Painting injection at 8 GeV to the Main Injector *

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1 Beam parameters

Proton momentum $P = 8.88889\ GeV/c$,
95% normalized emittance of the injected beam is $\varepsilon = 1.5\ \pi\ mm \cdot mrad$,
Momentum collimation is done in the beam transfer line before injection at $dP/P = 0.98 \cdot 10^{-3}$.
Painting injection to the Main Injector lasts 90 (1 msec) or 270 turns, and accumulated intensity of the circulating beam is $1.5 \times 10^{14} ppp$ in both cases. Emittance of the beam after painting is $\varepsilon = 40\ \pi\ mm \cdot mrad$. Main Injector repetition rate is 0.67 Hz. Power of the beam in the foil at injection is 143 KW.

2 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-10 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 horizontal plane at the beginning of injection by 21 mm to the thin graphite stripping foils to accept the first portion of protons generated by H^- in the foil (Figs. 1. Two foils can be used for foil temperature decrease (Fig. 2). First foil is very thin ($\sim 0.5\mu m$). It has a stripping efficiency of the order of $80-90\%$. Second foil thickness is big enough to produce good stripping efficiency ($\sim 5\mu m$). First foil has larger energy deposition per unit of length because of bigger electron component in a particle flux than the second foil. But because of small thickness it should have better cooling through the irradiation of heat from two surfaces compared to thick foil. This may decrease temperature rise during the time of injection (1-3 msec). Second foil has much smaller electrons in the particle flux, that effects less heating. Electrons are removed by a magnet (L=0.2 m, B=50 G) to the electron dump before the second foil. Four 0.34 m long kicker magnets are used to produce orbit displacement. The maximum field of the kicker magnets is 1 kG. Horizontal kick at the beginning of painting is shown in Fig. 4 and 5. Gradual reduction of kicker strength permits "painting" the injected beam across the accelerator aperture with the required emittance. Vertical kicker magnets located in the injection line (not shown here) provide injected beam angle sweeping during injection time, starting from maximum

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at the beginning of injection and going to zero at the end of painting process (Fig. 8). 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 horizontal plane and from the border of it in the vertical plane, and goes to the border of the beam in a horizontal plane and to to the center in a vertical plane. This produces a so called "uncorrelated beam" with elliptical cross section, thereby eliminating particles that have maximum amplitudes in both planes simultaneously.

A 9.6 m long septum-magnet located upstream of the foil (Fig 2) with field of 0.6 kG is used to separate the proton and H^- beams at the quadrupole upstream of the foil by 135 mm. This allows the H^- beam to pass outside the quadrupole body. The third foil located downstream of the third horizontal kicker provides final H^o atoms stripping to the protons, and horizontal septum-magnet located behind the stripping foil is used for removal of these protons to the external beam dump. An internal beam dump may be used instead of septum-magnet and external dump if the stripping efficiency is high enough. 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.

A multi-turn particle tracking through the accelerator is done with the STRUCT [3] code. Two stripping foil made of 100 μg/cm^2 (0.5 μm) and 1000 μg/cm^2 (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 $\times$ 1.2 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 for 90-turn injection as presented below:

- in the horizontal plane

$$B = B_o \left[0.4755 + 0.5245 \left(1 - \sqrt{\frac{2\,N}{90} - \left(\frac{N}{90}\right)^2} \right) \right] \qquad N < 90 \tag{1}$$

$$B = B_o \left[0.4755 - \frac{N-90}{12.6183} \right] \tag{2}$$

- in a vertical plane

$$Y' = Y'_o \sqrt{2\frac{90-N}{90} - \left(\frac{90-N}{90}\right)^2} \qquad Y'_o = 0.45\ mrad \tag{3}$$

Here N is the turn number from beginning of painting.

The normalized emittance of injected beam at 95% is equal to 1.5 mm·mrad. The circulating beam emittance after painting is 40 mm·mrad. Painting lasts during 90 turns, and after painting the circulating beam moves out of the foil during 6 turns. In the simulations the horizontal bump amplitude at the foil is 21 mm = 11 mm (painting) + 10 mm (removing from the foil) (Fig. 4 and 5). Vertical angle variation is 0.45 mrad. 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. 6 and 7.

Vertical kicker-magnet strength and horizontal angle of the beam in the foil during injection are presented in the top of Fig. 8. Circulating beam horizontal and vertical distributions are shown in the middle and at the bottom of Fig. 8.

As shown here the kicker strength decreases fast to $\sim$ 60% of maximum during 20 turns, and then slowly drop to 50% during another 70 turns. An unstriped part of the beam after interaction with the foil - the H^o Stark states hydrogen atoms - may be stripped to protons by a magnetic field of accelerator elements. The calculated lifetime $T = 1/\Gamma$ of Stark states hydrogen atoms in magnetic

field for hydrogen atoms of $E_{kinetic} = 8GeV$ is presented in Fig. 13. The stripping foil is located at the exit of painting kicker number 2 (Fig. 2 and 3), very close to the kicker edge in the fringe field of the magnet. The kicker magnet field is chosen such a way that during injection the magnetic field provide stripping of Stark states hydrogen atoms with principal quantum number $n \geq 5$ to protons. This corresponds to kicker length of 0.34 m and maximum field of 0.1 T. At these parameters of magnet magnetic field during $\sim 80\%$ of injection cycle is in the range of (0.05-0.06) T. A stripping probability of $E_{kinetic} = 8GeV$ H^o Stark states hydrogen atoms in the kicker magnets number 2 and 3, and in the quadrupole Q102 are presented in Table 1. We assumed here that H^o atoms pass a distance of (1-2) cm in a maximum fringe field of the kicker magnet number 2. This distance is enough for H^o atoms with $n \geq 5$ to be stripped. As shown in the table, all atoms with $n \geq 5$ are stripped to protons and go to the circulating beam without changing emittance of the beam, some part of atoms with n=4 are left unstriped and go to the beam dump, and, unfortunately, some fraction of them is stripped along the kicker number 3. These protons will contribute to the circulating beam halo and cause losses behind the kicker.

The probability of H^- stripping by magnetic field of kicker magnet number 2 during the first turn of injection (B=0.1 T) is 0.002. It drops to 0.00005 during five turns (B=0.08 T). This gives stripping of 5.e-05 of injected beam (7.5e+09 ppp) or 7 W of power lost in the injection region.

n	B	lifetime (Fig. 13)	mean decay length		
	T	sec	m		
injection kicker No.2, $L_{field} = (1-2)\ cm$					
4	0.1	<1.e-11	0.003	stripped	go to circulating beam
4	0.06	>1.e-10	0.03	unstriped	
5	0.06	<1.e-12	0.0003	stripped	go to circulating beam
4	0.05	>1.e-08	3.0	unstriped	
5	0.05	<1.e-11	0.003	stripped	go to circulating beam
quadrupole Q102, $L_{field} = 2.1\ m$, no particles with n>4					
4	0.025	>1.e+02		unstriped	
injection kicker No.3, $L_{field} = 0.34\ m$, no particles with n>4					
4	0.1	<1.e-10	0.03	stripped	go to circulating beam
4	0.06	1.e-10 - 1.e-06	0.03 - 300	some are stripped	go to beam halo
4	0.05	1.e-08 - 1.e-04	3 - 30000	unstriped	go to beam dump

Table 1: A stripping probability of $E_{kinetic} = 8GeV$ H^o Stark states hydrogen atoms in the kicker magnets number 2 and 3, and in the quadrupole Q102.

Particle hits population, and horizontal and vertical distributions of hits at the stripping foil are shown in Fig. 10. Average number of hits upon the stripping foil for each particle is equal to 4.4. This effects pretty high level of nuclear interactions and multiple Coulomb scattering in the foil at injection, and because of this causes 0.01% 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) increases the average number of hits upon the stripping foil to 16, that increases foil heating and beam loss at injection.

An analytically estimated instant temperature rise in a hottest point of the first stripping foil, calculated with contributions of ionization loss from protons and electrons accompanied stripping process and without cooling through the heat emission from two surfaces of the foil, is about 40000K

for 270-turn and 8000K for 90-turn injection. The second foil should have a factor of three less heating. The result of temperature rise calculations depends on the size of area for calculation of particle hits density. This temperature rise goes down from 8000K to 2000K at the distance of 3 mm from the hottest point (Fig. 15).

The temperature rise during injection pulse and steady state temperature of the foil must be calculated from distributions of proton hits using ANSYS code, taking into account the heat emission as a cooling mechanism of the foil.

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 (ionization loss) in the foil at one pass is $4{\cdot}10^{-20}$ of initial energy. The rate of nuclear interactions in the foil during the total process is $1.2{\cdot}10^{-4}$ of injected intensity for 270-turn injection and $8{\cdot}10^{-5}$ for 90-turn injection. The emittance of the circulating beam in the horizontal plane is small in the beginning of painting and it gradually reaches maximum only at the end of painting. Therefore particle horizontal 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 horizontal plane from the aperture restriction in the injection region because of reduction of painting kick amplitude. But in a vertical plane the beam is close to the aperture 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 $3.1 \cdot 10^{-4}$ of the injected intensity for 270-turn and factor of three less for 90-turn injection.

3 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 later.

An analytically estimated instant temperature rise in a hottest point of the first stripping foil, calculated with contributions of ionization loss from protons and electrons accompanied stripping process and without cooling through the heat emission from two surfaces of the foil, is about 20000K for 270-turn and 8000K for 90-turn injection. The second foil should have a factor of three less heating.

References

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

[2] “The proton driver design study”, Fermilab-TM-2136, December 2000. “Proton driver study II”, Fermilab-TM-2169, May 2002.

[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.

[5] ANSYS v5.5 Manual, 1994.

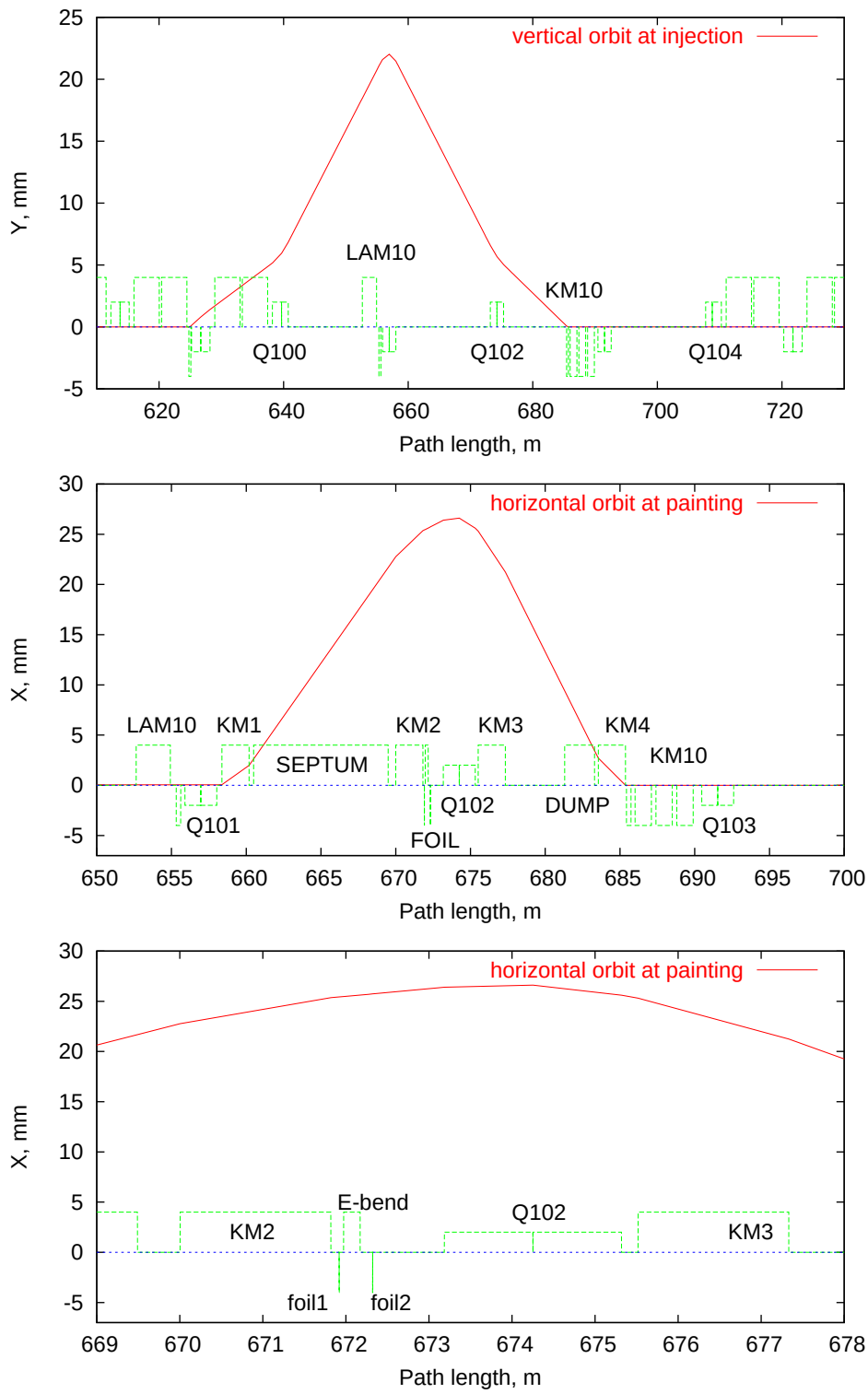

Figure 1: Existing vertical closed orbit at injection of the 8 GeV proton beam (top) and horizontal orbit at painting injection (middle and bottom) to the MI-10 straight section of the Main Injector.

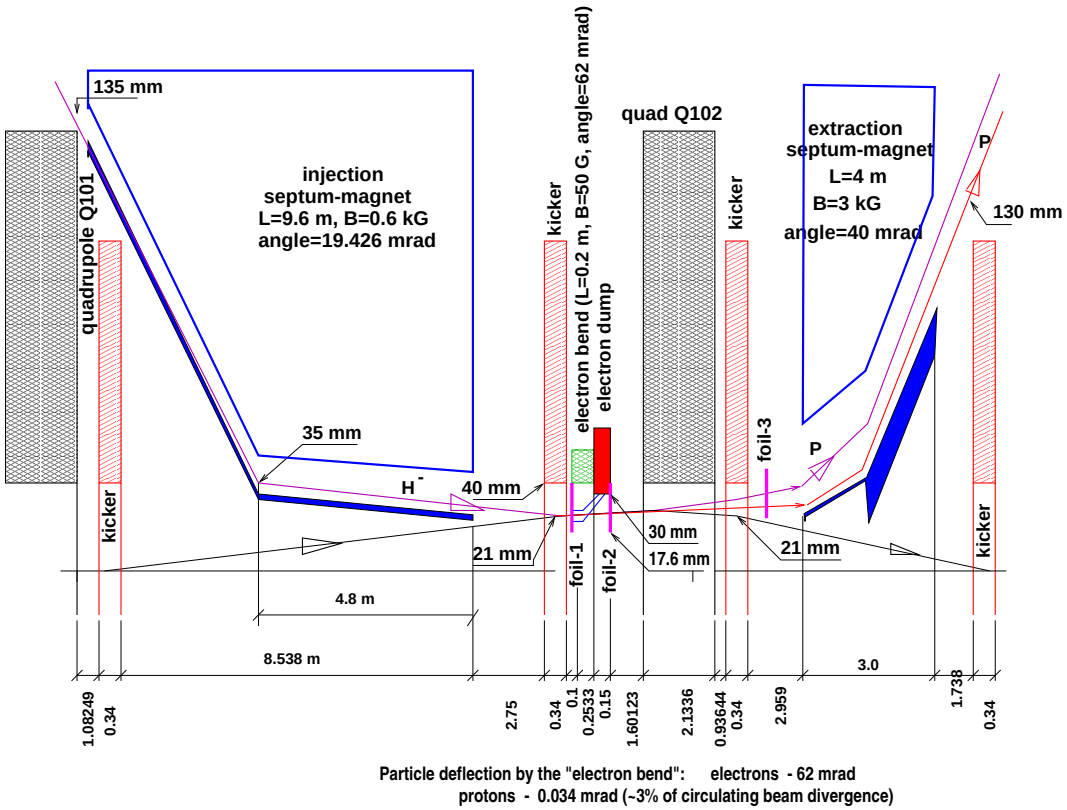

Figure 2: Two-foil painting injection with electrons removal downstream of the first foil.

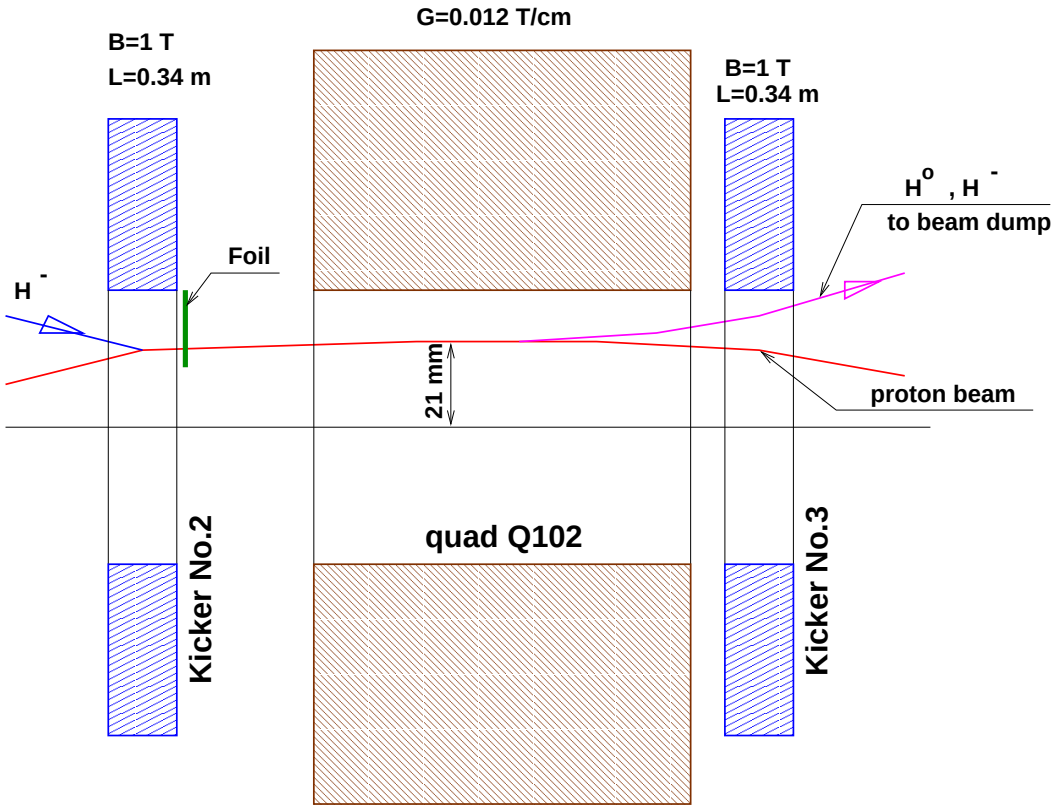

Figure 3: Position of H^o and H^- beam in the painting injection magnets.

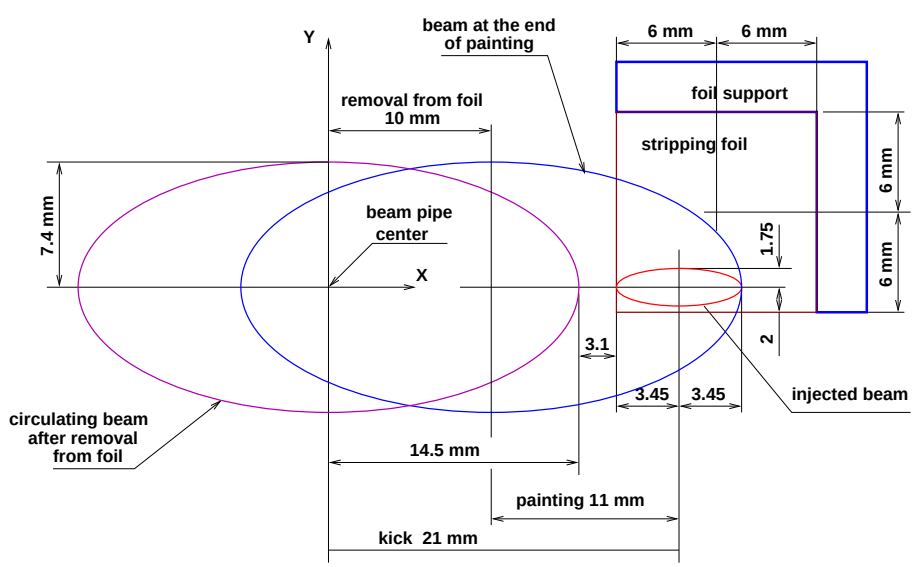

Figure 4: Injected and circulating beam location in the foil at painting.

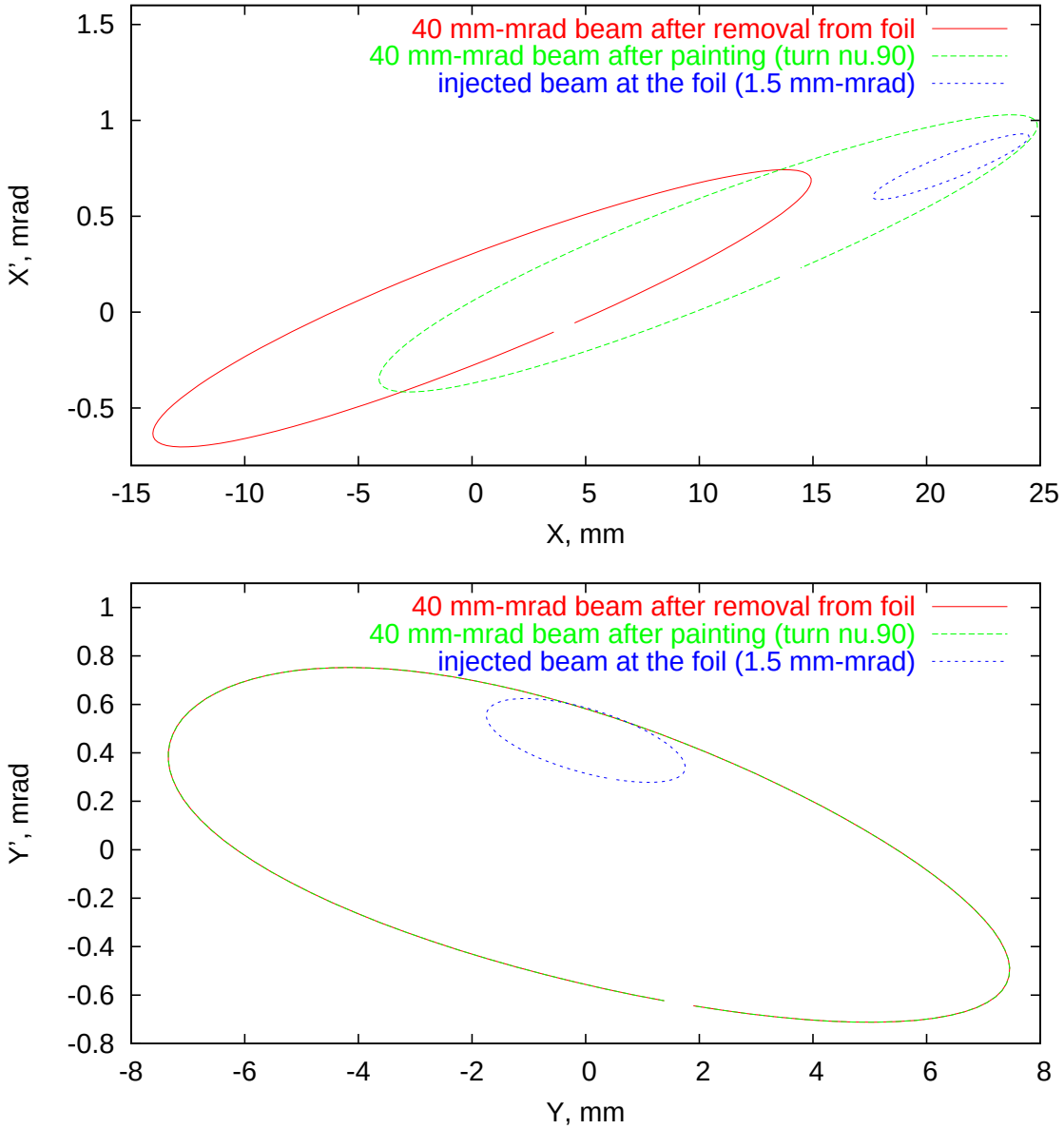

Figure 5: Injected and circulating beam location in the foil at painting (phase plane).

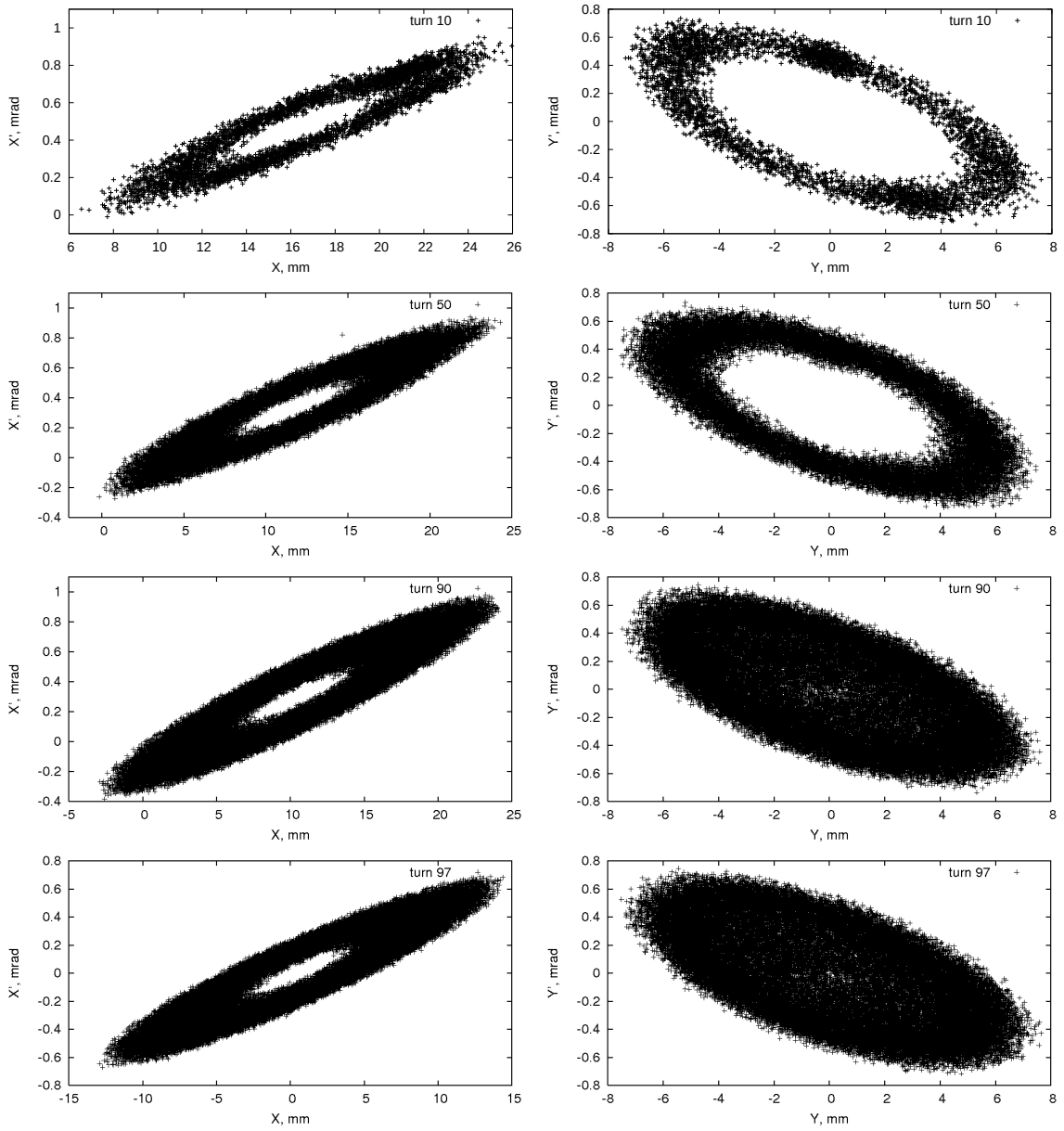

Figure 6: Horizontal (left) and vertical (right) phase plane of circulating beam after 10 turn of injection (top), after 50 turn (second line), after 90 turn (third line), after beam removal from the foil at 97 turn (bottom). Average number of each particle hits on the foil is 4.4.

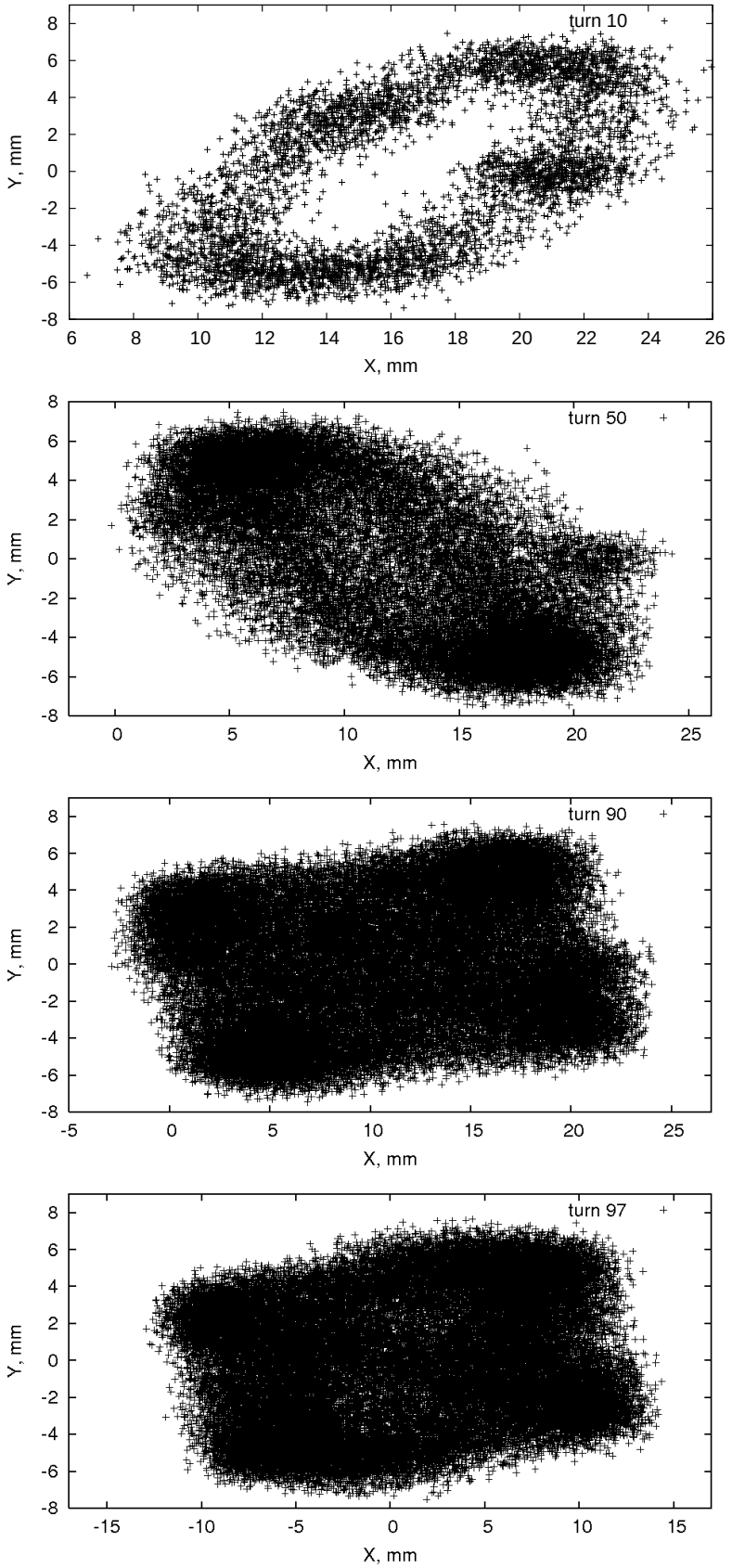

Figure 7: Transverse plane of circulating beam after 10 turn of injection (top), after 50 turn (second line), after 90 turn (third line), after beam removal from the foil at 97 turn (bottom).

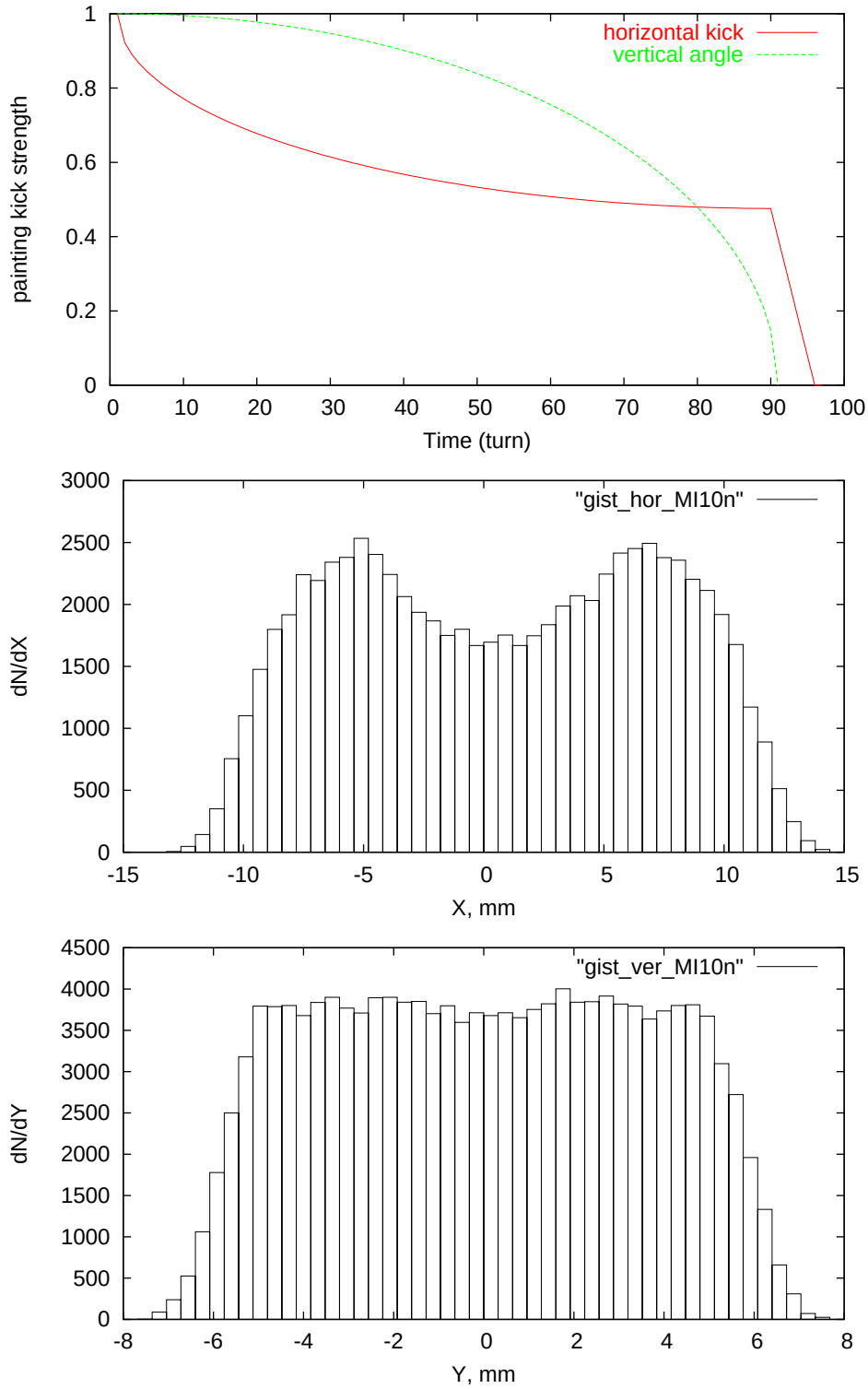

Figure 8: Vertical kicker strength and horizontal angle of the injected beam at the foil (top), circulating beam horizontal (middle) and vertical (bottom) density distribution after injection (97 turn).

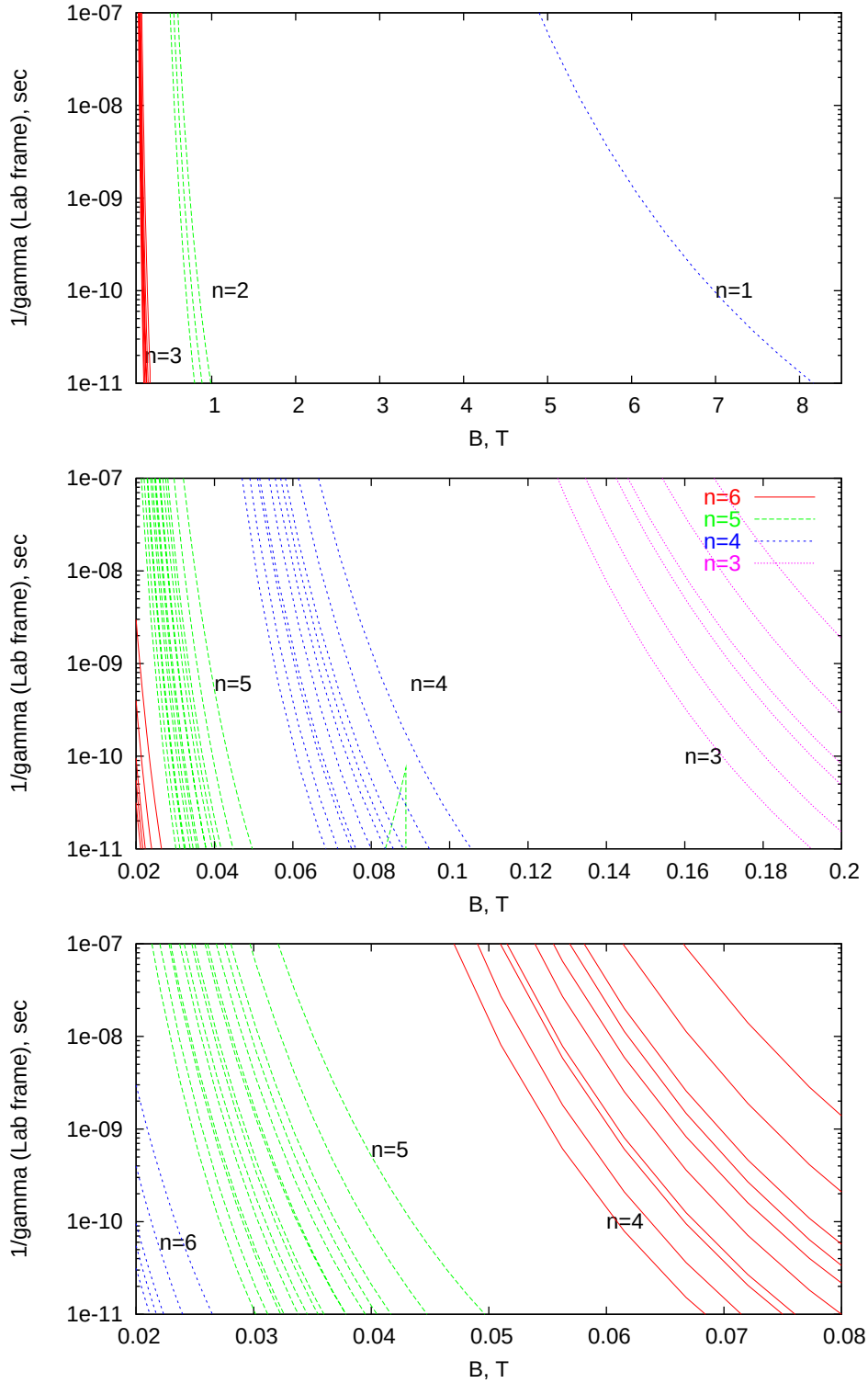

Figure 9: Calculated lifetime $T = 1/\Gamma$ of Stark states hydrogen atom in magnetic field corresponding to electric field for hydrogen atoms of $E_{kinetic} = 8GeV$ using equation **??**. Lifetime is in a laboratory frame.

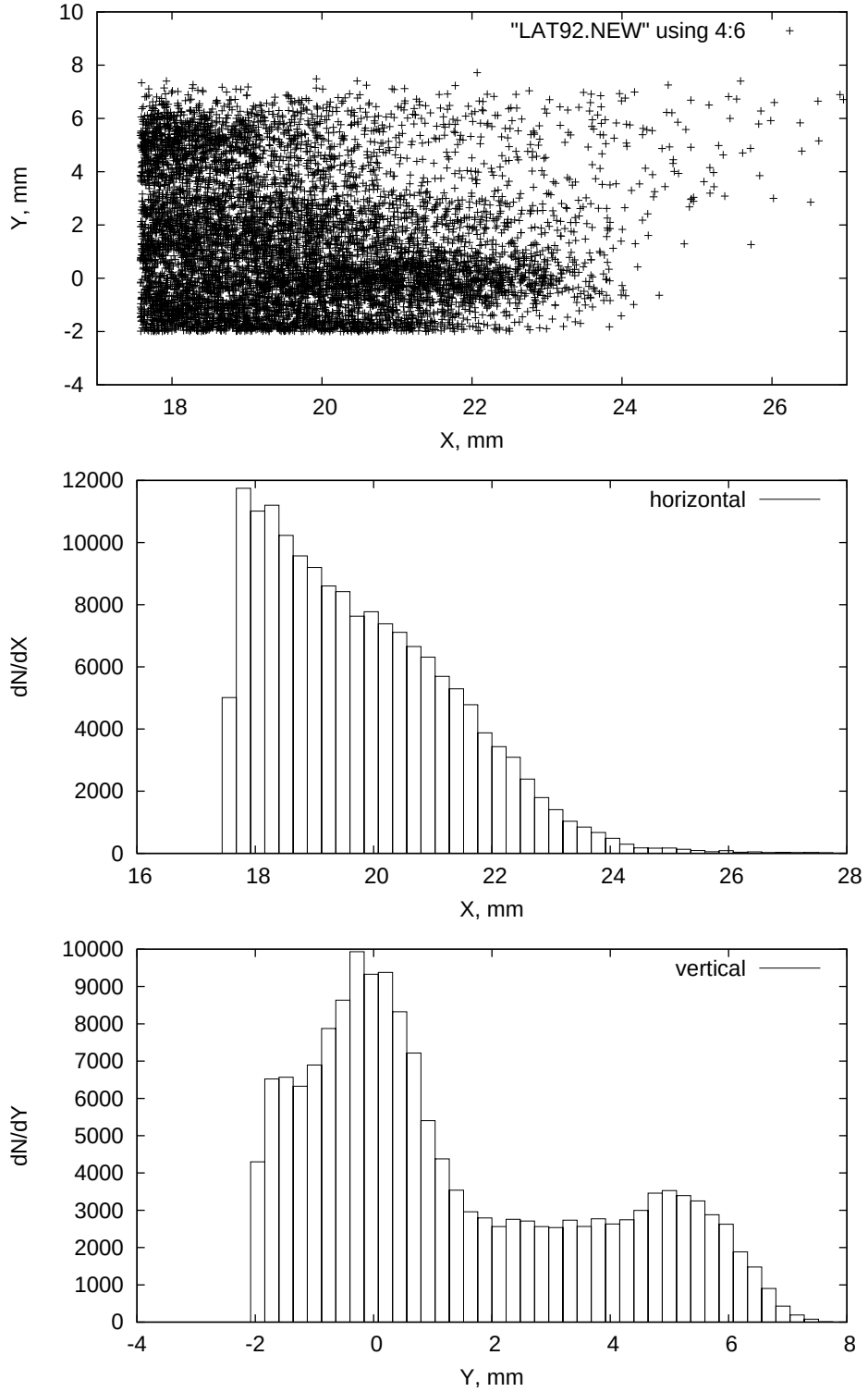

Figure 10: Particle hits population (top), and horizontal (middle) and vertical (bottom) distributions at the stripping foil. Average number of each particle hits on the foil is 4.4.

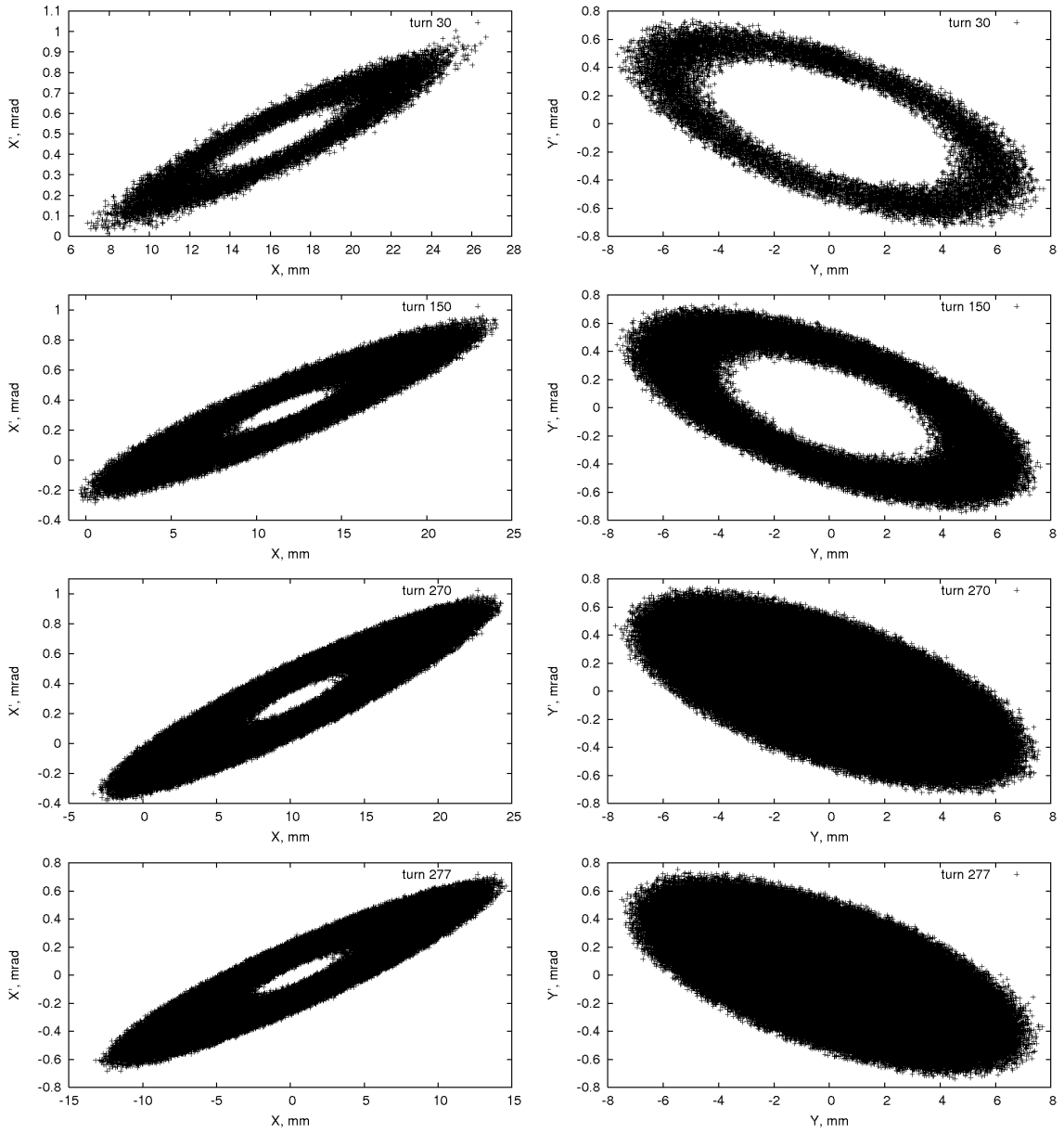

Figure 11: Horizontal (left) and vertical (right) phase plane of circulating beam after 30 turn of injection (top), after 150 turn (second line), after 270 turn (third line), after beam removal from the foil at 277 turn (bottom). Average number of each particle hits on the foil is 15.9.

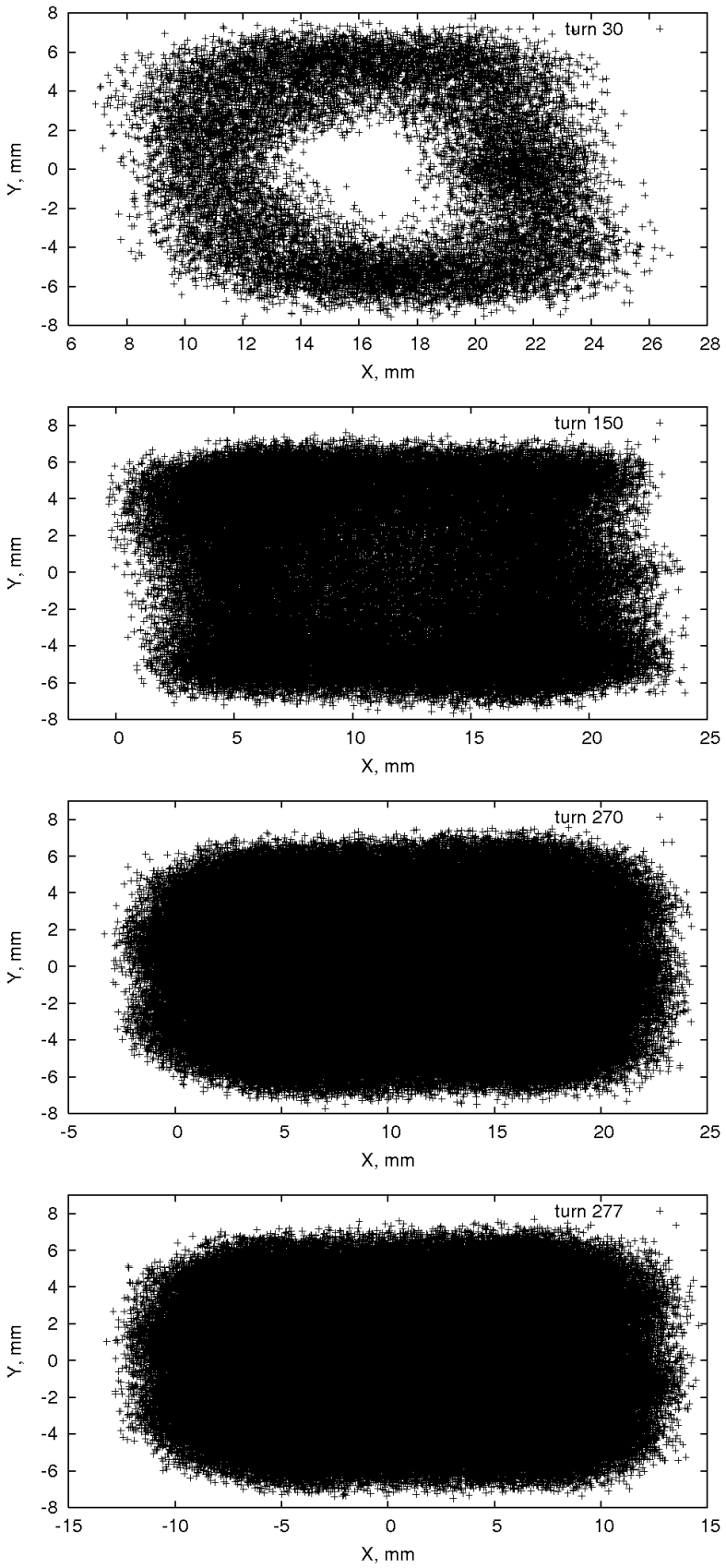

Figure 12: Transverse plane of circulating beam after 30 turn of injection (top), after 150 turn (second line), after 270 turn (third line), after beam removal from the foil at 277 turn (bottom).

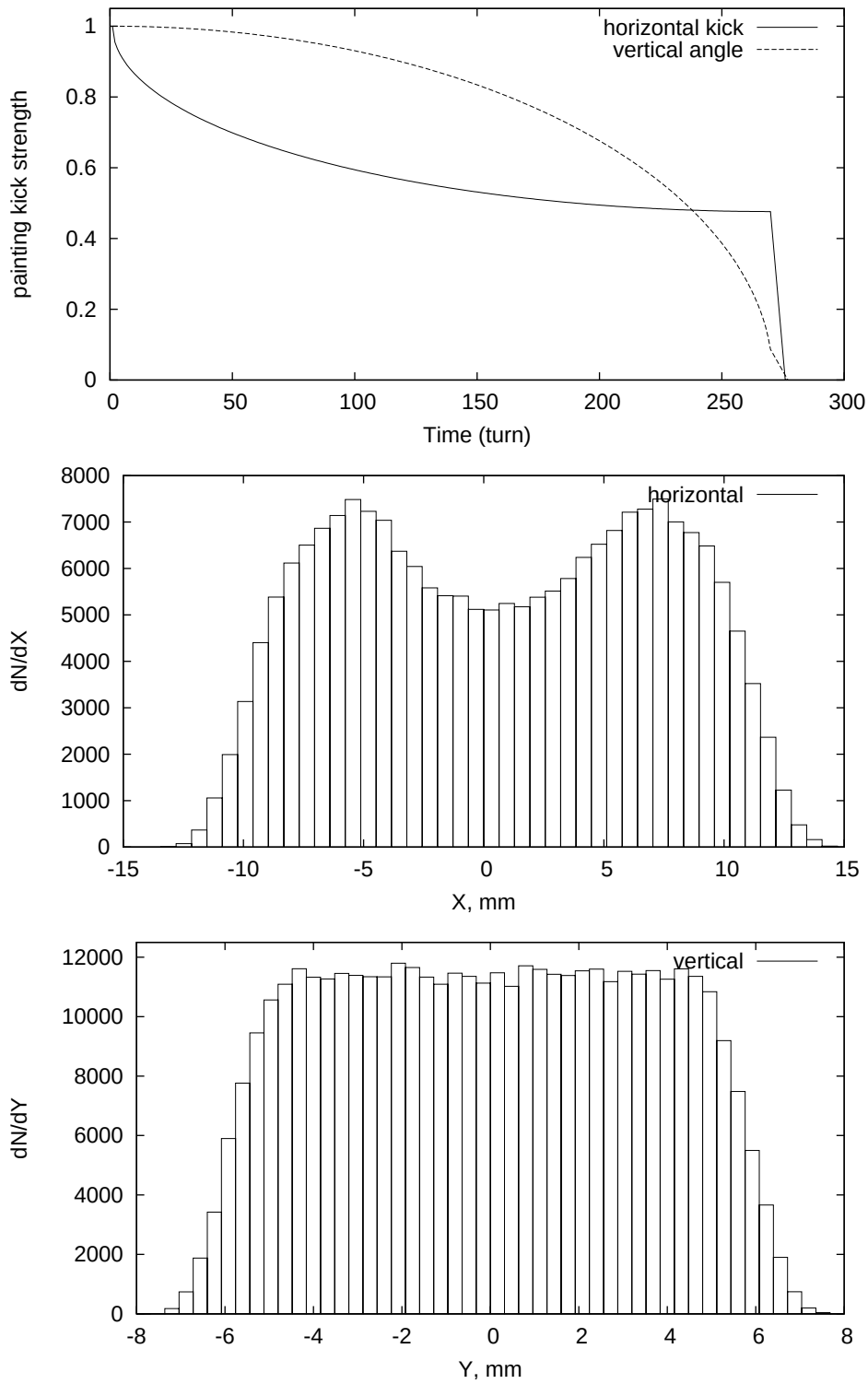

Figure 13: Vertical kicker strength and horizontal angle of the injected beam at the foil (top), circulating beam horizontal (middle) and vertical (bottom) density distribution after injection (277 turn).

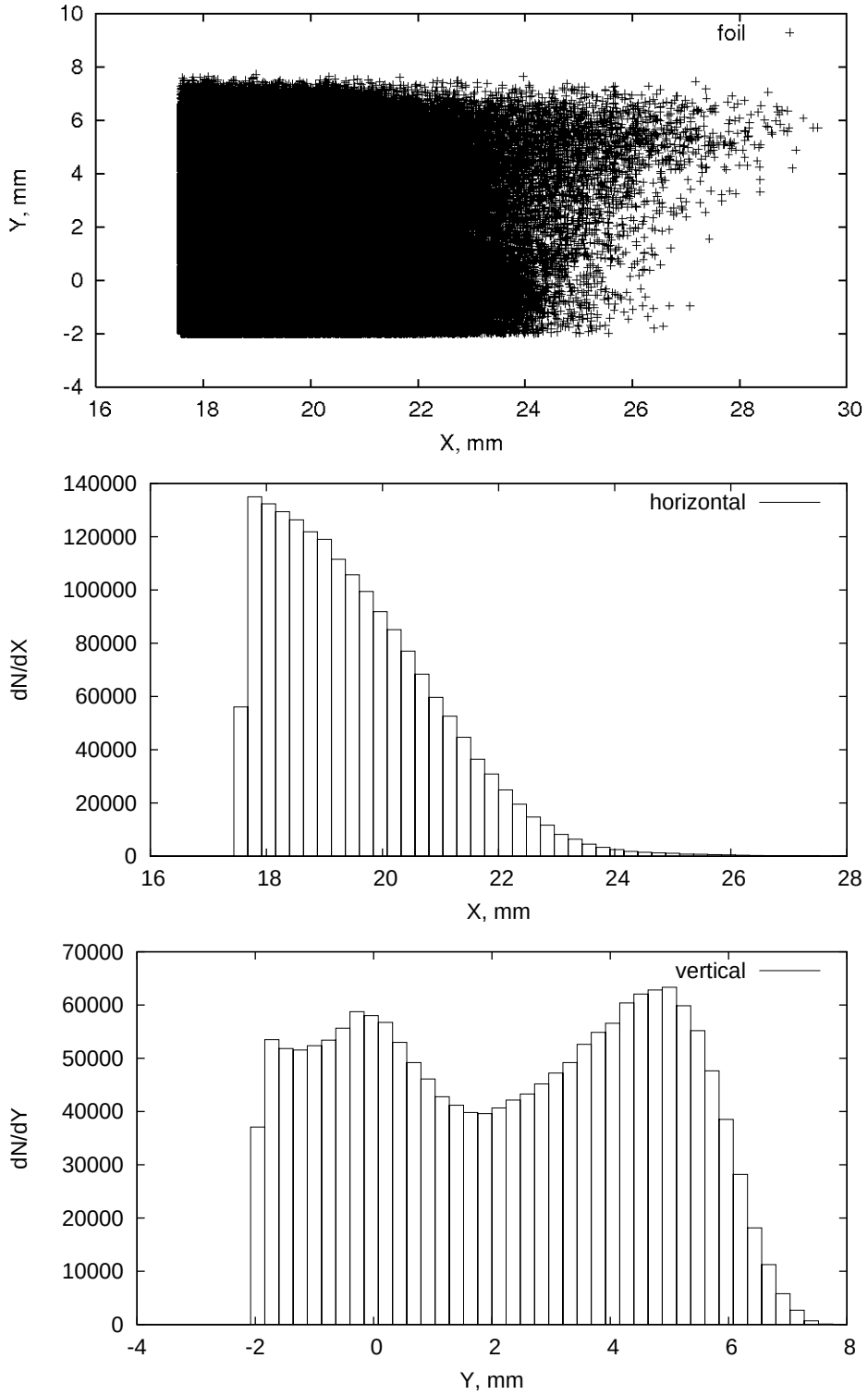

Figure 14: Particle hits population (top), and horizontal (middle) and vertical (bottom) distributions at the stripping foil. Average number of each particle hits on the foil is 15.9.

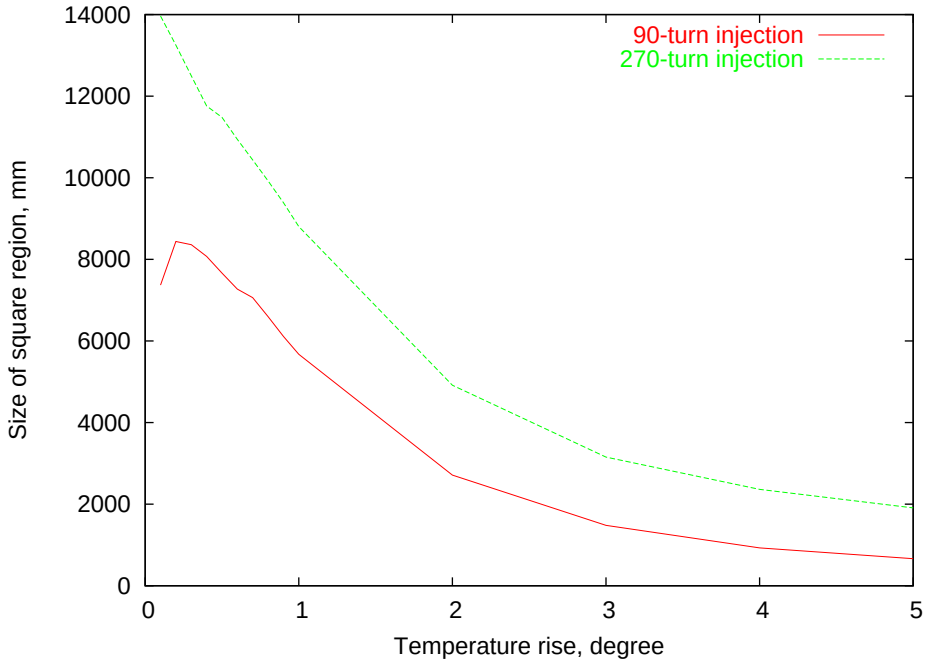

Figure 15: Analytically estimated instant temperature rise in a hottest point of the first stripping foil depending on the size of area for calculation of particle hits density.