Alberto Ruzzon INFN-LNL-284/2024

Estimation of the beam features at the exit of the Beam Cooler from the experimental measurements

Indice generale

During the Site Acceptance Test of the Beam Cooler (BC) several emittance measurements of the cooled beam were taken: in the present document they are the starting point of simulations evaluating the beam features in the case of different extraction settings (different beam energy and different extraction lens potentials) and what are the possible configurations of the beam line after the Beam Cooler (i.e. varying the SPES triplet position).

The method adopted to determine the new features of the beam at different Beam Cooler settings was to back trace the beam from the diagnostic position to the extraction of the Beam Cooler with Simion, in order to compute its features before the acceleration, and then, with a forward simulation with new settings in the extraction of the Cooler, to compute the new beam features.

In the following sections the computation for the $^{133}Cs^{+}$, $^{39}K^{+}$, $^{7}Li^{+}$ and $^{85}Rb^{+}$ beams are detailed.

1 $^{133}Cs^{+}$ beam

1.1 Experimental Measurements of the emittance for the $^{133}Cs^{+}$ beam

The Beam Cooler for the SPES project was tested injecting the beam produced by an ion source (Kimball igs-4) able to reach the energy of 5 keV and thus the measurements were taken at about this energy. The diagnostic for the emittance estimation (a pepper pot device by Dreebit) was located at 1722.5 mm from the end of the ground electrode of the Beam Cooler and between the two there was a triplet. A scheme reproducing the beam line and the distances between the elements is in figure 1.

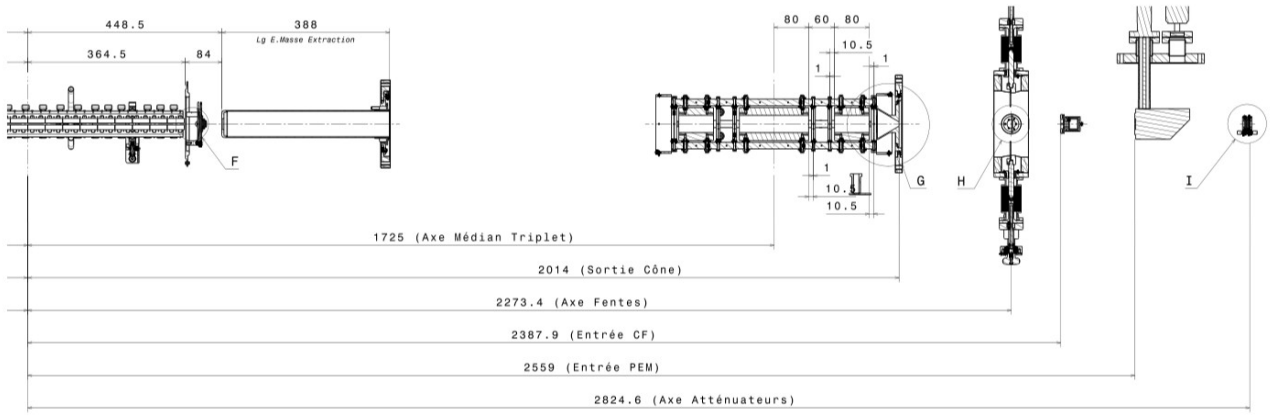


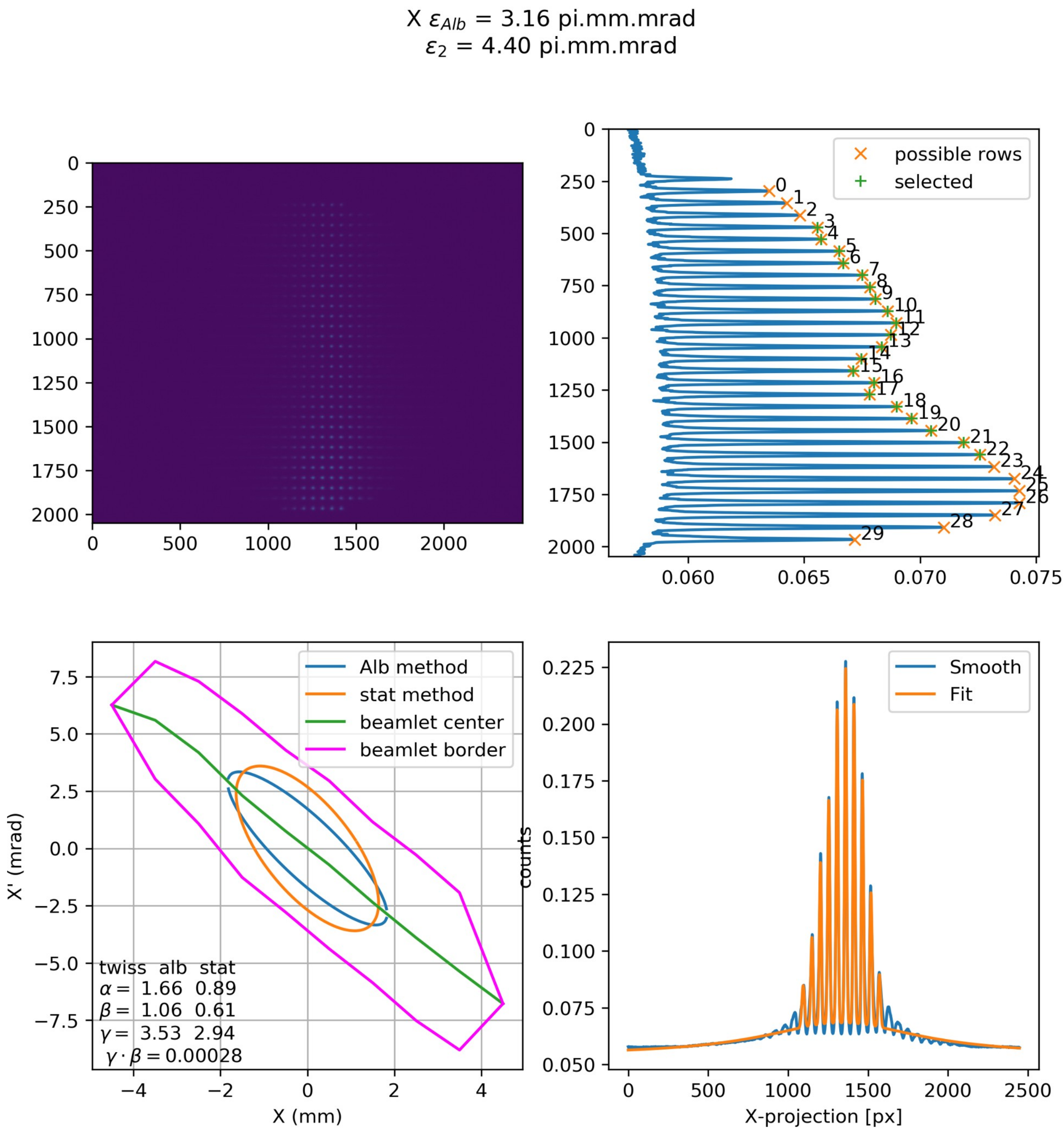
Figure 1: The scheme of the beam line from the Beam Cooler to the diagnostic chamber.

The pepper-pot was too far to take measurements without focusing the beam, but at the same time the triplet was too narrow to focus both the axis at the same time, so just one quadrupole was used instead of all those available in the triplet. In this way the emittance could be measured taking into account one axis at time: the emittance estimation in the vertical axis was obtained exploiting the first quadrupole while in the case of the horizontal axis the second (central) quadrupole was needed.

The operative settings of the Cooler for the Cs beam were:

Platform	4925 V (4927 V the last quadrupole sector)
Extraction Lens	E1 = 4489 V, E2 = 4695 V
Triplet	Q1 = 37 V (for the vertical axis) Q2 = 18 V (for the horizontal axis)

The results of the emittances computation are reported in the pictures below (Figure 2). In the pictures there are the emittances and the Twiss parameters determined using two methods, “Alb” and “Stat”. In the following the “Stat” method is kept as a reference. The “Stat” method refers to the computation procedure developed at the Fermilab and published in 1988.


X ϵ_{Alb} = 3.16 pi.mm.mrad
ϵ_2 = 4.40 pi.mm.mrad
possible rows
selected
Alb method
stat method
beamlet center
beamlet border
twiss alb stat
$\alpha =$ 1.66 0.89
$\beta =$ 1.06 0.61
$\gamma =$ 3.53 2.94
$\gamma \cdot \beta = 0.00028$
X' (mrad)
X (mm)
Smooth
Fit
counts
X-projection [px]

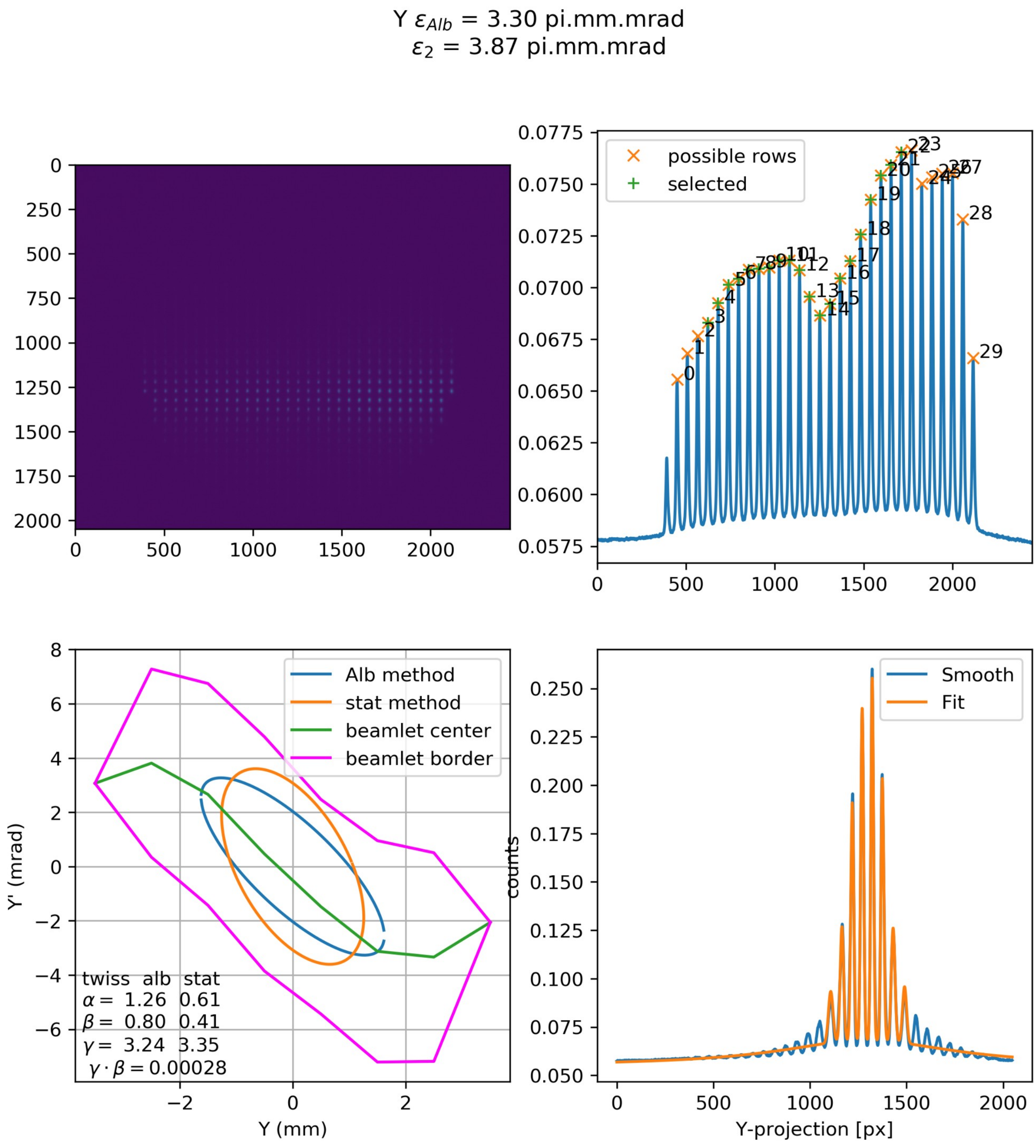


Figure 2: The pictures report the emittances measurements for the two transversal axes (the first picture shows the horizontal axis, indicated as X, the second picture shows the vertical axis, named Y). To obtain the first picture the second quadrupole was used, on the contrary, for the second picture the first quadrupole was used. In each pictures there are "Alb" and "Stat" results, that are the two methods adopted to determine the emittance.

1.2 Back trace method

In order to find the features of the beam at the BC exit a Simion workbench has been created in which there are the electrodes composing the BC extraction and the quadrupoles. The electric field of the former elements is computed directly in Simion (the potential array is realized by Anthony Mendez), vice versa, the quadrupoles are obtained importing external fields computed with a FEM code (ElmerFem).

For the sake of clearness, unless otherwise specified, the axes convention in the present document follows the Simion convention, that is the propagation axis is named X while in the transversal plane the horizontal axis is named Y and the vertical one is named Z.

At this point the beam features in the two transversal axes have to be investigated separately and thus two virtual beams are needed. The first one will have the Y axis emittance defined by the Twiss parameters of the first picture in Figure 2 while a very small emittance will be used in the Z axis. On the contrary, the second beam will have the Z axis emittance given by the Twiss parameters in of the second picture in Figure 2 and a very small emittance on the Y axis. Finally, to trace these two beams backwards, they will have to be mirrored, moving from the pepper pot toward the Beam Cooler.

The quadrupole number 2 has to be used in the simulations involving the first beam, the quadrupole number 1 has to be used in the simulations involving the second beam. The two quadrupoles have to be set to the voltages used during the measurements (18 V for the quadrupole number 2 and 37 V for the quadrupole number 1 for the Cs beam).

Once the two beams are traced backwards, the features obtained on the Y axis from the first beam and on the Z axis from the second beam are merged to describe the beam emerging from the Cooler.

1.3 Back trace results ($^{133}Cs^{+}$)

One of the purposes of this work is to determine the features of the beam produced by the Beam Cooler at different operative conditions, i.e. for different beam energy. For this reason the most suitable position where the beam features could be estimated is at the end of the RF-Quadrupole, before the acceleration takes place. In the Simion workbench the extraction iris extend from x=365 to x=367 mm and thus the beam features are computed at 365.1 mm.

The resulting beam has the following features:

		Y	Z
ε [mm mrad]		232	173
Twiss	α	0.32	0.10
	β	0.0040	0.0033
	γ	277	307
Energy [eV]		3.0	3.2
X position [mm]		365.1	

The low kinetic energy reported in the table certifies that most of the speed has been thrown away and thus such a beam can be used to verify what happens at higher platform voltage or with different extraction lens settings.

1.4 Forward trace ($^{133}Cs^{+}$)

The most critical energy is expected to be 20 kV. With this acceleration potential the results are reported in the table below, the reported data are at the longitudinal position of 850 mm, i.e. after the end of the ground electrode and thus in a region where there are not accelerating or focusing fields. In this case the platform was set to 19.925 kV and the two lens electrodes were 19.489 kV and 19.695 kV (the setting of the previous case was kept).

		Y	Z
ε [mm mrad]		2.67	1.94
Twiss	α	-29.5	-26.1
	β	11.9	10.5
	γ	73.6	64.7
Energy [eV]		19924.9	
γ·β		5.70E-04	
X position [mm]		850	

In the table there is also the relativistic parameter γ·β to normalize the emittance. The emittance plots are in Figure 3.

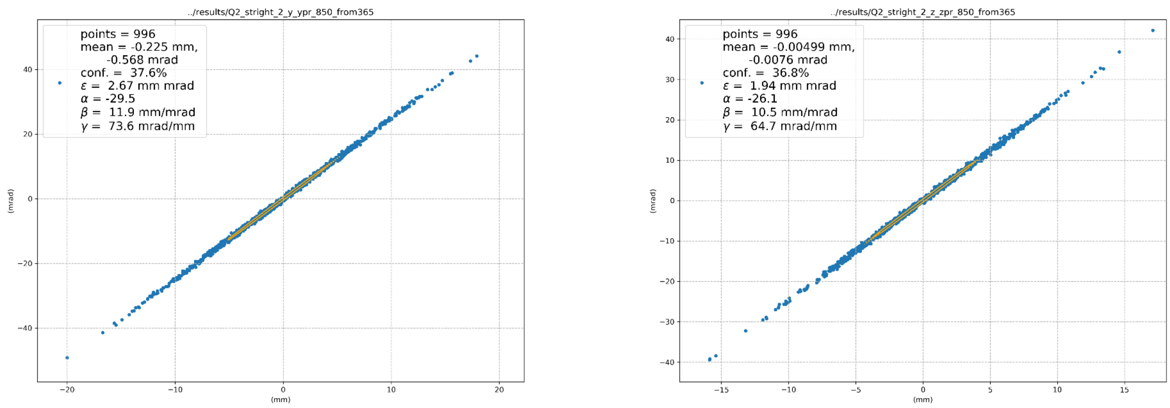


Figure 3: The beam at 850 mm from the Beam Cooler center for a platform voltage of 19.925 kV. The two pictures represent the beam in the trace spaces for the two axes (Y axis in the left and Z axis in the right).

In the picture below (Figure 4) there is a snapshot of the forward simulation.

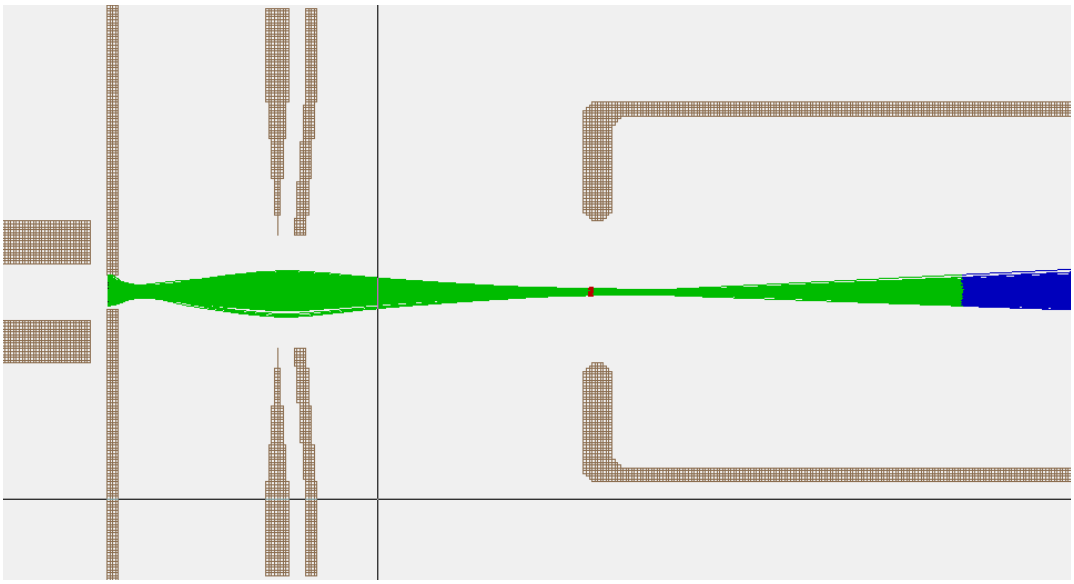


Figure 4: A snapshot of the simulation for the beam generated at 361.5 mm with the platform voltage equals to 19925 V and the extraction lens set equally to the measurements at 4925 V.

1.5 Scan of the extraction settings ($^{133}Cs^{+}$)

Once the extracted beam is built, one can try to find the best settings to extract it. Both the electrodes of the extraction lens can be biased from 0 to 3kV. In the following the most interesting configurations have been simulated.

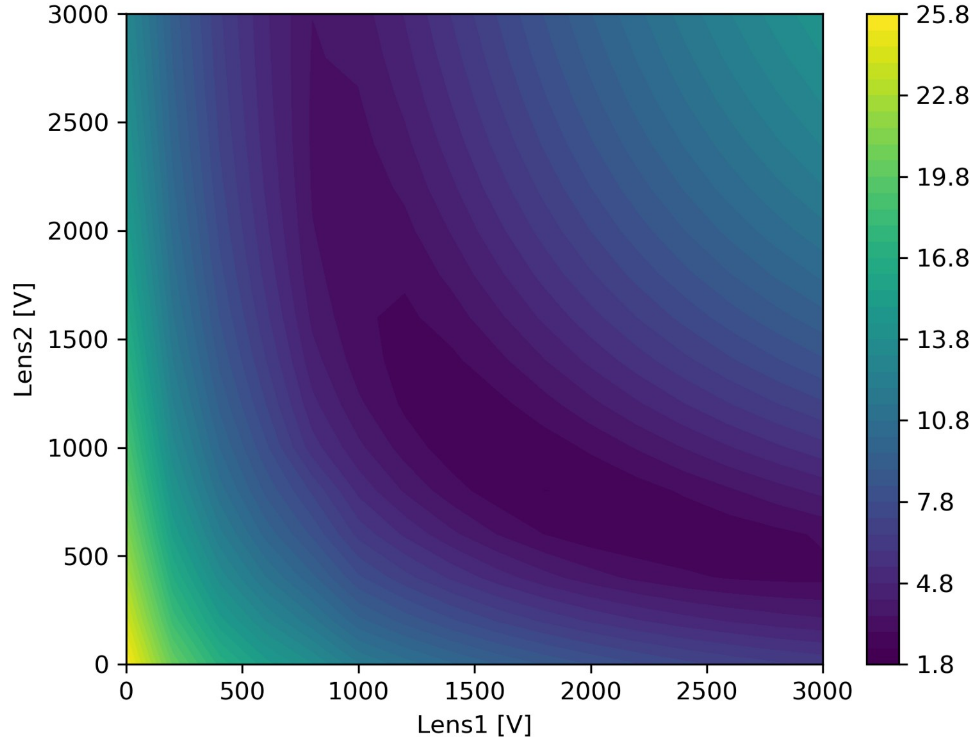


Figure 5: Radius of the Cs beam at 2559mm from the center of the Beam Cooler. The Cooler platform is at 19925 V. The two axes represent the voltages of the extraction lens electrodes.

In the scan, the electrodes of the extraction lens was changed from 0 to 3 kV and the dimension of the beam at 2559 mm from the center of the Beam Cooler is shown in Figure 5. The color in the contour plot represents the beam radius, which is computed as $R=\sqrt{A\cdot a/4}$ where A and a are the two axes of the beam transversal RMS emittance ellipse. The smallest beam diameter is about 3.6 mm and it requires the electrode 1 of the extraction lens at V_1=1.8 kV and the electrode 2 at V_2=0.8 kV. The Twiss parameters in this extraction configuration are reported in the following table.

		Y	Z
ε [mm mrad]		3.4	2
Twiss	α	-0.46	-0.68
	β	0.59	0.78
	γ	2.05	1.9
Energy [keV]		19.916	
γ·β		0.57e-3	
X position [mm]		850	

As reported in the last row of the table, the Twiss parameters are taken at 850 mm, that is before the triplet and outside the ground electrode of the Beam Cooler. The emittance in this place is equal to that at the end of the beam line and thus the triplet, with the experimental setting, does not introduce other non linear effect on the beam.

The same analysis was done also for the 40 keV and its results are reported here below, in

Figure 6.

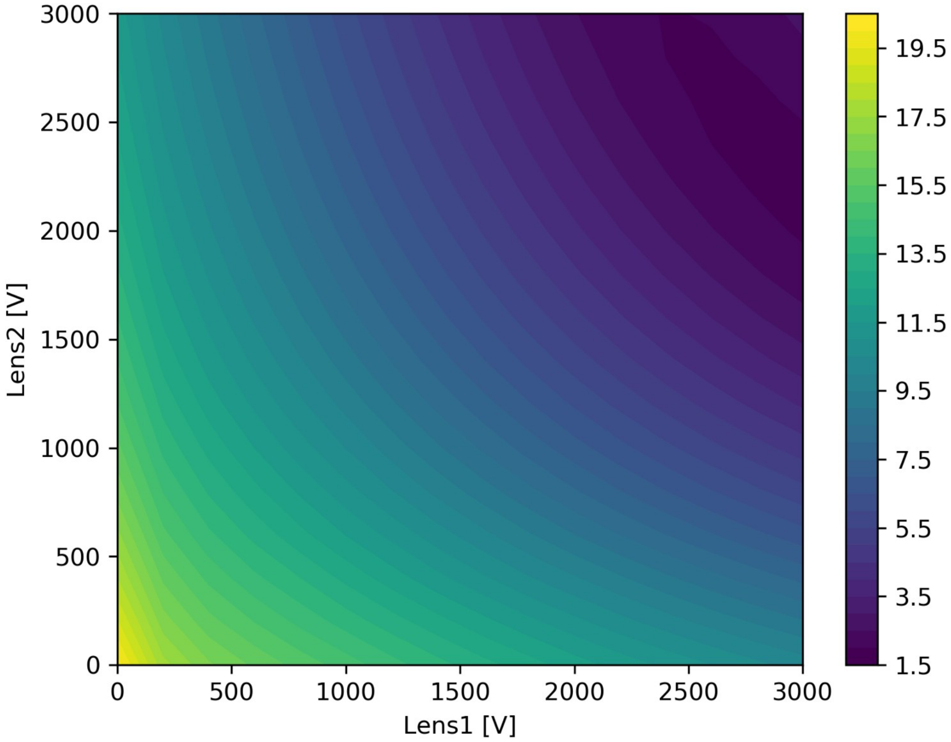


Figure 6: The contour plot representing the beam radius at 2559 mm from the Beam Cooler center as a function of the extraction lens setting. In this case it is a Cs beam accelerated by 39925 V.

In this case the thinnest beam is at V_1=3.0 kV and V_2=2.2 kV which is at the limit of the available configurations and thus, if the extraction lens could extend its settings, it is very likely that a better configuration may be find. Anyway the radius is smaller than the one obtained in the 20 keV case. In the table below are reported the parameters of the beam at 850 mm from the Beam Cooler centre.

		Y	Z
ε [mm mrad]		2.4	1.4
Twiss	α	-0.3	-0.52
	β	0.64	0.84
	γ	1.7	1.5
Energy [keV]		39.908	
γ·β		0.80e-3	
X position [mm]		850	

1.6 Limits of this analysis

This analysis investigates the beam features at the extraction iris of the Beam Cooler exploiting the emittances measurements at the end of an experimental beam line and performing a back trace. But the beam couldn't be perfectly transported: some aberrations are visible in the measurements and the simulations confirm that the extraction complex (iris and lens) generate non-linear effects, this implies that the experimental emittance considered in this analysis is over-estimated. Besides this, non-linear effects are present also in the back trace simulations and thus, once again, the emittance computed at the extraction iris is then over-estimated.

In order to have an idea about how much the emittance is increased due to the aberrations introduced by the extraction lens, one can compare the measured emittance and the one simulated with the same setting. In the plot in Figure 7 there are the results for the simulation of a Cs beam with the same setting used to focus in Y axis (in the Simion standard, which means the experimental horizontal axis named X in Figure 4).

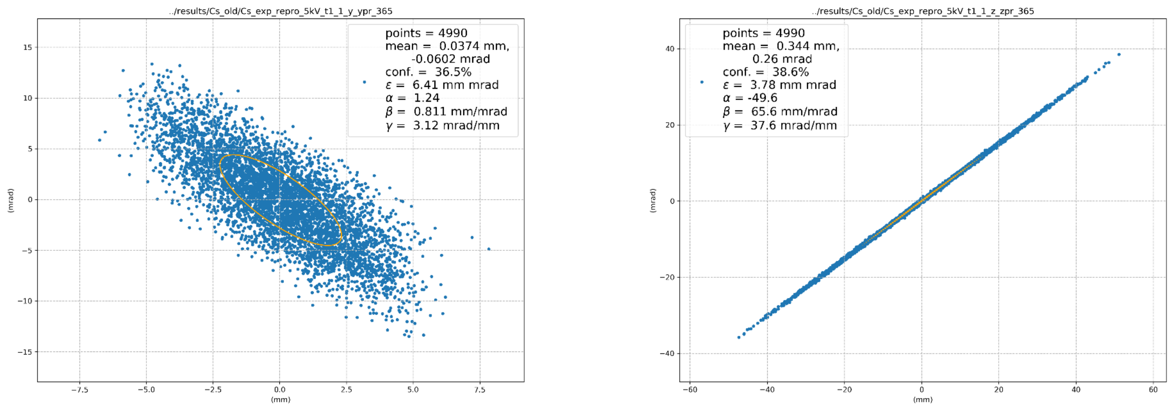


Figure 7: The emittance plots for the two transversal axis in the simulation of a Cs beam with the same extraction setting of the experimental measurements. Y axis in the left panel and Z axis in the right one.

In the Y axis the emittance resulted 6.4 mm·mrad, i.e. 1.45 times the original emittance.

At the same time the extraction electrodes effects could vary depending on the bias applied. Here below, in Figure 9, the contour shows the emittance as a function of the available extraction lens settings for a Cs beam accelerated with 4925 kV. At this energy, if the first electrode is kept below 1.5 kV, the emittance has just a slight dependence on the extraction electrodes bias.

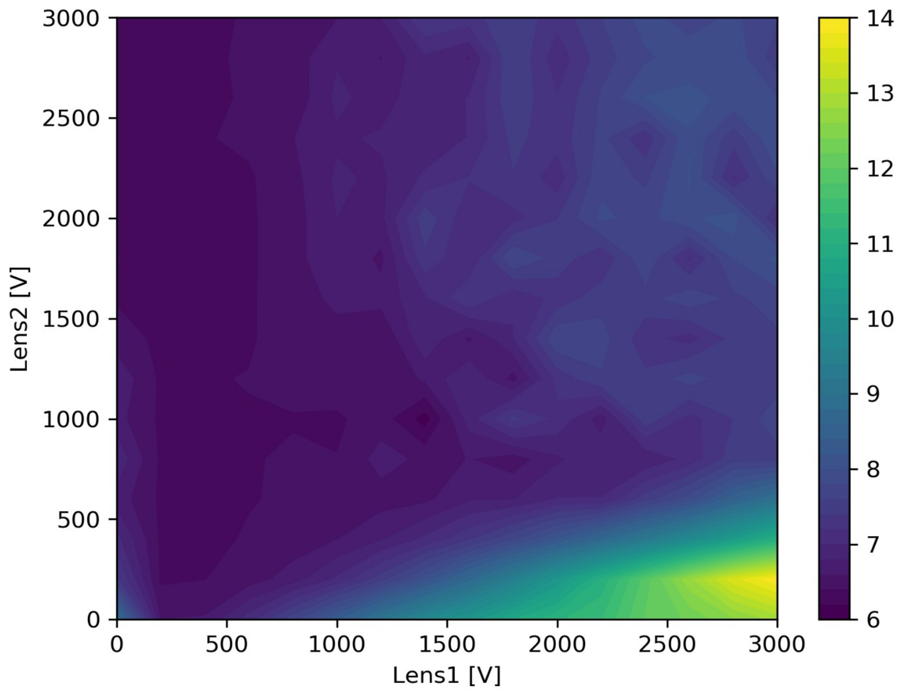


Figure 8: The contour of the emittance in the Y axis at 2559 mm from the Beam Cooler center as a function of the extraction lens setting. The ion is Cs and the accelerating potential is 4925 keV.

As a final remark, the extraction of the Beam Cooler has a cylindrical symmetry and thus the emittances of the two axes should be almost the same, but the two measurements differ. This is mainly due to the different dimension of the beam on the pepper pot when the measurements were taken: a bigger beam section on the pepper pot allows to compute a more precise emittance. In this document the best emittance measurements belong to the Y axis (named X axis in the experimental plots like those in Figure 4). As a consequence the best estimation of the beam features, and thus of the beam dimension, should be the one on the Y axis. This means also that the best beam radius estimation is given by $\sqrt{\beta \cdot \varepsilon}$ in the Y axis instead of the radius given in the contour plot, as the one in Figure 5, which is the average between the two axes.

2 $^{39}K^+$ beam

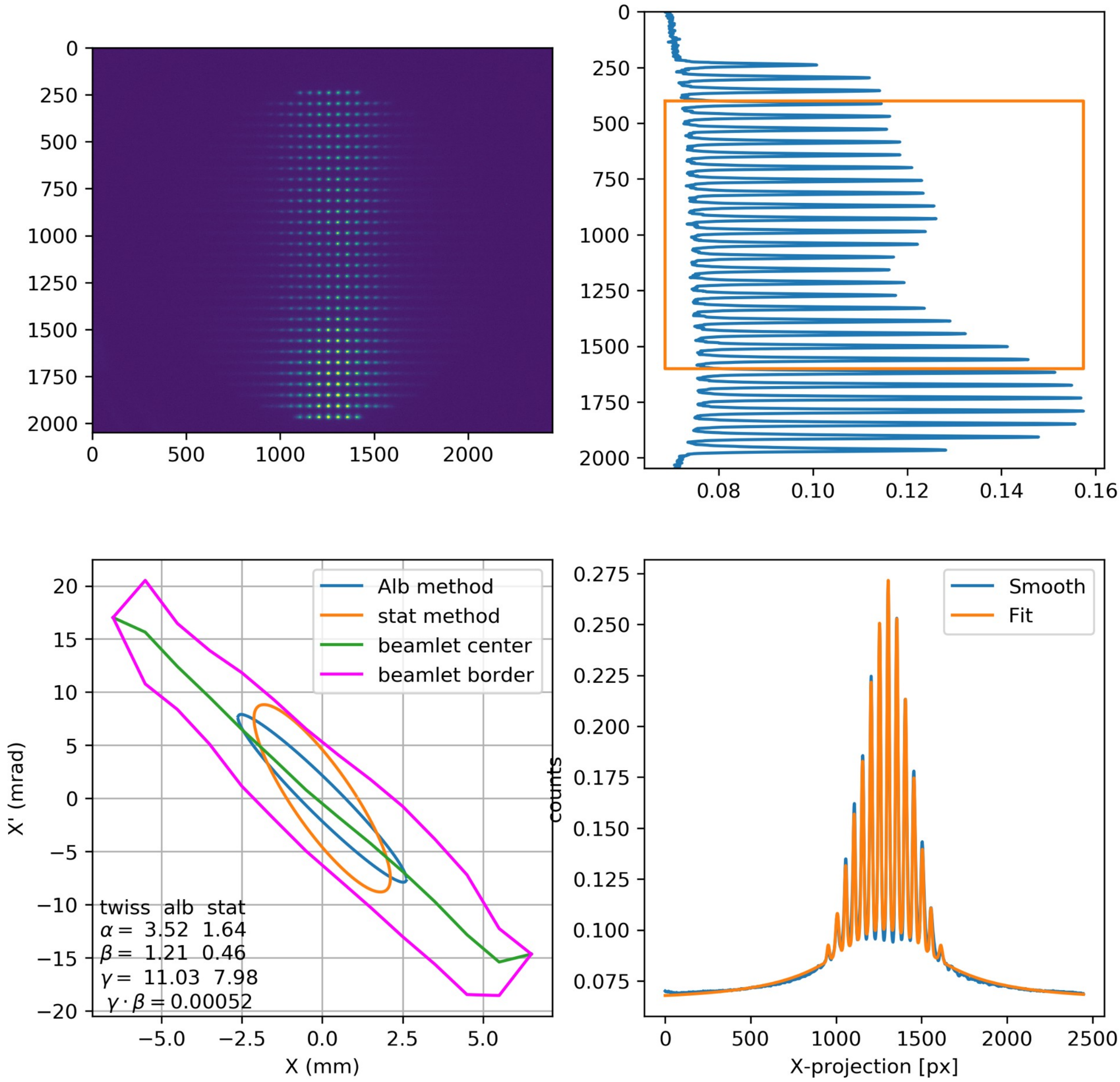
2.1 Experimental measurements of the emittance for the $^{39}K^+$ beam

In Figure 9 there are the plots and the computation results of the experimental pepper-pot pictures, one for each axis. The parameters of the beam line to have these measures are in the following table.

Platform	4905 V (4905 V the last quadrupole sector)
Extraction Lens	E1 = 4505 V, E2 = 4455 V
Triplet	Q1 = 37 V (for the vertical axis) Q2 = 19 V (for the horizontal axis)

Considering the energy of the beam equal to 4.905 keV, the $\gamma \cdot \beta$ parameter is 0.52e-3.

X ε_{Alb} = 5.66 pi.mm.mrad
ε_2 = 9.74 pi.mm.mrad



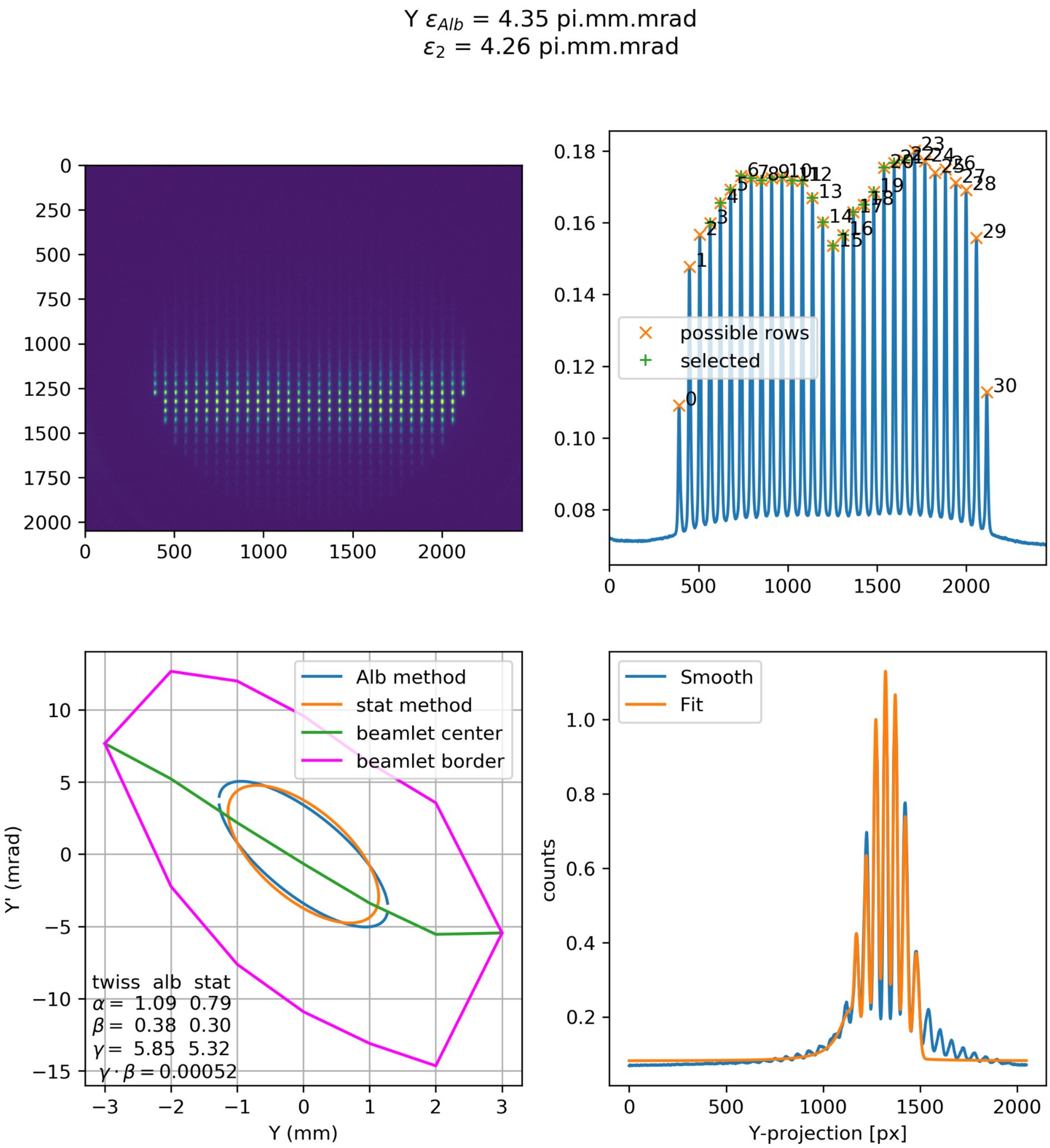


Figure 9: Emittance measurements for a K beam in the two transversal axes. In the first case (X or horizontal axis in the laboratory, Y axis in the Simion workbench) the second quadrupole is turned on at 19 V while, in the second case (Y or vertical axis in the laboratory, Z axis in Simion) the first quadrupole is operating at 37 V.

2.2 Back trace results ($^{39}K^+$)

The back trace allows to find the beam features at the extraction iris of the Beam Cooler, as done for the Cs beam, the beam features are computed at 365.1 mm.

The resulting beam has the following features:

		Y	Z
ε [mm mrad]		665	192
Twiss	α	0.42	0.31

	β	0.0024	0.0024
	γ	498	417
Energy [eV]		2.7	3.2
X position [mm]		365.1	

2.3 Forward trace ($^{39}K^{+}$)

As already done for the Cs beam, it is possible to accelerate the estimated beam at different energies and with several extraction settings in order to see what are the expected performances.

The contour plot in Figure 10 shows the beam radius at 2559 mm from the Beam Cooler middle point for the available voltages of the extraction lens electrodes. The platform voltage is 19905 V.

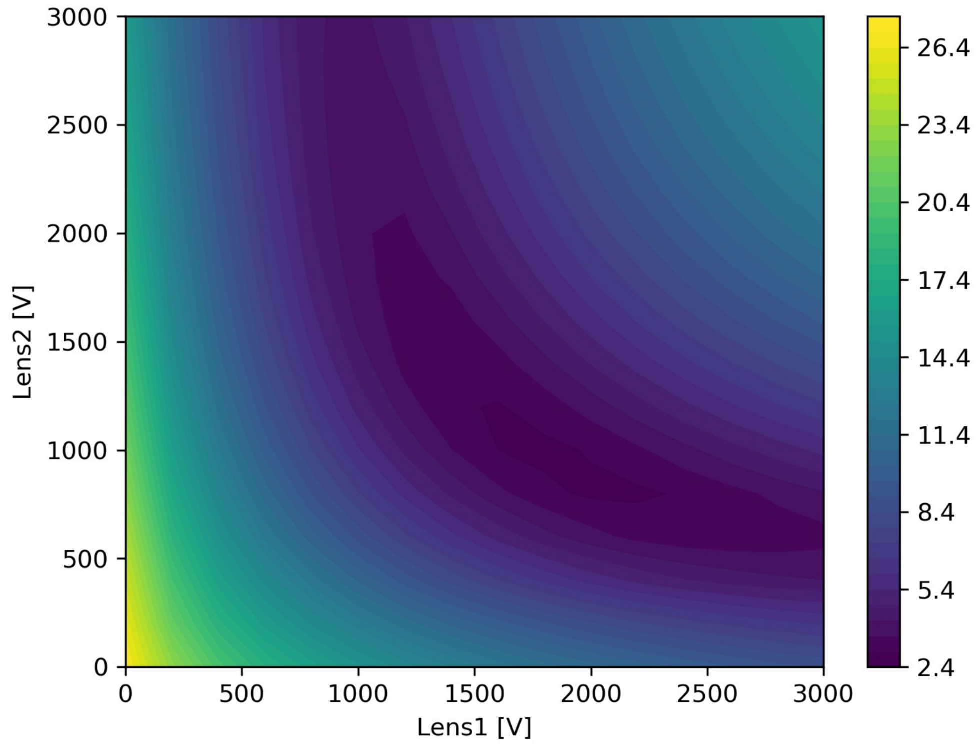


Figure 10: The beam radius at 2559 mm from the center of the Beam Cooler when the platform is ar 19905 V for a K beam. The two axes reports the voltages of the extraction electrodes.

The best region in the configuration space of the extraction lens settings is with electrode 1 set to 1800 V and electrode 2 to 1000 V. In this last configuration the Twiss parameters at 850 mm from the Beam Cooler center are:

		Y	Z
ε [mm mrad]		6.1	2.1
Twiss	α	-0.6	-0.81
	β	0.68	0.94
	γ	2	1.76
Energy [eV]		19897	
γ·β		1.05e-3	
X position [mm]		850	

Figure 12 shows the beam trace space in the Z axis at 850 mm from the center of the Cooler. Some aberration is visible: since there are not focusing elements after the extraction, this is exclusively due to the design of the Cooler extraction electrodes.

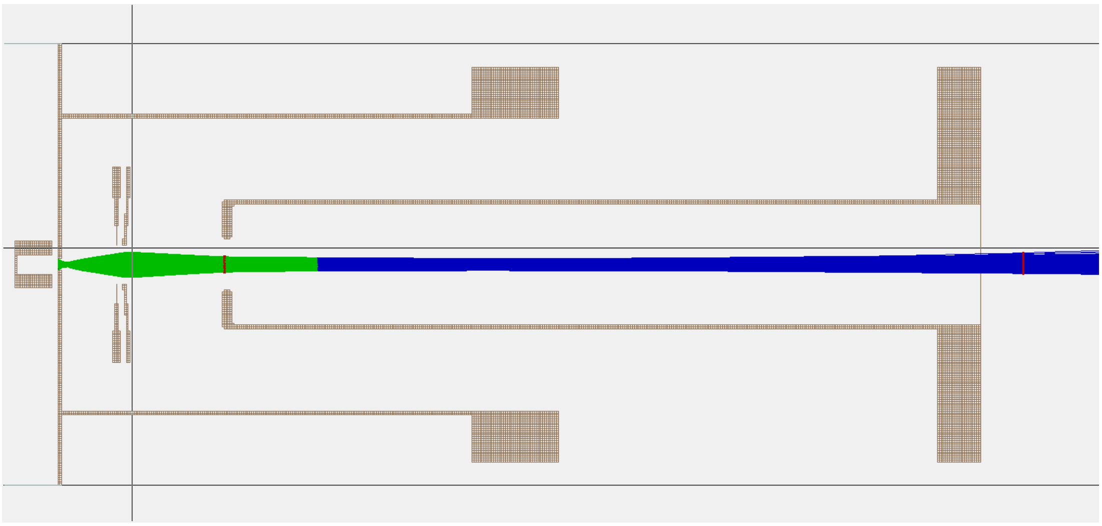


Figure 11: A snapshot of Simion during a simulation with the platform voltage 19.905kV.

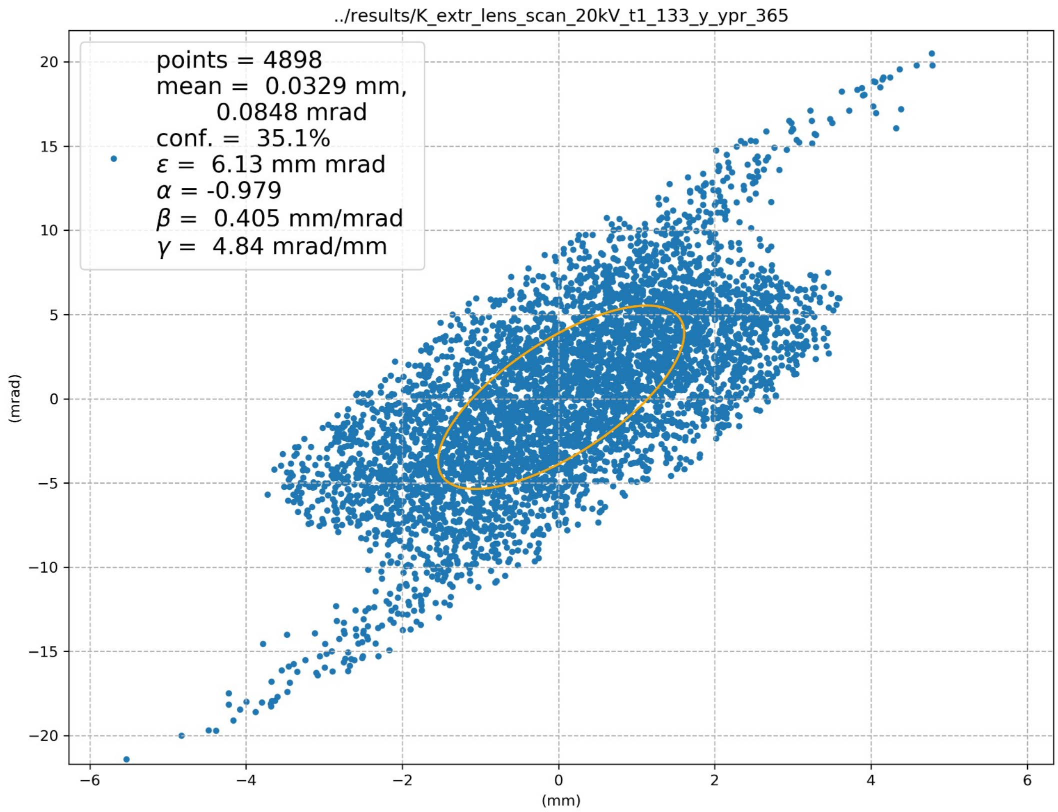


Figure 12: Emittance picture in the Y axis for the beam at 850 mm from the Cooler center.

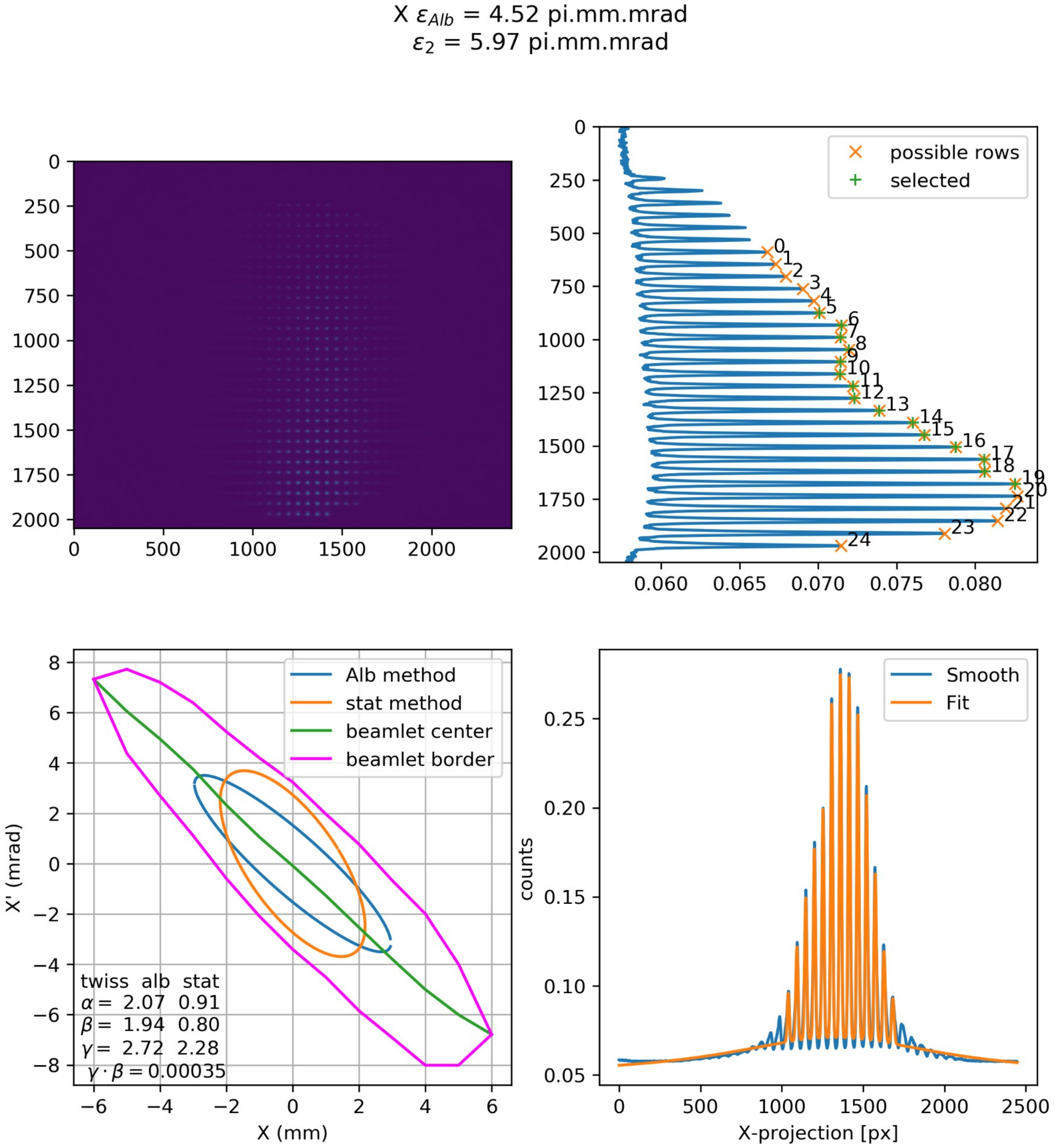
3 $^{85}Rb^{+}$ beam

3.1 Experimental measurements of the emittance for the $^{85}Rb^{+}$ beam

The parameters of the beam line to have the emittance measures are in the following table.

Platform	4910 V (4910 V the last quadrupole sector)
Extraction Lens	E1 = 4310 V, E2 = 4810 V
Triplet	Q1 = 35 V (for the vertical axis)
	Q2 = 20 V (for the horizontal axis)

Considering the energy of the beam equal to 4.91 keV, the γ·β parameter is 0.35e-3.



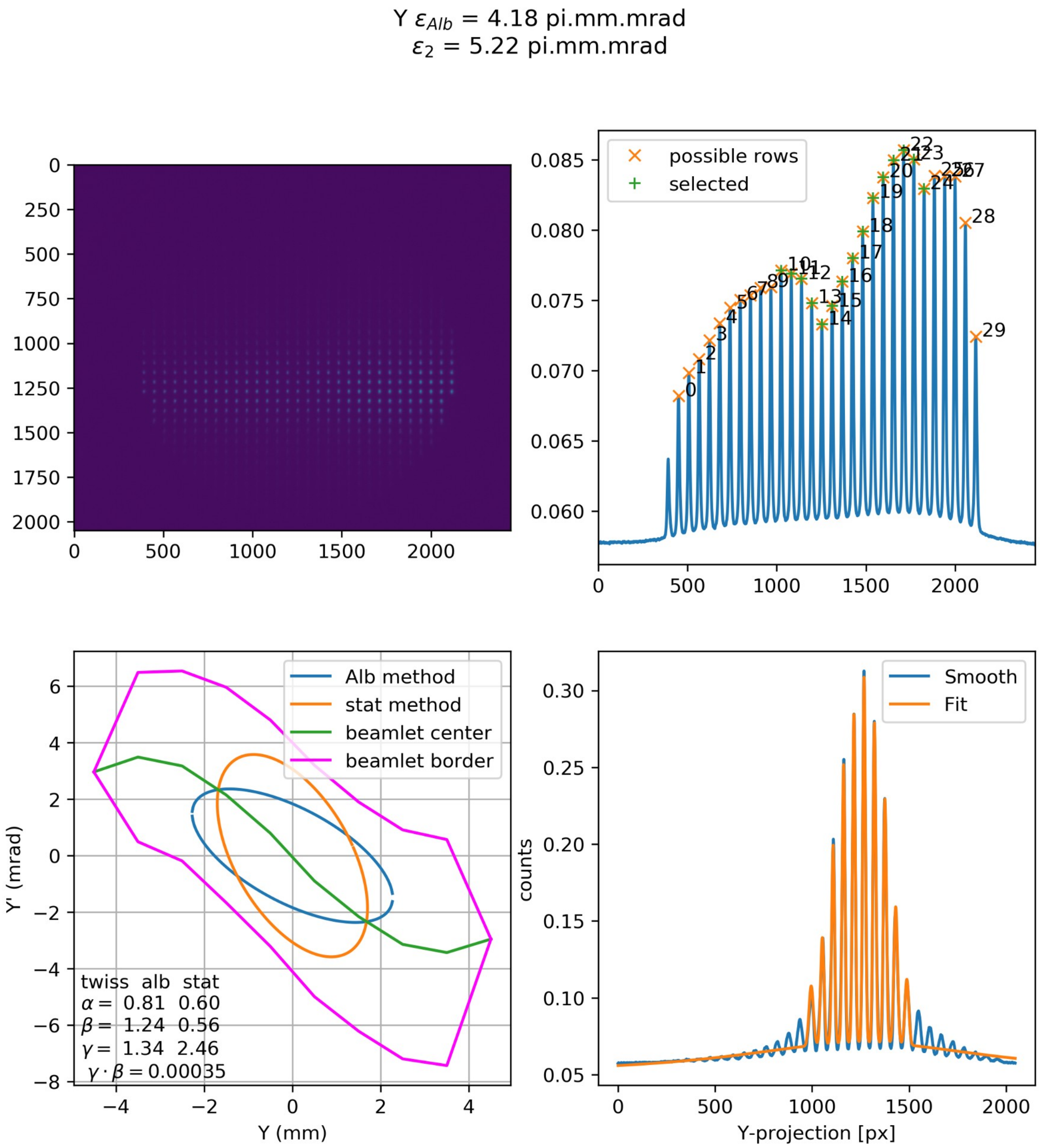


Figure 13: Emittance measurements taken with the pepper-pot diagnostic for the Rb beam. The first picture is for the X axis, the second one refers to the Y axis

3.2 Back trace results ($^{85}Rb^{+}$)

The back trace allows to find the beam features at the extraction iris of the Beam Cooler, as done for the Cs beam, the beam features are computed at 365.1 mm.

The resulting beam has the following features:

		Y	Z
ε [mm mrad]		317	359
Twiss	α	0.33	-0.11
	β	0.0029	0.0021
	γ	383	468
Energy [eV]		4.1	4.2
X position [mm]		365.1	

3.3 Forward trace ($^{85}Rb^{+}$)

As already done for the Cs beam, it is possible to accelerate the estimated beam at different energies and with several extraction settings in order to see what are the expected performances.

The contour plot in Figure 14 shows the beam radius of the beam at 2559 mm from the Beam Cooler middle point as a function of the extraction lens electrodes setting. The platform voltage is 19910 V.

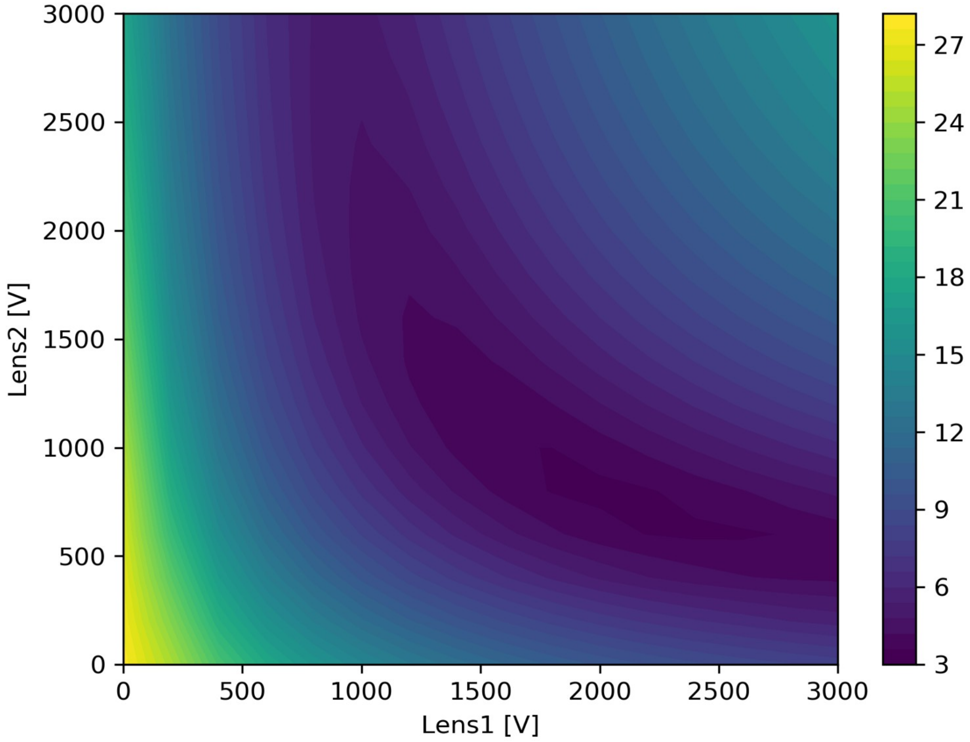


Figure 14: The beam radius at 2559 mm from the center of the Beam Cooler when the platform is ar 19910 V for a Rb beam. The two axes reports the voltages of the extraction electrodes.

The best region in the configuration space of the extraction lens is with electrode 1 set to 2000 V and electrode 2 to 800 V, the beam radius is 3 mm. In this last configuration the Twiss parameters at 850 mm from the center of the Cooler are:

		Y	Z
ε [mm mrad]		4.3	4.4
Twiss	α	-0.64	-1.2
	β	0.7	0.95
	γ	2	2.5
Energy [eV]		19901	
γ·β		0.71e-3	
X position [mm]		850	

In Figure 15 there is the emittance plot of the beam at the best extraction setting.

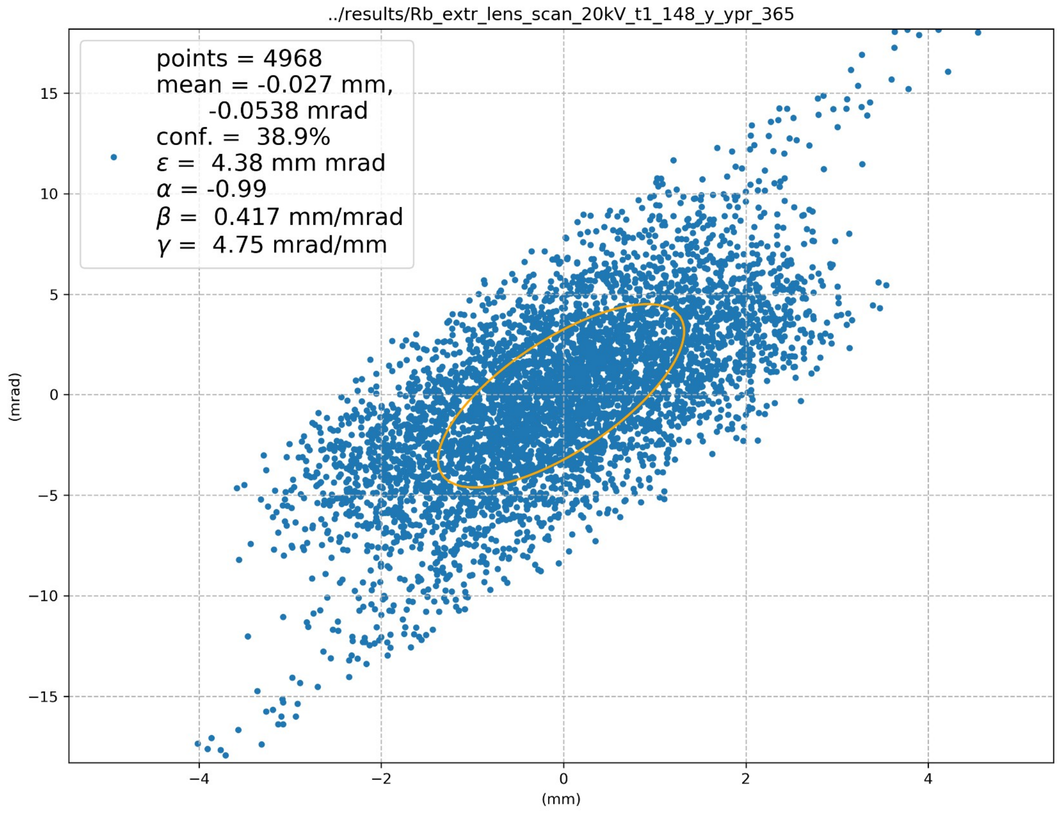


Figure 15: The emittance plot of the Z axis for the beam at 850 mm with the extraction lens set to (1800 V, 600 V) and the platform to 19910 V.

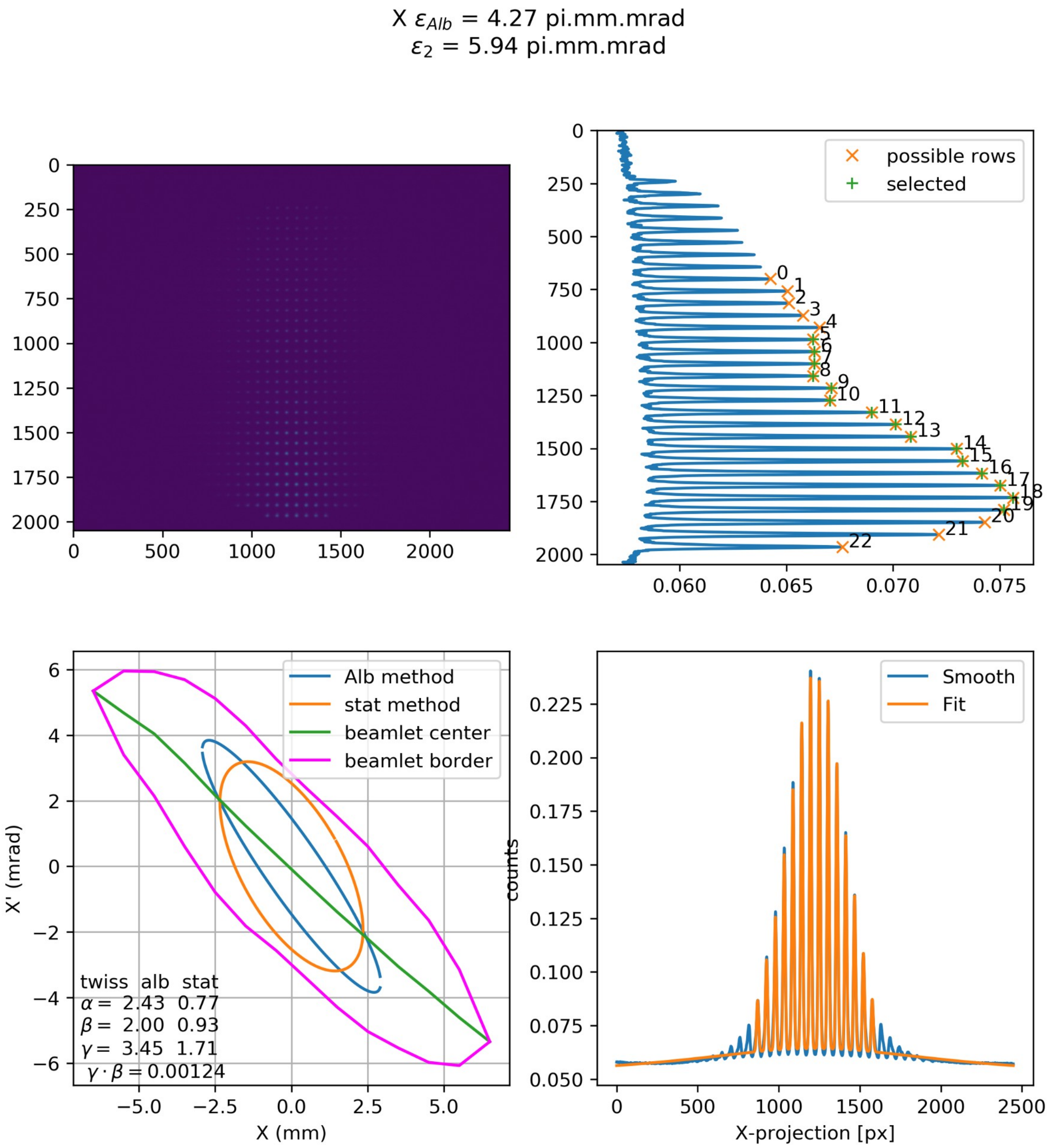
4 $^{7}Li^{+}$ beam

4.1 Experimental measurements of the emittance for the $^{7}Li^{+}$ beam

The parameters of the beam line to have the emittance measures are in the following table.

Platform	4970 V (4970 V the last quadrupole sector)
Extraction Lens	E1 = 4270 V, E2 = 4870 V
Triplet	Q1 = 35 V (for the vertical axis) Q2 = 15 V (for the horizontal axis)

Considering the energy of the beam equal to 4.97 keV, the γ·β parameter is 1.2e-3.



X ϵ_{Alb} = 4.27 pi.mm.mrad
ϵ_2 = 5.94 pi.mm.mrad
possible rows
selected
Alb method
stat method
beamlet center
beamlet border
twiss alb stat
α = 2.43 0.77
β = 2.00 0.93
γ = 3.45 1.71
$\gamma \cdot \beta$ = 0.00124
X (mm)
X' (mrad)
Smooth
Fit
counts
X-projection [px]

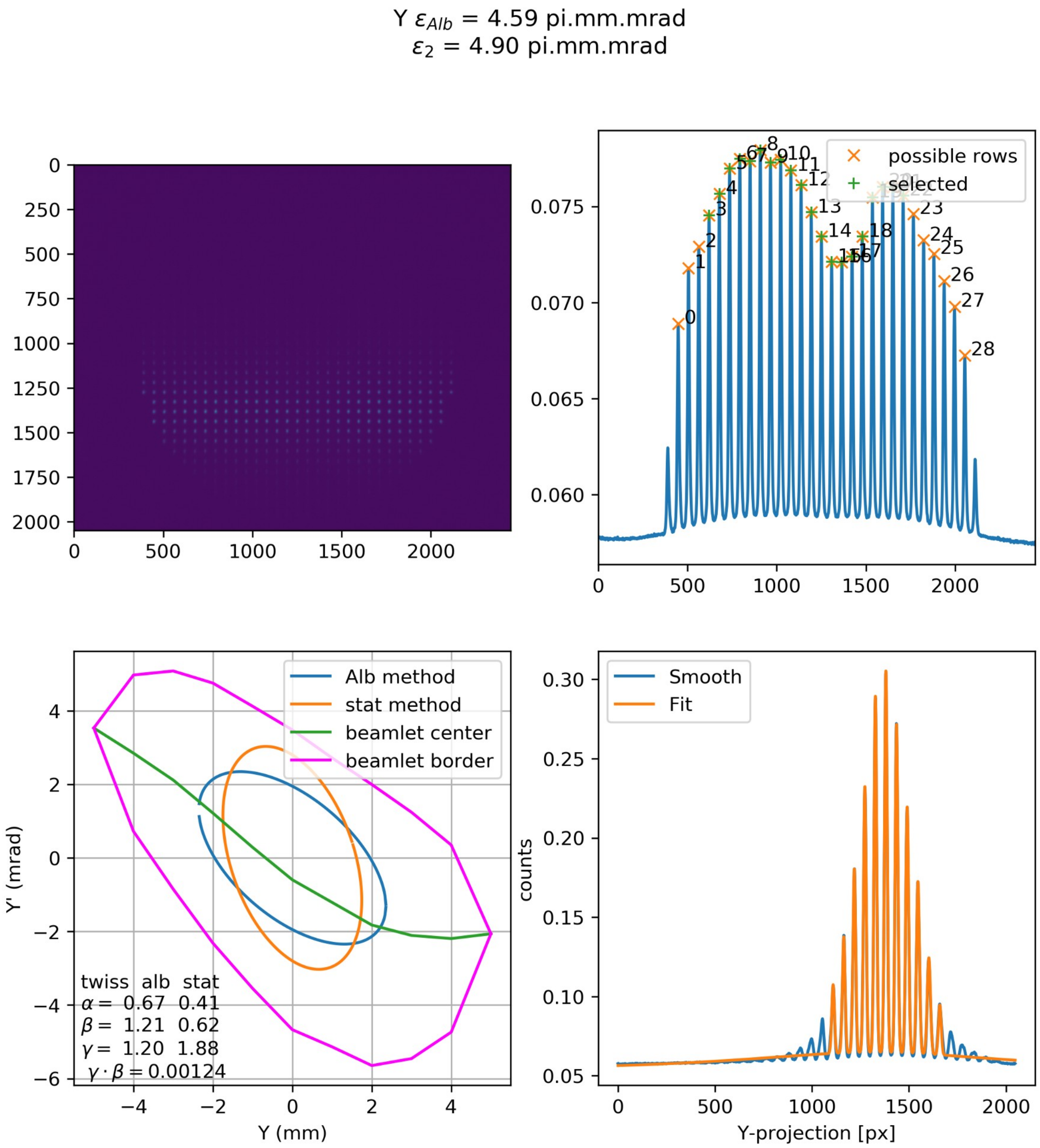


Figure 16: Emittance measurements taken with the pepper-pot diagnostic for the Li beam. The first picture is for the X axis, the second one refers to the Y axis

4.2 Back trace results ($^{7}Li^{+}$)

The back trace allows to find the beam features at the extraction iris of the Beam Cooler, as done for the Cs beam, the beam features are computed at 365.1 mm.

The resulting beam has the following features:

		Y	Z
ε [mm mrad]		317	359
Twiss	α	0.33	-0.11
	β	0.0029	0.0021
	γ	383	468
Energy [eV]		4.1	4.2
X position [mm]		365.1	

4.3 Forward trace ($^{7}Li^{+}$)

As already done for the Cs beam, it is possible to accelerate the estimated beam at different energies and with several extraction settings in order to see what are the expected performances.

The contour plot in Figure 17 shows the beam radius of the beam at 2559 mm from the Beam Cooler middle point as a function of the extraction lens electrodes setting. The platform voltage is 19970 V.

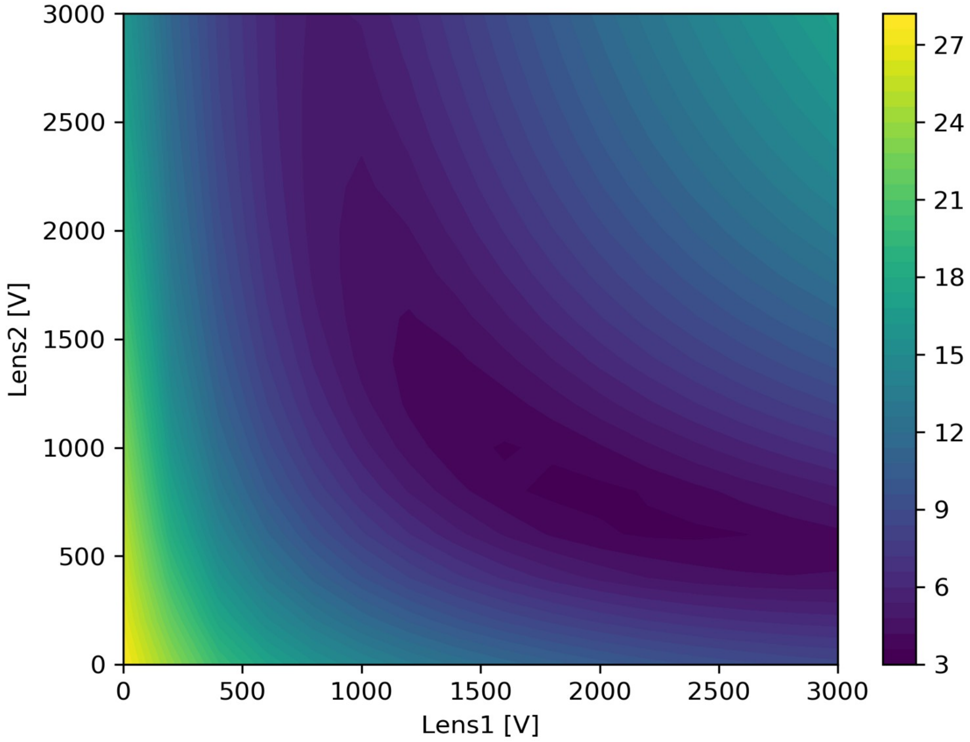


Figure 17: The beam radius at 2559 mm from the center of the Beam Cooler when the platform is ar 19970 V for a Li beam. The two axes reports the voltages of the extraction electrodes.

The best region in the configuration space of the extraction lens is with electrode 1 set to 1800 V and electrode 2 to 800 V, the beam radius is 3 mm. In this last configuration the Twiss parameters at 850 mm from the center of the Cooler are:

		Y	Z
ε [mm mrad]		4.8	4.1
Twiss	α	-0.79	-0.77
	β	0.69	0.7
	γ	2.4	2.3
Energy [eV]		19963	
γ·β		2.5e-3	
X position [mm]		850	

In Figure 18 there is the emittance plot of the beam at the best extraction setting.

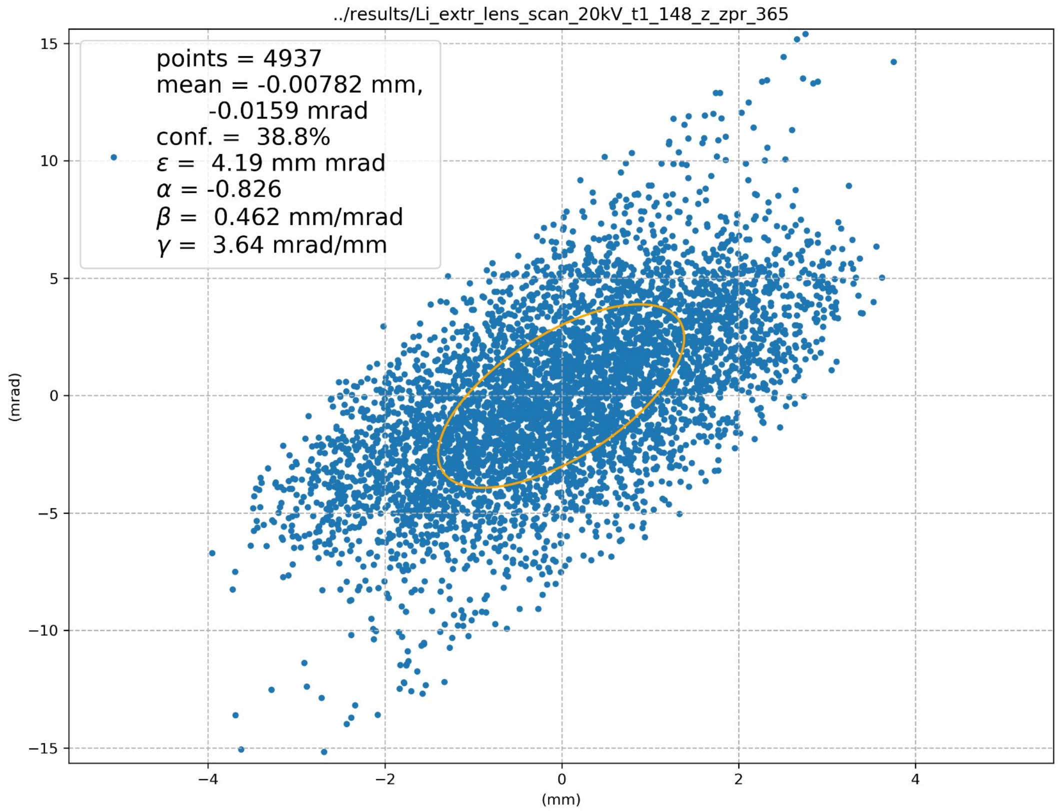


Figure 18: The emittance plot of the Z axis for the beam at 850 mm with the extraction lens set to (1800 V, 600 V) and the platform to 19970 V.

5 Resume of the results

The following table reports the settings and the beam features obtained so far with the simulation explained above.

	E [keV]	L1 [kV]	L2 [kV]	ε [mm·mrad]	α	β	γ	r [mm]
$^{133}Cs^{+}$	20	1.8	0.8	3.4	-0.46	0.59	2.05	1.8
$^{133}Cs^{+}$	40	3	2.2	2.4	-0.3	0.64	1.7	1.5
$^{85}Rb^{+}$	20	2	0.8	4.3	-0.64	0.47	2	3
$^{39}K^{+}$	20	1.8	1	6.1	-0.6	0.68	2	2.4
$^{7}Li^{+}$	20	1.8	0.8	4.8	-0.79	0.69	2.4	3

In the table the emittance is referred to the Y axis (Simion standard, which means the horizontal axis) since it is the axis with the best experimental emittance measurements. Emittances and Twiss parameters are taken at 850 mm from the Beam Cooler centre, while the radius are taken at 2559 mm. Finally the energy column reports the energy of the beam before the cooling: after the Cooler, the beam will have got the energy given by the potential of the platform.

It is worth to say that, as explained in paragraph 1.6, the emittance estimations obtained here are over estimated for the focusing given by the extraction lens which introduces non linear effects.