SPARC-RF-12/001
July 07, 2011

AN RF GUN PULSE SHAPING SYSTEM TO INCREASE THE ACCELERATING GRADIENT

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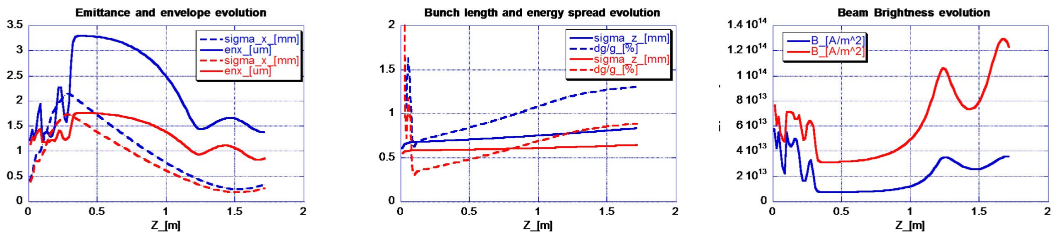
Abstract

In order to overcome the limitation of a 7 year operation aged 1.6 cells S-band RF gun, we designed and tested a LLRF pulse shaping system that bring back the actual RF accelerating field to the nominal value, minimizing the breakdown rate during the linac operation. We also report a new model to evaluate the transient field inside the RF gun and its effect on the beam dynamics.

PACS: 11.30.Er,13.20.Eb;13.20Jf;29.40.Gx;29.40.Vj



(a) (b) (c)

Figure 1: Beam parameters evolutions downstream the SPARC gun. Initial beam parameters: charge 300pC, length $5.8ps$, spot $0.58mm$. Peak field on the cathode: $100MV/m$ blue lines, $125MV/m$ red lines.

1 Introduction

In a RF photo-injector, electrons are emitted by a photo-cathode located inside an RF cavity that is illuminated by a laser pulse, so that the bunch length and the longitudinal shape can be controlled on a sub-ps time scale via the properties of the laser pulse. The emitted electrons are rapidly accelerated to relativistic energies, thus partially mitigating the emittance growth and bunch elongation due to space charge force effects. The beam quality is determined by the rms normalized projected emittance that for applications like FEL experiments has to be as low as possible and by the highest possible peak current. At the gun exit an approximate expression for the space charge induced emittance growth for a Gaussian bunch of longitudinal and transverse dimensions σ_z and $\sigma_x = \sigma_y$ is [1]

$$\epsilon_{sc} = \frac{c}{8\alpha\nu_{rf}} \frac{\hat{I}}{I_A} \frac{\sigma_z}{(3\sigma_x + 5\sigma_z)} \tag{1}$$

where $\alpha = \frac{eE_0}{2mc^2k}$, E_0 being the peak RF field, $k = \frac{2\pi\nu_{rf}}{c}$ with ν_{rf} the RF frequency and $I_A = 4\pi\epsilon_0 mc^3/e$ is the Alven current. Note that $\alpha \geq 1$ is the typical operational condition of a RF gun to enable electron capture and minimize the space charge emittance growth. An important contribution to the beam emittance comes also from time-dependent RF fields which can be evaluated as [1]

$$\epsilon_x^{rf} = \frac{k^3\alpha}{\sqrt{2}} \sigma_x^2 \sigma_z^2 \tag{2}$$

With a high charge ($> 200pC$) short bunch ($< 5ps$) with small initial spot size ($< 1mm$), the typical SPARC beam parameters [2], the space charge contribution is dominant with respect to the RF contribution, thus operation at high peak field in the RF gun is desirable to damp space charge forces. Space charge emittance growth, being highly correlated along the bunch, can be partially compensated in the drift downstream the gun exit by means of a solenoid [3,4]. HOMDYN simulations [5] show that by changing the peak field from $100MV/m$ (corresponding to $4.65MeV$ energy gain at the gun exit at $33deg$ injection phase) to $125MV/m$ ($5.87MeV$) the expected emittance reduction for a well matched bunch at the entrance of the linac is about 50%, see figure 1. Bunch elongation is also reduced leading to a final peak current 30% higher thus increasing the final beam brightness $B = \frac{2\hat{I}}{\epsilon_n^2}$. On the other hand a high peak field operation in the RF gun may cause RF breakdown leading to serious damage to the cavity and to the cathode performances. According to the RF breakdown scaling law: $E_0 \propto \Delta t_{RF}^{1/4}$ [8], it appears convenient to reduce the RF pulse length Δt_{RF} to allow a higher peak field. If the chosen RF pulse length is close to the cavity filling time $\tau = \frac{2Q_L}{\omega_{RF}}$, where Q_L is loaded quality factor and ω_{RF} the cavity frequency, the gun is still in the transient regime and the other modes of the fundamental pass band can reach a significant fraction of the accelerating mode voltage before decaying to a very low steady state value and might have an influence on the beam dynamics. For example in the case of the 1.6 cells S-band SPARC gun operating in the π-mode at $2856GHz$ with a $Q_L = 12000$, the filling time is $\tau = 0.67s$, thus some residual excitation of the $\pi/3$ mode [9] is expected if $\tau_{RF} < 6\tau = 4\mu s$.

1.1 RF gun multicell cavity model

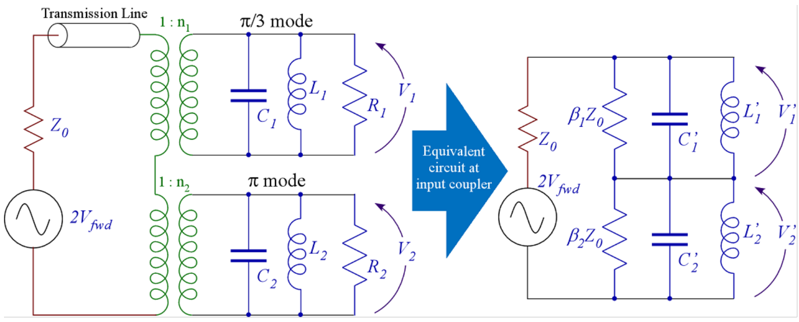


Figure 2: Equivalent circuit of the π and $\pi/3$ modes in the RF gun

To evaluate the relative excitation of the π and $\pi/3$ modes, one can represent the two modes oscillations in a multicell RF gun by a series of two RLC circuits (see figure 2). An extensive treatment will be reported in a dedicated publication. Here we report only the main steps of the calculation. By using the parameters of the two modes obtained by HFSS simulations and shown in table 1, one can calculate the total impedances of two equivalent RLC circuits. Since we have to study the field inside the structure during the transient, the Laplace representation of the impedances is calculated:

Table 1: Parameters of the π and $\pi/3$ modes

	f[MHz]	scaled f[MHz]	β	Q_0	Q_L	$\tau[ns]$	S11 delay $[ns]$
mode 1 ($\pi/3$)	2851.536	2852.523	0.6035	12500	7795	870.1	0.3317
mode 2 (π)	2855.0117	2856	1.234	13400	5998	668.8	0.3317

$$Z_k(s) = \beta_k Z_0 \frac{\omega_k/Q_{0_k} s}{s^2 + \omega_k/Q_{0_k} s + \omega_k^2}, k = 1, 2 \quad (3)$$

Then, the transfer function from the voltage at the input coupler V_{fwd} to the output voltages V_k is:

$$TF_k(s) = 2\frac{Z_k}{Z_1 + Z_2 + Z_0}, k = 1, 2 \quad (4)$$

Being $F(s)$ the system excitation in Laplace domain, the voltages V_1' and V_2' across each resonator in the model are given by: $V_k'(s) = F(s) \cdot TF_k(s)$, with $k = 1, 2$. For a step-confined sine wave excitation $F(s) = 2V_{fwd}\frac{s}{s^2+\omega_0^2}$, the corresponding voltages in time domain are obtained from the inverse Laplace transform of the complex $V_k'(s)$ functions:

$$V_k'(t) = V_{fwd}\left[A_{k_0}\cos(\omega_0 t + \phi_{k_0}) + A_{k_1}e^{\alpha_1' t}\cos(\omega_1' t + \phi_{k_1}) + A_{k_2}e^{\alpha_2' t}\cos(\omega_2' t + \phi_{k_2})\right] \quad (5)$$

Each voltage has one regime term oscillating at the generator frequency and two transient terms in the form of damped oscillations at the natural frequencies of the two-resonator system. For simplicity, here we do not report the expressions and the values of the A and ϕ coefficients of equation 5. For each mode the peak E-field on the cathode E_{C_k} is proportional to the square root of the RF power dissipated. Defining the coefficients $C_k = \frac{E_{C_k}}{\sqrt{P_k}}$, the total peak E-field at the cathode can be written as a superposition of the two $V_1'(t)$ and $V_2'(t)$ functions:

$$E_C = \sqrt{P_{fwd}} \sum_{k=1,2} \frac{C_k}{\sqrt{\beta_k}}\left[A_{k_0}\cos(\omega_0 t + \phi_{k_0}) + A_{k_1}e^{\alpha_1' t}\cos(\omega_1' t + \phi_{k_1}) + A_{k_2}e^{\alpha_2' t}\cos(\omega_2' t + \phi_{k_2})\right] \quad (6)$$

From HFSS simulations we validated the proposed model and we computed the regime values of the on axis E-field profiles for both $\pi/3$ and π modes at the resonant frequencies $\omega_{\pi/3}$ and ω_π. The C_k values can be extrapolated from e.m. simulations of the fields in the multi-cell structure. The results are shown in figure 3, considering $1\mu s$ RF pulse duration. The residual E-field due to the $\pi/3$ mode at the end of the pulse is about 10% respect to the π mode accelerating field.

1.2 Effect on the electron bunch

The main effect on the beam dynamics when the beam in injected in the gun cavity transient state is a different energy gain: $5.84MeV$, $30keV$ lower if compared to the steady

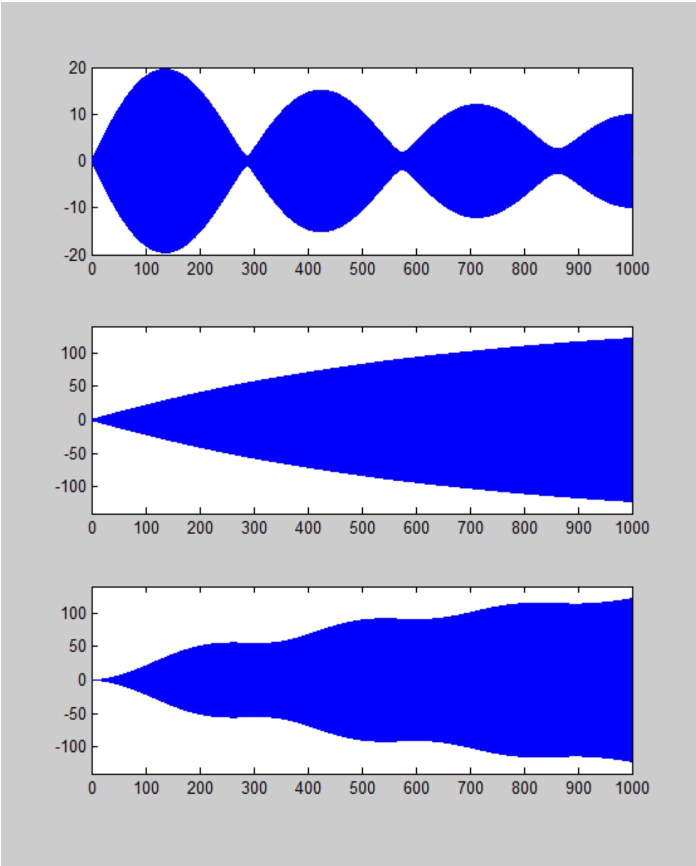
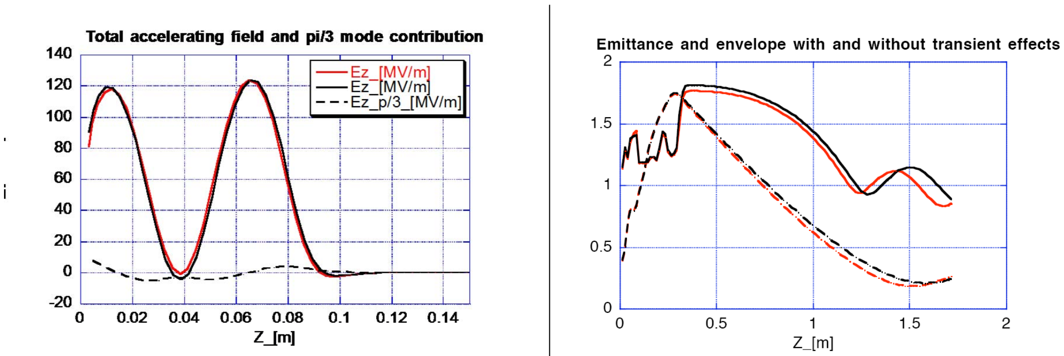


Figure 3: $\pi/3$ (top), π (center) and total (bottom) electric field at the cathode for a $1\mu s$ RF pulse feeding the gun



(a) (b)

Figure 4: (a) Accelerating field as seen by the bunch inside the the gun. Red line π mode only. Black line superposition of mode and $\pi/3$ modes. Dashed line $\pi/3$ mode contribution. (b) Optimized emittance (continuous lines) and envelope (dashed lines) evolutions downstream the SPARC gun. Peak field on the cathode: $125MV/m$ and injection phase $33deg$. Red lines: with fundamental mode only. Black lines: with fundamental and lower modes.

state injection. Figure 4(a) shows the accelerating field as seen by the electron bunch with and without the lower mode contribution. In the following drift envelope and emittance have a slightly different behavior that can be easily compensated by a different setting of the gun solenoid as shown in figure 4(b). In the following drift envelope and emittance have a slightly different behavior that can be easily compensated by a different setting of the gun solenoid. For a more detailed discussion see also [6,7]. In conclusion reducing the RF pulse length to $1\mu s$ in order to achieve higher peak field on the cathode has a clear advantage in terms of RF gun performances and no significant impact on beam dynamics.

2 Limitations of an old RF gun

The SPARC photo-injector is presently running for experiments that need a very good beam quality, especially in terms of current, emittance and longitudinal stability. Some of these experiments are the RF longitudinal compression [8], the COMB multi-bunch plasma acceleration experiment [9], TeraSPARC (THz radiation generation also with multiple e-bunch) [10], and also the FEL experiments [11]. The RF system has been designed to satisfy such requirements as reported in [12]. However the SPARC injector is running since 2004, thus discharge dameges and the wearing effect of the time did not permit us to feed the RF gun [13] at the nominal accelerating gradient of $120MV/m$ that corresponds to an RF peak level of about $10MW$ dissipated in the gun, with $4\mu s$ pulse duration. The nominal beam energy at the entrance of the linac is $5.6MeV$. With nominal $4\mu s$ pulse

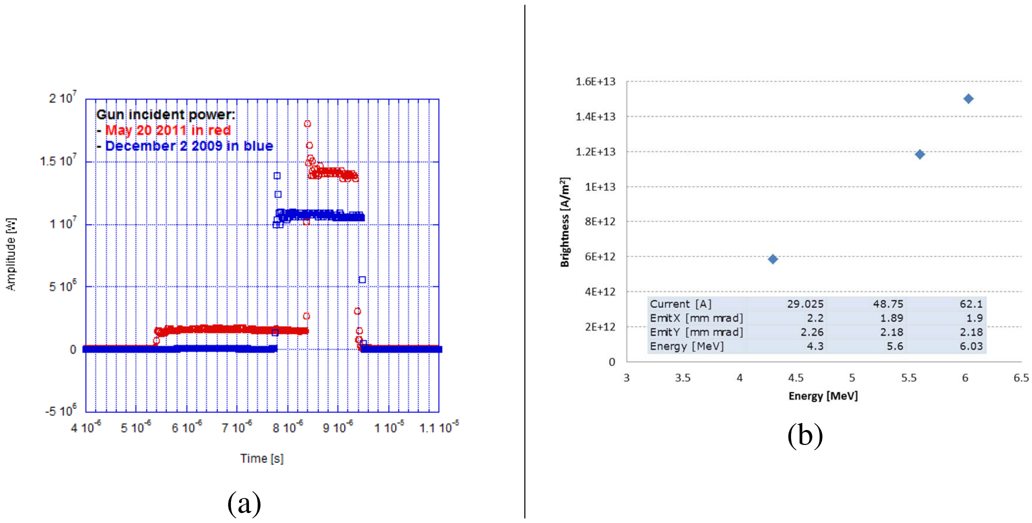


Figure 5: (a) Incident power before and after the installation of the RF pulse shaping system and (b) brightness at the end of the linac ($\approx 170MeV$) in function of the beam energy downstream the gun

length the operation was limited by a large breakdown rate and the maximum power inside the RF gun had to be significantly reduced, so that the measured energy at the exit of the gun went down to $4.5MeV$. Of course under these conditions the beam quality was spoiled because of the emittance degradation due to space charge effect inside the gun, as described in the introduction.

3 The new RF pulse shaping system

The solution that partially solved the problem was to shrink the duration of the pulse down to $1.5\mu s$, increasing the incident RF level. Our RF system foresees a PLL around the klystron to maintain the intra-pulse phase noise below $100fs$, as extensively described in [14]. Because of the PLL closed loop BW of $\approx 1MHz$, the system can react and preserve its performance in transients with minimum duration of $1\mu s \div 2\mu s$. Due to this limitation, we could not shrink the pulse more and more. We were also limited by a relatively small gun filling time (about $0.7\mu s$), since the more the pulse duration is reduced, the less the power can effectively go into the structure. Nevertheless, our aim was to reduce the pulse duration to $1\mu s$ or less to keep down the probability of discharge events and consequently to have a small breakdown rate also at the nominal accelerating gradient. To do that, we planned to shape the envelope of the RF pulse as shown in figure 5(a). In the first three microseconds the RF level is kept down to about $1MW$, so that the klystron PLL transient is in practice finished, but the probability of an arc inside the gun is almost zero. In the last

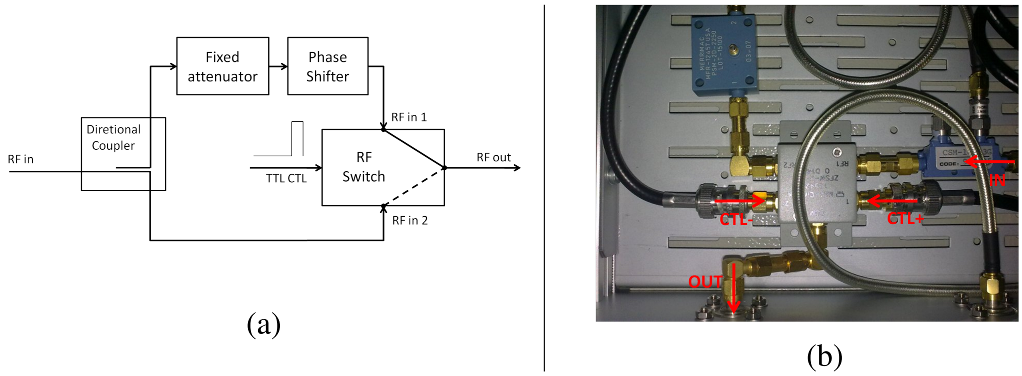


Figure 6: (a) Layout and (b) installed circuit of the LLRF gun shaping system

microsecond the RF level is led to a larger value so that the gun could fill up to the nominal accelerating gradient. This way, the performance of the klystron intra-pulse PLL in terms of phase noise compression is held down to $\approx 55fs_{RMS}$ inside the gun and the peak amplitude measured in the wave incident to the gun is $> 14.5MW$. The gun filling time is $\approx 0.7\mu s$, i.e. the peak power inside the structure is about 76% of the incident power. The effect on the beam quality was impressive. We report in figure 5(b) the brightness measurement in function of the beam energy at the exit of the gun. A maximum energy of $\geq 6MeV$ has been obtained, a value never reached before, even when the gun was fresh factory. To compare our the best results with the RF square pulse traditional gun feeding system, we decreased the gradient in the gun to reach the old value of $\approx 4.3MeV$.
Also the vacuum system had some significant benefits. Before the installation of the new shaping system we were working accepting a breakdown rate inside the RF gun of about 10 discharge per minute. Now, it has decreased to less than 1 discharge per minute, even with a larger accelerating gradient, and we can maintain a $10^{-10}torr$ vacuum level inside the gun during the machine operation.

4 Hardware realization

The realization of the pulse shaping system consisted in adding a dedicated board into an RF rack. The layout of the circuit is shown in figure 6. In practice using an RF switch controlled by a trigger signal coming from the machine trigger distribution, we can decide when the RF level switching described in section 3 take place. One can decide the power ratio between the two levels combining the DC coupling in the input branch and the value of the fixed attenuation in the upper branch (low power branch). The phase shifter is used to minimize the phase jump during the switching transition, due to the two different paths of the signal.

The switch is from Mini-Circuits®, model no.ZFSWA. For future development we are planning to use the ZFSWA-2 switch from the same manufacturer because its simpler control input circuit. This latter switch accept a standard TTL level pulse while the former one needs a custom $0V \div -8V$ signal. Nevertheless the ZFSW is a totally passive device while the ZFSWA needs a $5V$ power supply to work.

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