EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN/PS 92-38 (RF)

A 60 KV MODULATOR FOR THE TARGET VOLTAGE OF AN ON-LINE ISOTOPE SEPARATOR

D.C. Fiander
A. Fowler

Paper to be presented at the 1992 20th Power Modulator Symposium,
Myrtle Beach, South Carolina, U.S.A.
23 - 25th June, 1992

A 60 KV MODULATOR FOR THE TARGET VOLTAGE OF AN ON-LINE ISOTOPE SEPARATOR

D.C. Fiander, A. Fowler
CERN-PS
CH -1211 Geneva 23

Abstract

The on-line isotope separator facility ISOLDE has recently been transferred from the CERN 600 MeV Synchro-Cyclotron (SC) to the 1 GeV Proton Synchrotron Booster (PSB). This has required the design of new high voltage equipment to supply the target potential for ion acceleration, the stability of which is critical for the mass resolution of the downstream separator.

This paper describes a modulator which furnishes the 60 kV target voltage for PSB operation. Prior to beam impact the target is fully discharged in 33 µs by a resonant circuit which then restores the voltage close to its nominal value. A fast acting hard tube power supply regulates the target voltage back to the specified ±1 V within 6 ms. The supply is connected to the resonant circuit such that for a 60 kV swing of the target the change at the supply is limited to 700 V. The advantages of this modulation are that less energy is lost due to beam induced ionisation and the risk of flashover at beam impact in the air surrounding the target vacuum tank is minimised. Secondary ion beams have to be blanked off for only 6 ms in the cycle time of 1.2 s between impacts, still allowing the separator to detect short-lived nuclei.

The results of laboratory testing, including electrical simulation of beam ionisation effects, are reported, as are initial beam tests with the separator. The facility is expected to be fully operational for physics experiments later this year.

Introduction

ISOLDE, the isotope separator on-line facility, furnishes 60 keV radioactiveion beams derived from more than 60 elements. It is the world's largest such isotope separator and was installed on the CERN SC in 1967. After 24 years of service, ISOLDE operation was interrupted at the end of 1990 when the ageing SC was shut down. Wide interest in the ISOLDE ion physics programme has resulted in its recent transfer to an external beam line of the 1 GeV PSB (1). It is now in the process of being recommissioned[2)].

The ion source of ISOLDE is connected to a thick target which is periodically bombarded by a proton beam. The target is heated and the ions are released into the ion source at thermal velocities. The target and ion source must be held at a precise voltage with respect to a grounded extraction electrode to provide the requisite acceleration. If there is to be high mass resolution in the downstream separator it is extremely important that there be exceptional stability of this accelerating voltage. The target, ion source and extraction electrode are in vacuum and the vacuum tank of the target is raised to full accelerating potential. The impacting proton beam travels about 1 metre through air both upstream and downstream of the target vacuum tank and in so doing ionises the air. This ionisation can perturb the accelerating voltage because it represents a significant additional load on the power supply

This problem of stability was very satisfactorily addressed in SC operation by using a hard tube series regulated power supply with adequate range and response to deal with the effects of 600 MeV proton bursts of 20 µs duration arriving at regular 5 ms intervals. However, the 2.5 µs burst of the PSB beam (2E13 protons) has an instantaneous intensity some 4 orders of magnitude higher. The resulting ionisation is correspondingly greater, leading to severe shunt loading of the power supply and even to the risk of flashover between target vacuum tank and ground.

Concern over this risk and the major problem of voltage stabilisation prompted the proposal that the accelerating voltage should be modulated to zero for the critical period when protons would be striking the target. Agreement was reached with the physics community that this would be acceptable provided that the stable accelerating voltage of 60 kV ± 1 V would be interrupted for less than 10 ms, so still allowing the detection of very short life-time radio isotopes. Beam gating would be required to prevent ion beams entering the separator for the entire period that the accelerating voltage was modulated from its stable value.

Preliminary Tests

Accelerating voltage is not only applied to the target and its vacuum enclosure but also to other associated electrical and control equipment. This includes a 50 kVA, 3 phase, 380 volt isolation transformer, a 5 m coaxial line passing through concrete shielding and numerous 19" racks for step-down transformers, interlocks and CAMAC controls. From the outset this equipment had been conceived for operation only at stable d.c. potential.

The first preliminary test, performed at the SC, was to verify that this ensemble could be fast pulse charged to +60 kV without breakdown to ground or between elements and without disturbance to the controls. The test showed that charging to +60 kV in 900 µs did not incite breakdown nor did it interfere with the normal control functions. Analysis of the results indicated the total load to be 2.4 nF, shunted by 50 MΩ, the latter attributable to the demineralised water cooling circuits of the target and ion source.

The second preliminary test explored the risks of flashover of an air mounted target when struck by beam having the PSB time structure and quantified the leakage resistance in the post-impact period. This test was made with beams up to 1.8 E13 protons per pulse. No definitive target system was available so a simulation device, consisting of an isolated copper target block (ø150 x 200 mm) mounted in a ø650 mm coaxial earthed metal shroud, was used (Fig. 1). Two vacuum gaps, insulated for 60 kV, were axially aligned with the target block, permitting the proton beam to reach and leave the target without ionising air under high electrical stress. The simulation target capacitance (60 pF) was supplemented by adding a 2.7 nF capacitor via 20 m of cable for radiation reasons. Fast current transformers monitored both leakage and capacitor currents and a precision voltage divider the target voltage (Fig. 2).

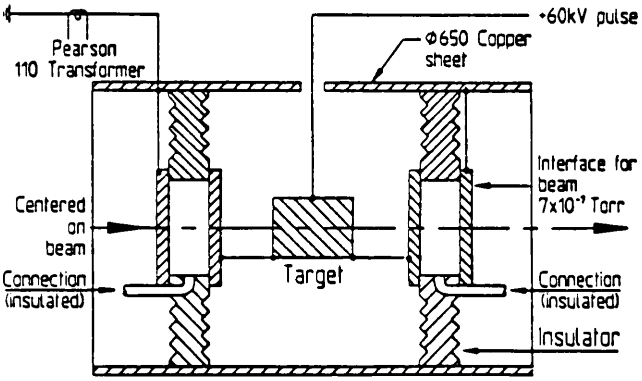


Fig. 1. Mechanical configuration, simulation target test

Measurements made with beam impacting the simulatio target, precharged to +60 kV, showed a voltage loss of 17 kV coincident with the impact period. Raising to atmospheric pressur the two axially aligned vacuum gaps doubled this loss (Fig. 3) Target leakage current measurements of 20 - 50 A confirmed a average resistance to ground of only 1 or 2 kΩ during impact whic these voltage loss figures suggested. Despite this enormous leakage voltage breakdown did not occur.

Further measurements were performed, allowing the beam to impact a discharged target and then recharging it to 60 kV a different moments in the post-impact period. From these could be deduced the evolution of the insulation resistance with time. The post-impact leakage seemed little influenced by the time structure of the incident beam. To a first approximation its amplitude was proportional to $\sqrt{N}$, N being the burst intensity. Unlike the case of leakage during impact, it was not influenced by pressure in the two axially mounted gaps, suggesting the leakage path was principally radial between copper block and surrounding shield. For an incident intensity of 1.8E13 the leakage resistance 100 µs after impact was as low as 700 kΩ, rising more or less linearly to 35 MΩ at 25 ms. This suggests a considerable current drain to ground which must be furnished by the power supply, extending beyond the time admitted for stabilisation of the voltage after modulation.

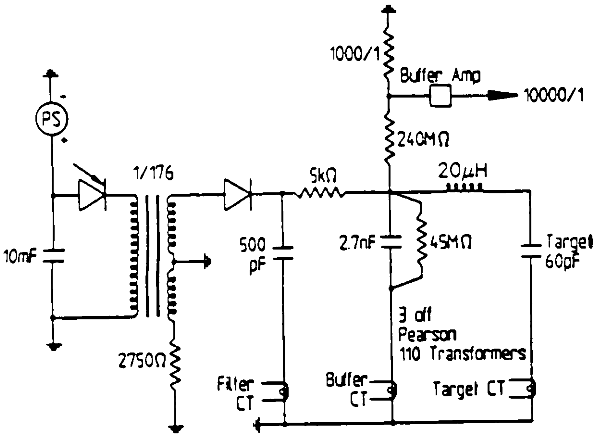


Fig. 2. Electrical circuit, simulation target test.

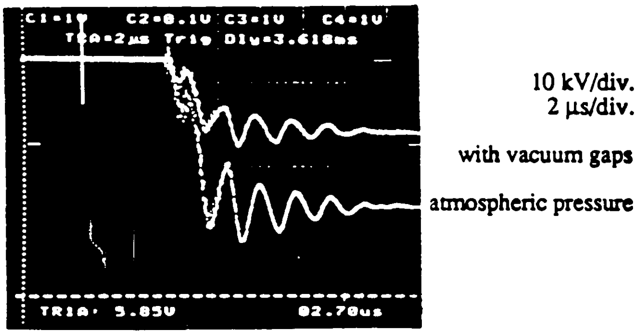


Fig. 3. Effect of 1.7E13 protons on precharged target.

Modulator Details

General Considerations

The modulator must reduce the stabilised target voltage to zero, hold it there during the 2.5 µs beam impact and then raise it close to its initial value, finally allowing the regulated high voltage supply to bring it back to ± 1 V within the specified 10 ms. This regulation must be made in the face of significant time varying leakage, the magnitude of which will also depend on beam intensity. Because intermittent sparking can occur at the extraction electrode the modulator must be designed not to significantly increase the energy lost in such sparks. Finally the modulator must in no way diminish the precision and long term stability of target voltage, essential for high resolution of the downstream separator.

Circuit Design

Modulating the target voltage to zero and then raising it back to near its original value requires that a current of appropriate phase and frequency be supplied to the target The frequency must be low enough to ensure a reasonable flat-bottom for beam impact. The modulator circuit which allows this is shown in Fig. 4 and its equivalent circuit, referred to the 60 kV level, in Fig. 5.

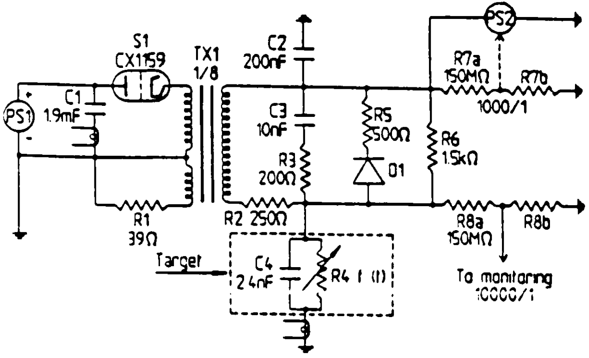


Fig. 4. Modulator circuit.

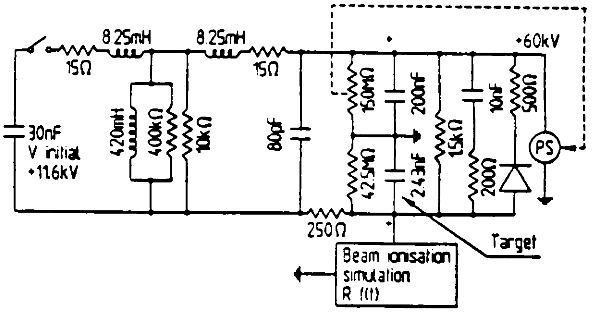


Fig. 5. Equivalent circuit referred to 60 kV level.

The target C4 is connected via R2, a resistor which helps reduce re-stabilisation time, to one secondary pole of pulse transformer TX1. Capacitor C2, almost two orders of magnitude larger than C4, is connected to the other secondary pole. Target modulation is initiated by triggering S1, a CX1159 thyratron. Primary capacitor C1, precharged from power supply PS1, then discharges into TX1, S1 remaining in conduction until its current tries to invert. Current flowing in the TX1 secondary discharges C4, the time of discharge determined mainly by the capacitance of the target and the leakage inductance of the transformer. The presence of C3, a capacitor directly across the secondary of TX1, ensures that S1 does not extinguish prematurely and allows C4 to partially recharge. Because C2 is much larger than C4, the full discharge of C4 causes a very much smaller increase of voltage on C2. Advantage is taken of this to connect the high precision, high stability power supply PS2, which is the 60 kV source, not to C4 but to C2, thus minimising the voltage excursion which this delicate equipment has to support at each modulation. PS2 output is regulated by the high prec[illegible]n voltage divider R7, also connected to C2. Two paths couple[illegible]e target to PS2, a fast path via R6 ($\tau < 4$ µs) and a slower path via TX1 and R2 ($\tau \sim 1.7$ ms). They are of sufficiently low impedance that the target voltage remains in specification for up to 4 mA change of target leakage.

Construction and Components

The circuit elements of Fig. 4, with the exception of the primary power supply PS1, are housed in a 1.7 x 1.0 x 0.8 m transformer oil filled tank. The oil is circulated and cooled to 20 ± 0.1 C. It is injected near supply PS2 and the two precision screened voltage dividers R7 and R8 to eliminate any variation of output voltage due to their temperature coefficients. Most control and voltage measuring equipment is installed in a distant, temperature controlled 19" rack. The output connection from the modulator is an open bushing on the tank cover.

The two components of main interest are the pulse transformer TX1 and the stabilised 60 kV power supply PS2. The transformer is a steel cored device with 8:1 step-up ratio. A tertiary winding is fitted, permitting diagnosis of the core state. The core has a 6 mm gap to reduce the magnetising inductance below 0.5 H, essential if stabilisation of target voltage is to occur within the allotted time. The leakage inductance of 16.5 mH determines, for a given target capacitance, the time to reduce target voltage to zero. The transformer has to withstand continuously 60 kV between secondary and primary. Oil and solid insulation barriers provide the dielectric. Power supply PS2 is a hybrid solid state, hard tube regulated device. Raw high voltage is produced by a 16-stage Cockroft Walton multiplier driven by a pulse width modulated 30 kHz oscillator. A beam power tetrode (C1583A) of 30 kV rated anode voltage regulates the output voltage to the reference value ± 1 V. The tetrode acts as a linear series regulator, operating with floating cathode. Tube auxiliaries are supplied via a ferrite cored isolation transformer driven at 10 kHz. An optical fibre link is used for grid control. A 12 bit DAC provides course voltage setting up to 65 kV with 20 V resolution. A second 12 bit DAC allows fine voltage setting, with 0.5 V resolution. For any given demand voltage the multiplier output has a fixed offset of + 15 kV, which is then dropped across the C1583A. The nominal maximum output current is 40 mA with rise time under 2 ms.

Voltage dividers R7/R8 are high accuracy (0.01%), high stability (0.005% per year) compensated and screened units with dual output ratios of 10000:1 and 1000:1. They are key elements in both the regulation of PS2 (R7) and the measurement of voltage (R8). An HP 3458A multimeter, capable of up to 5000 measurements per second at $6^1/2$ digit resolution is connected to R8, allowing computer acquisition of target voltage during and after stabilisation.

The remaining components follow conventional high power pulse engineering practice. PS1 is a commercially available 0-15 kV, 400 J/s capacitor recharging power supply which operates at 11.6 kV to resonate the target voltage through 60 kV.

Modulator Performance

Circuit Analysis

Transient analysis of the equivalent circuit (Fig. 5) was made with Microcap III. Pulse transformer TX1 was represented by its equivalent circuit and power supply PS2 as a device limited to a peak output of 40 mA and rise time of 1 ms, irrespective of signal error in the feedback loop. Ionisation loss was simulated by a time dependent resistor, satisfying the previously obtained experimental curve. Fig. 6 shows the predicted modulation of the target voltage and the corresponding voltage excursion of C2. Fig. 7 gives PS2 and target leakage currents for such modulation. Calculations for 60 kV target modulation in the absence of ionisation (Fig. 8) show how significantly reduced is the PS2 current, underlining the importance of including simulated ionisation for laboratory testing of the modulator. The essential predictions were that the target voltage reaches zero in 33 µs, remains close enough to zero during beam impact, does not overswing by more than 2.5 kV during recovery and finally, and of greatest importance, returns to its nominal value ± 1 V within 5 to 6 ms.

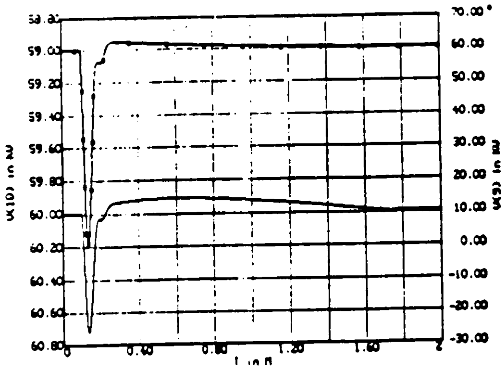


Fig. 6. Target (V9) and C2 (V10) modulation (ionisation effects included).

Laboratory Tests

The completed modulator was tested with the target replaced by a 2.4 nF capacitor shunted by 50 MΩ. The circuit of Fig. 9 was built to simulate the time varying shunt loading of the target during recovery. The summed charging current of capacitors C_A and C_B via their respective series resistors R_A and R_B is closely equivalent to the beam induced target leakage of Fig. 7. Simulation of this leakage is possible if C_A and C_B can be discharged in the early stage of the modulation. This discharge is brought about by triggering thyratron TH1 (CX1171) 10 µs into the modulation. C_A and C_B then lose their charge through R_C and R_D and are fully discharged before the target voltage starts to rebuild. Thyratron TH1 has sufficient time to de-ionise and withholds the full voltage which rises in the following 70 µs. The measured modulation in the presence of simulated ionisation is shown in Fig. 10. Acceptable agreement between the measured performance and the computer predictions was obtained (Table 1). Recovery time to the specified ± 1 V after modulation was not influenced by the presence or absence of the leakage simulation circuit, suggesting consistent modulator performance over a wide range of proton beam intensities.

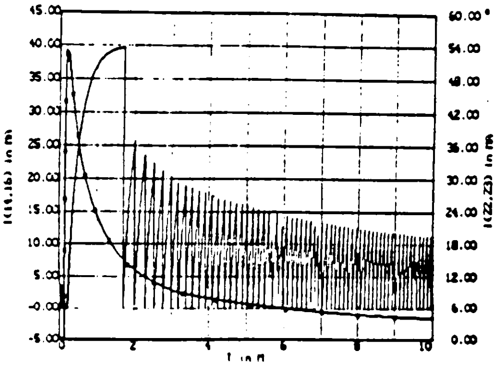


Fig. 7. 60 kV power supply (I14-16) and leakage simulation (I22-23) currents.

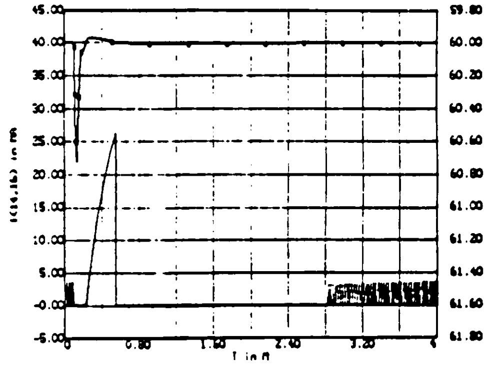


Fig. 8. Power supply current and C2 modulation (no ionisation).

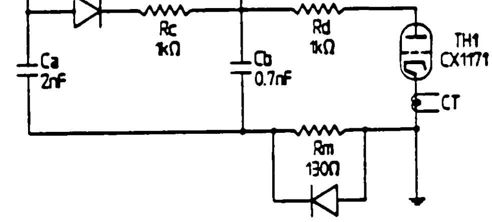
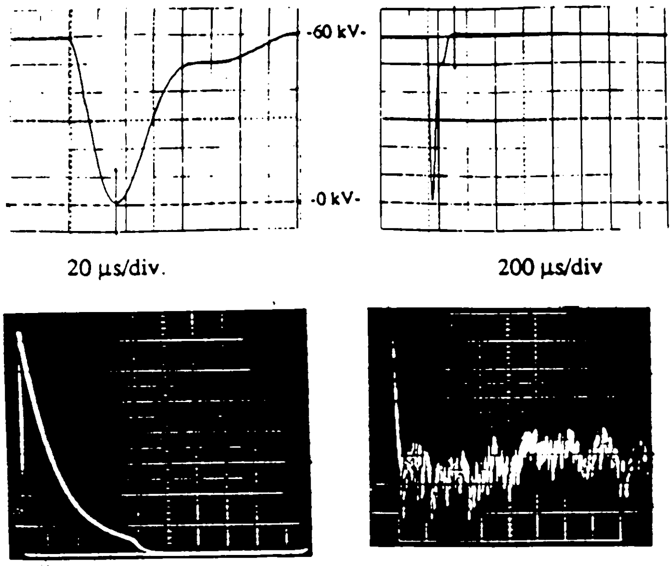


Fig. 9. Ionisation simulation circuit



20 µs/div. 200 µs/div

200 V/div, 1 ms/div. 1 V/div, 5 ms/div

Fig. 10. Target voltage during and after modulation.

Table 1

Performance Comparison (60 kV)

		Microcap III	Laboratory Test
Time to zero voltage	µs	33	32
Time to stabilise to ±1 V	ms	5.7	< 6
Primary voltage	kV	12.0	11.6
Peak primary current	A	560	500
Primary switch on-time	µs	162	199
Peak target overvoltage	kV	2.5	1.6
Beam induced leakage current.			
(peak)	mA	53	56
(at 2 ms)	mA	13	15

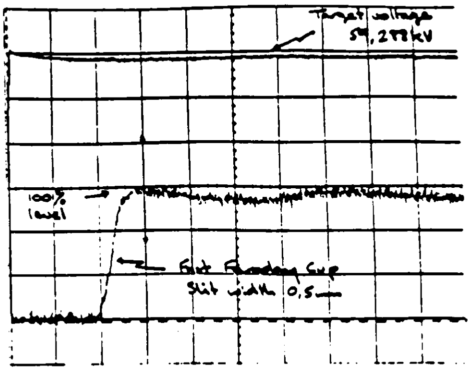
Tests with ISOLDE

Prior to its displacement to the PSB, the modulator was coupled to ISOLDE at the SC, but in the absence of primary beam. An irradiated target was installed and the separator set up with 0.5 mm slit and fast Faraday cup for ion beam monitoring. The target voltage was modulated with the same performance as reported for the laboratory tests. There was no electrical breadown. Recovery within 6 ms was confirmed by the fast Faraday cup signal (Fig. 11). The resolution of the separator was such that all signal from the Faraday cup was lost for a voltage error of ± 10 V.

The first tests with incident PSB beam were made on a 170g/cm^2 lead target to produce a high level of absorption and consequently heavy ionisation in the air surrounding the target. The target was not heated and there was therefore no secondary ion beam. The modulation remained as previously reported, there were no electrical breakdowns and target recovery was under 6 ms (Fig. 12). These encouraging results suggest that high quality secondary ion beams will soon be available from ISOLDE at the PSB.

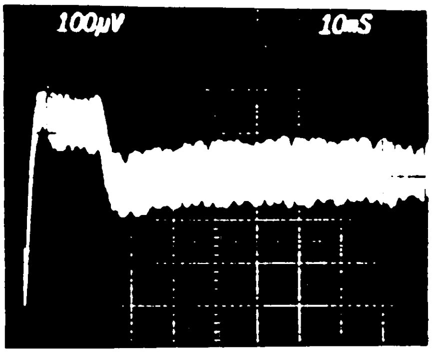
Conclusion

Despite initial foreboding, the development and testing of this equipment has shown that it is possible to modulate, in a controlled manner, a highly stabilised 60 kV voltage applied to a target and to bring it back to its original value in well under 10 ms. Further, this can be achieved in the face of time varying leakage initially greater than the rated power supply current.



2 ms/div

Fig. 11. Fast Faraday cup signal.



1 V/d

1.7E13 proto

Fig. 12. Target voltage recovery in presence of PSB beam.

Whilst such a modulator does not have universal application, it seems particularly suited to the task of furnishing accelerating voltage for ion beams of isotope separators where the target assemblies are subjected to intense ionisation provoked by the primary beam. The modulator has been extensively proven in the laboratory and is beginning to demonstrate itself on the reinstalled ISOLDE, operating with high intensity short burst proton beams of the PSB.

Acknowledgements

The authors would like to thank Richard Aston, previously of Astec Europe and now of General High Voltage Industries, Stourbridge, UK for his important contribution in designing the stabilised 60 kV power supply and later commissioning it on the modulator circuit.

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