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Production and measurements in the PS Complex of a high-brilliance proton beam in view of the LHC

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Abstract

Production of the high-brilliance proton beam for the LHC implies major hardware changes as well as mastering beam dynamics constraints in the PS Complex. Although the hardware modifications necessary to achieve this goal are not yet realized, and hence the final beam cannot be produced, meaningful beam experiments are possible.

This note presents the results of recent Machine Developments. The aim was to produce the highest beam brilliance possible with the present Linac preinjector, to simulate the LHC beam, and to measure the beam dimensions at 1 GeV with various instruments in the PSB, the PSB-CPS transfer line and in the CPS. Special emphasis is put on beam profile measurements and the cross-checking between various devices. A comparison of machine conditions for these Machine Developments with the proposed final LHC filling scheme should clarify the significance of these beam studies.

1 Introduction

Production of the high-brilliance proton beam for the LHC implies major hardware changes as well as mastering beam dynamics constraints in the PS Complex. Amongst the latter, the two most salient are:

- production of a high density beam at injection in the PSB;
- preservation of this beam during the 1.2 s (60 times longer than usual) CPS flat-bottom.

The hardware changes required are:

- a new RFQ, replacing the 750 keV Cockcroft-Walton preaccelerator of Linac 2;
- new RF systems (harmonics h=1 and h=2) in each of the PSB rings;
- increase of the PSB output energy from 1 to 1.4 GeV;
- installation of a 66 (40) MHz RF system in the CPS to generate the LHC bunch spacing of 15 (25) ns.

Although none of these devices is yet installed in the PS Complex, and hence the final beam cannot be produced, meaningful beam experiments are possible. In this note, the results of recent Machine Developments are presented. The aim was to produce the highest beam brilliance possible with the present Linac preinjector, to simulate the LHC beam, and to measure the beam dimensions at 1 GeV with various instruments in the PSB, the PSB-CPS transfer line and in the CPS. A comparison of machine conditions for these Machine Developments with the proposed final LHC filling scheme, given in Table 1, should clarify the significance of these beam studies.

Indeed, beams of transverse densities approaching the LHC performance specifications (cf. [1] chap. 12, [2]) have been generated. Special emphasis has been put on beam profile measurements and the cross-checking between various devices.

2 Machine conditions

2.1 Linac

The Linac output current was raised from the usual 145 mA to 165 mA (Fig. 1) by

- increase of the source arc current;
- opening the slit apertures in the LEBT (beam line between preaccelerator and Linac);
- increase of the RF power levels in the Linac tanks.

Note that the higher RF power reduces the useful beam pulse length from 100 to 20 μs. This is fine for the LHC beam but insufficient for high intensity users, thus these studies cannot be done in parallel with operation.

2.2 PS Booster

The beam was injected at 50 MeV into ring 3 by 3-turn betatron stacking. The Q-tuning supplies were programmed to set a working point which varies during the acceleration cycle, starting at injection with $Q_x = 4.28$, $Q_y = 5.45$. Third order resonances were compensated, and space charge effects were reduced by bunch-flattening with h=10 cavities (Laslett tune spread $\Delta Q_{x,y} \approx 0.3$). Five bunches were then accelerated to 1 GeV, within a momentum spread $\Delta p/p$ of $\pm 0.13\%$ prior to ejection (Fig. 2). About $1.8\,10^{12}$ protons per pulse were available for the CPS.

Thanks to the feedback systems, able to tackle 10^{13} protons per ring, these five bunches were strictly stable in both transverse and longitudinal planes.

2.3 CPS

The 5 bunches from the PSB were injected at 1 GeV into 5 consecutive, h=20 CPS buckets, filling one quarter on the CPS circumference. These bunches, 53 ns long and containing $3.4\,10^{11}$ particles **experience about the same space charge tune spread of 0.2 at 1 GeV as the future LHC beam of same normalized transverse emittance at 1.4 GeV.**

The beam was found particularly unstable in both transverse planes, with an instability rise time of the order of 100 ms. These instabilities were cured by careful adjustment of the horizontal transverse feedback and of the working point.

Injection oscillations were minimized down to less than 1 mm peak to peak. The longitudinal bunch dimensions are shown in Fig. 3.

The bunched beam was kept at 1 GeV for 1.2 s and then dumped onto an internal target.

	Final Scheme for LHC	Machine Study Sessions
Preinjector	RFQ 750 keV 200 mA	Cockcroft-Walton 750 keV 200 mA
Linac (50 MeV)	180 mA, $\epsilon^*_{x,y} = 1.2\ \mu m$[1]	165 mA, $\epsilon^*_{x,y} = 1.5 \mu m$
PS Booster	4 rings, h=1 bunch flattening by h=2 $1.8\,10^{12}$ p/ring $7.2\,10^{12}$ p/pulse 1.4 GeV $\epsilon^*_{x,y} = 2.5\ \mu m$ bunch length 190 ns	1 ring, h=5 bunch flattening by h=10 $1.8\,10^{12}$ p/ring 1 GeV $\epsilon^*_{x,y} = 2 \ldots 3\ \mu m$ measured bunch length 5 × 53 ns
CPS	flat bottom 1.4 GeV length 1.2 sec 2 PSB pulses @ 4 rings $1.44\,10^{13}$ p/CPS pulse acceleration on h=8 $\epsilon^*_{x,y} = 3\ \mu m$	flat bottom 1 GeV length 1.2 sec 1 PSB pulse @ 1 ring $1.8\,10^{12}$ p/CPS pulse 5 bunches on flat bottom $\epsilon^*_{x,y} = 2 \ldots 3\ \mu m$ measured

Table 1: Comparison of Machine Development beam with final LHC scheme

[1] r.m.s. normalized emittance.

3 Measurements and results

Four different measurement devices were used to measure the transverse beam emittances in each plane:

1. Beamscope [3], in the PSB ring, triggered a few ms before transfer to the CPS,

2. Three SEM-Grids [4] in the PSB measurement line,

3. Three SEM-Grids in the CPS ring, triggered at injection in the CPS,

4. A Wire scanner [5] in the CPS ring, triggered at various instants along the 1 GeV flat bottom.

The transverse r.m.s. normalized emittances are defined as

$$\epsilon^*_{x,y} = \beta\gamma \frac{\sigma^2_{\beta_{x,y}}}{\beta_{x,y}} \tag{1}$$

where β, γ are the usual relativistic parameters, $\sigma_{\beta_{x,y}}$ is the r.m.s. betatron amplitude and $\beta_{x,y}$ is the Twiss amplitude parameter in the measurement plane.

In the presence of momentum spread the horizontal beam size results from a convolution of the betatron distribution with the momentum distribution in the real space. Hence, assuming that the horizontal betatron beam size and the momentum deviation are uncorrelated random variables, the horizontal r.m.s. beam size writes

$$\sigma_x = \sqrt{\sigma^2_{\beta_x} + D^2_x\,\sigma^2_\Delta} \tag{2}$$

since the variance of the sum of two arbitrary uncorrelated random variables is equal to the sum of their variances. Here, σ_Δ is the r.m.s. momentum spread, and D_x is the dispersion function.

Samples of beam profiles and emittances measured by all 4 devices are presented in Fig. 4 to 7. All emittance measurements (normalized, at 1σ, and corrected for momentum spread) are plotted in Fig. 8 for comparison.

4 Conclusions and outlook

1. A beam of lower intensity but of comparable tune spread and similar transverse emittance as expected for LHC has been produced, measured and kept at 1 GeV in the CPS.

2. The apparent transverse blow-up between PSB and CPS is to be partially attributed to systematic divergence between the various devices.

3. No significant transverse blow-up is observed along the CPS flat-bottom at 1 GeV.

4. Recent improvements on beam diagnostics hardware and software, in particular on Beamscope and the SEM-Grids have been fruitful and improved consistency is found between measurements with the 4 different devices.

Other Machine Development sessions will allow further improvements of consistency between measurements and comparison to measurements with flip targets.

Dispersion matching between PSB and CPS can still be optimized. Moreover, flattening the bunches in the PSB before transferring them to the CPS could further reduce space charge effects there.

Acknowledgments

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References

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[2] R. Cappi et al., "The CERN PS complex as part of the LHC injector chain", CERN/PS 91–07 (PA), LHC Note 144, April 1991.

[3] H. Schönauer, "BEAMSCOPE - a novel device for measuring emittances and betatron amplitude distributions", IEEE Trans. Nucl. Sci., Vol. NS-26, 3294 (1979).

[4] M. Arruat et al., "New controls for the CERN-PS hadron injection process using operating tools and high-level accelerator modelling programmes", in International Conference on Accelerator and Large Experimental Physics Control Systems, Tsukuba, Japan, November 1991.

[5] Ch. Steinbach, M. van Rooij, "A scanning wire beam profile monitor", Proc. 1985 IEEE Particle Accelerator Conference, Vancouver, B.C., Canada, May 1985.

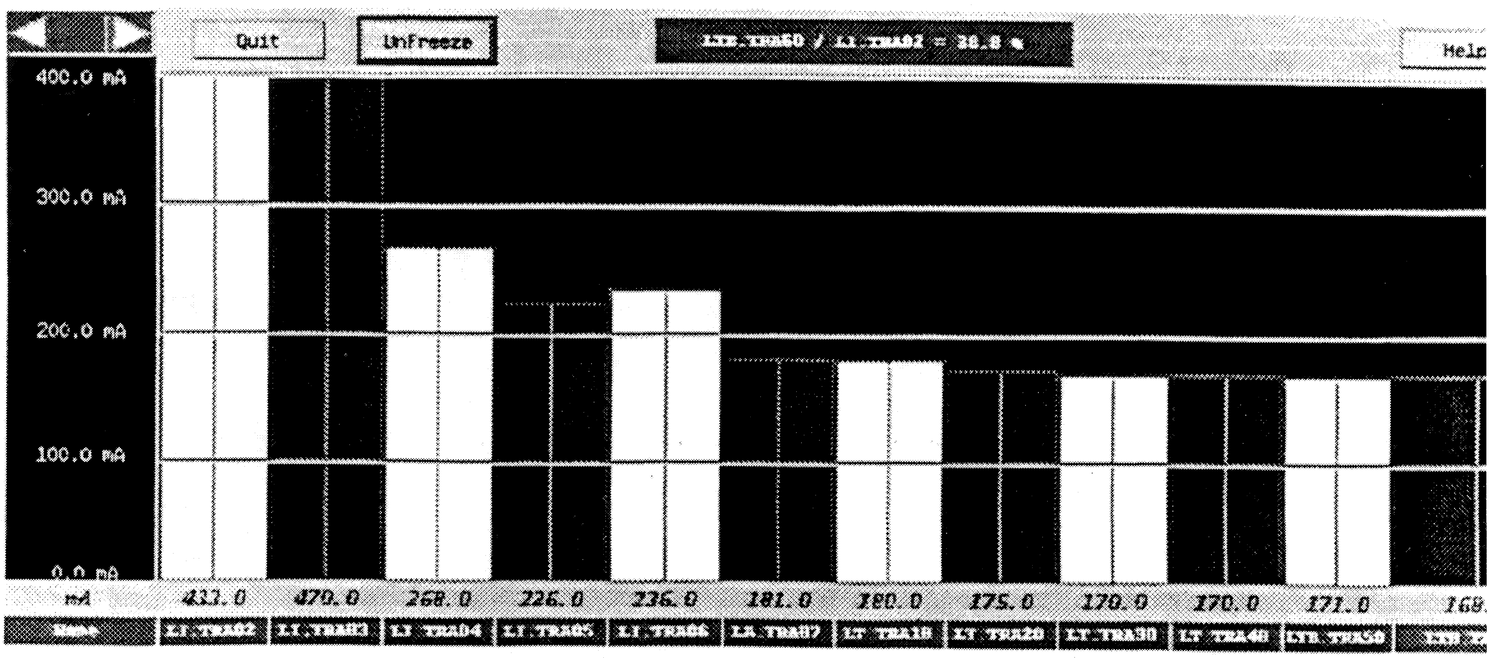


Fig. 1 Beam intensities from the source to the 50 MeV Linac output

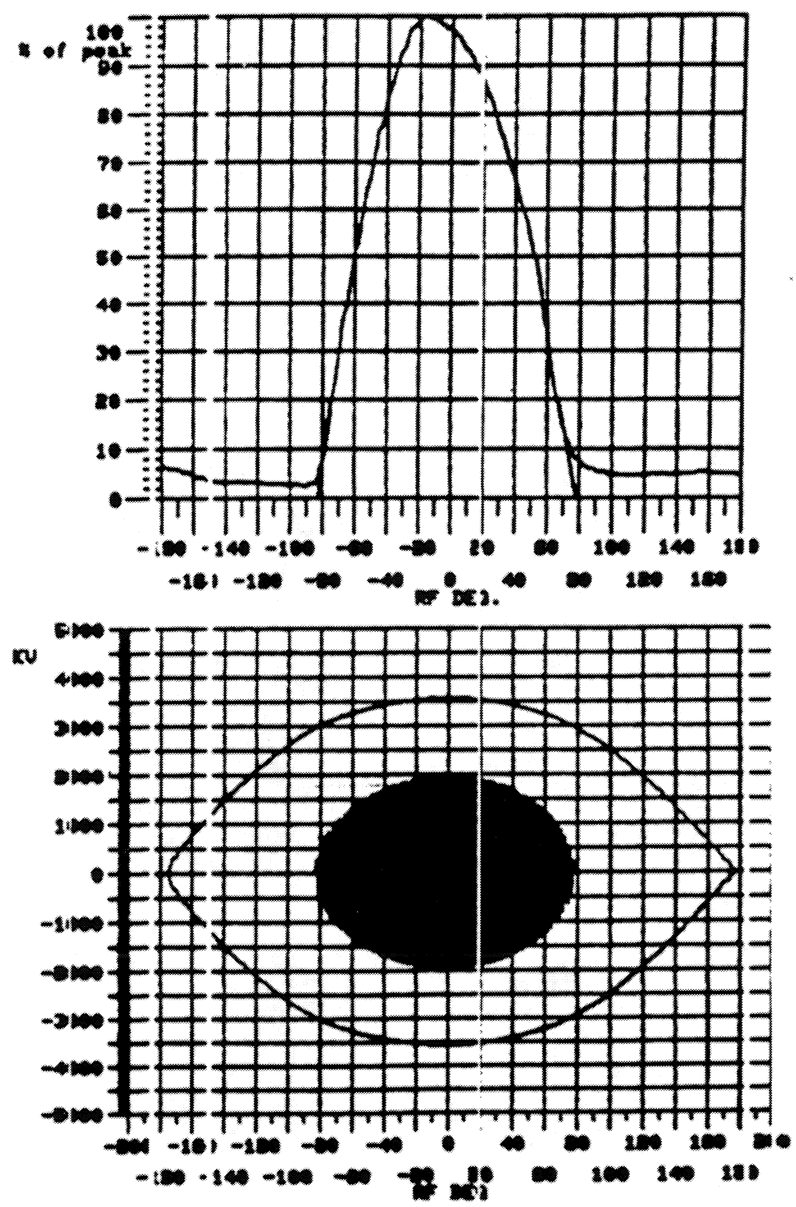


Fig. 2 Longitudinal bunch and bucket dimensions at 1 GeV in the PSB

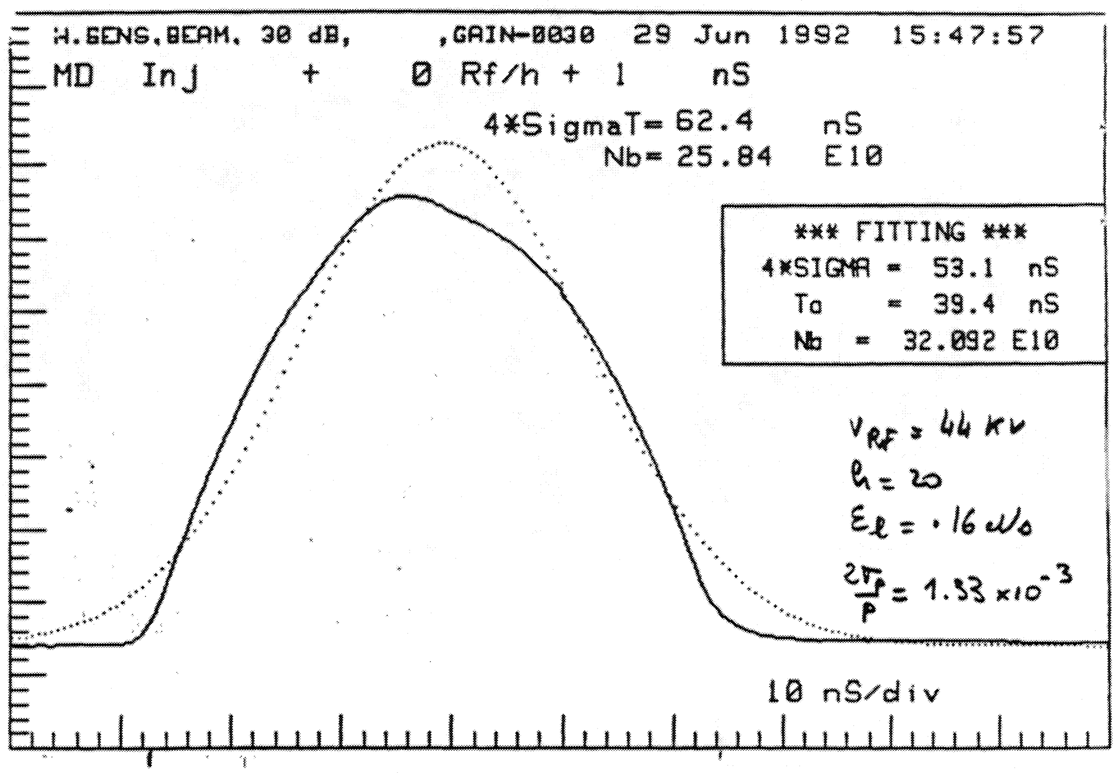


Fig. 3 Longitudinal bunch shape at injection
(1st turn) in the CPS.
The dotted line is the Gaussian fitting

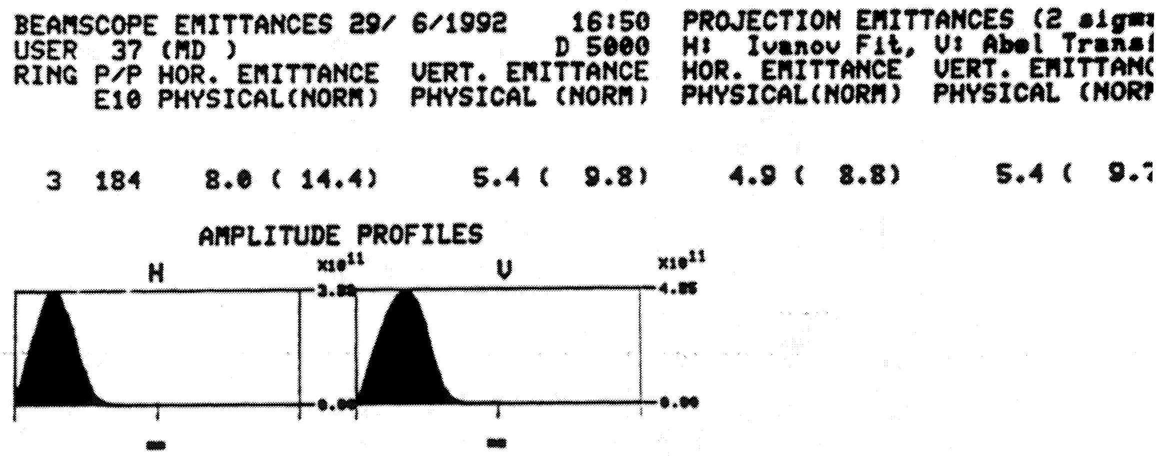
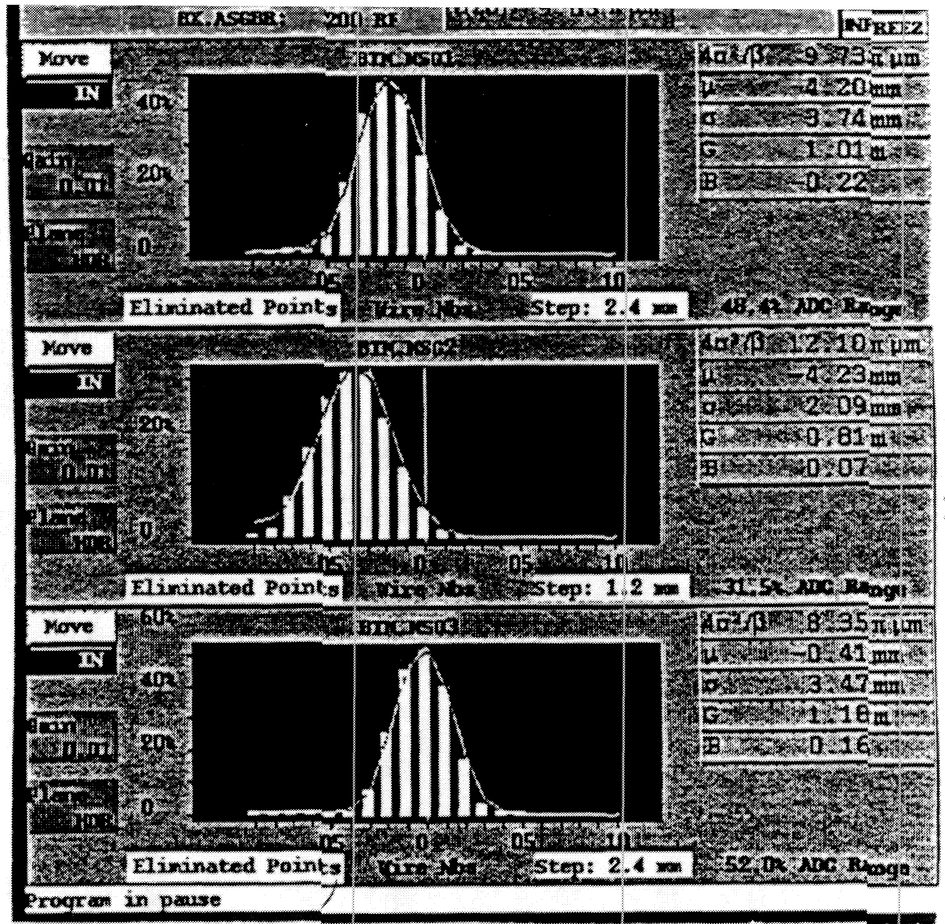
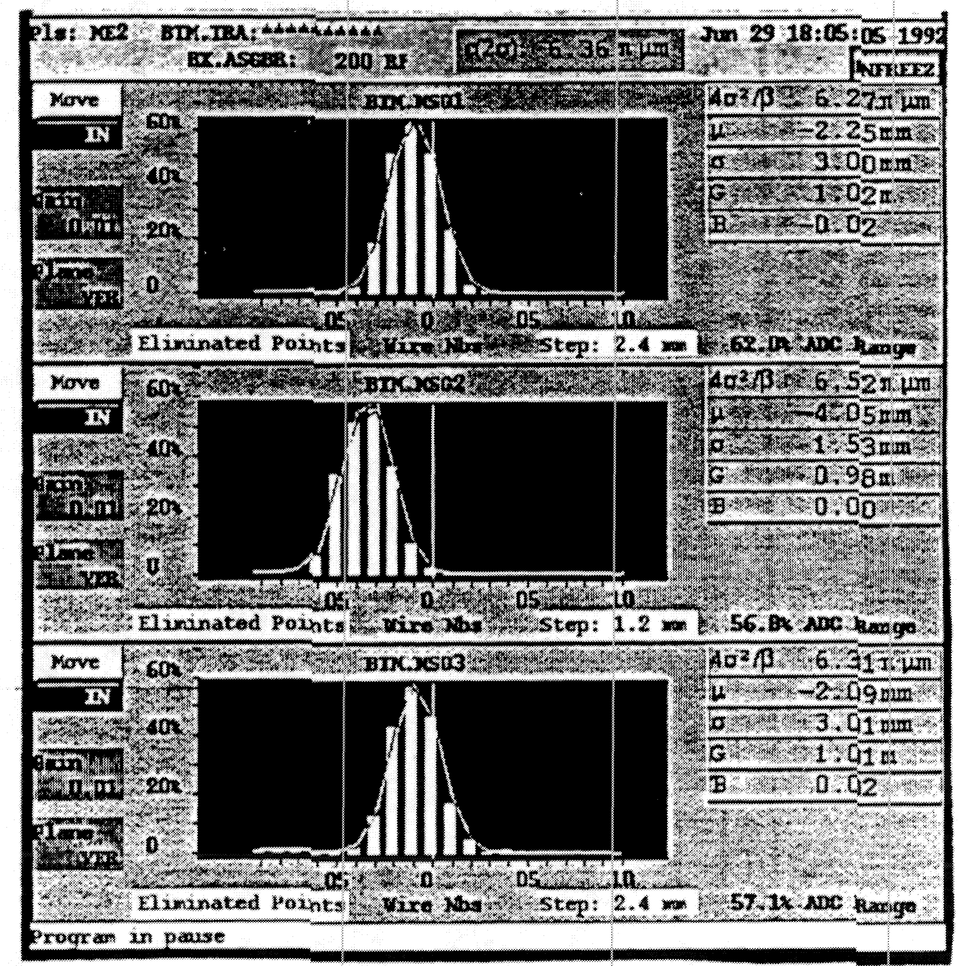


Fig. 4 Amplitude profiles of the beam in the PSB,
at 1 GeV, measured by Beamscope



Horizontal



Vertical

Fig. 5 Transverse beam profiles measured at 1 GeV on the SEM-Grids of the PSB/CPS transfer line

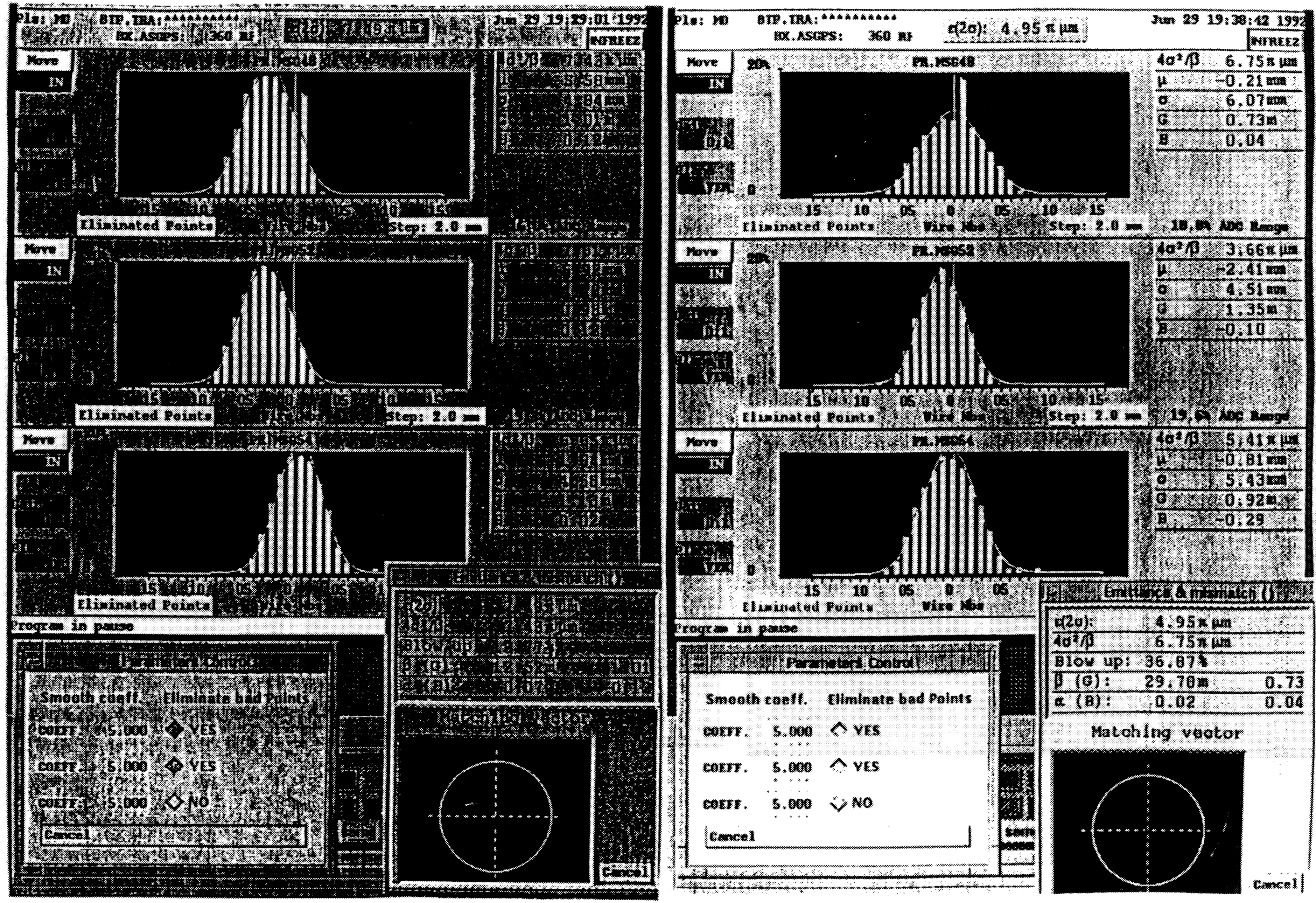


Fig. 6 Transverse beam profiles measured at 1 GeV on the CPS SEM-Grids.