

BEAM DYNAMICS OPTIMISATION OF LINAC4 STRUCTURES FOR INCREASED OPERATIONAL FLEXIBILITY

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Abstract

Linac4 is a new 160 MeV, 40 mA pulsed beam current H⁻ accelerator which will be the source of particles for all proton accelerators at CERN. Construction started in October 2008, and beam commissioning of the 3 MeV front-end is scheduled for early next year. A baseline design of the linac beam dynamics was completed 2 years ago and validated by a systematic campaign of transverse and longitudinal error studies to assess tolerance limits and machine activation levels. Recent studies have been mainly focused on optimising this design to achieve both a smoother performance for nominal beam conditions and to gain operational flexibility for non-nominal scenarios. These include a review of the chopper beam dynamics design, a re-definition of the DTL and CCDTL inter-tank regions and a study of operational schemes for reduced beam currents (either permanent or in pulse-to-pulse mode). These studies have been carried out in parallel to first specifications for a beam commissioning strategy of the linac and its low-energy front-end.

INTRODUCTION

Linac4 is a normal conducting H⁻ linac presently being built at CERN to replace the 50 MeV proton Linac2 and increase brightness of the injector complex. Its principal building blocks are a 3 MeV front-end (composed of an RF-driven 2 MHz ion source, a 2-solenoids LEBT, a 352 MHz RFQ and a chopper line) followed by a conventional Drift Tube Linac structure up to 50 MeV beam energy (three DTL tanks), a Cell-Coupled Drift Tube Linac up to 100 MeV (seven CCDTL modules of 21 tanks coupled in 3's) and finally a Pi-Mode Structure (twelve PIMS modules each composed of 7 cells) taking the beam to its final energy of 160 MeV. The baseline design was completed already a couple of years ago and validated with code-to-code comparisons of the nominal beam behaviour and statistical error studies to assess tolerances to machine errors [1]. Recent studies have focused instead on the optimisation of the base design for more efficient nominal performance or on the exploration of ways to build in extra flexibility in case of non-nominal conditions, in preparation for beam commissioning. Details on some of these are given in the following, starting from the front-end.

CHOPPER STUDIES

Chopper Efficiency

A 3 MeV chopper will be used to change the time structure of the pulse at the output of the RFQ to optimise Linac beam injection in the PS Booster (PSB) in presence

of energy modulation, remove unwanted beam, create gaps in the train during the rise time of the distributor and adjust beam intensities in pulse-to-pulse mode. Two chopper plates, separated by 20 mm and powered to 700 V applied voltage are housed inside two quadrupoles which control the beam size; the given angular kick is then amplified by a defocusing quadrupole between the chopper and the dump and by the RF defocusing effect of the downstream buncher cavity. Finally the dump collects the chopped bunches and collimates the transmitted ones (see Fig.1).

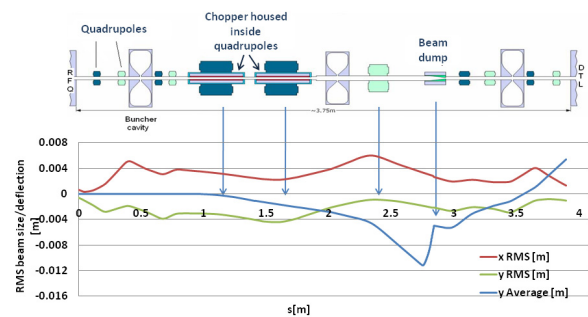


Figure 1: 3 MeV chopper scheme (top), nominal beam envelopes and chopped beam centroid deflection (bottom).

The optics in the chopper was recently reviewed to allow smoother matching to the DTL. As a result the emittance increase through the MEBT to the DTL was reduced from 40% to 20% for a non-chopped beam. When turning the chopping on, tracking simulations for nominal beam conditions (63.5 mA current, 0.04% duty cycle at 352.2 MHz) give a beam survival rate at the end of the MEBT of 0.06% for 700 V voltage applied. Most of this current (77%) ends up being transmitted through the Linac and transfer line all the way to the PSB and only a few distributed beam losses occur in the DTL. The acceptance of Linac4 is large enough to transport even deflected bunches with almost zero charge [2].

The chopper efficiency (percentage of the input beam stopped by the dump) drops for lower values of the voltage applied – see Table 1, setting a minimum requirement of 500 V for the chopper driver (or 6% transmission of partially deflected bunches). These will also be produced during the rise and fall times of the voltage pulse (if longer than the 2 ns bunch spacing), in case of flat-top jitter and delays or pulse length variations: a level of 1 or 2 partially chopped bunches per transition is however considered as an acceptable limit for operations at low duty cycle and nominal chopping scheme (133/352). Imperfections in the MEBT optics can also affect the chopping efficiency: an error study on the

Table 1: Chopper Efficiency for Different Applied Voltage

Voltage [V]	% stopped at dump
200	30.6
300	55.4
400	78.3
500	93.94
600	99.35
700	99.93

quadrupole powering has shown quite a strong dependence, with up to 6% undeviated beam transmission for 10% level fluctuations in the magnetic gradient. With 0.1% accuracy of the power supplies, nominal operations will not be affected, except in case of accidental powering faults. For all these scenarios, a tolerance window for degraded conditions of beam injection in the PSB needs to be specified for setting operational limits and a correspondingly safe interlock strategy.

Reduced Beam Currents

Another important functionality of the Linac4 chopper is the reduction of beam currents in pulse-to-pulse mode, in order to guarantee the present versatility of the injector chain in terms of co-presence of various users (with different beam intensity specifications) in the same super-cycle. Several strategies have been attempted to reduce the beam current at low energy (below the 3 MeV threshold for neutron production) by either scraping the beam on the LEBT vacuum chamber (by reducing the first solenoid settings), or changing the optics in the chopper line to increase beam sizes at the dump and use this effectively as a collimator. A combination of the two strategies has also been studied [3]. Results for the three different scenarios are listed in Table 2 (beam parameters at the Linac4 output). As is here shown, a reduction in current of a factor varying from 2 to 6 can be achieved by changing magnet settings in the LEBT and chopper line. Variations in the transverse and longitudinal emittances are very small and do not affect the beam dynamics and beam quality downstream. On the other hand, some chopping efficiency degradation (last column of Table 2) is observed especially for the last two schemes, due to the increased beam size in the vertical (chopping) plane at the entrance of the dump.

Current Flexibility

In synergy with the pulse-to-pulse intensity modulation, studies to assess the flexibility of Linac4 in accelerating beam currents different from nominal (65 mA) have also been carried out [4]. Several beams were generated at the RFQ input with 20, 40, 60, 70, 80 and 100 mA beam currents. The linac RF parameters and PMQs gradients were kept constant at all times, while EMQs and the MEBT bunchers were used to re-match the beams between consecutive structures. The LEBT solenoids were tuned to find matched Twiss parameters at the RFQ input (adapted for the change in phase advance for different beam currents). RFQ performance degrades with

increasing currents, with larger beam sizes and consequent beam losses in both the longitudinal and

Table 2: Beam intensity and parameters at the Linac4 output for reduced current cases. Emittances are normalised RMS.

	I mA	ϵ_x mm mrad	ϵ_y mm mrad	ϵ_z deg MeV	Inefficiency (transmitted current) mA
Nominal	61	0.33	0.32	0.18	0.03
LEBT	20	0.27	0.28	0.15	0.13
MEBT	30	0.23	0.26	0.18	0.44
LEBT+ MEBT	11	0.20	0.26	0.15	1.14

transverse planes (becoming higher than 10% above 80 mA). Only an increase in the vane voltage can improve transmission. The last MEBT FODO and third buncher were then used to match the beams to the DTL input. Further downstream, only the EMQs in the linac intertanks were used to match the beam at higher energy. Good transmission is achieved for low space charge and currents, while for higher current values emittance growth and losses (<5%) are observed, especially at the transition between the chopper and DTL. In conclusion, Linac4 was proved capable of accelerating currents in the range 20-100 mA while keeping constant the RF and the focusing strength in the DTL and CCDTL. A constant beam quality can be delivered up to 70-80 mA current (with RFQ-to-PIMS transmission higher than 90%). Above 80 mA we observe a saturation effect that cancels out the advantages of an increased beam current, with most of the beam quality degradation taking place at the transition between the chopper line and the DTL, with an emittance increase proportional to the beam intensity (see Fig.2).

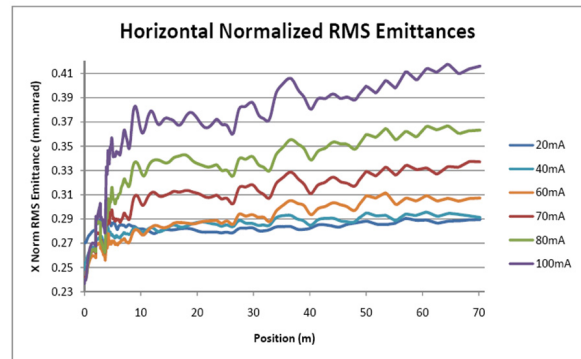


Figure 2: Horizontal RMS emittance evolution from MEBT to PIMS for different beam currents.

DTL FOCUSING SCHEMES

Further exploration of the beam dynamics at this transition point was done by comparing 3 different focusing schemes for the 111 PMQs housed in the DTL: 1) FDFD in all 3 tanks, 2) FFDD in Tank1 and FDFD in all other tanks and 3) FFDD in all 3 tanks (the logic behind the second scheme being to facilitate the transverse matching into the DTL and lower the gradient

of the first quadrupole, otherwise >100 T/m) [5]. No substantial differences between these were observed in the nominal beam performances (slightly bigger envelopes in FFDD and higher transverse emittance increase in FDFD). To evaluate the different sensitivity to machine errors, a campaign of error studies was launched, assuming ± 0.3 mm/mrad DTL input beam jitter, $\pm 0.5\%$ gradient error and ± 0.1 mm misalignments. For none of the schemes can lossless acceleration in presence of errors be achieved without a proper steering strategy. However, as was expected, the FDFD structure came out as more sensitive to transverse errors than the other two, with a ratio of beam losses near 8:1 and 30:1 with respect to the mixed scheme and FFDD respectively (Fig.3 top). For the FFDD case an automatic steering procedure is also expected to be easier. Transverse beam acceptances were finally compared, using two techniques: either scanning the phase space with a point-like beam of near-zero emittance in the 3 planes or just tracking a generated beam (with uniform distribution over an area covering the expected acceptance in one plane, and point-like in the other two) to check for surviving particles. The FDFD scheme in this case has the advantage of providing a slightly bigger transverse acceptance, as shown in Fig.3 (bottom). No significant differences were observed in the longitudinal plane for the 3 cases. Based on these results, an FFDD focusing was in the end adopted, as the case that proved more tolerant to quadrupole errors and requiring lower magnetic field gradients: two families of quads were assumed, of 45 mm and 80 mm length respectively in Tank1 and Tanks2-3. In the nominal beam case, a minimum aperture/RMS beam size ratio of 6 is maintained all along the DTL, providing quite a flexible margin for offsets and thus being a good transmission channel even for halo particles to be accelerated to high energy. In all error cases studied, beam losses were kept below a limit of 1 W/m at 6% d.c., emittance growth was less than 20% at 2 sigma and the final beam position and energy jitter were well within the tolerance window of the CCDTL. A corrective suite of 3 steerers and pick-ups and possibly beam loss monitors will be used for steering the beam back to the optimised trajectory during operation.

CCDTL FOCUSING

Layout simplification and cost saving measures have been the driving force behind a change in the CCDTL transverse focusing choice from EMQs to a mixed scenario with 2/3 PMQs and 1/3EMQs. The CCDTL is made of 21 tanks of 3 RF cells each, coupled by 3's in 7 modules. The scheme adopted has PMQs in between coupled tanks (14 in total) and 7 EMQs inter-modules. To assess any potential loss in machine flexibility, performance in non-nominal conditions has been studied. End-to-end simulations have shown that beam currents in the 20-100 mA range can be transmitted without changing the focusing in the DTL and CCDTL. An input beam with 40% higher nominal emittance can also be transported without losses and with a regular envelope, showing there is no significant restriction in the CCDTL acceptance.

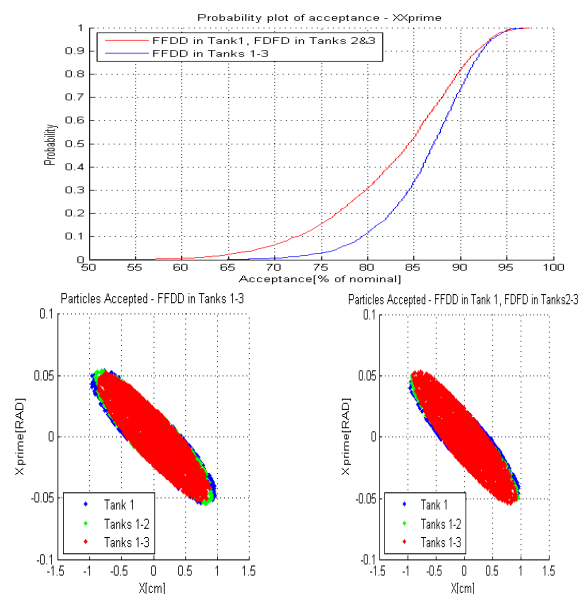


Figure 3: Probability curve for the $x-x'$ acceptance to be below the assigned value for two DTL focusing schemes (top) and nominal acceptance plots (bottom).

A smooth variation of the zero current phase advance and control over the transverse to longitudinal phase advance ratio have been applied in the design of Linac4 to ensure current independent matching and avoid resonance regions. A scheme with PMQs would restrict flexibility in varying the phase advance, though some changes would still be possible by using the EMQs. Finally transport of a 50 MeV beam through an unpowered CCDTL was achieved, with an increase in the beam size still manageable by the PIMS. In conclusion, even though EMQs are generally a better choice for machine flexibility, adopting a partial scheme with PMQs does not critically impair the CCDTL performance even for non-nominal beam conditions.

CONCLUSIONS

The Linac4 baseline design has been revised to optimise nominal beam performance while guaranteeing enough operational flexibility to still provide good beam quality in non-nominal cases. Machine acceptance limits in beam currents have been explored as well as schemes for producing reduced beam intensity in pulse-to-pulse mode.

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