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Linac4 source extraction re-design for higher current operation

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Summary

At the end of LS2, Linac4 will become the new injector of proton beams to the entire CERN accelerator complex. The maximum beam current reliably achieved so far in commissioning is 25 mA, well below the initial specifications of 40 mA. This is mainly due to the presence of pre-injector limitations, and in particular to extracted beam emittance exceeding the acceptance of the RFQ.

A new geometry of the Linac4 source extraction electrodes has been the object of the study presented in this note, with the aim of decreasing the extracted beam emittance and increasing the H^- beam current that can fit in the RFQ acceptance. The new source layout was studied with the CST Particle Studio™ [1] and IBsimu [2] codes. Encouraging simulation results prompted the launch in production of a new flange and extraction electrodes that should be tested with beam at the source test stand before the end of the year.

1. Introduction

Currently in the last preparatory phases before being put in operation, Linac4 is a normal conducting linac accelerating H^- ions to 160 MeV for charge exchange injection in the CERN Proton Synchrotron Booster (PSB). By the end of the second long shutdown (LS2), Linac4 will become the sole provider of protons for the entire CERN accelerator complex.

The Linac4 low-energy part consists of a 2 MHz caesiated RF ion source, a low-energy beam transport (LEBT) section, a 3m-long 352.2 MHz RFQ accelerating the beam to 3 MeV, and a Medium Energy Beam Transport (MEBT) line housing a fast chopper. This is followed by the linac, itself composed of three different RF structures, a Drift Tube Linac (DTL), a Cell-Coupled Drift Tube Linac (CCDTL) and PI-Mode Structures (PIMS), bringing the beam to its final energy.

All through the commissioning period, Linac4 has delivered a maximum peak current of 25 mA, representing only 60% of the nominal 40 mA current. Although the present source design was demonstrated to be capable of producing beam intensities larger than 60 mA at extraction, since the beam emittance at high currents exceeds the RFQ transverse acceptance, only a maximum beam current of 30 mA has been accelerated to-day to 3 MeV. This is still sufficient to produce all beams required for post-LS2 operation by increasing the number of injection turns in the PSB (to 45 and 150 turns respectively for high-brilliance LHC beams and high-intensity beams for fixed target experiments). However in view of more demanding intensity requirements in the future, studies have been launched to achieve an emittance reduction of the source's beam current output by either investigating the effect of layout modifications to the present Linac4 source or by exploring alternative source extraction designs. For the first category of studies, a thorough campaign of simulations and measurements at a dedicated source test stand [3] was pursued in 2018-2019 and the main results are reported in [4]. Simulation studies for an alternative source extraction geometry were started in 2019 and the main results and considerations are presented in this paper. The first part of this note describes the layout and performance of the presently installed Linac4 source and its operational limitations. The second part of the paper details the proposed modifications to the source extraction region geometry and shows the results of comparative simulation studies predicting potential operational gains.

2. The present Linac4 source

The present IS03 ion source is composed of a ceramic plasma chamber with an external five-turns antenna. Hydrogen gas is injected via a pulsed valve and a 2 MHz RF amplifier gives a 100 kW maximum power for plasma ignition. The source can be operated in either volume or surface production mode, with a one-off discrete or continuous Caesium injection. The extraction system consists of five electrodes: plasma, puller, ground, einzel lens and LEBT (see Fig.1). The beam is extracted from a 6.5 mm diameter plasma bore by an electric field generated by a dual purpose puller-dump electrode, normally operated at 5-12 kV voltages. Electrons are co-extracted with the H^- beam and deflected onto a cup inside the puller electrode by an external magnetic dipole field generated by two permanent magnets also housed in the same electrode. The H^- beam is then accelerated to 45 keV energy by an electrode connected to ground. An accelerating einzel lens provides some beam focusing before reaching the LEBT.

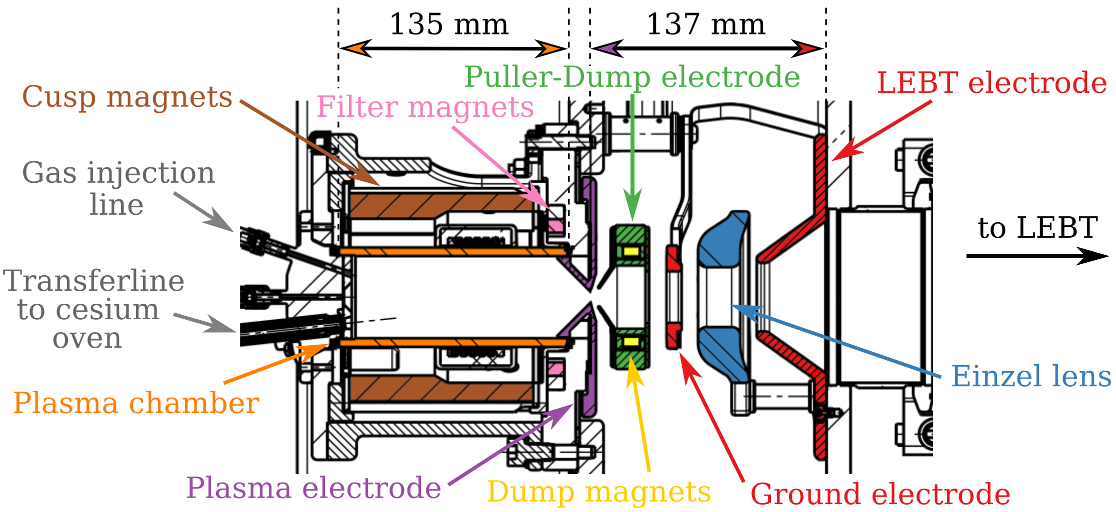

Figure 1: Current Linac4 source IS03 layout.

A systematic characterization of the source performance was done through campaigns of measurements at the source test stand. These unequivocally showed that, for the original unmodified IS03 design, the extracted beam emittance at large currents is a factor of 2-3 higher than both the design value (0.25 mm-mrad rms normalised emittance for 50 mA beam current), and the values found in literature for other H^- sources [5,6]. To better understand and cross-check these findings, extensive simulations of the IS03 source were carried out with the IBsimu code: Fig.2 shows typical output results, with co-extracted H^- (red) and electron (yellow) beam trajectories. After solving resolution issues in the area around the meniscus and increasing the plasma density by a factor of 30%, the simulation results were found to well reproduce the measurements taken at the test stand (Fig.3). Simulations pointed in particular to the large beam

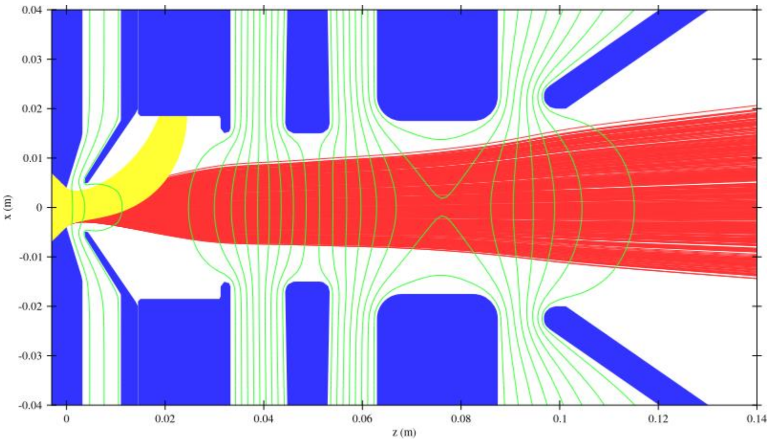

Figure 2: IS03 beam extraction simulations results with IBsimu: in blue are the extraction electrodes shapes in a cut-out view, in green the electromagnetic field lines, in red the extracted H^- beam trajectories and in yellow the extracted electron trajectories. The plane shown is x-z, with z being the main beam axis direction.

size at extraction, causing aberrations in regions with large transverse electric fields, as the main source of emittance growth both at the end plate of the puller electrode and in the einzel lens [4] (Fig.4). This effect could be mitigated by increasing the plasma bore radius aperture and decreasing the aperture of downstream electrodes to provide stronger focusing and recover transmission. With these modifications, IS03 with 9 mm bore diameter shows the same emittance behaviour as in the original geometry (6.5 mm bore diameter) but shifted towards higher current, thus getting closer to the original goal of extracting a 50 mA current in 0.3 mm-mrad RMS normalised transverse emittance (see the measurements' comparison in Fig.5).

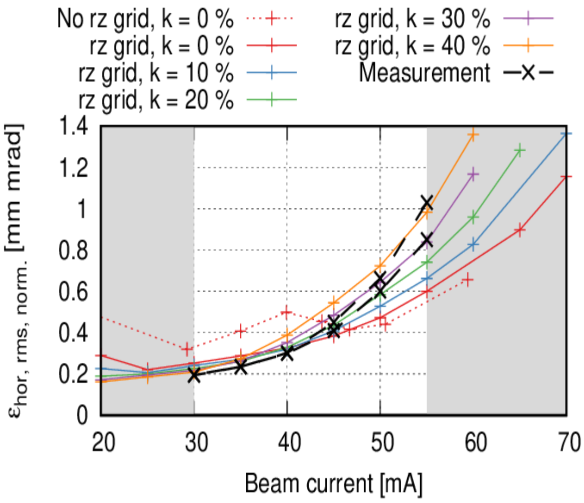

Figure 3: Influence of plasma density IBsimu modelling on the extracted beam RMS emittance for different beam currents in comparison to measurements.

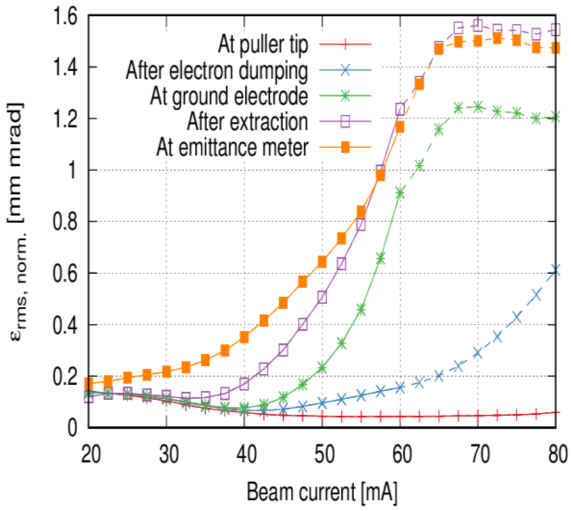

Figure 4: Simulated RMS emittances as a function of beam current at several locations of the source extraction at 10 kV puller voltage.

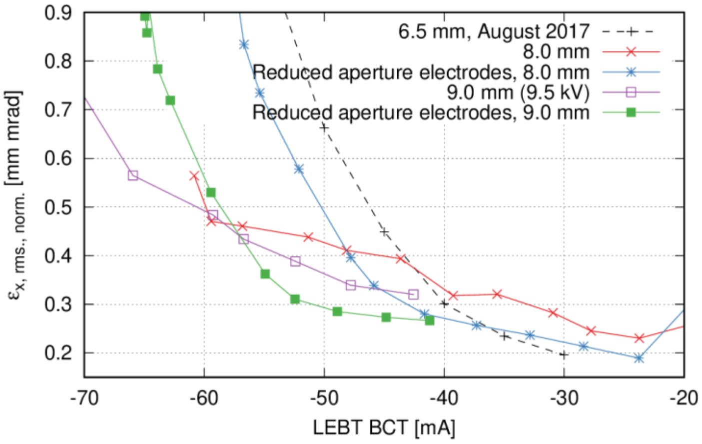

Figure 3: Combined larger bore diameter and reduced electrodes' aperture effect on the measured extracted beam RMS emittance for several currents, in comparison to the original 2017 layout measurements.

3. Source extraction re-design

In parallel to the studies on the IS03 source, an effort was launched to investigate alternative designs of the source extraction in the direction of a shorter geometry that could allow increasing the extracted beam current fitting in the RFQ transverse acceptance. Inspired by the more compact designs adopted in other labs [5], initial thoughts converged on a layout consisting of only three electrodes: plasma, puller and ground, making the whole extraction region 6 cm shorter than in the IS03 layout. Electrons are co-extracted onto a dedicated external dump after deflection by two permanent magnets housed at the base of the dump itself (see Fig.6 and 7). The dump is biased with a voltage of up to 1 kV, in order to both contain secondary electrons produced on the dump and create a potential barrier for the positive compensation particles collected in the beam in the low-energy beam transport section.

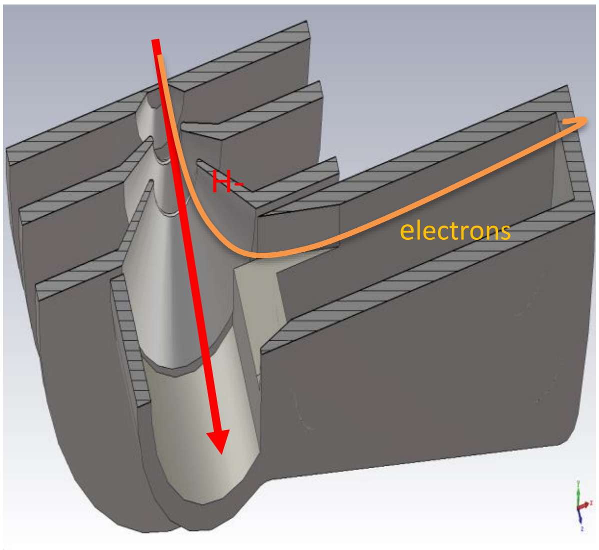

Figure 4: New source extraction region layout.

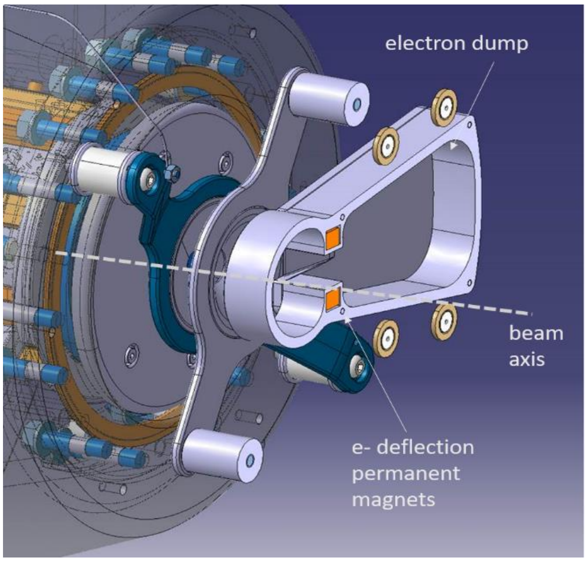

Figure 5: New source layout with zoom on the dedicated electron beam dump and base-ring housing the permanent deflection magnets.

Whereas the IS03 design was characterized by safe electron dumping at lower energy but long drift lengths (which degrade the extracted beam quality via space charge effects), a different trade-off was adopted in this new design, with a reduction of the source extraction region length (in favour of an improved H- beam dynamics), and dumping of the electrons at higher energy (implying more stress on the dump and a higher peak electric field between the electrodes, as addressed more in detail in the next section). Unlike the IS03 model, the source design presented here could therefore not work in volume mode, but only in a caesiated mode regime, characterised by a lower e/H ratio.

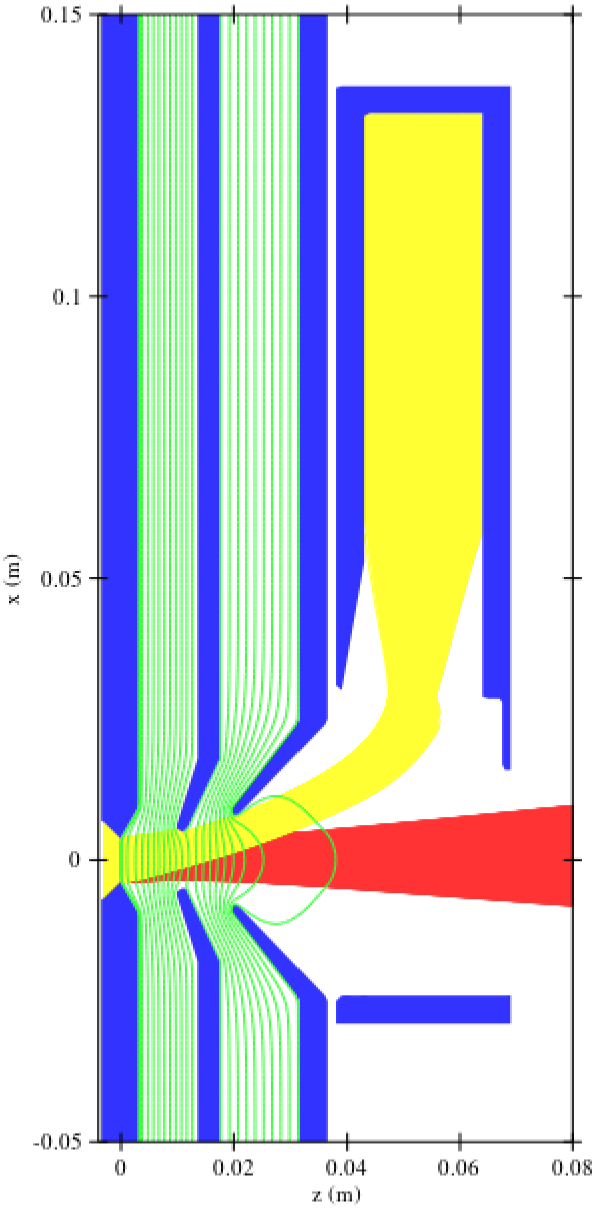

Figure 6: Short source extraction modelled in IBsimu In blue are the electrodes' shapes, in red and yellow the co-extracted H- and electron beam trajectories respectively.

The new extraction system was modelled in IBsimu (see Fig.8), using the same parameter settings that best matched experimental measurements in the IS03 case (namely the higher mesh resolution in the area around the meniscus and an increased plasma density at extraction). Several operational scenarios have been studied, changing the H^- beam current, the e/H ratio and the voltage applied to the puller electrode (at fixed extraction energy of 45 keV). An optimal dipole field value of 0.45 T was found to provide a clean deflection and dumping of the co-extracted electrons inside the dump for all these cases. The H^- beam was tracked in IBsimu from the plasma bore up to the location of the emittance meter on the source test stand (approximately 1m downstream), with operational settings of the LEBT solenoid, in order to reproduce experimental machine conditions and predict beam characteristics at the measurement location. Full space charge compensation is assumed to start acting right after the dump, about 9 cm downstream of the plasma bore. The extraction electrode potentials were varied in the study for each beam current value, and simulation results were compared. As shown in Fig. 9, in a range of optimal values of the puller voltage for each current (with higher values needed for higher currents), simulated rms transverse emittances are significantly lower than the corresponding values for the unmodified IS03 source (see Fig. 4 for comparison), and below the design value of 0.2 mm-mrad even for high currents.

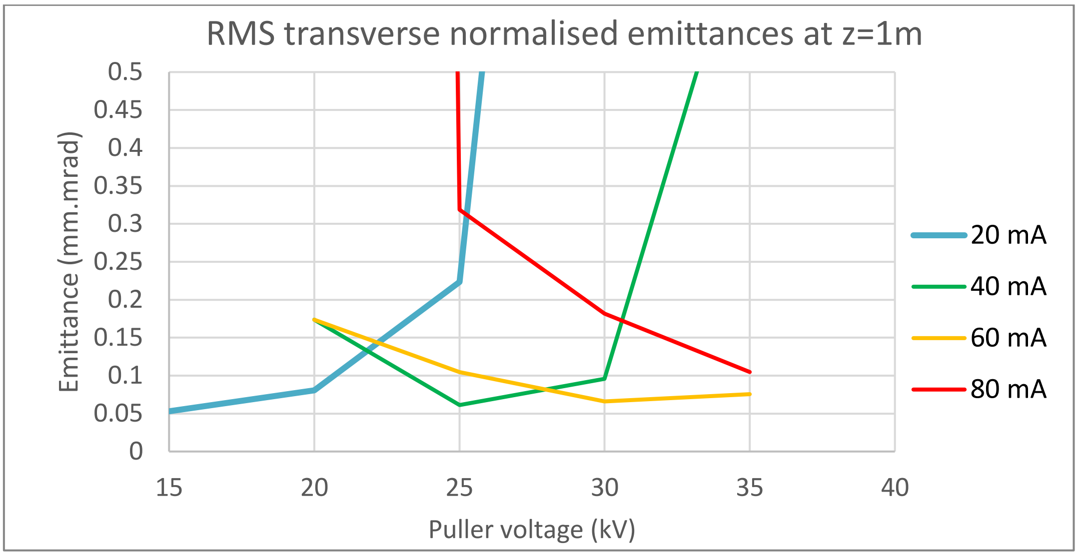

Figure 7: Extracted beam emittance for several beam current and applied puller voltage cases.

As further cross-check, particle beam distributions were extracted at z=0.09 m from the plasma bore, then tracked through the LEBT with the PATH code [7] using solenoid settings that maximize beam transmission through the zero-current RFQ transverse acceptance in conditions of nearly full space charge compensation. The same particles were successively transported through the RFQ using the PARMTEQ code [8], assuming this time full beam space charge effects (or zero compensation effects). Even though no correction was applied to cancel beam offsets, transmission values through the RFQ were found to exceed 80% for almost all studied cases (Fig 10).

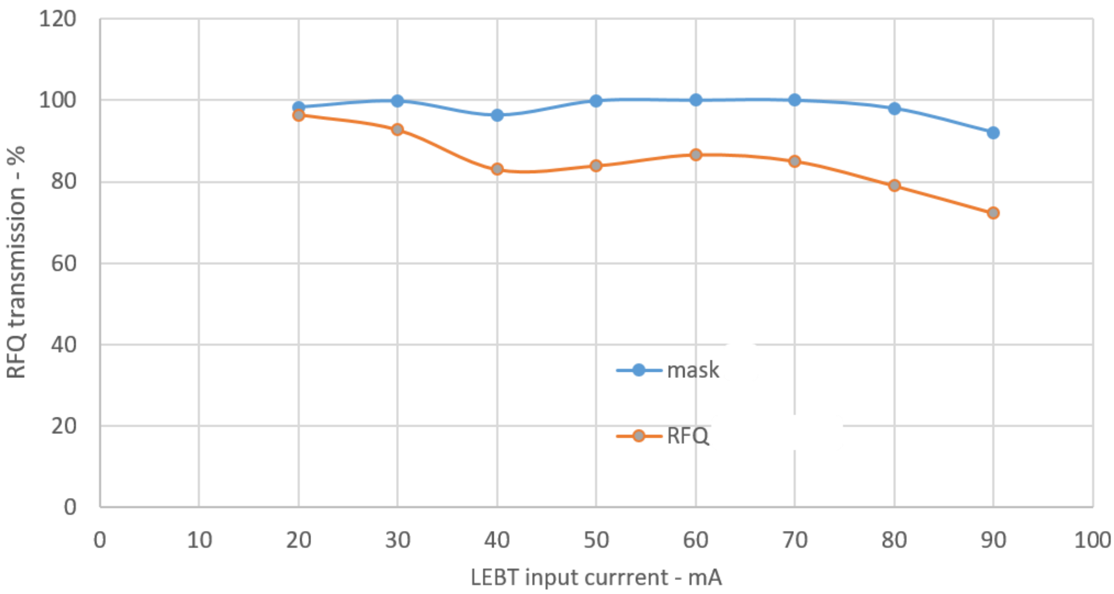

Figure 8: Simulated transmission through the RFQ (red) and its zero current transverse acceptance (in blue, 'mask') for several extracted beam currents.

The sensitivity of simulation results on the plasma model built in IBsimu was investigated by studying the effect of varying several plasma parameters. The most important ones affecting the beam extraction are the electron and ion transverse temperatures (T_t), the plasma potential (U_p) and the initial particle energy (E_0). Default values used in simulations are respectively: T_t=0.5 eV, U_p=7.5 eV and E_0=5 eV. These parameters were scanned over quite a wide range of values around the nominal one. In addition, variations to the meniscus shape as well as to the emittance and divergence of the extracted beam were studied for the case of a 50 mA extracted H^- beam at e/H=1 and various puller electrode voltages. Simulation results did not show great sensitivity to variations of these parameters: the biggest influence was given by changes in the transverse temperature T_t of the particles, but even in this case the effect observed was in the order of a few percent only (see Fig.11).

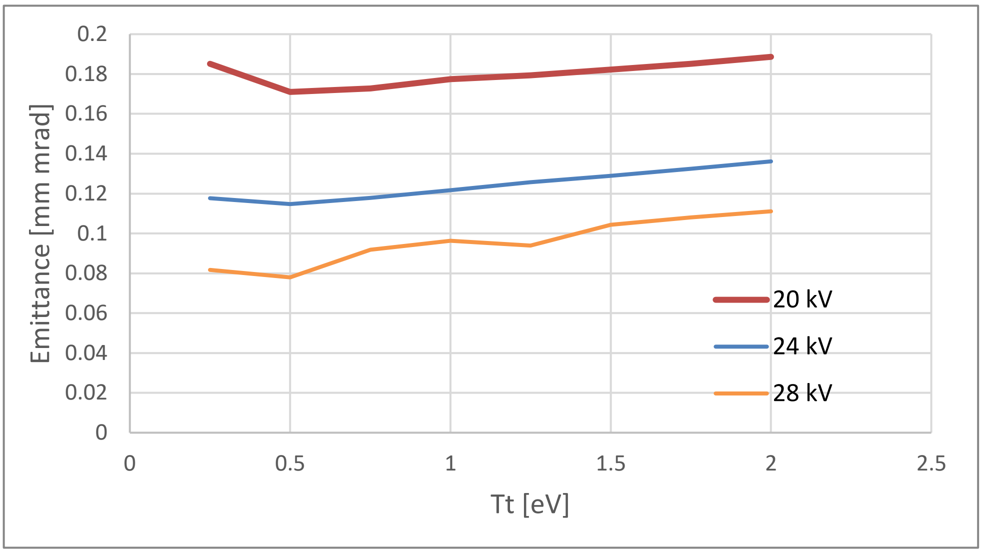

Figure 9: Sensitivity of the extracted beam emittance on the electron and ion transverse temperature used in the IBsimu plasma model. Simulation results are for the case of a 50 mA H^- extracted beam at 20 kV, 24 kV and 28 kV puller electrode voltage.

More in-depth studies of the electric field distribution between the electrodes of the new source extraction layout were done via electrostatic modelling in CST, in order to assess the sensitivity of the layout to electric breakdowns. The most critical points identified in this study were found to be located around the tips of the electrodes, where the highest values of the peak electric field were calculated (see Fig. 12 on the left). Applying a 25 kV voltage to the puller electrode (an optimal value for the extraction of large H^- currents, around 50-80 mA), the maximum peak field calculated amounts to approximately 6 kV/mm (Fig.12 on the right). This is comparable to the operational situation at the Linac2 proton source, where 90 kV were routinely applied across a distance of 16 mm between extraction electrodes, without any recurrent breakdowns being experienced.

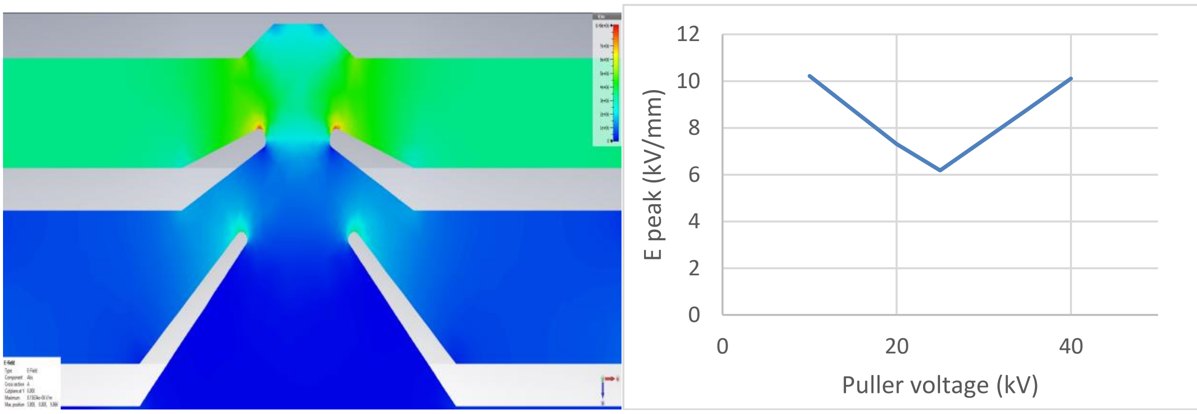

Figure 10: CST electro-static simulation results showing peak electric field distribution in the extraction region (left) and E peak values dependence on the applied puller voltages (right).

During this study it was observed that a non-negligeable percentage (20-30 %) of electrons could intercept the tip of the puller electrode in the case of large H^- beam currents (>40 mA)

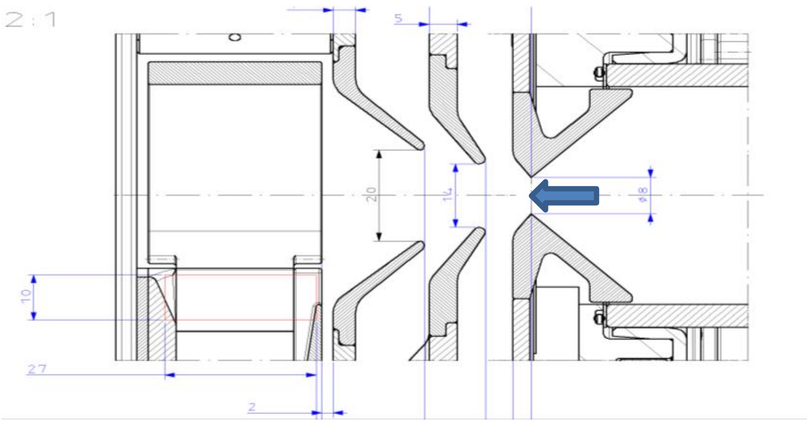

Figure 11: Re-optimised geometry of the extraction electrodes.

being extracted at lower puller electrode potential than optimal for beam transmission (< 25 kV). In order to limit this effect, which could increase the risk of breakdowns and thermally induced damage to the electrodes, a further re-optimization and tuning of the extraction electrodes' geometry was studied. By increasing the electrodes' apertures and tuning the plasma bore radius and angle to ensure correct beam focusing at extraction, the percentage of electrons hitting the puller electrode could be significantly reduced (to <1% level) without compromising the emittance and quality of the extracted H^- beam. The final extraction layout is shown in Fig. 13.

3.1 Electron dumping

Differently from the current IS03 source setup, in the extraction model here described, electrons are co-extracted at 45 keV energy onto a dedicated dump (see Fig.7).

At the beginning of the Linac4 source R&D, a similar setup had been tested with the DESY-type H^- source, first commissioned in 2009, where co-extracted electrons were deflected and dumped onto a graphite cup by a permanent dipole magnetic field. At that time it was found that voltage holding over the extraction gap was not possible for more than a few pulses, and later inspection of the dump showed beam induced damage on the graphite surface pointing to evaporated material as the main cause of the voltage breakdowns [9]. Transient thermal simulations made with the ANSYS code [10] showed that a pulsed power density of 1 kW/mm^2 for 500 μs long pulses could be sufficient to vaporize graphite. Simulations of beam extraction at 45 keV showed that a maximum power density of 3 kW/mm^2 could indeed be reached in the middle of the cup, confirming observations and prompting a re-design of the beam extraction region, which eventually led to the IS03 design.

In the knowledge of this setback, a detailed study of the electrons' footprint and deposited power density onto the dump was carried out for the new source extraction system. Compared to the DESY-source layout, the dump geometry presented here allows for a larger surface of impact of the electrons, colliding not just head-on but also on the lateral sides of the dump. The deposited power density for all studied operational scenarios with <100 mA co-extracted electrons' current is hence lower, staying below a limit of 100 W/mm^2 (see Fig.14, where the deposited power density is shown for several simulation scenarios on the three sides of the dump unfolded). Two extreme case scenarios were also simulated, closer to possible start-up situations of the source, when the e/H ratio has not yet stabilized around low values. It was found that even for 1 A equivalent electrons' currents and 15-20 kV puller potential, the deposited power density does not exceed 200 W/mm^2.

Beam power induced melting and sublimation limits vary from material to material at constant irradiation parameters. The values found in literature for 0.6 ms long beam pulses impacting at 1 Hz are of 0.4 kW/mm^2 for Titanium, 0.9 kW/mm^2 for graphite and 2 kW/mm^2 for Tungsten [11]. The construction material of the electron dump in the layout here presented has not been decided yet, though initial proposals tend to converge towards the idea of using a Tungsten heavy alloy, in order to benefit from the better performance of Tungsten on one side (in terms of higher resistivity to heat load), while ensuring better machinability and easier fabrication compared to pure Tungsten on the other.

Source start-up scenarios and procedures need to be defined with the aim of reducing the amount of time spent in high e/H regimes as a measure of possible damage mitigation. A few hours of plasma conditioning should be allowed at start-up with RF on. Pulse length and beam current (RF power) should then be reduced before switching on the HT extraction for the first time. A high temperature one-shot caesiation should be performed for the duration necessary to reduce the e/H ratio to below 1 and thus achieve a first, more substantial and quicker reduction of the co-extracted electrons current, before moving to continuous caesiation mode. The evolution of the e/H ratio can be monitored during caesiation by punctually switching on extraction for a few pulses. Once a sufficiently low value has been achieved, nominal operational conditions of the source can be established.

4. Conclusions and planning

A modified geometry of the Linac4 source extraction electrodes has been the object of a recent study, with the aim to overcome the present source performance limitations. Beam dynamics simulation results are rather encouraging, indicating that, with this new design, it would be possible to decrease the extracted beam emittance and increase the H^- beam current that can fit in the RFQ acceptance. These results have prompted the launch in production of the new source parts (flange and extraction electrodes), for experimental beam tests of the modified assembly at the source test stand before the end of the year

Construction material for the external flange has already been procured, and technical drawings have been approved. Production of the new source components should be completed and a first assembly put together by spring 2021. An initial testing period of six weeks has been reserved in the source test stand activities' planning. With input from the results achieved, further optimization of the electrodes' layout could be envisaged for a subsequent components' production and testing.

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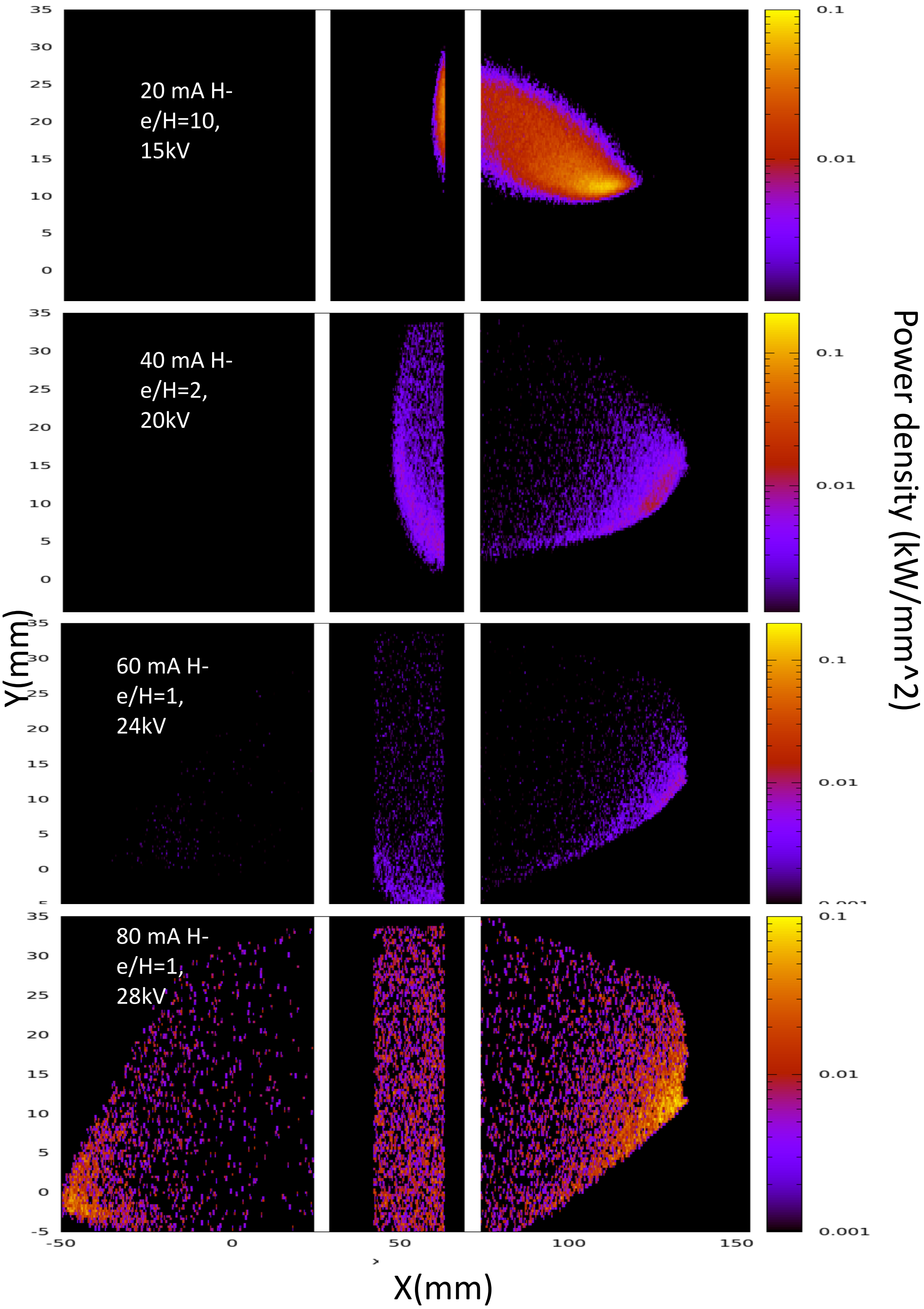

Figure 12: Deposited power density distribution on the three sides of the electrons' dump unfolded (bottom side at the center, lateral sides on the left and right) for different extracted beam currents, applied puller voltage and e/H ratio scenarios. Peak values stay below a limit of 100 W/mm^2.

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