Uniform beam transport

Summer student report

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Abstract

The purpose of this project was to simulate and investigate beam dynamics for an electron bunch at CLEAR at CERN. The study followed work by [1] and [2] on bubble-beam bunches, which can deliver uniform dose to irradiation and radiotherapy samples. This project aimed at study in particular how a bubble beam evolves in the accelerating structures in CLEAR, and to find the optimal parameters which give high energy bunches (up to 200 MeV) while maintaing the bubble shape. It was found that it is possible to have a bubble shaped beam at the end of the beamline, with momentum of 197.1 MeV/c and a kurtosis of 1.9548, meaning that it is possible to deliver uniform dose for high energy beams.

1 Introduction

Uniform accelerated beams have become a major topic of research in recent years due to their possible uses in radiotherapy and irradiation studies. In particular, uniform beams have shown promising results for FLASH radiotherapy techniques, as these beams can deliver uniform doses to samples throughout the area of interest.

The work for this project follows work from [1] and [2]. In these works, simulations have shown that it is possible to generate a beam with uniform intensity distribution in the initial structures of the accelerator (electron gun and solenoid). In particular it has been shown that a bubble shape configuration for the beam can deliver uniform dose across the transversal plane, and that for some combinations of gun phase and solenoid field, the bubble shape is preserved during drift motion [1].

The aim of my project, therefore, was to further develop on these results, and to simulate the beam dynamics in later stages of the CERN Linear Electron Accelerator for Research (CLEAR). In particular my aim was to determine whether it is possible to still obtain uniform distribution of the bubble beam after the three accelerating structures in CLEAR and to obtain the optimal parameters for this to happen.

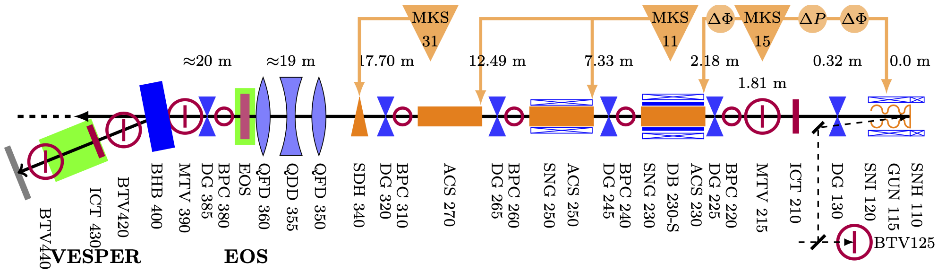


Figure 2: CLEAR beamline, courtesy of [3].

My work therefore relied on simulating beam dynamics and analysing the results of these simulations. For this purpose I used the RF-Track software [4], which can produce beam evolution simulations.

2 CLEAR Layout

CLEAR's complete beamline and description of structures can be found in [5]. For this project, the structures I implemented in my simulations were the three RF accelerating cavities (in orange in Figure 2).

It is important to note that the first RF cavity is powered by the same klystron as the electron gun, and that the 2nd and 3rd cavitites are powered by a second klystron. This means that the field in the 2nd and 3rd cavities will have the same phase. This should be the case aswell for gun and 1st RF cavity, however a phase changing knob is in place, which allow us to set different phases for the two of them.

The RF cavities have a gradient of 14.6MV/m and are each 4.5 meters long, meaning that it is possible to accelerate the bunch up to 197.1 MeV/c from the three structures alone, to which we can add the acceleration from the gun and solenoid, (usually in the order of 4-8 MeV/c).

3 Simulations Structure

As mentioned, to simulate the beam dynamics I used RF-Track software [4]. To simulate the beam evolution first I tracked the beam through the gun and solenoid up until 180 cm. Then, after extracting the particle distribution at this stage, I created the lattice for the cavities and simulated the beam evolution inside these. It is important to note that when creating the lattice for RF cavities, the timer is reset, setting time t=0 the moment the bunch enters the first RF cavity.

In order to establish what the optimal parameters to maintain uniformity are, I scanned through multiple phases and I tracked the beam inside and outside of the chambers.

Electron bunches at CLEAR are producing by shining a laser on a photocathode. This means we can create beams of elliptical shape for a desired length (measured in picoseconds) For my simulations I used a 10000 particles beam of 300 pC total charge, the beam was 2 ps long when generates, and it had radius of 1 mm.

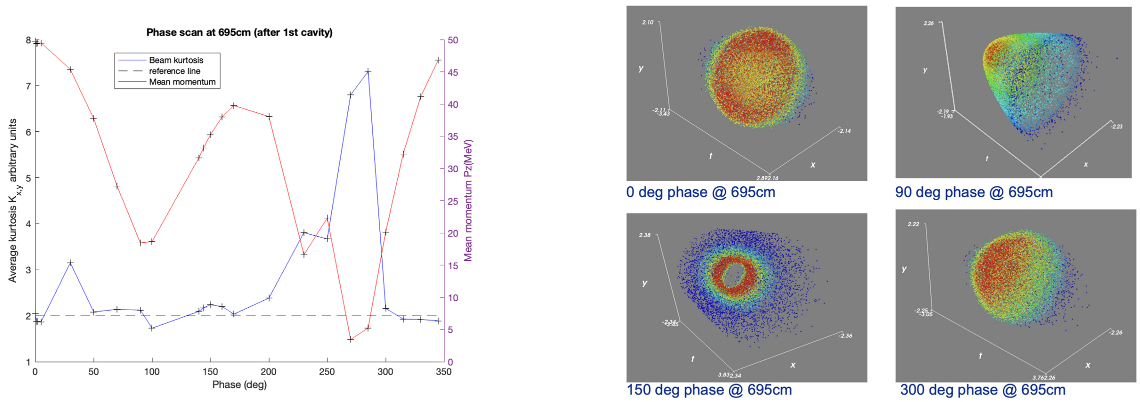
For the simulations there are some important parameters to be tracked:

- **Kurtosis**, defined as the expectation value of $((x-\mu)/\sigma)^4$, it represents a measurement of how flat is the beam: kurt $= 2$ means uniform distribution, while kurt $= 3$ can mean gaussian.

- **Average Z momentum**, P_z is important to track, because we need our beam to gain defined amounts of energy for its uses.

- **Bunch transverse dimensions**, this was tracked usually by measuring the standard deviation of the coordinates. It is important because we need our beam to be focused.

- **Shape of the bunch**, sometimes even if we get kurt $= 2$ and a small σ, we might still not have a bubble beam, so it is useful to double check the shape of the beam.



(a) Momentum and kurtosis phase scan.

(b) Snapshots of the beam shape at different phases.

Figure 3: Phase scan after the 1st accelerating cavity. We can see that the 0° phase gives us the best accelerating value and the kurtosis closest to zero. There are other phases where kurt = 2, for example at 170°, however we can see on the right that these phases do not produce the desired bubble shape.

4 Results

4.1 1st Cavity phase scans

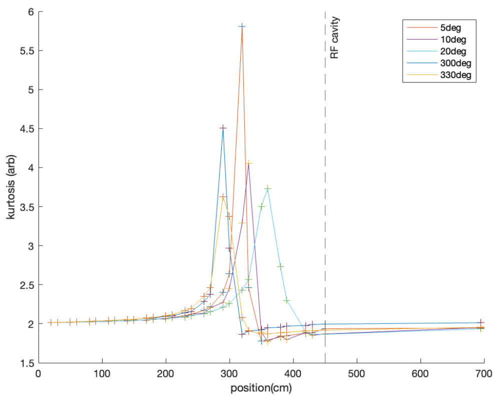
The beam enters the first RF-cavity with a bubble shape configuration (Kurt = 2.0011, $P_z = 5.077$ MeV/c). There are two major contributions to the beam shape evolution: one comes from the accelerating field, the other one from the electrons space charge forces. Space charge forces will tend to make the beam lose its bubble shape, however the timescale over which this happens is set, meaning that if the beam is accelerated, the timescale over which it travels across CLEAR is shortened, and much shorter than the space charge timescale. This means that by accelerating the beam, we can retain the bubble shape, which delivers uniform dose. This was tested by boosting the beam in the simulation and observing that the kurtosis remained constant for boosted beams, while it changed in those which were not accelerated [1].

Multiple scans at different phases have shown that the best result is achieved for a 0° phase. At this phase, kurtosis remains close to 2, we have the highest momentum and the bubble shape is preserved, as we can see in Figure 3b.

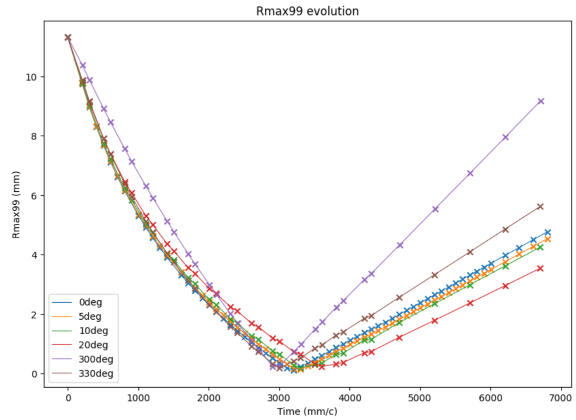
The reason for this marked difference in the shape of the beam is to be accounted for by the fact that the particle bunch is travelling along the axis of the chamber, and the field in the simulation is created by solving the Poisson equation in free space. Intuitively, since the divergence of the E filed must be zero, on the crest of the wave, we will also have a focusing effect in transversal plane, while in the pit of the wave we will have a defocusing effect. Therefore, particles at 0° phase will be entirely in the accelerating part of the wave, at 90° phase will be half accelerated (and focused), and half decelerated (and defocused), giving rise to the cone shape in Figure 3b. At 180°, the particles are pushed away from the center of the cavity from the defocussing effect, giving rise to the shape of cylindrical hole.

4.2 Bunch evolution inside RF cavity

It is also interesting to observe how the shape of the bunch evolves inside the RF cavity as well. This was done for some selected phases at multiple points inside the RF cavity. In these measurements it is useful to keep track of two parameters: the kurtosis and Rmax99, which corresponds to the largest radius which includes 99% of the particles of the bunch. From Figure 4 we can clearly see that the RF field first focuses the particles, until space charge forces take over and the beam expands again. In the kurtosis plot this corre-



(a) kurtosis evolution inside 1st RF cavity for some selected phases.



(b) Evolution of RMax99 over time for some selected phases inside the first RF cavity.

Figure 4: position scans inside and after 1st RF cavity.

sponds to the large spikes, which are due to the beam momentarily losing its bubble shape, before acquiring it again when it expands. It is important to note that for different phases the focusing effect will be different as well.

In particular, as the phase increases, the spike in kurtosis travels further along the cavity, meaning that there will be some phase where this points ends up being at the edge of the cavity or out of it, which is the reason why some phases do not go back to kurtosis 2, as seen in Fig 3b.

4.3 Simulating 2nd and 3rd cavities

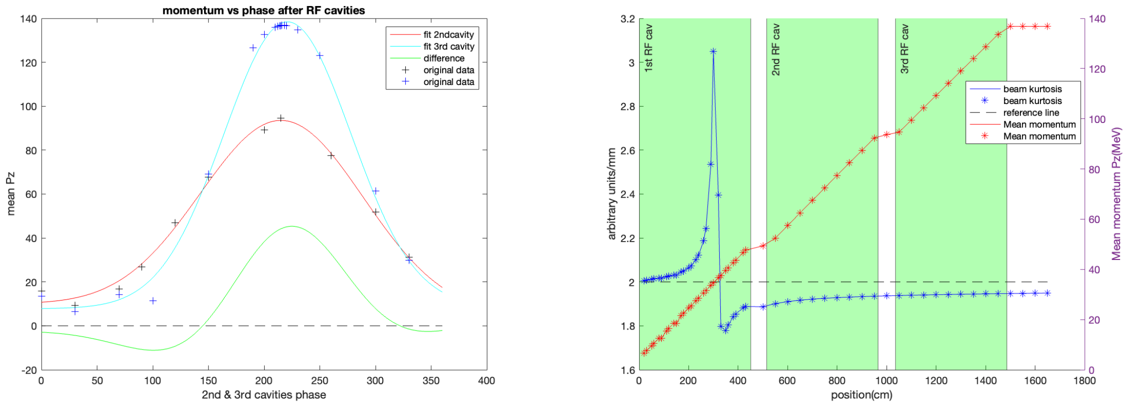
After the first cavities, also the second and third one were simulated. Again the first task was to do a phase scan, looking for the optimal phase for these two cavities, in order to accelerate the beam at maximum energy. The phase scan (Figure 5a) showed that the beam is accelerated the most at a 215° phase, both for the 2nd and 3rd cavity. It is interesting to note that both distributions fit to gaussian curves, and that if we consider the difference between these two curves we get positive acceleration for a 180° section, which is what we expected, given that the travelling wave inside the cavity will be accelerating only for half its period.

The position scan of Figure 5b shows us something else: the kurtosis has less variation in the 2nd and 3rd cavities than in the 1st one. A possible reasons for this effect, is that the beam has higher momentum when it enters the later structures. Therefore the focusing and defocusing effect occur with less intensity, as the timescale over which the bunch travels these structures is shorter, compared to the timescale over which it travels the first RF cavity.

4.4 Effective momentum

In Figure 5b we can clearly see that the maximum momentum we can achieve is 136.6 MeV/c. Multiple simulations have shown that this is indeed the maximum momentum achievable in the simulations. However, this is clearly at odds with the theory: since all cavities are 4.5 m long and have a 14.6 MV/m gradient, we should get a maximum momentum of 197.1 MeV/c, when accelerating on the wave crest. Since the gradient of momentum vs position is the same in all three cavities, we can rule out the possibility that the we are not accelerating on crest.

The reason for this inconsistency in the simulation is probably to be searched in the way the software recreates the field from the field map. However, to test wheter it was possible to achieve higher momentum, simulations with a 21.5 MV/m gradient were performed aswell. these gave positive results, delivering a bubble shaped beam (P_z = 197.4 MeV/c, Kurt = 1.9548, RMax99 = 11.362 mm).



(a) Phase scan of momentum for 2nd and 3rd cavities. Both cavities peak acceleration at 215°. Measurements were taken after both chambers.

(b) Evolution of momentum over time for 0° and 215° phases.

Figure 5: Analysis of momentum and kurtosis for 3 stage acceleration.

5 Conclusions

The simulations showed that it is possible to achieved high energy beam with uniform dose distribution using the CLEAR apparatus. By using a bubble shaped beam, we can achieve kurtosis 2 in the transverse plane, minimising the space charge repulsion, and with this project it has been shown that the bubble shape is preserved through RF cavities motion.

Results from the simulations show that the best combination of phases is for 0° in the first RF chamber and 215° for the following two. This gives an average transverse kurtosis of 1.9491, with a bubble shape. This means that the beam has lost part of its uniformity, since it entered the first RF cavity with kurt = 2.0011. However, this loss is acceptable in the context of delivering an almost uniform beam, as it is counterbalanced by the fact that our beam has now acquired energy up to 200 MeV.

While the simulations seem to give reasonable results, it would be important to test this in CLEAR on the accelerator. If experimental results were to match the simulations results, then this could be used for more studies about the FLASH effect. Further work could also include refining the simulations to get better uniformity, and eventually test this also on different distributions of particles (different charge or different number of particles).

References

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