6. IMPLEMENTATION OF THE FULL PROGRAM

6.1 The full-energy Booster Injector

This section describes the steps necessary to upgrade the Duke Free-Electron Laser Laboratory (DFELL) storage ring injection system to 1.2 GeV which will allow full energy injection (1.2 GeV) into the storage ring. Currently, the preferred approach in the design of modern storage rings is to utilize booster rings or synchrotrons which allow for a rapid ramp of the electron energy from a few 10’s of MeV to a few GeV [JAE95]. This design of booster injectors provides high reliability, low operation cost, and high efficiency without reduction in electron beam quality. In contrast to designs utilizing linac injectors, the booster rings provide electron beams without halos and low-energy tails. The booster rings provide high injection efficiency without increased radiation hazards during injection which reduces the facility cost.

Another reason for the modest cost of the booster ring is the availability of commercial sources for this technology. The current linac injector will be used during the initial phases of the nuclear physics program while the booster ring will be assembled. Commissioning of the booster can be accomplished within two months, i.e., the transition to the fully capable HIGS facility will be very short.

Another reason for the modest cost of the booster ring is the availability of commercial sources for this technology. The current linac injector will be used during the initial phases of the nuclear physics program while the booster ring will be assembled. Commissioning of the booster can be accomplished within two months, i.e., the transition to the fully capable HIGS facility will be very short.

6.1.1 Overview of the Booster Injector

The preliminary layout of the booster injector is shown in Figure 6.1. It consists of twelve bending magnets and sixteen quadrupole magnets made of laminated steel. The lamination is required for a 1-3 Hz injection rep-rate. The booster has two straight sections incorporating an

![Figure 6.1 Layout of the 1.2 GeV booster injector.](image-url)
injection system, an ejection system and a 178 MHz RF cavity. Two existing 2856 MHz linac sections are available to provide 50-80 MeV electron beam injection into the booster. The existing RF gun should be adequate for this system. Energies of 50 to 80 MeV are sufficient for reliable injection into the booster ring. The 50-80 MeV injector will be fed by an existing 30-MW, 2856 MHz klystron. A fast chopper will be installed after the RF gun to form the necessary train of pulses for single-bunch or multi-bunch injection.

The main parameters of the booster injector were given already in Section 2.2.1

We chose the robust FODO lattice for the booster ring to simplify its operation. We plan to use two main controllable power supplies: one for all dipole magnets and the other for all quadrupole magnets. A small number of auxiliary power supplies will be used for trim dipoles and sextupoles. The use of a small number of power supplies will allow the ejection energy from the booster (i.e. injection energy to the Duke storage ring) to be changed in a matter of seconds. This capability will lead to a convenient and efficient variation of the γ-ray energy in the HIGS facility.

The parameters of the electron beam are defined by the lattice of the booster ring and are listed in Section 2.2.1 also. These parameters are adequate for the full flux operation of the HIGS facility.

6.1.2 Magnets

The dipole magnets for the booster injector will be made from a laminated high quality magnetic steel. The stamp for the lamination profiles will be the same as that used for the dipole magnets for the LHC (CERN) injection system. The main parameters of the dipole magnets are listed in Table 6.1. There is a possibility to use the dipole design for the 1.9 (2.5) GeV BESSY II booster injector with a lower magnetic field and larger radius of curvature. In this case the size of the booster ring will increase by about 30% with no cost reduction.

We plan to use the same quadrupole, sextupole and trim dipole magnets which were designed and built for the 1.9 (2.5) GeV BESSY II booster injector [JA95]. This booster injector has been successfully commissioned this year and is operating successfully. Parameters of the quadrupole magnets are listed in Table 6.2.

The natural chromaticities of this lattice are rather small and can be corrected with four sextupoles. Twelve dipole correctors (six horizontal and six vertical) will be sufficient to correct the closed orbit to the required accuracy of ±0.25 mm.
Table 6.1. Main parameters of the booster dipole magnets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic length</td>
<td>1.20 m</td>
</tr>
<tr>
<td>Radius of curvature</td>
<td>2.30 m</td>
</tr>
<tr>
<td>Magnetic field, B, at 1.2 GeV</td>
<td>17.4 kG</td>
</tr>
<tr>
<td>Magnetic field, B, at 1 GeV</td>
<td>14.5 kG</td>
</tr>
<tr>
<td>Nominal magnetic field</td>
<td>0.5-18 kG</td>
</tr>
<tr>
<td>Maximum magnetic field</td>
<td>19.5 kG</td>
</tr>
<tr>
<td>Lamination transverse sizes</td>
<td>33.2x56.4 cm</td>
</tr>
<tr>
<td>Gap</td>
<td>2.5 cm</td>
</tr>
<tr>
<td>Region of homogeneity</td>
<td>5 cm</td>
</tr>
<tr>
<td>Homogeneity δB/B</td>
<td>&lt; 4 \cdot 10^{-4}</td>
</tr>
<tr>
<td>Ratio B_{core}/B_{gap}</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 6.2. Main parameters of the booster quadrupole magnets.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core length</td>
<td>0.30 m</td>
</tr>
<tr>
<td>Nominal gradient</td>
<td>1.4 kG/cm</td>
</tr>
<tr>
<td>Transverse sizes</td>
<td>33.2x56.4 cm</td>
</tr>
<tr>
<td>Aperture radius</td>
<td>3.5 cm</td>
</tr>
<tr>
<td>Homogeneity δG/G</td>
<td>&lt; 6 \cdot 10^{-4}</td>
</tr>
<tr>
<td>Resistance</td>
<td>7 mΩ</td>
</tr>
<tr>
<td>Inductance</td>
<td>1.76 mH</td>
</tr>
<tr>
<td>Coil current</td>
<td>630 A</td>
</tr>
<tr>
<td>Power loss</td>
<td>1.1 kW</td>
</tr>
</tbody>
</table>

Two Lambertson-type septum magnets will be used for injection to and ejection from the booster ring. The ejection septum magnet will be an exact copy of the one installed on the Duke storage ring [BUR93]. The injection septum magnet will be a down-sized (by a factor ten) version of the ejection septum magnet.
Two short-pulse kickers similar to the existing Duke storage ring design will be used; one for injection and the second for ejection of the electron beam. The booster-to ring transport line will use already available magnets, power supplies and vacuum chambers. A small number of new vacuum chambers and supports will be required.

6.1.3 Vacuum chamber

We will use thin stainless steel vacuum chambers for the magnets similar to those developed for 10 Hz operation of the BESSY II booster injector. Skin-effects in the walls of the vacuum chambers will not present any problems for the quality of the magnetic field due to the low (1 - 3 Hz) rep-rate. The vacuum chambers for the straight sections will be made from standard stainless tubes. A number of ion vacuum pumps will be distributed around the booster to provide a vacuum in the $10^{-9}$ torr range. Special vacuum chambers (designed and made for the Duke storage ring) will be used in the locations of the septum and kicker magnets. Overall, the vacuum system of the booster ring will be based on standard technology and existing designs.

6.1.4 RF system

The RF system of the booster injector will be an exact copy of the existing Duke storage ring system. We will buy a duplicate of the existing RF cavity and will use an existing 40 kW transmitter to feed the cavity.

Table 6.3. Main parameters of the booster quadrupole magnet.

<table>
<thead>
<tr>
<th>RF system</th>
<th>MHz</th>
<th>kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td>RF power</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>RF voltage</td>
<td>250-500</td>
<td></td>
</tr>
<tr>
<td>Energy losses per turn</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

6.1.5 Linac Injector

We will use existing linac components for the 50-80 MeV linac injector to the booster ring. An existing 30 MW klystron and 300 kV modulator will drive both accelerator sections and the RF gun.
Table 6.4: Klystron specifications.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency, nominal</td>
<td>2856 MHz</td>
</tr>
<tr>
<td>Output peak RF power</td>
<td>30 MW</td>
</tr>
<tr>
<td>Cathode voltage</td>
<td>270 kV</td>
</tr>
<tr>
<td>Pulse length</td>
<td>2 μs</td>
</tr>
<tr>
<td>Pulse Repetition rate</td>
<td>2 Hz</td>
</tr>
</tbody>
</table>

A fast beam-chopper and small chicane will be used to produce a 5-ns train of micropulses to match the RF bucket of the booster ring. The linac-to-booster transport line will use many of the existing vacuum components and magnets.

6.1.6 Instrumentation and control systems

The instrumentation and control systems consist of the electron beam diagnostic system, the data acquisition hardware, control computers, electronic measurement equipment, timing systems, power supplies, and power and data distribution cables. The Duke storage ring EPICS control system will be used for monitoring and controls. The control system for the injector will be fully integrated into the Duke storage ring control system. This means that the control of the booster injector will be “a slave” of the Duke storage ring control system. For example, the ejection energy of the booster will follow automatically the operation energy of the Duke storage ring. This will ensure continuous full energy injection during scans of the γ-ray energy.

6.1.7 Utilities, safety systems, and related upgrades

Some minor upgrades of the electrical and water utilities will be required. The only substantial cost is associated with radiation shielding of the entire system, which includes the injector and the storage ring.

6.2 Duke Storage Ring Modifications

6.2.1 Status of the OK-4/Duke storage ring FEL and the HIGS γ-ray source

The magnetic systems of the OK-4 undulator were installed and commissioned with electron beams in November, 1995. The wigglers performance was tested using OK-4 FEL diagnostics and was found to be consistent with theoretical predictions. The OK-4/Duke FEL operation in the spontaneous radiation mode was demonstrated in the energy range of 250 MeV-1.1 GeV. Measurements of the electron beam properties and the parameters of the spontaneous radiation confirmed our expectations.
The OK-4 diagnostics were re-commissioned at Duke in 1995. The OK-4 FEL optical cavity with sophisticated feed-back and control system was built and commissioned. A number of multilayer dielectric mirrors for the OK-4 optical cavity with central wavelength from 150 nm to 400 nm are in house or currently being manufactured. A typical optical resonator with multilayer dielectric mirrors has ±20-30% wavelength tunability. It is possible to enlarge the tunability range by a factor of two using broad-band mirrors with lower reflectivity. However, this technique is also limited in wavelength range. A new optical resonator, which is under development in the DFELL, will utilize the full FEL tunability. It will employ multi-facet Al reflecting mirrors and will provide for 4-to-8 fold tunability of the FEL wavelength from the VUV to the visible range. This will extend the γ-ray energy well above the pion threshold to 170 MeV. In addition, this cavity will optimize the collision conditions for high resolution γ-ray studies.

Modifications of the storage ring vacuum chambers, required for the OK-4 beam-line connections, were completed in the fall of 1996. The initial operation of the OK-4 FEL at a wavelength of 345 nm (3.6 eV) was achieved in November of 1996 with both one and two electron bunches in the ring. This was done at ring energies of 250-550 MeV. Results of these experiments were published in Ref. [LIT97A]. The production of γ rays began immediately after FEL commissioning, as discussed in Section 6.

6.2.2 Upgrades of the 178 MHz RF system

The present Duke storage ring 178 MHz RF system has one RF cavity fed by a 50-55 kW transmitter. This power is sufficient to support the 600 kV accelerating voltage in the RF cavity. This voltage is also sufficient to provide the HIGS operation in the no-loss mode with γ rays up to 20 MeV. Extension of the no-loss mode to 40 MeV requires upgrades of the 178 MHz RF system. In particular, it requires installation of a second RF cavity, a new 150 kW transmitter and an additional RF circulator. In addition to full flux HIGS operation below 40 MeV, these upgrades will increase the gain of the OK-4 FEL and will extend its range of operation below 120 nm (i.e. above 10 eV).

The limitations for the no-loss mode of HIGS operation are two-fold. First, at a given energy of the storage ring, the OK-4 FEL can be tuned 16 fold. Nevertheless, its longest wavelength is limited by:

\[ \lambda_{FEL,\text{max}}[nm] \equiv \frac{205}{E^2[GeV]} \cdot \]

This means that the energy of FEL photons can not be lower than:

\[ E_{\gamma,\text{min}}[eV] \approx 6 \cdot E^2[GeV] \cdot \]
and the peak energy of $\gamma$ rays can not be lower than:

$$E_{\gamma_{\text{min}}} [\text{MeV}] = \frac{92 \cdot E^2 [\text{GeV}]}{1 + 0.092 \cdot E^2 [\text{GeV}]}.$$ 

Higher energy $\gamma$ rays are possible, but it is impossible to go below this limit with the existing OK-4 wigglers. The maximum energy acceptance of the Duke storage ring is 5%. The minimum peak energy of $\gamma$ rays reaches this ultimate limit at an electron energy near 800 MeV, as shown on Figure 6.2.

![Figure 6.2 Plots of the minimum possible OK-4 FEL photon energy and minimum peak energy of $\gamma$ rays as a function of the electron beam energy. The minimum peak energy of the $\gamma$ rays cross the 5% energy acceptance line near 800 MeV. This means that operation in the no-loss mode is physically impossible above 800 MeV.](image)

Figure 6.2: Plots of the minimum possible OK-4 FEL photon energy and minimum peak energy of $\gamma$ rays as a function of the electron beam energy. The minimum peak energy of the $\gamma$ rays cross the 5% energy acceptance line near 800 MeV. This means that operation in the no-loss mode is physically impossible above 800 MeV.

![Figure 6.3 Plots of the RF voltage and power requirements for the HIGS no-loss operation.](image)

Figure 6.3: Plots of the RF voltage and power requirements for the HIGS no-loss operation.
6.2.3 Construction of the 717 MHz RF system.

High-resolution $\gamma$-ray experiments require the preservation of the small energy spread in the target bunch. There are two major effects which could increase its energy spread: a) lasing in the FEL, and b) microwave instability.

Lasing will occur when the FEL gain associated with the target bunch exceeds the optical cavity losses:

$$ G_{\text{FEL}} = a \cdot I_{\text{peak}} = a \cdot \frac{I_{\text{bunch}}}{\gamma^{2} \pi \sigma_{o}} \times C > L, $$

where $I_{\text{bunch}}$ is the current in one bunch, $C_{o}$ is the circumference of the storage ring and $\sigma_{o}$ is the bunch length. To prevent lasing it is necessary to keep the peak current low:

$$ I_{\text{peak}} < \frac{L}{a}; \ a = 0.2\% / \text{Amp}. $$

In order to have the maximum $\gamma$-ray flux, the maximum interactive power is required. Therefore, the optical cavity losses must be kept as low as possible. In this case, the target bunch will lase when its current exceeds a few milliamperes. When it lases, its energy spread grows far above its natural value of 0.046% (at 1 GeV). It is possible to use the optical cavity Q-modulator operating with 5.6 MHz to increase the losses for the target bunch while keeping them low for the lasing bunch. Nevertheless, microwave instabilities will occur at peak currents above 5-10 A and will cause a substantial growth in the energy spread.

A second RF system, operating on an odd harmonic could cure both problems at once. It will allow us to lengthen the target bunch by a factor of 6-10 and prevent both lasing and microwave instabilities. A schematic view of the system is shown in Figure 6.4.
Although the potential well created by two RF systems is flat for the target bunch, (Figure 6.5, right) it is steep for the lasing bunch (Figure 6.5, left). This makes it possible to lengthen the target bunch to \( \sqrt{2\pi}\sigma_l \approx 30 \text{ cm} \) and to run with a large current in the target bunch (\( \sim 50 \text{ mA} \) with 2% cavity losses) while preserving its energy spread characteristics.

This mode of operation, so called "RF gymnastics", is well known in accelerator practice and has previously been used to achieve bunch lengthening [KRA94]

Figure 6.5. Two RF systems create the potential well which is steep for the lasing bunch (left) and almost flat for the target bunch (right). It makes the target bunch 6 to 10 times longer than the lasing bunch and keeps it peak current below the lasing threshold and microwave instability threshold.

In addition to making an almost perfect target bunch, the 717 MHz RF system will shorten the lasing bunch and improve the OK-4 FEL lasing characteristics.

6.2.4 Upgrade of the electron beam optics at the collision point

At high electron energies, the natural emittance of the electron beam grows as the square of its energy. This means that contributions to the electron beam angular spread will grow as the fourth power in energy. For improvements of the \( \gamma \)-ray energy resolution at high energies it is desirable to modify the electron beam optics, i.e., the lattice, at the collision point. This will allow us to reduce the angular spread by a factor 5-to-10 and therefore improve the \( \gamma \)-ray energy resolution considerably.
The collision point will be displaced from the center of the OK-4 FEL down-stream into the area, where a special "large-β" insertion will be installed. This insertion will consist of three large diameter quadrupoles to provide a 40-m horizontal β-function at the collision point in order to match the electron beam optics with the rest of the storage ring. Whereas the current design gives an energy resolution of ±0.55%, increasing βx to 40 m should reduce this resolution to ±0.06%. This modification will require the installation of additional optical elements in the South Straight Section of the electron storage ring. The storage ring lattice modification required to incorporate the "large-β" insertion will be a part of this proposal. A schematic of the modified lattice is shown in Figure 6.6.

![Figure 6.6. Schematic of the modified FEL straight section with the "large-β" insertion.](image)

The total number of γ-rays which will be produced is directly proportional to the number of FEL photons contained in the optical cavity. This number can be maximized by making the appropriate choice of cavity mirrors. Because our proposed operating conditions require powers and energies which will be somewhat beyond present experience in some cases, some testing of the stability and reflectivity of various mirrors will be necessary. Funds are being requested for these tests.

### 6.2.5 Upgrade of the storage ring shielding

The existing shielding of the storage ring is adequate for the no-loss mode operation. Local shielding is required around the downstream optical cavity mirror to protect personnel from neutrons created in the mirror substrate (see following section). A substantial modification of the storage ring shielding is required for full flux HIGS operation in the loss mode. Electron losses will occur near the second dipole magnet in the East arc. The shielding of this area must be properly designed and constructed. The permanent solution for the radiation shielding will be a concrete roof above the storage ring. Design of the radiation shielding and its construction will be executed as a part of this proposal.

### 6.3 Flux Monitoring
The intensity and energy resolution of the $\gamma$-ray beam will be monitored using a pair spectrometer based on a previous design used at Mainz [Ahr97]. A thin metallic foil placed in the beam path will convert a known percentage of the $\gamma$ rays into electron-positron pairs. These pairs will be extremely forward-peaked, but will be deflected from the beam path by a magnetic field. Two multiwire proportional counters will measure the amount of deflection each particle experiences, giving a precise measurement of the initial electron momentum and therefore of the energy of the initial photon. The energy resolution of the pair spectrometer is expected to be below 0.1%. Two silicon strip detectors, placed downstream of each of the wire chambers, will provide complete information on the $\gamma$-ray beam, including its flux.

We have recently obtained the magnets needed for this pair spectrometer from our colleagues at the Max Planck-Institut in Mainz, Germany. The construction and commissioning of the pair spectrometer is being funded as part of a TUNL/Duke University Ph.D. dissertation project. Therefore, the cost of this detector system is not included in this proposal.

6.4 Targets

6.4.1 Liquid H-target

A liquid hydrogen target will be used in conjunction with the NMS spectrometer (Attachment F) system (see Section 6.6) in studies of the $p(\gamma,p^0)p$ reaction. We propose to use a spherical hydrogen target with a diameter of 5 cm. A similar design will also be used to construct a cylindrical 8 cm long target for our Compton scattering measurements of the proton polarizabilities. The best choice for cell wall material appears to be 2 mil thick aluminized mylar foil. This cell will have a spout attached at the top to allow filling and emptying of the target material. The cell itself will be equipped with a temperature sensor located on the fill tube to monitor the state of the target material. A heating element will be attached to the system to allow the target to be emptied for purposes of collecting empty-target background data.

In addition to the target cell itself, a cryostat to contain and support the target must be developed. This involves enclosing the target cell with a cylindrical heat shield of aluminum. The heat shield is in turn contained within a vacuum shroud. Both the heat shield and vacuum shroud will be made of aluminum. The cryostat will also contain a reservoir for the liquid hydrogen which will be surrounded by a jacket filled with liquid nitrogen. This entire assembly will reside within a large super-insulated vacuum dewar. This dewar will be equipped with vents for both the liquid nitrogen jacket and the hydrogen. Appropriate safety measures, including a hydrogen "tent" erected over the dewar and target system, will be taken.

The liquid hydrogen reservoir will have both a liquid "fill" line to the target and a gas "return" line from the target. When the target is to be emptied, a valve on the liquid fill line will
be shut, while the gas return will remain open. The target heating element is engaged and the liquid hydrogen is quickly evaporated, hence providing an "empty target". The typical emptying time is estimated to be 30 minutes, while refilling the target and the associated cool-down time will require approximately six hours.

It is anticipated that these targets will be constructed using a combination of in-house and outside user (e.g., U.Va.) funds.

### 6.4.2 Polarized Target

The polarized target which we are proposing to use here would be a solid dynamically pumped target, which will provide the thickness, accessibility and capability of rapid polarization reversal required for the proposed experiments (see Section 1.1.1). Such a target is presently operated by the Polarized Target Group at TUNL for studies of n-p scattering. This target facility is based upon a PSI design [VDB90] which employs a $^3$He evaporation cryostat operating at 0.5 Kelvin and a 2.5 Tesla split-coil superconducting magnet. The actual target is a cubic volume 14 mm on a side filled with beads of propanediol doped with EHBA-CrV complex. The effective thickness of the target is $4 \times 10^{22}$ protons/cm$^2$. Polarizations of approximately 70% have been achieved with an incident microwave power of 10 mW. The proton polarization direction can be reversed in 30 minutes by changing the microwave frequency. This target can be rather easily modified to provide a polarized deuteron target for use in initial studies of the DHG Sum Rule. Funds to permit this modification and installation of the modified target and support structure at the HIGS site are being requested.

The Neutral Meson Spectrometer which we are planning to use in the $(\gamma,\pi^0)$ experiments requires a horizontal dilution refrigerator with the target operating in the frozen-spin-mode [NII76] in order to permit large solid angle detection. The target will be polarized at 0.4 Kelvin in the field of a 2.5 Tesla solenoid. The target will then be cooled to 50 mK and the large polarizing magnet will be withdrawn. The target polarization will be maintained by a 0.3 Tesla holding field supplied by a smaller set of coils inside of the cryostat. In this mode of operation, the target polarization may be reversed in approximately 15 minutes by rotating the holding field [VDB95].

The TUNL dynamically polarized target system was constructed in collaboration with the group at the University of Texas and portions of the system must be returned to them upon completion of the present experiment at TUNL. Providing a dynamically polarized target for the present experiments will require the replacement of items returned to UT. Additional funds are needed for the construction of a horizontal cryostat and separate magnet dewar and for installation of the system in the DFELL laboratory. These costs are detailed in the budget request (see Section 11 and Attachment A).
6.5 Detectors

6.5.1 Available Detectors

Initial studies will be performed using TUNL detector systems. These include various detectors suitable for γ-ray, charged-particle and neutron detection. Included are:

1. Four 10"x10" NaI detectors
2. Three NE-110 plastic annuli which are designed to be used as anticoincidence shields for the NaI detectors listed above
3. Two large volume HPGe detectors (128% and 140%)
4. Four 60% HPGe detectors
5. Numerous silicon surface barrier detectors

6.5.2 The LANL Neutral Meson Spectrometer (NMS)

Accurately measuring the photoproduction of π⁰ near threshold will require a detector with good angular resolution. In addition, the detector will need to cover a large solid angle in order to accomplish the experiment in a reasonable time period. The primary reason for the demanding detector requirements is the short lifetime of the π⁰ and its subsequent decay into two photons. As a result, in order to extract information about the pion, the momentum vectors of the two photons must be added to determine the pion production angle. So, the ability to extract precise information about the pion depends on our ability to measure the kinematics of the photons. Furthermore, the photons are nearly isotropically distributed over 4π, so any reasonable efficiency requires a large solid-angle detector.

LANL has constructed a high resolution, large acceptance spectrometer for neutral mesons, called the NMS. The NMS is comprised of two arms, each of which contains a pure cesium iodide photon calorimeter, a bismuth germinate converter and a cathode-readout tracking chamber. The calorimeters are used to make measurements of the two gamma-ray energies and to confirm the measurements of the gamma-ray directions provided by the tracking chambers. Each calorimeter consists of 60 crystals, each of which is coupled to a photomultiplier tube. The converter is intended to provide a medium in which an electromagnetic shower is initiated by a π⁰-decay photon. The tracking chamber system enables one to provide excellent position resolution both for vertex reconstruction and to handle multiple tracks at high rates.
The two arms of the NMS can be moved independently and pivot about separate spherical bearings at the center point. Outriggers and adjustable mechanical jacks support the arms for any desired configuration. The arms cover the full angular range in the horizontal scattering plane and move vertically to accommodate a full range of opening angles. The radial distance from the scattering target to the front face of each arm is also variable. It is clear that the NMS is ideally suited to the photopion threshold experimental program which we have envisioned for HIGS. We have developed a memorandum of understanding with the LANL staff members who are responsible for the NMS (see Attachment F). We are expecting to have the NMS on-site when the new target room is completed, which should be in the late Fall of 1998 (see Attachment F).

6.6 The Data Acquisition System

The design specifications for the data acquisition (DAQ) system are defined by the first set of experiments proposed for the HIGS with the underlying requirements of convenient expandability to accommodate future growth and new experiments, and of compatibility with the data-acquisition systems used at TUNL for local maintenance, software and hardware sharing. Because of limited local human resources for developing a real-time data-acquisition system, we have chosen a design that has been demonstrated and has broad support in the nuclear physics community. The system will use commercially available network hardware and standard software protocol for transferring data from the hardware crates to the data-analysis computer. Some nuclear physics facilities that are supporting DAQ systems that use standard network technology are: The Thomas Jefferson National Accelerator Facility, Brookhaven National Laboratory, The National Superconducting Cyclotron Laboratory at Michigan State University, Oak Ridge National Laboratory and Indiana University Cyclotron Facility. A network based DAQ system will be developed for use in the tandem and high-resolution laboratories at TUNL during 1997, so there will be local expertise to install and maintain the system at the HIGS.

A diagram of the DAQ station is shown in Figure 6.7. The system has three hardware components: the digitizer crates, the read-out controller and the data-analysis workstation. The data from the digitizers and counters in the CAMAC and VME crates will be read out and buffered by the read-out controller, which is a single-board computer (a Motorola MVM167) that resides in the VME crate. The MVM167 will run the real-time UNIX VXworks operating system and it has 16 MB of RAM for code storage and data buffering. When strobed, the MVM167 executes a read-out program, writes header information at the top of the data stream.
for that event, transfers the header plus digitized data to the data buffer and resets the system for the next event. When a data buffer is full, the MVM167 will transfer the buffer to the data analysis work station across a FDDI (or ATM, depending on pricing) link using standard TCP protocol. The ethernet connection on the MVM167 will be used mostly for downloading executable codes from the data analysis workstation, where the compilers for VXworks will be maintained. Supporting both VME and CAMAC gives the system the flexibility needed for growth and for meeting the technical specifications required by the proposed experiments. For instance, the charge-to-digital and time-to-digital converters (QDCs and TDCs, respectively) will be CAMAC modules, because digitizers that meet the required specifications for the charge integration (differential nonlinearity (DNL) better than ±0.5%) and time measurements (least significant bit (LSB) about 0.5 ns and a DNL of ±0.5%) are not available in VME. The counters will be VME modules which offer more sophisticated programming than available in the CAMAC counterparts. In addition, having CAMAC capability allows for sharing of modules between the tandem laboratory at TUNL and for borrowing modules from other nuclear physics facilities, since the nuclear physics community has a long history of supporting real-time DAQ with CAMAC.

Count-rate estimates indicate that a data collection rate of about 0.5 MB/s is sufficient for the first set of experiments proposed to run at the HIGS. This is certainly achievable with the proposed system. The peak transfer rate of FDDI is 10 MB/s. Therefore, taking into account protocol overhead, 5 MB/s should be obtainable with a dedicated FDDI as used in our system. The transfer bottle-neck is the connection between the CAMAC and VME crates. The fastest commercially available link between CAMAC and VME, without using direct connections from each CAMAC module to parallel registers in VME, is the LeCroy 3922 parallel crate controller to the LeCroy 2917 VMEbus interface card with direct memory access. When properly tuned this connection should deliver a transfer rate of about 1 MB/s, which is adequate for the initial experimental program at the HIGS.

The CAMAC and VME crates will be equipped with the digitizers and counters needed to conduct the first set of experiments proposed for the HIGS facility. The most demanding experiments, in terms of digitizer and counter channels required, are the neutral-pion production measurements. So, these experiments are used to define the number of QDC, TDC and counter channels to instrument the crates. The DNL and LSB of the QDCs and TDCs are determined from the requirements of the few-nucleon experiments and the measurements of photoreactions in finite nuclei.

The budget for the proposed DAQ system is shown in Subsection VI of Attachment A. All prices reflect the university discount agreements with the vendors and are in 1996 dollars. Most of the budget items have been discussed above. For further clarification, additional
information on selected items is given below. The data-analysis workstation is equipped with 128 MB of RAM to increase its performance by minimizing swapping when executing complex analysis algorithms and running multiple tasks which is often the case during data acquisition. The large memory capacity is also needed for running Monte-Carlo simulations during beam-off periods. The $5k listed for workstation software will be used to purchase commercial software like compilers, system administration tools and graphics packages. The 2-GB internal disk drive will be used for storage of system software, general-use data-analysis codes and software development projects. The additional 4-GB external disk drive will be used for temporary storage of data and spooling of data to tape during data acquisition. We plan to have two media for on-line data storage, an Exabyte tape (or DAT) drive and a read/write CD drive. Recent developments in the read/write CD drives are making them practical for long-term storage of nuclear physics event data. For instance, Pinnacle Micro announced in January 1996 their new 16x speed optical disk drive that is capable of storing 4.6 GB (10 GB compressed). Two CAMAC crates are needed for the digitizers, for some instrumentation control modules and to allow for growth. The choice of the particular digitizers and counters listed in the Budget (Attachment A, Subsection VI) is only for pricing purposes. They are examples of modules that are reasonably priced and meet the specifications required by the initial set of experiments to run at HIGS. We are proposing a budget of $24k to purchase general-use DAQ modules such as high-resolution peak-sensing ADCs, hit registers and programmable logic units.
Figure 6.7. Block diagram of proposed data acquisition station.