US-APUL Proposal for the Cold Power Transfer System for the LHC IR Phase-1 Upgrade

Sandor Feher

What is APUL?

Accelerator **P**roject for **U**pgrade of **L**HC

Mission:

Participate and contribute to the LHC Phase I upgrade program.

History:

US HEP has a long standing relationship with CERN both on the detector and accelerator front.

The APUL project was launch by the DOE to continue this fruitful collaboration between European and American Laboratories.

Originally it was planned to contribute to both Linac 4 and IR Upgrade effort. Funding is limited => Current plan is to provide the D1 dipoles and Cold powering components.

APUL

Collaborations

LHC IR Upgrade Phase I

SLHC-PP
(CEA, CIEMAT, CNRS, STFC)

- Design and construction of the model quadrupole
- Design of the correctors
- Design of the cryostats

CERN

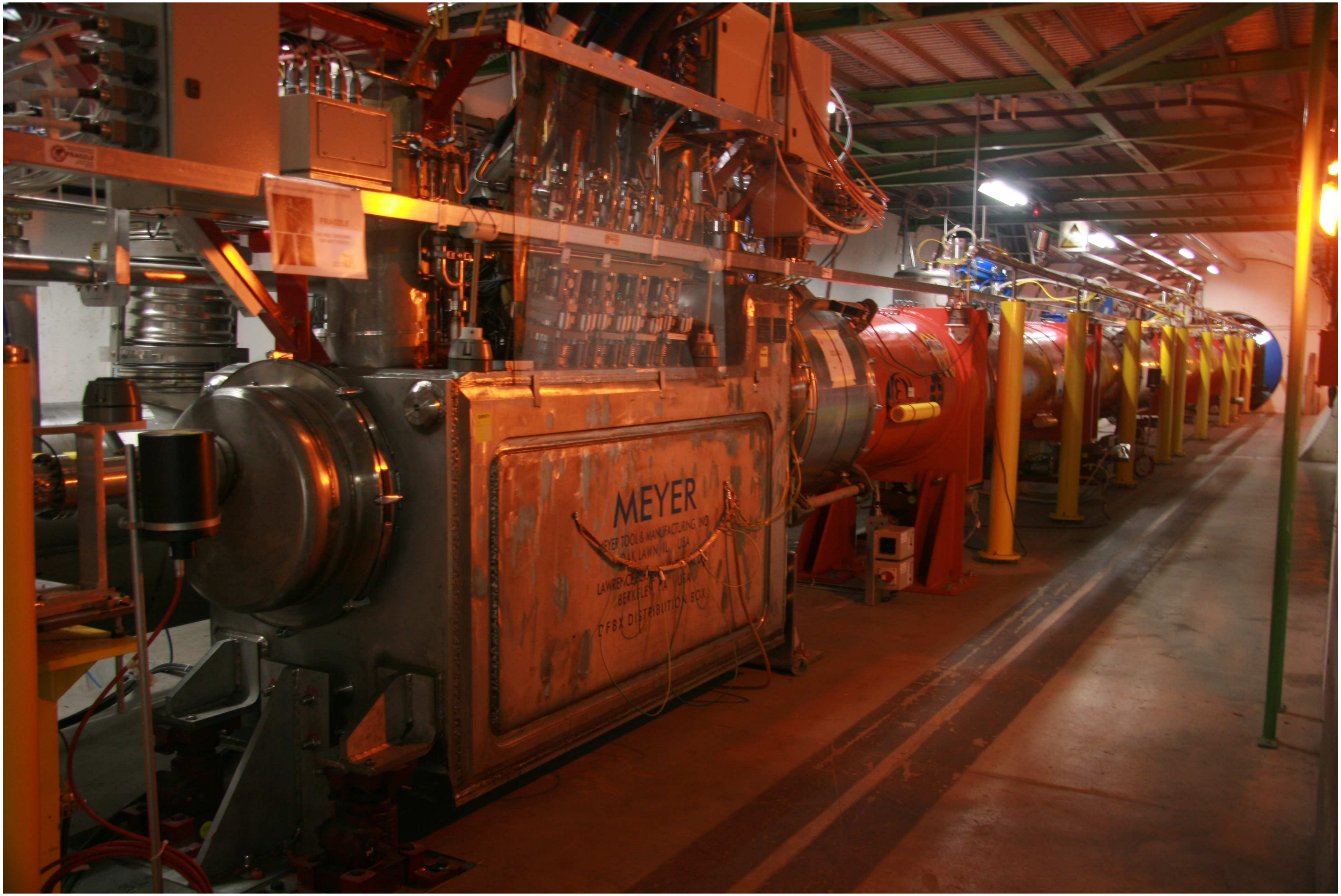
- Quadrupole production
- Cryostating and testing
- Power converters
- Protection
- String test
- Integration

Special French contribution
(CEA, CNRS)

- Quadrupole components
- Cryostat components
- Production of the correctors

US-APUL
(BNL, Fermilab)

- D1 separation dipole
- Cold powering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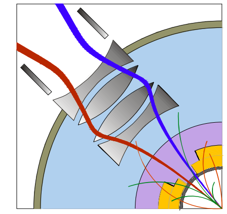
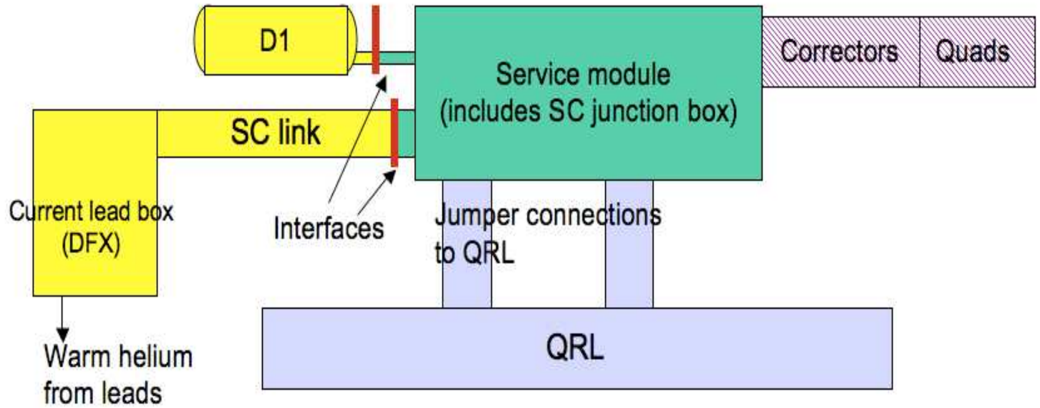
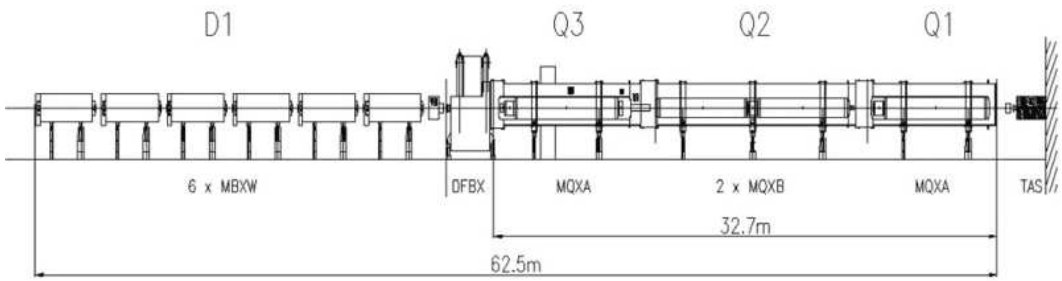
June 8th, 2009

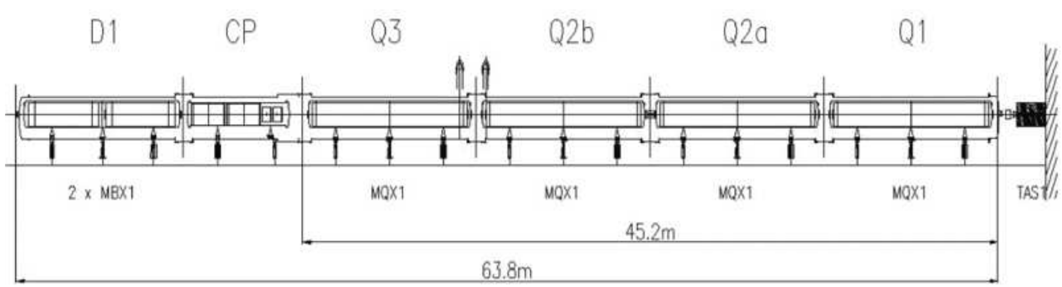
APUL Cold Powering
Sandor Feher



D1 Dipoles
Cold Powering (SC Link, DFX with Current Leads)







- Cold Powering will provide current for four locations. At each location for:
  - 4 IT quads 13 kA
  - 1 Dipole
  - 7 correctors
- In terms of SC links and Current leads:
  - 4 x 13kA
  - 2 x 2 kA
  - 2 x 7 kA
  - 6 x 2.5 kA
  - 8 x 0.6 kA
- This is more high current CLs than what we have in the current DFBX
- Additionally it has to have an instrumentation port for V-taps, Temp sensors, pressure gauges etc.
- The link length is 30 – 100 m long. The routing is still not known.

What is APUL?

- Two main subprojects for APUL:
  - D1 magnets - Brookhaven National Laboratory
  - Cold Powering - Fermilab

- Project status and plans

  DOE CD0 approval was achieved at the end of last October

  Budget review in June 19th – Limited budget; Everything counts: Labor, Overhead, Management cost, over 30% contingency.

  Fermilab CD1 director's review – middle of July pre-requisite for DOE review

  DOE CD1 review – planned to be in August => funds will be released for preliminary design studies (TDR)

  Fermilab CD2 director's review – November 2009

  DOE CD2/3a review in December => Baseline scope fixed, funds to be released for long procurement (SC strand) items.

  Fermilab CD3 review – Early summer 2010

  DOE CD3 review – middle of summer 2010 => funds to be released for purchasing equipment.

APUL Organization Chart

DOE Office of Science

DOE Office of HEP
D. Kovar, Acquisition Executive
B. Strauss, APUL Program Manager

Fermilab Directorate

DOE BNL Site Office,
R. Caradonna,
Federal Project Director

DOE Chicago
Operations Office

Laboratory Oversight Group
S. Holmes, Chair

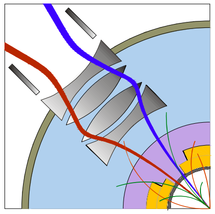
APUL PMG

APUL Technical
Advisory Committee

APUL Project Office
P. Wanderer, Project manager
S. Feher, Deputy Project Manager
M. Kaducak, Project Engineer
R. Prwivo, Project Controls

D1 Magnets

Cold Powering



APUL Cold Powering Team at FNAL

Project Manager Sandor Feher

Lead Technical Engineer Tom Peterson

Current Leads

Fred Nobrega

Eng/Phys (test)

Designer (as needed)

Technicians (assembly, test)

DFX

Jeff Brandt

Eng/phys (test)

Experienced designer

Technicians (assembly, test)

SC Link

Jeff Brandt

Eng/phys (SC expert, test)

Experienced designer

Technicians (assembly, test)

Test:
IB1 personnel

SC experts:
Rodger Bossert
Vadim Kashikhin
Emanuela Barzi

Cold Powering

Lot of effort has been already done at CERN (A. Ballarino, D. Nisbet, Y. Muttoni etc.) => IR Phase I Upgrade Conceptual Design Report

Fermilab joined at the time most of the CP Design Concept was in place. Fermilab's CP proposal share most of the elements found in the CERN CDR => strong collaboration with CERN group.

Last fall we made an agreement that Fermilab design group will not focus on superconductor R&D:

- Base line for the SC Link will be NbTi conductor.
- CERN will proceed with MgB_2 development until the end of 2009 then a decision will be made among the two choices.
- Baseline SC Link cryostat will be based on solid piping - flexible cryostat sections as necessary.
- If possible not to use HTS leads.
- If possible use only 3bar, 4.7K supercritical helium for coolant.

Cold Powering

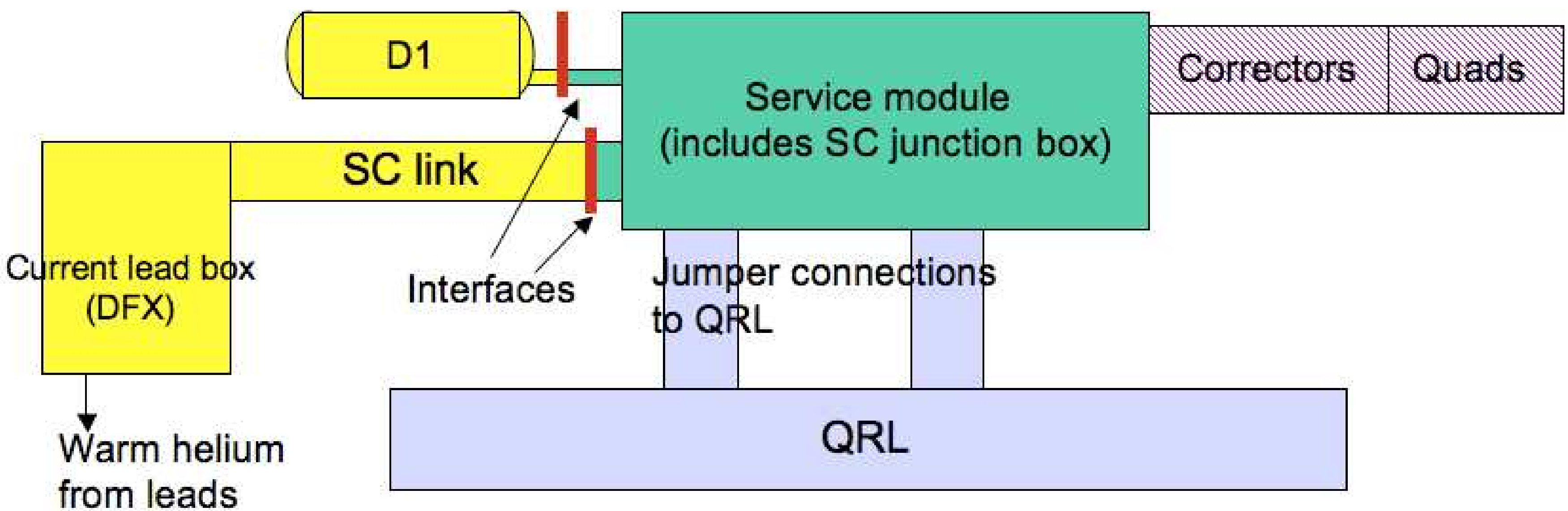
- APUL CP is in a conceptual phase.
- At this phase of the project the goal is to demonstrate the feasibility of the concept.
- At TDR level we expect to accomplish the baseline design.

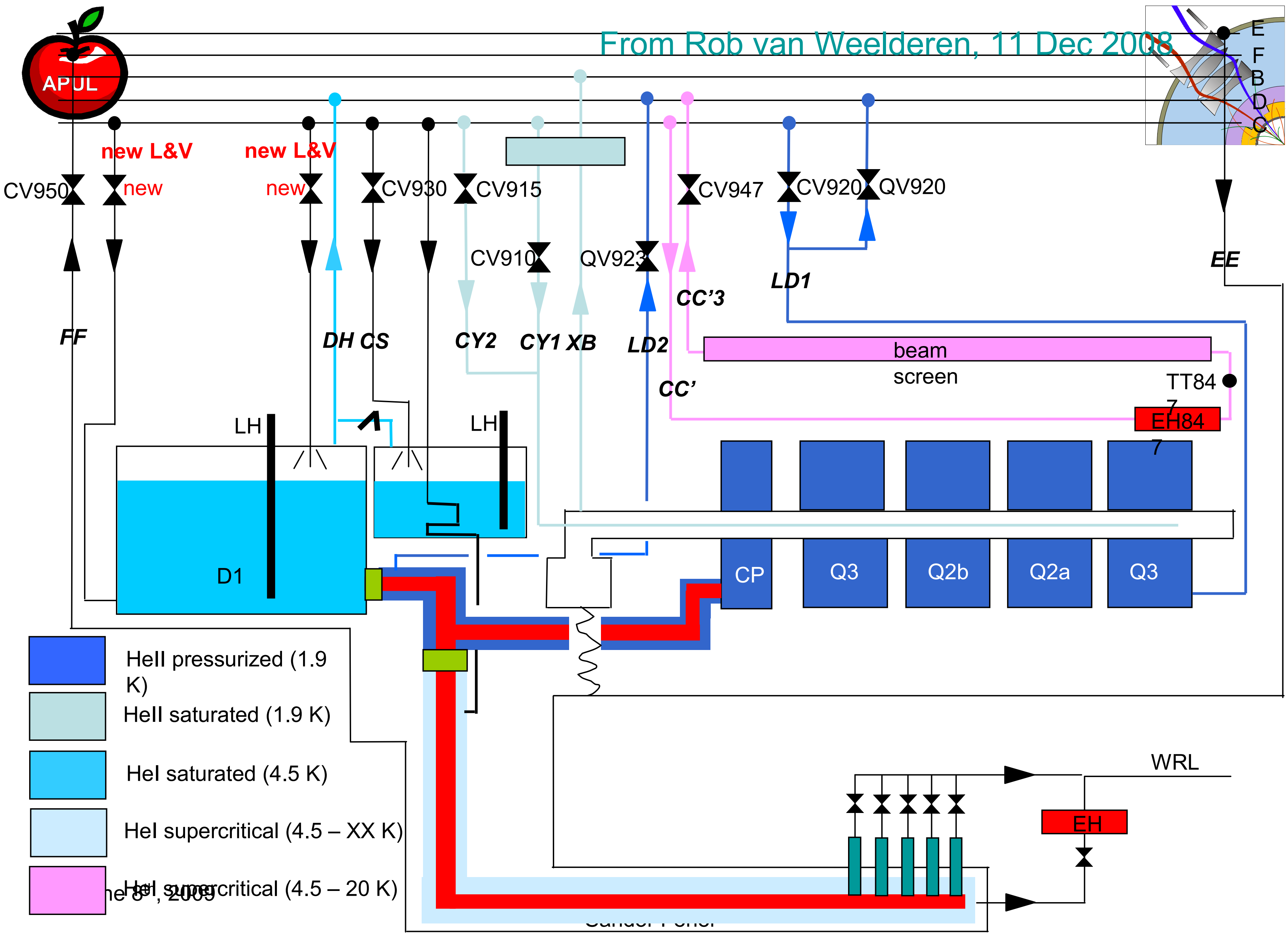
Outline:

- SC link cooling concept
- SC bus design options
- Current leads integrated into DFX design concept
- Testing

APUL Scope

- D1, superconducting link, and DFX are in the scope of supply from the U.S.
- Fermilab intends to do the DFX and link




From Rob van Weelderen, 11 Dec 2008
APUL
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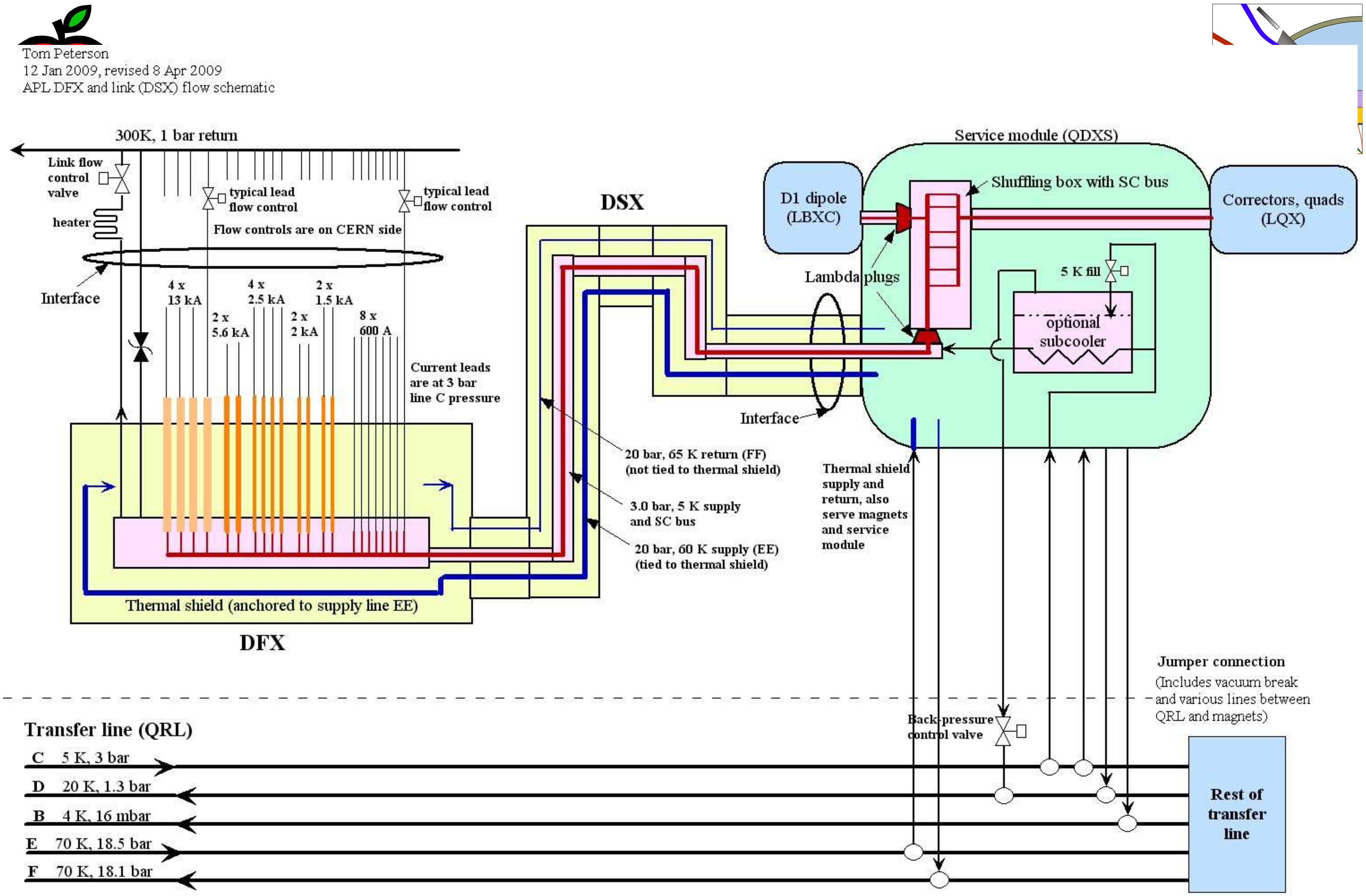
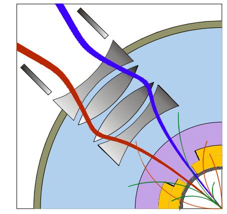
new L&V
new L&V
CV950
new
new
CV930
CV915
CV947
CV920
QV920
CV910
QV923
EE
LD1
CC'3
FF
DH CS
CY2
CY1 XB
LD2
beam
screen
TT847
CC'
EH847
LH
LH
D1
CP
Q3
Q2b
Q2a
Q3
WRL
EH
HeII pressurized (1.9 K)
HeII saturated (1.9 K)
HeI saturated (4.5 K)
HeI supercritical (4.5 – XX K)
HeI supercritical (4.5 – 20 K)


Tom Peterson
12 Jan 2009, revised 8 Apr 2009
APL DFX and link (DSX) flow schematic
300K, 1 bar return
Link flow control valve
heater
typical lead flow control
typical lead flow control
Flow controls are on CERN side
Interface
4 x 13 kA
2 x 5.6 kA
4 x 2.5 kA
2 x 2 kA
2 x 1.5 kA
8 x 600 A
Current leads are at 3 bar line C pressure
Thermal shield (anchored to supply line EE)
DFX
DSX
20 bar, 65 K return (FF) (not tied to thermal shield)
3.0 bar, 5 K supply and SC bus
20 bar, 60 K supply (EE) (tied to thermal shield)
Interface
Service module (QDXS)
D1 dipole (LBXC)
Shuffling box with SC bus
Correctors, quads (LQX)
Lambda plugs
5 K fill
optional subcooler
Thermal shield supply and return, also serve magnets and service module
Jumper connection
(Includes vacuum break and various lines between QRL and magnets)
Back-pressure control valve
Transfer line (QRL)
C 5 K, 3 bar
D 20 K, 1.3 bar
B 4 K, 16 mbar
E 70 K, 18.5 bar
F 70 K, 18.1 bar
Rest of transfer line

Current leads and flow requirements (conventional copper leads)



SC link current rating	Current lead current rating	Maximum operating current	Number of leads and SC links	Current lead flow rate at full current per current lead (per DFX) [g/sec]	Current lead flow rate at stand by current [g/sec]
14 kA	13 kA	13 kA	4	0.6 (2.4)	0.24
8 kA	7 kA	7 kA	2	0.45 (0.9)	0.24
3 kA	2.5 kA	2.5 kA	4	0.3 (1.2)	0.15
3 kA	2.5 kA	2.0 kA	2	0.25 (0.5)	0.15
3 kA	2.5 kA	1.5 kA	2	0.25 (0.5)	0.15
600 A	550 A	550 A	8	0.1 (0.8)	0.05

Link analysis input parameters

Input data (no contingency)	IP1-L		IP1-R		IP5-L		IP5-R	
Link length (m)	28		30		50		95	
He tube OD (cm)	7.60		7.60		7.60		7.60	
number of 90 deg bends	5		5		5		5	
5 K thermal rad (W/sq.m)	0.25		0.25		0.25		0.25	
5 K conductive heat (W/m)	0.09		0.09		0.09		0.09	
Number of 13 kA leads	4		4		4		4	
Flow per lead (g/s)	0.24	0.60	0.24	0.60	0.24	0.60	0.24	0.60
Number of 7 kA leads	2		2		2		2	
Flow per lead (g/s)	0.15	0.45	0.15	0.45	0.15	0.45	0.15	0.45
Number of 2.5 kA leads	4		4		4		4	
Flow per lead (g/s)	0.15	0.30	0.15	0.30	0.15	0.30	0.15	0.30
Number of 2 kA (incl 1.5 kA leads)	4		4		4		4	
Flow per lead (g/s)	0.15	0.25	0.15	0.25	0.15	0.25	0.15	0.25
Number of 600 A leads	8		8		8		8	
Flow per lead (g/s)	0.05	0.10	0.05	0.10	0.05	0.10	0.05	0.10
	Standby	Power	Standby	Power	Standby	Power	Standby	Power

5 K link heat and flow (w contingency)

Input data (no contingency)	IP1-L		IP1-R		IP5-L		IP5-R	
Link length (m)	28		30		50		95	
	Standby	Power	Standby	Power	Standby	Power	Standby	Power
Temperature Level	5K		5K		5K		5K	
"Best estimates" (without contingency)								
Lead liquid total (g/sec)	2.86	6.30	2.86	6.30	2.86	6.30	2.86	6.30
Additional link flow (g/sec)	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Total link flow (g/sec)	**4.86**	**8.30**	**4.86**	**8.30**	**4.86**	**8.30**	**4.86**	**8.30**
Design value (with contingency)								
Heat contingency factor	1.88	1.88	1.88	1.88	1.88	1.88	1.88	1.88
Link total heat with contingency (W)	7.86	7.86	8.42	8.42	14.03	14.03	26.66	26.66
Link total heat flux with contingency (W/m)	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.28
Link enthalpy rise with heat contingency (J/g)	1.62	0.95	1.73	1.01	2.89	1.69	5.49	3.21
Link exit enthalpy with contingency (J/g)	14.50	13.83	14.61	13.89	15.77	14.57	18.37	16.09
DFX inlet temperature with contingency (K)	**4.99**	**4.87**	**5.00**	**4.89**	**5.17**	**5.00**	**5.48**	**5.22**
Link delta-T with contingency (K)	0.29	0.17	0.30	0.19	0.47	0.30	0.78	0.52

Link Cooling Conclusions and Status

- Delta-T through the link (with contingency) of around 0.5 K for longest link
  - Less than 6 K at the DFX looks safely attainable
  - Heat load for hard-piped system is assumed
- Near-term refinements
  - Model heat at base of current leads through the DFX
  - Look at pressure drops
  - Consider off design flow rate limits (emergency venting, cool-down, warm-up)
  - Discuss flow scheme with CERN

CERN Conductor R&D

- CERN is currently investigating the possibility of using MgB_2 conductor.
- It is a great conductor for low field applications – H_{c2} is not high enough for high field applications.
- It is not as brittle as Nb_3Sn but it is not as ductile as NbTi
- There is company in Italy near Genova producing MgB_2 conductor => collaborating with Amalia Ballarino to develop round shape bus.
- Decision what conductor to be used will be made at the end of this calendar year.

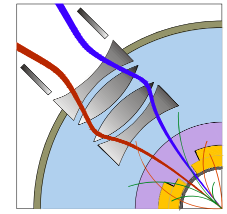
Bus bar conductor selection

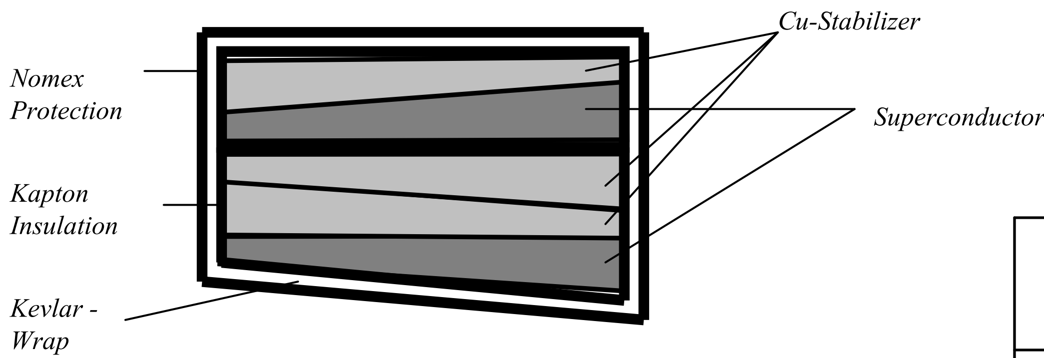
- Last summer examined all different possibilities for conductor
  - Pure Aluminum => too heavy might be an option for short length
  - HTS => too expensive IGC and Nexon have never given a quote.
  - Nb_3Sn too complicated manufacturing process.
  - NbTi was the best choice based on the fact that cooling conditions can be met.

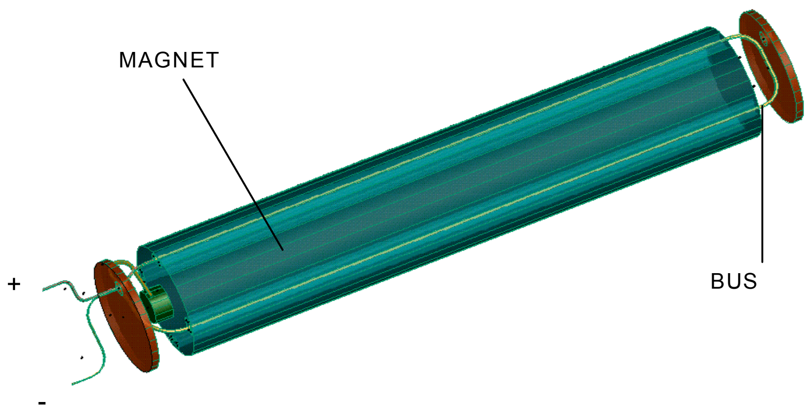
NbTi Bus Bar

- Extensive study of the bus bar currently used in the IR magnets at LHC.
- Three TD notes and an IEEE publication about the LHC IR bus bar studies.
- Both modeling and experiments have been performed and compared.

Bus Bar Studies





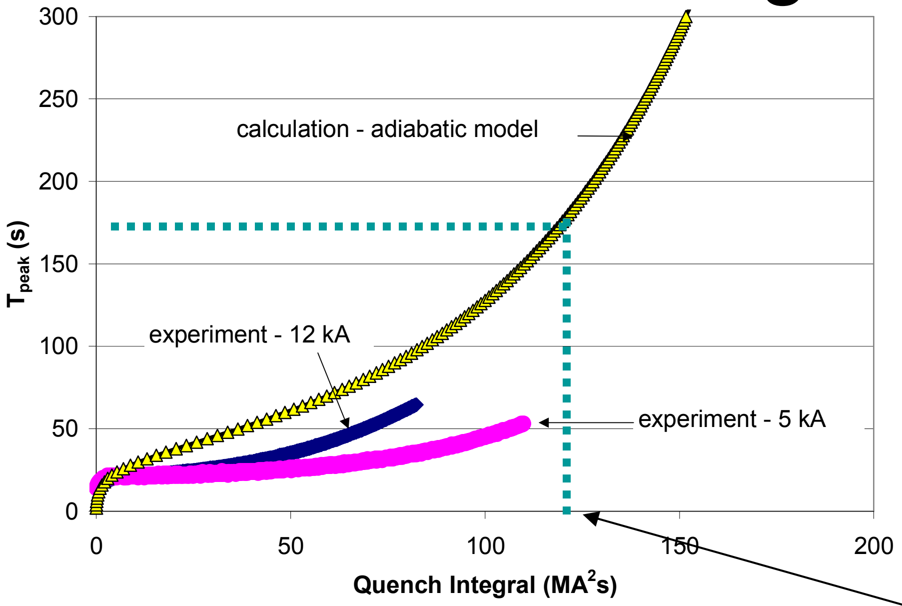


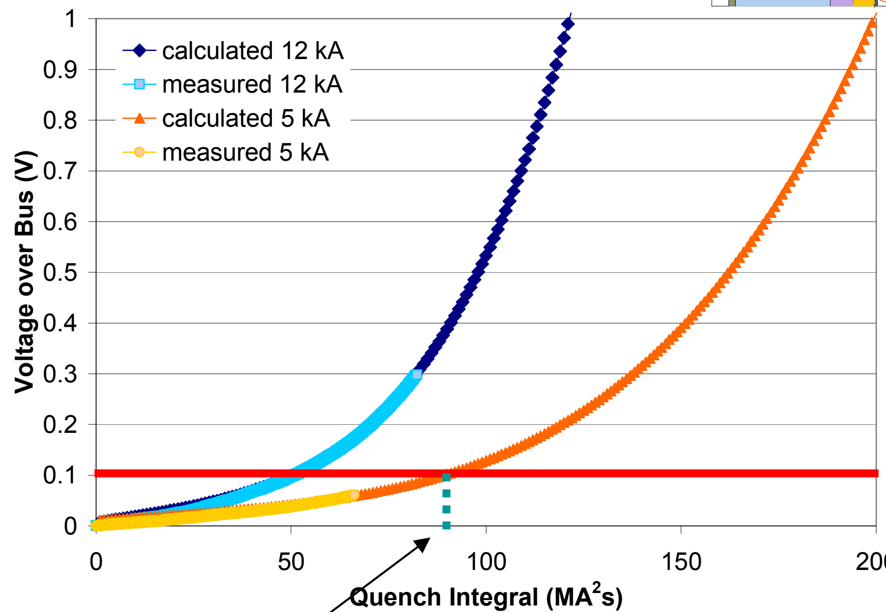
	# of stab.	A (mm^2)	A_{Cu} (mm^2)	Cu/Sc
2-bus	*1*	40.8	23.07	1.3
3-bus	*2*	61.2	34.60	1.3

	# of stab.	A (mm^2)	A_{Cu} (mm^2)	Cu/Sc
2-bus	***1***	**38.97**	**30.50**	**3.60**
3-bus	*2*	58.45	49.98	5.90

Used in LHC IR

Modeling and Test results





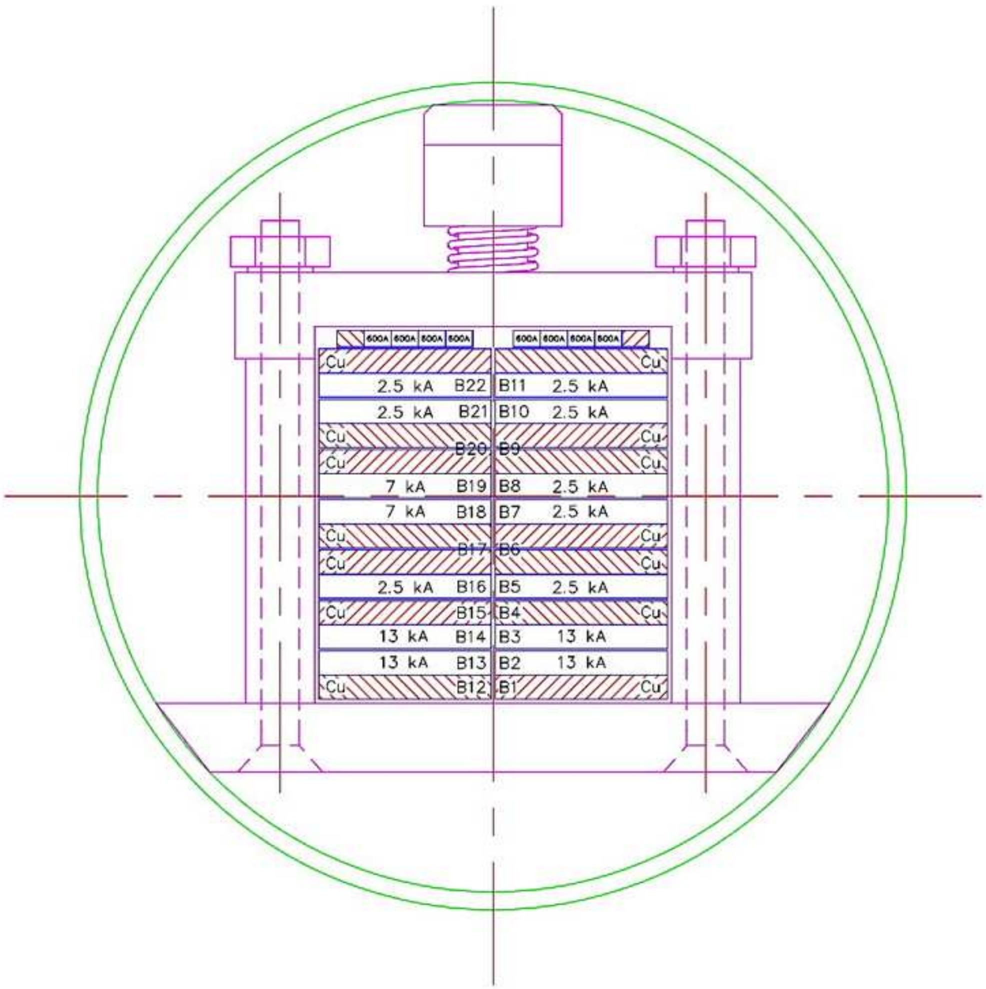
~90 MIITs

90 + 30 = 120 MIITs

~ 180 K

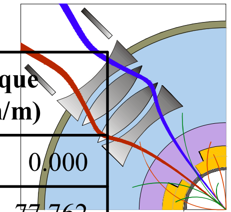
- LHC IR bus
- Threshold Voltage is 100 mV at LHC
- Upgrade LHC IR cable QI ~ 30 MIITs

Rectangular Bus Bar design



- One type of bus for the 13kA, 7kA, 2.5kA, 1.5kA current ratings and another type for 600A current ratings.
- LHC IR bus in two rows.
- Arranged to minimize cross-talk.
- Sparingly soldered together => flexibility
- Splice joints might be required at regions where the bus bends.
- Well established splice technique
- Special mechanical structure => insulation

Mechanical forces

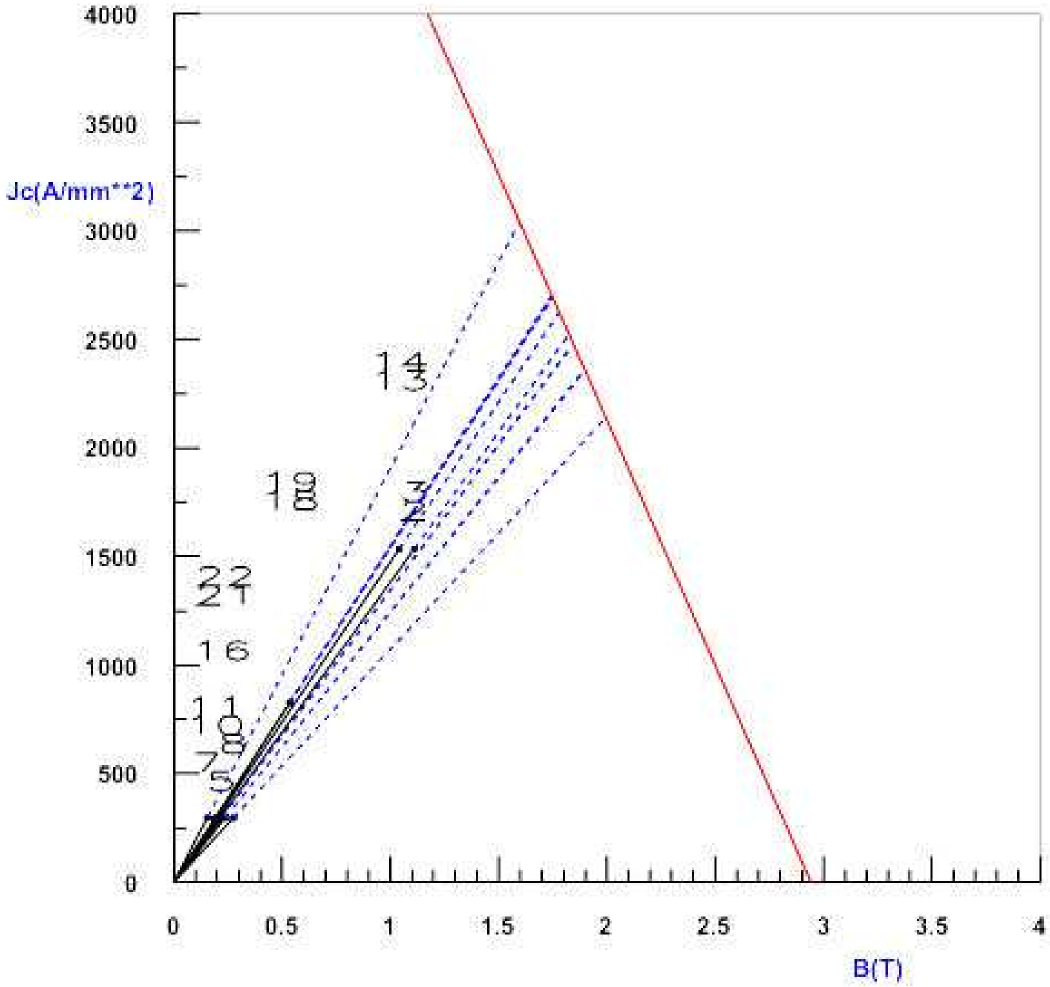


Block	Force X (N/m)	Force Y (N/m)	X-Pos (mm)	Y-Pos (mm)	Force R (N/m)	Torque (Nm/m)
1	0.000	0.000	7.7750	0.7285	0.000	0.000
2	-470.401	-10138.301	7.7750	2.2605	-3282.103	-77.762
3	250.700	10210.610	7.7750	3.8675	4771.964	78.418
4	0.000	0.000	7.7750	5.3995	0.000	0.000
5	36.927	-225.605	7.7750	6.9315	-122.5662	-2.010
6	0.000	0.000	7.7750	9.1920	0.000	0.000
7	-20.917	38.683	7.7750	11.4525	20.256	0.540
8	82.323	-14.026	7.7750	13.0595	30.061	-1.184
9	0.000	0.000	7.7750	15.3200	0.000	0.000
10	-58.724	-120.553	7.7750	17.5805	-134.004	0.095
11	42.606	178.911	7.7750	19.1875	181.816	0.574
12	0.000	0.000	-7.7750	0.7285	0.000	0.000
13	-197.354	-9094.869	-7.7750	2.2605	-2349.594	71.159
14	563.514	9025.368	-7.7750	3.8675	3515.089	-72.352
15	0.000	0.000	-7.7750	5.3995	0.000	0.000
16	-151.332	47.396	-7.7750	6.9315	144.500	0.680
17	0.000	0.000	-7.7750	9.1920	0.000	0.000
18	278.221	-2424.692	-7.7750	11.4525	-2162.348	15.666
19	-287.730	2452.506	-7.7750	13.0595	2254.505	-15.311
20	0.000	0.000	-7.7750	15.3200	0.000	0.000
21	-75.260	-421.506	-7.7750	17.5805	-355.050	4.600
22	79.181	411.816	-7.7750	19.1875	351.935	-4.721

Force summary for rectangular bus

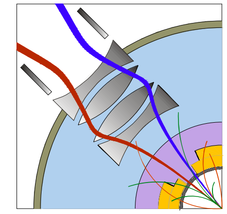
- Force Y (vertical) totals 44805 N/m, which is 22402 N/m in opposite directions
- Cable width = 15.55 mm, and we have two widths (31.1 mm) of cable seeing this total load
  - So area = 0.031 m^2/m
- Equivalent pressure on the cable surface is 22402 N/m / 0.031 m^2/m = 720321 N/m^2
  - = 7.2 bar surface pressure on the cable

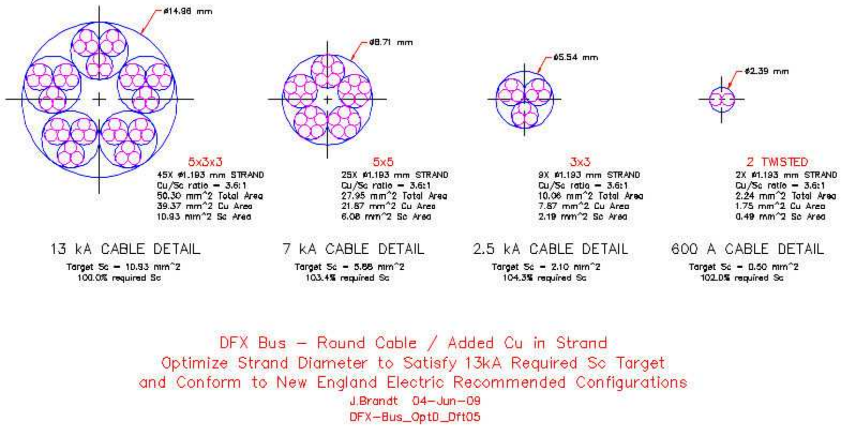
The load line and the critical current are plotted for the different conductor blocks at 6K.

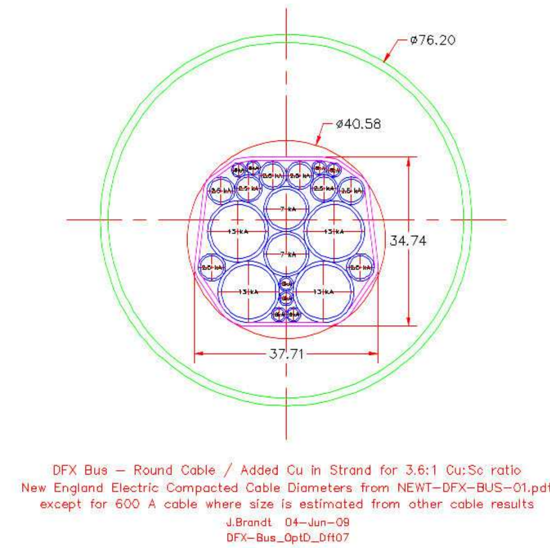


This figure and the force table on the previous slide show that we have good current margin and manageable forces.

Round Shape Bus Bar design



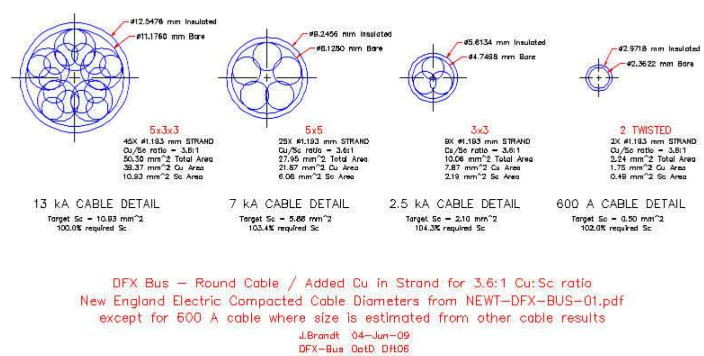




Round cable made from twisted strands:

a. Copper core
b. Strand with Cu/Sc=3.6

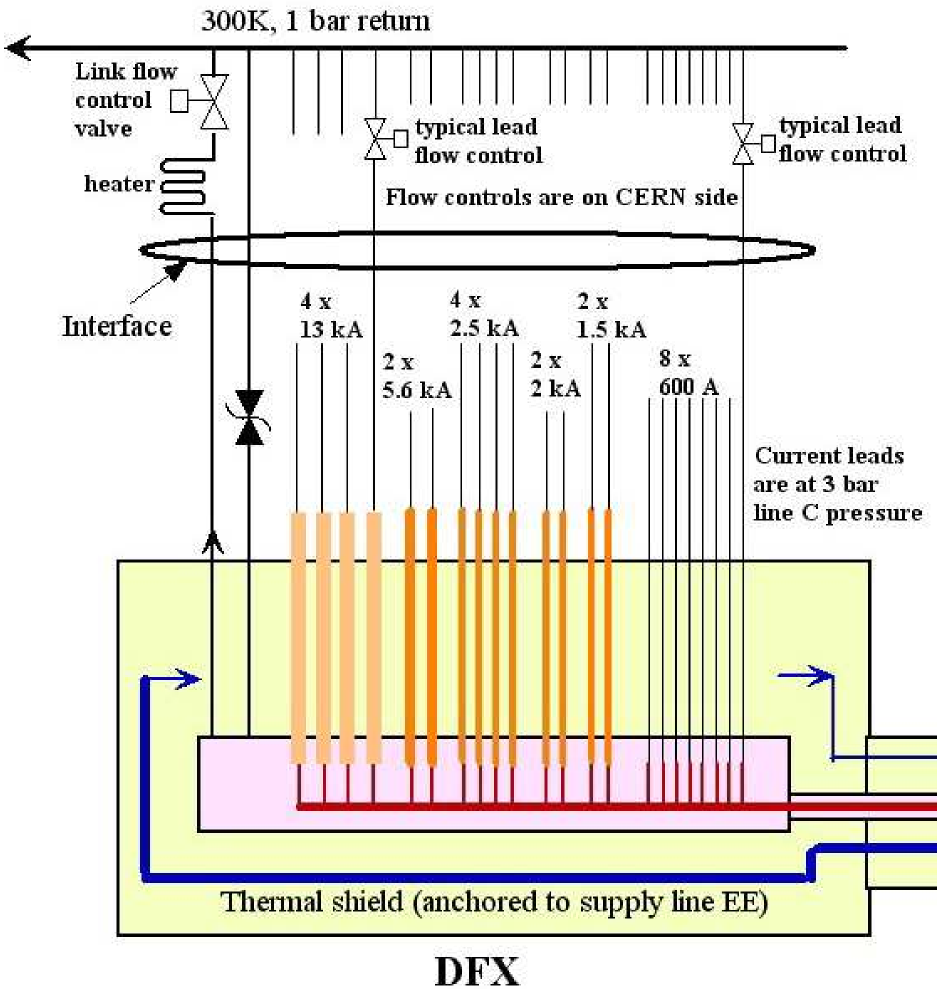
Round cross sections chosen to minimize the amount of conductor => bus bar cross section scales with the nominal current value.



Conductors grouped to improve cancellation of stray field.

The support structure details are not yet worked out. We also looking at cable position stability for twisting the bundle.

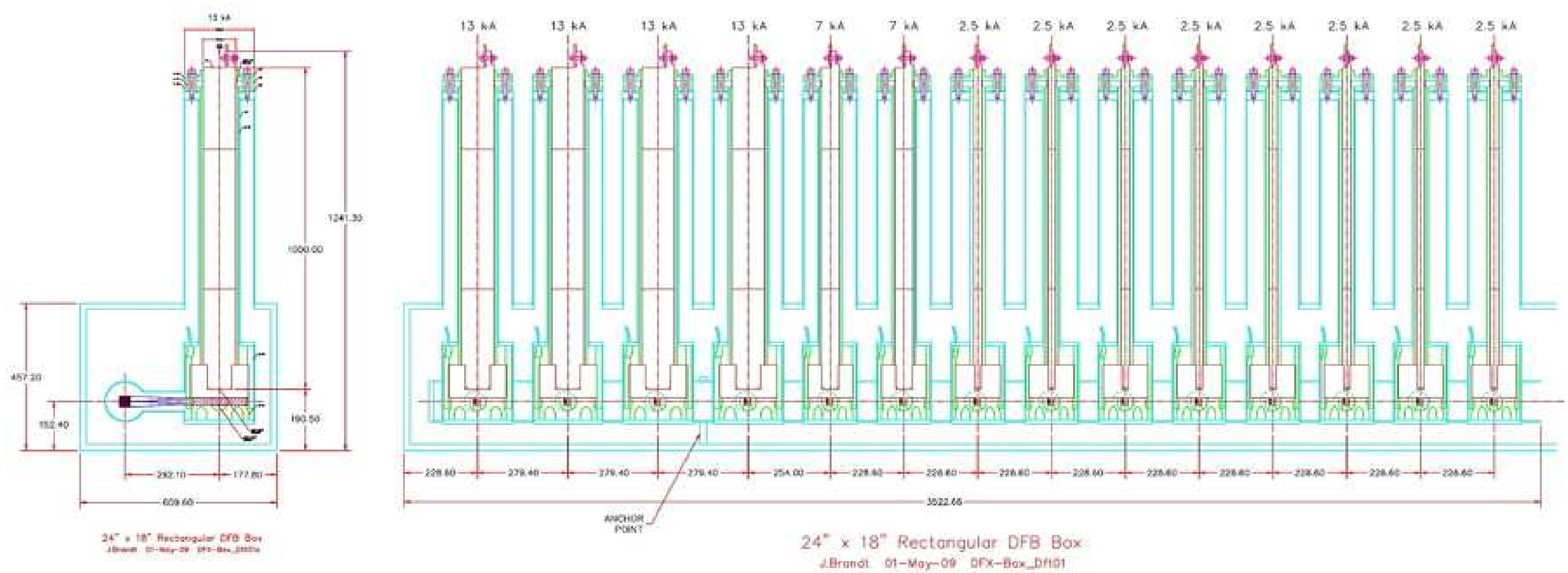
DFX concept



- Current leads in a row
- Flow to highest current last
- Still getting space constraints from CERN, but assuming
  - 4 identical boxes plus spare
  - All leads about same height (2 m)
  - Box about 5 m long
- No liquid helium (3 atm supercritical)

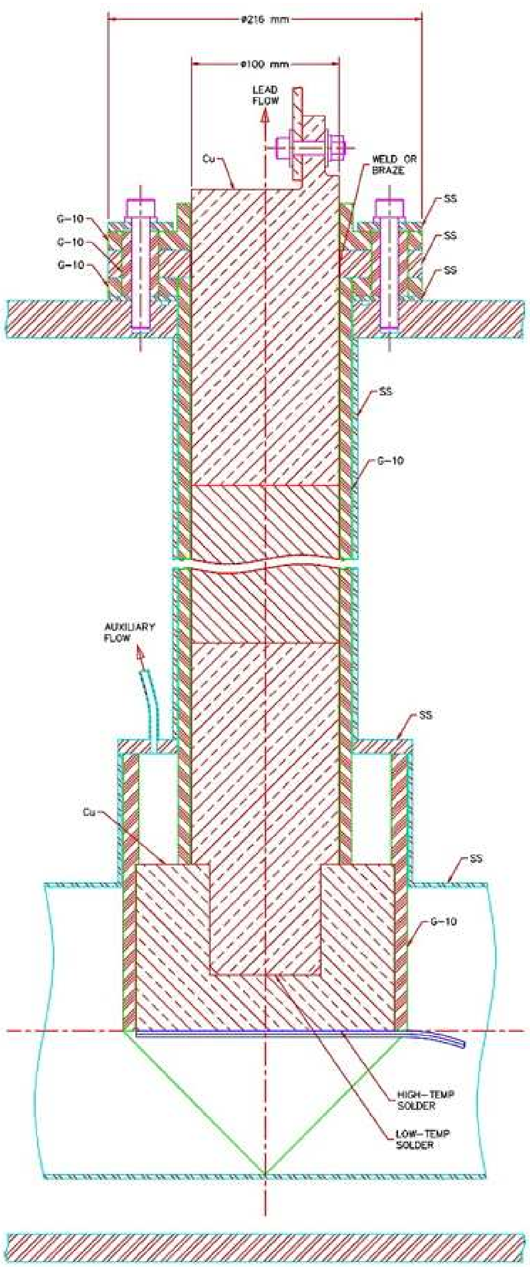
DFX concept based on DFB

- Current lead chimneys arranged linearly
- Helium supply pipe with connections to current leads to accommodate thermal contractions

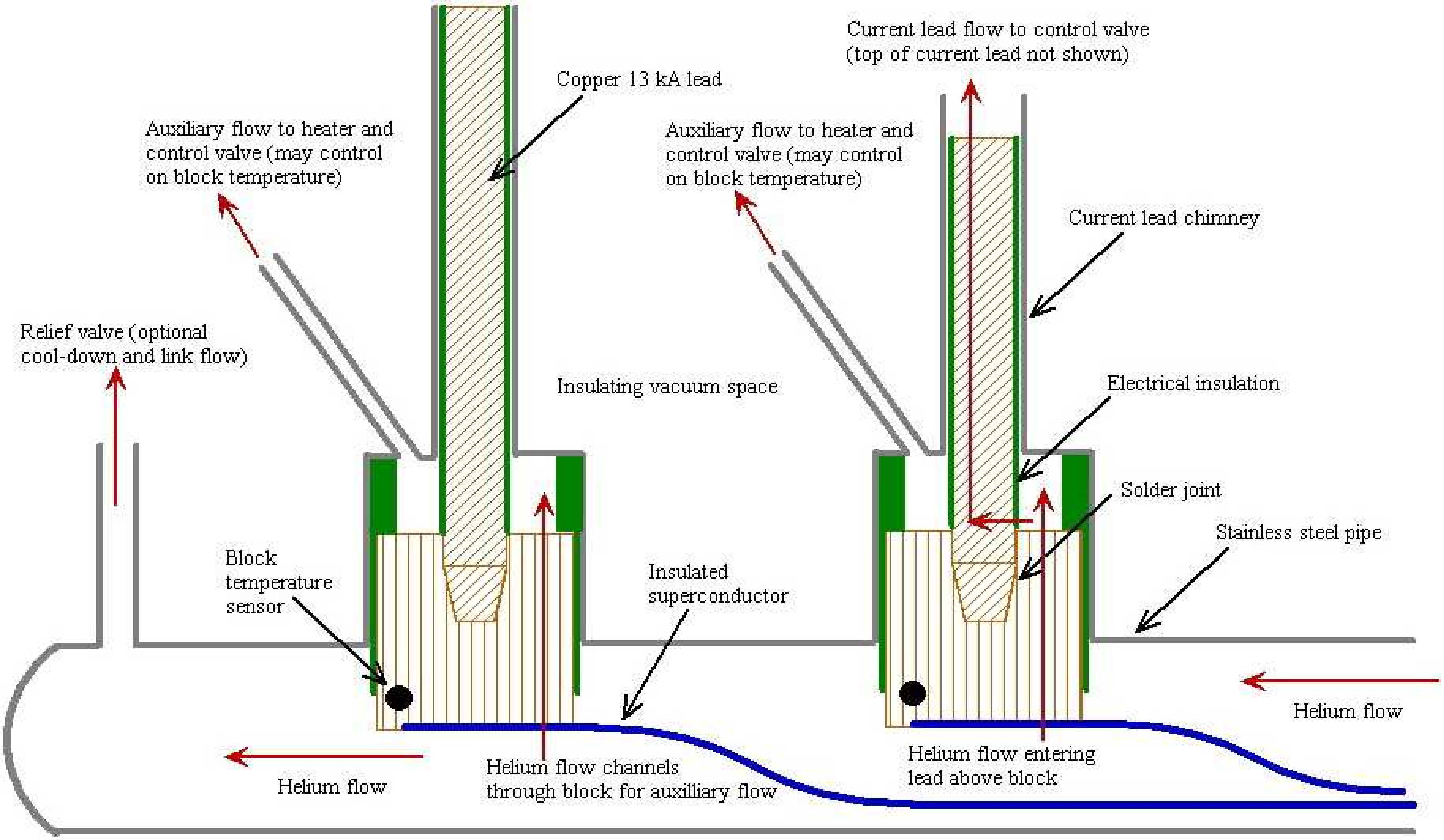


DFX Design Parameters

	Design pressure (bar abs)	Test pressure (bar abs)	Requirements, comments
5 K supply lines	20	25	ASME piping code (Fermilab ES&H Manual chapter 5031.1)
Helium vessel under current leads	20	25	ASME Boiler and Pressure Vessel Code (as applicable depending on vessel size) (Fermilab ES&H Manual chapter 5031)
Current leads	20	25	
Thermal shield			Copper with stainless trace piping
Thermal shield pipes	22	27.5	ASME piping code, stainless pipe
Vacuum vessel	1.5	Leak check	Fermilab ES&H Manual chapter 5033 (Vacuum Vessel Standard)



Start of a current lead layout. Concept is to use LHC copper heat exchanger design with custom designed top and bottom.



Notes:

1. Need to make solder joint while maintaining cooling passage continuity through block and current lead.
2. Each high current lead has its own auxiliary flow and flow control. (So 4 - 6 extra flow lines with control, but auxiliary flow may not need active control. To be assessed with analysis and during initial tests.)
3. High current leads are downstream (along helium pipe) of low current leads, which do not need auxiliary flow.
4. Copper block into which lead is soldered has ports for passage of auxiliary flow and heat transfer.
5. Copper block has robust, insulated support against downward motion (not shown) to allow installation and soldering of lead from the top.
6. Conventional leads and piping can all be rated for 20 bar.

Current lead cooling

- Supercritical flow (not a liquid bath)
  - Tevatron current leads successfully operate in single-phase helium (no liquid bath)
  - SSC test stand current leads at Fermilab all operated in 4 bar, 5 K helium
  - Enhanced heat transfer at base of current lead replaces isothermal nature of bath as insurance that superconductor is well cooled
- This design incorporates adjustable additional flow at base of current lead
  - Utilize extra link flow for lead cooling
  - This extra flow may be determined during testing and set with a fixed orifice for operation in LHC

Remote current lead soldering

- IGC and Fermilab developed a removable current lead
  - Final solder joint with 52:48 InSn solder, melts at

    118 C.
  - Non-corrosive Indalloy fluxes
  - 4 x 100 W heater cartridges were permanently embedded within the receiver cup
  - Two thermocouples measured temperature for soldering lead
- Built one lead box and installed successfully

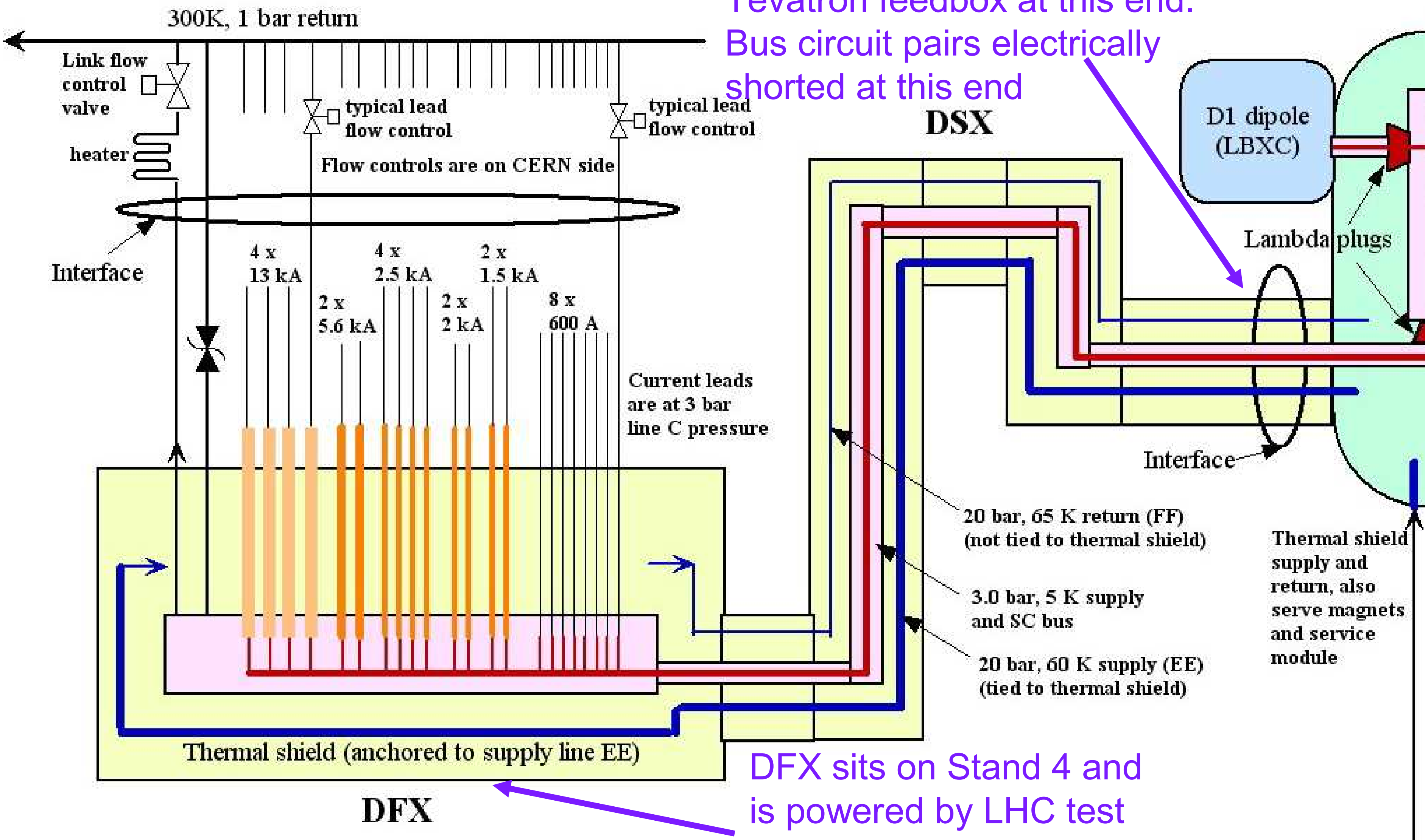
Test and fabrication plan

- Full size first DFX box and prototype link are used to test all current leads (no other prototype box nor other lead test box)
  - All current leads are tested in LHC operational configuration as opposed to in a dewar
  - Test with 3.6 bar, 5 K helium flow through the link to the current leads
- Cold testing in IB1 (Fermilab's magnet test facility)
  - Cryogens from stand 2 (favored by MTF management) or stand 6 (more convenient for us)
  - These two Tevatron magnet test stands can provide 5 K helium at 3 to 4 bar pressure
  - Place DFX box on stand 4 and power the current leads from the same 25 kA system which was used for the US LHC magnet tests
- First cold test is the first full sized DFX box with one complete set of current leads
- Design and fabrication of the rest of the leads follows the test of first set of prototype leads
- Design and fabrication of the rest of the DFX boxes and links follows the test of the first set of prototype leads

Test and fabrication plan (more)

- All current leads (except last set remaining in DFX test box) are shipped to DFX vendor after testing
- The four production DFX boxes have leads installed at the vendor
- The four production DFX boxes with leads and links are shipped to CERN as a final shipment after completion of all boxes
  - Current leads were cold-tested
  - Production DFX box was not cold-tested
  - Production link sections were not cold-tested
- Shipment of the DFX test box and test link follows the completion of all current lead testing (shipped with last set of tested leads)
- Strength of plan
  - Full-scale system, hence fully integrated design, is tested repeatedly while used as current lead test facility
  - Production of DFX boxes, leads, and links after full prototype tests
  - Current leads all tested in operational configuration

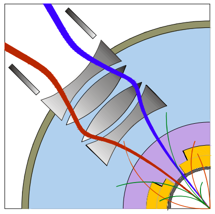
For testing, link is connected to MTF Tevatron feedbox at this end.
Bus circuit pairs electrically shorted at this end



DFX sits on Stand 4 and is powered by LHC test power supplies

IB1 -- Looking over stand 6 toward stand 4

IB1 -- Between stand 6 and stand 4



IB1 -- power bus from 25 kA power system emerges from floor to stand 4

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IB1 -- Stands 4 and 6 from the platform

IB1 -- Stand 2 (opposite side of central distribution box from stands 4 and 6). Shows Tevatron-style interface to cryo system. Possible routing up over the distribution box to power at stand 4.

Test measurements and goals

- Installation and assembly methods
  - Current leads, bus splices
- Bus behavior with current
  - Bus voltages, quench protection
  - Spot heater quench tests
- Temperatures in DFX
  - Heat load through link and DFX box
- Flow rates for current lead cooling
  - Frost-free current lead operation
  - Current lead voltages with full current