BNL-104065-2014-TECH

AGS.SN188;BNL-104065-2014-IR

Emittance Growth Due to Scattering by the Stripping Foil

L. Ahrens

May 1985

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

7/16/85 Number 188

AGS Studies Report

Date(s)	May 29, 1985	Time(s)	1900-2400
	June 4, 1985		2200-0600
	June 12, 1985		1000-1800
	June 19, 1985		0800-1400

Experimenter(s) L. Ahrens, D. Barton, C. Gardner, E. Gill, J-P Potier

Reported by D. Barton and J-P Potier

Subject Emittance Growth Due to Scattering by the Stripping Foil

Introduction

This report is the first of two concerning a series of injection studies carried out during the months of May-July, 1985. The aim of these studies has been to systematically study the behavior of the beam, especially in vertical phase space as a function of injection parameters including intensity. The ultimate goal of the injection work is the optimization of accelerated beam intensity at acceptable loss levels.

EMITTANCE GROWTH DUE TO SCATTERING BY THE STRIPPING FOIL

I. Theoretical Summary

The effect of scattering by a stripping foil during charge exchange injection has been theoretically described by Cooper and Lawrence,[1] with reference to an analysis of residual gas scattering by Bruck.[2] The foil problem is somewhat simpler than Bruck's case, since the source of scattering is localized to one point along the machine azimuth. The theoretical result of the analysis is that the process leads to diffusion in the transverse phase space of the beam due to the averaged vector sum of the kicks, $\delta y'$, from each scattering. The RMS size of the beam increases each turn by an amount:

$$\sigma_f^2 = \frac{1}{2}\, \beta_o n t \sigma_c \cdot \overline{(\delta y')^2}$$

where B_o is the value of the machine betatron function at the foil location, n is the atom density in the foil, t is the foil thickness, σ_c is the average effective Coulomb cross section, and $\overline{(\delta y')^2}$ is the mean square projection of the scattering angle in one plane. The theoretical expression for the product $\sigma_c \cdot \overline{(\delta y')^2}$ has been given by Bruck in the non-relativistic limit. The corresponding relativistic form appropriate for the AGS Linac energy is:

$$\sigma_c \cdot \overline{(\delta y')^2} = \frac{\pi}{2} \left(\frac{2Zr_p}{\gamma\beta^2} \right)^2 \left[2\ln \frac{\Theta_{max}}{\chi_\Gamma} - 1 \right]$$

where for our injection parameters:

$z = 6$

$r_p = e^2/4\pi\varepsilon_o m_p c^2 = 1.5 \times 10^{-18}$ m

$\left.\begin{array}{l}\beta = .566 \\ \gamma = 1.21\end{array}\right\}$ 200 MeV H^-

$\chi_\Gamma = 1.2\ \Theta_{min}\ (1 + 3.33\Gamma^2)^{1/2}$, $\Gamma = \frac{Z}{137\beta}$

$= 1.22\ \Theta_{min}$

$$\Theta_{min} = \frac{h/P}{5.3\text{x}10^{-11}\ Z^{-1/3}} = 1.05 \text{ x } 10^{-5} \text{ rad}$$

(corresponds to effective screened atomic size)

The parameter Θ_{max} depends on aperture size since large angle scatters contribute to losses, but not to effective emittance growth. For the AGS

$\Theta^V_{max} \sim 2.4$ mrad

$\Theta^H_{max} \sim 3.1$ mrad

For a 200 μg - cm^{-2} carbon foil, the product nt = 10^{23} atoms/m^2, the growth in emittance corresponding to an increase in the RMS projected beam size by an amount σ_f is equal to

$$\Delta\varepsilon_f^{(\text{rms proj.})} = \pi\sigma_f^2/\beta_o$$

for the AGS at the foil location

$$\beta_o^V \simeq 10.1\text{m} \quad , \quad \beta_o^H = 22.9 \text{ m}$$

so that we obtain the result:

$$\Delta\varepsilon_f^{(\text{rms proj.})} = \beta_o(\text{nt})\ \sigma_c\overline{(\delta y')^2}.\ \pi$$

vertical: $\Delta\varepsilon_f^V$ = .015 π mm-mrad/turn

horizontal: $\Delta\varepsilon_f^H$ = .033 π mm-mrad/turn

II. Initial Conditions and Preliminary Measurements

HEBT: During all study sessions the six matching quadrupoles in HEBT have been set to the currents in use on May 29th. These values were simply that day's operational values, but they were not such at the beginning of the other sessions. It was desirable to keep the same values in order to have the same betatron phase advance between the SEM units in the line to avoid systematic difficulties with the fits to the beam emittance using the SEM profiles. The results of typical fits to the beam emittance are given in Figure 1. There were measurements made during each study period during the first 10 microseconds of the beam pulse, since this period was typical of short and few-turn studies. In addition, on June 4th, SEM runs and fits were done at 100, 200, and 300 microseconds after the beginning of the pulse and at 200 microseconds on June 12th. The emittance values determined in these measurements were in close agreement from session to session, with the exception of the vertical emittance on June 12th, which was approximately 50% larger than at other times. The Twiss parameters vary as a function of the percentage cut of the beam profile, which is reflected in the changing size and orientation of the fitted ellipses. This systematic variation of the parameters will need to be verified using the destructive emittance device, which unfortunately was not working during these studies. The Linac beam was apparently quite stable from week to week, but the sensitivity of the SEM fits to variations in quadrupole settings needs to be established also.

Ring Equipment: An attempt was made to set up the AGS in a "bare machine" state which meant that all extraction equipment was OFF, all injection bumps for that equipment were OFF, low-field multipole correctors were OFF. In addition to the rf voltage being OFF, the cavities were mistuned to avoid self-bunching of the beam during spiraling. The low-field ν-quads were adjusted to move the operating point at injection well away from the coupling resonance. The values of the tune as determined by PIP were $\nu_x = 8.72$ and $\nu_y = 8.79$. The ring instrumentation used in this study comprised the PUE at D2 providing input to PIP, the fast beam transformer newly installed at B5, and the IPM (typically integrating for 25 microsec. every 100 microsec).

With the PIP program we have checked the effect of the low-field ν-quad. At a peaker delay of 2803 we have found:

	ν_x	ν_y
Quad off	8.592	8.666
Quad on	8.722	8.796
Measured effect	+0.130	+0.130
Calculated effect	0.125	0.125

This was for +1000 in V_{quads} and −1000 in H_{quads} (counts); measured and calculated effect are in a reasonable agreement.

Peaker: We encountered a lack of reproducibility in the initial set-up between the first two studies (May 29th and June 4th) and the following two (June 12th and 19th). The value of the peaker delay for which we found acceptable injection changed by about 130 counts. As a matter of record, work had been done to the peaker circuit during the June 12th maintenance period preceding the study. In addition, the replacement of the H20 power supply was made on the same day, and there is some question of whether the H20 septum was turned "OFF" in the same way before and after this event. In any case, the injection conditions during the third and fourth sessions were not as clean as previously. We observed a persistent beam loss of about 10% on the horizontal aperture in the injection bump region which could not be avoided without steering the H^- beam off the foil. For the studies reported here, this problem was primarily an annoyance, which simply made the extraction of the results from the data somewhat more difficult. In the future, this aperture problem and variations in operational peaker settings will have to be understood.

Betatron Oscillations and Coupling: We have used PIP to set up the steering of a short-pulse beam (half-turn) so as to have measurable betatron oscillations. The PIP results have been quite reproducible and a typical output is shown in Figs. 2. We have also introduced mis-steering in only one plane and looked for oscillations in the other and have seen no sign of coupling at this operating point. Finally, we have tuned the injection steering to give minimal oscillations ($<$ 2 mm peak-to-peak) with minimal losses.

III. Aperture Studies (May 29th and June 4th)

As we want to "paint" the vertical acceptance, we have made a few tests on aperture, particularly the vertical one. This was done with the injection bump used to bring the beam through the stripping foil.

First a half turn beam was injected into the AGS and the transverse oscillations cancelled by adjusting the last steering magnets of HEBT.

Then we mis-steered the vertical trajectory to set up vertical oscillations up to an amplitude where 25% losses occur after the first turn (see Fig. 3). In these conditions PIP indicates a 12 to 13 mm vertical oscillation amplitude at pickup C2, and we have no appreciable horizontal oscillations, so no evidence of coupling.

The vertical emittance of the beam, as measured by the SEM's emission monitors is ~ 6π mm-mrad measured at 90% and we can assume a mismatch of at least 50% from our observation giving ~ 9π mm-mrad.

The overall 1/2 aperture removed by the beam is:

$$E_l = \sqrt{\beta_l} \left(\frac{A}{\sqrt{\beta_{c_2}}} \right) + \sqrt{\varepsilon_v})$$

β_{c_2} = vertical β at C_2

ε_v = vertical emittance

β_l = local β where ε_v is needed

For	β_l(m)	E_l(mm)
	10.5	20.5
	15	24.6
	22	29.8

The most limiting vertical apertures in the AGS are ±1.5 inches, and with the beam going through the stripping foil (injection bump ON), ±1 inch at foil position. In the latter case, with an estimated closed orbit at the foil of the order of -4 mm and an oscillation amplitude of 13 mm, the beam is very close to the mechanical aperture. We conclude there is nothing abnormal in the vertical aperture during the injection process and we will be able to try to paint the vertical acceptance by mis-steering.

The horizontal aperture has not been studied. We have only to mention that losses were very sensitive to the amplitude of the horizontal bump and best results were obtained with the beam steered to the inside of the vacuum chamber. This is abnormal. Another indication is the fact that during the origial H^- set-up the foil had to be moved 1 to 2 cm inside from its theoretical position in order to get efficient injection. Both phenomena indicate a horizontal aperture restriction in the injection area which should be studied, and vacuum chamber positions should be checked carefully at survey time.

IV. Foil Blow-Up Studies

In Section 1, the foil induced blow-up has been estimated for Coulomb scattering. In the following we have done measurements on the actual blow-up encountered by the beam at injection.

The experimental procedure was the following:

The injection bumps were set to be larger than 500 μs; then a half-turn beam was first injected and the transverse oscillations reduced to ~ 2 mm peak-to-peak. During the spiralling of the beam through the foil, even after the initial losses, which can be attributed to a scraping of tails, we have still 5% losses during 500 μs. With the beam removed from the foil, no more losses occur during injection. An IPM scan was done starting 60 μs after the beginning of the beam, every 100 μs for 6 points. (See Fig. 4.)

A few scans were done inserting a target to restrict the vertical aperture in order to compare IPM profiles and target losses.

All studies have been done mainly with 5 turn injection which give approximately 2 x 10^{12} protons into the ring. Tests performed with 1 to 5 turns give the same results, but 5 turns enhance the signal to noise ratio of the IPM.

As described by the theory, at these levels of intensity, the beam blow-up is linear versus number of passes through the foil, with a good accuracy (see Fig. 5). The measured values are summarized below in terms of the 98% (±2.5σ) emittance measured by the IPM a well as a theoretical prediction

	$\Delta\varepsilon_V$ turn	$\Delta\varepsilon_H$ turn (π mm-mrad)
Theoretical values	0.094	0.27
June 12	0.042	0.074
June 19	0.050	0.11

Normally, as the ratio of the β functions of the horizontal to the vertical at foil level is around 2.2, one could expect the same ratio of the blow-up. On June 19th, the agreement was good, but on June 12th, we observed a smaller value in $\Delta\varepsilon_H$ which can be partially due to the horizontal aperture problem that we suspect (cf. Section 2).

If we compare the theoretical prediction with the experimental data, the discrepancy is a factor of 2. A few comments are in order.

1. By continued scattering in the foil, the beam is permanently mismatched, but the emittance calculation from the IPM profile assumes a matched beam. This effect gives only a few percent error.

2. We have done some cross checking measurements:

   a. By switching off the injection bump right after injection, the beams no longer pass through the foil. Then we have no more losses or growth.

b. By scraping the beam with the J19 target in the vertical plane, we measure no more vertical growth but the horizontal growth is still the same.

3. We have tried to relate target losses to IPM emittances. Top and bottom J19 targets were positioned respectively at +15.2 mm and −23.3 mm to avoid immediate losses during the stacking process, but giving ~40% losses after 500 μs. The corresponding profiles are shown in Fig. 6. One can observe that the vertical profile is clearly truncated and gives an emittance of 8.75π measured, to be compared with the 17π mm-mrad acceptance at the target level. Another test was done by positioning the vertical targets to limit the aperture to ±10 mm, that is, 4.5 π mm-mrad. In this case we have an immediate loss of about 15% and the profile width seen by the IPM gives an emittance of 4.6 π mm-mrad which is consistent with the target aperture.

   This will need further study but it seems obvious that the IPM sees mostly the beam heart and the target mainly the tails which are very substantial at injection.

References

1. R. K. Cooper and G. P. Lawrence, "Beam Emittance Growth in a Proton Storage Ring Employing Charge Exchange Injection", IEEE Trans. Nuc. Sci., NS-22 (1975) 1916.

2. H. Bruck, Accélérateurs Circulaires de Particules, Chapter XIV, Presses Universitaires de France, Paris (1966).

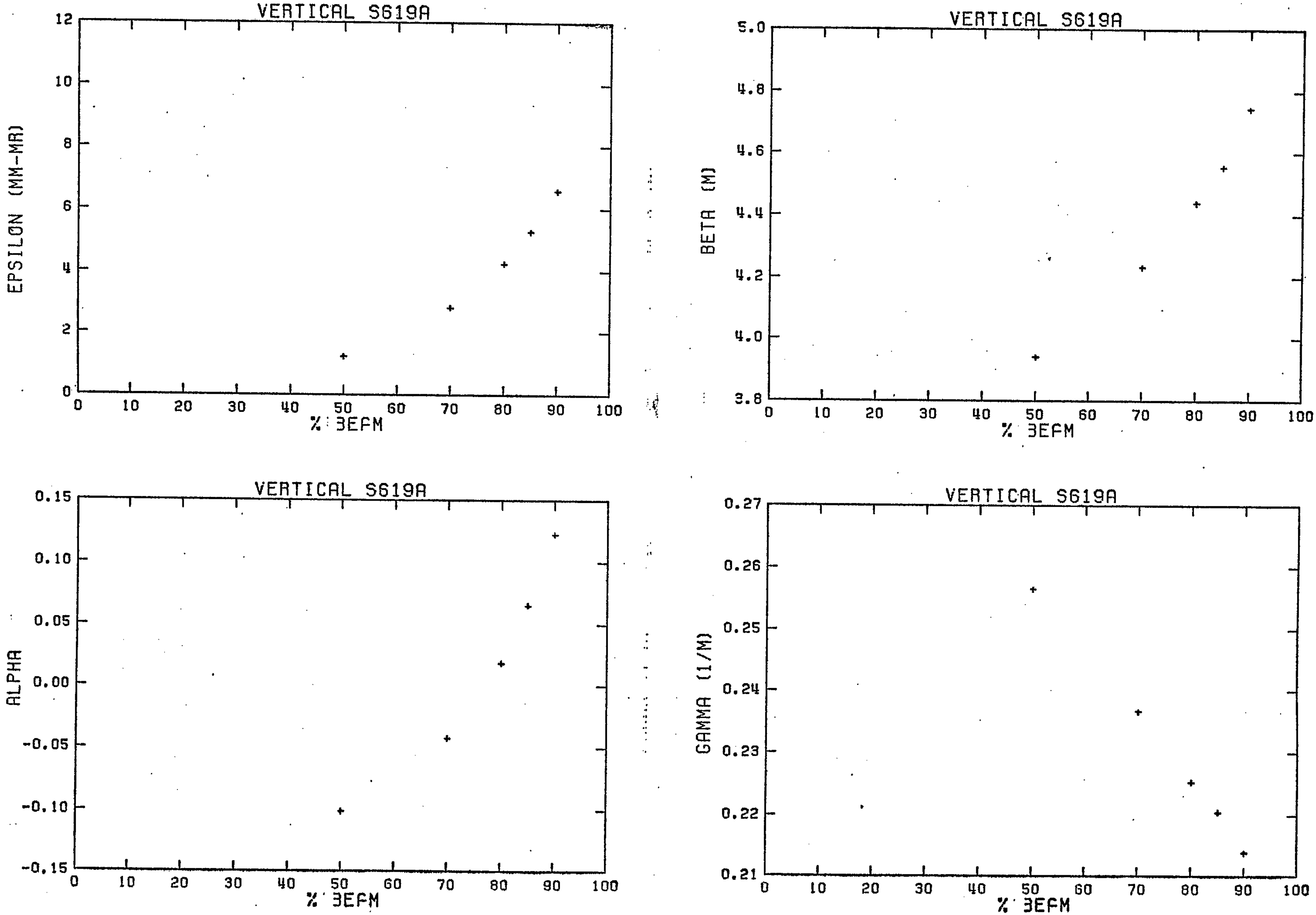

Figure 1 - Emittance parameters from HEBT SEM measurement.

```
F(X)=A * B(X,B) * COS(2PI)[(C+DX)X + EI + F + GX
A= 11.3405      +/-  .278129
B= .295762E-02  +/-  .801804E-03
C= .284571      +/-  .121332E-02
D= -.238595E-03 +/-  .419911E-04   29-MAY-85   13:41
E= .392838      +/-  .722551E-02
F= -3.30295     +/-  .247441
G= -.320175E-02 +/-  .152266E-01
***************************************************************

   EXTRAPOLATION FROM PUE C2 V

   POSITION AT FOIL =   3.848 +/-   0.412 MM

      ANGLE AT FOIL =   0.6933 +/-   0.0360 MR

            TUNE = 8.7954 +/-  .0012

   VERT CROMATICITY =  -0.793 +/-   0.115

          DELTA-P/P =  0.000598 +/-  0.000245
***************************************************************

   CHISQR IS  3.38483


F(X)=A * B(X,B) * COS(2PI)[(C+DX)X + EI + F + GX
A= 5.06740      +/-  .238525
B= .346439E-02  +/-  .570811E-03
C= .276641      +/-  .183911E-02
D= -.366604E-03 +/-  .525210E-04   29-MAY-85   13:59
E= .348550      +/-  .130020E-01
F= 22.9348      +/-  .209100
G= -.103892     +/-  .102739E-01
***************************************************************

   EXTRAPOLATION FROM PUE C2 H

   POSITION AT FOIL =   4.718 +/-   0.418 MM

      ANGLE AT FOIL =   0.3505 +/-   0.0176 MR

            TUNE = 8.7234 +/-  .0018

   HORZ CROMATICITY =  -1.015 +/-   0.145

          DELTA-P/P =  0.000792 +/-  0.000183
***************************************************************

   CHISQR IS  4.06488
```

Figure 2 - PIP results for "bare machine".

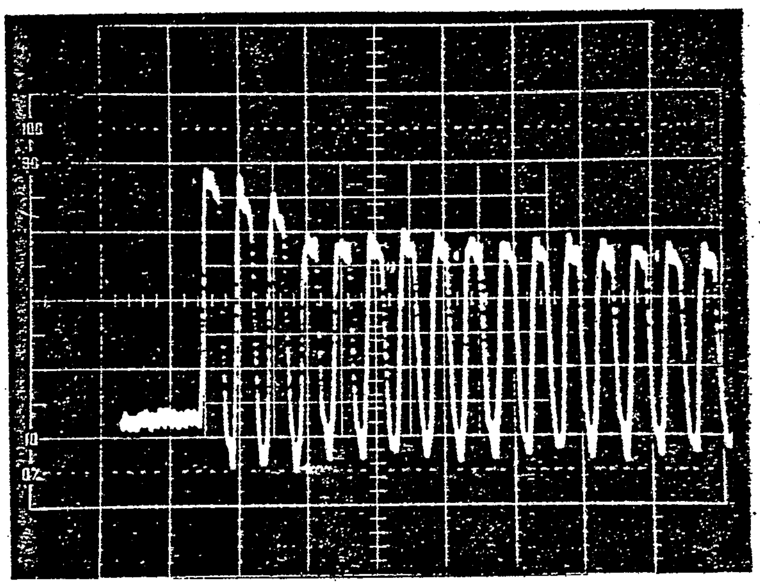

Figure 3 - B5 transformer signal - 1/2 turn vertical aperture studies. 13 mm amplitude oscillation.

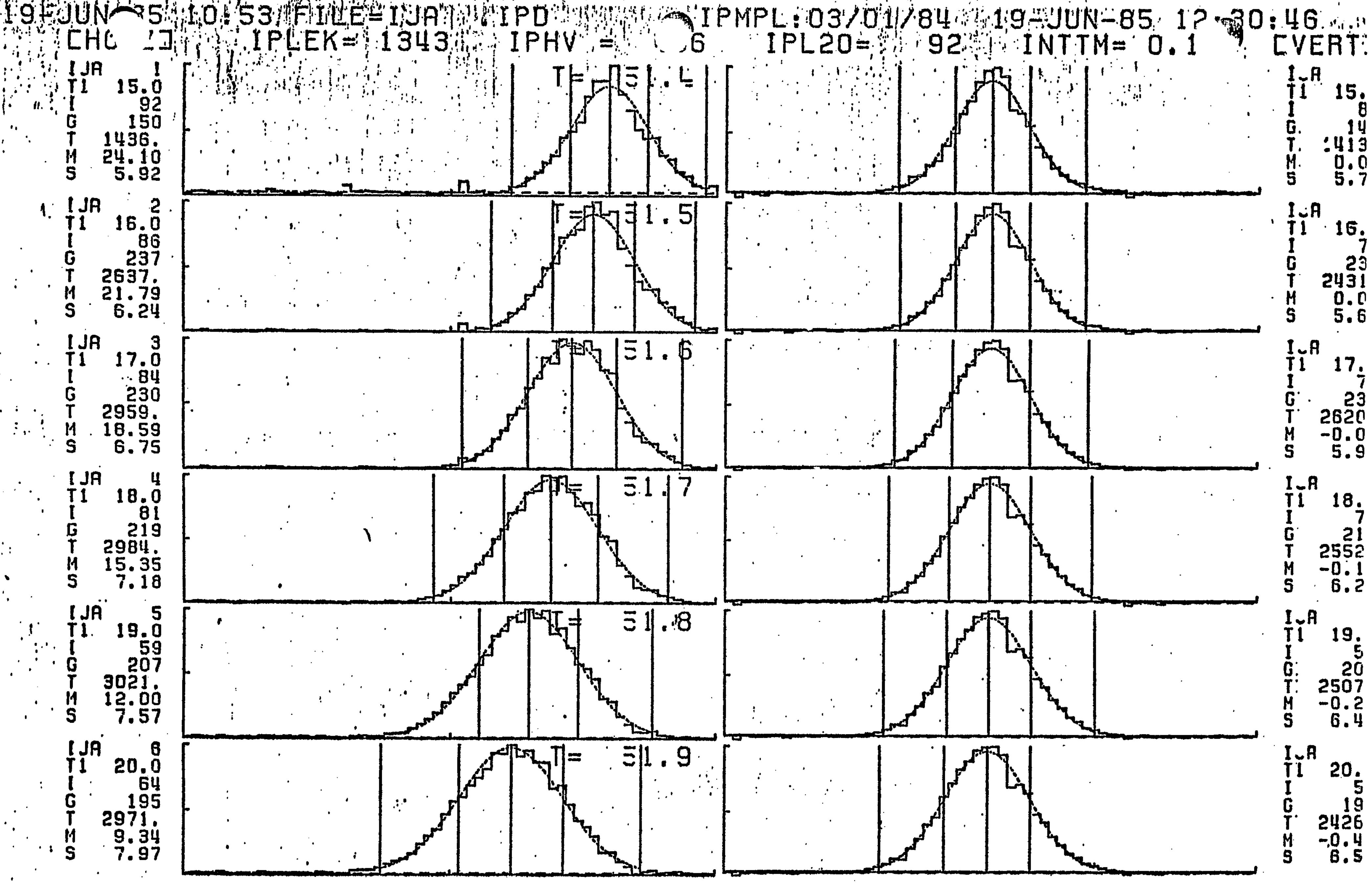

Figure 4 – IPM scan. 5-turn integrated for 25 μsec. Injection bump on.

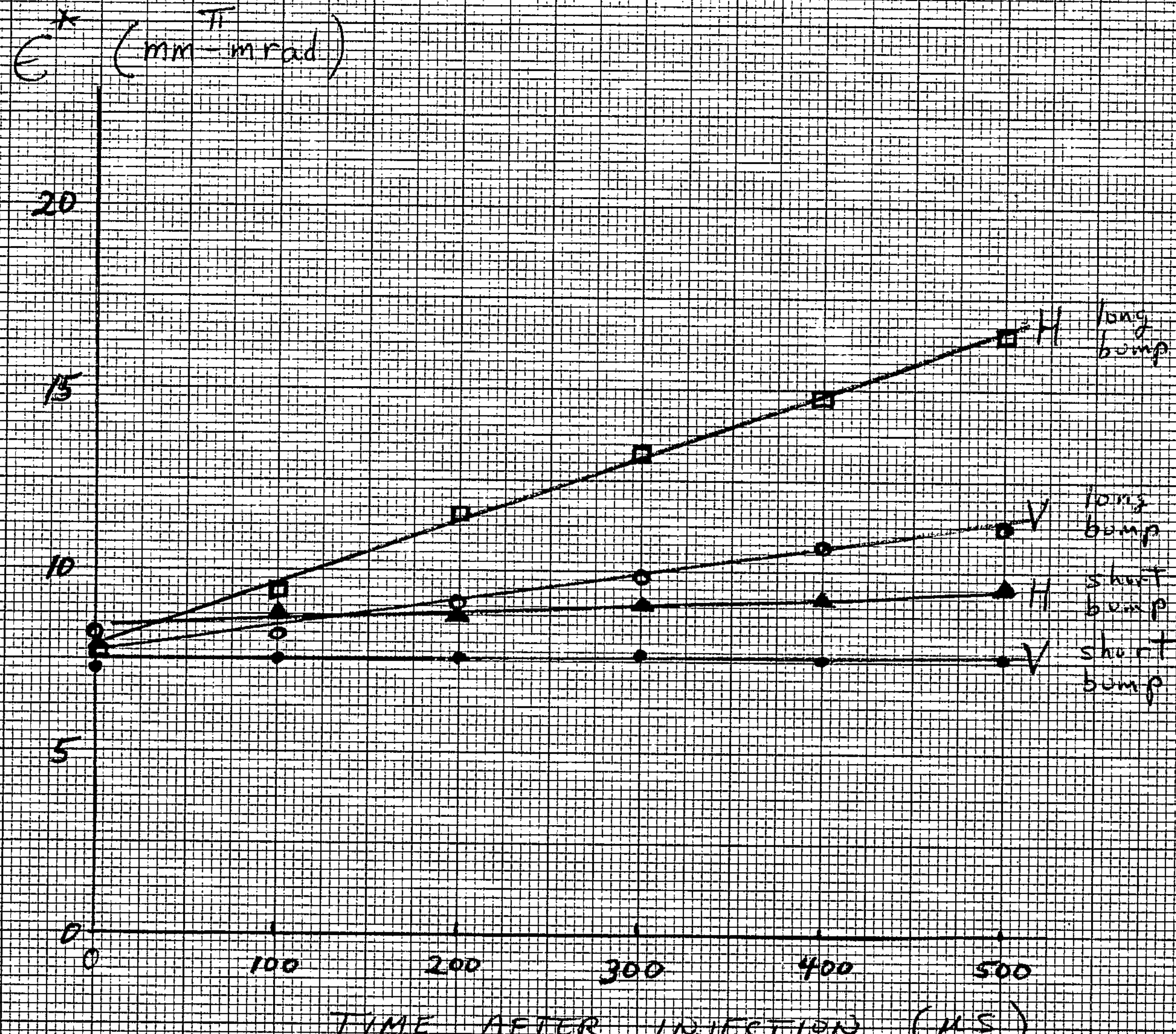

Fig. 5

5 TURN INJECTION —

BEAM GROWTH DUE TO FOIL

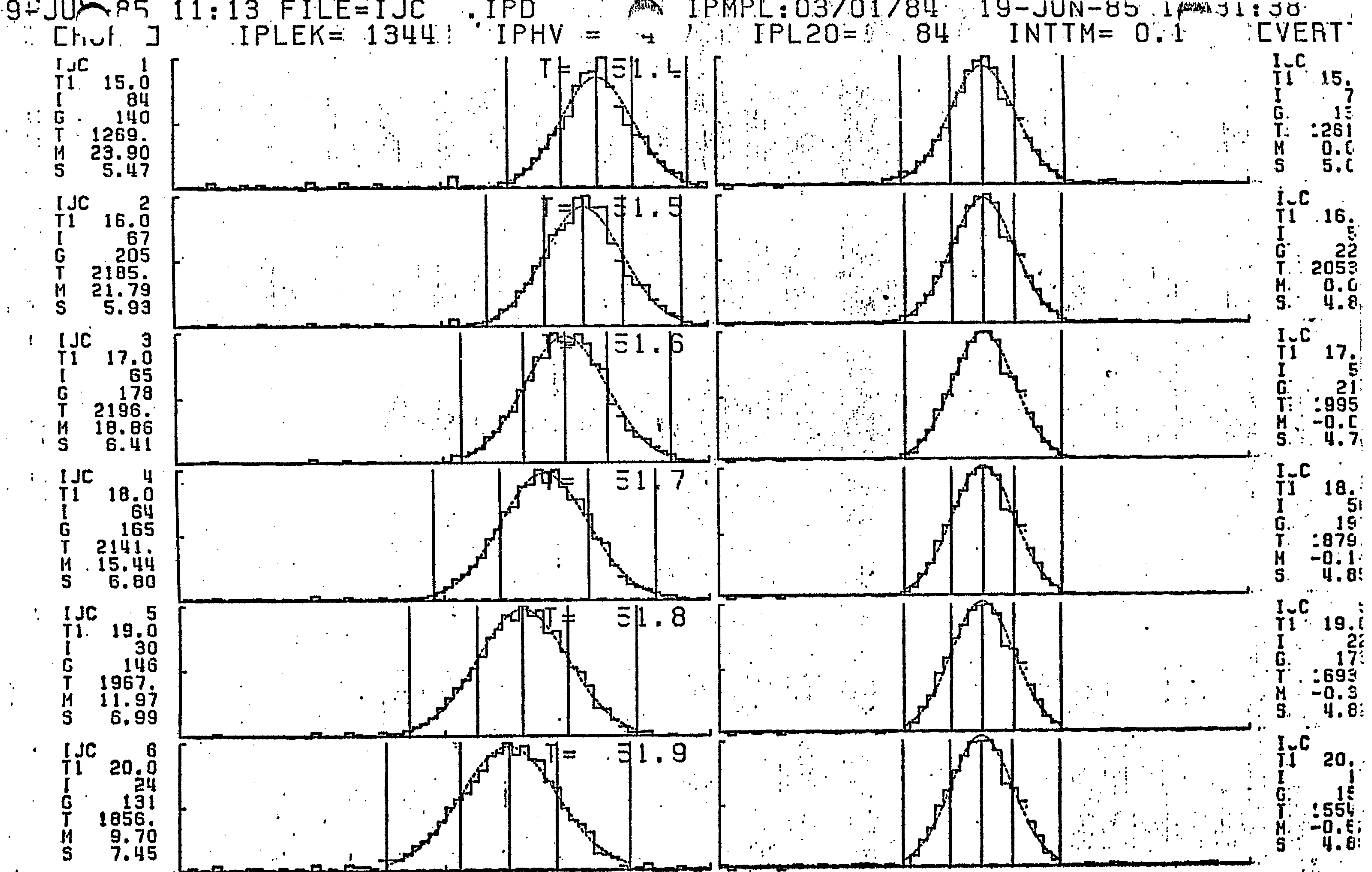

Figure 6 - IPM scan. Same conditions as Figure 4, but with J15 vertical target cutting 40% from top (pos = -600).