STUDIES OF EMITTANCE MEASUREMENT BY QUADRUPOLE VARIATION FOR THE IFMIF-EVEDA HIGH SPACE-CHARGE BEAM

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Abstract

For the high-power (1 MW) beam of the IFMIF-EVEDA prototype accelerator, emittance measurements at nearly full power are only possible in a non-interceptive way. The method of quadrupole variation is explored here. Due to the high space-charge regime, beam transport is strongly non-linear, and the classical matrix inversion is no more relevant. Inverse calculations using a multiparticle code is mandatory. In this paper, such emittance measurements are studied, aiming at checking its feasibility and evaluating its precision, taking into account the constraints of losses and quadrupole limitations.

INTRODUCTION

IFMIF-EVEDA is a Europe-Japan joint project aiming at studying and constructing an accelerator-based facility dedicated to materials study for future nuclear fusion reactors [1]. It includes two identical 125 mA (CW), 5 MW, 40 MeV D^+ accelerators. Due to these very challenging high intensity and high power, a prototype accelerator is being studied and installed in Japan, with the same beam current, but accelerating D+ to only 9 MeV. In the last section (HEBT) of this prototype, which drives the 1.1 MW beam to a beam dump, many diagnostics are foreseen for beam characterising. This plays a determinant role in the validation process leading to the approved options for the final IFMIF.

Beam emittance measurements will be performed at low duty cycle with a combination of slits and beam profile monitors. But such measurements at full power are only possible in a non-interceptive way. In this article, we present the simulations made in order to study the feasibility of emittance measurements by the quadrupole variation method.

MEASUREMENT METHOD

The measurements will be performed in the first part of the HEBT, by varying the gradient G of the first quadrupole located at the position e, and measuring at the position s (~2.5 m downstream) the beam size σ_s=f(G). The knowledge of at least three different points of this function allows to find out the beam characteristics at e, namely two Twiss parameters and the emittance: α_e, β_e, ε_e. In case of linear or nearly-linear beam transport, that can be done by inversion of the beam matrix. See for example [2], [3], and [4]. In our case, due to the very high space charge induced by high beam current at relatively low energy, the beam transport is strongly nonlinear, we have to use instead numerical inversion with a transport code and work in multiparticle mode.

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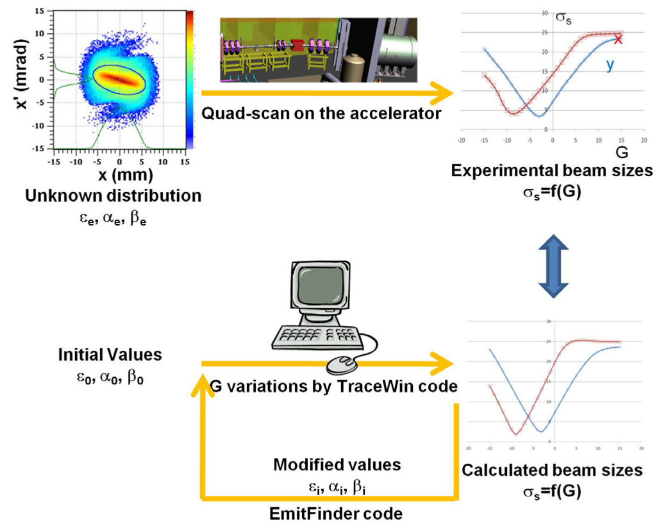

Figure 1: Principle of the emittance measurement.

The principle is schematically explained in Fig. 1. In a first step, the gradient G is varied on the accelerator for an input beam of which the parameters have to be determined, and the experimental curves σ_s=f (G) are measured in x and y. In a second step, the TraceWin transport code [5] is launched with an input beam characterised by α, β, ε, which allows to obtain the calculated curves σ_s=f(G). A home-made optimisation code called EmitFinder, based on a SImplex algorithm) will then search for the α, β, ε values in x and y (6 values at all) so that the above calculated and experimental curves are the closest.

For the present study, the first step is also simulated by the transport code, with a known input distribution, to which the distribution found out by EmitFinder can be compared. That allows to check the correctness of optimisation results and to estimate the quality of the proposed measurement procedure in various situations.

PRELIMINARY STUDIES IN 1, 2, 3D

First of all, the evolutions of σ_s are explored following the single variations of either quadrupole gradients or input beam parameters. The below results are obtained with the "nominal" input beam, represented by more than 1000 macroparticles, coming from the theoretical beam extracted from the ion source. Variations of G in the maximum available range of the quadrupole, ±15 T/m, fortunately include the σ_s minimums in x and y (Fig. 2), which occur resp. at ~ -3 and -9 T/m. A priori, G variations should largely cover this range for obtaining good results in emittance calculation. Evolution of σ_s as functions of input beam parameters are studied in Fig. 3.

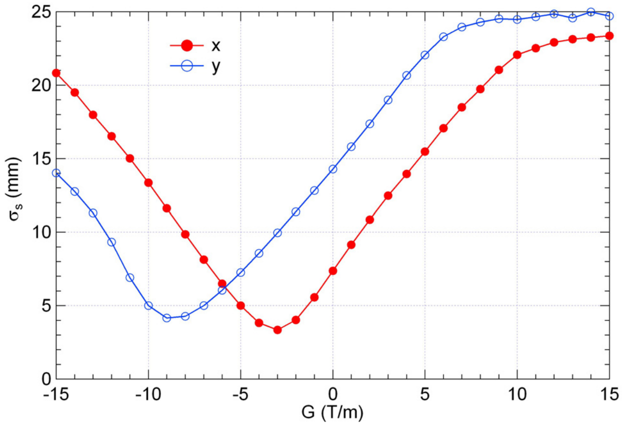

Figure 2: Beam sizes as functions of quadrupole gradients.

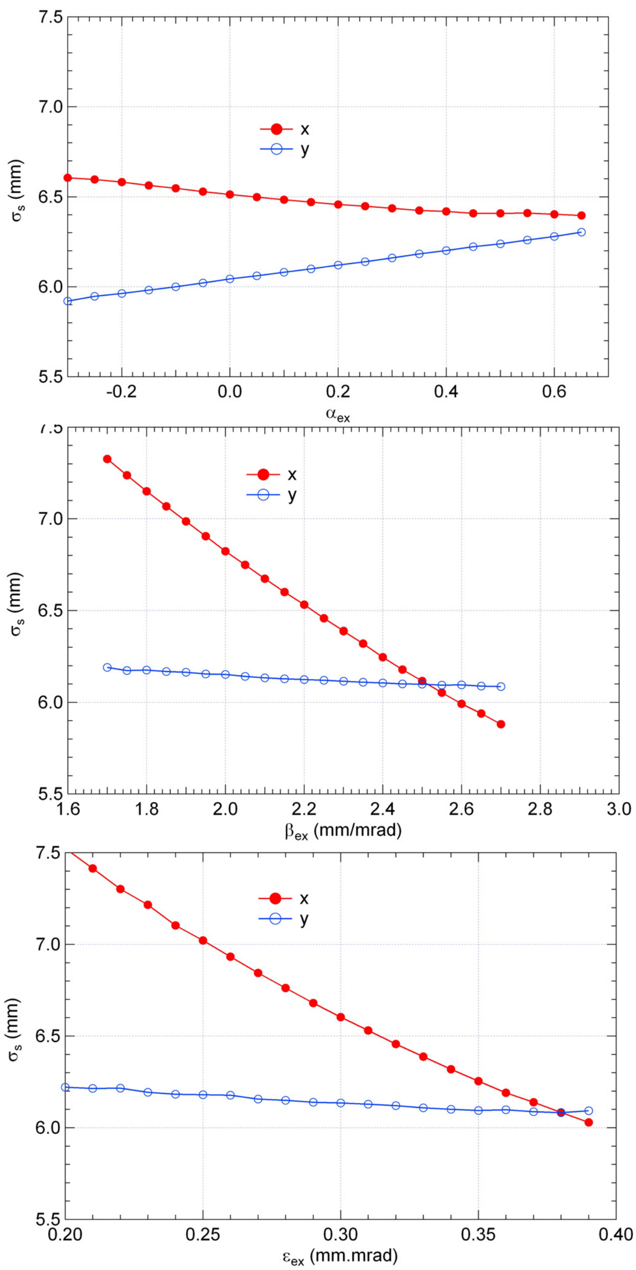

Figure 3: Beam sizes as functions of α_{ex}, β_{ex}, ε_{ex}.

The dependence to the Twiss parameter α is weak, indicating a possible less good precision when trying to determine it. The space-charge effect can be seen through the σ_s variation in vertical as well, in the presence of input parameter variations in horizontal only. This coupling requires to work in the two planes x and y at once, i.e. in a 6-dimensional space. Finally, one can notice the one-to-one correspondence between each beam parameter and the beam size, meaning that the solution is unique when searching one knowing the others. That is at least the case in 1D, when a single parameter is considered.

Then it is worth exploring the topology of the space in which the solution is sought to ensure there are no multiple minimums. That means studying the function F, which is the sum of the squared differences between the "experimental" and calculated curves, as a function of the input parameters. As it is a 6-dimensional space, we can only visualise F in two of these dimensions at once. A typical result is shown in Fig. 4. There is a "valley of minimums", where can be found a very sharp minimum, which EmitFinder must find. It looks unique in 2D.

After the above preliminary studies, the EmitFinder code is launched with an "experimental" σ_s curve obtained with G = -5 to +8 T/m, in 14 steps, and searching only the beam parameters in one plane x or y. The optimisation ends after several hundred iterations. The obtained result is perfect: the function F decreases from 10^3 to 10^{-7}, passing by a plateau, signature of the precedent valley of minimums. The Twiss parameters as well as the emittance are found with an excellent precision. The solution is thus again unique, which validates the present method, at least in 3D.

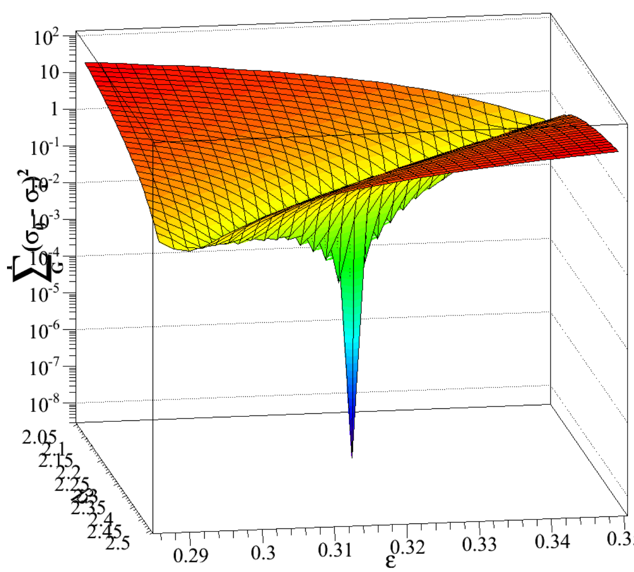

Figure 4: F, sum of the squared differences between experimental and calculated beam sizes, as a function of β_{ex}, ε_{ex}.

G-VARIATION RANGE

It should be mentioned that the above studies are very time consuming due to calculations in multiparticle mode. Optimisations in 6D will be much more tedious. A way to make them faster is to reduce the number of G values to be considered. Is it possible to do that, and also to reduce the variation range of G? These two questions are in fact determining for judging the feasibility of the method on the real machine. It depends indeed on the minimum constraints we have to impose on the acquisition of the experimental curve σ_s. For a given range, the number of different G values at which σ_s can be correctly measured will be limited on-line by the measurement resolution. Besides, the G-variation range is particularly important for high power machines where variations on beam focusing must be limited because they can induce downward either important particle losses when the beam is too expanded, or dangerous material heating when the beam is too concentrated.

In order to estimate the needed minimum number of G values and its minimum variation range, a series of simulations have been carried out with the following "experimental" curves:

- G variation range in the interval [-15, +3 T/m] i.e. around the two minimums of σ_s, first in 10 steps, then 8, 6, and finally 4 steps.
- G variation range in 10 steps, in smaller intervals, first at the left of the two minimums, then containing only the y one, the two minimums, and finally only the x one.

In order to save time, simulations are performed mostly in envelope mode, where the input beam is represented by its Twiss ellipse. Only some of them are checked in multiparticle mode. From all that, a single rule has emerged: the obtained results are much better when and only when there is one experimental measurement closer to the beam size minimums. If this condition is met in only one plane, the beam parameters are still correctly calculated in this plane, while the precision obtained in the other plane is very poor. It appears therefore that the number of experimental points, or the variation range are not so important. A number of six distinct experimental points, of which two are centred on the two minimums, seems to be enough to calculate the beam parameters in the two planes. This constraint alone does not appear too restrictive and this is a good point for the present emittance measurement method.

In our case, it has been estimated that, if zero loss is absolutely imposed, variations of G must be restricted to the range [-7.5, -1.4 T/m], and this could be furthermore reduced by the need of beam symmetry on the beam dump at the end of the line. In order to cover the two σ_s minimums, either we have to authorise more losses by reducing the duty cycle, either we can use the third quadrupole to cover the y minimum.

RESULTS IN 6D

The results in the following have been obtained with an "experimental" curve σ_s "measured" at six values of G: -2, -3, -4, -8, -9, -10 T/m. Three different types of input beam have been used, all with the same Twiss parameters, represented by:

- its envelope, i.e. Twiss parameters and emittance
- 1000 macroparticles in a Gaussian distribution
- 1000 macroparticles in the "nominal" distribution coming from the theoretical distribution extracted at the ion source (see the distribution sketched in Fig.1).

The final values of F obtained with EmitFinder are 10^{-8}, 10^{-7}, 10^{-2} for resp. the three above distributions. They are excellent for the two first cases, and just correct for the nominal case where the distribution is less "regular". In fact for the latter, α is obtained with only ~30% precision, while β and ε are obtained with a very satisfying ~3% precision. This is due to the beam size weak dependence to α noted above. When starting again calculations with the obtained values, F can be decreased down to 10^{-4}. This could mean that some numerical aspects like the optimisation procedure must be improved. Or else there would be local minimums different from the main one for the F function in 6D.

At last, the dependence to the particle distribution type is checked, by comparing the Gaussian and the "nominal" distributions. Due to different space-charge fields seen in each case, the corresponding σ_s "experimental" curves exhibit differences up to ~1 mm. And searching the emittance for one of them from an "experimental" curve obtained with the other one will lead to completely false results. This shows the importance of knowing the distribution type when using the present measurement method. This also point out that the precision of beam-size measurements must be well better than 1 mm. An error calculation shows that 0.1 mm measurement precision is necessary for obtaining 5% precision on the emittance determination.

CONCLUSION

Emittance measurements by quadrupole scanning in very high-intensity accelerators present additional issues: transport strongly nonlinear, numerical inversion in multiparticle mode, x-y coupling, and distribution dependent. The present simulations have demonstrated the measurement principle in such a context, and proved its good feasibility by pointing out the only constraint of measuring the minimum beam sizes. Nevertheless, a good knowledge of the particle distribution type is necessary beforehand.

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