OPTIMIZATION OF THE SLED PHASE MODULATION PARAMETERS OF THE FERMI LINAC*

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Abstract

FERMI is a single-pass, linac-based, FEL user-facility covering the wavelength range from 80 nm to 4 nm and is located next to the third generation synchrotron radiation facility Elettra in Trieste, Italy. The first FEL line in operation (FEL-1) has been opened to users at the end of 2012, while the second FEL line (FEL-2) covering the shorter wavelength down to 4 nm is in commissioning. The linac is composed of 16 S-band accelerating structures. Seven of them are Backward Traveling Wave (BTW) structures equipped with SLED system. Following the preliminary tests on one plant, in order to increase the operational accelerating gradient, phase modulation of the SLED drive power has been implemented on all BTW structures. The shape of the phase modulation is applied via the LLRF system firmware and can be modified if needed. This paper discusses the optimization of the phase modulation parameters.

INTRODUCTION

FERMI is a single-pass Free Electron Laser (FEL) driven by a normal conducting S-band linac composed of 16 accelerating structures. Seven of them are Backward Traveling Wave structures (BTW), coming from the old Elettra injector, with a filling time of $0.757\mu s$. Each structure is fed by a $45MW$ peak power, $4.5\mu s$ pulse width Thales klystron. Taking advantage from the short accelerating structure filling time, the peak power to the structure is increased by shortening the pulse length: each power plant is equipped with PEN (Pulse Enhancement Network) system [1] that stores the energy at the beginning of the pulse and release it near the end of it.
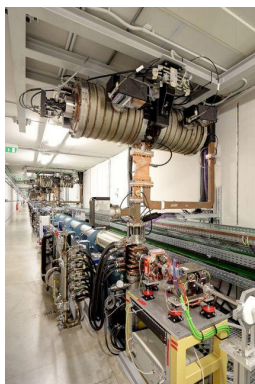

Figure 1: Pulse enhancement network system for a backward traveling wave structure.

To achieve the Linac target energy of 1.5 GeV, each BTW structure needs to be operated at a gradient of 26 MV/m corresponding to an energy gain of about 155 MeV. Past operation of those structures, showed that breakdown problems inside the sections, associated with the very high peak-field built up during conventional SLED operation, prevented from reaching the desired gradient in a reliable way.

A phase modulation technique was implemented to lower the high peak field inhered with conventional SLED operation: while a preliminary linear phase modulation has allowed to demonstrate the utility of this technique in our application and has allowed to increase the energy gain in the structures, the possibility of an optimization of the phase modulation parameters has been studied to get the optimal trade-off between lowering the peak field, thus improving reliability, and still having an acceptable energy gain.

PRELIMINARY PHASE MODULATION

The phase modulation feature was integrated in the LLRF firmware of FERMI. The preliminary implementation of the phase modulation technique foresees just a linear modulation [2] where two parameters (i.e. the initial phase ϕ_0 and the phase modulation slope m) can be modified to change the shape of the modulation as depicted in Figure 2.
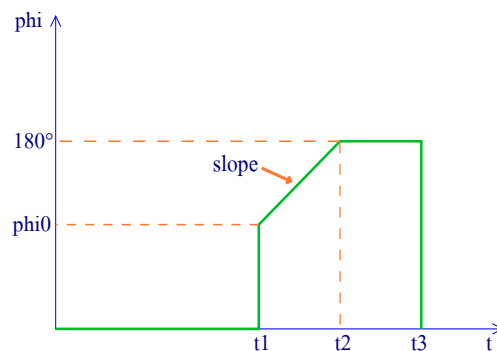

Figure 2: Linear phase modulation.

During a dedicated machine commissioning shift, different sets of parameters were tested: the optimal results (in terms of a trade-off between peak field and gradient loss) were achieved using an initial phase offset ϕ_0 of 95° and a slope m of 149 deg/μs.

A comparison between the pulse shape in case of conventional SLED operation and the one with the optimized linear phase modulation showed that for the same RF pulse
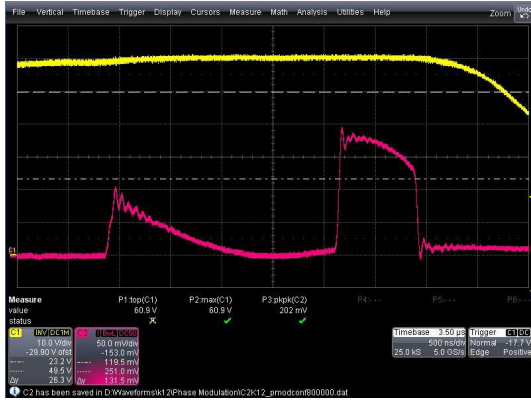
Figure 3: Input cavity field with phase modulation.

length (3000 ns), the peak field is reduced by almost 20%; correspondingly the energy gain loss is about 4%.

It must be noted that by simply using a linear phase modulation it was not possible to achieve a rectangular-like pulse shape. As depicted in Figure3 during the 770 ns pulse duration the normalized field amplitude varies from about 1.8 up to 1.4 (i.e. about 20% variation). Also, it can be pointed out that a huge phase slippage of about 46 degree between the begin and the end of the pulse occurs.

A way to get flatter pulse and smaller phase variations is to implement a continuous non-linear phase modulation.

NUMERICAL EVALUATION FOR A NON-LINEAR PHASE MODULATION

The phase modulation program for rectangular pulse shape has been numerically evaluated by solving the equations 1a and 1b for constant v_0 amplitude during pulse compression [3] [4]:

$$\begin{cases} \tau\dot{v}_c + v_c = -\alpha v_k & \text{(1a)} \\ v_0 = v_c + v_k & \text{(1b)} \end{cases}$$

where v_k and v_c are the generator and the pulse compressor equivalent complex voltages, β is the coupling coefficient between the SLED and the transmission line, $\alpha = 2\beta/(1+\beta)$ and τ is the filling time of the SLED cavities equal to $2Q_0/[(1+\beta)\omega_0]$. In the previous expression Q_0 is the unloaded quality factor of the SLED cavities and ω_0 is the angular frequency of the RF wave.

In our case, β is 10 and Q_0 is 190000. Accordingly, α is about 1.8 and the filling time τ is $1.832\mu s$.

Equation 1a assumes that the resonant frequencies of the SLED cavities and of the RF wave are equal. In case there is a small difference between these two frequencies the equation 1a must be replaced by 2a where $\Delta\omega = \omega_0 - \omega_c$ and ω_c is the angular frequency of SLED cavities [4] [5]. This is necessary to minimize the phase variation during the flat-top of the pulse delivered to the structure.

$$\begin{cases} \tau\dot{v}_c + v_c(1 + j\tau\Delta\omega) = -\alpha v_k & \text{(2a)} \\ v_0 = v_c + v_k & \text{(2b)} \end{cases}$$

Replacing $v_c = v_0 - v_k$ in equation 2a as derived from equation 2b and discretizing the differential equation 2a we get:

$$v_{k_{i+1}} = v_{0_{i+1}} - v_{0_i}\left[1 - (1 + j\tau d\omega)\frac{dt}{\tau}\right] + \\ + v_{k_i}\left[1 - (1 - \alpha + j\tau d\omega)\frac{dt}{\tau}\right] \quad (3)$$

Let's put:

$$w_i = v_{0_i}\left[1 - (1 + j\tau d\omega)\frac{dt}{\tau}\right] + \\ - v_{k_i}\left[1 - (1 - \alpha + j\tau d\omega)\frac{dt}{\tau}\right] \quad (4)$$

where w_i groups all the term at time instant i. We can write:

$$v_{k_{i+1}} = v_{0_{i+1}} - w_i \quad (5)$$

The goal of a non-linear phase modulation is to get a rectangluar-like pulse shape to the structure during the pulse compression. The amplitude square of the voltage to the structure at time instant $i + 1$ can be written into the form:

$$\left|v_{0_{i+1}}\right|^2 = \left|v_{k_{i+1}} + w_i\right|^2 \\ = \left|v_{k_{i+1}}\right|^2 + |w_i|^2 + 2Re\left\{v_{k_{i+1}}\bar{w}_i\right\} \quad (6)$$

So, we have:

$$\left|v_{0_{i+1}}\right|^2 = \left|v_{k_{i+1}}\right|^2 + |w_i|^2 + \\ + 2\left|v_{k_{i+1}}\right||w_i|\cos\left(\angle v_{k_{i+1}} - \angle w_i\right) \quad (7)$$

The phase modulation program must set the phase of the generator $\angle v_{k_{i+1}}$ such that the amplitude $v_{0_{i+1}}$ of the compressed pulse is kept as constant as possible.

If we call $v_{0_{PR}}$ the amplitude of the compressed pulse at the phase reversal time t_1, the phase of the generator at time instant $i + 1$ for getting a constant amplitude pulse shape (i.e. equal to $v_{0_{PR}}$) could be then calculated with the following equation:

$$\angle v_{k_{i+1}} = arccos\left(\frac{\left|v_{0_{PR}}\right|^2 - \left|v_{k_{i+1}}\right|^2 - |w_i|^2}{2\left|v_{k_{i+1}}\right||w_i|}\right) + \angle w_i \quad (8)$$

SIMULATION RESULTS

Running the simulation code it was possible to find a phase modulation program resulting in a flat amplitude pulse shape. Even if reaching a flat amplitude pulse for a given klystron power and pulse width is at expenses of the energy gain, lowering the peak fields could allow to increase the klystron output power without suffering of heavy breakdown phenomena in the structures' couplers and cells: in the end, this could finally result in a higher energy gain.

To reach a flat-top pulse it is necessary to change the phase by less than $180°$ at the phase reversal time and then

increase it slowly to keep the pulse flat. As depicted in Figure4 as the phase reaches $180°$ it cannot further keep the pulse amplitude constant, so it decays exponentially. To get more power to the structure, the phase jump at the phase reversal time should be larger, but then the power cannot be kept constant until the end of the pulse.
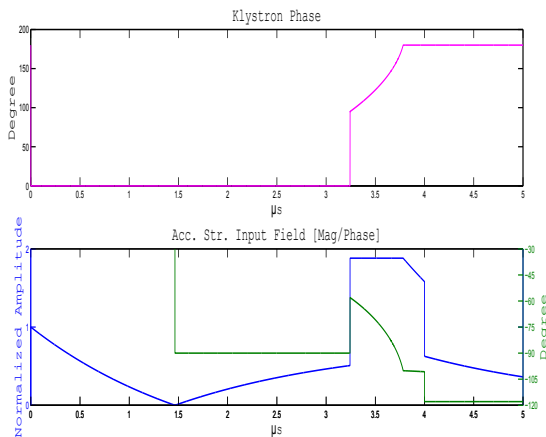

Figure 4: Non-linear phase modulation scheme.

So, for a 4μs pulse width, it was chosen an initial phase jump of 86 degrees: in this condition, the field amplitude at the phase reversal time is limited to about 1.75 (i.e. ≈ 3 in power). A non linear phase modulation than guarantees a constant amplitude field during the 770 ns pulse width. However, with this parameters the phase slippage along the RF pulse is about $50°$ as showed in Figure5.
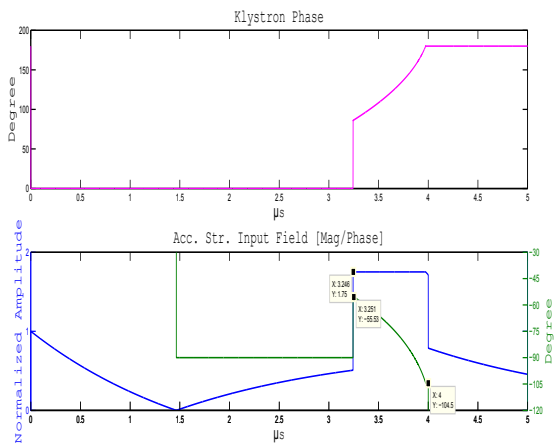

Figure 5: Pulse shape with non-linear phase modulation.

Nonetheless, the phase variation during the flat-top pulse can be minimized by slightly detuning the SLED cavities: this corresponds to choose a suitable $\Delta\omega$ in equation 2a. The frequency shift must be then compensated with a linear ramp of the phase in the first part of the klystron pulse. Figure6 shows the final pulse shape that could achievable with the new phase modulation program.
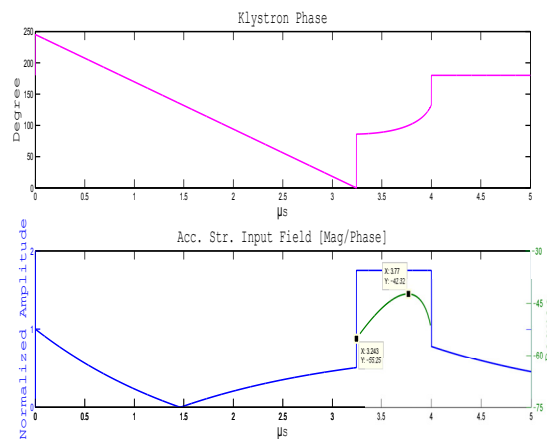

Figure 6: Pulse shape with non-linear phase modulation and SLED cavities detuning.

CONCLUSION

Based on our experience, we can say that our BTW accelerating structures can handle in a reliable way an input peak power of about 97 MW: using the actual linear phase modulation program, to stay below this limit, we operate the klystron at about 32 MW peak power with a 3.5μs pulse width resulting in a accelerating gradient of about 150 MeV.

The new phase modulation program, resulting in a flat amplitude pulse shape, lowers the peak field in the accelerating structure. This could allow to push the power of the klystron up to 36 MW and 4 μs pulse width while still keeping the peak power to the structure under the limit of 97 MW: in this operating conditions, the effective energy gain for each structure should reach about 165 MeV, assuring in this way a reliable margin for the operation of the FERMI Linac at the final target energy of 1.5 GeV.

REFERENCES

[1] G. D'Auria et alii, "The Impact of PSK Timing on Energy Stability of e-beam at FERMI@Elettra", EPAC'08, Genoa, Italy, MOPC008.

[2] C. Serpico et alii, "Phase-Modulation SLED Operation Mode at ELETTRA ", IPAC'11, San Sebastian, Spain, MOPC010.

[3] A. Fiebig, Ch. Schieblich, "A SLED Type Pulse Compressor with Rectangular Pulse Shape", EPAC'90, Nice, France.

[4] S.H. Shaker et alii, "Phase Modulator Programming to Get Flat Pulses with Desired Length and Power from the CTF3 Pulse Compressors", IPAC'10, Kyoto, Japan, TUPEA043.

[5] R. Bossart, P. Brawn, J. Mourier, I. Syratchev, L. Tanner, "High-power Microwave Pulse Compression of Klystrons by Phase-Modulation of High-Q Storage Cavities", CLIC-NOTE-592, June 2004.