END TO END BEAM DYNAMICS AND RF ERROR STUDIES FOR LINAC4

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Abstract

Linac4 is a normal conducting H$^-$ linac to be built at CERN as a new injector to the PS Booster and later on as a front end of a possible MultiMegaWatt Linac Facility. The layout consists of a H$^-$ RF source, a magnetic LEBT, a RFQ (accelerating the beam from 45 keV to 3 MeV), a chopper line, a conventional Drift Tube Linac (from 3 MeV to 50 MeV), a Coupled Cavity Drift Tube Linac (from 50 MeV to 102 MeV) and a π-mode structure (PIMS, from 102 to 160 MeV), all operating at a frequency of 352 MHz. End-to-end beam dynamics simulations have been carried out in parallel with the codes PATH and TRACEWIN to optimise the design and performance of the accelerator and at the same time to guarantee a cross-check of the results found. An extensive statistical campaign of longitudinal error studies (static and dynamic) was then launched for validation of the proposed design and to assess the maximum level of RF jitter/inaccuracies (in both phase and amplitude) the system can tolerate before beam quality at injection in the PS Booster - and later in the Superconducting Proton Linac (SPL)- is compromised.

LINAC4 LAYOUT

A 2 MHz RF volume source and 1.9m long 2-solenoid LEBT supply the initial H$^-$ beam at 45 keV (a 400 µs long pulse at 2 Hz repetition rate for 80 mA current). This is first accelerated to 3 MeV by a 352 MHz RFQ, before entering a 3.6 m long chopper line consisting of 11 EM quadrupoles, 3 bunchers and 2 deflecting plates. Here micro-bunches are removed from the pulse to achieve a cleaner injection of the Linac4 beam in the PS Booster ring downstream. The beam is then accelerated to 50 MeV by a 352 MHz conventional Drift Tube Linac (DTL), composed of 3 separate tanks each fed by one klystron. There are 111 drift tubes, each equipped with a Permanent Magnet Quadrupole. The DTL is followed by a Cell-Coupled Drift Tube Linac, which takes the beam to 102 MeV through a series of 7 modules (21 tanks coupled by 3’s) operating at 352 MHz and powered by individual klystrons. Transverse focusing is provided by 21 electromagnetic quadrupoles placed between tanks. Acceleration to the final energy of 160 MeV is then carried out by 12 Pi-Mode Structure (PIMS) tanks at 352 MHz, each composed of 7 cells, and 12 EM quadrupoles. The first 4 tanks are powered individually, while the last 8 are coupled in pairs onto a same klystron. The last 2 tanks have a lower nominal accelerating field, to allow for the possibility of energy painting at injection in the PSB [1]. The layout here described is the result of several revisions of previous designs [2], the main changes being in the values of the transition energies and in the final choice for one single frequency (352 MHz), to make for a simpler design.

END-TO-END BEAM DYNAMICS

Each section of Linac4 has been studied and optimized independently before a campaign of end-to-end simulations was launched to identify overall bottlenecks and limitations. The codes PATH[3], TRACEWIN[4], TOUTATIS[5], and PARMTEQ[6] have been used for these studies, providing mutual crosscheck of the results.

The H$^-$ beam pulse current from the source is 80 mA, and the duty cycle is 0.1% in an initial phase when Linac4 is used as injector of the PS Booster ring, and a duty factor of 6% for a later use as front end for the SPL (value used for the safety and loss studies).

Space charge effects dominate at low energy, causing some beam degradation and losses in the RFQ and chopper line. The RFQ can accelerate with <5% losses beams in the 20-100 mA range, with 8% transverse emittance growth for 70 mA current. The chopper line consists of two deflecting plates housed inside quadrupoles and driven at an effective voltage of 500V to remove 133/352 micro-bunches in the pulse, which are kicked onto a conical shaped dump. About 5% of the unchopped beam is lost here, whereas the fraction of chopped beam that is transmitted past the dump into the Linac, and might need to be eliminated at the lowest possible energy is ~0.05%. The beam current available at the end of the chopper line would thus be 65 mA per pulse without chopping, and 40mA with chopping on.

After the dump the beam is matched into the first tank of the DTL, with a FFDD focusing scheme. Most of the transverse emittance growth (almost 20%) occurs at this transition, when after a relatively slow phase advance

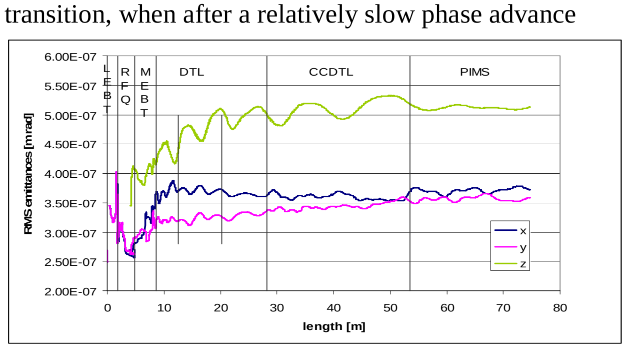

Figure 1: Transverse and longitudinal RMS emittance growth along the chopper line and Linac.

regime in the chopper (1 FODO per 10 βλ), the beam is compressed back in volume to fit a faster phase advance focusing channel (see Fig.1). The synchronous phase is ramped from -30 to -20 deg in Tank1 and then kept constant in the rest of the DTL (where the focusing scheme changes to a FODO type). At 50 MeV the beam is transferred to a CCDTL structure, composed of 3-gap cavities with an average phase of -20 deg, 4 MV/m accelerating field and a focusing period of 7βλ. Finally at 102 MeV a 352 MHz Pi-Mode Structure has been eventually adopted, with -20 deg average synchronous phase and a 9βλ focusing period.

Accurate matching between different types of structures allows for a very smooth variation of phase advances and good control over potential emittance growth. The evolution of the RMS emittances in the 3 planes is shown in Fig.1 for PATH calculations with a 2D space charge model. TRACEWIN results for a 3D model only differ by up to 10%. A measure of the design solidity is given by the aperture over RMS beam size ratio, shown for the transverse and longitudinal planes in Fig.2 and 3. The longitudinal acceptance has been defined in an "equivalent" way to the transverse one, as ratio between the phase and energy width of the linearised bucket, and the RMS beam phase and energy spread.

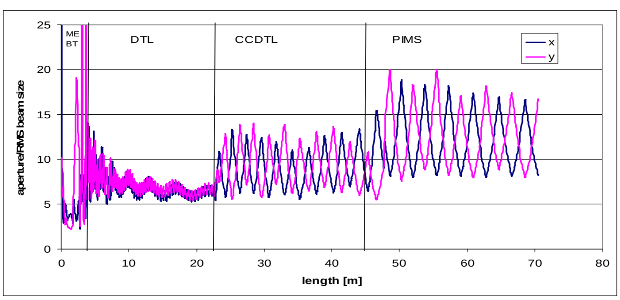

Figure 2: Aperture over RMS beam size ratio for chopper-DTL-CCDTL-PIMS.

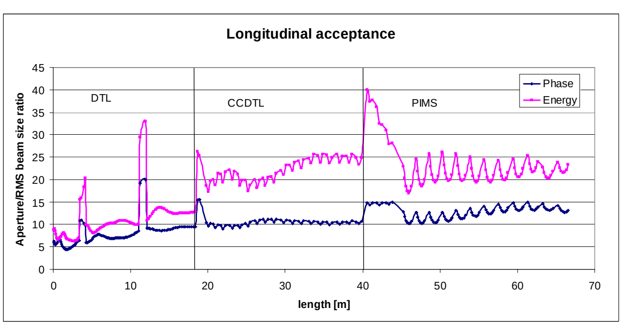

Figure 3: Longitudinal acceptance over RMS beam size ratio for DTL-CCDTL-PIMS. The bucket phase and energy width are taken as: $\Delta\phi=\pm 3/2\phi_s$ and $\Delta W=\pm 2\sqrt{[qmc^3\beta^3\gamma^3E_0T(\phi_s\cos\phi_s-\sin\phi_s)]}/\omega$.

The transverse acceptance bottleneck is located in the RFQ and chopper line, whereas for the longitudinal plane both the phase and energy acceptance minima are at the input of the DTL.

EFFECTS OF RF ERRORS

The beam dynamics results shown so far are for the case of a nominal, perfect machine. Beam degradation induced by machine imperfections has been the subject of a campaign of error studies, aimed at assessing the maximum level of inaccuracies the system can tolerate before beam quality at PS Booster injection is compromised. Several hundred to a few thousand runs were carried out with both PATH and TRACEWIN for a typical 50k particles input beam population for several error scenarios, and results for beam loss, emittance growth, average energy and phase jitter have been statistically analysed. The criteria followed to establish maximum tolerances are:

- maximum average losses (transverse) of 1W/m at 6% duty cycle (shielding requirements)
- maximum longitudinal losses (un-accelerated particles) of 5%
- maximum emittance growth of 15-20% at 2σ level (PSB budget)
- maximum energy jitter at 160MeV (1σ) below ±100keV (transfer line acceptance)

Transverse error studies and steering strategies have been described in detail in [7]. RF errors can be classified as either dynamic or static. To the first category belong klystron phase and energy jitters, varying in time and affecting several gaps at once (all the ones connected onto the same RF supply). In the static category, we have gap amplifier errors mainly due to tuning or machining imperfections. These do not vary in time, they are uncorrelated from gap to gap and can be mitigated by adjusting the RF power around the nominal value.

Table 1: Results of dynamic RF error studies for the DTL (RMS quantities).

Errors	**Phase jitter [deg]**	**Energy jitter [keV]**	**90% emittance [deg MeV]**
0% - 0deg	-	-	0.734
0.5%-0.5deg	0.82	13	0.745±0.014
0.5% - 1deg	0.88	18	0.751±0.017
0.5% - 2deg	1.14	31	0.774±0.034
1% - 0.5deg	1.6	23	0.757±0.024
1% - 1deg	1.6	28	0.762±0.027
1% - 2deg	1.77	36	0.786±0.047
2% - 0.5deg	5.12	43	0.794±0.07
2% - 1deg	5.66	46	0.799±0.07
2% - 2deg	8.55	49	0.830±0.1

Table 1 shows the results of RF klystron error studies for the DTL; the most left-hand column lists all the scenarios examined (amplitude and phase error), with uniformly distributed random errors within the given intervals. The output beam phase jitter is dominated by the klystron field amplitude errors, whereas the output energy deviation is more sensitive to phase errors, though these become negligible when the amplitude jitter is large enough (effects are even more balanced for the longitudinal emittance growth). The 1%-1deg case beam energy error is then propagated as input energy jitter downstream to the following structures (3σ uniformly distributed errors). Tables 2 and 3 list the equivalent results for the CCDTL and PIMS. In the PIMS case the sensitivity to the initial beam jitter is strong only for RF errors smaller than the 1%-1deg level. Above this threshold, klystron errors are the most significant source of deviation from nominal values. For this reason a balance should be kept between the two effects, and similar levels of RF tolerances specified for all types of structures. The criteria to be met at injection in the PSB impose that klystron phases and amplitudes be controlled ideally at the 0.5%-0.5 deg level (but 1%-1deg would still be acceptable).

Table 2: Results of dynamic RF error studies for the CCDTL (RMS quantities).

Errors	Phase jitter [deg]	Energy jitter [keV]	90% emittance [deg MeV]
0. -0.deg	-	-	0.769
0.5%0.5deg	0.5	39	0.771±0.013
1% - 1deg	1	63	0.773±0.018
2% - 2deg	2	115	0.780±0.030
5% - 2deg	4	237	0.794±0.047

Table 3: Results of dynamic error studies for the PIMS (RMS quantities).

Errors	Phase jitter [deg]	Energy jitter [keV]	90% emittance [deg MeV]
0% - 0deg	-	-	0.740
0.3%0.3deg	0.3	83	0.741±0.001
0.5%0.5deg	0.4	94.6	0.741±0.002
1% - 1deg	0.66	135	0.741±0.003
2% - 1deg	0.85	225	0.742±0.004
3% - 1deg	1.1	329	0.742±0.005

RF static error studies have been carried out, assuming either uniformly spread random errors (DTL) or a correlated tilt, i.e. a linear distribution of the errors over all the gaps in one tank, with the central gap at the nominal value (CCDTL) or an elliptical distribution with the nominal value for average (PIMS). The field error amplitude was varied between ±2% and ±10%. Results are summarized in Table 4. Unlike klystrons dynamic errors, that are relevant for causing a beam energy and phase jitter, in the case of gap errors, which are more similar to a systematic imperfection, energy and phase deviations can be adjusted by varying the level of the RF power supplied. What cannot be corrected for is the longitudinal emittance growth, which is therefore the quantity of interest when assessing beam quality degradation. Also, for dynamic errors, it only makes sense to consider RMS effects, whereas the impact of static errors is best evaluated by looking at extreme cases. The results in Table 4 show the different sensitivities of the Linac4 RF structures to gap errors (decreasing with beam energy). A tolerance budget of ±2% field variation for the DTL and CCDTL gaps and ±5% for the PIMS gaps has been assumed as RF specification. No significant beam losses have been observed in any of the error cases examined (both dynamic and static).

Table 4: Gap error studies: average emittance growth with respect to nominal and worst case deviation in no of σ .

Structure	Gap errors (±)	RMS average emitt. growth[%]	RMS emitt Std dev [deg MeV]
DTL	Spread 2%	5.4	0.011
	Spread 5%	31.1	0.076
CCDTL	Linear 2%	2	0.0025
	Linear 5%	1.5	0.0044
	Linear10%	<0.1	0.0086
PIMS	Linear 2%	0.6	0.00083
	Linear 5%	<0.1	0.00084
	Linear10%	0.6	0.00089
	Ellipt. 2%	0.18	0.0002
	Ellipt. 5%	0.4	0.0002
	Ellipt.10%	0.79	0.0003

CONCLUSIONS

Nominal beam dynamics for Linac4 has been studied with two different codes, indicating good performance. An extensive statistical campaign of longitudinal error studies has allowed to establish a tolerance budget on RF phase and amplitude errors that should guarantee good beam quality at PS Booster injection.

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