RESULTS OF THE INR DTL SERIES CROWBAR SYSTEM TESTING

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In the earlier paper description of existing at INR DTL crowbar system and some proposals, increasing its efficiency, were considered. Really it was a question of replacement of the bypass crowbar by the series crowbar system. The last one can be used as RF exciting of accelerator cavities is realized by means of vacuum tube power RF amplifier (PA) with plate pulse supply. At that, vacuum tube has to be used in the anode modulator regardless of the method of RF power control. For the last year the new series crowbar system, using the possibilities of the "hard" modulator, was installed at all DTL RF systems of the INR accelerator. The system was successfully tested during 700 hours of continuous accelerator operation. Some peculiarities and results of new system functioning are discussed.

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1. INTRODUCTION

The necessity of crowbar system is caused by the danger of powerful vacuum tubes damage due to breakdown of anode-grid gap and full discharge of the modulator supply storage capacities. At the INR linear accelerator there are two high-priced powerful vacuum tubes, which have to be protected from breakdowns by means of crowbar system: anode modulator output triode GMI-44A and RF output power amplifier (PA) triode GI-54A or GI-71A, which last time is a substitute for GI-54A [2]. However, as follows from long-term observations, the overwhelming part of the breakdowns takes place in the anode-grid cavity of the PA; hence, the crowbar system also considerably reduces damages of the anode-grid cavity surface due to breakdowns. View of inner surface of the PA coaxial anode-grid cavity after long-term operation is a strong evidence of the breakdown consequence. Reasons of breakdowns are different and connected with over voltages in the PA anode-grid cavity, appearing at the rising and falling edges of RF pulse [3], and with breakdowns in the coaxial transmitting line or in the accelerator cavity. It follows to mention that very often the breakdowns in the PA cavity are initiated by burning of contacts in tuning devices or in butt joints.

There are a few well-known methods of breakdown voltage increasing in PA cavities and transmitting lines but each of them greatly complicates the design, operation and repair of the RF system. That is why the operation of the INR DTL RF system is protected by crowbar system only. Below the main peculiarities of the bypass and series crowbar systems are considered in detail.

2. BYPASS CROWBAR SYSTEM

The bypass crowbar system (BCS), presented in Fig.1, had been in operation for 20 years. As a storage device in the modulator high voltage supply artificial forming line (AFL) with impedance 24 Ohm and time discharge 400 μs had been installed. The AFL impedance limits the value of breakdown current and that allows using thyristors with current near 1 kA as the discharge device. In turn, the discharge device consists of 110 thyristors in series for fast discharge of the AFL capacities and dissipation of the energy, accumulated in the storage. In Fig.1 the high voltage supply circuit is shown, where IVR – induction voltage regulator, HVR – high voltage rectifier, CB – high voltage circuit breaker, CP-current protection relay. The last one is in series with the HVR choke and protects the rectifier from the current load, exceeding the set point value SP1. Moreover, in Fig.1 the main components of the amplitude feedback are shown: amplitude detector AD, signal from which is compared with set point value SP2, summarizes with that of and after PI controller comes at the premodulator (modulator driver) input. The pulse transformer between the premodulator and the modulator vacuum tube GMI-44A separates high and low voltage circuits.

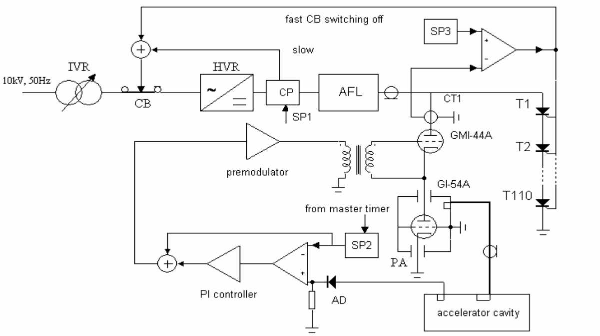

Fig.1 Block-scheme of the DTL RF system with the bypass crowbar system

Operation of the crowbar system starts in result of exceeding of current transformer (CT1) output signal the set point value SP3. Value of the set point, as a rule, is twice higher than load current – dc component of current through RF power amplifier vacuum tube. With delay 15…20 ms after starting of the BCS thyristors high voltage breaker CB opens the high voltage circuit between the induction regulator IVR and the rectifier HVR. Without BCS operation the breaker is controlled by the current protection relay but with greater delay – (80…100) msec. The necessity of fast switching off the high voltage supply circuit by means of CB is connected with peculiarity of BCS. The point is that operation of the crowbar system really results in short circuit of high voltage rectifier during discharge of the AFL. At that dangerous over voltage in the storage capacities appears due to the high value of choke inductance (12 H) at the HVR output. In Fig.2 results of modeling by means of Micro Cap 7, which are in good agreement with measurements, are presented [1].

In Fig.2 upper trace corresponds to AFL voltage during RF system operation with repetition rate 50 Hz and pulse length 400 μs right up to the crowbar starting, after which switching off RF system operation occurs.

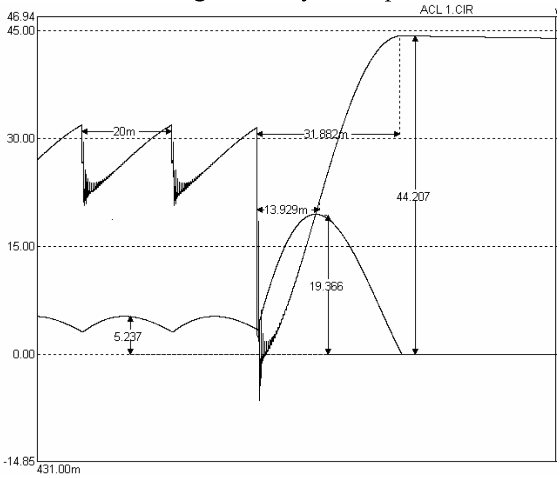

Fig.2. Over voltage in the AFL in result of the bypass crowbar system operation

Lower trace shows high voltage rectifier current. One can see that after discharge of the AFL in result of the BCS operation recovery of the AFL capacities charge takes place with ~ 50% over voltage. Maximum value of the over voltage is achieved in ~30 ms and maximum value of rectifier current in ~ 15 ms after crowbar starting. Thus, the AFL recovers its charge for one period and, despite of HV supply opening, breakdowns can repeat if only modulator driving won't be switched off right away after BCS operation. It is significant that the maximum value of current nearly four times exceeds the previous one and can be a reason of CP relay operation. Thus, opening (by means of CB) high voltage supply circuit in 15…20 ms after BCS operation allows avoiding the dangerous over voltage and reducing a possibility of breakdowns in the anode modulator due to the over voltage. So, each time after BCS operation the modulator HV supply of the RF channel is switched off and beam accelerating is stopped. Recovery of the RF channel takes place only in 15…20 min due to long process of the DTL cavity warming up after switching off RF channel [4]. That is why any operation of the bypass crowbar system results in decreasing of the efficiency accelerator operation as a whole.

During all previous years the behavior of the bypass crowbar system was carefully studying and a few modifications have been done, directed at improving of the crowbar system operation and decreasing of the false operation:

- "Temporal gates" had been installed at the premodulator (see fig.1) input to exclude a false drive of the modulator, which could be a reason of a false operation of the BCS.
- A part of the equipment had been shifted from the AFL location closer to the vacuum tube GMI-44A and the control devices, so that to decrease a coupling between high and low voltage equipment.
- The structure of the AFL was changed in order to provide for the reliable cutoff of the thyristors after the AFL discharge [1, 5].
- Interference immunity to false drive of the scheme, opening the thyristors, was increased.

Nevertheless, the significant improvement in the BCS operation hasn't been achieved. At that, it was occurred that the most part of BCS starting didn't connect with the real breakdowns in the modulator and RF power amplifiers vacuum tubes but were caused by false pickups. And there are a whole series of reasons, explaining this occurrence. Let's mention the main ones.

- Accommodation of the devices, controlling thyristors of the BCS, directly near high voltage charged AFL.
- Long length of communication between different parts of the DTL RF channel. At that, separation of high-current and low-current circuit communications is often lacking.
- Separation of the grounding networks for measuring and power devices is also lacking. So large value of current in the common grounding networks might be a source of disturbances for the control and measuring equipments.
- Large values of the high voltage supply disturbances in result of BCS operation in one from the RF channels. That can be a reason of over voltages and breakdowns in the near by RF channels almost simultaneously with the first one.
- Availability of common for all RF channel systems, such as the master oscillator and pulse synchronization, by way of which a stray coupling between RF channels can appear.
- Operation of a hundred high-speed thyristors in series during discharge of the AFL can be a source of disturbances.

Accumulated long experience has allowed getting over to new series crowbar system (SCS).

3. SERIES CROWBAR SYSTEM

Conversion from the bypass to the series crowbar system wasn't spontaneous one. First of all in the framework of the BCS a possibility of the fast circuit breaker CB switching off from current transformer CT1 (see Fig.1) was considered. At that, after discharge of the AFL (in result of BCS operation), driving of the anode modulator was interrupted during a few sec. During this time, on the one hand, accelerator cavity detuning wouldn't exceed 5…10% cavity pass band and, on the other hand, a broken gap had time for recovery. In this case starting of the BCS wouldn't be accompanied by a long (a few minutes) interruption of the accelerator operation. But, as follows from Fig.2, CB switching off results in increasing of the current protection relay (CP) set point SP1 in a few times, so that the BCS operation wasn't accommodated by high voltage supply opening and long interruption of the accelerator operation. Thus, the attempt to shorten the accelerator downtown during BCS operation resulted in decreasing of the current protection sensitivity and 50% GMI-44A plate over voltage (see Fig.2).

The next step assumed the full switching off of the BCS; at occurrence of breakdown (during RF pulse) driving of the anode modulator was interrupted for a few second, beginning with the next pulse. As in previous case during this time accelerator cavity detuning would change insignificantly and ionization in broken gap would be decreased to the extent that the repeated breakdown (after recovery of the modulator driving) wouldn't appear. But the tests showed that response of the HV supply at the breakdown didn't differ from that of at the BCS thyristors starting. In both cases full discharge of the AFL took place. It means that the dependencies, presented in Fig.2, are also true in a case of breakdowns with switched off BCS. Moreover, for realization of the system it is need to decrease the sensitivity of the current protection relay CP.

It follows also to add that though limiting of the breakdown current (by the AFL impedance), the most part of the energy, accumulated in the AFL, is dissipated in the broken gap. In the INR DTL RF system value of energy, stored in the AFL, nearly twice exceeds the energy, consumed from the AFL during regular operation. So, even the single breakdown can result in a damage of the RF equipment.

The next evident step consisted in increasing of operating speed during interruption of the anode modulator driving. The case in point is interruption of modulator driving in limits of RF pulse, so that the breakdown appearance didn't result in to full discharge of the AFL. For this purpose the modulator vacuum tube, connected in series with the load – RF output power amplifier (PA) vacuum tube, can be successfully used. The point is that the output PA is the final-control of the amplitude control system, stabilizing the amplitude of RF voltage in the accelerator cavity. There are two methods of the RF power control: by means of the PA plate pulse voltage control or by means of the RF exciting control at the input of the PA. In both cases there is a necessity of the PA plate control by means of the fast-acting "hard" modulator with vacuum tube: it is obviously for the first way of power control and not entirely for the second. But if to take into account changing of PA vacuum tube current dc component at the RF exciting control (due to operation with cutoff angle) it is become evident a necessity of the PA plate supply stabilization by means of the "hard" modulator. Hence, the PA plate modulator can fulfill two functions: control or stabilization of the modulator pulse amplitude and fast protection of all networks, which are under high voltage pulse, including RF amplifier vacuum tube and anode-grid cavity, from breakdowns. Such is indeed an operation of the series crowbar system SCS. There are two main advantages of the system:

- A lack of the additional devices in the anode modulator high voltage supply.
- Starting of the SCS doesn't results in discharging of the artificial forming line AFL and long interrupting of accelerator operation.
- As the AFL doesn't discharge the AFL the SCS operation isn't a source of disturbances for other DTL RF system channels and, hence the quantity of false crowbar starting has to be decreased.

The simplified block scheme of the INR accelerator DTL RF channel with series crowbar system and amplitude feedback is presented in Fig.3. The system involves the next additional devices:

- the current transformer CT1, signal of which comes to comparator;
- two single shot multivibrators M1 and M2;
- two logic units AND and NAND.

If, in result of breakdown, the signal from the CT1 exceeds the set point value SP3, a single shot multivibrator M1 changes the state and locks the premodulator input during a few sec. Transients in premodulator and pulse transformer (see Fig.3) determine a time delay between premodulator and modulator vacuum tube locking and its value can achieve a few μs.

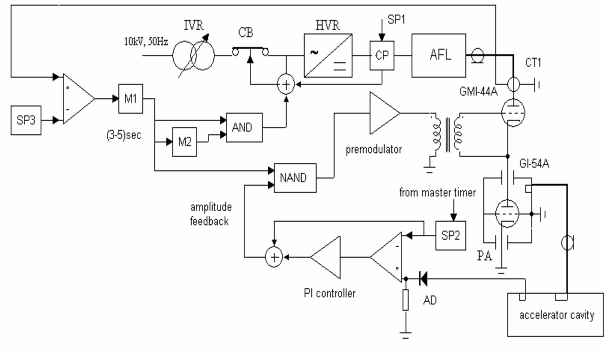

Fig.3. Block-scheme of the DTL RF channel with the series crowbar system

In turn, falling edge of multivibrator M1 pulse changes the state of multivibrator M2 with the similar pulse length. If during this time the second breakdown takes place, high voltage is entirely switched off by means of the high voltage breaker CB. SP1 and SP2 values determine the permissible high voltage rectifier HVR current and the control level of RF voltage in the accelerator cavity. All above-listed additional devices, realizing operation of the SCS, are placed at a short distance from each other, far off the high voltage equipment. That considerably decreases the level of disturbances from its own and other DTL RF channels.

4. RESULTS OF THE SERIES CROWBAR SYSTEM TEST

By now, the series crowbar system SCS, which can be also named as Interruption and Delay Crowbar System, has been in operation for 700 hours. It was installed at all five regular DTL RF channels and results of its operation exceeded all expectations. First of all, the downtime of the accelerator operation due to the DTL RF system defaults has been considerably (a few times) shortened in comparison with the previous bypass crowbar system. Then, simultaneous crowbar system starting in two and more RF channels, so frequent before, were lacking during all time of the SCS observation. Moreover, the common quantity of the crowbar starting in the RF channels was also decreased. All that confirmed the previous statement that the bypass crowbar system (BCS) was more subjected to disturbances in comparison with the series one. Efficiency of the new series crowbar system was particularly showed itself during the last two sessions of the accelerator operation. Before the first session the new vacuum tube GI-71A was installed in the output power amplifier of the RF channel # 4. Due to bad vacuum in the GI-71A, operation of the PA was accompanied by permanent inner breakdowns, common amount of which exceeded 1000. With the previous bypass crowbar system operation of the accelerator would be paralyzed.

With the series crowbar system both sessions were successfully completed.

In Fig.4 shots of PA vacuum tube GI-71A plate current (upper trace) and pulse plate voltage (lower trace) are shown. Inrush of the plate current was due to the PA vacuum tube GI-71A breakdown. As it was mentioned above, the SCS operation width depends on transients in the premodulator and pulse transformer at its output.

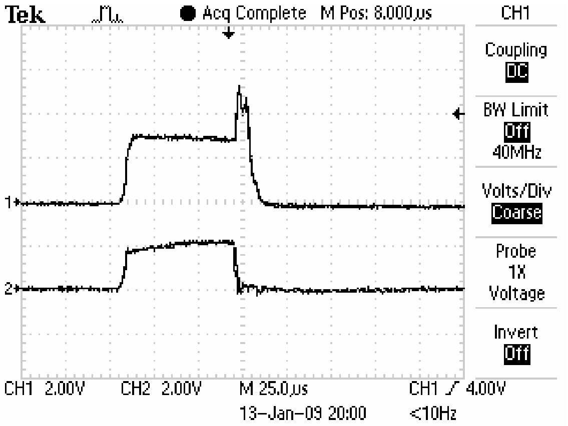

Fig.4. Processes during series crowbar operation

Just these devices determine duration of the breakdown. One can see that at once after the breakdown plate voltage pulse was shortened and duration of the breakdown didn't exceed 7…8 µs. During this time only one (the first) capacity of the AFL from 20 had time to discharge [1].

In Fig.5 the shots of processes during series crowbar operation are presented in detail – time scale was changed from 25 µs/dev (in Fig.4) to 1 µs/dev.

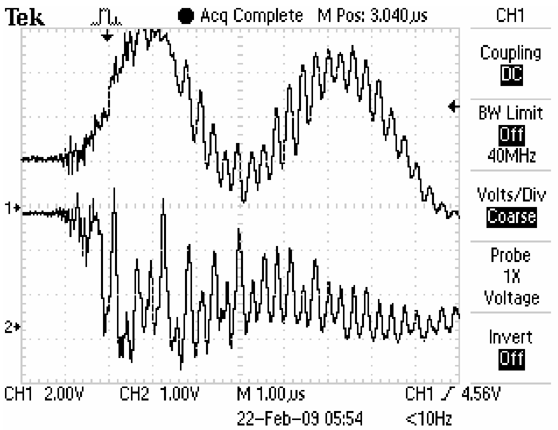

Fig.5. Processes during series crowbar system operation in detail

From the last shot pictures it follows that the process during SCS operation is accompanied by oscillations both of current and modulator pulse amplitudes. At that, the oscillations at both traces are in antiphase and the oscillation frequency value is a few times higher than modulator bandwidth. One could suppose that the breakdown current is interrupted when plate pulse voltage falls to the low value and appears again when it rises. The reasons of this phenomenon can be different ones. First of all, it follows to take into account that at all electrodes in the RF power amplifier, where breakdowns can appear, both pulse voltage and RF voltage exists. It is true for the vacuum tube and DTL PA anode-grid cavity. In the PA cavity structure (so called half-wave length coaxial cavity) is lacking isolating capacity, which bypasses RF around high voltage supply input. Hence, the inner stem of the PA cavity is both under high pulse voltage plate and RF voltage in the cavity, which amplitude can up to 10 times exceed plate supply voltage and achieves 300 kV. The breakdown appears as the result of the total action of both components. At that, due to voltage drop at the high voltage source (AFL) internal resistance, both components of the voltage fall to such extent that the breakdown can be interrupted up to that moment when plate voltage again will achieve the previous value. So, the observed oscillations frequency (see Fig.5) could be result of transients in the long coaxial cable (up to 50 m), connecting the AFL and the modulator valve GMI-44A, or in the low quality PA cavity. The issue remains open.

CONCLUSIONS

Results of new series crowbar system testing showed that the system allows successfully protecting from breakdowns the RF power amplifier vacuum tube and PA anode-grid cavity. Just here, in the main, breakdowns take place. Breakdowns in the modulator vacuum tube GMI-44A, as a rule, occur during time between RF pulses, when the plate voltage has maximum value. As between RF pulses PA vacuum tube internal resistance exceeds 1kOhm, the breakdown current value can't result in to the modulator vacuum tube damage.

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РЕЗУЛЬТАТЫ ИСПЫТАНИЙ ПОСЛЕДОВАТЕЛЬНОЙ ЗАЩИТЫ СИСТЕМЫ ВЧ-ПИТАНИЯ НАЧАЛЬНОЙ ЧАСТИ УСКОРИТЕЛЯ ИЯИ РАН

А.И. Кваша, Ю.М. Лопатников

Ранее рассмотрены особенности работы параллельной тиристорной защиты, предназначенной для защиты от пробоев мощных ламп в выходных каскадах системы ВЧ-питания начальной части ускорителя. В этой системе при возникновении пробоя через 10 мкс запускается тиристорная сборка, осуществляющая полный разряд накопителя в аноде модуляторной лампы. Предложена принципиально новая последовательная система защиты, лишённая недостатков существующей параллельной тиристорной защиты, использующая возможности модулятора с регулируемой лампой. В новой системе защиты при возникновении пробоя через 5…7 мкс происходит запирание модуляторной лампы с последующим прерыванием запуска на несколько секунд. За это время сохраняется настройка резонатора ускорителя и успевает восстановиться пробитый зазор. К настоящему времени новая система установлена на всех пяти каналах системы ВЧ-питания и успешно прошла испытания в течение ~ 700 часов непрерывной работы. В предлагаемой работе обсуждаются особенности функционирования новой системы и приводятся результаты её испытаний.

РЕЗУЛЬТАТИ ВИПРОБУВАНЬ ПОСЛІДОВНОЇ СИСТЕМИ ЗАХИСТУ ВЧ-ЖИВЛЕННЯ ПОЧАТКОВОЇ ЧАСТИНИ ПРИСКОРЮВАЧА ІЯД РАН

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Раніше розглянуто особливості роботи паралельного тиристорного захисту, призначеного для захисту від пробоїв потужних ламп у вихідних каскадах системи ВЧ-живлення початкової частини прискорювача. У цій системі при виникненні пробою через 10 мкс запускається тиристорна збірка, що здійснює повний розряд накопичувача в аноді модуляторної лампи. Запропоновано принципово нова послідовна система захисту, яка позбавлена недоліків існуючого паралельного тиристорного захисту, що використовує можливості модулятора з регульованою лампою. У новій системі захисту при виникненні пробою через 5…7 мкс відбувається замикання модуляторної лампи, з подальшим перериванням запуску на декілька секунд. За цей час зберігається настроювання резонатора прискорювача і встигає відновитися пробитий зазор. До теперішнього часу нова система встановлена на всіх п'яти каналах системи ВЧ-живлення і успішно пройшла випробування протягом ~ 700 годин безперервної роботи. У пропонованій роботі обговорюються особливості функціонування нової системи та наводяться результати її випробувань.