A Feedback Controller for the RFKO Method for Slow Extraction

for NIMMS Helium Synchrotron

Stamatina Detsi
Electrical and Computer Engineering
National Technical University of Athens

Supervisors: R. Taylor, E. Benedetto, M. Vretenar

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Contents

Chapter 1

Introduction

The NIMMS (Next Ion Medical Machine Study) Group is designing an accelerator for medical applications that needs to extract a uniform spill of particles to the tumor. This is performed by slow extraction via the RF-KO (radio-frequency knock-out) method.

The extraction of the accelerated particles (beam) with the desired energy from the synchrotron to the treatment rooms is one of the critical steps in radiotherapy. A stable beam of 1-30 seconds with a constant intensity is mandatory to achieve high-quality patient treatment. RF-KO, is a technique used in particle accelerators to extract a specific group of particles, categorized by their energy or frequency, from the circulating beam. It involves selectively changing the voltage that is applied to the accelerating beam, allowing only specific particles to be extracted while leaving the rest of the beam unaffected.

To scan the tumor, a uniform extracted beam is needed, which means a constant rate of extracted particles per time duration. Because of this, the voltage needed to be controlled as per the particle's extraction speed. For this purpose, a controller for Amplitude Modulation has been developed, with varying methods for Frequency Modulation in order to design a system that automatically creates a uniform spill in the output.

The target of this project was to create a feedback system that can control this beam extraction. It is one of the first approaches to create a feedback system in simulation in the simulation code XSuite and it is also a promising method both for Slow Extraction at the NIMMS Group and for other users of the Xsuite community.

Chapter 2

Theoretical Background:

2.1 Slow extraction, RFKO

In general there are two categories for extraction from accelerators: Fast extraction methods use strong kicker magnets to extract entire particle bunches from an accelerator, and slow extraction methods are used to extract a continuous spill of particles throughout a long duration of time.

In an accelerator, particles are accelerated using RF cavities that provide electromagnetic fields to accelerate the charged particles as they circulate. These RF cavities are typically tuned to match the harmonic frequencies of the particles. By manipulating the voltage in the cavities, the particles can gain or lose energy as they accelerate.

The particles are accelerated to maximum energy, and at flat-top, are put into resonant conditions, by moving the horizontal tune near a third-order resonance, and powering a strong resonant sextupole. Then Radio-Frequency Knock-Out (RF-KO) is performed to initiate extraction. In general for this method a voltage kick in the radio-frequency spectrum is applied in the accelerating beam. A strong difference with respect to other extraction techniques is that the stable triangle, formed from the sextupole near the resonance, is fixed in phase-space and the kick only affects the amplitude of the betatron oscillations. Figure 2.1

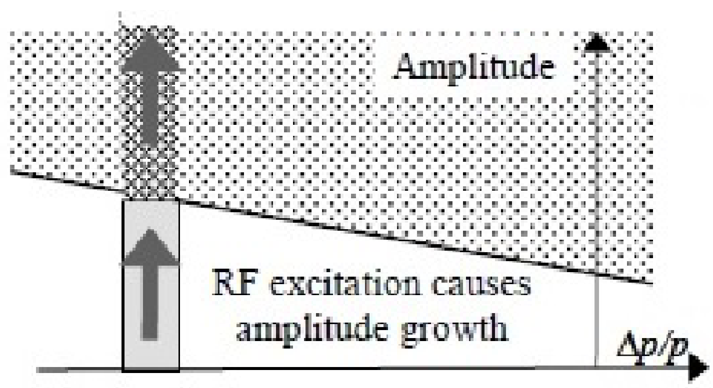


Figure 2.1: RFKO extraction in Steinbach diagram [1]

represents a Steinbach Diagram which demonstrates the effect of increasing the amplitude in order to send the particles in the extraction region. In the extraction process there are two regions that are effected by the beam. Firstly, the extraction region, when the kick frequency matches with the particles tune. In this case the betatron osculation's grown in amplitude and the particles are extracted by getting inside the unstable triangle. Secondly, the diffusion region: when the RF frequency matches with the tune region deeply but the particles there are diffused toward the boundary of the separatrix. In this case, these particles are not yet extracted.

In the extraction process there are two cases about the particles that are effected by the beam.

1. Extraction region: When the kick frequency matches with the particles tune. In this case the betatron osculation's grown in amplitude and the particles are extracted by getting inside the unstable triangle.

2. Diffusion region: when the RF frequency matches with the tune region deeply but the particles there are diffused toward the boundary of the separatrix. In this case, these particles cannot be extracted.

2.2 Modulation

Modulation is a technique used in computing, telecommunications and signal processing to vary a signal's properties, such as its amplitude, frequency, or phase, to encode information. In communications, this process allows data to be transmitted over a medium, like radio waves or cables, by imposing the information onto the carrier signal. Demodulation at the receiver's end extracts the original data.

1. Amplitude Modulation (AM):
   is the process of changing the Amplitude of a harmonic signal.

2. Frequency Modulation (FM):
   is the process of changing the frequency of the harmonic wave.

2.3 Controller

A controller is a device or component in a system that manages or regulates the behavior or operation of other elements. It processes inputs, makes decisions, and sends commands to ensure a desired outcome or maintain a specific state. Common examples include temperature controllers in heating systems and game controllers for video games.

PID Controller :

The PID controller calculates an error value e(t) as the difference between a desired set-point and a measured process variable and implies a correction based on proportional, integral and derivative terms.

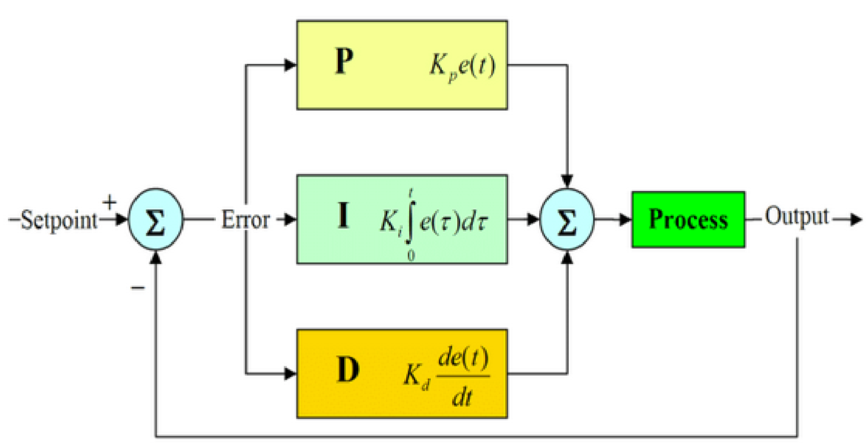


Figure 2.2: PID Controller [2]

1. *Proportional*: sets a factor Kp which is proportional to the current error, however using a P-control alone will results in an error between the set-point and the process value because the controller requires an error to generate the p-response.

2. *Integral*: akes an integral of past e(t) → it seeks to eliminate the residual error by adding control effect due to the historic e(t).

3. *Derivative*: it based on its current rate of change. The more rapid the change the greatest the controlling or damping effect.

In Slow extraction the majority of the institutes are using either a feedback control system or a feed forward system , or both as it is presented in figure 2.4. These systems use the previous amplitude of the beam frequencies to change the RF voltage.

Initially, a simple PI controller is implemented to see how the system responds.

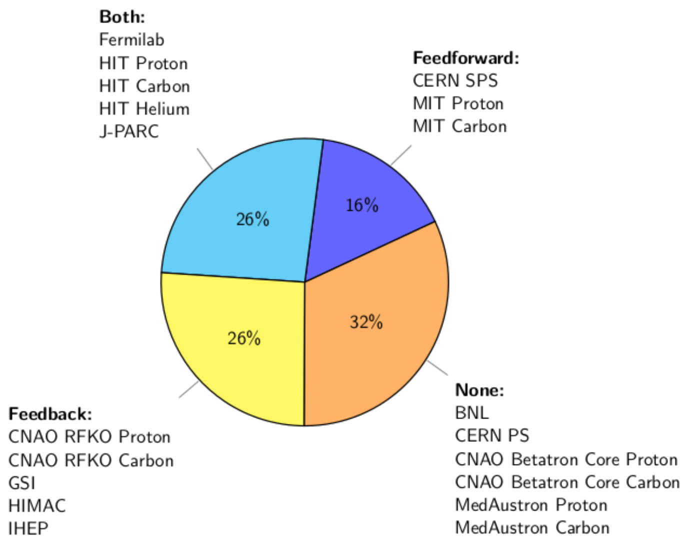


Figure 2.3: Type of controllers [3]

Chapter 3

Current Status - Other Facilities

3.1 Table with summary

The parameters that are used for Slow Extraction are shown in figure 3.1.

Physical quantity	**Unit**	**Meaning**
θ	μrad	kick given by the electric field
$\frac{\lvert V_x \rvert}{d}$	V/m	electric field imposed at the kicker plates
l_{eff}	m	effective length of the kicker
p	eV/c	momentum of the beam
β	-	relativistic Lorentz factor

Figure 3.1: Units [4]

	units	MedA	HIT	PS	CNAO	HIMAC
Particle			Carbon	Proton		Carbon
Tune Q_x		1.67	1.67	6.33	1.760	3.680/3.133
Mom. $\frac{\Delta P}{P}$		$-2.5 \cdot 10^{-3}$			5.392	
Chroma. dQ_x		[-1.5, -0.6]	-0.7, -1.589	-0.5(-1.67?)	-0.1	-1/-4.5
Emittance ϵ_{x_n}	mm·mrad			1.5		
Max Energy	MeV		48–430	5.3->24		
Max Voltage	V		300	1200	300	1200
Plate Gap	cm		150	0.070	13.724	150
Eff.Length	cm			935	37	
Length	cm		15	1000		700
Max Kick	μrad		1.4	10.8	0.8	2.1,5
Power	W		400	5000	500	
Rev. Freq.	MHz					1.653
Num of Particles			5×10^7			
Time Step	μsec		100			1/977.5Hz
Extraction Time	sec		5			

Table 3.1:

3.2 Some feedback diagrams

HIMAC uses the Chirp method for frequency modulation [5]. They also use feedback (PI controller) and feed-forward controllers for amplitude modulation. Additionaly they have an extra gain controller for amplitude adjustment and they provide an initial kick at the beginning of the process.[6]

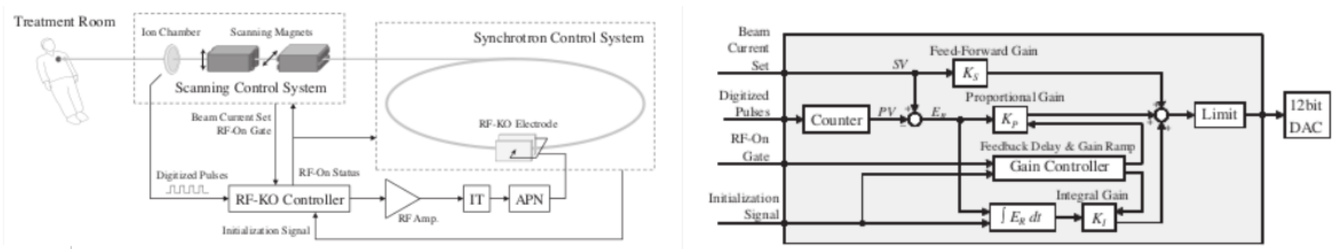


Figure 3.2: HIMAC controller [6]

HIT impliment a system called DIC to manage voltage control, which is similar to HIMAC. They apply BPSK [7] for changing the frequency and have both feedback (PI controller) and feedforward controllers to adjust the amplitude, leading to a simple rising curve[8].

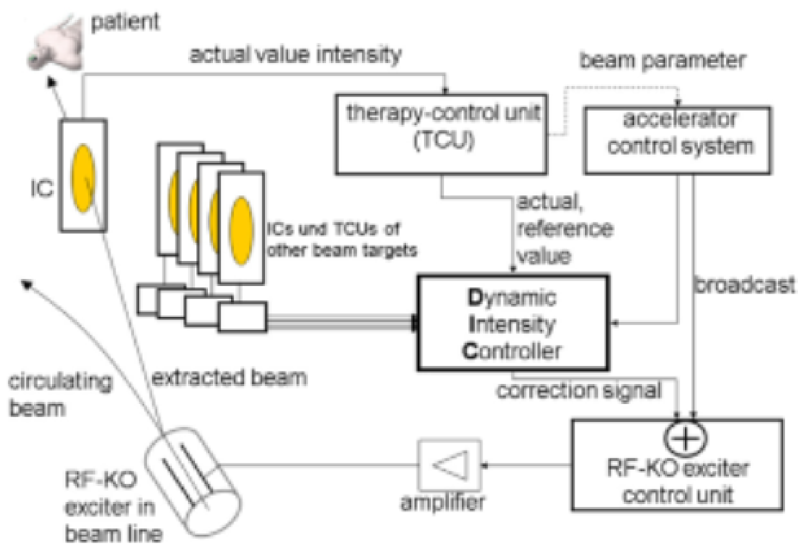


Figure 3.3: HIT controller [8]

Chapter 4

Simulation

4.1 Set Up

The NIMMS Group is designing a Helium-Synchrotron accelerator. A slow extraction method is needed and RF-KO was chosen to be implemented in order to be added to this structure. The RF-KO method is applied in a beam that has already been accelerated in the Helium-Synchrotron for a number of turns prior to this application. Following the application it is changing in every turn because part of the beam continue to be accelerated and part of it is extracted.

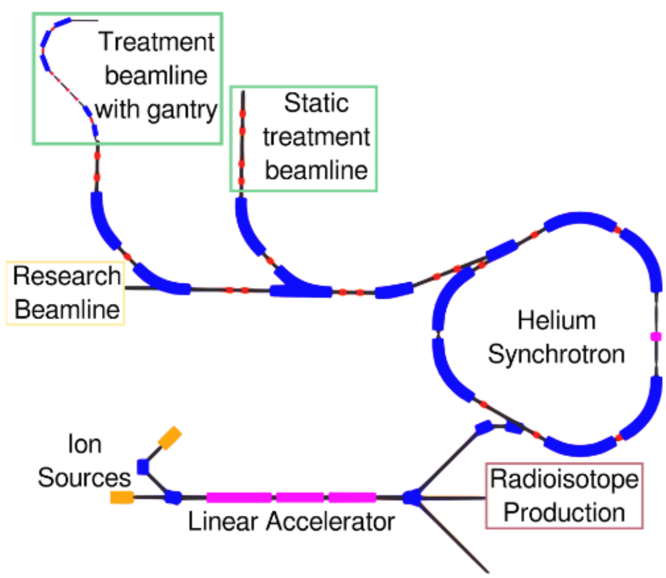
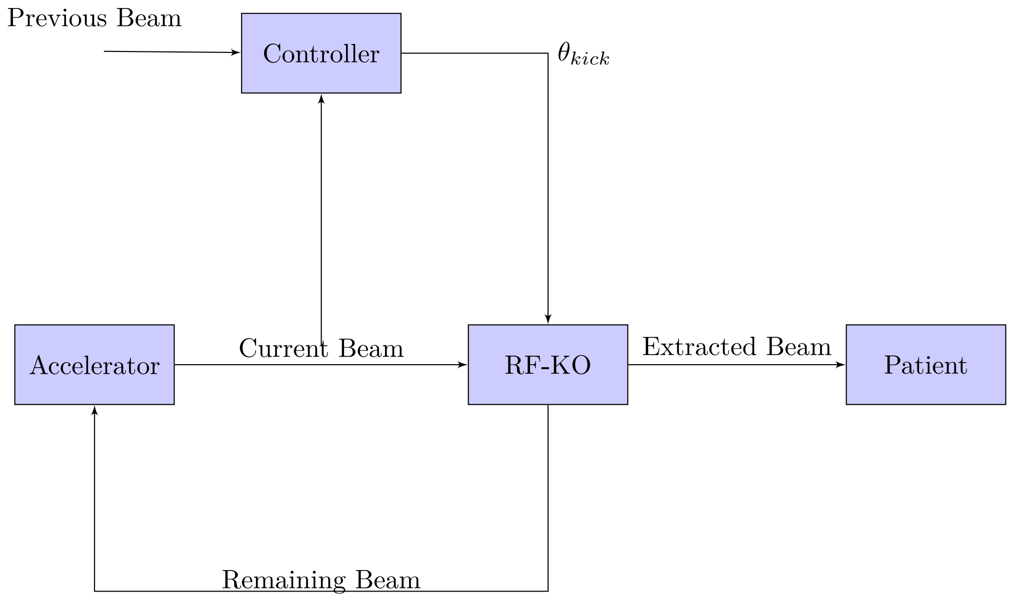


Figure 4.1: Helium Synchrotron [9]

In order to fullfil the medical requirements a uniform beam with specific duration is needed as output. This can be achieved by means of a controller that modifies the voltage kick as a function of the extraction of previous turns. That's why a class in Xsuite was created, which tracks a beam through the Helium Synchrotron, which is simplified to a .json sequence line. A Beam Interact function was used to calculate the number of particles extracted per window (defined by the electrostatic septum), and fed this into the controller's class.



The controller's class gets the beam data from Helium Synchrotron -which for me is a Blackbox- and passes them to the controller that calculates the necessary voltage kick and then applies this kick to the current beam. The Voltage kick increases the px coordinate of the 6D particle beam. I started by modulating the Voltage kick in every turn but it was shown that a window of turns was more appropriate; in the last simulation the chosen window was defined to be 500 turns, equal to 10 microseconds.

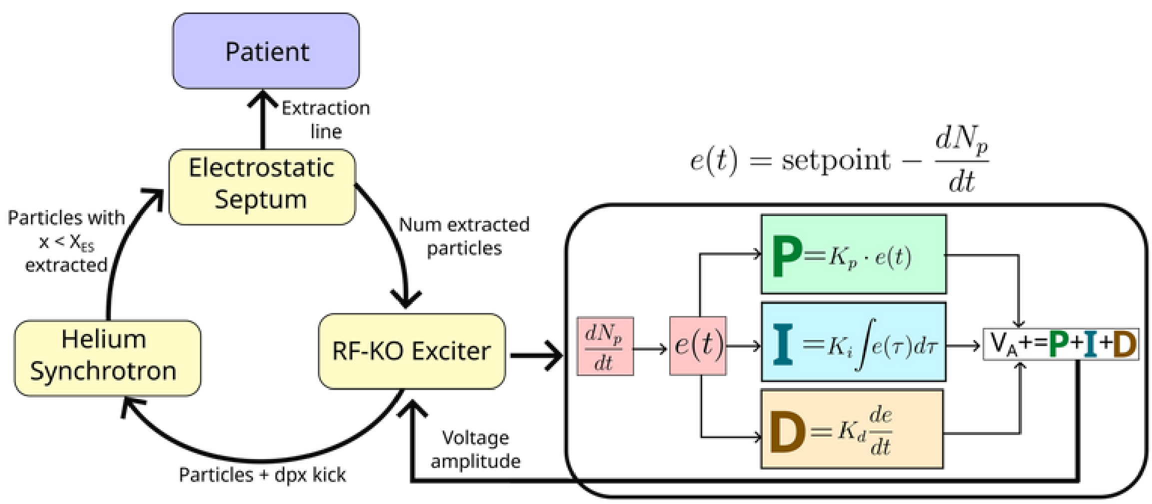


Figure 4.2: Control system of the extracted beam

4.2 Preliminary

The kick should have a stochastic aspect because not all of the particles are oscillating with the same tune. The easiest way to create such a kick is to use a random number within the limits of the voltage amplitude provided by the controller.

Two tests were run in order to observe the behavior of the beam when the voltage kick is applied. In the first case the limits were constant, while in the second the limit is changing exponentialy with each turn.

This method was already implimented by Giulia Russo [1].

1. Random value between constant limits

   The first attempt was with constant limits so as to understand how many particles can be extracted based just on one value of voltage.

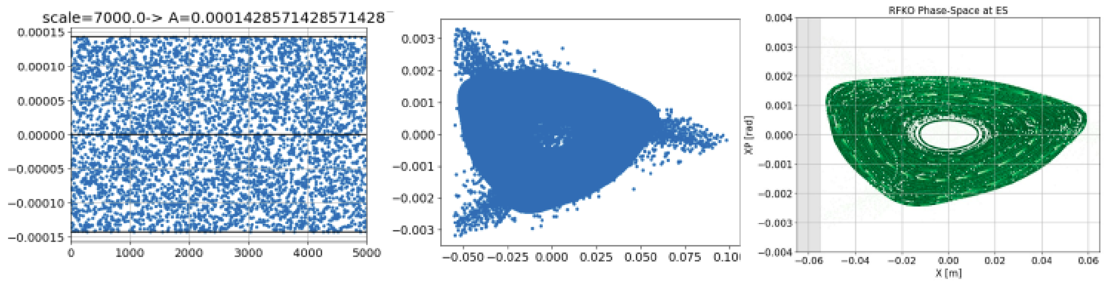


Figure 4.3: Random Value Between the limits

   From the above plot it is observed that that in scale 10^7 there is barely any extraction.

   So for the next steps I choose an amplitude in scale 10^{-5}

2. Random value between exponentialy growing limits

   To test how it works beyond set-limits, a kick is provided from the harmonic function with the frequency Q_x. From Figure 4.4. I observe that by adding white noise to this, more extraction values can be seen.

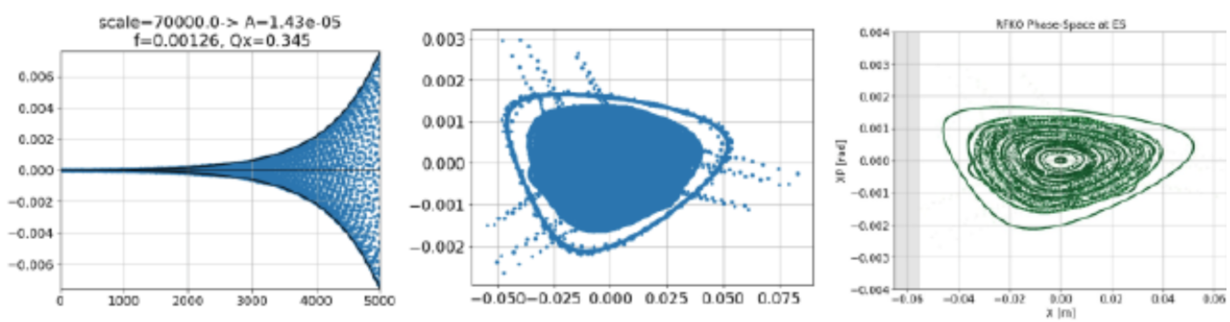


Figure 4.4: Value from sin function in Qx Between the limits

The outcome of this tests showed that by applying a big Voltage kick, the beam blew up and when the Voltage is increasing smoothly the extraction proccess is way closer to what is needed.

4.3 With Modulation

Both HIT [7] and HIMAC [6] use Amplitude and Frequency Modulation for Voltage changes. Amplitude Modulation corresponds to changing the ”limits” of the preliminary test, while Frequency Modulation is used instead of taking a random number between the limits. This is more efficient because the particles in the beam are oscilating with tunes in a specific bandwidth so it is better to apply a voltage within the frequency spectrum instead of a stochastic approach.

1. Amplitude Modulation (AM)

   In amplitude modulation, the amplitude of the wave is varied in proportion to that of the message signal which is the limit value updated by the controller. In the Figure 4.5 we can observe how the Amplitude of the kick is changing in a simulation over 10000 turns.

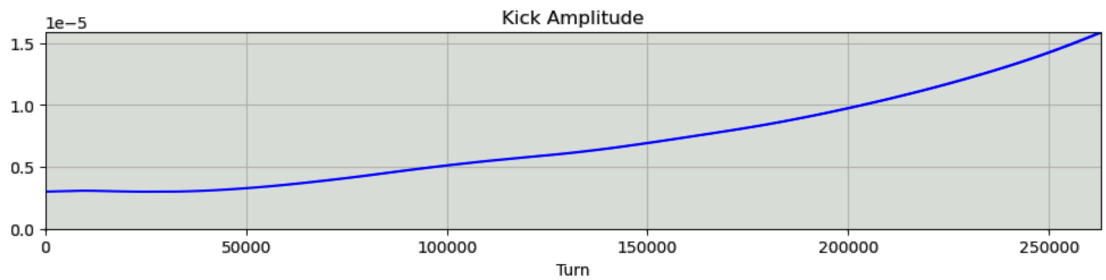


Figure 4.5: Kick amplitude as a function of turn number

2. Frequency Modulation (FM)

   In this case, the FM methods were adjusted to create a signal (kick) that is able to affect the tune of all the beam's particles. Figure 4.6 displays an example of FM.

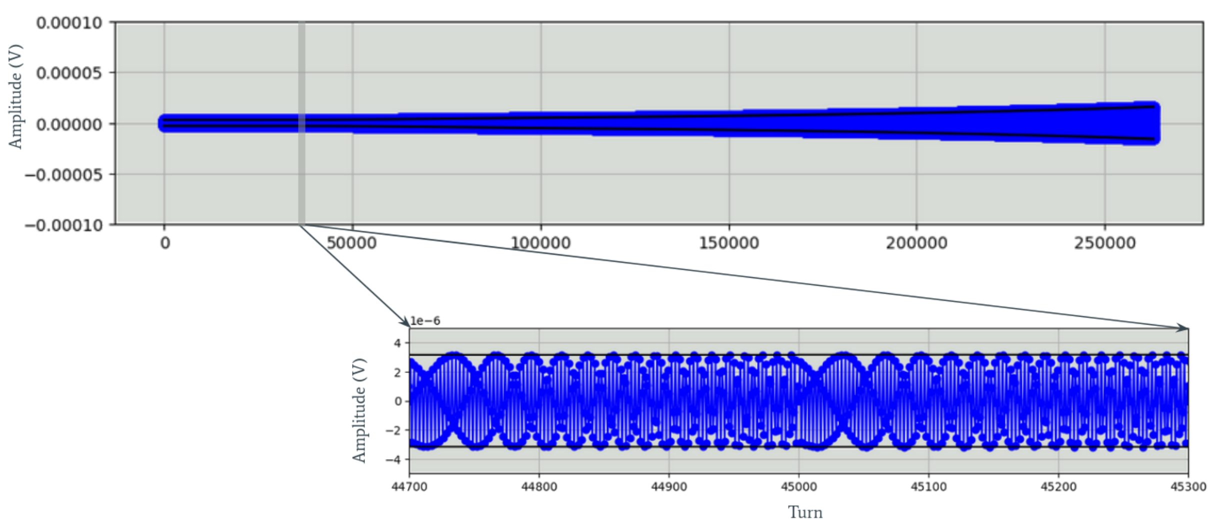


Figure 4.6: Effect of frequency modulation on signal

Two methods have been tested for FM, the use of a modulator signal and a chirp method.

(a) Modulator Signal:
The most widely used method for FM is creating a sine wave that oscillates in the range of frequencies we want to use.
The method is presented in the following equations:

$$\text{carrier\_frequency} = 2 \cdot \pi \cdot Q_x$$

$$\text{modulator\_frequency} = \frac{\text{carrier\_frequency}}{4}$$

$$\text{modulator} = np.sin(\text{modulator\_frequency} \cdot t)$$

$$\text{Modulator Signal} = sin(\text{carrier\_frequency} \cdot t)$$

$$\text{Modulated Signal} = sin((\text{carrier\_frequency} \cdot t + \text{Modulator Signal}))$$

The output of these equations is presented in figure 4.7.

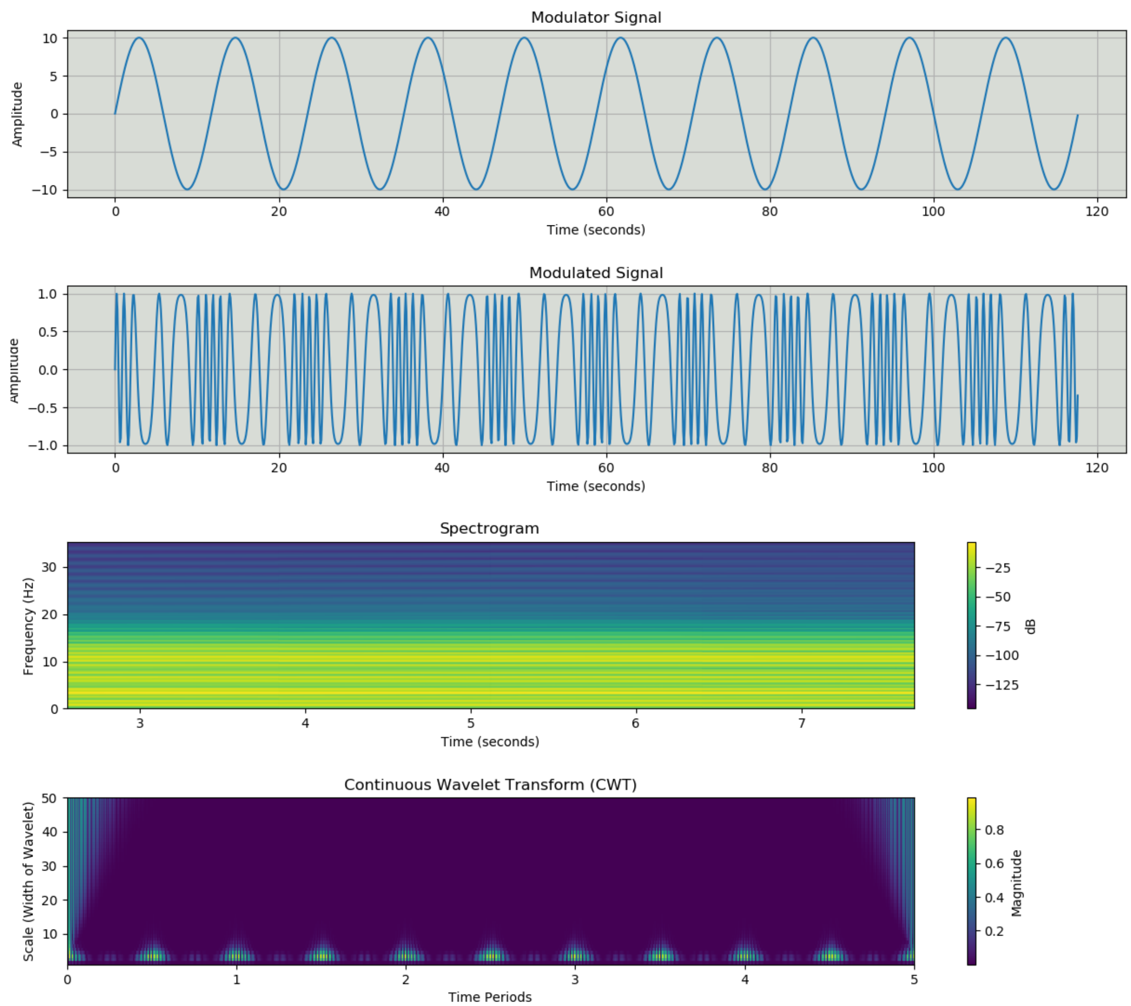


Figure 4.7: Visualisation of FM output with modulator signal in the frequency domain

(b) Chirp:

In the Chirp Method the frequency is changing linearly with time with a certain period and a minimum (f(0)) and maximum (f(last)) value.

The method is presented in the following equations:

$$freq = 2 \cdot \pi \cdot (f(0) + (f(last) - f(0)) * \cdot (t \cdot \text{chirp\_period})/\text{chirp\_ period})$$

$$\text{chirp\_signal} = sin(f \cdot (t\% \text{ chirp\_period}))$$

The output of these equations is presented in figure 4.8.

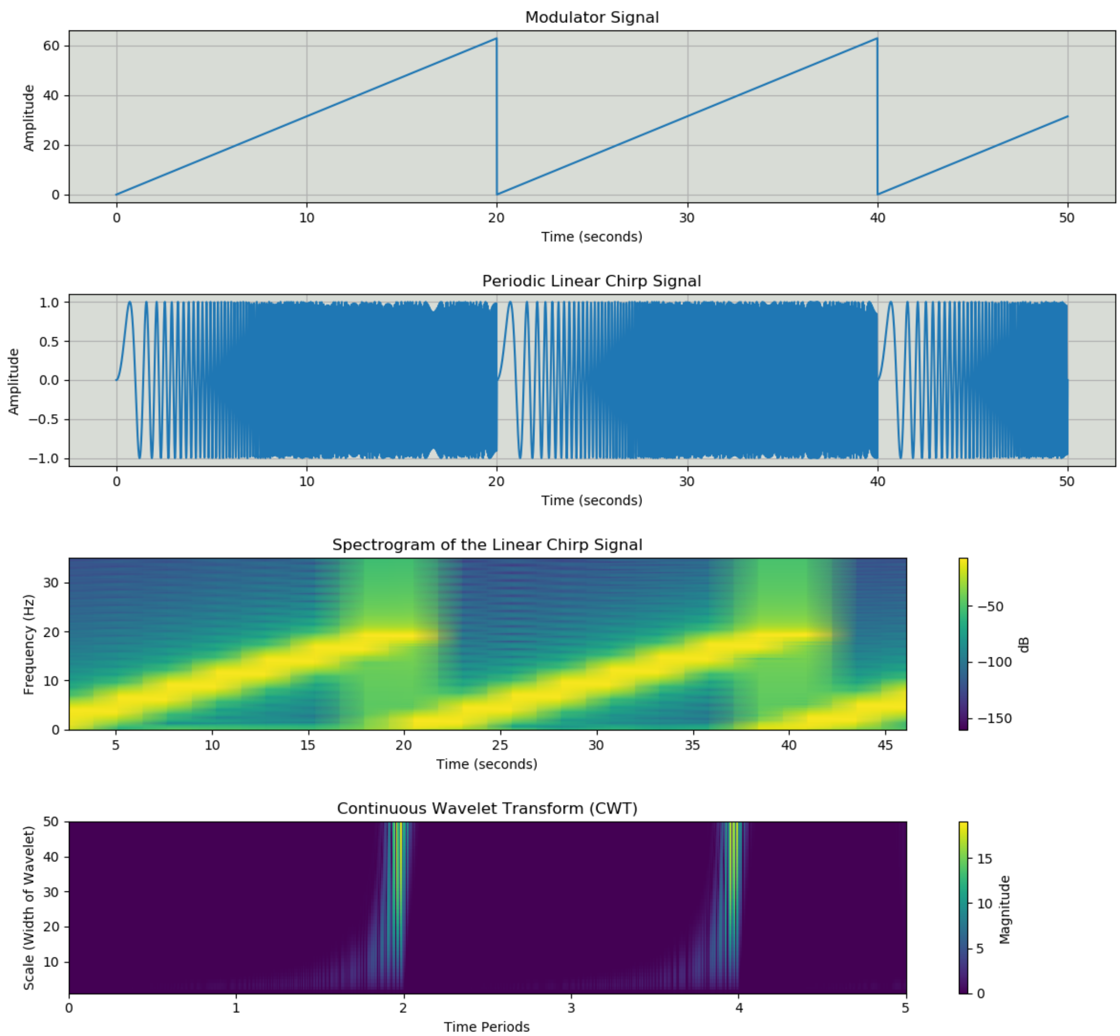


Figure 4.8: Visualisation of FM output with chirp method in the frequency domain

4.3.1 Outputs

1. **Single Sinwave Signal - 2000 particles**

   The first approch of the controller implemented modulates only the Voltage's Amplitude while the Frequency remains constant and equal to the Q_x.

   It is observed in Figure 4.9 that the spill is not uniform and only a few particles are extracted in the first 10000 turns. While the amplitude is increasing the beam started to blow up, resulting in an increasing rate of randomly extracted particles.

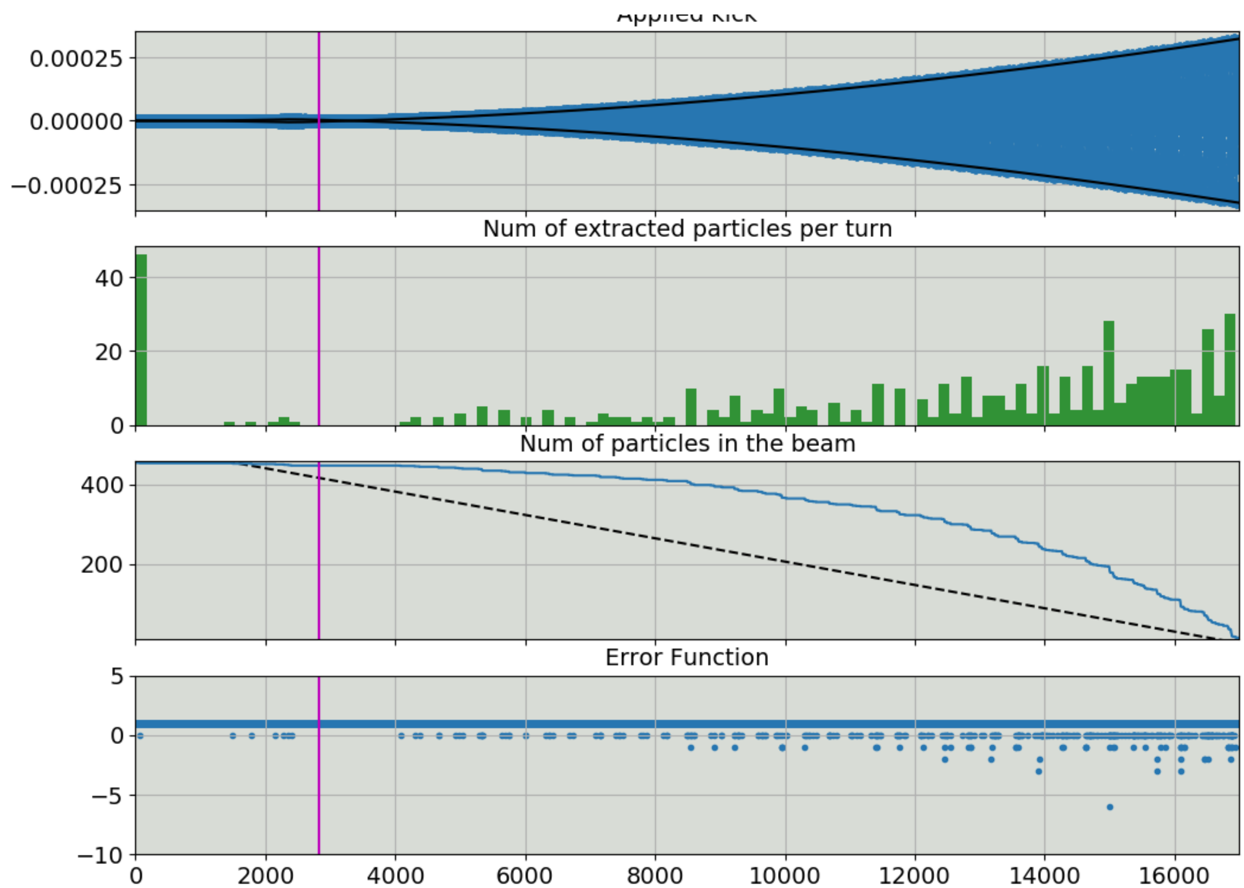


Figure 4.9: Visualisation of extraction output with single sign wave signal

2. **Modulator Signal - 2000 particles**

   In this case there is one particle extracted every time there is extraction, but it is not uniform because the rate of extraction is not constant, and also it lasts only as long as the voltage's amplitude is increasing. Additionally the error function does not tend to go to zero(Figure 4.10: Error Function). Basically it does not oscilate at all, in contrast a particles is extracted in random turns (Figure 4.10: Num of extracted particles).

With Maximum Limit

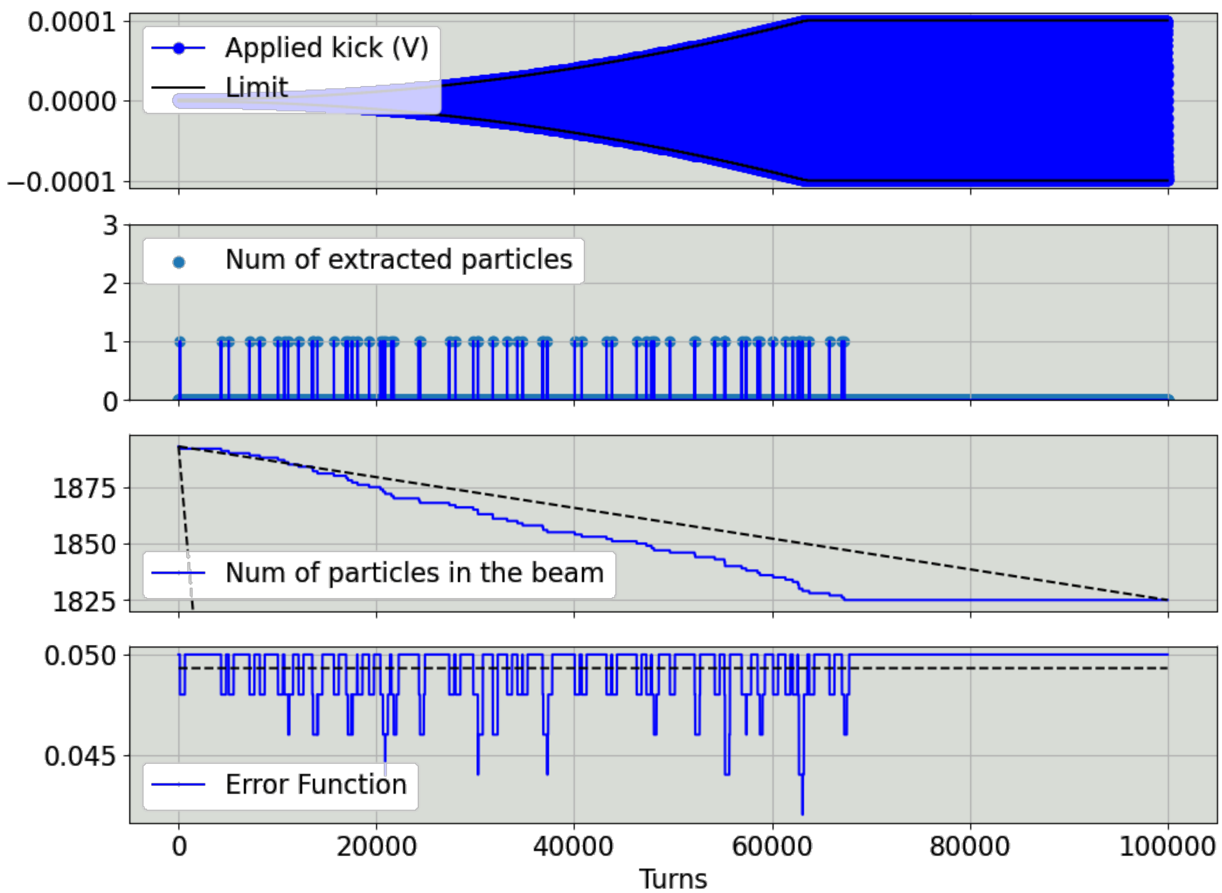


Figure 4.10: Visualisation of extraction output with modulator wave signal

The same method was impliemented without setting an upper limit, the results are shown in Figure 4.11. It was observed that the rate of extraction is still not constant and has a great difference from the requested one (Figure 4.11 Num of particles in the beam). However it is important that when extraction does occur, it is only one particle per turn (Figure 4.11 Num of extracted particles). The controller still doesn't work efficiently as the error function is not trying to reach the setpoint but changes randomly over time (Figure 4.11: Error Function).

Without Maximum Limit

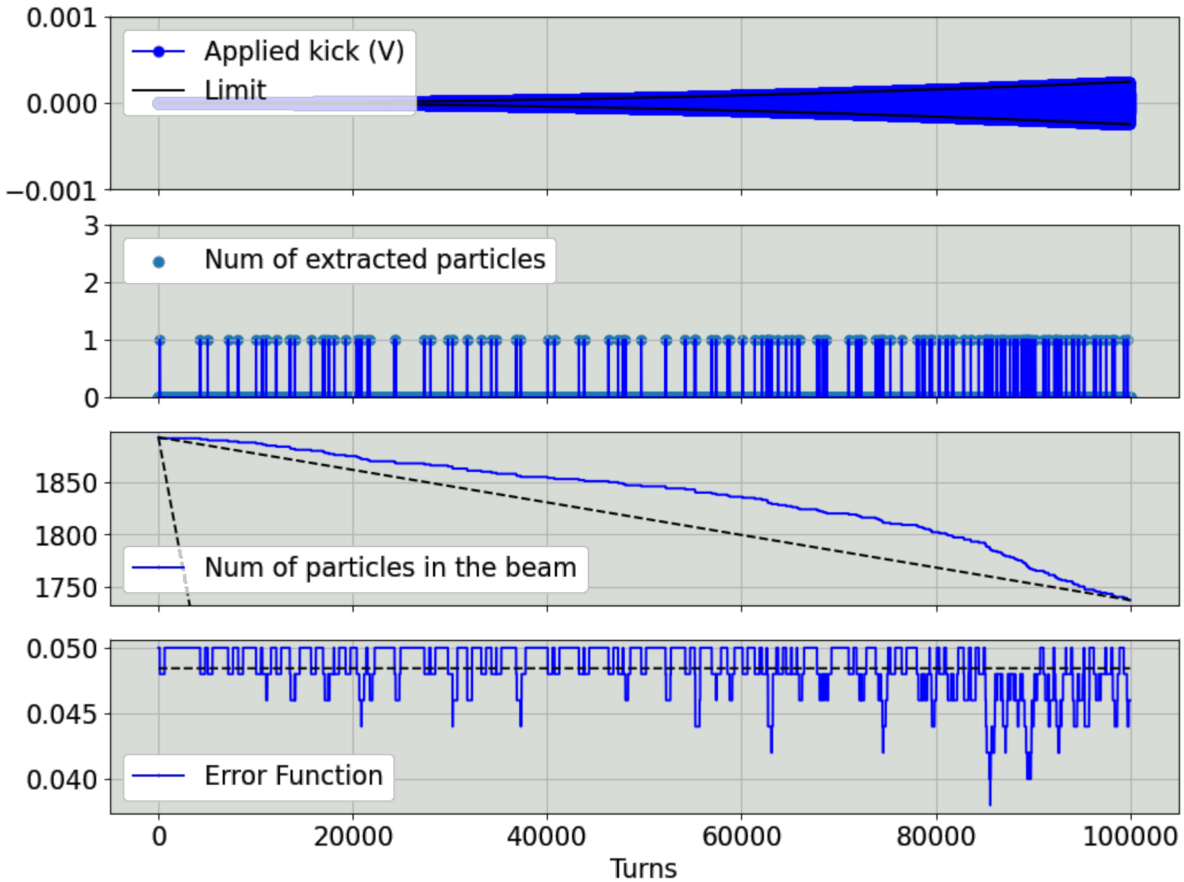


Figure 4.11: Visualisation of extraction output with modulator wave signal without max limit

3. **Chirp Result** The simulation was ran for a beam consisting of 2000 and 10000 particles.

   This time the controller eventually looks like it is working. It is obvious that our extraction rate is oscilating, and it tends to approach the setpoint (Figure 4.12:Num of particles in the beam).

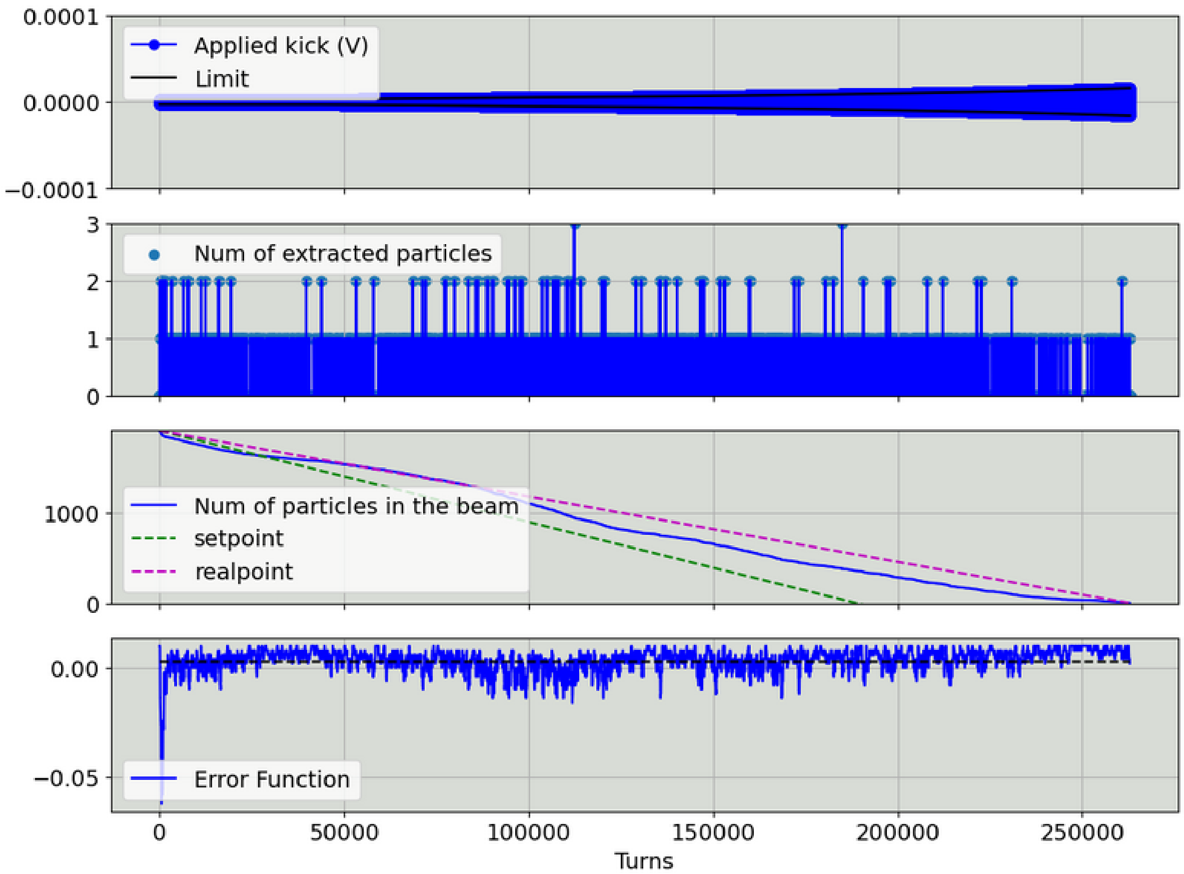


Figure 4.12: Visualisation of extraction output with Chirp method for 2000 particles

In order to have a clearer view, the same class was run for 10000 particles. Now the oscilations become wider, which is apparent both in the error function (Figure 4.13:Error Function) and the diagram with the number of particles in the beam (Figure 4.13:Num of particles in the beam).

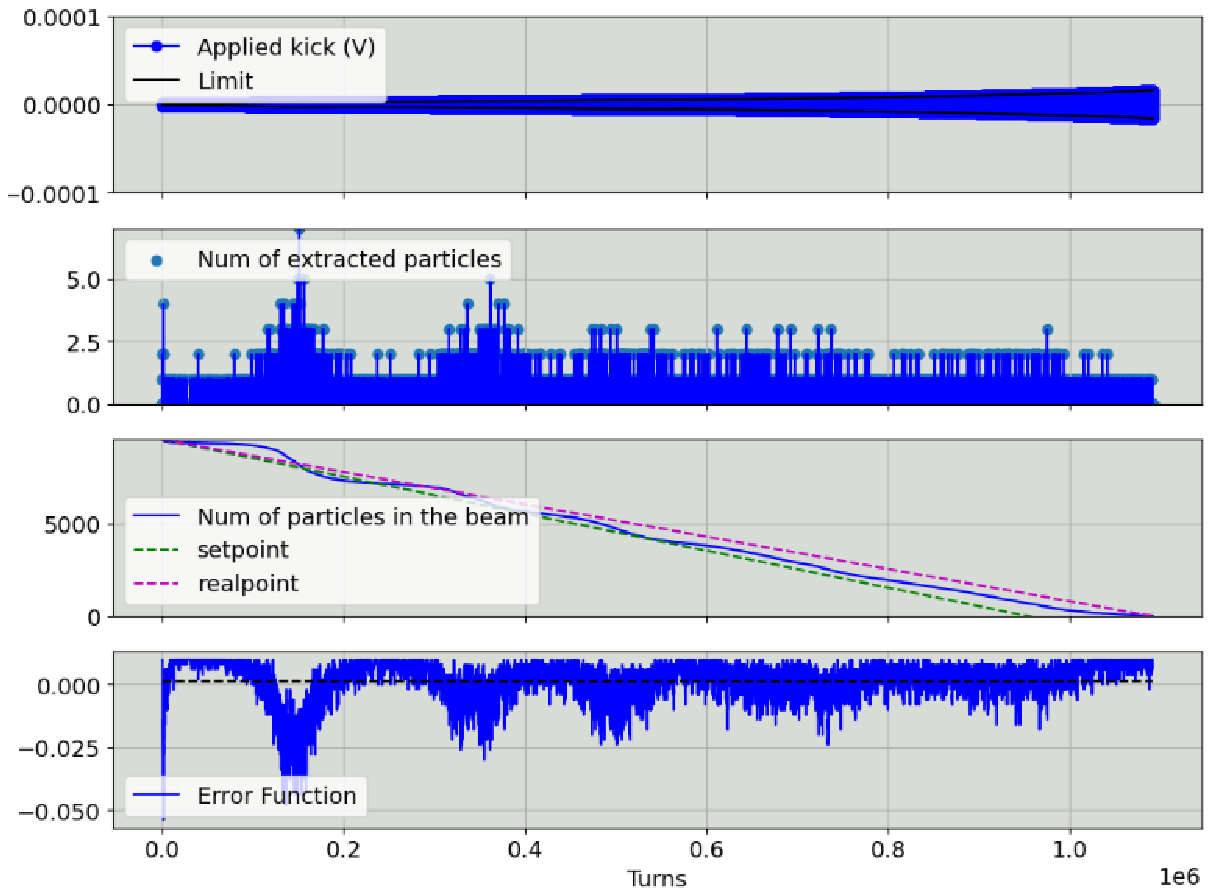


Figure 4.13: Visualisation of extraction output with Chirp method for 10000 particles

It is interesting to observe the outpout if the setpoint get 5 times larger: The oscilations are much smaller and the extraction rate achieved the smaller diference from the setpoint (Figure 4.14).

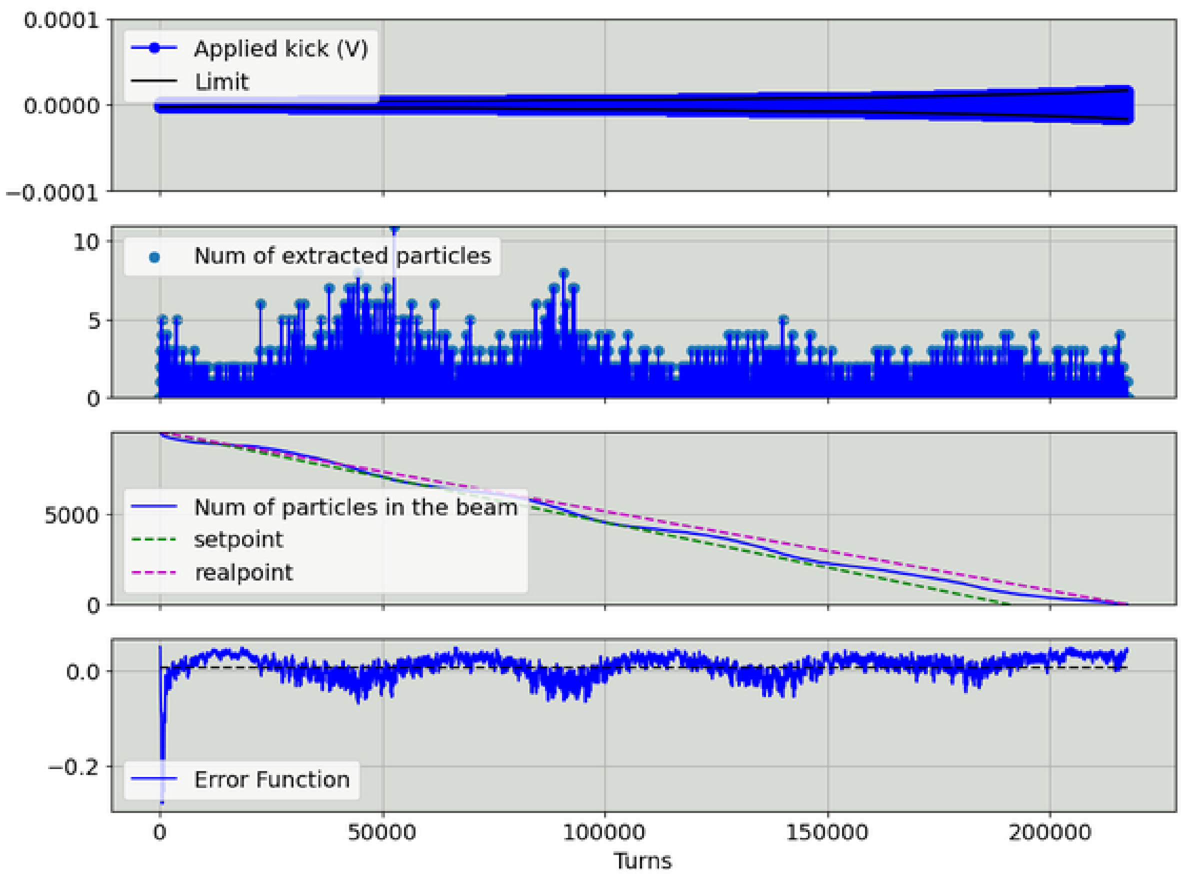


Figure 4.14: Visualisation of extraction output with Chirp method with 10000 particles - 5x setpoint

4. **Importance of Frequency Modultion**

   In Figure 4.15 the beam stautus before the extraction started is shown.

   When a Modulater Signal is used for FM, the kick neeeds to be too high to continue the extraction, which results to the beam blowing up (Figure 4.16). However, when the chirp method is used, as shown in Figure 4.17, the extracted beam is uniform and fits perfectly the requirements.

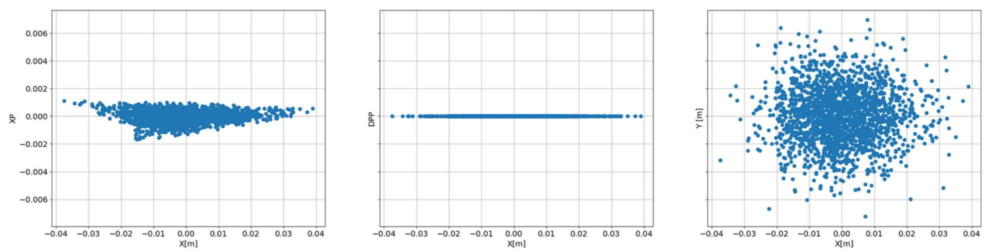


Figure 4.15: Initalize Beam

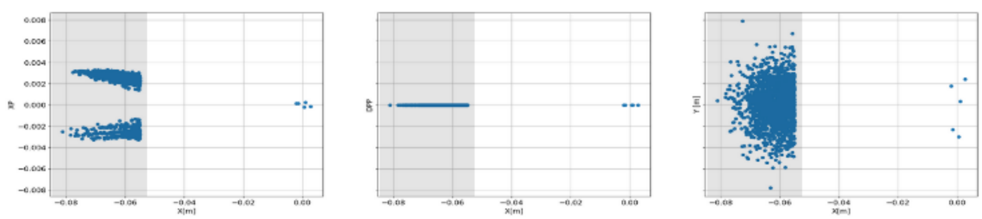


Figure 4.16: FM: Modulator Signal

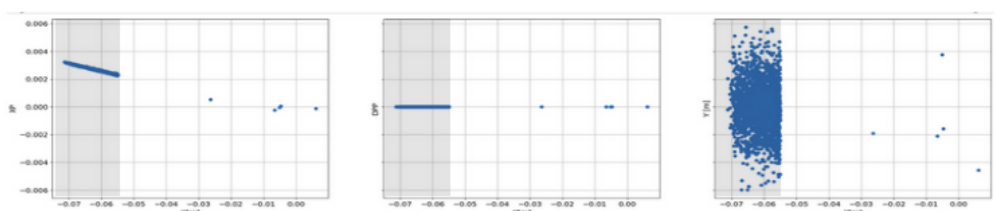


Figure 4.17: FM: Chirp Method

4.4 Statistical Analysis

4.4.1 Probabillity Mass Function (PMF)

The number of extracted particles in a certain amount of time (500 turns) can be described as a Poisson distribution. I.e. in a window t=500 turns, r=setpoint is the rate of events that occur. With a mean of $\lambda = r \cdot t =$ setpoint $\cdot$ window length. The probability mass function of the Poisson distribution is described by the equation:

$$P(x = k) = \frac{1}{k} \cdot e^{-\lambda} \cdot \lambda^{k}$$

In a Poisson process, the number of observed occurrences fluctuates about its mean λ with a standard deviation of $\sigma_k = \lambda$ (Figure 4.18) . These fluctuations are denoted as Poisson noise. i.e. in our previous case, where $\lambda = r \cdot t =$ setpoint $\cdot$ window length $= 500 \cdot 0.05 = 25$, the fluctuation is $\sigma = \lambda = 5$. So in the best scenario we expect to have 25 ± 5 extracted particles in each window.

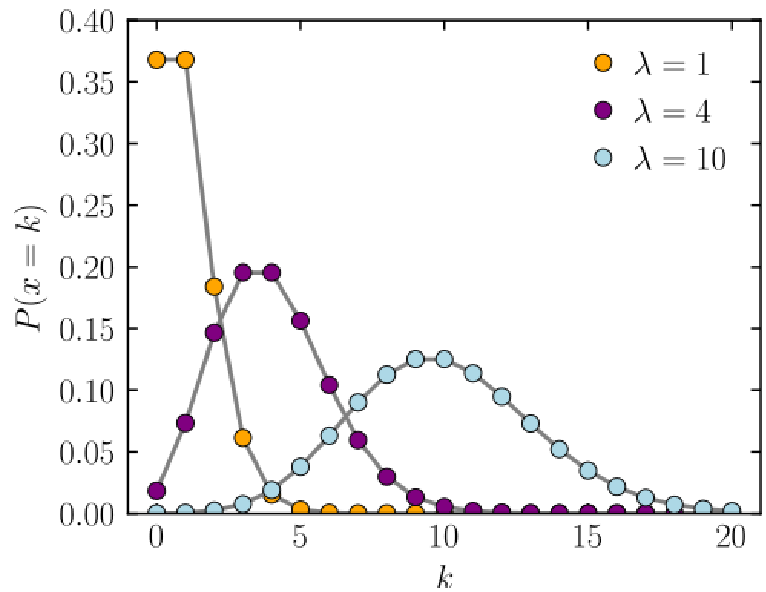


Figure 4.18: PMF in Poisson Distribution [10]

In Figure 4.19:Probability Mass Function, the blue curve is the PMF for the setpoint, so $\lambda = 5$, and the orange one is the PMF for the realpoint, so $\lambda = 0.03726 \cdot 500 = 1.863$. The magenta dots are calculated about the simulated beam. It is clear that the dots follow the PMF for $\lambda = 1.863$. This gives a high probability to extract 0 to $\sqrt{2}$ particles per bin but there is also a lower chance to have even more, when the error for the extraction is $\sqrt{\lambda} = 1.3649$.

In contrast in Figure 4.20:Probability Mass Function the PMF for the realpoint and for the setpoint are obviously closer, while the magenda dots still fit with the orange curve.

Modulator Signal - 2000 particles - setpoint = 0.01

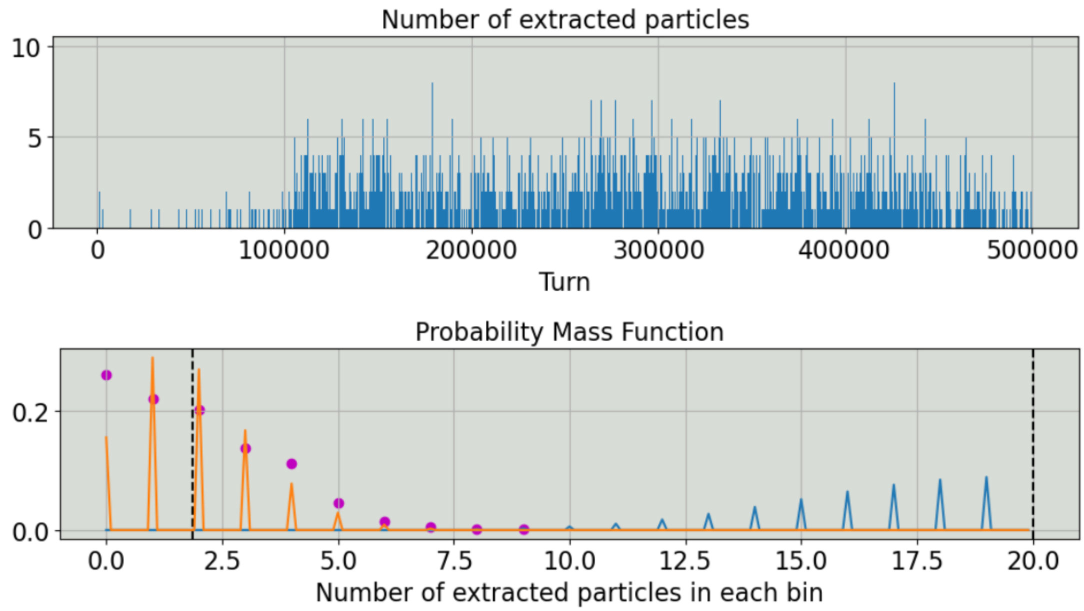


Figure 4.19: Statistical analysis of extracted particles number using modulator signal method

Chirp Signal - 2000 particles - setpoint = 0.01

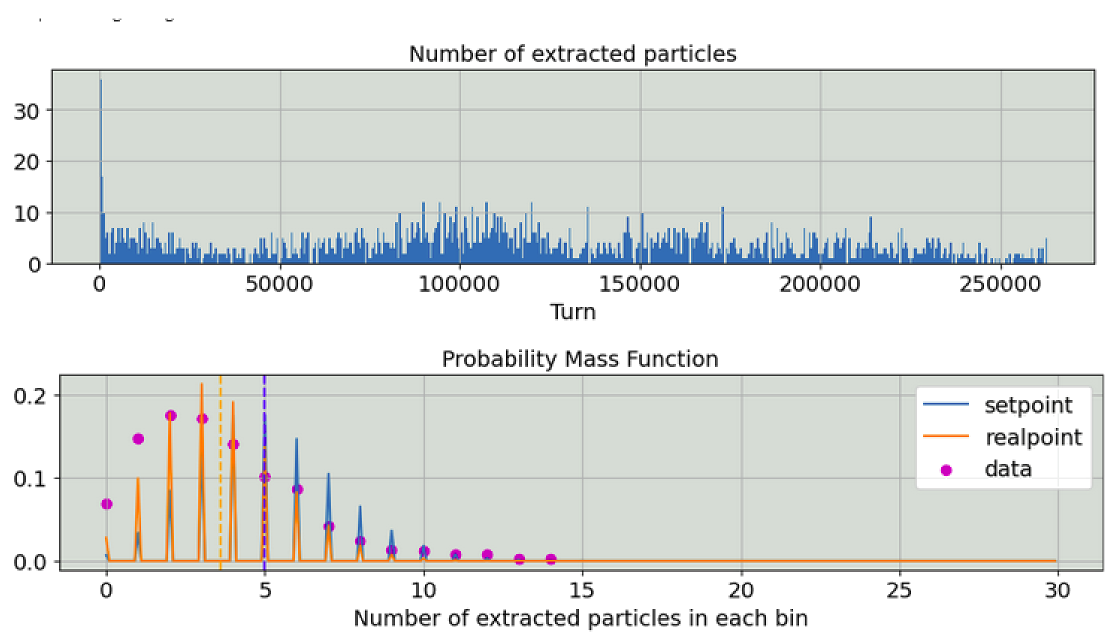


Figure 4.20: Statistical analysis of extracted particles number using chirp method

4.4.2 Duty Factor

It is used widly for comparison reasons.

$$F = \frac{(\sum(N_p/T))^2}{\sum(N_p/T)^2}$$

In my case, $F_{av} = 0.88758$ which is within the range reported by ceveral published studies [3].

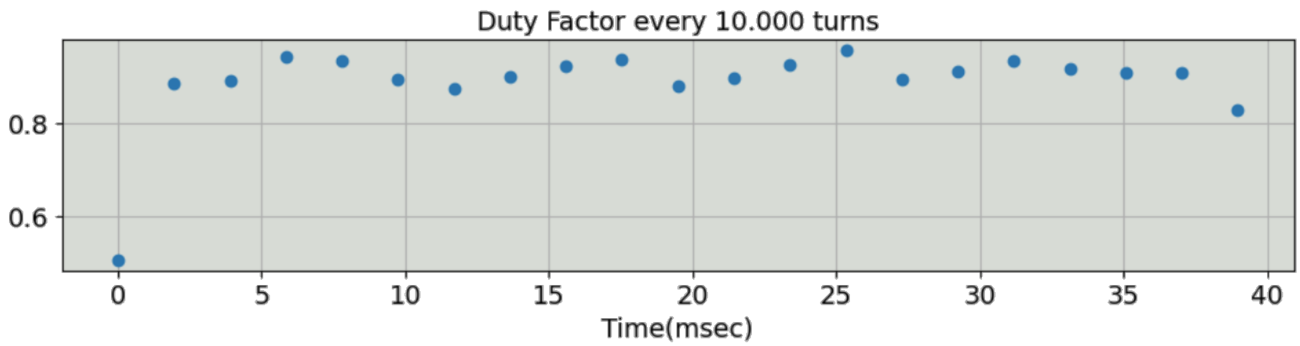


Figure 4.21: Chirp Signal - 10000 particles - setpoint = 0.05

Chapter 5

Conclusion

In conclusion, the tool's primary purpose is to facilitate control over the extraction process at the Helium Synchrotron, accommodating various factors such as the number of particles, emittance, sextupole strength, and tune distance. Previously, each RF-KO necessitated manual optimization based on an eight-variable function.

Future enhancements may involve further parameter optimization or the development of an automated optimization system. To comprehensively support the design of slow extraction at the Helium Synchrotron, it is important to add a D component of the PID controller or implement a Feed Forward System. This step will effectively reduce oscillations around the set-point, thus completing our control system.

Also a decision has been made to rewrite the tool in C, instead of using Python, in order to improve running time. It is worth noting that there is existing interest within the Xsuite community to utilize this tool, which is driving the effort to develop it into an element suitable for addressing different challenges in accelerator physics.

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