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STUDY OF THE BOOSTER INJECTION AT KEK

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Accelerator Division
Technical Note

AGS/AD/Tech. Note No. 373

STUDY OF THE BOOSTER INJECTION AT KEK

(A talk given at the AGS Machine Physics Meeting
held on February 5, 1993)

Yoshihiko Shoji*

April 9, 1993

*On leave from KEK.

Introduction

First, I wish to thank you for giving me a chance to talk about the KEK Booster. At KEK my duties involve working with the MR magnet and slow extraction. I am sure you may have questions that I will not be able to answer; in those cases, I will contact my colleagues at KEK and answer these questions later.

The AGS and the KEK-PS are similar; they are proton and heavy ion cascade machines although the collider project at KEK is not yet approved, there is H^- injection at the Booster (proton).

Today I will talk about the Booster injection of high intensity proton beams. This is one of the most important topics at KEK and also at the AGS.

Tables I and II show normalized emittance blow up at KEK and at the AGS. The emittance blow up at Booster injection stands out in both of the facilities. The experiences at the KEK Booster may be helpful to us at the AGS. Today I present these subjects.

List i lists the content of this talk (Study of Booster Injection at KEK). Some of these studies were not performed by me, so I have listed the main study members for each activity; perhaps you know some of these people. Motohiro Kihara is the head of the KEK-PS Complex. Tadamichi Kawakubo visited BNL for two months last year; he developed the IPM for the KEK-PS (we call it NDPM). Hikaru Sato once worked at BNL.

Since these studies were done, I have re-examined or re-analyzed the data. So, in some instances my conclusions are different from the original results.

The subjects as listed are too much to cover in the one hour we have for this meeting, so I will cover the subjects in their order of importance.

Table I Emittance of proton beam at the KEK-PS
Reported by T. Kawakubo [to be reported in KEK Accelerater Study Note]
The emittances in the ring based on the beam profile measured by the NDPM (the same as the IPM at BNL).

Accelerator	kinetic energy	normalized emittance (95% mm mrad) horizontal	vertical	LINAC pulse width (μs)
LINAC	40 MeV	7.4	4.5	40
BOOSTER	40 MeV	47 / 51	8 / 20	20 / 60
	500 MeV	44 / 57	10 / 41	20 / 60
MR	500 MeV	32	12	20
	12 GeV	50	83	20

Table II Emittance of proton beam at the AGS
Summarized by T. Roser.

Accelerator	kinetic energy	normalized emittance (95% mm mrad) horizontal	vertical	beam intensity (10^{13} ppp)
LINAC	200 MeV	7	5	3.6
BOOSTER	200 MeV	45	21	3.0
	1.5 GeV	60	40	2.0
AGS	1.5 GeV	72	34	1.5
	30 GeV	125	67	1.3

LIST i CONTENTS

STUDY OF THE BOOSTER INJECTION AT KEK

Y.Shoji

Introduction to the KEK Booster

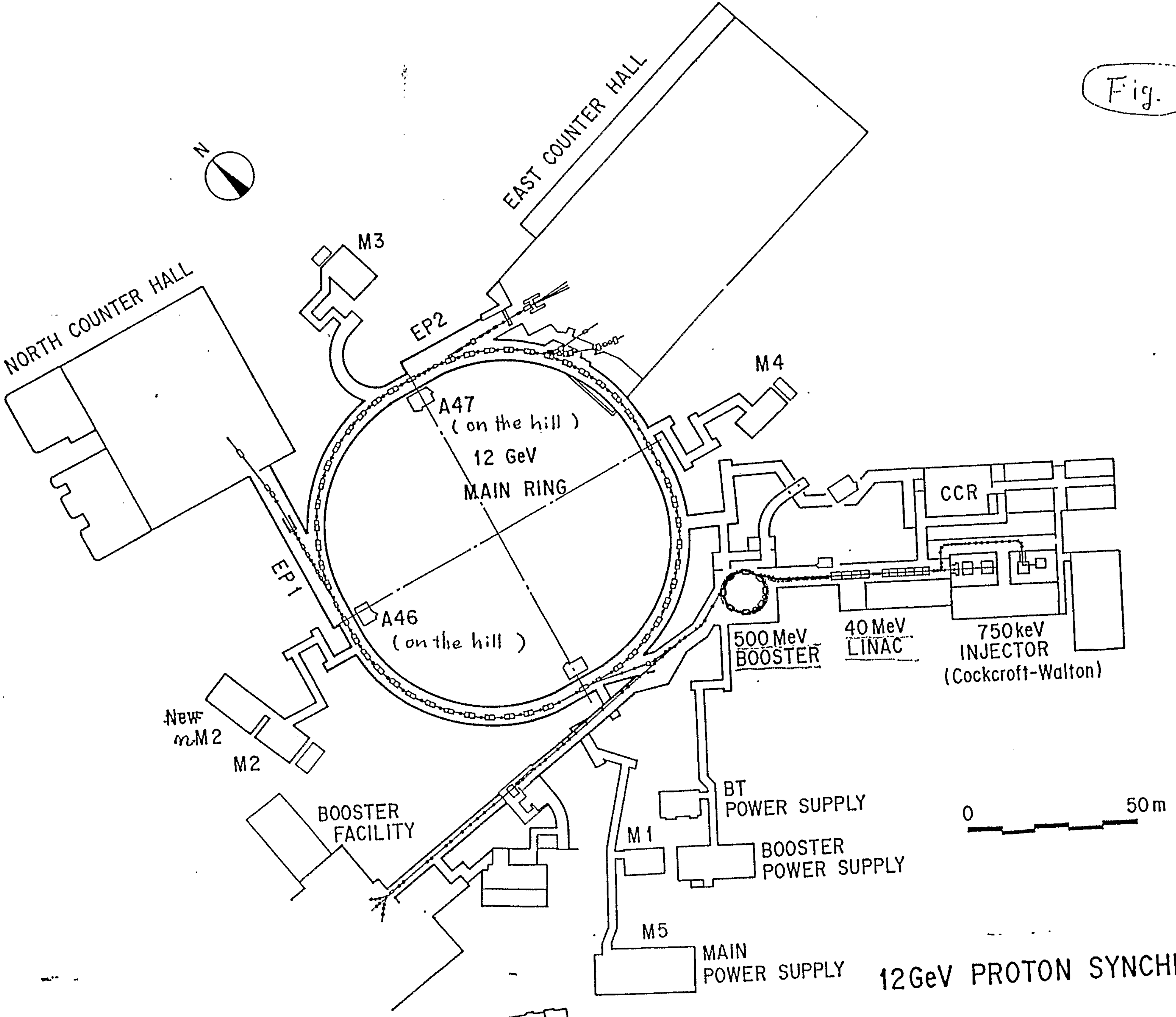
Figure 1 shows the KEK proton accelerator complex: 750 keV CW, 20 MeV and 40 MeV Alvarez Linacs, 500 MeV Booster Synchrotron, and the 12 GeV Main Ring (synchrotron). The construction of a heavy ion collider would be at ECH (4-7 GeV/u). A big water Cherenkov neutrino detector is going to be built here for the calibration of the KAMIOKANDE detector. The Alvarez Linac is separated into two: 20 MeV and 40 MeV. When the MR is accelerating and extracting the proton beam, the Booster supplies high intensity protons for the BSF. The intensity of the MR is much smaller than that for the BSF, because the MR cannot accept high intensity beam now. With the time length of the Linac beam, we control the intensities; normally 20 μs for the MR and 60-70 μs for the BSF. The operating cycle is normally 3 weeks (sometimes 4); maintenance is done once every 3 weeks (from Friday morning to Wednesday morning).

Table III shows the PS intensity. This is an example of the proton beam intensity of the KEK-PS. Unfortunately this is not a good sample--I don't remember what was wrong! Normally the Booster intensity is from 1.6 to 2 x 10^{12} ppp. The injection efficiency into the Booster is close to 100%. The injection efficiency into the MR is about 95%.

Figure 2 shows the KEK-Booster and the 40 MeV line. The KEK-Booster is a combined function synchrotron. The size is 1/9 that of the MR (37 m circumference). It accelerates 40 MeV Linac beam up to 500 MeV, 50 ms rapid cycle (injection to extraction = 25 ms).

The Linac-to-Booster transport line (we call it the 40 MeV line) consists of three parts: matching section (Q1-Q5), π-section (Pr3-B1), and π-phase achromatic section (B1-stripping foil). There are 7 multi-wire profile monitors along the line. This figures also shows the emittance monitor, the front slit, back sense wire and the momentum analyzer.

Fig. 1



12GeV PROTON SYNCHROTRON

INTENSITY

TIME : 02/07/92 14:33:17

CM-2	=	11.5	mA
CM-7	=	9.6	mA
20MeV CT	=	5.6	mA
40MeV CT-1	=	5.6	mA
40MeV CT-3	=	5.5	mA
(CT-1/CM-7)X100	=	58.3	%

< BSF >

BOOSTER (BSF)	=	14.75	E11	ppp
BSF UTIL.	=	14.5	E11	ppp
(BSF/BSTR)X100	=	95.6	%	((average of 6 times))
BSTR(BSF) MAX.	=	E	ppp	( )

< Main Ring >

BOOSTER (MR)	=	5.2	E11	ppp
MR K1	=	4.8	E11	ppp
MR P2	=	3.30	E12	ppp
MR P3	=	3.00	E12	ppp
EP2	=	2.94	E12	ppp
Internal Target	=	0.0	E10	ppp

TABLE III

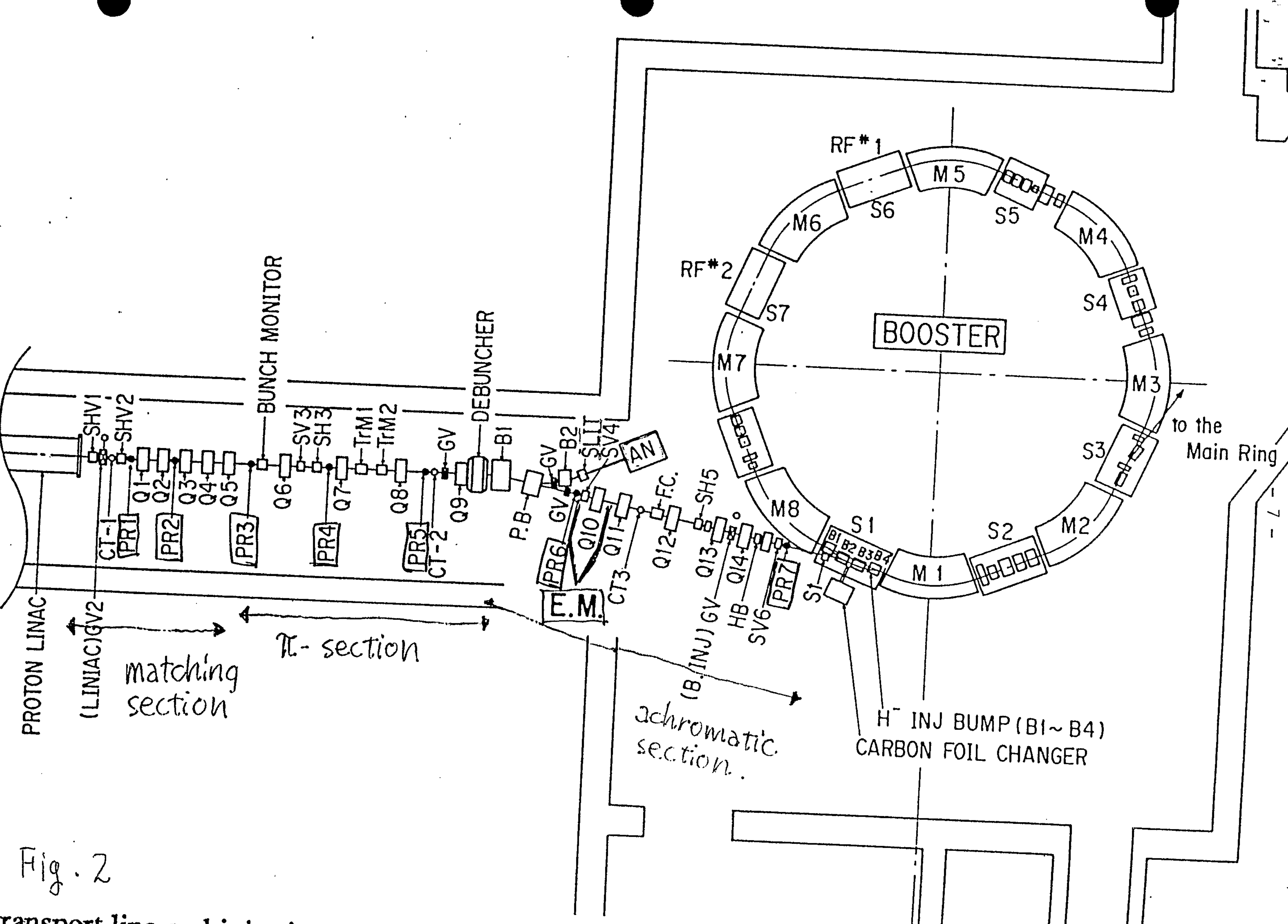


Fig. 2

ransport line and injection system in the Booster. The E.M. is an emittance monitor install...
space distribution are observed with th...

Figure 3 shows 40 MeV profiles. This is an example of the 40 MeV MWPM display of 32 channels (each 2.5 mm space, 30 μm W wire).

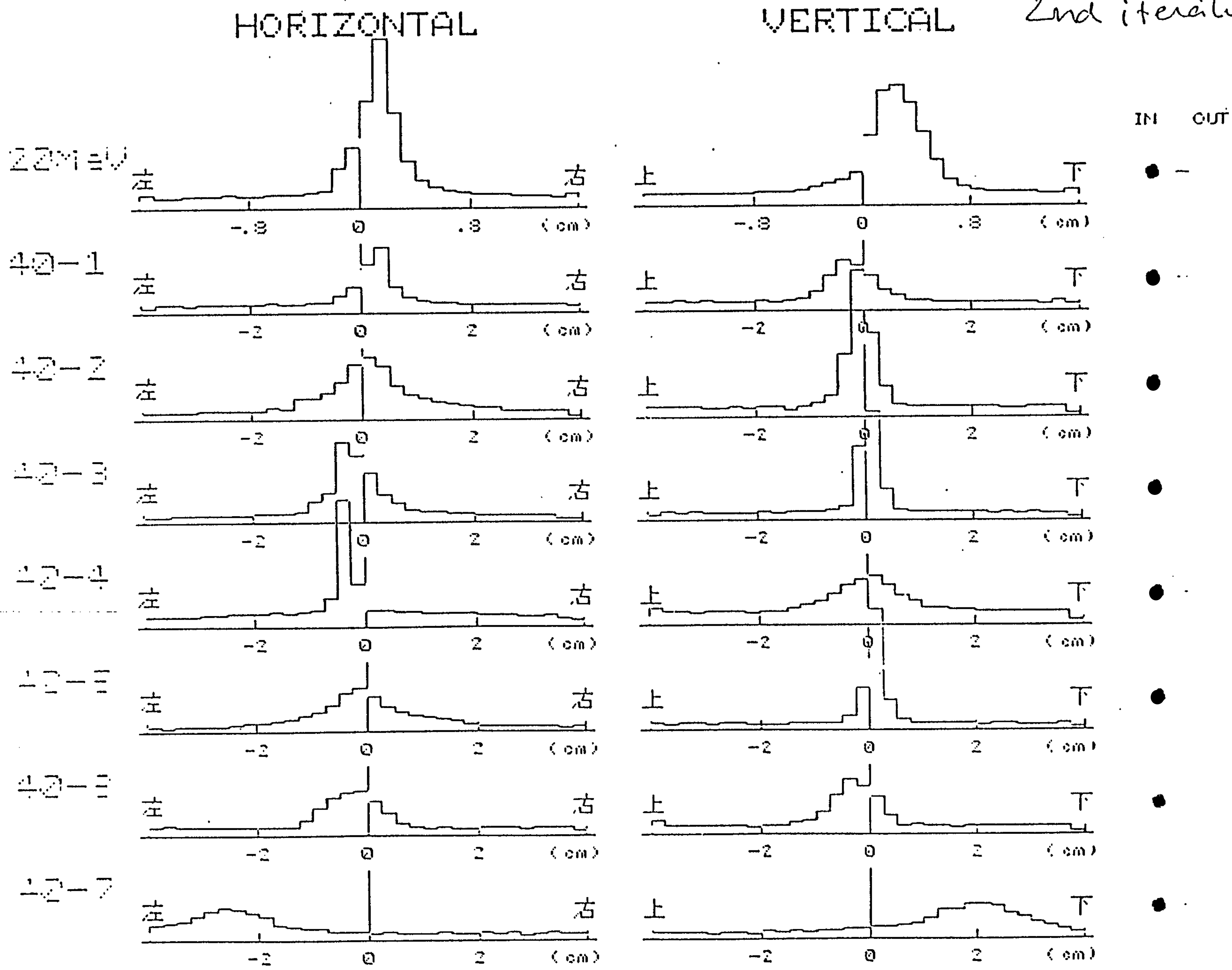
Figure 4 shows the 40 MeV line optics and Figure 5 shows the typical EM results. This is an example of the emittance measured by the EM. The slit at the upstream end and the sensing wire at the downstream end move to make two-dimensional density distribution contours. I have heard that the sensing wire will be replaced by the slit and the Faraday cup. The initial slit width is 0.05 mm and the thickness is 5 μm. The second slit width is 0.1 mm, corresponding to 0.13 mrad. One line shows the full width contribution of the dispersion at the initial slit. The measurement takes place every Monday morning. The results are plotted like this and posted on the CCR bulletin board. Figure 6 shows the long-term EM stability.

Next is the momentum analyzer consisting of two slits , and the vertical bend and the sensing wires. Figure 7 shows the Someya monitor. The measurement takes place once for every MR cycle (4 sec). The results are displayed on our CRTs and TV monitors.

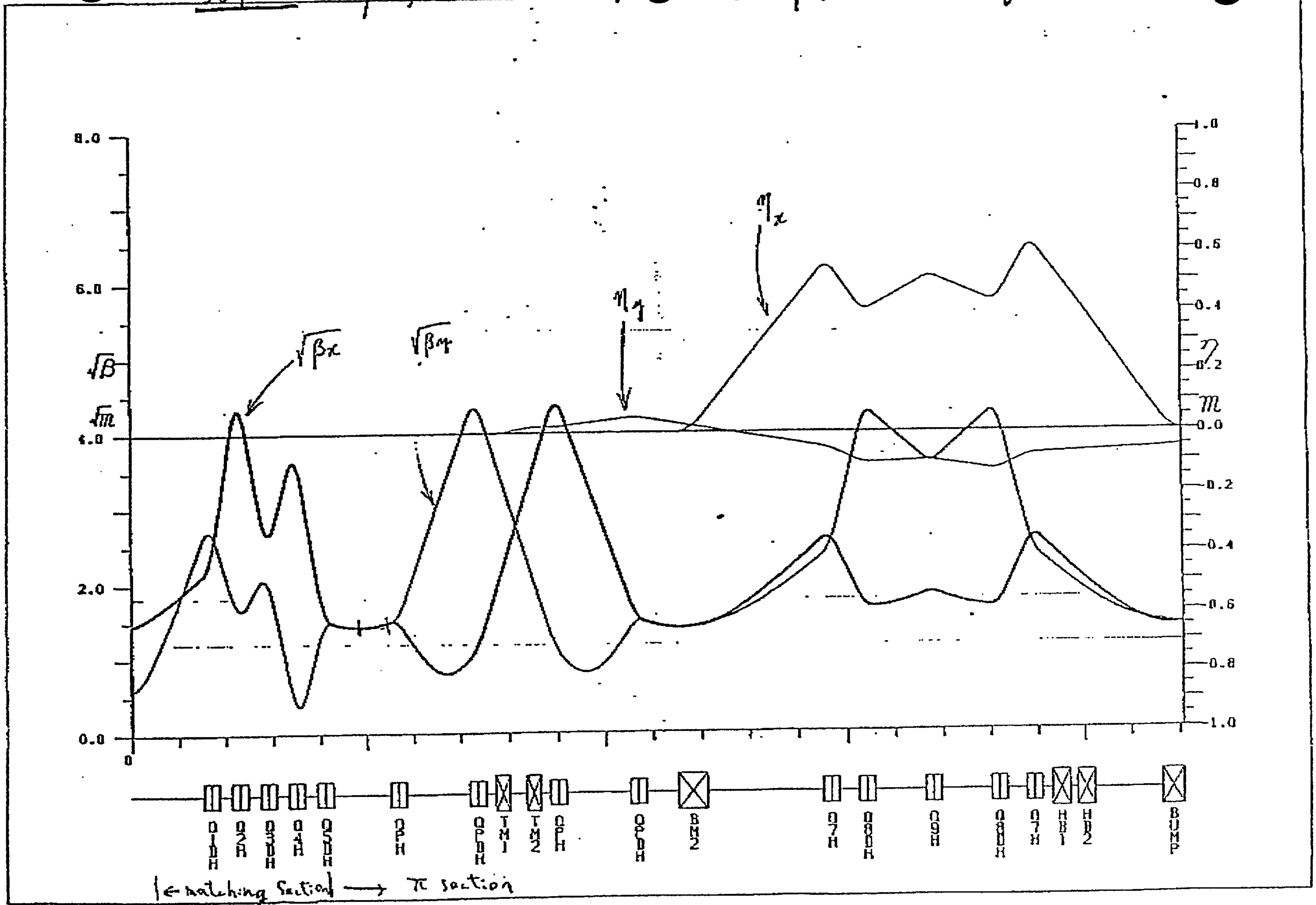
Figure 8 shows a Someya example. There are three examples. The horizontal full scale is 1.5% of the momentum spread. The vertical axis is the intensity and the time. The center section is the typical result when the Linac is tuned well. The initial change is due to the slow response of the compensation feedback of the beam loading. Usually the full momentum spread is 0.3 to 0.4%. The real display was more beautiful!

Fig. 3 20-40MeV PROFILE DISPLAY 09/30/91 18:56:02

2nd iteration

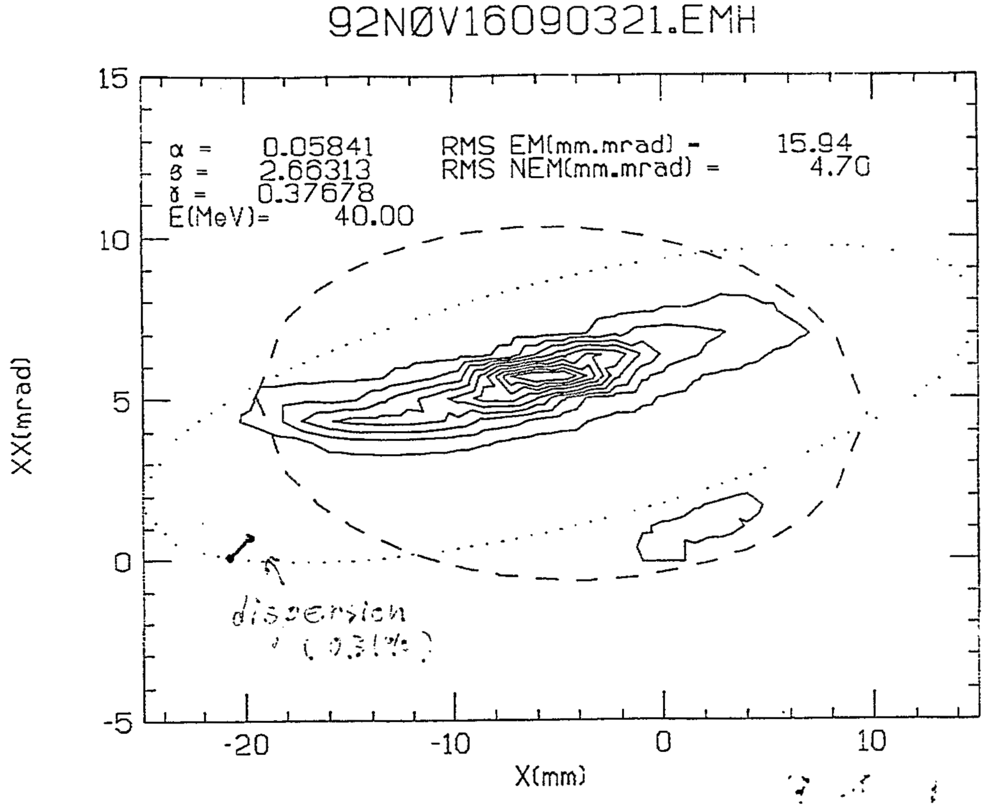


Step 4 βx fit = 2.0 αx fit 0.0, βy fit = 2.0 αy fit



Matching Section π section

Fig 4 Twiss parameters of the KEK 40MeV line (from KEK-PS manual)



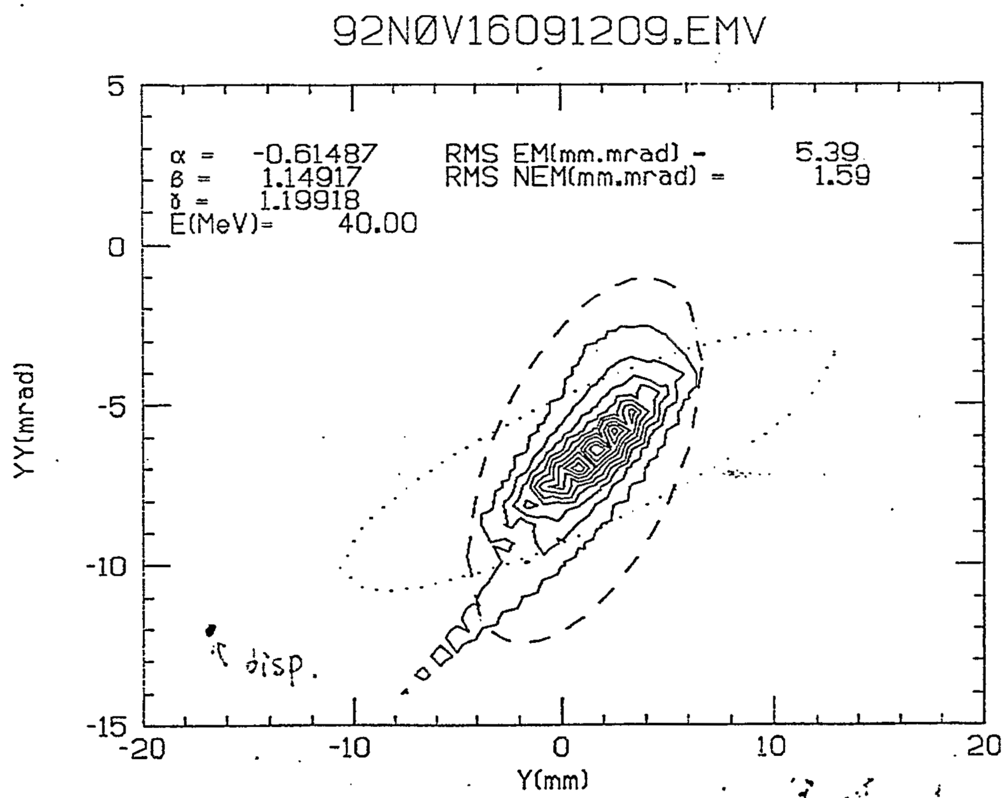
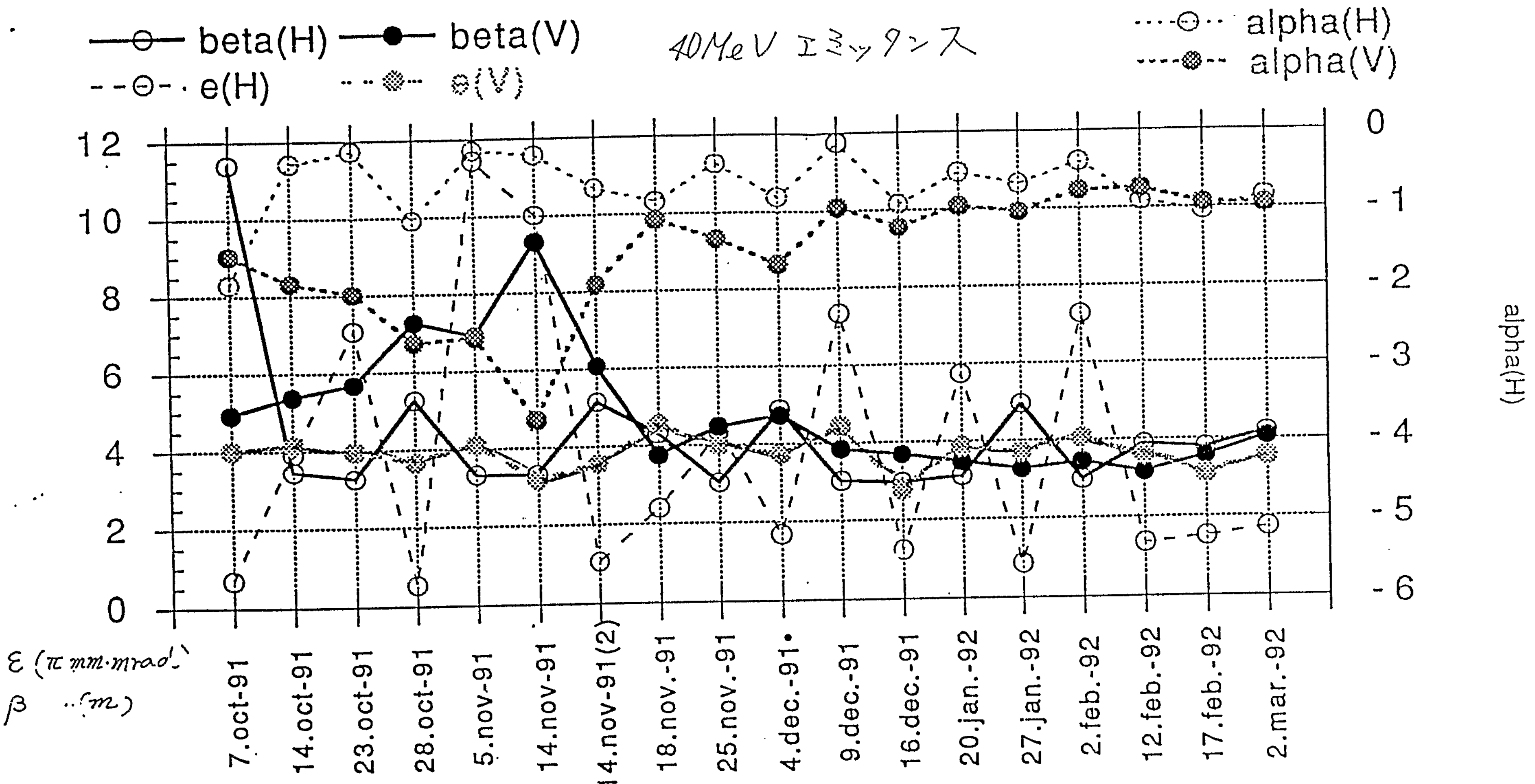


Fig. 5 Example of 40MeV line emittance

Measured on Nov.16 '92.

Broken ellipsoids — RMS emittance

Dotted ellipsoids — Calculated from 7 profiles of MWPM.



	date	beta(H)	alpha(H)	e(H)	beta(V)	alpha(V)	e(V)	H	I
1	7.oct-91	11.390	-1.8500	0.68697	4.9300	-1.4800	4.0170		
2	14.oct-91	3.4500	-0.29000	3.9142	5.3800	-1.8400	4.1314		
3	23.oct-91	3.2500	-0.14000	7.0668	5.6800	-1.9900	3.9634		
4	28.oct-91	5.2600	-1.0400	0.53283	7.2500	-2.6300	3.6546		
5	5.nov-91	3.3100	-0.15000	11.432	6.9000	-2.5700	4.1005		
6	14.nov-91	3.3000	-0.22000	10.022	9.3200	-3.6400	3.1599		
7	14.nov-91(2)	5.1400	-0.66000	1.0583	6.0700	-1.9100	3.5539		
8	18.nov.-91	4.3100	-0.84000	2.3972	3.7600	-1.0800	4.5420		
9	25.nov.-91	3.0200	-0.37000	4.3380	4.4700	-1.3400	3.9848		
10	4.dec.-91•	4.8700	-0.81000	1.6758	4.7300	-1.6800	3.7264		
11	9.dec.-91	3.0100	-0.13000	7.3337	3.8400	-0.96000	4.4259		
12	16.dec.-91	2.9500	-0.92000	1.2375	3.6800	-1.2200	2.7617		
13	20.jan.-92	3.0900	-0.53000	5.7307	3.4600	-0.96000	3.8599		
14	27.jan.-92	4.9400	-0.68000	0.85900	3.2600	-1.0400	3.6982		
15	2.feb.-92	2.9800	-0.40000	7.2500	3.4300	-0.77000	4.0500		

Fig.6 - long term drift of 40MeV line emittance parameters

MEASUREMENT OF MOMENTUM DISTRIBUTION OF THE 40MeV PROTON BEAM FROM THE KEK PS LINAC

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ABSTRACT
Momentum analyzing system for 40MeV proton linac was improvement in order to measure a time dependence of the momentum distribution within single beam pulse.By using this system, tuning oprator can get more detailed information on linac beam momentum.

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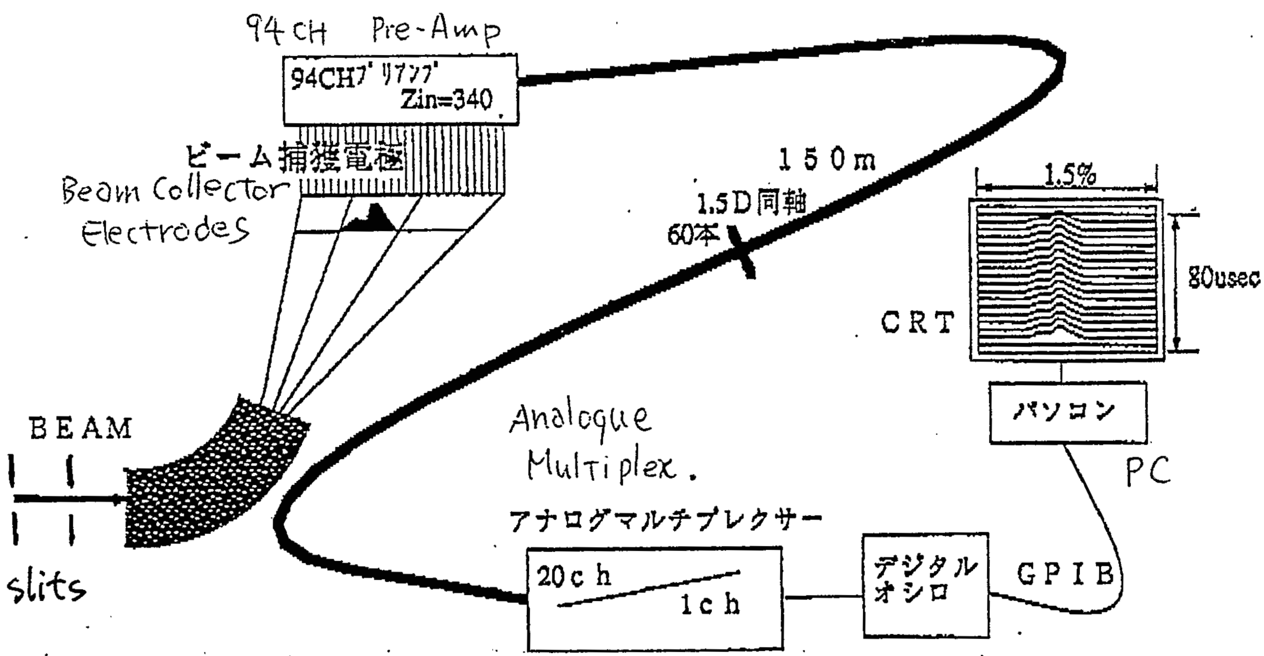
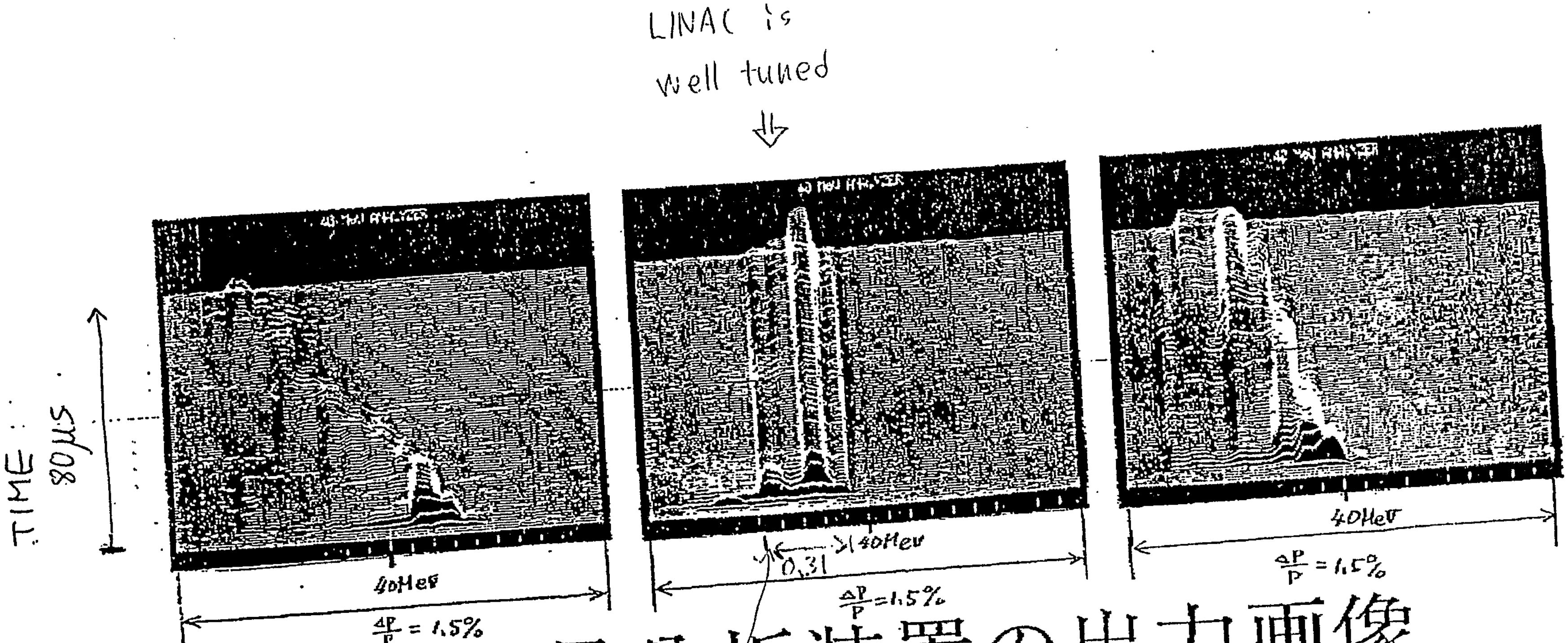


図2 運動量分析装置構成図

Fig. 7 Momentum Analyzer



運動量分析装置の出力画像

40MeV proton

Initial change

Feed back for the compensation of the beam loading was not sufficiently fast.

Fig.8. Typical ~~Result of Display of~~ Displays of the Momentum Analyzer

Figure 9 shows H^- injection and the injection point. The H^- charge exchange injection is like that at the AGS Booster. The bump orbit is produced by four bump magnets and a 30 $\mu g/cm^2C$ stripping foil.

397 eV/pass; 90 turn = 0.045% dp/P
Multiple scattering 0.048 mrad; 40 μs = 0.8 π μm(H), 2 π μm (V)
Charge exchange inefficiency = 2% (mainly H^0)
Sinusoidal B; $(dB/dt)/B_0$ = 0.03%/60 μs
Number of turns; 60 μs = 150 turns

Figure 10 shows the Booster intensity, rf. This is the typical particle number of the Booster and the rf voltage. It is captured with the adiabatic method. The beam is fully bunched in 200-300 μs. This is the beam profile in the Booster measured by NDPM (ionization profile monitor) at KEK developed by Dr. Kawakubo.

Figure 11 shows the Booster NDPM, V. This is the vertical beam size. The left line is the beam for the MR. The right line is the beam for the BSF. The only difference was the time length of the Linac beam. The upper figures show the 90% beam size during acceleration. The second is the profile just after injection. The third is the profile just before extraction.

Figure 12 shows the Booster NDPM, H. This is the horizontal profile. We saw the obvious intensity dependence of the beam size, especially on the vertical axis.

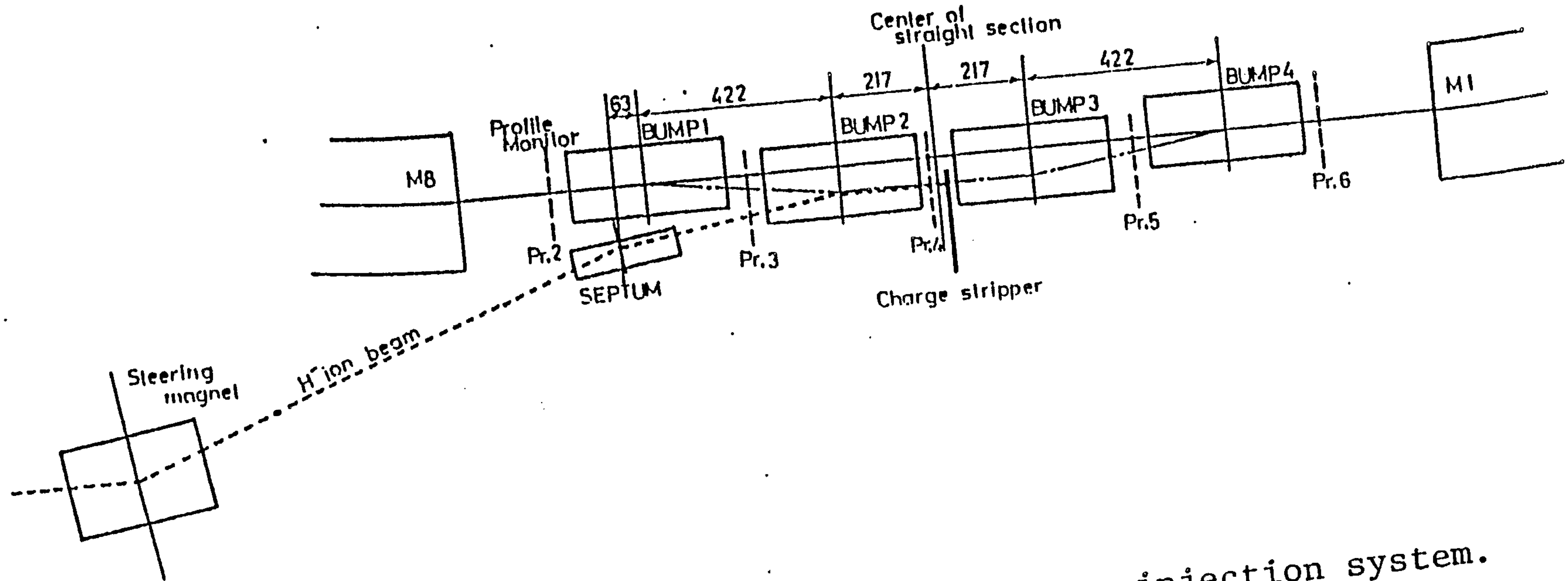


Fig. 9 Layout of the charge-exchange injection system.

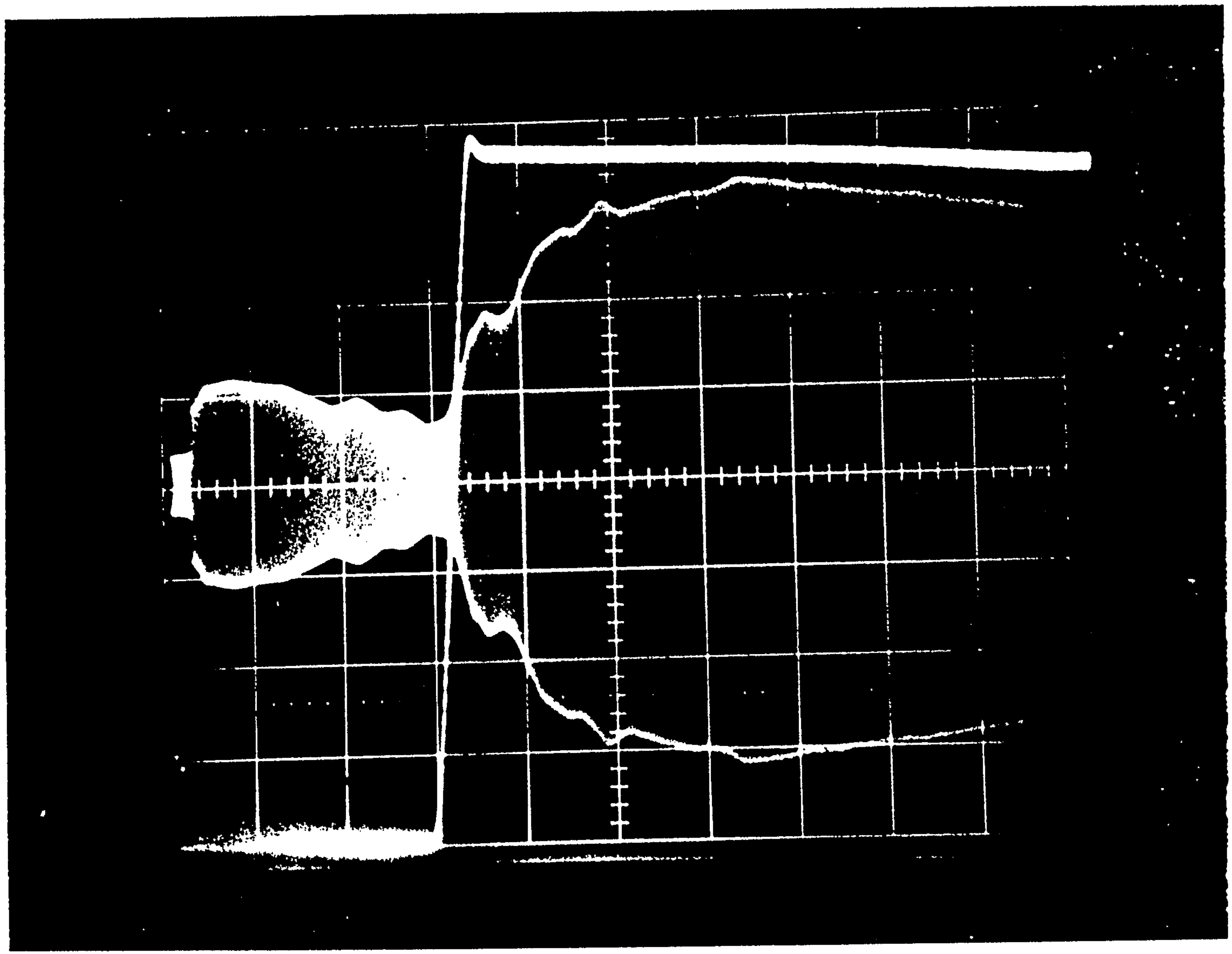


Fig. 10

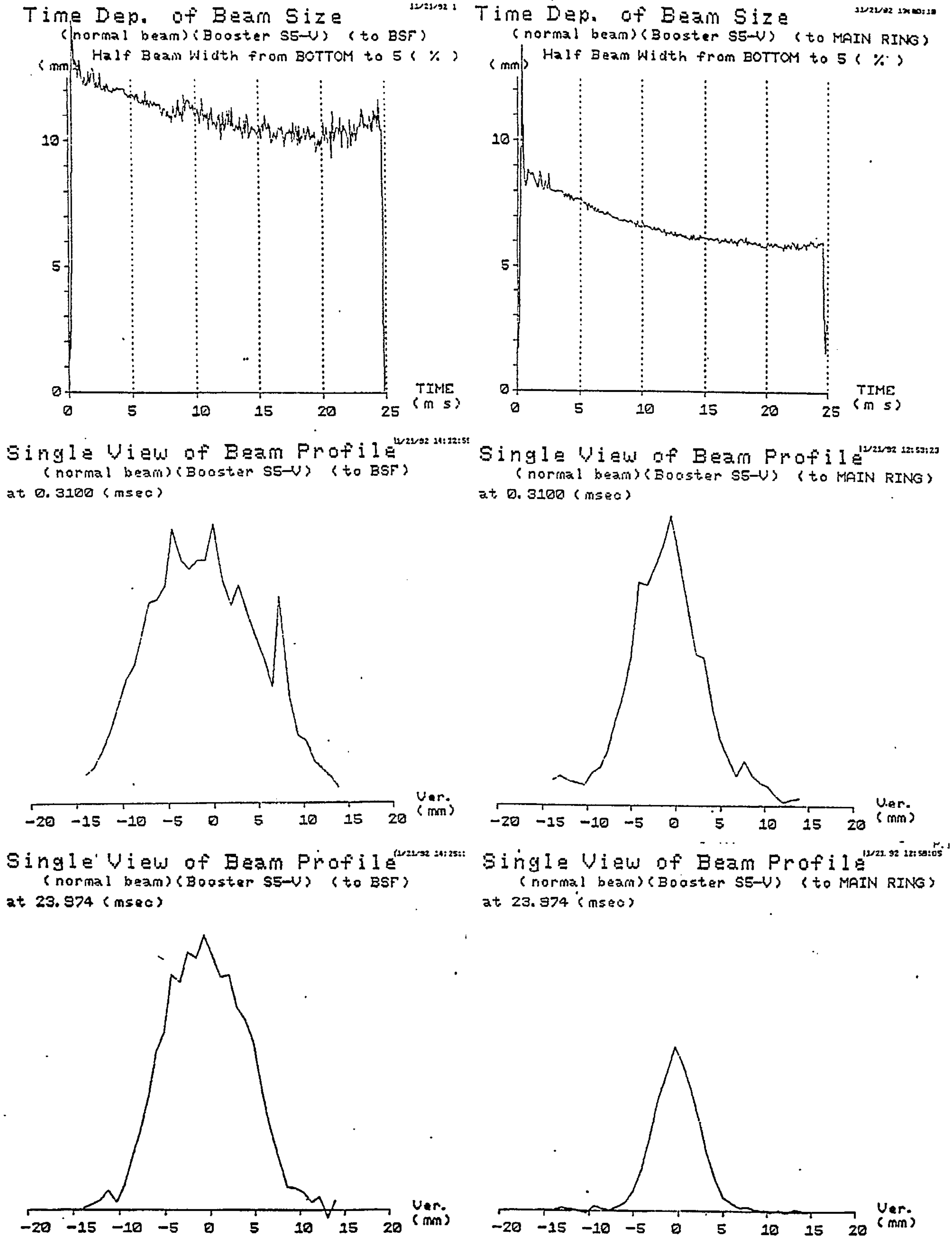


Fig. 11 Vertical Beam Profile in the Booster
measured by NDPM (= IPM)
left : to BSF (high intensity)
right : to MR (low intensity)

T. Kawakubo

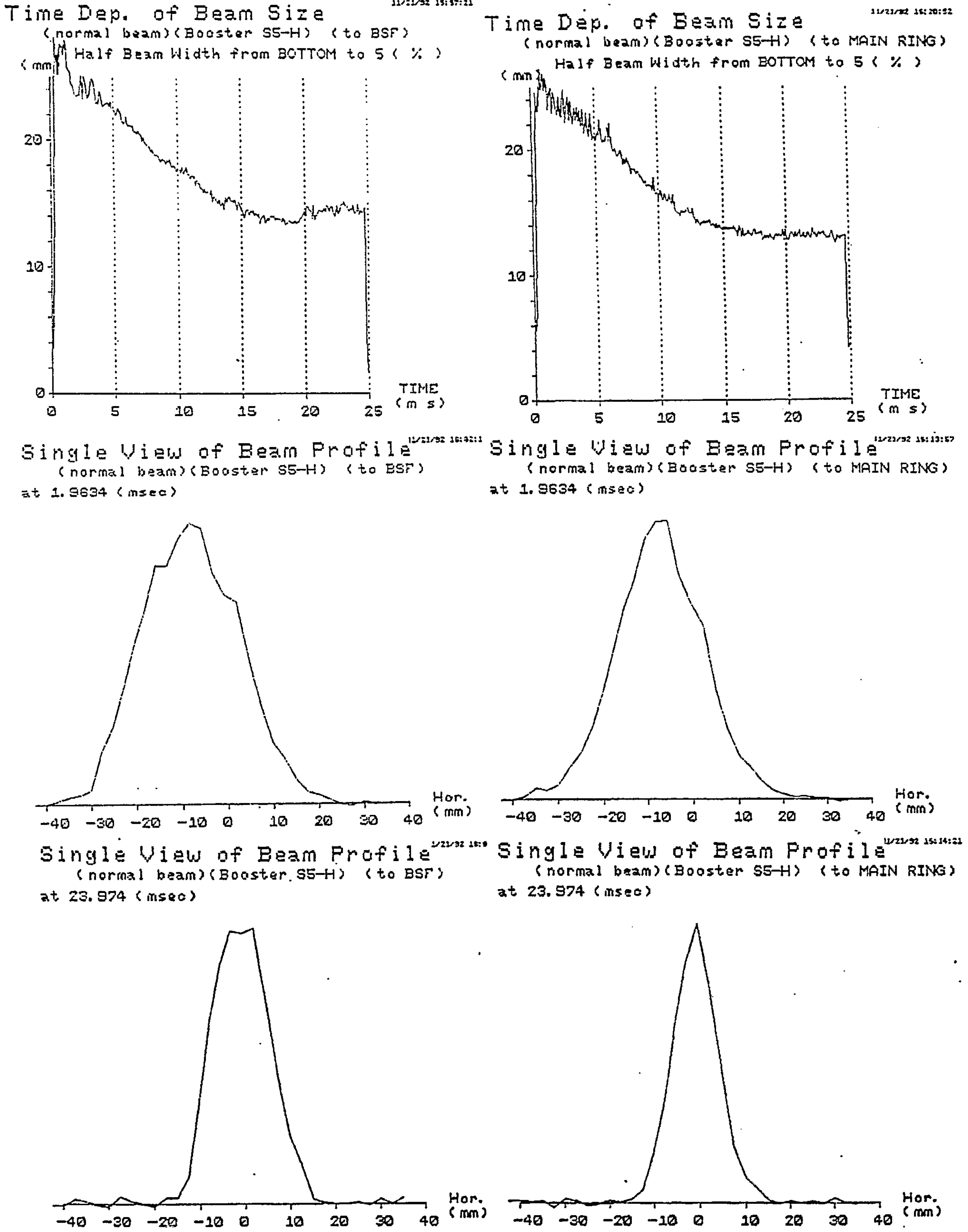


Fig 12 Horizontal Beam profile in the Booster
measured by NDPM (= IPM)

Comparison

In this section we will compare the KEK-Booster and the AGS Booster.

Table IV shows the Boosters parameters. We do not have time to examine all of these parameters; our interest is in the space charge tune shift.

Table V shows the space charge limits. These emittances are not the phase space area. They must be multiplied by π to translate to the area. Values in the brackets are normalized values.

The space charge limits of the KEK-PS and the AGS Booster are calculated in the same way in order to compare them.

$$\epsilon_{max} = [X_{max} - \Gamma max * dP/P_{max}]^2/\beta_{max} \quad \text{(H)}$$
$$\epsilon_{max} = Y_{max}^2/\ \beta_{max} \quad \text{(V)}$$

$$dQ_x = [N\ r_0]/[\ \pi\beta^2\tau^3]/\epsilon_x[1 + \sqrt{\epsilon_y/\epsilon_x}]\ [G/B]\ [4/3]$$

$1/B = 3$	bunching factor
$G = 2$	form factor
4/3	correction factor of the envelope modification

The space charge limit of the AGS Booster is 3 x 10^{13} ppp and the limit of the KEK Booster is 2.2 x 10^{12} ppp.

If we want to keep the very low Linac emittance in the ring, we will have big tune shifts and then we cannot avoid the emittance blow up here.

The table shows the calculated tune shifts at the present. These are much higher than expected, but here the form factor is assumed to be 2. In the real machine it may be smaller because of the painting and the emittances used are 95% emittance instead of the 100% emittances; 100% emittance must be larger.

Table IV Comparision of the KEK Booster and the AGS Booster

			AGS	KEK
Injector (LINAC)				
pre-injector			750keV	WC
kinetic energy		(MeV)	200	40
curent		(mA)	20	10
normalized emittance	H/V	(mm mrad)	7 / 5	7.4 / 4.5
momentum spread		(%)	0.33	0.31
Booster				
Circumference		(m)	202	37
Physical aperture	H X V	(mm)	132 X 132	100 X 60
Betatron tune	H/V		4.82 / 4.83	2.16 / 2.32
Resonance correction			YES	NO
focusing function			separated FODO	combined OFDFO
maximum beta	H/V	(m)	13.9 / 13.6	4.9 / 8.3
minimum beta	H/V	(m)	3.6 / 3.7	1.5 / 0.9
dispersion	max/min	(m)	2.95 / 0.54	1.4 / 0.9
Space charge				
space charge limit		(10^{13}ppp)	3	0.24
incoherent tune spread			0.35	0.11/0.2
maximum intensity (injection,10^{13}ppp)			3	0.26
H^- injection				
stripping foil material			Carbon	Carbon
stripping foil thickness		(ug/cm^2)	150	30
beta	H/V	(m)	10.93 / 5.23	3.5 / 1.55
alpha	H/V		-1.505/ 0.86	0 / 0
dispersion		(m)	2.621	1.4
dispersion angle		(mrad)	0.382	0
Number of turns			200	150
RF capture			Chopped	Adiabatic
harmonic number			3	1

Shoji

Table V

INCOHERENT SPACE CHARGE TUNE SHIFTS OF THE BOOSTERS

		AGS	KEK
Proton energy	(MeV)	200	40
β		0.566	0.283
γ		1.2132	1.0426
$\beta\gamma$		0.687	0.295
$1/\beta^2\gamma^3$		1.75	11.0
Horizontal aperture	(mm)	± 66	± 50
Maximum βx	(m)	13.9	4.9
Momentum spread (%)		0.33	0.31
Maximum dispersion (m)		2.95	1.4
Horizontal acceptance (um)		269(184)	455(134)
Vertical aperture	(mm)	± 66	± 15
Maximum βy	(m)	13.6	8.3
Vertical acceptance	(um)	319(219)	108(32)
Tune	H	4.82	2.16
	V	4.83	2.32
Tune spread limit	H	-0.35	-0.14
	V	-0.35	-0.27
Space charge limit	H	3.1	0.22
	V	3.1	0.23
LINAC emittance	H (um)	10.2(7)	25(7.4)
	V	7.3(5)	15(4.5)
Expected intensity (10^{13}ppp)		3	0.24
Expected tune spread	H	10.9	3.0
	V	12.8	2.3
BOOSTER emittance	H (um)	66(45)	173(51)
	V	31(21)	68(20)
Realized intensity (10^{13}ppp)		3	0.19
Calculated tune spread	H	1.8	0.29
	V	2.7	0.46

Booster Intensity Improvement

The intensity of the KEK-Booster was improved from 1987 to 1988. Then we reached the space charge limit (KEK Ann. Rep. 1988, N. Kumagai, KEK-PS SR-254).

List ii - Intensity Improvement

	1987	1988
Injection Efficiency	90%	97%
(int. 10^{12} ppp)	(1.0)	(2.2)
Extracted Int. 10^{12} ppp		
Maximum	1.5	2.2
Routine Operation	0.8	2.0
Beam Loss at the Booster		Slightly reduced
Pre-Booster (Linac n level)		1/10

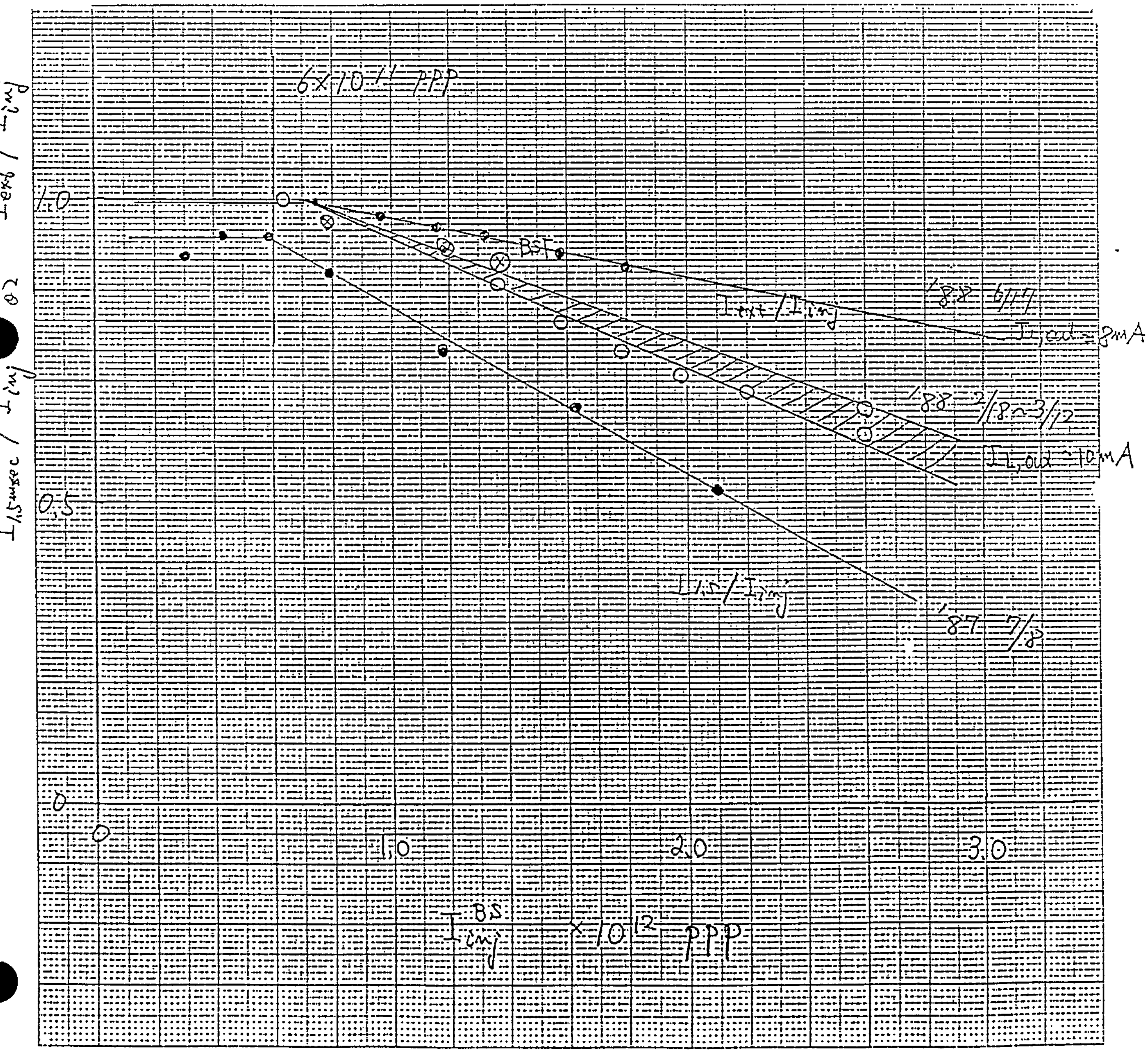
Basically, the intensity was improved by delicate tuning. A few new instruments were introduced. The improvement at injection was mainly due to the smaller emittance of the injected beam and the effective acceleration was due to the improvement of the rf. See List iii for parameter tuning that we did at the time.

図-2 入射ビーム強度と生存率

Injected and Survived beam

I_{inj}^{BS} 入射ビーム強度 injected beam intensity

生存率 ($I_{ext}^{BS}/I_{inj}^{BS}$) or ($I_{1.5msec}^{BS}/I_{inj}^{BS}$)	取り出しビーム I_{ext}^{BS} 又は 入射1.5m秒後のビーム強度 $I_{1.5msec}^{BS}$ を入射ビーム強度 I_{inj}^{BS} で割った値



LIST iii

Parameter tuning (KEK-PS SR-254)

1 LINAC Tank level 1 (20MeV) and 2 (40MeV)
--- optimum power depends on the intensity
(6.0, 5.8)-->(5.7, 6.2)

2 LINAC Tank phase

3 Phases of the pre-buncher and the de-buncher

4 Dipole injection error
--- easy tuning with 500MeV line profile

5 Beam injection timing
(relative to Bmin and Bump)
--- change Db/dt (to lower dB/dt)
--> improve adiabatic capture

6 40MeV line Q-magnet currents

7 LEBT (WC to LINAC) Q-magnet currents
--- LINAC transmission was improved
below 0.5 --> over 0.6

8 Vertical steering was newly installed
into the Booster

9 Reduce Ion source beam current to 1/2
--- LINAC emittance depends on the intensity
20MeV emitt. reduced to 70% of the former

10 Improve ground connection of the Booster RF
---- stable acceleration

Let's look at some of the data. Figure 13 shows intensity vs. Tank 2. This is the relation between the intensity and the optimum Linac rf power. It is the purely empirical result. When Tank 2 had higher levels, the average intensity was higher. For each point, other parameters are optimized.

Figure 14 shows dipole injection error vs. beam parameters. When there is vertical dipole injection error, the beam parameters respond like that. The peak height of the extracted beam line is most sensitive to the injection error. This time the intensity was 0.5×10^{12} ppp (it is low because the beam goes to MR). The emittance of the Linac beam increases as the beam current.

Figure 15 shows current vs. 20 MeV emittance. The Booster ring looks transparent. That means the status of the injection reflects on the extracted beam. Although the transverse emittances blow up greatly in the Booster, the efforts to minimize the emittance of the injected beam were still important. I don't know why--is it important for the efficient painting?

When the Pre-Booster parameters were optimized to have maximum intensity, the beam profiles in the 40 MeV line were much different from the prediction (π-section was not π). Then we decided to replace emittance monitors from 20 MeV to 40 MeV. At this time, I found a space on the line and designed the vacuum chambers (with Mr. Murasugi).

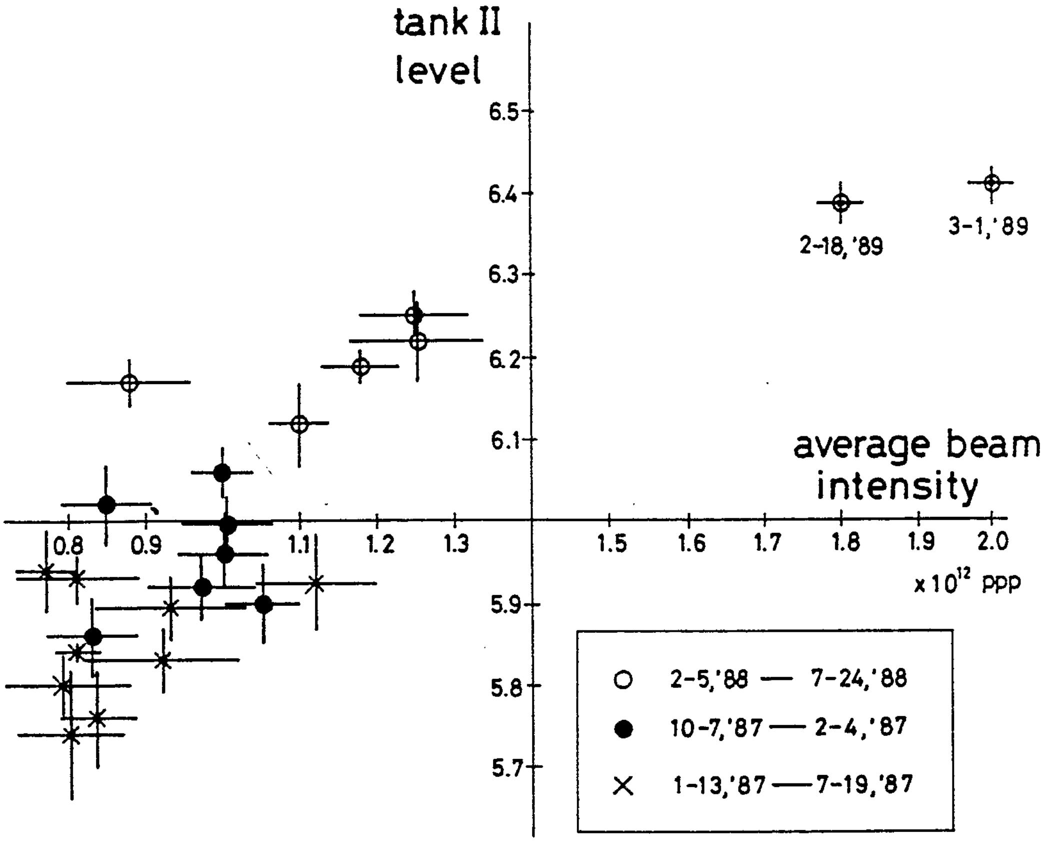


Fig. 13 Correlation between the average beam intensity of the Booster Synchrotron and the rf power level of the Proton Linac tank II.

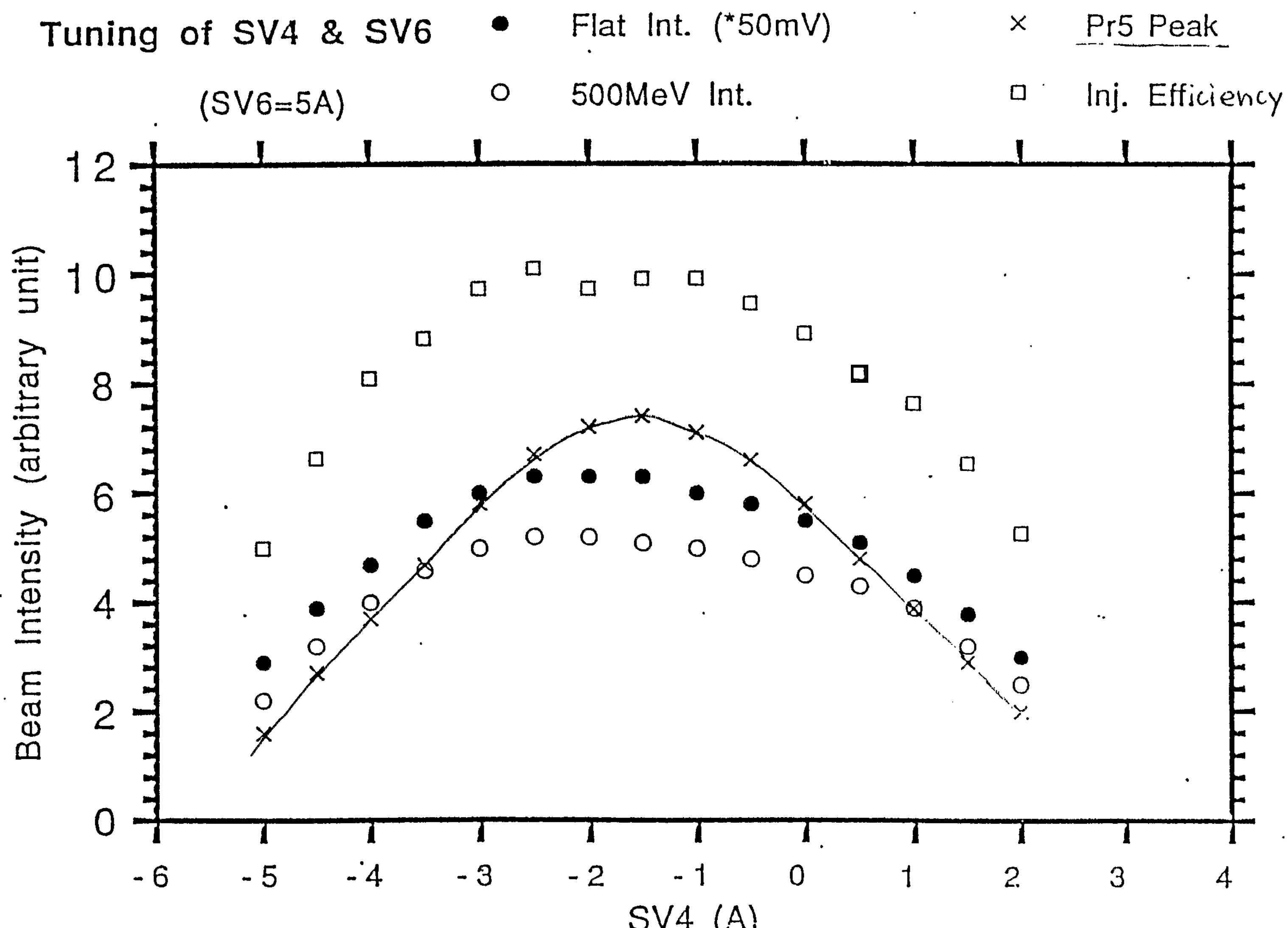
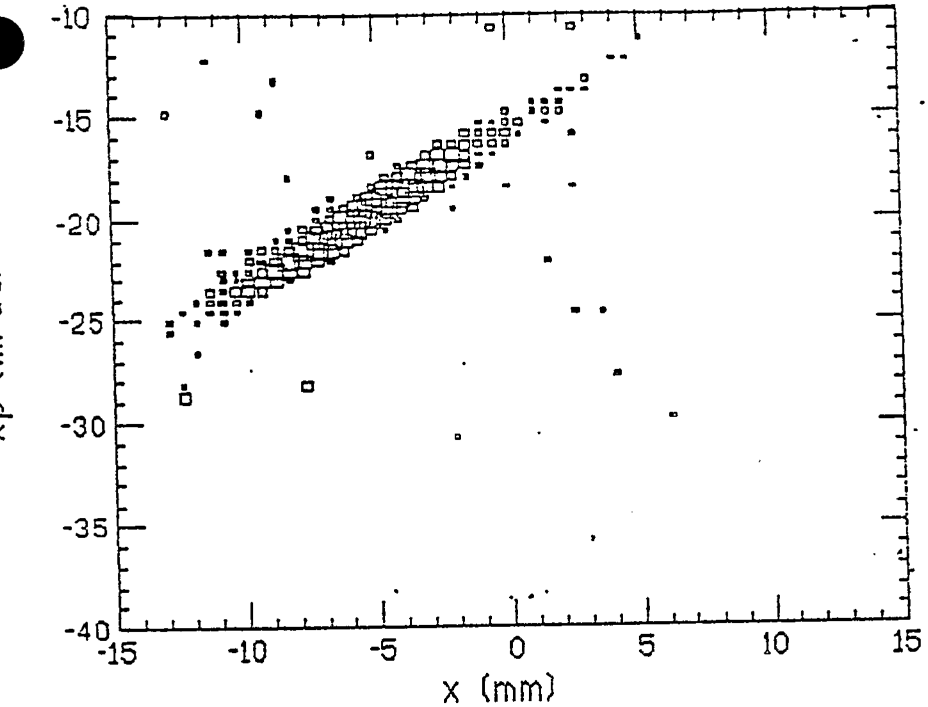


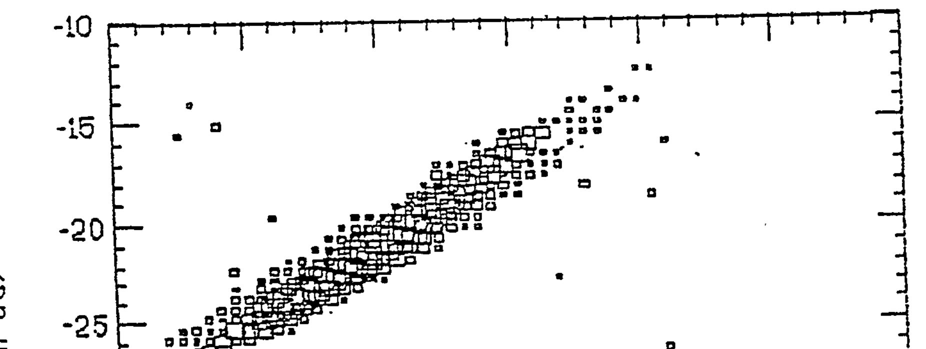
Fig 14 Sensitivity of beam size parameters to the injection error
M. Kihara '91

20 MeV エミッタンス
20MeV emittance

Pre-Injector.
7.5mA (W.C.)



15mA



Intensity vs. Beam Size

When the accelerators were well tuned, and the intensity was close to its space charge limit, what happened? The most important result was the intensity dependence of the beam size in the Booster.

Figure 16 shows the beam size vs. intensity. As the beam intensity increased, the beam size increased gradually, but the particle density at the center of the beam did not. It had a limit. It looked like there was a hard core in the beam. At low intensity, the beam profile looked Gaussian, but at the high intensity it looked more trapezoid (which had a smaller form factor). The intensity was limited by the aperture of the vacuum chamber, in this case 30 mm. It is reasonable! It was measured with the combination of the beam scraper and the fast study bump. The vertical bump rises to the top in 200 μs.

Figure 17 shows the S3 scraper and the fast study bump.

List iv - Beam Size Measurements

We changed the speed of the fast bump, but the result did not change.

We changed the intensity through two methods:

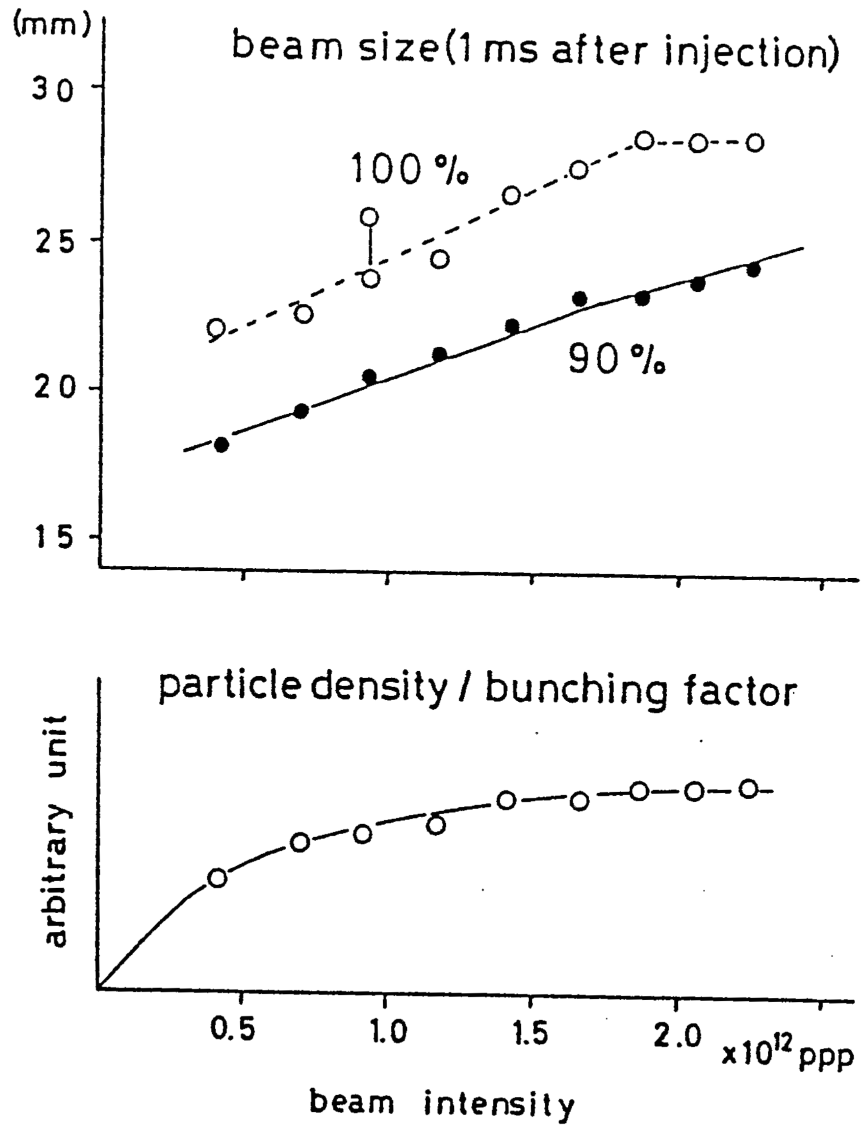
1. insert the thinning-out mesh plate into the 40 MeV line.
2. change Linac beam pulse width

There was not meaningful difference between these.

The beam profile of the extracted beam showed similar results.

With the accelerator finely tuned, then there were no serious beam losses in the Booster.

I am not sure whether we performed the painting, perhaps so. The parameters are tuned to obtain the maximum intensity with the minimum beam size. It was possible that we painted the beam, but not on purpose!



Intensity dependence of the vertical beam size 1 msec after injection.

Fig16

KEK Ann. Rep. 1988 より

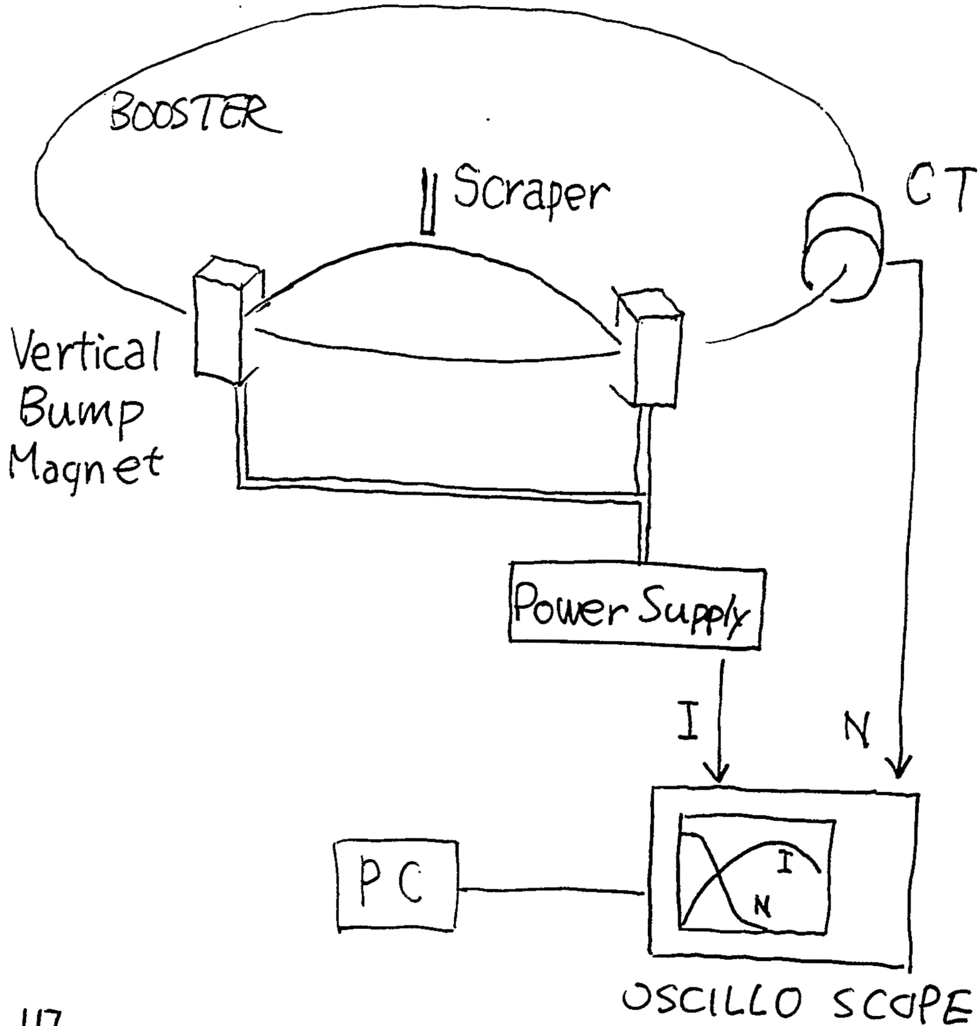


Fig 17

We changed the speed of the fast bump
    But the result did not change

We changed the intensity through two methods
1. insert the thinning-out mesh plate into the 40MeV line
2. change linac beam pulse width

No meaningful difference between these

The beam profile of the extracted beam
    shows the similar results

The accelerator was best tuned
Then there were no serious beam loss in the Booster

Transverse Twiss Parameter Matching

At the KEK-PS the emittance of the Linac beam is basically thought to be not predictable. Figure 18 shows the Linac emittance fluctuation. Shown are the emittances at the exit of the Linac. It is different for each three-week cycle; sometimes it is different every week. It would not be impossible to stabilize this emittance, but the adjustment of the transport line is much easier.

List v -- Matching Procedure

1. Measure the emittance by the Emittance Monitor (2-d density distribution).

2. Calculate the beam image at the stripping foil (α = 0).

3. Calculate the Twiss parameter (eye-ball fit).

4. Calculate the Twiss parameter at the exit of the Linac.

5. Calculate the 40 MeV line Q-magnet currents (use MAGIC).

6. Change Q-magnet current.

7. Measure again.

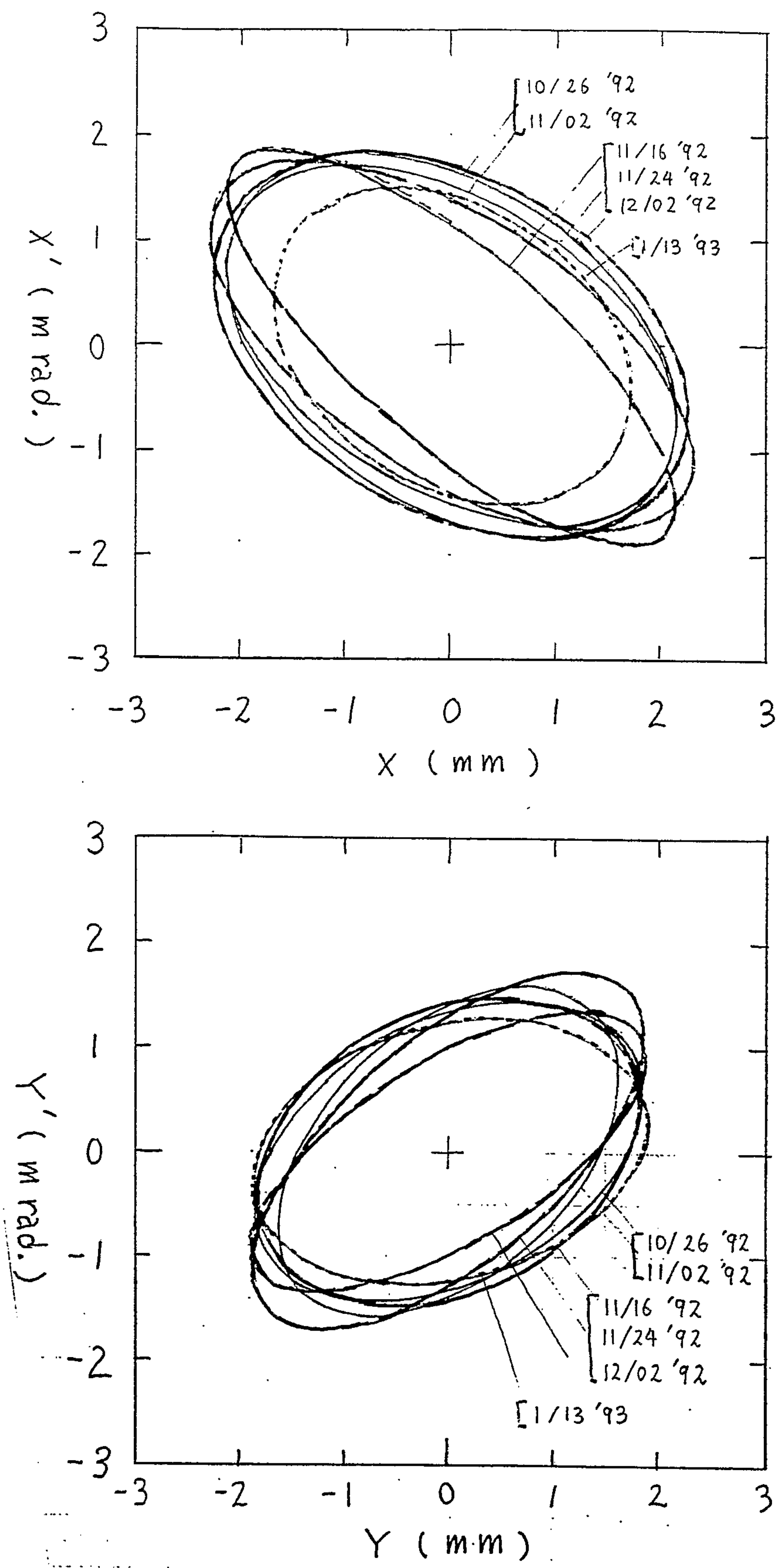


Fig. 18

Transverse emittance at the exit. of the LINAC.

meas. by Adachi , plotted by Shoji

Figure 19 shows the matching procedure. The top figures are the particle distributions in the phase space at the EM slit. The middle figures are the beam image at the stripping foil. Here $\alpha = 0$, then it can be easily recognized. The third figures are the same image after the matching procedure. They are close to the calculated matching conditions. We needed no iteration, that means the Q-magnet adjustment takes place only once. The transport line is well understood and is reliable. That procedure works but it has some problems.

List vi -- Problems of the Procedure

1. We did not subtract the contribution of the dispersion.

2. It is difficult to make simultaneous matching of the Twiss parameters and the dispersion (misdesigned ?). We have to separate the power supplies in the achromatic section (Q10 - Q14).

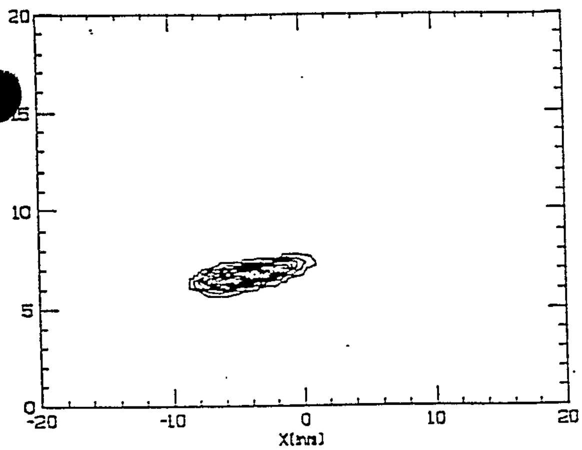
3. It takes a long time (5 min.). We had to stop the beam during the measurement.

4. The particle density distributions are not the simple ellipsoid. Eye-ball fit depends on personality. Difference (center and edge).

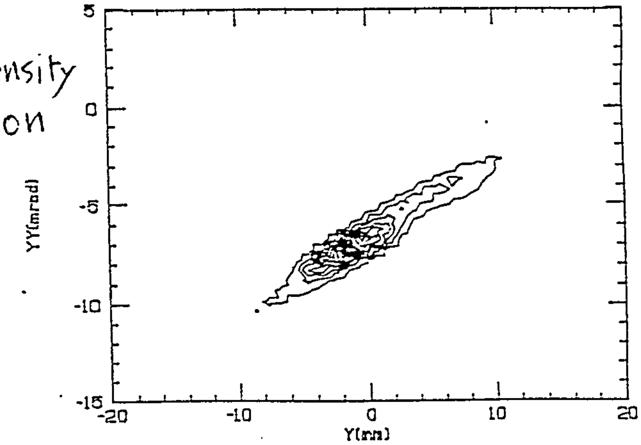
5. Only a small improvement was obtained.

HORIZONTAL

VERTICAL



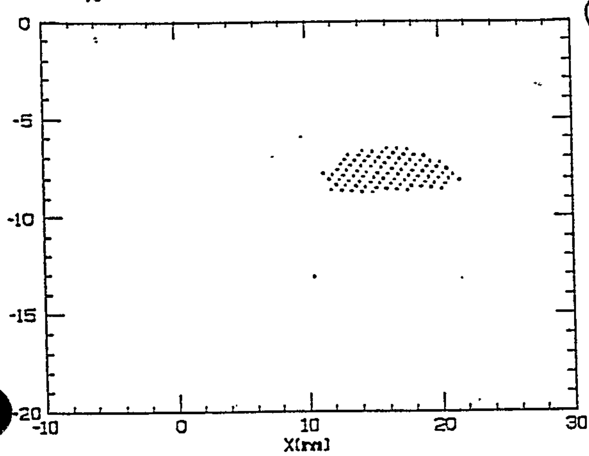
particle density distribution at the emittance monitor

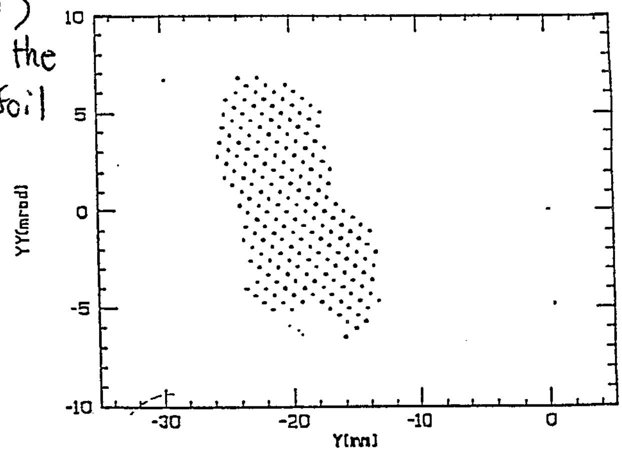


foil 上 100%

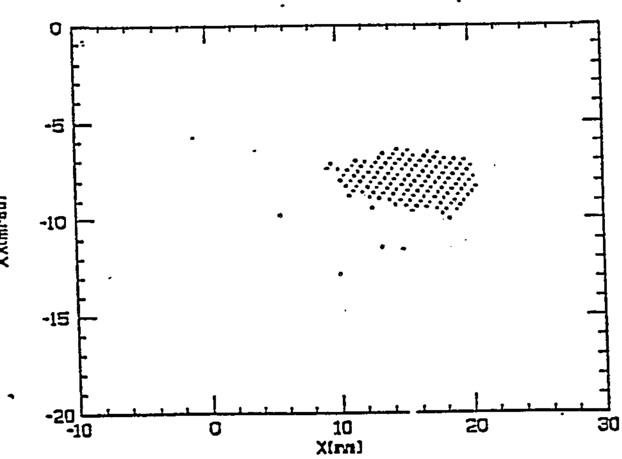
translated (calculated) image on the stripping foil

foil 上 100%





Adjust 40MeV line Qmagnet



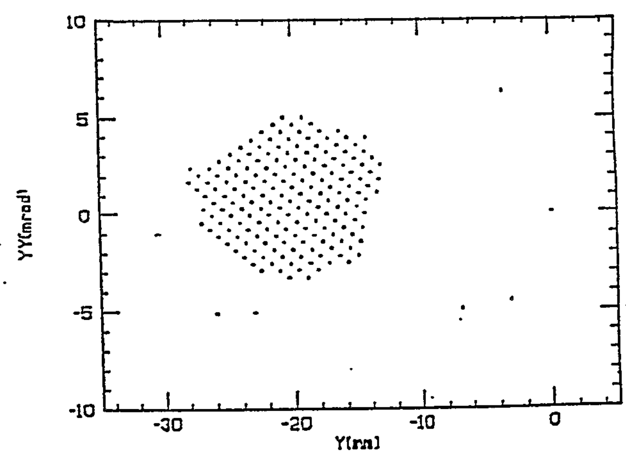


Fig. 19. Twiss parameter matching process. Nov. 14 '91
Beam image on the stripping foil
Before and After

Dispersion Mismatch

Figure 20 shows dispersion in the phase space of the foil. The line corresponds to the mismatch of 1.4 m dispersion and 0.3% momentum spread. The effect of the dispersion mismatch is considerable.

Intrinsic Mismatch

The iso-density contours at the center of the beam and at the edge are considerably different. Figure 21 shows the emittance contour. This is the measured particle density distribution. Compare the shape of the center and the edge.

Figure 22 shows two-scale contours. One shape (solid) is the contour at the edge. The other shape (broken) is the contour at the center, with the scale (position and angle), five times larger. I fitted these shapes with the ellipse.

The emittance blow up due to this mismatch between the center and the edge is 1.38 for horizontal and 2.28 for the vertical. The mismatch is considerable in the vertical. This mismatch produces not the simple blow up, but the deformation of the shape. This figure shows the schematic profiles. What we can do is to select one of these. Of course, this mismatch strongly depends on the Linac beam current. We have gotten data on this.

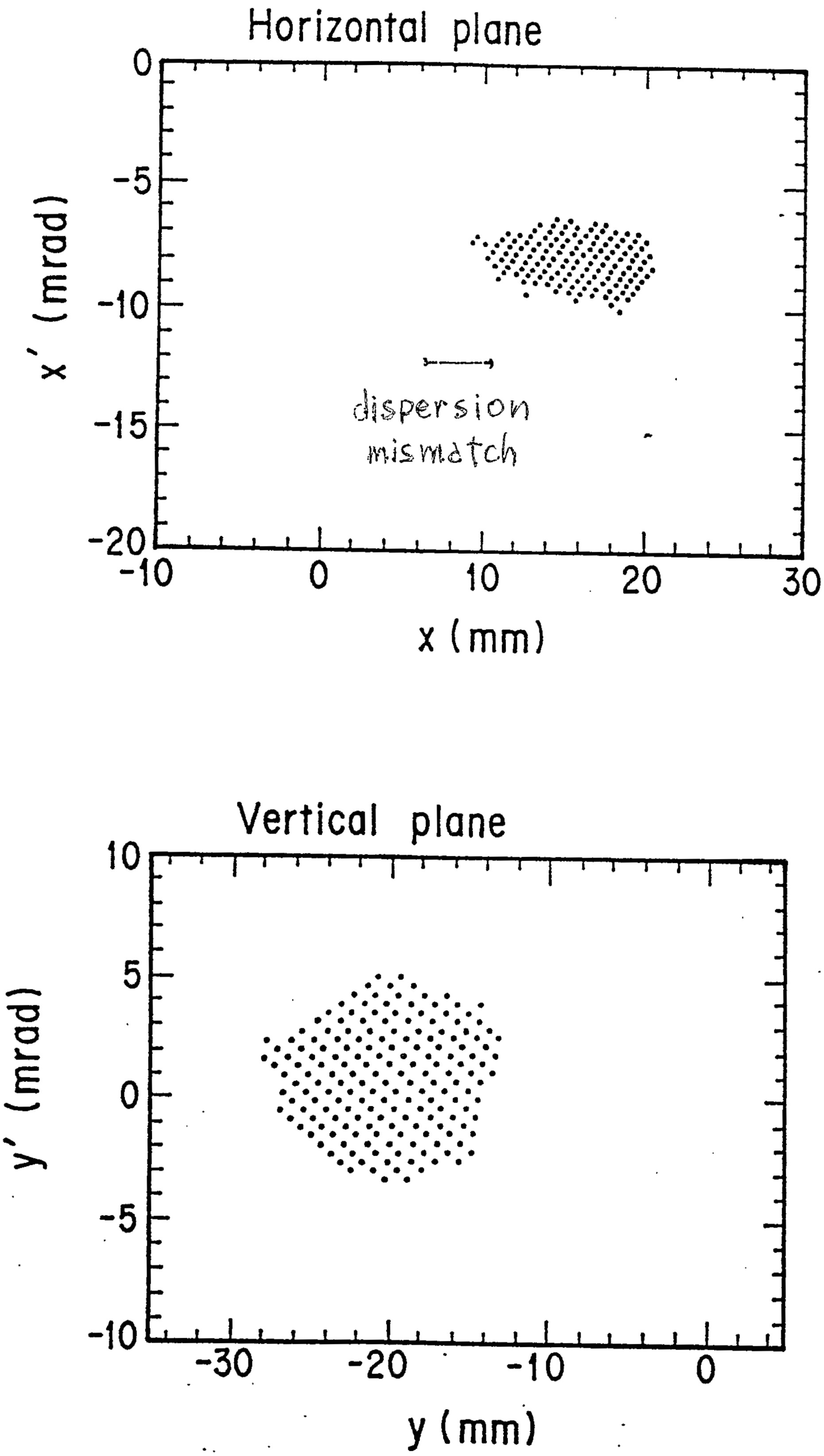
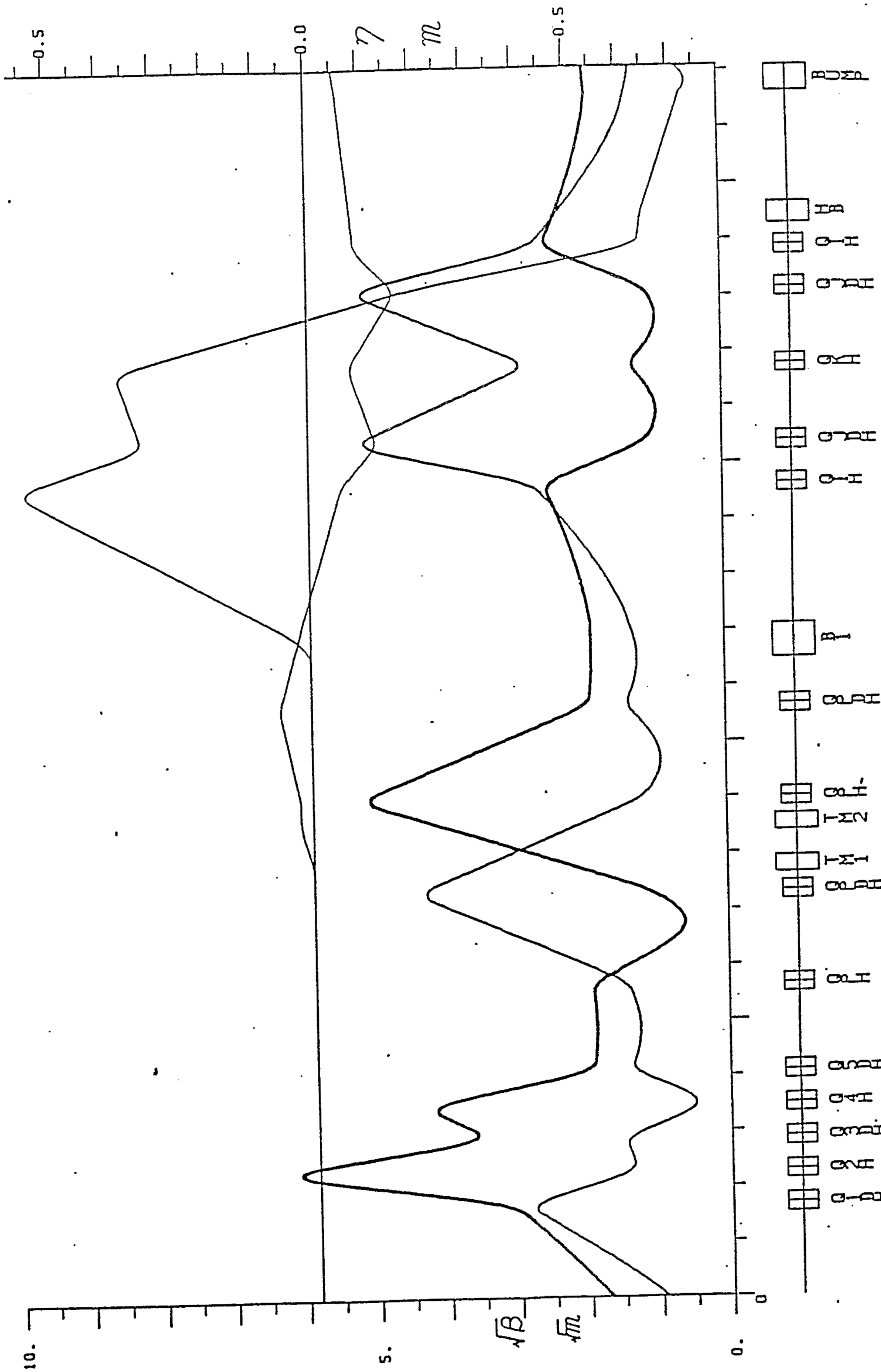
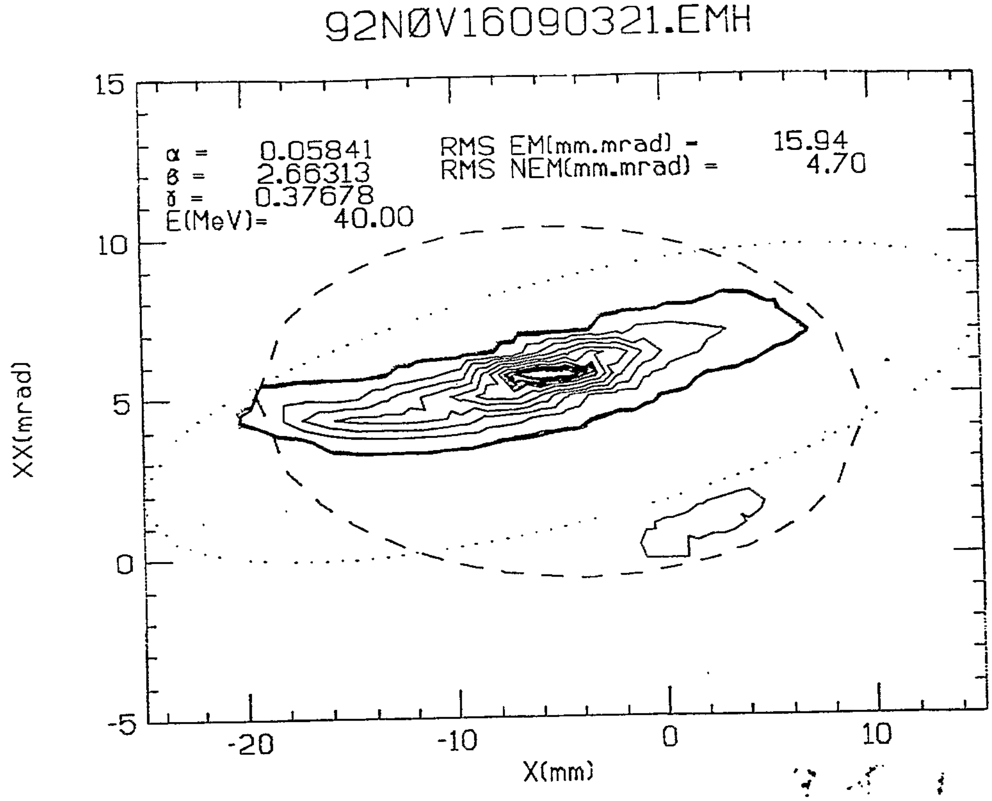


Fig. 20 Transverse phase-space distribution at the injection point. This phase-space distribution was calculated using the observed emittance and new currents of the quadrupole magnets calculated using the ...





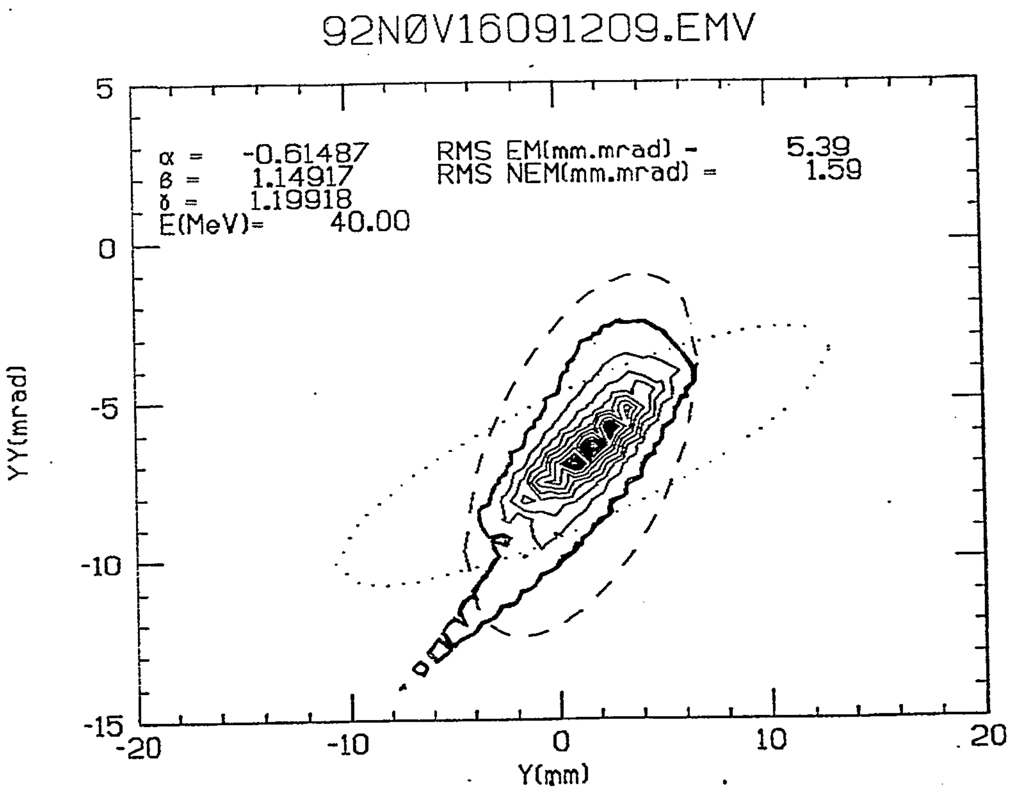
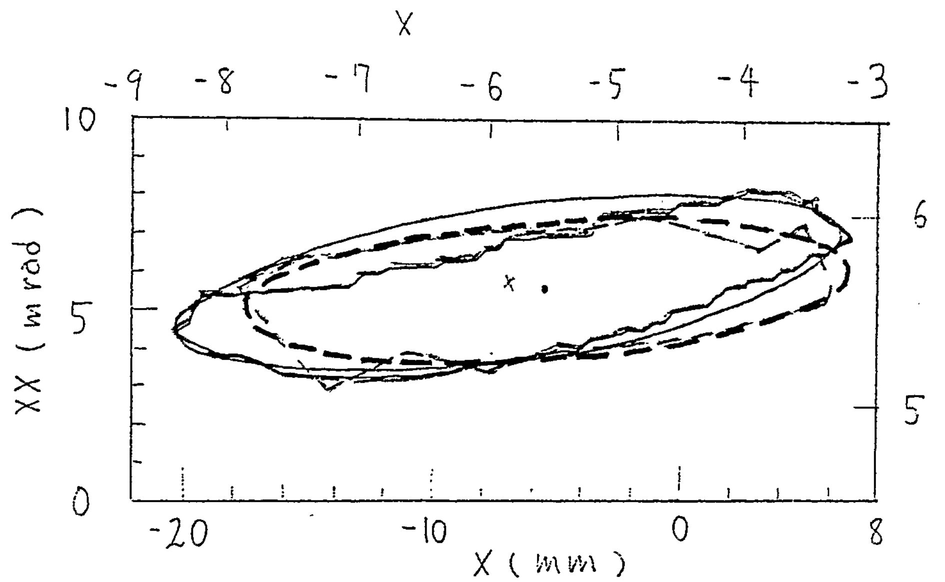
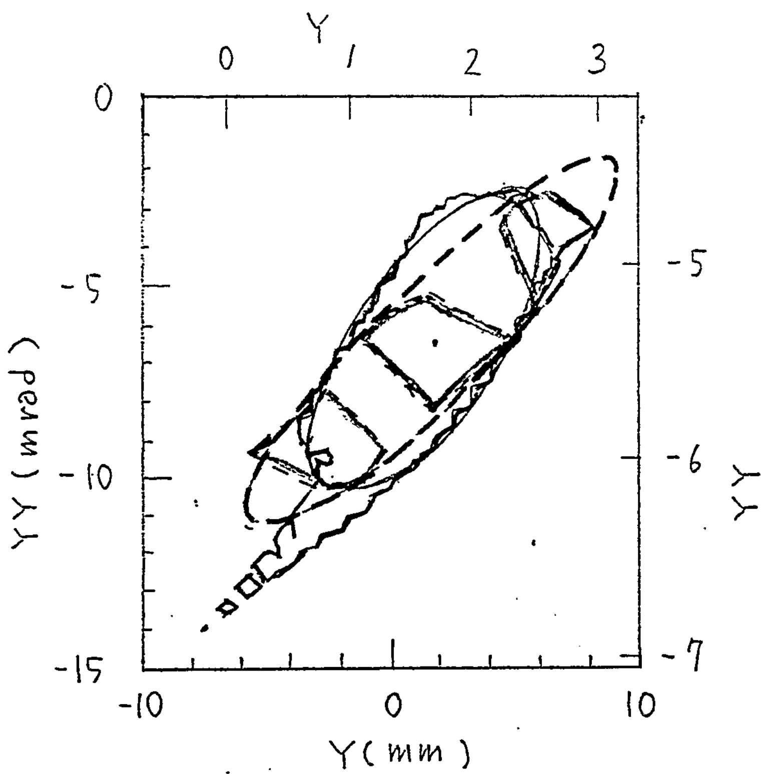


Fig. 21 Example of 40 MeV line emittance
measured on Nov.16 '92.
Broken ellipsoids — RMS emittance
Dotted ellipsoids — Calculated from 7 profiles of MWPM.



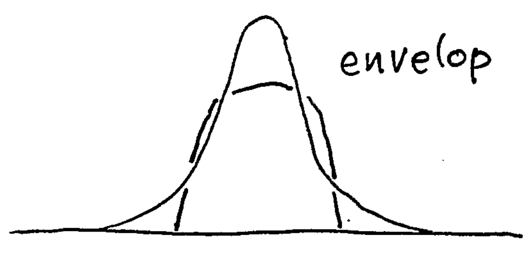
ε
1.38



2.28

Fig. 22 Approximated ellipsoids

matching - center



Simple Emittance Measurement

Dr. Adachi is now developing the more simple procedures to measure the emittance, using the seven profile monitors (talk by T. Adachi, KEK-PS Machine Study Meeting, 1992). The purpose is to make the matching procedure faster.

Measurement of the emittances, data analysis, optics calculation, and power supply control are done on the same computer (VME).

The old method:

Measurement	VAX
Optics	HITAC (Hitachi)
Power Supply	VME

There is no eye-ball fitting. The time needed to stop the accelerator is much shorter.

List vii -- Matching Procedure

1. Measure 7 x 2 (H & V) profiles.

2. Fit the profiles with Gaussian
   4 parameters: area, offset, width, center

3. χ^2 fit (Grid search)
   3 parameters: α, β, emittance

4. Calculate the Q-magnet currents (MAGIC).

5. Set Q-magnet current.

6 Return to 1.

Results

1. Needs some iterations (3 times); sometimes it did not focus to one value.

2. The results are close to the envelope emittance (V).

3. The other method gives more accurate results. Change Q-magnet current; measure 3 monitors.

The main control computer (VME) controls the whole process: profile measurement, parameter fitting, lattice calculation, and Q-magnet power supply control. Automatic control is planned for the future. The VAX is not connected to the VME.

Table VI shows the emittances by the various methods. They are different from each other. The RMS emittances are not correct because the far-aside islands are taken into consideration. The discrepancy is about a factor of 2 (emittance blow-up factor).

Figure 23 shows the 14 profile fit. The Gauss fittings are not always good in some channels. The two-dimensional density distribution can produce the profiles (experimentally almost the same), but the fitted profiles cannot reproduce the density distribution.

Figure 24 shows the profiles calculated from the emittance.

able VI Twiss parameters at the slit of the emittance monitor on Nov.4 '92. RMS fit gives the much different value. Because it takes into account the beam halo.

data	fitting method	Horizontal alfa	Horizontal beta	Vertical alfa	Vertical beta
1	RMS fit	0.66	2.66	-0.61	1.15
2	Eye ball fit to the envelope	-0.55	6.68	-0.93	1.64
3	Eye ball fit to the center	-0.47	6.84	-2.18	3.73
4	Fit 7 MWPM on 40MeV line	-1.5	13.10	-1.09	1.53

	emittance blow up factor (Horizontal)	emittance blow up factor (Vertical)
data 2 and data 3	1.38	2.28
data 2 and data 4	2.09	1.08
data 3 and data 4	2.16	2.55

$$(\varepsilon/\varepsilon_0)^2 + [\,(\beta_1-\beta_2)(\gamma_1-\gamma_2) - (\alpha_1-\alpha_2)^2 - 2]\,(\varepsilon/\varepsilon_0) + 1 = 0$$

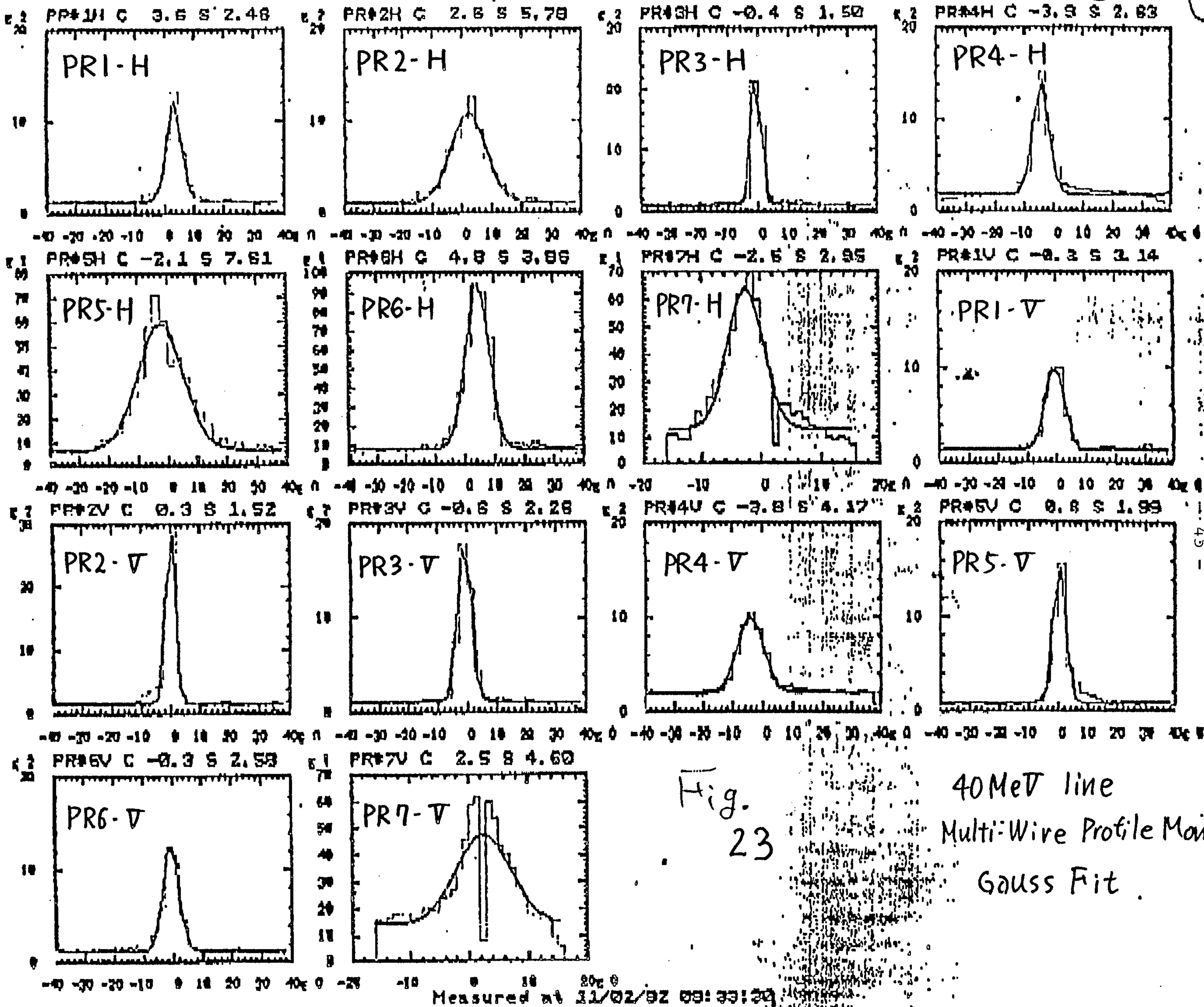


Fig. 23

40MeV line

Multi-Wire Profile Mon.

Gauss Fit.

Fig 24 1/4

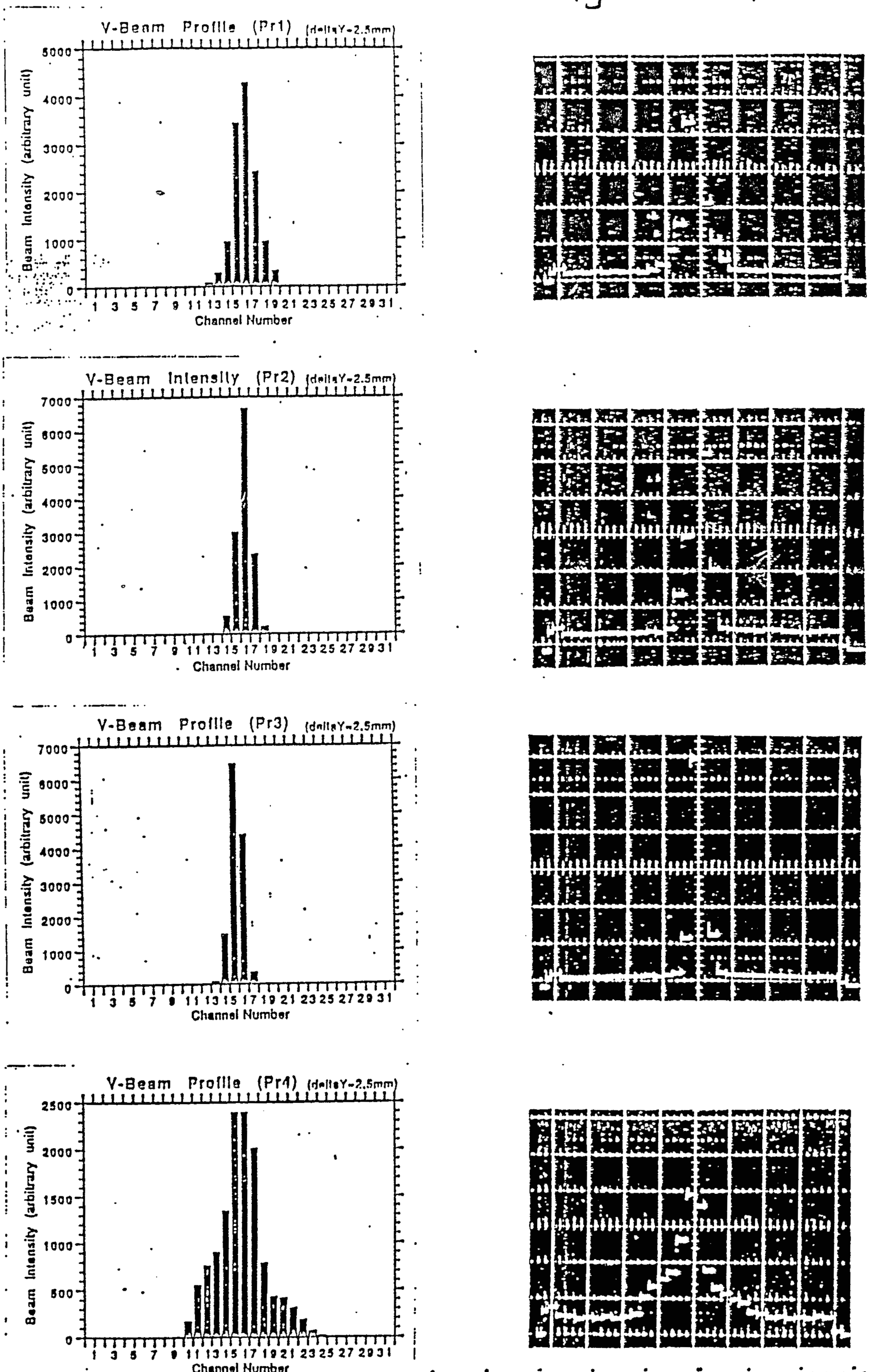
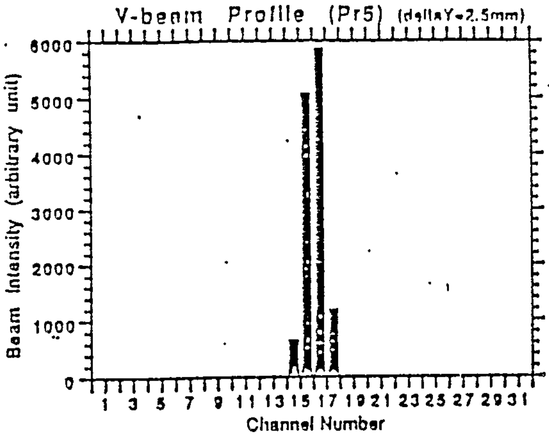
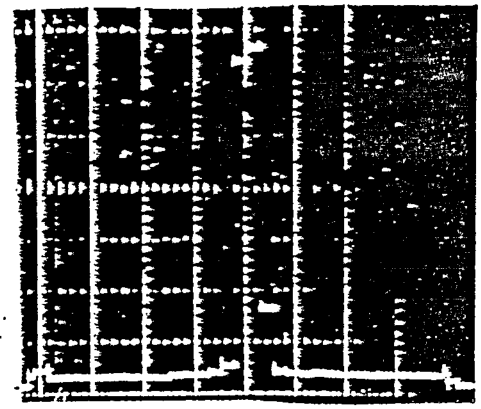
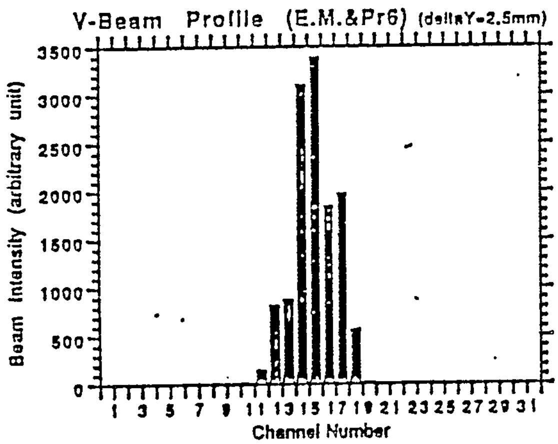
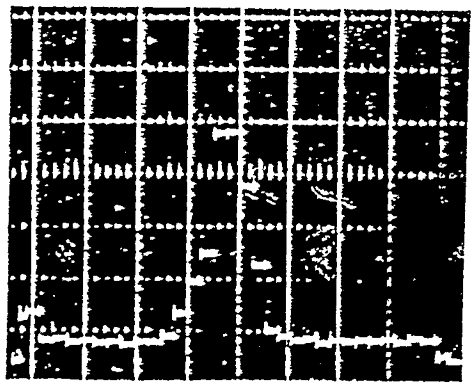

V-Beam Profile (Pr1) (deltaY=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number
V-Beam Intensity (Pr2) (deltaY=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number
V-Beam Profile (Pr3) (deltaY=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number
V-Beam Profile (Pr4) (deltaY=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number

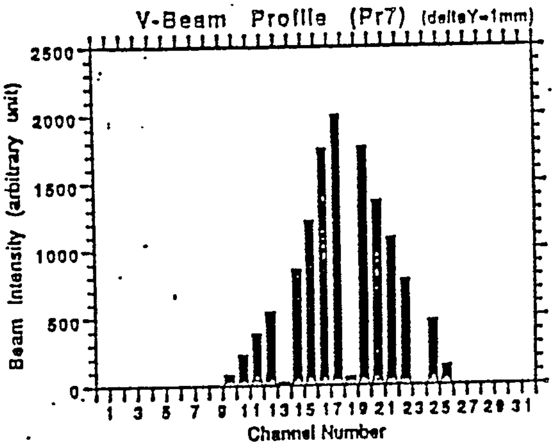
Fig 21 2/4

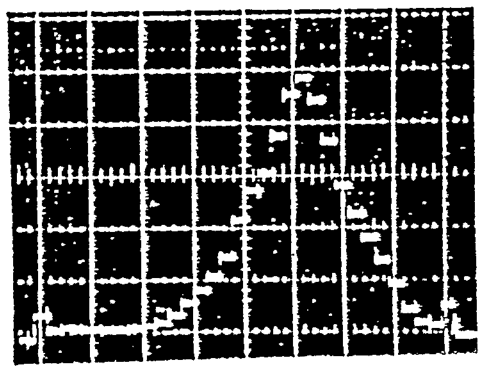

V-beam Profile (Pr5) (deltaY=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number

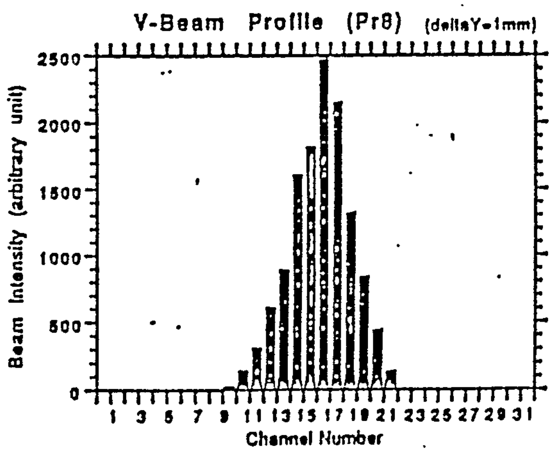


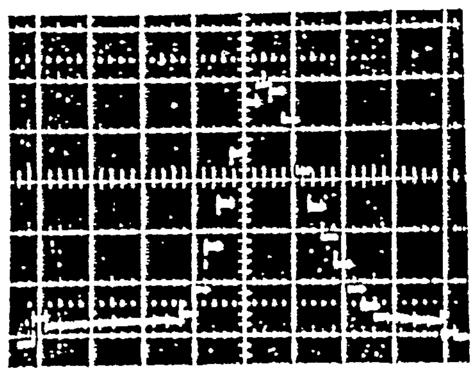

V-Beam Profile (E.M.&Pr6) (deltaY=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number

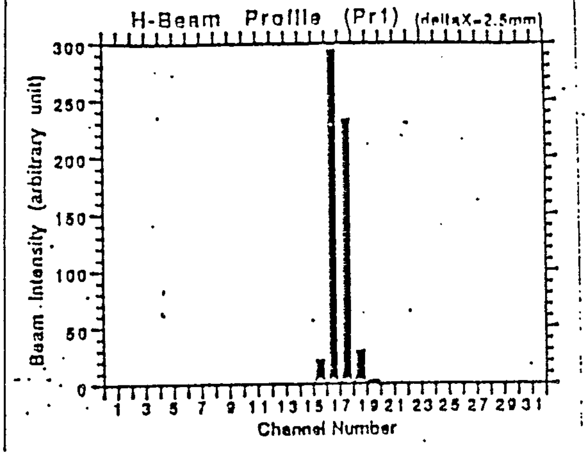


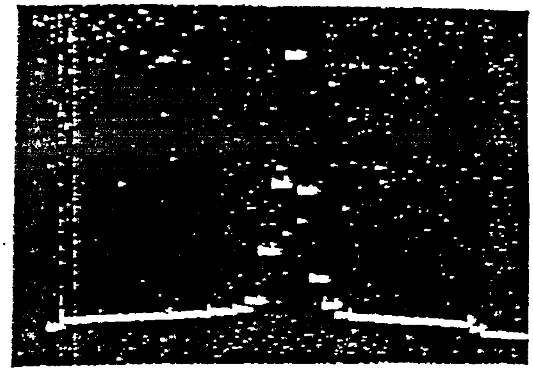

V-Beam Profile (Pr7) (deltaY=1mm)
Beam Intensity (arbitrary unit)
Channel Number

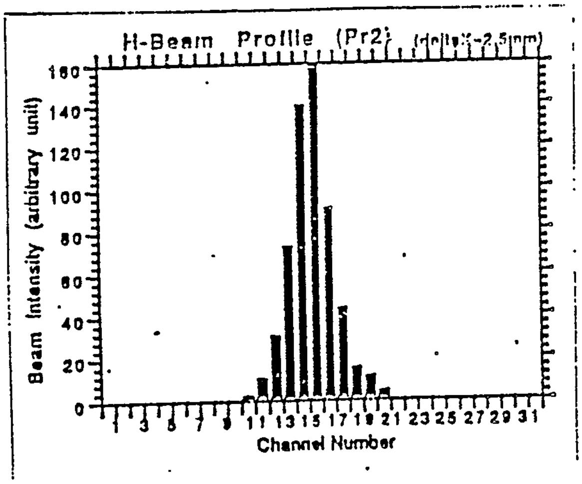


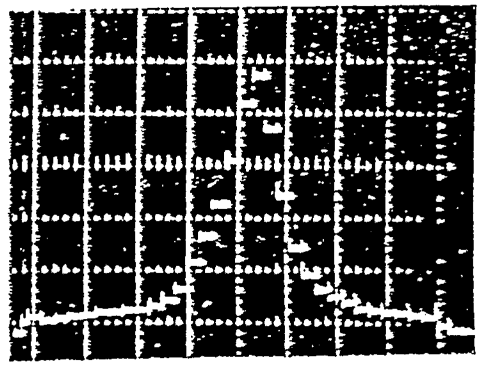

V-Beam Profile (Pr8) (deltaY=1mm)
Beam Intensity (arbitrary unit)
Channel Number

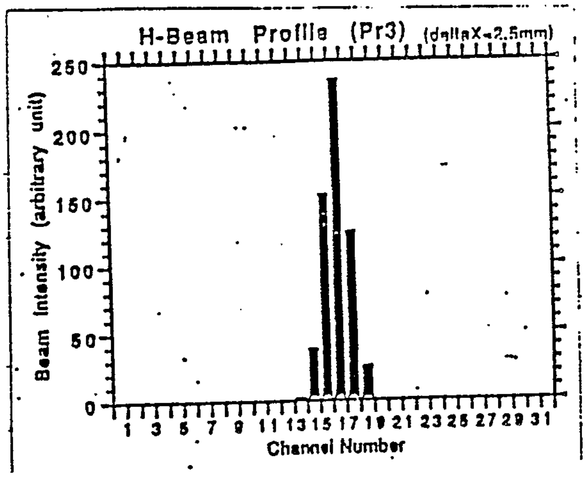


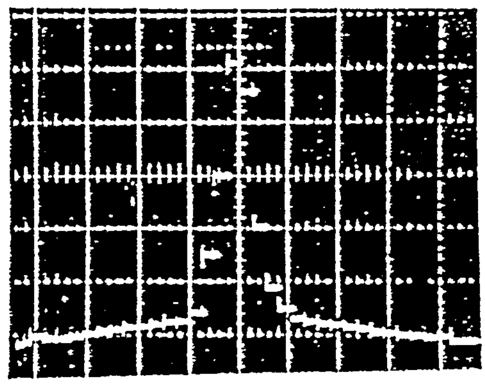

H-Beam Profile (Pr1) (deltaX=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number

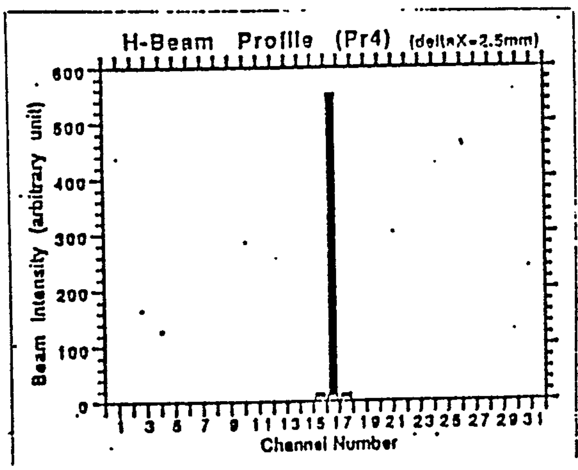


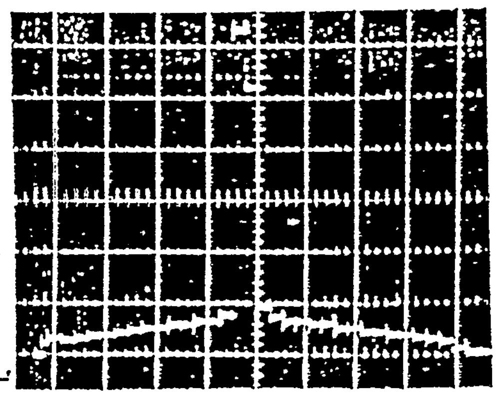

H-Beam Profile (Pr2) (deltaX=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number




H-Beam Profile (Pr3) (deltaX=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number

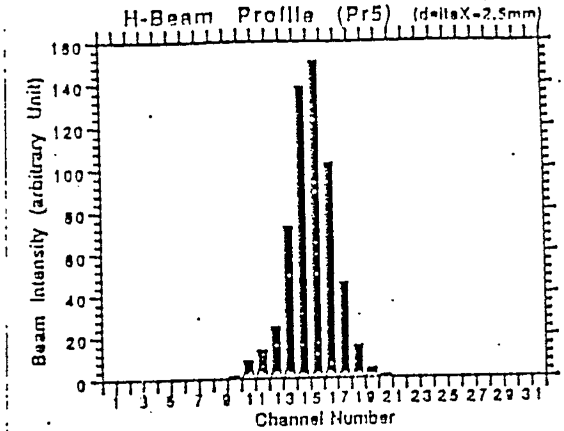


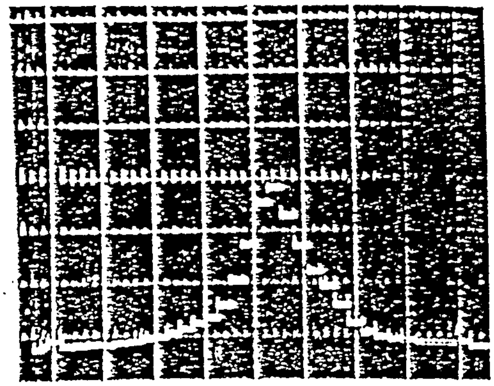

H-Beam Profile (Pr4) (deltaX=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number

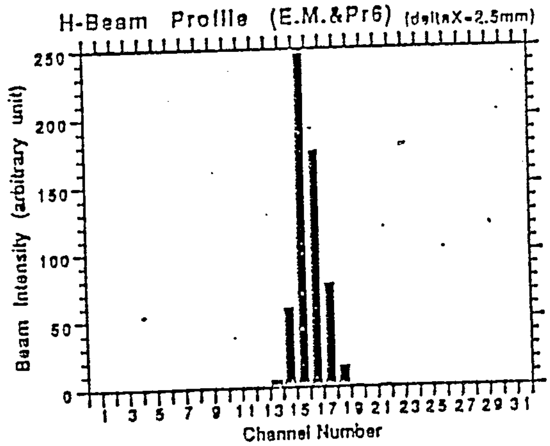


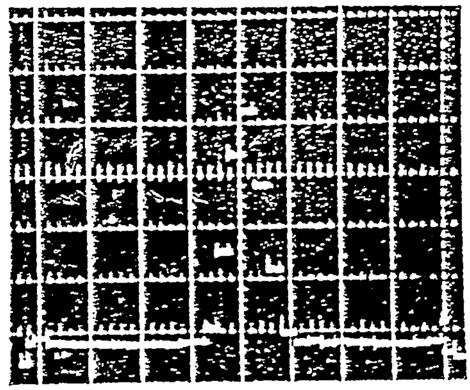
KEK

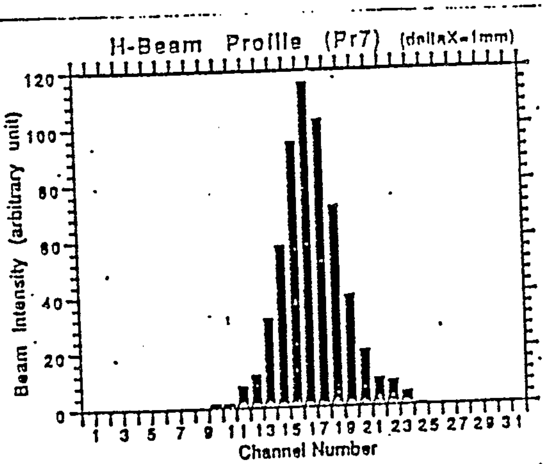
Fig 24 4/4

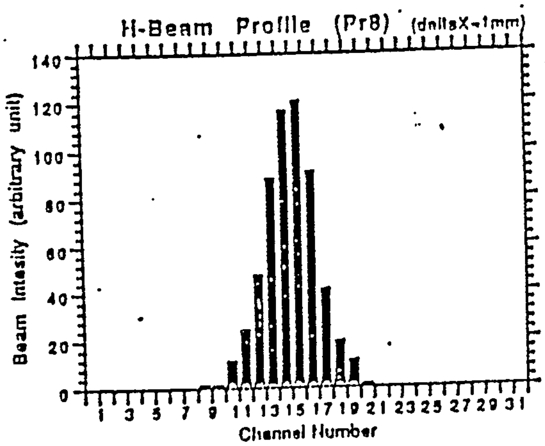

H-Beam Profile (Pr5) (deltaX=2.5mm)
Beam Intensity (arbitrary Unit)
Channel Number




H-Beam Profile (E.M.&Pr6) (deltaX=2.5mm)
Beam Intensity (arbitrary unit)
Channel Number




H-Beam Profile (Pr7) (deltaX=1mm)
Beam Intensity (arbitrary unit)
Channel Number


H-Beam Profile (Pr8) (deltaX=1mm)
Beam Intesity (arbitrary unit)
Channel Number

Before I close my presentation, I want to show you what the problems are at injection to the MR. I believe that they are also suggestive.

Intensity Dependence of the Resonance Line

Figure 25 shows the resonance lines at Qh = 7.40. The first data is about the resonance lines. This is the result of the vertical tune survey at Qh = 7.4. The beam is low intensity and de-bunched to a coasting beam. The resonance lines up to the 4th order are assigned as written below. But for the high intensity bunched beam, these resonances are connected and are deeper.

There is other data. Figure 26 shows the injection tune survey. We moved the tune from one point to another point to cross this resonance line (Qh - Qv = 0, 2Qh - 2Qv = 0) and looked at the beam loss. This is like the work Kip Gardner did at the AGS Booster. There are no resonances lower than the 5th order along the path.

Figure 27 shows the resonance Qh = Qv. When the beam is coasting, the loss is small and sharp, but when the beam is bunched, the loss becomes deeper and broader. My expectation was that the beam loss would not change much, but would be three times slower (bunching factor = 3). The resonances depend very much on the intensity or rf (bunched or unbunched). I think that we should first correct the resonance lines with low intensity, but we should remember that it will not be sufficient.

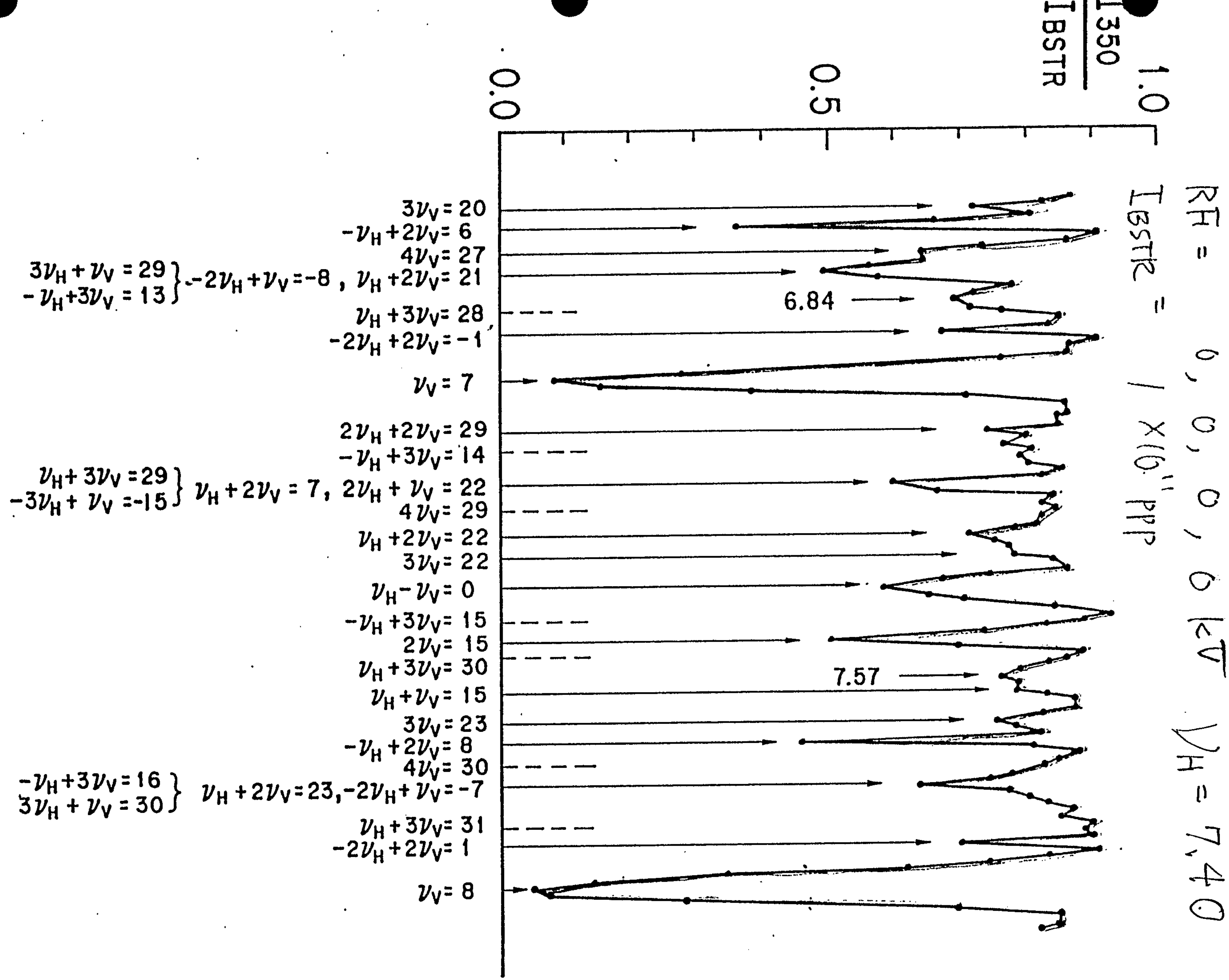

I1350
IBSTR
0.0
0.5
1.0
RF = 0, 0, 0, 0 kV
IBSTR = / ×10¹¹ ppp
νH = 7.40
3νV = 20
-νH + 2νV = 6
4νV = 27
3νH + νV = 29
-νH + 3νV = 13
-2νH + νV = -8 , νH + 2νV = 21
6.84
νH + 3νV = 28
-2νH + 2νV = -1
νV = 7
2νH + 2νV = 29
-νH + 3νV = 14
νH + 3νV = 29
-3νH + νV = -15
νH + 2νV = 7, 2νH + νV = 22
4νV = 29
νH + 2νV = 22
3νV = 22
νH - νV = 0
-νH + 3νV = 15
2νV = 15
νH + 3νV = 30
7.57
νH + νV = 15
3νV = 23
-νH + 2νV = 8
4νV = 30
-νH + 3νV = 16
3νH + νV = 30
νH + 2νV = 23, -2νH + νV = -7
νH + 3νV = 31
-2νH + 2νV = 1
νV = 8

Fig 25 1/2

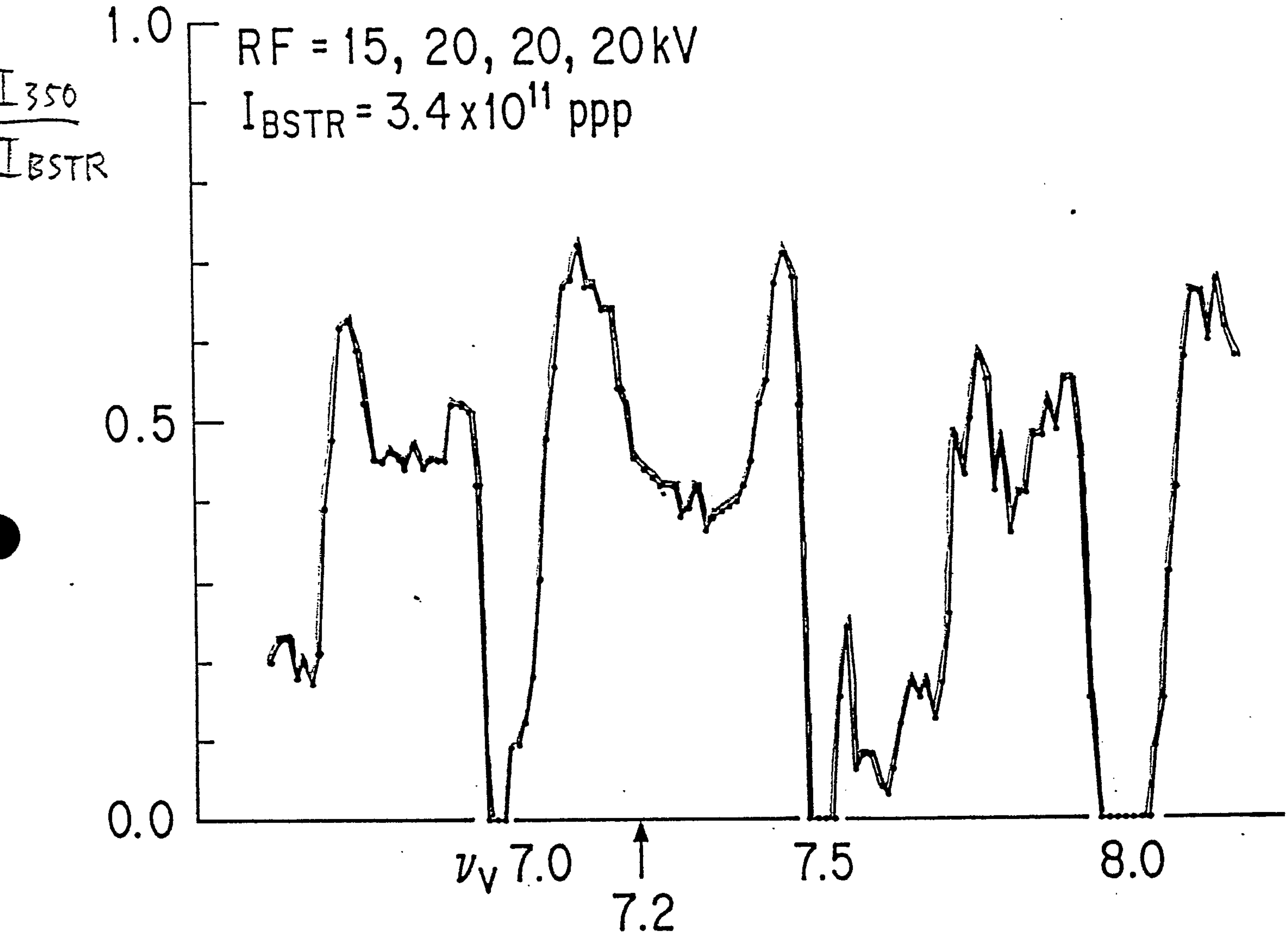

1.0
0.5
0.0
$\frac{I_{350}}{I_{BSTR}}$
RF = 15, 20, 20, 20 kV
I_{BSTR} = 3.4 x 10^{11} ppp
ν_V 7.0
7.2
7.5
8.0

Fig 25 2/2

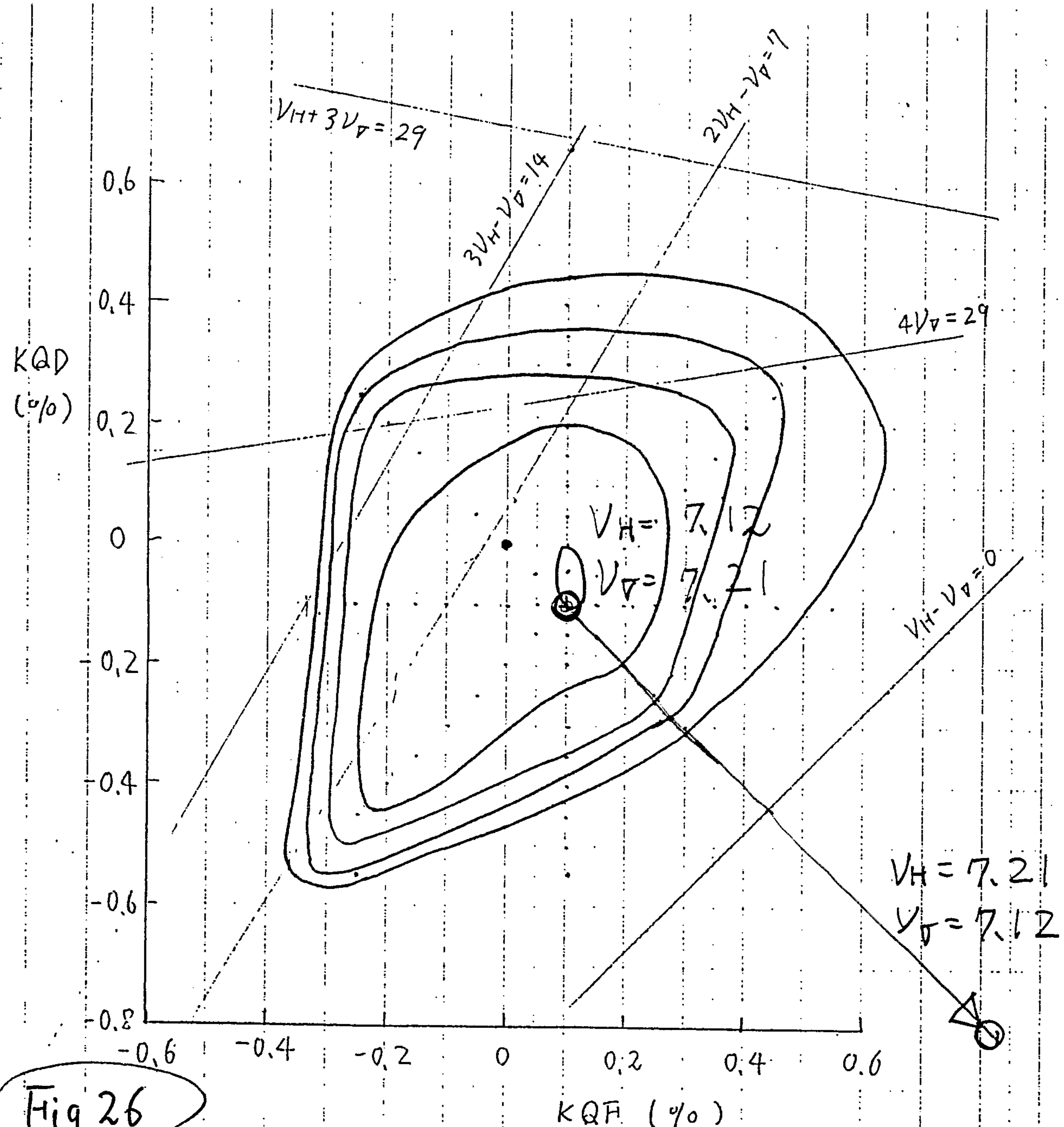


Fig 26

図26　MR Injection　Working Point 付近の tune survey.
等高線は、K9 の intensity で　1×10^{11} ppp 間隔。図中の・(ドット)が測定点を示す。　Sextupole は current = 0 で、remanent field のみ.

Tune spread は $\xi = -6$ とすると、$\Delta P/P = \pm 0.4\%$ なので $\Delta\nu = \pm 0.17$

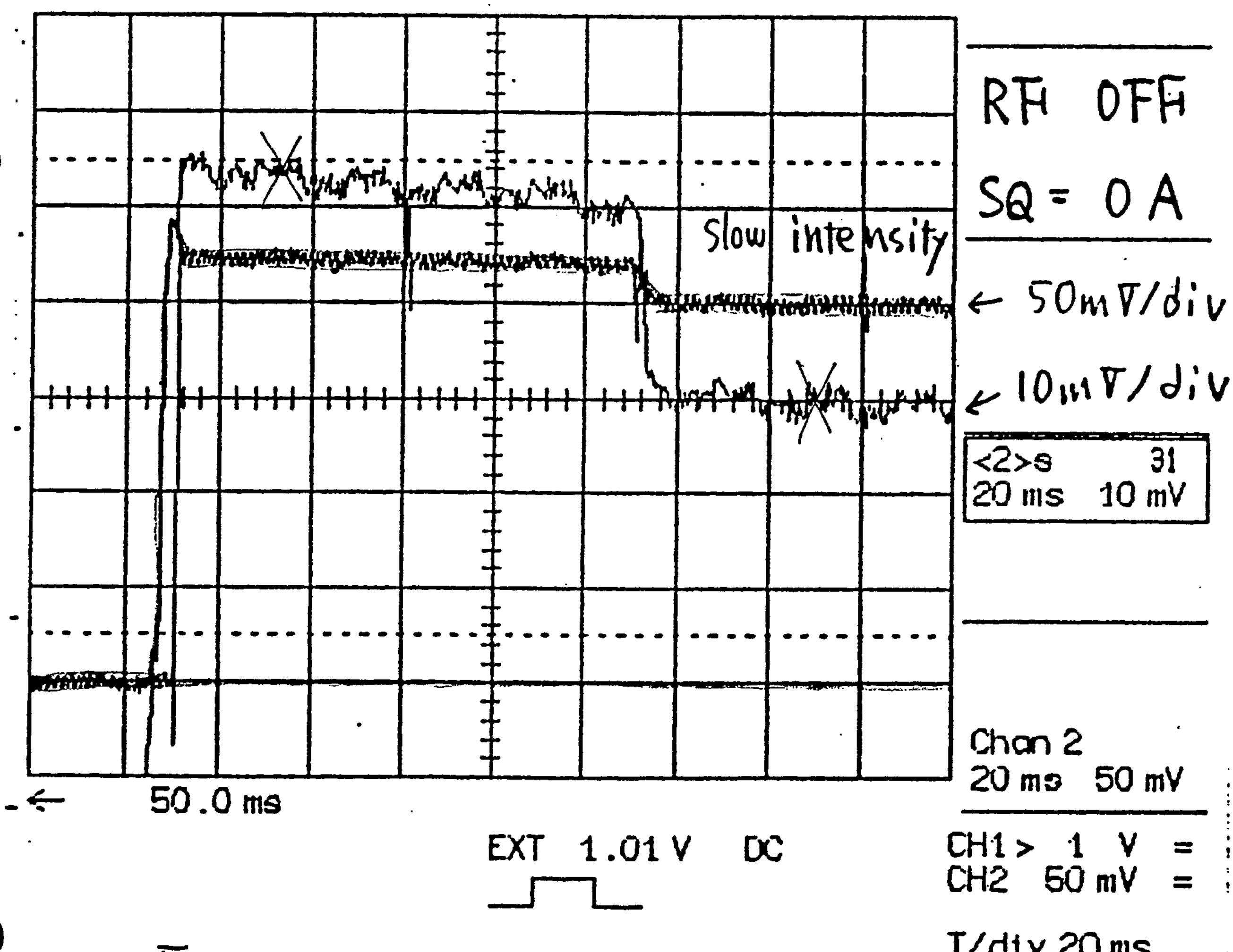

RF OFF
SQ = 0 A
Slow intensity
← 50mV/div
← 10mV/div
<2>s 31
20 ms 10 mV
Chan 2
20 ms 50 mV
50.0 ms
EXT 1.01 V DC
CH1 > 1 V =
CH2 50 mV =
T/div 20 ms

Fig 27 1/2

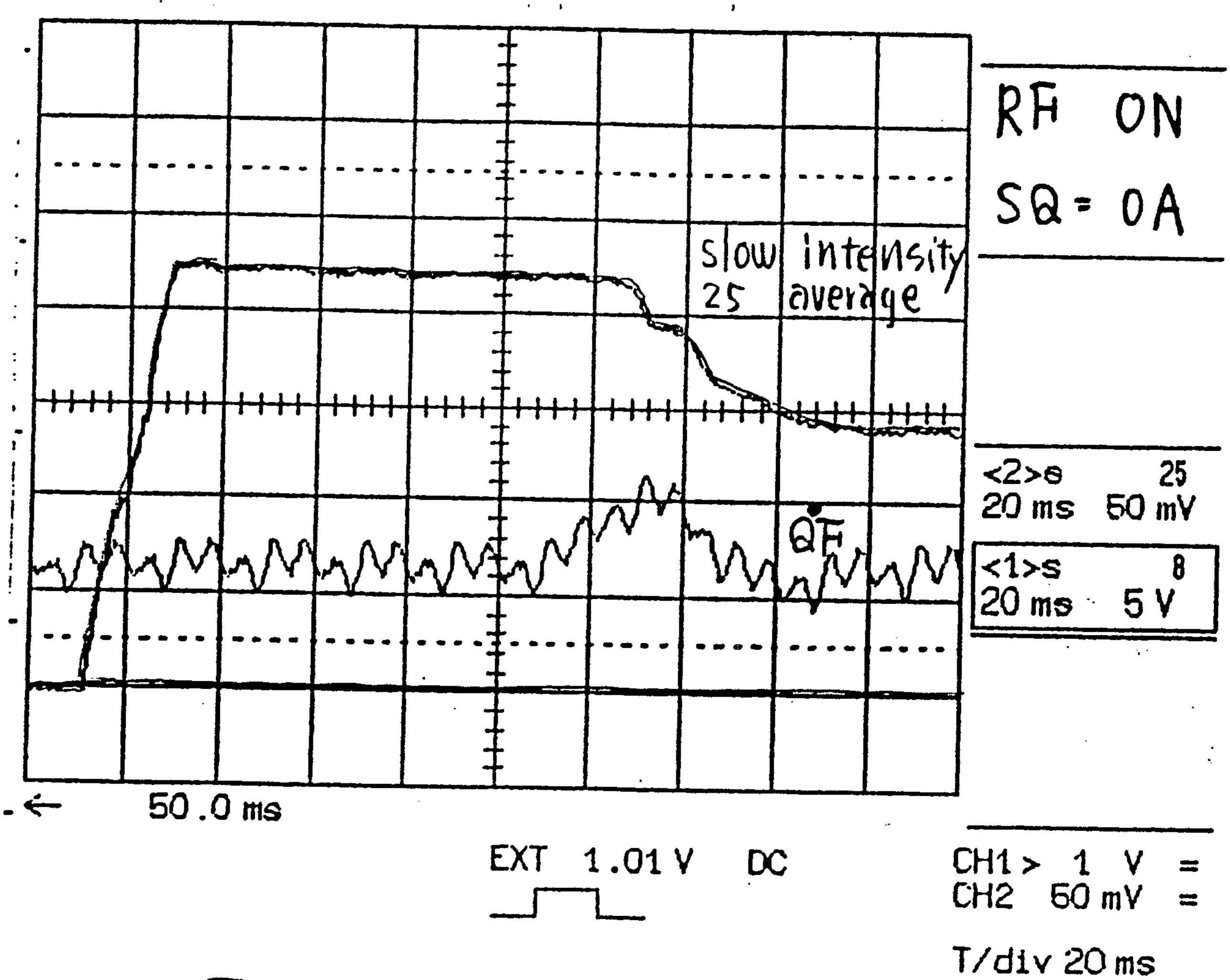

RF ON
SQ = 0A
slow intensity
25 average
QF
<2>e 25
20 ms 50 mV
<1>s 8
20 ms 5 V
50.0 ms
EXT 1.01 V DC
CH1 > 1 V =
CH2 50 mV =
T/div 20 ms

Fig 27 2/2

Coupled Bunch

This is the vertical beam size in the MR measured by NDPM; the line is the number of particles. At this point we start acceleration, transition, and extraction.

Figure 28 shows the MR NDPM. The vertical beam size did not damp adiabatically. In this case, only the number of bunches was different. There are nine rf buckets in the main ring. At one beam size, all buckets were filled with protons. At another size, there were five proton-filed buckets and four vacant buckets. At another, only one bucket was filled with protons. The number of protons in one bucket was the same. The space charge effect was almost the same, but the beam sizes were much different. This is the evidence of the existence of some kind of coupled-bunch effect.

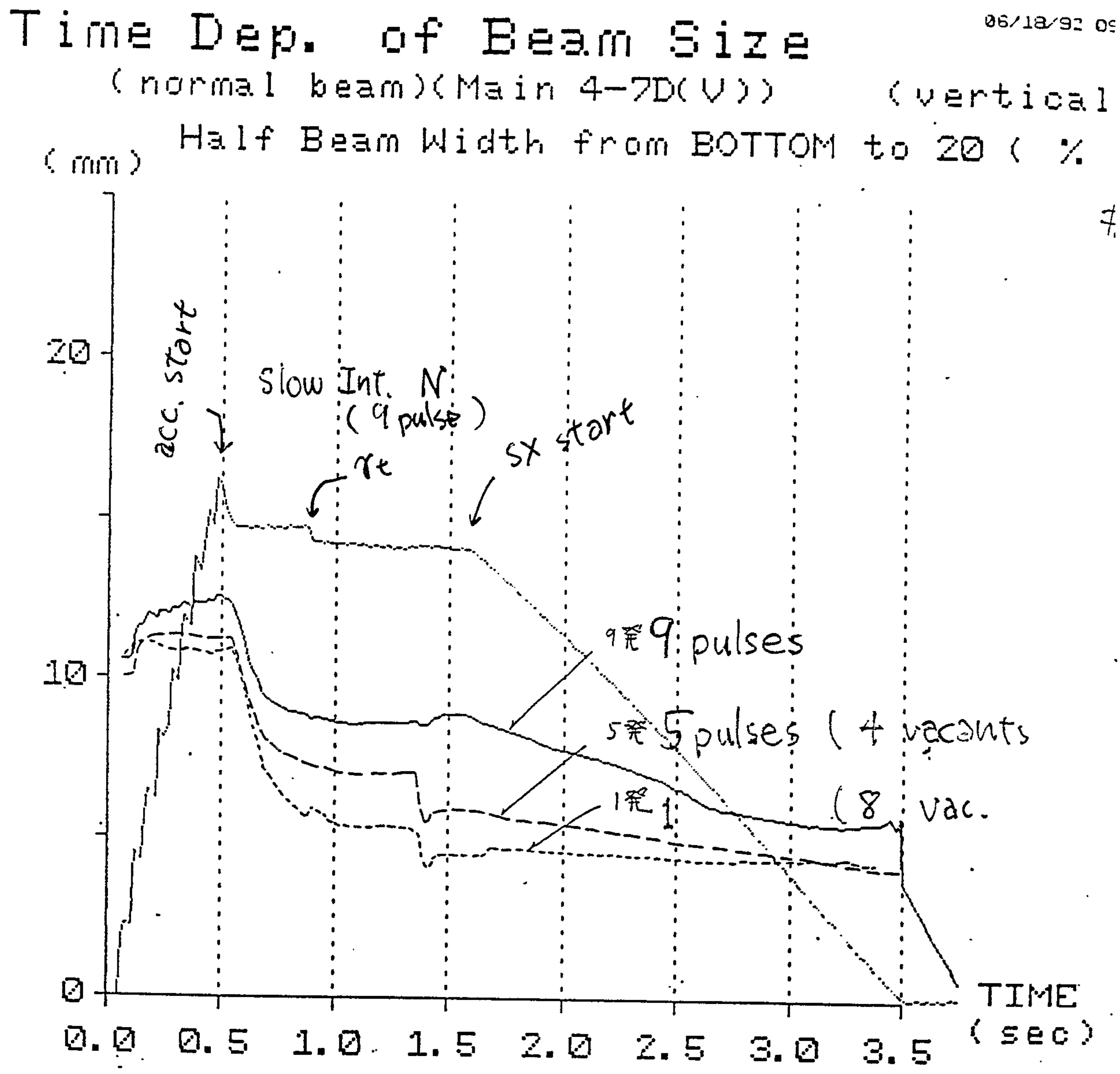


Fig 28

図 14 Vertical beam size と MR bunch 数

Edge Focus of the Bump Magnet

Figure 29 shows the normal optics. This is the Twiss parameters of the KEK-Booster, but when the injection bump magnets are working it changes. Figure 30 shows the abnormal cell. The edge focus of the bump magnets changes the optics. We did not recognize such a big effect until last month (January, 1993). We then had to reconsider the matching conditions; we have not examined the results experimentally. It changed the optics, including the horizontal tune. It becomes as low as 2.09. I don't think it will reduce the space charge limit because the beam is captured in the rf bucket after the bump has disappeared. At this time, the bunching factor is 1.

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I. Yamane

Fig 29 Normal Optics of Booster

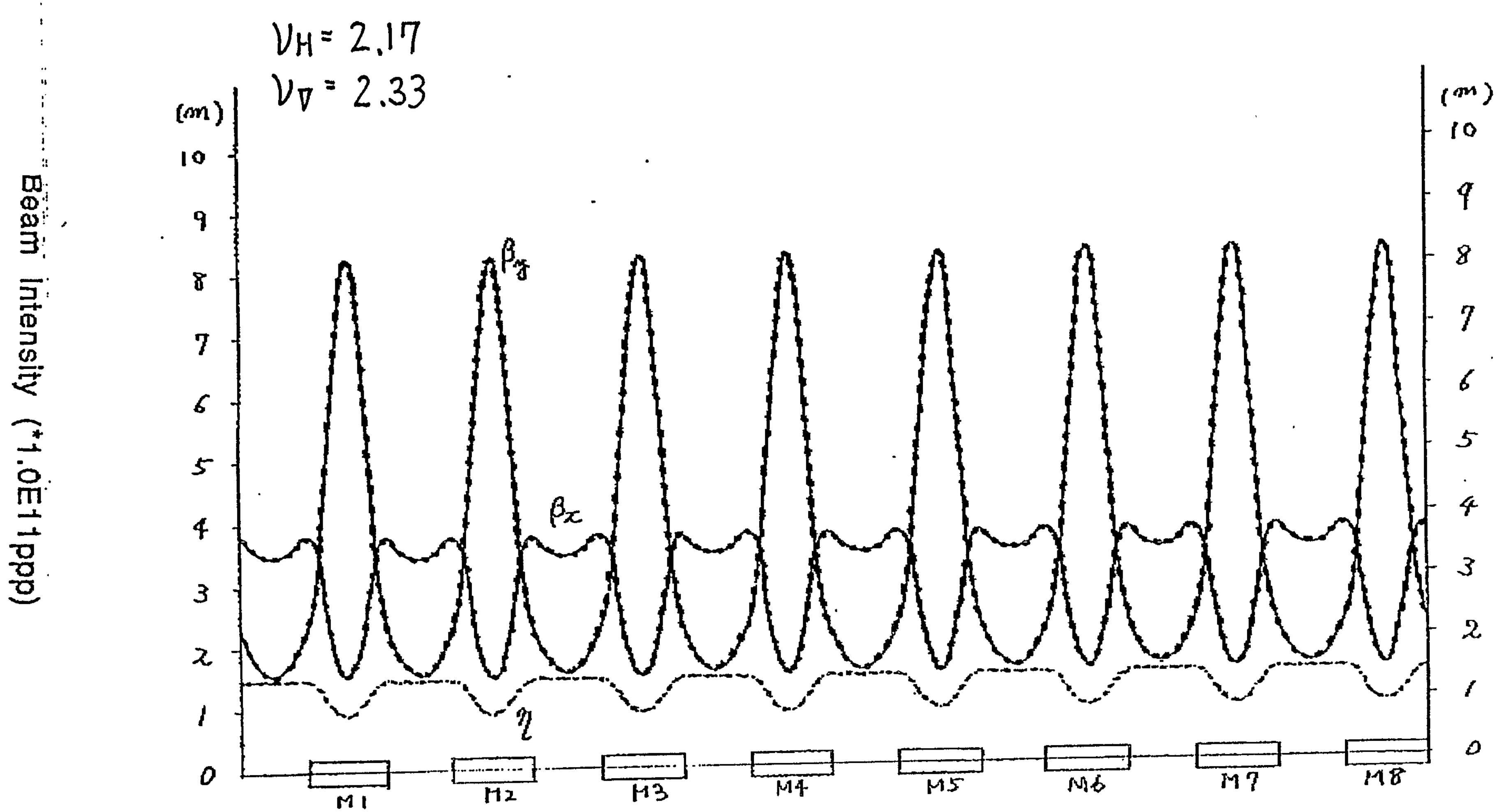

Fig. 30 Abnormal Optics of Booster due to H^- Bump Magnets