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Report A charge-pump 60kV modulator for the ISOLDE target extraction voltage

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Abstract

The ISOLDE facility at CERN provides radioactive ion beams to a number of experimental stations. These ions are produced by a metal target, floating at 60 kV, which is impacted by a 1.4 GeV high intensity proton beam. The ions are then accelerated by a grounded extraction electrode to 60 keV, before transport to the experimental area. During proton beam impact extremely high ionisation of the volume around the target gives rise to significant leakage current which results in loss of charge on the effective target capacitance of approximately 6 nF. If short life-time isotopes are to be studied, the 60 kV must be re-established within a maximum of 10 ms. Recharging the target capacitance to 60 kV and to the required stability of better than 10-4 precludes a direct charging system and an alternative method of re-establishing the 60 kV is used.

The present system [1], in operation since 1991, employs a resonant circuit which is triggered 35 µs prior to beam impact. This circuit transfers the charge on the effective target capacitance to a buffer capacitor and reduces the target voltage to zero; the resonance then restores the target voltage to within a few percent of its nominal value within a further 200 µs. Finally the high precision 60 kV d.c. power supply brings the target voltage back to the required ±0.6 V tolerance within a total of 6 ms.

In recent years, new types of ion sources (neutron converter targets) have been developed which present ever increasing ionisation loads with the result that it is becoming impossible to respect the maximum 10ms voltage recovery time. Future increases in beam energy to 2 GeV and higher intensity beams will further aggravate the situation.

To mitigate the problem new circuit topologies have been conceived and developed. One promising development is a "Charge pump modulator". In this circuit a 400 nF buffer capacitor and the target capacitance are charged to 60 kV by a low power, high precision d.c. power supply (HVPS). Immediately prior to beam impact the HVPS is disconnected from the target and buffer capacitors using a 90 kV rated semiconductor switch. During beam impact the target capacitance is rapidly discharged to ~54 kV after which the buffer capacitor, which is partially isolated from the beam impact ionisation by virtue of a series-connected 3.3 kΩ resistor, begins to re-establish voltage on the target. After 1ms a feedback loop controlling an auxiliary high voltage amplifier, which applies a voltage in series with the buffer capacitor, is switched in. This additional voltage brings the target voltage back to the required ± 0.6 V tolerance within 5 ms. Finally, when the target has recovered sufficient high impedance, the feedback loop is opened and the HVPS is re-connected to the target to maintain the stable 60 kV voltage.

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A charge-pump 60kV modulator for the ISOLDE target extraction voltage

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***Abstract*— The ISOLDE facility at CERN provides radioactive ion beams to a number of experimental stations. These ions are produced by a metal target, floating at 60 kV, which is impacted by a 1.4 GeV high intensity proton beam. The ions are then accelerated by a grounded extraction electrode to 60 keV, before transport to the experimental area. During proton beam impact extremely high ionisation of the volume around the target gives rise to significant leakage current which results in loss of charge on the effective target capacitance of approximately 6 nF. If short life-time isotopes are to be studied, the 60 kV must be re-established within a maximum of 10 ms. Recharging the target capacitance to 60 kV and to the required stability of better than 10^{-4} precludes a direct charging system and an alternative method of re-establishing the 60 kV is used.**

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To mitigate the problem new circuit topologies have been conceived and developed. One promising development is a ''Charge pump modulator''. In this circuit a 400 nF buffer capacitor and the target capacitance are charged to 60 kV by a low power, high precision d.c. power supply (HVPS). Immediately prior to beam impact the HVPS is disconnected from the target and buffer capacitors using a 90 kV rated semiconductor switch. During beam impact the target capacitance is rapidly discharged to ~54 kV after which the buffer capacitor, which is partially isolated from the beam impact ionisation by virtue of a series-connected 3.3 kΩ resistor, begins to re-establish voltage on the target. After 1ms a feedback loop controlling an auxiliary high voltage amplifier, which applies a voltage in series with the buffer capacitor, is switched in. This additional voltage brings the target voltage back to the required ± 0.6 V tolerance within 5 ms. Finally, when the target has recovered sufficient high impedance, the feedback loop is opened and the HVPS is re-connected to the target to maintain the stable 60 kV voltage.

I. INTRODUCTION

At ISOLDE, radioactive nuclides are produced via spallation, fission, or fragmentation reactions in a thick target, irradiated with a proton beam from the Proton Synchrotron Booster (PSB) at an energy of 1.4 GeV and an intensity up to 2 µA. The volatile nuclear reaction products are released from the high temperature target into an ion source via chemically selective processes and are extracted as a radioactive ion beam. The target and ion source are held at +60 kV ±0.6 V with respect to a grounded electrode to allow extraction at a well-defined energy before transport to the experimental area.

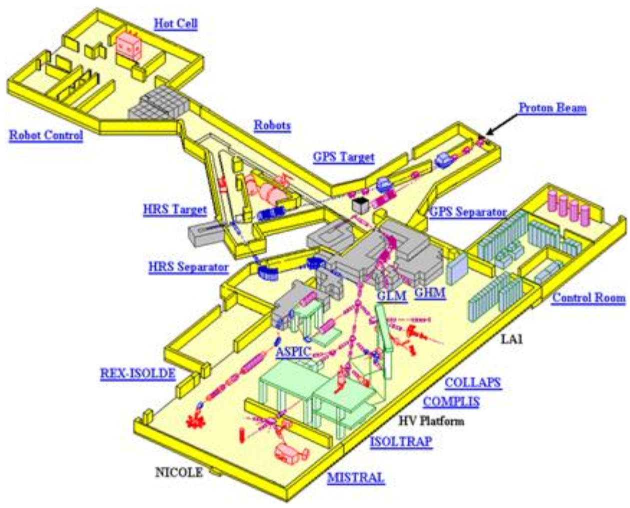

Fig. 1. Plan view of the ISOLDE facility

Ionisation around the target during and immediately after beam impact produces resistive loading on the power supply which reduces the target voltage level. To ensure extraction of short life-time isotopes this voltage is required to recover to its stable value within 10ms. A modulation system is used in which the charge on the effective target capacitance is resonantly transferred to a buffer capacitor during the heaviest ionisation period (a few tens of us after beam impact) and re-established ~200 us later on the target capacitance.

The first beams at the present ISOLDE facility were produced in 1992, since when the ion sources have continually evolved. Recent developments in neutron converter targets have resulted in increased dynamic electrical loads seen by the target voltage modulator. In addition, an upgrade program for the PSB will result in an increase in primary beam energy from 1.4 GeV to 2 GeV and an increase in beam intensity. This is expected to result in increased dynamic loading of the modulator and is the primary motivation for the development of a more 'robust' circuit topology.

II. PRESENT SYSTEM

The present modulator system [1], in operation since 1991, employs a resonant circuit which is triggered 35 µs prior to beam impact. This circuit transfers the charge on the effective target capacitance to a buffer capacitor and reduces the target voltage to zero; the resonance then restores the target voltage to within a few percent of its nominal value within a further 200 µs.

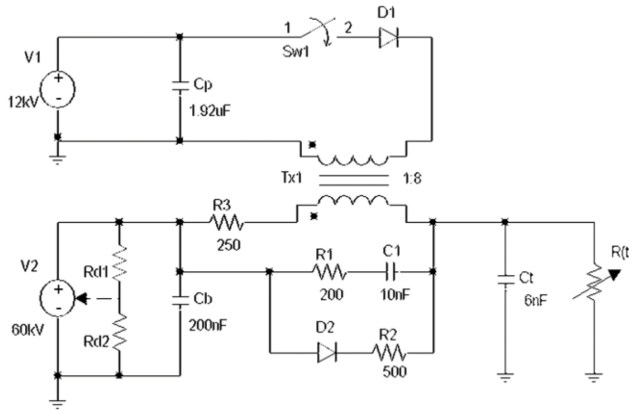

Fig. 2. Simplified circuit diagram of the resonant modulator

Finally the high precision 60 kV d.c. power supply brings the target voltage back to the required ±0.6 V tolerance within a total of 6 ms as shown in Fig. 3.

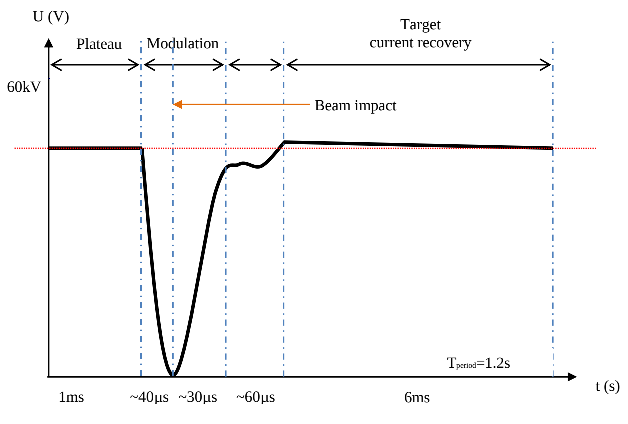

Fig. 3. Modulated target voltage

Recently it has been seen that with the use of the latest neutron converter targets that the maximum recovery time of 10ms can no longer be achieved. This is primarily due to the relatively low output power of the high precision power supply; maximum d.c. output current is 5 mA and transient output current is limited to ~50 mA for a few ms.

III. TARGET LOAD CHARACTERISATION

The performance of the modulator in terms of stability and transient recovery are to a large extent determined by the dynamic and static loads seen by the modulator. An attempt to characterize these loads was made at the inception of the initial ISOLDE project in 1991.

Further measurements had been limited due to the lack of access to the equipment during the physics runs however a further series of measurements were able to be made late in 2012. These measurements were made with a neutron converter target, which was assumed to represent the worst-case loading for the modulator, with and without proton beam impacting on the target. The results of this test showed that the loading due to the effective resistance in the first few milliseconds after beam impact was substantially greater in 2012 than in 1991.

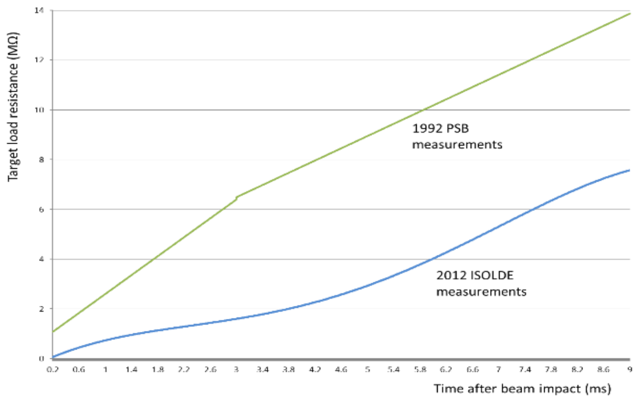

Fig. 4. Effective resistive loading from the target

The 2012 results were obtained using a dedicated measurement bench which was inserted in series between the modulator and the target. To capture the full dynamic range of the transient current two current transformers (CTs) were used, each with a different current range. Results were somewhat difficult to interpret due to ambiguous signals which appeared after desaturation of a Hall-effect CT used to measure the lower range current. An improved measurement bench has now been developed with a desaturation compensation circuit.

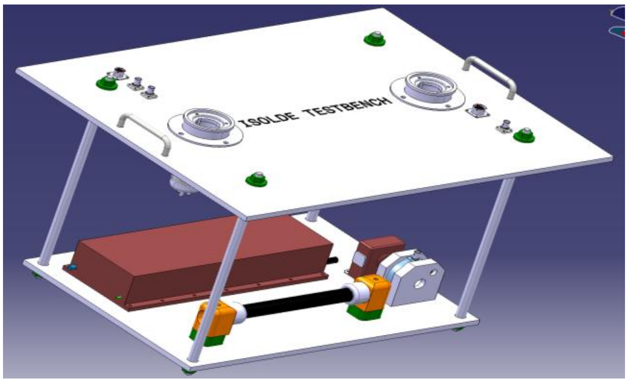

Fig. 5. Measurement test bench with the oil-immersible components mounted on the lower plate

A matched pair of Ross HV dividers was also used in addition to the measurement bench components shown in Fig. 5.

IV. HV Switch Characterisation

The opportunity was also taken at this time to test the performance of a Behlke HTS 901-10-LC2, previously selected as a possible candidate for use as a high voltage switch within a new modulator (Fig. 6). The device was integrated in the test bench as a switch connected in series between the modulator and the target.

Fig. 6. Behlke switch under test

The measurements allowed the following device characteristics to be validated:

- Variable on time up to continuous operation
- Easy control by TTL signal
- High peak current (100 A peak)
- Low Ron
- Good shot-to-shot stability of Ron
- Good long term stability of Ron.

V. Charge Pump Modulator

A new circuit topology is being studied in which a 400 nF buffer capacitor and the target capacitance are initially charged to the nominal accelerating voltage up to 60 kV by a low power, high precision d.c. power supply (HVPS). This HVPS would be a commercial power supply (e.g. Heinzinger PNChp) with a voltage residual ripple of 10^{-5} and with a maximum output current of 40 mA.

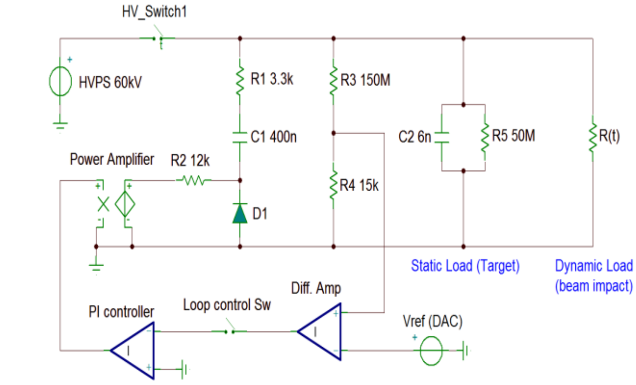

Fig. 7. Circuit used for simulation of the modulator

Initial charging delay to the maximum operating voltage of 60 kV is less than one second. Charging starts with the closing of HV_Switch1 which is triggered by a TTL-level signal. HV_Switch1 is a commercial semiconductor switch of type Behlke (Behlke HTS901-10-LC2). Immediately prior to beam impact the HVPS is disconnected from the target and buffer capacitor by opening HV_Switch1.

Measurements made with beam impacting the target pre-charged to 60 kV at Isolde has confirmed a shunt loading with leakage current of ~20 A during the beam burst of 2.5 µs duration. This indicates an average resistance to ground of the ionised air during beam impact of 3 kΩ.

Despite this large leakage no breakdown voltage occurs and the target is rapidly discharged to ~54 kV. The buffer capacitor, which is partially isolated from the beam impact ionisation by virtue of a series-connected 3.3 kΩ resistor, begins to re-establish voltage on the target. Charge flows from the buffer capacitor and the diode D1 onto the target capacitance. As a result, the target is charged to a voltage close to its initial value (Fig. 8).

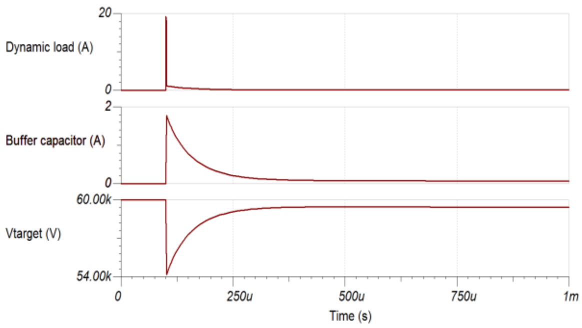

Fig. 8. Transient analyses showing the effect of the beam impact and partial voltage recovery of the target

After 1 ms a feedback loop that controls an auxiliary high voltage DC-stable power amplifier is switched on by closing the loop control analog switch. The power amplifier (model TREK PZD700A M/S) provides precise control of the output voltage with a gain of 200 V/V in the range of 0 to 1.4 kV and output current capability of 100 mA. Active output stage sink or source current. High output slew rate (100 V/us) and small signal bandwidth of greater than 100 kHz achieves an accurate output response, allowing fast analog external loop control technique with a fast a.c. response and good d.c. precision with an output noise of less than 10 mV rms. Voltage divider R3/R4 is high accuracy (0.01 %), high stability (0.005 % per year) compensated and screened with output ratios of 10000:1. It is a key element in the regulation of the power amplifier.

Accurate DAC (LT Demo circuit 1485A) with 18 bit precision allows for fine control of the voltage reference. High precision instrumentation amplifier subtracts the actual voltage measured on the target through the divider with the accurate DAC reference, and the resulting error signal is fed into a Proportional Integral (PI) analog controller (Fig. 9) which controls the voltage output of the power amplifier.

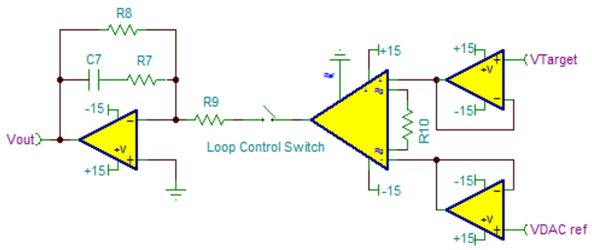

Fig. 9. Circuit used for simulation of the PI controller

The power amplifier applies a voltage in series with the buffer capacitor and brings the target voltage back to the required +/- 0.6 V tolerance in 5 ms. (Fig.10).

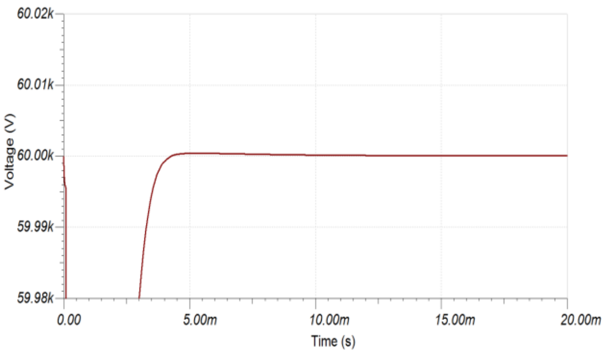

Fig. 10. Target recovery to 60kV +/- 0.6V, close loop control mode.

The regulation maintains the voltage in the tolerance band and compensates for the secondary ionisation currents that recover slowly (Fig.11), ionisation is negligible after 50 ms.

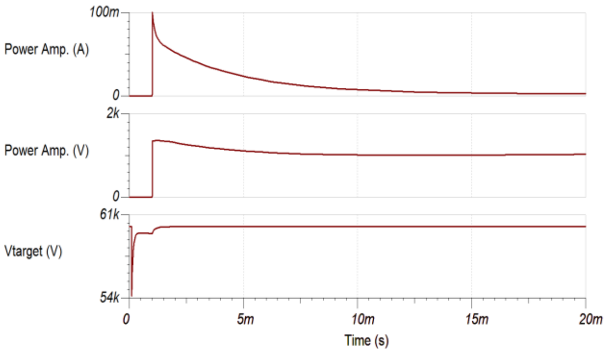

Fig. 11. Power Amplifier current and voltage outputs maintain the target at 60kV +/- 0.6V.

Finally, when the target has recovered to sufficient high impedance, the feedback loop is opened by opening the loop control switch and the HVPS is reconnected to the target at the same time by closing HV_Switch1. The opened loop makes the voltage decrease slowly with the leakage resistor R8, bringing the auxiliary voltage to ground potential over the 1.2 s of the PSB machine cycle. HVPS stabilizes the voltage of the target at 60 kV and maintains it in the tolerance band by delivering only a small current of a few mA with slow variation in regards of the HVPS control time (Fig.12).

This slow open loop control restores the buffer capacitor differential voltage to 60 kV without impacting the voltage stability and prepares for the next proton beam impact on a cycle to cycle basis.

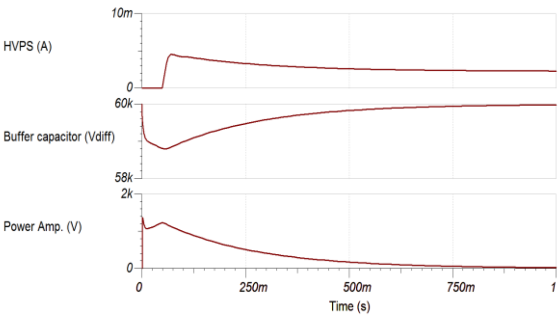

Fig. 12. Open loop control mode simulation results

A prototype of the new modulator is under development with a dynamic test load to simulate the beam impact load effect (Fig. 13). First testing is expected to commence in 2015.

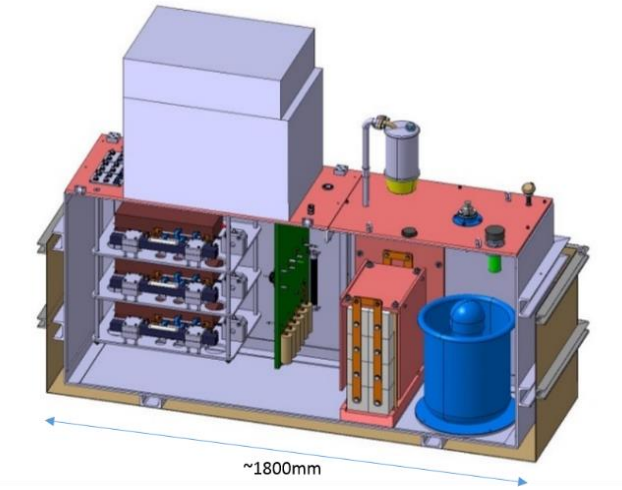

Fig. 13. 3D model of the modulator prototype

VI. CONCLUSIONS

Increasing ionisation due to new target materials and neutron converters has stretched the limits on the voltage recovery time to greater than 10 ms. Future upgrades in beam energy and beam intensity will further exacerbate this trend and a new modulator development will be required. The charge pump modulator topology appears to be a good candidate and will provide a robust and accurate charging device capable of re-establishing the 60 kV with improved recovery time and with relatively low power components. In addition BEHLKE high voltage MOSFET switch modules appear to provide the required functionality for the 60 kV switch foreseen in the charge pump modulator.

References:

[1] D. Fiander, A. Fowler, "A 60 kV modulator for the target voltage of an online isotope separator", Proceedings of the 20th IEEE Power Modulator Symposium; Myrtle Beach South Carolina, USA, June 1992.