Chapter 2. Machine Layout and Performance

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2.1. Overview

The synchroton based Proton Driver design includes the following items:

1. A new 8 GeV rapid cycling synchrotron (the Proton Driver) in a new enclosure.
2. A new linac extension of 200 MeV (to bring the total linac energy to 600 MeV) in a new gallery and enclosure.
3. A new 400 MeV beam transport line connecting the existing Linac and the new linac extension.
4. A new 600 MeV beam transport line in a new enclosure.
5. A new 8 GeV beam transport line extending from the existing MI-8 line.
6. A modest improvement of the H^- source and the existing 400 MeV Linac.

The layout of this new accelerator complex is shown in Figure 2.1.

The H^- beam will be extracted from the present Linac to the 400 MeV transport line via the Linac access way. This beam is injected into the new linac extension and accelerated to 600 MeV. It is then transported via the 600 MeV beam line and injected into the Proton Driver in the same way as in the present Booster, namely, through a charge exchange process, in which the electrons are stripped by a foil and dumped. The H^+ (proton) beam will then be accelerated to 8 GeV in about 38 ms and extracted to the 8 GeV transport line. It is then injected into the MI-10 section of the Main Injector.

The new 400 MeV beam line is about 90-m long. It includes a vertical drop from the existing linac level (near surface) to the new linac level (13.5 ft. deep). The new linac extension has five CCL modules for a total length of 45-m. The 600 MeV beam line is about 254-m long. This leaves room for a future linac energy upgrade. This beam line also includes a vertical drop from the new linac level to the Proton Driver level (27 ft. deep). It has a bend near the end where a beam dump can be placed.

The Proton Driver has a circumference of 474.2-m, the same as the present Booster. It is racetrack in shape and has 2-fold symmetry as shown in Figure 2.2. It has two arcs (P10 and P30) and two long straight sections (P20 and P40). Each arc is about 161.66 m-long and each straight section about 75.44-m long. Of the two straight sections, P20 is used for injection and rf, P40 for extraction and rf. A number of trim magnets and diagnostics can also be located in these straight sections in addition to available slots in the arcs. Details of the lattice structure are in Chapter 3.

The 8 GeV extraction beam line has a total length of about 900-m. It consists of two sections. The upstream section, about 420-m, connects the synchrotron to the present MI-8 enclosure. It is followed by a 480-m section in the MI-8 enclosure. This beam line uses permanent combined function magnets, as in the present MI-8 line.

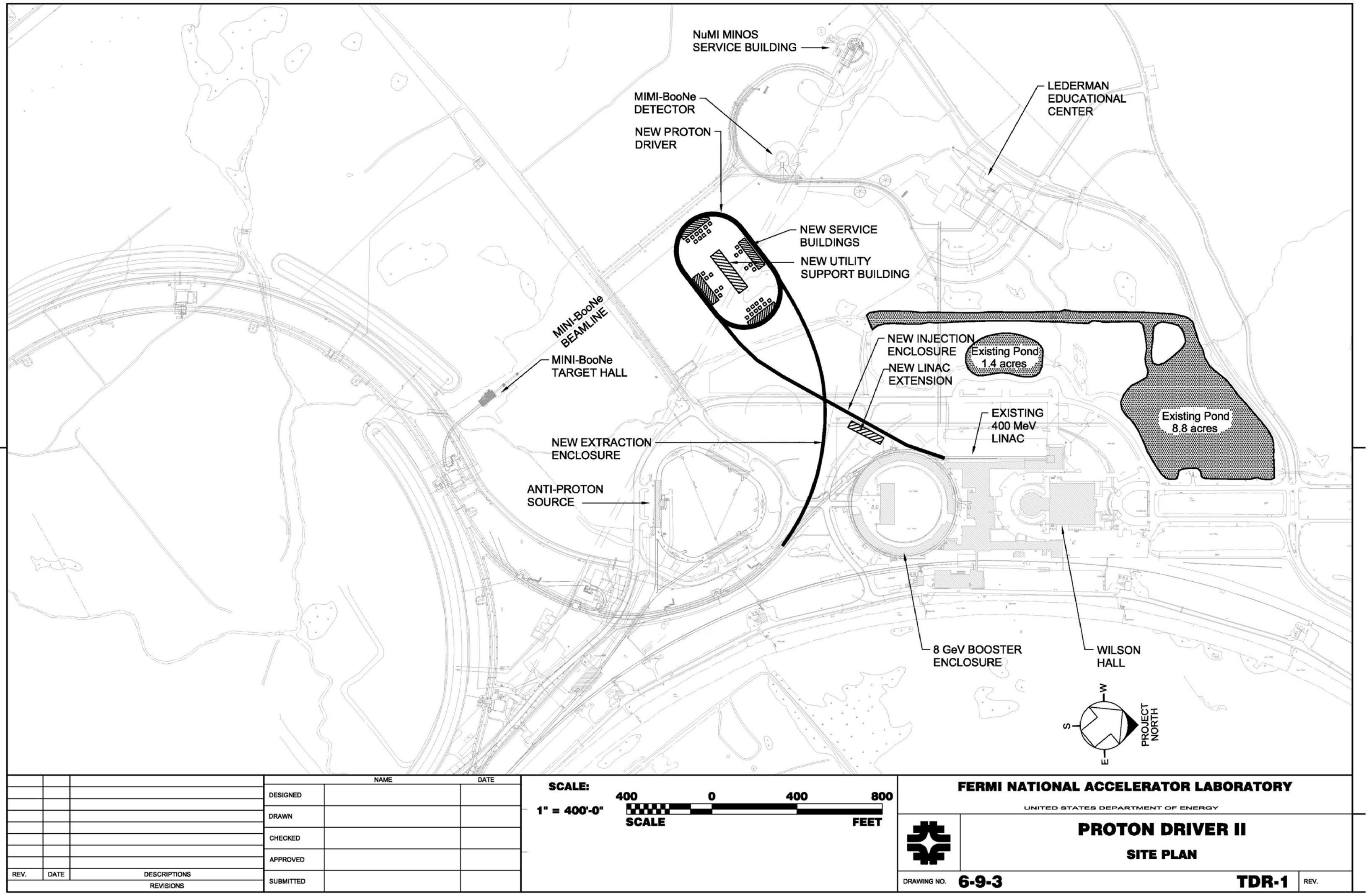

Figure 2.1. Layout of the 8-GeV Synchrotron-based Proton Driver Accelerator Complex.

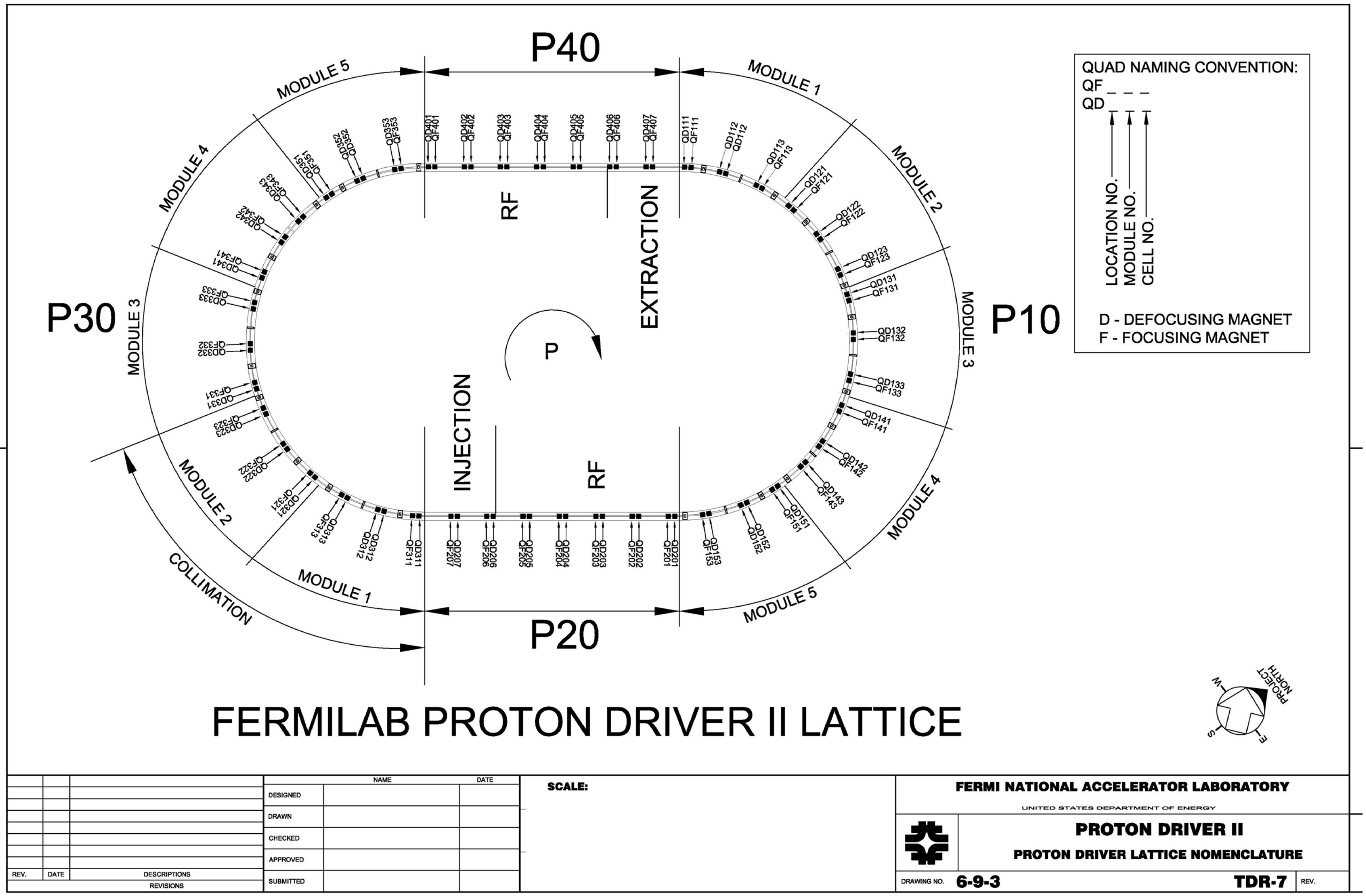

Figure 2.2. Layout of the PD2 8-GeV Synchrotron Ring.

2.2. Siting

Based on PD1, the site of the Proton Driver is chosen at the west side of Kautz Road (see Figure 2.3). The elevation of the Proton Driver is the same as that of the Main Injector. This ensures adequate radiation shielding. The NuMI beam line is deeper so the NuMI line and the Proton Driver do not intersect. Although the Proton Driver intersects the neutrino beam from the MiniBooNE target, this is not a problem. The location of this site in a wetland area raises concerns addressed in Chapter 11.

Another possible location for a racetrack type Proton Driver is in the vicinity of the MI-8 beam line, between the MI-8 and MI-10 buildings. This would shorten the lengths of the 600 MeV and 8 GeV beam lines and reduce their cost. However, it has a number of disadvantages because the new linac extension would have to be in the present MI-8 enclosure: (1) Although the CCL modules can fit into the MI-8 enclosure, it would be crowded. The transportation of hardware in the enclosure would be difficult. (2) A curved linac structure is not preferred. (3) The installation of the new modules would interrupt the ongoing RunII program. (4) Because only the permanent magnet portion of the MI-8 enclosure has room for a new linac, the usable space for a future linac upgrade would be limited. Therefore, this siting option is rejected at this time.

2.3. Major Design Parameters

The main differences of the PD2 parameters from PD1 are: lower energy (8 GeV *vs*. 16 GeV) and lower beam power (0.5 MW *vs*. 1.2 MW). The major PD2 design parameters are listed in Table 2.1 and compared with the parameters of the present Proton Source.

The linac maximum beam energy is increased from 400 MeV to 600 MeV. The required beam intensity is 50 mA, usable pulse length 90 μsec, and repetition rate 15 Hz, all achievable in the present Linac. These numbers correspond to 2.8×10^{13} protons per pulse injected into the Proton Driver. Allowing reasonable beam losses during the cycle (10% at injection, 1% during ramp and at extraction), the design value is 2.5×10^{13} protons per pulse extracted from the Proton Driver. At 15 Hz and 8 GeV, the beam power is about 0.5 MW.

It should be pointed out that the injection beam power from the Linac is only 40 kW, much lower than the output beam power from the Proton Driver. This is a main advantage of using a synchrotron to obtain high beam power, compared with, say, the approach adopted by the Spallation Neutron Source, which uses a full energy linac and an accumulator.

Table 2.1. Parameters of the Present Proton Source and the Proton Driver (PD2)

Parameters	Present Proton Source	Proton Driver (PD2)
Linac (operating at 15 Hz)		
Kinetic energy (MeV)	400	600
Peak current (mA)	40	50
Pulse length (μs)	25	90
H^- per pulse	6.3×10^{12}	2.8×10^{13}
Average beam current (μA)	15	67
Beam power (kW)	6	40
Booster (operating at 15 Hz)		
Extraction kinetic energy (GeV)	8	8
Protons per bunch	6×10^{10}	3×10^{11}
Number of bunches	84	84
Protons per cycle	5×10^{12}	2.5×10^{13}
Protons per second	7.5×10^{13}	3.75×10^{14}
Normalized transverse emittance (mm-mrad)	15π	40π
Longitudinal emittance (eV-s)	0.1	0.2
RF frequency (MHz)	53	53
Average beam current (μA)	12	60
Beam power (MW)	0.1(*)	0.5

(*) Although originally designed for 15 Hz operations, the present Booster has never delivered beam at 15 Hz continuously. In the past it has run at 2.5 Hz. In the near future it will run at 7.5 Hz for the MiniBooNE experiment.

Table 2.2 lists the parameters of the PD2 8-GeV synchrotron. A major feature in the design is that it employs a lattice that is transition-free ($\gamma_t = 13.8$) and has zero-dispersion straight sections. This is important for reducing beam loss and emittance dilution. The required good field region is determined by the following aperture criterion:

$$A = \{3\ \varepsilon_N \times \beta_{max} / \beta\gamma\}^{1/2} + D_{max} \times \Delta p/p + \text{c.o.d.}$$

in which A is the required half-aperture, ε_N the normalized emittance, $\beta\gamma$ the relativistic factor at injection, β_{max} the maximum beta-function, D_{max} the maximum dispersion, c.o.d. the closed orbit distortion, generously assumed to be 10 mm. The factor of 3 is for accommodating the beam halo, which has been observed in high intensity proton machines. Using the parameters in Table 2.2, the required good field region is (rounded up to) 4 in × 6 in. The dynamic aperture should be at least three times as large as the beam emittance so that it is consistent with the good field criterion.

Table 2.2. Parameters of the PD2 8-GeV Synchrotron

Circumference (m)	474.2
Super-periodicity	2
Number of straight sections	2
Length of each arc (m)	161.66
Length of each straight section (m)	75.44
Injection kinetic energy (MeV)	600
Extraction kinetic energy (GeV)	8
Injection dipole field (T)	0.2
Peak dipole field (T)	1.5
Bending radius (m)	19.77
Peak quad gradient (T/m)	10
Good field region	4 in × 6 in
Number of dipoles	
Long (5.646 m each)	20
Short (1.188 m each)	10
Number of quads (44 × 1.261 m, 44 × 1.126 m)	
In the arcs	60
In the straight sections	28
Max β_x, β_y (m)	15.14, 20.33
Min β_x, β_y (m)	4.105, 4.57
Max D_x in the arcs (m)	2.52
Dispersion in the straight sections	0
Transition γ_t	13.8
Horizontal, vertical tune ν_x, ν_y	11.747, 8.684
Natural chromaticity ξ_x, ξ_y	-13.6, -11.9
Revolution time at injection, extraction (μs)	2.0, 1.6
Injection time (μs)	90
Injection turns	45
Maximum Laslett tune shift	0.24
Normalized transverse emittance ε_N (mm-mrad)	
Injection beam (95%)	3 π
Circulating beam (100%)	40 π
Longitudinal emittance (95%, eV-s)	
Injection beam	0.1
Circulating beam	0.2
Extracted bunch length σ_t (rms, ns)	1
Momentum acceptance $\Delta p/p$	±1%
Dynamic aperture	> 120 π

2.4. Operation Modes

Three possible operation modes of the Proton Driver have been considered.

1. *Main Injector 120 GeV fixed target experiments: (NuMI, KaMI, CKM, other Meson Area beams, etc.)*
   The Main Injector will take six Proton Driver batches to fill its ring. Each batch gives 2.5×10^{13} protons. So the Main Injector will operate at 1.5×10^{14} protons per cycle, a factor of five higher than its baseline design intensity (3×10^{13} protons per cycle). The required modifications and upgrades of the Main Injector and the associated beam lines for such an intensity increase are discussed in detail in part B of this report (chapters 13 through 21). The upgraded cycle time of the Main Injector in NuMI operation will be 1.533 seconds (23 PD cycles, see Ch. 13) and therefore will use 6/23 of the protons available from the Proton Driver. The other 17/23 of the protons can be used for the other programs (see below).

2. *Proton Driver fixed target experiments: (MiniBooNE, etc.)*
   The MiniBooNE experiment uses the 8 GeV beam from the present Booster with a beam power of about 30 kW. When the Proton Driver replaces the Booster, this beam power will be increased by an order of magnitude. Seventeen out of every twenty-three Proton Driver cycles can be dedicated to this experiment. This gives an average proton flux of 2.8×10^{14} per second or 0.36 MW beam power to this experiment. In addition to MiniBooNE (or a full BooNE), it is also possible to establish new physics programs based on the stand-alone capabilities of the Proton Driver that can be carried out in parallel to the Main Injector experiments. The high intensity secondary particle beams produced by the proton beams will enable a rich class of physics programs based on muon, kaon, neutron, and neutrino beams.

3. *Antiproton production:*
   In this mode, the Main Injector will take one Proton Driver batch every 1.467 seconds (22 PD cycles). Each Proton Driver batch contains 2.5×10^{13} protons, five times more than the present Booster batch (5×10^{12}). This means the antiproton production rate would be increased by a factor of five, provided that the production target, the cooling systems in the Debuncher and Accumulator, and the acceptance of the associated beam lines would be upgraded accordingly. This mode of operation can be performed simultaneously with operation mode 1.

In the long run, the Proton Driver also serves as the first stage in a staged implementation of a neutrino factory and/or a muon collider. It could provide neutrino superbeams to the detectors, or high intensity muon beams that would be phase rotated, cooled, accelerated and stored in the next stages of such a project. This is because the beams from the Proton Driver have not only high intensity, but also a short bunch structure. The latter is essential for a neutrino factory.

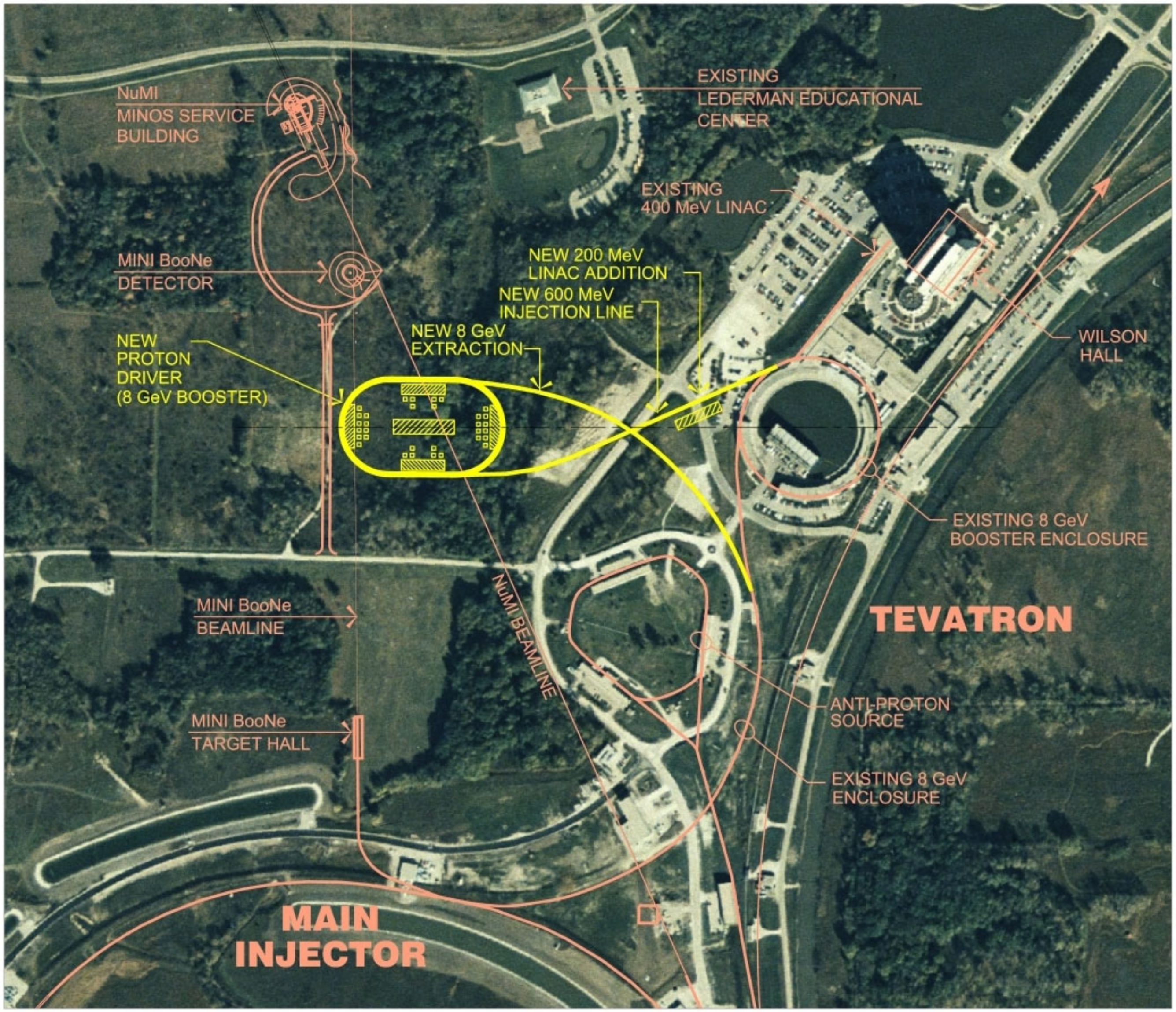

Figure 2.3. Synchrotron-based Proton Driver Site Plan.