INVESTIGATION OF INR DTL RF SYSTEM OPERATION AT 100 HZ REPETITION RATE

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Abstract

INR Linac has been operating with 50 Hz beam repetition rate so far. Increasing the repetition rate up to 100 Hz is of importance as it results in doubling of the beam intensity. To solve the task several accelerator systems have to be modernized but the most critical one is DTL RF system (up to 100 MeV). The problems related to DTL RF system repetition rate increasing are described. One of the problems is a 50 Hz modulation of a 100 Hz RF pulse sequence. Though the instabilities of accelerating field due to the modulation are reduced by the feedback systems, nevertheless investigation of the effect and its minimizing is of importance. The analysis of the effect is given and the results of experimental studies are presented. Other problems to be overcome to increase the repetition rate are mentioned as well.

INTRODUCTION

Operation with the repetition rate of 100 Hz was foreseen by initial design of INR linac [1]. However since commissioning for more than twenty years accelerator operated with 50 Hz repetition rate satisfying requirements of beam users. Recently the goal of doubling of the repetition rate has been formulated with the aim of increasing the beam intensity and efficiency of the accelerator. Several problems have to be solved: increasing of the repetition rate of HV proton injector, commissioning of beam pulse separation system [2] etc. However the most complicated task is related to RF system of the accelerator. The accelerator consists of low energy part (100 MeV, DTL, 198.2 MHz) and high energy part (600 MeV, Disk and Washer structure, 991 MHz). Initial tests of RF equipment with 100 Hz repetition rate revealed modulation of rf field pulses with 50 Hz frequency. One of the origins of the effect was found to be biperiodic triggering of rf equipment. Accelerator clocking pulses are coupled to one of the mains phases and a 100 Hz sequence is generated at zeroes of 50 Hz voltage. Due to distortions of sinusoidal waveform the clocking pulses were not equidistant thus resulting in a different levels of charging of pulse forming lines used to generate HV pulsed for klystrons (high energy part) and power grid tubes (low energy part). Special measures taken to provide exact periodicity of 100 Hz series enabled to eliminate the effect for high energy part but appeared to be ineffective for low energy part. Further study showed that the main reason of the effect in low energy part is using of AC current for directly heated cathodes of power grid tubes.

DTL RF SYSTEM

DTL RF system includes seven RF channels: one for RFQ and six for five accelerating cavities, one of them being a spare channel. A simplified block diagram of one RF channel is shown in fig. 1. The channel represents a four stage amplifier (K1÷K4) with two anode pulse modulators MB and M1.

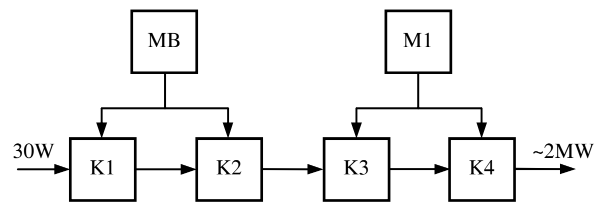

Figure 1: Block diagram of DTL RF channel.

Both amplifier stages and pulse modulators use power grid tubes. The upgrade of DTL RF system with replacement of grid tubes is under way now [3]. The type of grid tubes used in RF channels at present is given in table 1.

It will be shown that the mode of cathode heating (direct or indirect) is essential for 100 Hz operation. It is listed in table 2 for all the types of tubes used in DTL RF system.

Table 1: Type of grid tubes

Unit	RF channel						
	RFQ	1	2	3	4	5	6
K1,K2	GS-31B	GS-31B	GS-31B	GS-31B	GS-31B	GS-31B	GS-31B
K3	GI-51A	GI-51A	GI-51A	GI-57A	GI-57A	GI-51A	GI-51A
K4	GI-54A	GI-71A	GI-54A	GI-71A	GI-71A	GI-71A	GI-54A
MB	GMI-34A	GMI-34A	GMI-34A	GMI-34A	GMI-34A	GMI-34A	GMI-34A
M1	GMI-44A	GMI-44A	GMI-44A	GMI-44A	GMI-44A	GMI-44A	GMI-44A

Table 2: Mode of cathode heating

Tube	GS-31B	GI-51A	GI-57A	GI-54A	GI-71A	GMI-34A	GMI-44A
Directly heated cathode		*	*	*	*		*
Indirectly heated cathode	*					*	

50 HZ MODULATION OF 100 HZ RF PULSE SEQUENCE

After switching the RF channels from 50 Hz mode to 100 Hz mode of operation a 50 Hz modulation of RF channel output power and hence of the envelopes of RF fields in DTL cavities was immediately revealed. As an example Fig. 2 demonstrates a screen view of oscilloscope with the envelopes of RF field in DTL cavity

ISBN 978-3-95450-125-0

#5 and modulator M1 output pulses. The 100 Hz series represents a superposition of two 50 Hz trains shifted in time by 10 ms.

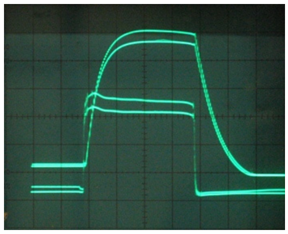

Figure 2: Typical envelopes of RF field in accelerating cavities (upper beam) and stages K3-K4 anode pulses (lower beam). Horizontal scale – 100 µs/div.

This information is routinely available for operator and the first explanation of RF field modulation was corresponding modulation of modulator M1 pulses. Several effects were considered as the reason of modulator pulses biperiodicity but the most realistic appeared to be 50 Hz modulation of cathode-grid bias in the M1 modulator tube GMI-44A. The cathode of the tube is a directly heated one and is powered from two phases of the mains. Filament voltage modulates cathode-grid bias, the magnitude of modulation being different for different point along the cathode. This effect is specific for tubes with directly heated cathodes and must be absent for tubes with cathodes heated indirectly. This statement is confirmed by observations of RF power at the output of stage K2. Neither modulator MB nor stages K1 and K2 use tubes with directly heated cathodes (Table 2). As a result no power modulation at the output of K2 is observed.

The duration of RF pulses is equal to 400 µs, which is appreciably smaller than the period of 50 Hz mains. In this case the bias is almost invariable within the beam pulse, its value being dependent on the modulator triggering delay with respect to the mains. Figure 3 demonstrates RFQ modulator M1 pulses for two delays with respect to the mains. The left picture corresponds to triggering at the maximum of filament AC voltage and the right one - at zero. One can see that proper triggering delay effectively minimizes the effect of modulator pulses biperiodicity.

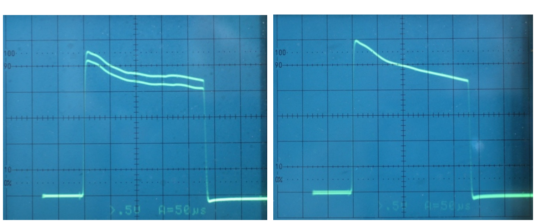

Figure 3: Modulator pulses for different delay with respect to the mains.

Initially the filaments of the modulator tubes were powered from different phases of the mains. To remove modulation of the pulses we have powered the filaments of all the modulator tubes from the same phases of the mains and have triggered modulators at a zero point of AC filament voltage.

One should note that the pictures presented in Fig. 2 and Fig. 3 were observed with no modulator pulse stabilization and no saturation of the tube. In reality both measures are used thus decreasing the effect. Fig. 4 demonstrates the same pulses as in Fig. 3 but with modulator tube input saturation as well as stabilization of the pulse flat top.

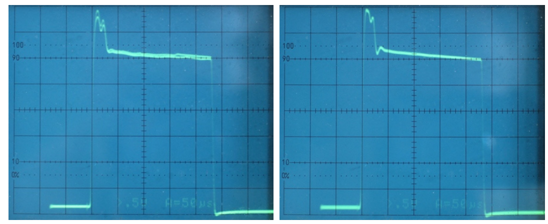

Figure 4: Effect of modulator tube input saturation and stabilization of the pulse flat top.

Minimization of modulator pulses biperiodicity resulted in decreasing of 50 Hz modulation of RF channels output power but not to complete elimination of the effect. An assumption was done on existence of similar effect of the bias modulation in the RF tubes, also with directly heated cathodes, used in K3 and K4 stages (Table 1, 2). The effect is not related to the tube GI-54A as its cathode is heated with a current supplied from the 12-phase rectifier with minor pulsations.

The filaments of the tubes GI-71A are power from two phases of the mains similarly to the modulator tube GMI-44A. In RF channels #1 and #3 adjustment of the filament power is done by changing the voltage with induction regulators and in channels #4 and #5 - by thyristor phase control. In order to minimize bias modulation in the tubes GI-71A their filaments have been switched to be powered from the same phases of the mains as modulator tubes GMI-44A. Filament voltages of GI-71A and GMI-44A for RF channel #4 are presented in Fig.5. The modulator is triggered when the filament voltage is near zero.

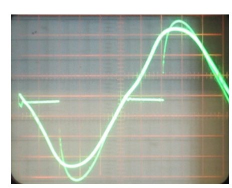

Figure 5: Filament voltages of GI-71A and GMI-44A for RF channel #4.

Unlike GMI-44A and GI-71A the filaments of the tubes GI-51A and GI-57A are powered from one phase of the mains. In this case exact phasing of their filament voltages with those of GMI-44A and GI-71A is impossible and the minimum possible phase difference equals 30°. Adjustment of the heating power is done with bidirectional triode thyristor phase control. It turned out that for the nominal heating power the thyristor is closed when the GMI-44A filament AC voltage crosses zero, which is demonstrated in fig. 6. In this case the RF modulator is triggered when the distortion of the cathode-grid bias is small.

ISBN 978-3-95450-125-0

The above described measures resulted in essential reduction of the effect of accelerating field modulation in all DTL cavities. Figure 7 demonstrates a dependence of deviations of the amplitudes of even and odd pulses of the 100 Hz series of the RF field in the anode-grid cavity of K4 stage of channel #5 versus delay with respect to the phase of the mains. One can see that the value of deviation is close to zero within the delay range of 3÷7 ms. Similar behavior of pulse modulations was also obtained for RF fields in all accelerating cavities. The middle of the above range of 5 ms was selected as a reference for triggering of all the accelerator equipment. As an example Fig. 8 demonstrates the envelope of RF field in DTL cavity #2 as well as modulator M1 pulse. No visible modulation can be observed.

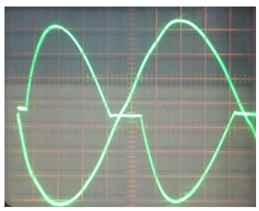

Figure 6: Filament voltages of GI-51A and GMI-44A for RF channel #2.

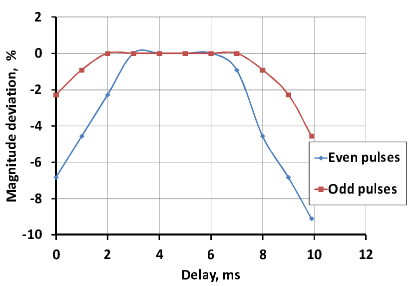

Figure 7: Deviation of even and odd pulses of RF field in anode-grid cavity vs delay.

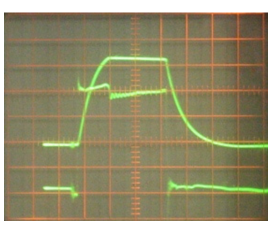

Figure 8: Envelope of accelerating field in DTL cavity #2 (upper beam) and modulator M1 pulse.

ADDITIONAL PROBLEMS

Additionally to the above described problem several other problems must be solved to implement a 100 Hz mode. Among them the most important are:

Doubling of Average RF Power

Doubling of the repetition rate results in doubling of RF power dissipating at grid and plate of powerful vacuum tubes GI-57A and GI-71A, anode-grid and cathode-grid resonators of RF power amplifiers, coaxial transmitting lines between K4 and drift tube cavities, numerous RF junctions etc.

Increasing the Cavity Warm-Up Time After Switching Off the RF Power Due to Breakdowns or Other Reasons

DTL cavity resonant frequency control is done by means of drift tube cooling water temperature control. Water temperature is varied by changing the electric heater power and the flow of water through heat exchanger. Before switching RF power on the drift tubes have to be warmed up to the resonance temperature and after switching on the temperature of cooling water has to be decreased to maintain the cavity drift tube temperature invariable. The value of water temperature decresing depends on the cavity and amounts to several degrees at 50 Hz repetition rate. In case of unexpected switching RF power off the temperature of the drift tubes goes down to water temperature in 10÷15 s. Subsequent switching RF power on is possible only after warming up the whole amount of water to the cavity temperature. The warm up time is proportional to the temperature change and one can show that this change in its turn is proportional to the average RF power. For 100 Hz repetition rate the warm up time increases up to 20÷30 minutes thus essentially decreasing availability of the accelerator beam.

Increasing of High Voltage in the Pulse-Forming Lines of the Modulators M1

In pulse modulator M1 plate voltage supply of GMI-44A is realized by means of a pulse forming line (PFL) as storage device. The PFL consists of 20 cells with time discharge 400 μs and impedance ρ = 24 Ohm. The DC load of the PFL is near 200 Ohm and, hence, it operates with partial discharge [4]. A recovery time of PFL charge is determined by HV rectifier parameters (choke inductance and internal resistance) and full capacity of AFL and is near 30 ms. As follows from measurements, at 100Hz repetition rate rectifier HV value has to be increased at 4-5 kV.

CONCLUSION

The problem of 50 Hz modulation of 100 Hz RF pulse series in DTL RF system of INR linac has been investigated. The solution found enables to essentially eliminate the problem providing the base for further activity in increasing the intensity of INR linac. Several other problems exist and their contributions in accelerator operation at 100 Hz repetition rate require additional studies.

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ISBN 978-3-95450-125-0