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Simulation of Booster Proton Injection - Longitudinal

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Technical Note

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I. Summary

1. The lower RF voltage at the Booster injection, for the $h = 1$ scheme, might be responsible for the smaller bunching factor in the Booster, compared with the Booster $h = 2$. The smaller bucket and lower synchrotron frequency affect the longitudinal painting in the injection.
2. To get a larger moving bucket, lower \dot{B} at the injection is needed. To overcome the slower synchrotron motion, injecting more turns will help.
3. The RF frequency tracking program, the second harmonic RF, and the manipulation of the fast chopper affect the beam defined during the stacking.

II. Introduction

In 1998 HEP run, the Booster and AGS harmonic numbers become 1 and 6, respectively. This scheme opens a door to further push the intensity at the AGS. Interesting issues associated with this change include the Booster injection. In fact, the bunching factor observed so far is smaller than the one achieved at the Booster $h = 2$. The beam peak current is higher, and the early beam loss, dominated by the space charge effect, is increased. Of more concern is that the shorter bunch at the Booster will affect the BTA transfer efficiency. The increased beam loss power there could pose a limit for the AGS beam intensity push.

The Booster longitudinal stacking is studied by simulations. The results shown in this report are reasonably agreeable to the observed beams. For the $h = 1$ scheme, the RF voltage at the Booster injection is lower, which gives rise to a smaller moving bucket, and a lower synchrotron frequency. The particle distribution in the longitudinal phase space is significantly different from the $h = 2$ scheme in the stacking. The transient beam loading effect is trivial, the static beam loading effect and the longitudinal space charge effect are not critical.

To get a larger moving bucket, lower \dot{B} at the injection is needed. A lower \dot{B} implies a smaller momentum span during the injection period, which is needed in terms of vertical painting. A higher \dot{B} could help. To overcome the slower synchrotron motion, more turns of beams could be injected. Longer Linac pulse is also beneficial to keep the momentum span at the injection, for \dot{B} not changed.

RF frequency program can affect the beam stacking. However, the room for manipulation is not large, because of the limited transverse space. We leave this to operations.

Double RF significantly affects the particle distribution during the stacking period. Experience shows that once an adequate injection scheme is settled, double RF is always able to add benefit on it. Some discussions will be presented on the double RF, but it is not taken as an essential issue.

Some very preliminary results obtained by the manipulation of fast chopper, to avoid the high peak current, are also presented.

III. Simulation

The Booster injection in the longitudinal phase space is a fairly complex process. The factors affecting stacking include:

1. Linac beam
 - momentum spread,
 - center momentum deviation from that of the RF bucket,
2. Stationary and moving bucket, area and height
 - Booster magnetic field, B and \dot{B} ,
 - RF voltage,
3. Fast chopper
 - width,
 - center of chopped beam with respect to the RF bucket,
4. RF frequency program
 - for RF frequency f_{RF} tracked the Booster magnetic field, only moving bucket is relevant,
 - for zero \dot{f}_{RF} at the injection, stationary bucket is relevant, the beam radial deviation occurs, RF capture needed after stacking,
 - anything between these two extreme situations,
5. Bucket variation and motion
 - longitudinal space charge effect,
 - transient and static beam loading,
6. Double RF
 - voltage and phase,

Key parameters and assumption used in simulations are:

1. Linac beam momentum spread $dp/p = \pm 0.1\%$,
2. There are 360 turns in the injection, taking $437 \mu s$,
3. The total injected beam is 15 TP per Booster cycle,

4. Booster $\dot{B} = 3.4 T/s$ at the start, $\dot{B} = 3.6 T/s$ at the end, of the injection,
5. RF voltage is 90 KV for $h = 2$, 1997, and 45 KV for $h = 1$, 1998,
6. The chopper width is 230 degrees, centered at 18 degrees ahead of the stationary bucket center,
7. RF frequency f_{RF} is tracking the Booster magnetic field,

In this scheme, the beam is injected into the moving bucket, defined by the magnetic field and RF voltage. During the injection period, the Linac beam to bucket momentum mismatch span is 1.06%. Therefore, the center momentum of injected beam is placed at $dp/p = 0.53\%$ above, and gradually shifted to same amount below the vertical center of the bucket, from the start to the end of the injection.

In Fig.1, the simulations for the $V_{RF} = 45 KV$, $h = 1$ and $V_{RF} = 90 KV$, $h = 2$ are shown in the first column. Significant difference between the two cases can be observed. The lower RF voltage for $h = 1$ scheme gives rise to an about 30 degree smaller moving bucket, and about half of the synchrotron frequency, compared to the $h = 2$ scheme.

To look into a little more detail of the particle distribution, in Fig.2, the distribution at the end of the stacking is plotted for every 90 turns injection of the two schemes. For the $h = 1$ scheme, each 90 turns injection dumps a dense particle distribution in the center of the bucket, while the $h = 2$ scheme shows a smooth painting in the phase space. The moving bucket at the early of stacking is also plotted, which can be used to estimate the beam loss. Note that at the end of stacking, the bucket is shrunked a little.

In the second column of Fig.1, the injections with longitudinal space charge effect are shown. In the third column, the injections with space charge and static beam loading are shown. The loaded RF cavity resistance for each station is 5 K Ω (resulting a bucket shift of 60 degrees at the end of stacking), which is larger than the one estimated by J.M. Brennan. It is shown that neither the space charge nor beam loading is responsible for this year's short bunch. The transient beam loading effect is trivial, especially at the $h = 1$ scheme, where a much large capacitance is added to the cavity.

In Fig.3, the bunch waveforms for 1998 and 1997 HEP are shown, where the beam injected at 17 ms, and extracted at 82 ms. The simulation is reasonably agreeable to the observed bunch waveform, in each case.

IV. Injection Modification

It is important to get a larger moving bucket at the injection, therefore, a lower \dot{B} at the injection is desired. The lower \dot{B} , however, would give rise to a smaller momentum span during the stacking, which is not desired in terms of vertical painting. One solution of this is to use the higher \ddot{B} . There is a limit

to raise the \ddot{B} . Also, the bucket would shrink rapidly during the stacking, if \ddot{B} is high.

To overcome the low synchrotron frequency, extending the injection turns is a choice. A longer injection period also gives rise to a larger dp/p span, reducing the pressure on a higher \ddot{B} .

In Table 1, the bucket length, its variation during the stacking, and the dp/p span are given for different \dot{B} , \ddot{B} and injection turns. Case I represents the present status. In case II, it shows that at $\dot{B} = 2 T/s$, and the same \ddot{B} , the dp/p span is reduced from 1.06% to 0.66%. By increasing the injection turns to 540, \ddot{B} does not need to be raised to keep a comparable dp/p span. For instance, the situation between the case IV and V, which has the similar \ddot{B} as the case I, has a bucket length increase of 26 degrees, a moderate shrink rate of the bucket length during the stacking, and also a similar dp/p span.

The case VI shows that at $\dot{B} = 1 T/s$, even at the very high \ddot{B} , the dp/p span is still small, although the bucket becomes much longer.

Case	Turns	Time	\dot{B}	\ddot{B}	ϕ_1	ϕ_2	$\phi_2 - \phi_1$	dp/p Span
I		17	3.4	0.40	-91	168	259	
	360	17.43	3.57		-89	167	256	1.06
II		17	2.0	0.40	-112	173	285	
	360	17.43	2.17		-109	172	281	0.66
III		17	2.0	0	-112	173	285	
	540	17.64	2.0		-112	173	285	0.82
IV		17	2.0	0.31	-112	173	285	
	540	17.64	2.2		-109	172	281	0.95
V		17	2.0	0.63	-112	173	285	
	540	17.64	2.4		-106	171	277	1.08
VI		17	1.0	0.94	-132	176	308	
	540	17.64	1.6		-120	174	294	0.78
Unit		ms	T/s	$T/s/ms$	deg.	deg.	deg.	%

Table 1: Bucket length and dp/p span for different \dot{B} , \ddot{B} and injection turns.

In Fig.4, simulation results for cases V and VI, with chopped length of 230 and 258 degrees, respectively, are shown. Compared with the case I, the bunch length is increased, and the peak current is reduced.

V. Double RF

During the beam stacking, the particle distribution in phase space is defined. It is possible that the beam line density at the end of stacking is fine, but the

particle distribution is not acceptable. In this case, the particle evolution after the stacking would produce undesired beams.

The RF frequency program and the double RF all play roles in defining the particle distribution during the stacking. The double RF is more important, because that the room in tuning the RF frequency program is limited.

Experience shows that a double RF is always able to add benefit on the machine performance, given a machine setting.

In Fig.5, simulation results are shown, for a double RF with half of the voltage of the first harmonic. The chopped beam is 180 degrees, which is shifted by 22 degrees with respect to the center of a stationary bucket. The relative phase of the second harmonic is the only variable played here. The moving bucket is also shown. The improvement is not difficult to achieve, but none of the particle distribution in the simulated case is very satisfactory. In Fig.6, the corresponding mountain ranges are shown.

In Fig.7, simulation results for the $V_{RF} = 90 \text{ KV}$, $h = 2$ are shown. The double RF with -60 degree phase shift is apparently acceptable, which produces a smaller peak current, yet the particle distribution is still smooth. In Fig.8, the corresponding mountain ranges are shown.

No conclusion can be drawn from these very preliminary simulation results. Indeed, these are rather illustrative.

VI. Fast Chopper

The manipulation of the fast chopper can also significantly modify the particle distribution during the stacking.

J.M. Brennan has been trying to cut the middle of the chopped beam, to avoid the sharp peak current. A simple program is applied to the simulation, which is shown in Fig.9. Improvement can be observed.

T. Roser suggests that to use a partial chopping, by cutting one side of the injected beam. Together with the beam synchrotron motion, this might produce a better beam. A close examination of the particle distribution in Fig.2 shows that the sum of the right half side of the chopped beam might produce smoother beam, compared with the fully chopped beam. In Fig.10, some simulation results are shown, indeed, there are some improvements.

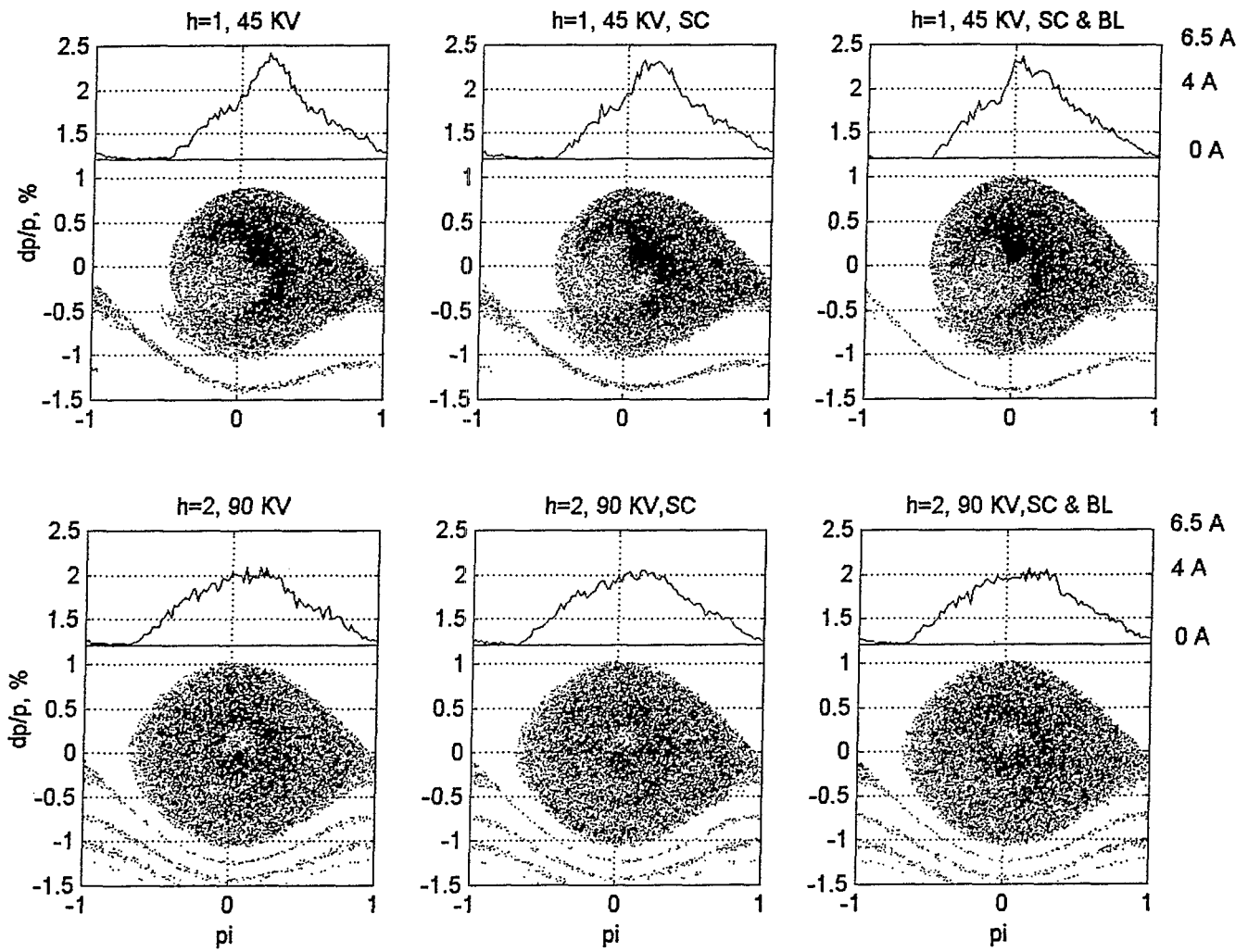


Fig.1. Injection simulations for $V_{RF} = 45 \text{ KV}$ and $V_{RF} = 90 \text{ KV}$,
 Second column is with space charge. Third column is with static beam loading,
 as well.

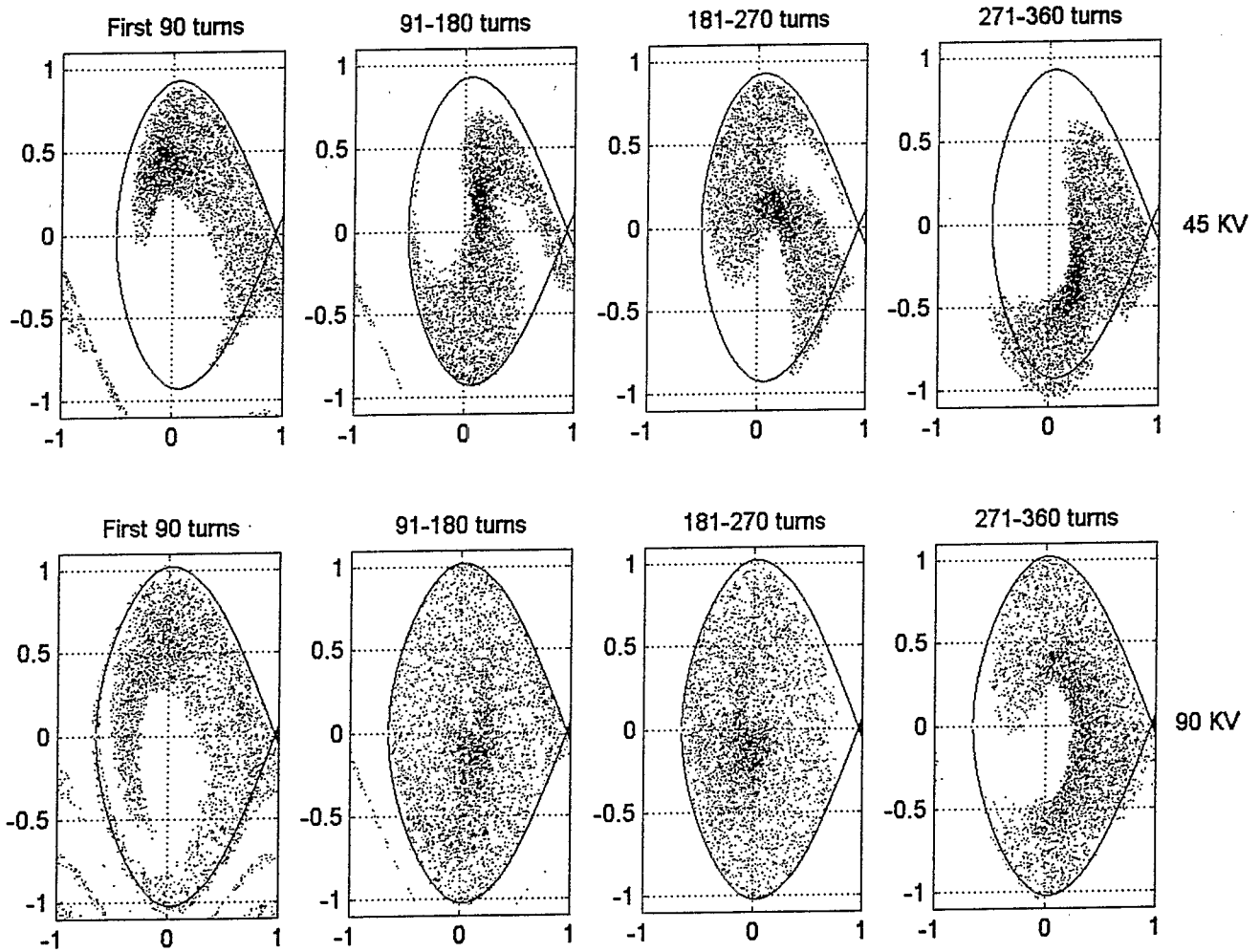


Fig.2. Particle distribution at the end of stacking, for each 90 turns,
for $V_{RF} = 45 \text{ KV}$, $h = 1$ and $V_{RF} = 90 \text{ KV}$, $h = 2$

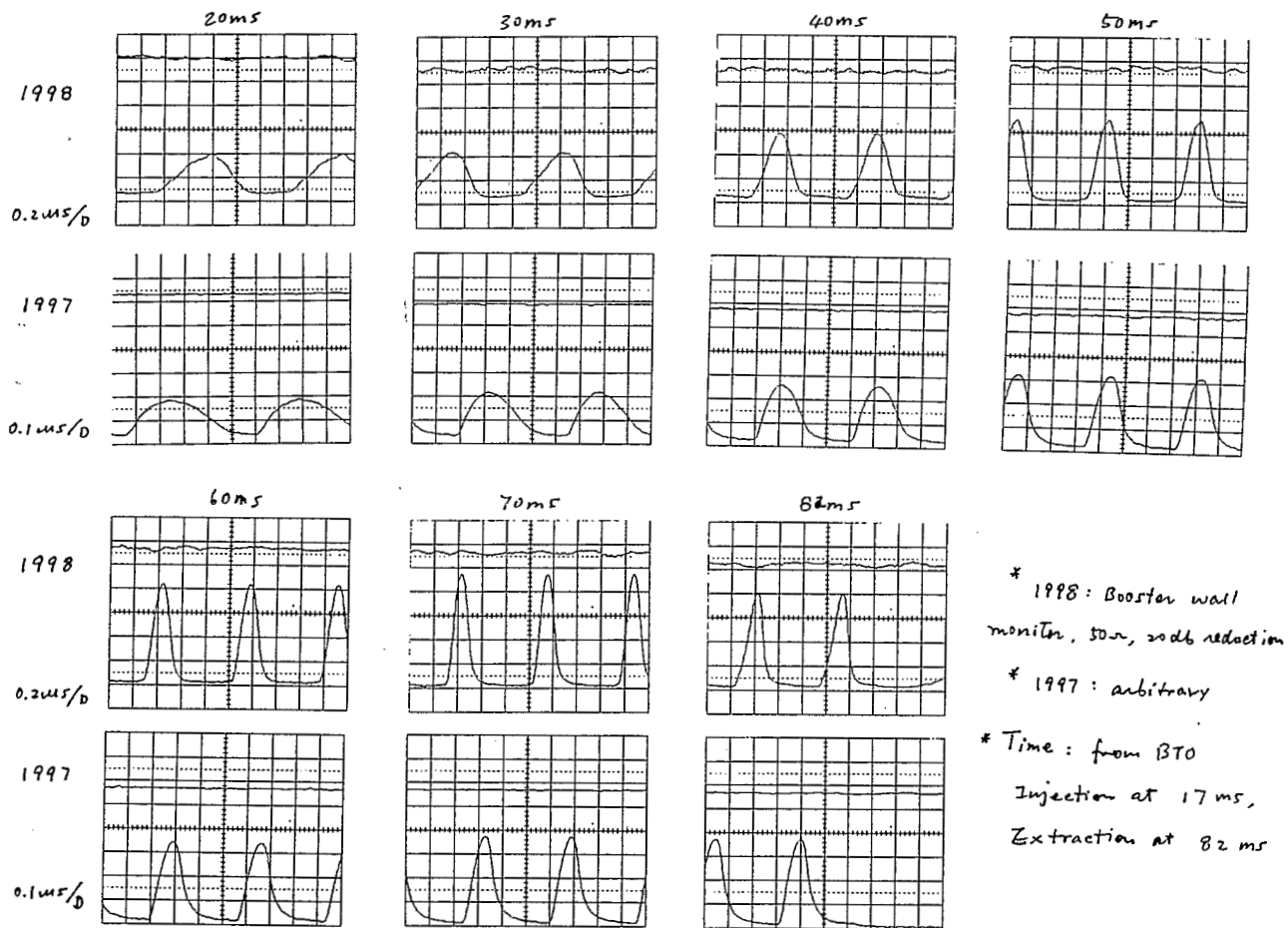


Fig.3. Observed beam waveform of 1997 and 1998. Beam injected at 17 ms, extracted at 82 ms.

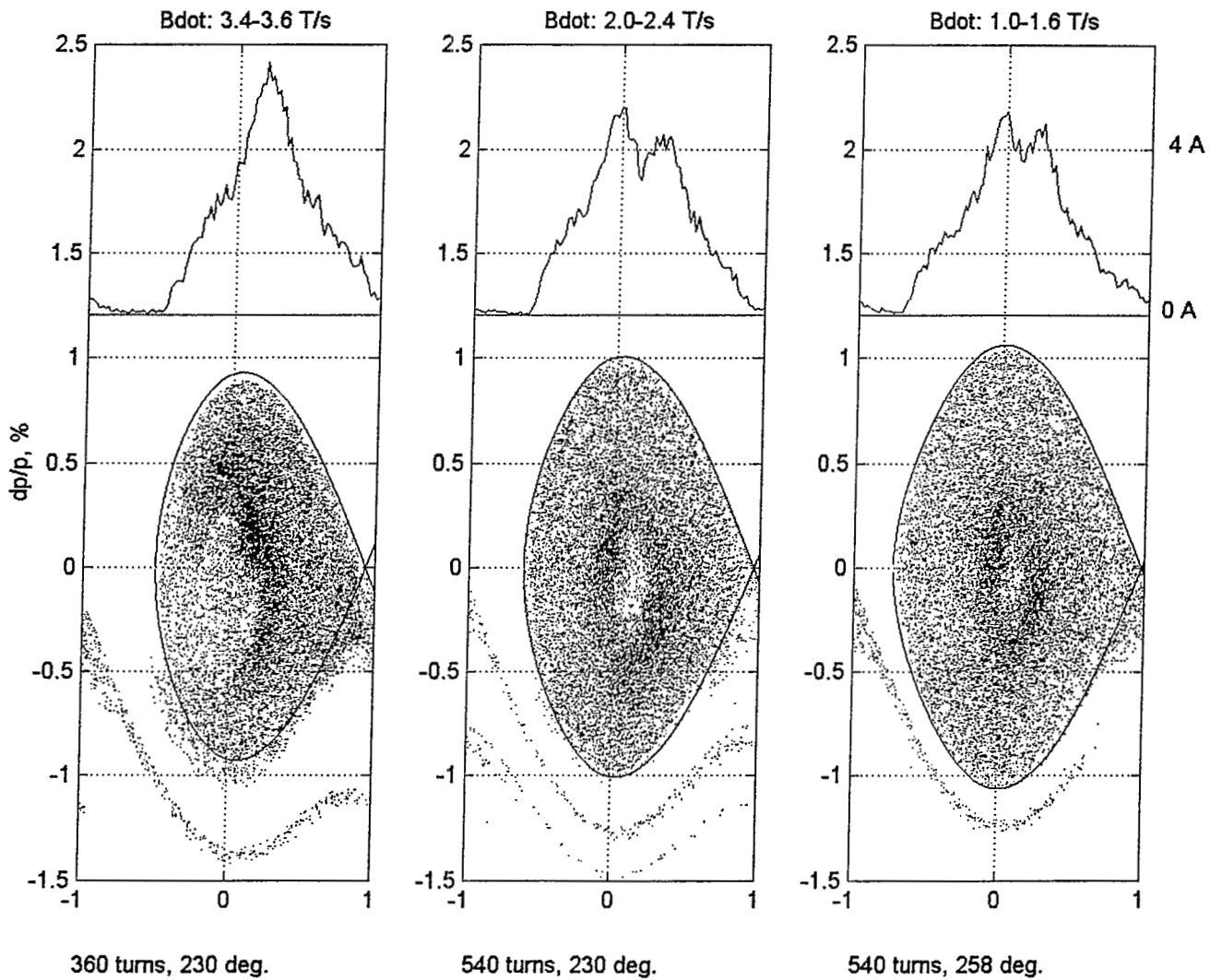
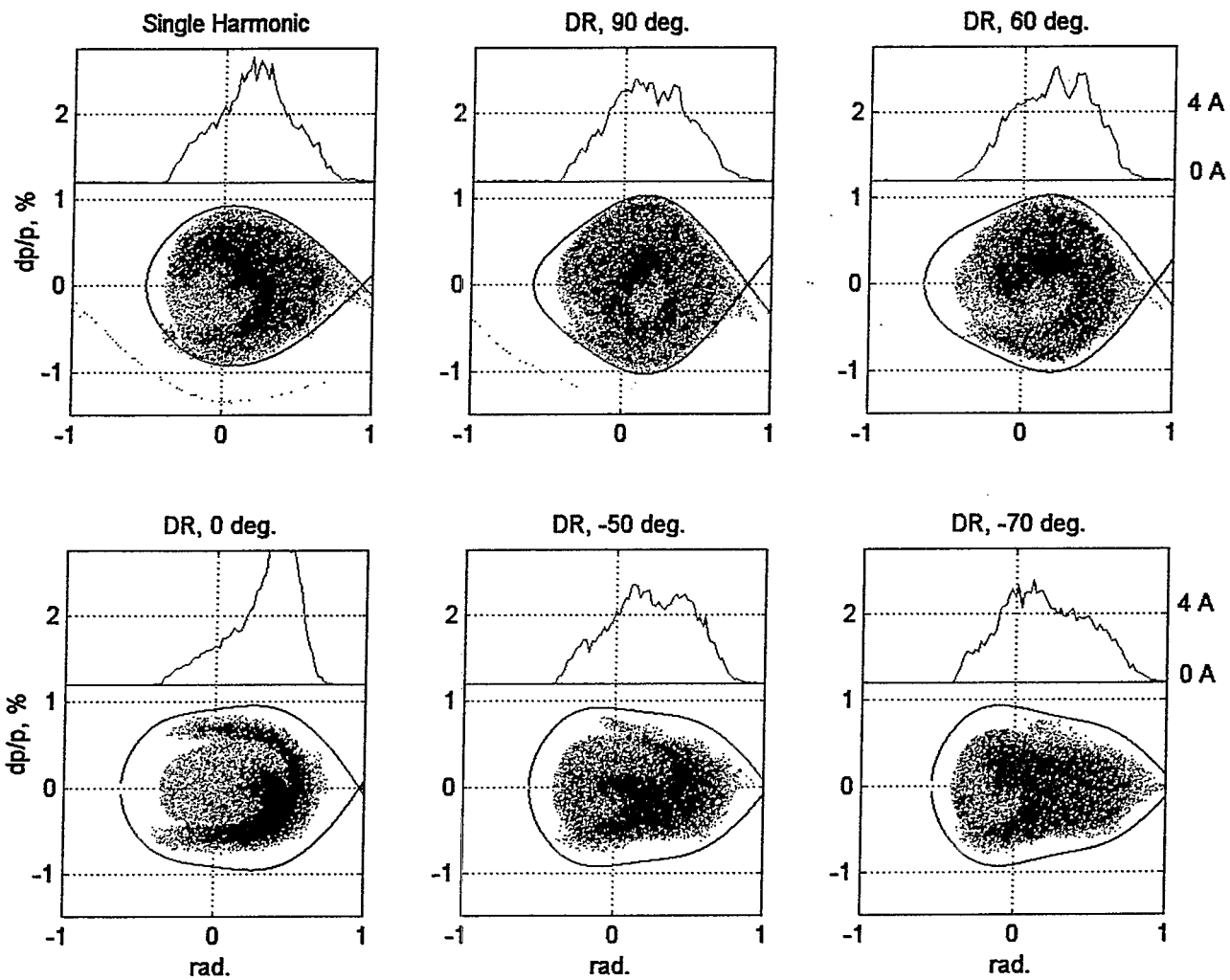


Fig.4. Simulation for different \dot{B} and injection turns.



$V=45$ KV, Chopper 180 deg. shifted 22 deg. 15 TP, 360 turns, Bdot 3.4-3.6 T/s

Fig.5. Double RF with difference phase, compared with the single harmonic,
 $V_{RF} = 45$ KV, $h = 1$.

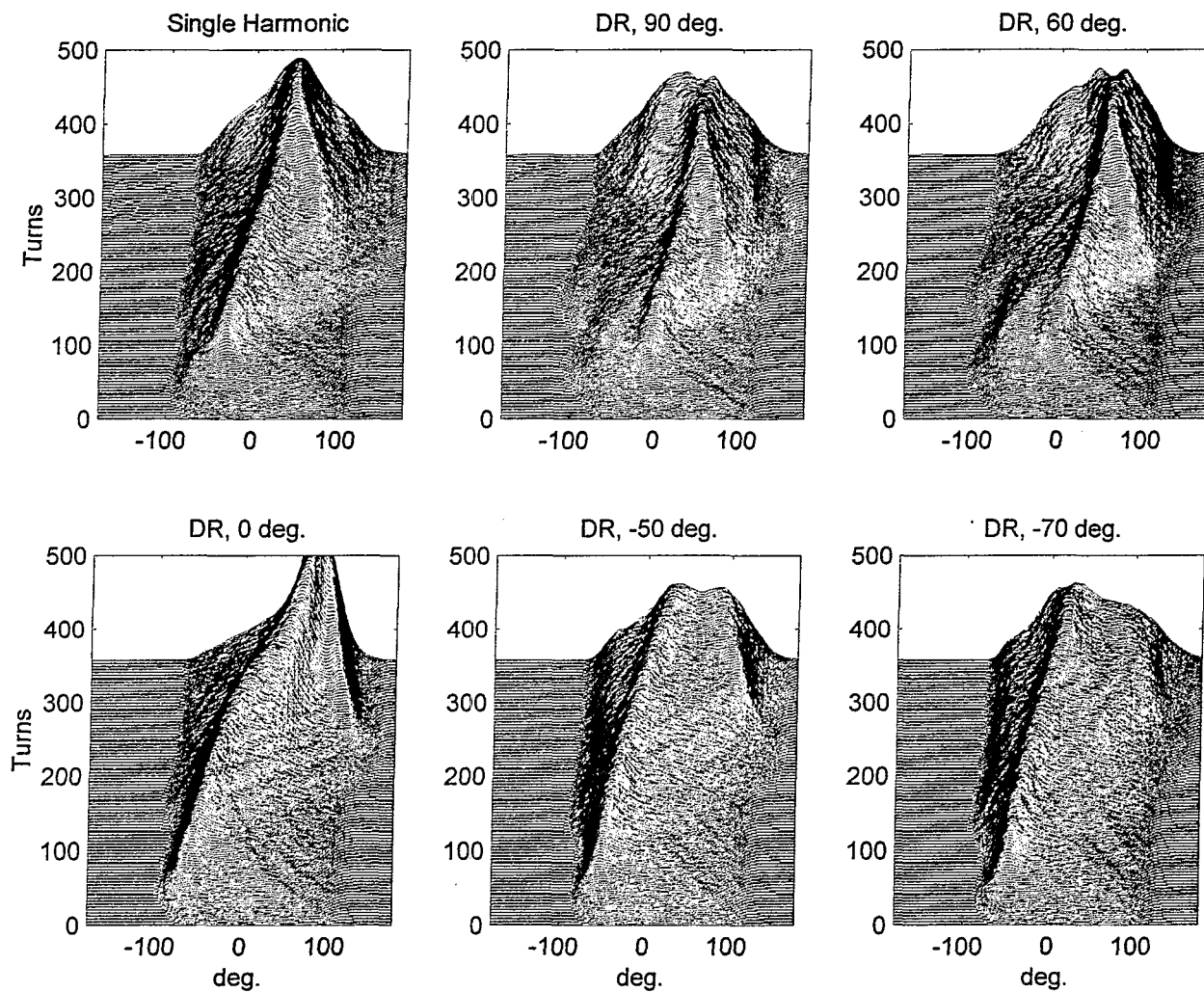
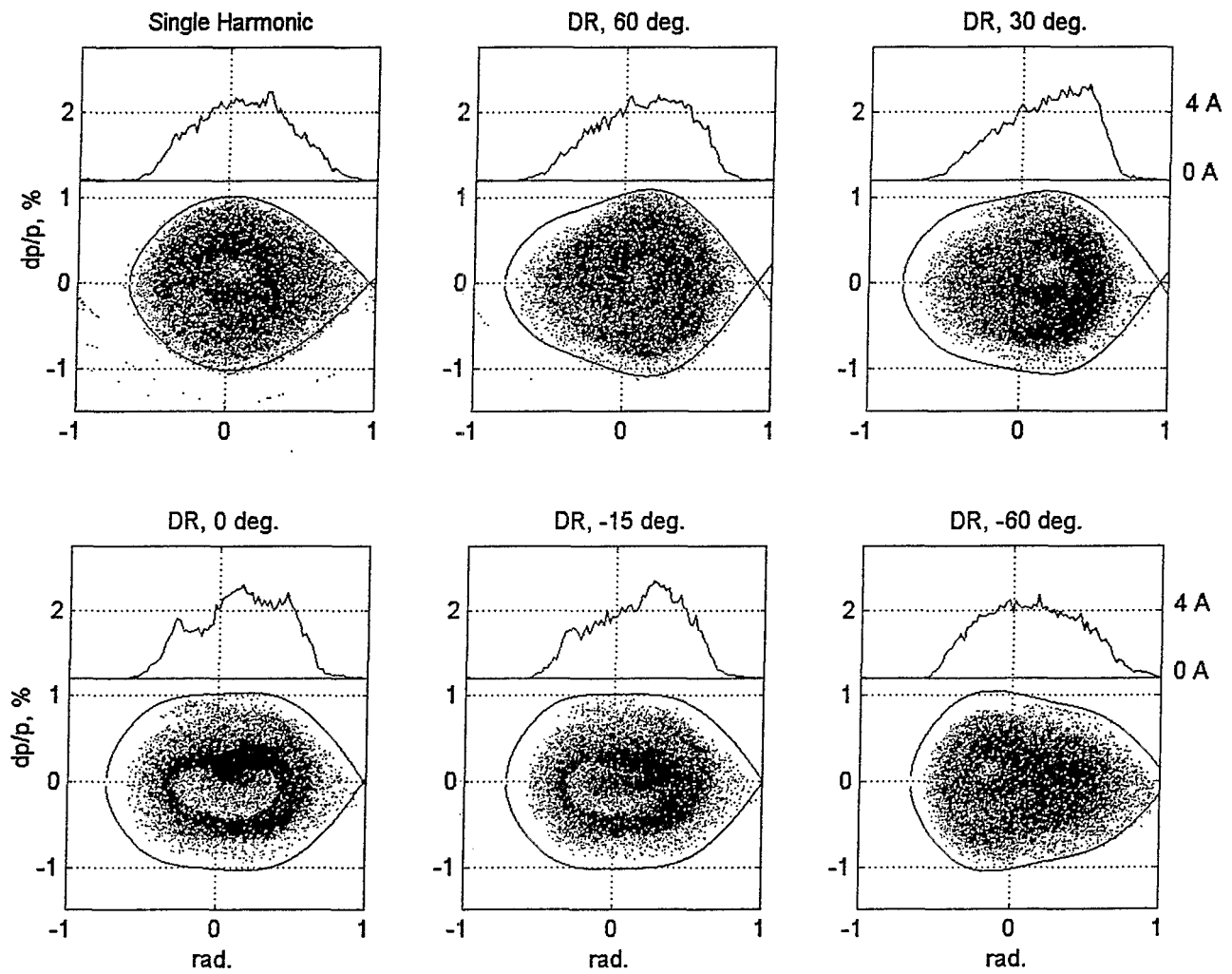


Fig.6. Mountain range of double RF with difference phase,
 $V_{RF} \approx 45 \text{ KV}$, $h = 1$.



$V=90$ KV, Chopper 180 deg. shifted 15 deg. 15 TP, 360 turns, Bdot 3.4-3.6 T/s

Fig.7. Double RF with difference phase, compared with the single harmonic,
 $V_{RF} = 90$ KV, $h = 2$.

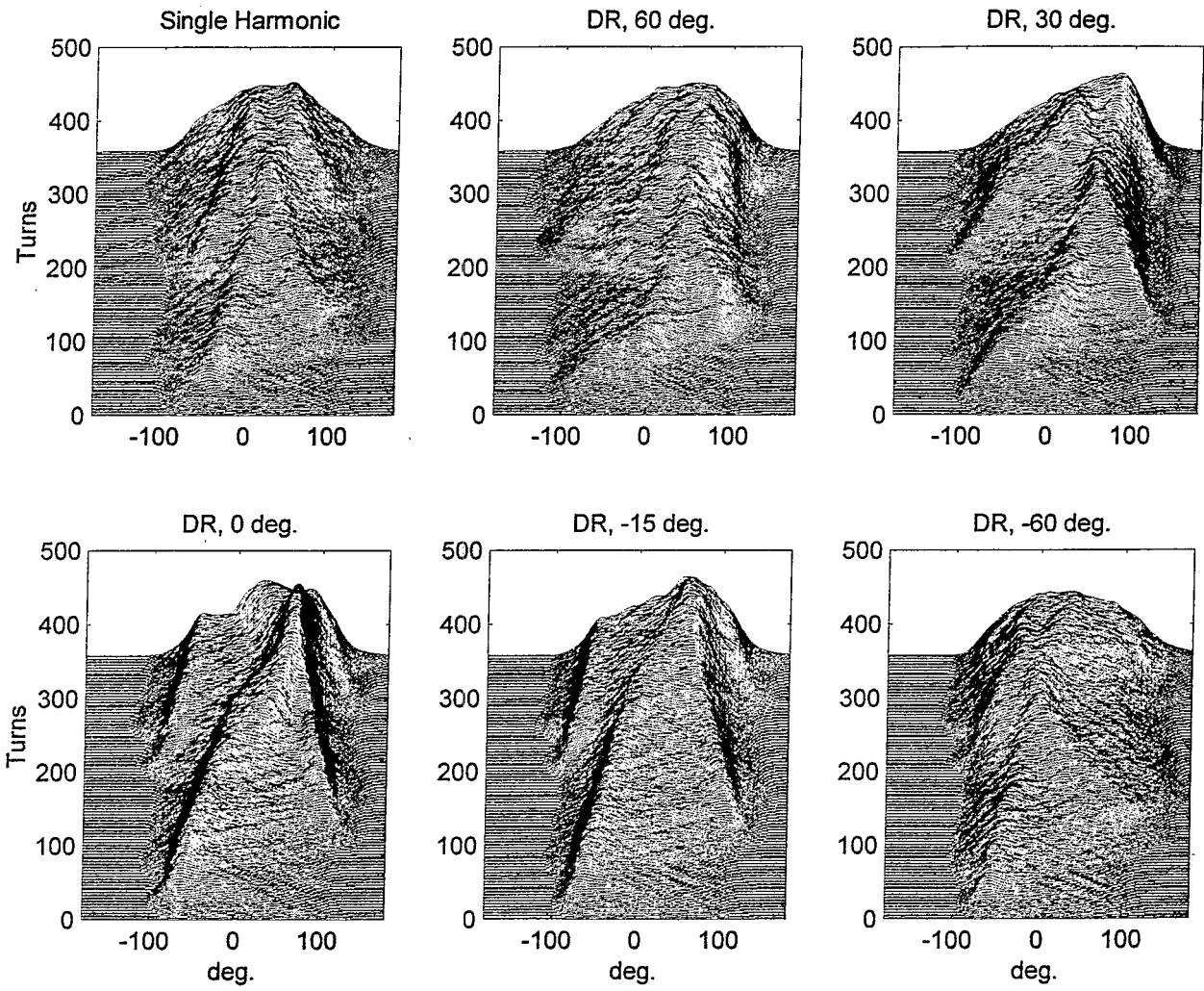


Fig.8. Mountain range of double RF with difference phase,
 $V_{RF} = 90 \text{ KV}$, $h = 2$.

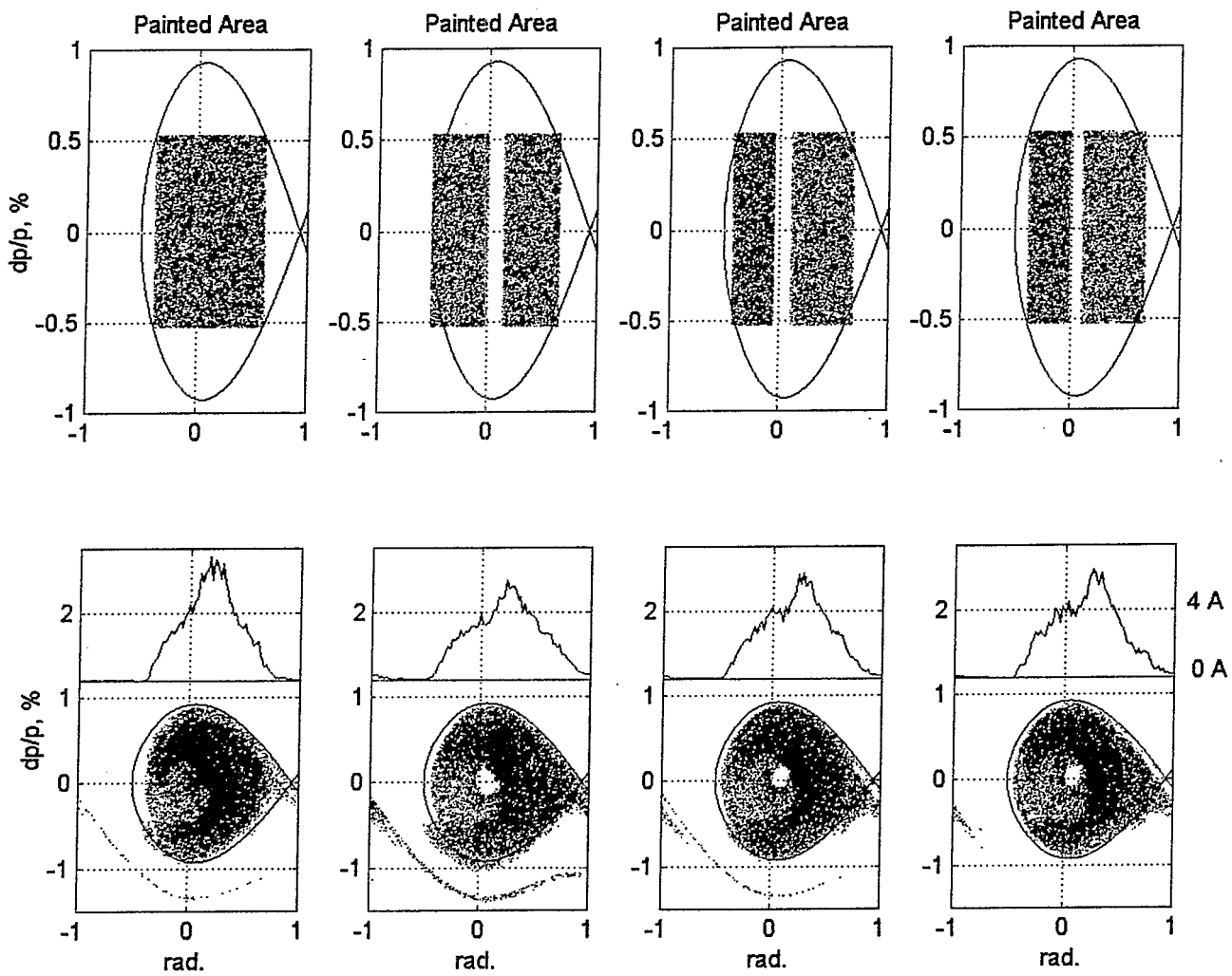


Fig.9. Injection with manipulation of fast chopper, cutting the middle of the beam.

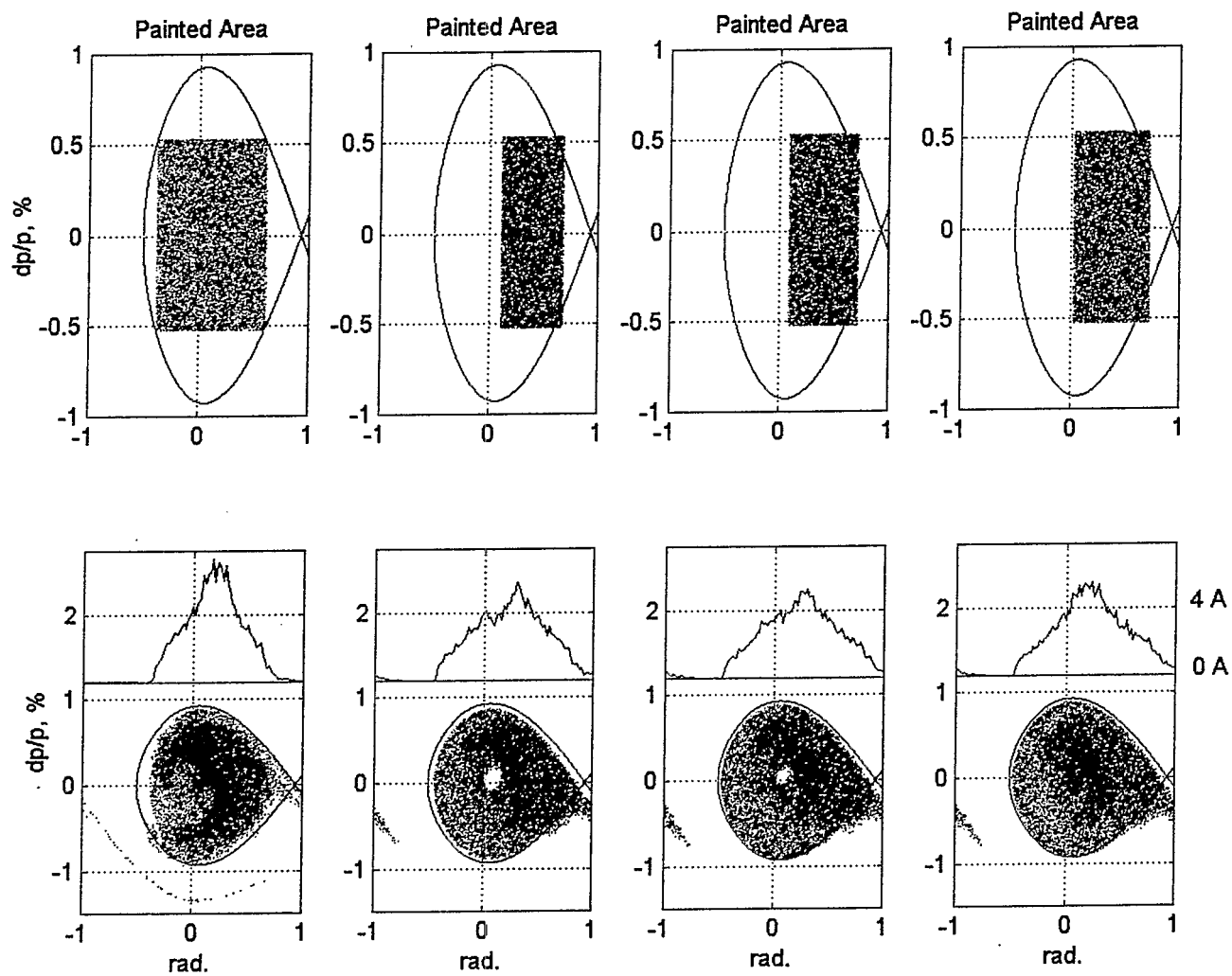


Fig.10. Injection with manipulation of fast chopper, cutting the left side of the beam.