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Operation and Thermal Modeling of the ISIS H– Source from 50 to 2 Hz Repetition Rates

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CERN's Linac4 accelerator H− ion source, currently under construction, will operate at a 2 Hz repetition rate, with pulse length of 0.5 ms and a beam current of 80 mA. Its reliability must exceed 99 % with a mandatory 3 month uninterrupted operation period. A Penning ion source is successfully operated at ISIS; at 50 Hz repetition rate it reliably provides 55 mA H− pulses of 0.25 ms duration over 1 month. The discharge plasma ignition is very sensitive to the temperatures of the discharge region, especially of its cathode. The investigation by modeling and measurement of operation parameters suitable for arc ignition and H− production at 2 Hz is of paramount importance and must be understood prior to the implementation of discharge ion sources in the Linac4 accelerator. In its original configuration, the ISIS H− source delivers beam only if the repetition rate is above 12.5 Hz, this paper describes the implementation of a temperature control of the discharge region aiming at lower repetition rate operation. The experimental results of the modified source successfully operated down to 1.6 Hz and providing 30 mA H− pulses of 0.75 ms duration are presented. A thermal modeling of the ISIS ion source gives insight to the relevant parameters. The analysis demonstrates the adaptability of discharge sources for the operating conditions of the Linac4.

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Abstract. CERN's Linac4 accelerator H^- ion source, currently under construction, will operate at a 2 Hz repetition rate, with pulse length of 0.5 ms and a beam current of 80 mA. Its reliability must exceed 99 % with a mandatory 3 month uninterrupted operation period. A Penning ion source is successfully operated at ISIS; at 50 Hz repetition rate it reliably provides 55 mA H^- pulses of 0.25 ms duration over 1 month. The discharge plasma ignition is very sensitive to the temperatures of the discharge region, especially of its cathode. The investigation by modeling and measurement of operation parameters suitable for arc ignition and H^- production at 2 Hz is of paramount importance and must be understood prior to the implementation of discharge ion sources in the Linac4 accelerator. In its original configuration, the ISIS H^- source delivers beam only if the repetition rate is above 12.5 Hz, this paper describes the implementation of a temperature control of the discharge region aiming at lower repetition rate operation. The experimental results of the modified source successfully operated down to 1.6 Hz and providing 30 mA H^- pulses of 0.75 ms duration are presented. A thermal modeling of the ISIS ion source gives insight to the relevant parameters. The analysis demonstrates the adaptability of discharge sources for the operating conditions of the Linac4.

Keywords: Linac4, ISIS, H^-, ion source, low repetition rate, thermal model.
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INTRODUCTION

Linac4 is a 160 MeV H^- linear accelerator planned to replace the existing Linac2 as an injector to the Proton Synchrotron Booster (PSB). Linac4 aims at doubling the beam brightness out of the PSB, thus allowing an upgrade of the Large Hadron Collider (LHC) injectors for higher intensity and eventually an increase of the LHC luminosity [1].

The H^- ion source for CERN's Linac4 accelerator is currently under construction. It will operate up to 2 Hz repetition rate, with 0.5 ms pulses [2]. A beam current of 80 mA within a normalized rms emittance of 0.25 mm mrad is a challenging goal. A discharge ion source based on the BNL's magnetron is being investigated.

The BNL magnetron operates at a frequency of 7.5 Hz delivering 100 mA H^- pulses with 0.7 ms duration, at 35 kV [3]. It is required to demonstrate that a discharge ion source such as the BNL magnetron is capable of performing at 0.8 and 2 Hz repetition rates.

TABLE 1. BNL, ISIS and Linac4 operational source running parameters.

Source	BNL	ISIS	Linac4
Discharge current (A)	8-18	55	
Discharge voltage (V)	140-160	60-70	
Discharge pulse length (μs)	700	600-1100	500-600
Repetition rate (Hz)	7.5	50	0.8-2
Duty factor (%)	0.5	3-5	0.04-0.12
Average discharge power (W)	1.7-5.4	99-212	
H^- beam current (mA)	100	50-55	80

The Penning H^- source of ISIS is used to study the behavior of the discharge source at low repetition rates. The H^- Penning source provides beam for the ISIS spallation neutron source routinely producing 55 mA of H^- ions during 0.2–0.25 ms pulses at 50 Hz, for uninterrupted periods of up to 50 days [4]. Table 1 compares relevant operating parameters of the BNL, ISIS and Linac4 ion sources.

In order to investigate the relation between the energy dissipated during the discharge and the operation of the source, the ISIS source is operated at lower repetition rates while operation parameters and the beam current is recorded. The original Penning source delivers beam down to 12.5 Hz. With an added heater element to the cathode spacer, repetition rates as low as 1.6 Hz were achieved. A finite element thermal model provides insight to the thermal equilibrium.

In this publication the source is briefly described, and the experimental results are presented.

ISIS ION SOURCE

The ISIS H^- source is comprised of a molybdenum cylindrical anode, capped with cathode electrodes at each end, with a magnetic field along the anode cylinder axis. A Penning discharge is produced in hydrogen gas and cesium vapor (Fig. 1). Cesium vapor is delivered from an oven by a transport line held at 300 °C and is fed into the discharge region via two openings in the anode. Another hole on the anode provides hydrogen pulsed via a piezoelectric valve. A molybdenum aperture

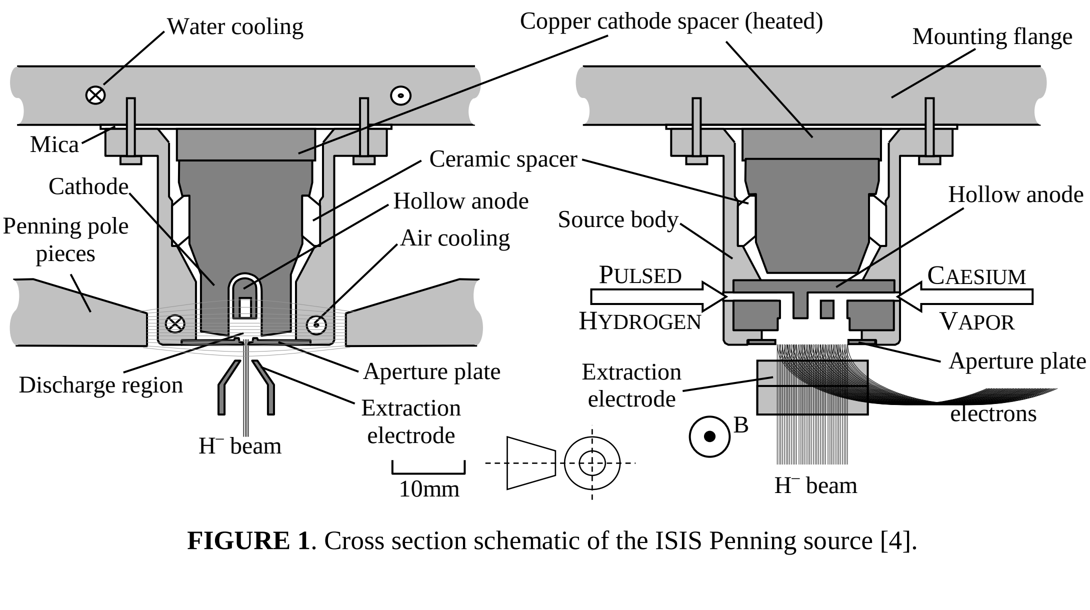

FIGURE 1. Cross section schematic of the ISIS Penning source [4].

plate allows the beam extraction through a 0.6 mm by 10 mm slit. A stainless steel source body supports the anode and the aperture plate and encloses the cathode. The source body is placed on a mounting flange with three thin mica sheets serving as electrical insulators. A ceramic ring electrically insulates the body from the cathode. The source body is cooled by air flow and the mounting flange is cooled by water [4].

ISIS Ion Source Operation at Low Duty Factor

The source in its nominal configuration is tested on the Ion Source Development Rig (ISDR) with an discharge of 55 A and 40 V and a pulse duration of 1.1 ms, starting at 50 Hz and stepwise reduced by a factor of 1/2, until the source became unstable.

The cathode temperature decreases as the power input from the discharge decreases proportionally to the repetition rate. At 25 and 12.5 Hz it is necessary to decrease the air and water cooling flows for the source electrodes to reach a temperature at which the source produces a stable H^- beam, of about 60 mA. The anode and body temperatures do not decrease with the repetition rate reduction as the cathode temperature since the body air cooling flow is reduced, therefore allowing the body and anode to maintain stable temperatures.

Temperatures of the cathode, the anode and source body measured by thermocouples are summarized in Fig. 2 along with the discharge power, the delivered H^- beam current and the flow from the air and water cooling circuits.

The average discharge power at 12.5 Hz is 30 W. At lower repetition rates the source stops delivering beam as the discharge power is insufficient to keep the electrodes at working temperatures, even if the cooling is stopped.

Temperature Controlled ISIS Ion Source at Low Duty Factor

A resistive wire heater is added to the copper cathode spacer (Fig. 1) to bring the electrodes to a temperature above 400 °C, and the source is tested to lower repetition rates. In addition, the following modifications were made: two mica sheets are placed between the spacer and the cathode and one mica sheet is placed between the cathode spacer and the mounting flange. The arc discharge pulses are reduced to 0.75 ms duration.

The temperature controlled source successfully delivers 30 mA of H^- beam at low repetition rates, down to 1.6 Hz. Figure 3 shows the electrodes and body temperature during operation, the H^- beam current, the discharge power and the applied power to the resistive heater required to operate the source. The minimum discharge power at which the source can operate stably at 12.5 Hz is 30 W. With 150 W resistive heating applied to the cathode spacer it is possible to successfully operate the ISIS Penning ion source at repetition rates down to 1.6 Hz. However, a slight reduction of the H^- current is observed. Further investigation to understand the current decrease and optimization of the different parameters should be performed.

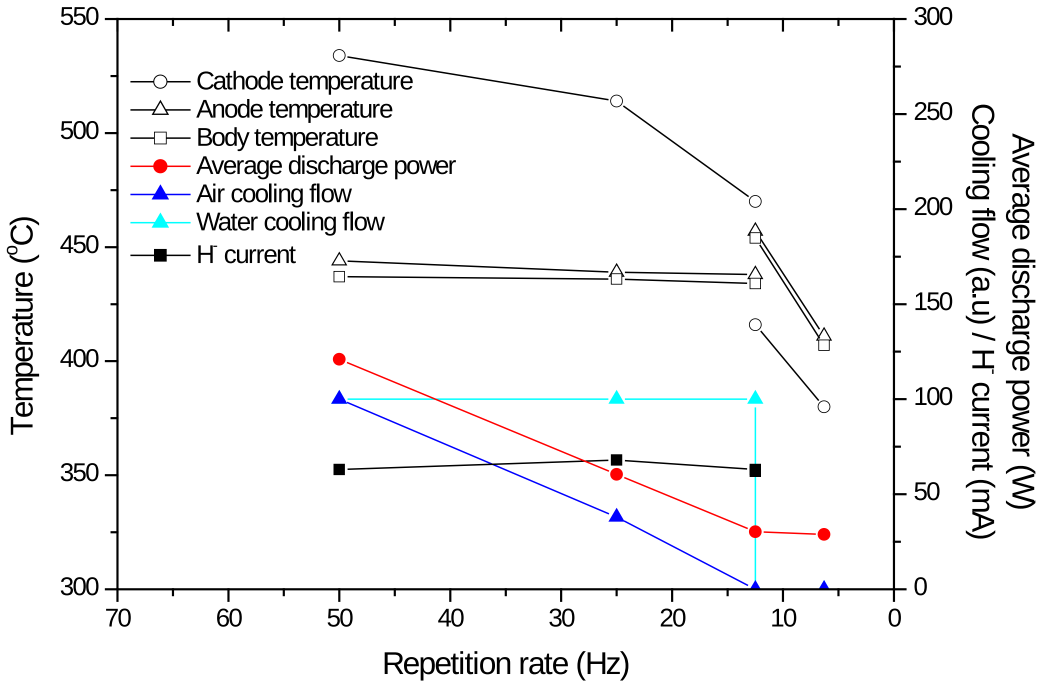

FIGURE 2. Temperature at the ISIS ion source cathode, anode and body, average discharge power, air and water cooling flow (in arbitrary units) and H^- beam current for the original source configuration.

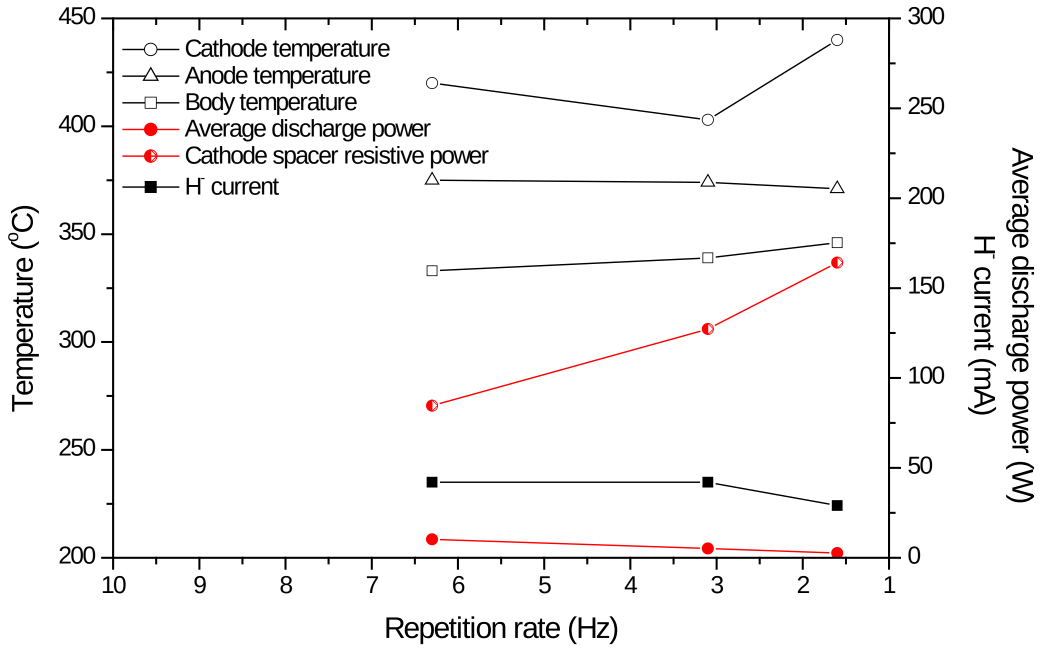

FIGURE 3. Temperature at the ISIS ion source cathode, anode and body, average discharge power, cathode spacer heater resistive load and H^- beam current for the modified source configuration.

ISIS SOURCE THERMAL MODEL

The finite element analysis (FEA) software ANSYS has been used to build a 3-dimentional model of the original ISIS ion source and a model with its cathode spacer resistive heating system (see Fig. 4). The boundary conditions on the two configurations are set to reproduce the source operation at repetition rates from 50 to 1.6 Hz. Source operation is modeled without resistive heating down to 12.5 Hz and with the cathode spacer heater for lower repetition rates.

The main heat source is the Penning discharge. It is assumed that all power applied to create the plasma is converted into heat on the surfaces of the anode, the aperture plate and the cathode. The load is calculated proportionally to the surface area in direct sight of the plasma (40 mm^2 for the cathode and anode and 83 mm^2 for the aperture plate). The transport line is at a constant temperature of 300 °C.

The cooling mechanisms considered are the natural convection at the surfaces in contact with air at ambient temperature (5 $W\ m^{-2}\ K^{-1}$ at 22 °C) and the forced convection at the inner surfaces of the air (source body) and water (piezo valve and mounting flange) cooling circuits. The heat transfer coefficients are calculated using Dittus-Boelter correlation [5]. A maximum air flow at ambient temperature of 30 L/min (655 $W\ m^{-2}\ K^{-1}$) is used, and a water flow at 10 °C of 1.1 L/h (396 $W\ m^{-2}\ K^{-1}$) at the mounting flange and 0.5 L/h (427 $W\ m^{-2}\ K^{-1}$) at the piezo valve are set. The mounting flange surface in contact with the vacuum chamber is set at 22 °C.

The thermal contact conductance of the most critical components of the source are estimated according to Teertstra [6] by simultaneously varying the contact pressure between the different components to best reproduce the thermal results of the laboratory measurements at 12.5 Hz, without cooling. Table 2 shows the used thermal contact conductance.

Heat radiation is applied to surfaces separated by relevant gaps. The outside surfaces of the source body and the aperture plate radiate to the environment at 22 °C. The surfaces of the cathode, the anode and the inner surface of the aperture plate exchanges thermal radiation with the inner surfaces of the source body.

A steady-state analysis of the model is performed at different repetition rates. The results are summarized in Fig. 4 and Table 3.

The anode and body temperatures are calculated, and are within 18 % of the experimental results. The cathode temperature calculation follows the experimental tendencies but the model predicts much higher temperatures at high repetition rates.

TABLE 2: Thermal contact conductance calculated for the FEA model.

Contact components		**Thermal contact conductance ($W\ m^{-2}\ K^{-1}$)**
Source body	Aperture plate	304
Source body	Mica sheet	10
Mica sheet	Mica sheet	14040
Mica sheet	Mounting flange	8
Mica sheet	Cathode spacer	2330
Mica sheet	Cathode	474
Cathode	Cathode spacer	9825

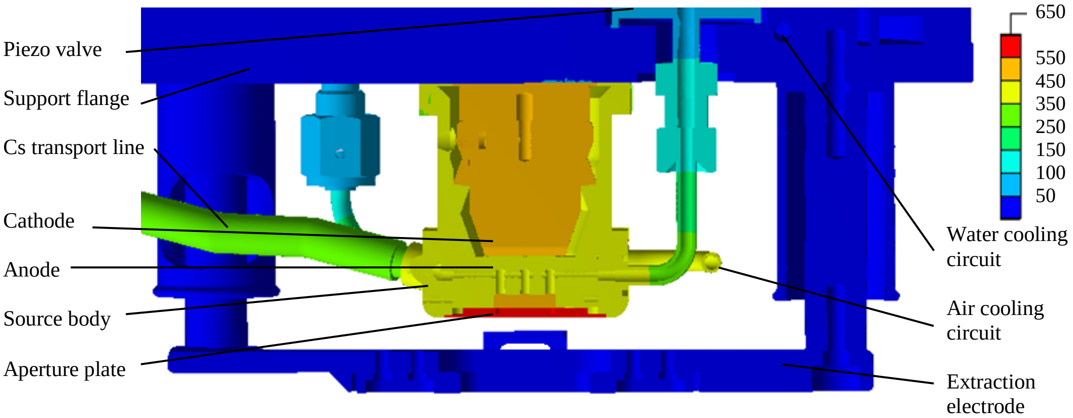

FIGURE 4. ISIS ion source cross section showing the temperature distribution, along the main components, during operation at 12.5 Hz, without cooling.

TABLE 3: Temperature of the ISIS ion source components measured during operation and results of the FEA for the tested configurations. The heat load and cooling power refer to the boundary conditions applied to the FEA model.

Repetition Rate (Hz)	**Temperature (°C)**						**Average Power (W)**		**Cooling Power (W)**	
	Cathode		**Anode**		**Body**					
	Measured	**FEA**	**Measured**	**FEA**	**Measured**	**FEA**	**Discharge**	**Spacer Heater**	**Body Air Flow**	**Mounting Flange Water Flow**
50.0	534	819	444	467	437	447	121.0	-	59	10
25.0	514	618	439	411	436	400	60.5	-	23	10
12.5	470	509	438	424	434	420	30.3	-	-	10
12.5	416	508	457	409	454	405	30.3	-	-	-
6.3	413	594	404	340	352	338	10.3	10	-	-
3.1	403	527	374	307	339	306	5.2	9	-	-
1.6	438	511	369	306	344	305	2.6	9	-	-

The minimum power input into the ion source deemed necessary for it to produce stable beam is 30 W, according to the operation of the ion source in its nominal configuration at a repetition rate of 12.5 Hz, without cooling. For lower repetition rates, a smaller average heat load (concerning the discharge and the resistive heater on the cathode spacer) is applied to the FEA model in order to achieve temperatures at which the ion source is expected to deliver stable beam.

CONCLUSIONS

A test of the ISIS ion source at repetition rates lower than 50 Hz shows that the source operates with a stable beam down to 12.5 Hz at the current configuration. At lower repetition rates the source is able to deliver beam by adding resistive heating to the system.

This proves the concept that it is possible to operate a discharge H^- source at repetition rates as low as 1.6 Hz by controlling the temperature distribution of the system.

A finite element model of the source estimates the source temperature distribution with good accuracy for all the measurement points inside the source (except for the cathode temperature). This method can now be used to also study the reduction in the repetition rate for a magnetron H^- ion source that is considered an option for the Linac4 ion source.

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