PIP-II Cryogenic System and the evolution of Superfluid Helium Cryogenic Plant Specifications

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Abstract

PIP-II cryogenic system: Superfluid Helium Cryogenic Plant (SHCP) and Cryogenic Distribution System (CDS) connecting the SHCP and the SC Linac (25 cryomodules)

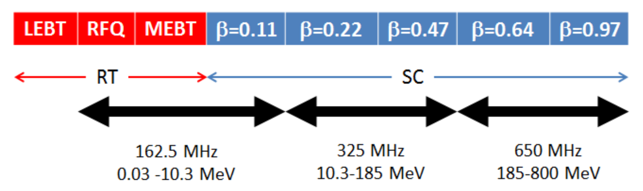
Static and dynamic heat loads for the SC Linac and static load of CDS listed out

Simulation study carried out to compute SHe flow requirements for each cryomodule

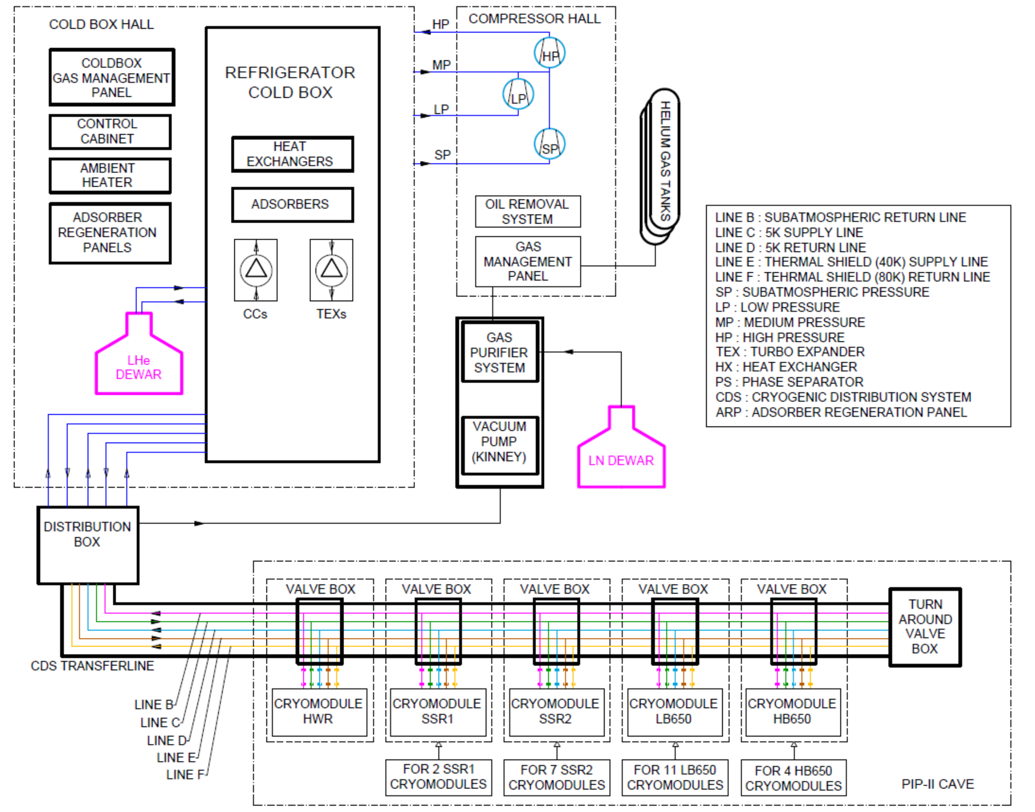
Comparison between the flow requirements of the cryomodules for the CW and pulsed modes of operation presented

From computed heat load and pressure drop values, SHCP basic specifications evolved

PIP-II Cryogenic System



PIP-II Linac layout



PIP-II cryogenic system layout

Basic requirements

- **20 years of operation with 98% reliability**
- **Provide sufficient cooling for all possible operating scenarios**
- **Controlled cool-down and warm-up of cryomodules**
- **Maintain stable pressure (+/- 100 Pa) in the cryomodules to minimize microphonics**
- **Reduce system perturbations during fault conditions**
- **Provide full segmentation of the SRF Linac and installation/removal of a cryomodule under cold conditions**
- **Provide proper protection of process fluids from contamination and minimize loss of cryogens**
- **Compliance with the Fermilab ES&H manual**

Modes of operation

- **4.5 K standby: extended shutdown**
- **2 K standby: shorter shutdown**
- **2 K pulsed mode: reduced dynamic heat load**
- **2 K CW mode: maximum heat load**

Table 1. Heat load budget of the PIP-II cryogenic system (CW and pulsed modes).

Cryomodule	Static heat load, 2 K (W)	Dynamic heat load, CW (W)	Total 2K heat load, CW (W)	Dynamic heat load, pulsed (W)	Total 2K heat load, pulsed (W)	LTTI[a] heat load (W)	HTTS[b] heat load (W)
HWR	37	24	61	24	61	60	250
SSR1	24	46	70	2	26	176	332
SSR2	63	366	429	20	83	434	882
LB650	22	611	633	32	54	176	528
HB650	16	519	535	27	43	128	344
CMs Total			1728		267	974	2336

[a] 4.5 – 9K LTTI loads.
[b] Includes the intercept loads as well as 45 – 80K thermal shield loads.

Cryogenic Distribution System (CDS)

- **Includes a distribution box (DB), cryogenic transfer lines, valve boxes equipped with cryogen transfer tubes with 25 inline bayonets (U-tubes) and a turnaround box**
- **U-tubes provide flexibility for positive isolation of tunnel components and strings of cryomodules from the SHCP**
- **SHCP will supply (in steady state) supercritical helium (SHe) stream at around 4.5 K and with a maximum supply pressure of 4 bar to the CDS**
- **SHe line divided into two streams inside each cryomodule, one directed to a sub-atmospheric heat exchanger (SP HX) and subsequently to a JT valve, while the other to the Low Temperature Thermal Intercepts (LTTI)**
- **LTTI gaseous helium (GHe) return stream from each of the cryomodules enters the CDS transfer line and returns to SHCP via the DB at a temperature of about 9K**
- **Sub-atmospheric (SP) GHe return stream from each of the cryomodules enters the CDS transferline and returns to SHCP via the DB at a temperature of about 4 K**
- **SHCP will supply high-pressure helium gas at 35-40 K to the CDS for the High Temperature Thermal Shield (HTTS). This shield flow is returned from the CDS to the CB at around 80K**

Table 2. Budgeted pressure drop and heat load along the CDS.

Circuit	Operating pressure (P) (MPa)	Pressure drop (kPa)	Heat load (W)
2 K return, line B	3.13e-3	0.4	170
4.5 K supply, line C	$0.22 \leq P \leq 0.4$	25	60
LTTI return, line D	$0.22 \leq P \leq 0.4$	3	50
HTTS supply, line E	$0.3 \leq P \leq 1.8$	5	150
HTTS return, line F	$0.3 \leq P \leq 1.8$	7	1800

Cryomodules

- **Operating temperature: 2 K (He vapour pressure: 31 mbar)**
- **Thermal intercepts at 70 K and 5 K**
- **Single thermal shield, GHe cooled, 45 – 80 K**
- **GHe at 4.5 K – 9 K for 5 K LTTI cooling**

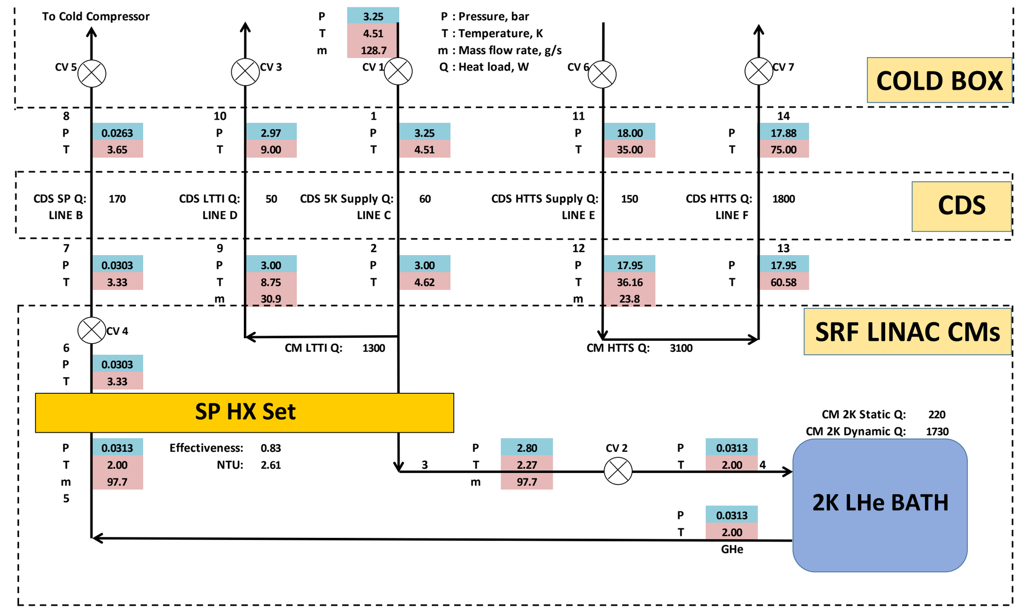
Simulation Studies

Motivation and aim

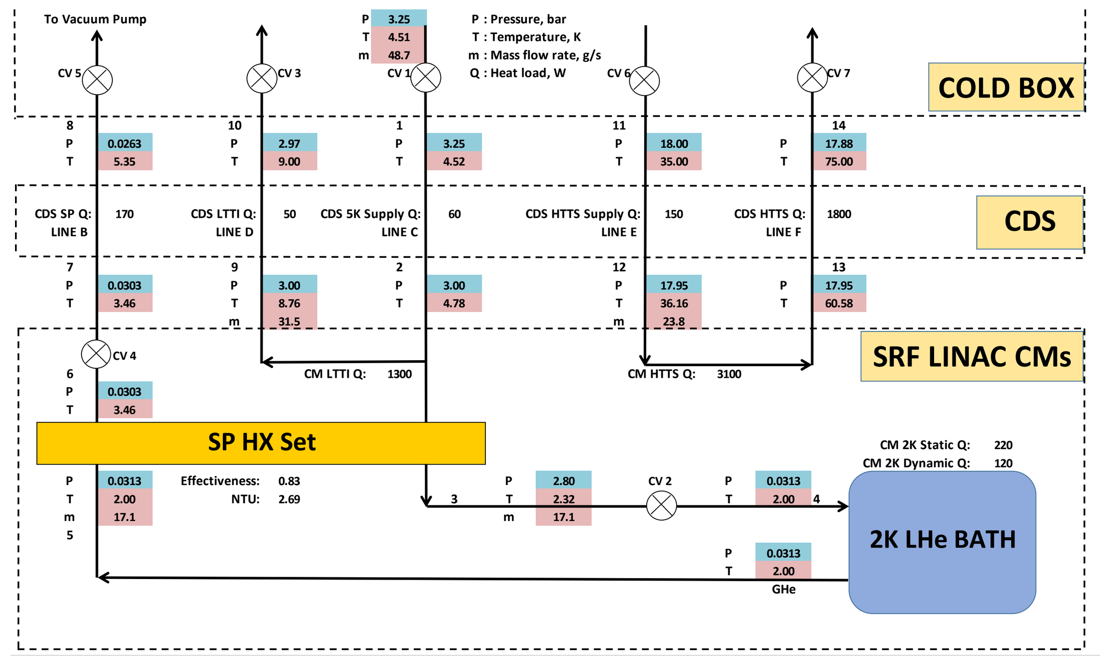
- **Wide ranging heat load mitigation requirements pertaining to different modes of operation**
- **Holistic simulation study including the entire system**
- **Determination of mass flow rate (for CW and pulsed modes) in all the cold helium lines B, C, D, E and F in the CDS as well as 2 K GHe helium flow in cryomodules**
- **Estimation of helium supply requirements from SHCP**

Table 3. Computed flow in different cooling circuits (CW and pulsed modes).

Mode	2 K SHe flow (g/s)	Line B (g/s)	Line C (g/s)	Line D (g/s)	Line E (g/s)	Line F (g/s)
CW	97.7	97.7	128.7	30.9	23.8	23.8
Pulsed	17.1	17.1	48.7	31.5	23.8	23.8



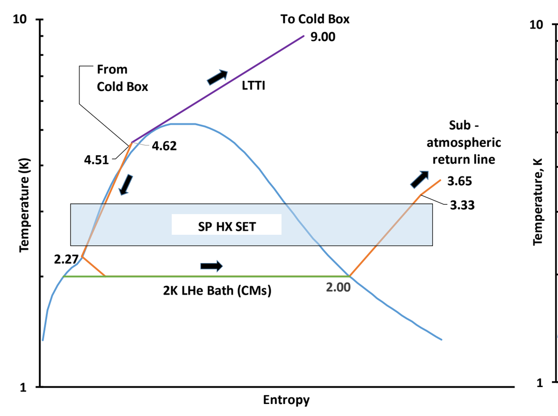
Thermodynamic state points – CW mode



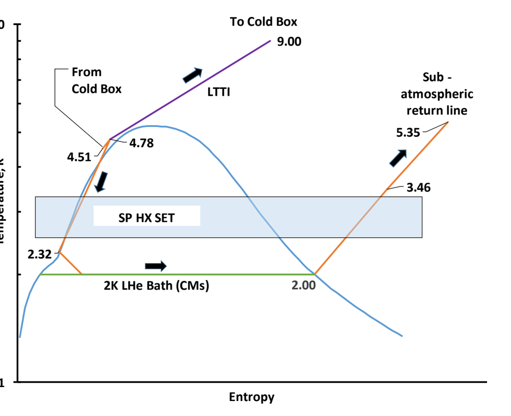
Thermodynamic state points – pulsed mode

Numerical model

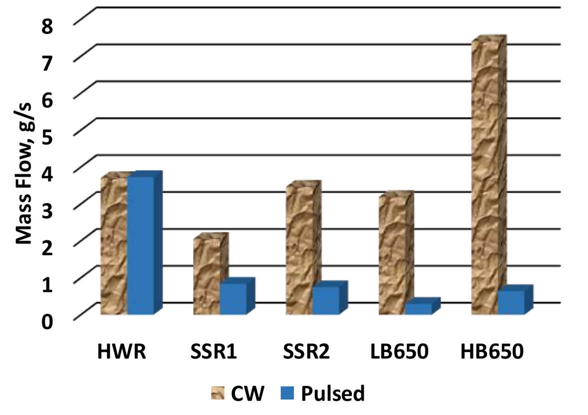
- **Numerical model incorporates CDS and its interface with the SHCP cold box, the cryomodules including SP HX set and JT valves**
- **Basic assumption: All SP HX possess same effectiveness and hydraulic characteristics**
- **First law energy balance and continuity equations written down for SP HX set, helium piping circuit, LHe bath inside cryomodules and cryogenic valves**
- **For SP HX set, second law limitations imposed through device effectiveness**
- **Set of equations solved iteratively**
- **Helium properties obtained from HEPAK®**



T-s diagram – CW mode



T-s diagram – pulsed mode



He flow in different modes

Conclusion

2 K flow in the cooling circuits of the cryomodules and the CDS computed

Spread of GHe flow requirements for different modes of operation quite large

Economic SHCP operation with cold compressors may be challenging

All systems including SP HX to be designed as per CW mode for best cryogenic system efficiency

Basic specifications for the SHCP generated and procurement action initiated

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