EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/79-96
3 September 1979

ELECTRON COOLING EXPERIMENT AT CERN

M. Bell, J. Chaney*), S. Cittolin, H. Herr, H. Koziol, F. Krienen,
G. Lebée, P. Møller Petersen, G. Petrucci, H. Poth**),
T. Sherwood, G. Stefanini, C. Taylor, L. Tecchio***),
C. Rubbia, S. Van der Meer and T. Wikberg

ABSTRACT

Beams of 46 MeV protons have been cooled by means of electrons in the ICE (Initial cooling Experiment) storage ring. Six two-day runs starting in May 1979 have shown, for proton intensities of up to 3×10^8, a density increase in six-dimensional phase space of over a factor of 10^6, with cooling times in momentum spread and betatron amplitudes of 0.3 and 1.2 s, respectively. The proton beam lifetime was increased by a factor of 40. Measurements of the evolution of momentum spread, beam profile, and neutral atom production rate are in reasonable agreement with theory.

(Submitted to Physics Letters)

---

*) Visitor from Queen Mary College, University of London, England.

**) Visitor from the Institut für Kernphysik, Kernforschungszentrum Karlsruhe, Germany.

***) Visitor from INFN, Sezione di Torino, Italy.

The electron cooling method was conceived by Budker [1] in 1966, and experimentally confirmed at Novosibirsk in 1974-75 [2]. These tests were made with beams of small emittances and small momentum spread. The objective of CERN was to cool a beam of larger phase space, as would be a secondary antiproton beam, in order to test the feasibility of a high-luminosity $\bar{p}p$ collider.

Electron cooling is based on repeated interactions of protons (or, in general, heavy ions) circulating in a storage ring with a dense and cold electron beam. The electron beam is admitted in one straight section of the storage ring where the electrons travel along a few metres together with the protons and with almost the same velocity. Within the limits of space-charge effects and optics imperfections, the electrons in the beam have nearly the same energy and almost parallel trajectories.

The generation of an electron beam with these properties and in the energy range of the order of 100 keV, is best achieved with an electron gun utilizing thermal emission and electrostatic acceleration. Parallelism of trajectories is obtained by guiding the beam in a solenoidal magnetic field. In the rest frame of the electron beam the electron temperature is anisotropic; the transverse temperature can be of the order of 1 eV, whereas the longitudinal temperature is several orders of magnitude smaller. In this frame the velocities of the circulating protons can initially be quite high, and their temperature may amount to hundreds of electronvolts. Owing to Coulomb interactions, protons transfer heat to the electrons and tend to assume their temperature without observably heating the electrons, since they are continuously renewed. The frictional restoring force is, in the first instance, inversely proportional to the square of the proton velocity, as long as the latter is larger than the r.m.s. electron velocity. Below this, the force tends to be proportional to the proton velocity. Cooling times are thus determined by the highest proton velocity, whereas the ultimate phase-space reduction is determined by the electron temperature and the multiple scattering on residual gas.

The experiment was performed in the ICE (Initial Cooling Experiment) storage ring. This ring, with a circumference of 74 m, presents four magnetic quadrants and four straight sections, one of which is occupied by the electron cooler. The initial conditions (momentum spread and geometrical emittances) of the proton beam circulating in ICE were: $\Delta p/p$ (FWHM) = 0.25%, $E_H = 60\ \pi$ mm mrad, $E_V = 30\ \pi$ mm mrad. The main parameters of the experiment were: electron energy 26 keV matching 46 MeV protons, electron current 1.3 A, electron beam diameter 5 cm, cooling length 3 m, and magnetic field 500 G.

Considerable effort was necessary to obtain a good enough vacuum to reduce ionization of residual gas and avoid high-voltage breakdown in the gun [3]. During the experiment the vacuum pressure reading in the cooler ranged between 2×10^{-10} and 3×10^{-9} Torr. The average vacuum pressure around the ring was about 2×10^{-9} Torr.

No absolute measurement of the transverse electron temperature was made, but the detection of microwave radiation, presumably emitted by the electrons spiralling in the solenoidal magnetic field [4], provided an effective means of optimizing the electron gun parameters.

Owing to the space-charge potential of the electron beam, electron energy and hence velocity vary with radius. The parabolic potential well across the beam amounts to 130 V, although variations are possible because of ionization of the residual gas and subsequent trapping [3]. Figure 1 shows, for the median plane of the storage ring, the velocity variation (approximately linear) of the protons as a function of the radial position of their equilibrium orbit, together with the electron velocity profile. An essential requirement for the cooling process to occur is that the two velocity profiles intersect; then cooling will produce an accumulation of protons around the intersection point A with the exception of the fraction of the proton beam situated at the left of B, which will be accelerated by the electrons and pushed towards the outside of the cooling region.

The following characteristics of the cooling process have been evaluated: a) cooling rates; b) equilibrium proton beam dimensions; c) increase in proton beam lifetime; d) rate of neutral atoms formed through combination of protons and electrons in the cooling straight section.

The diagnostic devices allowing the measurement of the above quantities included a momentum pick-up (that is, a pick-up sensitive to the Schottky noise of the circulating beam), a beam profile monitor (horizontal: H, and vertical: V) [5], a neutral atom beam profile detector (H and V), and a beam current transformer. Furthermore, horizontal and vertical scraping was employed to measure the transverse sizes of the beam.

The construction of the electron cooler started in the summer of 1977. The cooler was tested early in 1979 and mounted in the ICE ring in April 1979.

Momentum cooling effects were observed on the first day of experimentation as soon as the electron and proton beams were aligned and the velocities matched. This early test showed a momentum spread reduction from 2×10^{-3} down to 3×10^{-4} with a peak density increase by a factor of about 3. Transverse cooling was also very soon observed, with a factor of 5 reduction in size as shown by the beam profile monitor in both the horizontal and the vertical plane. The neutral production rate under these conditions was about 50 H^0/s per 10^8 circulating protons.

In the following runs the electron gun parameters were better optimized, aiming in particular at minimizing the microwave signal and maximizing the neutral hydrogen production rate, which increased up to about 300 H^0/s per 10^8 protons. In these new conditions, corresponding to considerably more effective cooling, longitudinal instability of the circulating beam leading to short bunches was observed. A substantial increase in the proton beam lifetime was obtained; at a pressure reading of 1.5×10^{-9} Torr it was increased from 3 min to about 140 min, this last value being in close agreement with theory for single scattering losses. The transverse temperature of the electron beam was estimated from the neutral-atom forming rate, which is determined by the highest temperature of either the protons or the electrons. A value of about 0.2 eV temperature averaged over the part of the electron beam seen by the cooled proton could be calculated from this rate. The transverse cooling results were in reasonable agreement with theoretical prediction for such temperatures.

Further experimental runs were performed, changing the working point of the ICE ring in order to operate below transition. In this new mode the previously observed longitudinal instabilities of the circulating protons disappeared and a further improvement in the cooling process was observed.

Figure 2 shows an example of longitudinal cooling obtained during the last run by means of frequency analysis of the Schottky noise spectrum of the proton beam. The frequencies are displayed around a harmonic (in the picture, the 25th) of the revolution frequency and are proportional to the particle momenta; the vertical signal is proportional to the square root of the particle density. The broad spectrum was obtained in a fraction of the first second after injection and shows the starting of proton accumulation at the low-energy side (low frequency), whereas the narrow peak corresponds to the equilibrium spectrum after cooling and was taken about 10 s after injection. The accumulation frequency corresponds to the position of intersection point A of fig. 1. The momentum spread was reduced by more than one order of magnitude. This picture was taken at an intensity of about 10^8 circulating protons. Figure 3 shows the shrinking of the horizontal beam profile as measured by the profile monitor. Here again the broad profile, taken in a fraction of the first second after injection, already shows the beginning of cooling.

To measure longitudinal cooling rates, rectangular pulses of different height and length were applied to the gun high-voltage, and the evolution of the radial beam displacement was followed. Similarly, to measure transverse cooling rates, magnetic kicks as short as the revolution frequency ($\sim$ 700 ns) were applied to the protons to excite coherent oscillations, and the evolution of the proton profile was followed. Figure 4 shows an example of such a measurement with a step of 80 V applied to the gun high-voltage for 5 s. Histogram (i) shows the horizontal beam profile at time intervals of 800 ms. The radial position, the horizontal FWHM, and the intensity of the circulating beam versus time are shown in histograms (ii), (iii), and (iv), respectively. During the pulse, a shift towards higher momenta and a broadening of the beam profile are observed. Still in fig. 4, histograms (v) and (vi) show respectively the horizontal and the vertical neutral beam profiles integrated over time intervals of 5 s. Finally, the inserted columns (vii) in histogram (iv) show the integrated neutral rate over time intervals of 5 s.

Figure 5 is an example of transverse cooling, studied by applying a 2 mrad kick to the cooled protons in the horizontal plane. The display is the same as in fig. 4 but the time interval between the horizontal beam profiles is now 400 ms. A small particle loss occurs at the moment of the pulse owing to particles hitting the inside of the ring. The beam is rapidly cooled to its previous dimensions.

The most significant results of this experiment are shown in Table 1 together with the essential parameters.

The results obtained so far are very convincing. In the near future we intend to pursue this study, our aim being to increase the precision of our measurements and to extend them to higher proton intensities. Several important applications of this method are already envisaged.

Acknowledgements

We wish to thank our colleagues L. Hoffmann, P. Lefèvre, D. Möhl, B. Sadoulet, D. Simon, L. Thorndahl and B. Vosicki for encouragement and contributions.

We acknowledge the untiring efforts of F. Cataneo, E. Chesi, W. Glessing, M. Hauer and R. Pintus during the preparation and the running of this experiment.

Table 1

Proton beam energy	46.2 MeV
Initial $\Delta p/p$ (FWHM)	2.5×10^{-3}
Emittances E_H/E_V	60/30 π mm mrad
Intensity of proton beam	$\sim 3 \times 10^{8}$
Electron beam high-voltage	25.9 kV
Electron beam current	1.3 A
Solenoidal magnetic field	500 G
Momentum cooling time $\tau_{L1/e}$ $[\Delta p/p$ (FWHM) $\sim 1.5 \times 10^{-3}]$	300-400 ms
Betatron cooling time $\tau_{T1/e}$ $[\theta_p$ (FWHM) $\sim$ 1.5 mrad$]$	1.2 s
Average vacuum pressure	2×10^{-9} Torr
Lifetime of the cooled beam	140 min
Lifetime gain factor	40
Equilibrium momentum spread of the cooled protons (FWHM)	4×10^{-5}
Equilibrium cross-section of the cooled proton beam (FWHM)	$\sim 0.5 \times 0.5$ mm
Six-dimensional phase-space density increase	$> 10^{6}$
Neutral beam rate	650 H^0/s per 10^8 protons

REFERENCES

[1] G.I. Budker, At. Energ. 22 (1967) 346.

[2] G.I. Budker et al., Part. Acc. 7 (1976) 197.

[3] M. Bell et al., Proc. Joint CERN-KfK Workshop on Physics of Low-Energetic Antiprotons, Karlsruhe, May 1979, report KfK 2836, 1979, p. 43.

[4] Proposal by C. Rubbia (private communication) to measure the synchrotron radiation of electron spiralling in a magnetic field, and worked out by C. Taylor and S. Hancock (in preparation).

[5] G. Stefanini, A profile monitor for low-intensity circulating beams (in preparation).

Figure captions

Fig. 1 :	Qualitative velocity profiles in the radial plane of electrons and protons.
Fig. 2 :	Momentum spectrum of the circulating protons before and after cooling.
Fig. 3 :	Horizontal beam profile before and after cooling.
Fig. 4 :	Longitudinal cooling study. Effect of an electron gun voltage step on the cooled proton beam.
Fig. 5 :	Transverse cooling study. Effect of a horizontal kick on the cooled proton beam.

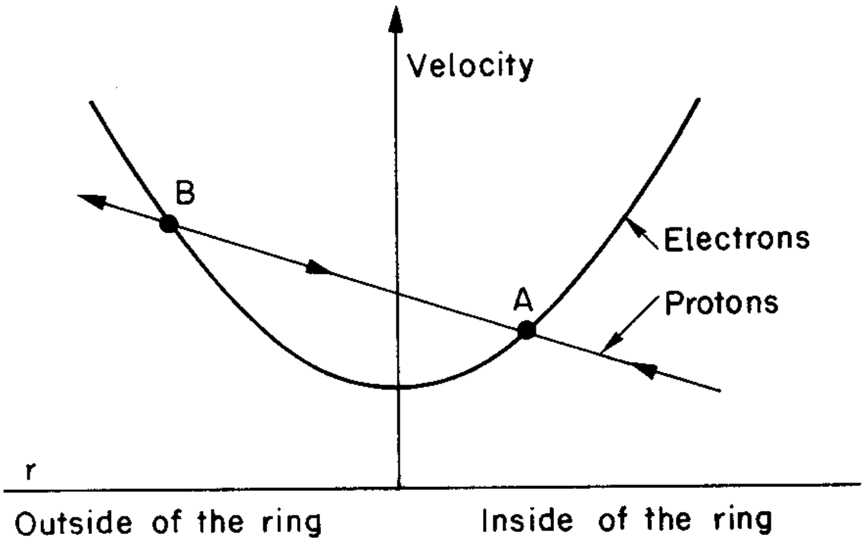
Velocity
B
A
Electrons
Protons
r
Outside of the ring
Inside of the ring

Fig. 1

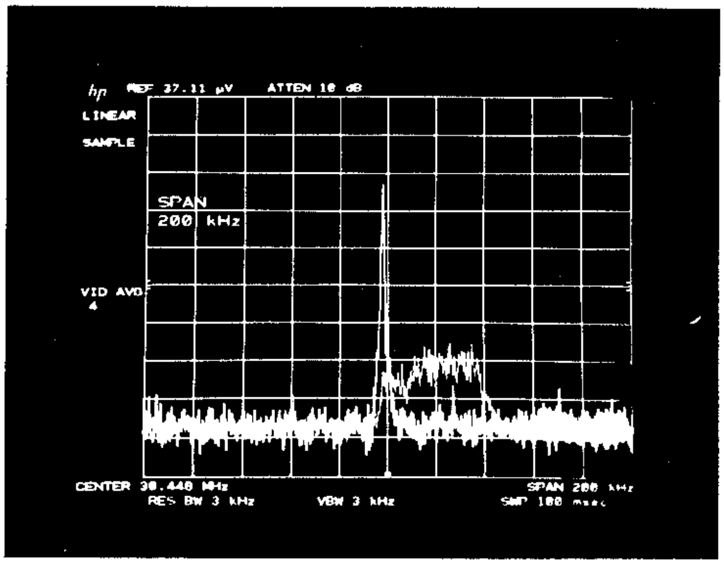
hp REF 37.11 µV ATTEN 10 dB
LINEAR
SAMPLE
SPAN
200 kHz
VID AVG
4
CENTER 30.440 MHz
RES BW 3 kHz
VBW 3 kHz
SPAN 200 kHz
SWP 100 msec

Fig. 2

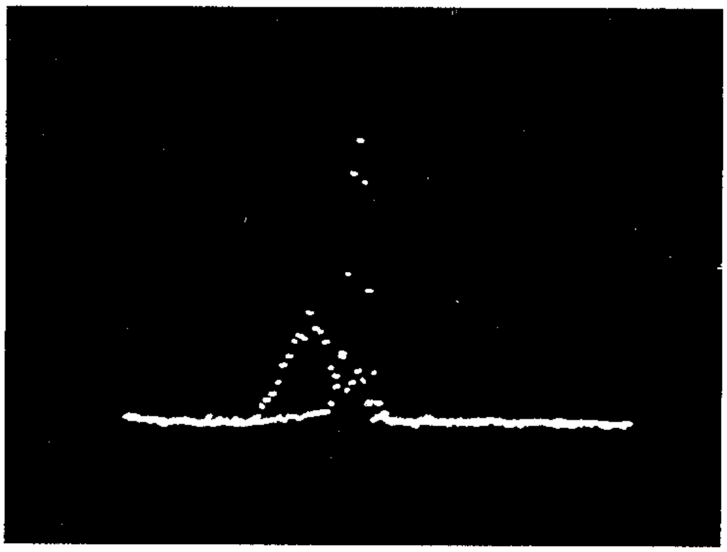

Fig. 3

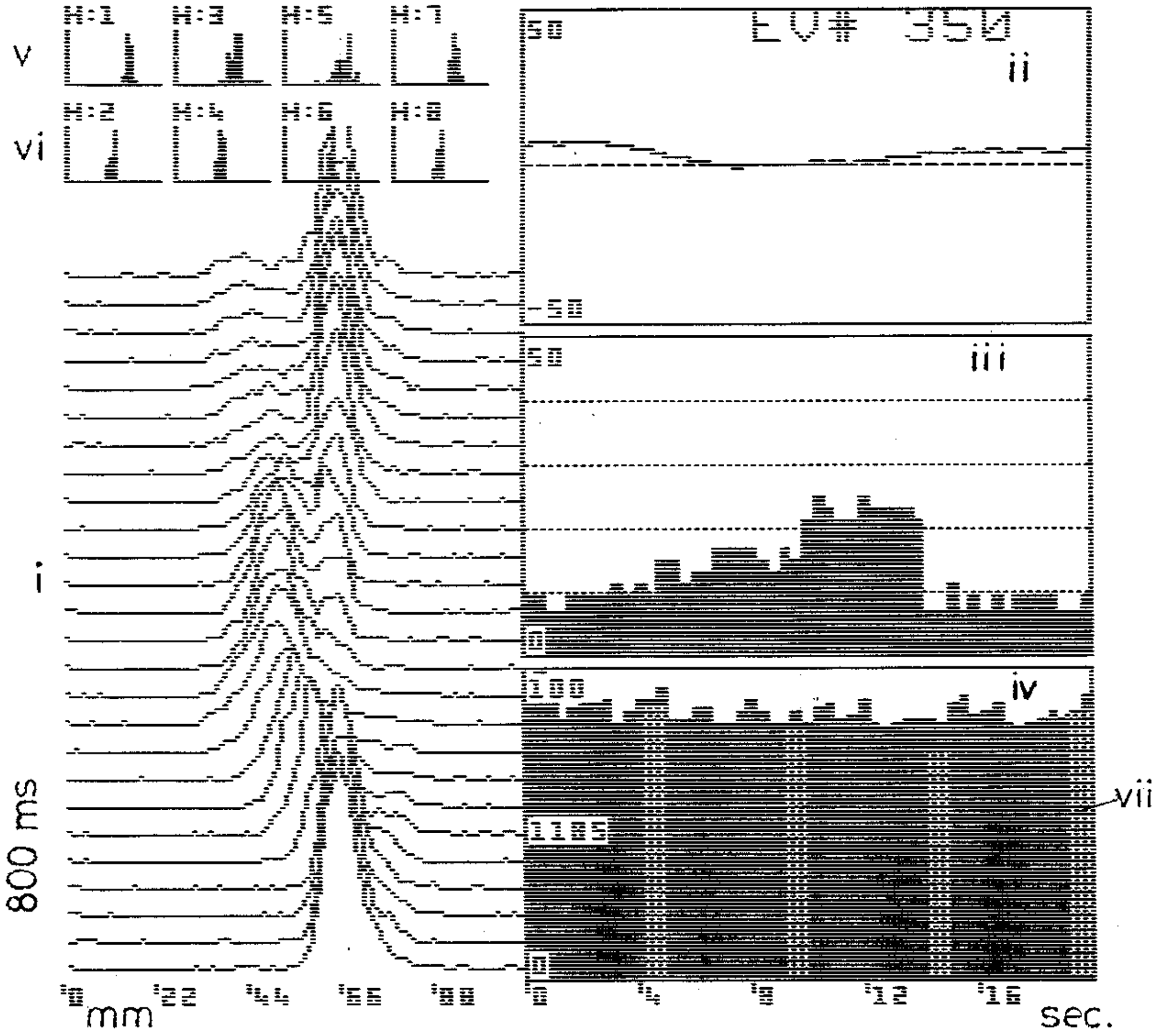
H:1
H:3
H:5
H:7
v
H:2
H:4
H:6
H:8
vi
i
800 ms
0
22
44
66
88
mm
EV# 350
50
ii
-50
50
iii
0
100
iv
1185
vii
0
0
4
8
12
16
sec.

Fig. 4

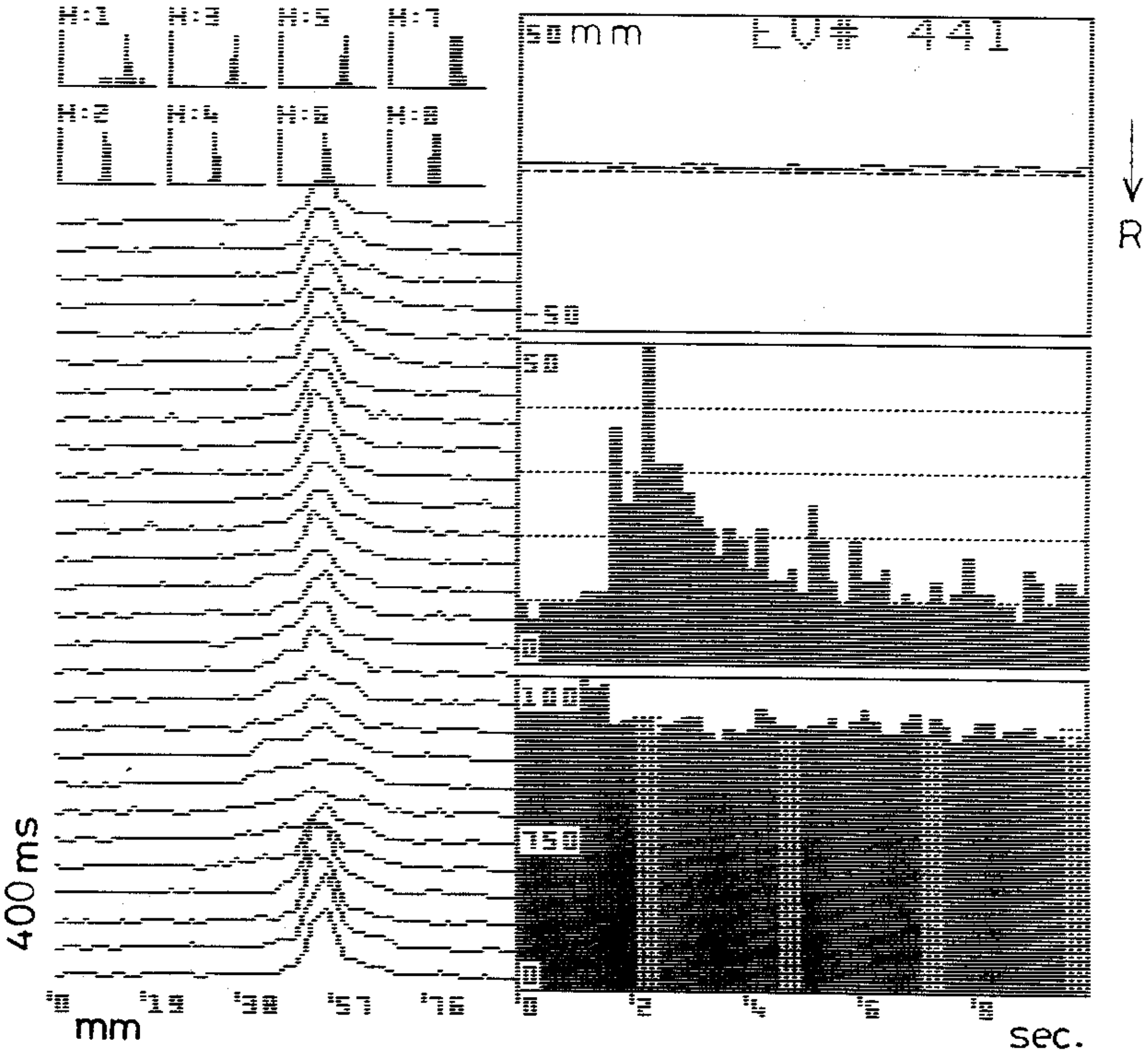
H:1
H:3
H:5
H:7
H:2
H:4
H:6
H:8
50mm
EV# 441
-50
50
0
100
750
0
400ms
0
19
38
57
76
mm
0
2
4
6
8
sec.
R

Fig. 5