Beam collimation in the beam transfer line from 8 GeV linac to the Main Injector and painting injection and collimation in the Main Injector

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May 6, 2004

1 Beam collimation in the 8 GeV beam transfer line

2 Painting injection and beam collimation in the Main Injector

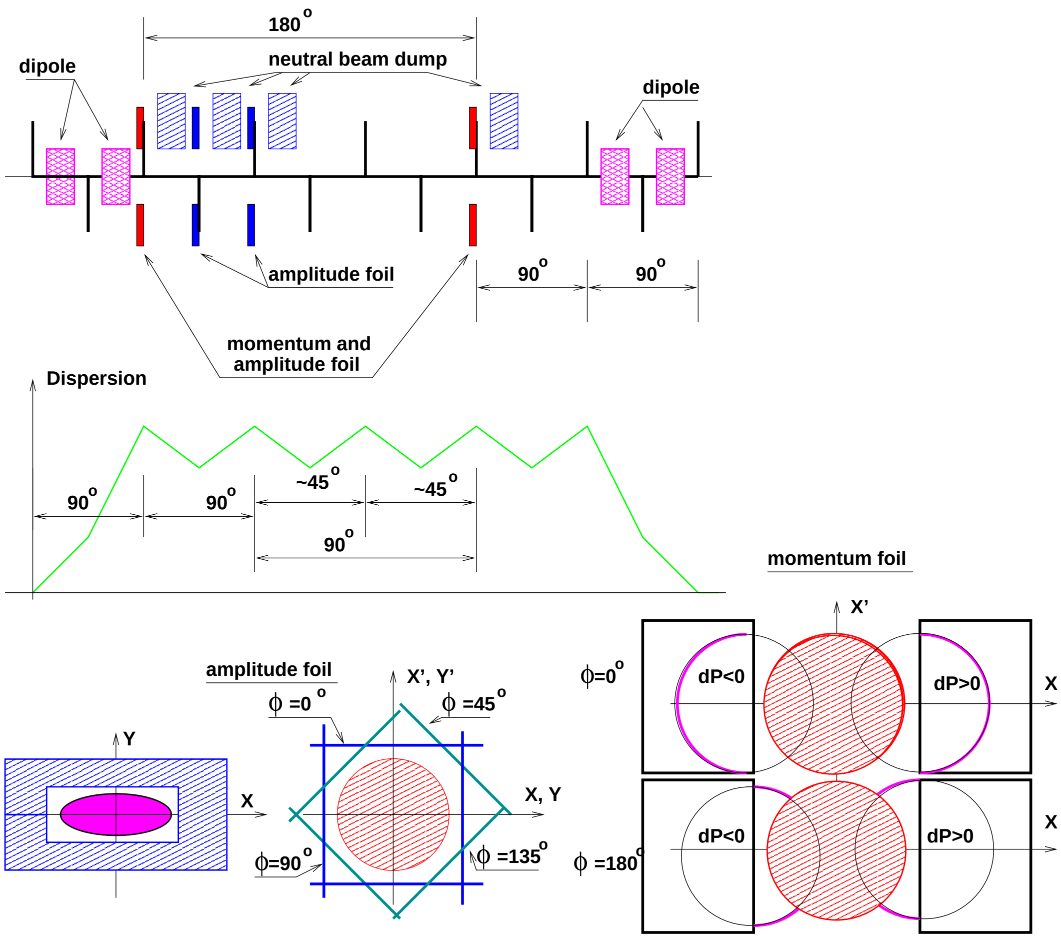

Figure 1: Collimation system requirements for the transfer line.

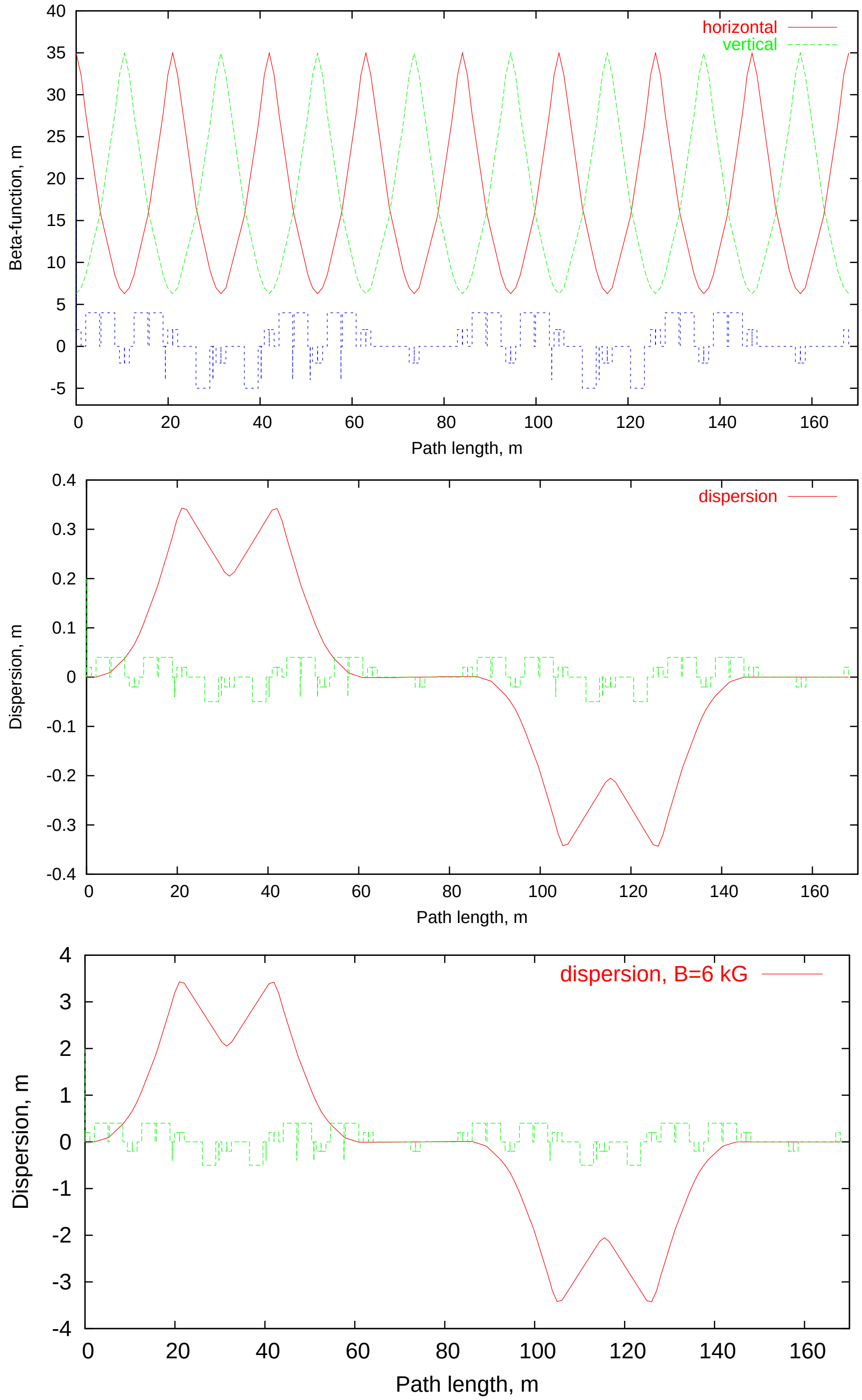

Figure 2: An example of beam transfer line that fits the collimation system requirements. To prevent H^- stripping the magnetic field in the quadrupoles and dipoles of beam line must be less than 0.6 kG. The maximum dispersion at that field is only 0.35 m. For momentum collimation it should be bigger than 3 m. The transfer line beta (top), dispersion at $B_{dipole} = 0.6\ kG'$ middle and at $B_{dipole} = 6\ kG'$ (bottom).

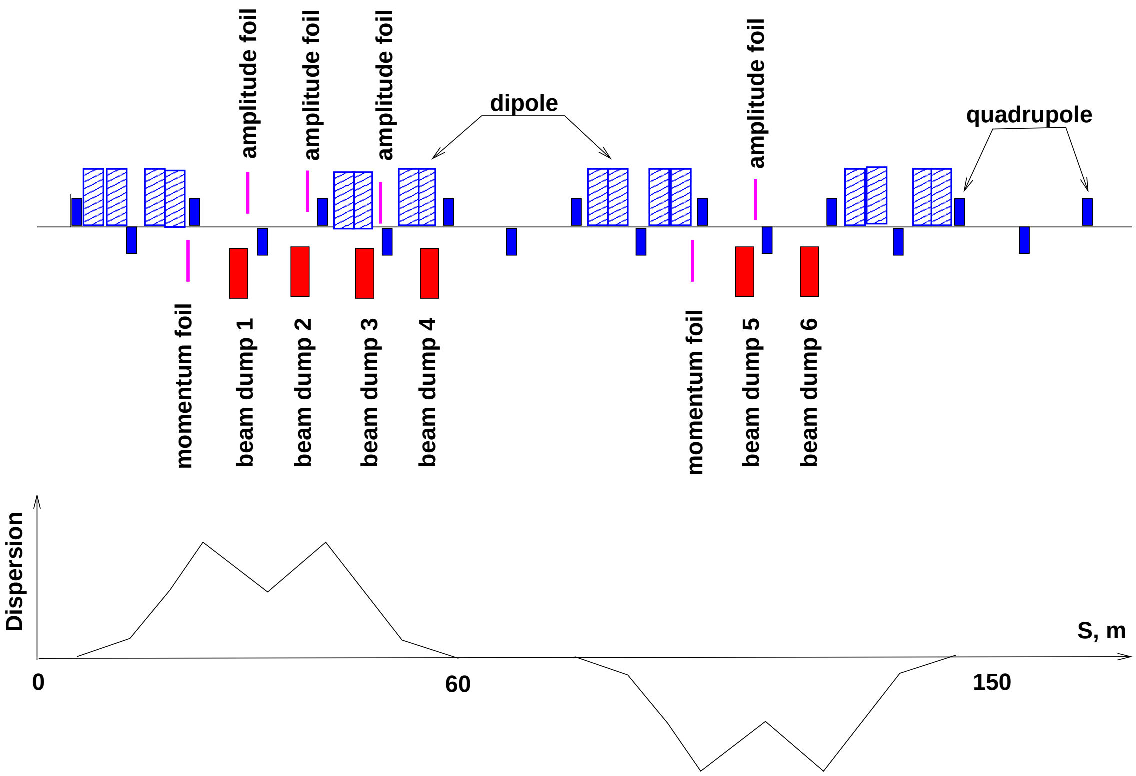

Figure 3: Collimation system location in the beam transfer line.

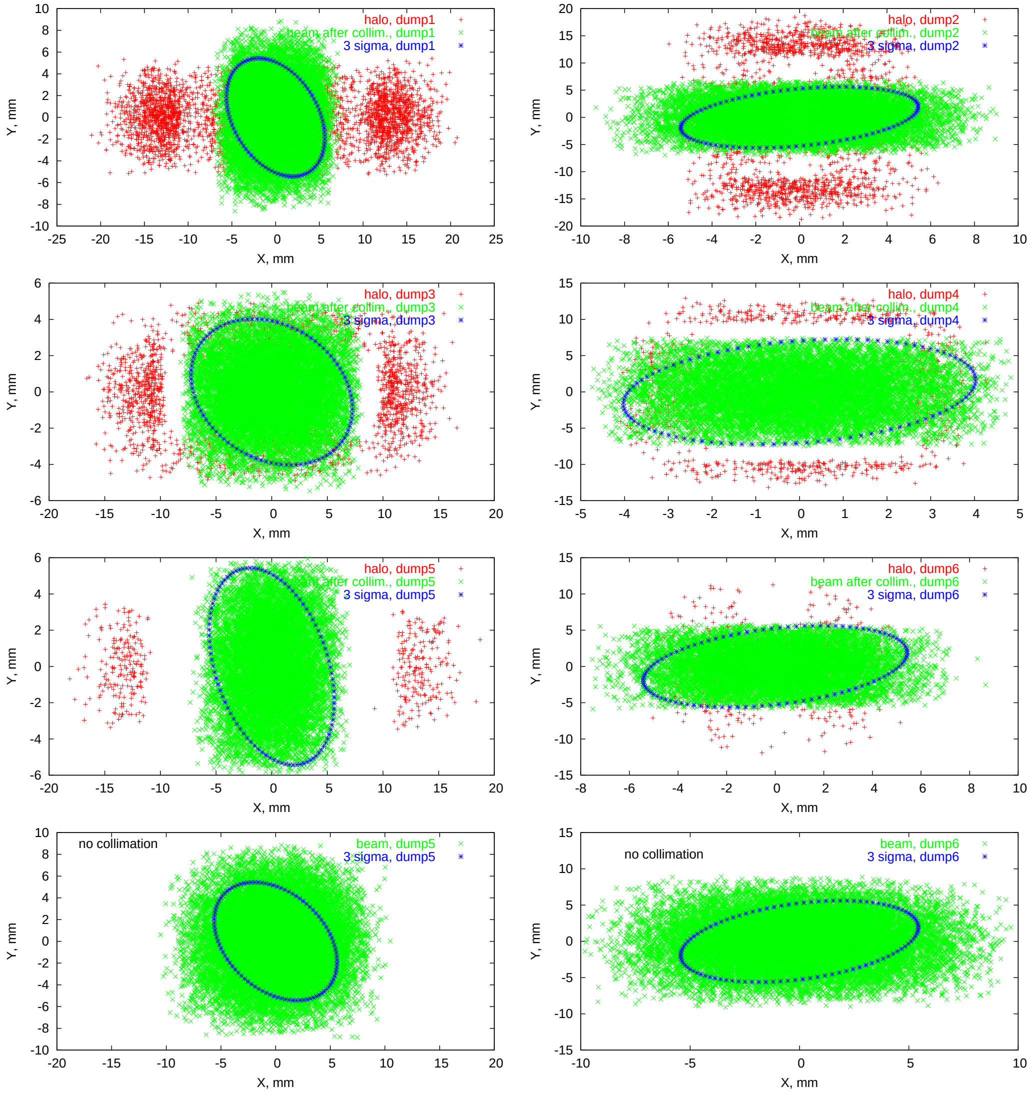

Figure 4: Beam after collimation at every 45^o (green) and intercepted halo (red) at the neutral beam dump number 1 and 2 (top), number 3 and 4 (second line) and number 5 and 6 (third line). Beam without collimation at dump number 5 and 6 (bottom). Collimation at all six foils from four sides of the beam by a frame shape foil.

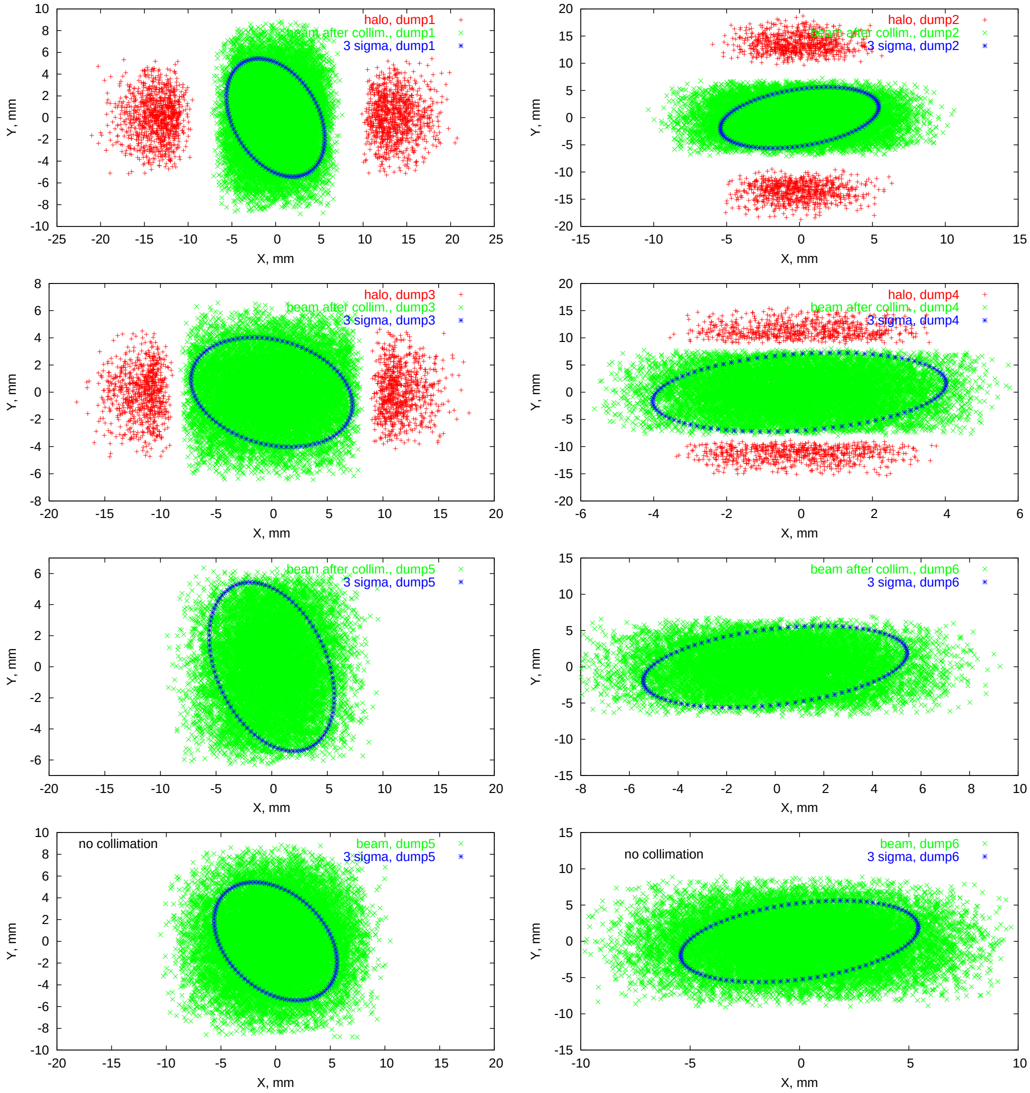

Figure 5: Beam after collimation at every 90^o (green) and intercepted halo (red) at the neutral beam dump number 1 and 2 (top), number 3 and 4 (second line) and number 5 and 6 (third line). Beam without collimation at dump number 5 and 6 (bottom). Collimation at foils number 1, 3 and 5 in horizontal plane, and at foils number 2, 4 and 6 in vertical plane.

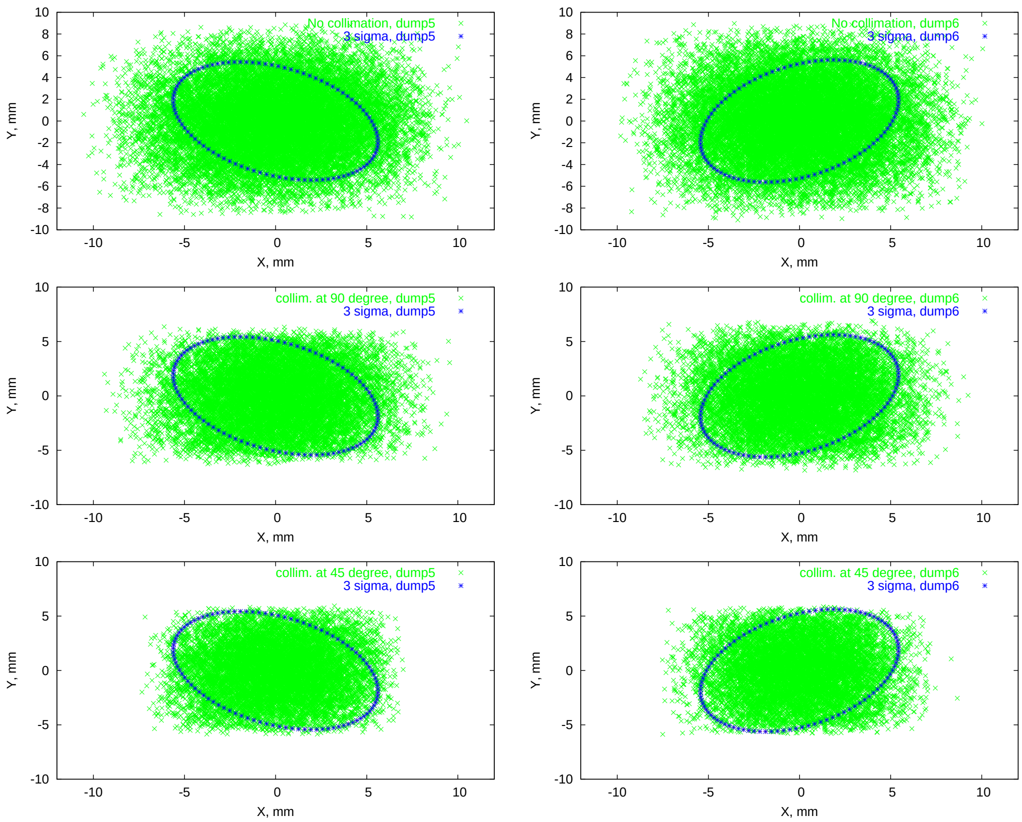

Figure 6: Beam without collimation (top), after collimation at every 90^o (middle) and every 45^o (bottom) at the neutral beam dump number five (left) and six (right).

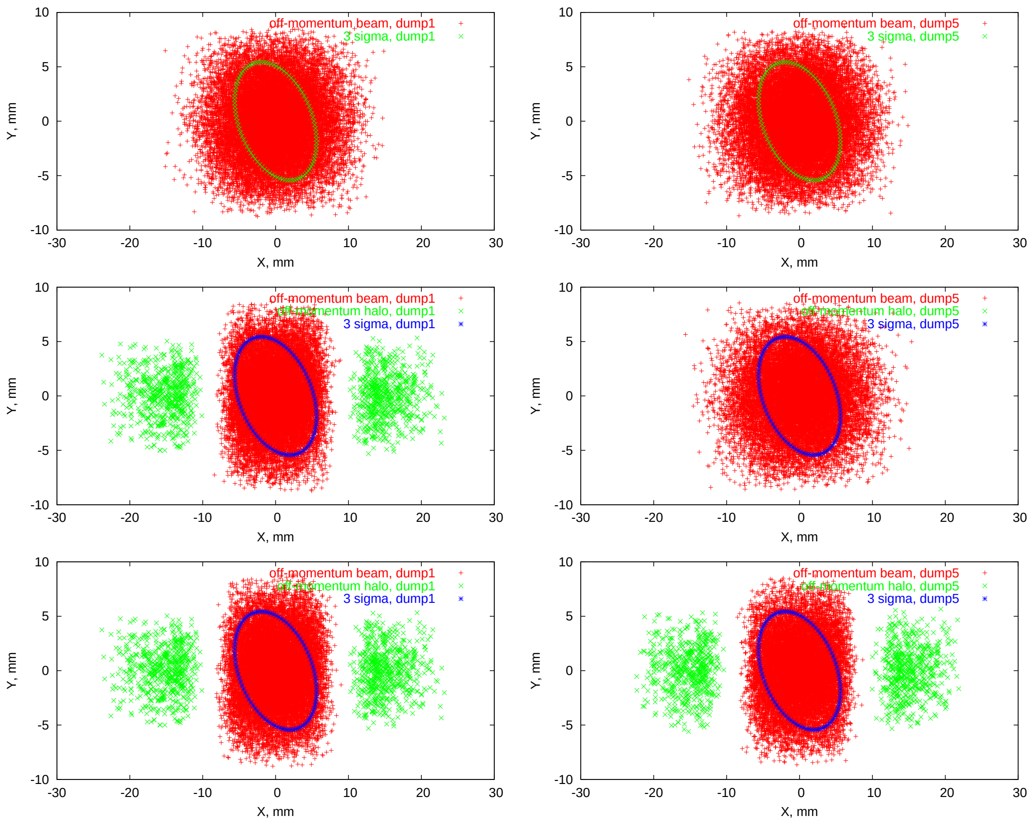

Figure 7: Off-momentum beam (only particles with dP/P=0.001 and dP/P=-0.001 are in the beam) without collimation (top), with collimation only at foil number one (middle) and at foil number one and five (bottom). Left - at the dump number one and right - at the dump number five entrance.

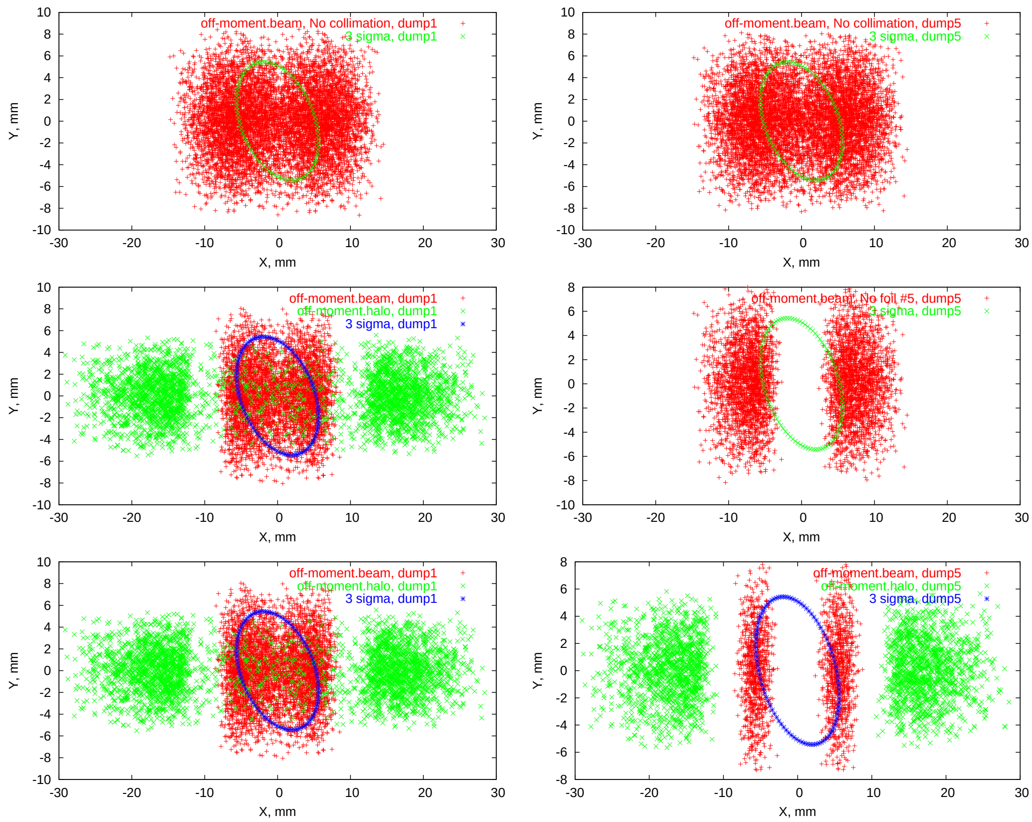

Figure 8: Off-momentum beam (only particles with dP/P=0.002 and dP/P=-0.002 are in the beam) without collimation (top), with collimation only at foil number one (middle) and at foil number one and five (bottom). Left - at the dump number one and right - at the dump number five entrance.

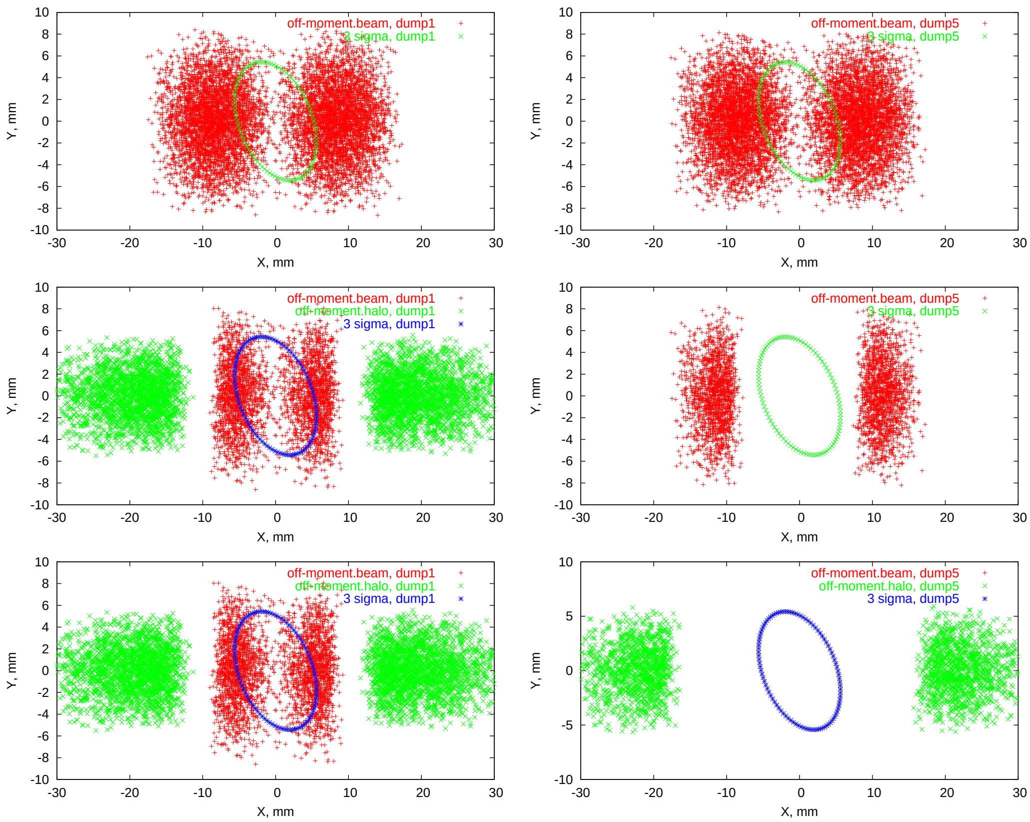

Figure 9: Off-momentum beam (only particles with dP/P=0.003 and dP/P=-0.003 are in the beam) without collimation (top), with collimation only at foil number one (middle) and at foil number one and five (bottom). Left - at the dump number one and right - at the dump number five entrance.

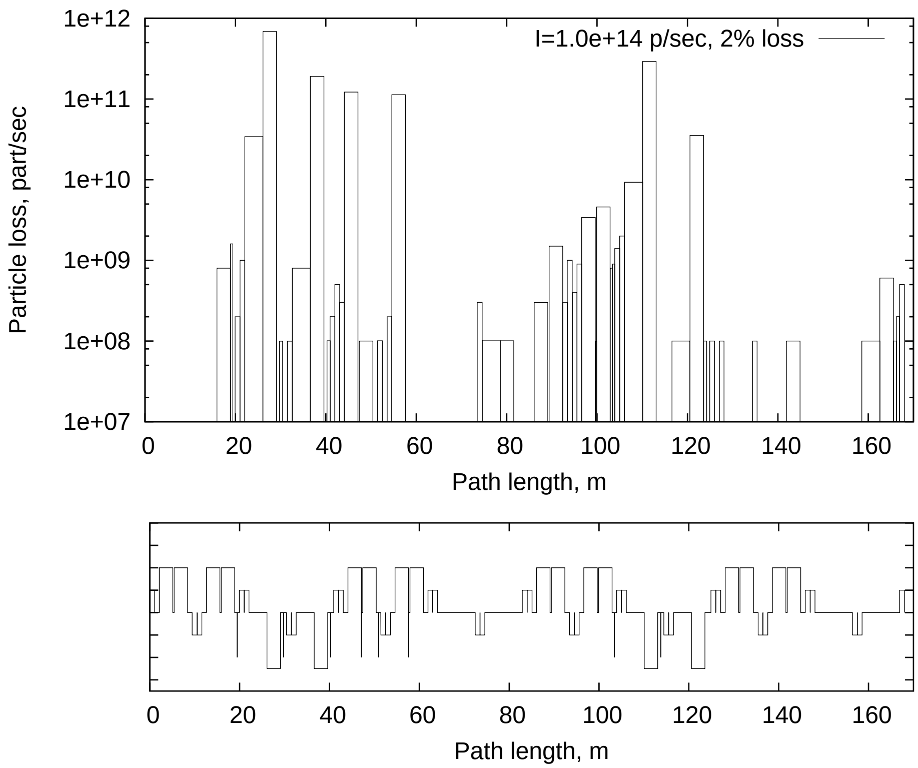

Figure 10: Beam loss along the beam line at collimation. Beam line aperture is D=60 mm. Foils are at $X = \pm 7.6\ mm$ and $Y = \pm 3.9\ mm$ upstream of focusing quads and at $X = \pm 3.9\ mm$ and $Y = \pm 7.6\ mm$ upstream of defocusing quads. Beam dumps are at $X = \pm 10\ mm$ and $Y = \pm 8\ mm$ upstream of focusing quads and at $X = \pm 8\ mm$ and $Y = \pm 10\ mm$ upstream of defocusing quads.

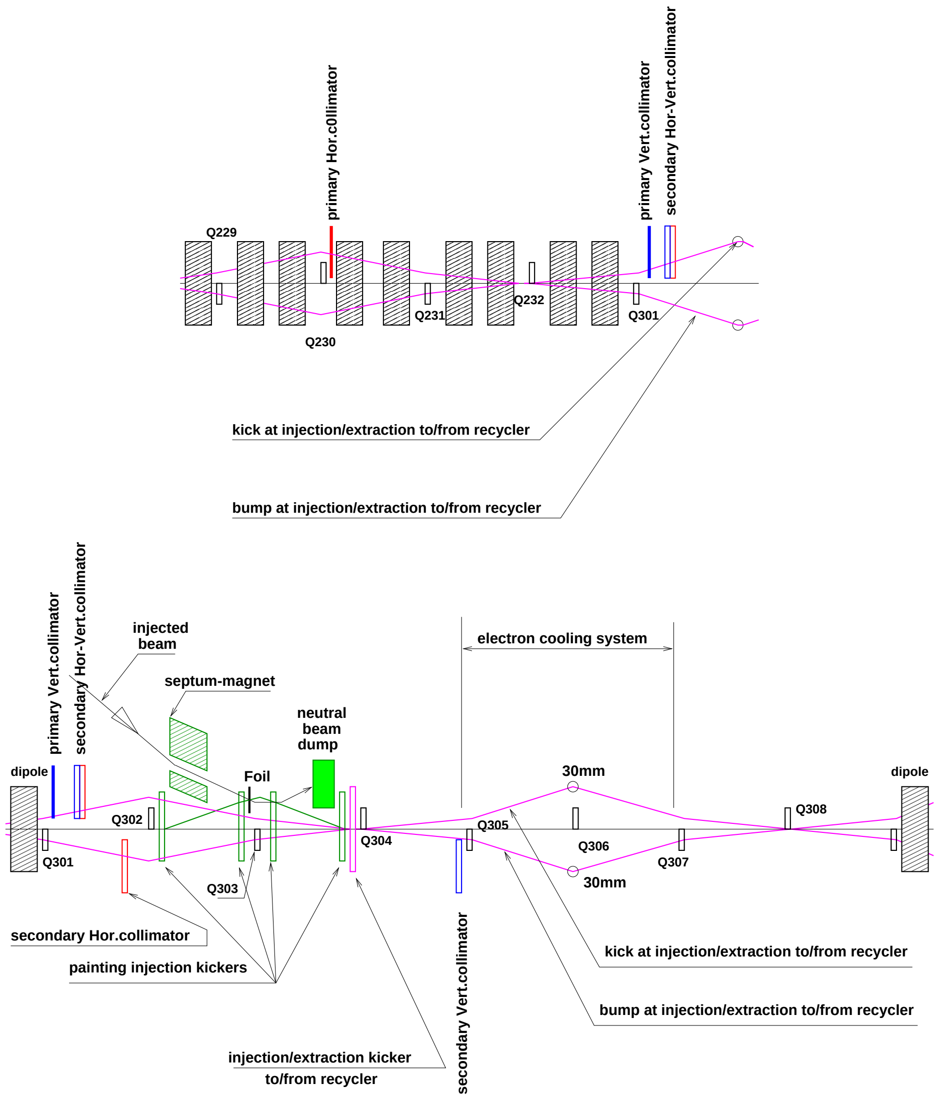

Figure 11: Horizontal primary collimator is located in the arc preceding the MI-30 straight section in a region with dispersion D=1.4 m. Secondary collimators are in the optimal phase advances with respect to the primary ones. Painting injection is performed by using two sets of fast horizontal and vertical kicker magnets. The maximum field of these magnets is 0.38 kG. A 9 m long (B=0.6 kG) septum-magnet located upstream of the foil is used to separate the proton and H^- beams at the quadrupole upstream of the foil. The beam dump located behind the stripping foil is used for excited states H$^o(n)$ atoms interception.

3 Painting injection

Painting injection is required to realize uniform density distributions of the beam in the transverse plane for space charge effect reduction. This preserves emittance at injection.

Injection of 8 GeV H^- beam into the MI-30 straight section of the Fermilab Main Injector [1] is simulated. Painting injection [2] is performed by using two sets of fast horizontal and vertical magnets (kickers). The proton orbit is moved in the vertical plane at the beginning of injection by 24 mm to the thin graphite stripping foil to accept the first portion of protons generated by H^- in the foil (Figs. 12 and 13). Four 1.8 m long kicker magnets are used to produce orbit displacement (Fig. 11). The maximum field of the kicker magnets is 0.38 kG. The vertical kick at the beginning of beam painting is shown in Fig. 14. Gradual reduction of kicker strength permits "painting" the injected beam across the accelerator aperture with the required emittance. Horizontal kicker magnets located in the injection line (not shown here) provide injected beam angle sweeping during injection time, starting from maximum at the beginning of injection and going to zero at the end of painting process (Fig. 13). Horizontal and vertical kickers produce particle betatron amplitude variation during injection. This results in a uniform distribution of the circulating beam after painting. Painting starts from the central region of phase space in the vertical plane and from the border of it in the horizontal plane, and goes to the border of the beam in the vertical plane and to to the center in the horizontal plane. This produces a so called "uncorrelated beam" with elliptical cross section, thereby eliminating particles that have maximum amplitudes in both planes simultaneously.

A 9 m long septum-magnet located upstream of the foil (Fig 11) is used to separate the proton and H^- beams at the quadrupole upstream of the foil by 167 mm with septum-magnet field of 0.6 kG. This allows the H^- beam to pass outside the quadrupole body. The beam dump located behind the stripping foil is used for H^o interception. Injection kickers cause negligible perturbation of the β functions and dispersion at injection. Vertical dispersion in the foil at injection produced by the bump is equal to 0.023 m.

Multi-turn particle tracking through the accelerator is done with the STRUCT [3] code. A stripping foil made of 300 μg/cm^2 (1.5 μm) thick graphite has the shape of so-called corner foil, where two edges of the square foil are supported and the other two edges are free. The foil size is 1.2 cm $\times$ 1.4 cm.

The dependence of kicker-magnets strength on time is chosen to get uniform distribution of the beam after painting both in horizontal and vertical planes. An optimal waveform of bump-magnets [4] was simulated in the STRUCT code as presented below:

- in the vertical plane

$$B = B_o \left[0.4167 + 0.5833 \left(1 - \sqrt{\frac{2\,N}{90} - \left(\frac{N}{90}\right)^2} \right) \right] \qquad N < 90 \qquad (1)$$

$$B = B_o \left[0.4167 - \frac{N - 90}{14.3988} \right] \qquad N > 90 \qquad (2)$$

- in the horizontal plane

$$Y' = Y'_o \sqrt{2\frac{90 - N}{90} - \left(\frac{90 - N}{90}\right)^2} \qquad Y'_o = 0.65\,mrad \qquad (3)$$

Here N is the turn number from beginning of painting.

The normalized emittance of injected beam at 95$\%$ is equal to 2 mm·mrad. The circulating beam emittance after painting is 40 mm·mrad, and accumulated intensity of the circulating beam is $5 \cdot 10^{13}$ protons. Painting lasts during 90 turns, and after painting the circulating beam moves out of the foil during 6 turns. In the simulations the vertical bump amplitude at the foil is 24 mm = 14 mm (painting) + 10 mm (removing from the foil) (Fig. 12). Horizontal angle variation is 0.65 mrad. The transverse plane of the beam in the foil at turn number 10, 50, 90, and 97 from the beginning of beam painting are presented in Fig. 15 and 16.

Vertical kicker-magnet strength and horizontal angle of the beam in the foil during injection are presented in the top of Fig. 17. Particle transverse population and particle density distribution after painting at the foil location are shown in the middle and at the bottom of Fig. 17.

Average number of hits upon the stripping foil for each particle is equal to 6. This effects pretty high level of nuclear interactions and multiple Coulomb scattering in the foil at injection, and because of this causes 0.021% of particle loss at injection. The increase of painting injection duration to 270 turns (that is likely to become the baseline for the 0.5MW linac) permits to increase accumulated intensity of the circulating beam to $1.5 \cdot 10^{14}$ protons, but the average number of hits upon the stripping foil will increase to 21, that increases foil heating and beam loss at injection.

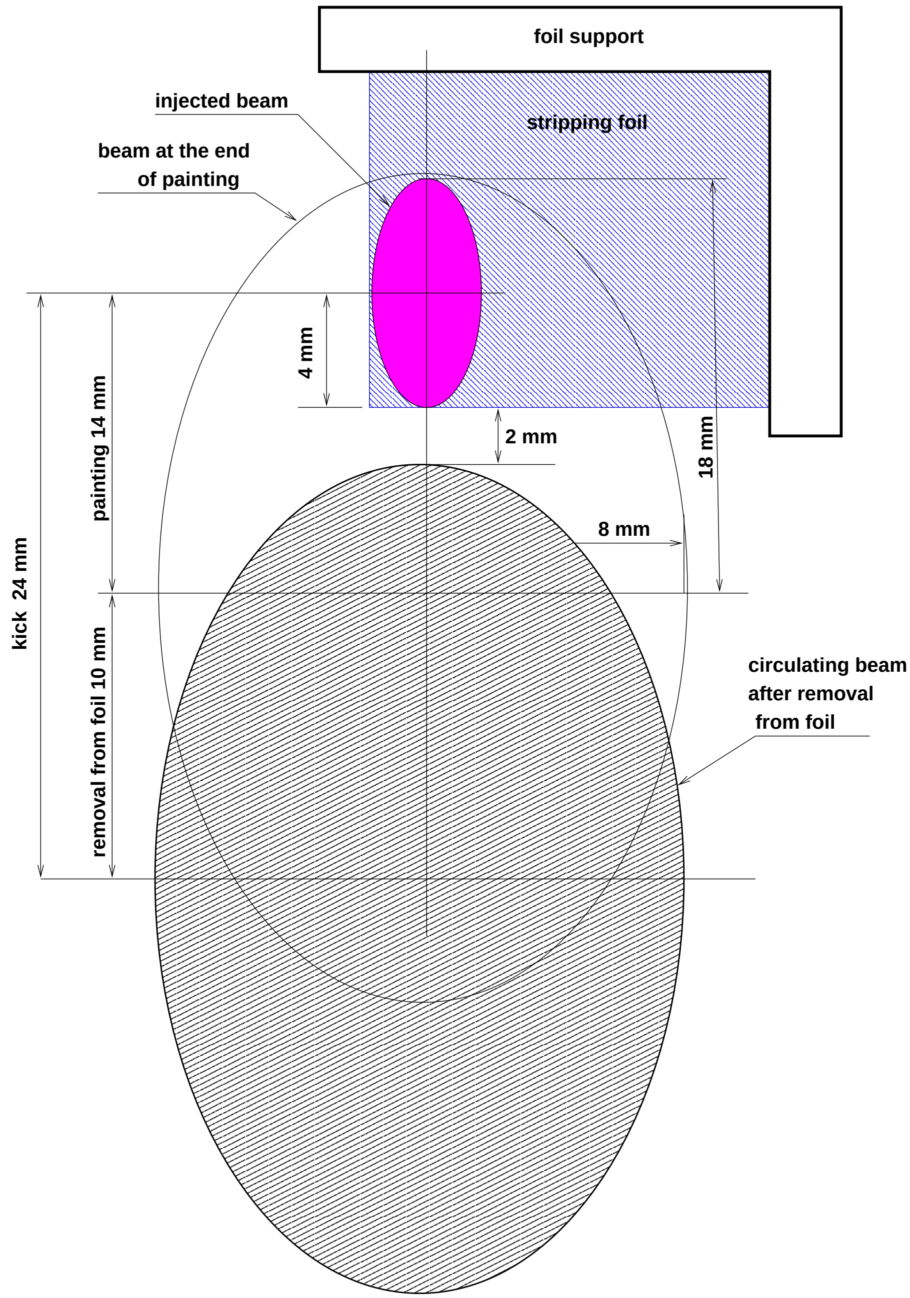

Figure 12: Injected and circulating beam location in the foil at painting.

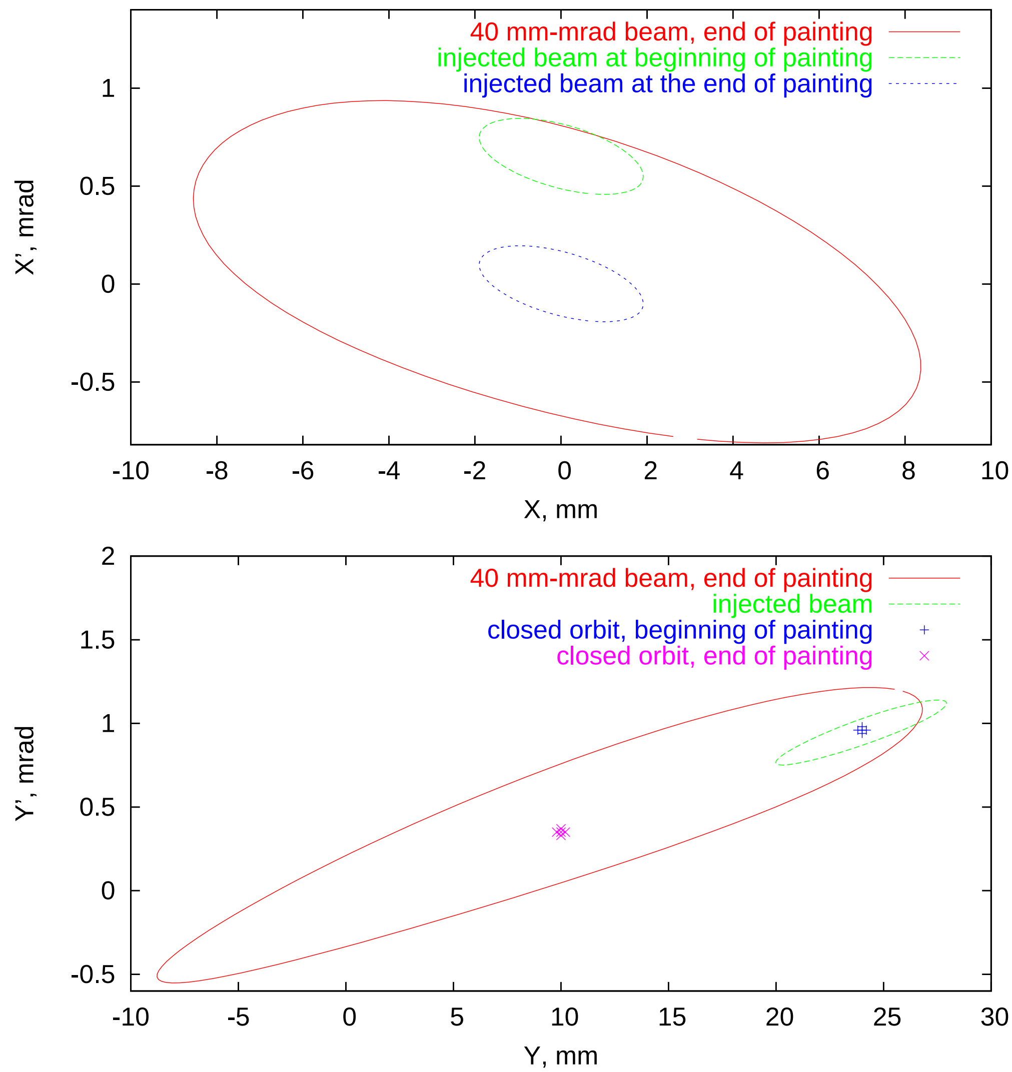

Figure 13: Injected and circulating beam location in the foil at painting (phase plane).

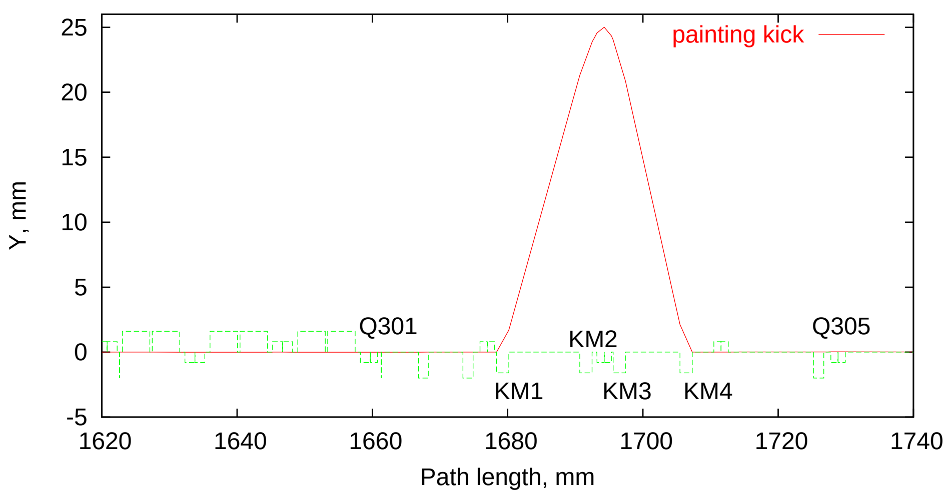

Figure 14: Vertical painting kick

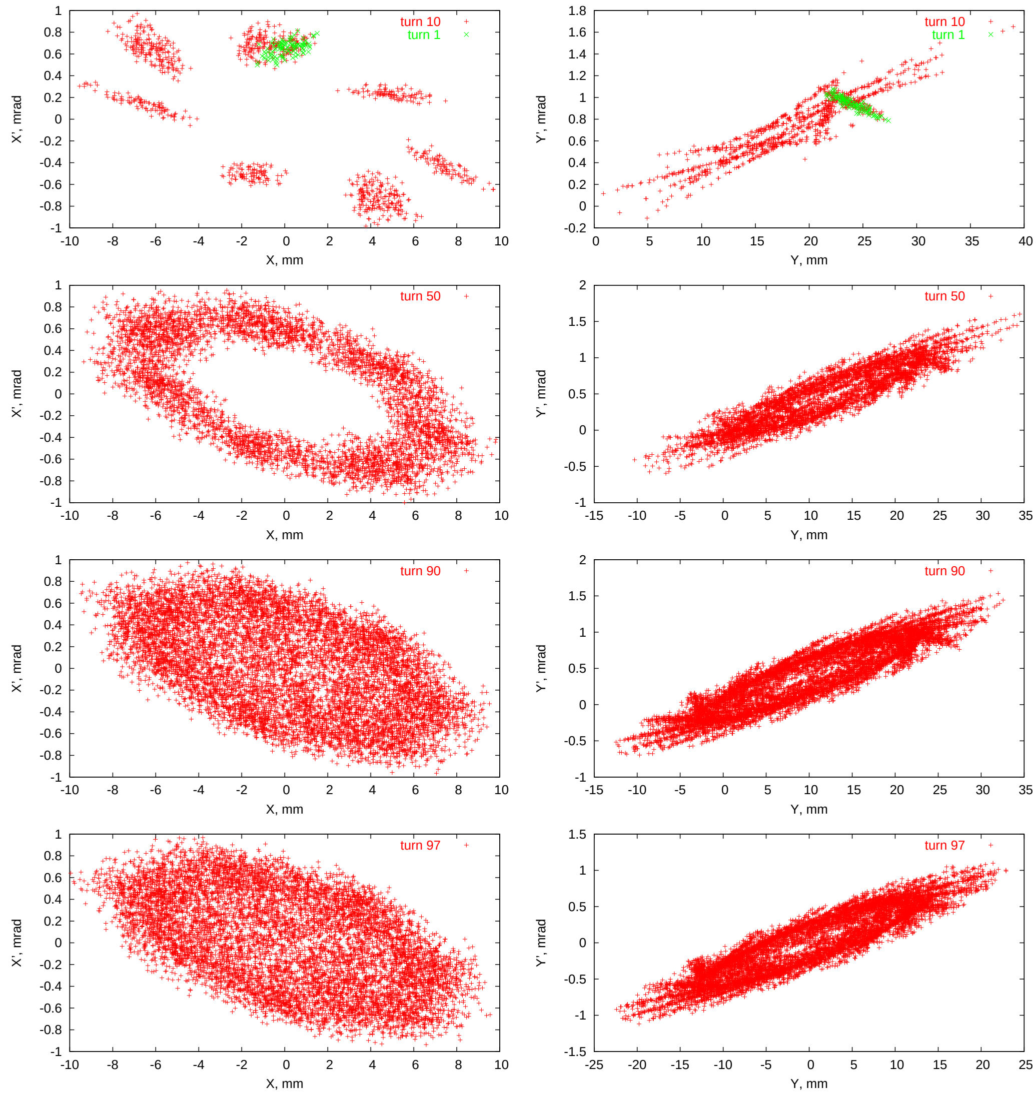

Figure 15: Horizontal (left) and vertical (right) phase plane of circulating beam after 10 turn of injection (top), after 50 turn (second line), after 90 turn (third line), after beam removal from the foil at 97 turn (bottom). Average number of each particle hits on the foil is 272192/45000=6.

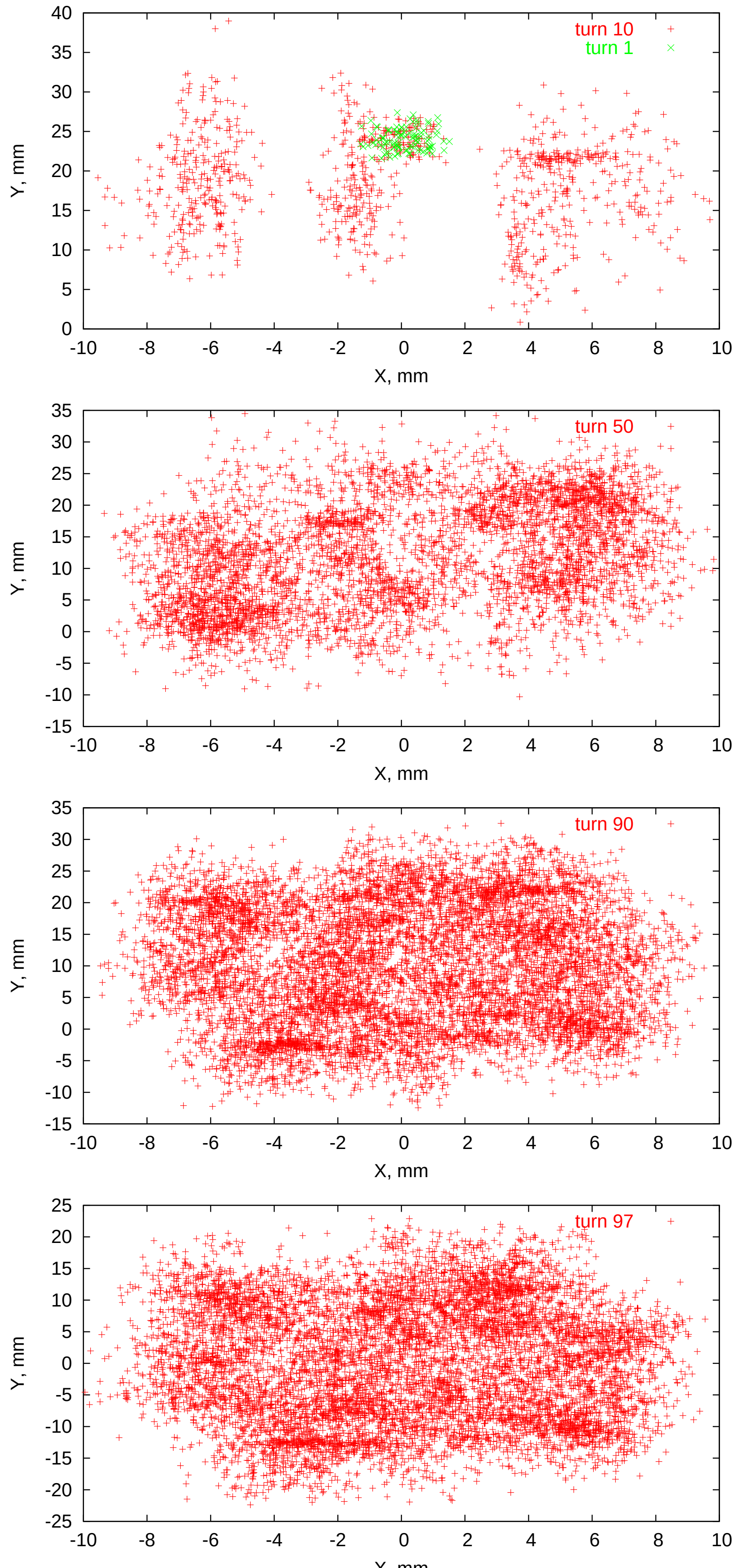

Figure 16: Transverse plane of circulating beam after 10 turn of injection (top), after 50 turn (second line), after 90 turn (third line), after beam removal from the foil at 97 turn (bottom). Average number of each particle hits on the foil is 272192/45000=6.

The circulating protons pass several times through the foil and some of them can be lost because of scattering in the foil. Multiple Coulomb scattering is small because of small foil thickness. Particle energy loss in the foil at one pass is $4{\cdot}10^{-8}$ of initial energy. The rate of nuclear interactions in the foil during the total process is $6.6{\cdot}10^{-5}$ of injected intensity for 270-turn injection and $2.0{\cdot}10^{-5}$ for 90-turn injection. The emittance of the circulating beam in the vertical plane is small in the beginning of painting and it gradually reaches maximum only at the end of painting. Therefore particle vertical amplitude, in average, is sufficiently less compared to the accelerator aperture. Particles can be lost only during the first few turns after injection, and only in the region of injection kick maximum and MI Lambertson magnets where the beam is close to accelerator aperture. At every next turn after particles are injected, they move away in vertical plane from the aperture restriction at the injection region because of reduction of painting kick amplitude. But in the horizontal plane the beam is close to the Lambertson magnet septa during the total cycle of injection, because painting starts from large vertical amplitudes. Simulations shown that the rate of particle loss in the accelerator at interaction with foil is as low as $7.4 \cdot 10^{-4}$ of the injected intensity for 270-turn and factor of three less for 90-turn injection.

4 Collimation in the Main Injector

5 Conclusions

Painting injection system, which consists of two sets of horizontal and vertical kicker magnets, permits to realize quasi-uniform density distribution of the circulating beam required for the beam space charge effect reduction and emittance preservation at injection.

The calculated stripping efficiency is 99.6%. The yield of excited states $\mathrm{H}^o(n)$ atoms will be estimated at discussion with invited to Fermilab experts on May 15-17 of this year.

The temperature rise during injection pulse and steady state temperature of the foil are calculated from analytical distribution of proton hits using ANSYS code. An instant temperature rise, calculated with contributions of multiple collisions, ionization loss from protons and electrons accompanied stripping process, is about 2400K for 270-turn injection. With only emission as a cooling mechanism the foil temperature reaches a steady state of $\sim$ 3500K after 2 cycles of injection. An instant temperature rise for 90-turn injection is about 800K and the temperature reaches a steady state of $\sim$ 1700K after 5 cycles of injection.

References

[1] Main Injector Technical Design Handbook, Fermilab, November 1995

[2] “The proton driver design study”, Fermilab-TM-2136, December 2000.

[3] I. Baishev, A. Drozhdin, and N. Mokhov, ‘STRUCT Program User’s Reference Manual’, SSCL–MAN–0034 (1994), http://www-ap.fnal.gov/~drozhdin/

[4] ’JHF Accelerator Design Study Report’, KEK Report 97-16, JHF-97-10, March 1998, p3-67 - 3-71..

[5] ANSYS v5.5 Manual, 1994.

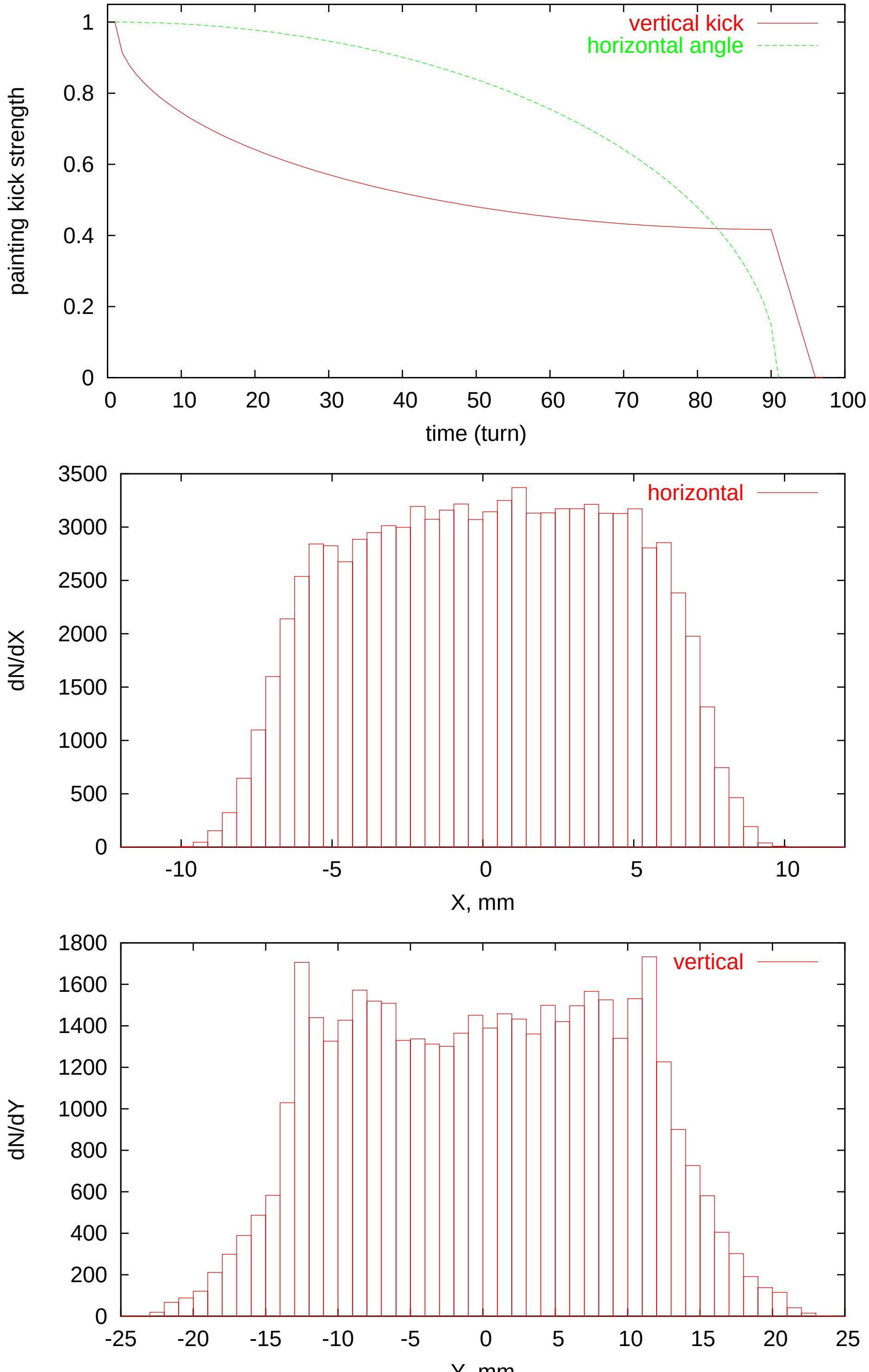

Figure 17: Vertical kicker strength and horizontal angle of the injected beam at the foil (top), circulating beam horizontal (middle) and vertical (bottom) density distribution after injection (97 turn).