RFQ beam dynamics design
IFMIF project

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Introduction

The Radio Frequency Quadrupole (RFQ) linac proposed for the IFMIF project is a 100 % duty factor (CW, continuous wave) linac which will produce an output current of 125 milliamperes beam of deutons with energy of 5 MeV. This document addresses to the physics and engineering design of the IFMIF project. The reader is supposed to be familiar with RFQ beam dynamics. The information presented herein represents a detailed description and justification of the reference design parameters.

The choice of the 5 MeV output energy for the RFQ is the result of a desire to extend it to the highest practical level in order to relax the Drift Tube Linac manufacturing. Such DTL tanks would incorporate the smallest magnets and would have high design and manufacturing cost. Using electromagnetic magnets allows a tunable focusing during commissioning. It implies a minimum energy in terms of focusing efficiency (magnetic forces) and technical feasibility (magnetic gradient, cooling). According to the IPHI project feasibility study, it appears that 5 MeV is a good compromise. This compromise takes into account the discrepancies coming from frequency choice (175 MHz/352MHz) and the particle type (deutons/protons) respectively for IFMIF and IPHI. Such output energy requires very long RFQ cavity. The feasibility of such cavity has been demonstrated especially for four vanes cavity with RF modes control by resonant coupling.

The choice of the frequency is function of several parameters:

- powerful RF source availability,
- beam dynamic efficiency,
- mechanical feasibility,
- RF modes control.

From the beam dynamics point of view, less is the frequency better is the transverse focusing. This is particularly relevant with the high current beam of IFMIF accelerator (125 mA). In the other hand, too low frequencies induces very big cavity (diameter and length). A good compromise has led to choose 175 MHz. This choice is compatible with RF power source developments, induces a electrode machining which is mechanically feasible (IPHI, LEDA) and allows a relaxed RF modes control.

The input energy is equal to SILHI extraction voltage: 95 keV. This ECR source has demonstrated its availability to produce high current protons (100 mA) with an important reliability (up to 99.96% during 100 hours). Several deutons runs are planed this year.

The last contrainst on the design is the peak field. This value is a compromise between sparking rate and strong focusing which is required to compensate such space charge level. LEDA experience has demonstrated that 1.8 E_k is a reasonnable value. We will see that this value is large enough to permit the required output current of 125 mA.

RFQ design codes

Conception

An important effort has been performed to produce design softwares at Saclay for high current linacs. For the conception of the design, the BELENOS code is used [1]. This code is based on an analytical approach to describe the bunching process which occurs in RFQ. This document will not describe in detail the method. Only the main points will be developed.

The real beam is represented by an equivalent ellipsoïdal bunch with radial symmetry, an uniform charge density and same rms parameters. The beam dynamics can then predicted by 2D rms envelopes equations (R,Z). In order to avoid losses, a constant transverse size of the beam is forced, this induces that derivative of transverse size is null. The longitudinal size evolution (bunching) can be forced using an arbitrary function. The only two unknown parameters of the obtained system are the required forces to get such process.

This is the basis of the model. The limits in the way to produce the required forces come from peak field, geometrical and thermal considerations. For example, in order to simplify the cooling, BELENOS keeps the inter vane voltage constant. The process is then iterative in order to converge to acceptable cavity parameters. The main difficulty for IFMIF RFQ is to respect the level of 1.8 E_k in respect to the high beam current. At such intensity, it will ease the conception in increasing this value, however if the source is able to produce a 130 mA deuton current in CW with an input emittance of 0.25 π.mm.mrad, it's possible to reach the required performances at a level of 1.8 E_k.

Transport

The validation of the design is performed by the code: TOUTATIS [2]. This code uses time as independent parameter to integrate the motion. This is the only way to simulate accurately self forces (space charge and image effects). The fields are computed in 3D grids using multigrid method. The scheme allows to take into account:

- space charge
- image effects
- real shapes of the electrodes

Mechanical defects and discontinuities as coupling gaps can be easily simulated. This last point is very important in the case of very long such IFMIF RFQ.

Design Parameters

According to R.A. Jameson, project leader for the accelerator part, design described in this document is the reference design. It has been built following the procedure described in the previous

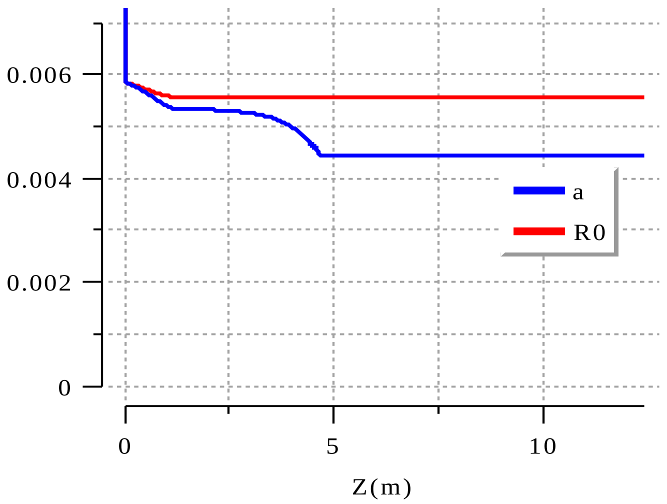

Figure 1: Evolution of minimum and mean aperture.

section. Table 1 shows various parameters that define the design of the IFMIF RFQ. Their evolutions in respect to the position are shown in figures 1-3. Figure 4 shows the peak electric field on the vane tips throughout the RFQ. It is interesting to notice that this value is one for LEDA and Chalk River RFQ1-1250. Peaks fields of 2.1 times Kilpatrick's criterion were reached in RFQ1-1250. The detailed evolution of parameters is compiled at end document. The format is similar to TOUTATIS input file.

Parameters	Values
length	12,498 m
Voltage	106 kV
Peak field	1,82 kp
Minimum aperture	4,41. . . 5,83 mm
Mean aperture	5,56 . . . 5,83 mm
Modulation	1 . . . 1,52
Frequency	175 MHz
Synchronous phase	-90 . . . -35,25 deg
Input current	130 mA
Input norm. rms ε	0,25 π.mm.mrad
α	2,4
β	14,069 cm/rad
Injection energy	0,095 MeV
Output energy	5 MeV

Table 1: Main parameters

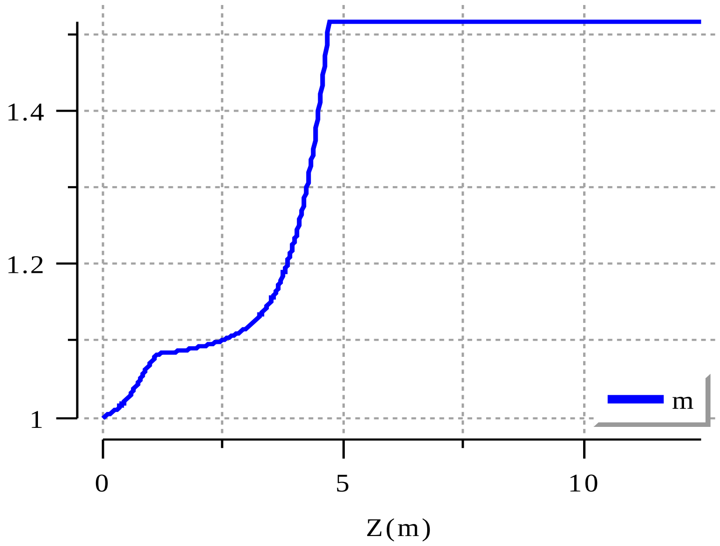

Figure 2: Evolution of modulation.

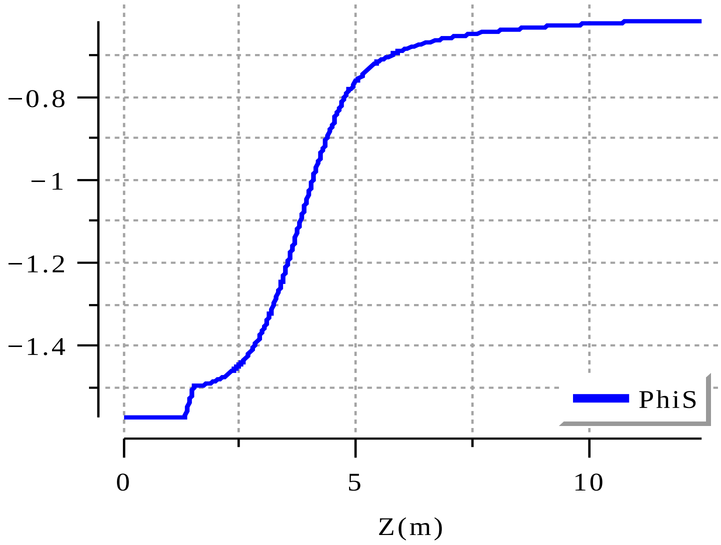

Figure 3: Evolution of synchronous phase (in radians).

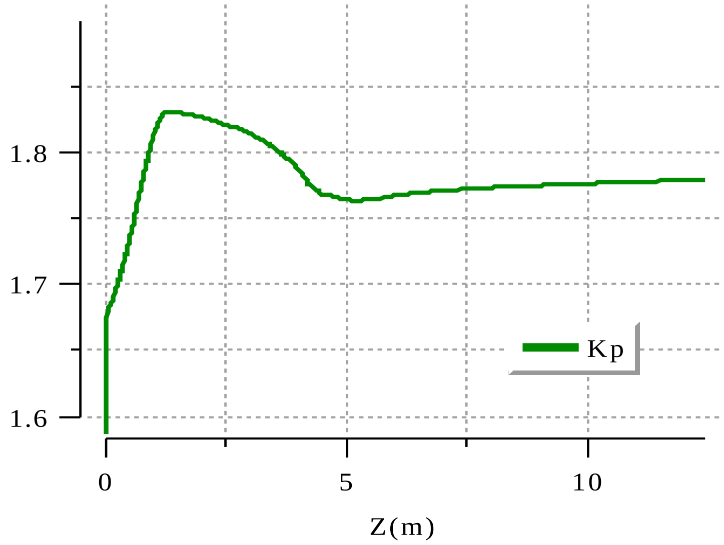

Figure 4: Evolution of peak field in Kilpatrick unit.

Simulations results

This section describes the evolution and the output parameters calculated by TOUTATIS for the design described above. Figure 5 shows the output distribution of the beam in phase space.

Table 2 shows various parameters corresponding to this distribution. Evolution of envelop is decribed in picture 6 and 7. It can be noticed that transverse envelop is not constant as expected by the model described above. The reason is that the model has been corrupted by the kilpatrick limitation (evolution of mean aperture modified). Without this limitation, theoritical transmission of 100 % without transverse emittance growth are possible for such current (130 mA) but implies higher peak field (> 2 kp according to this model). The energy law is plot in picture 8.

Parameters	Values
Total output current	124,7 mA
Useful output current	124,2 mA
Output norm. rms εx	0,27 π.mm.mrad
αx	-2,56
βx	46,83 cm/rad
Output norm. rms εy	0,27 π.mm.mrad
αy	1,55
βy	24,61 cm/rad
Output rms εz	0,18 deg.MeV
αz	0,01
βz	1225 deg/MeV

Table 2: Main results.

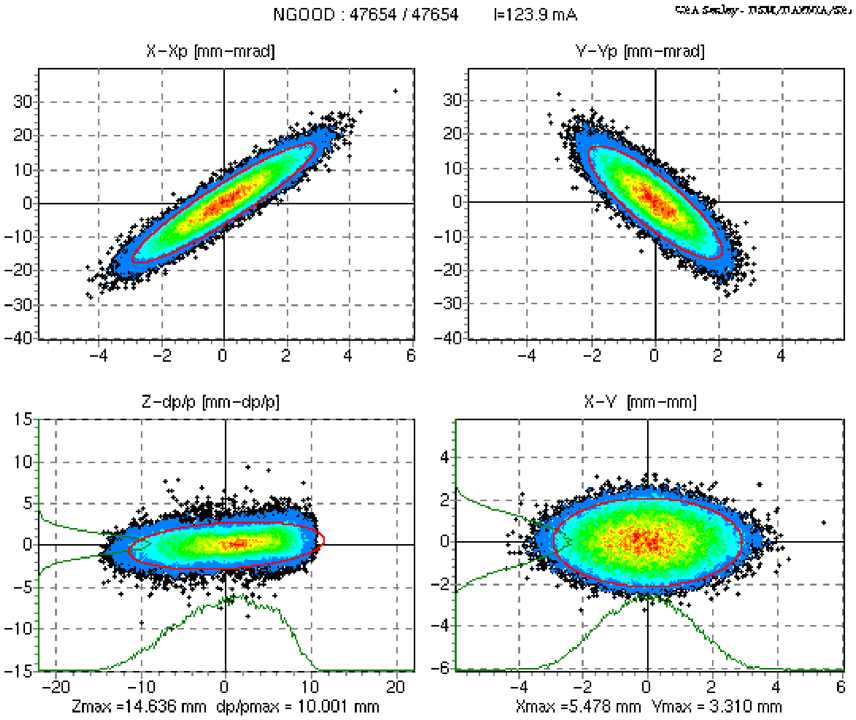

Figure 5: Output beam distribution in phase space.

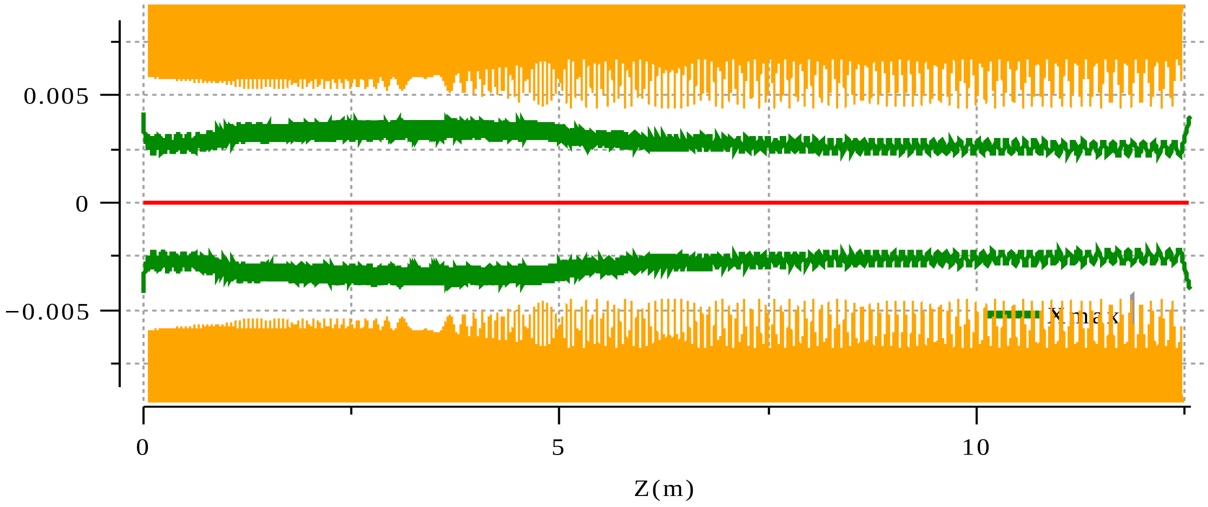

Figure 6: Evolution of X envelop in meter with RFQ vane.

Figures 9-11 show plots for phase advance with and without current and tune depression evolution in the linac. Quantities including space charge have been calculated during the run. Figure 12 shows evolution of rms emittances in each planes. The halo parameters are plotted in figure 13. It can be noticed that halo in longitudinal “explodes”, this is the consequence of

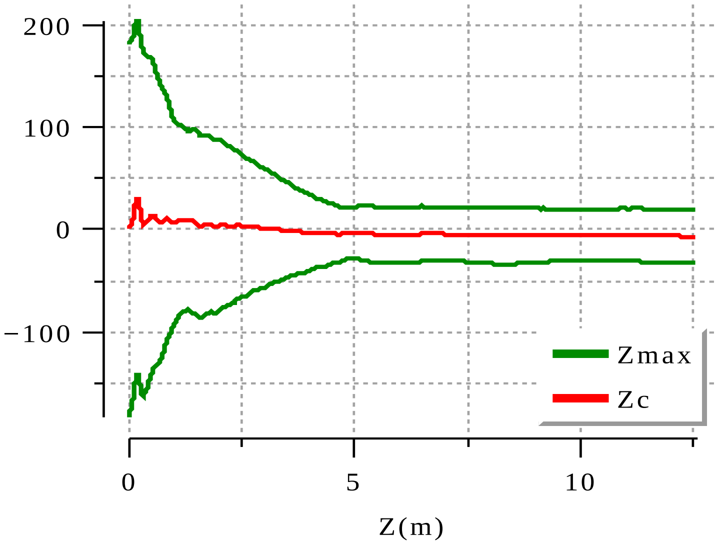

Figure 7: Evolution of longitudinal envelop in degrees.

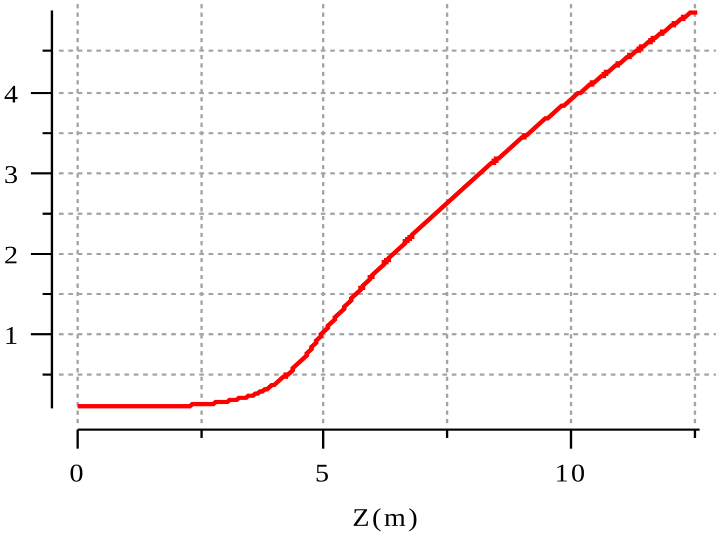

Figure 8: Evolution of kinetic energy in MeV.

particles outside the bucket after the bunching process.

A main interest in the design of a high intensity RFQ is the control of the particle losses. These losses, even concerning a very low fraction of the beam, can be sufficient to considerably complicate the maintenance of the structure. Three plots represents below three different ways to illustrate losses for this design (see figure 14 - 16). The first graph represents the evolution of the number of lost particle as a percentage. The sesond one shows the deposited power by the beam on electrodes. The last one shows that mainly low energy particles are lost.

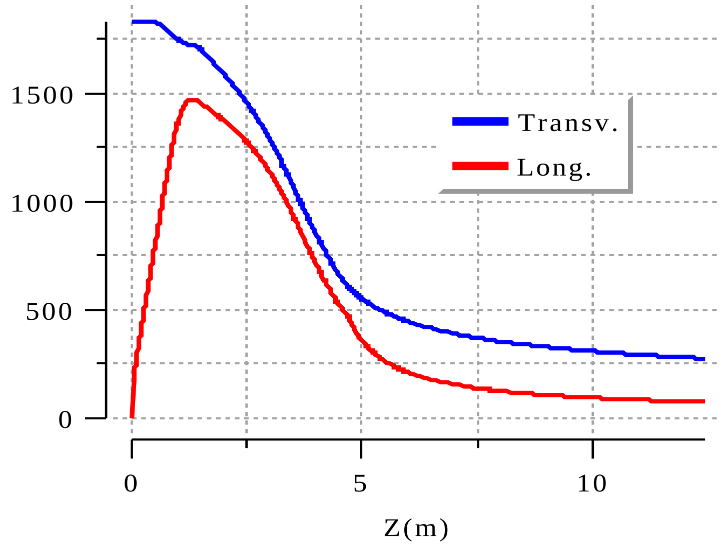

Figure 9: Evolution of phase advance in deg/m at zero current.

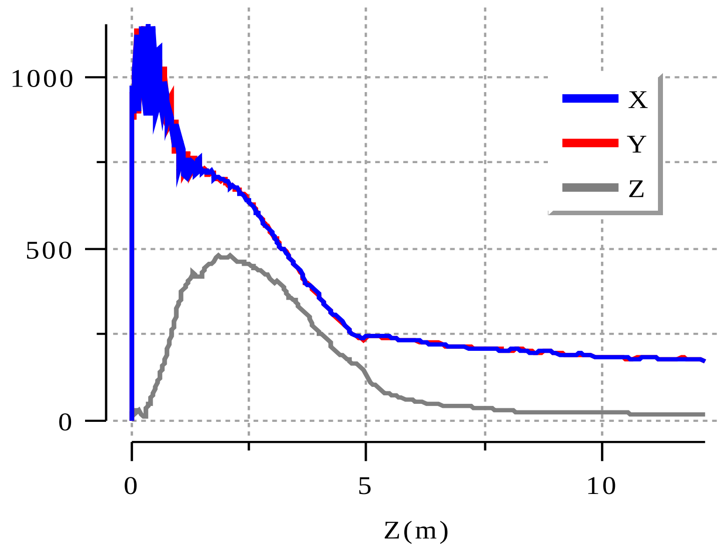

Figure 10: Evolution of phase advance in deg/m with space charge.

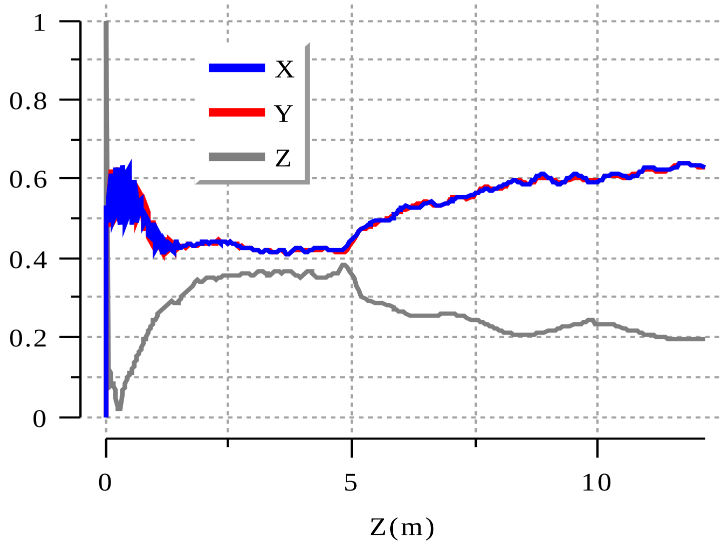

Figure 11: Evolution of tune depression.

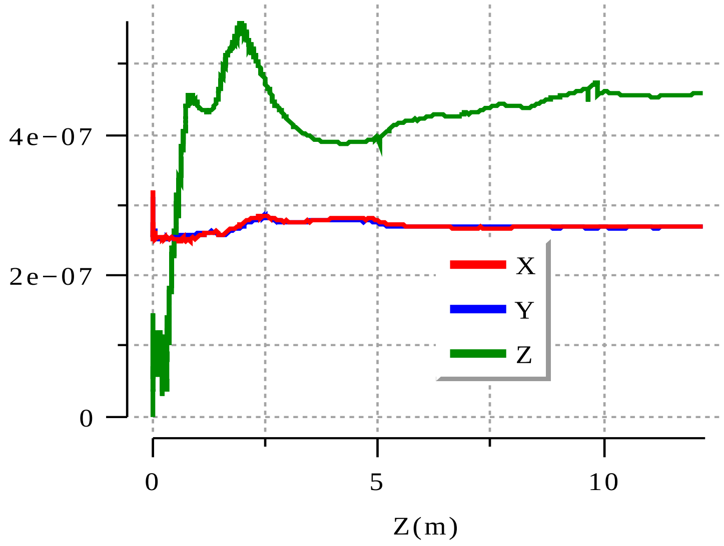

Figure 12: Evolution of rms emittance in π.m.rad.

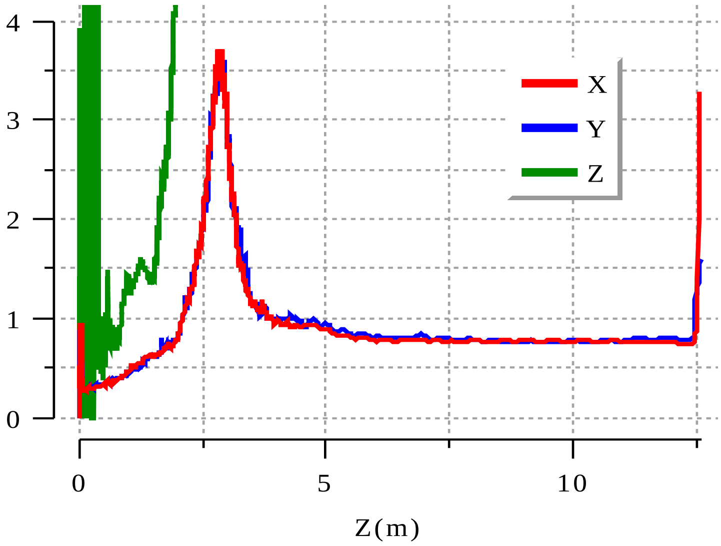

Figure 13: Evolution of halo parameters.

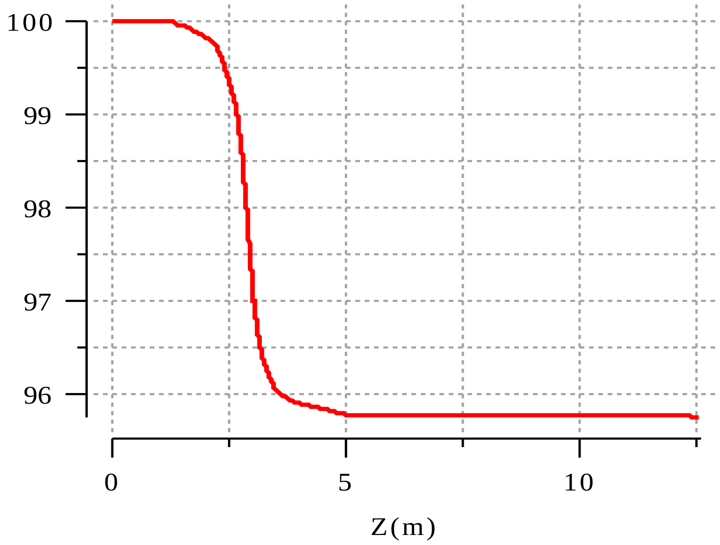

Figure 14: Evolution of transmission in %.

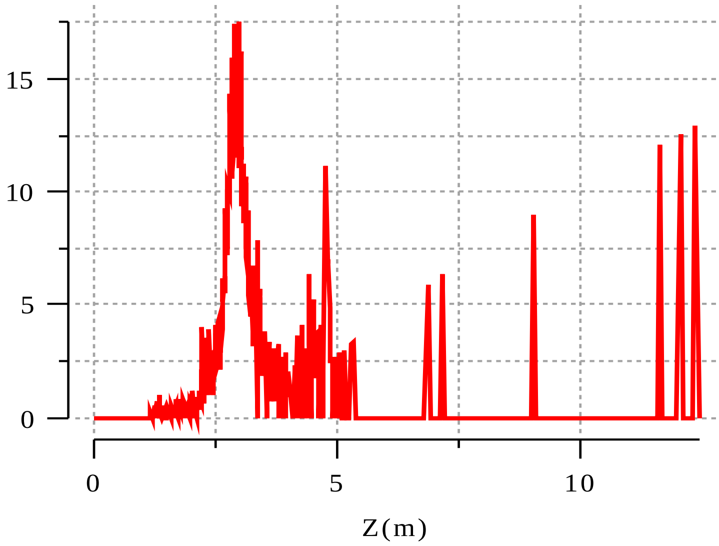

Figure 15: Deposited power (W) in the linac by beam loss in respect to the position.

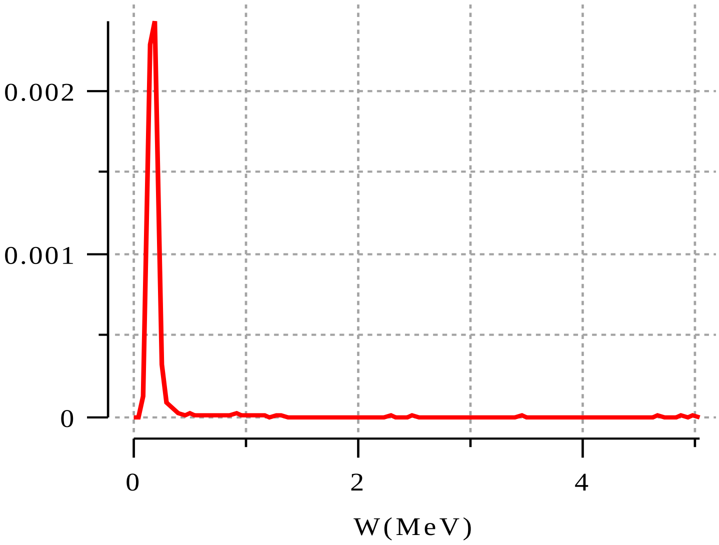

Figure 16: Lost current (A) in respect to the energy of particles.

Detailed design description (TOUTATIS input file)

(rfq.inp)

```
theSpecialLostFlag 0
theAcceleratedFlag 1
theEquivalentBeamFlag 0
theNewPotFlag 0
theLossesCriteriaFlag 0
theSavingRunFlag 0
theRunCartoonFlag 0
theGeometryFileFlag 0 0
WallAperture 0.008
SemiWidthWall 0.0025
diaphragme 1.
theDirectionFlag 1
LBECompensation 1.0
theStartingModulation -1
theRhoR0RatioInRMS 0
GapRMS 0.0181771
GapFFS 0.0160991
thespacechargeperiod 1
theextfieldperiod 1
theTrancellFlag 1
theSpeciesFlag 0
theDistribution k none
NbRMSCell 6
theBreakOutAngle 10.
theAccuracyFlag 0
NStep 8
NumberOfCouplingGap 0
End
RHO 0.85
linac 1 0.095 175.00 2.0145 1.0
trancell
{ } Tank 1 Length= ll cm, 606 cells
 Cell   cl      tl     curlt   curll
0 106 0.095 0.010064927 0 0 -90 104.94 1 104.94 89.199 0 0.857212858 0 0 0
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2 106 0.095 0.010064927 0 0 -90 64.71 1 64.71 55.0035 0 0.857212858 1.714425717 0 0
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593 106 4.708210267 0.070899575 0 0.388281575 -35.319706 0.4418028 1.519341 0.556525954 0.473047061 0 6.038619947 1167.113859 0 0
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input -6 5000 2.400 14.069 0.0149067456756 2.407 14.104 0.0149067456756 180. 0.
scheff 130.0
exitffl 3.764
vfac 1.0
end
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