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DESIGN OF A PROTON TRAVELLING WAVE LINAC WITH A NOVEL TRACKING CODE

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Abstract

A non-relativistic proton linac based on high gradient backward travelling wave accelerating structures was designed using a novel dedicated 3D particle tracking code. Together with the specific RF design approach adopted, the choice of a 2.9985 GHz backward travelling wave (BTW) structure with 150° RF phase advance per cell was driven by the goal of reaching an accelerating gradient of 50 MV/m, which is more than twice that achieved so far.

This choice dictated the need to develop a new code for tracking charged particles through travelling wave structures which were never used before in proton linacs. Nevertheless, the new code has the capability of tracking particles through any kind of accelerating structure, given its real and imaginary electromagnetic field map. This project opens a completely new field in the design of compact linacs for proton therapy, possibly leading to cost-effective and widespread single room facilities for cancer treatment.

INTRODUCTION

A collaboration between TERA Foundation and CLIC was established to study a novel linear accelerator for proton therapy. The main goal of the collaboration is to transfer the knowledge acquired by the CLIC group, mostly in terms of RF design, high-gradient limitations and linac optimization, to a medical linac.

Funds of the Knowledge Transfer group of CERN permitted the construction of a prototype based on the design discussed in [1]. High power RF test of this accelerating structure is under preparation at the present time, to validate its capability to reach the maximum accelerating gradient of 50 MV/m.

A backward travelling wave linac was never used for accelerating protons. Moreover, a medical linac has a certain number of peculiarities with respect to high energy physics linacs, as for instance the need to vary the kinetic energy of particles over a wide range to reach tumour tissues at different depth into the patient body. So it was decided to develop a completely new tracking code, called *RF-Track*. The main features of such code will be discussed in the present paper, together with the results of the benchmark study and a preliminary BTW linac design.

RF-TRACK

In order to evaluate and maximise the transmission through backward-travelling accelerating structures, a new *ad-hoc* tracking code was developed: *RF-Track*. The decision to develop a new code was motivated by the need to perform accurate tracking of continuous, unbunched, inherently relativistic beams of protons or ions (with beta = ~0.35 for the protons, even less for the ions), through 3D field maps of BTW structures. No code in our knowledge featured the required flexibility and had the capability to handle real and imaginary field maps of travelling-wave RF structures (forward or backward).

RF-Track can input and combine the 3D phasor maps of both electric and magnetic fields, in order to represent an RF field in all its complexity, as 3D solvers such as HFSS [2] generate. This possibility allows the accurate representation of (backward) travelling-wave structures, differently from most of the codes, which can only input static field maps or can only simulate standing wave structures (and require to overlap two standing waves to mimic a travelling wave).

RF-Track performs full 6D transport and maintains the proper time of each particle. This allows computing the correct timing of the RF fields felt by each particle. It must be noticed that, thanks to this strategic choice, the code is not bounded by the notion of “bunch” or “reference particle” and can track continuous beams consistently. It implements exact transfer maps for drifts, quadrupoles and sector bends in both the transverse plane and the longitudinal planes, with the exception of the quadrupole longitudinal map, which features a second-order expansion of the path length to take into account the particle’s incoming position and angles. The approximated solution of the longitudinal quadrupole map (already better than the standard “drift-like” map adopted by many codes) doesn’t undermine the tracking accuracy, because each element can be integrated in an arbitrary number of steps, recovering accuracy whenever a second-order tracking is not sufficient.

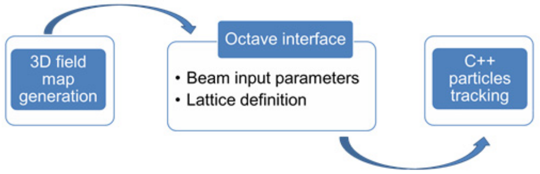

Figure 1: Simplified scheme of *RF-track* software architecture.

The code is written in modern, fast, parallel C++ that exploits multi-core CPUs. Its fast computational core is accessible by the user through a powerful SWIG Octave interface [3,4], which permits to write complex, yet readable and concise, simulation scripts that can directly benefit from a large number of optimization toolboxes

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already existing for Octave. An analogous interface toward Python [5] has also been created, for those who prefer this language to Octave. A simplified scheme of *RF-Track* architecture is shown in Fig. 1.

CODE BENCHMARKING

A Side Coupling Linac (SCL) was considered for the validation study of *RF-Track*, given the lack of tracking codes capable of accepting travelling wave accelerating structures. Nevertheless, since a standing wave (SW) regime is a particular case of a TW regime, the results are not limited to the first case only. The codes used for the benchmark are *LINAC* [6] and *TraceWin* [7]. While *LINAC* demands as an input the shunt impedance (ZTT) and transit-time (TT) factor of the accelerating structures on the z-axis, and then computes the field distribution with a Bessel function expansion, *TraceWin*, like *RF-Track*, allows to directly entering a field map distribution computed in 3D. For coherence with *RF-track*, this last option was used in *TraceWin*. It must be noticed that *TraceWin* accepts only maps of real numbers, which can only represent standing wave structures, whereas RF-Track directly accepts maps of complex numbers.

The 2D electromagnetic code *Superfish* [8] was used to generate the electromagnetic field maps, and a short linac made of three accelerating structures embedded in a FODO lattice was considered in the benchmark. The steps followed in the study are summarized in Fig. 2.

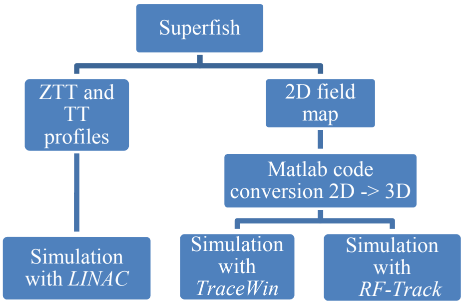

Figure 2: Blocks view of the approach adopted for benchmarking the codes.

The results of the benchmark showed that the three codes agree, both in terms of transmission and phase space distribution of the particles [9].

LINAC DESIGN

The linac design was carried out with two dedicated tools: a Matlab code was developed for setting the accelerating structure lengths, then *RF-Track* was used for optimising the FODO lattice design, maximising the transmission and validating the design.

Accelerating Structures Design

A simplified model was adopted to generate the electromagnetic 3D field maps of the different structures. Regular cells for five different betas of the structure were designed with the 3D electromagnetic code HFSS, in order to compute the shunt impedance and transit-time factor profiles of the linac. This RF design was carried out with the same goals and constraints as the reference 0.38 beta prototype. For this reason the different structures of the linac are equivalent in terms of maximum accelerating gradient and Breakdown (BD) behaviour.

Starting from these data, a Matlab code was written to compute the accelerating structure lengths, the final energy at the end of each structure, and the average beta per structure. Inputs to this program are the initial energy, the minimum final energy of the linac, the RF power per accelerating structure, the synchronous phase, and the average axial electric field. The code was written for a 5pi/6 phase advance linac, but it is fully parameterized and can be easily adapted to other designs.

A compact 18 accelerating structures linac was chosen, with a constant number of 12 cells per structure, and a full recirculation of the power was considered. A synchronous phase of 20 degrees was chosen. The attenuation in the 3dB-hybrid and in the waveguides was taken into account by means of a 10% losses coefficient in the klystrons power. Given the power attenuation in standard S-band waveguides of 0.02 dB/meter, this would lead to the possibility of installing up to 20 m long waveguides. The linac layout is presented in Fig. 3.

3D Field Maps Generation

With the average betas computed, HFSS regular cell design for each of the 18 structures was made. Only one cell per structure was modelled to save computational time. Afterwards, the generated field maps were converted into the whole accelerating structure field maps. This approach cannot take into account the effects introduced by couplers. This aspect will be addressed in the future.

Lattice Design

A round beam has the maximum acceptance with a phase advance of 90° per focusing period. Keeping this as a fixed parameter, the gradient G of the Permanent Magnetic Quadrupoles (PMQ) that will form the FODO-like lattice focusing the beam could be easily computed with the equation:

$$\mathrm{G} = \frac{2 \cdot sin(\mu/2) \cdot mc\beta\gamma}{qL_qL}, \qquad (1)$$

where μ is the phase advance per cell, $\beta\gamma$ are the relativistic factors, L_q is the length of the quadrupoles and L is the length between them.

It must be noticed that, in this particular project, Eq. 1 does not apply in a straightforward way, because:

- the linac lattice is not a regular FODO;
- the relativistic β is not constant.

The first bullet comes from the fact that the accelerating structure lengths increase along the linac, following the increase of particles relativistic beta. As a result, so do the distances between quadrupoles. The second bullet comes from the peculiarity of this project, where the kinetic

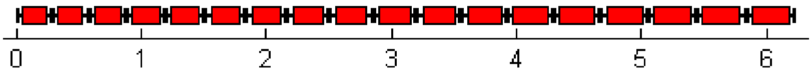

Figure 3: Basic layout of the linac. Transverse and longitudinal dimensions are in scale [m].

energy of the beam has to vary depending of the depth of the tumour tissues to be treated. This is achieved by turning on and off the last active accelerating structures (see Chapter 1 of [10]). In addition, Eq. 1 does not take into consideration the RF defocusing introduced by the accelerating cavities. This contribution is not negligible and has to be counteracted through an increase of the quadrupoles strength with respect to the ideal value of a FODO lattice.

The goal of the FODO optimization is to find the gradient that maximizes the transmission at all the different energies. The simplified approach of Eq. 1 led to a good particles envelope for minimum and maximum energy, while for intermediate energies the FODO could be optimized (Fig. 4). A second method, consisting in zeroing the second derivative of the phase advance for the minimum energy, brought to similar results. The optimum will be reached numerically through an algorithm of *RF-Track* currently under preparation.

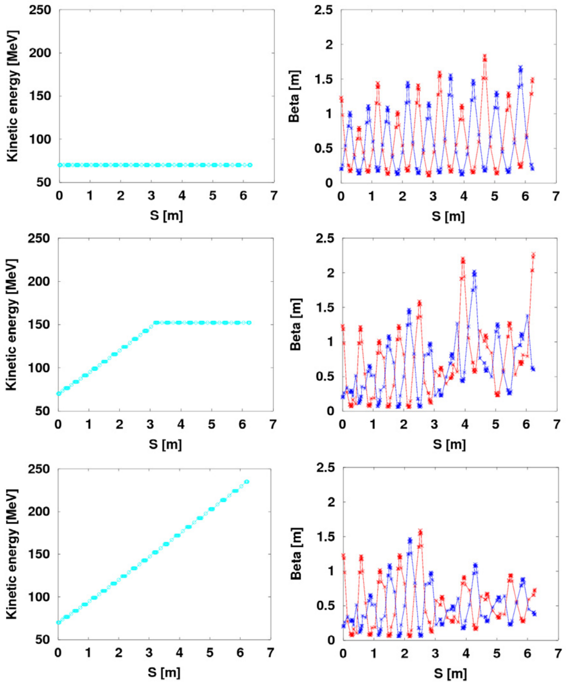

Figure 4: Kinetic energy along the structure S (left) and beta function (right) for 70 MeV (top), 152 MeV (middle) and 236 MeV (bottom) protons.

PRELIMINARY TRACKING RESULTS

Tracking of a bunch of particles was performed with typical input parameters and the results are presented in Fig. 5 for the transverse phase-space and in Fig. 6 for the longitudinal phase-space. In case of *on-crest* acceleration, one can notice the presence of particle *tails*, which are formed by particles outside the longitudinal buckets.

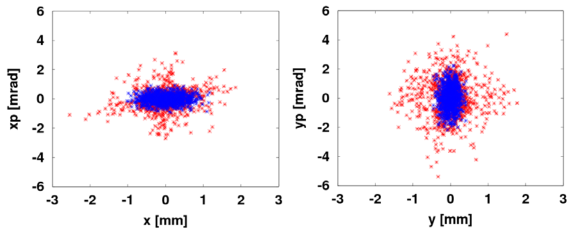

Figure 5: Transverse phase-space representation at the beginning (blue) and at the end (red) of the linac.

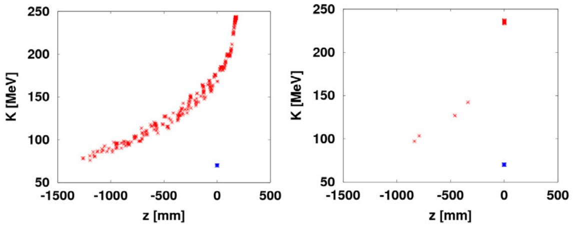

Figure 6: Longitudinal phase-space representation for -20° (left) and 0° (right) input phase. Input (blue) and output (red) particles.

The fraction of transported particles was evaluated using *RF-Track* on the preliminary design here presented.

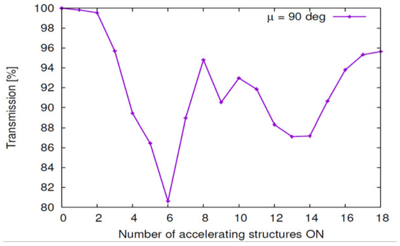

Figure 7: Particles transmission as a function of the final energy of the beam.

Figure 7 clearly shows that the design is not yet optimal, since the transmission varies as a function of the energy. In a medical linac instead, one wants to get a transmission as constant as possible throughout the structure. Such optimization will have to take into consideration the Twiss parameters profile, as well as the emittance growth. Space-charge is not an issue due to the very low currents (below mA peak) needed for tumour treatment.

SUMMARY AND FUTURE STEPS

A new tracking code, called *RF-Track*, was developed to design a novel non-relativistic proton linac based on BTW accelerating structures. The main code characteristics and the successful benchmark were discussed in this paper. The linac accelerating structures were designed and a first lattice was studied and presented. A careful optimisation of the transmission is ongoing.

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