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H- Ion Sources For CERN's Linac4

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Keywords: Ion source, negative ions.
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INTRODUCTION

The Linac4 [1] is an 86 m long normal conducting 160 MeV H^- linear accelerator; it is foreseen to replace Linac2, today's 50 MeV proton injector to the Proton Synchrotron Booster (PSB) and shall improve the PSB's beam brightness and contribute to the upgrade of CERN's injector complex. In the event of an early failure of the ageing Linac2, the first section of Linac4 will have to be ready to deliver a 50 MeV proton beam by mid-2014. The commissioning of the first volume H^- source [2] allowed identifying the challenges induced by co-extracted electrons namely the sublimation of the dump surface by the tens of kW power of the 1-2 A co-extracted electron beam leading to high voltage breakdown and the induced increase of the H^- beam emittance. A three stages increase of the H^- beam current form 20 to 80 mA is planned; for each stage, a reduction of the co-extracted electron ratio and of the emittance will be pursued by selecting the most appropriate H^- production mechanism and by tuning the beam formation optics.

A test stand dedicated to the commissioning of the ion source prototypes, the Low Energy Beam Transport (LEBT) and the 3 MeV Radio Frequency Quadrupole (RFQ) accelerator presented in figure 1 is being assembled. A second H^- ion source and LEBT will be the first components to be installed into the Linac4 tunnel by end 2012 where they will provide beams for the staged commissioning of the Linac4. Following the installation of the RFQ into the Linac4 tunnel, the test stand will be dedicated to improvements and long term stability tests of cesiated Linac4 H^- ion sources.

The IS-01 prototype is based on the DESY 2 MHz ion source, using volume production of negative ions and aims at delivering 20 mA H^- and while operated in reversed polarity 80 mA protons; it is equipped with a multistage extraction and an electron dump that is set to a potential limiting the electron energy below 10 keV. The second prototype (IS-02) inspired by the SNS H^- source is scheduled for production in 2013 and installation at the Linac4 by March 2014 and aims to deliver 40 mA H^- ion produced on a cesiated molybdenum surface facing the hydrogen plasma. Furthermore, the mandatory modifications of BNL's magnetron H^- ion source to match the low repetition rate 80 mA Linac4 requirements will be investigated (IS-03).

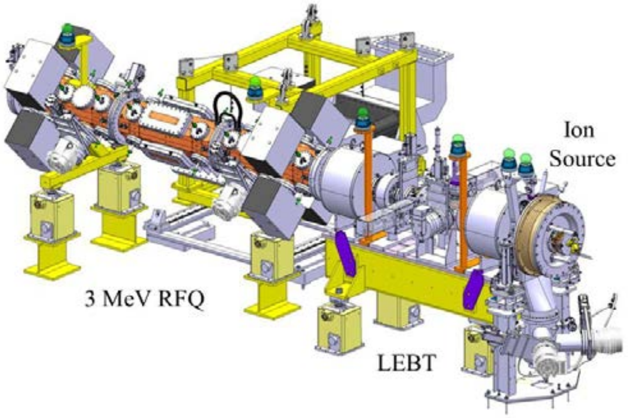

FIGURE 1. Layout of the ion source, LEBT and RFQ of the Linac4 accelerator.

ION SOURCES DESIGN

In this section, the key components of the Linac4 ion source and of the ancillary equipment are described. The ion source support and alignment systems, a front end designed to accommodate various type of plasma generator and extraction geometries and a pumping system are described. The target parameters of the ion sources prototypes and of reference cesiated H^- sources are listed in table 1. The ion sources of each of the three stages are inspired form successfully operating ion sources however at different extraction voltages and duty factors. IS-01 is largely inspired by the DESY volume source [3], IS-02 from the 60 Hz SNS Cs-seeded ion source [4,5] and IS-03 by BNL's magnetron [6]. The reduction of the co-extracted electron current will be addressed via cesiation. It is deemed necessary to track Cs-deposition and demonstrate Cs-cleaning procedures before connecting a cesiated source to the Linac4 LEBT and RFQ as the latter may be affected by Cs contamination.

TABLE 1. Linac4 ion source parameters; the requirements of the stage 1 and 2 of the Linac4 project and the expected ion source prototypes target parameters and reference Cesiated surface (Cs-surf), Penning (P-dis) and Magnetron (M-dis) ion source operated at accelerator facilities [5-7] are given.

Parameter	**unit**	**Linac4**	**IS-01**	**IS-02**	**IS-03**	**ISIS**	**SNS**	**BNL**
Beam Energy	keV	45				17-35	65	35,40
Pulse duration	ms	0.5				0.5		
Repetition rate	Hz	0.8/2				50	60	6.6
H^- current	mA	40/80	*20*	*40*	*80*	35	60	65,100
p, H_2^+, H_3^+ current	mA		*80*					
Co extracted electrons	A		*1*	*0.2*	*0.1*			
H^- Production mode			Volume	Cs-surf.	Cs-surf	Cs-Arc	Cs-surf.	Cs-surf
Plasma heating:			RF	RF	M-dis	P-dis	RF	M-dis
Emittance Norm RMS	μmRad	0.25	*~0.5*			0.2	0.25	0.4,0.56

Support, Front End and Pumping Unit

The ion source support (IS-Support) provides an adjustable table dedicated to the alignment of the ion source front end (IS-front end) with the Linac4 survey network. The tuning range of the support table is ±15mm in all directions. A beam based alignment of the IS-front end is implemented to cope with minor corrections possibly induced by ion source optics, vacuum forces and mechanical loading or tightening. A mechanical system for the rotation of ±3° around the horizontal and vertical beam axes has been implemented, while a slider provides a ±3mm horizontal movement. The functionality is illustrated in figure 2.

The ion source Front end is the backbone supporting the pumping systems, the Einzel lens and the plasma generator, its structure was engineered for mechanical stability [8]. The pulsed injection of hydrogen into the plasma generator leads to pressures of the order of 10^{-3} mbar in the extraction region. In the LEBT gas density will be driven by space charge compensation criteria up to 10^{-5} mbar. A differential pumping is implemented in the region between the source outlet and the LEBT. An Einzel lens accommodates the divergence of the ion beam entering the LEBT. This lens is located within the differential pumping aperture reductions and ensures independence of the extraction and LEBT pumping systems. The extraction region is linked with a high conductance port to the two 700 l/s turbo molecular pumps (TMP). The TMPs, roughing pumps and vacuum gauges (Penning and Pirani) are redundant, if one of the pumping streams fails, a valve can be closed to isolate the fault and operation can resume with the remaining unit. An important aspect to validate this redundancy lies in the impact of a reduced pumping speed on the delivered ion beam properties; measurements showed that a 45 keV proton beam is not affected and similar measurements on the H^- beam are pending. The pumping system is illustrated in figures 3; the ground electrode and the Einzel lens end plate are shaped to reduce the conductance between front end and LEBT. If deemed necessary, an additional pumping system (60 l/s) can be coupled to the differential pumping region.

Very detailed simulations of the pulsed Hydrogen injection and pumping system were made [9] and demonstrate the independence of the LEBT gas density from nominal gas hydrogen injection conditions. The conductance of the complex geometries of all accelerator components was estimated and, with the TMP's hydrogen pumping speeds, inserted into an electrical equivalent model leading to time dependent pressure evolution of the regions of interest some of which are equipped with vacuum gauges.

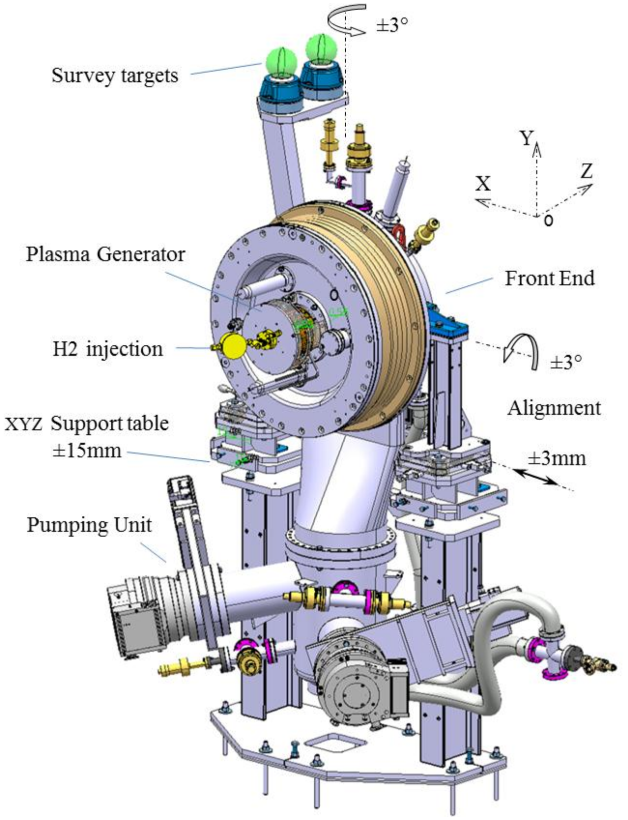

FIGURE 2. Layout of the ion source, support, the positioning range of the support table and the horizontal slider and angular fine tuning range and axis are indicated.

This simulation was complemented by thorough dynamic pressure measurement [10] in the source plasma chamber and beam formation region. Modeling and measurement are in good agreement within the measurement accuracy and modeling approximations. A port is available for the installation of a Residual Gas Analyzer. The low repetition rate of the Linac4 allows pulsed gas injection to be used, which gives, for a given pumping system, a wide range of hydrogen pressures in the plasma chamber. Hydrogen is injected through a piezo valve, its opening time, backing line pressure and delay between valve aperture and RF pulse are adjustable allowing a possible pressure range in the plasma chamber from 10^{-3} to 10^{-1} mbar. A redundant hydrogen flow measurement is implemented; an excess flow interlocks the injection system.

IS-01 Plasma Generator and Beam Formation

The IS-01 plasma generator is shown in figure 4, it consists of an arc discharge plasma ignition system, a ceramic plasma chamber surrounded by a 6 turn RF solenoid and a Halbach-offset octupole cusp of permanent magnets and two electrodes; the collar facing the plasma and the plasma electrode with the 6.5 mm extraction hole.

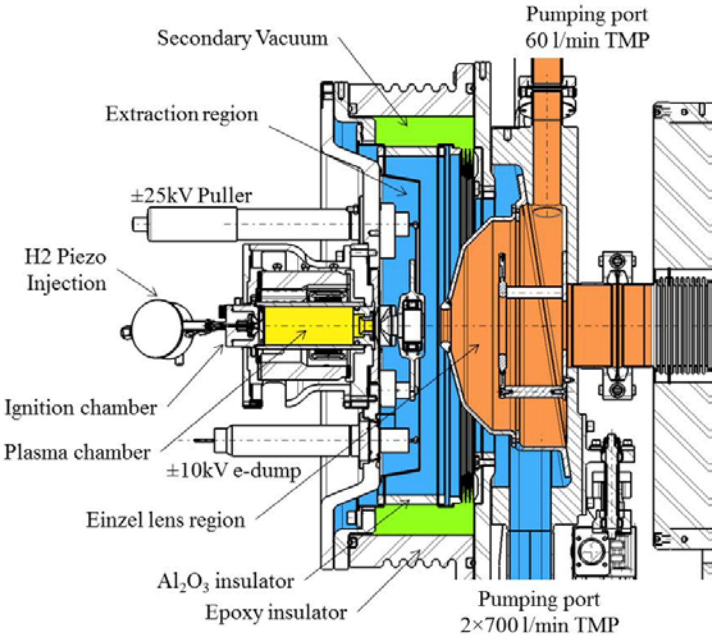

FIGURE 3. Layout of the ion source inner volumes; the differential pumping between the extraction region and the LEBT achieved by aperture reductions around the Einzel lens regions is illustrated. An optional 60 l/ min TMP that can be used to pump the Einzel lens region is indicated.

The ignition arc is localized between the gas injection pipe and the plasma chamber, the expanding gas ionized via the discharge provides a substantial amount of electrons to be inductively heated by the RF-solenoid. The filter field permanent magnets provide a 20 mT field perpendicular to the beam axis between the plasma chamber and the extraction hole. Its function is to reduce the average electron energy in the region before extraction. Measurements of the Electron Energy Distribution Function (EEDF) by means of a Langmuir gauge [11] show that for this filter strength an average energy of 1 eV is expected. Optimum settings of the collar and plasma electrode potentials should allow minimizing the co-extracted electron current, however, at the time of writing systematic measurements are pending. First Particle In Cell (PIC) simulations of the inductive coupling of the RF to the plasma [12] do not yet reach the nominal plasma density but illustrate the plasma particle dynamics in a solenoid induced magnetic field. PIC-Monte Carlo Collision (MCC) plasma meniscus formation simulations were performed [13] based on nominal plasma parameters in order to compare the extraction from the volume source to H$^-$ and co-extracted electron current measurement. The puller-plasma electrode angle and the puller horizontal position can be tuned.

RF Generator, Insulation Transformer and Matching Network

The main source plasma discharge is generated using RF at a frequency of 2 MHz, and a power of up to 100 kW, supplied from a multi-stage amplifier with a tube as the final stage. The amplifier has a bandwidth of ±0.2 MHz and the forward power and frequency are controlled via function generators, allowing frequency and power modulation during the RF pulse. The power is fed to the source helical antenna through an isolation transformer to the source high voltage platform of 45 kV, with the addition of a matching network between the source transformer and the source (the layout of which is shown in Figure 5).

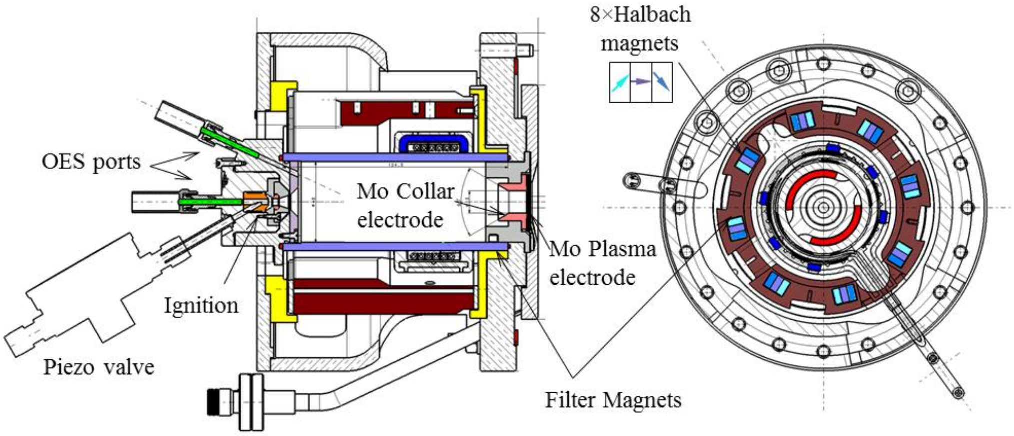

FIGURE 4. Layout of the Linac4 IS-01 plasma Generator. The Halbach-offset octupole magnet cusp, the filter field magnets and the on beam axis and off axis light collection ports are indicated.

Frequency switching during the source pulse is used, with a first frequency f_0 used to ignite the plasma in a stable way after the injection of gas, and a second frequency f_p that minimizes the reflected power from the source load once the plasma is ignited. The switch between the two frequencies is made either using a trigger system based on the generation of light from the plasma, or by a pre-set delay. It is also being investigated to make a smoother transition from one frequency to the other in order to minimize the length of the transition period, and to make automatic frequency scanning.

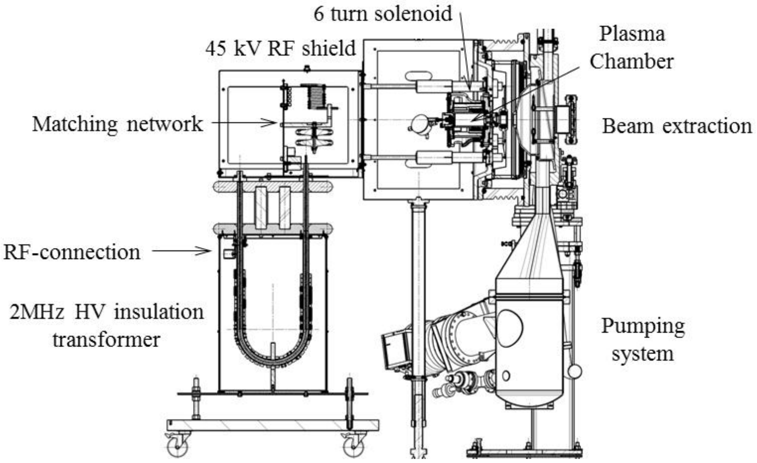

FIGURE 5. View of the Linac4 ion source, the RF-insulation transformer, RF-matching network, the insulator and the pumping system are indicated.

It has been shown that the use of a different frequency to ignite the plasma means that the ignition arc discharge may not be needed in operation, but is maintained at present in order to allow investigation of the influence of the hydrogen pressure on the production of H- ions. The RF coupling efficiency to the plasma is obtained from the measured injected and reflected power and of their phase [14]. Two Optical Emission Spectroscopy view ports dedicated to the monitoring of the plasma [15] are implemented.

Pulsed High Voltage System and Power Converters

Pulsed High Voltage (HV) is an added technical challenge in itself; it was chosen to mitigate two aspects of sparking: The pulsed gas injection increases pressure in the extraction gap region after the H^- ion pulse and can lead to gas discharge conditions. The energy stored in capacitors, passively stabilizing DC high voltage systems during the ion and electron pulse is released during breakdown. This can damage electrodes and leads to a long recovery time to recharge the capacitors, or requires a high average current high voltage power supply. Flexibility in the beam optics tuning was implemented via multistage extraction and minimization of the dumping energy of the co-extracted electrons achieved by floating the electron dump to up to 10 kV from the plasma generator. The scheme of the high voltage system is presented in figure 6a, where three identical 1 kV power converters are connected to HV transformers designed to deliver HV pulses of typically 2 ms duration and ±50 kV (ion source), ±25 kV (Puller electrode) and ±10 kV (electron dump). The arc discharge ignition, the collar and plasma electrodes are based on DC power converters and capacitors.

TABLE 2. High Voltage system parameters and nominal settings for H^- and proton source.

	Power converter - transformer	**Nominal Potential H^-**	**Nominal Potential p^+**
Plasma chamber, Racks RF Matching network	±50 kV, 0.1A, 2 ms	-45 kV	45 kV
Puller electrode	±25 kV, 1A, 2 ms	-20 kV	25 kV
Electron dump	±10 kV, 1A, 2 ms	-35 kV	35 kV
Einzel lens (DC + 30 nF)	±50 kV, 0.1A, 1 ms	±35 kV	±35 kV
Ignition (DC + 1.3 μF	+1.2 kV, 20A, 0.1 ms		
Collar & plasma electrode (DC + 22 mF)	±60 V, 20 A, 1 ms		

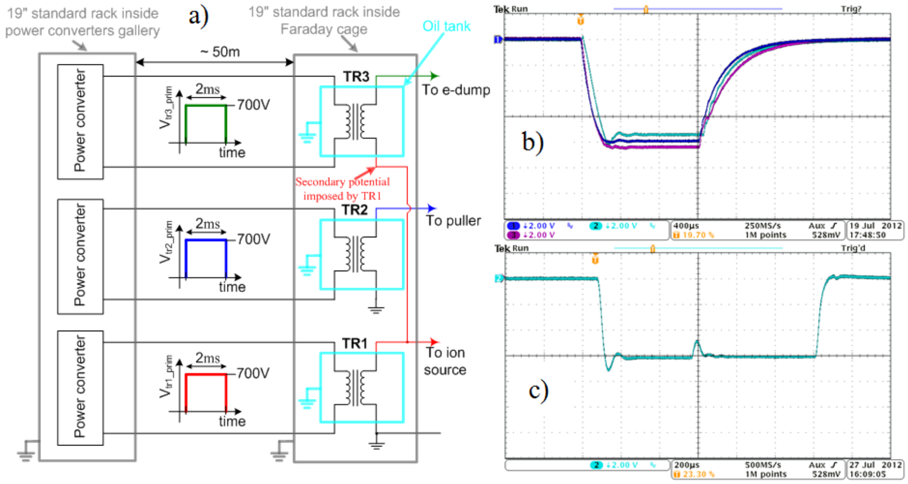

FIGURE 6. a) Configuration of the three identical pulsed power converters connected to the 3 different HV pulsed transformers; b) Experimental test at nominal voltages of the 3 power converters on a capacitive load; c) E-dump power converter pulse with sudden current of 1A on the flat-top (emulation on a test bench equipped with trigged spark-gap).

The Einzel lens voltage can be set to ±35 kV and operated in decelerating or accelerating mode where the impact on the emittance growth is lowest. High voltage power converter parameters and nominal operation settings are summarized in table 2.

Beam Formation, Beam Diagnostics

A compromise between various aspects of H^- ion sources is required when designing the extraction and acceleration optics; the dumping of co-extracted electrons must be controlled and emittance growth must be minimized. Eventually, the beam needs to be matched into the LEBT. An iterative sequence of simulations and measurement of the ion and electron current and current densities is necessary to improve the simulation's input. Changes of plasma parameters (e.g. plasma density, electron average energy, electron to ion ratio) will affect the beam formation. The beam formation system has inbuilt flexibility in the puller and electron dump potential. On the test unit, a motorized puller position is foreseen. The ion source plasma generator, puller electrode and electron dump are mounted on a base plate equipped with high voltage feed through. In the front end, the ground electrode provides the final acceleration. It is followed by an Einzel lens dedicated to the tuning of the beam divergence that can be operated in acceleration or deceleration mode. Combined new extraction [16] and Einzel lens electron dump designed for minimizing the e-beam power density from the volume source [17] reduced the surface power density by two orders of magnitude.

The LEBT beam optics consists of the two solenoid-steerer pairs between which a pre-chopper, a diagnostics box and a Beam Current Transformer (BCT) are inserted [18]. During accelerator operation, the BCT provides the integral of the charge, the beam evolution and the average beam intensity. On the test stand, a Faraday cup provides a beam current cross check, a set of horizontal and vertical grids and an emittance meter will provide beam positions, profiles and emittances. Careful analysis of the emittance meter data should allow qualitative observation of neutrals in the H^- mode and H_2^+, H_3^+ and neutral in the proton operation mode. Gas injection is foreseen into the LEBT to allow the optimization of the space-charge compensation conditions and beam loss from gas stripping.

Volume Source Commissioning

The volume source is being commissioned at the time of writing. The high voltage pulses of the ion source, puller electrode and electron dump are illustrated in figure 6. At this stage of the prototype development, a Proportional Integral Differential (PID) regulation system is used to stabilize the voltage applied to the electrodes. The system is operational and will be later upgraded to a digital control. The plasma generator is operational, first plasma light emission collected through on axis and 30 deg. view ports and recorded with a 10 MHz photomultiplier through a H_α narrow band filter is presented in figure 7. A leak on the diamond Al-seal and insulator material outgassing limit the pressure in the intermediate vacuum sector to $2.1\ 10^{-2}$ mbar and prevent high voltage pulsing. Both issues are being addressed. The H_2-injection, safety and local control systems are operational.

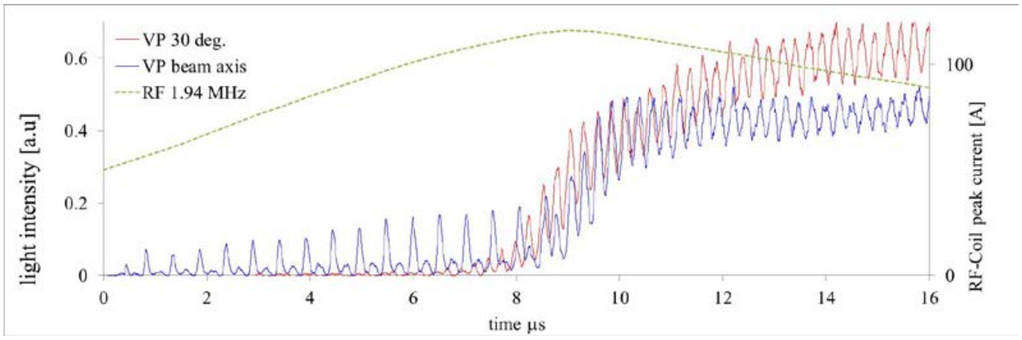

FIGURE 7. Light emissions from the IS-01 plasma, pulse without ignition. H_α line from the on axis and 30° view ports. The RF-coil peak current is indicated.

CONCLUSION OUTLOOK

Volume Ion Source: The volume production based H^- ion source IS-01 was produced and is being commissioned.

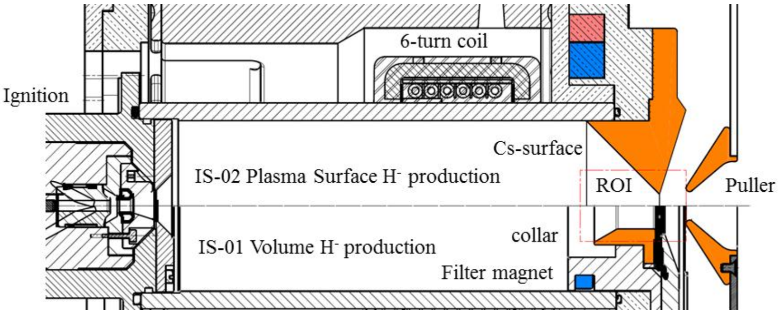

FIGURE 8. Comparative scheme of the IS-01volume H^- ion source prototype and of the IS-02 Cesiated surface ion source design. The region of interest (ROI) for beam formation simulation is indicated.

Cesiated Surface Ion Source: The model of a cesiated surface based H^- ion source IS-02 is presented in figure 8. Almost identical plasma generators and extraction system are foreseen to minimize design work and to ensure similar plasma condition close to the specific beam formation regions. These controlled conditions are the basis of experimental benchmarking of volume vs. cesiated surface H^- production mechanisms. A particle in cell simulation of the beam formation region based on Langmuir gauge characterization of the plasma is presented in [19] for both ion source configurations. A temperature control of the Mo-surface is foreseen.

Magnetron Ion Source: BNL’s Magnetron is illustrated in figure 9, it can be implemented into the ion source front end. One of the lifetime limitations of this type of ion source is the damage on the cathode. Simulation has shown that this could be explained by the ionization of Cs vapor and hydrogen by electrons or H^- ions in the beam extraction region which are accelerated back towards the extraction field [19, 20]. If the operation life time of the magnetron scales with the beam duty factor and if repetition rate down to 2 Hz can be achieved the magnetron becomes an option for the nominal Linac4 beam. For this purpose, the ISIS Penning discharge electrodes temperature was investigated and hints to promising results at low repetition rates [21]. Temperature regulation of the discharge region is foreseen. The Cs consumption at Linac4 operation condition, its bookkeeping and cleaning process must be experimentally assessed.

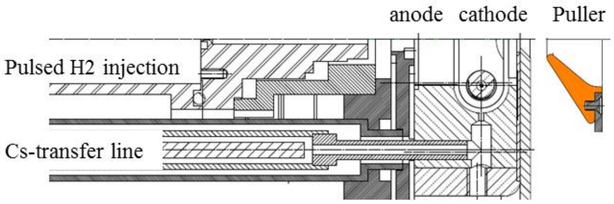

FIGURE 9. BNL's Cesiated Magnetron discharge H$^-$ ion source.

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