CHAPTER 4. CONTROLLING THE FN ACCELERATOR

4.1 Description of the Problem

Figure 4-1 is a schematic diagram of the High Voltage Engineering model FN Tandem Accelerator, as installed at McMaster University.

Either of two sources -- Duoplasmatron or Sputter Source -- can provide an ion beam for acceleration. Each can produce negative ions of various elements, and accelerate them to a modest voltage (kilovolts).

The desired ion beam is selected by a steering magnet in the Injection subsystem. This subsystem also contains components to focus, steer, and analyze the beam, before it enters the main accelerator tank via evacuated stainless steel tubes ("beamlines").

The Generator is a large tank which contains a Van de Graaff generator. This generator charges a central electrode to several megavolts positive, accelerating the incoming ion beam. At the center, electrons are stripped from the ions, changing them to positive ions. The electrode then provides an additional several megavolts of acceleration as it drives the positive ion beam out of the tank and into the high-energy beamline.

The Analysis subsystem uses a steering magnet to turn the beam and guide it through a set of slits. Since the beam deflection is a function of the ion energy, charge state, and mass, this provides accurate control of beam energy.

The Distribution subsystem contains additional focusing elements, and a steering magnet to route the ion beam to one of eight "beam lines." Each beam line ends in a different experimental "target."

Figure 4-1 also shows the devices which are used to monitor the beam. The "cup" is a Faraday cup, which safely collects the beam and directly indicates beam current. Since this blocks the beam, it cannot be employed while the beam is in use; it doubles as a safety device to stop the beam. The "BPM" is

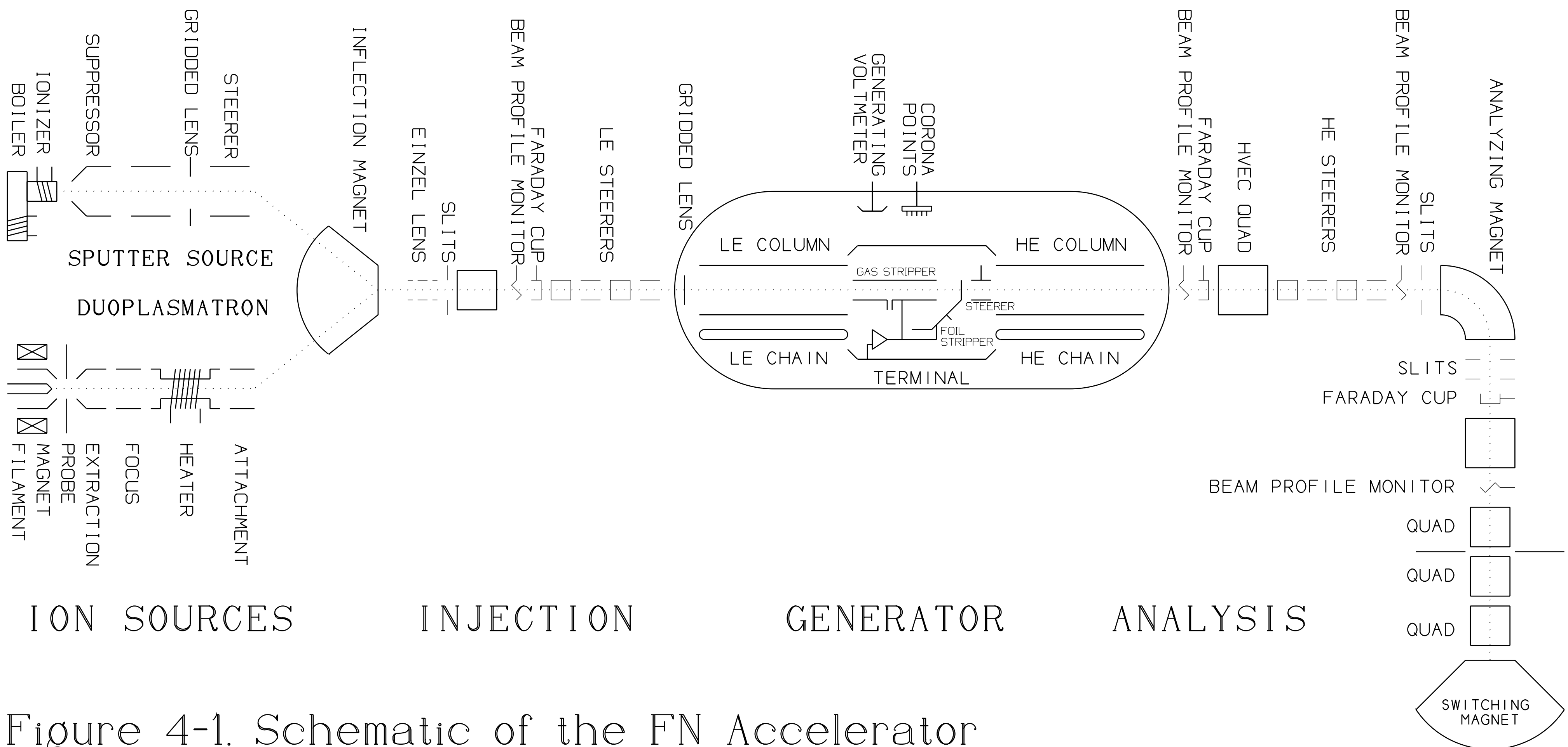

Figure 4-1. Schematic of the FN Accelerator

a Beam Profile Monitor. It observes the beam with relatively little disruption, and can be employed while the beam is in use; however, its interpretation is much more complex.

4.2 Basic Operating Sequence

The basic operating sequence of the FN accelerator, as documented by the manufacturer (High Voltage Engineering 1968), is as follows:

a) Activate the generator, and adjust for the desired terminal voltage.

b) Activate the desired ion source, and adjust for desired output.

c) Adjust the injection subsystem to select the ion source and for desired output.

d) Adjust the generator subsystem for desired output.

e) Adjust the analysis subsystem for desired output.

f) Adjust the distribution subsystem (switching magnet) to select the desired beam line, and adjust for desired output.

The phrases "adjust" and "desired output" are deceptively simple in this description. For example, the injection subsystem has seven adjustments, which must select the desired ion source and the desired ion mass, steer the beam into the accelerator, and achieve the desired beam profile and intensity. This description also omits the problem of keeping the beam in adjustment, once the accelerator is running. However, it does illustrate an important characteristic: the accelerator subsystems are largely independent. For instance, the injection subsystem can be adjusted without reference to the analysis subsystem.[1]

4.3 The Terminal Charging Subsystem

An example of the complexity of even one subsystem can be seen in the terminal charging mechanism, Figure 4-2. Two variable high-voltage power supplies deposit charge on the charging chains. The chains, moving in an endless loop, carry this charge to the terminal. As charge accumulates on the terminal, its voltage increases. Charge bleeds off from the terminal through the two fixed column

1. There is some interaction between subsystems, which becomes important in the "steady-state" operation of the accelerator.

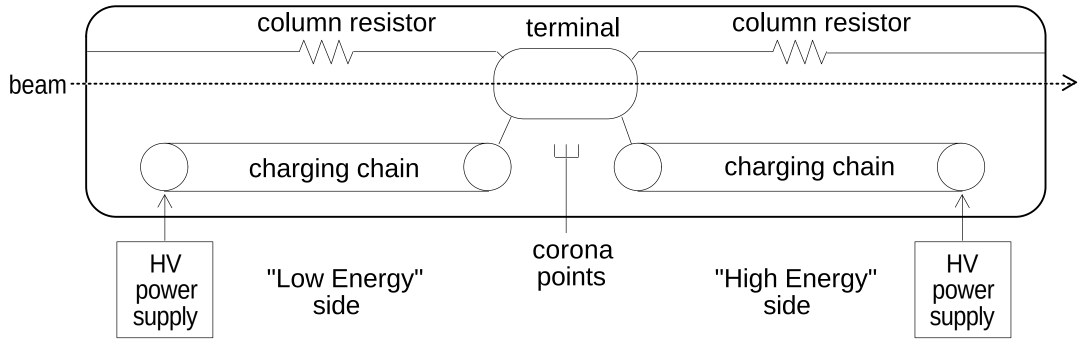

Figure 4-2. Terminal Charging Mechanism

resistors, and also by corona discharge to the adjustable corona points.

Mathematically this can be modeled by assuming:

a) The DC high voltage output of the supply is some function f_{HV} of the AC input voltage.

b) The charge current deposited on the chain is proportional to the DC voltage.

c) The motion of the chain introduces a fixed time delay (about 0.5 second) in the charging current.

d) The terminal has a fixed capacitance to ground.

e) The corona discharge current is proportional to terminal voltage, for any given position of the corona points.

f) There is a time delay from the terminal to the corona points, which is fixed for any given position of the points.

g) There is a fixed time delay in the terminal voltmeter (not shown in Figure 4-2).

The charging model using these approximations is shown in Figure 4-4. This model can be subjected to a classical feedback system analysis.

4.4 The Distributed Processor Hardware

Figure 4-3 illustrates the control system for the FN Tandem Accelerator. It includes six "local" controllers, corresponding to the six subsystems of the accelerator, plus a central control station.

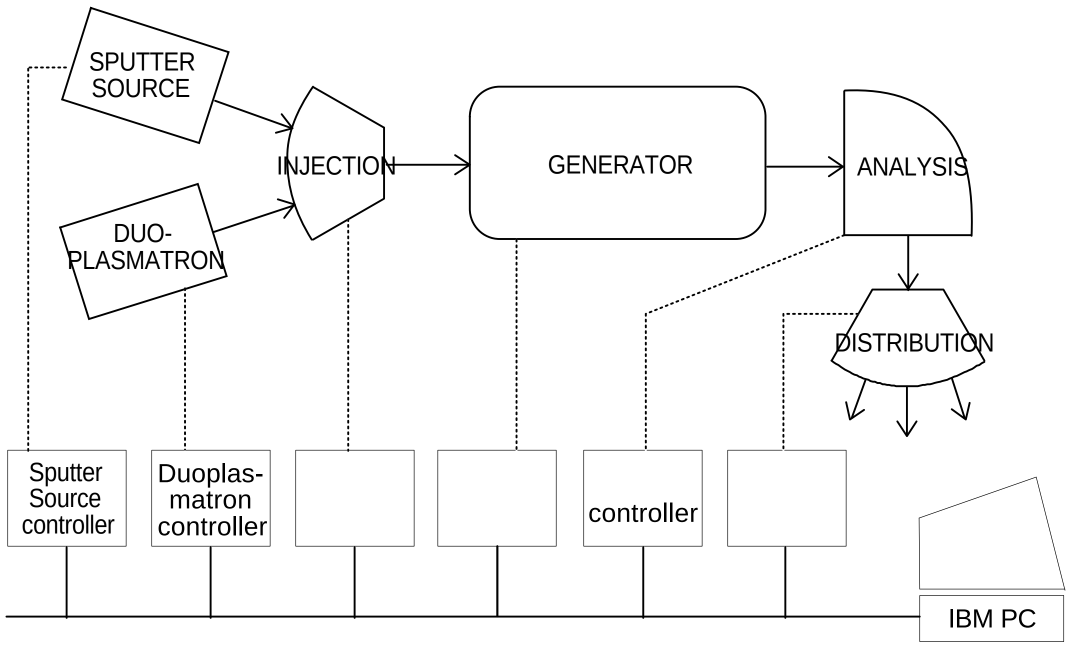

Figure 4-3. The Distributed Processor Hardware

Local Controllers

Each local controller is a New Micros Inc. NMIX-0026 single-board computer, employing the Motorola 68HC16 microprocessor. Two New Micros interface boards are added to provide the "standard" I/O complement for each controller:

Eight 10-bit analog-to-digital converters

Four 12-bit analog-to-digital converters

Two 12-bit digital-to-analog converters

Six TTL inputs

Three TTL outputs

The local controllers incorporate both simple active control algorithms, such as PID[2] loops, and inference engines for rule-based reasoning.

2. Proportional-Integral-Derivative, or PID, refers to a feedback system in which the control signal is a linear combination of the error signal, its time integral, and its first derivative.

Operator's Console

All system functions are controlled from the operator's console, an IBM PC with 80386 processor and a VGA graphics display. This system is responsible only for operator input, display, and network supervision. No inferencing tasks are performed by the PC.

Network Communications

Eventually it will be desired to install the local controllers as close as possible to their respective subsystems, i.e., at the accelerator machinery. Since some of this machinery is at a potential of several kilovolts, the staff of the Accelerator Laboratory requested the use of fiber optic communications. This led to the development of a token-ring network using the asynchronous ports of the 68HC16s and the IBM PC (described in Appendix B). The development hardware uses point-to-point RS-232 serial cables to simulate the fiber optic links.

Safety Considerations

Licensing regulations under the Atomic Energy Control Board (AECB) require that no accelerator functions be left solely under control of the computers. It must be possible for the human operator to gain control of the accelerator at all times, regardless of any system malfunction. Prior work at the McMaster Accelerator Laboratory has used mechanical linkages from the computer to the physical control knobs of the accelerator (Lind, Poehlman, and Stark 1993). This project uses entirely electronic controls with "fail-safe" operation.

Most sensor readings are displayed on panel meters in the Tandem electronics rack. The local controllers were designed and developed to noninvasively sense the meter readings through the "Meter Repeater," a circuit board which mounts on the back of each panel meter and monitors the current or voltage at the meter terminals. Each board includes a simple first-order RC filter to reduce high-frequency noise.

The Tandem accelerator uses Variacs for many of its control actuators. These variable autotransformers provide from 0 to 110 VAC to a number of accelerator subsystems, such as high voltage power supplies. For computer control each is replaced with a "solid state Variac," a phase-controlled Triac. The Triacs can be operated manually on command or if the computer fails.

These interfaces, and others devised for this project, are described in more detail in Appendix A.

4.5 I/O Processing Software

Additional conditioning of the sensor inputs is performed in software by the local controllers. A second-order infinite-impulse response (IIR) filter, operating at a sample rate of 18.2 Hz, attenuates high-frequency noise on the inputs. The "zeros" of this filter are adjusted to eliminate any aliased 60 Hz noise. These filters use the DSP capability of the 68HC16 microprocessor.

Control outputs are also assisted by numerical software. For instance, a Proportional-Integral-Derivative (PID) feedback loop achieves a desired DC charging voltage by adjusting the AC input to the HV power supply. The nonlinear transfer functions of the Triac control and the HV power supply are

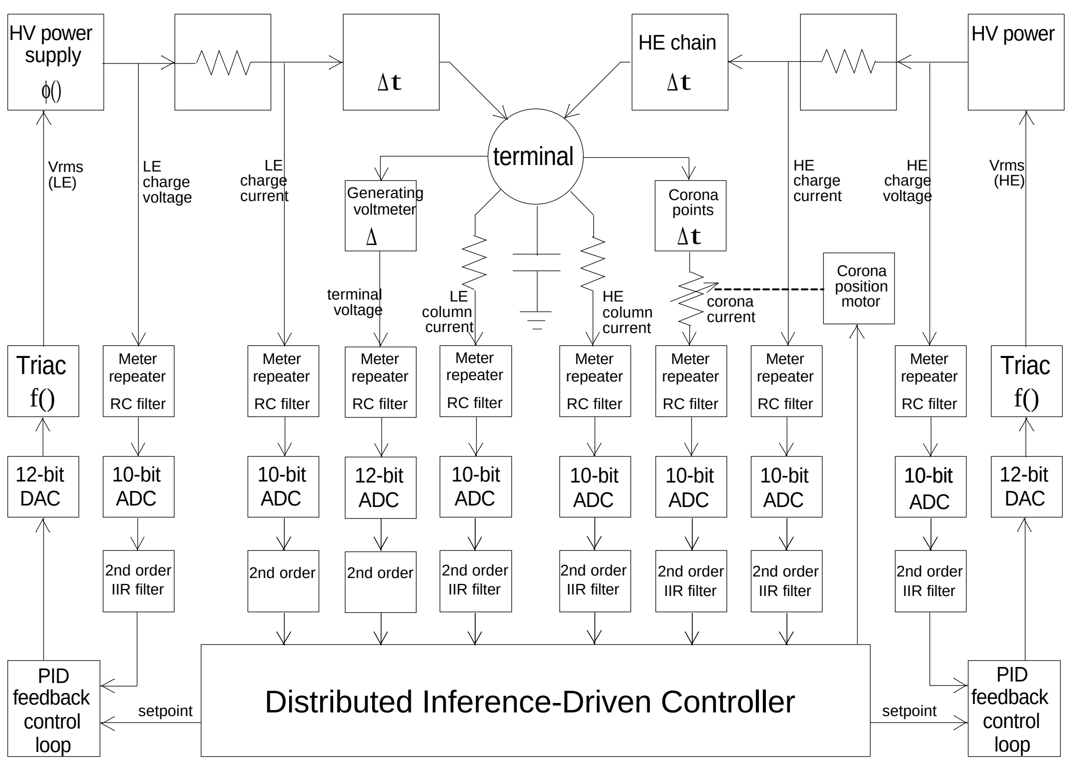

Figure 4-4. Terminal Charging Model

"hidden" from the expert system, which only need to specify a desired charging voltage "setpoint."

These processing functions are illustrated in Figure 4-4.

4.6 Operator Interface

Since the purpose of this research is to investigate a control technology, and not to produce a finished product for accelerator control, only a rudimentary operator interface is included. Sensor data is displayed in tabular form on a text-only screen. A command interpreter resides on the PC and also on the local controllers. The operator may issue commands to any or all local controllers via the network; this is a great aid in development and debugging.

4.7 The Terminal Control Strategy

The objective of the terminal control subsystem is to achieve a specified voltage on the terminal, with a usable corona current, while avoiding sparks. The corona current must be within a limited range (typically 50 to 100 uA) in order for the terminal stabilizer hardware to function (Cairns, Greene, and Kuehner 1974). Excessive corona current must be avoided, as it will cause potentially damaging sparks from the highly charged terminal. Sparks may also occur if the terminal voltage is excessive, or if the terminal is charged too quickly (rate of change of terminal voltage is excessive).

The terminal voltage is increased by supplying charge faster than the column resistors and corona points are bleeding off charge. Corona current is increased by moving the corona points inward, and

Terminal Voltage Corona Current	Low	OK	High
Low	Increase charge	Extend points	Extend points
OK	Increase charge	Do nothing	Reduce charge
High	Retract points	Retract points	Reduce charge

Figure 4-5. Terminal Charging Heuristic

decreased by moving the points outward. There is a strong interaction between these two adjustments. Corona current is proportional to terminal voltage. Also, withdrawing the corona points will cause a rapid increase in terminal voltage -- as the corona current decreases, the net charging current will increase.

After discussions with Jim Stark, Director of Operations of the McMaster Accelerator Laboratory, the decision matrix of Figure 4-5 was devised. This represents the following heuristic reasoning:

a) If the terminal voltage and the corona current are both low, increasing the charge will increase both.

b) If the terminal voltage is low and the corona current is OK, more charge is required.

c) If the terminal voltage is low and the corona current is high, retracting the points will both increase the terminal voltage, and decrease the corona current.

d) If the terminal voltage is OK and the corona current is low, it is necessary to extend the points.

The remaining four adjustments are the "mirror image" of these. The ninth case, when the terminal voltage and the corona current are both OK, requires no action.

The effectiveness of this control strategy, and some modifications to it, are discussed in Chapter 6.