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HIGH VOLTAGE SYSTEM DESIGN FOR THE IUCF 300 KV ELECTRON COOLING SYSTEM*

T. Bertuccio, B. Brown, G. Donica, T. Ellison, D.L. Friesel

Indiana University Cyclotron Facility, Bloomington, Indiana 47405

Summary

A summary of the electron beam high voltage system design for the IUCF Cooler[1,2,3], now under construction, is presented. There are extremely stringent regulation requirements (~10ppm) on the main high voltage power supply (-300 kVDC, 15 mA), and less stringent requirements on the gun anode power supply, in order to achieve the regulation needed to store beams in the IUCF Cooler with very low momentum spreads ($\Delta p/p \approx 2x10^{-5}$). An overview of the main high voltage power supply (HVPS) specifications and design, as well as provisions and plans to improve the regulation are discussed. The electron collection system, modeled after the FNAL collector which was able to collect between 99.9% and 99.99% of the electron beam, is discussed along with the requirements of the associated power supplies. The designs of the high voltage acceleration structures and high voltage platform are discussed, as well as practical design considerations based upon experience with the Fermilab 120 keV electron cooling system.

Introduction

The electron cooling technique for reducing the phase space volume of an ion beam was first proposed by Budker[4] in 1966 and demonstrated by the Novosibirsk group in 1974 using protons with energies up to 70 MeV.[5] Interest in using electron beams for rapid cooling and accumulation of very hot antiproton beams prompted further investigations at CERN using 46 MeV protons in the ICE ring,[6] and at Fermilab using 114 Mev[7]and 203 MeV[8] protons. Today, there is widespread interest in the study of nuclear physics using electron cooled ion beams and very thin ($\sim 10^{-8}$ -10^{-7} g/cm^2) internal targets. Electron cooling is ideally suited for the regime of intermediate energy ($\gamma < 2$) nuclear physics. The higher energy-resolution beams and thin internal targets, which will allow the observation of heavy recoils, may provide an improved method of studying the nucleus.[9]

High Voltage Power Supply System Overview

Figure 1 is a simplified schematic of the high voltage power supply system. A 0-2 Amp, 25.4 mm diameter electron beam is accelerated from a dispenser cathode, which is biased between 7 and 275 kVDC negative relative to ground through a 28 element acceleration column. After traversing the 3 m cooling region, the electron beam is decelerated to the collector anode before being accelerated into the collector. The electron beam is confined by a 1.5 kG solenoidal magnetic field throughout the electron cooling system. The beam current is determined by the gun anode voltage, and the beam energy is mainly determined by the cathode potential.

The cathode power supply (HVPS) will provide current only if portions of the electron beam strike electrodes powered by power supplies referenced to ground. The primary beam limiting aperture in the IUCF electron cooling system is the collector anode which is powered by a supply referenced to cathode potential. This will limit the amount of current the HVPS will have to provide and will catch electrons which have escaped the collector at their lowest possible energy. All the power needed to circulate the electron beam is provided by the collector power supply (CPS). A more detailed description of the power supplies, accelerating structures, high voltage terminal and spark protection elements is given belew.

Cathode High Voltage Power Supply (HVPS)

The longitudinal cooling rate will be very fast so a stored proton beam will be able to track voltage fluctuations with slew rates of up to about 1000 V/s, which will produce coherent energy changes in the stored ion beam of $e(\Delta V_{HVPS,pp})M/m$, where m and M are the electron and proton rest mass. Higher slew rate voltage fluctuations will lead to coherent energy changes as well as to an energy spread if the proton beam is interacting with an internal target in the storage ring.[10]

To minimize these effects, the HVPS has very stringent regulation requirements. The power supply will be built by Nichicon Capacitor Ltd. Nichicon has agreed to a regulation specification of $<2.5x10^{-5}$ $(\Delta V_{pp}/V_{max})$ with a 5 mA load current and has set a target value for the regulation of $<1x10^{-5}$. Nichicon's engineers hope to achieve this target value after installation at IUCF. The oil-insulated power supply will use an 18 kHz pulse-width-modulated power amplifier, a times 4 transformer, and a times 10 high frequency transformer which is capacitively loaded to form an 18 kHz resonant circuit. The transformer feeds a 42 stage symmetric Cockroft-Walton multiplier with a capacitance of 1.2 μF per stage. The theoretical ripple for this power supply is given by:[11]

$$\Delta V_{pp} = I_{lp}N/2fC = 15V\ (\pm\ 2.5x10^{-5})\ \text{at 15 mA.}$$

where: f = operating frequency
N = number of stages
C = capacitance per stage
I_{lp} = peak load current

There is a two stage RC filter on the output (10 kΩ, .016 μF) to filter the ripple voltage. A 40 kΩ series output damping resistor will limit spark currents to less than 10 Amperes.

The DC regulation signal will be provided by a Haefely 30,000:1, 5ppm/°C, DC to 100 kHz compensated divider.

Haefely is also providing a 1 nF, 100:1 AC divider with an average partial-discharge intensity of 5 pC, which should allow good signal to noise monitoring of high frequency ripples of less than 1 V. The lowest useful frequency of this divider will be determined by the amount of leakage current (specified at < 100 nA) which is sensed by the high input impedance amplifier at the low end of the divider. The ripple voltage sensed by this divider will be amplified and applied to a liner (drift electrode) inside the main cooling solenoid vacuum chamber to buck out the effect of the ripple on the electron beam energy. The amplifier driving this electrode will also be used to ramp the electron beam energy at high frequencies since the power supply frequency response will be limited to a few Hz by the output filters.

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In addition, this feedforward system will compensate for voltage fluctuations caused by sudden load changes.

The transition energy of the IUCF Cooler storage ring is 4.6 GeV, which is about ten times the maximum beam kinetic energy. This makes the beam revolution frequency relatively insensitive to fluctuations in the bend field, which will be regulated to about 5 ppm. For these reasons, the ion beam longitudinal Schottky noise frequency can be used to measure the effective electron beam energy with a precision of 0.1 to 1 ppm, depending upon the electron beam energy. This, however, will require the ion beam relative energy spread to be small. Using the longitudinal Schottky noise frequency as the ultimate reference for the power supply will also provide automatic compensation for changes in the ion beam energy due to the electron beam space charge depression and heating by internal targets in the ring.[10]

Gun Anode Power Supplies

The electron beam current, (I), is determined by the voltage between the cathode and the gun anode (V_{ga}):

$$I = k(V_{ga})^{3/2} \quad \text{(Child's Law)}$$

where k is the electron gun perveance and is determined by the gun geometry. The IUCF gun[3] has a perveance of about 0.7 $\mu A/V^{3/2}$.

Ripple in the gun anode power supply (ΔV_{ga}) will cause changes in the electron beam energy (ΔE) due to the changing space charge depression:

$$\Delta E = 1.5eI(\Delta V_{ga}/V_{ga})\left(\ln(r_v/r_b) + 1/2\right)/2\pi\varepsilon_0\beta c$$

where r_v is the radius of the cooling drift tube (51mm), and r_b is the electron beam radius (12.7 mm). The gun anode will be powered by two Glassman PH50P40 power supplies operating in parallel. The peak to peak ripple for each supply is specified to be less than 50 V_{pp} for a load current of 20 mA. These regulation specifications will limit the electron beam energy shifting due to the changing space charge depression to about ± 3 eV with maximum beam output (4 A) in a grounded gun anode configuration. The residual ripple present at the gun anode will add about a 1 mA AC component to the electron beam current. This AC current will be used to monitor the electron beam horizontal and vertical positions at the upstream and downstream ends of the cooling region using split capacitive electrodes and high (200 kΩ) input impedance electronics.

In order to regulate at low voltages, these supplies must be able to sink the current flowing through R3G, as well as any corona current present. Power supply PS1 provides bias current to the gun anode power supplies, enabling them to either source or sink current. In addition, PS1 will provide enough current to discharge the gun anode power supplies to less than 500 V in one second, which allows the gun anode power supply to be used as part of an interlock system which quickly turns off the electron beam if there are high electron beam losses to ground, or if there is a radiation hazard present.

Collector Power Supplies

The Collector Power Supply (CPS)

The collector power supply, (CPS), is being built by the Universal Voltronics Corp. This supply provides all the power needed to circulate the electron beam. The output voltage of this line frequency supply is controlled by a servoed variac at the input, and an LC filter on the output reduces the ripple to less than 1%. Active filtering is not needed since studies have shown that the collection efficiencies are very insensitive to small voltage changes at the collector electrode.[12]

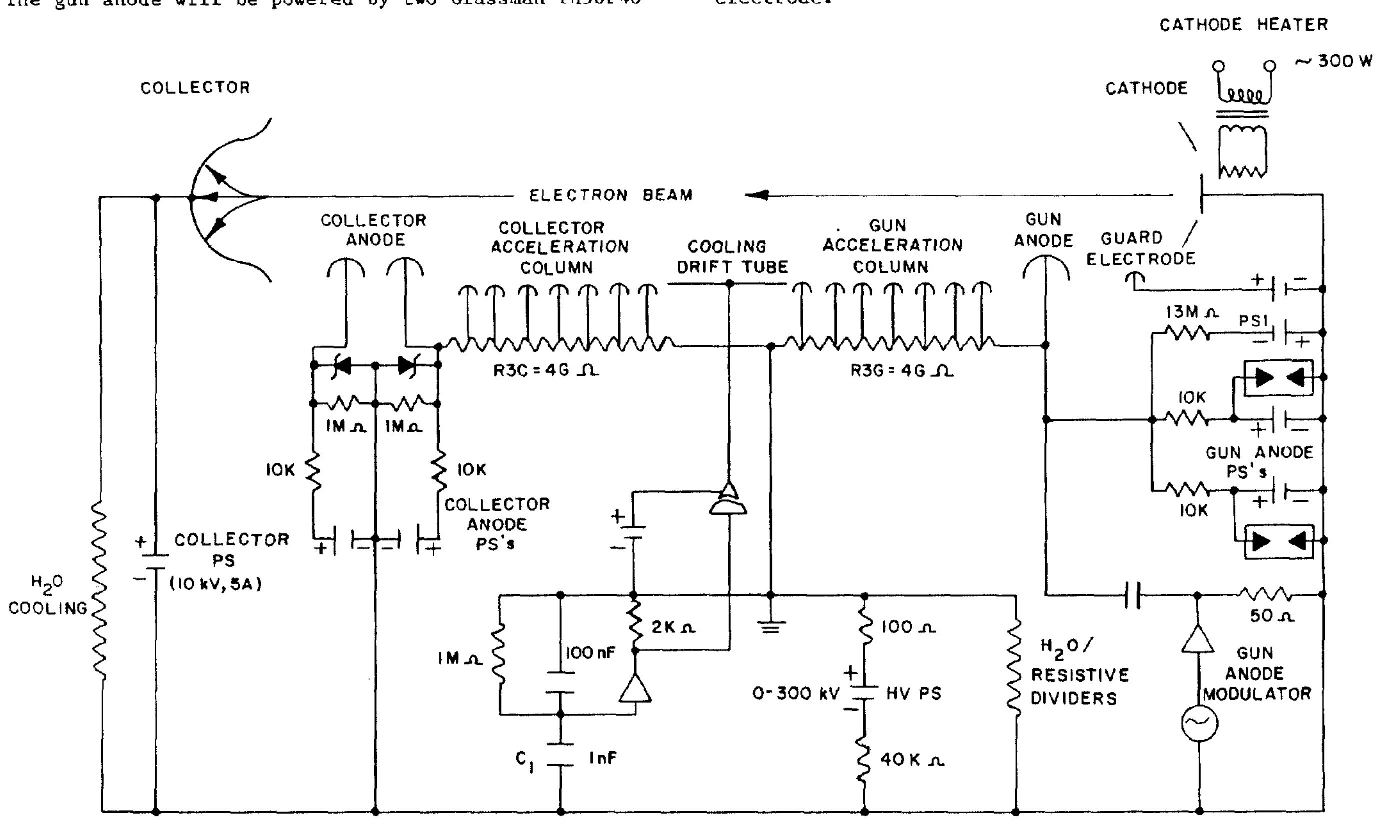

Figure 1. Schematic of electron cooling device high voltage power supply system.

Collector Anode Power Supply

The collector anode acts as a suppressor for electrons comming back from the collector. Studies have shown that the collection efficiency is maximized by biasing the collector anode electrode just above the potential at which a virtual cathode is formed;[12] only the electrons emitted from the collector surface with small angles relative to the magnetic field and energies nearly the same as the energy of the bombarding electrons are able to escape through the collector anode. The measured perveance of the FNAL collector anode ($45\ \mu A \cdot V^{-3/2}$) shows that there is a significant amount of space charge neutralization present in this region. These electrodes will be powered by two Glassman WG10P30 power supplies with a measured ripple of 13 V_{pp} while sourcing 16 mA. Bias current for this supply will be provided by a 1 MΩ load. Figure 2 shows a mechanical schematic of the collector region and acceleration structures.

Acceleration Stuctures

The acceleration structures will use two 14-gap National Electrostatics Corp. Dynamitron tubes. The tubes are fitted with spark-gaps, aluminum corona rings, and non-inductive bakeable resistors. The total column resistance is 4 GΩ, and the length and diameter are 14 inches, excluding the flanges. The columns will be surrounded by a 24 inch diameter cylinder which measures the corona current and fits inside the surrounding solenoid. A column of this type was tested at -300 kVDC in 1 atmosphere absolute of SF_6 for about three months. There were no problems with sparking, and the average measured corona current to the surrounding cylinder was about 20 nA. There is a radial gradient of 2.5 MV/m, and an axial gradient of 0.85 MV/m. The rated gradient for the Dynamitron tubes is 1.4 MV/m. The electrodes inside the column should not intercept any of the electron beam current due to the 1.5 kG solenoidal confinement field and the beam-limiting apertures at the gun and collector anodes.

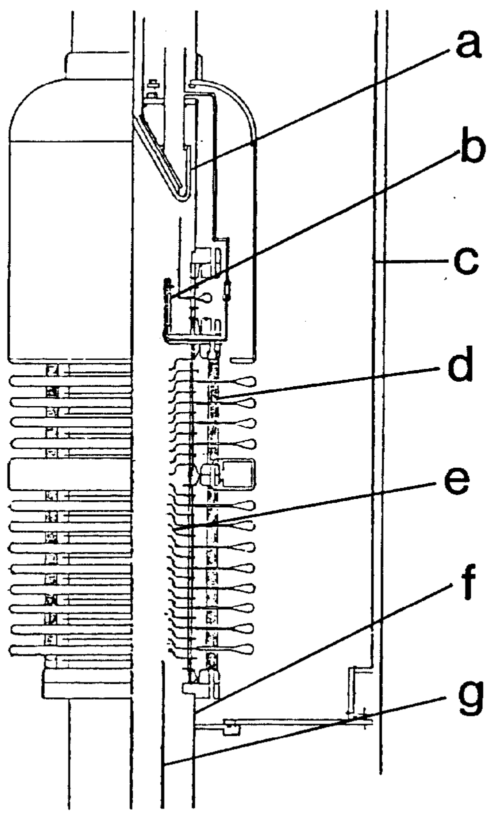

Figure 2. Electron collector. a - collector electrode; b - collector anode; c - corona monitoring screen and SF_b enclosure; d - delrin rods for compression; e - acceleration column insert electrodes; f - vacuum chamber; g - drift electrode.

Terminal and Faraday Cage Design

Tests at IUCF have shown that a 3 foot spacing from the Faraday cage walls to the terminal walls which are made of perforated aluminum sheet is necessary to keep the corona current density at a level of about 10 nA/m^2. All radii of curvature are 12 inches. The terminal will sit on commercial powerline 350 kV BIL station post insulators which have been tested and found to behave as very large 20 TΩ resitors.

Experience at IUCF and other laboratories[13,14] shows that a solid metal Faraday cage with low resistance joints is necessary to protect equipment outside the Faraday cage from interference due to sparking. Experience also shows that EMI gasketing is not necessary in the seams of the terminal, but that holes in the terminal walls should be avoided and care should be taken to provide a good ground return path for currents which flow inside the terminal when power supplies located in the terminal discharge. Sensitive controls should be isolated and kept inside an EMI-shielded relay rack. All the low current power supplies in the terminal which connect to loads outside the terminal should have a series output resistance of about 10 kΩ and should be spark gap protected. Added inductance on cables leaving the terminal (ferrite toroids) help prevent transients from entering the terminal.

Three phase 460 VAC power to the terminal will be provided by a Haefely 60 kVA, 350 kV isolation transformer similar in design to those in operation at LANL, LLNL, SIN and GSI.

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