DEVELOPMENT OF 400 kA PULSED POWER SUPPLY FOR MAGNETIC HORN AT FAIR ANTIPROTON TARGET

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Abstract

This report presents an overview of the magnetic horn and its pulsed power system at the upcoming FAIR (Facility for Antiproton and Ion Research) complex at GSI Helmholtzzentrum für Schwerionenforschung, Darmstadt, Germany. In the planned antiproton (pbar) separator scheme [1] a magnetic horn will be used as a device for collection and focusing of highly divergent antiprotons emerging from the target with energies around 3 GeV and within a cone of about 80 mrad [2].To achieve the desired focusing effect, the horn needs to be powered with a current pulse of 400 kA peak amplitude at the same repetition rate as the primary proton beam, i.e. 0.1 Hz. In future, operation up to 0.2 Hz is planned without major design alterations. Due to civil construction and radiation protection limitations, possible technical realization of this system has some key design issues. The aim is to develop a reliable and efficient magnetic horn system for effective focusing of antiprotons by producing a very strong pulsed magnetic field.

INTRODUCTION

The Magnetic Horn is the first ion optical element in the pbar separator line. It consists of two coaxial aluminium conductors, namely inner and outer conductor, which encompasses a closed volume. The longitudinal current of 400 kA produces a circular magnetic field in that closed volume. The field intensity within that region varies as the inverse of the distance from the horn axis as shown in Fig. 1. Antiprotons entering the magnetic volume are deflected by the field and thereby focused in the forward direction.

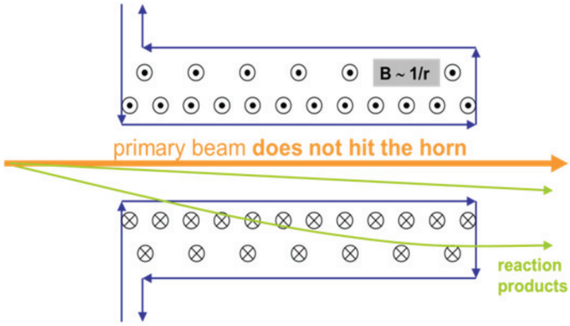

Figure 1: Focusing antiprotons: A simplified sketch showing working principle of the magnetic horn.

Basic design of the magnetic horn, especially the geometric profile of the inner conductor, at FAIR will be nearly identical to the CERN AAC (Antiproton Accumulation Complex) horn solution [3]. However, its electrical and mechanical connections and auxiliary components are quite different.

To produce the required (half-sine) current pulse, energy stored in the capacitor bank will be released through high voltage switches into the discharge path, which includes a set of coaxial cables, a so- called adaption box, the stripline, and finally to the horn as shown in Fig. 2. To limit the power consumption and thermal losses, pulse duration should be as short as reasonably possible.

Due to civil construction and radiation protection limitations, distance between the power supply (capacitor room) and the horn (load) is ≈ 65 m. The power supply room and cables are situated in an area with low radiation level and only the adaption box, the stripline and the horn are exposed to significant radiation.

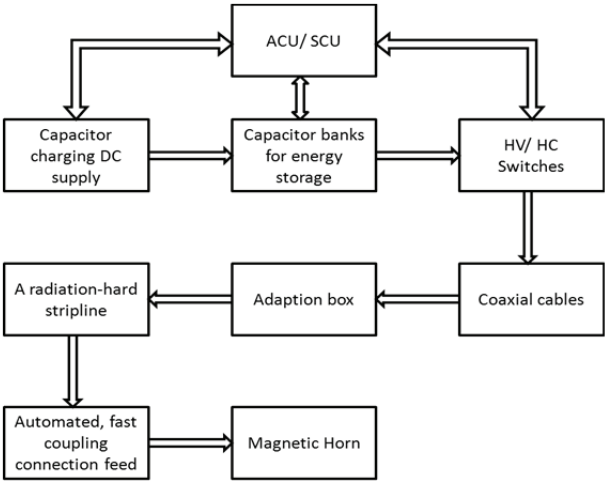

Figure 2: Major system components: horn and its pulsed power supply.

This relatively long discharge path means additional parasitic impedance and therefore more energy storage requirement at the capacitor bank. An Adaptive Control Unit (ACU) will provide communication interface between the accelerator main control system and horn system. At required horn current of 400 kA and the significant stray inductance of the discharge path, especially stripline, energy management between the power supply and the horn is a critical issue.

BASIC OPERATION

For 0.1 Hz operation, capacitor charging power supply E_c (Fig. 3) charges a bank of energy-storage capacitors C (~2 mF) in <10 s to the rated voltage (~14 kV). This

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stored energy (~200 kJ) is discharged through switch S_D in a directly coupled damped circuit with total load impedance assumed not to exceed L_S ~1.5 µH and R_S ~5 mΩ at the output of the pulser and taking into account all system components and skin effect considerations.

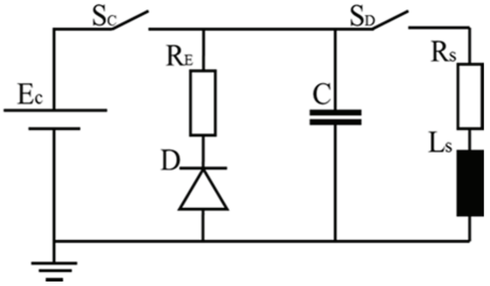

Figure 3: Horn pulser: simplified electrical circuit.

The impact of temperature on system resistance will also need to be taken into account. For optimum circuit design low impedance transmission path is preferred [4]. Flattop duration of the current pulse with 400 kA peak amplitude (±1%) should be around 5-10 µs with pulse to pulse repeatability of 1%. To keep the design simple and since it is not economically worthwhile, no energy recovery scheme is envisaged at present. Electrically, horn can be regarded mainly as an inductive load (~200 nH) with small series resistance (~400 µΩ). At 0.1 Hz operation, the RMS current through horn will be ~1300 A.

SIMULATION

To study the transient electrical behavior of the pulser circuit an LTspice simulation [5] has been performed using calculated values of electrical parameters of the major system components.

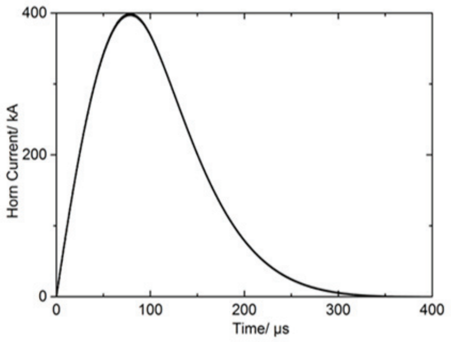

Figure 4: LTspice simulation: A roughly half-sine horn current waveform with 400 kA peak amplitude and duration of 130 µs (FWHM).

During rising period (T_r ≈86 µs) from 0 to 400 kA, in Fig. 4, damping is caused only by the system resistance R_s. The reverse (magnetic) energy is dissipated in a dump resistor, $R_E = (1/2)\sqrt{(L/C)}$, switched into the circuit by a diode D and prevents an oscillating discharge. Diode D remains forward-biased till the whole energy is dissipated and the circuit will be de-energized during each operating cycle. Critically-damped horn current waveform with duration 130 µs (FWHM) can be obtained.

KEY DESIGN ISSUES

Key design issues of the horn pulser are:

Selection of Switch

For the given operating parameters and life-time expectations of at least 4 million discharges (a year of operation, i.e. 200 days, at 0.2 Hz) selection of switch is a critical issue. Principle switching requirements are forward blocking voltage up to 20 kV and di/dt of >7kA/µs including 20% safety margin. Two practical possibilities are ignitrons and solid-state switches. While the use of ignitrons is a proven possibility, its mercury content is an issue and need to be addressed due to health and safety concerns. Solid-state switches are an expensive option. Also, they are quite sensitive to the over-current/over-voltage and therefore need to be operated very carefully compared to ignitrons. However, given the 30 years of expected operational life-time of FAIR accelerator complex, long-lasting switching arrangements will be preferred.

Stripline Design

Since coaxial cables cannot withstand highly radioactive environment in area surrounding the target station, we will use specially designed, high-current transmission line called stripline. It is made of aluminium and is radiation-hard i.e. fairly insensitive to radioactive environment. This parallel strip transmission line consists of 3 identical aluminium plates of rectangular cross-sections i.e. 2 outer plates for the return current and the middle plate for the horn supply current or vice versa depending on the final circuit design. As per the present design, each plate has to be maximum 400 mm wide or less, ~5 mm thick and ~32 m long (sub-divided into 2 or 3 parts). The spacing between the plates will be around 1 to 2 cm.

From engineering design point of view, stripline has to be regarded as an electromechanical system [6]. While, high voltage hold-off and ampacity are prime electrical requirements, its mechanical design is governed by electromagnetic forces and the resulting mechanical stresses as well as thermal and radiation fatigue. While the use of stripline addresses the problem of energy transmission through harsh radioactive environment with very long lifetime requirement i.e. ~30 years, on the other hand it adds complexity to the overall system design:

- Stripline has major contribution in total system inductance. Optimal stripline design will effectively help for pulse-length optimization.
- In order to contain the large electromagnetic forces, stripline has to be clamped precisely with the help of insulated mechanical clamps/ support structure across its length.

- Design considerations must address the issue of possible thermal expansion in stripline as well as in connection feed/ horn without compromising the operational performance.

Connection Feed and Coupling-Clamp Design

A short stripline (~3 m), so-called connection feed, will be an integral part of the horn. It consists of 3 parallel aluminium plates. Each plate will be 300 mm wide and 5 mm thick.

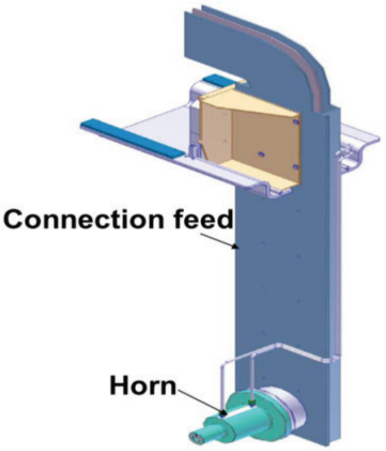

Figure 5: A sketch showing an integrated unit of magnetic horn and its connection feed.

It will hold the horn at the right position and ensure the necessary electrical connectivity between the horn and the pulser. A sketch of the horn and its connection feed is shown in Fig. 5.

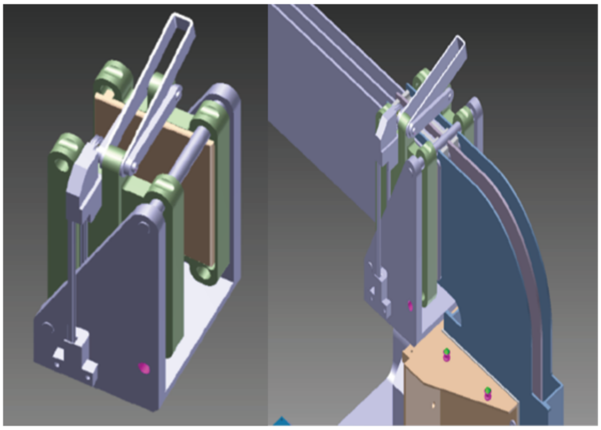

Figure 6: (Left) Sketch of the coupling-clamp. In reality, it will be more complex and remote controlled. (Right) A clamp coupling the stripline and the connection feed.

In the event of a fault in the horn, this integrated unit will need to be replaced by an automated, remote-controlled transportation mechanism. The clamp has to provide an efficient electrical coupling between the horn (precisely the connection feed) and the stripline. This will probably best be done by pneumatic operations, i.e. use of compressed air, as radiation prevents the use of electrically active components. Compressed air can be used also for the cooling purposes.

The clamp has to provide electrical connections with very low contact resistance. Multi-lamella contacts between the stripline and the connection feed may help to realize it. Figure 6 (left-side) shows a sketch of the coupling-clamp. This clamp alone is unlikely to offer the required electrical and mechanical connections at the same time. Therefore, most likely, an additional mechanical fixation will be needed. On the right-side, in Fig. 6, the stripline and the connection feed are joined together with the help of clamp. The whole scheme of pbar target station and other major components of horn system are shown in Fig. 7. A separate testing facility is planned for the horn and the pulser to ensure their performance before transportation to their final location.

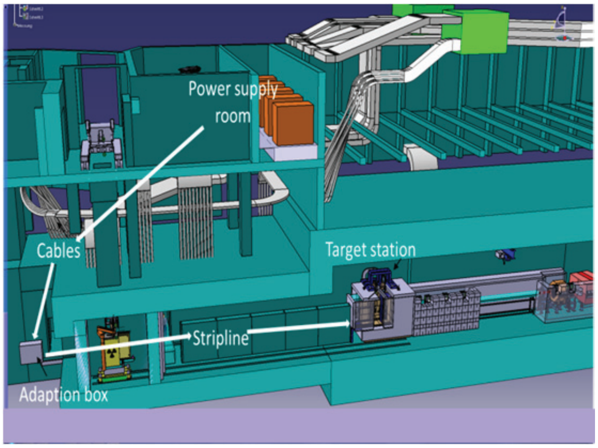

Figure 7: In FAIR Accelerator Complex, planned pbar separator and horn system will be housed in building K0321A/6C.

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