BEAM DYNAMICS FOR A NEW 160 MeV H^- LINAC AT CERN (LINAC4)

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Abstract

Linac4 is a normal conducting H^- linac proposed at CERN to provide a higher proton flux to the CERN accelerator chain. It should replace the existing Linac2 as injector for the PS booster (PSB). The same machine can also operate in the future as the front end of the SPL, a 2.2 GeV superconducting linac with 1.8 mA average current. At present Linac4 consists of a Radio Frequency Quadrupole (RFQ), a chopper line, a Drift Tube Linac (DTL), and Cell Coupled DTL (CCDTL) all operating at 352.2 MHz and finally a Side Coupled Linac (SCL) at 704.4 MHz. This paper discusses the overall beam dynamics concept, presents the optics for the different sections of the machine and compares end-to-end simulations realised with two tracking codes (PATH and IMPACT). The influence of phase/energy errors is discussed and the challenging features in the current design are highlighted.

CONCEPT

The guidelines for the design of Linac4 are high beam quality, low losses, low activation and, where possible, reuse of existing equipment. In the initial stage Linac4 will be used as a new injector for the PS Booster, providing 30 mA of H^- at 160 MeV in 0.5 ms long pulses at a 2 Hz repetition rate. At the same time it is conceived and designed as the normal conducting "front-end" of a 2.2 GeV superconducting proton linac with an average power of 4 MW, delivering a 13 mA beam with 2.8 ms pulse length and a repetition rate of 50 Hz [1]. With such high beam power involved, beam quality and halo formation must be carefully controlled in order to avoid activation and to ensure hands-on-maintenance. For this purpose the lattice is designed to provide a smooth evolution of the phase advance per metre across all transitions. This could be achieved for the whole of Linac4 (Fig. 1) with the exception of the LEBT and chopper line where mechanical constraints prevent this approach. Furthermore an effort was made to avoid resonant emittance exchange by adapting the transverse phase advance to the longitudinal one, yielding, in our case, a full current phase advance ratio of $0.5 < k_l/k_t < 0.8$ throughout the machine which successfully prevents any exchange of emittances between the planes (compare Fig. 3).

The fundamental frequency of 352.2 MHz was chosen in order to re-use the LEP klystrons, and the source extraction energy of 95 keV was determined by the availability of the IPHI RFQ [2].

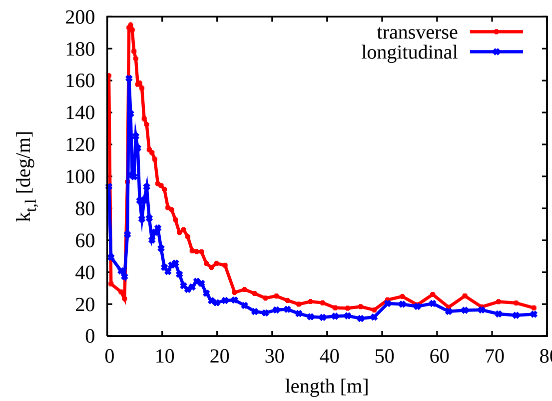

Figure 1: Phase adv. per metre from RFQ (out) to 160 MeV.

BEAM DYNAMICS

LEBT and RFQ

The Linac4 source beam will be matched into the RFQ by means of 2 solenoids and provision is made to house a pre-chopper between the two of them. Space charge effects are not severe as the beam is continuous and they can be compensated for by the solenoids. They account for less than 1% of the simulated emittance increase. The energy spread, expected to be around 4%, has instead a very strong effect, not only generating transverse emittance increase up to 30%, but also significantly spoiling the beam distribution because of the strong chromatic distortion when focused into the RFQ acceptance. The RFQ has been designed and optimised for 100 mA CW operation. It shows excellent transmission and good beam qualities also at 40 mA. The emittance increase, however, which occurs mostly in the first coupling gap, is more pronounced in the presence of the source energy spread.

Chopper Line

The chopper line dynamics is dominated by the chopper structure itself [3], [4]. The requirements for fast rise time (2 ns) and the timing structure of the CERN NuFact accumulator [1]) limit the maximum effective voltage to 800 Volts. In order to separate the beam by more than 1% we are forced to use a 1 m long chopper. The chopper line consists of 5 FODO cells with 2 periods on each side to match from the fast phase advance in the accelerating structures to a slow phase advance in the chopper (see Fig. 2). The chopping takes place in the (20 $\beta\lambda$ long) central FODO cell. The chopper itself is housed inside the first focussing quadrupoles (F5 and F6) and provides a 7 mrad kick to the beam. The separation in phase space is then ampli-

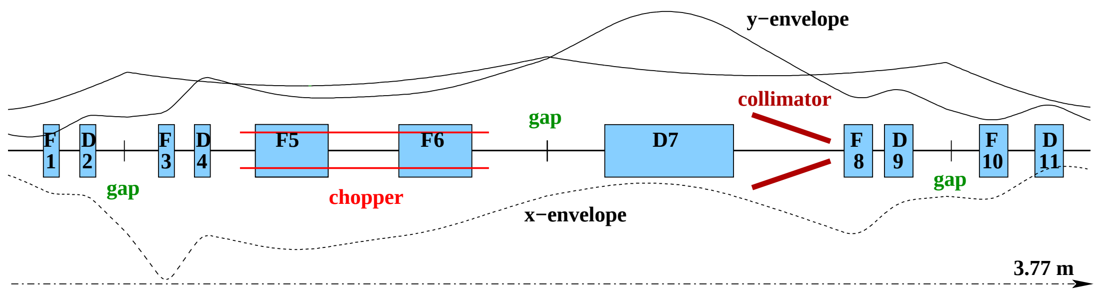

Figure 2: Chopper line and beam envelopes from TRACE3D.

fied and transformed by the second defocussing quadrupole (D7) into a physical separation at a cone shaped collimator which acts as a beam dump for the chopped bunches. In order for the chopping to work properly the centre of the beam must experience 90 deg phase advance between the (centre of) the chopper and the dump. The transverse matching to the DTL is guaranteed by the last two FODO periods. The matching was optimised, starting from the conventional envelope matching, by a genetic algorithms routine which has been implemented in the tracking code PATH [5] and which optimises the lattice elements for maximum transmission and minimum emittance growth. The longitudinal matching is done with 3 bunchers, equally spaced in the line.

DTL, CCDTL, SCL

The DTL section uses a FOFODODO structure which is able to provide strong transverse focussing, even with the relatively short quadrupoles, at 3 MeV and 352.2 MHz. A field and phase ramp in the first DTL tank ensures that the longitudinal zero-current phase advance per period stays below $\approx$ 65 deg. Thus the maximum transverse phase advance can be pushed to values close to 90 deg in order to prevent resonant emittance exchange between the planes as well as unstable envelope oscillations at or above 90 deg phase advance. At 40 MeV longer focussing periods become possible and the beam is matched into a CCDTL (FODO) structure using short 3-gap DTL tanks, coupled with single cell cavities in the $\pi/2$ mode. From 90 MeV onwards a Side Coupled Linac (SCL) structure (FODO) at 704.4 MHz is used to accelerate the beam to its final energy of 160 MeV. Before and after each transition (between DTL tanks, DTL/CCDTL, and especially around the frequency jump CCDTL/SCL) the synchronous phase is ramped either to compensate for the "missing gaps" between the structures or to squeeze the beam into the shorter bucket of the SCL.

OVERALL PERFORMANCE & CODE COMPARISON

For these first end-to-end simulations we use an input beam of 95 keV with 4% energy spread as it is expected from the H^-source. The linac has been simulated with PATH using cross-checks with IMPACT [6] and TRACE_WIN [7]. Using this "nominal" beam we observe a total rms emittance growth of 73% in the transverse plane and 18% in the longitudinal plane. The seemingly large transverse emittance growth occurs mainly in the front-end and breaks down into: 33% within the LEBT, 14% in the RFQ, 5% in the chopper line and the remaining 8% in the DTL, CCDTL, and SCL (see Table 1).

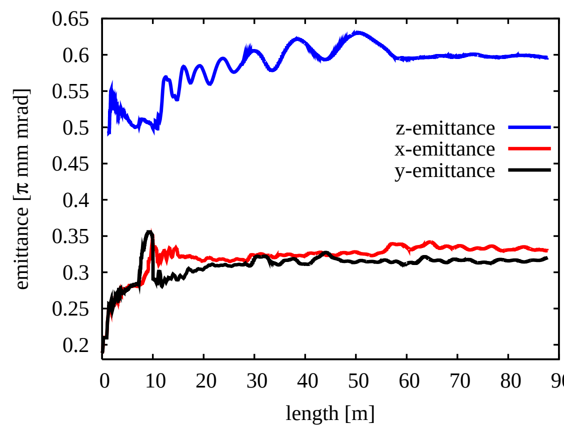

Figure 3: End-to-end (LEBT to 160 MeV) rms emittance evolution (from PATH).

The initial 4% energy spread was identified to double the "intrinsic" transverse emittance growth in the linac (Fig. 4) and it was found that source distributions with less than 2% energy spread can dramatically reduce these values.

In Fig. 5 we show a comparison of rms emittance evolution between PATH and IMPACT. The differences in the transverse plane can be explained by slightly different amounts of lost particles in the chopper line, which are due to differences in the geometric modelling of the two codes. Longitudinally, however, the simulations show up to 20% difference, which still has to be understood. Using IMPACT with nonlinear Lorentz Force integration instead of the standard linear transfer maps further enhances the differences in the results. At this point it is also not clear why the longitudinal emittance growth starts to differ $\approx$ 0.5 m after entering the DTL.

Despite the frequency jump at 90 MeV, energy & phase jitter remain very limited. 90% of all bunch centres are within values of ± 0.2 MeV and ± 3.4 deg as depicted in

Table 1: Emittance growth, transmission, and energy per section from PATH (50000 particles).

section	**freq. [MHz]**	**length [m]**	W_{out} **[MeV]**	$\varepsilon_{rms,t}*$ [πmm mrad]	$\varepsilon_{rms,l}$ [πmm mrad]	$\Delta\varepsilon_{rms,t}*$ [%]	$\Delta\epsilon_{rms,l}$ [%]	**transm. [%]**
LEBT		1.27	0.095	0.188	-	33	-	100
RFQ	352.2	5.96	3	0.25	-	14.4	-	98.9
CHOPPER	352.2	3.77	3	0.286	0.5	4.9	0.6	91
DTL	352.2	16.71	40	0.3	0.5	5.0	16.3	99.9
CCDTL	352.2	30.54	90	0.315	0.58	3.8	1.2	100
SCL	704.4	27.78	160	0.327	0.59	-0.6	0.2	100
TOTAL		86.03	160	0.325	0.59	73	18	89.9

* average

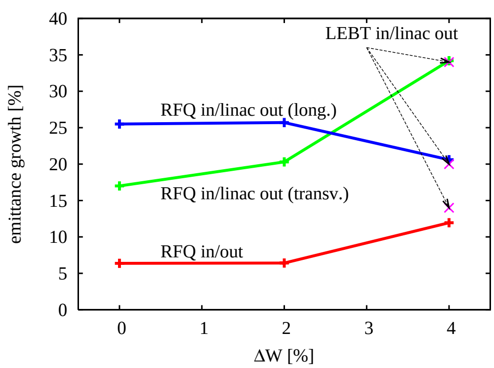

Figure 4: Influence of source energy spread on rms emittance growth.

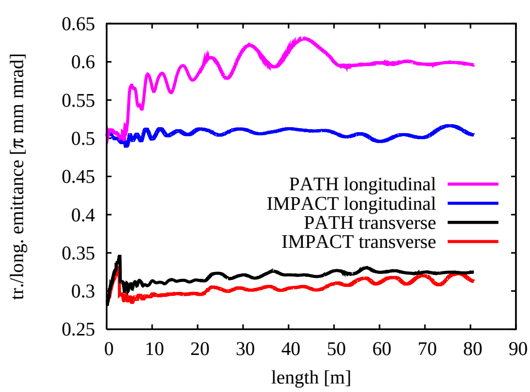

Figure 5: Rms emittance evolution simulated with PATH and IMPACT.

Fig. 6 and are thus close to earlier estimates which formed the basis of the transfer line design to the PS booster. [8].

SUMMARY

The first end-to-end simulations for Linac4 predict a substantial transverse emittance growth of $\approx$ 73%, which can be reduced considerably by assuming less than 2% source energy spread instead of the estimated 4%. Nevertheless, the overall design seems to be feasible and neither the chopper line dynamics nor the frequency jump seem to

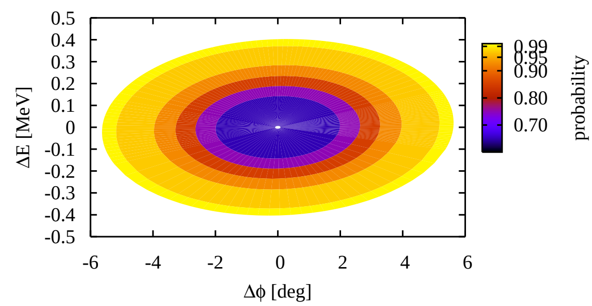

Figure 6: Energy & phase jitter at the linac output, assuming ± 0.5% and ± 0.5 deg variation (rms with Gaussian distribution and cut-off at 2·rms) in all RF systems.

pose any unsurmountable difficulties. Comparative simulations with PATH and IMPACT show differences in emittance growth that remain to be understood but which do not endanger the performance of the design.

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