SC Magnets
at Fermilab

Project X with Superconducting Rapid Cycling Synchrotron & Superconducting Dual Storage Ring

Henryk Piekarz

Accelerator Physics Center, FERMILAB

February 14, 2011

Motivation

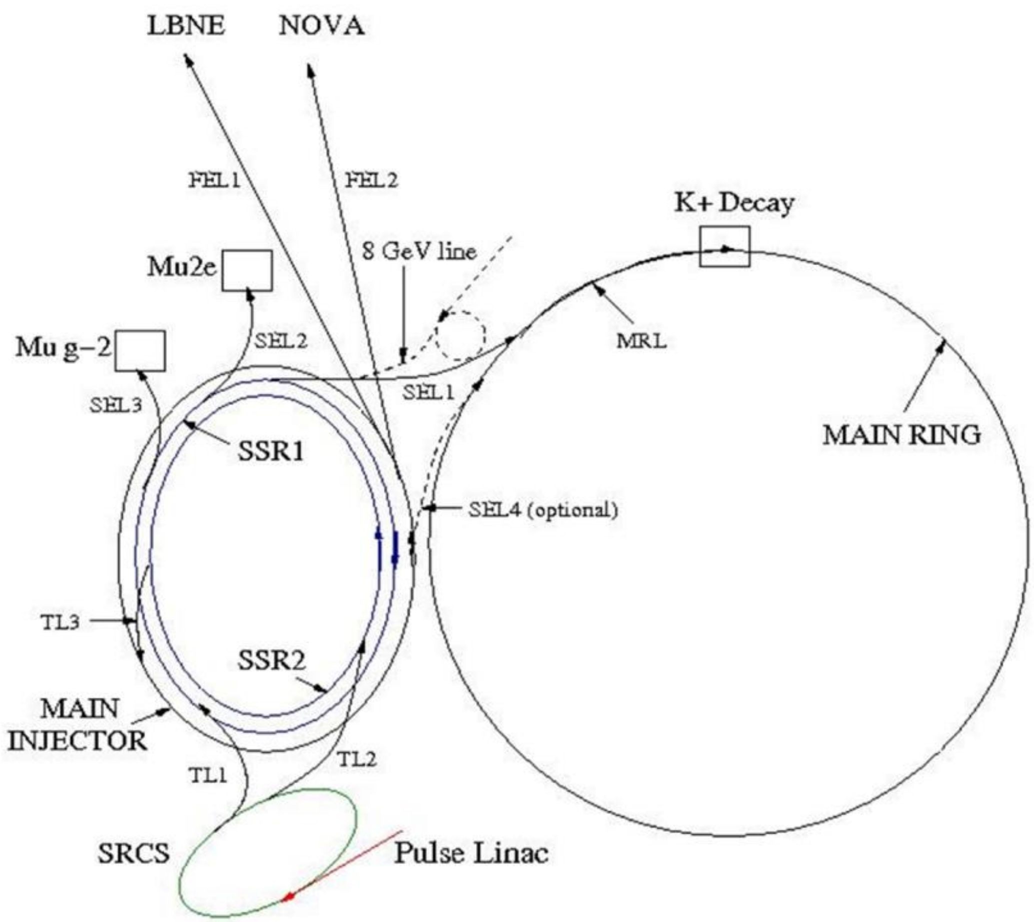
❖ *Allow to accomplish physics goals of Project X using accelerator subsystems which are neither technologically very challenging nor exceedingly expensive*

❖ *Saved in this way human and financial resources will allow to enhance R&D of accelerator technologies necessary to secure the future of High Energy Physics in the US and elsewhere*

Outline

- *Design and operation of Project X accelerator complex with Superconducting Rapid Cycling Synchrotron (SRCS) and Superconducting Dual Storage Ring (SDSR)*
- *Main parameters of proposed accelerator subsystems*
- *Expected beam power for Neutrino, K^+ and Muon experiments*
- *K^+ production with SRCS and SDSR synchrotrons versus World*
- *Linac options for synchrotron-based accelerator complex*
- *SRCS magnet parameters, design and development status*
- *SDSR magnet parameters, design and development status*
- *Other potential applications of SRCS and SDSR technologies*
- *Estimated cost of synchrotron-based accelerator complex*
- *Summary and conclusions*

Synchrotron-based Accelerator Complex for Project X



Main components:

PULSE LINAC

SRCS
(Superconducting Rapid Cycling Synchrotron)

SDSR (SSR1 & SSR2)
(Superconducting Dual Storage Ring)

MAIN INJECTOR

TL 1,2,3 (Transfer lines: 1- SRCS -> SSR1, 2- SRCS -> SSR2, 3- SSR2 -> Main Injector)

SEL 1,2,3,4 (Slow Extraction Lines: 1- SSR1 -> MRL, 2- SSR1 -> Mu2e, 3- SSR1 -> Mug-2, 4- Main Injector -> MRL)

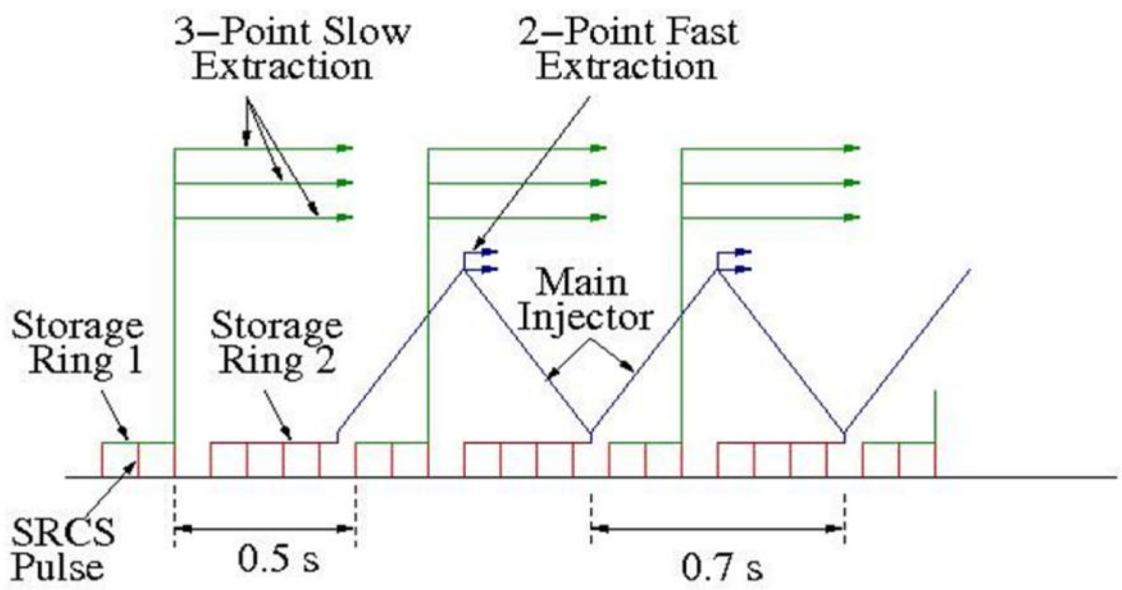
FEL 1,2 (Fast extraction Lines: 1- Main Injector -> LBNE, 2- Main Injector -> Nova)

MRL (Main Ring Line)

SC Magnets
at Fermilab

Beam Stacking, Acceleration and Extraction with SRCS and SDSR Synchrotrons

(1) 1 GeV H^- beam of Pulse Linac is striped of charge and stacked in SRCS,
(2) SRCS accelerates protons to 8 GeV,
(3) 3 SRCS pulses are stacked in SSR1 and then slow-extracted at 3 points
(4) 4 SRCS pulses are stacked in SSR2, transferred to MI, accelerated to 60 GeV
and then fast-extracted at 2 points



SC Magnets at Fermilab

Main Parameters of Synchrotron-Based Accelerator Complex for Project X

LINAC

Energy:	1 GeV
Length:	335 m
Pulse rate:	10 Hz
Pulse width *):	4.33 ms
Beam current *):	2 mA
Beam power:	125 kW

*) 8.66 mA-msec chosen for 1 MW SRCS's beam power

SRCS

Energy:	8 GeV
Circumference:	829.9 m
Pulse rate:	10 Hz
Protons/pulse:	$5.4\ 10^{13}$
Beam power:	1 MW
Pulses to Storage Ring 1:	3
Pulses to Storage Ring 2:	4

MAIN INJECTOR

Energy:	60 GeV
Circumference:	3319.4 m
Cycle time:	0.7 sec
Protons/cycle:	$2.16\ 10^{14}$
Type of beam extraction:	fast
Extraction points:	2
Beam power:	2.8 MW

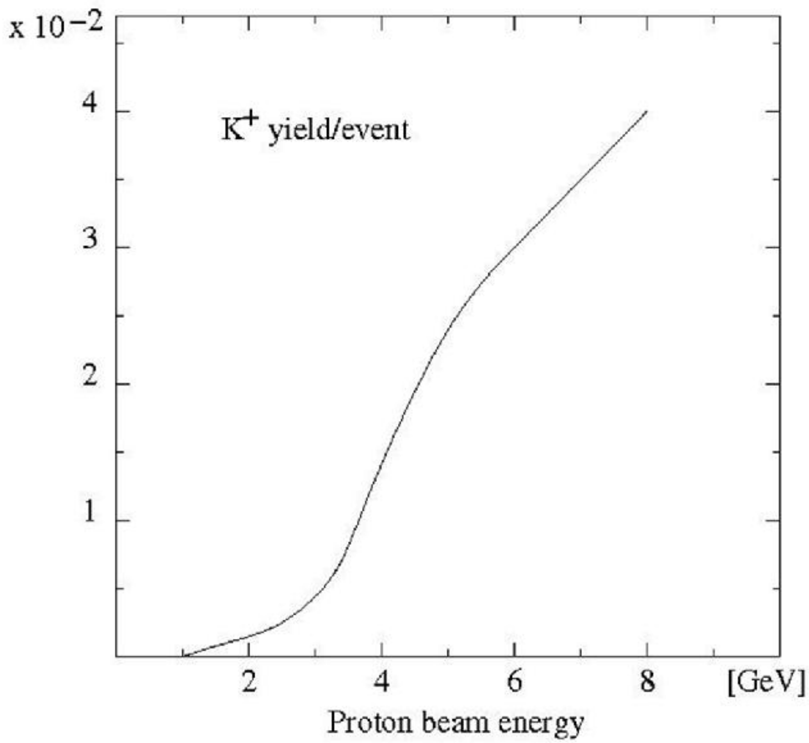
SDSR	**Storage Ring 1**	**Storage Ring 2**
Energy:	8 GeV	8 GeV
Circumference:	3319.4 m	3319.4 m
Cycle time:	0.7 sec	0.7 sec
Protons/cycle:	$1.62\ 10^{14}$	$2.16\ 10^{14}$
Beam extraction points:	3	1
Type of beam extraction:	slow (0.5 sec)	fast
Beam power/extraction point:	100 kW	400 kW

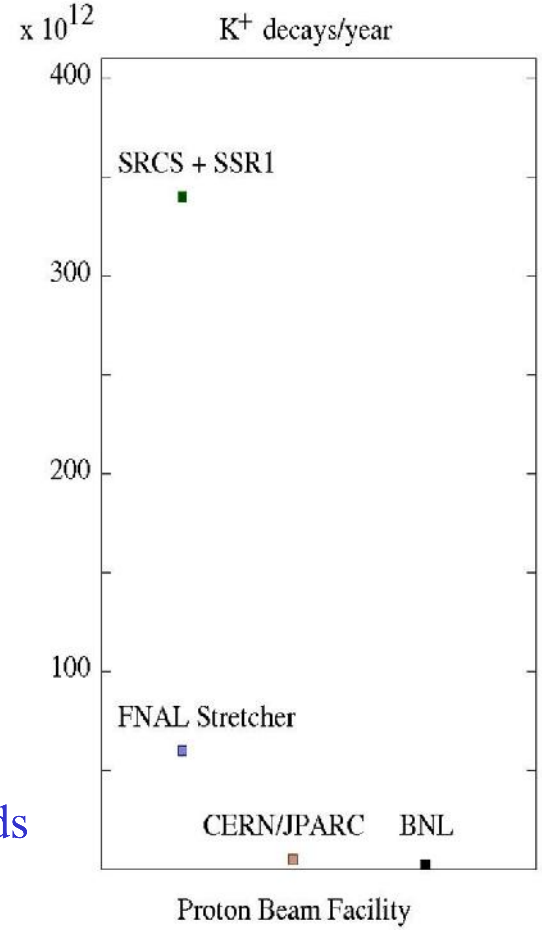
SC Magnets
at Fermilab

Beam Power for Neutrino, K^+ and Muon Production – Synchrotron vs Linac-Based Options

Phyics Channel	Linac Option	Synchrotron Option	Synchrotron / Linac
	[kW]	[kW]	
Neutrino	2000	3000	1.5
K^+ decay	1500	400	0.27
μ -> 2e	375	100	0.27
Muon-G2	375	100	0.27

K^+ Production with Synchrotron-Based Project X versus World

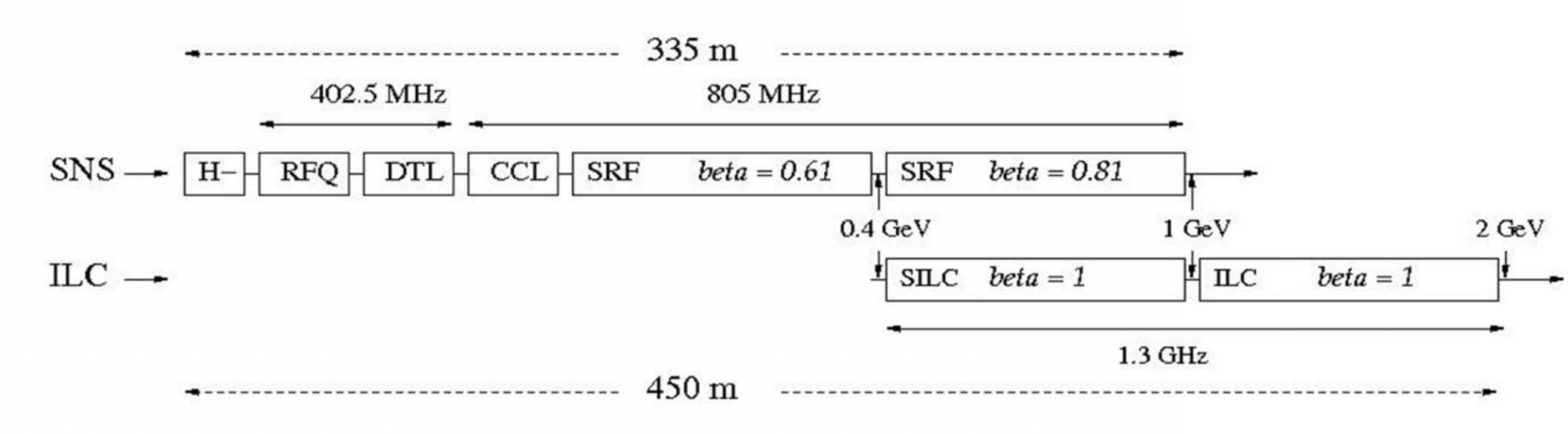




K^+ production with synchrotron-based Project X exceeds by order of magnitudes similar experiments elsewhere!!

SC Magnets

Linac Options with SRCS Synchrotron



Modified SNS-type Pulse Linac is used as injector to SRCS.With H^- charge per pulse of 15 mA-msec, repetition rate10 Hz, 65% transmission efficiency and 3% duty factor H^- -beam of 1 GeV and 1 MW power is produced.

NOTE: in order to use the ILC-style SRF modules the linac energy should reach energy of 2 GeV.

PULSE LINAC	FNAL	SNS
Energy: [GeV]	1	1
Length: [m]	335	335
Beam current: [mA]	5.0	26
Pulse length: [ms]	3.0	1
Repetition rate: [Hz]	10	60
Duty factor: [%]	3	6
Beam power: [MW]	1	1.4

SC Magnets at Fermilab

Parameters of SRCS Synchrotron for Project X and Comparison with FAIR

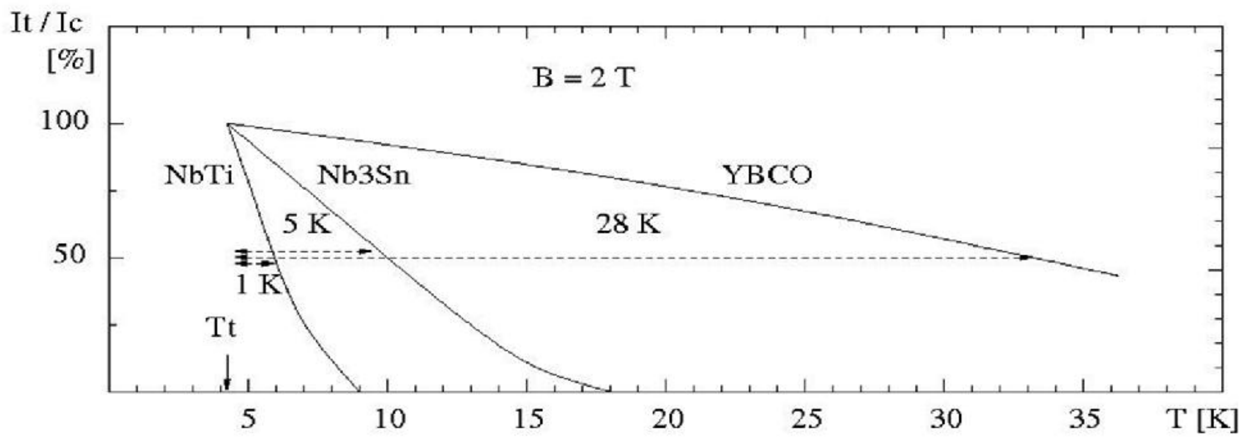
Parameter		SRCS	FAIR
Ring length	[m]	830	1100
Magnet string length	[m]	550	628
Magnet gap	[mm]	50	60
B inj / B ext	[T/T]	0.1 / 0.6	0.24 /2
dB/dt	[T/s]	10	4
Rep. rate	[Hz]	10	1
Superconductor		344C-2G	NbTi
Operational temperature	[K]	5	4.5
Temperature margin	[K]	25	0.5
Power loss @ 5 K	[W/m]	30	74
Power loss/accelerator	[kW]	16.5	46.5

SRCS Magnet Design (I)

HTS vs LTS Cable Operational Temperature Margin

1. Temperature margin for safe and possibly quench-free operations is ***make or break*** parameter of superconducting power cable in fast-cycling magnet application: with operations at 4.2 K and I t /I c = 50%, YBCO offers temperature margin 30 times wide than that with NbTi, and 6 times wider than that with the Nb_3Sn conductors.

2. The 344C-2G (YBCO) strand was also found strongly radiation hard !



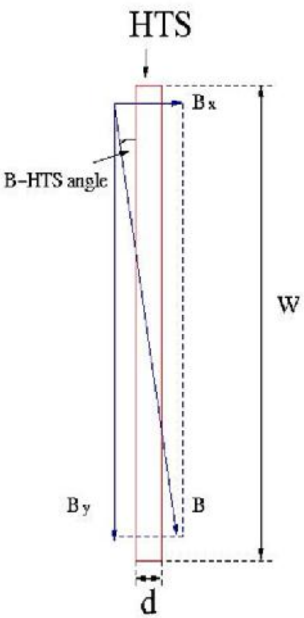
SC Magnets at Fermilab

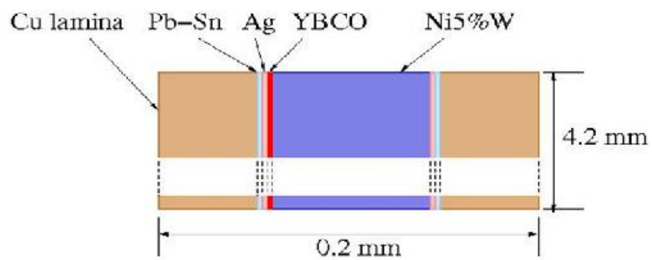
SRCS Magnet Design (II)

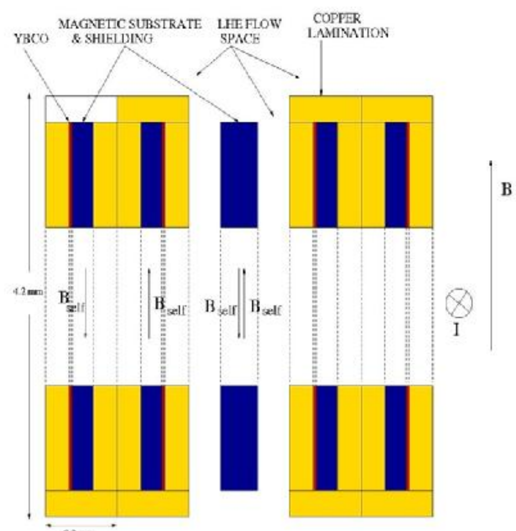
HTS Cable Arrangement & Magnetic Design for Low AC Losses

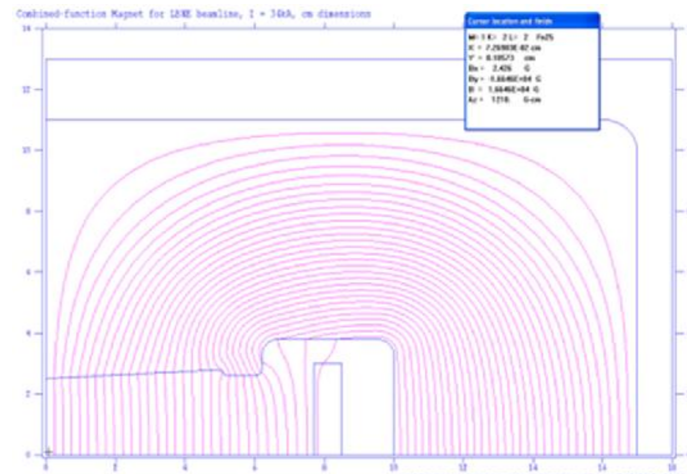
Magnetic field nearly parallel to strand minimizes exposure, and so the eddy and hysteresis losses.

HTS of tape shape facilitates low AC losses for a dipole magnet with window frame core. Main losses are: hysteresis, eddy and self-field coupling.









Magnetic substrate in YBCO can be used to suppress self-field coupling by pairing strands and inserting also substrate between each YBCO pair

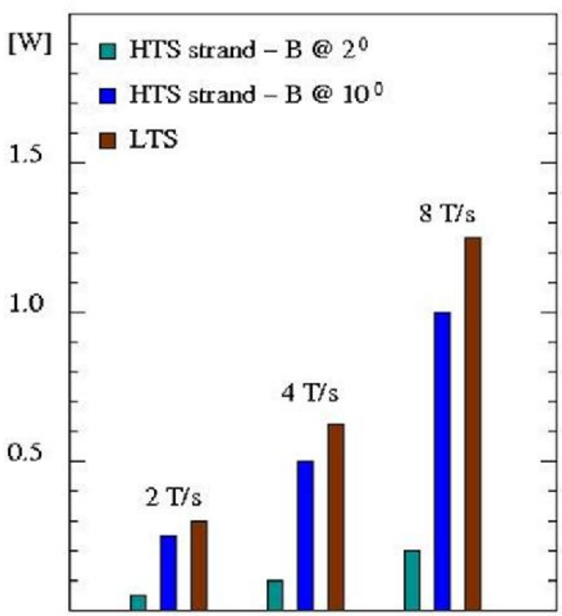
Combined function magnetic core design above features B-field to strand angle of 2^0 - averaged over entire cable space.

Beam gap: 100 mm (H) x 50 mm (V, x = 0)

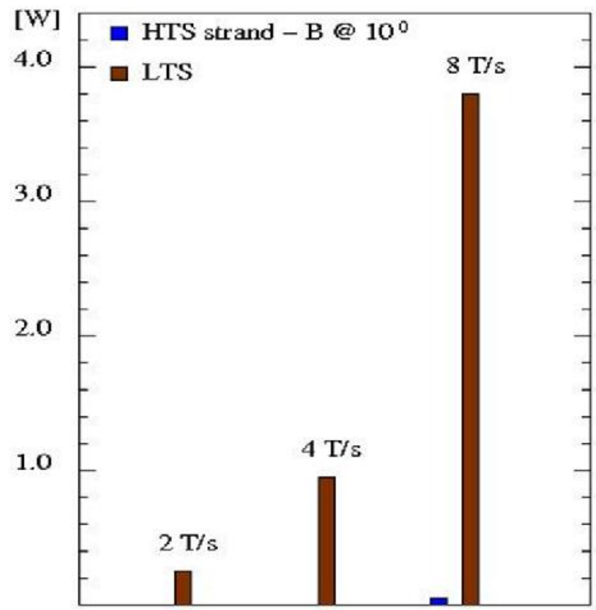
B =1.76 T @ $I_{transport}$ = 90 kA

Power Loss Expectations: HTS & LTS Cables for Dipole Magnet of 2 T and 40 mm Gap

SC Magnets at Fermilab



Hysteresis losses



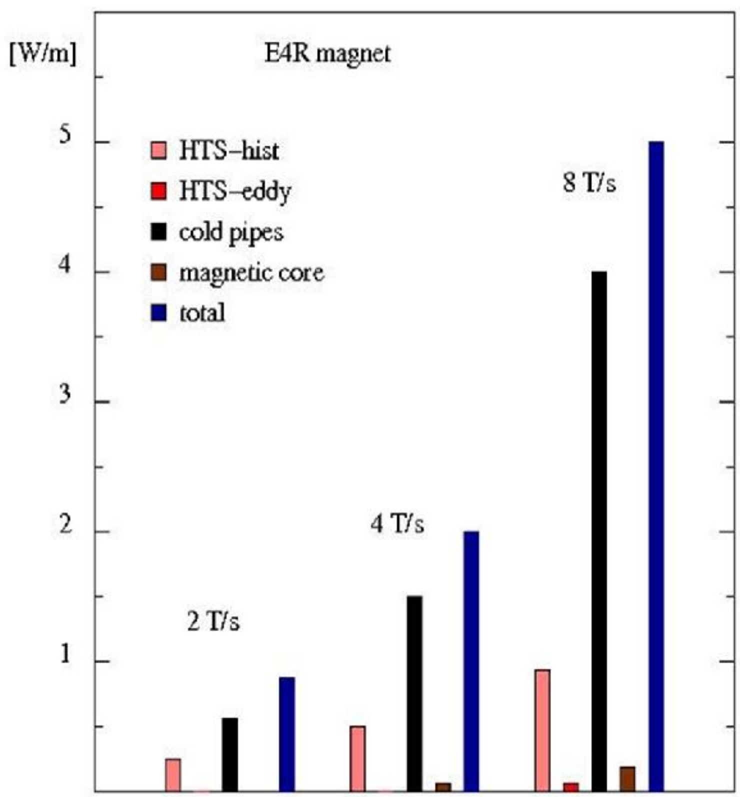
Eddy losses

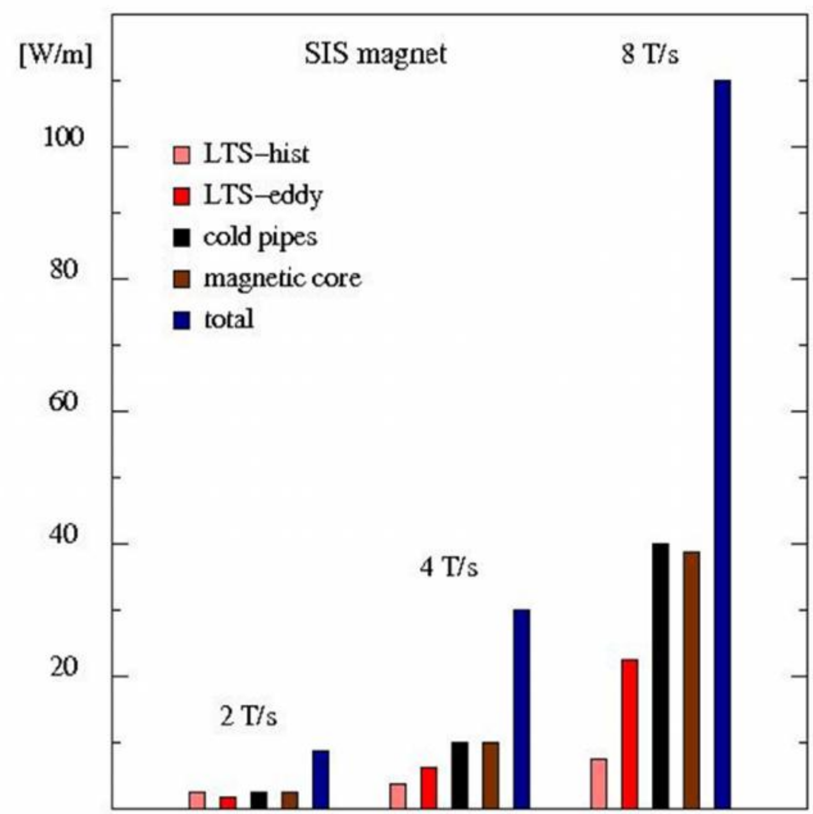
Projected hysteresis and eddy losses of a power cable for a 2 T, 1.2 m long, 40 mm gap magnet powered with HTS or LTS cables. For the HTS cable 2^0 or 10^0 angle of B-field inclination to the strand's wide surface was assumed.

SC Magnets at Fermilab

Power Loss Expectations for Magnet of 1 m Length, 40 mm Gap, 2 T

E4R (HTS) versus SIS (LTS)



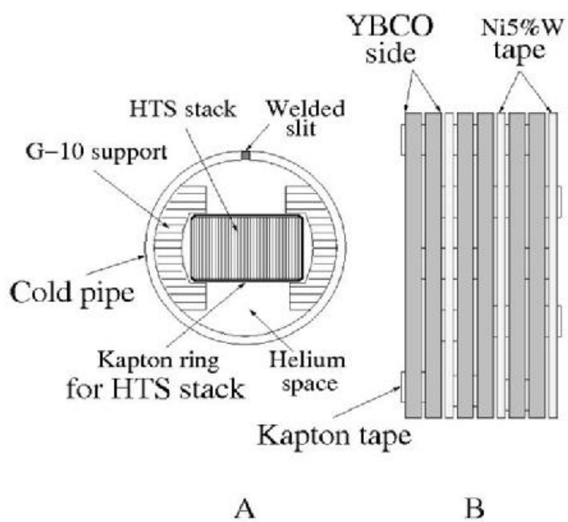


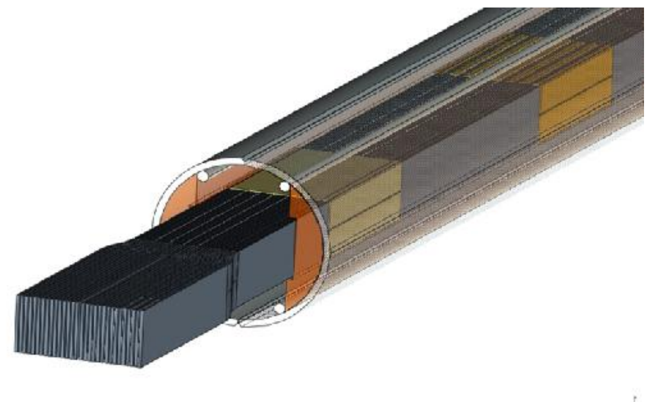
Power loss for E4R magnet can be from 10x (2 T/s) to 20x (8 T/s) times lower than with SIS magnet.

HTS & LTS Cables for Test in Sweeping Magnetic Field

SC Magnets at Fermilab

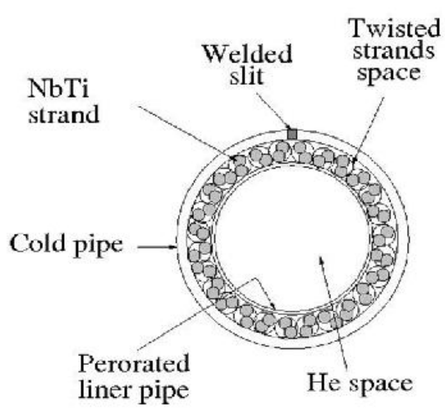
HTS test cable arrangement





HTS test cable assembly inside cryogenic pipe

LTS test cable arrangement

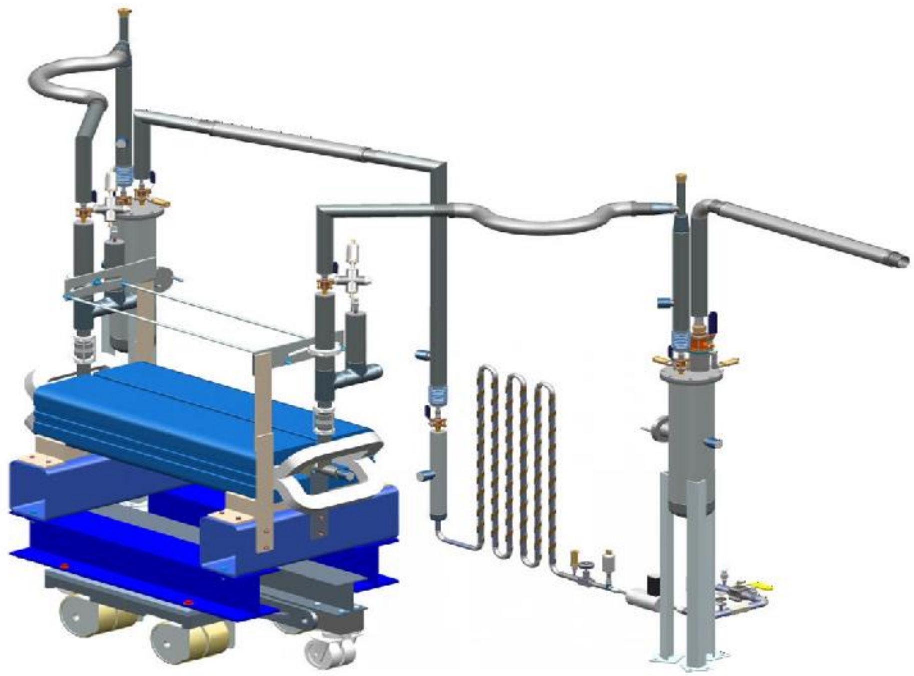


Parameters of test cables

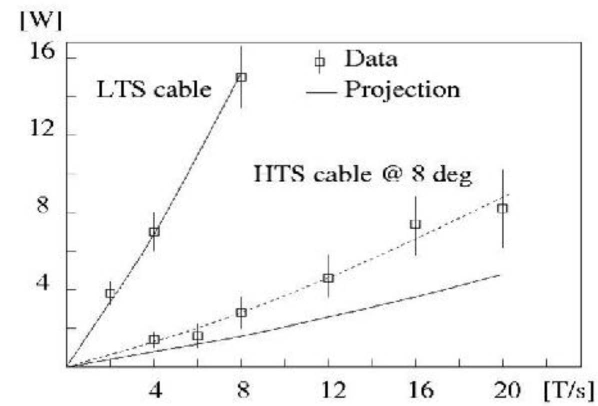
HTS	LTS
20 344C-2G strands	54 NbTi strands
Size: 4.5 mm x 0.2 mm	Size: 0.8 mm dia.
Volume: 0.9 mm^2	Volume: 0.5 mm^2
Length: 1.4 m	Length: 1.4 m
Ic = 16 kA @ 2 T_15 K	Ic = 16 kA @ 2 T _7 K

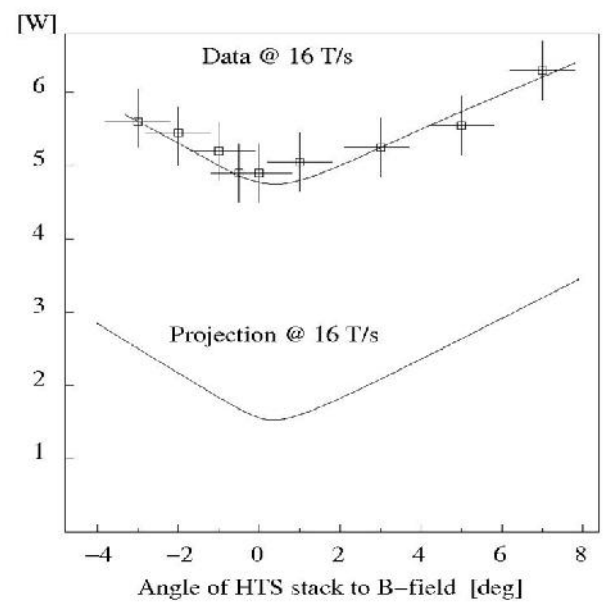
Results from HTS & LTS Cables in Sweeping Magnetic Field

SC Magnets at Fermilab



Setup for testing HTS and LTS cables

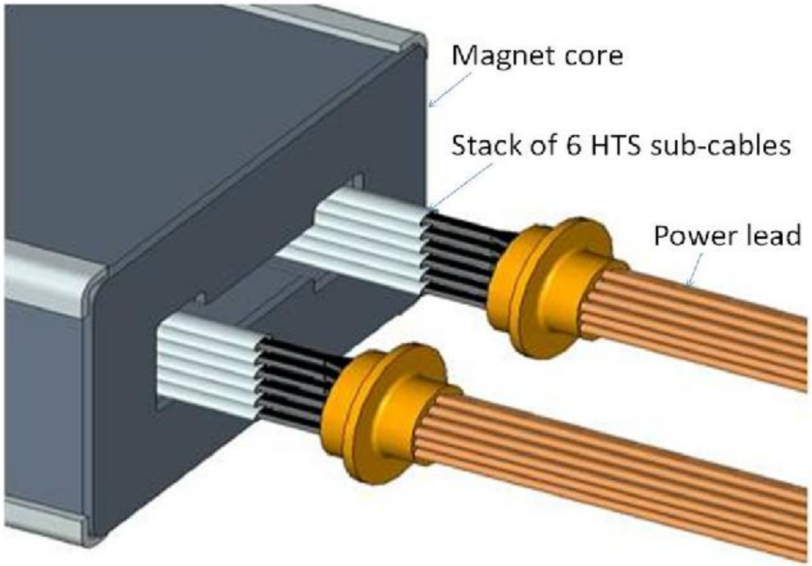


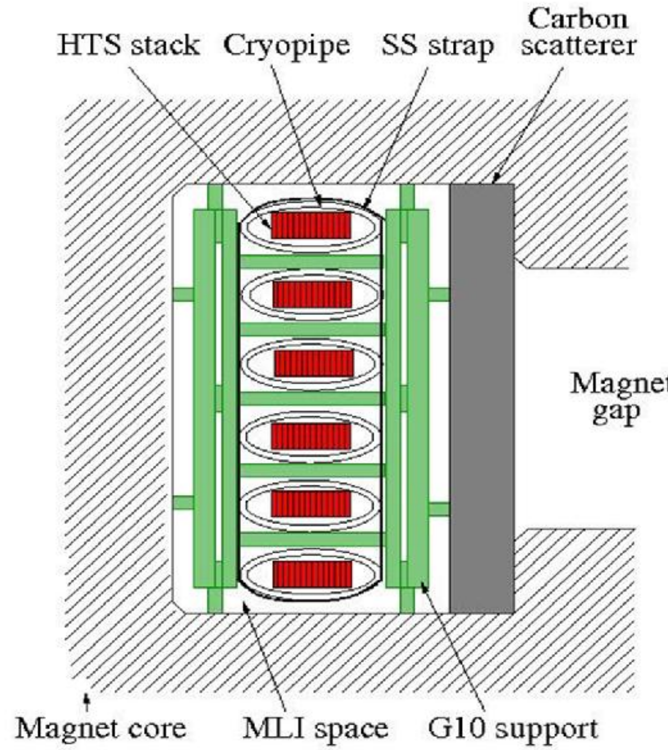


Magnetic field: 0.5 T, dB/dt = (2 - 20) T/s
HTS wide surface to B-field angle: -10^0 - $+10^0$
Cryogen: single-phase liquid helium: 8 K, 0.23 MPa, (0.4-0.8) g/s

SC Magnets
at Fermilab

Magnetic Core & Cable Designs for SRCS Magnet





TEST MAGNET PROPERTIES:

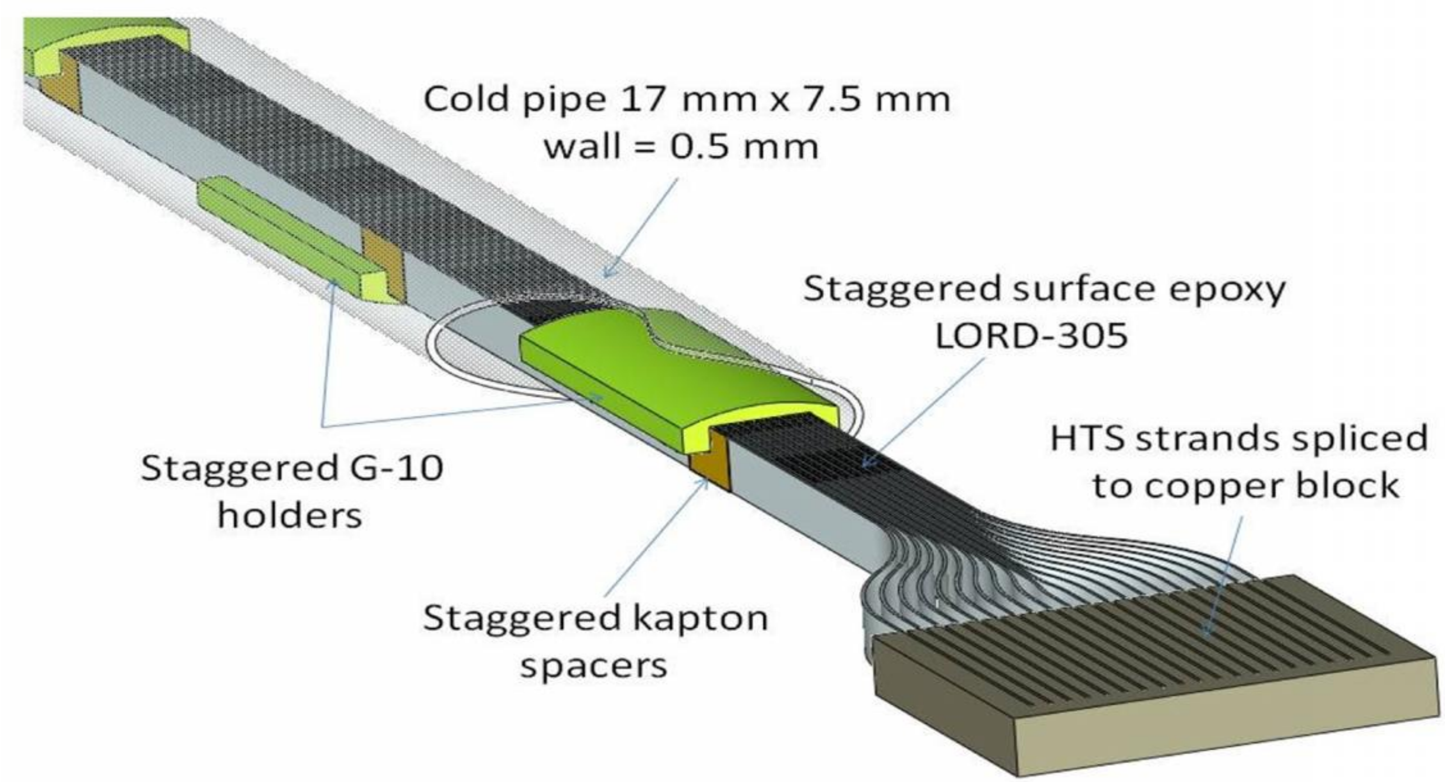
Core: Fe5%Si, 0.1 mm
Core temperature: RT to 80 K (test of cool iron yoke)
Length = 1200 mm, Gap = 40 mm x 100 mm
Cable: 2 x 96 344C-2G strands (~ 600 m of HTS strand)
Projected $\langle Angle_{HTS-B\text{-}FIELD} \rangle \approx 2^0$
B_{max} = 1.8 T, I_{max} = 90 kA, dB/dt_{max} = 18 T/s
T_{oper} = 5 K, T_{max} = 25 K

E4R operations are limited by Power Supply and Leads, thus:
B_{max} = 0.5 T, I_{max} = 27 kA, dB/dt_{max} = 10 T/s

Arrangement of sub-cables in test magnet core:

There will be only 5 layers of MLI at the top and bottom surfaces of the most outer sub-cable cryo-pipe while the sides of the entire 6 sub-cable stack will be covered with 40 layers.

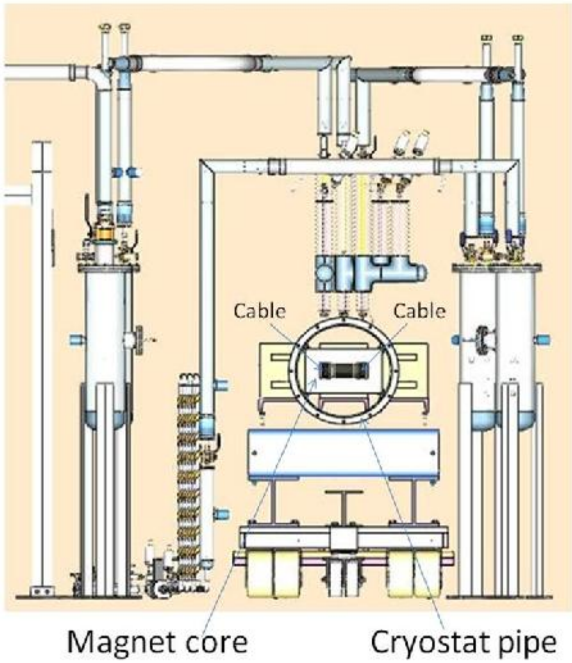
Sub-Cable Design for SRCS Magnet



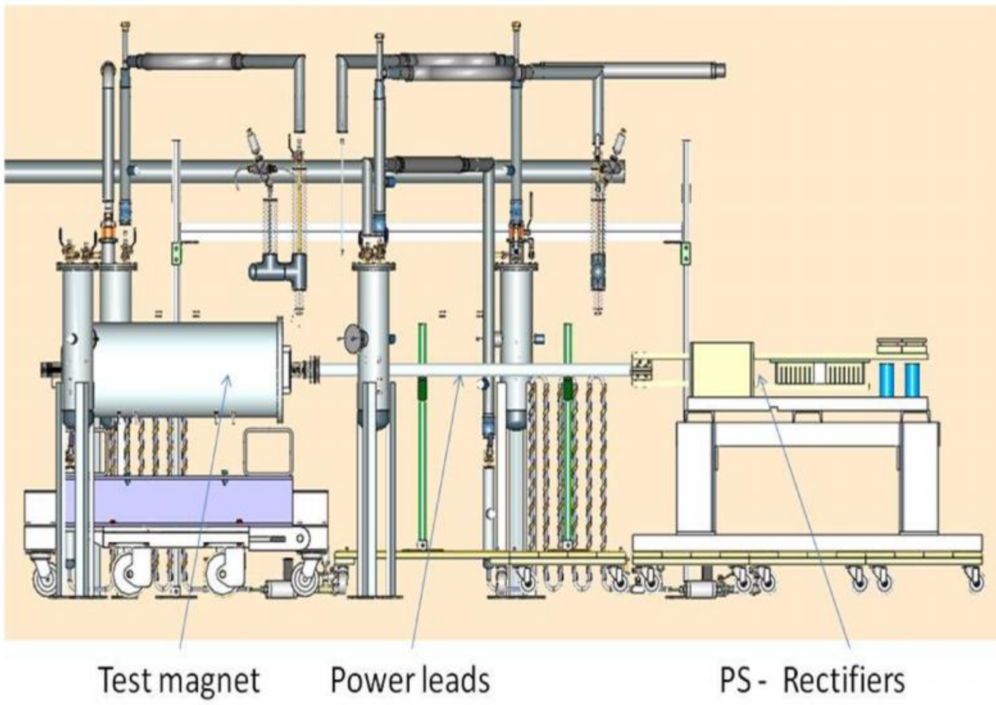
Sub-cable assembly shown above immobilizes HTS stack while forcing liquid helium to flow up and down between the strands

SRCS Magnet Test Arrangement at E4R

Design & Assembly Work in Progress



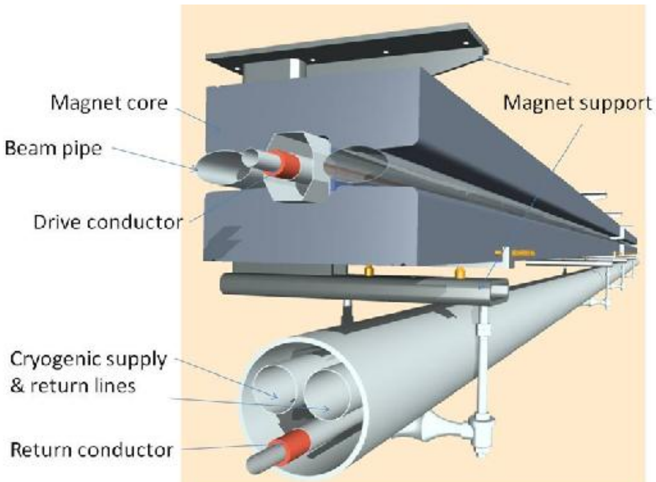
Front view



Side view

SC Magnets
at Fermilab

SDSR Magnet Design -
Scaled-down from VLHC-1



Preliminary design of SDSR magnet and cryogenic support lines using the existing (slightly modified) support from the Recycler magnet string.

Parameter	SDSR	VLHC-1
Magnetic design	Combined function	Combined function
Magnetic core	AISI 1008, 1mm	AISI 1008, 1mm
Beam gap (x = 0) [mm]	2 x 50	2 x 20
B_{max} [T]	0.15	1.96
d B/ dx T/m]	1.5	9.7
Superconductor	NbTi and 344C-2G *)	NbTi
I_{max} [kA]	30	105
Current mode	DC	DC
$T_{operation}$ [K]	4.5	4.5
T_{margin} [K]	2.5 and 25 *)	2.5

*) Slow beam extraction sections use HTS cable

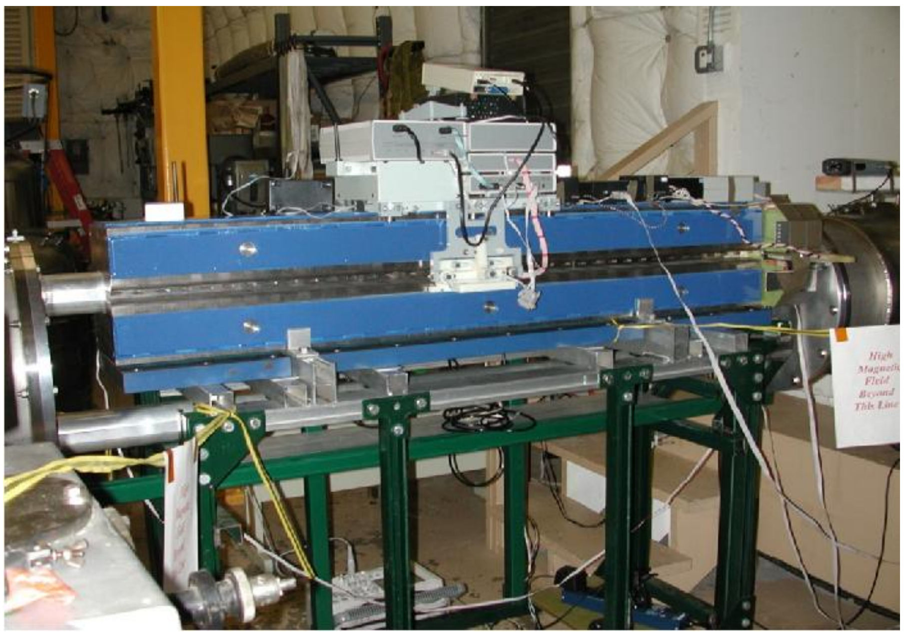
SDSR Magnet Prototype

Benefit of VLHC-1 Magnet Design & Tests

SC Magnets at Fermilab

VLHC-1 magnet successfully tested for B_{max} = 1.96 T, I_{max} = 102 kA

For SDSR B_{max} = 0.15 T, I_{max} = 30 kA



SDSR prototype magnet can be designed, built and tested right now !

SDSR Magnet in Main Injector Tunnel

SDSR magnet ring in Main Injector tunnel. Return conductor and helium supply/return lines run parallel to magnet ring

SC Magnets
at Fermilab

Possible Use of SRCS & SDSR Accelerator Technologies in Other Near-Term Applications: PS2 and S-SPS at CERN

Accelerator	Energy [TeV]	Ring [km]	B-field [T]	dB/dt [T/s]
PS2 [1]	0.05	1.25	1.8	1.5
S-SPS [2]	0.5 - 1	6.9	2.0 -4.5	1

[1] L. Bottura et al., "A conceptual design study for a super-ferric PS2", CERN Report, 2007
[2] W. Scandale, "Luminosity Upgrade for LHC", CARE-HHH-APD-LUMI-05, 2005

SC Magnets
at Fermilab

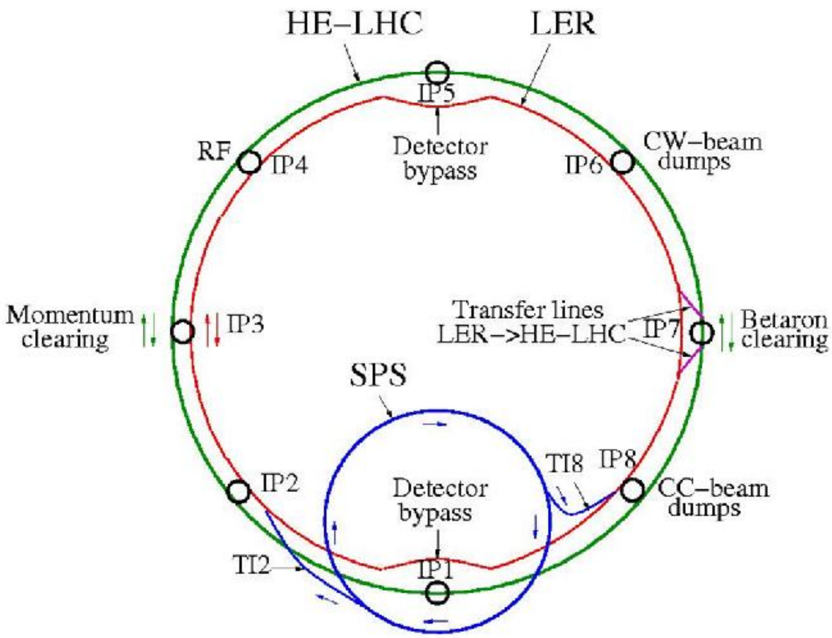
Examples of Possible Use of SRCS & SDSR Accelerator Technologies in Longer Term Applications

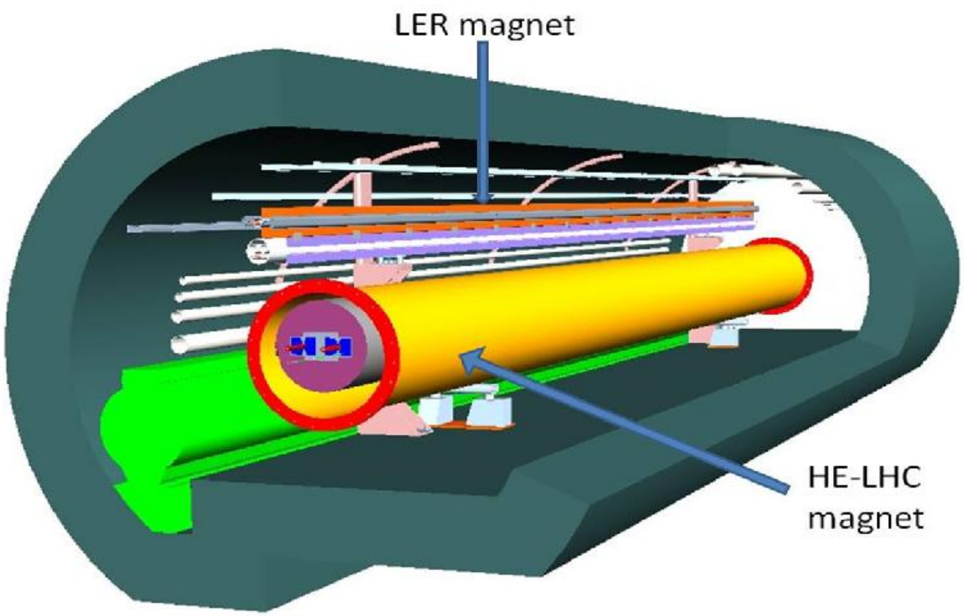
Accelerator	Energy [TeV]	Ring [km]	B-field [T]	dB/dt [T/s]
LER for HE-LHC [1]	1.65	26.6	1.76	0.02
ERL (LHeC) [2]	0.06	6.2	0.5	10
DSFMR [3]	0.5 - 1	6.3	2.0 – 4.5	2
LER for VLHC [3]	7.2	106	2.0	0.01

[1] H. Piekarz, "Using Tevatron Magnets for HE-LHC or New Ring in LHC Tunnel", HE-LHC Workshop, Malta, 2010
[2] F. Zimmermann, "LHeC Linac-Ring Option", EuCARD-AccNet-RFTech Workshop, 2010
[3] H. Piekarz, "Dual fast-cycling superconducting synchrotron at Fermilab and a possible path to the future of high energy physics", JINST 4 P08007, 2009

*LER – 1.65 TeV Dual Injector to 33 TeV HE-LHC *)*

LER magnet string runs parallel to HE-LHC ring bypassing detectors. HE-LHC beams are stacked first in LER, then simultaneously transferred to both HE-LHC rings. While the HE-LHC is in collision mode the LER will produce 2 beams of energy (0.45 - 1.65) TeV for the fixed target physics experiments.

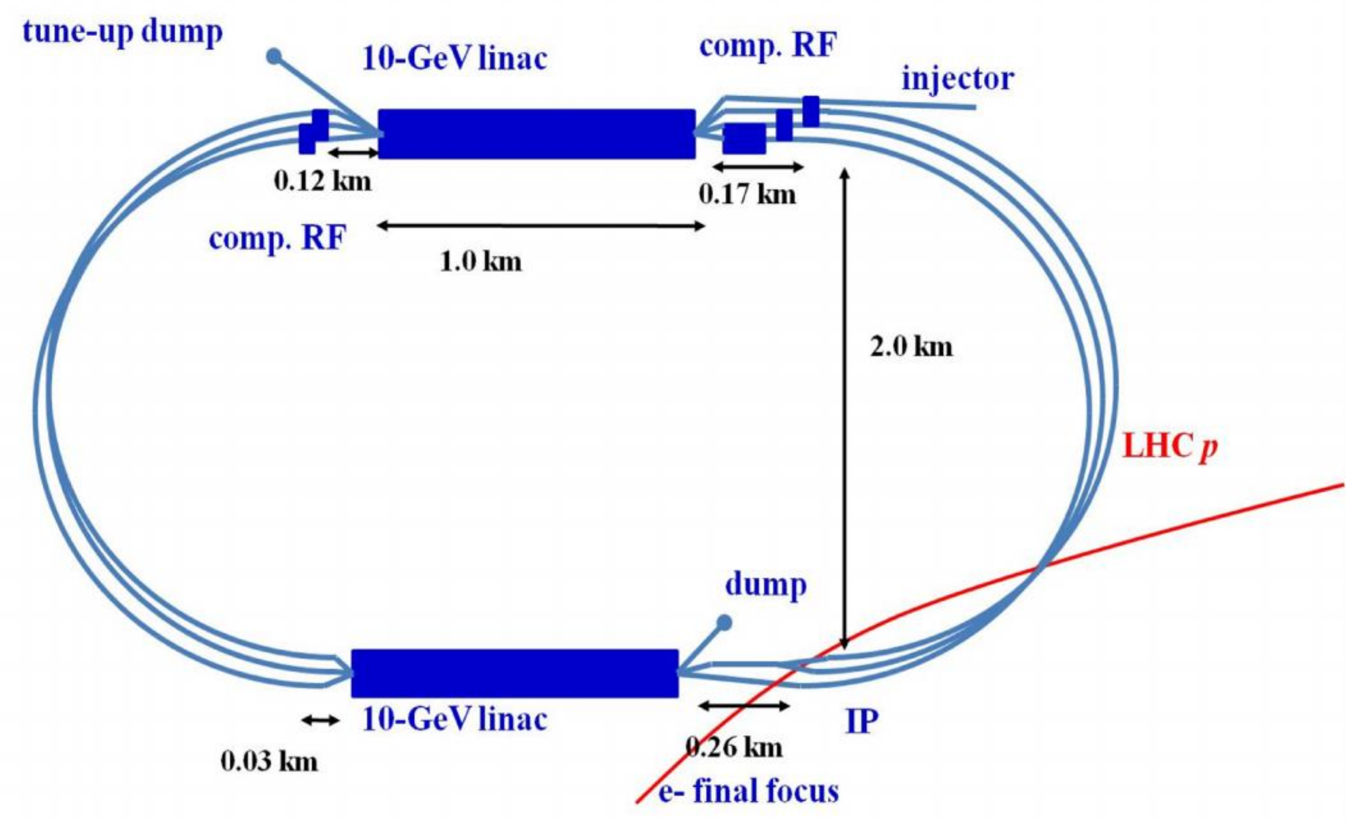




*) H. Piekarz - EuCARD - HE-LHC'10 AccNet mini-workshop, October 14-16, Malta, 2010

LHeC - Electron-Proton Collider

LHeC: 60 GeV electrons (ERL) on 7 TeV protons (LHC) *)



Synchrotron for ERL:

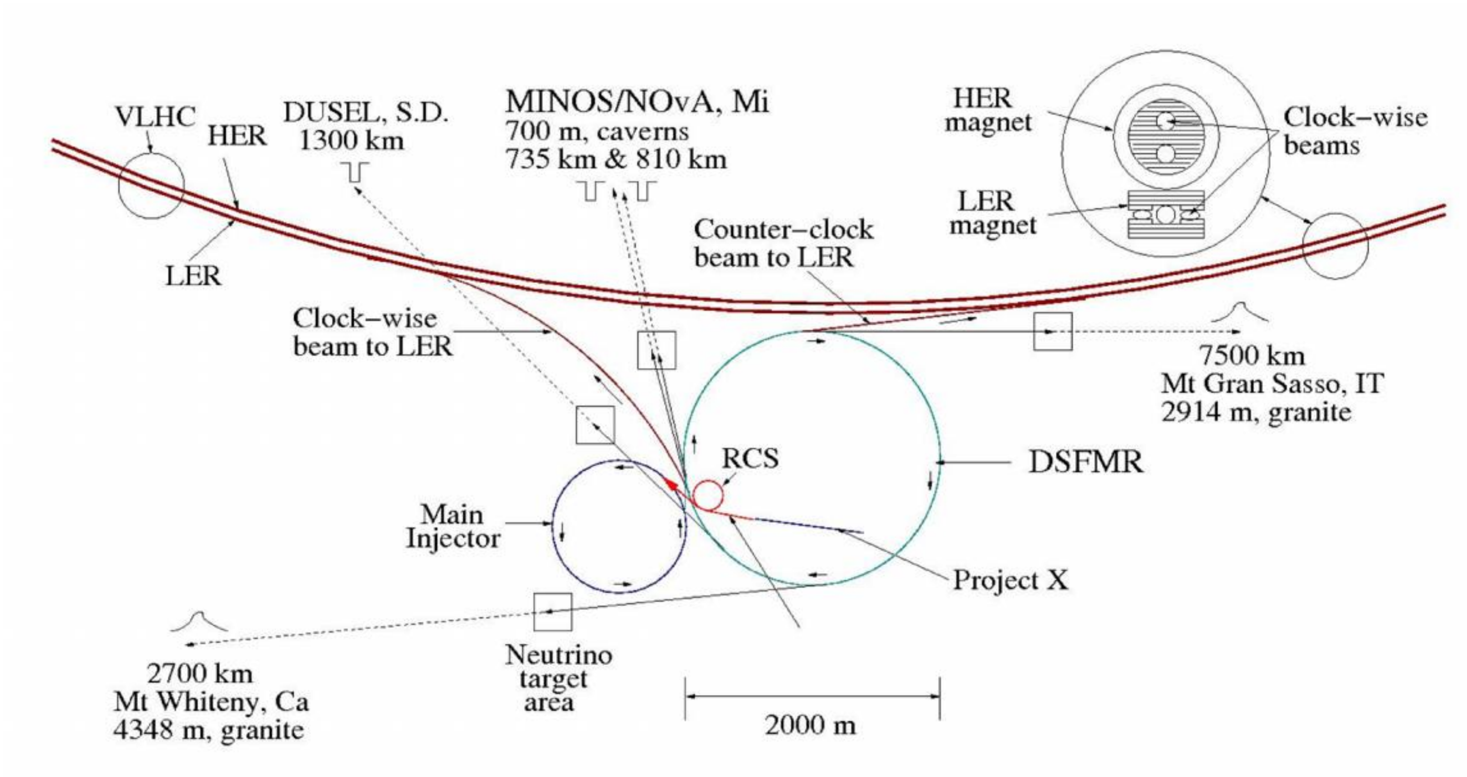
Ring length: 3150 m
B max = 0.5 T
Rep. Rate = 10 Hz
dB/dt = 10 T/s

SRCS magnet design matches requirements of ERL synchrotron!

F. Zimmerman - EuCARD - AccNet-RFTech Workshop, PSI, 2010

DSFMR – 0.5 TeV Dual Ultra-High-Power Proton Source and Dual Injector to 7.2 TeV VLHC-I (LER)

LER – 7.2 TeV Dual Fast Injector to (60-120) TeV VLHC



H. Piekarz – "Dual fast-cycling superconducting synchrotron at Fermilab and a possible path to the future of high energy particle physics", JINST 4 P08007, 2009

SC Magnets
at Fermilab

Estimated Cost of Synchrotron-Based Project X Accelerator System

Component	Unit cost [M$]	Contingency [%]	Total cost [M$]
Pulse Linac (1 GeV)	261	35	**352**
SRCS			
Magnet string	32	100	64
Magnet power system	8	35	11
RF system	34	35	47
Cryogenics system	5	100	10
Civil construction	30	35	40
SRCS total			**172**
SDSR			
Magnet string	40	35	54
Magnet power system	5	35	7
RF system	17	35	23
Cryogenics	20	35	27
SDSR total			**111**
MAIN INJECTOR upgrade			**90**
Synchrotron- based			**725**
Linac-based *)			**1800**

*) S. Holmes, “Project X”, https://slacportal.slac.stanford.edu/…/ProjectX-Holmes-201105020.pptx

Summary & Conclusions

Synchrotron-based accelerator system will allow for:

- ***Standard Model high-precision experiments at the level satisfying very well the Project X physics goals***
- ***Neutrino experiments with beam power likely exceeding the projected one with the linac-only injector accelerator scheme***

Proposed synchrotron accelerator technologies are sufficiently developed to reasonably expect that technical difficulties, construction time and cost will be manageable leading in turn to a timely start of physics experiments.

Final note:

In selecting synchrotron-based accelerator option for the Project X physics we engaged technologies that not only well satisfy this near-term research but also allow to build foundation for the long-term High Energy Physics in the US and elsewhere.