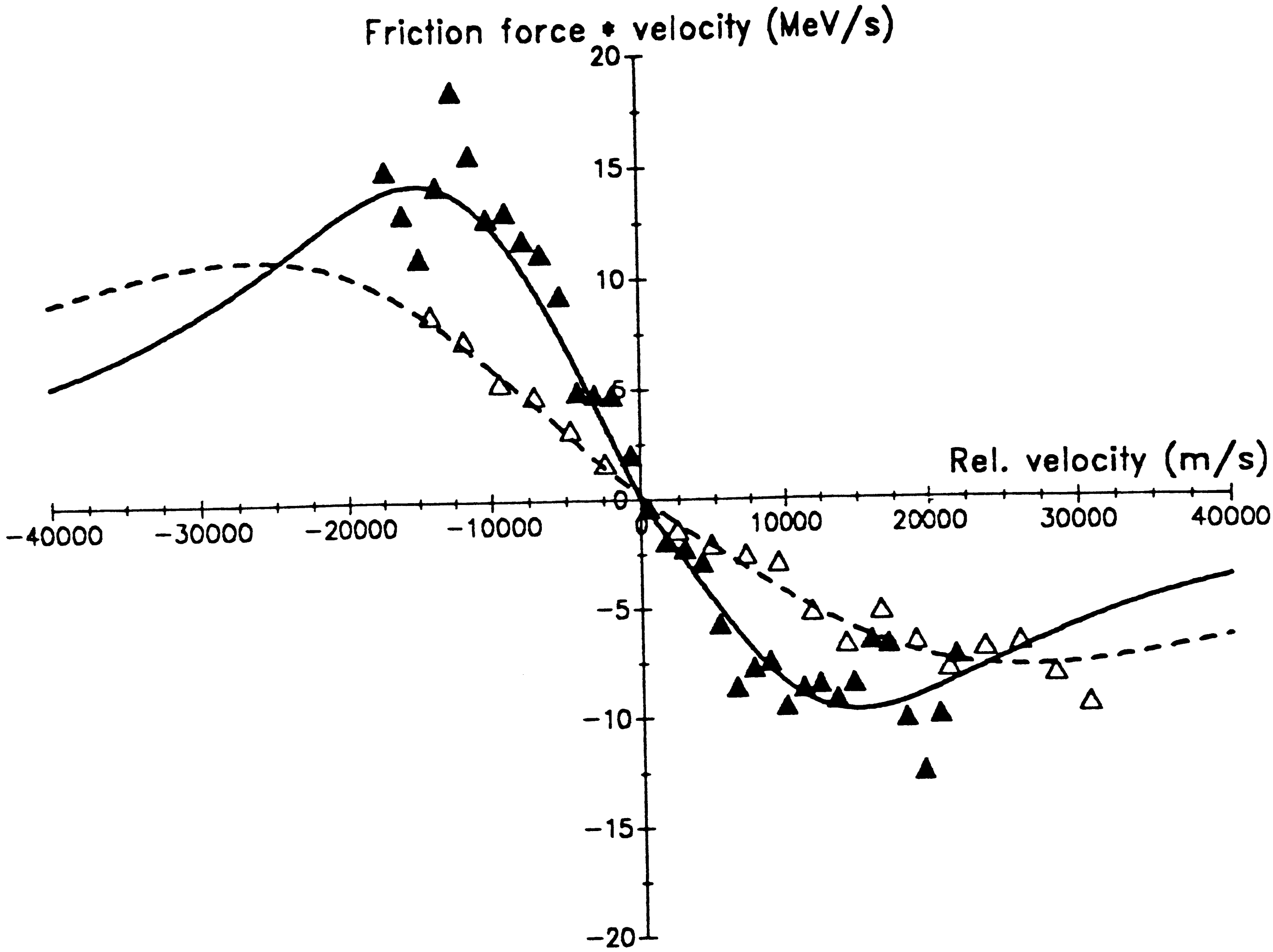

Friction force * velocity (MeV/s)
20
15
10
5
0
-5
-10
-15
-20
Rel. velocity (m/s)
-40000
-30000
-20000
-10000
0
10000
20000
30000
40000

Fig. 6