PROJECT X WITH RAPID-CYCLING AND DUAL-STORAGE SUPERCONDUCTING SYNCHROTRONS *

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Abstract

Investigation of neutrino oscillations and rare meson decays are the main physics goals of Project X [1]. The successful physics outcome relies on the feasibility of high-intensity neutrino and meson (K^+ and μ) beams. In order to meet this goal we propose a synchrotron-based accelerator system (Option A) as technologically easier and cost-effective alternative to the accelerator system dominated by the linear accelerators (Option B [2]). The synchrotron-based accelerator system is outlined and the expected proton beam power for the neutrino and meson beams production is presented and discussed. Further conceptual and technical details of the synchrotron-based accelerator system for Project X are outlined in [3].

SYNCHROTRON-BASED ACCELERATOR COMPLEX FOR PROJECT X

The proposed synchrotron-based accelerator complex for Project X is illustrated in Fig. 1, and the time sequence for beam stacking, extraction and acceleration is shown in Fig. 2. The H^- beam from the 1 GeV PLA (Pulse Linear Accelerator) after being stripped of charge is stacked in the SRCS (Superconducting Rapid Cycling Synchrotron). The SRCS beam pulse is ramped to 8 GeV and extracted sequentially to SSR1 and SSR2 (Superconducting Storage Ring 1 and 2) synchrotrons. The SSR1 is filled with 3 and the SSR2 with 4 SRCS pulses. As both PLA and SRCS operate with the repetition rate of 10 Hz stacking 7 SRCS pulses in the SSR1-2 allows match the 0.7 s cycle time of Main Injector (MI) required for proton beam acceleration to 60 GeV. The main parameters of the accelerator sub-systems are listed in Tables 1 and 2.

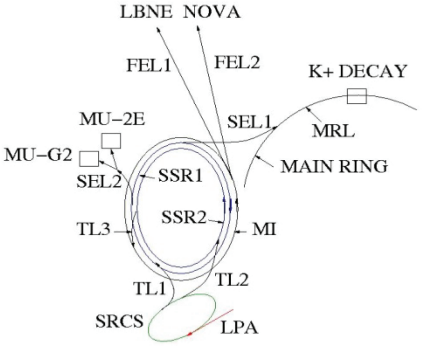

Figure 1: Schematic view of synchrotron-based accelerator complex for Project X at FNAL.

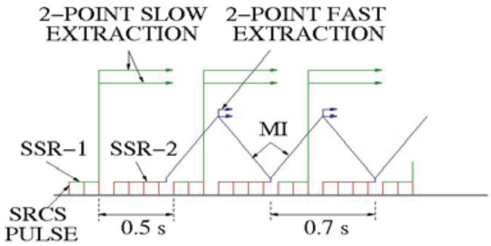

Figure 2: Time sequence for SRCS, SSR1-2 and MI beam.

Table 1: Main Parameters of PLA and SRCS

Parameter	PLA	SRCS
E_{inj} [GeV]	0.005	1
E_{extr} [GeV]	1	8
Path/Ring length [m]	335	829.9
Pulse rate [Hz]	10	10
Beam current [mA]	10	-
Pulse width [ms]	1	-
Protons per pulse	-	5.4 10^{13}
Beam power [kW]	125	1000

Table 2: Main Parameters of SSR1, SSR2 and MI

Parameter	SSR1	SSR2	MI
E inj [GeV]	8	8	8
E extr [GeV]	8	8	60
Ring length [m]	3319.4	3319.4	3319.4
Cycle time [s]	0.7	0.7	0.7
SRCS pulses	3	4	4
Extraction mode	Slow (0.5 s)	fast	fast
Extraction points	2	1	2
Beam power [kW]	300	400	3000

The SRCS beam is stacked in the SSR1and SSR2 rings using TL1 and TL2 transfer lines. The SSR1 and SSR2 beams circulate in the opposite directions. From the SSR1 ring the beam is simultaneously slow-extracted into the SEL1 and SEL2 lines. The SEL1 line extends to MRL line in the Main Ring bringing proton beam to the K^+ decay experiment. The SEL2 line delivers proton beam to the μ-> 2e and μ -> g2 experiments. From the SSR2 ring the proton beam is fast-extracted to the TL3 transfer line which directs beam to the Main Injector where protons are accelerated to 60 GeV. This is followed by the 2-point sequential fast extraction into the FEL1 and FEL2 lines

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which direct proton beams to the neutrino production targets of the Nova and LBNE experiments.

The total available beam power of 300 kW for the slow extractions from the SSR1 ring is lower than 750 kW one projected for the J-PARC MR [4]. As the slow extraction related beam losses may very strongly affect working of accelerator components we propose to further minimize the beam losses at the extraction point by subdividing the extraction to two far-apart points in the SSR1 ring, each with 150 kW beam power. For the 3320 m long SSR1 ring and 0.5 s long the beam extraction time there will be ~ 45000 beam crossings through each point. We propose use the 3rd order resonance to drive the beam across the septa kicking beam particles out of the circulation in the ring. The sextupole fields in the SSR1 ring will be used to convert the circular phase-space of particle trajectories into the triangular stable area with the separatrix branches allowing septa deflect a small fraction of the circulating beam at each crossing. For the electrostatic septa of ≤ 100 μm effective thickness the extraction efficiency of 98% can be expected [5], leading possibly to 3 kW of beam power loss at each extraction point. The beam optics symmetries, especially the betatron phase between the extraction points, need to be carefully considered for such a multi-point resonant extraction system.

BEAM POWER FOR PRODUCTION OF NEUTRINOS, K^+ AND μ MESONS WITH SRCS AND SSR1-2 SYNCHROTRONS

In Option B of Project X accelerator system the 3 GeV linear accelerator provides beam for the production of mesons. As Option A uses the 8 GeV beam the proton beam energy must be considered to compare the meson productions. The projected neutrino and the equivalent beam power for the meson productions were elaborated in [3] and are given in Table 3. With the exception of the neutrino channel the beam power with Option A constitutes 40 % for the K^+ and 20 % for the μ channels of those of Option B. As illustrated in Fig. 3, however, the K^+ production with the SRCS + SSR1 synchrotrons much exceeds those planned for any future facility [6].

Table 3: Expected Beam Power for Project X Physics

Physics channel	Option A [kW]	Option B [kW]
Neutrino	3000 (6000)	2000
K^+ decay	600 (1200)	1500
μ -> 2 e	75 (150)	375
μ - g 2	75 (150)	375

We note that the PLA can deliver higher beam intensity, so by increasing the stored beam capacity of synchrotrons a higher beam power for the particle production can be achieved. It was shown in [7] that upgrading the Main Injector RF system from the 53 MHz to 212 MHz would allow doubling the proton bunch intensity. Consequently, upgrading RF frequency of all the Project X synchrotrons may allow matching Options A and B expectations for the K^+ decay rate at 80% level, and at 40% level for each μ channel (values in brackets in Table 3). The beam power per extraction point would increase to 300 kW, or 40% of the planned extracted beam power at J-PARC MR.

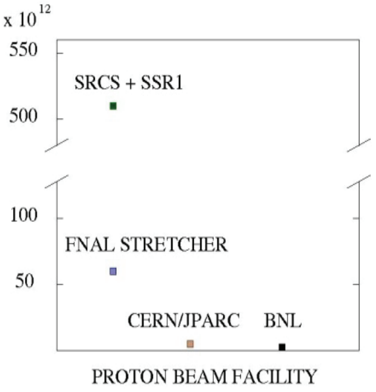

Figure 3: Projected K^+ decays/year at various facilities.

LINEAR ACCELERATOR OPTIONS FOR AN INJECTOR TO SRCS

We propose the SNS-like [8] 1 GeV proton pulse linear accelerator as an injector to the SRCS synchrotron. As the SNS accelerator is successfully operating it can be used as a “blue-print” for the construction of an injector to the SRCS synchrotron. However, if the ILC-type modules were to be tested as part of the FNAL long-term strategy, then the PLA energy should be increased to no less than 2 GeV, adding a considerable development and construction time as well as substantially increasing the overall cost in required human resources and material.

MAIN ARC MAGNETS FOR SRCS AND SSR1-2 SYNCHROTRONS

For the SRCS and SSR1-2 synchrotrons we propose application of superconducting magnets as they are less expensive both to build and operate than the equivalent resistive magnets. In addition much smaller space is needed inside the accelerator tunnel. Both SRCS and SSR1-2 synchrotrons magnet systems must feature wide operational temperature. The rapid cycling mode of the SRCS and the slow beam extractions from the SSR1 ring may significantly raise magnet cable temperature possibly leading to a quench. The application of the HTS cable to power the magnets strongly meliorates this problem as the operational temperature can be practically set up to 30 K below [9] the cable superconductivity limit. For the SRCS the entire magnet string will be powered with the HTS cable but for the SSR1-2 only in the slow beam extraction sections the HTS cable needs to be applied.

The SRCS magnet is currently being developed [10] at FNAL and its HTS cable was successfully tested [9].

For the SSR1-2 synchrotron we propose a scaled-down version of the VLHC-1 magnet [11]. A comparison of the SRCS and the SSR1-2 magnet parameters with those for the FAIR [12] and VLHC-1 [11] synchrotrons is given in Tables 4 and 5, respectively. One can see that parameters of the proposed SSRC and SSR1-2 magnets are much less stringent than their counterparts for FAIR and VLHC-1.

Table 4: Parameters of SRCS vs FAIR Magnet

Parameters		**SRCS**	**FAIR**
B_{inj} | B_{oper}	[T | T]	0.1 | 0.6	0.24 | 2
Beam gap	[mm]	50	60
I_{oper}	[kA | N_{turns}]	30 | 1	7.5 | 16
Rep. rate	[Hz]	10	1
$(dB/dt)_{oper}$	[T/s]	12	4
Power cable	[SC]	344C-2G	NbTi
N strands		124	496
T_{oper}	[K]	4.5	4.5
T_{margin}	[K]	25	1
Power loss @ 5 K	[W/m]	30	74

Table 5: Parameters of SSR1-2 vs VLHC-1 Magnet

Parameters		**SSR1-2**	**VLHC-1**
B_{inj} | B_{extr}	[T | T]	0.15 | 0.15	0.05 | 1.96
Beam gap	[mm]	2 x 50	2 x 20
Beam separation	[mm]	200	150
dB/dx	[T/m]	1.5	9.7
Superconductor		NbTi | 344C-2G	NbTi
N strands		112 | 36	576
I_{max}	[kA | N_{turns}]	30 | 1	100 | 1
T_{oper}	[K]	4.5	4.5
T_{margin}	[K]	2.5 | 30	2.5
Power loss @ 5 K	[W/m]	0.3	0.3

A new tunnel has to be constructed for the SRCS synchrotron but the SSR1-2 synchrotrons will be installed in the Main Injector tunnel replacing the Recycler. The large size of the MI tunnel also provides sufficient space for the multiple beam injections and extractions at the well-separated points of the SSR1 and SSR2 rings.

We propose the main arc magnets of both SRCS and SSR1-2 synchrotrons to be energized with transmission-line power cable. This method of powering magnet string simplifies magnet construction and arrangement of the power supply including the quench detection/protection systems, as elaborated in some detail in [11]. The low material cost and the simplicity of the magnet string construction of both the SRCS and SSR1-2 synchrotrons suppress the overall cost of the Option A relative to the Option B, possibly up to about 2/3 [3].

SUMMARY AND CONCLUSIONS

The synchrotron-based accelerator complex for the Project X at FNAL will provide neutrino and meson beam intensities strongly exceeding planned anywhere else. The proposed technologies are either established or enough advanced to be considered for the accelerator design and component prototyping. This will fast-forward schedule of Project X physics operations allowing competing in the fast-evolving particle physics field. In addition, and very importantly, by applying the accelerator technologies of a much lower cost the Project X will become more likely affordable meliorating in turn its potentially adverse impact on the new accelerator R&D very much needed now to secure the future of High Energy Particle Physics in the US and elsewhere.

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