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Slow Resonant Extraction at the LHC

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Summary

This Summer Student project presents the study on the possibility to perform slow extraction from the Large Hadron Collider (LHC) for future Fixed Target (FT) experiments. Slow extraction is a technique used to deliver a continuous flux of particles at a desired location. To do so, a technique which is called third integer resonance is used to drive particles into instability and extract them using appropriate methods. The main challenge of this project is to design a resonant slow extraction system from a super conductive machine, like the LHC, which has a tight aperture delimited by its collimation system. Slow extraction at TeV-scale is a novel topic and this summer student project aim at open the path to this possibility.

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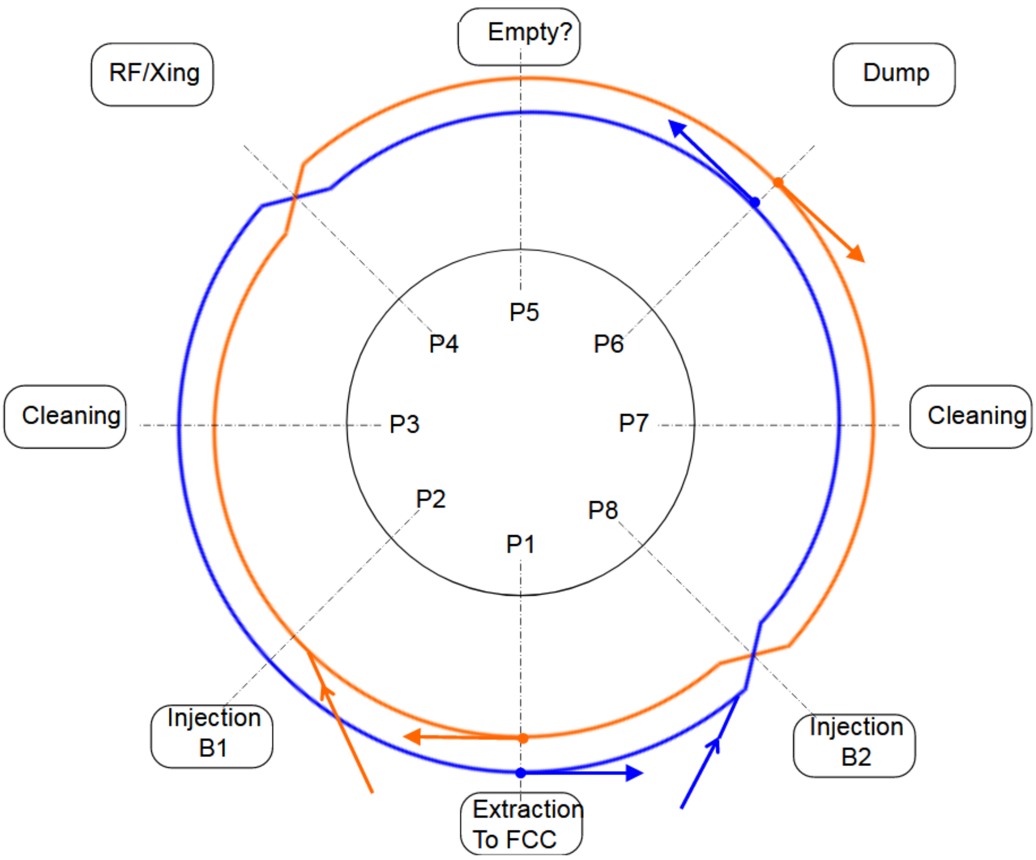
1 Introduction

Slow extraction [1] is a procedure by which particles are extracted from accelerators at a rate which gives a continuous flux of particles. This methodology is used to deliver particles to FT stations which require a continuous supply of beam.

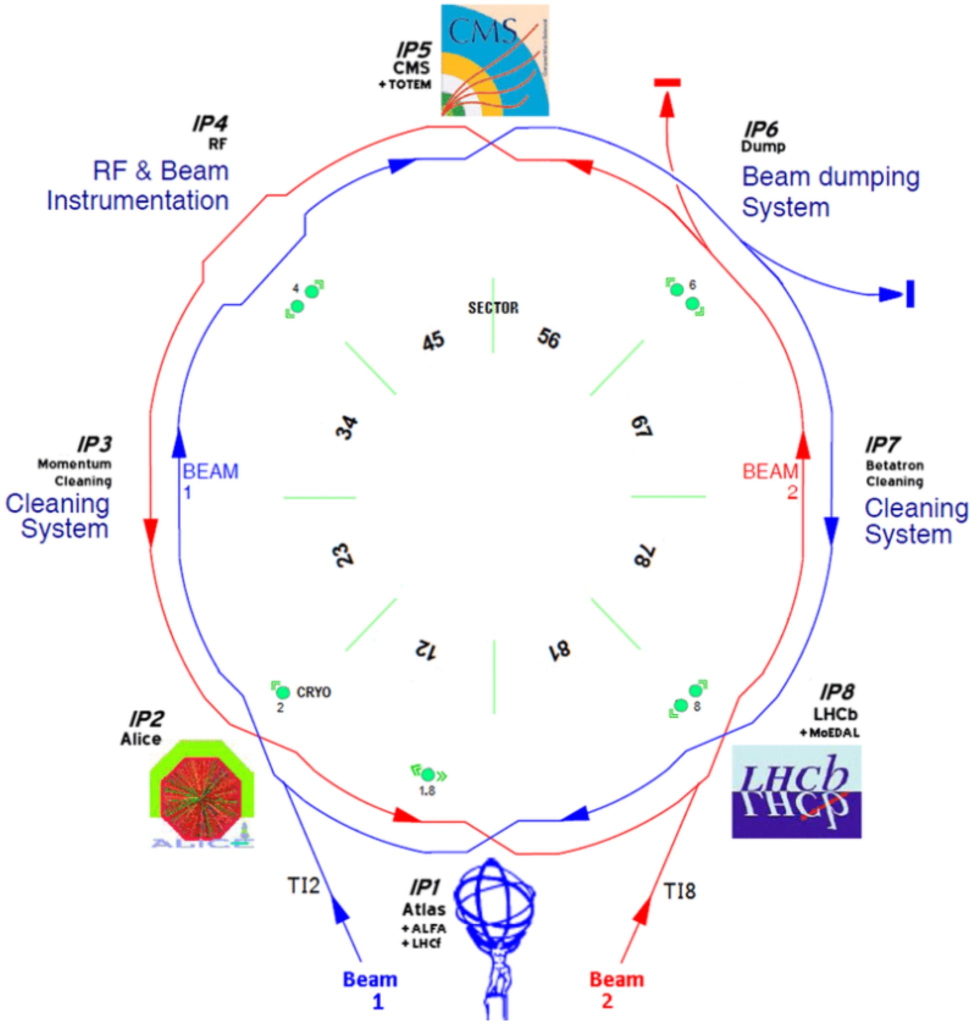
In the context of the studies for possible scenarios of operations for the Future Circular Collider (FCC) injectors, one proposal is to use the LHC to provide a beam for FT experiments while waiting to re-fill the FCC. The main challenge here is the tight aperture of the LHC collimation system and the super conductive nature of its magnets, since resonant slow extraction needs circulating particles at large amplitudes.

Current FT experiments use beams from the Super Proton Synchrotron (SPS) which delivers protons at an energy of 400 GeV and muons at around 200 GeV. The LHC offers the possibility of reaching energies at the TeV and this is seen with large interest from the experiments community. This would give the possibility to perform experiments out of reach today.

One proposal for possible FCC injectors foresees a High Energy Booster (HEB), i.e. a re-arrangement of today's LHC:

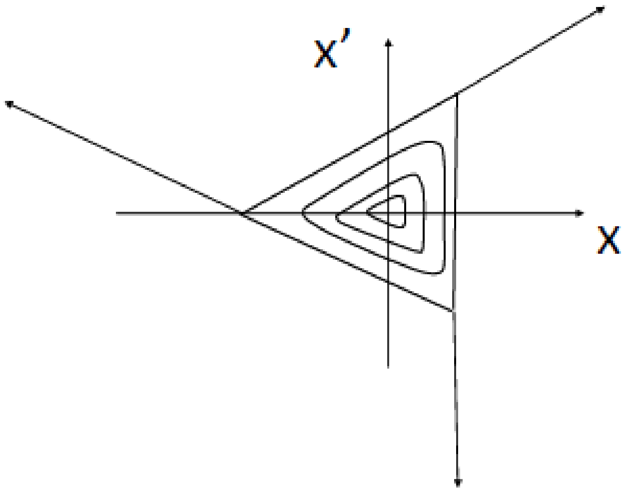


In the context of this project, the layout used is the one of the present LHC. The FT experiment is imagined to be installable in IP6:



Important concepts that play a key role in understanding the content of this project are explained next. The first concept is the **horizontal tune** [2] of the machine. In this project, a circular accelerator as the LHC is used. An ideal particle is the one that has zero horizontal momentum offset, zero vertical momentum offset and zero transverse momentum offset. The trajectory that this particle describes along the machine is called the design orbit. There are many elements in the LHC, but the main ones are dipoles and quadrupoles. This two are respectively responsible for bending particle trajectories and focusing the beam along the machine. Overall focusing can be reached with proper combination of focusing and defocusing quadrupole. The number of oscillations around the ideal orbit per turn is referred to as the horizontal tune of the machine Q_1.

The concepts mentioned above play a role of major importance in slow extraction [3]. In synchrotrons, slow extraction can be achieved exploiting **third-integer resonance**. Particles are driven unstable increasing the overall sextupolar field in the ring and then approaching the third-integer part of the tune. Doing so, particles that manage to have tunes close enough to the resonance and with amplitudes sufficiently large to fall outside the stable region (region in phase space delimited by the so-called separatricies) will grow in amplitude for finally be extracted. A classical representation of the phase space as perturbed by sextupoles and being sufficiently close to the resonant tune is shown in the following figure.



The previous plot shows the ideal case, on which the triangular shape is perfect and the separatrices are not bent. The area of stability decreases as the tune draws nearer to the one-third integer.

Separatrices are very important in slow extraction, particles in the unstable area move from one branch or separatrix to the other, turn after turn. That means that a particle on a certain branch will be on the same branch three turns later.

Now that the concepts are explained, is time to apply it to the problem at hand: studying the possibility to perform slow extraction at the LHC. Suppose there is a point in our accelerator which is where the particle extraction is done. This spot will have a certain aperture size. So, if a phase-space diagram like the one above is produced at the extraction point, particles will have an increasing amplitude on the horizontal direction, and eventually exceed the aperture. When the amplitude gain is large enough to jump to the other side of the septum blade, the particle is extracted. In the case that a particle has a horizontal position infinitely close to the aperture, but on the side of the circulating beam, the amplitude increase in three turns is referred to as **spiral step**.

2 Simulations and data

In this section the procedure, data and results of the simulations are presented in chronological order. **MADX** [5] has been used to run simulations and python (SWAN Notebook Service from CERN) has been used for the analysis.

To have a better understanding of what happens in phase space, a first simulation with a thousand particles, Gaussianly distributed on x and x' with a Gaussian momentum distribution PT with $\sigma = 1.0 \cdot 10^{-4}$ is performed. Normalised coordinates are also used in the course of this report. For linear motion, this transformation changes the shape of the trajectory followed by particles in phase space from ellipses to circles. The relationship between the new set of coordinates $(\bar{x}, \bar{x'})$ and the regular ones (x, x') is given by these algebraic expressions:

$$\bar{x} = \frac{x(s)}{\sqrt{\beta_x}(s)}, \bar{x'} = \frac{\alpha_x(s)x(s) + \beta_x(s)x'(s)}{\sqrt{\beta_x}(s)}$$

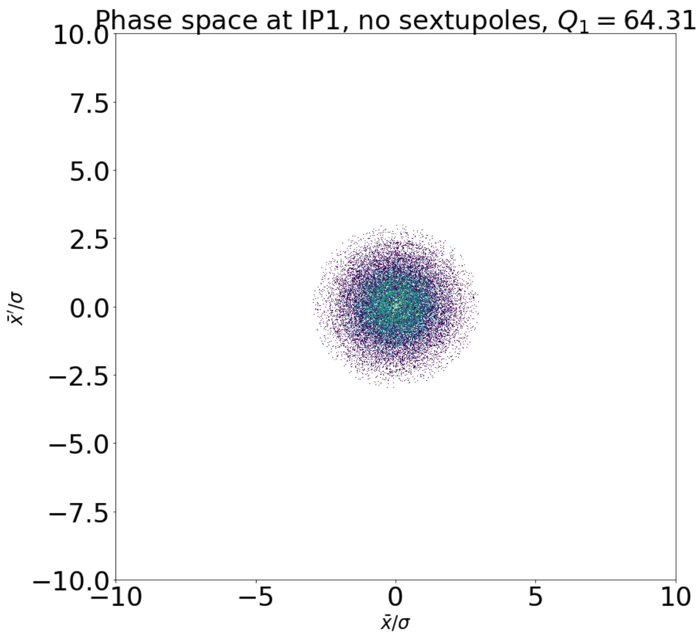
where α_x, β_x and γ_x are the optics functions, and ϵ_x is the geometrical emittance.

Substituting the new coordinates in the ellipse equation for the original coordinates, the equation of a circle is now obtained:

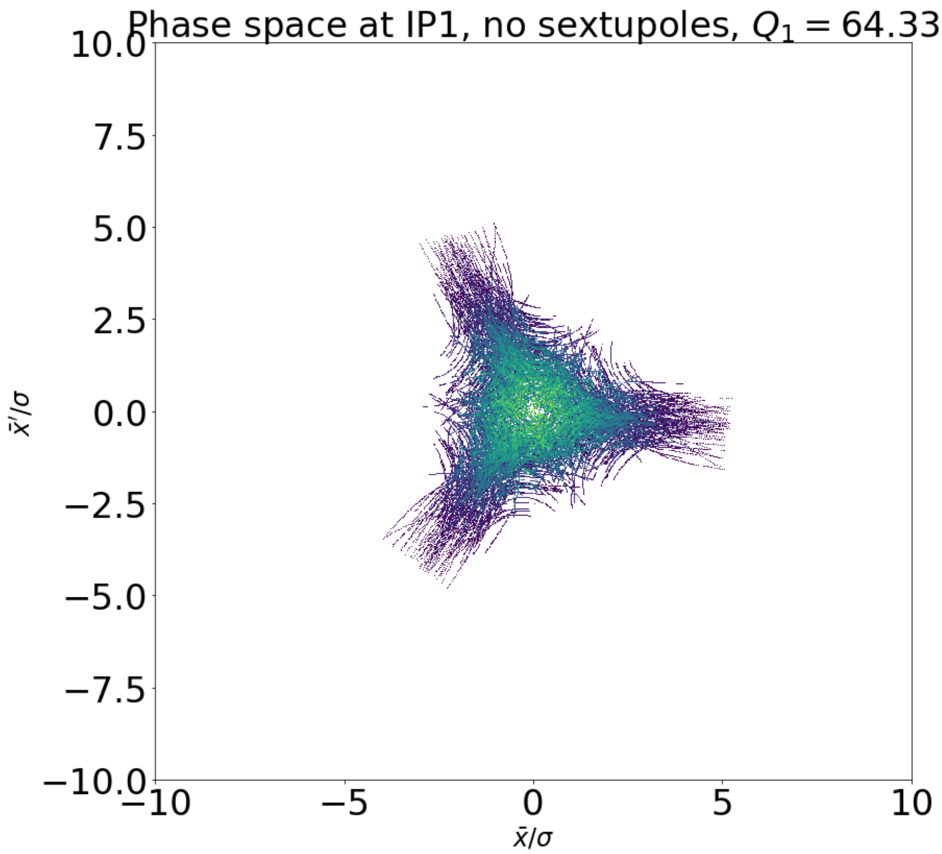
$$\epsilon_x = \bar{x}^2 + \bar{y}^2 \longrightarrow 1 = \left(\frac{\bar{x}}{\sqrt{\epsilon_x}}\right)^2 + \left(\frac{\bar{y}}{\sqrt{\epsilon_x}}\right)^2$$

By dividing the new set of normalised coordinates by $\sqrt{\epsilon_x}$ these would be given in units of beam size (σ).

Bellow, the phase space at the LHC IP1 for the operational tune, $Q_1 = 64.31$:



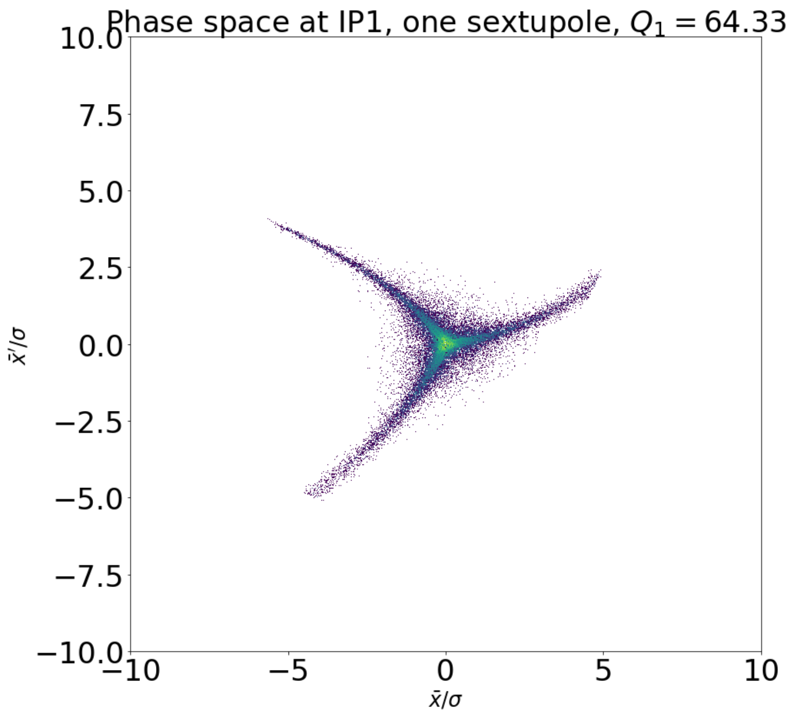
Next step, it is to vary the LHC tune to approach the third-integer. That is achieved by changing the quadrupole strengths, using MADX's match command. The nominal tune of the machine is $Q_1 = 64.31$ (see diagram above), hence the closest third-integer value is $Q_1 = 64.33333$. Ideally, a similar diagram phase space to the one before should be obtained, but the result is the following:



Phase space is not circular as before, but what looks like separatrices starts to appear. This should not happen, but like before, that is what would be expected in an ideal case. This outcome is because in reality, the dipole magnets in the LHC have a non-zero, non-linear component, which, together with the tune, originates this shape.

In order to reduce the stable area when on the one-third resonance, sextupoles are used. In order not to perturbe the machine chromaticity and only act on the separatricies orientation at the extraction location, harmonic sextupoles shall be used. These are sextupoles installed in low dispersion regions (ideally zero).

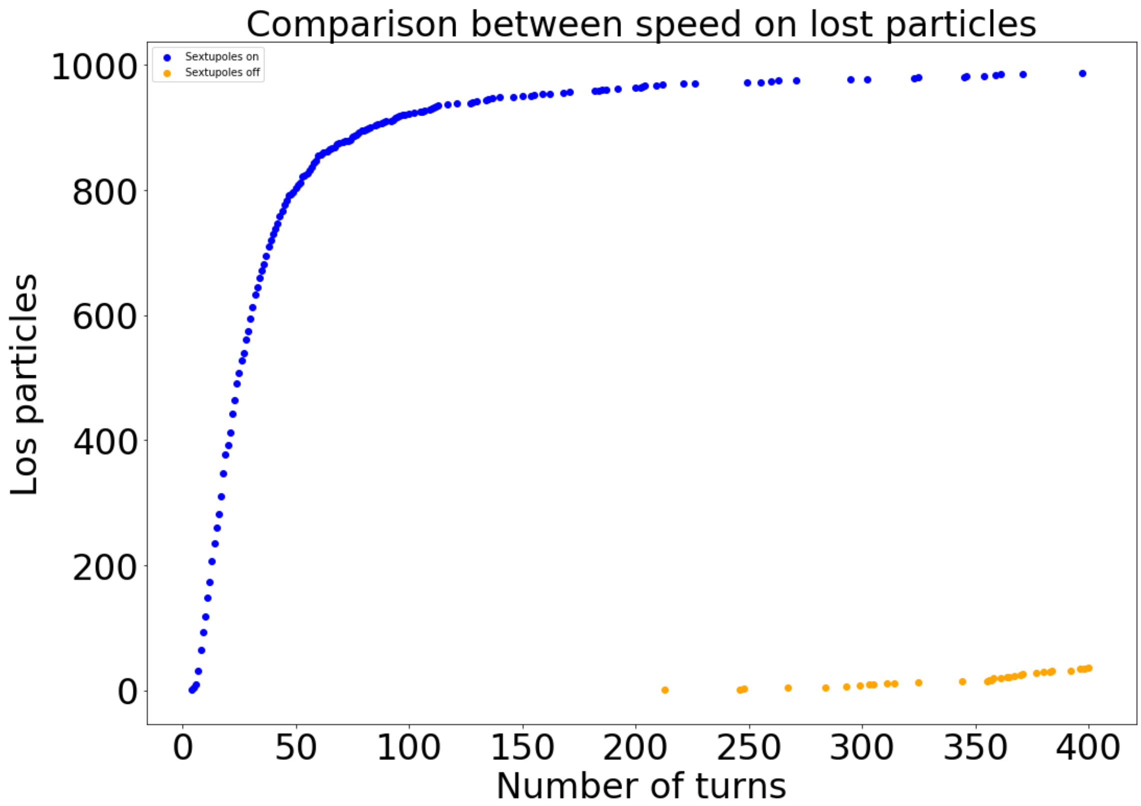
If one harmonic sextupole is active in the lattice, the difference of phase space diagrams is clearly noticeable compared with the case on which there are only non-linearities from the dipoles:



Doing so, the stable is significantly reduced, almost to zero, as it is shown in the previous figure. It is possible to note as particles with sufficiently large momentum offset have larger stable area. The main differences between the two cases observed so far are:

- Both present a triangle in the centre, but the one with the strongest sextupole component presents a smaller stable area (given by the are of the triangle) compared with the case where there are no sextupoles.
- The branches in the case where there are sextupoles the branches are longer than in the case where there are not active sextupoles. Also the orientation is slightly different.

To give an idea on how having an active sextupole in the lattice affects the rate at which particles are extracted compared to when there are no active sextupoles, these two cases can be compared. The number of extracted particles per turn is plotted with respect to the number of turns, comparing the case with and without sextupoles:

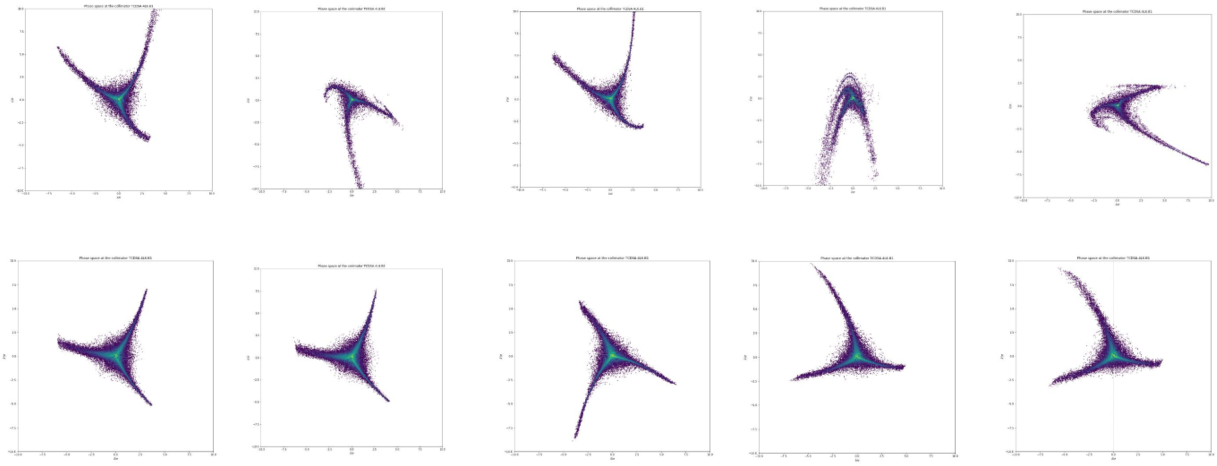


As expected, much faster extraction rate is achieved when sextupoles are used.

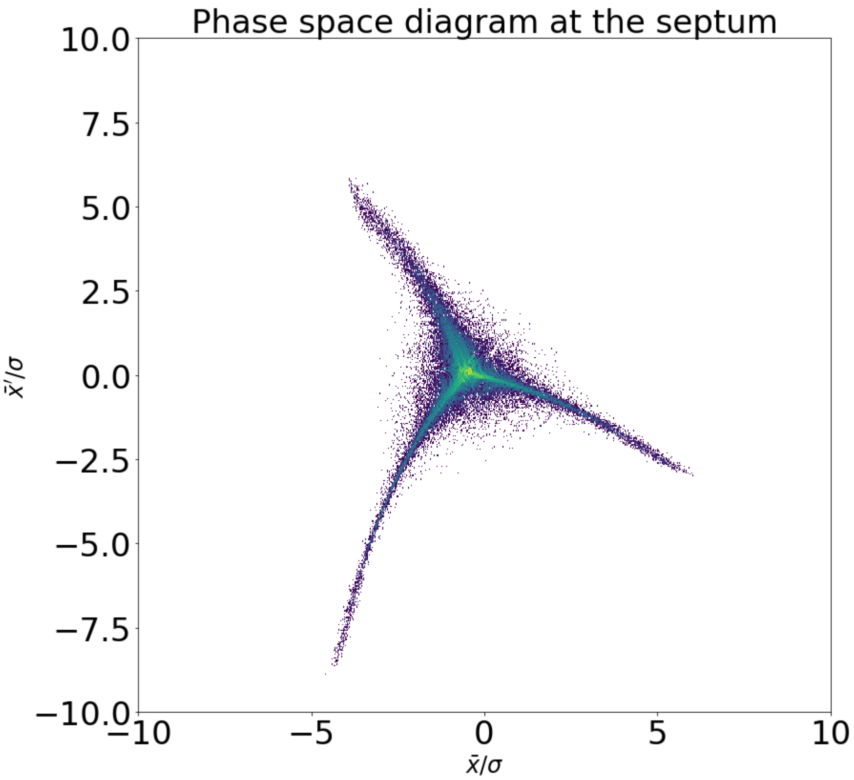
Next step is looking at how phase space looks on the **TCDSA.4L6.B1**, which is the protection device for the LHC extraction septum. This has been chosen as the extraction point and where particles are considered extracted if their amplitude is larger than the blade transverse position. A first approach is done studying the phase space diagrams at the septum, activating one sextupole at a time to 10% of their maximum strength. Of course harmonic sextupoles are the ones used.

The criteria for choosing one sextupole or another is based on the conditions that have been mentioned along this project. A phase space diagram which presents a branch going into our septum is sought, and if possible providing a large spiral step. The requirement for the spiral step to be large is needed in order to jump the blade that the septum presents separating the circulating beam from the extraction channel. A larger spiral step means that the density that the septum blade will intercept to separate the extracted beam from the circulating one will be lover.

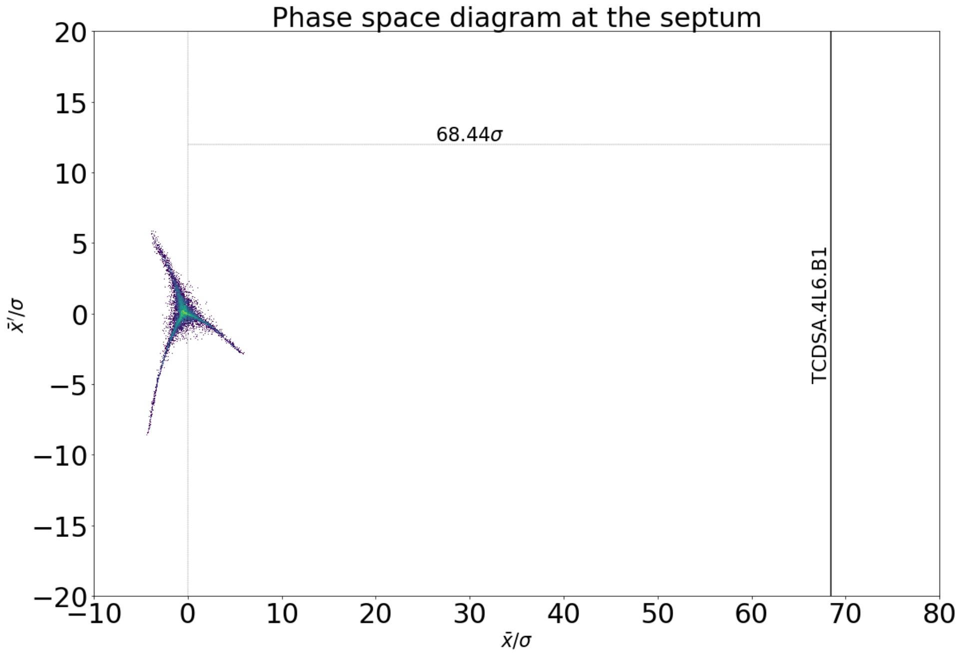
Bellow the ten plots showing phase space at the septum for each one of the active sextupoles are shown:



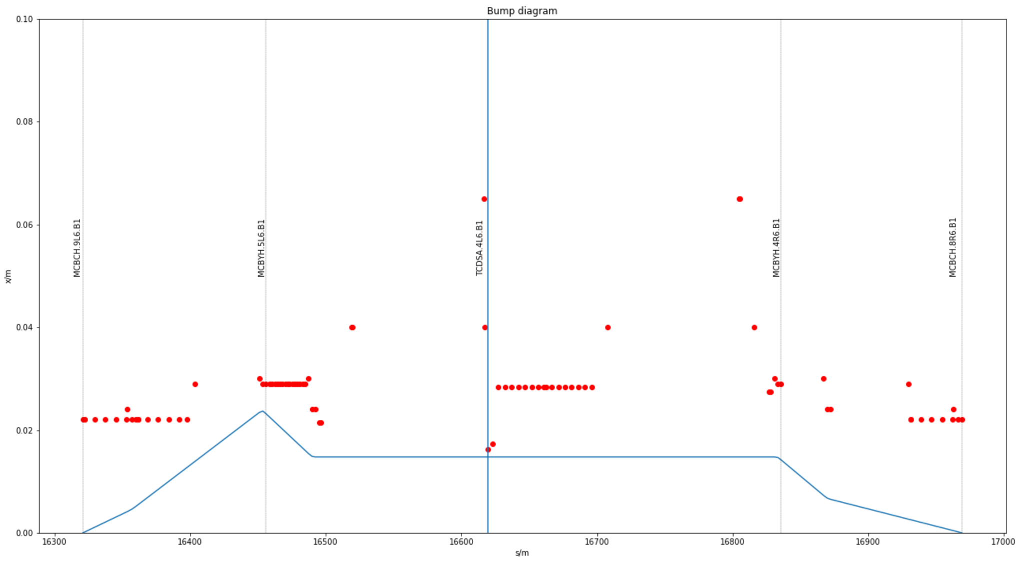
The diagram that is best suited for our purpose, regarding separatrices orientation is the one that corresponds to the sextupole labelled as **MCS.B8L4.B1**:



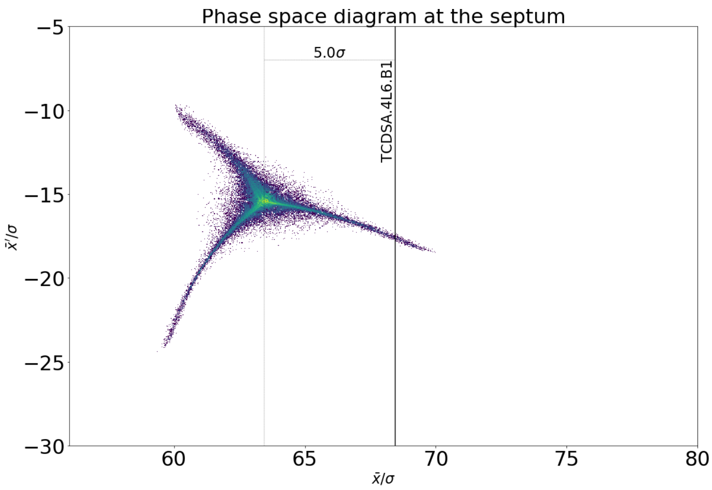
Now that a first starting point is found, the real aperture has to be found. Drawing it as a vertical line, the aperture is 68.44σ away from the design orbit:



That is a very big gap, and it would be impossible to extract particles with this setup. Since the aperture cannot be brought closer to the beam, the beam is then brought closer to the aperture. To do so, a **closed orbit bump** is produced, which is a local deviation of the design orbit. In reality that is achieved by means of using bumpers magnets surrounding the area. In this simulation that is achieved once again using the match command that MADX offers and varying correctors magnets strengths. A first approximation is to bring the design orbit to be 5σ away from the aperture of the septum. In this next graph, the dashed vertical lines are the correctors used, the blue line is the new design orbit at this segment, the vertical blue line is the septum and the scattered red dots represent the apertures.

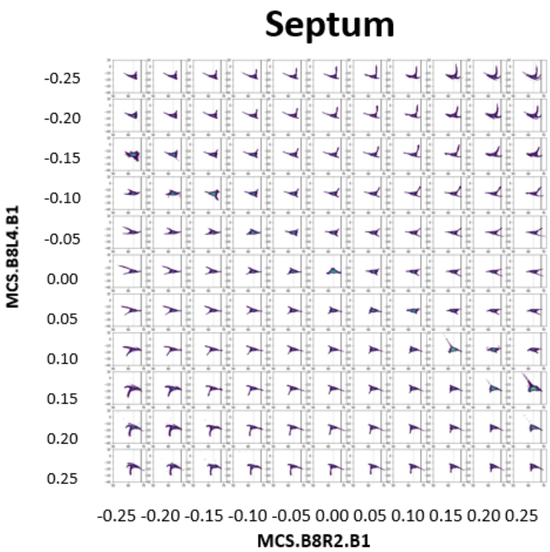


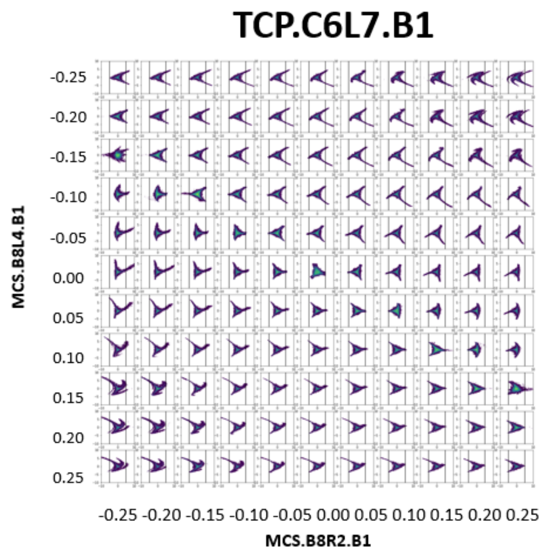
Which in phase space translates to:



Initially the beam was 68.44σ away from the septum, now it is just 5σ away from the septum. Knowing which sextupole could provide a proper phase-space shape, it is time to look for the optimum setup; again, looking to have a large enough spiral step and having most (ideally all of them) of the losses at the septum instead of other locations on the LHC.

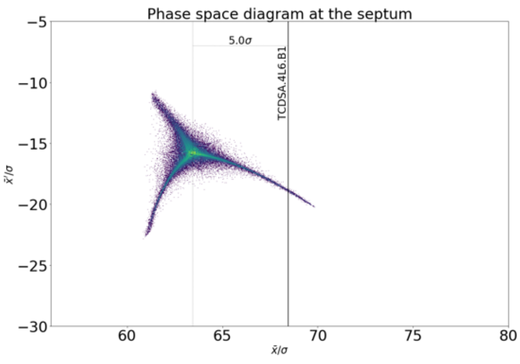
Scanning through sextupole strengths, always using the sextupole which gives good results. The plots are the following:



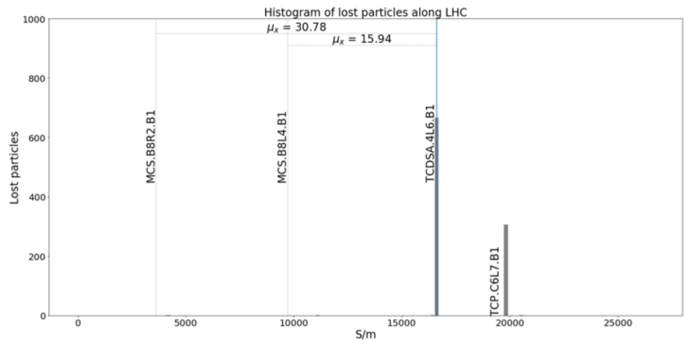


Out of all the cases, two of them stand out. The setups are the following:

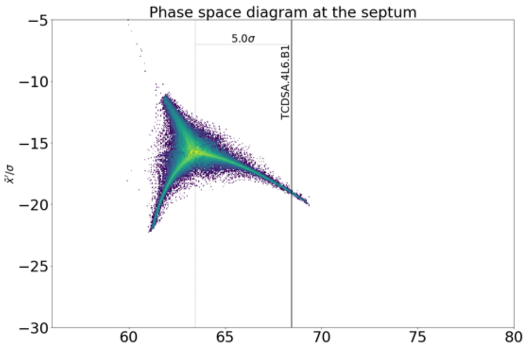
Sextupole MCS.B8R2.B1 at 2.4% MAX



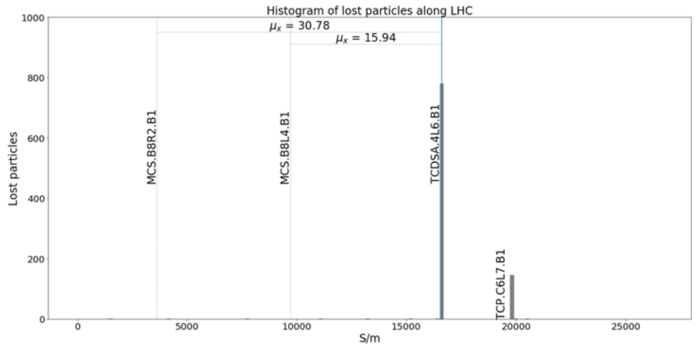
Sextupole MCS.B8L4.B1 at 15% MAX



Sextupole MCS.B8R2.B1 at 3.2% MAX



Sextupole MCS.B8L4.B1 at 15% MAX



The first case gives a 67% of extracted particles and spiral step of 1.4σ. Whilst the second case gives an 83% of extracted particles and an average spiral step of 0.76σ. In the diagrams bellow both tables show where the losses are for these two cases:

Losses with the first setup

ELEMENT	
TCDSA.4L6.B1	666
TCP.C6L7.B1	306
MB.A19R2.B1	1
MB.A23R4.B1	1
MCS.B8L6.B1	1
MCS.C14R7.B1	1

Losses with the second setup

ELEMENT	
TCDSA.4L6.B1	780
TCP.C6L7.B1	144
TCP.D6L7.B1	2
MB.A19R2.B1	1
MB.A23R4.B1	1
MB.A30L6.B1	1
MB.C31R1.B1	1
MCS.B8L6.B1	1
MCS.C14R7.B1	1
MCS.C22R3.B1	1
MQSX.3L5	1
TCSG.B4L7.B1	1

In order to perform slow extraction in the most efficient way, losses have to be reduced everywhere else and the spiral step has to be increased.

Two different possibilities arise to improve these setups:

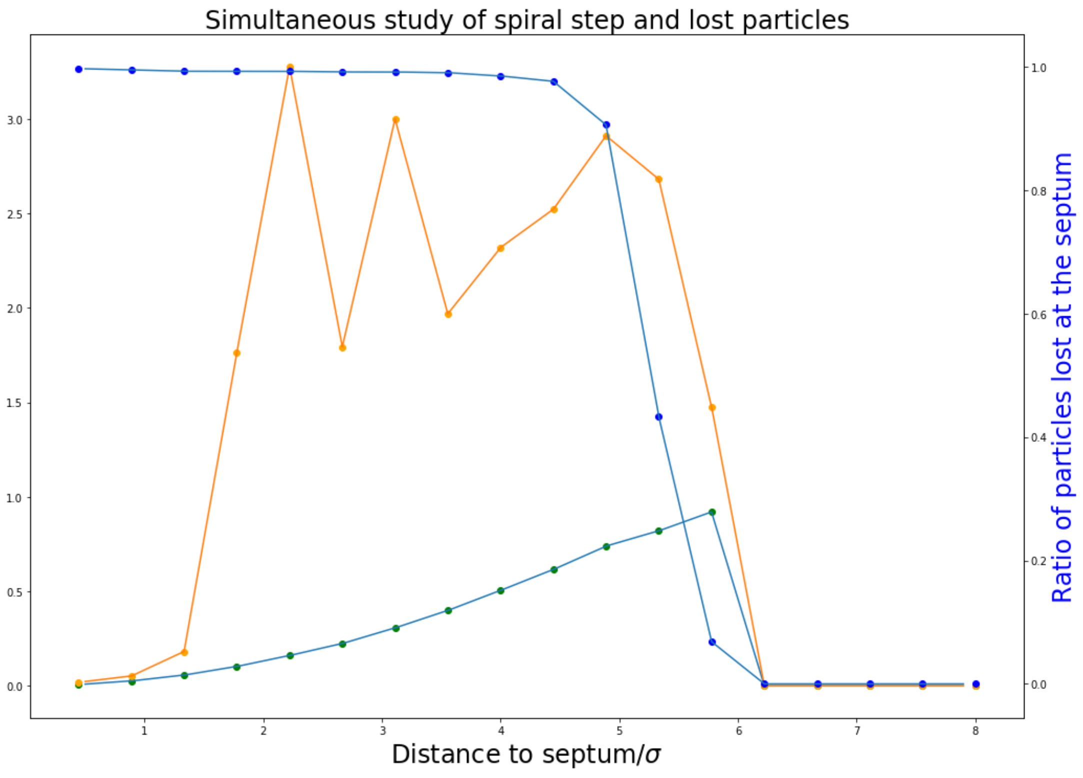
- Vary the bump amplitude to study how it affects the studied magnitudes
- Enclose the collimator where other losses occur with sextupoles that are in phase with each other, and alter phase space locally in order to minimise losses at that region

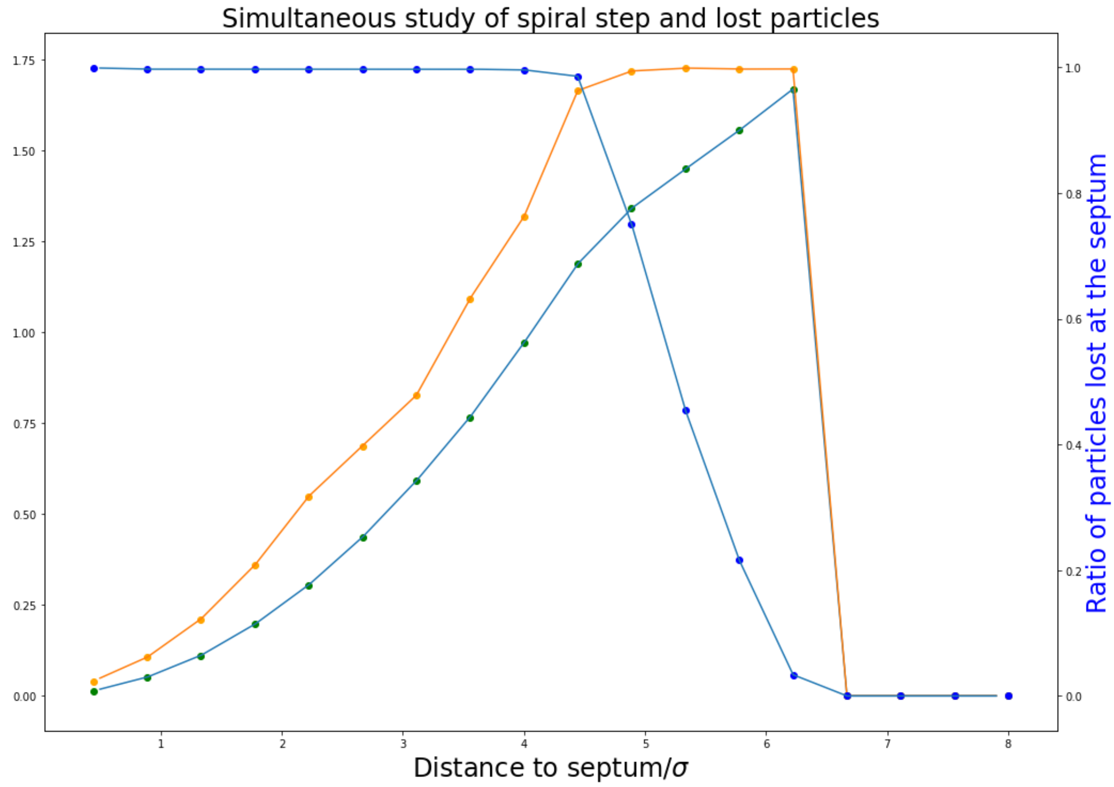
2.1 Varying the bump distance

As a first option varying the bump distance is going to be tested. Taking both pairs of cases mentioned before, a bump distance scan is done, starting 8σ away from the septum and bringing it to the septum.

As one would expect, bringing the bump closer to the septum, translates into a bigger number of particles being extracted, which is what is looked for. Doing so, the spiral step is reduced as the maximum amplitude at which particles can circulate has now being reduced.

Both cases show a similar behaviour; the ratio of extracted particles goes to 1 (means all the particles are extracted at the septum) bellow a certain bump distance to the septa. And the spiral step has an opposite behaviour; it increases with the distance from the bump to the septa. This makes sense, because the further away you are from the septa, more space and time the particles have to reach a higher resonance, and hence make a larger spiral step. The spiral step becomes zero at large distances to the septum, which also makes sense; this means that particles are not extracted if the bump is far away from the septum, they are extracted at other points in the lattice.



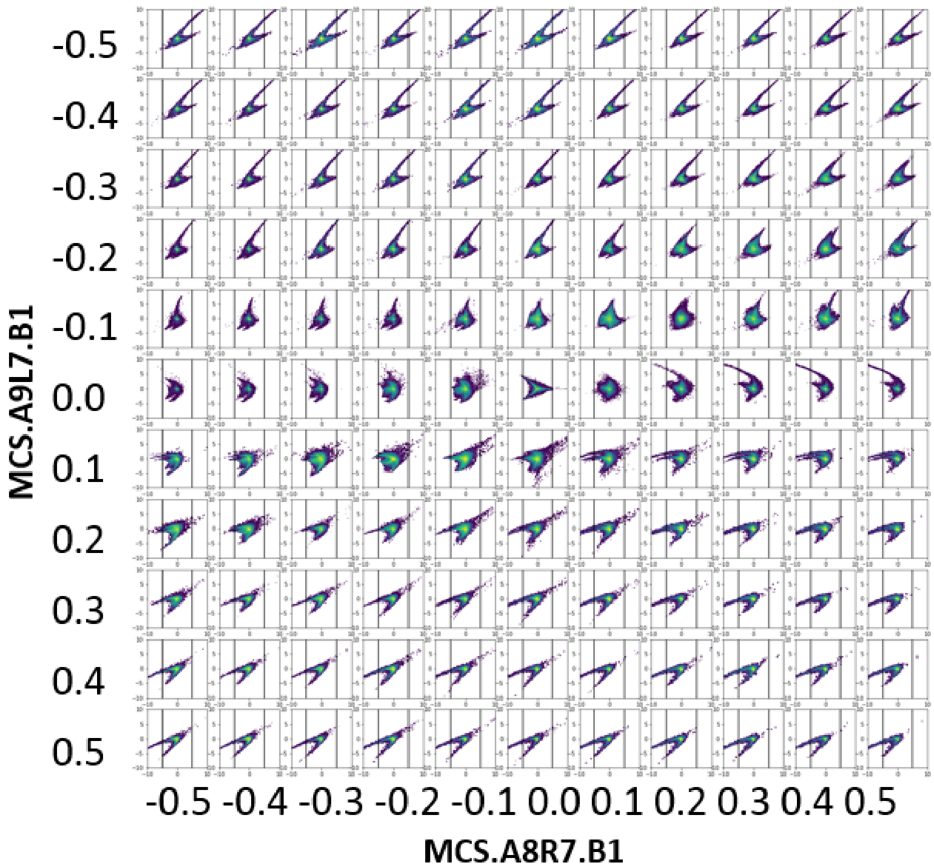


The results obtained here are not completely satisfactory, because the spiral step is too small when all the particles are extracted. This means that the maximum allowed amplitude from the collimator settings is not sufficient to allow a resonant slow extraction with the sextupoles chosen.

One possibility to overcome this issue could be to locally perturb the dynamics at large amplitudes in the region of the limiting collimators. This possibility is expolerd in the following section.

2.2 Enclosing the collimator with sextupoles

Looking at our lattice, two sextupoles almost in perfect phase advance, and reasonably small dispersion are available. By doing a scan varying these sextupole strengths, two matrices where its components are the phase space diagrams at the septum and at the collimator causing losses are constructed. In the matrix the diagrams are arranged in such a way that the rows go from −50% of the maximum strength to 50% of maximum strength of the sextupole before the collimator, and the rows do likewise for the sextupole afterwards:



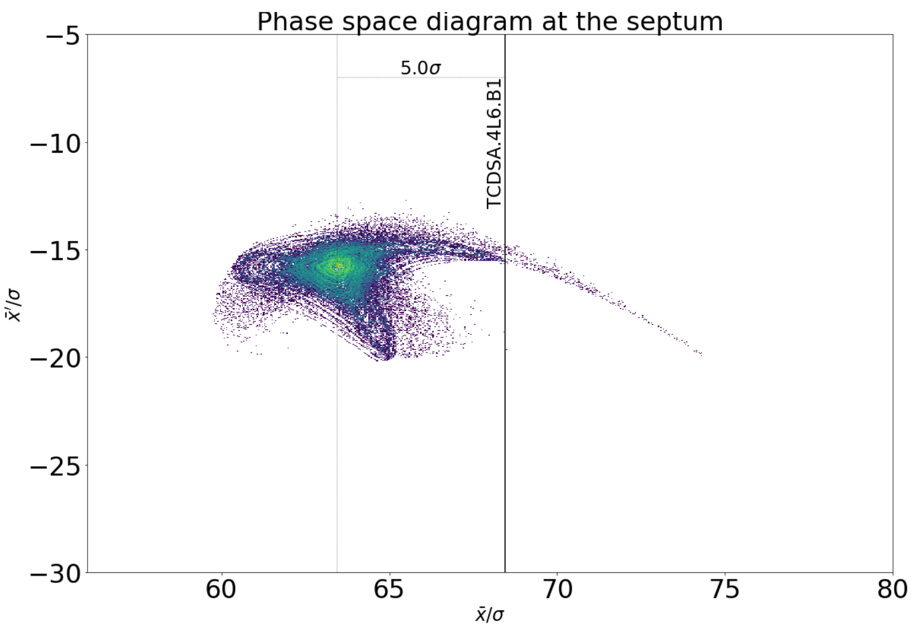
After analysing the results obtained on this scan, and using our intuition new scans with different combinations of these sextupoles are done to try and find a setup that works well. The best result obtained involves the two sextupoles that were used in the first run of scans, and just one from the pair used in distorting phase space. The best configuration of settings observed so far is:

- **MCS.B8R2.B1 at 3.2% MAX**
- **MCS.B8L4.B1 at 8.8% MAX**
- **MCS.A9L7.B1 at -8% MAX**

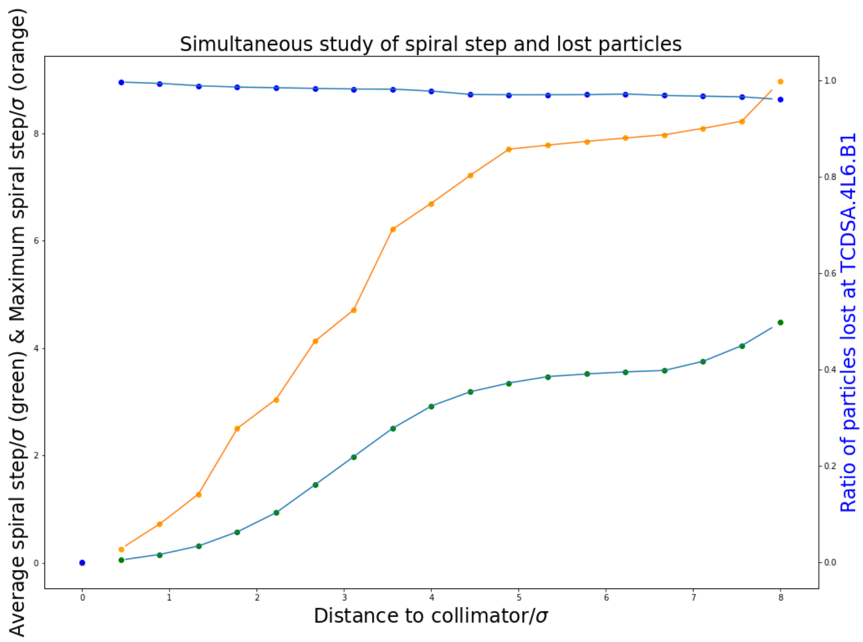
Regarding the results the percentage of extracted particles rises up to 97.3%, compared to the first scans it is a significant improvement from what was obtained before (83 %). The problem is that the few losses are at cold magnets, which is not good. In the next table all the locations for the lost particles is shown:

ELEMENT	
TCDSA.4L6.B1	725
MQY.5L6.B1	4
TCP.C6L7.B1	2
MB.A17L7.B1	1
MCS.C22R4.B1	1
MCS.C12R5.B1	1
MCS.B29R2.B1	1
MCS.B19R1.B1	1
MCS.B11R5.B1	1
MB.A12L6.B1	1
MCS.A14R2.B1	1
MCS.A14L6.B1	1
MB.C17L6.B1	1
MB.C12R4.B1	1
MB.B28L1.B1	1
MB.B14R7.B1	1
MB.A34R3.B1	1
MCS.A8L6.B1	1

Phase space now looks like this:



More scans have been done, but have not been able to improve this last setup. So it is interesting to perform another study varying the bump distance with this new configuration, because maybe it would be possible to reduce even further the few losses that occur. A graph similar to the ones before is presented now:



Looking back at the first results it is clearly visible that the ratio of extracted particles does not change as abruptly. Also the spiral step is significantly larger, this is due to the fact that this new setup is much better than the first approximations. A very good ratio of extracted particles and also a larger spiral step (compared with the previous cases) is given. These simulations could be improved by doing more thorough scans or using an automatic optimiser.

3 Conclusions

Results and conclusions from this study can be summarised in the following points:

- As expected, a slow extraction design for a machine with tight apertures is very challenging
- In this first exercise, it was used the LHC nominal optics at extraction and nominal collimator settings from 2019 operation
- New optics could be designed to simplify the design and procedure
- The first main observation is that the sextupolar field components of the main magnets are already sufficient to significantly excite the 1/3 integer resonance; there are many sextupoles available in the ring and a good fraction at very low dispersion. This gives quite a lot of possibilities for a SE design
- Automatic optimisation needed to explore the full parameter space available

- The idea to locally perturb the beam transverse distribution to escape the collimation system has been tested with interesting results but more thorough studies to be performed
- A solution that allows to have a max spiral step of about 8 sigma (similar to the one achievable in the SPS) and about 2% losses in the machine was found

Further studies are needed to finalise the slow extraction system design. An optimiser is needed to handle all the available degrees of freedom; include more sextupoles or higher order multipoles since they could probably help as well, but complication increases exponentially.

Due to the small spiral steps obtained in these simulations, crystals seem to be needed in order to produce a bigger jump and avoid the septum.

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