Input parameters for BTA/AGS harp simulation

N particles	10000
G	1.792847
$G\gamma$	4.500000
M_{beam}	938.272000 [MeV/c^2]
Data set:	Nick's-BTA-model
Initial beam parameters at start of BTA:	
$\epsilon^{\text{N}}_{95\%x}$	12.000000 [μm]
$\epsilon^{\text{N}}_{95\%y}$	4.000000 [μm]
$\frac{\sigma_p}{p}$	0.000160
β_{x0}	4.530000 [m]
α_{x0}	0.836000
η_{x0}	1.282000 [m]
η'_{x0}	-0.581000
β_{y0}	10.982000 [m]
α_{y0}	-1.691000
AGS lattice parameters at A15:	
β_x	7.628000 [m]
α_x	1.568000
η_x	-3.405000 [m]
η'_x	0.223000
β_y	42.593000 [m]
α_y	-4.187000
q_x	0.784022
q_y	0.843957
x_{off} (horiz injection error at A15)	0.000000 [m]
Harp material parameters:	
L_{rad}	6.770000 [g/cm^2]
wire density	19.250000 [g/cm^3]
Constants for energy loss:	
Z_{wire}	74
A_{wire}	184.000000 [g/mole]
mean excitation energy	790.000000 [eV] from Ref. 2
Approximate aperture cuts for rest of AGS other than at A15:	
$\beta_{x,\text{max}}$	45.445000 [m]
$\beta_{y,\text{max}}$	72.830000 [m]
x_{cut}	0.040000 [m]
y_{cut}	0.030000 [m]

Harp parameters (units in [mm])

Harp	# x wires	x wire diam	x wire spacing	x_{min}	x_{max}	# y wires	y wire diam	y wire spacing	y_{min}	y_{max}
MW006	32	0.10	1.50	-24.00	24.00	32	0.10	1.50	-24.00	24.00
MW060	32	0.10	2.50	-40.00	40.00	32	0.10	2.50	-40.00	40.00
MW125	32	0.10	2.50	-40.00	40.00	32	0.10	2.50	-40.00	40.00
MW166	32	0.10	2.50	-40.00	40.00	32	0.10	2.50	-40.00	40.00
A15	64	0.10	2.00	-64.00	64.00	32	0.10	2.00	-32.00	32.00

Transport matrices between harps: From beginning of BTA to MW006:

$$\begin{pmatrix} 1.000000 & 1.251800 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 1.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 1.000000 & 1.251800 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 1.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 & 1.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 1.000000 \end{pmatrix}$$

From MW006 to MW060:

$$\begin{pmatrix} 5.415429 & 4.924036 & 0.000000 & 0.000000 & 0.000000 & 2.353812 \\ -0.749419 & -0.496760 & 0.000000 & 0.000000 & 0.000000 & -0.193009 \\ 0.000000 & 0.000000 & -3.554684 & 19.001910 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & -0.573749 & 2.785713 & 0.000000 & 0.000000 \\ -0.718767 & -0.218897 & 0.000000 & 0.000000 & 1.000000 & -0.435368 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 1.000000 \end{pmatrix}$$

From MW060 to MW125:

$$\begin{pmatrix} 3.315529 & 17.914047 & 0.000000 & 0.000000 & 0.000000 & 0.203545 \\ 0.035413 & 0.492949 & 0.000000 & 0.000000 & 0.000000 & 0.015563 \\ 0.000000 & 0.000000 & -1.318182 & 5.794729 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.023651 & -0.862588 & 0.000000 & 0.000000 \\ -0.044390 & -0.178454 & 0.000000 & 0.000000 & 1.000000 & -0.000020 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 1.000000 \end{pmatrix}$$

From MW125 to MW166:

$$\begin{pmatrix} 1.051199 & 9.952291 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.141458 & 2.290556 & 0.000000 & 0.000000 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.389916 & 12.420484 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & -0.135632 & -1.755804 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 & 1.000000 & 0.000003 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 1.000000 \end{pmatrix}$$

From MW166 to A15:

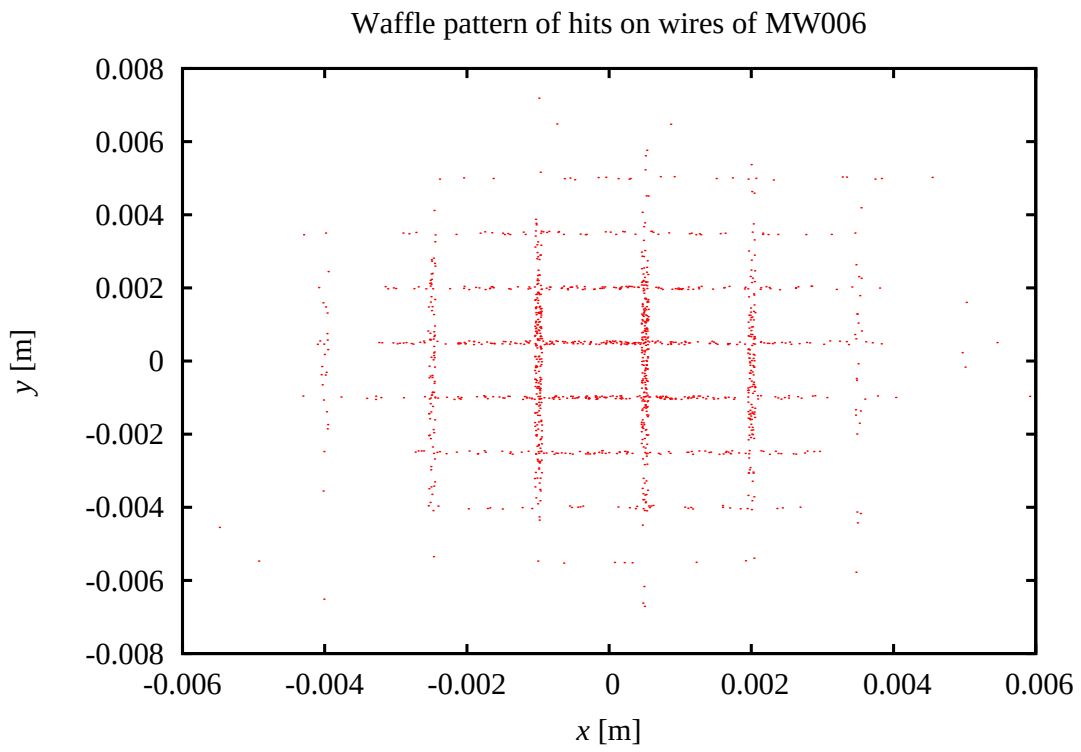
$$\begin{pmatrix} 0.410263 & -8.632307 & 0.000000 & 0.000000 & 0.000000 & -2.076254 \\ 0.109794 & 0.127538 & 0.000000 & 0.000000 & -0.000000 & -0.068879 \\ 0.000000 & 0.000000 & -3.582099 & -26.543644 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & -0.120213 & -1.169949 & 0.000000 & 0.000000 \\ -0.200072 & -0.865965 & 0.000000 & 0.000000 & 1.000000 & -0.342005 \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 1.000000 \end{pmatrix}$$

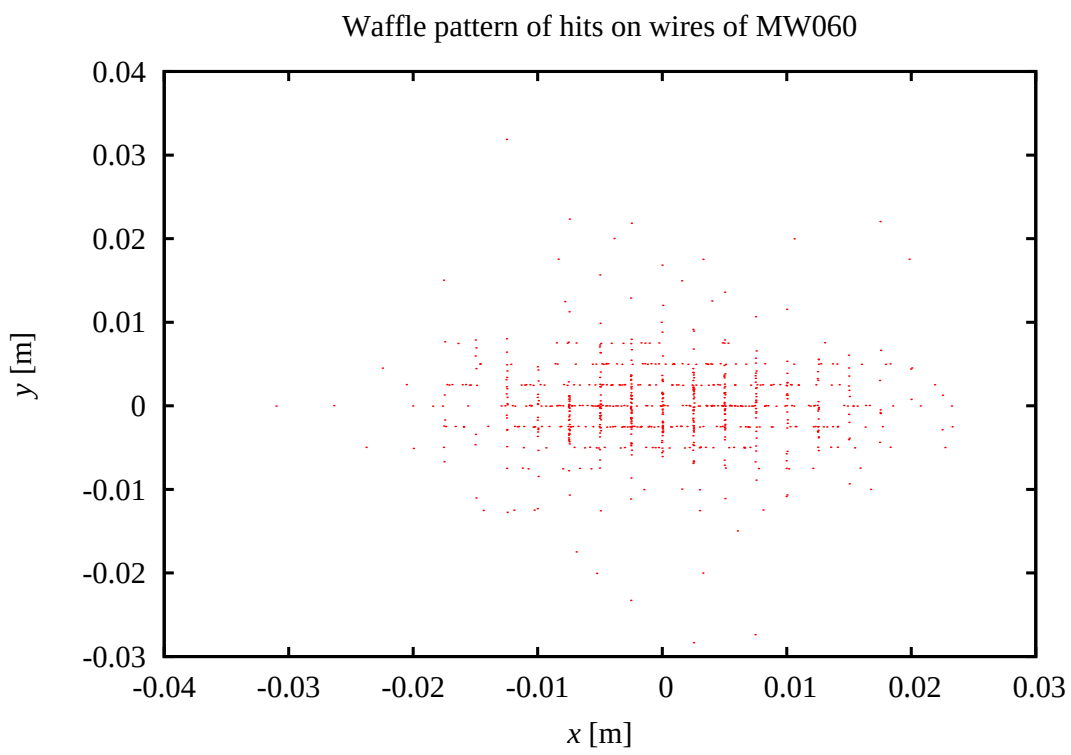
AGS one-turn matrix at A15 harp:

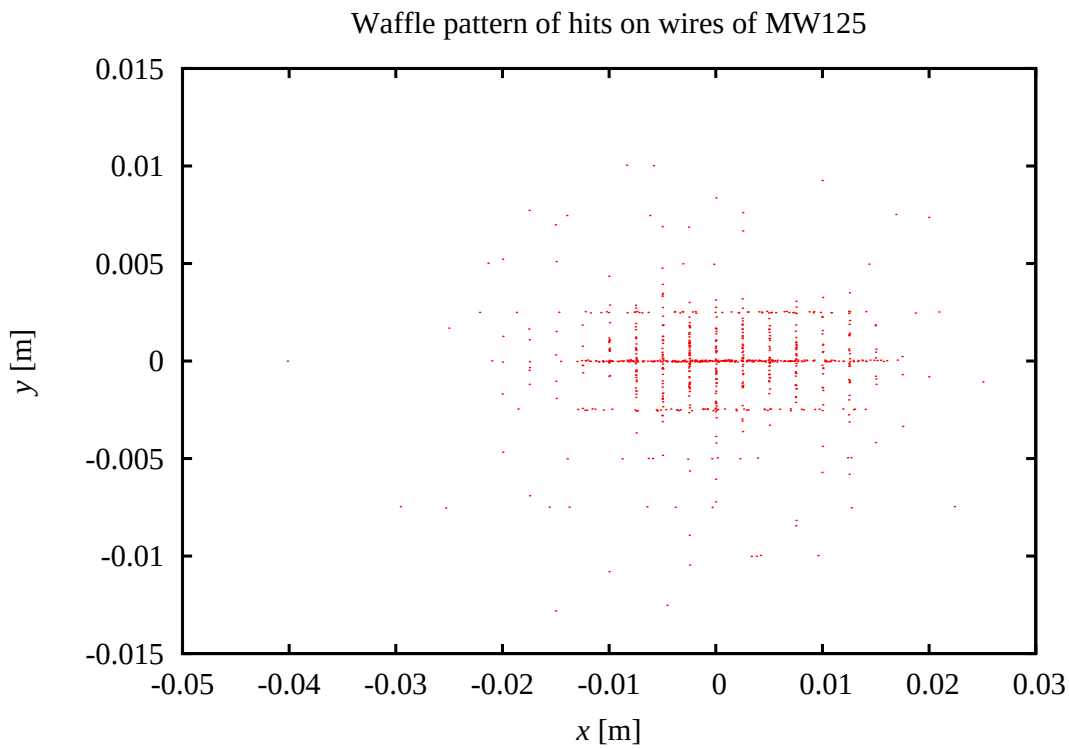
$$\begin{pmatrix} -1.320168 & -7.454378 & 0.000000 & 0.000000 & 0.000000 & -6.237847 \\ 0.443091 & 1.744453 & 0.000000 & 0.000000 & 0.000000 & 2.119713 \\ 0.000000 & 0.000000 & 4.034986 & -35.383978 & 0.000000 & 0.000000 \\ 0.000000 & 0.000000 & 0.361433 & -2.921684 & 0.000000 & 0.000000 \\ — & — & 0.000000 & 0.000000 & 1.000000 & — \\ 0.000000 & 0.000000 & 0.000000 & 0.000000 & 0.000000 & 1.000000 \end{pmatrix}$$

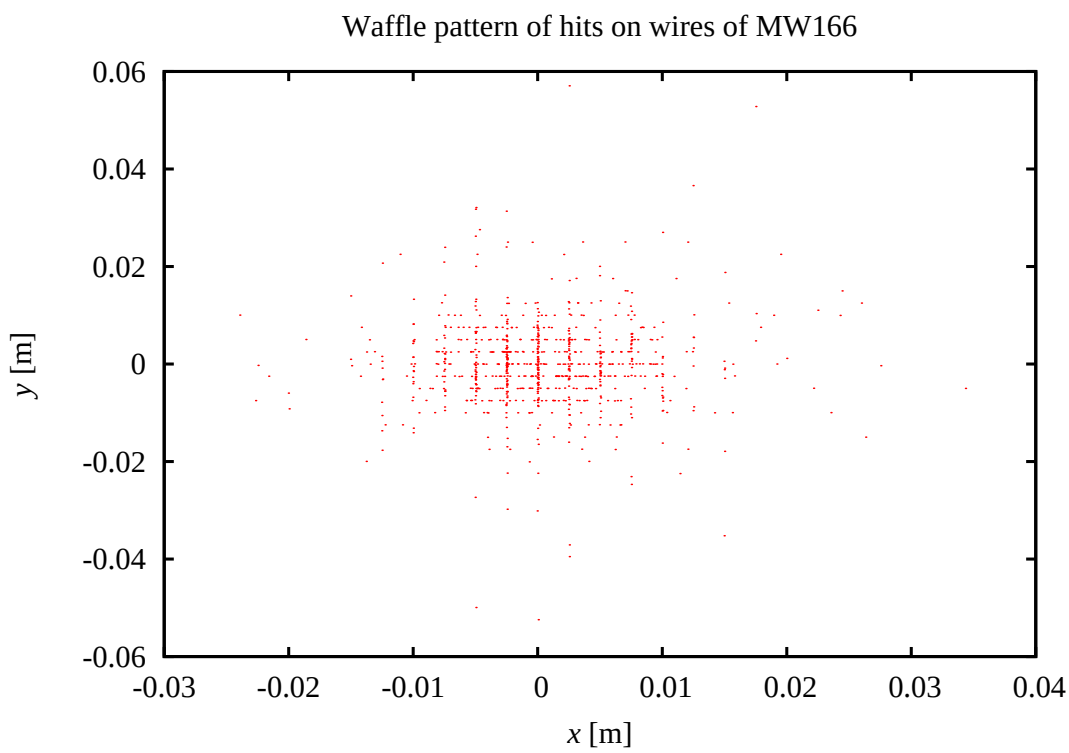
References

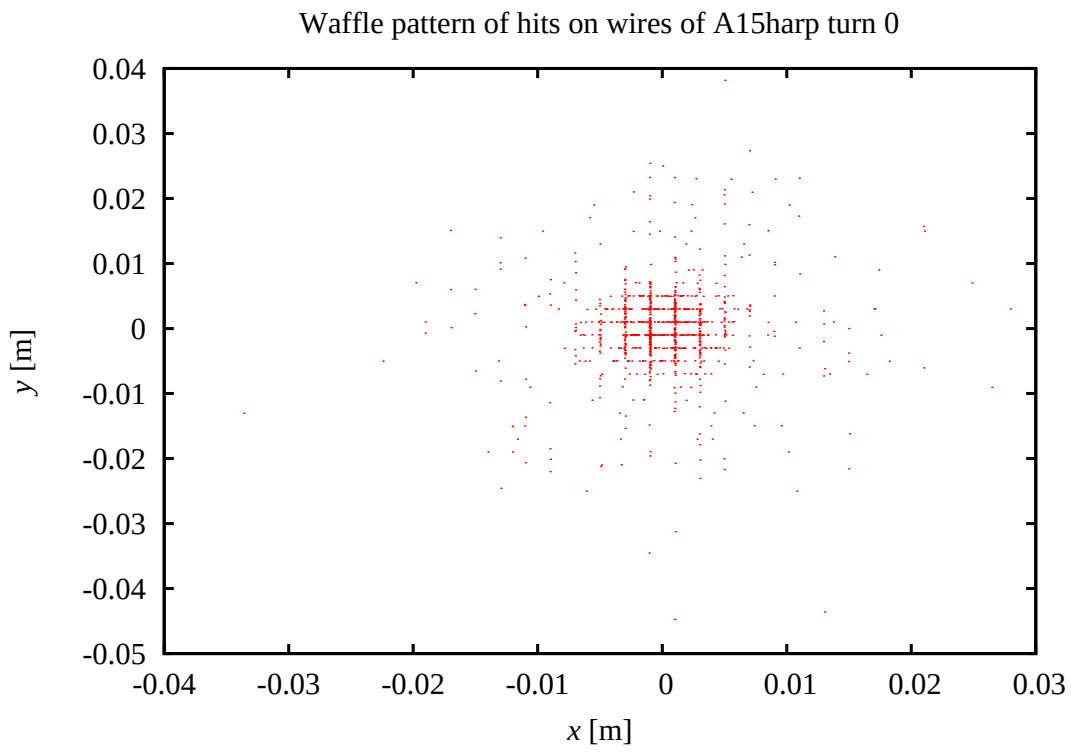
1. W. R. Leo, **Techniques for Nuclear and Particle Physics Experiments** Springer-Verlag (1987).
2. http://www.srim.org/SRIM/SRIMPICS/IONIZ.htm
3. http://pdg.lbl.gov/

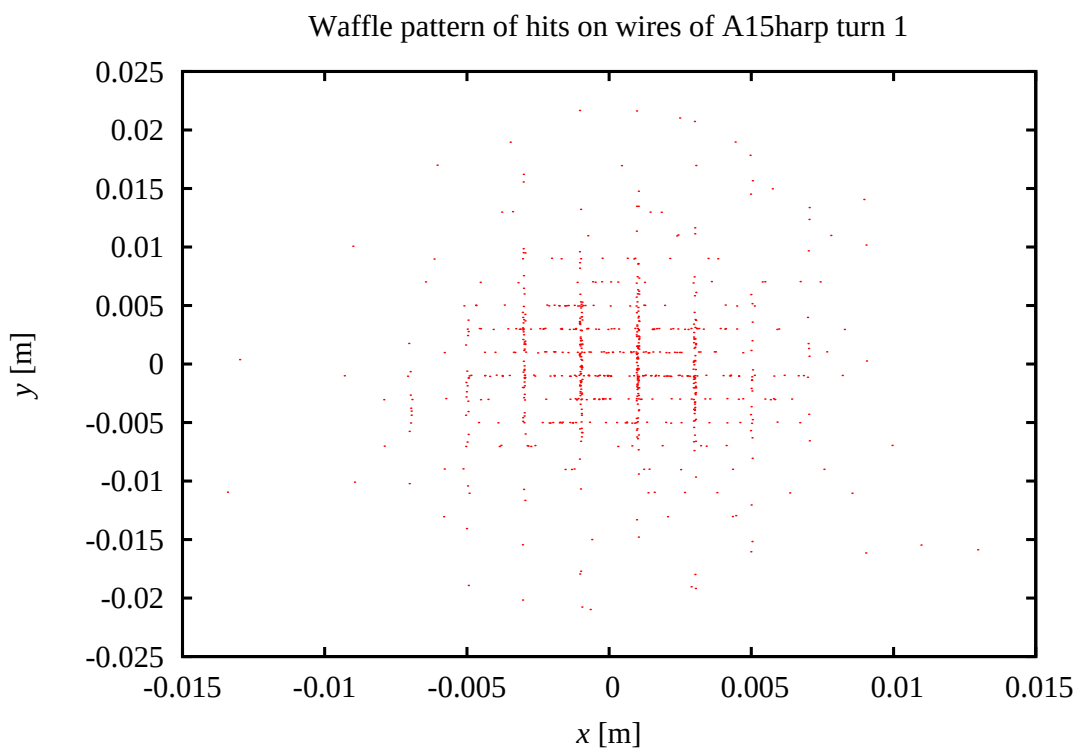

Waffle pattern of hits on wires of MW006
0.008
0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
y [m]
-0.006
-0.004
-0.002
0
0.002
0.004
0.006
x [m]

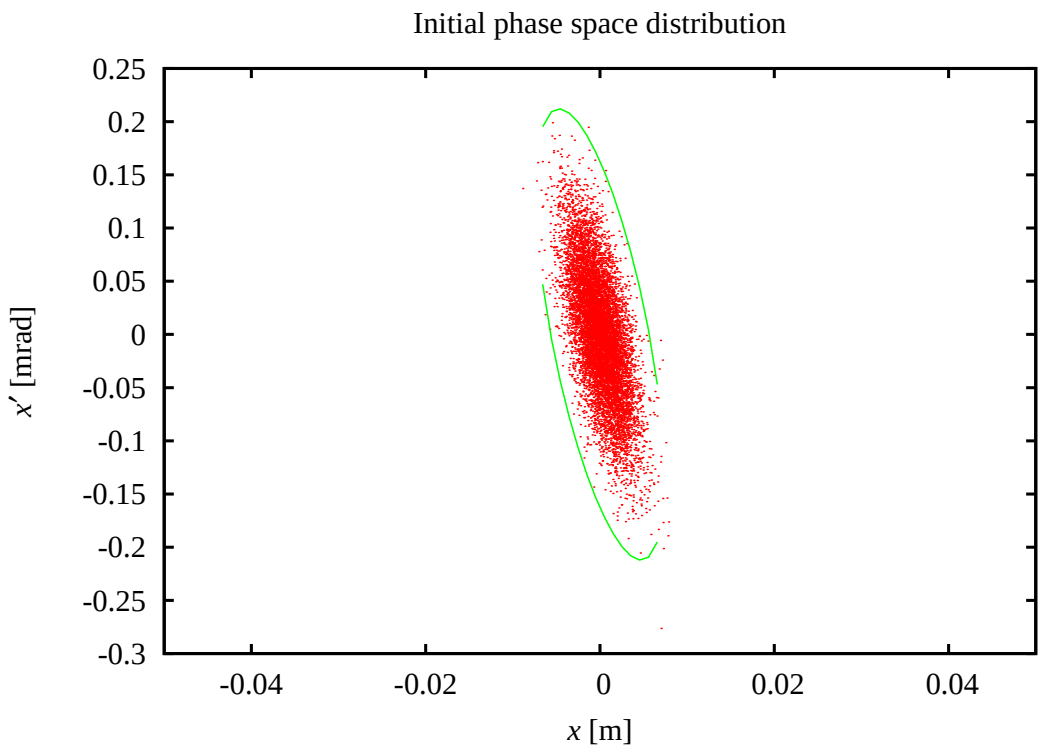

Waffle pattern of hits on wires of MW060
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
y [m]
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
x [m]

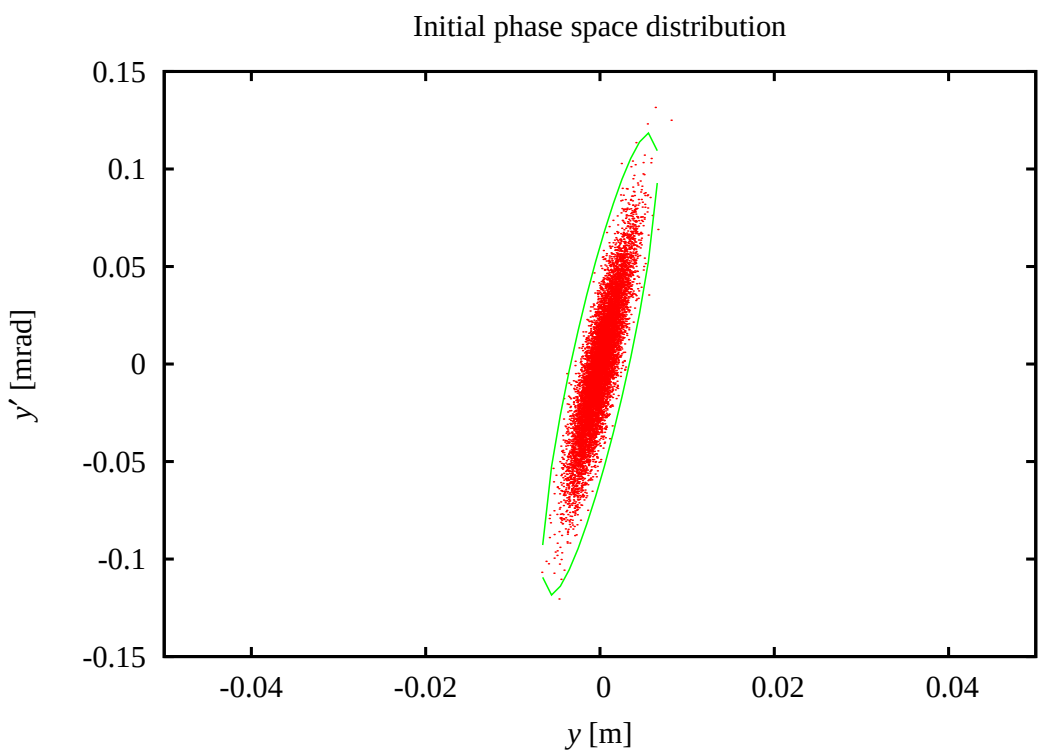

Waffle pattern of hits on wires of MW125
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
y [m]
-0.05
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
x [m]

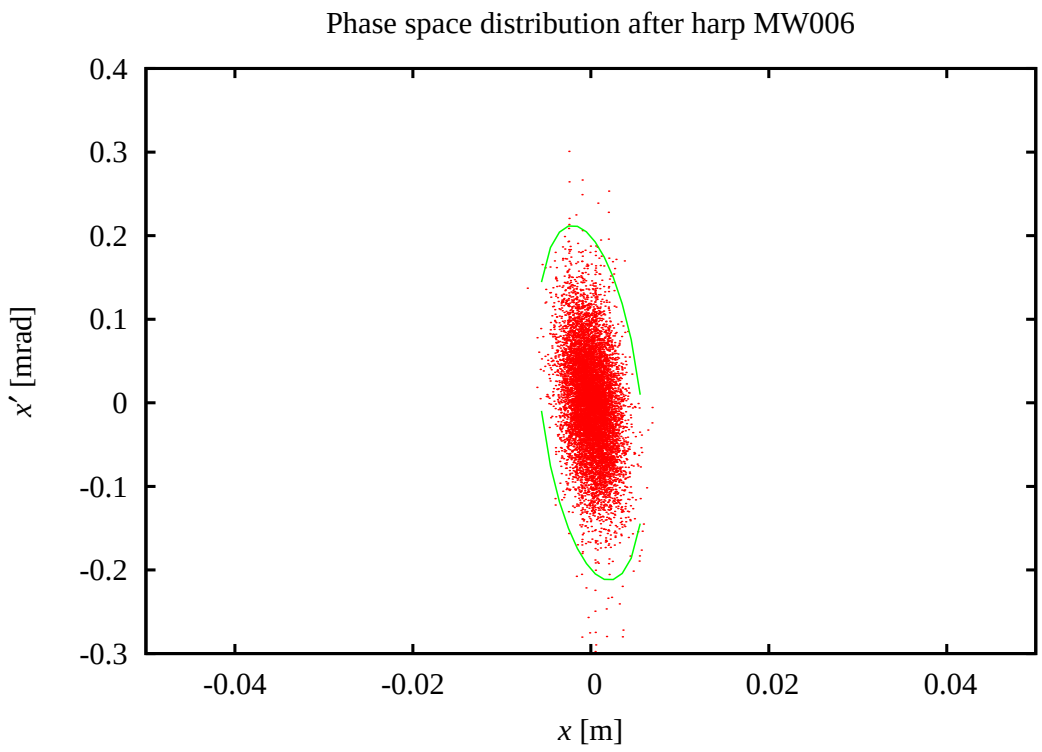

Waffle pattern of hits on wires of MW166
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
y [m]
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
x [m]

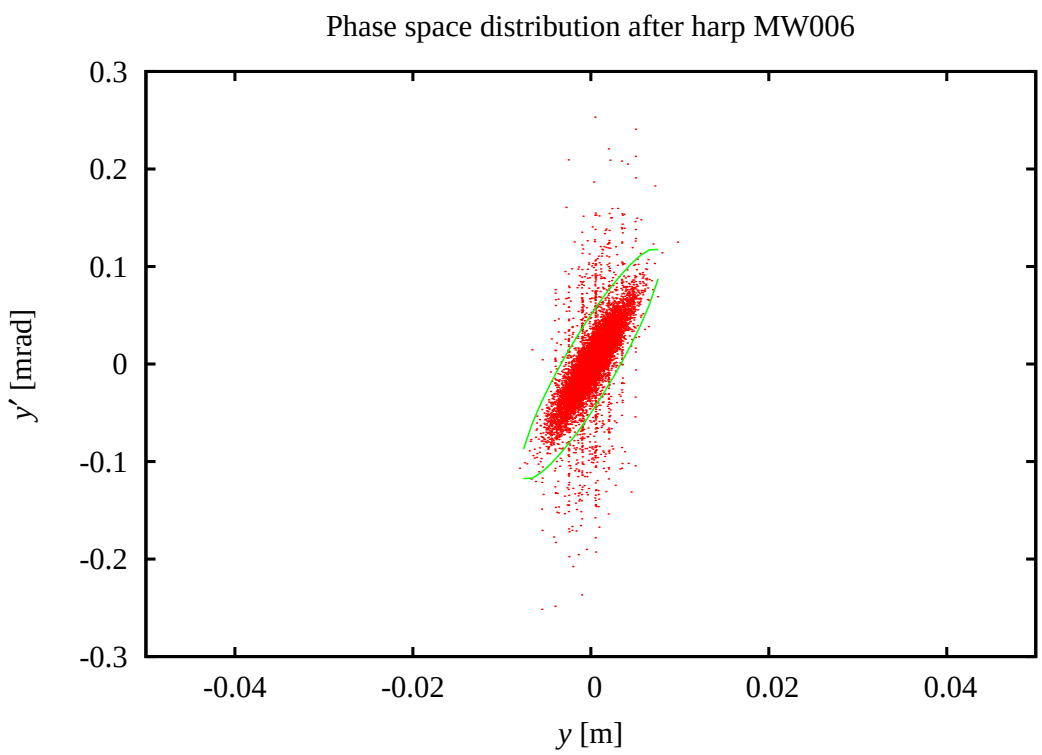

Waffle pattern of hits on wires of A15harp turn 0
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05
y [m]
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
x [m]

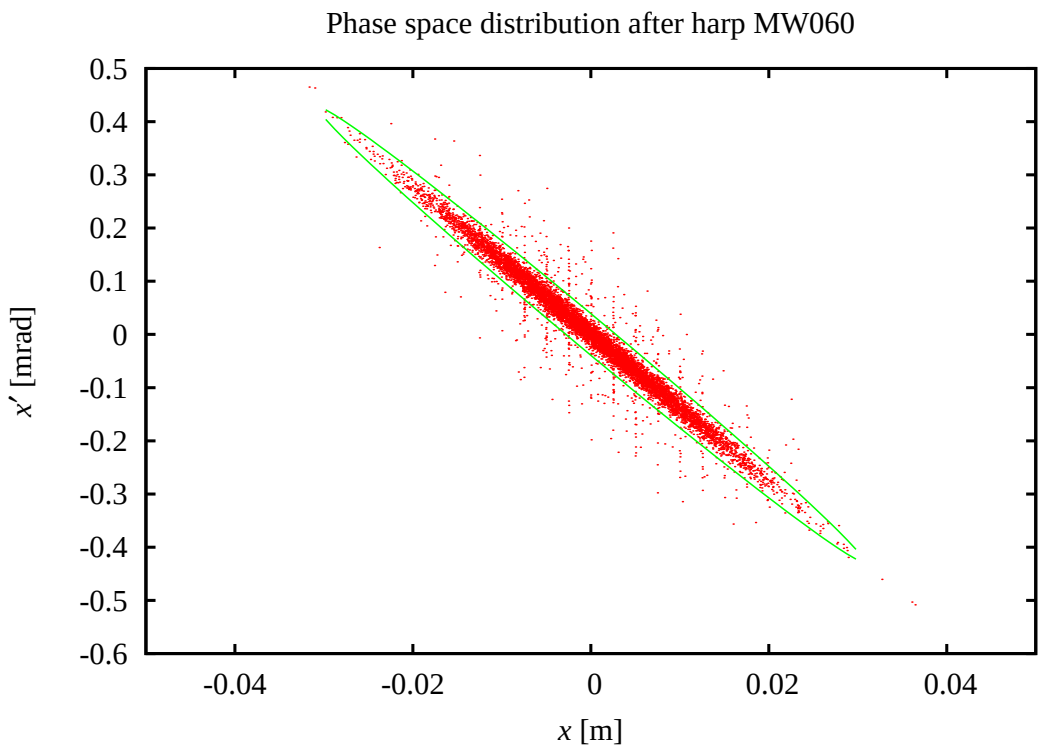

Waffle pattern of hits on wires of A15harp turn 1
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
y [m]
-0.015
-0.01
-0.005
0
0.005
0.01
0.015
x [m]

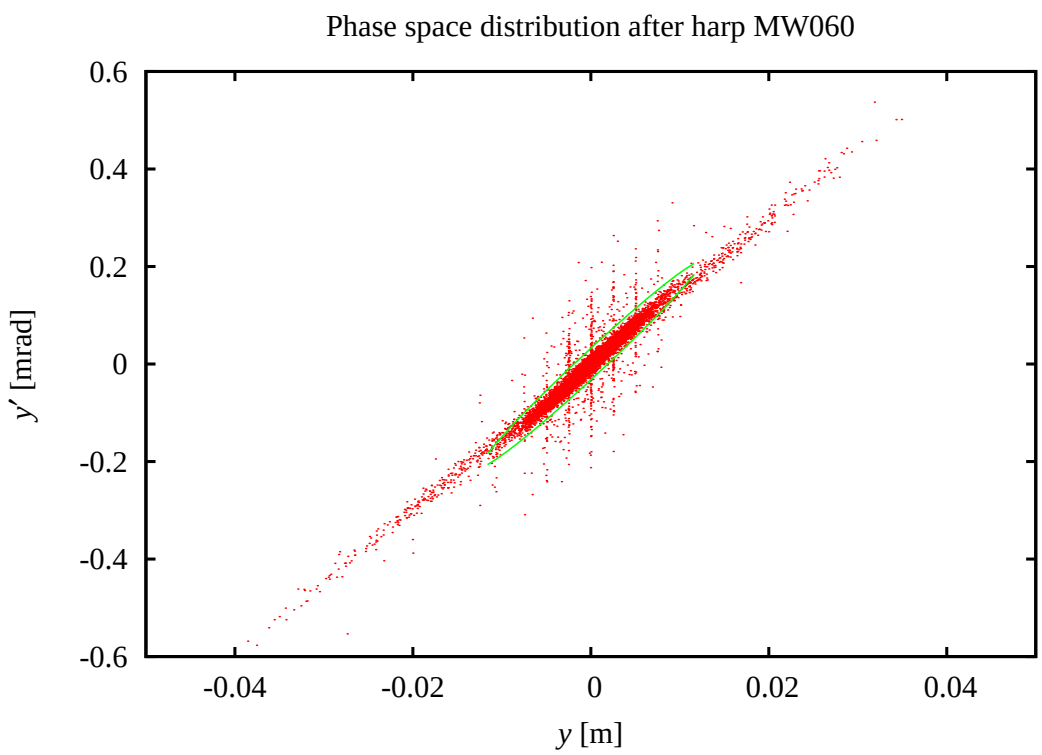

Initial phase space distribution
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
x' [mrad]
-0.04
-0.02
0
0.02
0.04
x [m]

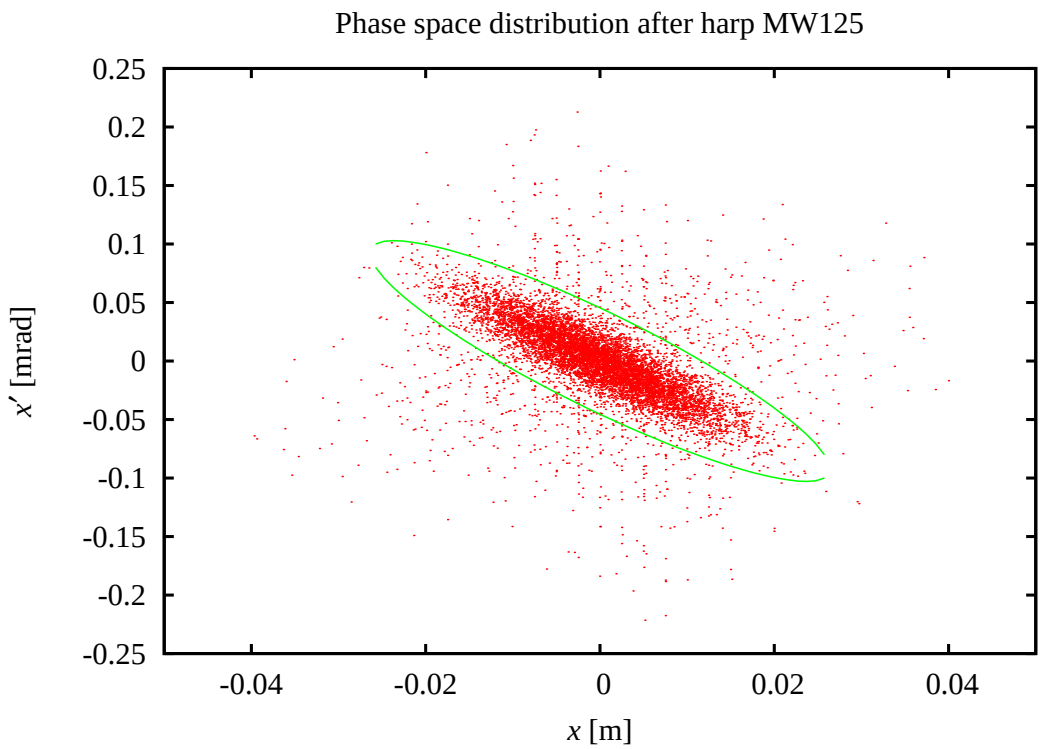

Initial phase space distribution
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
y' [mrad]
-0.04
-0.02
0
0.02
0.04
y [m]

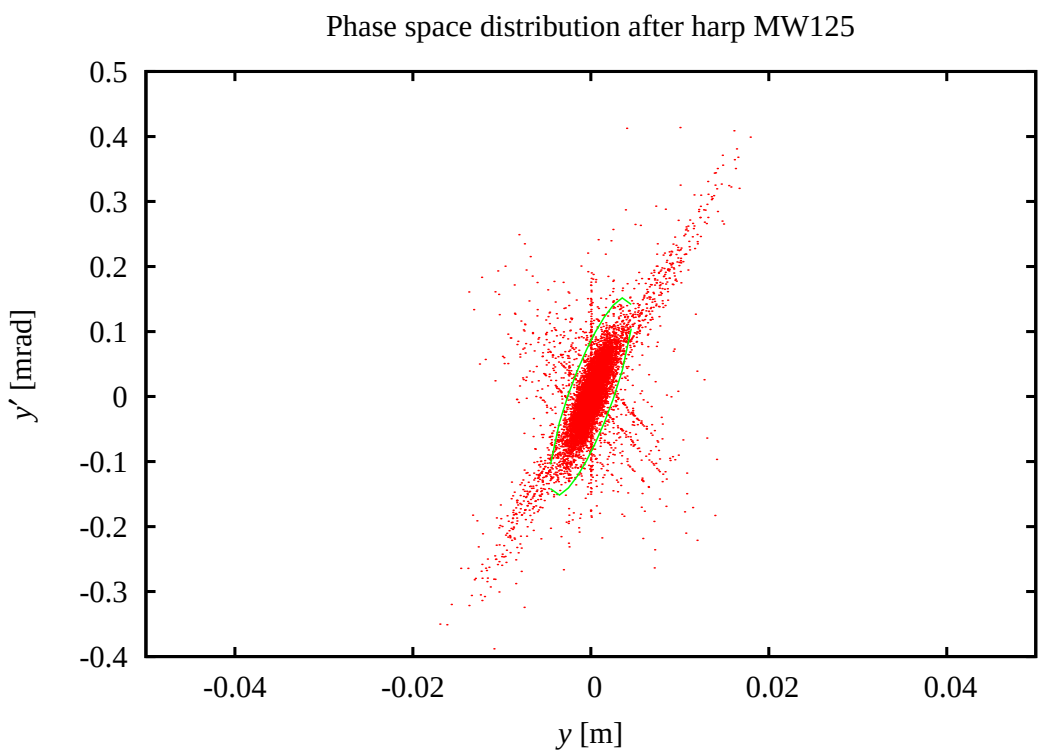

Phase space distribution after harp MW006
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
x' [mrad]
-0.04
-0.02
0
0.02
0.04
x [m]

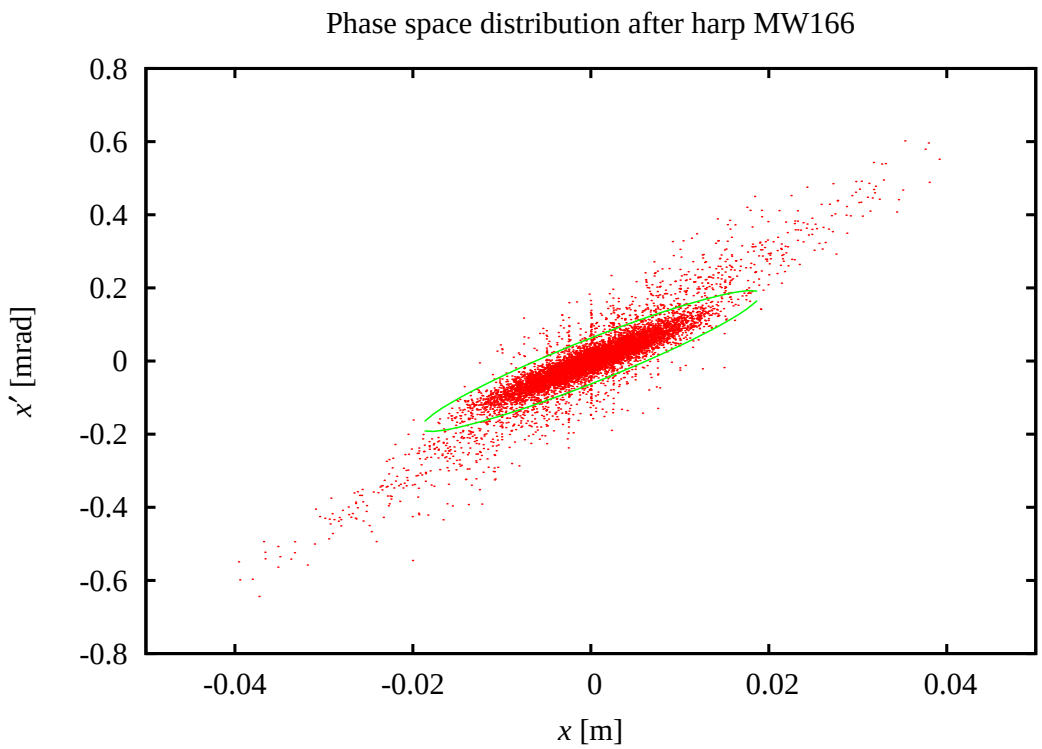

Phase space distribution after harp MW006
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
y' [mrad]
-0.04
-0.02
0
0.02
0.04
y [m]

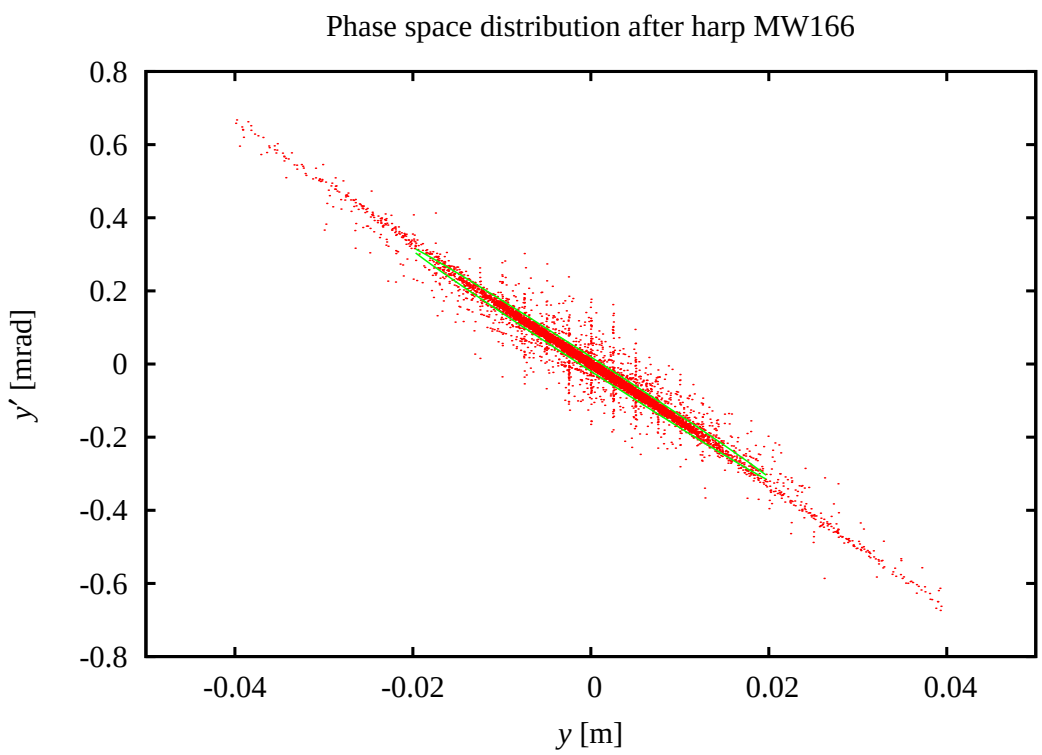

Phase space distribution after harp MW060
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
x′ [mrad]
-0.04
-0.02
0
0.02
0.04
x [m]

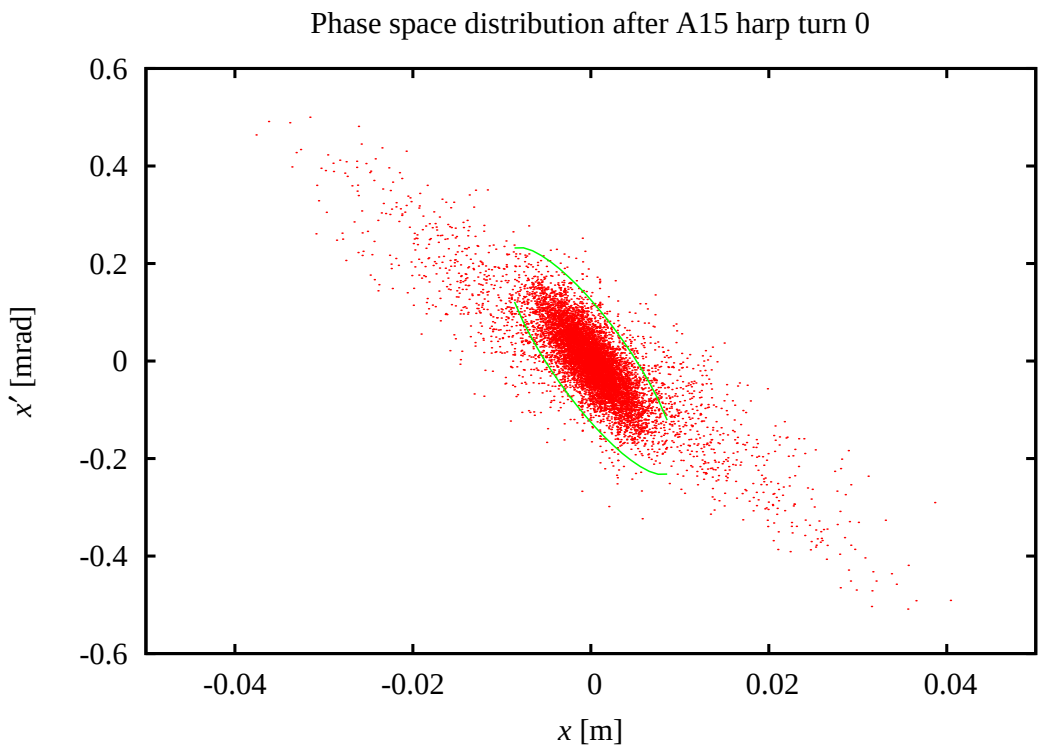

Phase space distribution after harp MW060
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
y′ [mrad]
-0.04
-0.02
0
0.02
0.04
y [m]

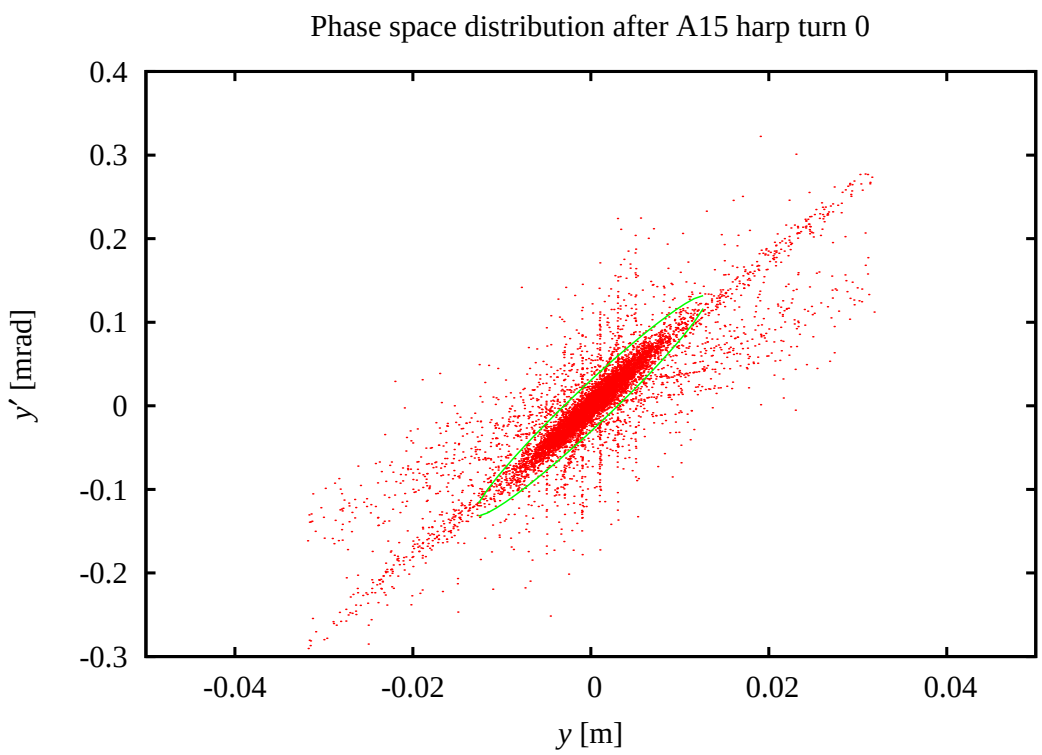

Phase space distribution after harp MW125
0.25
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
x' [mrad]
-0.04
-0.02
0
0.02
0.04
x [m]

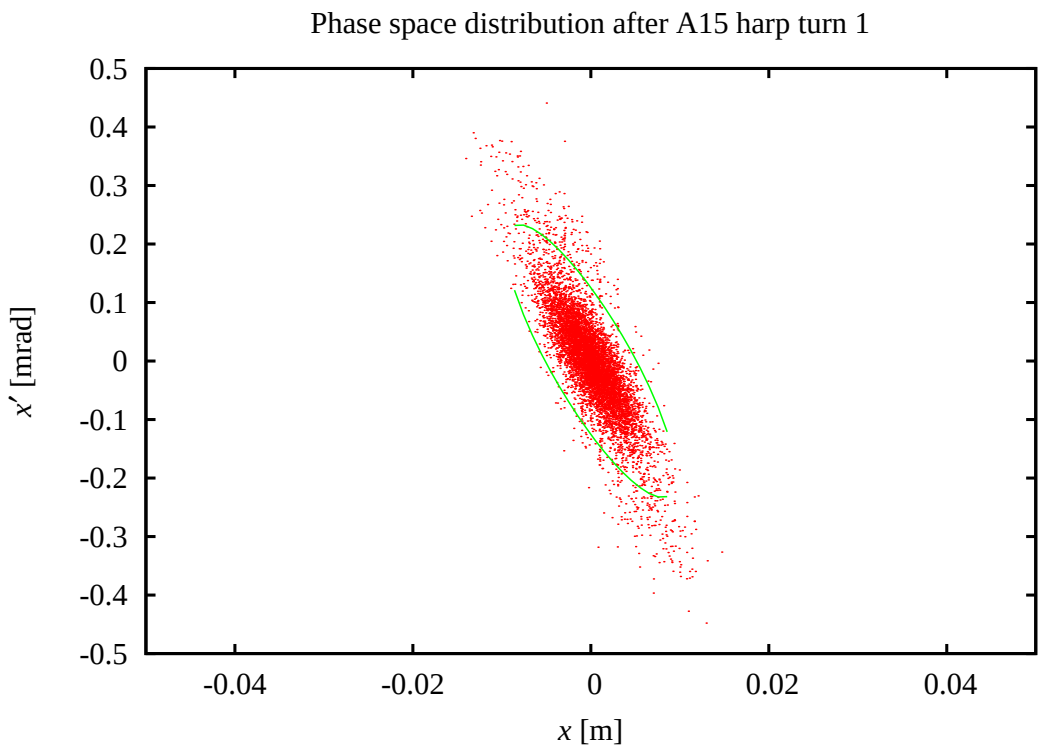

Phase space distribution after harp MW125
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
y' [mrad]
-0.04
-0.02
0
0.02
0.04
y [m]

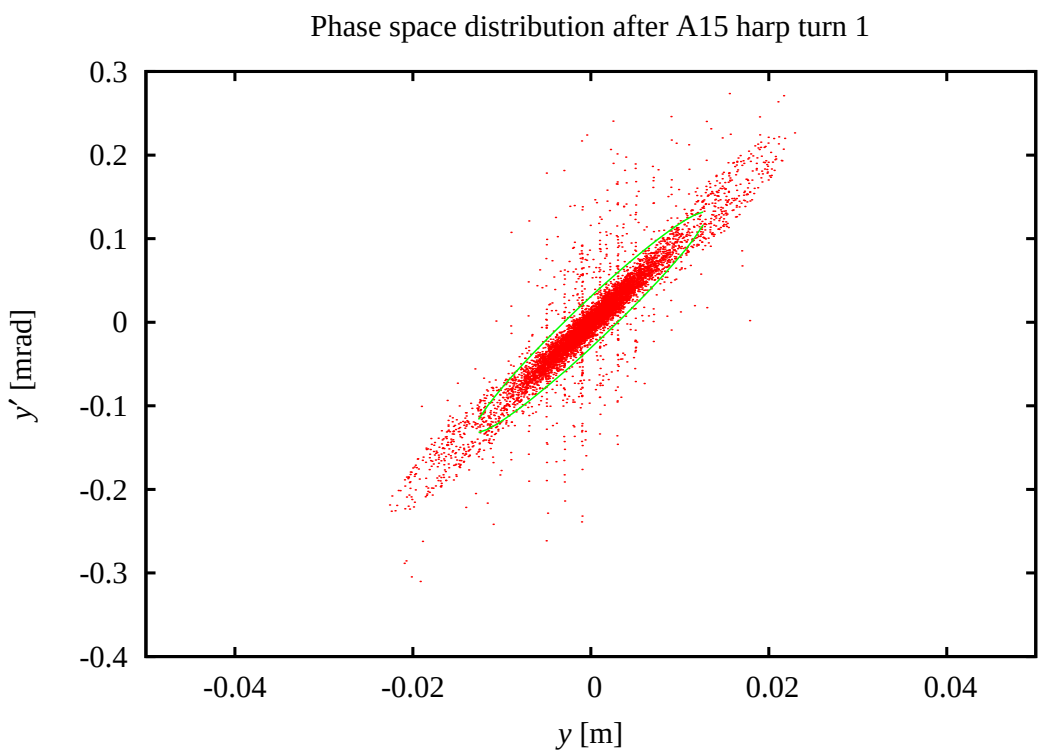

Phase space distribution after harp MW166
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
x' [mrad]
-0.04
-0.02
0
0.02
0.04
x [m]

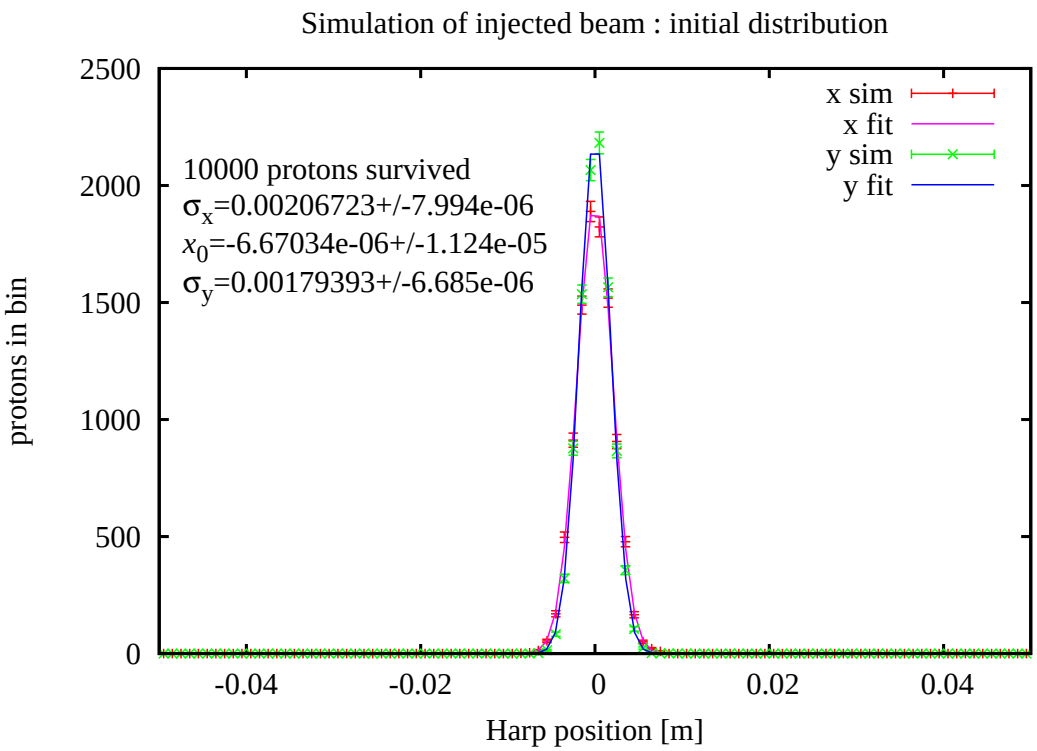

Phase space distribution after harp MW166
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
y' [mrad]
-0.04
-0.02
0
0.02
0.04
y [m]

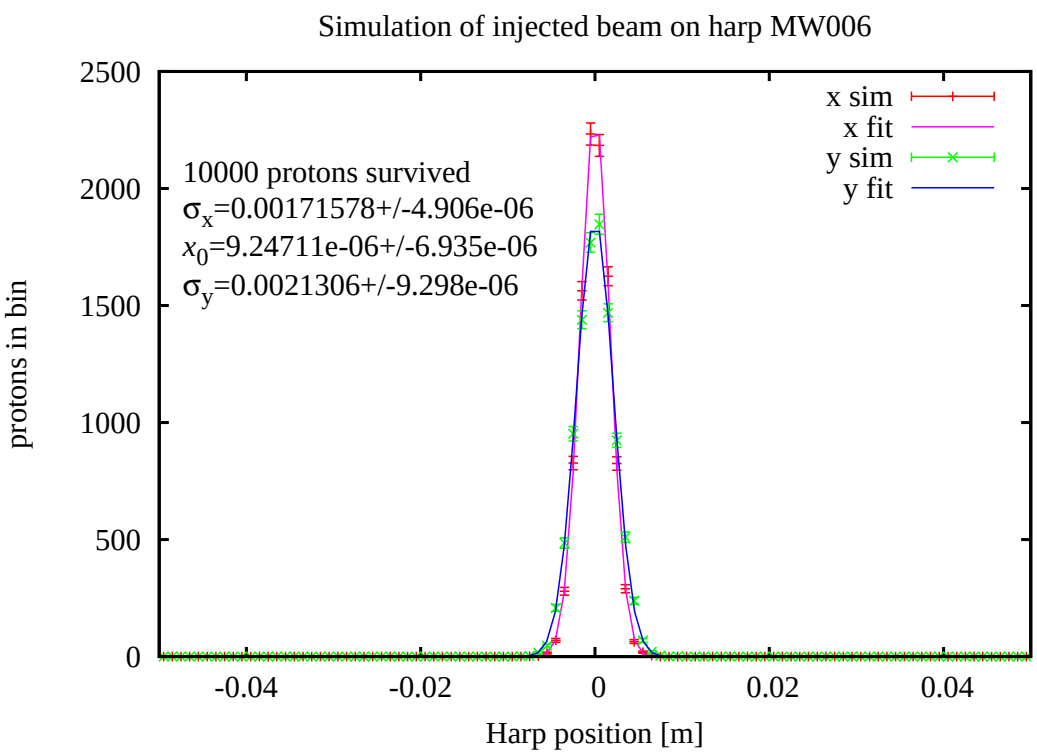

Phase space distribution after A15 harp turn 0
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
x' [mrad]
-0.04
-0.02
0
0.02
0.04
x [m]

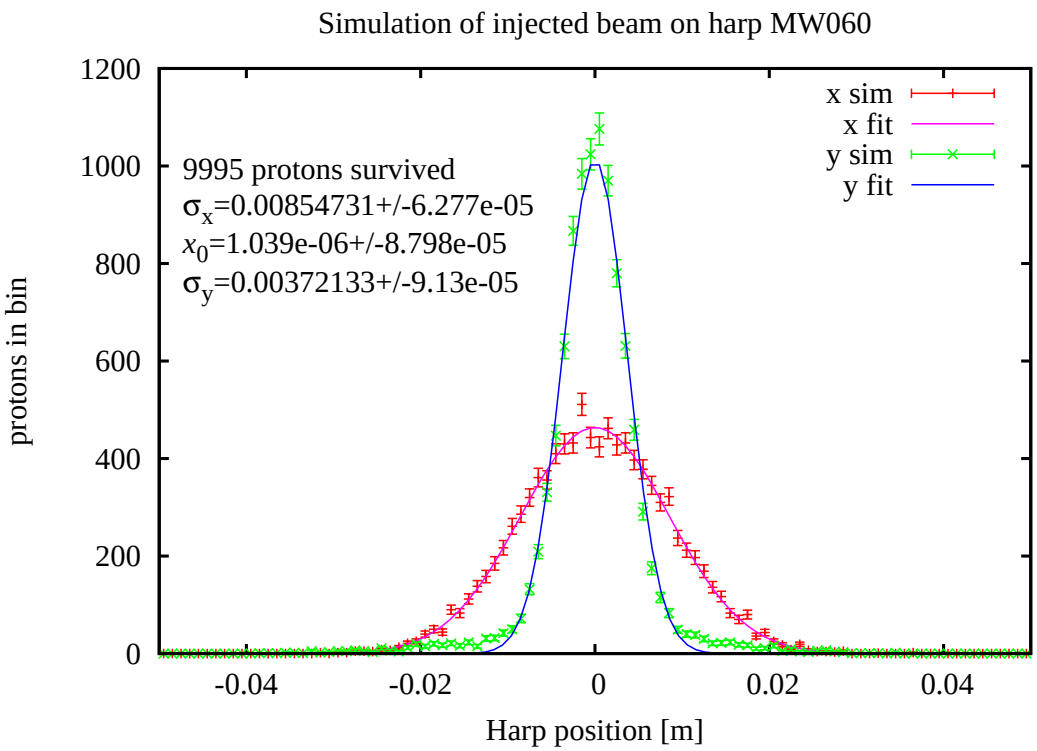

Phase space distribution after A15 harp turn 0
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
y' [mrad]
-0.04
-0.02
0
0.02
0.04
y [m]

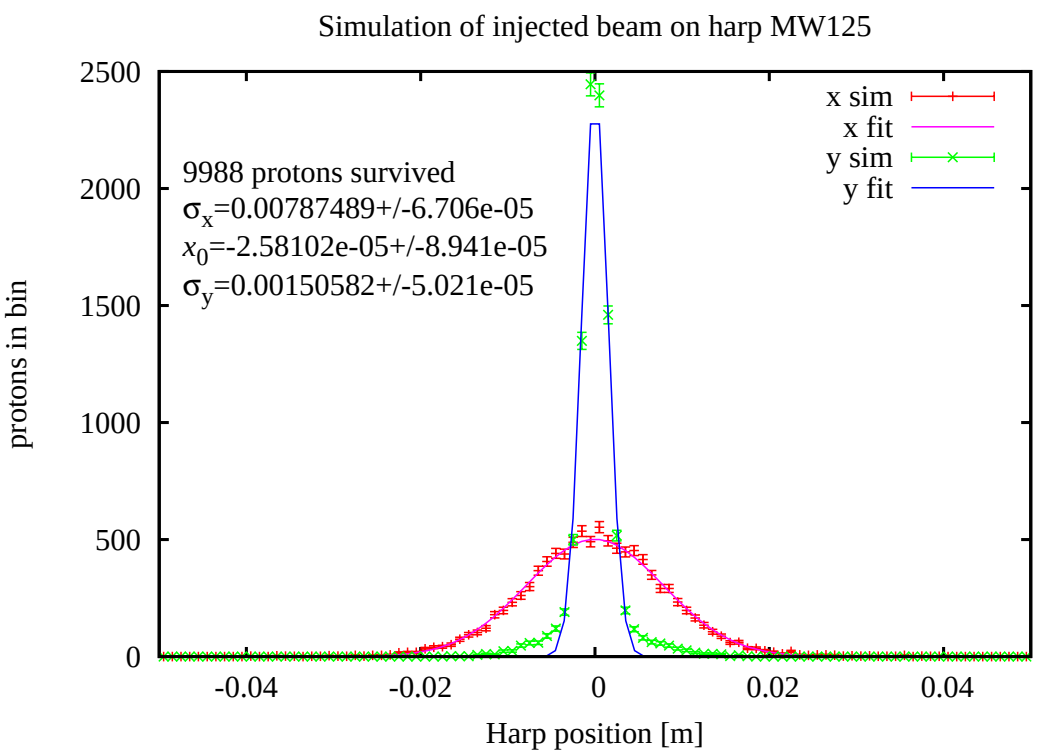

Phase space distribution after A15 harp turn 1
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
x' [mrad]
-0.04
-0.02
0
0.02
0.04
x [m]

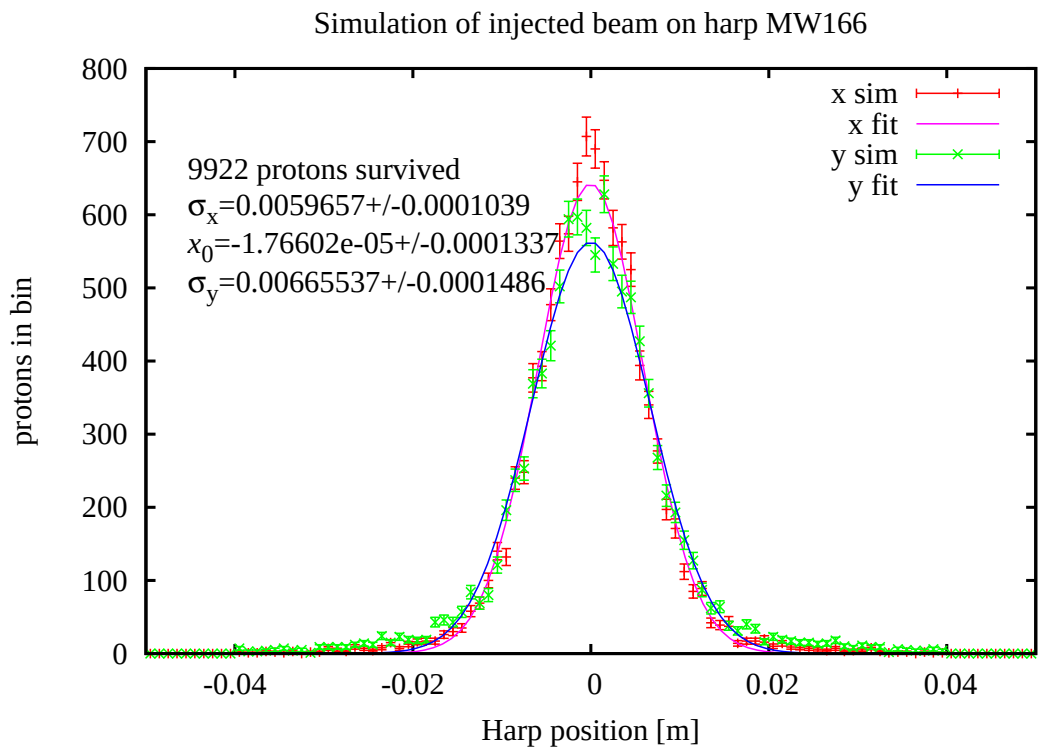

Phase space distribution after A15 harp turn 1
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
y' [mrad]
-0.04
-0.02
0
0.02
0.04
y [m]

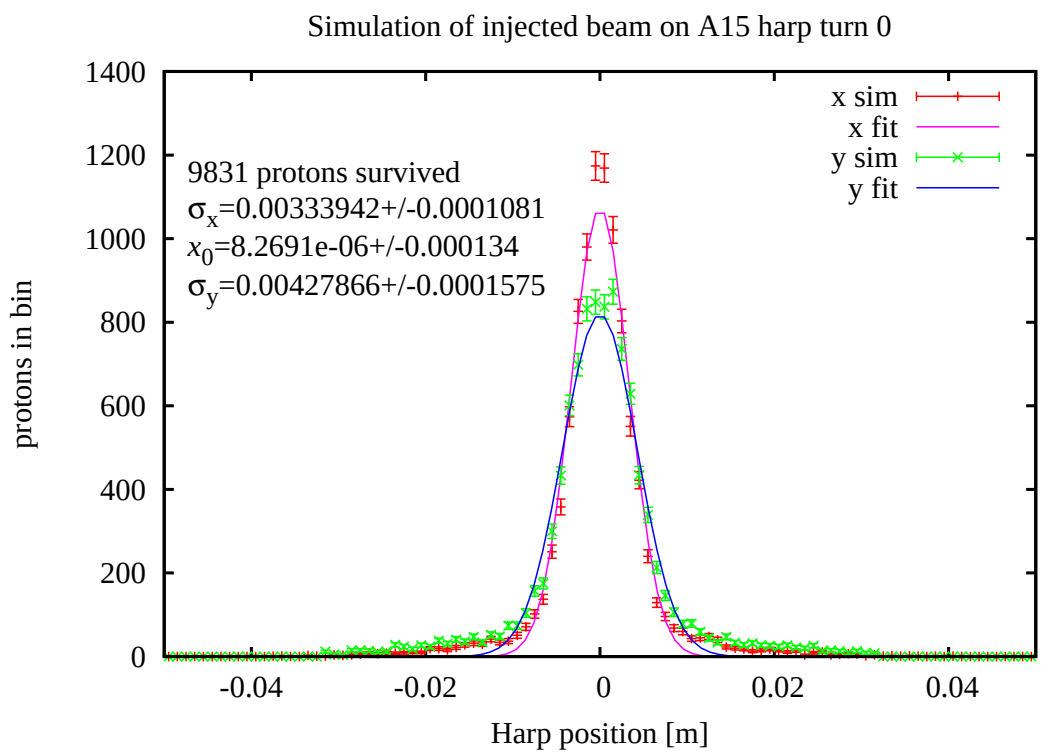

Simulation of injected beam : initial distribution
10000 protons survived
σx=0.00206723+/-7.994e-06
x0=-6.67034e-06+/-1.124e-05
σy=0.00179393+/-6.685e-06
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
2500
2000
1500
1000
500
0
-0.04
-0.02
0
0.02
0.04

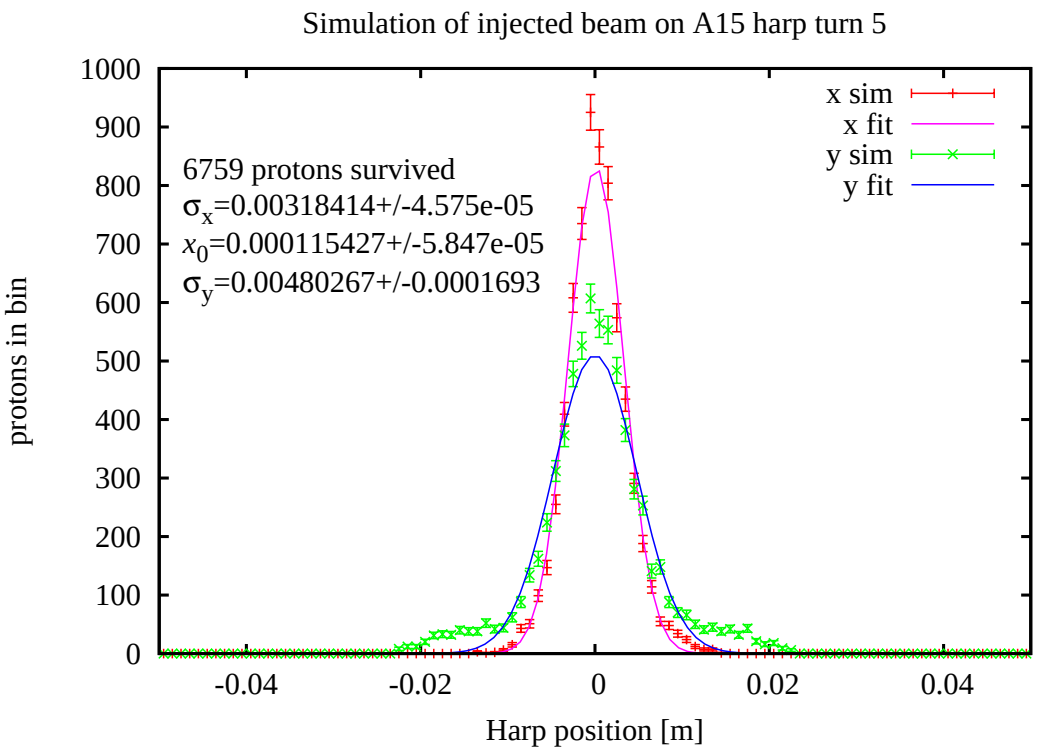

Simulation of injected beam on harp MW006
10000 protons survived
σx=0.00171578+/-4.906e-06
x0=9.24711e-06+/-6.935e-06
σy=0.0021306+/-9.298e-06
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
2500
2000
1500
1000
500
0
-0.04
-0.02
0
0.02
0.04

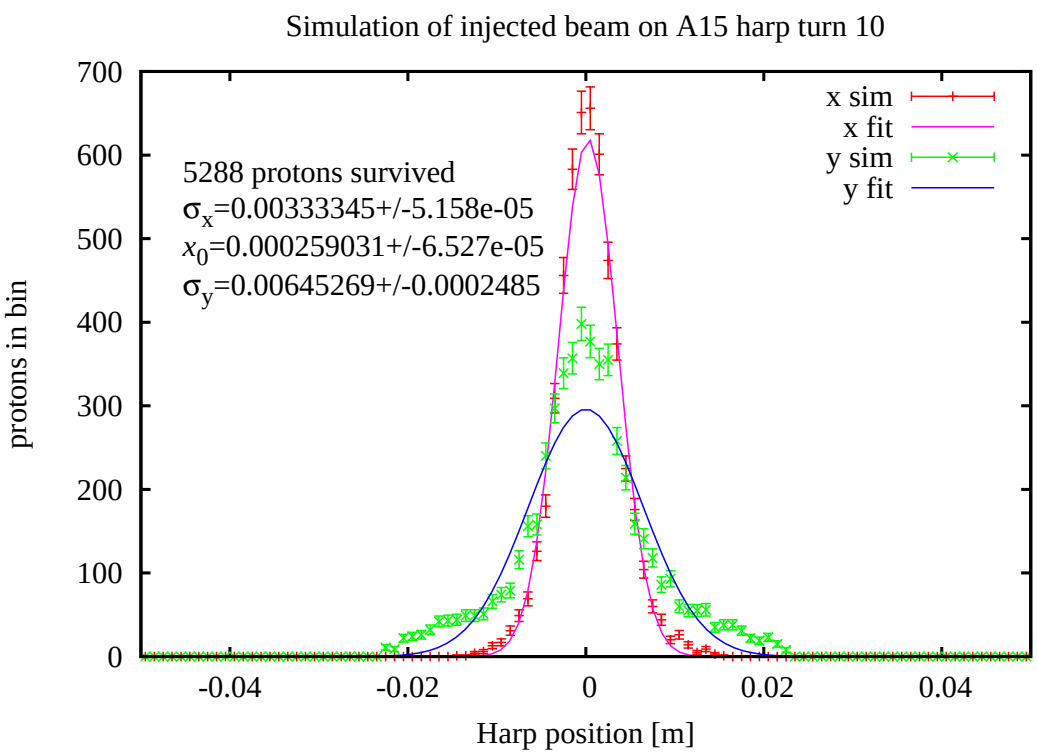

Simulation of injected beam on harp MW060
9995 protons survived
σx=0.00854731+/-6.277e-05
x0=1.039e-06+/-8.798e-05
σy=0.00372133+/-9.13e-05
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
1200
1000
800
600
400
200
0
-0.04
-0.02
0
0.02
0.04

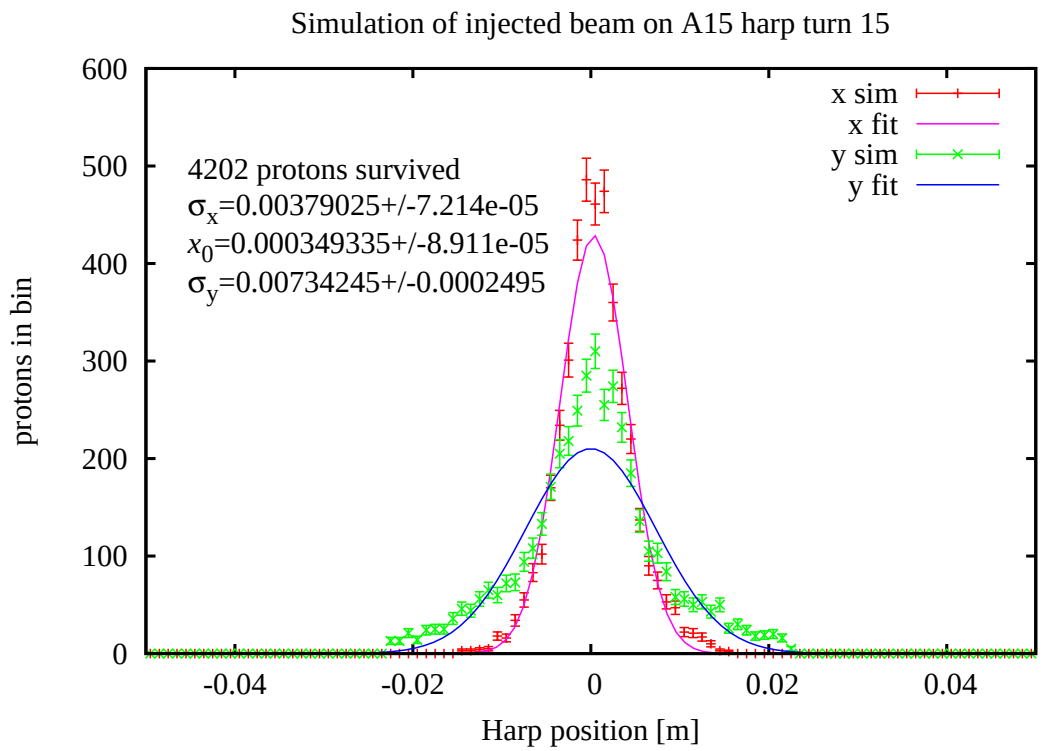

Simulation of injected beam on harp MW125
9988 protons survived
σx=0.00787489+/-6.706e-05
x0=-2.58102e-05+/-8.941e-05
σy=0.00150582+/-5.021e-05
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
2500
2000
1500
1000
500
0
-0.04
-0.02
0
0.02
0.04

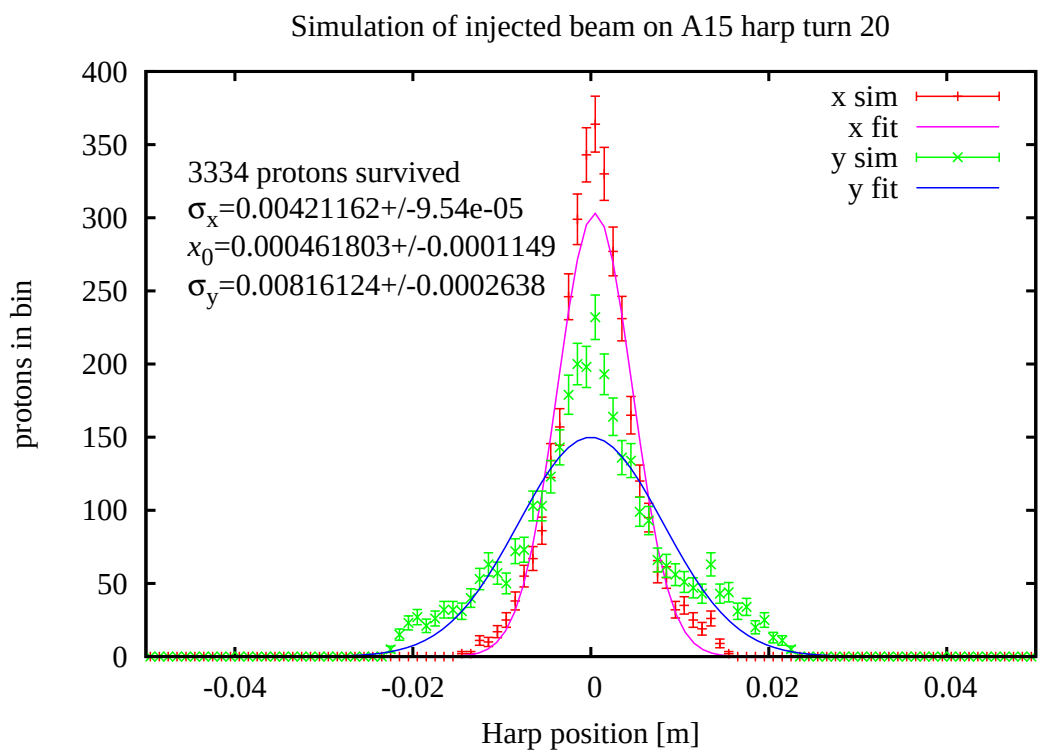

Simulation of injected beam on harp MW166
9922 protons survived
σx=0.0059657+/-0.0001039
x0=-1.76602e-05+/-0.0001337
σy=0.00665537+/-0.0001486
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
800
700
600
500
400
300
200
100
0
-0.04
-0.02
0
0.02
0.04

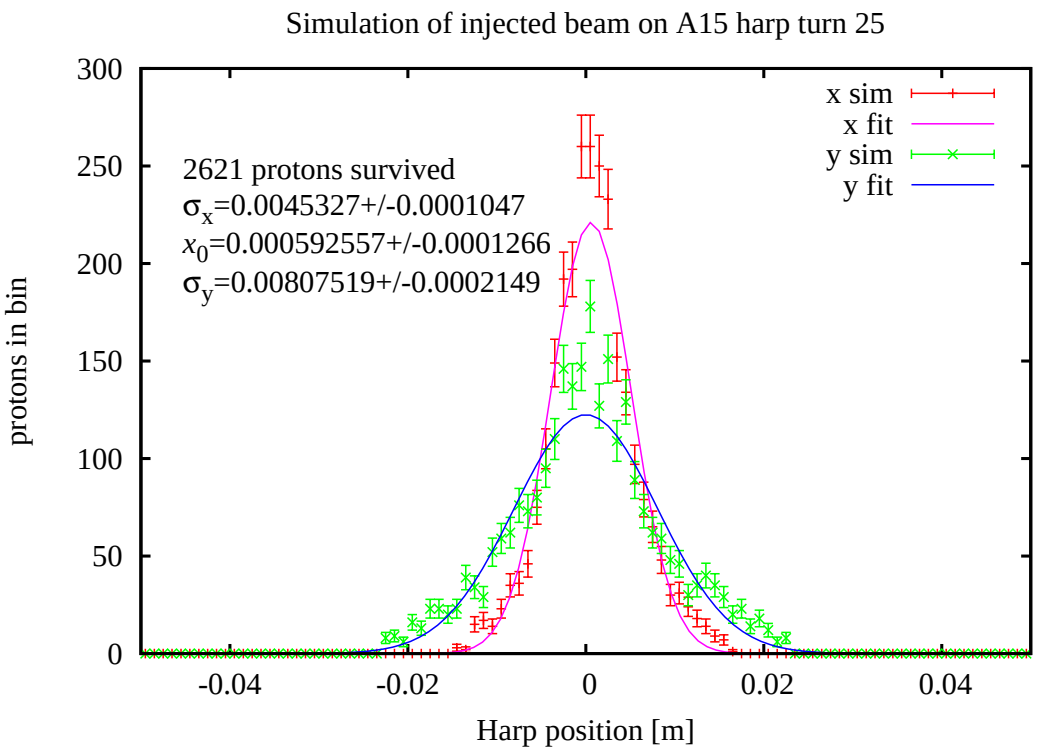

Simulation of injected beam on A15 harp turn 0
9831 protons survived
σx=0.00333942+/-0.0001081
x0=8.2691e-06+/-0.000134
σy=0.00427866+/-0.0001575
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
1400
1200
1000
800
600
400
200
0
-0.04
-0.02
0
0.02
0.04

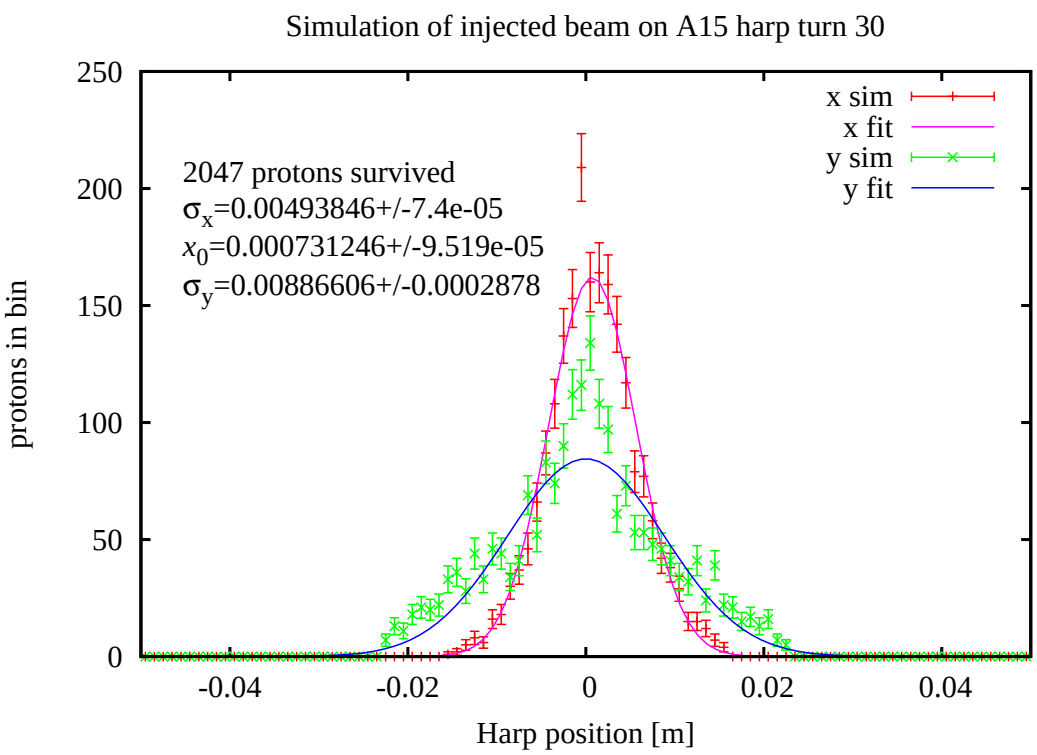

Simulation of injected beam on A15 harp turn 5
6759 protons survived
σx=0.00318414+/-4.575e-05
x0=0.000115427+/-5.847e-05
σy=0.00480267+/-0.0001693
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
1000
900
800
700
600
500
400
300
200
100
0
-0.04
-0.02
0
0.02
0.04

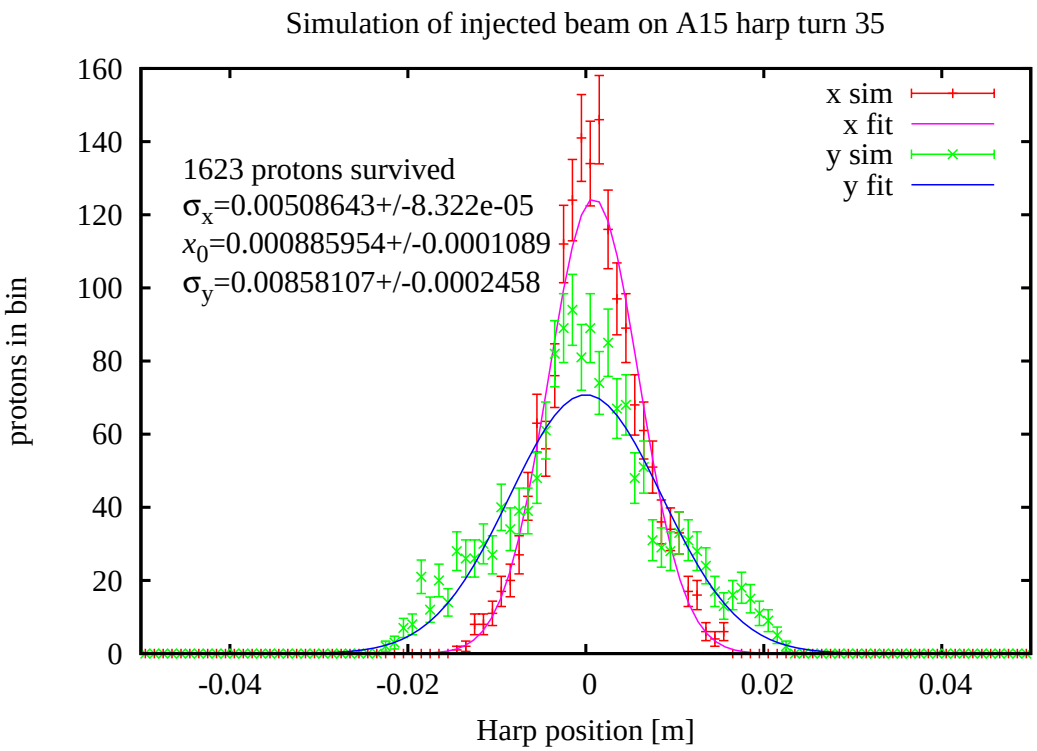

Simulation of injected beam on A15 harp turn 10
5288 protons survived
σx=0.00333345+/-5.158e-05
x0=0.000259031+/-6.527e-05
σy=0.00645269+/-0.0002485
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
700
600
500
400
300
200
100
0
-0.04
-0.02
0
0.02
0.04

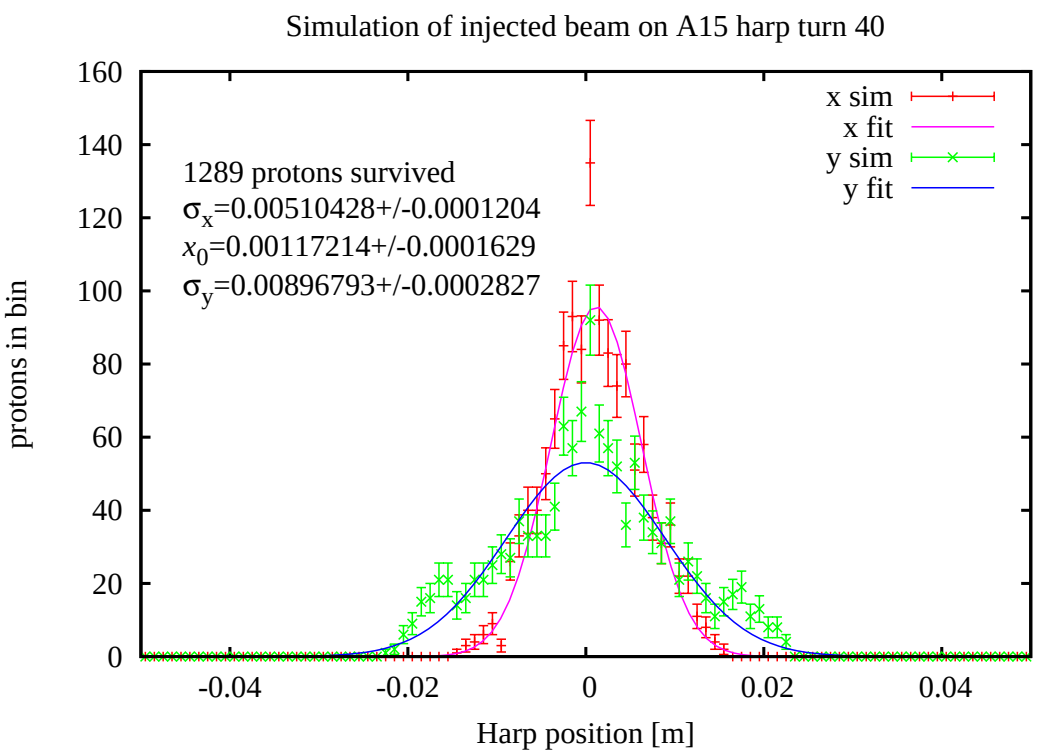

Simulation of injected beam on A15 harp turn 15
4202 protons survived
σx=0.00379025+/-7.214e-05
x0=0.000349335+/-8.911e-05
σy=0.00734245+/-0.0002495
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
600
500
400
300
200
100
0
-0.04
-0.02
0
0.02
0.04

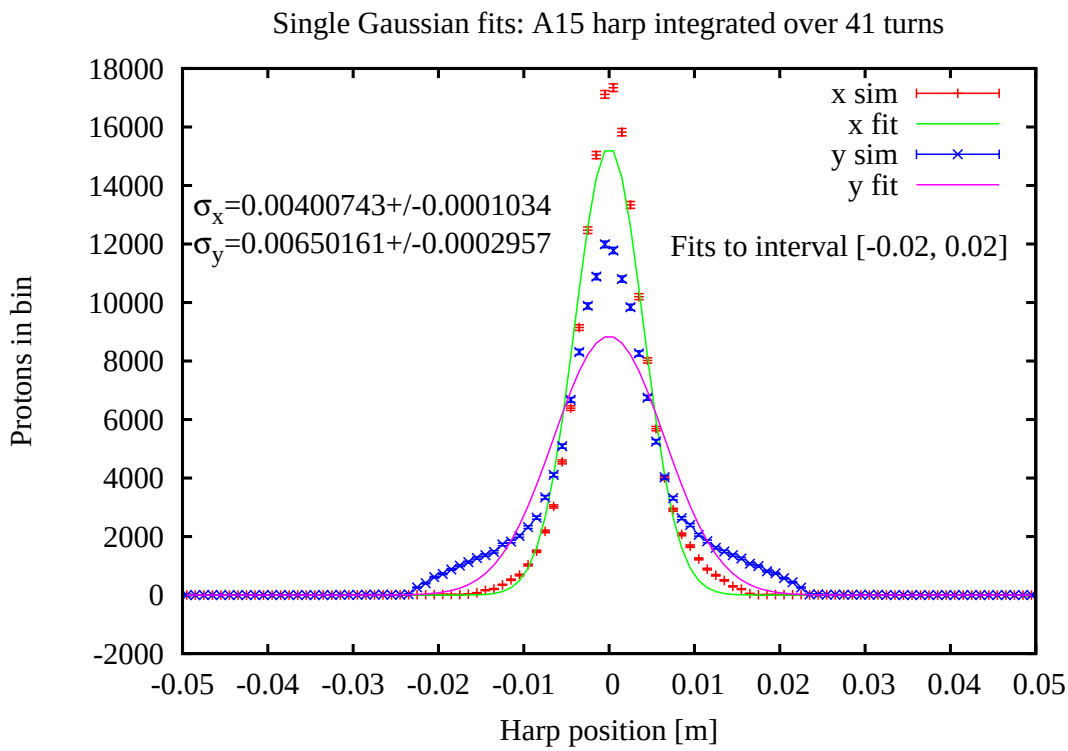

Simulation of injected beam on A15 harp turn 20
3334 protons survived
σx=0.00421162+/-9.54e-05
x0=0.000461803+/-0.0001149
σy=0.00816124+/-0.0002638
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
400
350
300
250
200
150
100
50
0
-0.04
-0.02
0
0.02
0.04

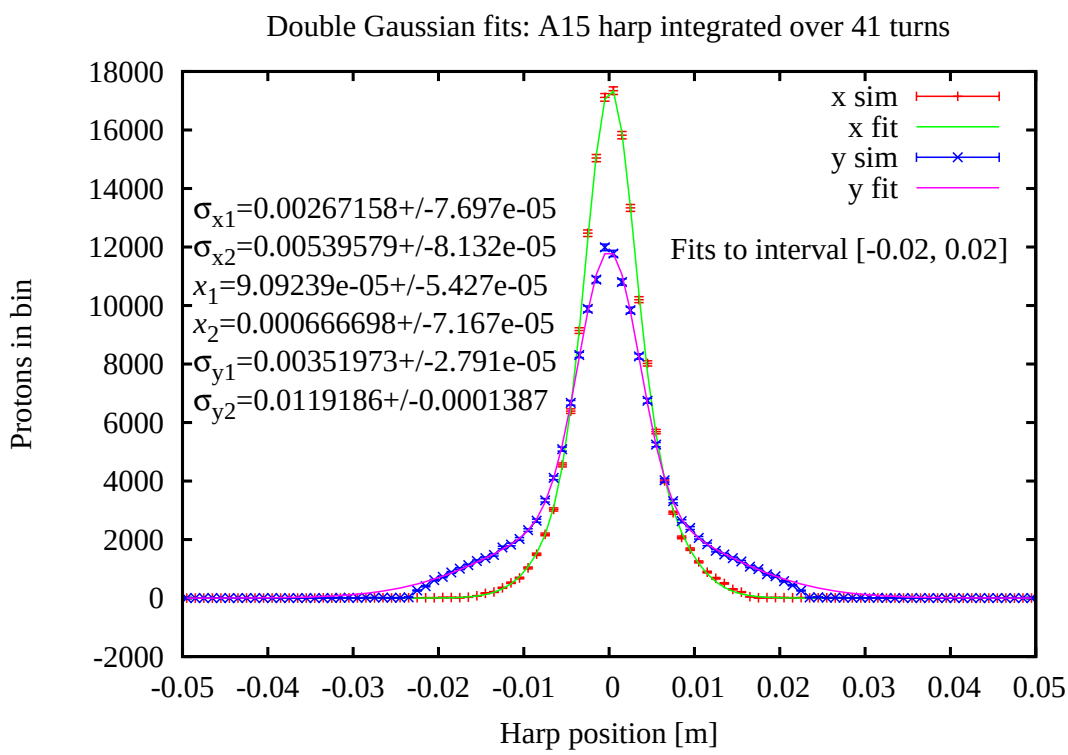

Simulation of injected beam on A15 harp turn 25
2621 protons survived
σx=0.0045327+/-0.0001047
x0=0.000592557+/-0.0001266
σy=0.00807519+/-0.0002149
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
300
250
200
150
100
50
0
-0.04
-0.02
0
0.02
0.04


Simulation of injected beam on A15 harp turn 30
2047 protons survived
σx=0.00493846+/-7.4e-05
x0=0.000731246+/-9.519e-05
σy=0.00886606+/-0.0002878
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
250
200
150
100
50
0
-0.04
-0.02
0
0.02
0.04


Simulation of injected beam on A15 harp turn 35
1623 protons survived
σx=0.00508643+/-8.322e-05
x0=0.000885954+/-0.0001089
σy=0.00858107+/-0.0002458
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
160
140
120
100
80
60
40
20
0
-0.04
-0.02
0
0.02
0.04


Simulation of injected beam on A15 harp turn 40
1289 protons survived
σx=0.00510428+/-0.0001204
x0=0.00117214+/-0.0001629
σy=0.00896793+/-0.0002827
x sim
x fit
y sim
y fit
protons in bin
Harp position [m]
160
140
120
100
80
60
40
20
0
-0.04
-0.02
0
0.02
0.04


Single Gaussian fits: A15 harp integrated over 41 turns
x sim
x fit
y sim
y fit
σx=0.00400743+/-0.0001034
σy=0.00650161+/-0.0002957
Fits to interval [-0.02, 0.02]
Protons in bin
Harp position [m]
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
-2000
-0.05
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
0.05


Double Gaussian fits: A15 harp integrated over 41 turns
x sim
x fit
y sim
y fit
σx1=0.00267158+/-7.697e-05
σx2=0.00539579+/-8.132e-05
x1=9.09239e-05+/-5.427e-05
x2=0.000666698+/-7.167e-05
σy1=0.00351973+/-2.791e-05
σy2=0.0119186+/-0.0001387
Fits to interval [-0.02, 0.02]
Protons in bin
Harp position [m]
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
-2000
-0.05
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
0.05

The double Gaussian fit was to the function

$$f(x) = \frac{N_{x1}}{\sqrt{2\pi}\,\sigma_{x1}} \exp\left(-\frac{(x-x_1)^2}{2\sigma_{x1}}\right) + \frac{N_{x2}}{\sqrt{2\pi}\,\sigma_{x2}} \exp\left(-\frac{(x-x_2)^2}{2\sigma_{x2}}\right),$$

for the x distribution and

$$f(y) = \frac{N_{y1}}{\sqrt{2\pi}\,\sigma_{y1}} \exp\left(-\frac{y^2}{2\sigma_{y1}}\right) + \frac{N_{y2}}{\sqrt{2\pi}\,\sigma_{y2}} \exp\left(-\frac{y^2}{2\sigma_{y2}}\right),$$

for the y distribution. Taking the sigmas of the fitted narrow Gaussian distributions,

$$\sigma_{x1} = 2.67 \text{ mm}, \quad \text{and} \quad \sigma_{y1} = 3.52 \text{ mm},$$

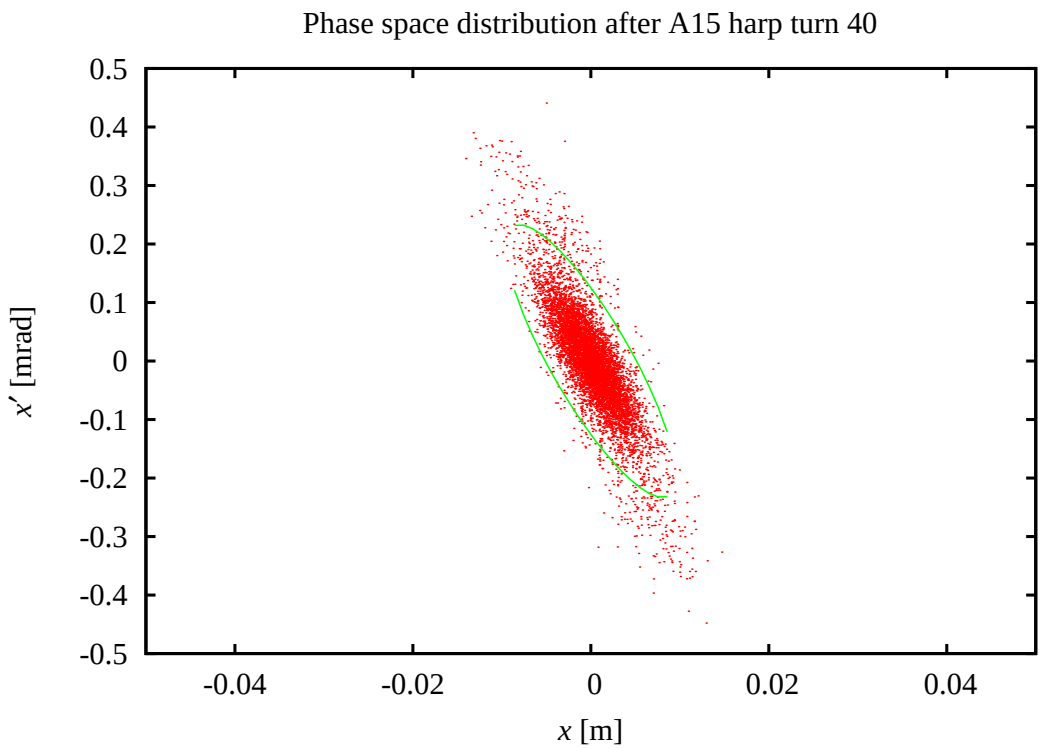
together with the lattice parameters at the A15 harp:

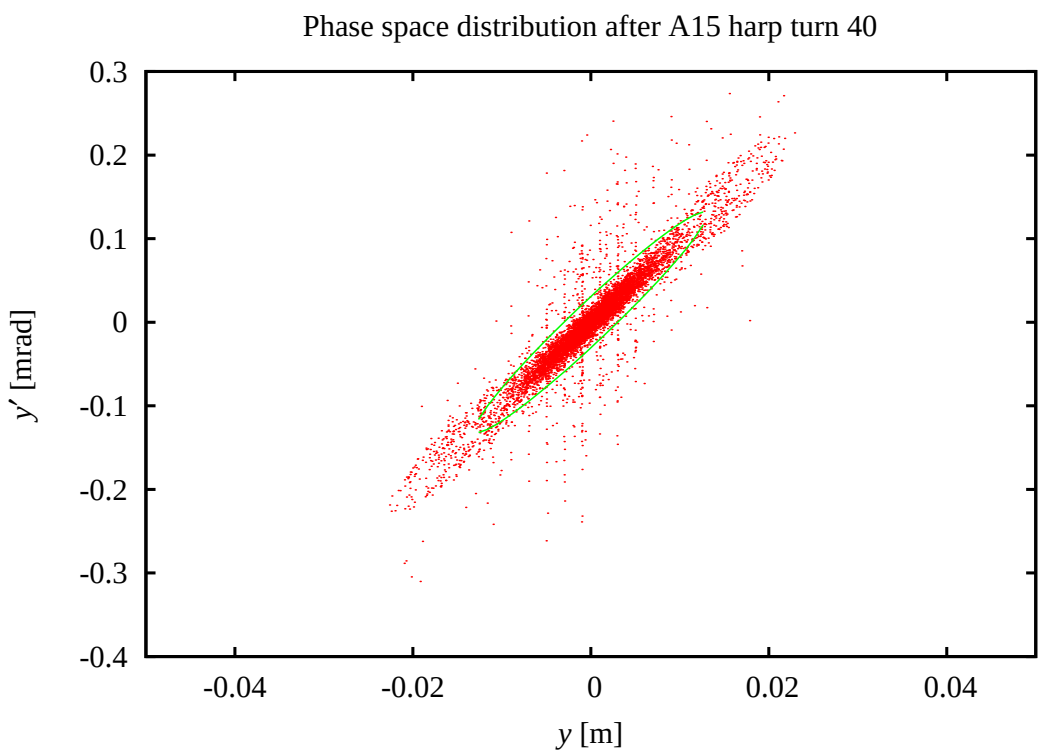
$$\begin{aligned} \beta_x &= 7.628 \text{ m}, \\ \eta_x &= -3.405 \text{ m}, \\ \beta_y &= 42.593 \text{ m}, \end{aligned}$$

with $\gamma\beta = 2.3022$ and $\sigma_p/p = 1.6 \times 10^{-4}$ I estimate the transverse emittances to be

$$\begin{aligned} \epsilon_{N,x}^{95\%} &= 5.991\gamma\beta\,\frac{\sigma_{x1}^2 - (\eta_x\sigma_p/p)^2}{\beta_x} = 12.36\ \mu\text{m}, \\ \epsilon_{N,y}^{95\%} &= 5.991\gamma\beta\,\frac{\sigma_{y1}^2}{\beta_y} = 4.01\ \mu\text{m}, \end{aligned}$$

to be compared with the initial emittances of 12 μm and 4 μm respectively. The vertical estimate agrees extremely well with the initial emittance, and the horizontal estimate is only slightly larger (3%) than the initial horizontal emittance. This can be seen also in the phase space plots of the 40th turn on the following page. The green curves are the 95% contours from the lattice functions at A15 with the original emittances and no harps.


Phase space distribution after A15 harp turn 40
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
x' [mrad]
-0.04
-0.02
0
0.02
0.04
x [m]


Phase space distribution after A15 harp turn 40
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
y' [mrad]
-0.04
-0.02
0
0.02
0.04
y [m]