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# Bunching of a High Intensity Heavy Ion Beam

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**Abstract:** A key issue for high intensity heavy ion RF drivers for inertial confinement fusion (ICF) is the control of space charge effects. In order to provide extremely high energy deposition in the target, short pulses in the order of few nanoseconds are necessary. Pre-bunching compresses the particle bunches by a factor of 7-8. This study determines the distribution of higher RF harmonics needed to optimize the bunch rotation voltage for pre-bunching for the example of the "Ignition Facility" which is under study of the European Study Group [1].

## Introduction

A heavy ion accelerator for heating and compressing matter to the conditions required for inertial fusion energy is under study by the European Study Group. It is the goal of the study to demonstrate the feasibility of an RF heavy ion driver for ignition of a low-gain pellet. Part of this study is a RF system to provide pre-bunching of a high intensity heavy ion beam by linear bunch rotation. This RF system must be adjusted in order to compensate for space charge forces and requires several higher RF harmonics. The process of bunch rotation distribution and the RF system are described in this report.

## 1. Linear bunch rotation

Longitudinal bunch compression can be achieved by bunch rotation of 90°. Tails might be introduced during this process. Linear bunch rotation is applied in order to avoid such tails. A linear RF wave-form requires several higher RF harmonics and additional RF cavities - which require additional space in the ring. The linear wave-form can be approximated by the use of several harmonics in order to minimize the number of cavities. The bunch rotation has to be performed fast, in order to avoid defocusing by space charge. Fast bunch rotation requires a high RF voltage and slow rotation leads to longitudinal defocusing and therefore to a larger phase spread. The compression factor, which is defined as the ratio of the bunch lengths before and after compression, should be in the order of 7-8.

## 2. Effect of space charge

Space charge forces are caused by high particle intensities. They aim to defocus the bunch. In order to control the space charge effects, the applied RF voltage has to be high compared to the space charge voltage. The space charge voltage increases with increasing bunch rotation, e.g. with increasing bunching. Therefore the bunch rotation has to be performed within a short time in order to avoid tails in the longitudinal particle distribution. (Space charge could be compensated dynamically: during the process of bunch rotation the charge distribution changes continuously and consequently the space charge forces. Space charge could therefore be dynamically compensated by the RF system.)

## 3. Input parameters for the simulation

For the simulation of the bunch rotation the program LONG1D [4] was used. The code was adapted in order to provide higher RF harmonics. The simulation should give an indication for the required number of RF harmonics and the corresponding RF voltages for pre-bunching of the high intensity heavy-ion bunches. Therefore the input parameters of the simulation are not optimized.

### 3.1. Initial particle distribution

The bunches are represented by 10’000 macro-particles in 100 phase bins. The initial longitudinal particle distribution is uniform with a length of 22.9 m, which corresponds to 62.5% in RF phase, e.g. 252°.

The energy spectrum is parabolic with an initial total energy spread of $\Delta E/E = \pm 3.32\times 10^{-4}$, corresponding to $\Delta E = 3.26$ MeV. The total number of particles in the ring is $N_{\text{part}} = 1.56\times 10^{14}$ divided in to twelve bunches. The mass number is $A = 209$ and the charge state is $q = 1$. The kinetic energy per nucleon is 47.157 MeV/u and the total energy per atom is 9855.81 MeV.

### 3.2. Ring Parameters

The radius of the ring is $R = 70.5$ m. The dipole field is $B = 6.0$ T and the bending-field radius is $\rho = 34.9952$ m. There is one RF accelerating cavity operating at a harmonic number of $h = 12$, which corresponds to a RF frequency of $f = 2.48$ MHz. A detailed parameter list [1] of the ICF is given in Table 1.

### 3.3. Space charge

For the estimation of space charge forces the longitudinal beam distribution is approximated by its charge line density $\mu(z)$. Space-charge forces act continuously and produce an incremental energy change per turn which is expressed by

$$\frac{q^2 e^2}{4\pi\varepsilon_0}\cdot\frac{g_0 2\pi R}{\gamma_b^2}\cdot\frac{d\mu}{dz},$$

where $g_0$ denotes a geometric factor. The mean energy of the particles is $E_b = \gamma_b m_0 c^2$. The acting space charge force scales linearly with the gradient of the particle distribution $d\mu/dz$ where $z$ denotes the coordinate around the machine circumference.

The gradient at the boundaries of the initial particle distribution determines the initial crest of the space charge voltage. The choice of the initial longitudinal particle distribution is therefore a very sensitive parameter for the simulation.

The program LONG1D provides the possibility of smoothing the initial particle distribution by truncating its Fourier series. The number of Fourier harmonics was set to 13 resulting in an initial crest space-charge voltage of $u_{\text{s.c.}} = 0.8$ MV.

| ICF PARAMETERS | | |
|---|---|---|
| **HEAVY IONS** | | |
| Mass number | $A$ | 209 |
| Charge state | $q$ | 1 |
| | | |
| **RING PARAMETERS** | | |
| Kinetic energy per nucleon | $T$ | 47.157 MeV/u |
| Relativistic parameters | $\gamma$<br>$\beta$<br>$\beta\gamma$ | 1.0503<br>0.3056<br>0.3210 |
| Momentum | $p$ | 301.1890 MeV/c |
| Beam rigidity | $B\rho$ | 209.9710 Tm |
| Radius of ring | $R$ | 70.5 m |
| Dipole field | $B$ | 6.0 T |
| Bending-field radius | $\rho$ | 34.9952 m |
| Number of accelerating cavities | $N_{cav}$ | 1 |
| Harmonic number | $h$ | 12 |
| RF frequency | $f$ | 2.48 MHz |
| | | |
| **BEAM PARAMETERS** | | |
| Number of particles in the ring | $N_{PART}$ | 1.56E+14 |
| Total momentum spread | $\Delta p/p$ | ±1.70E-04<br>±10.7 MeV/c |
| Total energy spread | $\Delta E/E$ | ±3.32E-04<br>±3.26 MeV |
| Average current | $I$ | 5.16 A |
| Chopping factor | | 0.7 |
| Initial bunch-length | $L_0$ | 22.9 m<br>225° |
| Longitudinal emittance | $\varepsilon_z$ | 1.8 eV·sec |
| Transverse emittance | $\varepsilon_t$ | 50 π·mm·mrad |
| Horizontal tune | $Q_h$ | 8.65 |
| Vertical tune | $Q_v$ | 8.78 |
| Transition energy | $\gamma_t$ | 3.0 |
| Compression factor | | 7-8 |
| | | |

Table 1: ICF parameter list

*3.5. RF voltage*

The linear RF wave-form can be approximated by the use of higher harmonics:

$$u_{RF} = \hat{u}\sum_n h_n \sin(2\pi nt),$$

where $\hat{u}$ denotes the crest voltage and $h_n$ denote the amplitudes of the harmonics. The number of harmonics is limited by space in the ring. As the beam is already compressed to 62.5% at the injection into the ring, the linear function can be approximated by a linear characteristic within the phase range of ±112.5° and a nonlinear characteristic outside these boundaries. A good approximation was found with three RF harmonics [2]. The amplitudes of the harmonics are given in Table 2 and the shape of the wave-form is shown in Figure 1.

| Harmonic number | harmonic amplitudes |
|---|---|
| $h_1$ | 1 |
| $h_2$ | -0.30 |
| $h_3$ | 0.08 |

Table 2: RF harmonics

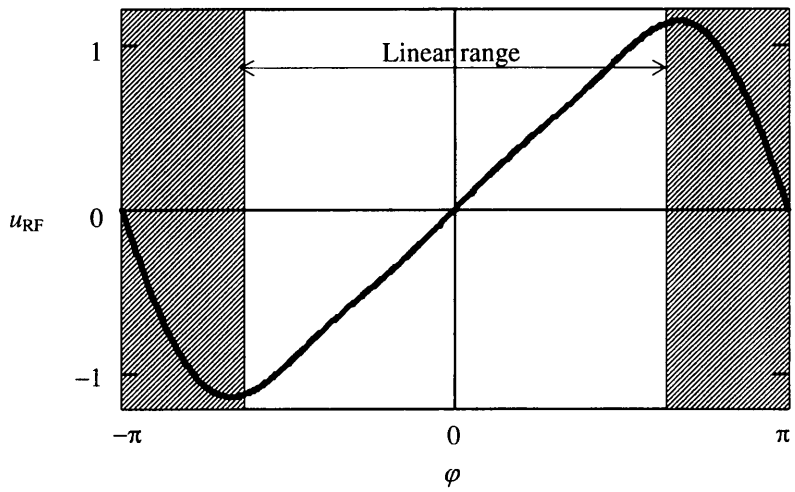


Figure 1: RF wave-form with three harmonics (1, -0.30, 0.08)

The crest voltage $\hat{u}$ will determine the speed of the bunch rotation and therefore the final phase spread. A high voltage will result in fast rotation and in short bunches and vice versa.

## 5. Results of the simulation

In the simulation the RF voltage was switched on without regarding a time constant of the RF system. For this case the impact of the RF voltage on the compression factor was studied. The result is shown in Table 4.

| $\hat{u}$ [MV] | Compression factor | Number of revolutions | Time [µs] |
|---|---|---|---|
| 2.5 | 4.1 | 25 | 120.5 |
| 5 | 8.0 | 17 | 81.9 |
| 10 | 9.5 | 11 | 53.0 |

Table 3: RF voltage vs. compression factor

The simulation showed that a compression factor of 8 can be achieved by a linear RF voltage with a peak amplitude of $\hat{u}$ = 5 MV. The bunch rotation requires 17 revolutions and 81.9 µs, respectively. Table 4 shows the main parameters of the required RF system.

| Cavity number | $\hat{u}$ [MV] | $f$ [MHz] |
|---|---|---|
| 1 | 5 | 2.48 |
| 2 | 1.5 | 4.97 |
| 3 | 0.4 | 7.45 |

Table 4: Main parameters for the RF cavities

### *4.1. Phase spread*

The minimum phase spread is 28°, corresponding to bunch length of 2.9 m. The total phase spread vs. the number of turns is shown in Figure 2.

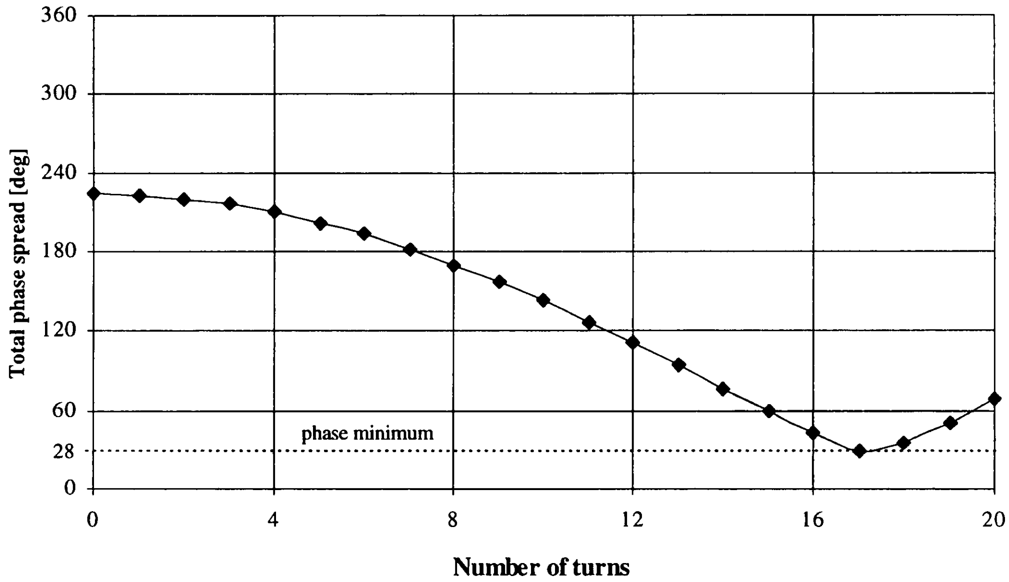


Figure 2: Total phase spread vs. number of turns

## *4.2 Space charge voltage*

The crest of the space charge voltage is initially 0.8 MV and peaks at 8.9 MV. The peak space charge voltage vs. the number of turns is shown in Figure 3.

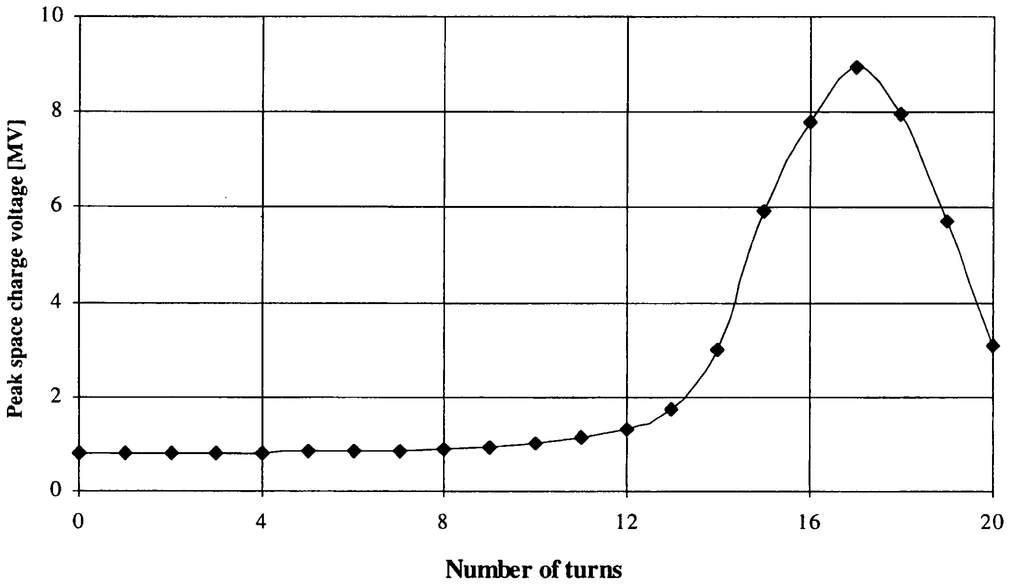


Figure 3: Peak space charge voltage vs. number of turns

*4.3 Tune shift*

The incoherent horizontal tune shift due to direct space charge peaks at -1.48. (see Figure 4).

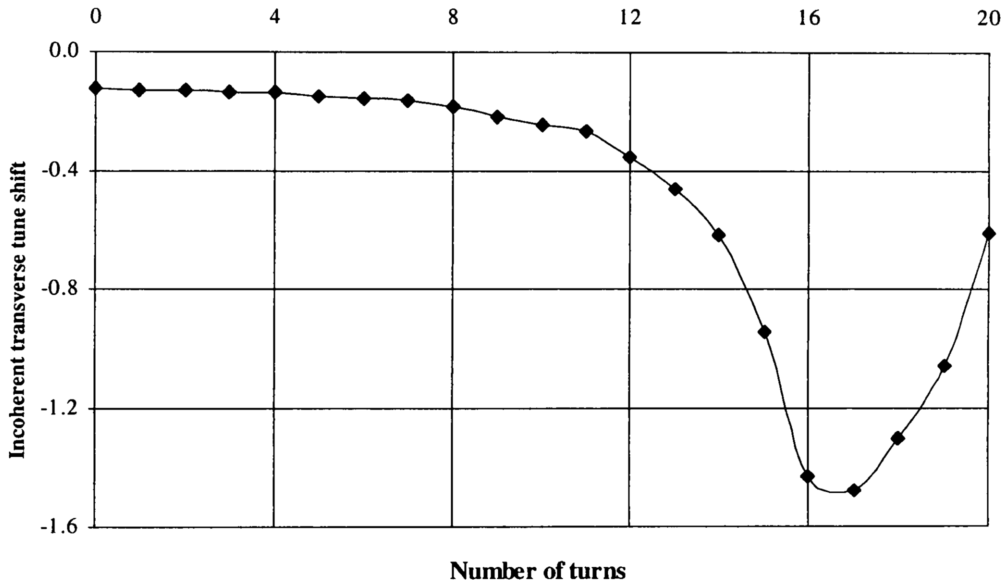


Figure 4: Incoherent transverse tune shift vs. number of turns

*4.4. Particle loss*

The simulations showed no particle loss.

## Conclusion

Pre-bunching can be applied by linear bunch rotation. Therefore a RF system with higher harmonics is required. The linear shape of the RF voltage can be approximated by the use of three harmonics. A possible combination for the amplitudes of the harmonics is 1, -0.30 and 0.08. A RF voltage of $\hat{u}$ = 5 MV results in a compression factor of 8, corresponding to a total phase spread of 28° and to a bunch length of 2.9 m. The 90° bunch rotation requires 17 turns (81.9 μs) around the 443 m circumference of the synchrotron.

## References


[1] I. Hofmann, Inertial Fusion With Accelerators, EPAC Conference, June 10-14 1996.
[2] H. Schoenauer, private communication, July 1996.
[3] W. Pirkl, private communication, August 1996.
[4] S.R. Koscielniak, LONG1D User Guide, TRIUMF Vancouver B.C., May 1988.


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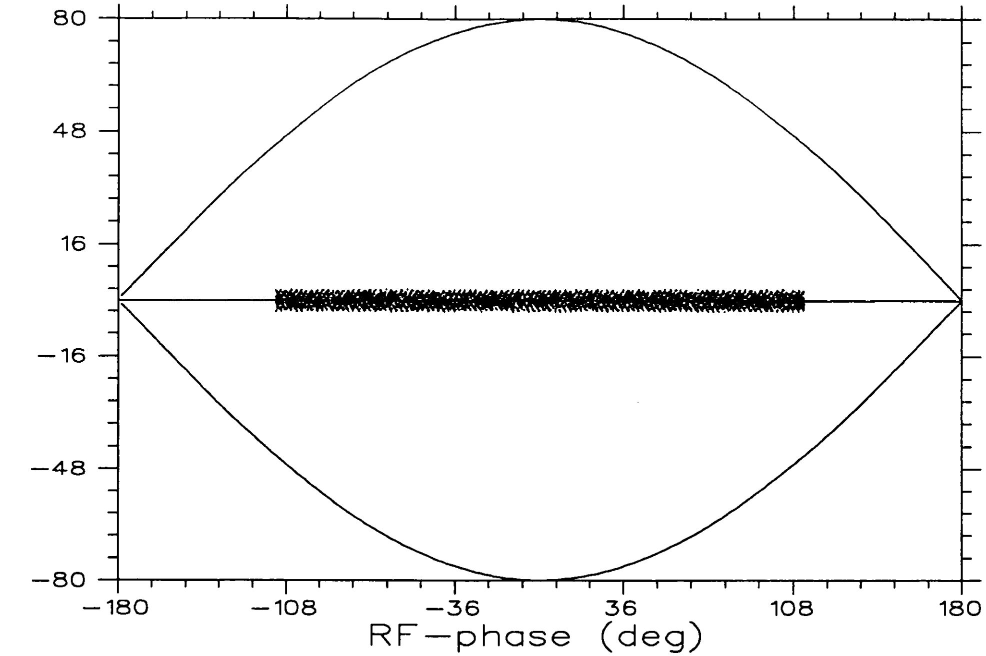
## Appendix:

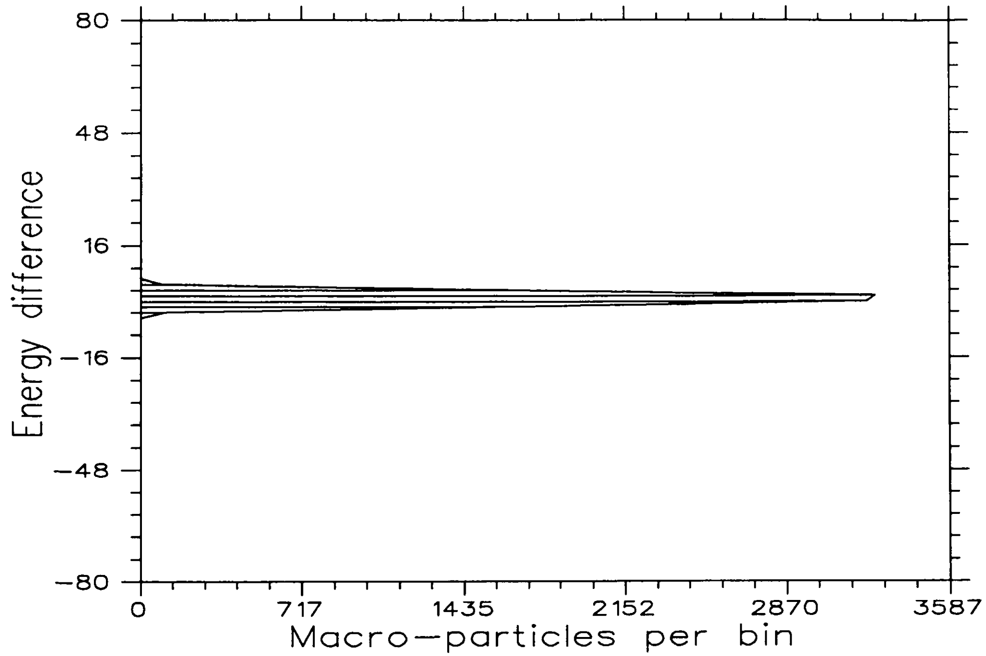
The following plots show displays of the phase-space, energy spectrum, bunch shapes and space-charge voltage of the procedure of bunch rotation with three harmonics and a RF voltage of 5 MV.

## Longitudinal Phas Space



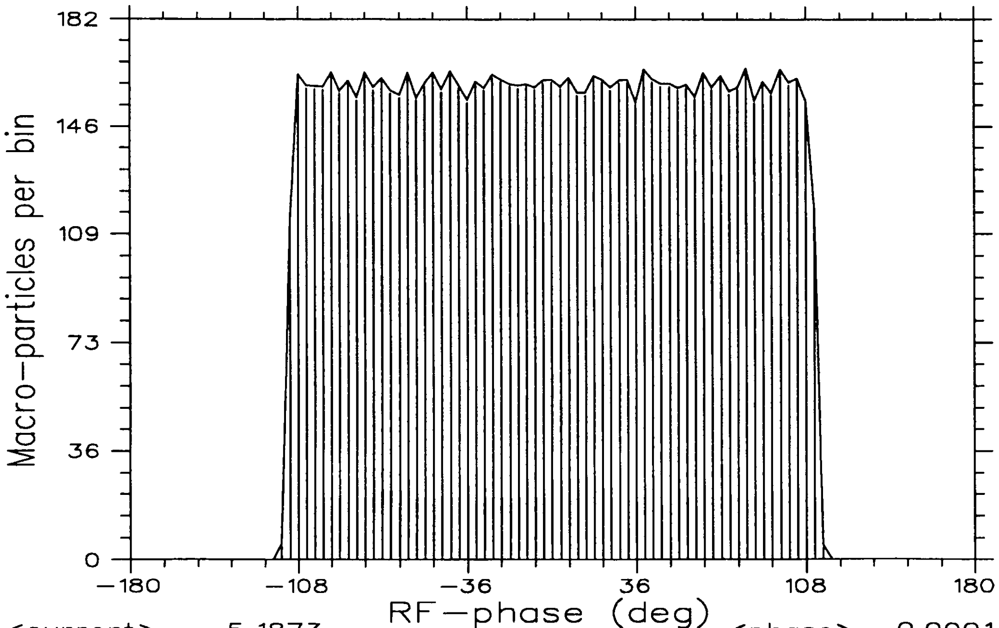

Time 0.00 (us) <Energy> −0.00916 (MeV) Revs 0
Npart 10000 Energy(s) 9.99 (GeV)

## Energy Spectrum



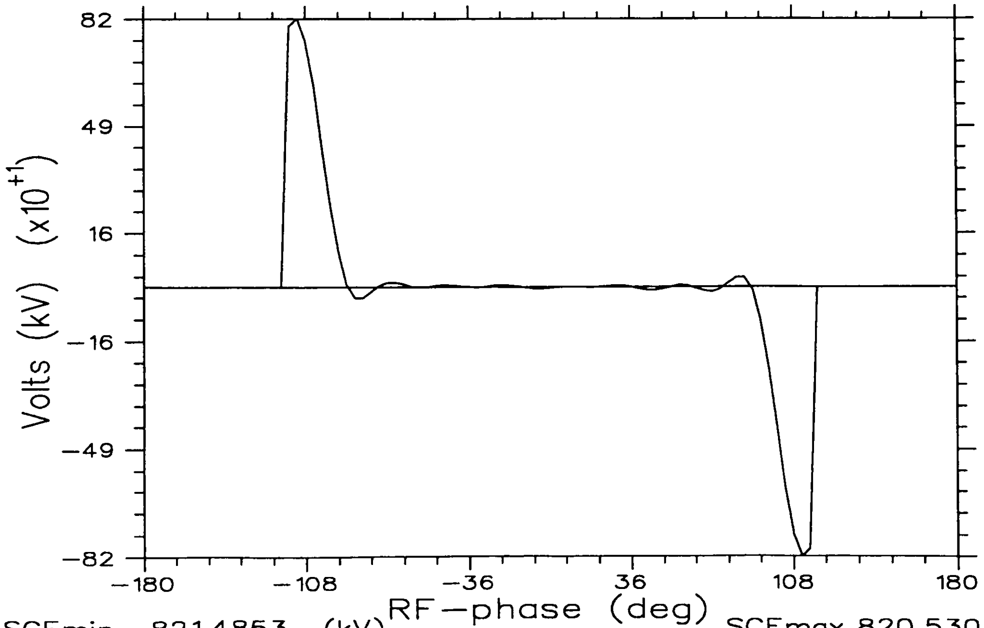

Energy spread 6.4702 (MeV) Momentum spread 0.0003
Harmonics 13

## Line Density

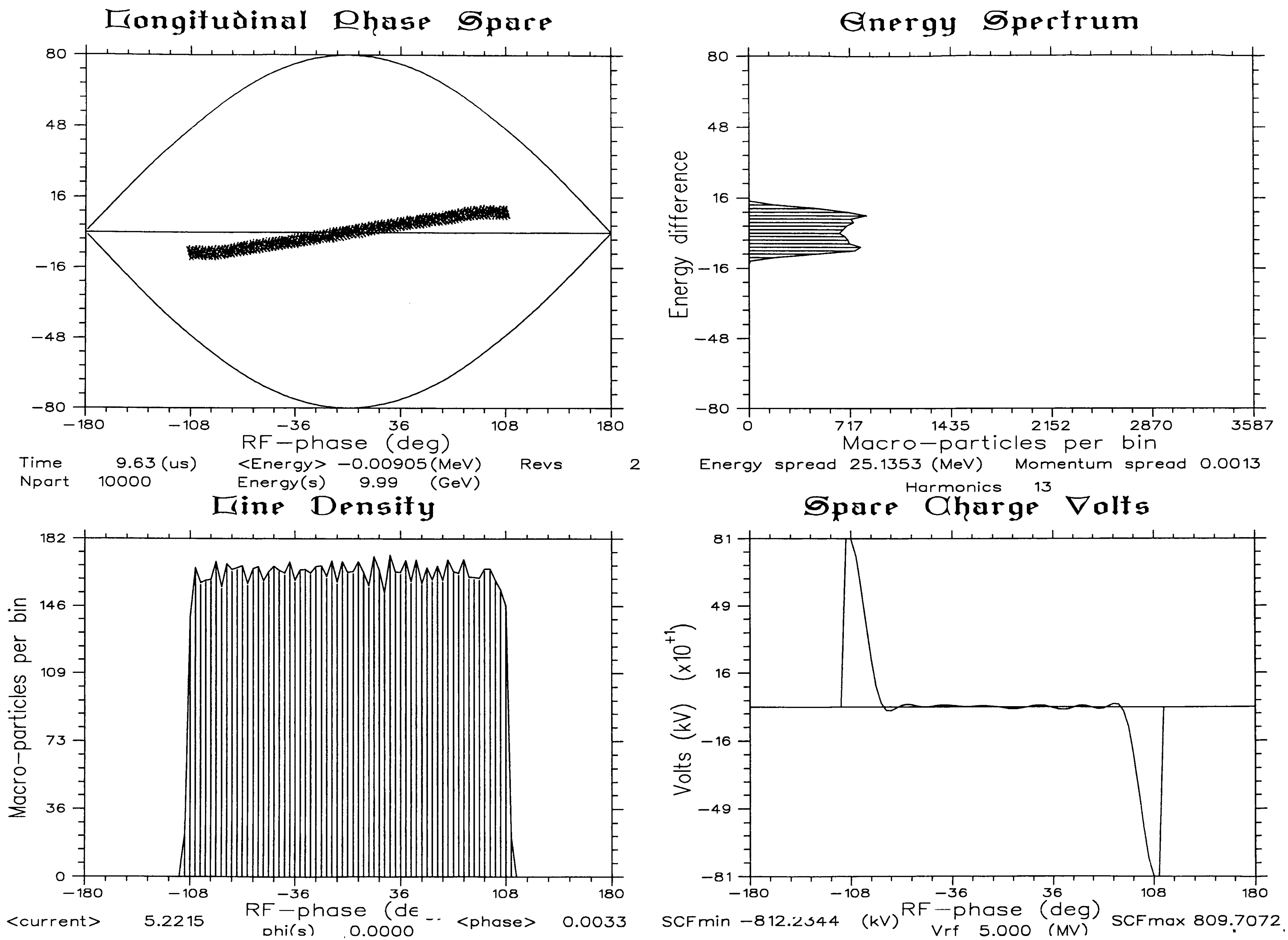



<current> 5.1873 phi(s) 0.0000 <phase> 0.0001

## Space Charge Volts

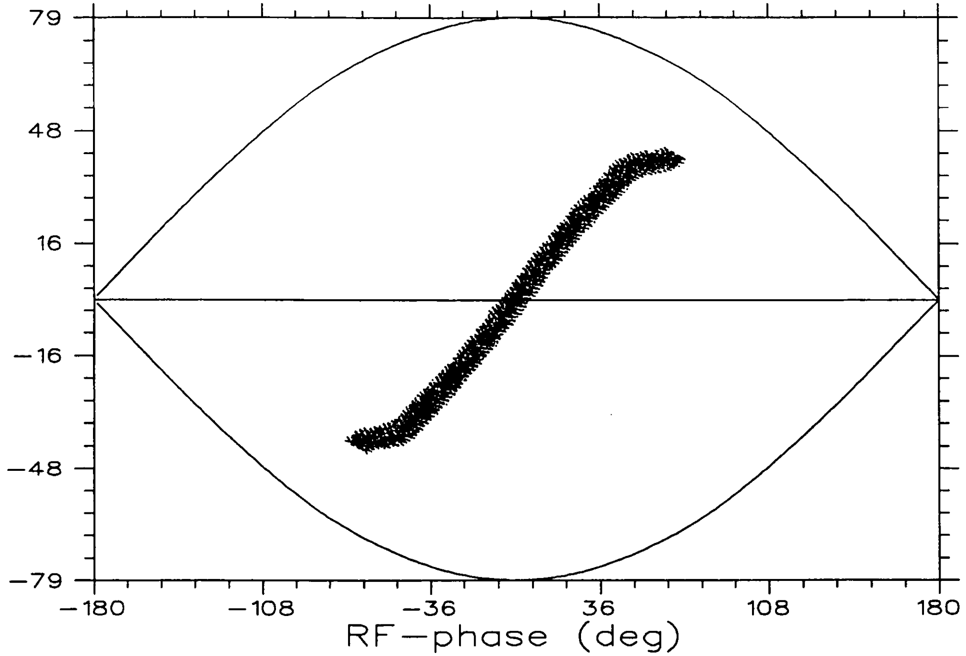



SCFmin −821.4853 (kV) Vrf 5.000 (MV) SCFmax 820.5303



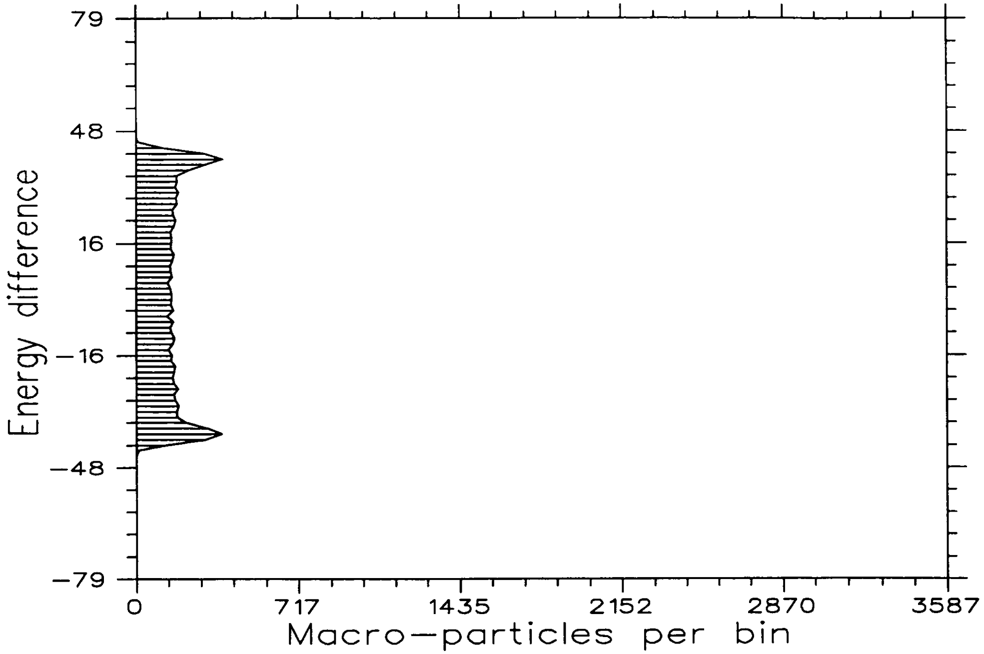
Longitudinal Phase Space
80
48
16
−16
−48
−80
−180
−108
−36
36
108
180
RF−phase (deg)
Time 9.63 (us)
Npart 10000
<Energy> −0.00905 (MeV)
Energy(s) 9.99 (GeV)
Revs 2
Energy Spectrum
Energy difference
0
717
1435
2152
2870
3587
Macro−particles per bin
Energy spread 25.1353 (MeV)
Momentum spread 0.0013
Harmonics 13
Line Density
Macro−particles per bin
182
146
109
73
36
<current> 5.2215
phi(s) 0.0000
<phase> 0.0033
Space Charge Volts
Volts (kV) (x10$^{+1}$)
81
49
−49
−81
SCFmin −812.2344 (kV)
Vrf 5.000 (MV)
SCFmax 809.7072

## Longitudinal Phas Space



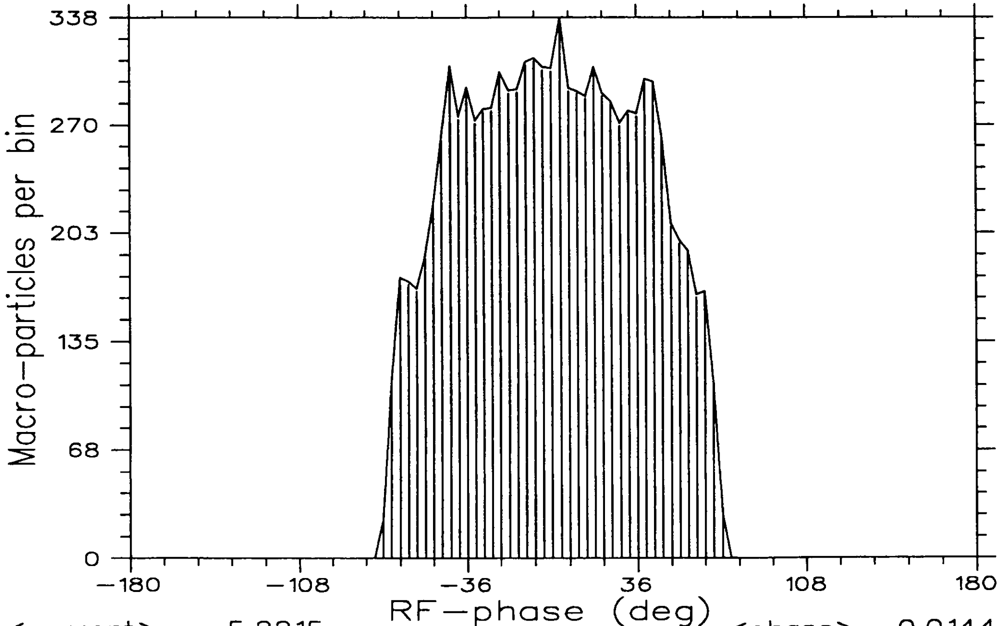

Time 48.18 (us) <Energy> −0.00626(MeV) Revs 10
Npart 10000 Energy(s) 9.99 (GeV)

## Energy Spectrum



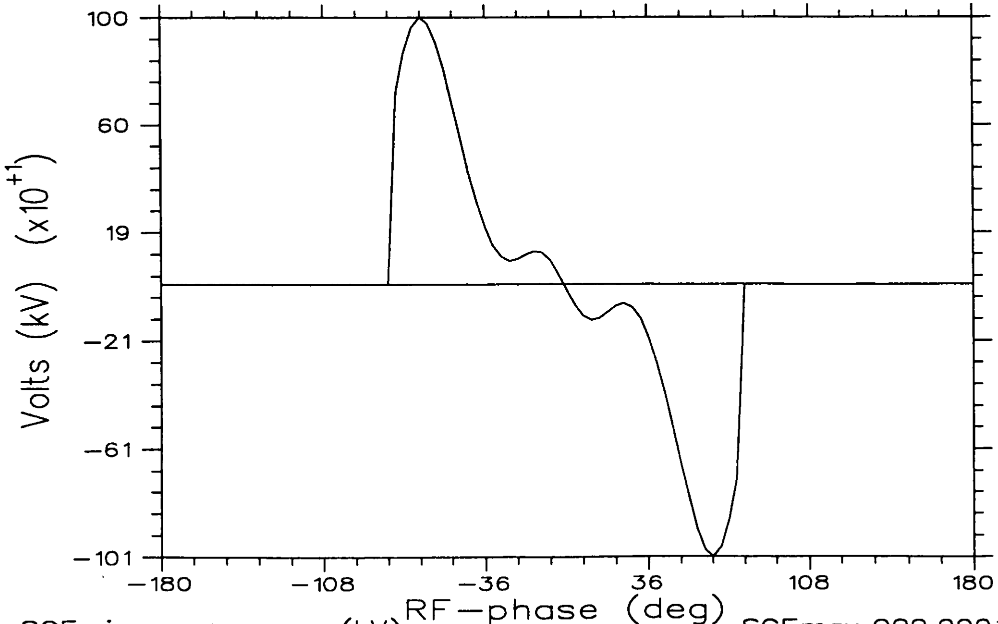

Energy spread 86.1293 (MeV) Momentum spread 0.0044
Harmonics 13

## Line Density

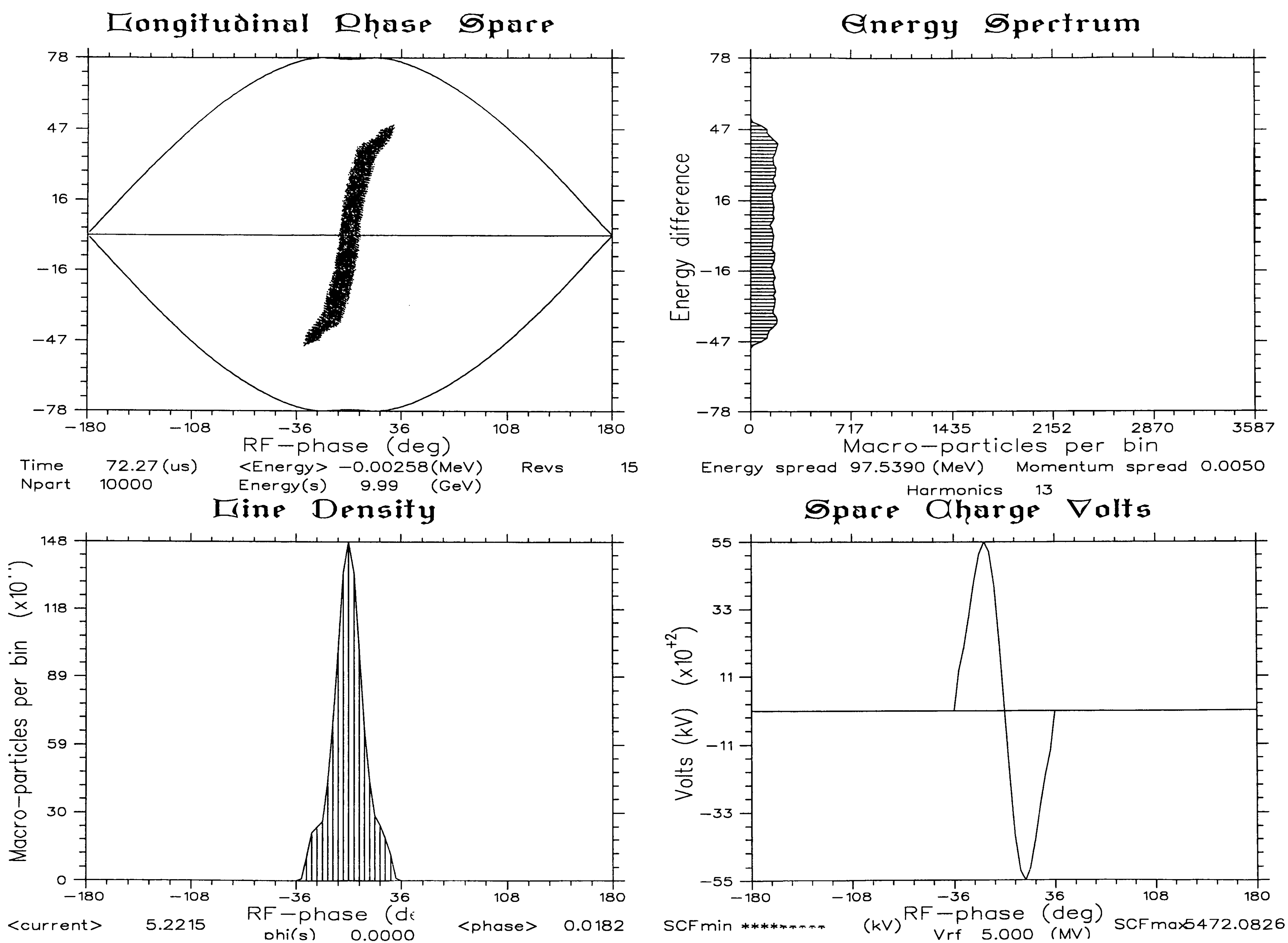


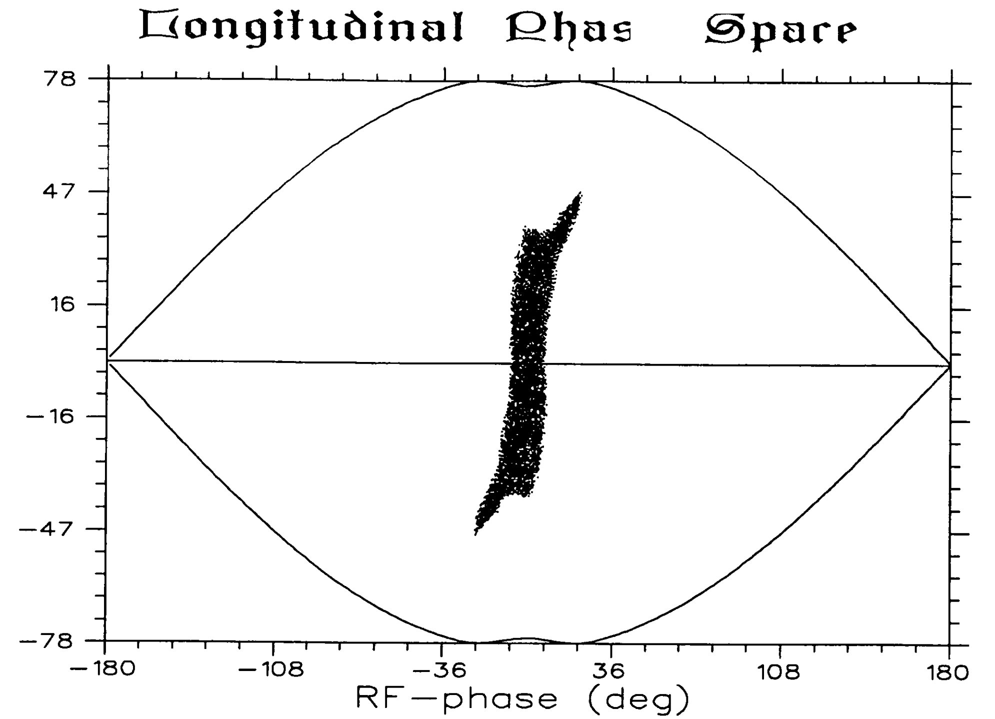

<current> 5.2215 phi(s) 0.0000 <phase> 0.0144

## Space Charge Volts

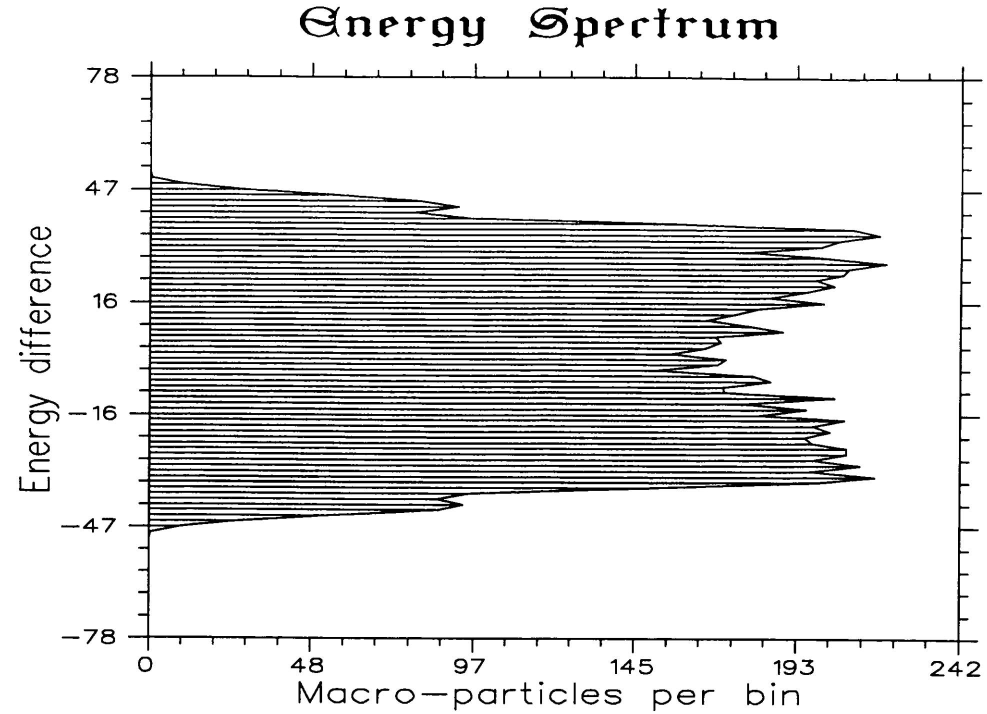



SCFmin ********* (kV) Vrf 5.000 (MV) SCFmax 999.9091

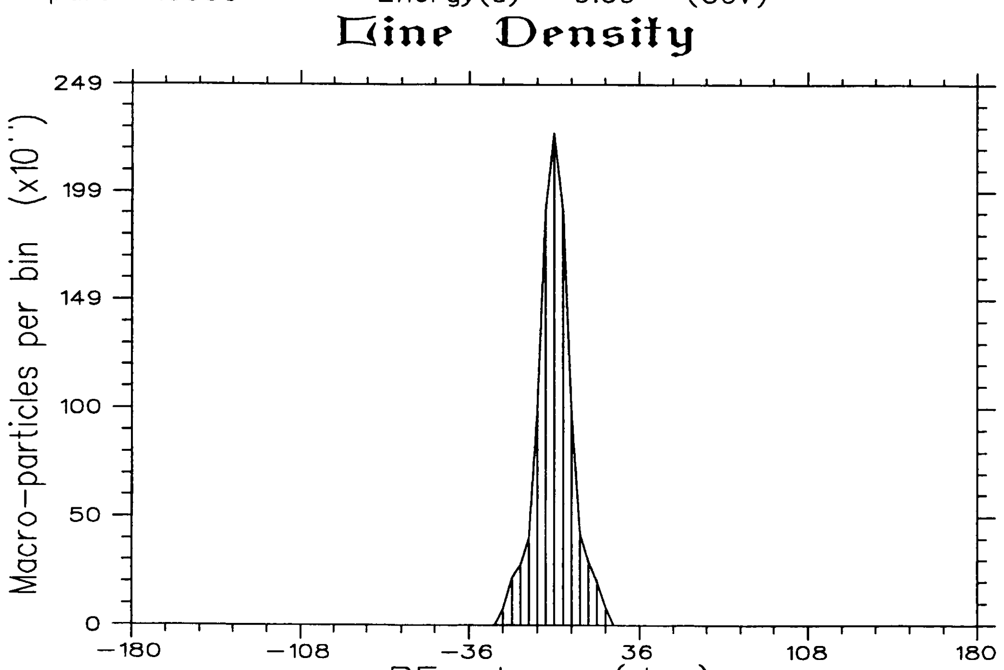

Longitudinal Phase Space
78
47
16
-16
-47
-78
-180
-108
-36
36
108
180
RF-phase (deg)
Time 72.27 (us)
Npart 10000
<Energy> -0.00258 (MeV)
Energy(s) 9.99 (GeV)
Revs 15
Energy Spectrum
Energy difference
0
717
1435
2152
2870
3587
Macro-particles per bin
Energy spread 97.5390 (MeV)
Momentum spread 0.0050
Harmonics 13
Line Density
148
118
89
59
30
Macro-particles per bin (x10'')
<current> 5.2215
phi(s) 0.0000
<phase> 0.0182
Space Charge Volts
55
33
11
-11
-33
-55
Volts (kV) (x10+2)
SCFmin *********
(kV)
Vrf 5.000 (MV)
SCFmax5472.0826



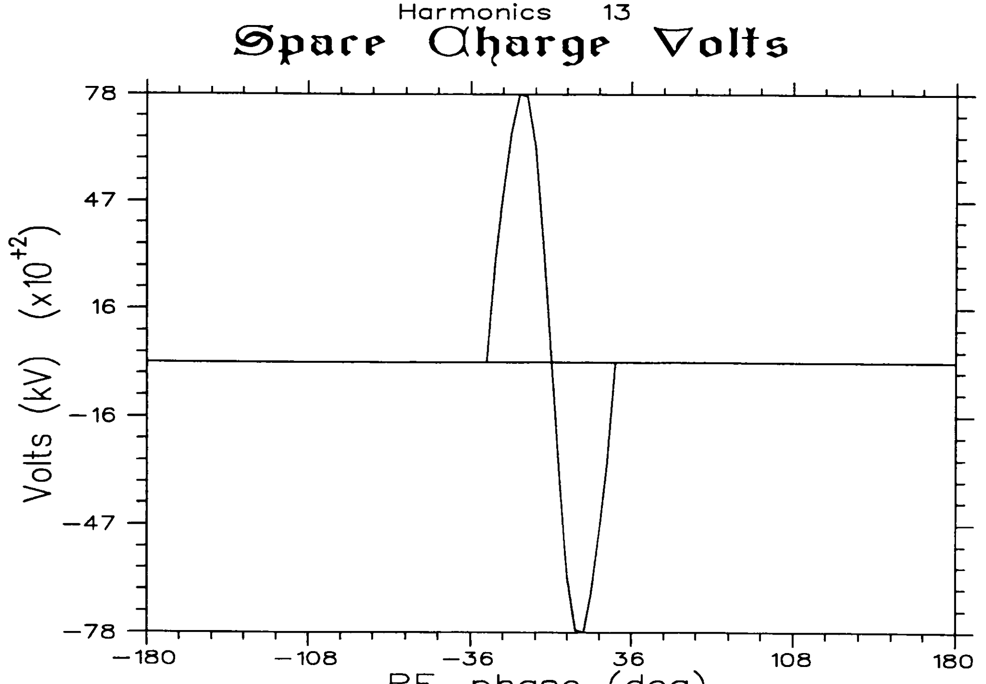

Time 77.08 (us) <Energy> −0.00161 (MeV) Revs 16
Npart 10000 Energy(s) 9.99 (GeV)



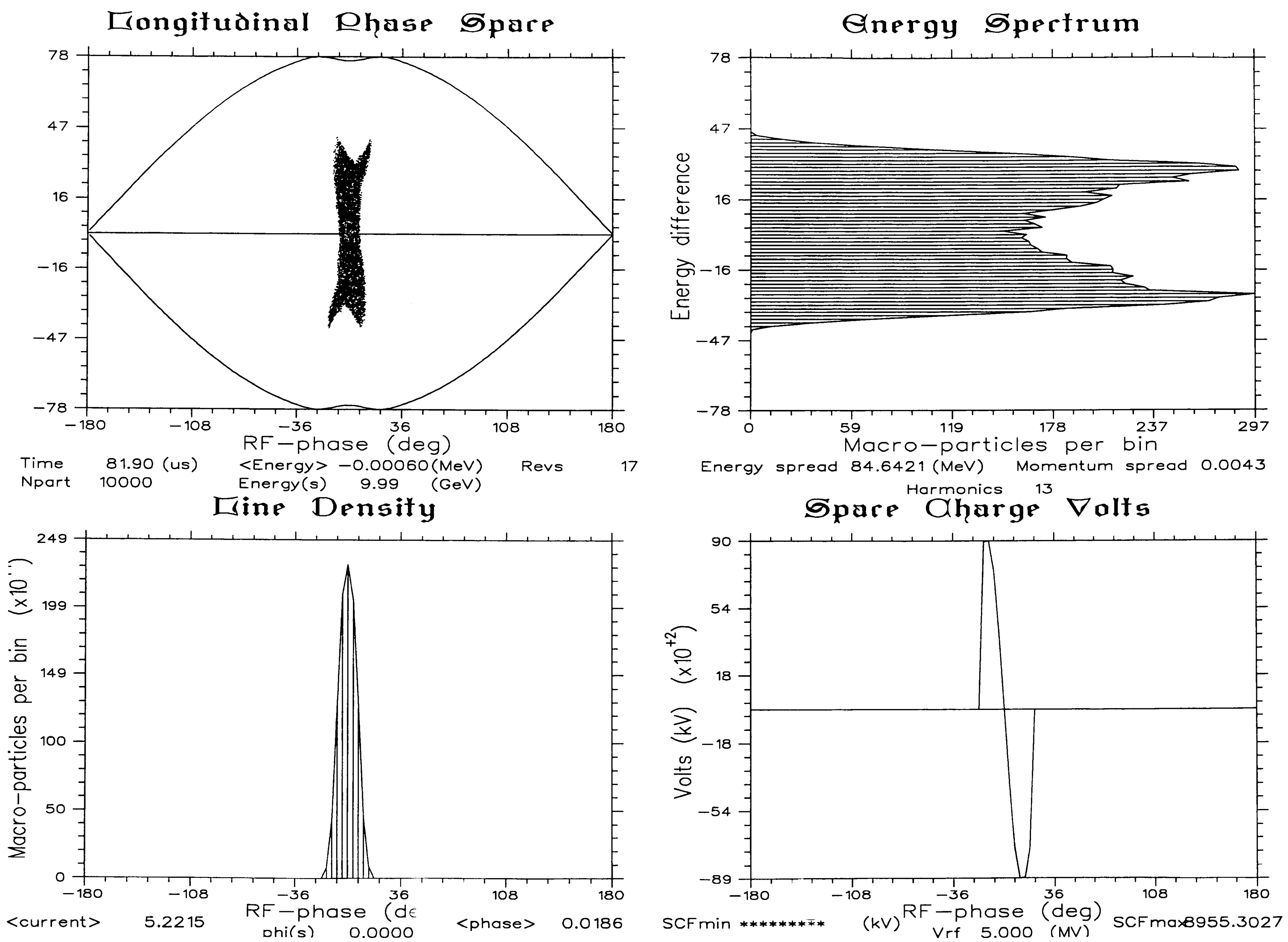

Energy spread 95.2655 (MeV) Momentum spread 0.0049
Harmonics 13



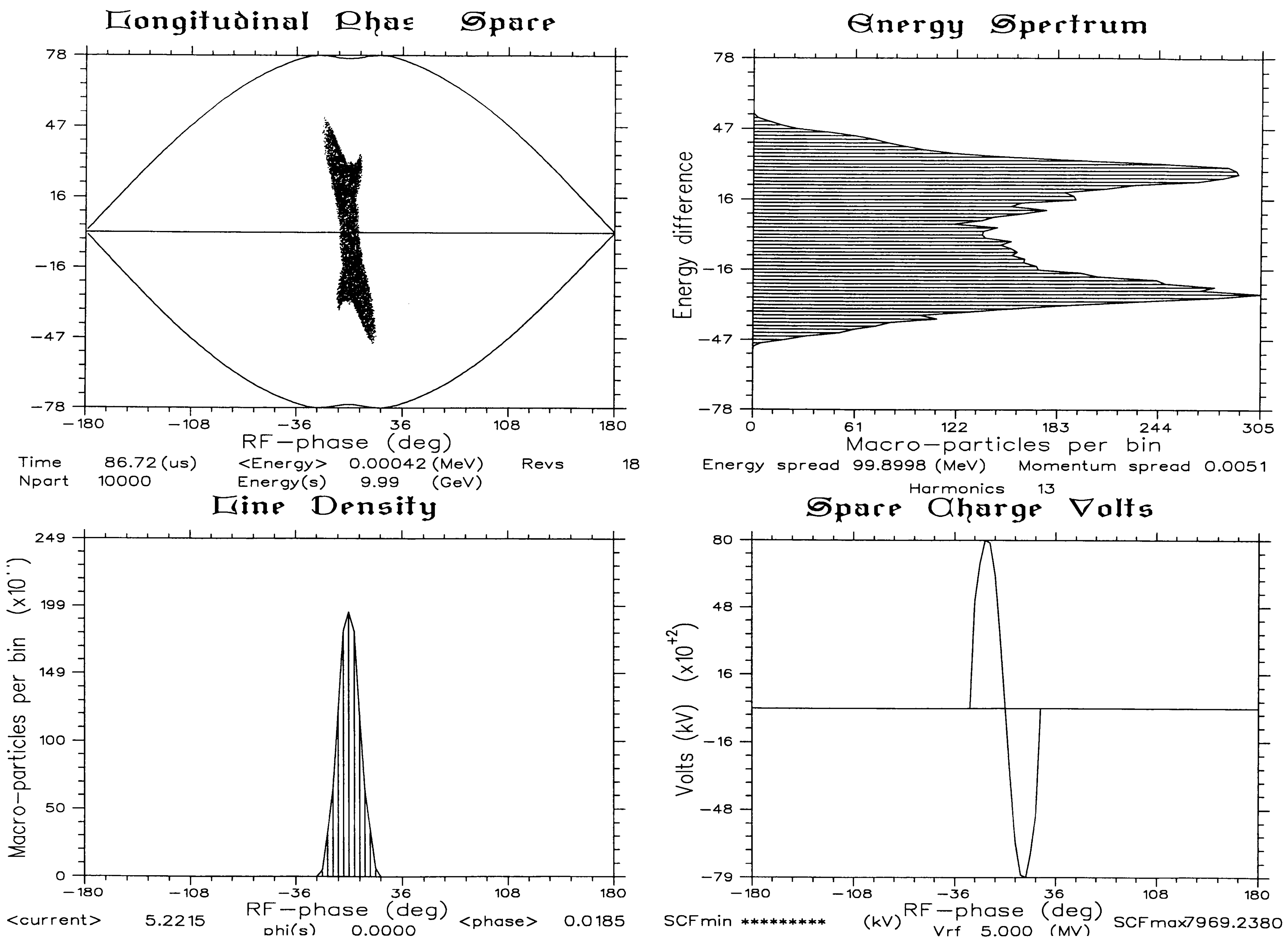

<current> 5.2215 phi(s) 0.0000 <phase> 0.0185

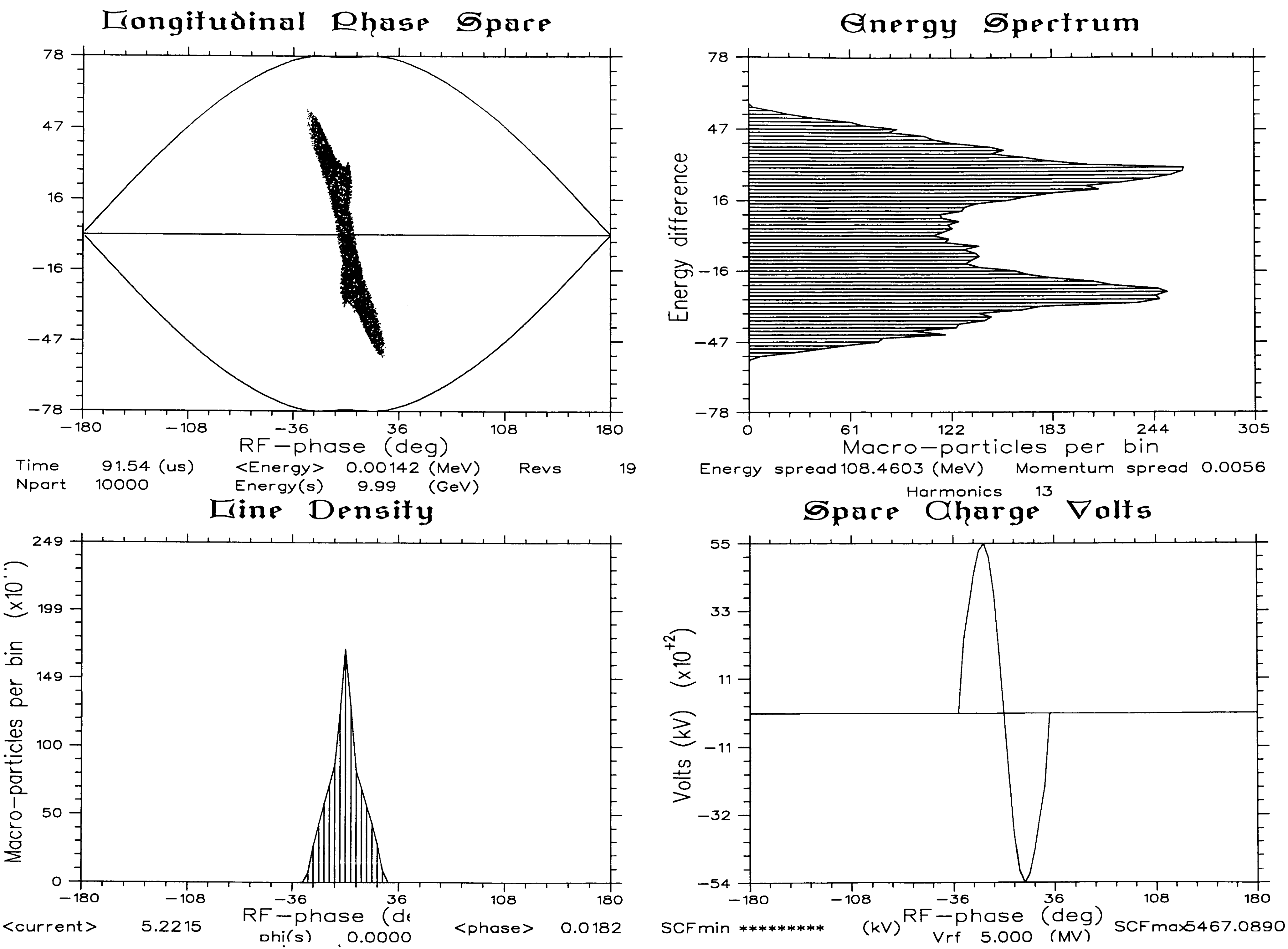



SCFmin ********* (kV) Vrf 5.000 (MV) SCFmax7831.9701

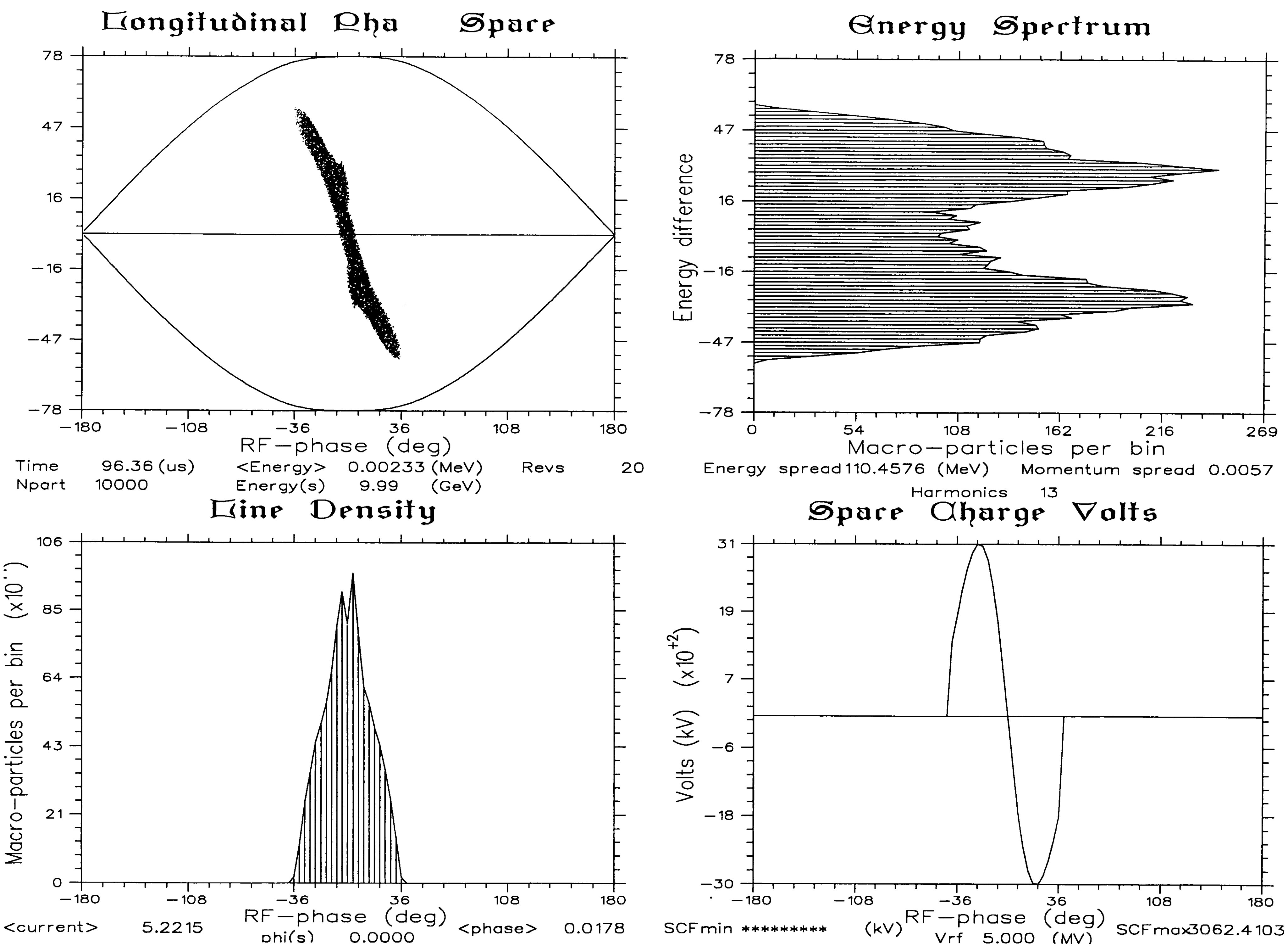


Longitudinal Phase Space
78
47
16
−16
−47
−78
−180
−108
−36
36
108
180
RF−phase (deg)
Time 81.90 (us)
Npart 10000
<Energy> −0.00060 (MeV)
Energy(s) 9.99 (GeV)
Revs 17
Energy Spectrum
Energy difference
0
59
119
178
237
297
Macro−particles per bin
Energy spread 84.6421 (MeV)
Momentum spread 0.0043
Harmonics 13
Line Density
249
199
149
100
50
0
Macro−particles per bin (x10⁻¹)
RF−phase (de
<current> 5.2215
phi(s) 0.0000
<phase> 0.0186
Space Charge Volts
90
54
18
−18
−54
−89
Volts (kV) (x10+2)
RF−phase (deg)
SCFmin *********
(kV)
Vrf 5.000 (MV)
SCFmax8955.3027


Longitudinal Phase Space
78
47
16
−16
−47
−78
−180
−108
−36
36
108
180
RF−phase (deg)
Time 86.72 (us)
Npart 10000
<Energy> 0.00042 (MeV)
Energy(s) 9.99 (GeV)
Revs 18
Energy Spectrum
Energy difference
0
61
122
183
244
305
Macro−particles per bin
Energy spread 99.8998 (MeV)
Momentum spread 0.0051
Harmonics 13
Line Density
Macro-particles per bin (x10⁻¹)
249
199
149
100
50
0
<current> 5.2215
phi(s) 0.0000
<phase> 0.0185
Space Charge Volts
Volts (kV) (x10+2)
80
48
16
−16
−48
−79
SCFmin *********
(kV)
Vrf 5.000 (MV)
SCFmax7969.2380



Longitudinal Phase Space
RF−phase (deg)
Time 91.54 (us)
Npart 10000
<Energy> 0.00142 (MeV)
Energy(s) 9.99 (GeV)
Revs 19
Energy Spectrum
Energy difference
Macro−particles per bin
Energy spread 108.4603 (MeV)
Momentum spread 0.0056
Harmonics 13
Line Density
Macro−particles per bin (x10˙˙)
RF−phase (de
<current> 5.2215
phi(s) 0.0000
<phase> 0.0182
Space Charge Volts
Volts (kV) (x10+2)
RF−phase (deg)
SCFmin *********
(kV)
Vrf 5.000 (MV)
SCFmax5467.0890



Longitudinal Pha Space
78
47
16
−16
−47
−78
−180
−108
−36
36
108
180
RF−phase (deg)
Time 96.36 (us)
Npart 10000
<Energy> 0.00233 (MeV)
Energy(s) 9.99 (GeV)
Revs 20
Energy Spectrum
Energy difference
0
54
108
162
216
269
Macro−particles per bin
Energy spread110.4576 (MeV)
Momentum spread 0.0057
Harmonics 13
Line Density
Macro-particles per bin (x10¹)
106
85
64
43
21
0
<current> 5.2215
phi(s) 0.0000
<phase> 0.0178
Space Charge Volts
Volts (kV) (x10+2)
31
19
7
−6
−18
−30
SCFmin *********
(kV)
Vrf 5.000 (MV)
SCFmax3062.4103