SLAC-AP-138
October 30, 2001

Increasing SLEDed Linac Gradient*

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Introduction

This note will show how to increase the SLED [1] gradient by varying Q_e, the external Q of the SLED cavity, by increasing its Q_0 and by increasing the compression ratio. If varying the external Q is to be effective, then the copper losses should be small so that $Q_0 >> Q_e$. Methods of varying Q_e will be indicated but no experimental data will be presented. If we increase the klystron pulse width from 3.5 to 5 μS and increase Q_0 from the present 100000 to 300000, then the gradient increases by 19% and the beam energy increases from 50 to 60 GeV. This note will also discuss SLED operation at 11424 MHz, the NLC frequency. Without Q_e switching, using SLED at 11424 MHz increases the SLAC gradient from 21 MV/m to 34 MV/m, and at the same repetition rate, uses about 1/5 of rf average power. If we also double the compression ratio, we reach 47 MV/m and over 100 GeV beam energy.

Definitions

The compression ratio is the duration of the input pulse T_k, divided by the duration of the compressed SLED pulse, T_{sp}. The pulse compression efficiency, η_{pc} is the energy of the compressed pulse U_{sp} divided by the energy of the input pulse U_k. They are, respectively

$$C_r = \frac{T_k}{T_{sp}}, \quad \eta_{pc} = \frac{U_{sp}}{U_k} \ . \tag{1}$$

Define the gradient, $E_g = 1/L_s \int_0^{L_s} E(z,t)dz$. The steady state gradient [2]:

$$E_{gs} = \sqrt{\eta_s s T_f P_s / L_s} = \sqrt{\eta_s s P_s / v_{ga}} \ . \tag{2}$$

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Here, T_f is the fill time, s is the elastance/m, η_s is the section efficiency, P_s is the power into the section and L_s is the section length. Substituting the SLAC section parameters: $\eta_s = 0.608$, $s = 73.4\mathrm{M}\Omega/\mu\mathrm{S/m}$, $, T_f = 0.82\ \mu S$, $P_s = 13.8$ MW, $L_s = 3.01\ m$, we have $E_{gs} = 12.9$ MV/m.

The SLED gain S_g is the ratio of the maximum noload gradient with pulse compression E_{gm} to that without pulse compression E_{gs}. The SLED gain efficiency is the ratio of the square of the maximum noload gradient with pulse compression to that without pulse compression, divided by the compression ratio. The SLED power gain is the peak power required without SLED divided by the peak power required with SLED. They are respectively,

$$S_g = \frac{E_{gm}}{E_{gs}}, \quad \eta_{sg} = \frac{S_g^2}{C_r}, \quad S_{pg} = S_g^2\ . \tag{3}$$

Pulse compression reduces the required peak power by a factor of $1/S_{pg} = \frac{1}{\eta_{sg}C_r}$. If the compressed pulse is flat then $\eta_{pc} = \eta_{sg} = \eta$, the same as the efficiency defined in Ref. [3] . But with SLED, maximizing η_{pc} will not maximize the noload gradient, and hence the SLED gain efficiency, η_{sg}. Nor will it maximize the peak compressed power.

Define E_{gi} as the gradient at beam injection time, I_b as the beam current, η_b as the beam induced gradient efficiency [4], L_g the length with RF, and L_b the length with beam. The lengths are not necessarily equal because some klystrons can be turned off. The rf to beam energy conversion efficiency [4]

$$\eta_{rb} = \frac{\text{Beam pulse energy}}{\text{Input pulse energy}} = \frac{U_b}{U_k} = \frac{I_b E_{gm} v_{in} L_k T_b}{P_k T_k}\quad . \tag{4}$$

$$I_b = \frac{E_{gm}(1-v_{in})L_g}{\eta_b s T_f L_b/4}, \quad \eta_{rb} = \frac{4E_{gm}^2(1-v_{in})L_g v_{in} L_k T_b}{\eta_b s T_f L_b P_k T_k} = \frac{4S_{pg}\eta_s(1-v_{in})v_{in}T_b L_g}{\eta_b T_k L_b}\ .$$
$$v_{in} = E_{gi}/E_{gm}, \quad E_{gm} = S_g E_{gs}, \quad S_{pg} = \eta_{sg} C_r, \quad T_b/T_k = (T_b/T_{sp})/C_r \tag{5}$$

Without SLED $S_g = S_{pg} = 1$. At steady state: $T_b = T_k = \infty$ and

$$\eta_{rb} = \frac{4\eta_{sg}\eta_s(1-v_{in})v_{in}L_g T_b}{\eta_b L_b T_{sp}}, \quad \eta_{rbs} = \frac{4\eta_s(1-v_{in})v_{in}L_g}{\eta_b L_b}\quad . \tag{6}$$

If $T_b = T_k - 2T_f$ then $\quad \eta_{rbc} = \eta_{rbs}(T_k - 2T_f)/T_k$.
The charge per pulse, $q_p = I_b T_b = E_{gm}(1-v_{in})L_g T_b/(\eta_b s T_f L_b/4)$.

The decrease in efficiencies are due to the following:

1. RF energy dissipation.
2. Reflection during charging of the energy storage cavities.
3. Leftover rf energy in the cavities.
4. Shape of the compressed pulse.

The reflected and dissipated energies during each region of duration T, are respectively:

$$U_r = \int_0^T E_r dt, \quad U_d = \int_0^T E_d dt, \quad E_d = E_c/\sqrt{Q_0}\ . \tag{7}$$

Performing the integration we have, $U_{r,d}$, during each time interval T:

$$\Delta E = E_{r,d}(0) - E_f, \quad \tau = T/T_c$$

$$U_{r,d} = TE_f^2 + 2T_c E_f \Delta E(1 - e^{-\tau}) + 0.5T_c(\Delta E)^2(1 - e^{-2\tau})\ . \tag{8}$$

Here, the final field at infinity E_f stands for either E_{fr} or E_{fd}.

The energy in the cavities at the end of charging divided by input pulse energy during charging is the filling efficiency $\eta_f = U_{sc}/U_{ic}$.

Fig. 1 plots the emitted and reflected fields, E_e, E_r and the stored energy, U_s, for the SLAC SLED system, where the number of times we switch Q_e, $n_{qe} = 0$. At this klystron pulse width and compression ratio, the Q_e during charging that maximizes η_f is nearly the same as the Q_e during the SLED pulse that maximizes η_{sg}. Fig. 1 lists the fraction of the reflected and dissipated energies during charging U_{rcn}, U_{dcn}, η_f, the fraction of total dissipated energy U_{dtn}, η_{pc}, S_g, the SLED gain divided by the present SLED gain $S_{gn} = S_g/1.618$, S_{pg}, and η_{sg} . It also lists the power into the section, P_s, section length, L_s, power/meter, P_{ol}, fill time, T_f, steady state gradient E_{gs} and maximum SLEDed gradient, E_{gm}. With $P_k = 55$ MW $P_{ol} = 4.57$ MW/m, $E_{gs} = 12.9$ MV/m and $E_{gm} = 21$ MV/m . The noload gradient, E_{gt}, the shifted beam induced gradient, E_{bts}, the loaded gradient as a function of time, E_{lt}, the median loaded gradient, E_{al}, and the current amplitude, I_b, are plotted in Fig. 2 for constant current and in Fig. 3 for the variable current that reduces the energy spread to zero, $E_{lt} = E_{al} = E_{gi}$. E_{gi} is set by choosing the appropriate T_b. With $T_b = 700$ nS, $E_{al} = 8.57$ MV/m, and the rf to beam energy transfer efficiency is 38.9%. For a nonSLEDed RF pulse and the same E_{al}, $\eta_{rbc} = 38.2\%$. At steady state $\eta_{rbs} = 72.0\%$. Fig. 4 plots the charge/pulse and rf to beam energy transfer efficiency as a function of v_{in}. The charge per pulse varies as E_{gm}, hence it should be multiplied by $E_{gm}/20.9$. The rf to beam energy transfer efficiency is a function of v_{in} and is independent of E_{gm}. If E_{gm} and E_{al} are known then $v_{in} = E_{al}/E_{gm}$ and we can determine η_{rb}. If $P_s = 31$ MW then $E_{gm} = 31.4$ MV/m. If E_{al} is set to 16.7 MV/m, then $v_{in} = E_{al}/E_{gm} = 0.532$, $T_b = 630\ nS$, $q_p = 815$ nC/pulse and $\eta_{rb} = 37.5$ %.

The value of the currents can be changed somewhat without significantly increasing the energy spread. At lower currents we can modulate the input pulse to reduce the energy spread. [5]

Minimizing RF Energy Dissipation

To make the dissipation negligible it is sufficient to make $Q_0/\pi f >> T_k$, which implies that $Q_e/Q_0 << 1$. The effect of increasing Q_0 can be seen in Table 1. If Q_0 is 150000 then the gradient increases 0.25%. If $Q_0 = 300000$ the increase is 5% and if we also increase the klystron pulse width to 5μS the increase is 19%. A 10% increase is equivalent to adding 3 sectors.

The size of the SLED cavity is: D=20.4 cm L=33.6 cm. It operates in the TE_{015} mode and its theoretical $Q_0 = 108000$, its actual $Q_0 = 100000$. The size of the CERN cavity is D=44.35 cm L=58.5 cm. It operates in the TE_{035} mode and its theoretical $Q_0 = 207000$, its actual $Q_0 = 150000$ because it is made of aluminum. At 2856 MHz, a 30 by 116 cm copper cavity operating in the $TE_{0,1,20}$ mode has a $Q_0 = 313000$. We assume that we will not have any problems with mode interference, because we use SLED-II type circular coupling. Also use SLED-II type automatic tuning.

Minimizing Reflections During Charging

The reflection can be minimized by varying Q_e during charging. The pulse compression efficiency is maximized by choosing Q_e during the compressed pulse that reduces the energy left in the cavities to zero. But a somewhat different Q_e has to be chosen to maximize η_{sg}.

If Q_e is constant during charging, then [6]

$$\eta_f = \alpha \frac{(1 - e^{-\tau_c})^2}{\tau_c} \quad \text{where} \tag{9}$$

$$\alpha = \frac{2}{1+Q_e/Q_0} \approx 2(1-Q_e/Q_0),\ T_c = \frac{\alpha Q_e}{2\pi f},\ \tau_c = \frac{T_{ch}}{T_c} = \frac{2\pi f T_{ch}}{\alpha Q_e}$$

T_{ch} is the charging time, $T_{ch} = T_k - T_{sp}$.
The maximum filling efficiency $\eta_{fm} = 0.407\alpha$ when $\tau_c = 1.257$. For the dissipated energy to be a small fraction of the stored energy, $Q_0 >> Q_e$, and $\alpha \to 2$. Assume $\alpha = 2$. Then the value of Q_e that maximizes η_f and η_f at that point, are:

$$Q_{efm} = \frac{\pi f T_{ch}}{\tau_c}, \quad \tau_c = 1.257, \quad \eta_{fm} = 0.814 \quad . \tag{10}$$

For SLED at SLAC, $T_{ch} = 3.5 - 0.82 = 2.6\mu s$, and $Q_{efm} = 19000$. This is close to the Q_e needed during discharge to maximize SLED gain efficiency.

The filling efficiency can be increased by dividing the charging time into several regions and solve for the external Q during each region and for the duration of each region so that the reflection is minimized. Let the incident field $E_i = 1$. We minimize the reflection during charging by choosing a low Q_e so that the emitted field reaches fast $1+\delta$, $\delta << 1$, where the reflection is minimal. Then we vary Q_e such that the emitted field varies between $1+\delta$ and $1-\delta$ and consequently, the reflected field $E_r = E_e - E_i$, varies between $\pm\delta$. The emitted field hovers about unity and the reflected field about zero reflection. To calculate the Q_es during each region and the duration of each region that maximize the filling efficiency we proceed as follows. Let U_s be the rf energy stored in the cavities for unit input pulse power amplitude. Define

$$E_c^2 \equiv \omega U_s = Q_e E_e^2, \quad E_c = \sqrt{Q_e E_e} \ . \tag{11}$$

Let r_n be the region number, t_{rn} the duration of the nth region.

$$E_c = E_{cf} + [E_{ci} - E_{cf}]e^{-t/T_c}, \quad \sqrt{Q_{e(n+1)}}E_{ei}(t_{r(n+1)}) = \sqrt{Q_{en}}E_{ei}t_{rn}$$

Unlike the emitted field E_e, the cavity field E_c, does not change if Q_e changes apruptly. During the first and last regions, the input field $E_i = 0$. During charging $E_i = 1$, during the SLED pulse $E_i = -1$. In each region

$$E_{cf}(r_n) = E_i(r_n)\sqrt{Q_e(r_n)}\alpha(r_n) \quad . \tag{12}$$

Region 1: $E_{ei} = E_{ef} = E_c = 0$, $\quad t_{r1}$ is arbitrary. $Q_{e1} = Q_{e2}$.
Region 2: $E_{ei} = 0$, $\ E_{ef} = \alpha$, $\ E_e(t_{r2}) = 1+\delta$. Let n_{qc} be the number of Q_es

during charging. Using

$$1+\delta=\alpha(1-e^{-t_{r2}/T_{c2}}) \text{ and } T_{c2}=\frac{\alpha Q_{e2}}{2\pi f}$$

we choose $Q_{e2}=Q_{efm}/n_{qc}$ and solve for $t_{r2}=\frac{\alpha Q_{efm}}{2\pi f n_{qc}}\ln\frac{\alpha}{\alpha-(1+\delta)}$.

Region 3: $E_{ei}=1-\delta$, $E_{ef}=\alpha$, $E_e(t_{r3})=1+\delta$.

$$Q_{e3}=Q_{e2}\left[\frac{1+\delta}{1-\delta}\right]^2$$

$$1+\delta=\alpha+[1-\delta-\alpha]e^{-t_{r3}/T_{c3}}$$

$$t_{r3}=\frac{\alpha Q_{e3}}{2\pi f}\ln\frac{\alpha-1+\delta}{\alpha-1-\delta} \quad .$$

To make the charging time the same as the specified charging time, that is, $t_{r2}+t_{r3}=T_{ch}$, we have:

$$T_{ch1}=t_{r2}+t_{r3}, \quad m_{f1}=\frac{T_{ch}}{T_{ch1}}, \quad Q_e=m_{f1}Q_e, \quad t_r=m_{f1}t_r$$

We chose region 3 to be the last region during charging, so that we switch once during charging. The next region is the compressed pulse.

Region 4: Compressed Pulse. We switch just before phase flipping. In this region we can choose a Q_e to obtain zero leftover energy in the cavity maximizing η_{pc} or a Q_e that maximizes the gradient, and hence η_{sg}.

$$E_{ei}=1+\delta, \quad E_{ef}=-\alpha, \quad E_e(t_{r4})=0 \ .$$

$$0=-\alpha+[1-\delta+\alpha]e^{-T_{sp}/T_{c4}}$$

$$Q_{e4}=\frac{m_{f2}\alpha}{2\pi f T_{sp}}\ln\frac{\alpha+1+\delta}{\alpha}$$

We can choose m_{f2} so that no rf energy is left in the cavity, which maximizes η_{pc} or we can choose an m_{f2} that maximizes η_{sg}. The effect of Q_e switching can be seen in Table 1.

Let n_{qe} be the number of times we switch Q_e. For Fig. 5 and Fig. 6, Q_0 is large enough so that the copper losses can be neglected and with $n_{qe}=4$ the reflected energy is reduced to 3%. In Fig. 5 η_{pc} is maximized and the pulse compression efficiency increases to 98%. In Fig. 6 η_{sg} is maximized, thereby increasing the gradient by 14%.

SLED at 11424 MHz

Assume an NLC design with the section fill time $T_f = 0.1\ \mu S$ and length $L_s = 1.8$ m. For a compression ratio of 6, the klystron pulse width is $0.6 \mu S$. To decrease the losses, $Q_0/\pi f T_k << 1$. Thus, because T_k is smaller, Q_0 can be smaller. Also, because for the same diameter the cylinder loss decreases with frequency we can have a higher Q_0 with a small diameter and long cavity.

Replacing an S-band station with an X-band station involves replacing the present klystron with the 75 MW permanent magnet klystron and in the tunnel, instead of dividing each of the two klystron outputs by 2, feeding four 3m sections, we divide each output by 3 and feed six 2m sections as developed for the NLC. Thus the accelerator length per klystron remains the same 12 meters.

Fig. 7 plots the SLED fields for 11424 MHz SLED with no Q_e switching. The steady state noload gradient without SLED, E_{gs}, increases from 12.9 MV/m at 2856 MHz to 17 MV/m, an increase of 35%. The maximum gradient with SLED increases from 21 MV/m to 33 MV/m. For the same pulse of 120 Hz, the site RF average power is reduced from 6.2 MW to 1.3 MW due to the narrower rf pulse width. In addition about one MW of ac power will be saved due to the use of permanent magnets. The decrease in modulator efficiency can be reduced by reducing the modulator rise time. Fig. 8 plots the SLED fields when Q_e is different during charging and during the compressed pulse, $n_{qe} = 1$. The assumed Q_0 of 300000 can be achieved with a copper cavity with D=8 cm L=141 cm, operating at 11424 MHz in the $TE_{0,1,100}$ mode. Again, we assume that we will not have any problems with mode interference, because we use SLED-II type circular coupling.

The noload gradient, E_{gt}, the shifted beam induced gradient, E_{bts}, the loaded gradient, E_{lt} and the current amplitude, I_b, are plotted in Fig. 9 for constant current and in Fig. 10 for the variable current that reduces the energy spread to zero. The section length is 1.8 m. The rf to beam energy transfer efficiency is 21.7%. With 66 MW klystrons feeding 6 sections, the the maximum noload gradient is 36.9 MV/m and the loaded gradient is 30.4 MV/m, the charge is 27.6 nC per pulse.

Fig. 11 plots the SLED fields for $C_r = 12$ and $n_{qe} = 0$. Fig. 12 plots the SLED fields for $C_r = 12$ and one-time switching, $n_{qe} = 1$. As with the resonant delay line in Ref. [7], if we switch Q_e, we are not limited to a maximum power gain of 9.

Summary

Table 1 lists the efficiencies and gradients as a function of Q$_0$, n_{qe}, T_k and frequency with η_{sg} maximized, except for line 6, where η_{pc} is maximized. Presently, at SLAC, the SLEDed maximun gradient is 21 MV/m. With 198 working klystrons, the beam energy is 50 GeV. In the last column, $E_{gm} = 21 \times S_{gn}$, at 2856 MHz, and $E_{gm} = 21 \times 1.35 \times S_{gn}$, at 11424 MHz. An increase in E_{gm} of 0.1% represents an additional 2.4 klystrons and of 10% an additional 3 sectors. If $Q_e/Q_0 << 1$ then with $n_{qe} = 4$, η_f changes from 0.81 to 0.97.

Q$_0$[10^5]	n$_{qe}$	S_g, S_{gn}	U_{rcn}[%]	U$_{dcn}$[%]	η_f [%]	η_{pc} [%]	η_{sg} [%]	E_{gm} [MV/m]
f= 2856 MHz $T_k = 3.5$ $T_{sp} = 0.82\ \mu S$ $C_r = 4.27$ E$_{gs}$=12.9 MV/m								
1	0	1.623, 1.000	17.7	14.9	67.4	70.6	61.7	21
1.5	0	1.666, 1.026	17.9	10.4	71.7	74.1	65.0	21.5
3	0	1.704, 1.050	18.2	5.5	76.3	77.8	68.1	22
1.5	2	1.723, 1.061	7.3	12.8	79.9	78.9	69.5	22.3
3	2	1.765, 1.087	9.4	6.4	84.2	82.4	73	22.8
1000	4	1.792, 1.104	3.2	0.02	96.8	97.6	75.2	23.2
1000	4	1.856, 1.143	3.2	0.02	96.8	92.9	80.7	24.0
f= 2856 MHz $T_k = 5.0$ $T_{sp} = 0.82\ \mu S$ $C_r = 6.10$ E$_{gs}$=12.9 MV/m								
3	0	1.924, 1.186	1.8	7.3	73.3	67	60.7	24.9
3	3	2.060, 1.268	4.2	10.8	85.5	78.7	69.6	26.6
6	3	2.117, 1.304	4.4	5.6	88.9	73.5	73.5	27.4
f= 11424 MHz $T_k = 0.6$ $T_{sp} = 0.10\ \mu S$ $C_r = 6$ E$_{gs}$=17.4 MV/m								
3	0	1.970, 1.210	18.1	4.2	77.7	67.3	64.7	34.3
3	1	2.060, 1.268	18.1	4.2	77.7	78.2	70.7	35.9
3	4	2.117, 1.304	3.0	5.5	91.5	87.6	74.7	36.9
f= 11424 MHz $T_k = 1.2$ $T_{sp} = 0.10\ \mu S$ $C_r = 12$ E$_{gs}$=17.4 MV/m								
6	0	2.332, 1.437	28.4	4.7	67.2	48.2	45.3	40.7
6	1	2.712, 1.671	18.0	4.6	77.3	73.9	61.3	47.3

Table 1. Efficiencies and gradients as a function of Q$_0$, n_{qe}, T_k and f.

Without Q_e switching, we can reach 60 MeV at 2856 MHz and 97 MeV at 11424 MHz.

Methods of Varying External Q

Ref. [7] describes optical switching and a method of one-time switching the coupling to the resonant delay line, $n_{qe} = 1$. This method can also be used with SLED where the change in the reflection coefficient is even smaller. A variation of this method is as follows. A mode transducer transforms the TE_{10} in rectangular guide to TE_{01} in circular guide which couples to the cavity. A TE_{01} choke is placed in front of the coupling aperture and a plasma or a silicon annular ring is placed inside the choke. Before phase flipping, the choke in combination with the aperture act as low coupling, high Q_e. The plasma switch is actuated at the same time as the phase is flipped causing a lower Q_e determined only by the aperture.

We may take advantage of the phenomena that before phase flipping, the rf energy is flowing toward the aperture and after the phase is flipped it flowing at a higher level in the opposite direction away from the aperture. Thus the plasma switch may turn on spontaneously as the phase is flipped. Or a ferrite annular ring may be placed between the aperture and choke of such length that before phase flipping the distance between then is 180° and the reflections add and after phase flipping it is 90° and the reflections subtract.

Other methods are possible. The external Q varies as the sixth power of the aperture diameter. We can vary the aperture size, by putting in the aperture and annular ring whose resistivity can be changed by laser light or by a voltage. Another way of changing the external Q, is to vary the field amplitude in the coupling guide at the coupling aperture by means of a moveable short, or by changing the mode of the reverse RF. As in Ref. [7] the short can be in a TE_{01} guide.

Conclusion

It was shown that the accelerating gradient can be increased by varying the external Q. But there are two obstacles to varying the external Q. One, the decrease in Q_0 due to dissipation in the switch, and two, rf breakdown due to the switch. Hopefully, the small area of the switch will cause the dissipation to be small.

Increasing the klystron pulse width increases the efficiency and charge per pulse but it causes high pulse energy. There is a limit to pulse energy. With SLED at 11424 MHz, the klystron pulse width, C_rT_f, is narrow and it is unlikely that the pulse energy limit will be reached. Work is going on to minimize the reduction of efficiency due to modulator rise time.

At 2856 MHz, increasing Q_0 to 300000 increases the gradient by 5% and if we also increase the pulse width to $5\mu S$, the gradient increases by 19%. Without Q_e switching, replacing the 2856 MHz stations with 11424 MHz stations will increase SLEDed gradient from 21 MV/m to 33 MV/m and, for the same repetition rate, decrease the average RF power by a factor of about 5. Increasing C_r to 12, increases the gradient from 21 to 40 MV/m. Also using one-time switching will increase the gradient to 47 MV/m and the SLAC beam energy from 50 to greater than 100 GeV.

References

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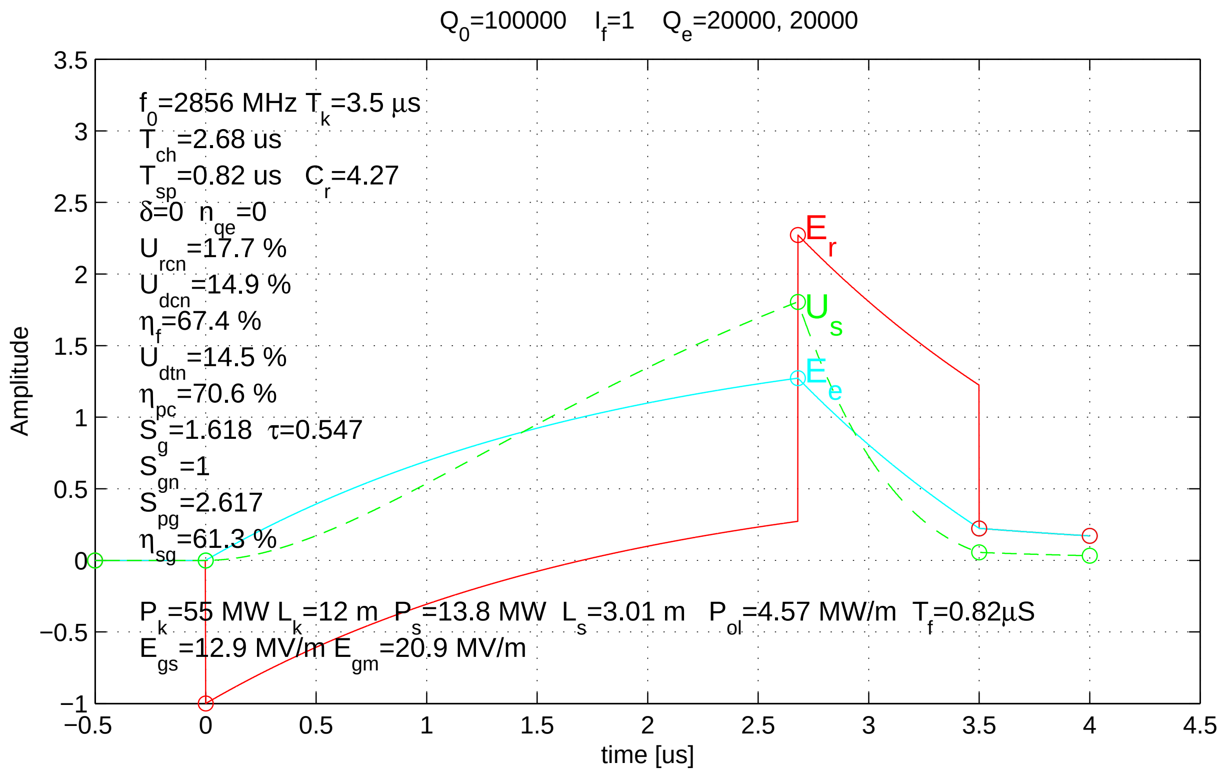

Fig. 1. Emitted field, E_e, Reflected field, E_r and Stored Energy, U_s vs time.

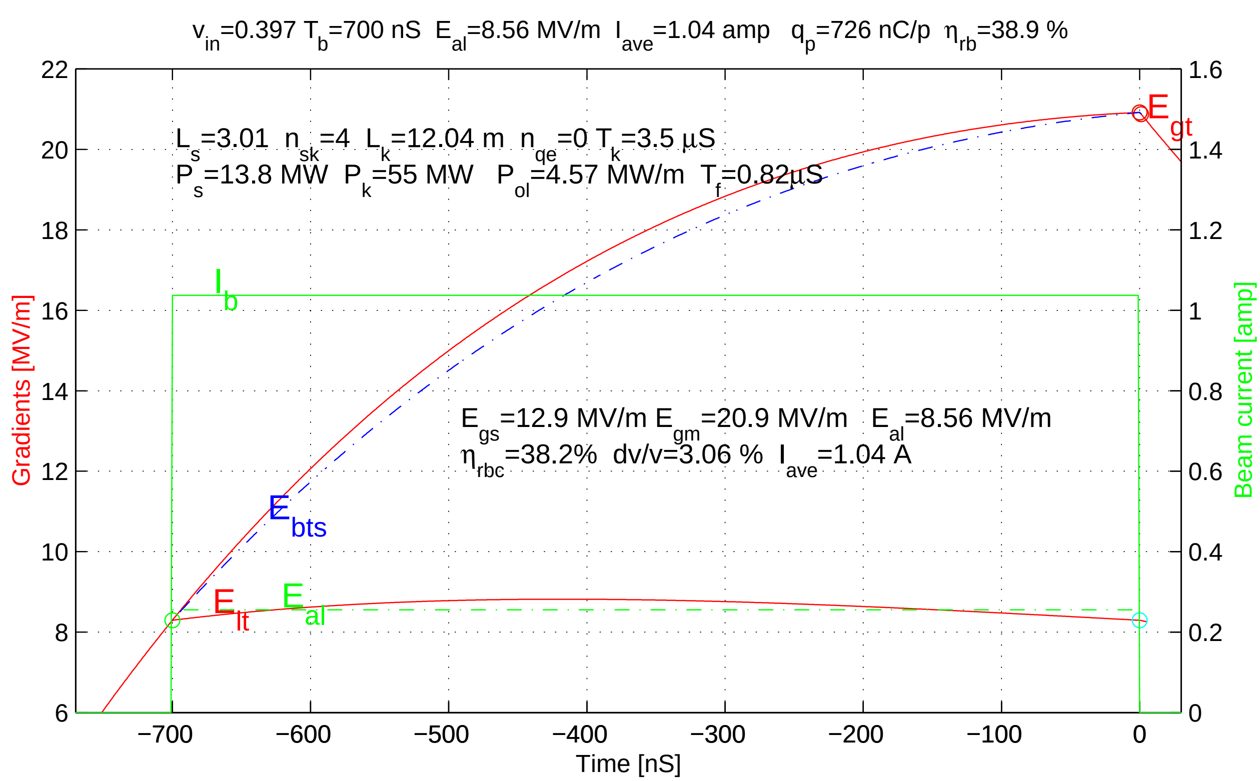

Fig. 2. Noload, beam induced, loaded gradients and constant beam current

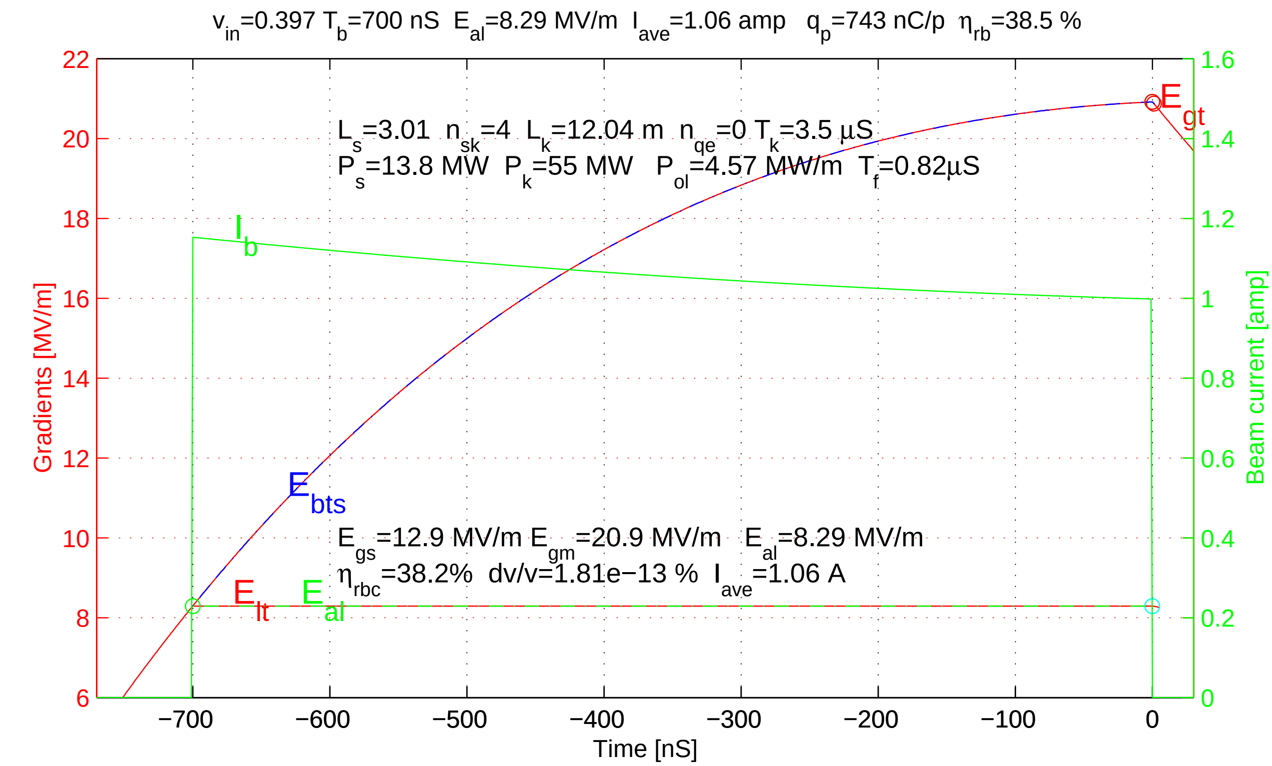

Fig. 3. Noload, beam induced, loaded gradients and required beam current

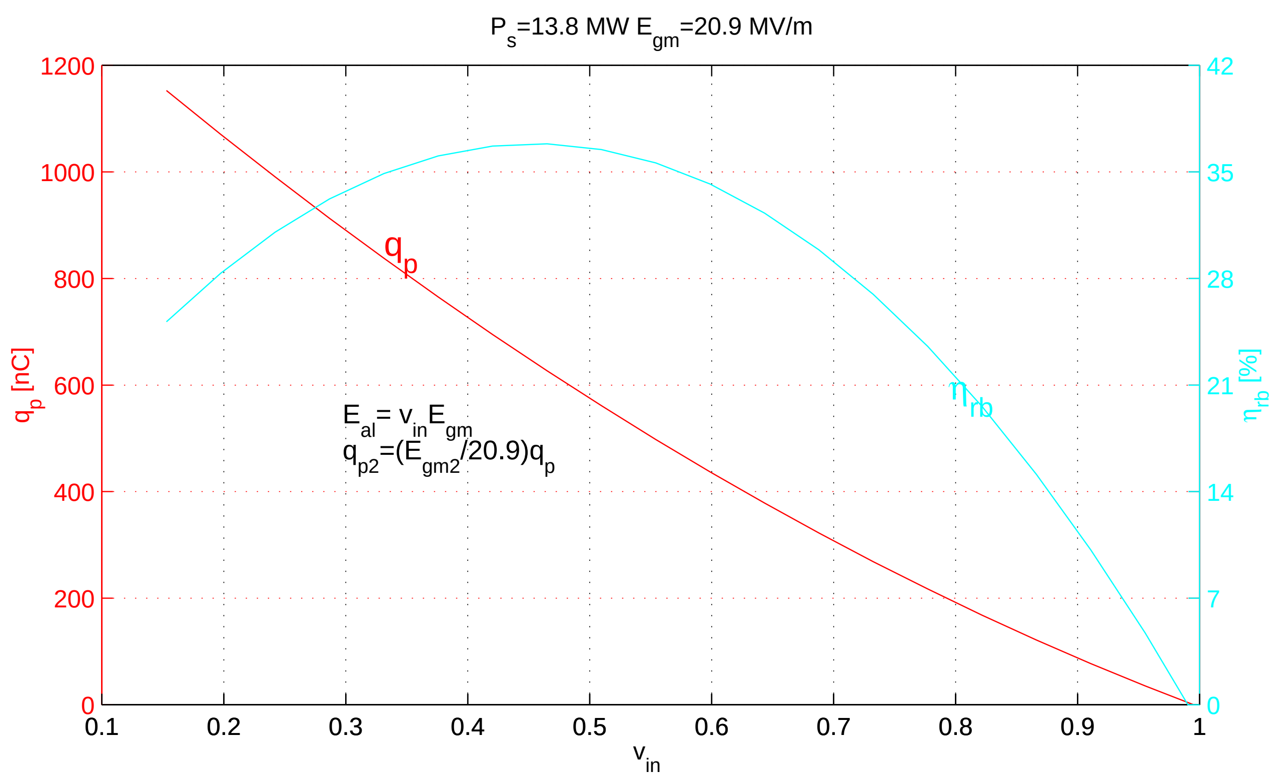

Fig. 4. Charge/pulse, q_p and rf to beam efficiency η_{rb}
as a function of normalized loaded gradient.

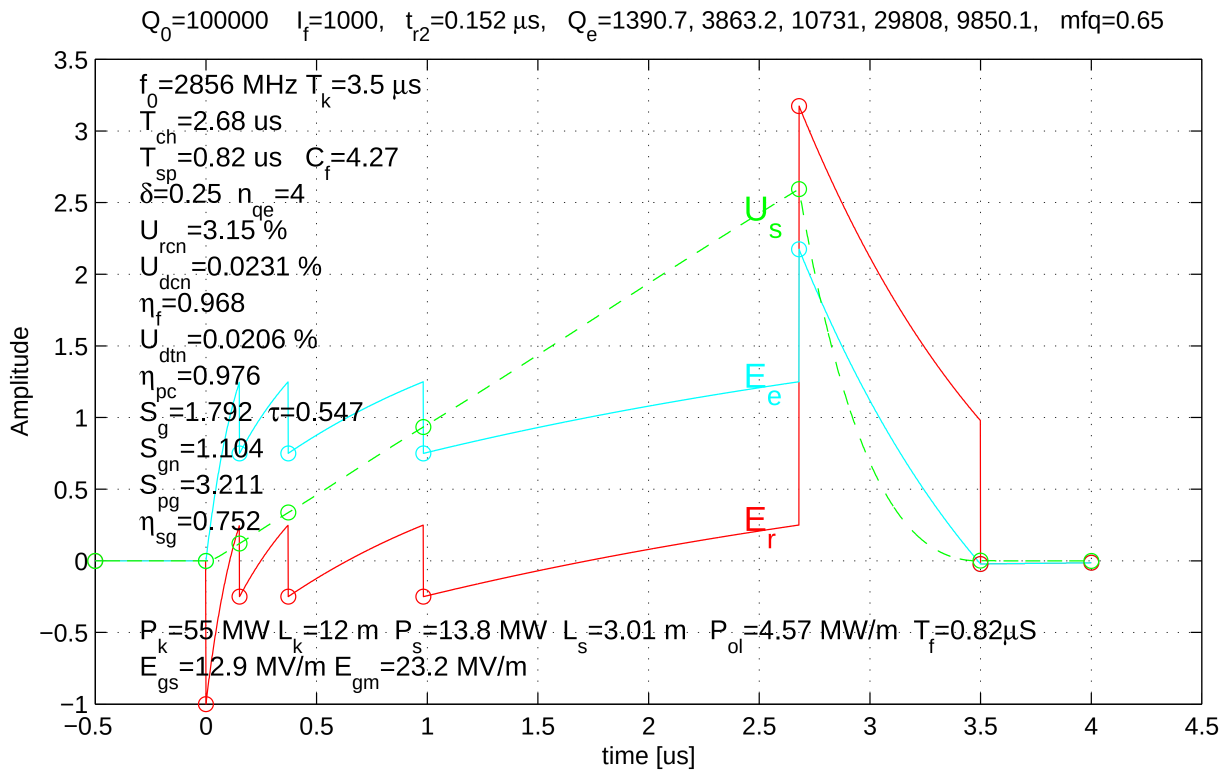

Fig. 5. SLED Waveforms. Variable Q_e. Maximum η_{pc}

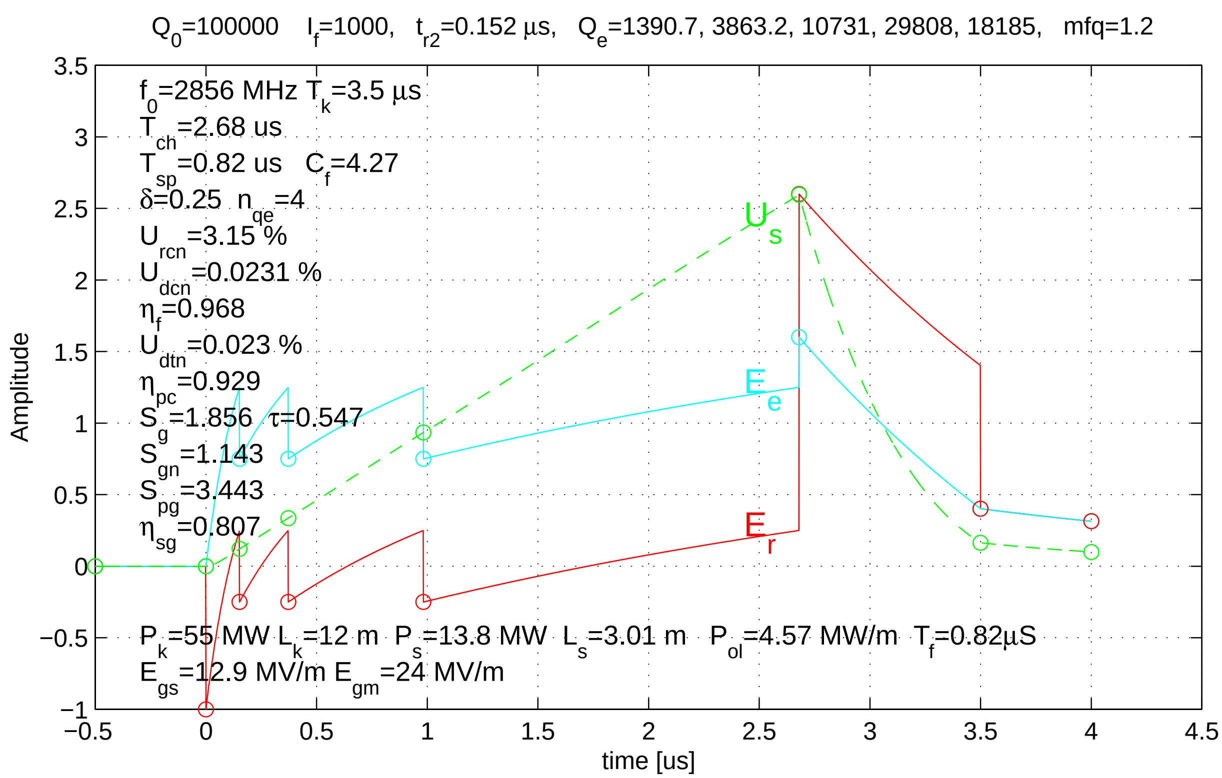

Fig. 6. SLED Waveforms. Variable Q_e. Maximum η_{sg}

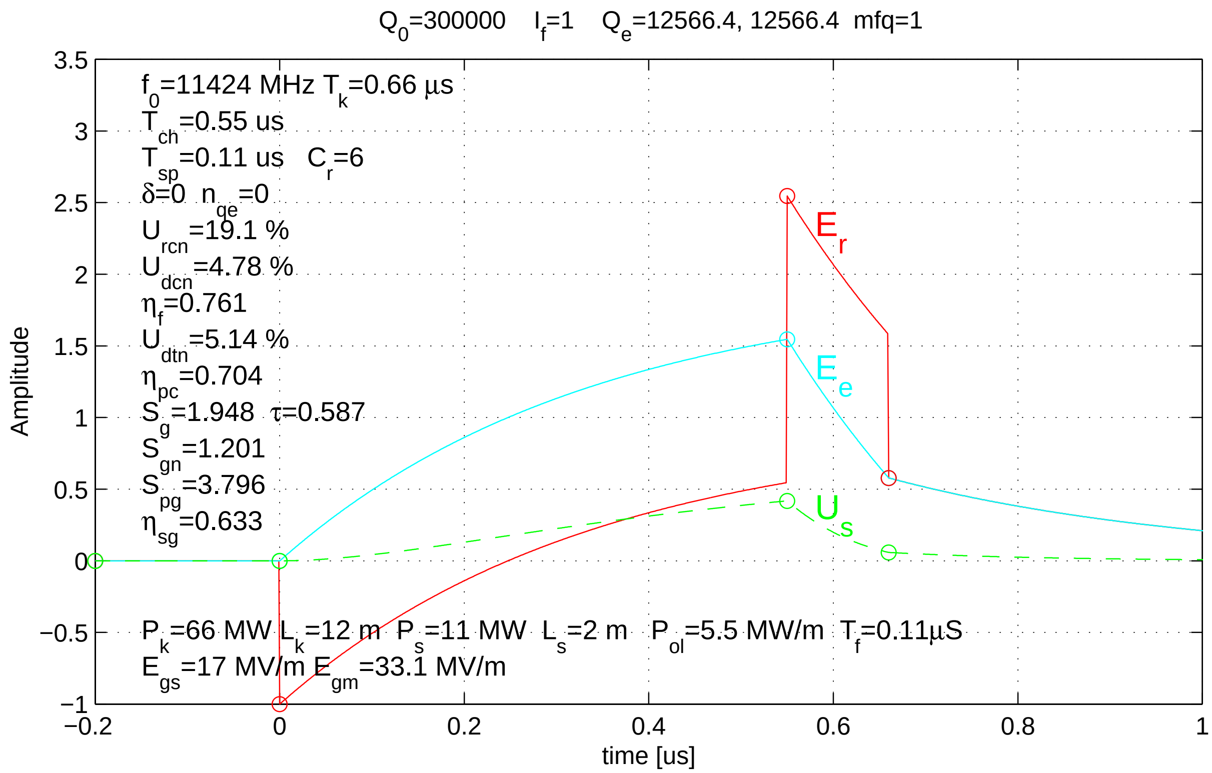

Fig. 7. SLED Waveforms. Constant Q_e

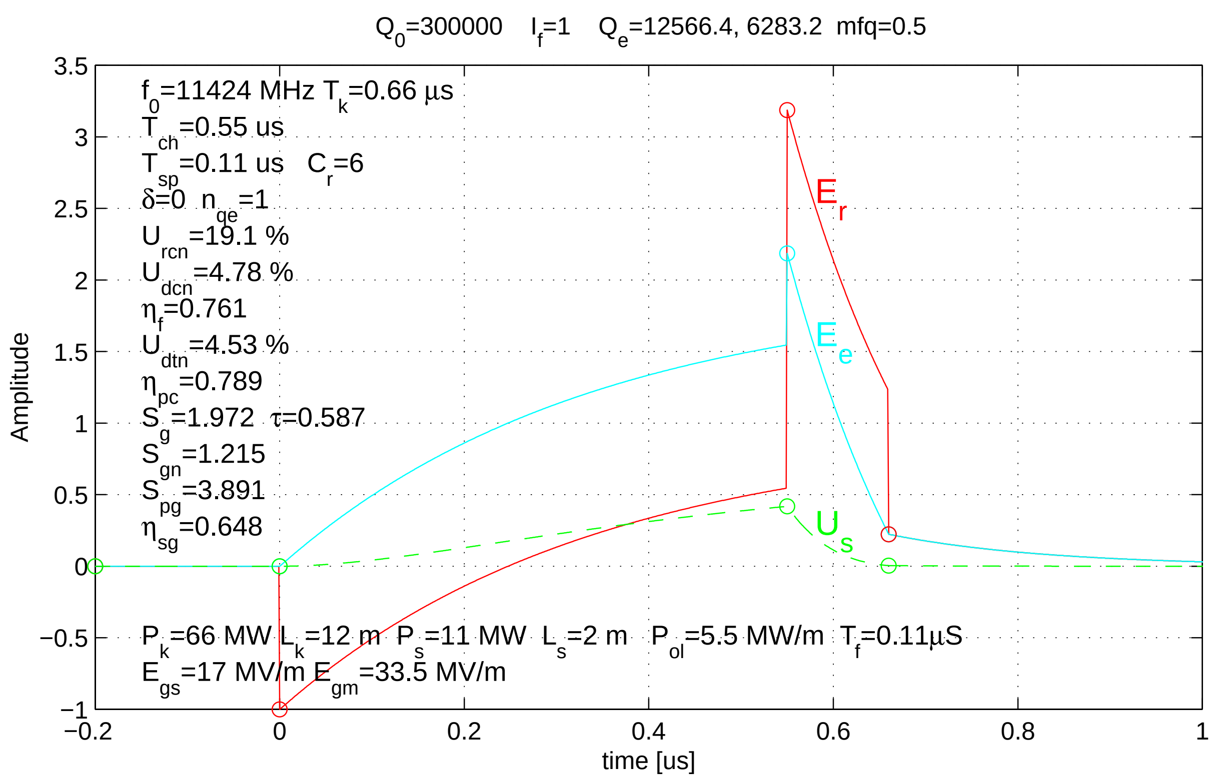

Fig. 8. SLED Waveforms. Two Q_es. Maximum η_{sg}

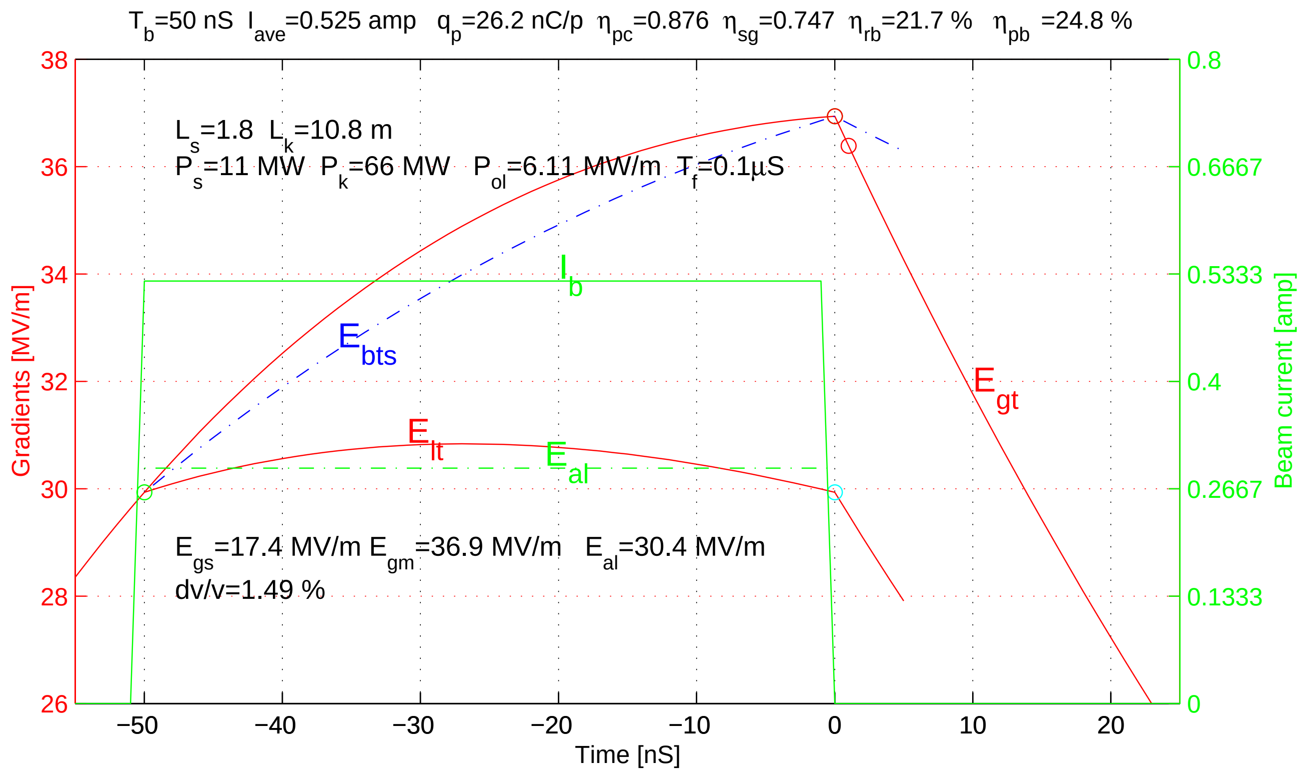

Fig. 9. Noload, beam induced, loaded gradients and constant beam current

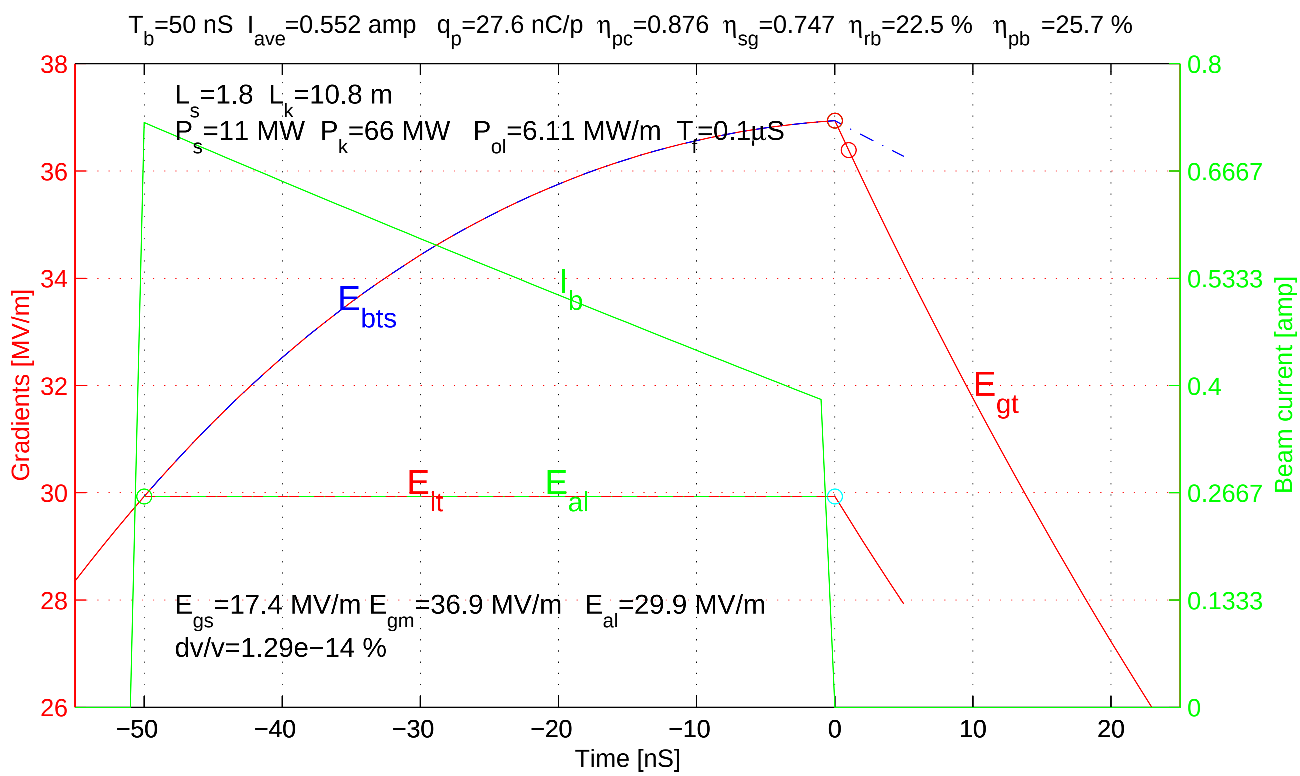

Fig. 10. Noload, beam induced, loaded gradients and variable beam current

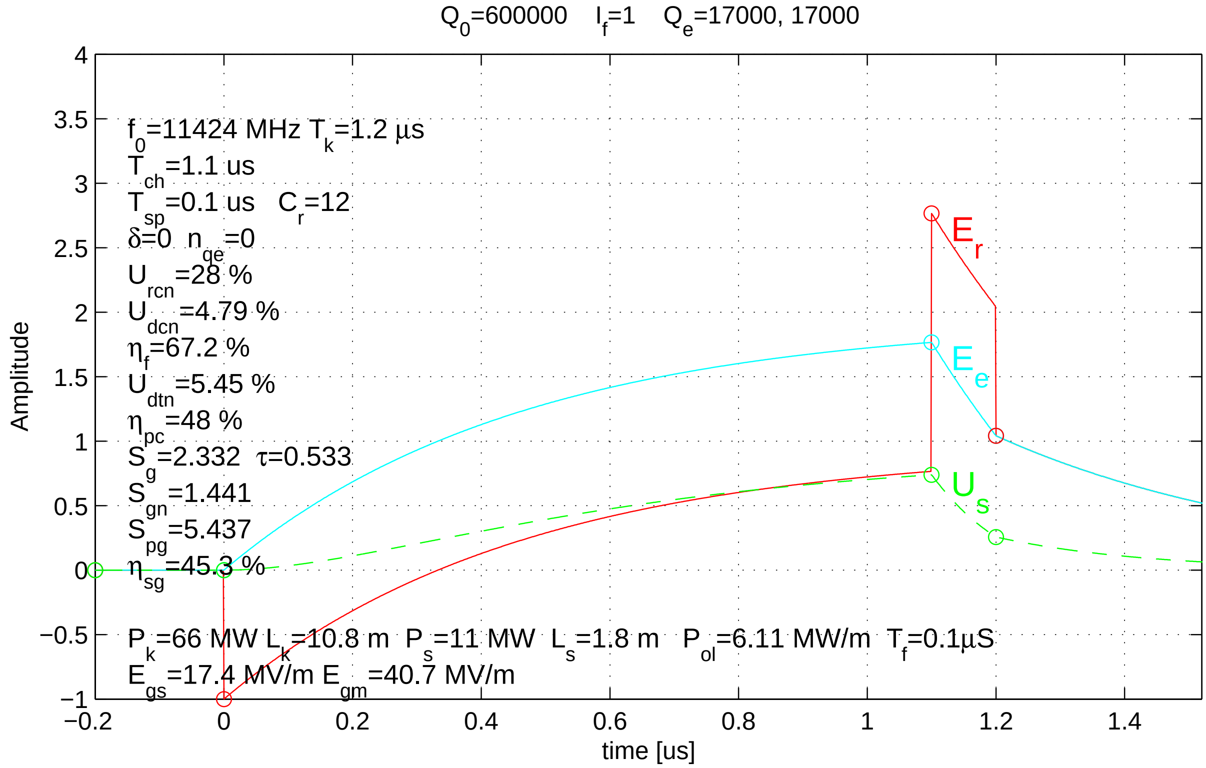

Fig. 11. Emitted field, E_e, Reflected field, E_r and Stored Energy, U_s vs time. Constant Q_e

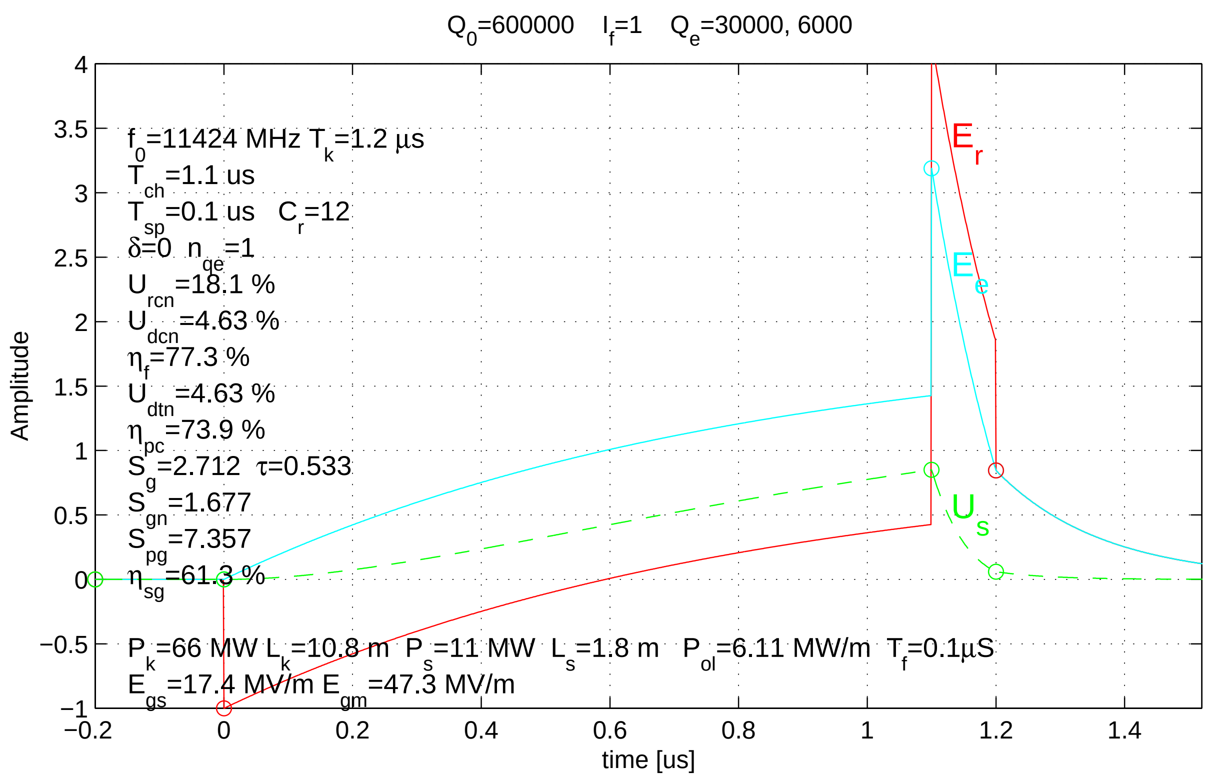

Fig. 12. Emitted field, E_e, Reflected field, E_r and Stored Energy, U_s vs time.