Interconnected High-Voltage Pulsed-Power Converters System Design for H^- Ion Sources

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Abstract—This paper presents the design and experimental validations of a system of three new high-voltage (HV) pulsed-power converters for the H^- sources. The system requires three pulsed voltages (50, 40, and 25 kV to ground) at 2-Hz repetition rate, for 700 μ s of usable flat-top. The solution presents ripple-free output voltages and minimal stored energy to protect the ion source from the consequences of arc events. Experimental results on the final full-scale prototype are presented. In case of short-circuit events, the maximal energy delivered to the source is in the Joule range. HV flat-top stability of 1% is experimentally achieved with a simple Proportional-Integral-Derivative regulation and preliminary tuned H^- source (e.g., radio frequency control, gas injection, and so forth). The system is running since more than a year with no power converter failures and damage to the source.

Index Terms—Control nonlinearities, high-voltage (HV) techniques, ion sources, pulse transformers, pulsed-power supplies.

NOMENCLATURE

$IGBT_{lin}$	Voltage regulating linear IGBT.
$IGBT_{sw}$	Main IGBT switch.
C_1	Pulse transformer (PT) primary capacitance.
C_2'	PT secondary capacitance (referred to primary).
C_{12}'	PT primary to secondary cap. (referred to primary).
C_{main}	Converter main capacitor bank.
C_{USN}	Undershoot network capacitor.
L_m	PT magnetizing induct.
L_t	PT leakage induct.
R_{dis}	Discharging output resistor.
R_{preld}	Preloading resistor.
R_s	Series, arc-protection, resistor.
R_t	PT windings resistance.
R_{USN}	Undershoot network resistor.

I. INTRODUCTION

THE new linear accelerator (Linac4) under construction at CERN [1] is designed to provide a 160-MeV negative hydrogen ions (H^-) beam to the proton synchrotron booster. Linac4 is intended to replace the aging 50-MeV Linac2 and

Fig. 1. H^- source simplified cross-sectional view.

aims to increase the Large Hadron Collider beam luminosity. Several H^- sources are under development [2] in view of gradually increasing the H^- beam intensity to 80 mA with a limited coextracted electron beam of 1–1.5 A. Previous attempts to reach this intensity showed the necessity of replacing the source's high-voltage (HV) dc power supplies with HV pulsed-power converters. Originally, the system was composed of commercial HV power supplies feeding the source through capacitor banks, with the objective of stabilizing the voltage during the perturbing extracted beam's image current. However, such stored energy was damaging the source electrodes during internal arc events. Two main issues of supplying the H^- source with dc voltages can be identified:

- 1) high probability of arc events due to dc electric fields;
- 2) electrode damage caused by energetic arc events due to high energy stored into the capacitor banks.

The solution consists in developing dedicated pulsed-power converters, which decrease the arc event probability, by supplying the HV only when needed and presenting very low-energy storage. This paper presents all the design and experimental validation of such a system, which includes three synchronized pulsed voltages of 50, 25, and 40 kV to ground.

II. H^- SOURCE DESCRIPTION AND VOLTAGES SPECIFICATIONS

An introduction and a review on H^- sources for particles accelerators can be found in [3]. Fig. 1 presents a simplified cross-sectional view of the H^- source under consideration.

Molecular hydrogen (H_2) is injected into a ceramic chamber (plasma chamber), where it is heated up by a radio frequency

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TABLE I
H⁻ SOURCE PULSED-POWER CONVERTERS SPECIFICATIONS

Common specifications			
Flat-top length	t_{flat}	700	μs
Pulse rise/fall times	t_{rf}	<300	μs
Flat-top stability	S_{ft}	<1	%
Pulse repetition rate	Rep_r	2	Hz
Under-shoot voltage	V_{US}	0	V
Energy/Plasma chamber			
Nominal voltage (to ground)	V_{eg}	± 50	kV
Nominal pulse current	I_e	0.2	A
Puller/extraction electrode			
Nominal voltage (to ground)	V_{pg}	± 25	kV
Nominal voltage (to Energy)	V_{pe}	± 25	kV
Nominal pulse current	I_p	0.2	A
Electron dump electrode			
Nominal voltage (to ground)	V_{dg}	± 40	kV
Nominal voltage (to Energy)	V_{de}	± 10	kV
Nominal pulse current	I_d	1.7	A

power, because of a 2-MHz fed coil. H⁻ ions are then extracted from the plasma chamber because of intense electric fields produced by voltage potentials applied to the Puller electrode.

The objective of the source is to extract a 45-keV H⁻ beam. The Energy power converter (Fig. 1) is designed to deliver 50 kV. The energy of the beam is imposed by the potential difference between the plasma chamber and grounded electrodes in Fig. 1. A Puller electrode with a potential of -25 kV is used to extract the H⁻ ions from the plasma chamber. The generated plasma consists of protons, electrons, H⁻, H₂⁺, and H₃⁺. The issue with a negative-ion source lies in the coextraction of electrons (same polarity as H⁻). The coextracted electrons are dumped in a dedicated electrode, called *e*-dump (Fig. 1). Due to their lower mass compared with H⁻ ions, the electrons are deflected toward this electrode (*e*-dump) because of a weak magnetic field produced by a dipole magnet, whereas the ions continues toward the exit of the source. Furthermore, a so-called Einzel lens electrode, supplied in dc, is used to focus the beam before exiting the source.

For Linac4, the nominal H⁻ beam intensity is 80 mA and the extraction period is 700 μs with a repetition rate of 2 Hz. The flat-top stability specification has been set to 1% and voltage rise and fall times should be minimized to reduce are event probabilities.

As in capacitive pick-ups, in each electrode, a beam image current is induced when a H⁻ bunch is extracted. The analytic evaluation of the precise image current value in each electrode can be tedious and depends on many variables [4] (such as electrode shape and dimension, longitudinal bunch distribution, bunch velocity, and so forth).

A first estimation of image currents led to a maximal peak value of 200 mA. The *e*-dump electrode catches real coextracted electrons (estimated at 1.5 A). The maximal peak current flowing in the *e*-dump electrode is then 1.7 A (real caught electrons plus H⁻ beam image current). Table I summarizes the specifications. Notice that voltages are bipolar since the source shall be able to produce H⁻ as well as proton beams.

Fig. 2. Pulsed voltages (to ground) versus time definition.

Fig. 3. Energetic issues versus connection of HV one-quadrant power converters. (a) *e*-dump electrode supplied by a -40 kV power converter referred to ground. (b) *e*-dump electrode supplied by a +10 kV power converter referred to the Energy electrode.

Fig. 2 presents the pulsed voltages specifications in the two operating modes.

III. POWER CONVERTERS DESIGN

A. Energetic Problematic and Special HV Connection

There are several power converter topological solutions; however, at these voltage levels, four-quadrant converters become a technically challenging choice. One-quadrant converters topologies (unipolar output voltage and current) are the most used in these applications. Let us consider the power converter connected between ground and *e*-dump electrode as depicted in Fig. 3(a). With this connection, the power converter shall produce a negative voltage with respect to ground, and the electrons caught from the beam are flowing toward the power converter negative potential. The electric current is positively defined in opposite direction of the electrons flow. Therefore, in configuration of Fig. 3(a),

Fig. 4. Simplified cross-sectional view of the Linac4 building and power converters integration.

the energy is oriented toward the power converter. This is an issue since a one-quadrant converter cannot manage to regulate the output voltage when absorbing energy from the load. Suppose that the electron dump power converter is operating at its nominal voltage value of -40 kV to ground. Then, electrons are caught from the e -dump electrode and they tend to negatively increase the voltage below -40 kV. The one-quadrant converter cannot decrease the voltage to reach the nominal value of -40 kV, since its output current cannot be reversed.

The only solution using a one-quadrant converter consists in referring the e -dump power converter to the Energy one (-50 kV) as illustrated in Fig. 3(b). In this case, when electrons are caught from the e -dump electrode, the power converter voltage tends to decrease, making the voltage correction possible. Notice that in this configuration, the e -dump power converter must deliver -10 kV only, compared with the -40 kV of the solution of Fig. 3(a). This voltage decrease divides the nominal power by a factor four. Ideally, the Puller (-25 kV) power converter could be referenced to ground, since in principle no electrons are caught from the corresponding electrode. In practice, some electrons are caught by the Puller electrode as well, leading to the same issue as for the e -dump power converter. It is therefore necessary to refer the Puller power converter to the Energy (-50 kV) one.

B. Mechanical Integration and General Converters Topology

Mechanical integration limitations greatly affect the general power converter system topology. Because of cable stray capacitance, HV pulsed-power systems usually need the load to be physically close to the power converter (voltage rise and fall time minimization). As shown in Fig. 4, the H^- source is placed inside a Faraday cage in a beamline tunnel. A solution may consist in placing the whole power converter system inside the Faraday cage; however, due to long access times in case of failure, this configuration is not suitable. Notice that Linac4 will produce the beam for the entire accelerators complex at CERN, and a very high beam availability is required. The cables distance between the dedicated power converters rack and the Faraday cage is 50 m.

Fig. 5. General HV converters system configuration.

The solution naturally converges toward a topology where the converter power electronics systems are placed on the first floor, and a step-up pulse transformer system is integrated inside the Faraday cage, as presented in Fig. 4. This configuration presents the advantage of having long cables on the low-voltage side, which do not catastrophically affect the system dynamics, and only reliable passive components in the tunnel.

C. Power Converter Topology Selection

Fully solid-state converters topologies, such as Marx-type bipolar generators [5], resonant step-up converters, or other hybrid/alternative solutions [6]–[10], could have an interest for this application. However, due to the above-mentioned global integration requirement, a low-voltage section for the medium-distance power transmission and final voltage step-up stage are required. The general configuration of the system is presented in Fig. 5. The solution includes three identical, low voltage, power converters, connected to three different HV pulse transformers. The three power converters are strongly coupled via the secondary pulse transformer special connection. Indeed, the Puller and e -dump pulse transformers (TR2 and TR3) are referenced to the Energy one (TR1). The primary winding of each transformer is referred to ground and rated at 700 V, simplifying the design of the three power converters. Due to restricted space inside the Faraday cage, all three transformers must fit in one standard $19''$ rack.

Fig. 7 shows two typical converter basic topologies, which can be employed. In Fig. 7(a), a typical switch-mode buck topology is shown, whereas Fig. 7(b) presents a classical power modulator, often used for feeding a klystron. In this application, the issue is the unknown behavior of the ions source with respect to switching harmonics. The initial specification of 0.1% of maximal voltage ripple during the voltage flat-top is very challenging if the necessary voltage bandwidth (voltage rise time) is considered.

Fig. 6. Final topology of one-pulsed HV system for the H^- ions source.

Fig. 7. Possible power electronics topologies. (a) Switch-mode buck topology. (b) Classical bouncer-based klystron modulator topology.

Solutions, such as multiphase interleaved topologies [11] or special active filtering methods [12], could be used to extend the bandwidth and keep low-voltage ripples. However, due to the need for high reliability, the choice consisted in selecting a topology based on the one of Fig. 7(b), combined with a linear-driven insulated-gate bipolar transistor (IGBT)-based bouncer circuit to avoid switching harmonics while retaining a good-voltage bandwidth performance.

The final retained topology is presented in Fig. 6. It consists of a main switch S_w , permanently closed during the pulse, a step-up pulse transformer, and an IGBT ($IGBT_{Lin}$) working as controllable resistor to regulate the output pulsed voltage. The utilization of IGBTs in their active region is a proven technique employed in high-performances pulsed current converters [13]. At the end of a pulse, S_w is opened and diode D_{HV} opens in order to force the demagnetizing current of the transformer to flow through D_{USN} , R_{USN} , and C_{USN} network and to preserve the H^- source from negative voltages. A discharging resistor R_{dis} is placed at the output of the circuit in order to discharge the capacitive load (the source and HV cables) between two pulses. A series resistor R_s is also placed in the oil tank to protect the power converter and

load from high currents due to arc events inside the source. At the beginning of the voltage pulses, no beam is delivered by the source, meaning that the pulse transformer is not loaded. To help in damping, the pulse transformer voltage response during this phase, an RC network is placed at its output. During the same phase, the load current is very low and thus the regulating IGBT ($IGBT_{Lin}$) cannot be properly operated in its active region, hence the reason of a preloading resistor R_{preld} (with a series diode D_{preld}). To reverse the voltage operation, the system requires the reversal of the transformer primary winding connection as well as the diode D_{HV} .

D. Design Considerations for Arc Protection

One of the main purposes of the proposed system is to mitigate arc events as well as their damaging effects inside the ions source. The calculation of the series resistance value R_s derives from a tradeoff between the minimization of the maximal arc energy inside the source and power converter voltage regulation capabilities to correct the output when the beam image current flows into it. When an arc is detected, the system reacts by turning off S_w in roughly $5 \mu s$. At nominal operating conditions, the maximal arc energy (to ground) for the 50-kV power converter is 375 mJ, 234 mJ for the 25 kV, and 6 J for the 10-kV one. Arc energy mitigation for the 10-kV power converter is limited since the series resistance must be low enough to reduce the voltage perturbation created by the pulsed current of 1.7 A.

Fig. 8(a) illustrates the experimental setup used to test the rapid reaction to a ground short circuit on each power converter. A spark-gap was used to create an arc event on the pulse flat-top. Fig. 8(c) shows the result of one short-circuit test on the 50-kV power converter.

E. Control Method

The control objectives are the rejection of the perturbations created by the pulsed H^- beam, minimization of the secondary voltage overshoot, and total pulse length. The general control scheme is presented in Fig. 9(a).

The purpose of the internal voltage V_1 loop is to further linearize the V_{ge}/V_1 characteristic (V_{ge} being the gate-emitter voltage of the linear IGBT). Fig. 9(b) illustrates the schematic view, which can be used to derive the transfer functions for

Fig. 8. Spark-gap utilization for short-circuit and full load tests. (a) Circuit for arc protection tests. (b) Circuit for nominal load condition tests. (c) Ch.1: 10 kV/div. and Ch.4: 1 A/div. (d) Ch.2: 10 kV/div.

Fig. 9. (a) General control scheme. (b) Transformer and load equivalent circuits.

control design purposes. The form of the open-loop transfer functions V_1/V_{CE} and V_2/V_1 are given in (1) and (2), without any simplifications

$$\frac{V_1}{V_{CE}} = \frac{N_4 s^4 + N_3 s^3 + N_2 s^2 + N_1 s + N_0}{D_4 s^4 + D_3 s^3 + D_2 s^2 + D_1 s + D_0} \quad (1)$$

$$\frac{V_2}{V_1} = \frac{1}{k} \frac{n_3 s^3 + n_2 s^2 + n_1 s + n_0}{d_3 s^3 + d_2 s^2 + d_1 s + d_0} \quad (2)$$

All exact coefficients in (1) and (2) are given in the Appendix, and k is the transformer ratio. Fig. 10 presents the Bode characteristics of these transfer functions considering the parameters of the 50-kV prototype power converter illustrated in Fig. 11.

The pulse transformer equivalent circuit parameters have been derived from the identification method presented in [14]. Fig. 10 presents the total open-loop characteristic V_2/V_{CE} as well. The V_1/V_{CE} characteristic shows a flat behavior in the operational frequency region (1–10 kHz). Therefore, a simple proportional gain can be considered as V_1 controller [Fig. 9(a)] in order to further linearize the IGBT V_{CE}/V_{GE} . At low frequencies, the same characteristic shows the effect

Fig. 10. Bode-plots of the V_2/V_1 , V_1/V_{CE} , and V_2/V_{CE} transfer functions.

Fig. 11. Prototype system. (a) Under test. (b) In operation at the test stand.

of a zero (capacitive behavior given by C_{main}). In this case, this zero has no impact on the dynamic of a voltage pulse in the millisecond range; therefore, no particular precaution has to be considered. However, if the capacitor bank value C_{main} is increased, this zero could be easily compensated by measuring the main capacitor bank C_{main} voltage, as presented in [15].

The V_2/V_1 transfer function behaves as a second-order system in the range of frequency of interest (up to 100 kHz). As a consequence, the output voltage V_2 regulator can be in the classical Proportional-Integral-Derivative form, where the two dominant poles of the system can be compensated by the two zeros of the controller.

IV. EXPERIMENTAL VALIDATION OF THE FULL SCALE SYSTEM

A first full-scale prototype and a series of two additional systems have been constructed. First tests were performed on a dummy load consisting of a spark gap in series with a resistor to emulate the load current during the pulse as depicted in Fig. 8(b). Fig. 11(a) shows the system under preliminary tests in a laboratory. The left rack contains the

Fig. 12. Front and rear views of the extractable transformer top cover holding all HV components (resistors, HV divider, current transformer, and HV connectors).

Fig. 13. Measured voltages on the prototype and electron-dump current.

three control and power electronics chassis, and the right rack contains the three HV pulse transformers.

The first prototype was commissioned and operated at a H^- test stand at CERN, and Fig. 11(b) shows the transformer rack integration (just beside the source Faraday cage).

Fig. 12 shows two views of the extractable top cover of a transformer tank, which holds all HV components illustrated in Fig. 6. The transformers (mounted as drawers) and top cover mechanical system have been developed for fast intervention in the Linac4 tunnel in case of failure. First results of the prototype system under nominal operation are depicted in Fig. 13. These results are obtained using an analog controller, which will be soon replaced by a fully digital version.

The system respects the required specifications. Because of the capacitive coupling between the three systems, via secondary stray capacitances, the electron current caught by the e -dump electrode greatly affects the three pulsed voltages. To mitigate this issue, one can either adopt a multivariable control, or simply and drastically improve the perturbing current rejection capabilities of the e -dump power converter. For this purpose, a generalized polynomial RST controller [16] will be used with the new digital controller to separately define the tracking and rejection dynamics. A feedforward action with the measured e -dump current is under evaluation as well.

V. CONCLUSION

A new system of pulsed-power converters for H^- ion sources has been designed and experimentally validated. The topology is based on a series of three HV pulse transformers with their secondary windings interconnected, and a linear-driven IGBT allowing for fast regulation and ripple-free output pulsed voltages. Experimental results on the final full-scale system show excellent behaviors, even with a preliminary analog electronic control system prototype. Since February 2013, the new ion source is operating successfully, and in particular, the issue of damaging arc events previously observed has now been resolved by the use of pulsed powering. Further work includes controller optimization via a digital electronics system, allowing better reference tracking and perturbation rejection performance.

APPENDIX

V_1/V_{CE} AND V_2'/V_1 TRANSFER FUNCTIONS COEFFICIENTS

A. For V_1/V_{CE}

The exact transfer function coefficients expansion of equations (1) and (2) are listed below.

$$N_0 = 0$$

$$N_1 = 0$$

$$N_2 = C_{\text{main}} L_m R_{\text{preld}} (R'_{\text{dis}} + R'_s) R_t$$

$$N_3 = C_{\text{main}} L_m R_{\text{preld}} (L_t (R'_{\text{dis}} + R'_s) + C'_{\text{load}} R'_{\text{dis}} R'_s R_t)$$

$$N_4 = C'_{\text{load}} C_{\text{main}} L_m L_t R'_{\text{dis}} R_{\text{preld}} R'_s$$

$$D_0 = R_{\text{preld}} (R'_{\text{dis}} + R'_s) R_t$$

$$D_1 = (L_m + L_t) R_{\text{preld}} (R'_{\text{dis}} + R'_s) + (C'_{\text{load}} R'_{\text{dis}} R_{\text{preld}} R'_s + L_m (R'_{\text{dis}} + R_{\text{preld}} + R'_s)) R_t$$

$$D_2 = C'_{\text{load}} L_t R'_{\text{dis}} R_{\text{preld}} R'_s + L_m (L_t (R'_{\text{dis}} + R_{\text{preld}} + R'_s) + (C_1 + C'_{12} + C'_2 + C_{\text{main}}) R_{\text{preld}} (R'_{\text{dis}} + R'_s) R_t + C'_{\text{load}} R'_{\text{dis}} (R'_s R_t + R_{\text{preld}} (R'_s + R_t)))$$

$$D_3 = L_m ((C_1 + C'_{12} + C'_2 + C'_{\text{load}} + C_{\text{main}}) L_t R'_{\text{dis}} R_{\text{preld}} + L_t (C'_{\text{load}} R'_{\text{dis}} + (C_1 + C'_{12} + C'_2 + C_{\text{main}}) R_{\text{preld}}) R'_s + C'_{\text{load}} (C_1 + C'_{12} + C'_2 + C_{\text{main}}) R'_{\text{dis}} R_{\text{preld}} R'_s R_t)$$

$$D_4 = C'_{\text{load}} (C_1 + C'_{12} + C'_2 + C_{\text{main}}) L_m L_t R'_{\text{dis}} R_{\text{preld}} R'_s.$$

B. For V_2'/V_1

$$n_0 = R'_{\text{dis}} + R'_s$$

$$n_1 = C'_{\text{load}} R'_{\text{dis}} R'_s + C'_{12} (R'_{\text{dis}} + R'_s) R_t$$

$$n_2 = C'_{12} (L_t (R'_{\text{dis}} + R'_s) + C'_{\text{load}} R'_{\text{dis}} R'_s R_t)$$

$$n_3 = C'_{12} C'_{\text{load}} L_t R'_{\text{dis}} R'_s$$

$$d_0 = R'_{\text{dis}} + R'_s + R_t$$

$$d_1 = L_t + (C'_{12} + C'_2) (R'_{\text{dis}} + R'_s) R_t + C'_{\text{load}} R'_{\text{dis}} (R'_s + R_t)$$

$$d_2 = (C'_{12} + C'_2) L_t R'_{\text{dis}} + C'_{\text{load}} L_t R'_{\text{dis}} + (C'_{12} + C'_2) L_t R'_s + (C'_{12} + C'_2) C'_{\text{load}} R'_{\text{dis}} R'_s R_t$$

$$d_3 = (C'_{12} + C'_2) C'_{\text{load}} L_t R'_{\text{dis}} R'_s.$$

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