Emittance Measurement in the Proton Accelerators at DESY

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1. INTRODUCTION

The accelerator complex at DESY consists of a number of linear and circular accelerators for acceleration and storage of electrons, positrons and protons. Most of the accelerators are used for the injection scheme of the proton-electron/positron collider HERA. The layout of HERA with its preaccelerators is shown in Fig. 1.

The protons are injected into the proton synchrotron DESY III with a momentum of 310 MeV/c. They are bunched and accelerated to 7.5 GeV/c within 2 s. 8 fills of DESY III can be accumulated in PETRA II, resulting in 70 Bunches and a design current of 150 mA. They are accelerated up to 40 GeV/c within 2.5 minutes and injected into HERAp. HERAp can accumulate 200 bunches. The acceleration to 820 GeV/c takes about 30 minutes where the lifetime of the proton beam is a few hundred hours.

The electrons/positrons are injected with an energy of 450 MeV from the LINAC II and the intensity accumulator PIA into the electron synchrotron DESY II. They leave the synchrotron with an energy of 7 GeV into PETRAII which accelerates them up to 12 GeV. After injection into HERAe the electrons are accelerated up to 30 GeV and stored for a few hours. The counterrotating electron and proton beams collide head on in three interaction points.

To achieve a high luminosity in the HERA ep collider, it is necessary to control the emittance of the proton beam through the entire chain of preaccelerators while the electron beam has its natural emittance. This talk concentrates on the transverse emittance of the proton beam through the chain of proton accelerators DESY III, PETRA II and HERAp. The performance of the profile monitors used in the accelerators is discussed and the different types are compared. Also results of the emittance behavior in the accelerators are presented.

1.1. *Emittance*

A number of different definitions of emittance can be found in the literature. We define the normalized 2σ-emittance ε_n in the following way:

$$e_n = \frac{(2s_{x,z})^2 - \left(D_{x,z}\frac{\Delta p}{p}\right)^2}{b_{x,z}} \cdot bg \qquad [p\ m\ rad],$$

where: D = Dispersion[1], p = momentum, β = beta-function, βγ = relativistic parameters, x,z = transverse directions. σ is the measured beam width. In the following, ‘emittance’ refers to this definition.

The beam width σ is calculated by measuring the full width at half maximum (FWHM) and σ=FWHM/2.355; σ is not determined from a fit of a gaussian to the data. This method ensures that the part of the beam which is important for luminosity determination (collisions with the electron beam) is included. If the beam is gaussian, which is the normal condition, 86.5% of the beam particles are included in ±2σ (true only for 2 dimensional gaussian).

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[1] see also Ref. 1. The author agrees with a quadratic addition of the dispersion term.

2. DESY III

Detailed information about DESY III can be found in Ref.2. DESY III is a proton accelerator with a circumference of 316 m and a cycle time of about 4 s. Protons with a momentum of 310 GeV/c, a current of more than about 15 mA in 50 μs and a normalized emittance of 8 π mm mrad (2σ-emittance) in both directions is accumulated using multi-turn charge exchange injection from the Linac III. The circulating DC beam is formed into 11 bunches by adiabatic capture. The bunches are accelerated to 7.5 GeV/c, extracted in a single turn and transferred to PETRA. Gamma transition crossing is avoided because $\gamma_t = 9.5$ is well above γ_{max}. The first protons were accelerated in the beginning of 1989. The design intensity of $1.02 \cdot 10^{11}$ protons per bunch (160 mA at 7.5 GeV/c) is routinely reached.

Two types of profile monitors are used in DESY III: wire scanners and residual gas ionization profile monitors. Both devices were constructed (1988) in view of their later applications in the PETRA and HERAp storage rings. Therefore a fast readout was not foreseen, and a few hundred turns are needed to measure a beam profile.

2.1. *Wire scanner*

Wire scanners for measuring beam profiles have been used for many years around the world. They are very precise devices and resolutions of a few microns have been achieved (Ref. 3). The scanner used at DESY III is a mechanically simple device which moves the wire linearly through the beam (Ref. 4). The motion is made by compressed air, therefore no special start and stop (hard- or software control) is necessary which avoids accidents. The compressed air cylinder starts and stops the wire smoothly and a maximum speed of more than 1 m/s is possible. In our case it is not necessary to manipulate the speed. A carbon filament with a diameter of 8 microns is stretched with 12 g over a 7 cm wide ceramic fork. The profile measurement is performed by detection of scattered particles by using a scintillation counter with photomultiplier readout. The signal is integrated over all bunches in the machine which can be from 1 to 11. The resolution of the profile measurement is limited by the uncertainty ($\sigma = 59$ microns) in the position of the carbon filament which is measured with a linear potentiometer. Fig. 2 shows the signals during a scan. The signals from the photomultiplier and from the potentiometer are sampled at the same moment by an analog to digital card added into a PC. The beam profile is derived from the signal versus the (fitted) position. The profile is displayed in the control-room, together with the calculated beam FWHM, σ and emittance ε_n. Only a single horizontal scanner in DESY III is installed because of the limited space for diagnostic instrumentation.

We expect an emittance blow-up of 0.01%/scan at 7.5 GeV/c and a beam loss of less than 0.1%/scan. No effect has been measured. At 160 mA beam current, the maximum temperature of the wire is estimated to be 4400 °C without taking into account the loss of about 70% of energy through secondary particles. No wires have been broken or burned since 1988.

2.2. *Residual gas ionization profile monitor (IPM)*

In contrast to the wire scanner, the IPM is designed for continuous beam observation. Fig. 3 shows a cross sectional schematic of the monitor (Ref. 5, 6).

The electrons and ions created by the proton beam are accelerated towards a grid by an extraction voltage applied at the grids. Depending on the polarity of the voltages, one can accelerate (1) electrons, (2) ions or (3) secondary electrons created by the impact of the ions on the cathode towards the phosphor screen. The third method is the most reliable and most sensitive (Ref. 7). The path of the low energy ionization electrons are much more strongly affected by the space charge of the bunch than the heavier ions. A direct measurement of the ions is not possible because a thin (100 Å) aluminum layer covers the phosphor screen in order to provide a homogeneous field between the grid and the screen.

A video camera readout of the phosphor screen offers a number of advantages:

- Continuous view of the beam via TV-screen
- Simple and standard signal transfer
- No additional vacuum feedthrough
- Adequate resolution
- Image acquisition by standard frame grabbers

With standard video the refresh rate of a picture is 25 Mhz which is adequate for accelerators with a cycle time of more than a few seconds. To improve the trigger rate and precision fast shutter image intensifier cameras can be used. Tests of such cameras are planned at DESY III for the near future. CCD cameras are not radiation resistant; two CCD cameras have failed after 2 weeks of operation while the SIT tube cameras have been in operation since 1988 without problems.

The sensitivity of the IPM has been calculated (Ref. 7) and found to be in good agreement with the measurements. The sensitive SIT cameras give reliable signals at beam currents from 7 - 200 mA with a vacuum pressure of 10^{-8} mbar. At these low light levels, the phosphor screen and the video cameras have been shown to be linear (Ref. 7).

2.3. *Measurements and Comparison*

The profile monitors in DESY III are located at positions with similar optical parameters. Therefore the beam profiles measured with the wire scanner and the IPM can be easily compared. Unfortunately there is no vertical wire scanner, so that the comparison is restricted to the measurements in the horizontal plane. In the first measurements we found that the profile measurements with the IPM was larger by a constant amount than that from the wire scanner (Ref. 8). The cause was found to be the angular distribution of the secondary electrons emitted from the cathode. With this effect taken into account, the agreement of the measurements is very good (Fig. 4). No space charge distortions have been observed for currents of up to 200 mA because of the relatively long bunches (DC to 3 m).

The beam width increases with increasing beam current as result of space charge forces; this effect is seen in the measurements in Fig. 4. The emittance behavior during the acceleration cycle for a medium current in DESY III is plotted in Fig. 5. In the horizontal plane one observes an emittance blow-up during the beginning of the acceleration. The following decrease might be a result of vertical beam scraping (losses) and some small beam coupling. This coupling may also be the reason for the opposite emittance behavior between the horizontal and vertical planes during acceleration. A detailed analysis of the coupling has not yet been done. Note that the horizontal dispersion term contributes about 50% to the measured beam width, especially at top energy. The uncertainty in the emittance at high currents is very large because of the large dispersion and the unknown momentum spread, and in addition because of a longitudinal phase instability. The instability is damped using a feedback system at flat top (Ref. 9).

3. **PETRA II**

PETRA was a electron/positron storage ring with a circumference of 2.3 km, which has been redesigned to be used as an electron/positron and proton booster for HERA. Up to 70 proton bunches can be accelerated to 40 GeV/c within about 2.5 minutes. The design maximum current is about 150 mA. The protons bypass the high impedance electron RF cavities in an extra beam line. The profile monitors are located in this bypass to avoid causing higher order mode losses of the electron beam. Unfortunately the dispersion in the horizontal plane reaches nearly 7 m so that a reliable emittance calculation needs a precise value for the momentum spread. For the profile measurement we have installed two IPM, one for each plane. It is foreseen in the near future to install two additional wire scanners and a prototype profile monitor utilising beam induced gas scintillation (Ref. 10).

3.1. *Residual gas ionization profile monitor*

We improved the IPM of the DESY III type by adding a micro channel plate (MCP)[2] in front of the phosphor screen (Ref. 8). This has three advantages: first; the ions are accelerated directly to the MCP where they are converted into electrons with a gain of up to 10^4/ion. This eliminates the uncertain path of the secondary electrons from the cathode. Second; we can match different current conditions (from 1 - 60 bunches) by adjusting the gain of the MCP and third; a simple and much cheaper Newvicon video camera can be used which has a better resolution and is less noisy.

The aging of the MCP could have a big influence on the measured beam width (Ref.12). We have measured the influence by moving the beam to an unused part of the MCP. Up to now, no effect has been detected. Otherwise we have to exchange the MCP.

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[2] Reference about MCP see e.g. Ref. 11.

The bunch length in PETRA II is shorter than 3 m therefore the space charge of the bunches is larger than in DESY III. The collection of ions is distorted by the space charge forces. The increase of the measured beam width due to space charge forces is a single bunch effect, and the correction can be described by the following formula (Ref. 13):

$$FWHM_{meas,x} = \sqrt{2\ln 2} \cdot \sqrt{s_{beam,x}^{2} + a\,\frac{I \cdot U_a \cdot r_p \cdot d_g}{e \cdot N_b \cdot c} \cdot \sqrt{\frac{2 m_p c^2}{e \cdot V_g}} \cdot \sqrt{\frac{b_x}{b_z}}}$$

where: $\mathrm{FWHM}_{meas,x}$: measured full width at half maximum (in x direction), σ^2_{beam}: actual beam width, I: beam current, U_a: circumference of the accelerator, r_p: classical proton radius, d_g: space between the grids, e: elementary charge, N_b: number of bunches, c: velocity of light, m_p: proton mass (for H_2 ions), V_g: voltage between the grids, β_x: value of the beta function at the monitor (direction of measurement), β_z: value of the beta function (perp. to direct. of meas.).

α is a fit parameter = 1.96. The second summand is the correction σ_{corr}. The good agreement between the formula and simulated data (by ion tracking in the presence of a short bunch) can be seen in Fig. 6.

The resolution of the IPM is determined mainly by the space charge distortion, but also by the following effects (Ref. 12):

Thermal velocity of the ions: $\sigma_t = 0.29$ mm ,

Resolution of the camera: σ_c = 70 - 200 microns, depending on the camera,

Effects such as optic, calibration, ionization kick, MCP and Phosphor screen can be neglected.

The width of the beam is then given by:

$$\sigma^2_{beam} = \sigma^2_{meas} - \sigma^2_{corr} - \sigma^2_{t} - \sigma^2_{c}$$

3.2. ***Measurements***

There are currently no wire scanners installed in PETRA II, therefore the correction of the beam width measurement using the IPM are checked using the following method: At top energy (40 GeV/c) the beam width is measured before and after debunching the beam (i.e. coasting beam) by switching off the RF. This has no effect on the actual beam width, therefore both measurements should be equal after including the correction for the bunched beam. This is shown in the following table:

beam		bunched		coasting
	I/N_b [μA]	σ_{meas} [mm] ±0.1	σ_{beam} [mm] ±0.1	$\sigma_{coasting}$ [mm] ±0.1
horizontal	510	2.27	**1.98**	**2.08**
vertical	510	1.62	**1.34**	**1.34**

Within the errors (due to readout by oscilloscope) the agreement is very good.

The emittance behavior and the beam profiles are displayed in the control room (Fig. 7). The normalized vertical emittance is constant during the acceleration cycle while the horizontal emittance grows with a constant slope between 30 and 40 GeV/c. This effect is probably a result of an increase of the momentum spread, but no detailed measurements of this are available. In the beginning of the acceleration the emittance decreases a little simultaneously with small beam losses. This might be a result of loss of untrapped beam particles. The same behavior is observed with higher currents, but the initial emittance of the beam coming from DESY III is larger (see Chap. 2).

4. **HERAp**

On May 31, 1992, protons and electrons were first collided at energies of 820 GeV and 26.6 GeV, respectively, and HERA began delivering luminosity to the experiments Zeus and H1. In 1994 an average proton current of about 40 mA in 170 bunches were stored with a lifetime exceeding more than a few hundred hours. The proton beam can survive a few refillings of HERAe because of this long lifetime. Hera[3] consists of an superconducting proton ring and a conventional electron ring with a circumference of 6335 m. In total, about 1000 superconducting coils are needed to bend and focus the proton beam in the four arcs of HERA. Three of the four straight sections were designed to incorporate high energy physics experiments while the fourth (Hall West) was designed for injection, acceleration, dumping and diagnostics of the proton beam. Two wire scanners and two IPM for the horizontal and vertical planes are installed in this region. Both systems do not provide a very fast profile measurement. The wire scanner crosses the beam in about 1 ms, and the integration time of the IPM is 20 ms. A synchrotron radiation profile monitor based on the edge effect (Ref. 6) will be set in operation in 1995 which will provide a single pass profile measurement.

4.1. *Wire scanner*

The wire scanners in HERA are of the same type and have the same parameters as those used in DESY III (see chap. 2.1). They are used for precise emittance and beam shape measurements as well as for predictions of the specific luminosity. Fig. 8 shows the good agreement between the predicted specific luminosity and that determined by the experiments. Routineously the emittance of the proton beam is measured after injection of the beam and before refilling the electron beam, and if the expected luminosity is too small the beam is dumped.

The wire scanners were installed in 1990. Since this time no wires have been broken or burned, and there has been no detectable beam losses or emittance blow-up due to wire scans. An increased background rate is measured by the experiments during a scan.

A new gating system is now in operation. It allows profile measurements of single selected bunches. Detailed studies of bunch-to-bunch shape variations can be performed.

4.2. *Residual gas ionization profile monitor*

The vacuum pressure in HERA is about one order of magnitude lower than that in PETRA. The number of bunches is between 1 (for machine studies) and up to 200 for luminosity runs. Very low intensities can be observed when using a SIT-camera. The first circulating beam in HERA in 1991 was observed using the IPM; the beam current then was about 0.01 μA(!), the vacuum was about 10^{-8} mbar and the beam width was FWHM = 10 mm. A high dynamic range is achieved by adjusting the gain of the MCP. Beam currents of more than 50 mA in 170 bunches have been measured.

A continuous monitoring of the beam by the IPM is most helpful during machine manipulations. Fast changes of the emittance can be observed directly with this monitor. Fig. 9 shows an emittance blow-up of the proton beam due to the exitation caused by the electron feedback system as a result of the beam beam interaction.

4.3. *Measurements and Comparison*

Fig. 10 shows a comparison between measurements of the wire-scanner and the IPM in HERA. The agreement is very good at low bunch currents. The IPM underestimates the beam width a small amount ($\approx$150 μm) especially in the horizontal plane and at high currents. This is a result of the space charge correction; the vertical β-function at the location of the horizontal IPM is very small and therefore the correction is very large ($\approx$100%). At higher bunch currents and with smaller beams we expect that the uncertainty of the IPM becomes too large for reliable measurements of the emittance.

An example of the emittance behavior of the HERA proton beam is plotted in Fig. 11. Typically there is no emittance growth during acceleration, but ocassionally a transversal beam instability (probably a head tail instability) is observed, which can lead to an emittance blow-up. It can often be avoided by a large negative chromaticity.

During collision, we can observe an emittance groth of around 0.5 π mm mrad/h which is in very good agreement with calculations (Ref. 15). For small beams the emittance increase is dominated by intra-

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[3] A lot of detailed information about HERA can be found in Ref. 14.

beam scattering; for example, a growth of ≈0.48 π mm mrad / h is expected for ε_n = 16.4 π mm mrad at 820 GeV/c (Ref. 15).

For larger beams the beam beam interaction becomes dominant and the rate of emittance growth becomes larger (Ref. 16).

5. SUMMARY

Two profile measurement systems are used in the proton accelerators at DESY: wire-scanners and residual gas ionization profile monitors (IPMs). Both systems have been found to work very reliably. The measurements with the two techniques are in good agreement in all machines when the space charge distortions present in the IPM are taken into account.

Typical emittance behavior in the proton accelerators is summarised in the following table:

Transfer	Momentum [GeV/c]	horizontal ε_n(h) [π mm mrad]	vertical ε_n(v) [π mm mrad]	**Design e$_n$ (h,v) [p mm mrad]**
Linac - DESY III	0.3 - 0.3	8.0	8.0	**8.0**
DESY III	0.3 - 7.5	8 - 13	8 - 11	**8.0 - 9.6**
DESY III - PETRA II	7.5 - 7.5	13 - 18	11 - 15	**9.6 - 11.5**
PETRA II - PETRA II	7.4 - 40	18 - 30[a]	15 - 15	**11.5 - 13.9**
PETRA II - HERAp [c]	40 - 40	30[a] - 12	15 - 12	**13.9 - 16.9**
HERAp - HERAp accel. storage	40 - 820 820	12 - 12 (17[b]) 0.5 /h[d]	12 - 12 0.5 /h[d]	**16.9 - 20.0**

[a]: large error due to unknown momentum spread, [b]: with instability, [c]: about 20% beam losses, [d]: in-tra beam scattering

The vertical emittanceis close to the design assumptions, except for the small decrease due to particle losses in the transport from PETRA II to HERAp. The error in the momentum spread is probably the reason for the large implied horizontal emittance values in PETRA II; the relatively small losses in the transport from PETRA II to HERAp cannot explain the large decrease in the emittance. The emittance blow-up at 820 GeV/c in HERAp during luminosity run due to intra beam scattering is small enough to keep the beam for more than a day without significant luminosity reduction.

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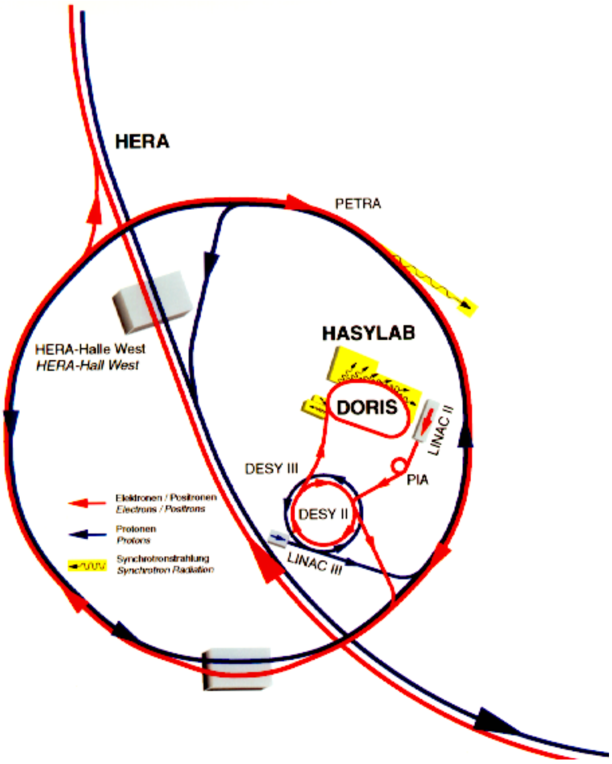


Fig. 1: Layout of HERA and the preaccelerators

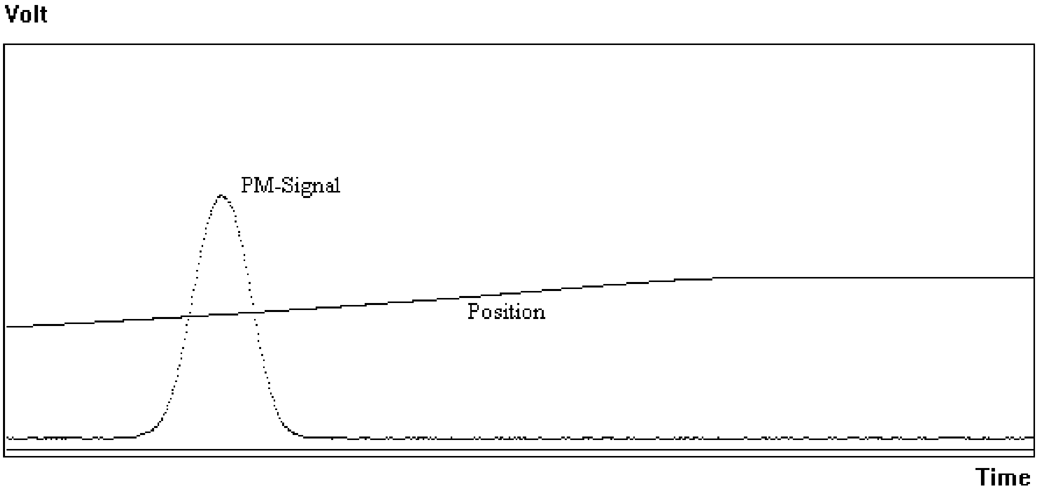


Fig. 2: Signals from the wire scanner

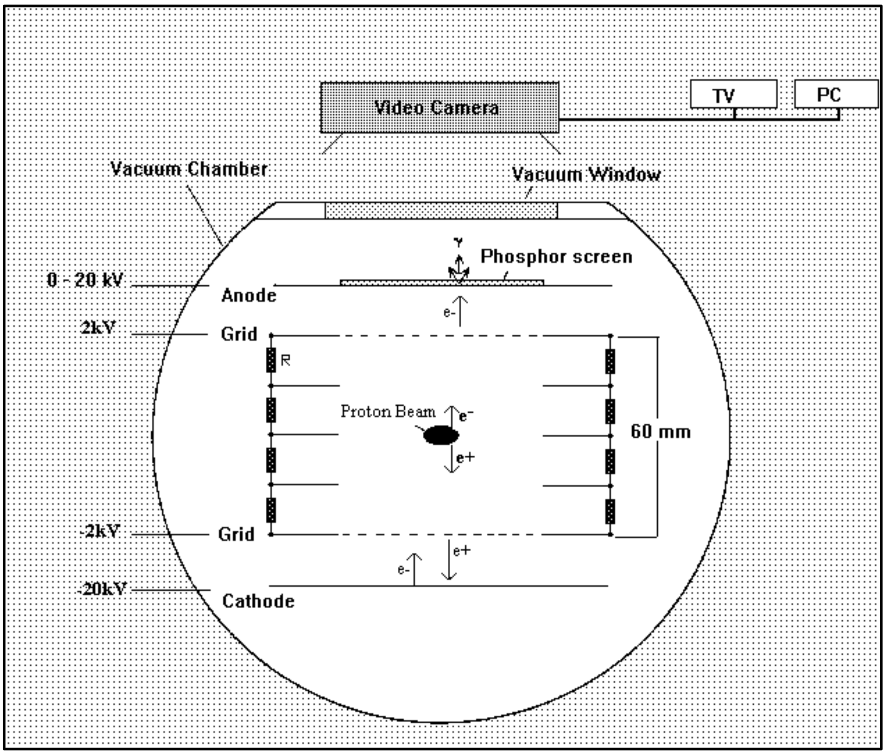


Fig. 3: Sketch of the IPM in DESY III

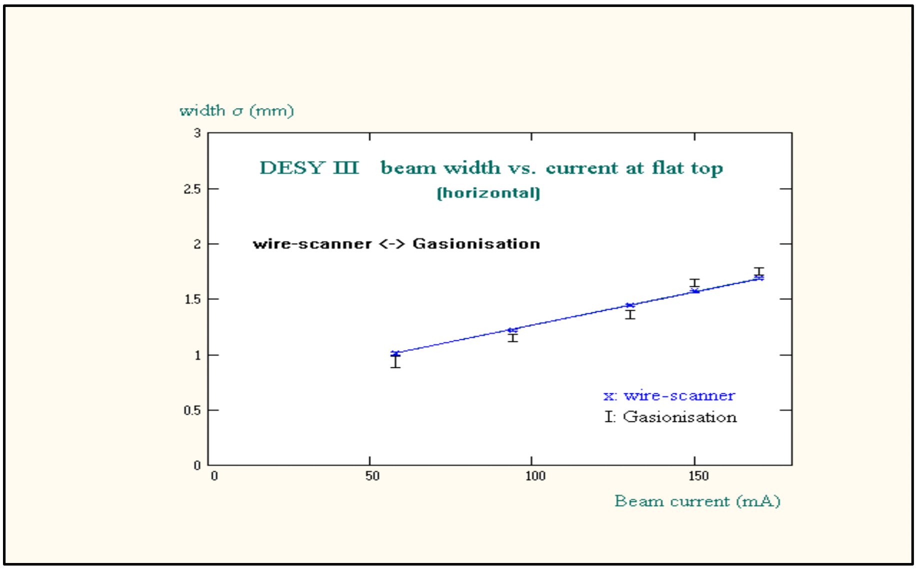


Fig. 4: Comparison of wire scanner and IPM measurements versus beam current in DESY III

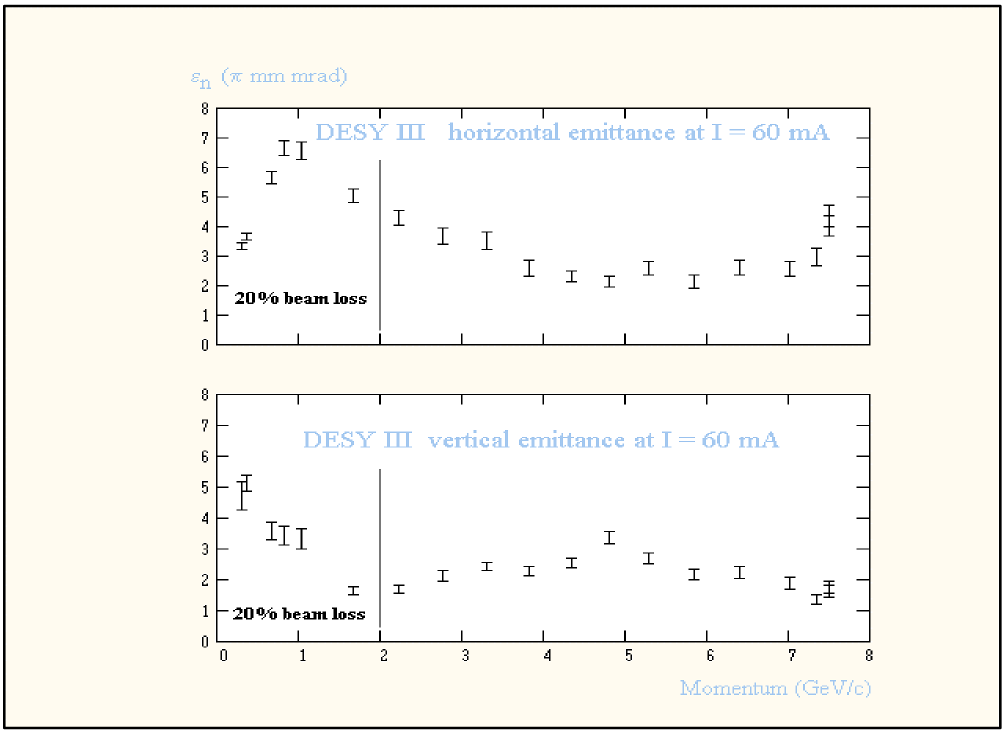


Fig. 5: Emittance behavior during acceleration in DESY III

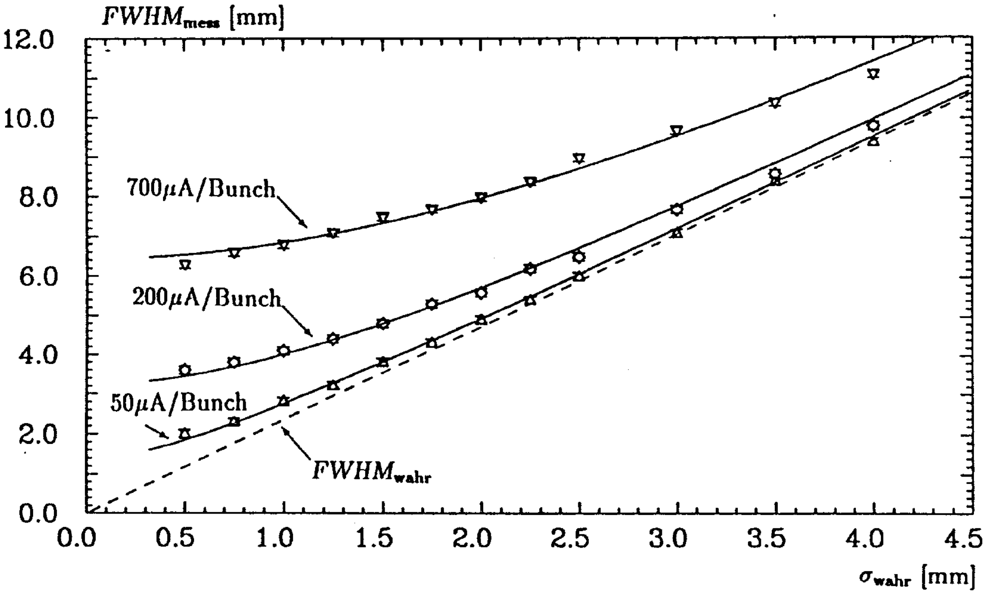
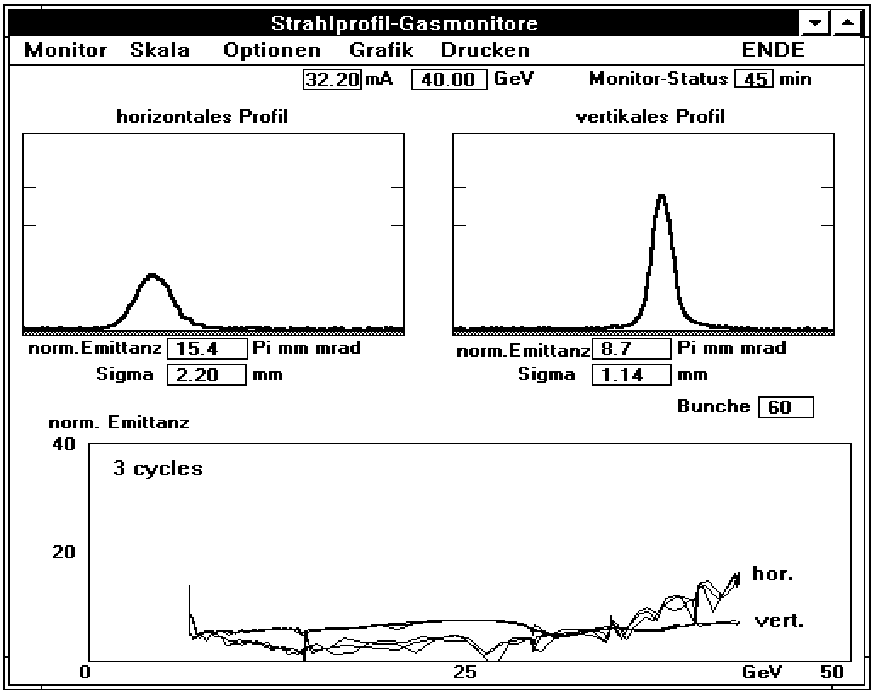


Fig. 6: Effect of space charge distortion in the IPM. Comparison between simulated data (ion tracking in the present oa a bunch crossing) and the formula (see text). The lines represent the results of the formula. From Ref. 12



32.20 mA 40.00 GeV Monitor-Status 45 min

horizontales Profil: norm.Emittanz 15.4 Pi mm mrad, Sigma 2.20 mm

vertikales Profil: norm.Emittanz 8.7 Pi mm mrad, Sigma 1.14 mm

Bunche 60

Fig. 7: Transverse beam dimensions in PETRA II at 40 GeV/c. The dips in the emittance lines are results of the transverse movement of the beam crossing a calibration mark on the phosphor screen.

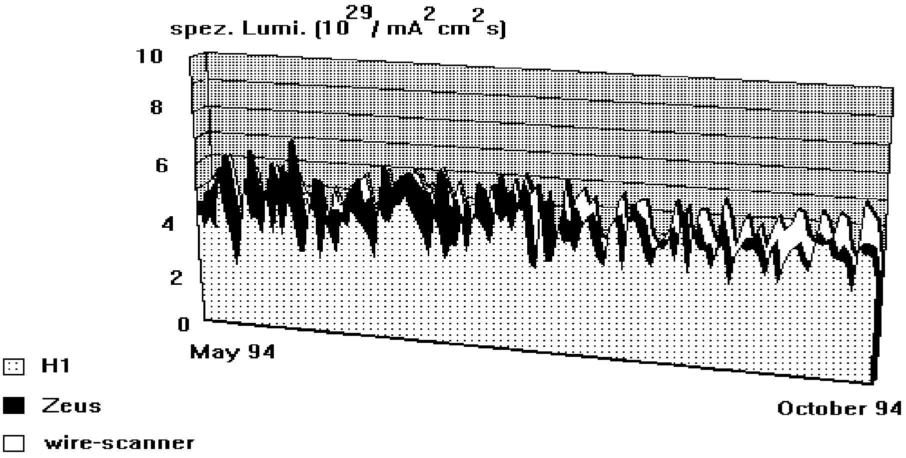
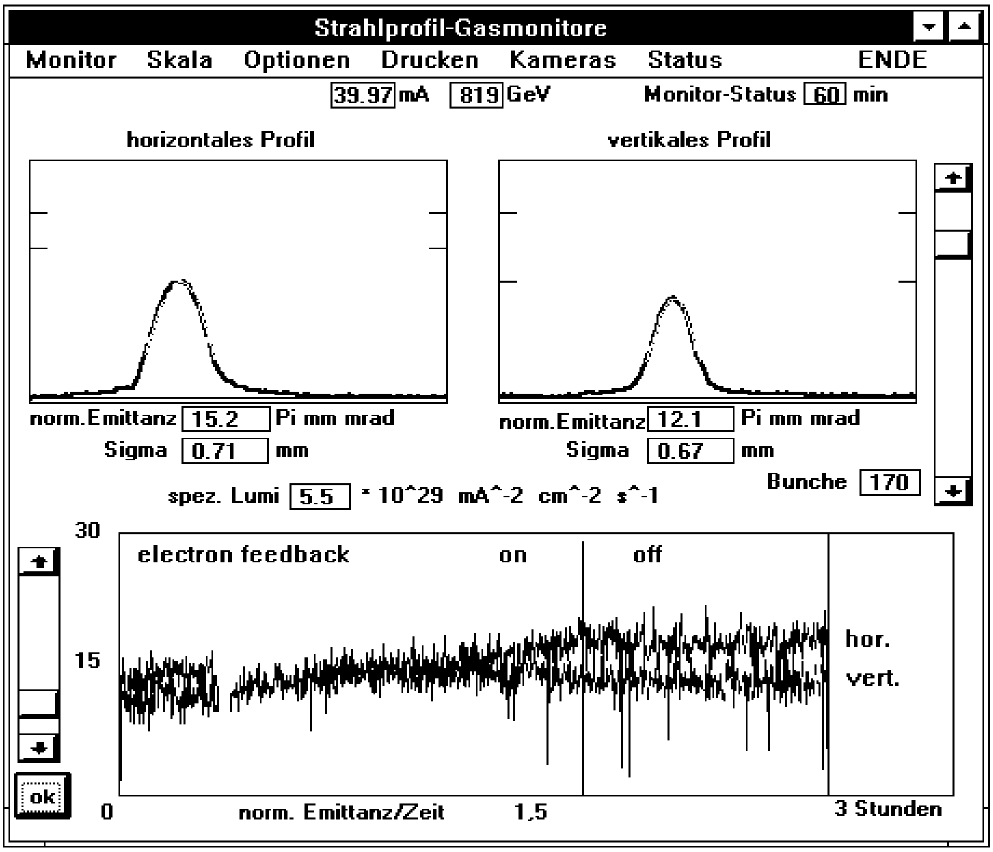


Fig. 8: Specific luminosity measured by the experiments H1 and Zeus and the based on wire scanner measurements and expected electron beam profiles



39.97 mA 819 GeV Monitor-Status 60 min

horizontales Profil: norm.Emittanz 15.2 Pi mm mrad, Sigma 0.71 mm

vertikales Profil: norm.Emittanz 12.1 Pi mm mrad, Sigma 0.67 mm

spez. Lumi 5.5 * 10^29 mA^-2 cm^-2 s^-1

Bunche 170

Fig.9: Emittance blow up seen by the IPM

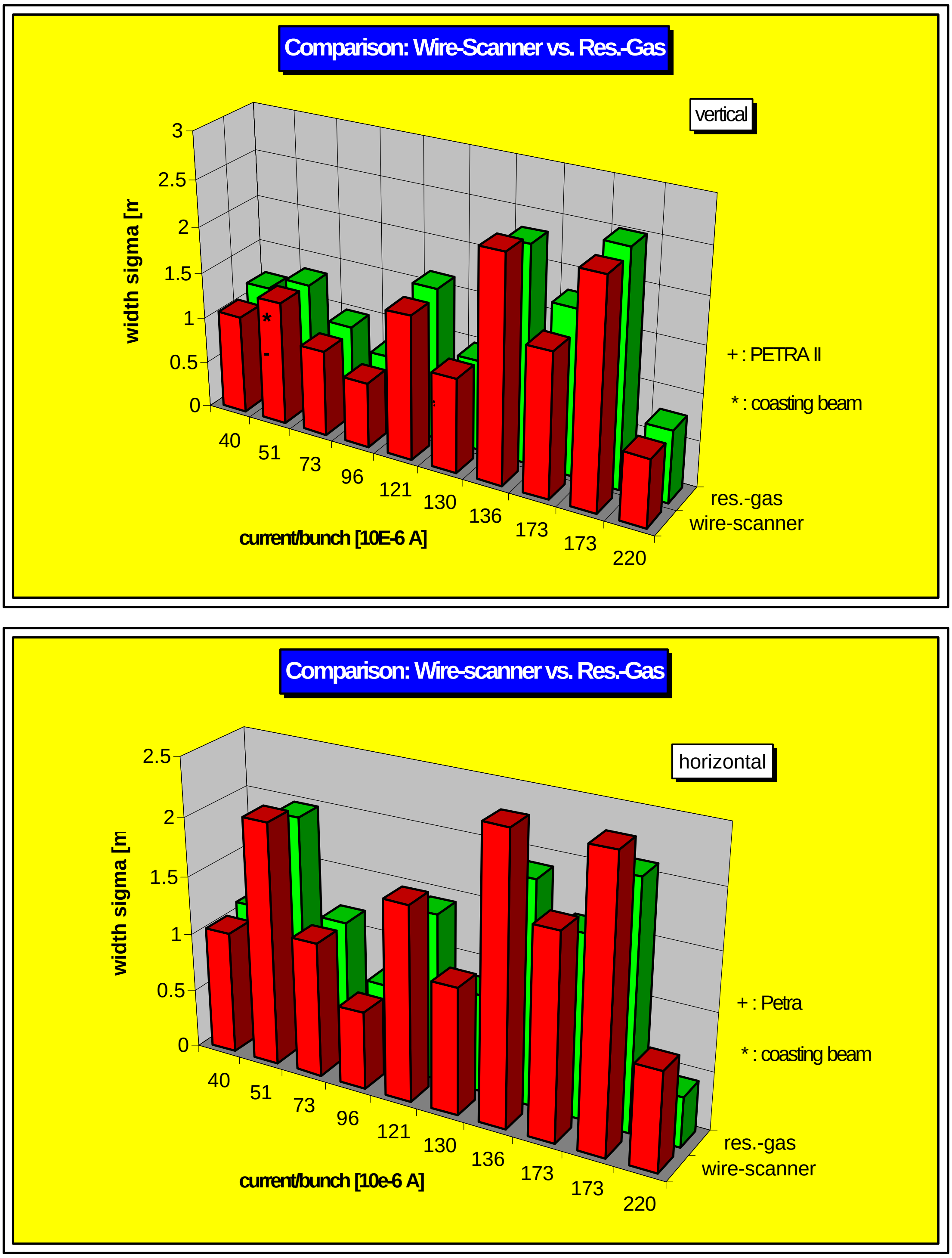


Fig. 10: Comparison between the wire scanner and the IPM

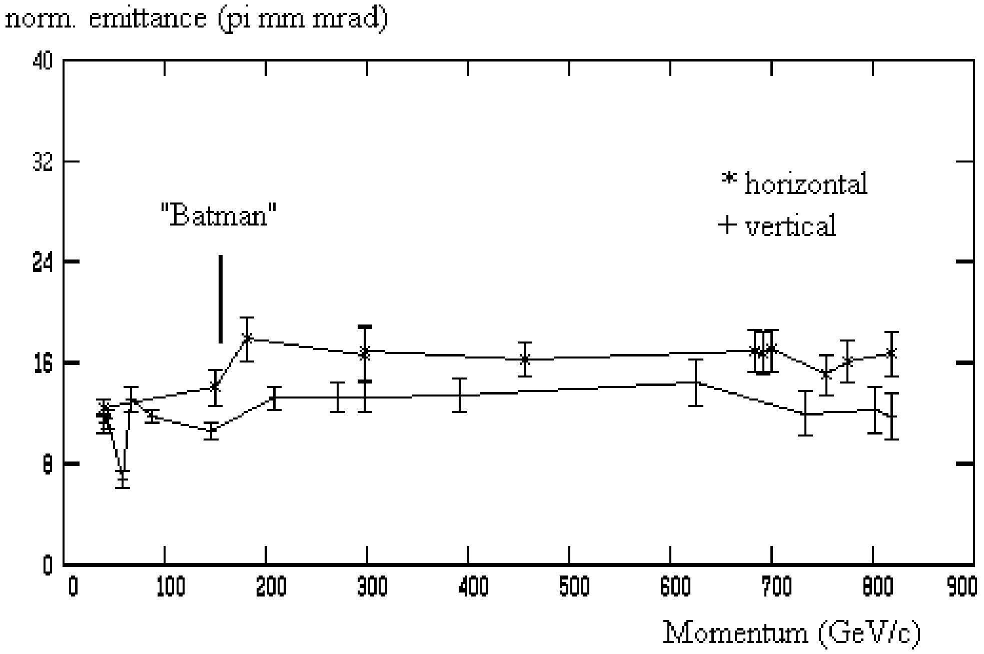


Fig. 11: Emittance behavior in HERAp during acceleration