Draft Report from the ICD-2 Research Program Task Force.

Sept 8th 2009.

1. Introduction:

In April of 2009 the Fermilab directorate charged a task force of accelerator physicists and experimental physicists to explore the opportunities and challenges presented by an alternative design to the Project-X accelerator. The first baseline design of the Project-X accelerator is described in the Initial Configuration Document (ICD) [1]. The charge for the task force can be found in Appendix-I and the task force membership can be found in Appendix-II. The task force met three times in May of 2009 and prepared an interim report that was presented to the Fermilab Physics Advisory Committee (PAC) in Aspen Colorado on June 24th. The response of the Fermilab PAC to the interim report can be found in Appendix-III. The PAC found the research potential of the alternative design to be high and consequently advised that the two accelerator designs be referred to as ICD-1, and IDC-2 for the previously referred to "alternative design".

The research program for Project-X is described in the "Golden Book" [2] which was developed during the 2008 Project-X workshops. The broad research program described in the Golden Book includes long-baseline neutrino experiments, neutrino interaction experiments, quark flavor Tevatron fixed target experiments (Appendix IV), ultra-rare muon and kaon decay experiments and experiments driven by anti-protons (Appendix V) from the Fermilab anti-proton complex. The long-baseline neutrino experiments and rare-decay experiments benefit most directly from the high proton beam power afforded by Project-X. This beam power presents simultaneously the promise of extraordinary physics reach and the substantial accelerator physics challenge of generating and handling enormous beam power.

The initial baseline design (ICD-1) of the Project-X accelerator complex can generate and handle the beam power required for the long-baseline neutrino program, however the high beam power available at 8 GeV is not readily useable by the rare-decay experiments. Further, the auxiliary accelerator concepts developed to handle and condition 8 GeV beam power for near-term muon experiments [3] does not scale well with increasing beam power and precludes the use of the Debuncher and Accumulator for the anti-proton research program described in the Golden Book.

The accelerator physics challenge presented by the ICD-1 in serving the long-baseline neutrino program and rare-decay program (and more broadly the full Golden Book research program) has motivated consideration of the ICD-2 alternative design. The ICD-2 is based on a 2 GeV Continuous Wave (CW) linac, and its impact on the Project-X research program is the subject of this report. As with the ICD-1 the ICD-2

can readily drive the long-baseline neutrino program, hence this report focuses on how the ICD-2 can drive the Project-X rare-decay research program.

This report outlines an accelerator architecture where a 2 GeV CW proton linac directly drives next generation rare decay programs. This scheme is the basis of ICD-2 and is a significant departure from the Project-X ICD-1 architecture. The findings of this report serve as an exploration of a 2 GeV-driven research program and more broadly the research program of the Fermilab accelerator complex other than neutrino physics.. The cost and schedule of the ICD-2 accelerator concept is discussed in a parallel document [XX].

1.1 Rare Decay Experiment Accelerator Requirements of the Proton Complex:

(Adapted from the Project-X Golden Book, ver. 1, Feb 3, 2008.)

The next generation of rare-decay experiments require kaon and muon beams of extraordinary quality. These experiments operate at the intensity frontier, where conventional decay and interaction processes can conspire in a high-rate environment to mimic the sought-after rare decay signatures. The principal weapon to control these backgrounds is the partnership of detectors that deliver excellent time resolution with high duty-factor beams which minimize the instantaneous rates that the detectors must face. Project-X is an exceptional opportunity to build a high intensity proton beam complex with nearly 100% duty factor and high availability (nominally 5000 hours per year). The joint potential of high duty factor and high availability would make the Fermilab complex a unique resource for rare-decay experiments.

Both the muon and kaon rare decay programs could have Phase I operation before the high-power Project X era (Phase II). A conceptual scheme has been developed to establish the required RF structure for Phase-I operation of the Mu2e and (g-2) experiments with an evolution of the existing Accumulator and Debuncher complex. These schemes are described in some detail in the Mu2e and (g-2) proposals [3]. The proton beam RF train requirements for the kaon and muon programs are listed below in Table 1.

	Train Frequency	Pulse Width (nanoseconds)	Inter-Pulse Extinction
Kaon experiments	20-30 MHz	<0.2	10^{-3}
Muon conversion experiment	0.5-1.0 MHz	<100	10^{-9*}
Muon g-2 experiment	30-100 Hz	50	---

*muon conversion extinction is achieved by a combination of extinction in the circulating beam/extraction and in an external device in the proton beam transport

Table 1: RF train requirements for the kaon and muon rare decay programs.

2. Summary of Project-X accelerator R&D and Issues

2.1 Update on Fermilab Accelerator Complex R&D since the Golden Book (v1):

i) Ongoing accelerator upgrades should allow the Booster to accelerate $4x10^{12}$ protons (4 Tp) to 8 GeV (kinetic) at a 15-Hz cycle rate. This corresponds to a total beam power of 77 kW. Of this 50 kW is required for NOvA, leaving ~25 kW for other Phase-I applications (such as rare decays).

ii) The Recycler ring was determined to be unfavorable for a resonant slow extraction scheme mainly due to its small transverse aperture, large circumference (for an 8-GeV ring) and inflexible permanent-magnet lattice.

iii) The bunch structure for the Mu2e experiment (Table 1) can be provided by a resonant slow extraction from the Debuncher ring, which has a factor of 6 smaller circumference than the Recycler and a factor of 6 larger transverse aperture. The Mu2e experiment requires about 25 kW of protons. Higher beam power (and thus a higher muon flux) may be accommodated by the present detector design although the ultimate capabilities of the slow extraction from the Debuncher in the Mu2e scenario have not yet been studied exhaustively. One can argue that the beam power during the extraction will be limited by: uncontrolled beam losses (i.e. the 1 W/m loss limit), extraction inefficiencies because of the space charge, and tune ripple and momentum spread. From scaling considerations it is thought that beam power limit for the Mu2e scenario lies somewhere between 50 and 200 kW.

iv) The bunch structure for the kaon experiments in Phase-I would also require a resonant slow extraction. However, such a scenario was not yet seriously considered, aspriority was given to developing the Mu2e and g-2 proposals. It is however clear that meeting the pulse width (aka bunch length) requirements for Kaon experiments would be quite challenging. Nominally, the Fermilab Booster and the MI operate with a 53-MHz bunch structure, which is close to Kaon train frequency requirements. However, the nominal bunch length is 1-2 ns – a factor of 10 longer than required. Since for a given longitudinal emittance the bunch length scales inversely with the fourth power of RF cavity voltage, reducing the bunch length by a factor of 10 would require substantial upgrades to the RF systems.

2.2 Summary of Phase-I opportunities and constraints:

Mu2e

Opportunities:

- Bunch structure can be met by employing the existing Recycler and Accumulator rings for re-bunching and the Debuncher ring for slow extraction.
- Ultimate extracted proton beam power is likely limited to 50-200 kW.

Constraints:

- Kaon, g-2, anti-proton experiments cannot operate simultaneously with the Mu2e experiment. Beam time per experiment will have to portioned through program planning.

g-2

Opportunities:

- Bunch structure can be met by employing the existing Recycler ring. It also utilizes the anti-proton source target, AP-2 line and Debuncher but does not require decommissioning of the anti-proton source.

Constraints:

- Kaon, Mu2e, anti-proton experiments cannot operate simultaneously with the g-2 experiment. Beam time per experiment will have to portioned through program planning.
- The intent of the experiment to use the anti-proton source infrastructure has a time conflict with the Mu2e experiment expected to start data acquisition in 2016.

Kaons

- Unlikely to meet the bunch requirements of the neutral kaon decay experiment (proton ping timing σ<200 psec) with the existing 8-GeV complex.

Additional physics opportunities in rare decays and neutrinos can be pursued with a slow and/or fast extraction from the Tevatron. These opportunities are complementary to Phase-I program and are described in section 3.2.3 and Appendix III.

2.3 Summary of the Project-X Initial Configuration Document

The initial configuration design (ICD-1) of Project X [2] is designed to meet the following design criteria:

1. It must provide 2.1 MW of a single-turn extracted beam from the Main Injector at energies ranging from 60 to 120 GeV
2. It must provide 150 kW of 8-GeV beam to the Accumulator/Debuncher for the Mu2e experiment.
3. There must exist a plausible beam-power upgrade scenario (up to 4 MW at 8 GeV) for future neutrino and muon facilities.

The selected initial configuration consists of a pulsed 8-GeV linac capable of delivering up to $1.6\text{x}10^{14}$ protons to the Recycler in a 1.25 ms long pulses at a 2.5-Hz rate. The theoretical beam power available at 8 GeV is 0.5 MW. Of this, 150 kW (300 kW) is delivered to the Main Injector for acceleration to 120 (60) GeV and 150 kW is delivered to Mu2e in a specific bunch structure. The feasibility of slow extraction of such a beam power from the Debuncher was not studied. Figure 1 shows an accelerator timeline for a 60-GeV MI operation with a cycle of 0.8 seconds. A similar scenario also exists for a 120-GeV MI operation.

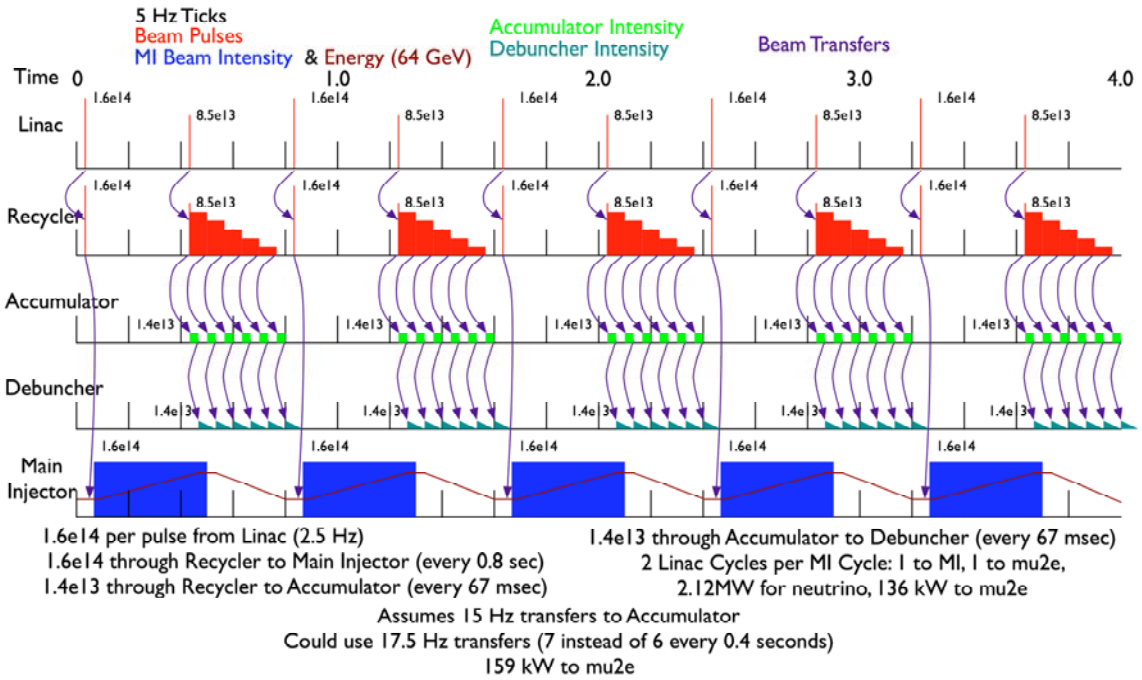


Figure 1: The Project X ICD-1 operational scenario for the MI running at 60 GeV.

The details of this design can be found in Ref. [1]. In summary, the ICD provides the following opportunities and constraints:

1. The 2.1-MW MI Neutrino program is supported.

2. Rare decays and precision measurements:
   - The Mu2e scenario is an evolution of the present Mu2e proposal [3]. The proposed power level of 150 kW is within the estimated range of Debuncher slow extraction beam power limits (50-200 kW) mentioned above. Since the slow extraction for the mu2e is outside of the ICD scope, the feasibility of extracting beam at this high power was not explored.
   - The g-2 scenario was not explored.
   - The Kaon experiment scenario was not explored. However, the ICD is unlikely to meet the bunch requirements in Table 1 for reasons described above.

3. A path to beam-power upgrade to 4 MW exists.

2.4 Summary of the ICD-2

The initial Project X ICD-1 design and goals were mainly driven by the Project X synergy with the ILC and the 2 MW operation of the MI for neutrino program. The details of operation with a slow extracted beam at 8 GeV were not considered in the Initial Conceptual Design [2]. While the ICD-1 has evolved, it still follows the same path as the initial Project X proposal but with an increased beam current. A preliminary study of the slow beam extraction with the ICD-1 indicates intrinsic problems and lack of flexibility. The ICD-2 is motivated to address the deficiencies found in the ICD-1.

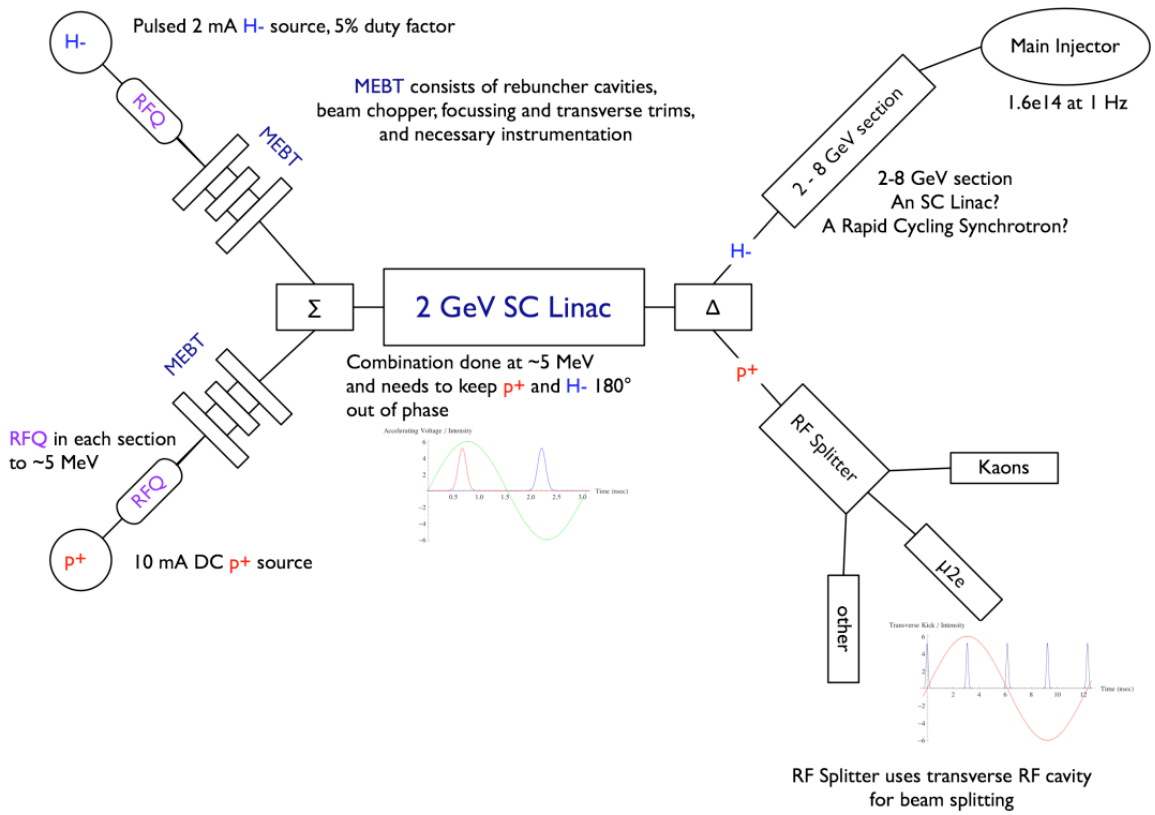


Figure 2: The schematic layout of the ACD concept

The main concept of the ICD-2 is to replace slow extracted beam at 8 GeV with the beam accelerated in a Continuous Wave (CW) linac operating with a nominal frequency of 325 MHz which could be implemented with 1300 MHz cavities. This concept has a number of notable advantages. First, the RF separation of the beam after acceleration allows simultaneous operation of several experiments (similar to the three hall operation at Jefferson Lab). The time structure and the intensity of each beam can be varied independently. Second, the beam quality of a CW linac is significantly better than for slowly extracted beams; in particular, the linac beam intensity does not have fluctuations inherent to slow extracted beam from a synchrotron. Third, the power of beam accelerated by a CW linac is set by high energy physics requirements (ability to use this power by experiment) rather than by technical or accelerator physics requirements.

Fourth, the bunch length in a linac (<10 ps rms) is much smaller than can be reasonably achieved in a ring which enables unprecedented Time-Of-Flight resolution that will be invaluable to next generation rare-decay experiments.

The energy of the linac is determined by the threshold of particle production. The linac energy of 1 GeV would be sufficient for muon production but the threshold of kaon production is slightly below 2 GeV. This sets the linac energy to 2 GeV. Note that this energy is below the threshold for anti-proton production which results in a reduced background for stopping muon experiments.

Energy, min/max, GeV	2/8
Repetition rate, Hz	10
Circumference, m (MI/6)	553.2
Tunes	18.44
Transition energy, GeV	13.36
Number of particles	2.67E13
Beam current at injection, (Amps)	2.2
Harmonic number	98
RF frequency, MHz	50.33 – 52.81
Maximum RF voltage, MV	1.2
95% n. emittance, mm mrad	25
Space charge tune shift at injection [1]	0.16
Norm. acceptance, mm mrad	40
Injection time for 1 mA, ms	4.3
Linac energy correction during injection	0.8%
RF bucket size, eV s	0.25
Number of RF cavities	10
Cavity shunt impedance, kΩ	100

Table 2. Main parameters of the synchrotron

Two MW Main Injector (MI) operation for the long-baseline neutrino program requires 8 GeV beam injection into the MI. Therefore an additional acceleration stage from 2 to 8 GeV is required in the ICD-2. This can be achieved with a synchrotron or a pulsed linac. Both choices require the linac beam current to be 1 mA or above. For the ICD-2 we choose a beam current to be 1 mA. This sets the total power of CW linac to 2 MW. Figure 2 presents a layout of the ICD-2 accelerator complex. To increase the reliability of the ion source we plan to have two ion sources: a pulsed one to supply H^- for strip injection and a continuous one to supply protons for the rare-decay physics program. These source beams are merged in the medium energy beam transport (MEBT) at 2-5 MeV. After the acceleration to 2 GeV the H^- and proton beams are split. The first one is directed to the MI, and the second one is split again and sent to three experimental halls.

[1] For a Gaussian beam at injection. The tune shift will be 3 times less for the KV distribution.

Presently, the ICD-2 studies are concentrating on a synchrotron for the 2-8 GeV acceleration stage. A pulsed linac is also possible; such a linac would be comparable to the ICD-1's 2-8 GeV portion. Table 2 presents the main parameters of the synchrotron. The circumference of the synchrotron should be kept sufficiently small to mitigate effects of the beam space charge and instabilities. We choose it to be 1/6 of MI circumference. This sets the repetition rate to be 10 Hz so that 6 injections could be delivered to the Recycler during a 0.8-s MI cycle at 60 GeV. The beam is stored in the Recycler and then it is transferred to the MI in a single transfer. Two out of eight injections sent to the Recycler in one MI cycle are available for a fast extraction 8-GeV program such as (g-2).

The use of a pulsed linac (2-8 GeV) instead of the synchrotron can be justified by co-development of ILC technology and a possible simplification of future upgrades for a neutrino factory or a muon collider. This pulsed linac should have a duty factor of 2-5%. The time structure of the linac can range from one 27-ms long pulse every 0.8-1.4 s (then a direct injection into the MI is possible) to a 2-ms pulse at 10-20 Hz with an injection (and accumulation) into the Recycler.

The accelerating gradient of the CW linac will be lower than that for the pulsed linac because of the larger cryogenic load. Roughly we can estimate the reduction from 25 MV/m (as in the ICD) to 18 MV/m. This results in lengthening of the CW linac relative to the corresponding part of the ICD-1 from 300 to 420 m.

Presently the future upgrades are determined by the needs of a neutrino factory and muon colliders. Both of these concepts require 2 to 4 MW beam power in the energy range of 8 to 20 GeV. In the case of a synchrotron the power increase can be achieved by increasing the synchrotron energy from 8 to 11 GeV, the repetition rate from 10 to 20 Hz, and by doubling the injected beam intensity. It will also require an increase of the CW linac current from 1 to 2 mA. Such an upgrade will be relatively inexpensive and will result in a beam power of about 2 MW at 11 GeV. In the case of a 2-8 GeV pulsed linac an upgrade will require a replacement of all linac RF sources. It will be more expensive than the described upgrade of the synchrotron but can deliver significantly higher power. The linac current increase from 1 to 25 mA would result in 4 MW power if pulse length and the repetition rate are not changed (2 ms and 10 Hz). The drawback of such an upgrade is that it requires the CW linac to be converted to a pulsed linac and a consequent termination of the corresponding 2 GeV physics program.

3. Rare Decay Physics with the ICD-2 Accelerator Complex

3.1 Next Generation Muon Experiments:

The conceptual design for the Mu2e 8 GeV proton source uses the Recycler, Debuncher and Accumulator rings to establish the required 500 kHz pulsed beam. The mu2e duty factor during Nova operations will be relatively low (<50%) and the beam power will likely be limited to about 50kW due to space-charge effects in the Debuncher

ring. A conceptual design exists for a secondary extinction channel that will be required to achieve the extraordinary intra-pulse beam extinction of 10^{-9} in the proton pulse train delivered to the production target.

Muons stopped in the aluminum foils of the Mu2e experiment predominantly originate from pions with kinetic energy below 100 MeV. There are few experimental measurements for pion yields at these low energies. Thus the stopped muon yields for Mu2e rely on production models tuned to the measured π^- cross section for pions with larger kinetic energies and extrapolated to the region of interest. For an incident proton beam of 8 GeV the π^- yield at low kinetic energies varies by a factor of 2-3 depending on the choice of production model, e.g., MARS15 [4], LAQGSM [5] or FLUKA [6]. Benchmarking [7] confirms these uncertainties in production model predictions in this region.

From measurement of π^- yields from protons on Carbon and Lead/Tantalum at various incident proton energies we estimate that the *total* π^- yield for a 2 GeV (kinetic) proton beam is about a factor of 15 smaller per incident proton than for an 8 GeV beam. Using fits to FANCY data [8] data for 3 GeV/c protons on aluminum and 4 GeV/c protons on aluminum and lead, we can extrapolate the π^- yields to the lower kinetic energies. The fits reasonably reproduce HARP data [9] for 3 GeV/c protons on carbon, which extend down to pion kinetic energies of about 30 MeV. A prediction for the π^- yields for 8 GeV/c protons is obtained by normalizing the 4 GeV/c proton on lead fit from FANCY to HARP data for 8 GeV/c protons on lead for pions at large angles and kinetic energies above 100 MeV. After normalization, the FANCY fit reproduces the shape of the HARP data at large angles important for Mu2e. Based on these fits, the π^- yields for kinetic energies below 100 MeV scale roughly linearly with the proton kinetic energy independent of angle. Thick target effects can be important for low pion energies and have not yet been explicitly considered. We are planning to perform a systematic study of low energy pion yields for a 2-GeV proton beam, and hopefully to improve the production models used at Fermilab.

Despite the above uncertainties, there are several in-principle advantages in driving future stopping muon experiments with a 2 GeV CW linac. These are:

1) The CW linac proton beam can directly impinge on the production target with a very high duty factor which finesses the substantial challenge of extracting high power beam from a synchrotron.

2) Production model uncertainties in the low energy π^- yield from 2 GeV proton drive beam can be compensated with the large beam power reserve of the CW linac.

3) The extraordinary intra-pulse extinction required by stopping muon experiments (10^{-9}) is intrinsic to the CW linac accelerating structure. A secondary extinction channel may not be necessary.

4) Experimental backgrounds from kaons and anti-protons produced in the production target will be substantially reduced (eliminated in the case of anti-protons) with a 2 GeV drive beam.

3.2 Next Generation Kaon Experiments:

The 2008 Project-X workshops identified $K \rightarrow \pi\nu\nu$ experiments with 1000 Standard-Model event sensitivity as attractive goals of a new high power proton accelerator. At proton beam energies above about 5 GeV the rate of useful kaons in a secondary beam is proportional to proton beam power. The proton kinetic beam energy threshold for producing kaons is 2.1 GeV (on protons) and the kaon cross section fraction grows with the increasing number of exclusive production channels that saturate at around 5 GeV. The total pp cross section as a function of beam energy is shown in Figure 3 (PDG). The threshold production channels for kaons in pp interactions is shown if Figure 4 (measured at the COSY facility).

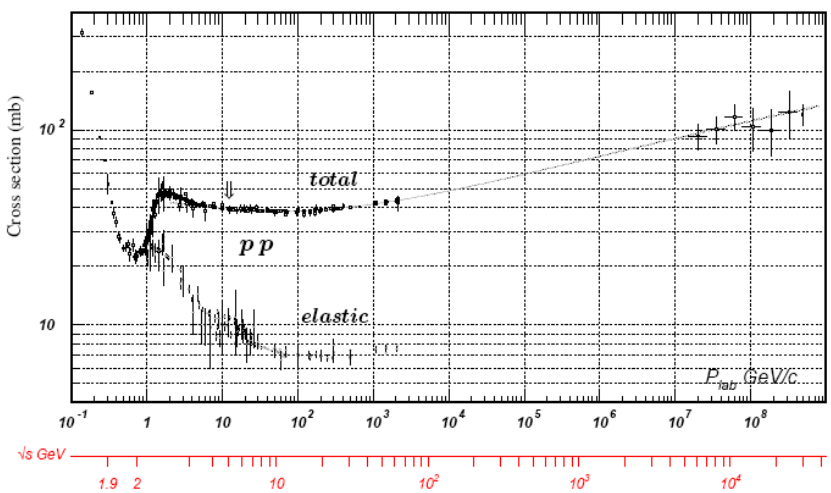


Figure 3. pp total cross section vs p beam momentum.

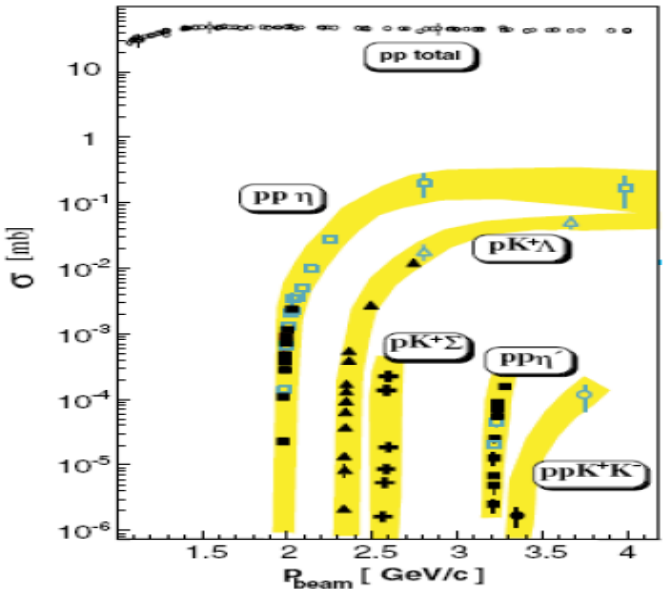


Figure 4. (Strangeness production thresholds from COSY)

Despite the relatively low cross-section near threshold, there are in principle experimental advantages for producing kaons just above the threshold of exclusive production channels. Strangeness is conserved in the production of kaons, and the associated hyperon might be useful in tagging the production of the kaon. The 2-body and 3-body kinematics such as $p^+n \rightarrow p^+\Lambda K^0$ could also be exploited to constrain the momentum of produced neutral kaons. Kaons can also be produced with a secondary π^- drive beam from the π^-p^+ total cross section which is shown in Figure 5. The $\pi^-p^+\rightarrow K^0\Lambda$ exclusive reaction has particularly well constrained kinematics with a π^- drive beam near 1 GeV. This concept for driving a $K_L\rightarrow\pi^0\nu\nu$ experiment was explored by Akira Konaka (TRIUMF) in the 1990s but was not published.

The high beam power of a 1 mA 2 GeV CW linac proton drive beam can compensate the reduced kaon production cross section near production thresholds. Further, the high duty factor and excellent time resolution of CW linac pinged beams would support unprecedented neutral kaon beam momentum resolution through TOF techniques developed by the KOPIO initiative. Experimental design concepts based on hyperon tagging, kinematically constrained beams, and excellent TOF momentum measurements will be discussed in turn.

3.2.1 Concepts based on π^- drive beams:

For π^-s incident on a liquid hydrogen target with beam momentum below 1033 MeV/c the only strangeness producing reaction is $\pi^-p \rightarrow K^0$-bar,Λ. Just above threshold (π^- momentum ~ 900 MeV/c) the cross section for this reaction is about 0.1% of the total cross section, but the fraction rises to greater than 1% by ~980 MeV/c and is ~1.2% at 1033 MeV/c (threshold for $\pi^-p \rightarrow K^0$-bar,Σ^0). Two body kinematics limit the range of K^0 momentum, and the Q of the reaction insures that a large fraction of the K^0_Ls have $\beta\gamma$~1.

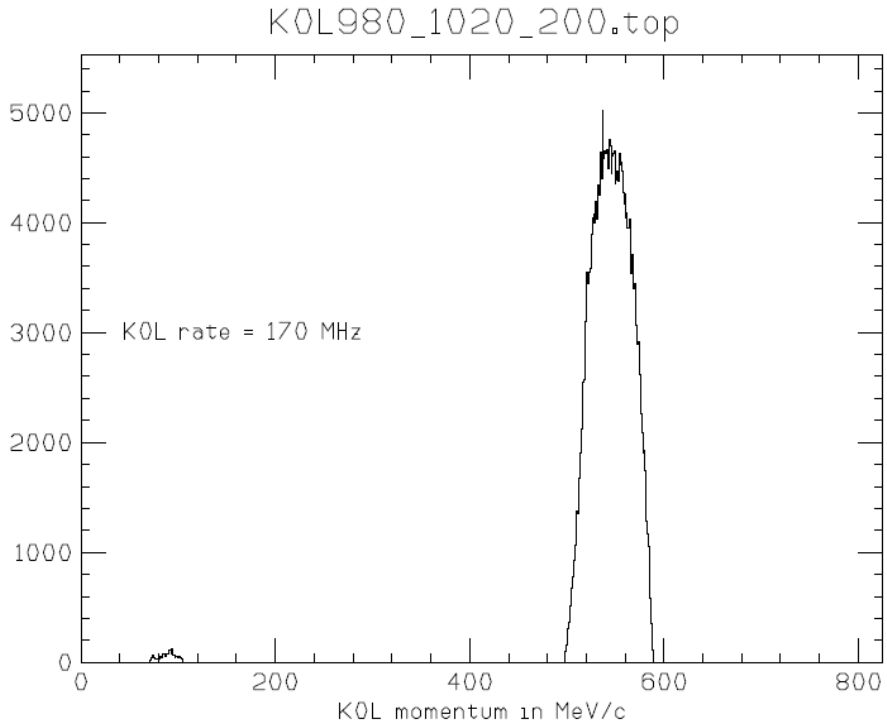
An initial MARS study of π^- production by a 2 GeV (kinetic) proton beam indicates that the yield of π^- with momentum in the range 950-1033 MeV/c is likely to be 4-7 π^- per 10,000 beam protons. The study assumed an 80 cm long carbon target and counted pions that crossed a 50 cm radius disc located 200cm downstream of the start of the target (subtending ~300 mrad from the center of the target). With default MARS settings, the yield of π^- in this momentum range was ~7E-4. The yield dropped to ~$4x10^{-4}$ with the Los Alamos quark gluon string model option (LAQGSM). The pion momentum distribution is peaked at low momentum, but extends beyond 1.5 GeV/c and is essentially flat in the range 950 – 1033 MeV/c. Assuming a proton beam current of 1mA and the lower MARS estimate, but 100% efficiency for collection of π^-s within a 300 mrad cone, the π^- beam intensity would be $6x10^{15}$/sec x $4x10^{-4}$ = $2.4x10^{12}$/sec ($2.8x10^{10}$/sec per MeV/c).

The differential cross section for $\pi^- p \rightarrow K^0$-bar,Λ as a function of incident pion momentum was well measured in the 1960s and 70s. It is therefore straightforward to compute the yield and momentum spectrum of K^0_L as a function of angular acceptance for any assumed LH_2 target configuration and pion beam momentum spectrum. The table below gives the K^0_L rate for a range of angular acceptance assuming an 80 cm long LH_2 target and pion beam with a flat momentum distribution of $2.8x10^{10}$/sec per MeV/c.

Incident π-Momentum	50 mrad	100 mrad	200 mrad	300 mrad
980 – 1020 MeV/c	13 MHz	48 MHz	170 MHz	395 MHz
950 – 1033 MeV/c	25 MHz	93 MHz	331 MHz	656 MHz

Table X: K^0_L production rate into angular acceptance indicated.

The figure below shows the momentum spectrum of K^0_Ls produced into a forward cone of 200 mrad by a pion beam with a flat momentum spectrum between 980 and 1020 MeV/c.



A K^0_L beam of 300 MHz might yield 200 MHz of decays in a reasonable sized detector. A branching ratio of 3E-11 for $K^0_L \rightarrow \pi^0\nu\nu$ would then translate into 60,000 events per 1E7 seconds. A sample of 1000 recorded events could be achievable in a 3-5 year run. K^0_L beams produced by high energy protons invariably contain a large neutron contamination. One of the most problematic backgrounds for the KOPIO experiment was expected to be neutral pions created by neutron scattering on residual gas (mostly hydrogen) in the decay vacuum via the reaction $np \rightarrow np\pi^0$. This background would be reduced in a K^0_L beam produced by a low energy pion beam in $\pi^- p \rightarrow K^0$-bar,Λ. Initial results from a MARS study indicate that the ratio of neutrons capable of background pion production to K^0_L would be well under x50.

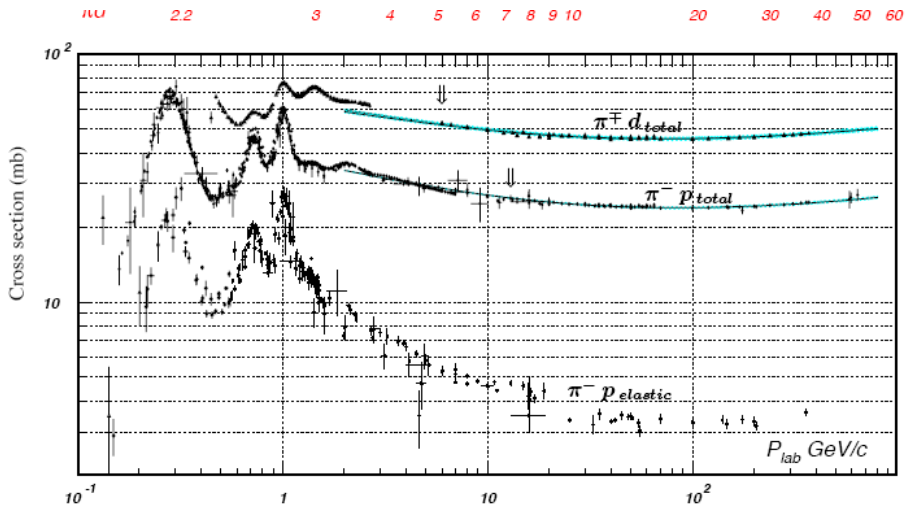


Figure 5. The $\pi^- p^+$ total cross section vs beam momentum.

3.2.2 Concepts based on exclusive production states with proton drive beams:

For a 2.1 GeV kinetic energy proton beam incident on low Z targets the yield of charged and neutral kaons is about 10×10^{-4} and 5×10^{-4} respectively per proton interaction. Each kaon is produced in association with a hyperon, mainly Λ^0's. The total kaon production rate from 20μa of average proton current on a 1% target is ~1 GHz. The experimental challenge to measure the rate of an ultra-rare kaon decay like $K_L \rightarrow \pi^0 \nu\nu$ is to handle all backgrounds in a very high rate environment.

There are two potential experimental approaches to exploit the available kaon fluxes. Focusing on neutral kaons we can envision a $K_L \rightarrow \pi^0 \nu\nu$ experiment similar to the BNL KOPIO design. KOPIO used a neutral beam defined by a production target and neutral beam collimator produced by a 25.5 GeV proton beam from the BNL AGS at a targeting angle of about 45^0. This beam had an average kaon momentum of 750 MeV/c with ~2000 neutrons and photons for each kaon.

In the KOPIO design the kaon momentum is measured by time of flight (TOF). It was a major challenge for the BNL AGS to produce proton bunches as narrow as 200 psec (σ). This ultimately limited the momentum resolution from the TOF measurement. Another major issue with the KOPIO design is the background and dead time from the flux of neutrons that dominate the neutral beam. The details of a KOPIO-based experimental concept are currently under study.

Another experimental approach is look at the primary associated production reaction reconstructing both the Λ^0 in its neutral decay mode and the π^0 from a kaon decay. A 4π neutral detector would surround the strangeness production target with a solenoidal magnetic field to trap and remove charged tracks and the un-scattered proton beam. This geometry works in continuous beam. The kaon momentum is measured by the time of flight difference between the Λ^0 and kaon decay daughters. Challenges include handling

the large rate of photons from π^0 production in the primary target and the requirement to see some charged particle to distinguish charged from neutral kaon decays.

As of this writing, detailed LAQGSM [5] simulations of the 2.1-GeV proton interactions with low-Z targets have just become available, with one of the first results shown in Figure 6. The initial message from the yields and momentum spectrum in Figure 6 is that the kaon flux per proton of $>5\times10^{-4}$ (with a high flux in a narrow forward cone) is a good place to start for design of a high sensitivity experiment. The effective (K/p) provided to an experiment will be far less than the total yield and will depend on experiment design. For comparison the KOPIO design at the BNL AGS was based on 3×10^{-6} K_L/p into 500 μsr at the detector with twelve times the beam energy per proton. Experimental concepts are continuing to be developed using these new results and tools.

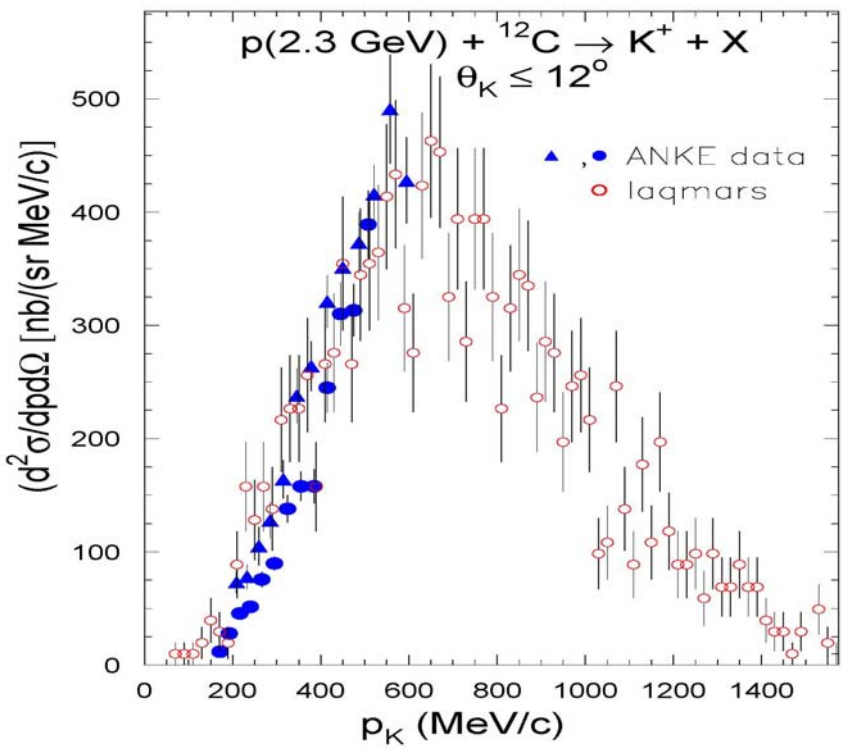


Figure 6. K^+ momentum spectrum from 2.3 GeV protons (kinetic) on a thin carbon target simulated with LAQGSM and MARS [5]. The simulated rate is absolutely normalized, and models the measured (ANKE) momentum spectrum and rate quite well.

3.2.3 High duty factor kaon beams driven by the Tevatron stretcher

As previously noted the Project-X rare-decay program benefits greatly from high duty factor drive beams. The use of the Tevatron in the post-RunII era as a stretcher ring to condition Main Injector pulses into beams with nearly 100% duty factor has been studied [10] and is discussed in some detail in Appendix III. Configuring the Tevatron stretcher to accept 10% of the Main Injector beam power would provide a slow extraction beam facility in excess of the beam power achieved at the BNL AGS (which holds the world record in SEB power) but with much higher duty factor. Initial studies based on the K^+ production yield from the120 GeV Tevatron Stretcher suggest that a 1000 event $K^+ \rightarrow \pi^+ \nu\nu$ experiment based on the demonstrated BNL stopping beam technique (BNL-E949, [11]) is plausible. A new technique based on in-flight decays developed by the CKM experiment [12] could likewise exploit Tevatron stretcher beam to plausibly achieve a 1000 event $K^+ \rightarrow \pi^+ \nu\nu$ experiment. Splitting and sharing beam between multiple experiments in a 120 GeV program would be straightforward, and such a program could include the E906 Drell Yan experiment and driving the test-beam facility which would both greatly benefit from high duty factor beams.

Appendix I

Charge:

The laboratory is now developing a conceptual design for the Project-X accelerator complex required to drive the research program described in the defined in the Project-X Initial Configuration Document (ICD, http://projectx.fnal.gov/): The elements of that research program are:

A neutrino beam for long baseline neutrino oscillation experiments. A new two or more megawatt proton source with proton energies between 50 and 120 GeV that would produce intense neutrino beams, directed toward a large detector located at a distant underground laboratory.

Kaon and muon based precision experiments driven by high intensity proton beams running simultaneously with the neutrino program. These could include a world leading muon-to-electron conversion experiment and world leading rare kaon decay experiments.

A path toward a muon source for a possible future neutrino factory and, potentially, a muon collider at the Energy Frontier. This path requires that the new proton source have significant upgrade potential.

The accelerator complex defined in the ICD can drive the long-baseline neutrino program, but does not readily provide a platform to pursue a research program in rare muon and kaon decays which requires high duty-factor proton beams.

As part of the standard DOE review process the Project-X design team is considering Alternate Conceptual Designs (ACDs) that can meet the research goals of the eventual Mission Need statement. Some of these ACDs may be more readily suited than the ICD The Project-X Research Program Task Force is charged to evaluate if and how the ICD and the ACDs can meet the research goals and recommend what R&D is necessary to refine the Project-X specifications required to drive the research program.

Appendix II:

Task-Force members:

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D. Christian	Fermilab
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Appendix III

Remarks from the June 2009 Aspen Meeting of the Fermilab PAC:

Project X and ICD-1&2

The broad research program of Project X described in the "Golden Book" includes long-baseline neutrino experiments, neutrino interaction experiments, ultra-rare muon and kaon decay experiments, quark flavor experiments, and experiments with antiprotons. The Committee strongly recommends that Fermilab include budget estimates for the highest priority projects, such as muon-to-electron-conversion, $K^+ \to \pi^+ \nu\bar{\nu}$, and $K_L^0 \to \pi^0 \nu\bar{\nu}$ experiments, in the budgetary planning for Project X in order to insure a broad initial program of high-impact intensity frontier physics.

The long-baseline neutrino experiments and rare-decay experiments benefit most directly from the high beam power afforded by Project X. Although the design of the Project X accelerator complex described in ICD-1 provides for the beam power required for the long-baseline neutrino program, the high beam power produced at 8 GeV is not readily available for a full rare-processes program. As a result, the accelerator group is considering ICD-2 based on a 2 GeV CW linac containing some ILC-like modules, providing both higher beam power and a more flexible beam distribution scenario for the rare-processes program. This would be followed by a 2-8 GeV accelerating section similar to the SC linac of ICD-1 or a rapid-cycling synchrotron. This combination can provide great prospects for satisfying the broad goals of Project X. The ICD-2 can drive the long-baseline neutrino program while also providing nearly ideal beams for the important Project X rare-processes research program.

The ICD-2 concept is extremely promising. The Committee strongly endorses further study of the prospects to realize the great potential of the high-sensitivity studies of rare muon and kaon processes which will be essential elements of the intensity frontier explorations of new physics at high mass scales. The Committee strongly encourages Fermilab to further develop the accelerator aspects of this proposal, including cost considerations, and to continue to consider the synergy with the ILC linac technology. The Committee supports further detailed studies of the ICD-2 kaon and muon beams to confirm their suitability for next generation experiments.

Appendix IV

Opportunities and Issues of the 120 GeV Tevatron stretcher and 800 GeV operation.

As discussed in Ref [10], the Tevatron could be used quite readily as a "stretcher ring" for 120 GeV Fixed Target operations to the existing Fermilab Switchyard. Operation at 150 GeV, the Tevatron's design injection energy, could also be considered, but 120 GeV would allow for the use of standard NOvA-type cycles for the Main Injector. For example, assume the 1.333 s cycle time for the Main Injector that will be used for NOvA operation. With slip stacking employed, this will deliver 12 pulses from the Booster at approximately 4 Tp each, or 48 Tp into the Main Injector. As two MI pulses fill the Tevatron, one can envisage up to nearly 100 Tp stored in the Tevatron and slowly spilled using resonant extraction. The SY120 beam line set up could, in principle, be used "as is" or, if deemed necessary, the extraction point from the Tevatron can be moved to its original A0 location.

To investigate the range of possible operating scenarios, envision using 2 MI cycles out of every n (n>1) for use in this "Tev120" operation, with the remaining n-2 cycles sent to NOvA. Slow spill would occur during n-1 cycles, as depicted in Figure 2. The duty factor for Tev120 would be (n-1)/n, and the macro-duty factor of NuMI/NovA operations would be reduced by a of factor 2/n. Table 1 shows the particle throughput and average beam power delivered to Tev120 for a range of values of n. For example, a 10% reduction in the NOvA macro-duty factor program would support a Tev120 program which could deliver approximately 70 kW with 95% duty factor over a 26.7 s cycle time to experiments and the MTest program. In the absence of NuMI/Nova operations the Tev120 program could conceivably take all of the MI beam, and deliver 700 kW with a 50% duty factor.

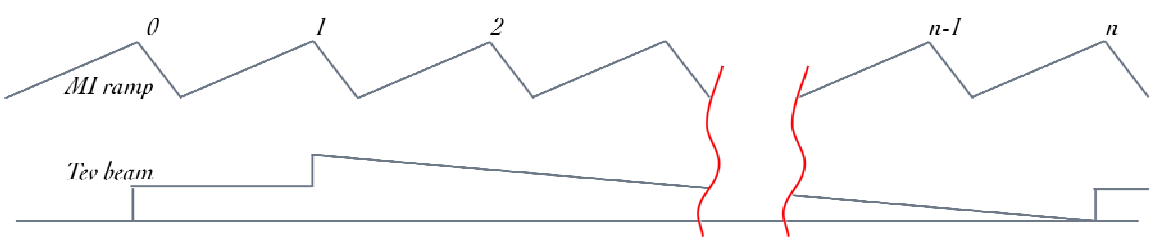

Figure 2. Main Injector energy ramps (top curve) and Tevatron beam intensity (bottom curve). Out of n, beam is injected over two cycles, and spilled for n-1.

n	T [s]	Duty factor [%]	NovA reduction [%]	P_{ave} [kW]	P_{max} [kW]	dN/dt_{Ave} [Tp/s]	dN/dt_{Max} [Tp/s]
2	2.667	50	100	691	1382	36.0	72.0
3	4.000	67	67	461	691	24.0	36.0
4	5.333	75	50	346	461	18.0	24.0
5	6.667	80	40	276	346	14.4	18.0
10	13.333	90	20	138	154	7.2	8.0
20	26.667	95	10	69	73	3.6	3.8
50	66.667	98	4	28	28	1.4	1.5
100	133.333	99	2	14	14	0.7	0.7
200	266.667	100	1	7	7	0.4	0.4

Table 1. Available power to Tev120 program and impact on Main Injector neutrino program. Here, beam is taken on two pulses out of *n* for TeV120. An initial Tevatron intensity of 96 Tp is assumed.

The Tevatron intensity used in the example above, ~100 Tp per pulse, was chosen as this is what the MI should be able to deliver. The record intensity achieved in the Tevatron during its fixed target history, however, was only approximately 30 Tp. The intensity was mainly limited then by beam instabilities at high energy, typically around 600 GeV. Additionally, the MI did not exist, and ~30 Tp was the limit that could be transferred from the old Main Ring injector. Operation at a constant 120 GeV, and improvements in beam feedback and damping systems, should allow for a much higher intensity throughput. For reference the Tevatron routinely delivered 64 kW (averaged over 60 seconds, 30% duty cycle) of 800 GeV extracted beam to experiments during the 1997 fixed target run.

Other items of note:

1) The existing A0 abort system can be used in this scenario, as 100 Tp @ 120 GeV is roughly equivalent to 12 Tp @ 1000 GeV.

2) Improvements made to impedances and to damper systems in the Tevatron during Run II would help with possible beam intensity-related instabilities.

3) The use of the existing F0 Lambertson magnet for both injection and extraction can be contemplated, which would require a polarity reversal switch. The electrostatic septum would then be placed in the C0 straight section, or at E48, and the existing SY120 beam line could be used, relinquishing the need to re-establish the A0 extraction area. The QXR air core quadrupole system would be re-commissioned for tune feedback.

4) The beam is 2.5x larger at 120 GeV than at 800 GeV (for same emittance), so somewhat less aperture will be available for slow spill process.

5) A barrier bucket scheme can be employed to contain beam during injection and slow spill. Thus, no 53 MHz RF would be necessary (relinquishing these RF systems for possible use in MI/NOvA).

6) The Tevatron would be reconfigured to 1983 optics in long straight sections in order to lower the heat leak in the system and to improve extraction efficiency. The necessary magnetic elements are in storage.

7) As there will be no magnet ramping, no low-beta optics, and a lower operating current, there will thus be higher operating margin and more reliable operation of the magnet system.

8) The sextupole moment, b_2, at 120 GeV would be ~25% worse than at 150 GeV, potentially affecting chromaticity tuning, dynamic aperture, etc. However, b_2 drifts with time and would eventually reach its asymptotic value (toward zero). Thus, except following start-ups, etc., the dynamic aperture at 120 GeV should be not so different than at 150 GeV for Run II operation.

9) Operation of Tev120 would not affect the 8 GeV program whatsoever. Booster batches to fill MI on Tev120 cycles would be the same as on NOvA cycles. Thus, the same spare Booster cycles are still available for an 8 GeV program.

The main drawback of this scenario which immediately comes to mind is the operating cost of the cryogenic system and of the supporting infrastructure for the four-mile ring to support a 120 GeV fixed target program. The cost of running the Tevatron today is estimated at approximately \$6-10M/year, not including labor to maintain the systems (perhaps up to ~\$15M/year). Unfortunately, the fact that the power use of the Tevatron cryogenics system is dominated by the heat leak inherent in the magnets and in high temperature power leads, and the fact that the two-phase helium system cannot function above about 5°K prevent any savings from operating at a higher temperature with the present cryo equipment. However, power losses due to ramping would be avoided. Corrector circuits, which also produce a significant source of heat leak through their power leads, will be running at much reduced currents. The monthly power and cryogen M&S costs are expected to reduce from \$710K/mo (collider operations) to \$590K/mo (stretcher operations). Reduced demands on the RF system will also help the operational costs, and the reduced stress of all system components due to the DC operation should save maintenance costs. The main advantage of this program would be that it could easily come on line with very little additional up-front costs and with very little interruption to other laboratory operations. Since this proposal uses mostly already-existing equipment, initiating this program would be straightforward and relatively low cost.

Tevatron 800 GeV Fixed Target

The Tevatron remains the world's only high energy (TeV-scale) synchrotron capable of rapidly ramping to full field and thus able to support a viable TeV-beam fixed target program. Although the fixed target operation was halted in 2000, the Tevatron is still capable of producing quality fixed target beams in the TeV energy range (800 GeV being the nominal high energy limit).

Using the scenarios described above, where beam intensities on the order of 50-100 Tp can be injected into the Tevatron from the Main Injector, and assuming that these intensities can be maintained to 800 GeV, a fixed target program with much higher throughput than in previous runs can be contemplated. Potential fixed target experiments at 800 GeV have been examined recently in both the charm and neutrino sectors [13] . One particular example is a high energy neutrino experiment proposed to Fermilab by the NuSOnG collaboration [14]. Here, a 40 s cycle time for the Tevatron and a 1 s flat top for fast extractions to the experiment have been suggested. Assuming the 1.333 s cycle time for the Main Injector, this would constitute a 2.667/40 = 6.7% impact on the running of the 120 GeV neutrino program from the MI. This Tevatron program would deliver an average of 250 kW of beam power at 800 GeV, and approximately 4×10^{19} POT/yr, assuming 80 Tp/pulse. NuSOnG, for example, would then reach its goal of 1.5×10^{20} within about 4 years of running.

To facilitate the return of a Tevatron 800 GeV fixed target program, in addition to the various items noted in the previous section, the C0 area beam abort would have to be re-commissioned and the extraction point would definitely need to be re-established at A0 (as there would not be room for 800 GeV extraction at F0, where the RF system is located). The necessary components for these all exist. Spare Tevatron magnets exist for running a fixed target program for 4-5 years, perhaps longer. Further details on reinstituting an 800 GeV program can also be found in [10].

Appendix V

Opportunities and Issues of Antiproton Source Operation

The existing Fermilab Antiproton Source can be easily used for an Accumulator based antiproton physics program after the conclusion of Run II. The only physical modification of the Antiproton Source would be to break Accumulator vacuum to install a detector. There are a few control issues that would have to be implemented since the CPU-network that communicated the deceleration commands was removed for Run II. In addition there would need to be several months to re-establish Accumulator deceleration ramps.

V.1 Antiproton Sources:

There are only two operating antiproton sources in the world. CERN operates the Antiproton Decelerator (AD) where the antiprotons are created every two minutes, captured and decelerated to very low energies. The extracted antiprotons are then used in several trapping experiments. CERN produces at most 3.5×10^{12} antiprotons each year. Fermilab operates the Debuncher/ Accumulator complex to produce antiprotons for the Tevatron collider program. During May 2009, 145×10^{12} antiprotons were produced; the stacking rate is > 25×10^{10} antiprotons per hour and routinely stacked to 10^{12} antiprotons.

A new antiproton source is proposed as part of the FAIR (Facility for Antiprotons and Ion Research) project that is to be hosted at GSI in Germany. The goal of the FAIR antiproton source is to stack at 3.5×10^{10} antiprotons per hour to a maximum of 10^{11} antiprotons. The FAIR project is to support both a trapping antiproton physics program as well as medium energy experiment with antiproton beam momentum between 1.5 and 15 GeV/c in a separate ring from the FAIR accumulation ring. The accumulation ring will spend half of its operation supporting the ion aspect part of FAIR as well. This means if FAIR achieves its goals, 95×10^{12} antiprotons per year will be available to the two antiproton physics programs.

V.2 Potential Accumulator Stacking:

After Run II, the Recycler will be recast as a proton accumulator which will allow one turn injection into the Main Injector. The ramp cycle time for the Main Injector to 120GeV will become 1.333s (currently at 2.2s due to having to load batches from 11 Booster cycles directly into the Main Injector). The future cycle time is too fast for the antiproton complex; therefore, antiproton production would be done every other Main Injector ramp cycle at 2.666s. Due to the relative size of the Antiproton Source rings to the Main Injector, only a fraction of the proton beam accelerated in the Main Injector is used for antiproton production: currently 2 out of 11 Booster batches and in the future 2 of 12.

With the longer time between batches for antiproton production and going to larger stack sizes, we expect the stacking rate will average ~20×10^{10}. To support an antiproton physics program based in the Accumulator, stacking will be halted after collecting ~10^{12} antiprotons which are then decelerated to the momentum of interest (4 to 8.9 GeV/c has been achieved). If stacking, deceleration and data taking occur is a 24 hour cycle and roughly a quarter of that time is spent stacking, the reduction of protons for the NuMI/NoVa program will be (1/4 x 1/2 x 1/6) or ~2%. At 10^{12} antiprotons per day would mean that an Accumulator based program could use >200×10^{12} antiprotons per year. An Accumulator antiproton physics program will use more than twice the projected number of antiprotons at FAIR and the time frame will be 5 years before FAIR starts operation.

With a moderate increase to the gas jet target density that was used for E760/E835, luminosity of 1-2×10^{32} $cm^{-2}s^{-1}$ is possible. Depending upon the beam energy, the beam lifetime will be 10-20 hours. With a 24 hour cycle to stack and take data, a program can expect to record ~8 pb^{-1} per day.

V.3 Unique Technique for Study of Charmonium and XYZ States:

The B-factories and collider experiments have center-of-mass energies much greater than the Charmonium or XYZ states. Much luminosity is expended at these higher center-of-mass energies and Charmonium and XYZ states are seen in low rate decays from these higher mass states. The data peaks observed are a convolution of a Briet-Wigner and the detector resolution for the overall decay channel being observed. The detector resolutions are mostly based upon Monte Carlo simulations and are very complicated. The typical detector resolution is a few MeV.

As shown by the previous Accumulator experiments E760/E835, the data peaks observed are a convolution of a Briet-Wigner and the beam distribution [1]. This is achieved since the antiproton beam energy width is small (a few hundred keV in the center-of-mass frame) and the beam energy is chosen such that the antiproton-proton annihilations sample a part of the Briet-Wigner resonance. The Accumulator is a spectrometer while the detector is a large scalar.

The beam energy is set and data are taken. The beam energy is changed and more data are taken. A scan across a state of interest is done. Electron-positron colliders can perform this technique only for $J^{PC} = 1^{--}$ states (for example J/ψ and ψ') while needing to make corrections for initial state radiation. Even though the 1^{--} states are as/more narrow than the antiproton beam distribution, the resulting de-convolution is straight forward and has resulted in the most precise measurement of the ψ' width [2] with many fewer events than the lepton colliders.

Once the peak of a resonance is established, the beam energy can be set to maximize the number of particles formed and studies of angular distributions and measurements of different low rate decays can be performed.

V.3.1 Example X(3872):

The X(3872) was discovered and confirmed after the last E835 run. X(3872) has been seen by Belle [3], CDF [4], D0 [5] and BaBar [6] in several channels: $J/\psi\ \pi^+\pi^-$, $J/\psi\ \pi^+\pi^-\pi^0$, $J/\psi\ \gamma$, and $D^0\ D^{*0}$. All measurements show that a resonance is narrow even though it is above the open charm threshold. In fact, mass determinations using the J/ψ channels and the D-state channel disagree with the former resulting in a mass less than the $D^0\ D^{*0}$ threshold. Are these the same particle or two resonances? An Accumulator scan of the resonance region counting inclusive J/ψ and the D-state channel will be able to resolve the resonance/resonances.

Since the range of masses reported for the X(3872) covers several MeV, an Accumulator scan using 0.25MeV steps over 10MeV will be necessary. Each scan point will take about a day. The branching fraction for formation of the X(3872) in antiproton-proton annihilation is not known, but it has estimated to be similar to the χ_c states. The decay rates are listed as seen except for $J/\psi\ \pi^+\pi^-$ being greater than 1% [7]. For E835, the number of events observed at the χ_{c0} peak was 30 events per pb^{-1} where the radiative decay to J/ψ is ~1% with no background. Within a factor of two, this is the number of events per pb^{-1} that would be expected at the X(3872) peak. Even if the production is down by an order of magnitude, the expected number of events for a day sitting on the peak will be a few tens of events. A two month scan triggering upon inclusive J/ψ and charmed particles could result in two distinct resonances. If needed, further scanning (smaller steps and/or more integrated luminosity per point) of the region could clarify the resonance(s). Sitting on the mass peak, the different branching fractions can be measured while measuring the angular distribution of the decay products.

V.3.2 Charmonium and other XYZ states:

The same technique can be used to scan the charmonium states η_c, h_c and $\eta_c^{/}$. The Accumulator's maximum beam energy corresponds to a center-of-mass energy about 4.3 GeV which allows the Accumulator to investigate at least six other XYZ states other than the X(3872).

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