OPERATION OF AN L-BAND RF GUN WITH PULSES INSIDE THE BURST MODE RF PULSE

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Abstract

The Free-Electron Laser in Hamburg (FLASH) is a user facility since 2005 [1], delivering femtosecond short radiation pulses in the wavelength range between 4.1 and 44 nm using the SASE principle. In FLASH, the electron beam is accelerated to 1.25 GeV with L-band superconducting cavities. The electron source is a normal conducting RF-gun photoinjector. The L-band standing wave RF gun has one and a half cells. The gun is operated in burst mode with an RF pulse length of up to 900 µs and a repetition rate of 10 Hz. Several hundreds to thousands of bunches are accelerated per second. With 5 MW of pulsed forward power, the dissipated power inside the RF gun is 45 kW [2, 3]. In this paper we propose an operational mode which allows to reduce the dissipated power to ease operation or to increase the effective duty cycle in the gun by pulsing the gun within one burst. We report on first experimental results at FLASH, where an RF burst of 46 micro RF-pulses with a length of 10 µs separated by 10 µs has been successfully generated reducing the dissipated power by a factor of 2. Later, we have successfully run RF gun in SASE conditions with following RF pulse structure: full pulse length 820 µs with 33 RF pulses with 16 µs RF on and 9 µs RF off time, up to 23 bunches with SASE, with energy of 60 µJ.

PIP MODE: CONCEPT DESCRIPTION

"Pulses Inside one RF Pulse" (PIP) mode aims are a reduction of the average heat load of a cavity by splitting a long RF pulse into many short pulses with power free gaps in between [1]. The time structure of RF and laser pulses in PIP mode is shown on Fig. 1.

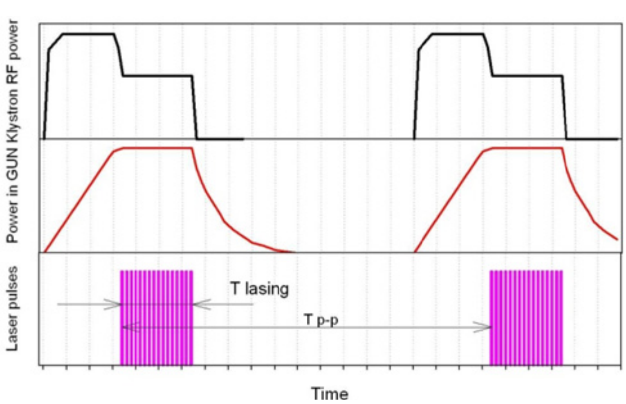


Figure 1: Shapes of first two pulses, above: output power from the klystron, high amplitude during filling time, low amplitude during flat top, middle: an electric field in the gun, bottom: a laser pulses.

A minimization of the heat load is desirable also in case of a cold gun [4], so that the requirements for the cooling system are minimized and even for special operation modes of superconducting cavities this might be desirable. Since for the cold gun or a superconducting cavity the required RF power is low as compared to a standard warm cavity; an operation mode which makes use of a large overhead of RF power is considerable. The total time required to fill a cavity up to the design gradient can be reduced by filling it with a power larger than actually required to reach the design gradient. When the design gradient is reached the power needs hence to be reduced. The RF pulse divides into the three phases: filling – flat top – decay. During the filling of the cavity the voltage rises as [5]:

$$U(t) = \left(1 - \exp\left(-\frac{t}{\tau}\right)\right)\sqrt{P_f 2R}\,\frac{2\sqrt{\beta}}{1+\beta} \qquad (1)$$

with the cavity filling time $\tau = \dfrac{2Q_0}{\omega_0(1+\beta)}$, the shunt impedance R and the coupling constant β. The minimal power to achieve the design gradient in FLASH gun cavity is: $U_0 = \sqrt{P_0 2R}$, for $\beta = 1$. Equation (1) is hence rewritten as:

$$\left(1 - \exp\left(-\frac{t_f(1+\beta)}{2\tau_0}\right)\right)\sqrt{P_f 2R}\,\frac{2\sqrt{\beta}}{1+\beta} = \sqrt{P_0 2R} \qquad (2)$$

where t_f is the total time required to fill the cavity up to the design voltage if the input power is equal to P_f. Resolving t_f from (2), for $\tau_0 = Q_0/\omega = 2.82$ µs and $\beta = 1$, in Fig. 2 t_f is shown as function of the power ratios. The cavity can be emptied faster by increasing

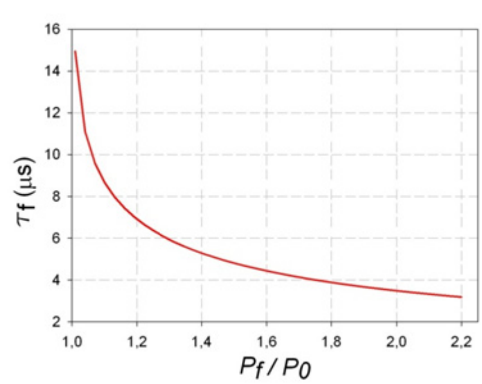


Figure 2: Total time to fill the gun cavity to the design gradient versus power ratios.

the power again while switching the RF phase by 180 degrees. Presently on FLASH is the possibility to increase the input power only to 8% relative to the nominal level. Filling time can be about 10 µs and if a free gap between RF pulses will be 10 µs also, there is a possibility to reach repetition rate of 50 kHz, in the case if a single laser pulse will be on the end of each RF pulse. A thermal power loss in the gun cavity is twice low as in the normal mode. Late, when a 10 MW klystron will be available the filling time can be reduced up to 4 µs and we will get a flat top time of 6 µs, which allow us to reach up to 20 laser pulses during one short RF pulse and a total number of laser pulses as in standard operation.

CONTROL ALGORITHM

The FLASH RF gun control system uses a completely digital feedback system [6]. The control algorithm employs tables for feed-forward set-point and feedback gain settings to allow time varying of those parameters. The algorithm is implemented in firmware in FPGA (Field Programmable Gate Array) based digital controller board. Access to the FPGA recourses is provided via controller server. RF gun cavity has no field probe. RF field inside the cavity is determined by the forward and reflected power measured at the directional coupler in front of the gun. The signals are down-converted to the baseband and digitized with ADCs (sampling rate is 81 MHz). The resulting field vectors of forward and reflected signals are multiplied by a rotation matrix to calibrate amplitudes and phases. The vector sum of the forward and reflected powers represents the total voltage and phase seen by the beam at the gun. This signal is regulated by a feedback control algorithm which calculates corrections to the driving signal of the klystron.

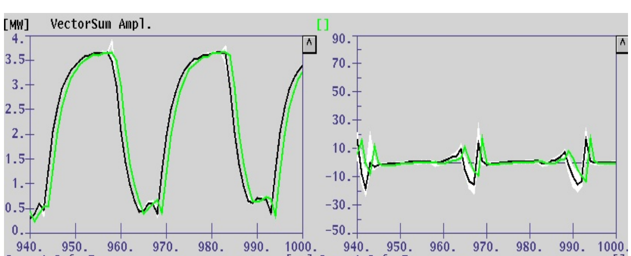


Figure 3: Set-point (green) and measured vector-sum (black) amplitude and phase signals.

The measured vector sum (virtual probe) is subtracted from the set-point table and the resulting error signal is amplified and filtered to provide a feedback signal to the vector modulator controlling the incident wave. A feed-forward signal is added to correct the averaged repetitive error components. The real and imaginary parts of the calculated table are converted by the DACs separately and control the RF vector, applying the correction signal to the vector modulator.

In order to provide RF gun operation in PIP mode dedicated table generation algorithm has been implemented to allow generation of control tables like feed-forward, set-point and gain according to required RF pulse structure. Gain scheduling for RF micro-pulses has been implemented as well to achieve maximum feedback gain exactly in time when the beam arrives. In Fig. 3 are shown set-point and measured vector sum signals for two consecutive micro-pulses in close loop with nominal gain of 12.

PIP MODE: TEST RESULT

The testing of PIP mode in FLASH was done in three stages. The goal of the first run (August 2009) was the examination of the hardware, software and optimization of RF pulse shape to reduce a level of reflected power from RF gun. The source of RF power for the gun in FLASH is 5 MW klystron (TH2104C), the bandwidth of this klystron is about 8 MHz which allows to use very short RF pulses with rise time less than 1 µs [4]. The RF gun of FLASH consist of a 1.5 cells normal conducting copper cavity with operating at 1.3 GHz and a peak accelerating field of 45 MV/m on the cathode, the external quality factor is about 23000 [2, 7].

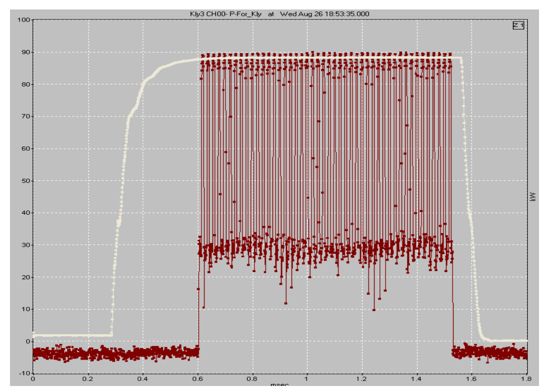
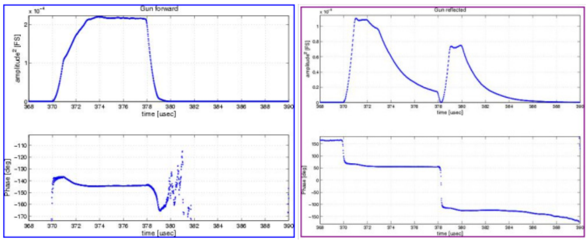


Figure 4: Example of wave shapes of klystron current (white) and output power (brown). Vertical scale is in (A) for the current and in (dBm) for klystron output power.

The length of the klystron high voltage pulse is about 1.3 ms this allows to get a RF pulse length up to 900 µs. On Fig. 4 are shown wave shapes of 46 RF pulses each of 10 µs RF on and 10 µs RF off time. In a second stage it was tested a transmission of 30 bunches through FLASH linac. Finally we have successfully run RF gun in PIP mode with SASE conditions and feedback loop closed. RF pulse structure settings: full pulse length 820 µs with 33 RF pulses and 16 µs RF on and 9 µs RF off time, up to 23 bunches with SASE, with energy of 60 µJ, measured in GMD (Gas Monitor Detector), beam charge of 0.7 nC, beam energy of 960 MeV, wavelength of 7.01 nm. SASE intensity distribution was very flat during the time duration up to 575 µs. The klystron was working with full output power about 5.2 MW; no breakdown in the gun cavity was observed. On Fig. 5 and 6 are shown wave shapes of amplitude and phase of forward and reflected power. Data was taking with 81 MHz ADC [8] on Fig. 5.



(a) (b)

Figure 5: (a) Wave shapes of input power and input phase of RF gun and (b) wave shapes of reflected power and phase of reflected power, after optimization of reducing a level of reflected power.

and 1 MHz ADC on Fig. 6. The wave shape of forward power was optimized for reducing the maximum level of reflected power and reducing an emptied time. Figure 7 shows the first SASE signal (μJ) in FLASH in PIP mode for a 20 pulse bunch train.

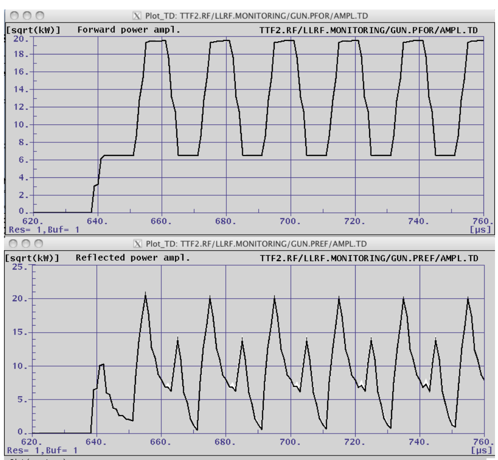


Figure 6: Wave shapes of first six from 46 pulses. Forward power (above) and reflected power (bellow). Data was taken with 1 MHz ADC.

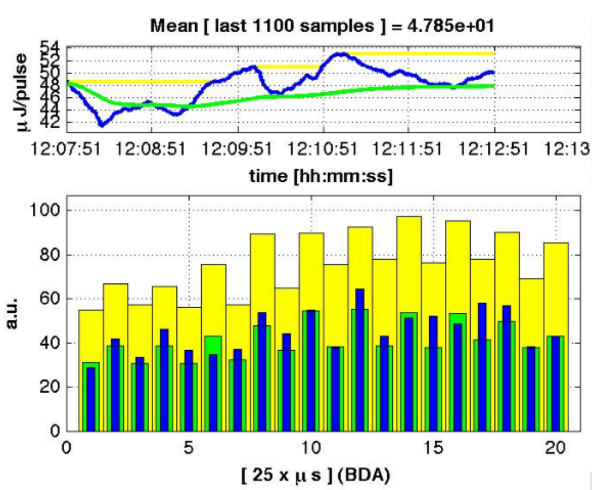


Figure 7: Photon bunch energy for 20 bunches in PIP mode of FLASH operation. Recorded with GMD detector; blue - actual pulse, green - running average, yellow - peak readings.

CONCLUSIONS

Thermal losses [2, 3, 9] in the normal conductive RF gun are a main limiting factor to reach a high gradient and high repetition rate of operation. The proposed PIP mode of operation can allow reducing power losses in the RF gun by splitting one long RF pulses into many short pulses with power free gaps in between. The flat top of this short RF pulse can be used for acceleration of many of electron bunches. A relation between a length of free gaps and flat top gives a factor of reduction power losses in the gun. The filling and decay time in the gun cavity can be reduced by increasing the level of input RF power and switching phase to opposite phases during emptied time.

Operation FLASH in PIP mode can provide to users several new options: two light pulses separated by 900 μs, three separated by 450 μs, etc. up to 25 μs between two adjacent pulses.

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