RESONANT SLOW
EXTRACTION IN THE LHC

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What is resonant slow extraction?

• Slow extraction uses resonance to provide a continuous particle spill which is useful for fixed target experiments

• In the context of the studies for possible scenarios of operations for the FCC injectors, one proposal is to use the LHC to provide beam for Fixed Target experiments

• The main challenge here is the tight aperture of the LHC collimating system and the SC nature of its magnets → resonant slow extraction needs circulating particles at large amplitudes
Why we want to perform slow extraction using the LHC

- Current fixed target experiments use beams from the SPS which delivers protons at an energy of 450 GeV and muons at around 200 GeV
- The LHC offers the possibility of reaching very high energies (6.5 TeV)
- This would give the possibility to perform experiments out of reach today
Using the LHC as an injector for the FCC

- A High Energy Booster (HEB) could be added to the existent LHC layout
- This new system would be used to deliver particles to the FCC
- IP5 could potentially be used for a FT station
Extraction point

- In order to use today’s existing layout, we have investigated IP6
- We used nominal collimation settings for 6.5 TeV (worst case) and all results are reported normalised
How we achieve slow extraction

• Sextupoles are non-linear elements which are usually exploited for third-order resonant slow extraction

• Sextupolar field, when present, and machine tune close to 1/3 integer give the well-known triangular phase-space

• This triangular area defines the stability region for the circulating particles

• The boundary of stability is represented by the separatrix

• Particles are pushed towards the separatrices when outside the stable region and their amplitudes will grow indefinitely
Why do we want phase space to look like this?

• As we have a very well defined path in phase space for the growing amplitude particles, we can think of exploiting this growth for extraction proposes.

• Usually, a thin septum is used to separate the circulating from the extracted beam.
How phase space looks like in our simulations

This phase space distortion is produced because dipoles present a non-zero non-linear multipolar contribution
Comparison of the effect that active sextupoles produce

• The blue line represents the collided particles when there are active sextupoles and the orange one when there are not

• There is a very big difference between the two curves

• The sextupoles are said to drive the resonance
Finding the ideal sextupole
Best option: Sextupole MCS.B8L4.B1

- Out of the ten previous cases, this sextupole is the one that gives the best results
- Its separatrices are oriented in a way that one of them can be cut with a septum thin blade
Distance from beam to septum

• Our beam is very far away from the septum; it is impossible to achieve high resonances proper for this setup
• We need to find a solution
• Bringing the beam closer somehow?

Phase space diagram at the septum

\[68.44\sigma\]
Solution: produce a closed orbit bump

- We use horizontal kicker magnets to produce the bump.
- Here we have plotted the x position of the ideal particle trajectory.
- Now the distance from the ideal orbit to the septum is just 5 $\sigma$.
Region with bump

Apertures
Kickers
Design orbit
This is how phase space looks like now.

We can see that some particles are being extracted at the septum!
Next steps

• We have brought the beam closer to the collimator

• Now we have to find a setup that minimizes losses everywhere else but the collimator we want, and get the largest spiral step possible

• We have an idea of which sextupole to use, so now we do a scan on sextupole strengths using that sextupole to find the best setup matching our conditions
Sextupole strength scan

**Septum**

**TCP.C6L7.B1**

MCS.B8L4.B1

MCS.B8R2.B1

MCS.B8R2.B1

MCS.B8L4.B1
First option

68.2% of particles extracted

Losses at septum and collimator TCP.C6L7.B1

Sextupole MCS.B8R2.B1 at 2.4% MAX  
Sextupole MCS.B8L4.B1 at 15% MAX

Phase space diagram at the septum
Second option

83.4% of particles extracted

Losses at septum and collimator TCP.C6L7.B1

Sextupole MCS.B8R2.B1 at 3.2% MAX

Sextupole MCS.B8L4.B1 at 15% MAX
**Losses with the first setup**

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**Losses with the second setup**

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Possible techniques to reduce losses

1. Compromise the spiral step and bring the bump closer to the collimator → reduction of losses everywhere else, and more extracted particles. This is a trade-off between bump amplitude and sextupole strengths

2. Distorting phase space locally at the collimator where we have most losses in order to reduce them
Vary bump distance to septum

• The first solution is to bring the beam even closer to the septum
• By doing so it is more likely for particles to be extracted when they are in resonance, because they are closer to the extraction point
• But they also have less time to become resonant on high amplitudes, and thus a smaller spiral step
Study of the spiral step & ratio of extracted particles for the first case presented before

Setup: Sextupole MCS.B8R2.B1 at 2.4% MAX, Sextupole K8 MCS.B8L4.B1 at 15% MAX
Study of the spiral step & ratio of extracted particles for the first case presented before

Sextupole MCS.B8R2.B1 at 3.2% MAX

Sextupole MCS.B8L4.B1 at 15% MAX

Simultaneous study of spiral step and lost particles

Average spiral step/σ & Maximum spiral step/σ

Distance to septum/σ

Ratio of particles lost at the septum

0.0

0.2

0.4

0.6

0.8

1.0

0

1

2

3

4

5

6

7

8
Distort phase space

• The idea is to perturb the phase-space locally in order to escape the collimation system and maintain a large spiral step at the septum
• Distort phase space around the place where we have unwanted losses (primary collimators in IP7)
• There could be a solution where the phase space can be perturbed only locally → trying using 2 sextupoles in phase...this is most likely not enough and more degrees of freedom are needed
• Scan the strengths of these sextupoles to find the best settings...
Scan

- On the right we have a scan varying sextupole strengths for these magnets, the plots are at \textbf{TCP.C6L7.B1}
- Now it is time to study which phase space could serve for our purpose
Best result

- This setup gives a 96.5% of extracted particles
- Losses are reduced completely at TCP.C6L7.B1
- Although some losses are at cold magnets
Changing the previous magnet strengths proportionally

- In this new scan we have managed to increase the number of extracted particles up to 97.4%
- Slightly reduce the number of losses at cold magnets
  - MCS.B8R2.B1 at 3.2% MAX
  - MCS.B8L4.B1 at 8.8% MAX
  - MCS.A9L7.B1 at -8% MAX
Summary

- After scanning throughout multiple combinations of sextupoles this is the best setup I have found.
- 97.2% of the particles are extracted!!
- Although there are some lost particles on cold magnets, which could be harmful...

<table>
<thead>
<tr>
<th>Setup</th>
<th>Losses</th>
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</table>
Histogram of lost particles along LHC

$\mu_x = 30.78$

$\mu_x = 15.94$

$\mu_x = 57.18$

Lost particles

MCS.B8R2.B1

MCS.B8L4.B1

TCDSA.4L6.B1

MCS.A9L7.B1

TCP.C6L7.B1

S/m
• Studying how varying the bump distance shows that the ratio of extracted particles is more or less maintained

• The larger the distance to the septum the larger spiral step
Conclusions I

- As expected, a slow extraction design for a machine with tight apertures is very challenging.
- In this first exercise, I have 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.
Conclusions II

• 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

• But having so many options also makes things more complicated as the resonant driving term will be a combination of all this! → automatic optimisation needed

• 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
Conclusions III

• 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

• This is a first step and it should be further optimised → 2% losses in cold magnets not good
Outlook

• Further studies needed to finalise the SE design
  • Optimiser needed to handle all the available degrees of freedom
  • Include higher order multipoles → they could probably help as well, but complication increases exponentially!

• Look at IP1 and 5 with possible dedicated insertion optics

• Evaluate the extraction system → crystals seems to be nevertheless needed due the small spiral step achievable

• Estimate realistic operation for a FT facility → POT per year, flux, activation, etc.