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ENTROPY PRODUCTION AND EMITTANCE GROWTH DUE TO THE IMPERFECTION IN LONG PERIODICAL ACCELERATION CHAINS

M. Droba†, O. Meusel, H. Podlech[1], S. Reimann[2],
IAP, Goethe University, Frankfurt am Main, Germany
[1]also at Helmholtz Research Academy Hesse for FAIR(HFHF), Frankfurt am Main, Germany
[2] also at GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany

Abstract

Contemporary design of efficient linear accelerator is based on ideal periodical structures with an optimisation for perfect periodicity. However, practical realisation involves random errors in the structure (e.g. position of elements, off-sets, non-linearity of the fields etc.) which make prediction of emittance growth difficult. Error studies helps to understand critical points, but they are normally used at the end of the design process. The concept of beam entropy in very simple approximation (assumption of Ornstein-Uhlenbeck model) is used to evaluate emittance growth in perfect periodical chains. The analysis will be performed and differences in modern designs on some examples discussed. Focus will be laid on linac designs with short acceleration structures (RF-phase settings versus position error) and external transversal focusing magnets.

INTRODUCTION

Existing and planned linear accelerators cover wide range of parameters like energy, species, beam current, momentum spread, frequency, acceleration gradient, focusing elements etc. Therefore, it is hard to compare efficiency of such accelerator complex due to the individual goals and also to choose best design for future accelerators.

However, despite cost estimations and economic parameters, there is need for the best beam quality thus minimum emittance growth along the whole chain. Accelerator theory for beam motion in perfect periodical structures and design rules are already well known since many years, but there will be unavoidable imperfections in technical realisation.

The progress in solid state RF power technology opened new options in the DTLs design with relatively short H-mode cavities (number of gaps of about 6-15) and external focusing lenses. The development and the production of the new class high power solid-state amplifiers P>100 kW in a frequency range between 50-300 MHz are very attractive for application in proton and hadron linear accelerators. Additionally, a 6D beam handling along the acceleration chain could be active done by longitudinal phase plane control and steering through RF-phase settings individually in each cavity. In high space charge situation, there will be coupling between transversal and longitudinal planes hence control of RF-phase and transversal magnetic coupling will be coupled as well.

† email address: droba_m@yahoo.com, droba@iap.uni-frankfurt.de

THEORY

Commonly, the rms-emittance is used to evaluate the beam quality. It gives the luminosity for the experiments and represent the compactness of the whole phase space. The emittance along an accelerator chain growth, because of the Liouville's theorem, therefore, the emittance growth as a function of z is often a parameter to evaluate the performance of an accelerator.

In this paper, we express the rms-emittance by entropy of the beam plasma.

$$S = k_B \ln \varepsilon_{n,rms} + const.$$

Following the Ohrenstein-Uhlbeck entropy model [1, 2] it is possible to investigate the change of the beam entropy as a function of time. An assumption is made of the entropy production staying constant in time, which means constant impact on all periodic lengths along whole chain.

$$\frac{dS}{dt} = \frac{k_B}{\varepsilon_{n,rms}} \frac{d\varepsilon_{n,rms}}{dt} = k = const.$$

The solution can be rewritten in linear approximation $k/k_B \cdot t \ll 1$, which in proper design can be always applied,

$$\frac{1}{\varepsilon_{n,rms}} \approx 1 - \frac{k}{k_B} \cdot t.$$

The collection of the simulation results of some projects is depicted in Fig. 1.

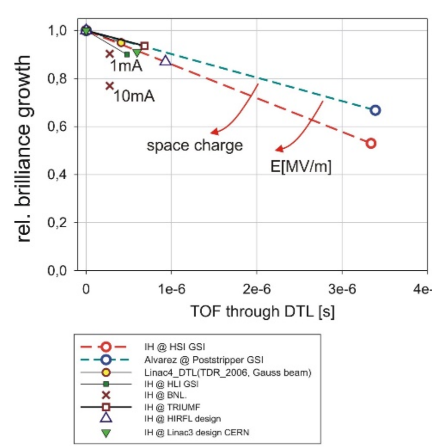

Figure 1: Comparison of the simulation results for various linear accelerators based on the theory [3].

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Statistical decrease of the brilliance in time can be demonstrated. It causes by the production of entropy, which can be applied by increasing beam space charge and acceleration field strength. As an example, the normalised entropy growth rate as a function of the equivalent electrostatic acceleration field strength is plotted in Fig. 2 for several project.

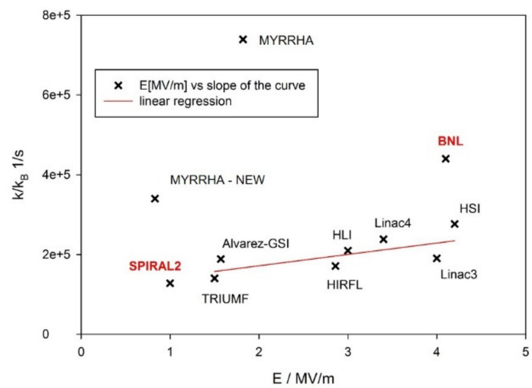

Figure 2: Comparison of slopes k/kB with average acceleration gradient.

The linear regression shows that accelerators for light hadron beams as well as heavy ions can be designed in a way to keep the growth rate of the entropy during the acceleration as low as possible. Because of the nature of this effect, it is impossible to prevent a relative emittance growth, even for very low beam currents. Also, the starting conditions e.g. the emittance of the ion source, as well as, the ion density distribution have an impact on the time Δt needed for the growth of the entropy rate.

Inspired by the picture of the conventional thermalisation, one could state that the beam is being thermalized by imperfection of the accelerator, which additionally can lead to an intrinsic heat up of the beam plasma. Also the stored non-linear field energy of the beam leads to a growth of the entropy. This effect is a result of space charge driven redistribution of the beam particles.

APPLICATION

We have started our investigation on the entropy production in accelerator chain with relatively short acceleration structures. We chose parameter beam settings from Post-stripper Review [4] as an example. For all simulations we have used the simulation tool TraceWin [5]. Figure 3 shows the U^{28+} 15mA beam parameters that were used.

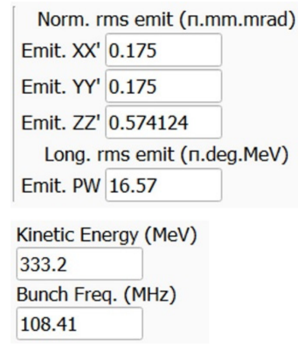

Figure 3: Beam parameters used in simulation with TraceWin simulation tool.

Short H-Mode(βλ/2) structures with 6-8 gaps were chosen with external triplet transversal focusing. The relatively high phase spread for one setting is shown on Fig. 4. Maximum electric field of 9MV/m were used. High phase spread can be used to minimize space charge effects and balance in focusing fields.

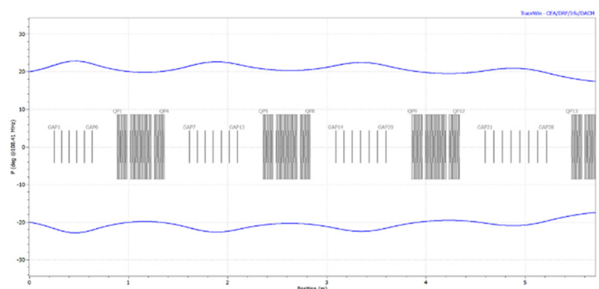

Figure 4: Accelerator chain and beam phase spread.

In Fig. 5, imperfection in a balance of focusing force can cause some unwanted betatron oscillation of the transversal envelopes and hence emittance growth (Fig. 6), due to the effect similar to the magnetic pumping in plasma physics.

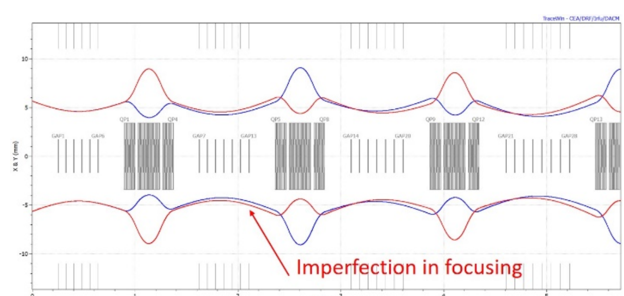

Figure 5: Transversal beam envelopes.

At the beginning, there will be the increase of emittance due to the non-linear field energy stored in starting distribution. Different distributions, expressed by the 4th momentum, lead to different emittance growth. In all cavities, there is small entropy production due to the non-linearity in gaps.

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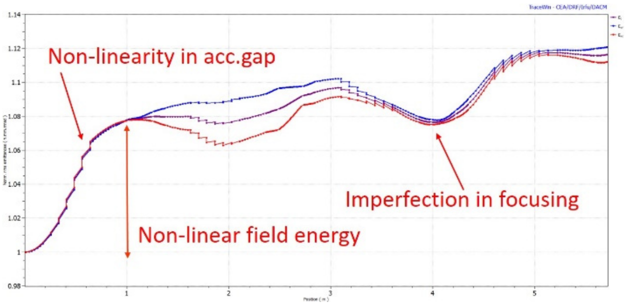

Figure 6: Rms-emittance growth along the chain with imperfect settings.

To find the optimum settings for whole chain and to minimize emittance growth could be very challenging and time demanding depending on a scale looking for (even simulation itself has entropy growth depending e.g., space charge calculation).

However, error studies can help to find a realistic desired scale and to define precision of the simulation. An example of the error study for the RF-phase error of about 0.1° and gap positioning of about dz=±0.1mm, distributed with probability function along whole chain, is depicted in Fig. 7.

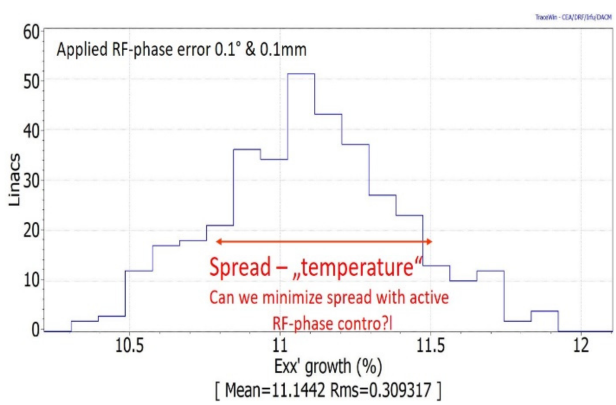

Figure 7: Error studies on the acceleration structure with applied phase errors 0.1° and positioning dz=0.1mm.

The resulting emittance growth spread in x-x′ plane of about ±1% at 11% for centre is already a huge number. Already such small errors and in relatively still short chain lead to conclusion that space charge effect are still too high.

New beam injection will be modelled in a near future and active control of cavities RF-phase will be implemented. Also approach using genetic algorithm for coupled cavity RF-settings and magnetic focusing strengths could help to optimize chain settings in future designs.

CONCLUSION

The concept of beam entropy was chosen to evaluate the thermalisation of a particle beam in a linear accelerator. All imperfections in the geometry as well as field strength and phase position lead to a growth rate of the entropy. The process seems to be enhanced by space charge forces as well as high acceleration gradients.

REFERENCES

[1] J. Struckmeier, “Concept of entropy in the realm of charged particle beams,” *Phys. Rev. E*, vol. 54, no. 1, p. 830, July 1996. https://doi.org/10.1103/PhysRevE.54.830

[2] J. Struckmeier, “Stochastic effects in real and simulated charged particle beams,” *Phys. Rev. ST Accel. Beams*, vol. 3, p. 034202, Mar 2000. https://doi.org/10.1103/PhysRevSTAB.3.034202

[3] M. Droba, O. Meusel, H. Stöcker, “Heavy Ion Linac for Synchrotron Injectors,” *JPS Conf. Proc.*, vol. 8, p. 011007, 2015. https://doi.org/10.7566/JPSCP.8.011007

[4] A. Rubin, X. Du, L. Groening *et al.*, “Status of the Beam Dynamics Design of the New Post-Stripper DTL for GSI – FAIR,” in *Proc. IPAC'17*, Copenhagen, Denmark, May 2016, pp. 4414-4416. https://jacow.org/ipac2017/papers/THPVA003.pdf

[5] TraceWin. https://irfu.cea.fr/dacm/logiciels/codesdacm/tracewin/tracewin.pdf