Machine Studies at MAX-IV 1.5GeV Ring (R1)

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Report of experiments carried out during 19/11/2022 and 20/11/2022 (week 46) at the 1.5GeV ring of MAX-IV.

1 R1 parameters

The parameters presented in Table 1 were considered for simulations.

Table 1: Main parameters for longitudinal dynamics

Energy	E_0	1.5 GeV
rf frequency	f_{rf}	99.931 MHz
Harmonic number	h	32
Momentum compaction	α	3.05×10^{-3}
Energy spread	σ_δ	7.41×10^{-4}
Energy loss per turn	U_0	114.4 keV
HC type		Passive normal-conducting
HC rf harmonic		3
HC shunt impedance	R_s	5.5 MΩ
HC quality factor	Q	20 800
Number of HCs		2

2 Voltage calibration

2.1 Main voltage

With low current (single-bunch) in the ring and Landau cavities parked, the synchrotron frequency was measured as $f_s = 7.18\,\mathrm{kHz}$. The relation between synchrotron frequency and main rf voltage is

$$f_s = f_{\mathrm{rf}}\sqrt{\frac{\alpha}{2\pi h E_0}}\left(V_{\mathrm{rf}}^2 - U_0^2\right)^{1/4}. \tag{1}$$

Therefore, for a given synchrotron frequency f_s, the relation can be inverted to determine the main voltage:

$$V_{\mathrm{rf}} = \left[\left(\frac{f_s}{f_{\mathrm{rf}}}\right)^4\left(\frac{\alpha}{2\pi h E_0}\right)^2 + U_0^2\right]^{1/2}. \tag{2}$$

Considering the parameters from Table 1, the measured synchrotron value corresponds to a main cavity voltage of $V_{\mathrm{rf}} = 522.3\,\mathrm{kV}$. This value was used throughout the analysis.

2.2 Landau voltage

To calibrate the voltage of Landau cavities we injected about 2.3 mA in uniform fill in the ring and tuned the Landau voltages towards resonance. This was achieved by maximization of the voltage readings. Then the current was reduced in steps with the vertical scraper until

0.3 mA and the corresponding measured Landau voltages were recorded for each current, always adjusting the cavities to be on resonance.

For uniform filling and the passive Landau cavity on resonance, the Landau voltage peak value should be simply $V_{\mathrm{HC}} = R_s I$, where R_s is the cavity shunt impedance and I is the stored current. The result of measured Landau voltage in hardware units (mV) and expected Landau voltage in physics units (kV) calculated by $R_s I$ is presented in Fig. 1.

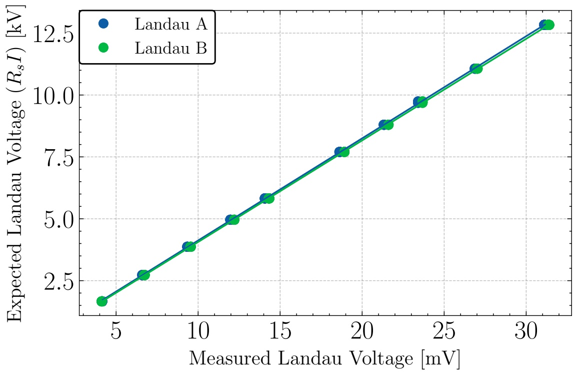

Figure 1: Measured calibration curve of Landau voltage.

The data points were fitted to a linear polynomial, with the following coefficients:

$$\begin{aligned} V_{\mathrm{HC,A}}\ [\mathrm{kV}] &= 0.4126\ V_{\mathrm{meas,A}}\ [\mathrm{mV}] - 0.0028, \\ V_{\mathrm{HC,B}}\ [\mathrm{kV}] &= 0.4103\ V_{\mathrm{meas,B}}\ [\mathrm{mV}] - 0.0410. \end{aligned}$$

3 Fitting bunch profiles measured with the streak-camera

The bunch profiles were measured with the streak-camera integration feature and also with the sequence option, capturing 100 snapshots of profiles. The streak-camera provides a 2d image with an axis corresponding to a fast scan, with a timescale within bunch separations (nanoseconds) and an axis related to a slow scan, with a timescale within a revolution period (microseconds). In Fig. 2 an example of streak-camera image is shown. The time axis can be easily converted to a z axis with $\tau = z/c$, where c is the speed of light.

The longitudinal equilibrium bunch profiles in the presence of Landau voltage can be calculated by solving self-consistently the Haissinski equation. Let $\lambda_m(z_i)$ be the measured average bunch profile with the axis z_i. The calculated bunch profile can be adjusted to fit the measured profile. Two fitting parameters were used: the Landau voltage V_{fit} (which is controlled by the cavity detune for passive cavities) and an offset z_{fit} to match the measured and simulated axis z_i. The axis offset was not fundamental to the fitting as the cavity detune, which determines the bunch profile. The axis offset was included as a fitting parameter just as an automatic way to account for the undetermined offsets between the origin of the streak-camera time axis and the real coordinate z. Furthermore, including the offset in the fitting improved visually the comparison between measured and calculated bunch profiles.

The fitting parameters were obtained by solving the least squares minimization problem:

$$\chi^2 = \sum_i \left[\lambda_m(z_i) - \lambda(z_i - z_{\mathrm{fit}}, V_{\mathrm{fit}})\right]^2, \tag{3}$$

where $\lambda(z, V_{\mathrm{fit}})$ is equilibrium bunch distribution calculated in the presence of a main rf voltage and a third-harmonic voltage V_{fit} in the Landau cavities.

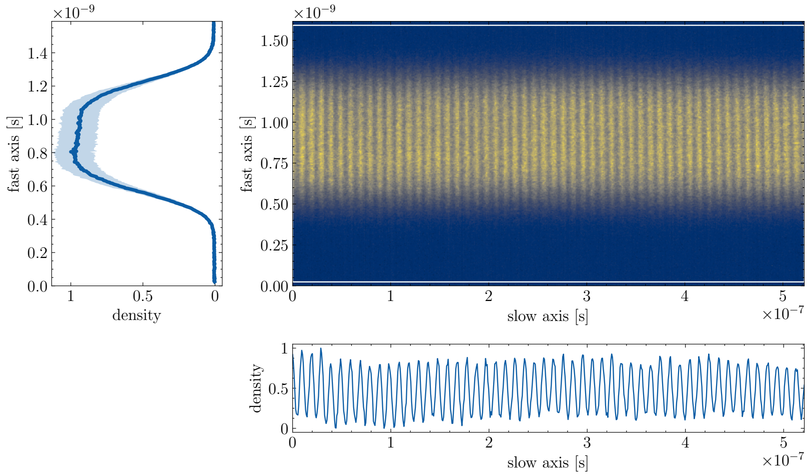

Figure 2: Example of streak-camera image acquired with 200mA in uniform fill. On the left plot, the solid curve is the average projection along the slow axis and the shaded region is the std variation over bunches.

A comparison of measured and fitted bunch profiles is presented in Fig. 3.

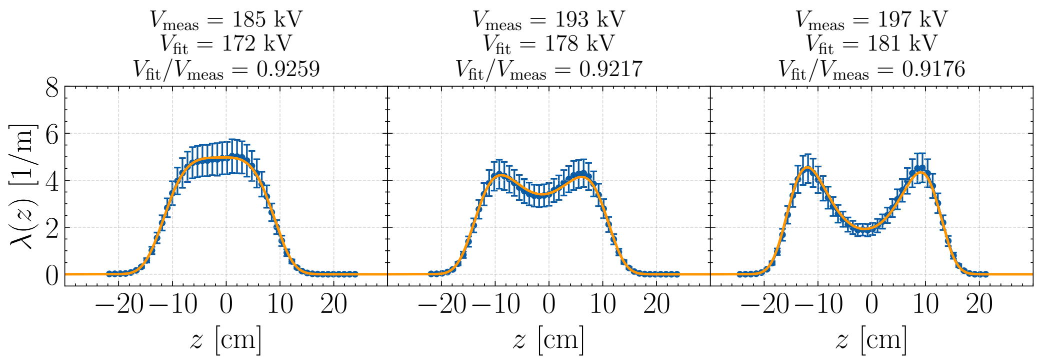

Figure 3: Measured and fitted bunch profiles for 200mA. Dots represent the average and error bars represent the variation of charge densities over bunches.

The measured total Landau voltage (sum of 2 cavities) and the fit voltage are presented in the figure subtitles. The required total voltages in simulation to match the measured bunch profiles are systematically lower than the measure voltage. A constant difference could be explained by an error on the shunt impedance considered in the Landau voltage calibration. However, the discrepancy between the measured and fit voltages increases linearly with the total voltage[1], as shown in Fig. 4 for the set of fittings based on measured bunch profiles with different currents. Data for 400mA and 300mA lies on the same line. Only data for 200mA differs for total voltages lower than 190kV.

Based on the difference between fit and measured voltages, the linear coefficient of the polynomial used for Landau voltage calibration was readjusted by a factor 0.93. This makes

[1]The calibration curve of Landau voltages is measured at low currents, setting the cavities to resonance condition, which makes this measurement at higher currents impossible. The discrepancy made me question the validity of this linear calibration curve for higher currents. Perhaps some non-linearity in the voltage measurement device in the cavity could explain a non-linear calibration curve

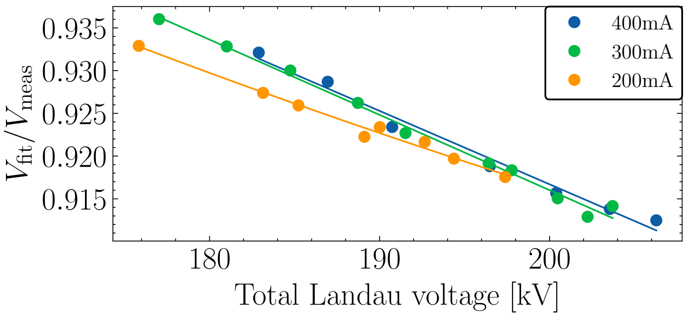

Figure 4: Ratio between fit and measured Landau voltage obtained after fitting bunch profiles acquired with different currents.

the measured total voltages of 180 kV match with the fit voltage from bunch profiles, but a small discrepancy that increases with the voltage remains, reaching an error of $0.915/0.93 = 0.98$ for higher voltages as 210 kV. The adjust of 0.93 can be interpreted as if the actual shunt impedance of Landau cavities is 5.115 MΩ, i.e., 7% smaller than the value of 5.5 MΩ considered previously.

All references to "measured Landau voltages" below are values already adjusted by the factor 0.93. Therefore, to recover the value of the voltage setpoint used in the control room during the experiments, one must divide the reported values by 0.93.

4 Lifetime optimization

The increment on Touschek lifetime due to the bunch lengthening provided by the Landau cavities can be estimated by the factor:

$$R = \frac{\int \lambda_0^2(z)dz}{\int \lambda_{\mathrm{HC}}^2(z)dz},$$

where $\lambda_0(z)$ is the longitudinal bunch profile without the Landau cavity and $\lambda_{\mathrm{HC}}(z)$ is the profile in the presence of Landau cavity fields.

It is well-known from simulations that profiles corresponding to Landau voltages higher than the flat potential condition (when the first and second derivatives of longitudinal voltage are approximately zero) have a higher value for the parameter R, as shown in Figure 5. The bunch profiles with higher Landau voltages have a double-peaked shape and this situation is often referred as overstretched condition. This result indicates that overstretched distributions can produce longer Touschek lifetimes than the flat-potential condition, due to the reduced peak current in the bunch.

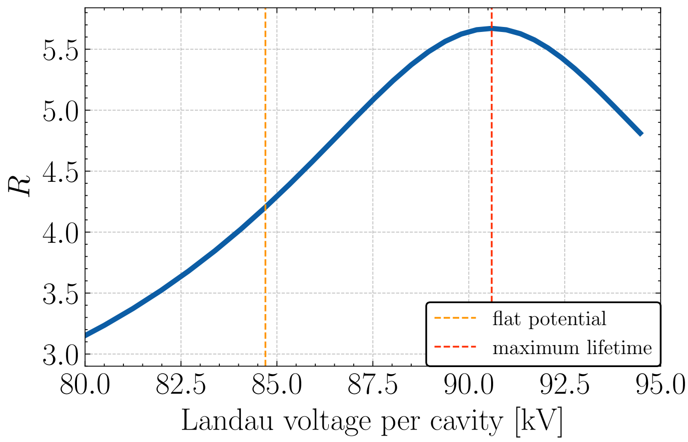

Figure 5: Simulated Touschek lifetime improvement as a function of Landau voltage per cavity for MAX-IV 1.5GeV ring. The lifetime improvement (R factor) for the flat potential voltage is about 4.2, while the maximum improvement in the overstretching condition is about 5.6. Thus, the maximum lifetime have an R factor about 30% higher than the flat potential condition.

Based on this simulation results, the goal of the machine studies was to verify experimentally if overstretched conditions are in fact better than the flat potential case regarding lifetime. We measured the stored current and lifetime provided by the DCCT device while changing the voltage setpoints of Landau cavities. The measured voltages of Landau cavities were also registered during the process. For each setpoint of Landau voltage, a set of measurements were performed with the streak-camera.

4.1 200mA

At 200mA, we observed that for Landau voltages per cavity around 96 kV, a coupled-bunch mode-0 instability (probably a Robinson instability caused by the small detuning of the Landau cavities). This instability limited the maximum value of Landau voltage for the scan in this current.

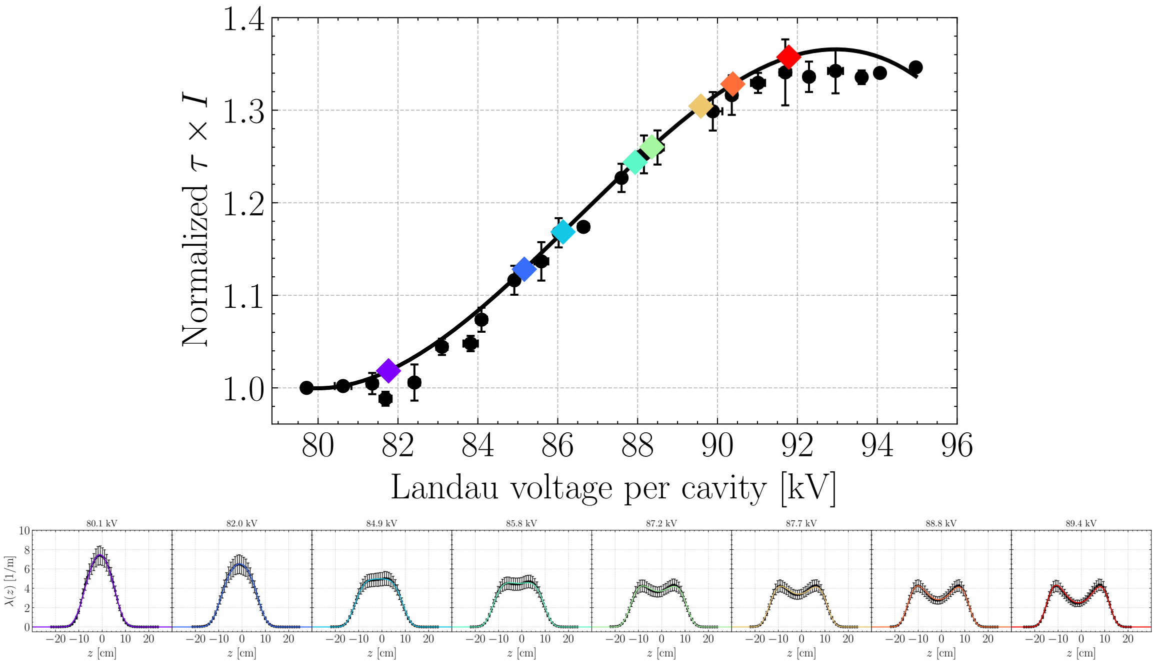

Figure 6: (Top) Experimental results of the product lifetime × current normalized by the initial value during Landau voltage scan with 200mA. The initial value is $(\tau \times I)_0 =$ 4600 mA h, which corresponds to a lifetime of 23 h for 200 mA. Error bars represent the variation of measured voltage and lifetime related to the mean value (black dots). The colored squares indicate the longitudinal profile presented on the bottom plots. The Landau voltage per cavity required to produce the bunch distribution in the simulation is shown in each subtitle.

4.2 300mA

A Robinson instability limited the maximum Landau voltage in the scans with 200mA. Then we repeated the voltage scan with 300mA, since we can achieve the same voltage with larger detunes at higher current. However, at 300mA, we observed that for Landau voltages per cavity around 94 kV, two coupled-bunch mode instabilities (modes 12 and 24) were excited. Since these instabilities were probably caused by HOMs from Landau cavities, we changed the Landau cavity temperatures setpoints (from 46ºC to 49ºC). The temperature adjusted shifted the HOMs frequencies and suppressed the instabilities. More precisely, we observe that the change in the temperature of Landau cavity A is what caused the stabilization. In the new operating temperatures, it was possible to further increase the Landau voltages while keeping the beam stable. The drop of lifetime around 94 kV shown in Fig. 7 is related to these coupled-bunch instabilities.

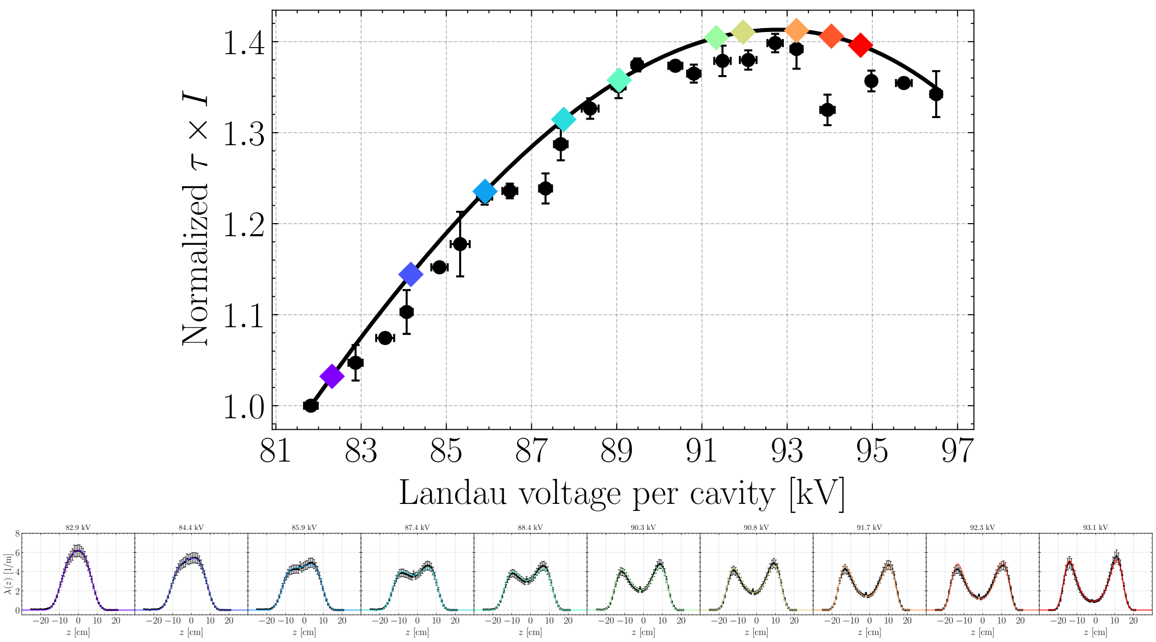

Figure 7: (Top) Experimental results of the product lifetime $\times$ current normalized by the initial value during Landau voltage scan with 300mA. The initial value is $(\tau \times I)_0 =$ 4860 mA h, which corresponds to a lifetime of 16.2 h for 300 mA. Error bars represent the variation of measured voltage and lifetime related to the mean value (black dots). The colored squares indicate the longitudinal profile presented on the bottom plots. The Landau voltage per cavity required to produce the bunch distribution in the simulation is shown in each subtitle.

4.3 400mA

A set of measurement with a higher current of 400mA was conducted, since instabilities were limits the maximum Landau voltage in the experiment with lower currents. During this scan, the initial value of Landau voltage was already at the flat-potential condition, taking into account the 7% difference in the calibration of voltage setpoints. The result is shown in Fig. 8.

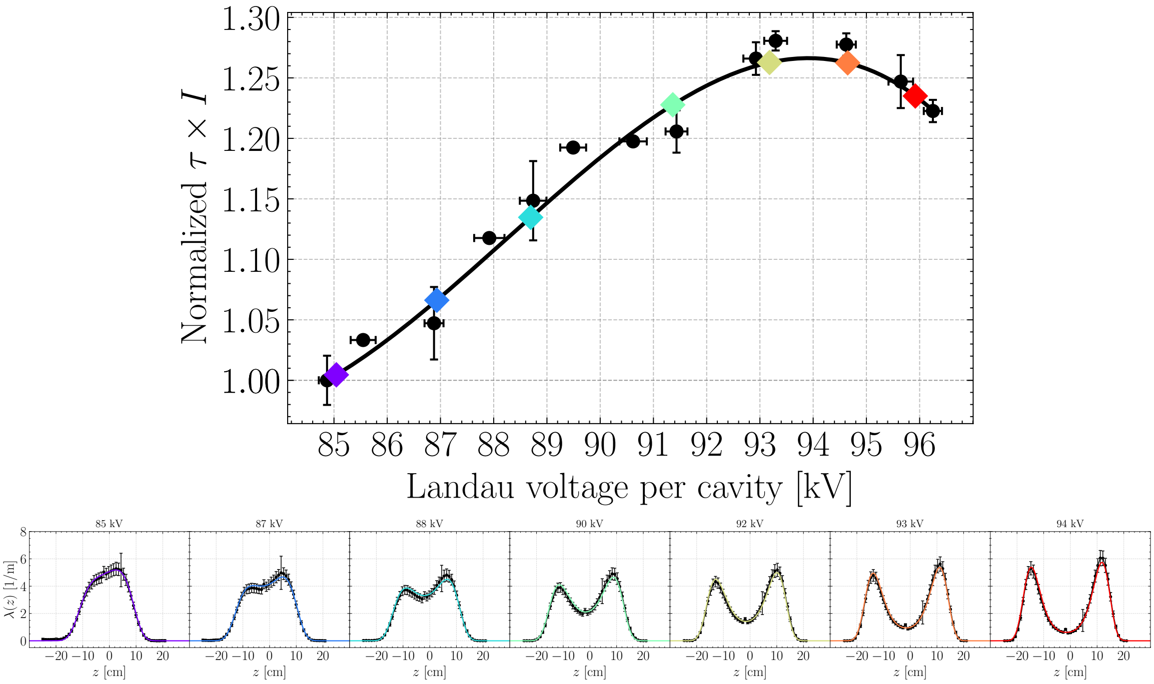

Figure 8: (Top) Experimental results of the product lifetime $\times$ current normalized by the initial value during Landau voltage scan with 400mA. The initial value is $(\tau \times I)_0 =$ 4660 mA h, which corresponds to a lifetime of 11.6 h for 400 mA. Error bars represent the variation of measured voltage and lifetime related to the mean value (black dots). The solid black curve is a cubic polynomial fit to the data. The colored squares indicate the longitudinal profile presented on the bottom plots. The Landau voltage per cavity required to produce the bunch distribution in the simulation is shown in each subtitle. The data with high variation around $z = 5$ cm is probably a damaged pixel area in the streak-camera for the configured settings on this current, i.e., it is not a real feature of bunch profiles.

5 Discussion and conclusion

In the first run with 200mA, we did not know about the difference between the measured Landau voltage and the value that must be considered in simulation to best explain the measured bunch profile with streak-camera. Then the voltage scans started with a condition below the flat-potential. It was observed that overstretched profiles in fact correspond to longer lifetimes. However, a Robinson instability prevented reaching higher Landau voltages. Even so, from the data it was possible to infer that the maximum lifetime should be observed with the Landau voltage of about 93 kV (100 kV in the control system setpoint).

In the second run we increased the stored current to 300mA. During the scan we observed coupled-bunch instabilities for higher Landau voltages and a temperature adjust had to be done to suppress the instabilities. Nevertheless, it was possible to reach higher Landau voltages corresponding to a region of maximum lifetime and overstretched bunch profiles.

The last run was performed with 400mA and no instabilities were experienced during the voltage scanning. The maximum lifetime was reached with a voltage per cavity of 100 kV in the control system setpoint. The bunch profile measured in this condition was reproduced in simulation with 92 kV per cavity.

In summary, we confirmed experimentally that overstretched profiles are beneficial for beam lifetime until the bunch peak current can be reduced, increasing about 25% the lifetime with respect to the flat-potential condition with a Landau voltage per cavity less than 10% higher (setpoints: 91 kV $\rightarrow$ 100 kV per cavity). For 400mA in R1, this can represent a lifetime increase from 12h to 15h. Increasing the Landau voltages even further also increases the peak current, the two peaks of the overstretched profile become more separated and the lifetime is reduced.