SLHiPP-2, Catania, Italy

A cryogenic system for the MYRRHA linac

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Outline

1°) Cryogenic system requirements : heat loads

2°) Temperature optimization,
possible 4K operation of Spoke cavities

3°) General description, distribution scheme

Introduction

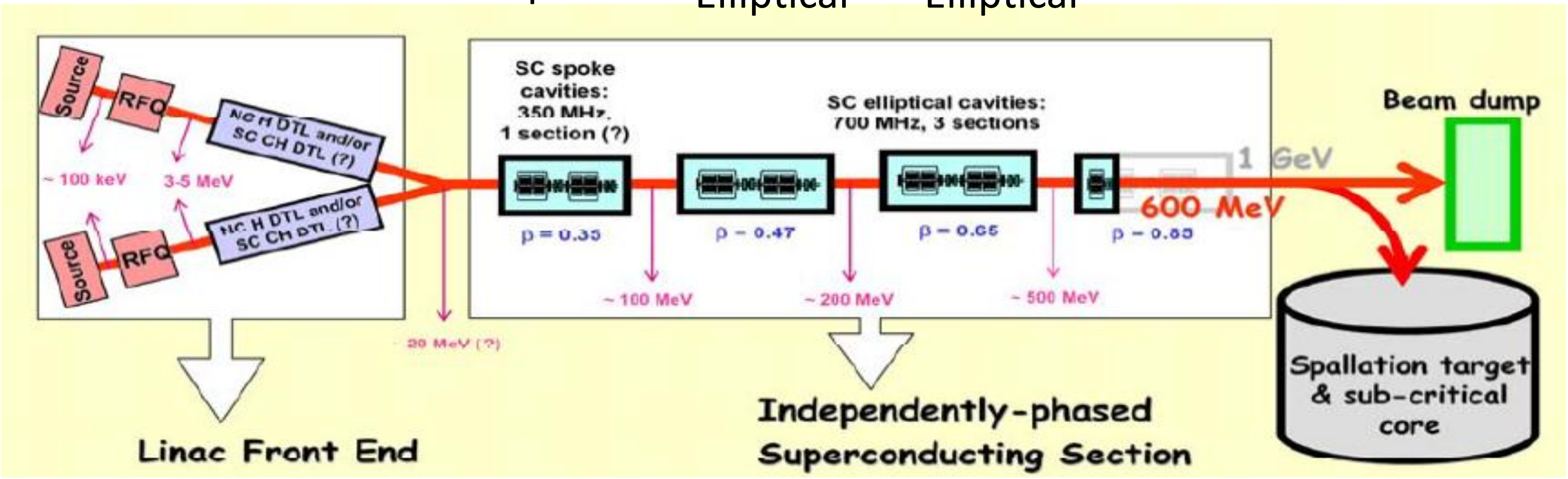
Temperature levels :

- 2K : cavities
- 5-20 K : couplers
- 40-80 K : thermal shield

Contributions to heat load :

- Static
- Dynamic (RF)

2 x 4 CH	63 Spoke	30 β=0.47 Elliptical	64 β=0.47 Elliptical



Static heat load

	SNS [10]		XFEL [11]	CEBAF [12], [13]	Project X [14]
Cryomodule content	3 med-β elliptical	4 high-β elliptical	8 β=1 elliptical	8 β=1 elliptical	18 single spoke
Focusing magnets	outside cryomod	outside cryomod	1 inside	outside cryomod	18 solenoids inside cryomod
Cryomodule Length (m)	4.24	6.29	12.2	8.25	11.2
Static Loss into 2 K (W/m)	**4.64**	**3.55**	**0.11**	**1.8**	**1.73**
Static Loss into 5-8 K (W/m)	-	-	0.9	-	-
Static Loss into 40-K (W/m)	**36.55**	**30.36**	**5.82**	**17**	**8.24**

For MYRRHA, short cryomodules :
- **5 W/m at 2K**
- **40 W/m at 40 K**

Dynamic heat load on 2K

	Spoke **β=0.36** **352 MHz**	Elliptic **β=0.47** **704 MHz**	Elliptic **β=0.65** **704 MHz**
R_{res} (nΩ)	10.0		
R_{BCS} (nΩ)	0.8	3.2	3.2
Q_0 theoretical	9.35E+09	1.0E+10	1.3E+10
E_{acc} (MV)	5.3	8.5	10.3
Q_0 exp*	2.2E+09	1.0E+10	3E+10
P_{cav} (W)	**5**	**11.1**	**12.7**

* Bosotti et al. , Visentin et al., Olry et al.

Coupler heat loads at 5K

Coupler cooling by supercitical helium at 5 K (Mehdi Souli PhD thesis)

Current design : 1-2 loops, thermalization point (temperature range : 5-20 K)

	Spoke 350 MHz	**Elliptic 700 MHz β=0.47**	**Elliptic 700 MHz β=0.65**
Number of cavities	63	30	64
RF power per cavity (kW)	6	20	35
Power in external conductor of coupler (W)	**0.7**	**3**	**5.3**
Static coupler losses (W)	**0.15**	**0.15**	**0.15**

Coefficient of performance of cryoplant

$$\eta = \frac{1}{COP} = \frac{T}{T_r - T}\alpha(power, T)$$

Accelerator	LHC (one sector)		SNS		Project X		XFEL	
Type of data	measured				specifications			
Operating Temperature (K)	1.8		2		2		2	
Cryo Power (kW) @ 4.5 K	18		10		41		12	
Cryo Power (kW) at op. temp.	2.4		2.4		4.3		2.8	
COP (W/W) of 2K | 4.5 K	**950**	**240**	**1150**	**386**	588	240	870	-
COP(T2)/COP(T1)	**3.96**		**2.97**		2.45		-	

For MYRRHA, cryo power at 2K : ~13 kW → Close to XFEL or one LHC unit

Realistic goal : **COP(2K) = 720 , COP(4K)= 220, COP(2K)/COP(4K) = 3.3**

Overcapacity and total heat load budget

LHC recipe :

Overcapacity factor : 1.5 → speed cool-down, use machine < 100 % performance
Uncertainty factor : 1.25 → imperfect Nb, electron loading, MLI wrapping etc.

→ **Overall margin : 1.875**

Power @ 4.5 K	Temperature (K)	Heat Load (kW)	COP (W/W)	Function
13.1 kW	**2.1**	**4.75**	720	Cavities
	5	**1.1**	220	Coupler cooling
	40	**13.6**	20	Shield

→ **Overall power similar to :**
LHC (18 kW), JLAB (11 kW),
XFEL (12 kW), 2 x SNS (2 x 6.4 kW)

Heat load breakdown

- **Heat load distribution along linac** :

100 W	640 W	540 W	1325 W
~3.5 %	~24.5 %	~21 %	~51%

- heat load is roughly 25 % | 20 % | 50 % across the three sections
- static losses ~ ½ dynamics losses → small cryomodule, low field

- **Dynamic range at 2K**: Load beam on/beam off = (dynamic + static)/static

Total Static (W)	Total Dynamic (W)
970	1670

→

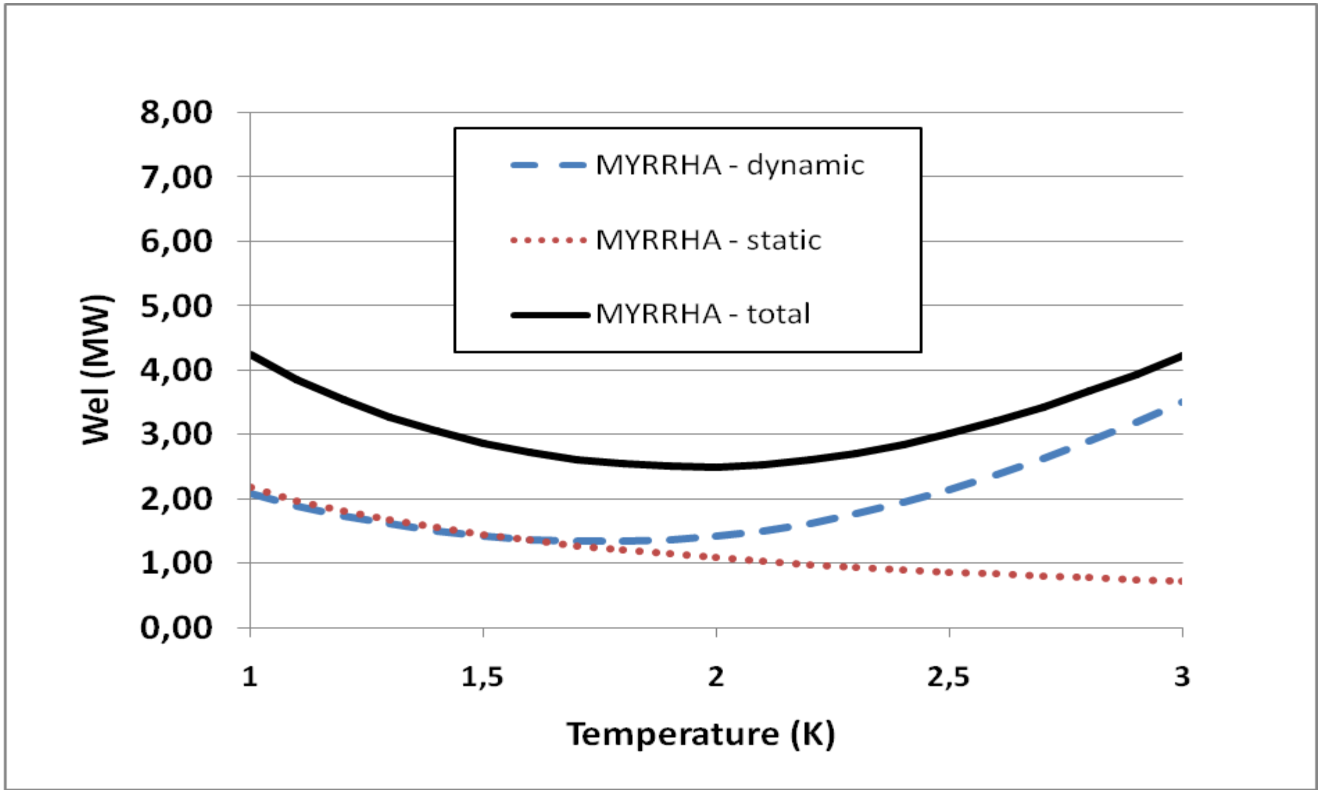
Dynamic range = 2.7

LHC : 3

Important parameter for choice of refrigeration scheme (full cold compression or mixed compression)

Temperature optimization of the MYRRHA linac

COP decreases with T, R_{BCS} increases with T → optimum of power consumption

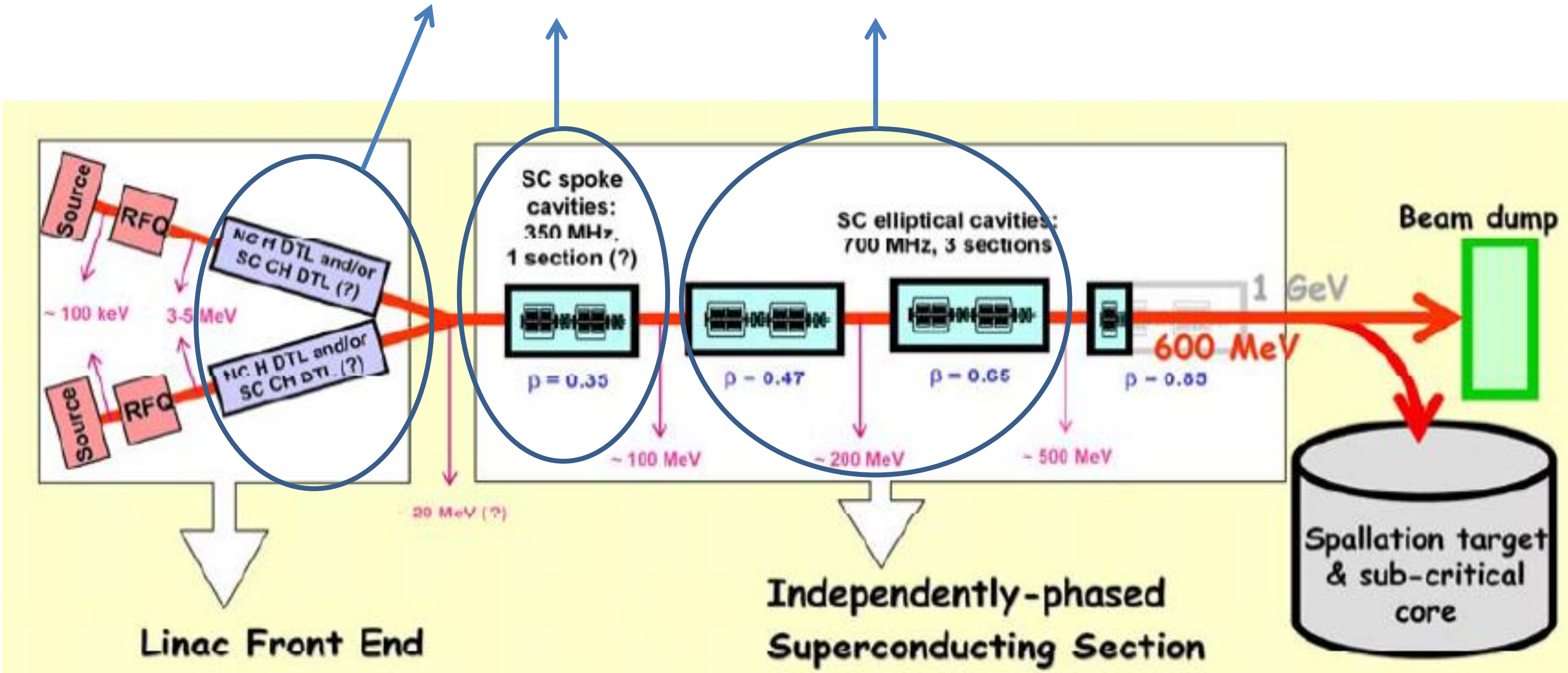


→ **Optimal temperature is 1.95 K, i.e ~2K**

Possible 4K operation of Spoke cavities

2K or 4K
refrigeration ?

2K refrigeration



Possible 4K operation of Spoke cavities

For Spoke cavities,
at R_{res} =10 nΩ :

$$P_{cav,4K} / P_{cav,2K} \approx 5$$

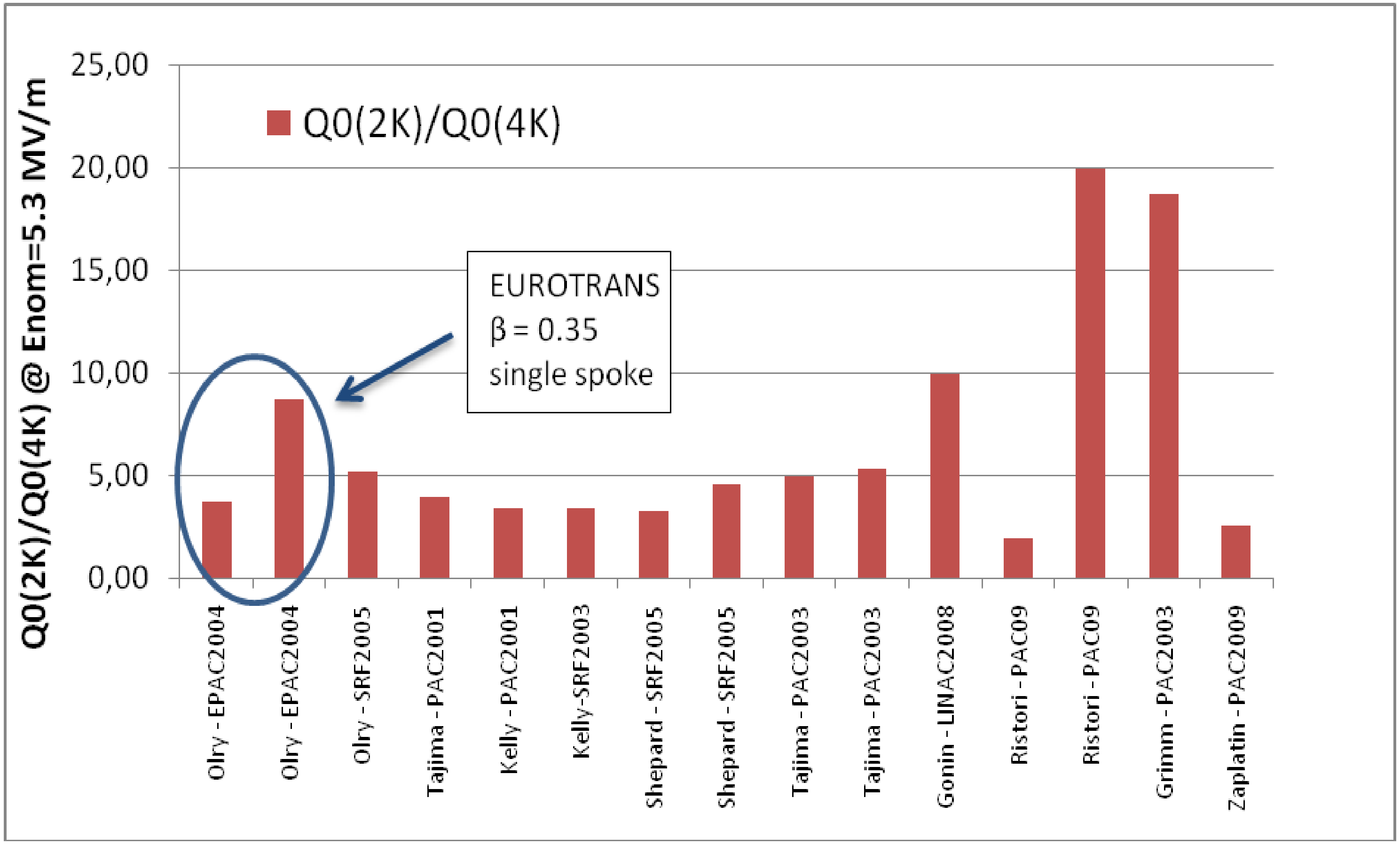
Coefficient of Performance
of cryogenic plant:

$$COP_{2K} / COP_{4K} \approx 3-4$$

Considering only dynamic losses, operation at 2K is favorable, however :

- Is R_{res} = 10 nΩ a reasonable assumption ?
- Static losses of 5W/m will be applied at 4K, not 2K
- Other factors : bath stability, microphonics

Experimental Q_0 at 4K and 2K of Spoke cavities



$$\to \quad < \frac{Q_0(2K)}{Q_0(4K)} >= 5.6$$ agrees with theoretical estimate

Total power consumption
Comparison of 4K-2K and full 2K solutions

	Total Electric (MW)	Electrical Cost (M€/year)
Mixed 4K-2K Scheme	2.092	1.83
Full 2 K Scheme	2.1	1.84

→ Unsignificant difference between the 2 schemes

Other aspects of 2K vs 4K : nucleate boiling & microphonics

- In 4K Helium, nucleate boiling occurs at fluxes ~ 1 W/cm²
- In MYRRHA, typical heat fluxes in cavities are 10^{-3} W/cm²

⟶ Nucleate film boiling is not an issue in MYRRHA

Microphonics

- Pressure fluctuations in 4K bath >> in 2K Bath → trigger microphonics
- For Spoke cavity :

$$\Delta f_L = 150 Hz$$

- Fast (>1Hz) pressure fluctuations in 4K: 0.1-0.5 mbar (Conway et al.)
- Sensitivity : $\Delta f / \Delta p = 108 Hz / mbar$

⟶ 50 Hz detuning, one third of bandwidth !

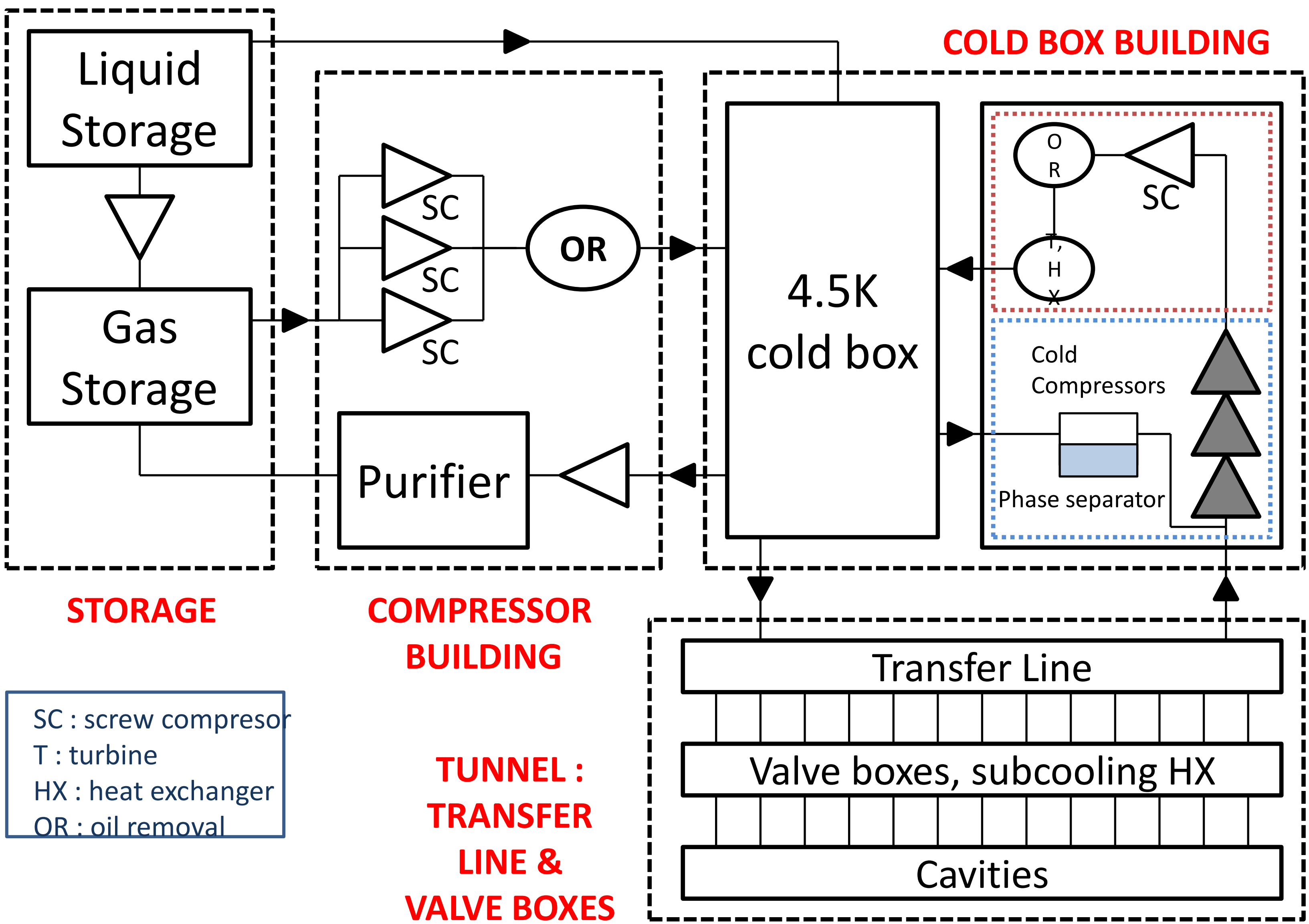
Conclusions on possible 4K operation of Spoke cavities

4K operation	2K operation
Easier to implement (no JT, subcooling heat exchanger, etc.)	More stable against microphonics
More reliable	A 2K pumping line will anyway be installed for elliptical cavities
Overall consumption is the same as 2K	
Cavities are cooled to 4K before pumping to 2K	

→ **4K-2K operation should be tested on prototype Spoke cryomodule**

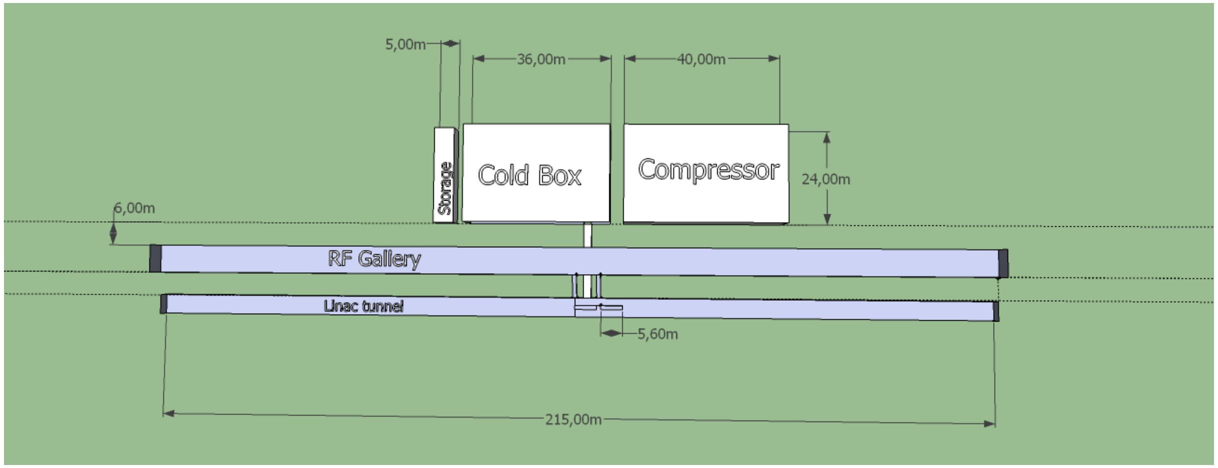
→ **In the design phase, pipes should be sized to allow 4K and 2K operation**

General scheme of cryogenic system

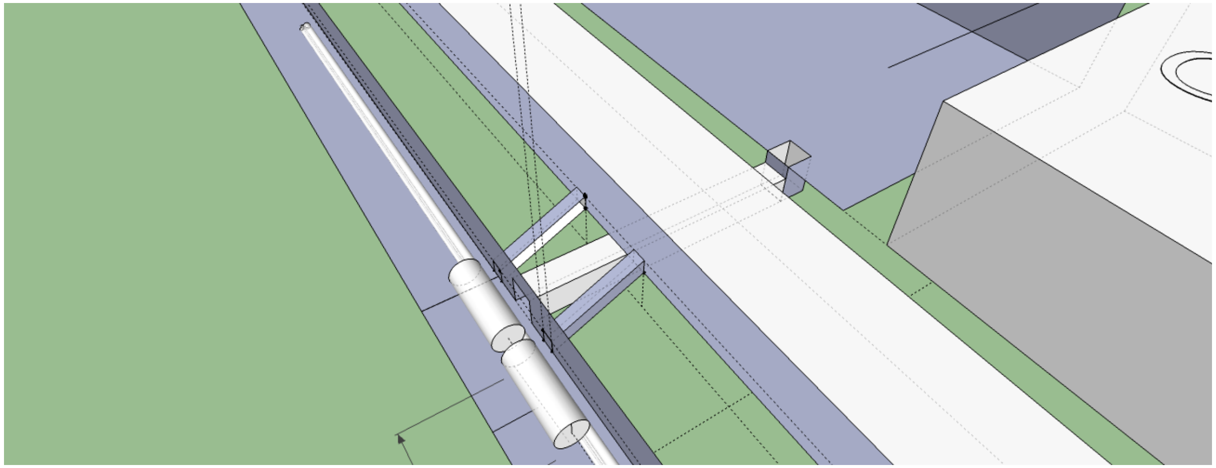


Preliminary sketch of cryoplant layout

General



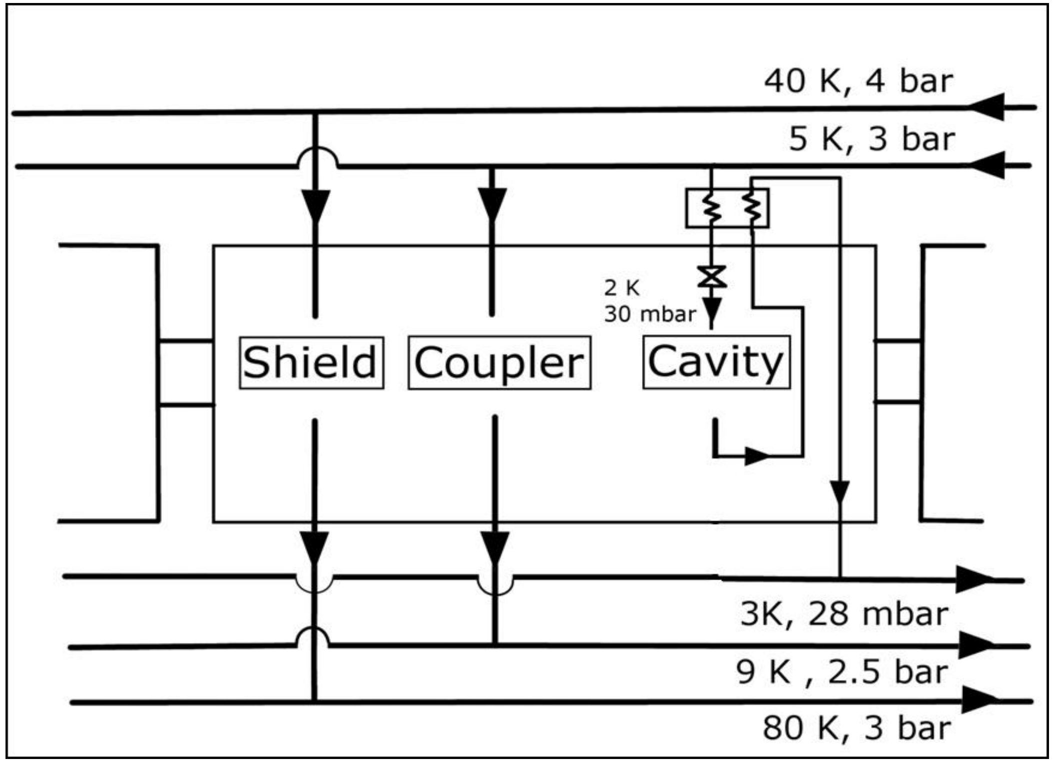
Detail of cryogenic connection tunnel



Cryofluid distribution

Idea :

Make optimal use of supercritical helium supply line (SNS)



We are currently studying different schemes :

- Distributed heat exchanger : subcool and expand helium in each valve box (SNS, LHC)
- Centralized heat exchanger : subcool in central cold box, expand locally (JLAB)
- How many cryomodules per valve box ?

General conclusion

- Coolant : superfluid helium at 2K – 30 mbar, possible 4K operation of Spoke cavities
- 13 kW @ 4.5 K, including 4.7 kW at 2K
- Estimated cost (without manpower) : 21-26 M€
- Reference cryogenic systems : LHC, XFEL, SNS
- Many open questions : distribution, transfer line design, etc.

One thing we know for sure is that it will look somewhat like this :

Thank you for your attention !