EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/PS 92-10 (HI)

EXPERIENCE WITH THE BEAMSCOPE EMITTANCE MEASUREMENT SYSTEM AT THE CERN PS BOOSTER

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ABSTRACT

BEAMSCOPE (BEtatron Amplitude Scraping by Closed Orbit PErturbation) is a device developed more than a decade ago at the CERN Proton Synchrotron Booster (PSB). Its main use is for fast, automated emittance measurements at any moment in the acceleration cycle but it also allows the display of the distribution of betatron amplitudes, physical or normalized. Experience gained over the years and problems encountered are presented and results are related to other types of emittance measurement devices.

Paper presented at the Workshop on Advanced Beam Instrumentation
KEK, Tsukuba, Japan, 22-24 April 1991

Geneva, Switzerland
February 1992

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Abstract

BEAMSCOPE (BEtatron Amplitude Scraping by Closed Orbit PErturbation) is a device developed more than a decade ago at the CERN Proton Synchrotron Booster (PSB). Its main use is for fast, automated emittance measurements at any moment in the acceleration cycle but it also allows the display of the distribution of betatron amplitudes, physical or normalized. Experience gained over the years and problems encountered are presented and results are related to other types of emittance measurement devices.

1 Introduction

Since the beginning of operation of the PSB, the four-ring stacked injector synchrotron of the CERN Proton Synchrotron, knowledge of the emittances of each of its four beams has been important for the smooth operation of the PS. Moreover, accelerating protons from 50 MeV to 1 GeV, the PSB was at all times limited by space charge at low energy, with the concurrent risk of transverse blow-up at stopbands. In anticipation of these problems the PSB had been equipped from the outset with a set of Ionization Beam Scanners of crossed-field type (a profile detector using electrons from ionization of the residual gas), as well as flip measurement targets. The former failed to produce quantitative results whereas use of the targets turned out to be tedious for four rings in a pulse-to-pulse varying-beam environment. Consequently an automated measurement was proposed by P. Krempl who also proved its feasibility [1]. Presented at the 1979 PAC [2], it has been regularly used in operation since more than one decade without any upgrading. Over these years it has helped the understanding of the transverse behaviour of intense beams at low energy [3] and thereby to the PSB reaching almost four times the design intensity [4]. Having praised its successes, it is only fair to present the problems, as awareness of them may be instructive in the design of future emittance measurement systems. Most of the effects to be taken into account have been described in an internal report [5]. Those, together with some more recently discovered ones, are the main subject of this contribution.

2 Principle of operation and computer processing

2.1 Basic method

It is very likely that at almost every proton synchrotron (e.g. also at KEK) the BEAM-SCOPE method has been used at least occasionally to determine beam dimensions : Deflecting the circulating beam into a known aperture limitation with simultaneous recording of the beam current allows determination of the beam radius through computing the orbit amplitude at the collimator from the deflecting dipole fields. Undoubtedly one obtains a coarse result with little effort, but, as will be explained below, one should not expect too high accuracy. The basic layout is depicted in the "artists view" of Fig. 1. The typical appearance of the five digitized electronic signals is shown in Fig. 2. An important feature is the electronic differentiation of the beam current (I) transformer signal, yielding a raw representation of the betatron amplitude distribution. In the subsequent computer processing I and dI/dt are normalized, whereas the bump amplitude at the precision aperture is computed from the three dipole currents (Fig. 3). The beam radius, traditionally quoted at the CERN PS as containing 95% of the particles, is simply the difference of the bump amplitudes of the 95% crossing of the normalized beam current, and at the moment of reaching zero, i.e. the beam centre. The latter is more easily found by putting a tangent to the slope of the derivative (assuming constant phase space density in the vicinity of the origin). We call this procedure the "single-pulse" or "closed-orbit reconstruction (COR)" method. If beam radii, e.g. those containing 95% of the beam are the only parameters to be measured, the search for the beam centre can be avoided for stable beams by measuring twice on consecutive machine cycles with alternating excitation polarity of the bumpers. As can be read from Fig.4, obtaining the mean beam radius $\bar{x}$ from the two bump amplitudes $y_1(95)$ and $y_2(95)$ is trivial, without the need to know the closed orbit nor the beam centre. In fact the bumpers may be stopped after the 95% level has been crossed, limiting the beam loss to about 10%. This so-called "double-pulse method" is the one used in operation. On the other hand, recording the beam centre for both bump polarities provides an excellent tool for autocalibration: From Fig.4 one notes that the sum of the bump amplitudes for complete loss should be the full aperture $2a$. Any deviation of the "computed aperture" from the true one can be used to correct the computation.

2.2 Straightforward items taken into account

These enter into the calculations of the bump amplitude; the physics is simple but this does not necessarily imply little computational effort:

1. Evaluation of the lattice functions for the given tunes : the lattice program BOOM, developed for the PSB during its design, is resident in the NORD-100 measurement computer and runs automatically prior to each measurement.

2. The magnetization curves $\int Bdl$ vs. I of all 32 dipoles (four rings - two planes - three stacks) involved, have been measured and are stored in polynomial approximation in the code.

3. The effect of eddy currents $B_{eff}(t) = B(t) - \dot{B}T_{eddy} \cong B(t - T_{eddy})$ is included by shifting the computed bump numerically backwards by T_{eddy}. The latter is easily computed for the circular vacuum pipes, but has also been measured together with the magnetization curves and found to be $\simeq 130\mu s$.

4. Calibration of the electronic chain for all computer-controlled sensitivities is done periodically and stored coefficients are updated, if necessary.

2.3 Less straightforward items and conceivable error sources

In this category one distinguishes several types of effects and/or errors:

1. Known errors that can be corrected at processing :

    - Finite bandwidth and filtering of the electronic processing chain. Observing fast ejection of the beam, the falling edge ($90 \rightarrow 10\%$) is found to be 120 μs, corresponding to 3 kHz bandwidth. This limitation, generated in the CAMAC multiplexer, can be considered as a pure delay for normally behaving beams whose spectrum rolls off steeply beyond 1 kHz. The delay is then simply added to T_{eddy} . Sharp-edged beams, however (e.g. being scraped by a target) appear to have broadened edges due to this filtering.

2. Errors known and checked to be negligible:

    - Intrinsic resolution limit : this is a geometrical effect related to the penetration speed of the interceptor : it takes a number of turns to entirely scrape an annulus in phase space. Close to a resonance this number becomes large, as the scraper essentially intercepts the same phase space slice it had intercepted before. Calculations yield an off-resonance resolution of a few tenths of a mm, which is neglected so far. In a first crude approximation, it may be compensated by an appropriate delay, but this delay would depend on scraping speed and the instantaneous beam radius being scraped.
    - Parasitic shaving on another aperture restriction than the BEAMSCOPE aperture is a rather insidious error that may occur when the bump is not perfectly local, the closed orbit is off-centre and the beam is large. Extensive simulations have been performed before choosing the aperture to prove that the effect should not occur in normal operating conditions.
    - Magnet field inhomogeneity and finite length of the bumpers: Both effects have been measured and computed, respectively, and are insignificant.

3. Errors difficult to evaluate or of unknown magnitude :

    - Error in coherent Q-values : The computed bump amplitude being very sensitive to the tune parameter, e.g. $dY/YdQ_v \simeq -0.5$ around the operational tune, the coherent tune has to be entered correctly. The latter is not measurable since the Q-meter of the PSB has fallen into disuse because of complexity and unreliability, and is replaced by the more useful tune calculation system yielding the bare working point (and not the coherent tune). Consequently, the manually entered tunes (stored per intensity range on the data file) are not always correct, as working points drift slightly.

- Deviation of real lattice functions from computed ones : As β-functions and phases cannot be measured directly, at least not at the precise azimuth, possible deviations from theoretical values will entail erroneous bump amplitudes. The only way to check the latter is the auto-calibration procedure mentioned above, and to compensate errors in the 'computed aperture' by a correction factor. This is indeed done in the processing code, but one should bear in mind that the three delays already quoted and tune errors enter equally into the computation. This renders the calibration extremely lengthy until a consistent set of parameters is found. Nevertheless, in the vertical plane, results are (almost surprisingly) good and the best correction factor is unity. Less satisfaction must be reported for measurements/calibrations in the horizontal plane – mainly due to the following two effects.

- Influence of momentum spread : As the horizontal dispersion function in the PSB is non-zero everywhere (and roughly proportional to β_x), the momentum spread of the beam is folded into the measured distribution. This renders emittances measured less precise, and, for extreme cases with large momentum spread and small beam, almost meaningless; note however, that the situation in the PS and in most transfer lines is nearly the same, so that comparison of these "emittances" is still useful.

  Another undesirable effect is that the beam centre is not well-defined but subject to dispersion too : the measured amplitude distribution exhibits a tail around the origin (while in the vertical plane it takes off sharply and linearly). The tangent fitting method described in Sec. 2.1 is frequently ambiguous and cannot be automated. The resulting uncertainty in the beam centre found this way is of course reflected in an uncertain calibration.

- Reaction of the beam control system to the horizontal bump : At top energy, the RF frequencies of the four rings are synchronized and then locked to a common reference oscillator. The bump changes the orbit length inducing a change in momentum and in radial position

$$\frac{dp}{p} = -\frac{1}{\eta}\frac{dC}{C}, \quad \frac{dR}{R} = -\frac{1}{\gamma^2\eta}\frac{dC}{C},$$

  where $\eta = 1/\gamma_t^2 - 1/\gamma^2$ and dC/C is the change in orbit length due to the bump proper and dR/R the total change including the effect of fixed RF frequency. This is equivalent to a calibration error of the bump amplitude which can be computed to be $\simeq 3\%$, and is confirmed (within limited accuracy) by measurements with beam position monitors. The effect is compensated by a calibration correction factor found to be 1.04 . Beyond this calculable effect one can unfortunately observe some wild reaction at the end of the scraping process, when only 10 to 20% of the beam is left : Amplitude profiles are asymmetrical (in/out) and frequently exhibit pathological oscillations in the vicinity of the beam centre. It is known that the phase pick-ups do not like beam loss and it looks as if the phase loop is breaking up in the last phase of the measurement. These facts seem indeed to produce systematic calibration errors that are not yet assessed quantitatively. They are also the reason that, for horizontal operational measurements, we are bound to use the double-pulse method of Sec. 2.1.

The three delays described above being cumulative, they are all incorporated into one delay parameter, which is adjusted empirically in vertical calibrations with different scraping speeds until the calibration error is independent of speed. This way even the resolution error is taken into account to some extent.

3 Operational experience

Over the years the type of beams subject to measurement has evolved : While a few years ago knowing the rather large emittances of high intensity beams was first priority in order to make sure they pass the transfer line to the PS, collider physics (present and future) requires bright low-emittance beams. Owing to unavoidable blow-up in each transfer, emittances need to be even smaller in the PSB, which has to prove frequently that emittances judged too large in the PS or SPS are still normal at its exit. Now beams of unprecedented density are being prepared for LHC, featuring (95%)radii of about 7 mm. To measure these emittances to 10% accuracy means measuring beam radii to better than 0.35 mm. This corresponds to a relative calibration error in the reconstructed aperture of 0.7% (horizontal) or 1.2% (vertical). This accuracy appears perfectly feasible : Careful calibration to $\leq$0.2% aperture error is possible and reproducible. The single-pulse emittances are probably more precise than those measured with the standard double-pulse procedure, hence we will probably switch to the former in future.
This is evidently impossible for horizontal measurements, were we are faced with an untrustworthy calibration and, on top of that, with the observation that measurements of the same, but debunched, beam – to exclude all caprices of the beam control system – , systematically yield 6–12% larger emittances. Again, this may be due to growth of the momentum spread in the debunching process...

As an example of an application, Fig. 5 shows a measurement after capture of a high-density beam of which the tail has been blown up at a third-order stopband.

4 Comparison with other emittance measurement devices

For any measurement device it is of utmost importance to compare its results with other devices, possibly of different design. Although there are sometimes devices of such simplicity that it is hard to imagine errors, like activated foils in external beams, comparisons between such methods can exhibit amazing differences [6].

It may be useful at this point to recall a few facts about the differences between (i) devices that measure betatron amplitudes like BEAMSCOPE and flip targets, and (ii) devices measuring the projected density of a beam (profile detectors).

- Group (i) is of destructive type (ruling out its use in storage rings), necessarily rather slow (because of its intrinsic resolution limit, cf. Sec. 2.3), but, if speed is not required, can in principle provide high resolution and accuracy. Details of the amplitude distribution are obtained directly and easy to display. Emittances are naturally given with respect to a cicumscribed fraction (95% in the PS complex) of the particles, but transformation to parameters of the projection (to compare with type-(ii) instruments) is possible by performing the Abel transform numerically [7].

- Group (ii)-instruments can be non- (or sligthly) destructive. The duration of the measurement is in general limited only by the signal/noise ratio, allowing to gain insight into phenomena whose observation is out of reach for group-(i) devices. The price to pay in general is poor resolution (SEM-grids feature step sizes of 1.5-3.5 mm – not quite adequate for 7 mm beam radius as quoted above), and in some cases sensitivity to space-charge, and other hidden effects. Emittances typically quoted refer to multiples of the variance ($\sigma, 2\sigma$ etc.). Theoretically, display of the amplitude distribution is possible by performing the inverse Abel transform, but fails in practice (this is related to the fact that numerical integration works better by far than differentiation).

This comparison suggests that the two groups are rather complementary and a well-equipped machine should have both types in the ring and additional profile detectors in the external beams. The data processing unit should offer the possibility of transforming type-(i) emittances into those measured by the instrument of type (ii). For Gaussian beams, the type-(i) 95% emittances are almost exactly 1.5 times the 2σ emittances derived from projected density, and this factor appears to be a fair approximation also for most real proton beams. Note that this is not strictly correct for horizontal measurements in presence of dispersion.

BEAMSCOPE has been compared extensively with flip targets in the same ring(s) [5], occasionally (because these instruments have been out of order for a long time and have been revived only recently) with secondary emission monitor (SEM)-grids in the 1 GeV Measurement line of the PSB and at the entrance of the PS, as well as with the PS wire scanner [8]. Note that comparison with the latter means comparing different beams : The beam in the PS has been subject to steering- and matching errors, blow-up at stopbands etc. before being measured.

There follow tabulated comparisons with the first three devices – those that measure the same beam. In Table 1 the difference of the horizontal results is rather systematic,

	Horizontal	Vertical
$(d\varepsilon/\varepsilon)_{BEAMSCOPE}$ w.r.t. targets	-9.0 %	21 %
Target offset [mm]	0.11–0.46	0.36–0.94

Table 1: Comparison of emittances measurements BEAMSCOPE vs. flip targets

suggesting a fault of BEAMSCOPE in this case (or a deviation of the real from the theoretical lattice functions). Vertical errors are scattered between rings and probably reflect target errors. This coincides with larger 'target offsets', denoting by this term a systematic target position readout error that can be deduced from series of measurements of beams with varying dimensions. Such an offset is not necessarily a static one but may be caused by vibrations of the target arms. Fig. 6 shows the effect on a beam progressively intercepted by a well- and an ill-functioning flip target and illustrates why target measurements are sometimes difficult to interprete. It also shows the effect of limited resolution (intrinsic and by electronic bandwidth) Not many comparisons

Emittance [π mm mrad]	Horizontal	Vertical
BEAMSCOPE: $\varepsilon(95\%)$	9.3	10.3
same, debunched	10–13	
$\varepsilon(2\sigma)$ computed	8.3	6.0
SEM-Grid BTM.SGx1 $\varepsilon(2\sigma)$	14.8	11.8
SEM-Grid BTM.SGx2 $\varepsilon(2\sigma)$	12.2	10.8
SEM-Grid BTM.SGx3 $\varepsilon(2\sigma)$	13.5	11.5

Table 2: Comparison of emittances measurements BEAMSCOPE vs. SEM-Grids of the 1 GeV Emittance Line

have been performed yet, but they all show the trend to yield comparable figures (at least in the vertical plane) for emittances, unfortunately of different definition. Transformation of BEAMSCOPE emittances into projected-density defined ones reveals that the SEM-grids see more than 50% larger emittances. At present the physics behind this divergence is not understood.

High Density 1E12 p/p		
Emittance [π mm mrad]	Horizontal	Vertical
BEAMSCOPE: $\varepsilon(95\%)$		3.2
$\varepsilon(2\sigma)$ estimated		2.14
SEM-Grid PR.MSG48 $\varepsilon(2\sigma)$		2.09
SEM-Grid PR.MSG52 $\varepsilon(2\sigma)$		absurd
SEM-Grid PR.MSG54 $\varepsilon(2\sigma)$		absurd
Medium High Intensity 5.6E12 p/p		
Emittance [π mm mrad]	Horizontal	Vertical
BEAMSCOPE: $\varepsilon(95\%)$	20.6	11.8
$\varepsilon(2\sigma)$ estimated	13.8	7.9
SEM-Grid PR.MSG48 $\varepsilon(2\sigma)$	31.0	16.9
SEM-Grid PR.MSG52 $\varepsilon(2\sigma)$	absurd	absurd
SEM-Grid PR.MSG54 $\varepsilon(2\sigma)$	22.2	11.5

Table 3: Comparison of emittances measurements BEAMSCOPE vs. SEM-Grids at the PS entrance

The situation is similar when comparing BEAMSCOPE emittances of more intense beams with results from the SEM-grids in the PS inflection area; but surprisingly, they almost agree for low-intensity, but dense beams (Table 3). Is there a space-charge effect in the SEM-grids ? Future measurements may tell, but at present there is no clue. It should however be noted that the differences between BEAMSCOPE and flip targets are considerably smaller than the differences encountered in comparison with monitors based on SEM, which may be a hint that those devices suffer from yet unknown effects. Note that the discrepancies between vertical target and SEM-grid measurements would be worse than those with BEAMSCOPE.

Measurements of the proton pencil beams for the Sp$\bar{p}$S collider at 26 GeV/c with the wire scanner [8] often yield matching figures, again for different emittance definitions... To facilitate future comparisons, a postprocessor for BEAMSCOPE output is being implemented [9][10], computing the projected-density emittances for an arbitrary beam.

5 Conclusions and outlook

It is not easy to draw a conclusion in a few words. While one can state that no flaw is visible in vertical measurements and, apart from particular sensitivity to the tune, measurements are very reproducible and could be automated, one has to admit the unexplained and significant discrepancies compared to SEM-grid results. For horizontal measurements, one has to add to these the known and the unsolved problems of the interaction between measurement and beam control system. At present, no obvious improvement is in sight, let alone the possibility to force debunching systematically prior to a horizontal measurement, which opens up a new dimension of trouble related to the stability of the debunching and debunched beam.

Resuming, one may say that the decision made in the seventies, to go for a (electronic) BEAMSCOPE rather than a mechanical device, was certainly justified by the significantly lower cost of the present design, where, apart from the signal processing gear required in any case, only three pulsed supplies plus a multiplexer had to be built (the dipoles, standard orbit correctors, were already in the machine!). This had to be compared with the cost of eight mechanical units.

Nevertheless, in the light of experience and the ever more ambitious demands, a mechanical "BEAMSCOPE", if well-designed, will pay off in the long run. It does, of course, not merit the acronym 'Closed Orbit PErturbation': "General target" or "Dynamic Target' would be a better fitting designation. "General", because the same drive could either move a scraper or a wire across the beam, "dynamic", because it is not set to a particular position but is moving during all the interception. In view of the experience with flip targets and other devices that *reconstruct* the actual interceptor position (e.g. from potentiometers linear to only $\simeq 1\%$!), the position of the scraper edge has to be measured directly by an *optical position sensor*. A sketch (not a design proposal!) of such a Dynamic Target is depicted in Fig. 7: It features a cheap, smooth, but not necessarily precise linear drive, that accelerates the target structure to convenient speed, lets it drift through the beam, then stops it. Its instantaneous position is aquired by an optical sensor, here drawn as a fibre optics transmission system reading position marks on the guiding rod. The structure must be stiff enough to keep deformation vibrations down to a few microns. The position readout replaces the computed

bump amplitude in the BEAMSCOPE computer processing scheme, and is independent of machine tune and energy. The orbit circumference is not altered, which means that the beam control system would not react, as it seems to be the case in present vertical BEAMSCOPE measurements.
In a real design one would very likely prefer a rotary drive to a linear one, and it is surprising to note that exactly such a device built at KEK [11] has been presented at the same 1979 PAC as BEAMSCOPE. One may wonder, why has the mechanical device been phased out years ago [12], while the electronic one has to work harder than ever.

6 Acknowledgements

I would like to thank D. Möhl, H. Koziol and D. Warner for the careful reading of the manuscript and for the suggested improvements.

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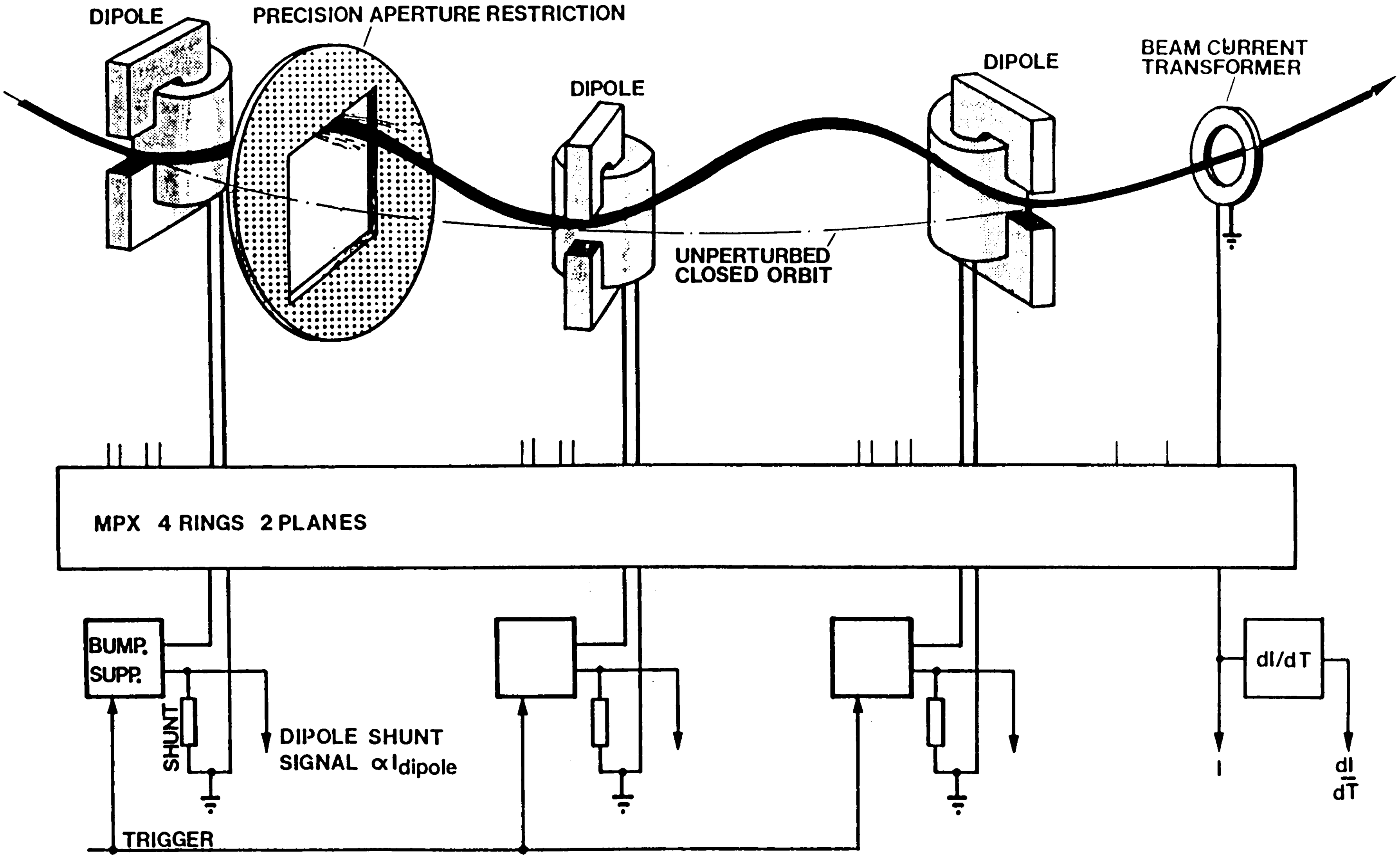


Fig. 1 "Artist's view" of Beamscope measurement system.

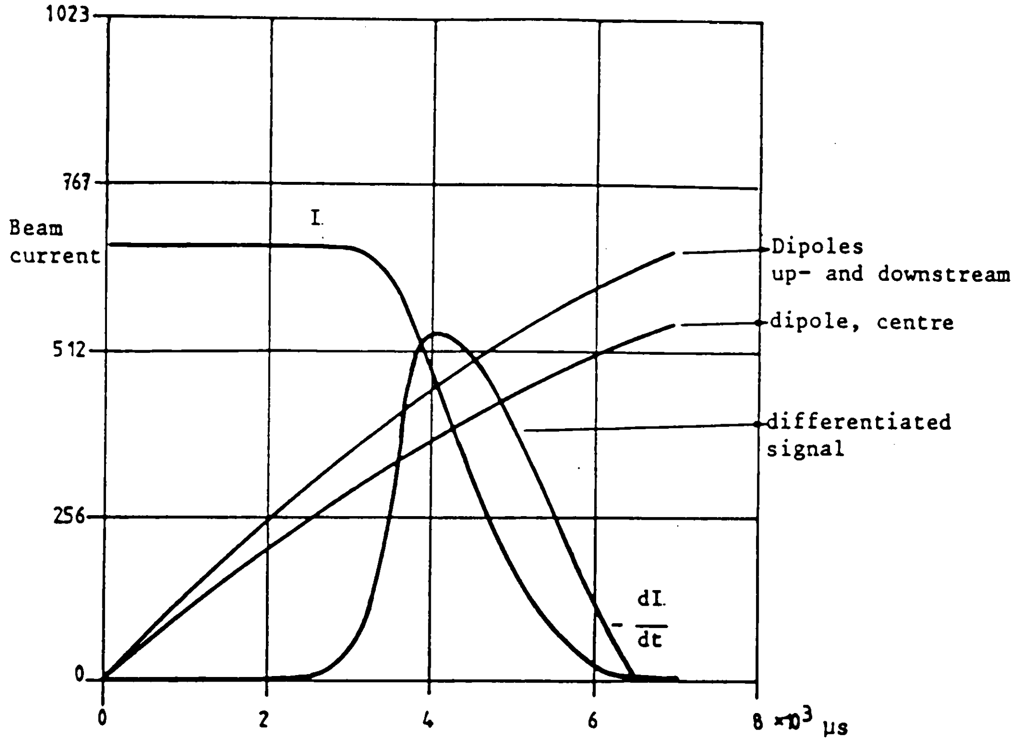


Fig. 2 The five "raw" Beamscope signals (the shunt signals of the two outer dipoles appear as one single trace).

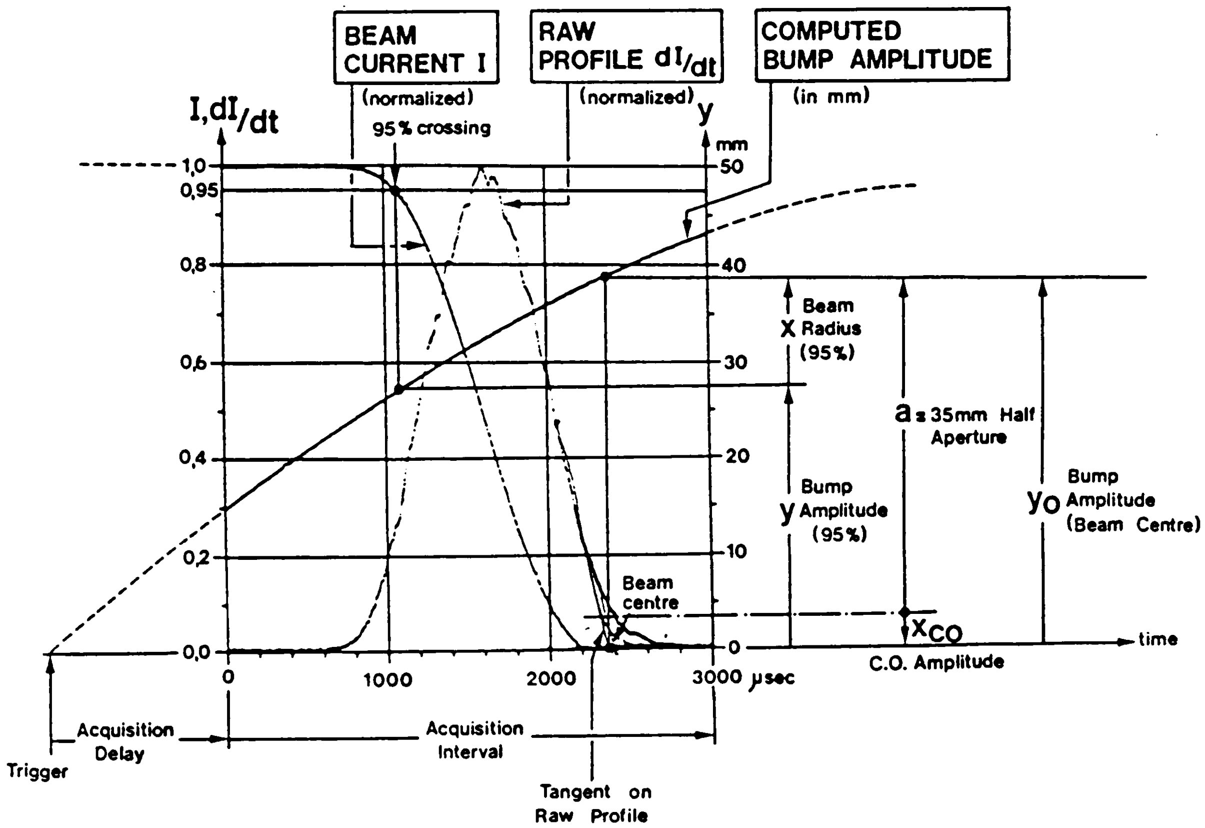
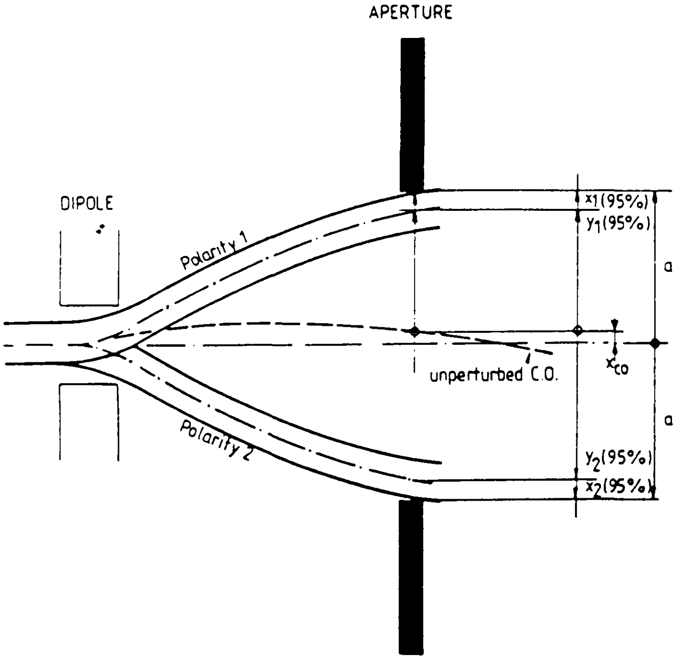


Fig. 3 The three basic Beamscope signals and their interpretation.



$$a = x_{co} + y_1(95) + x_1(95)$$

$$a = -x_{co} + y_2(95) + x_2(95)$$

$$2a = y_1(95) + y_2(95) + x_1(95) + x_2(95)$$

$$x = \frac{x_1(95) + x_2(95)}{2} = \bar{x}$$

$$= a - \frac{y_1(95) + y_2(95)}{2}$$

Auto-calibration :

At complete loss it should hold $y_{1,2}(0) = y_{1,2}(95) + x_{1,2}(95)$, hence : $y_1(0) + y_2(0) = 2a$

Fig. 4 Principle of the double-pulse method.

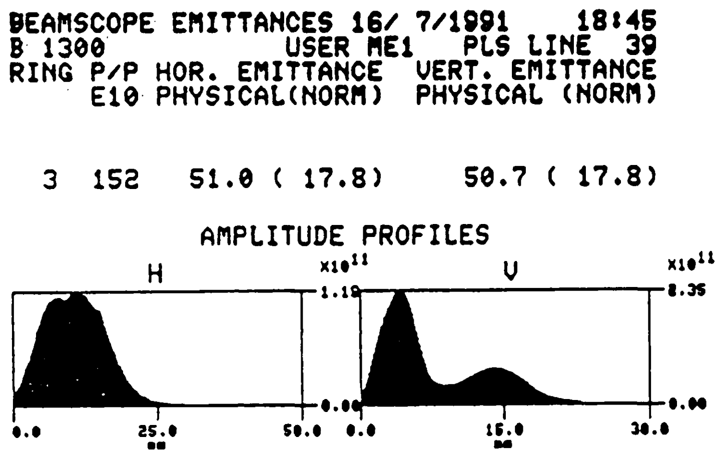


Fig. 5 BEAMSCOPE measurement of a single-turn high-density beam after capture. The vertical double-hump distribution stems from a tail in the linac distribution blown up at a 3rd order stopband.

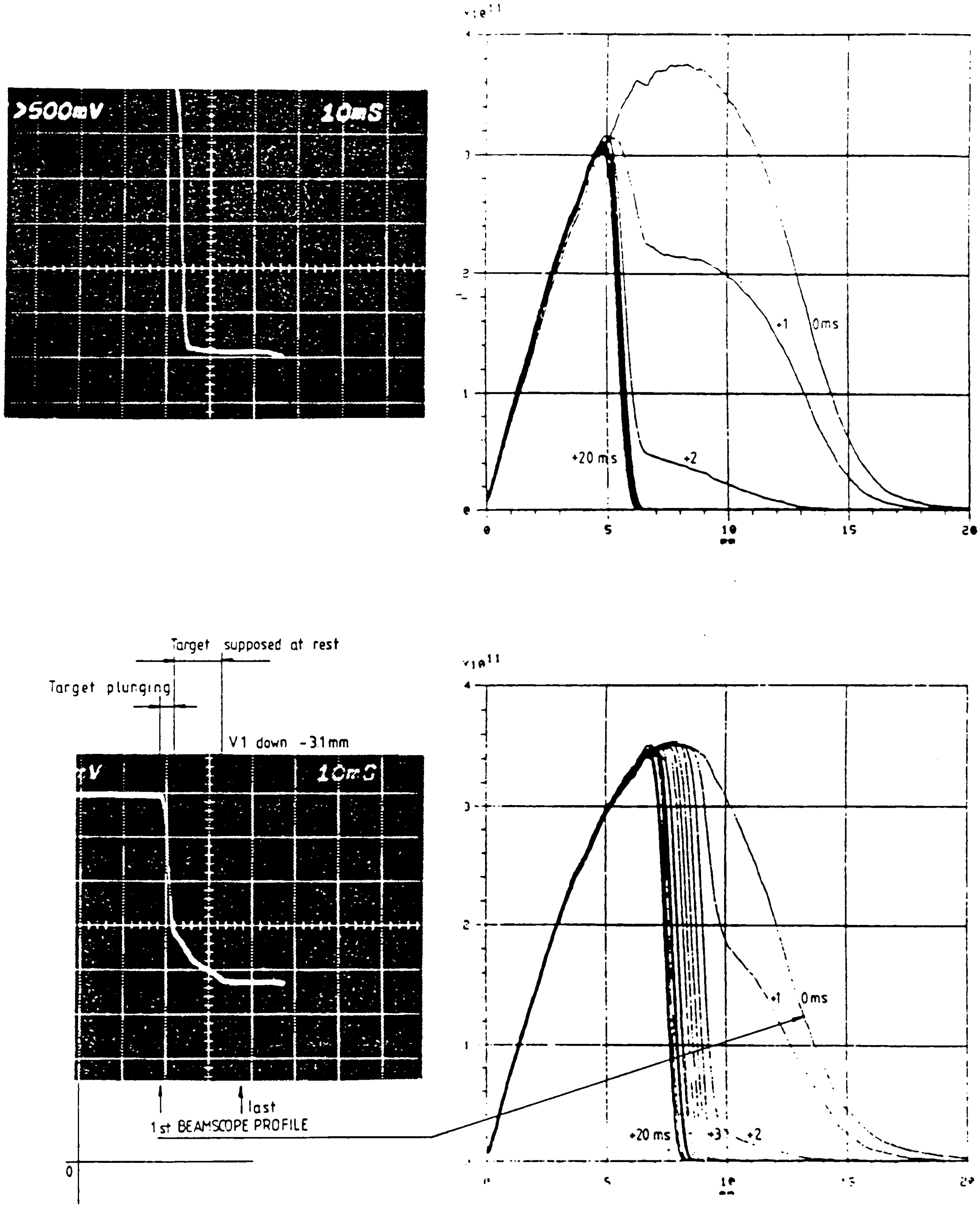


Fig. 6 Beamscope profile series showing a) correct and b) faulty behaviour of a plunging target. In (b) the target continues to penetrate slowly into the beam, causing slow loss which is visible on the beam current signal (left). In (a) the target stays quiet once plunged and there is no beam loss during this phase. Time increment: 1 ms between Beamscope profiles.

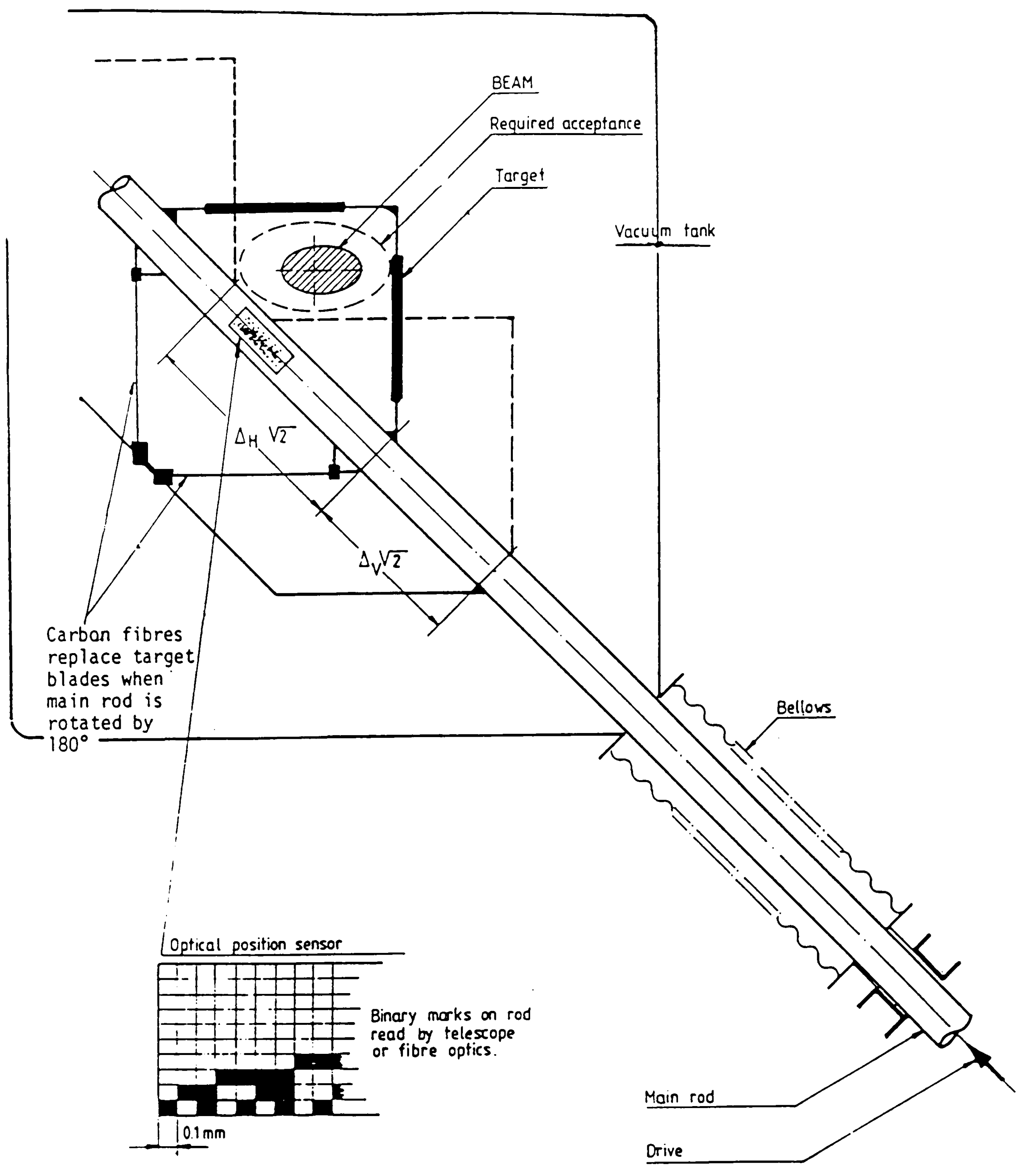


Fig. 7 Schematic of a "Dynamic Target" (not a design proposal!)

It consists of a cheap, smooth, but not necessarily precise linear drive, that accelerates the target structure to convenient speed, lets it drift through the beam, then stops it.Its instantaneous position is acquired by an optical position sensor, here drawn as a fibre optics transmission system reading position marks on the guiding rod. Alternatively the drive can move a wire to measure the density profile of the beam rather than the amplitude distribution.