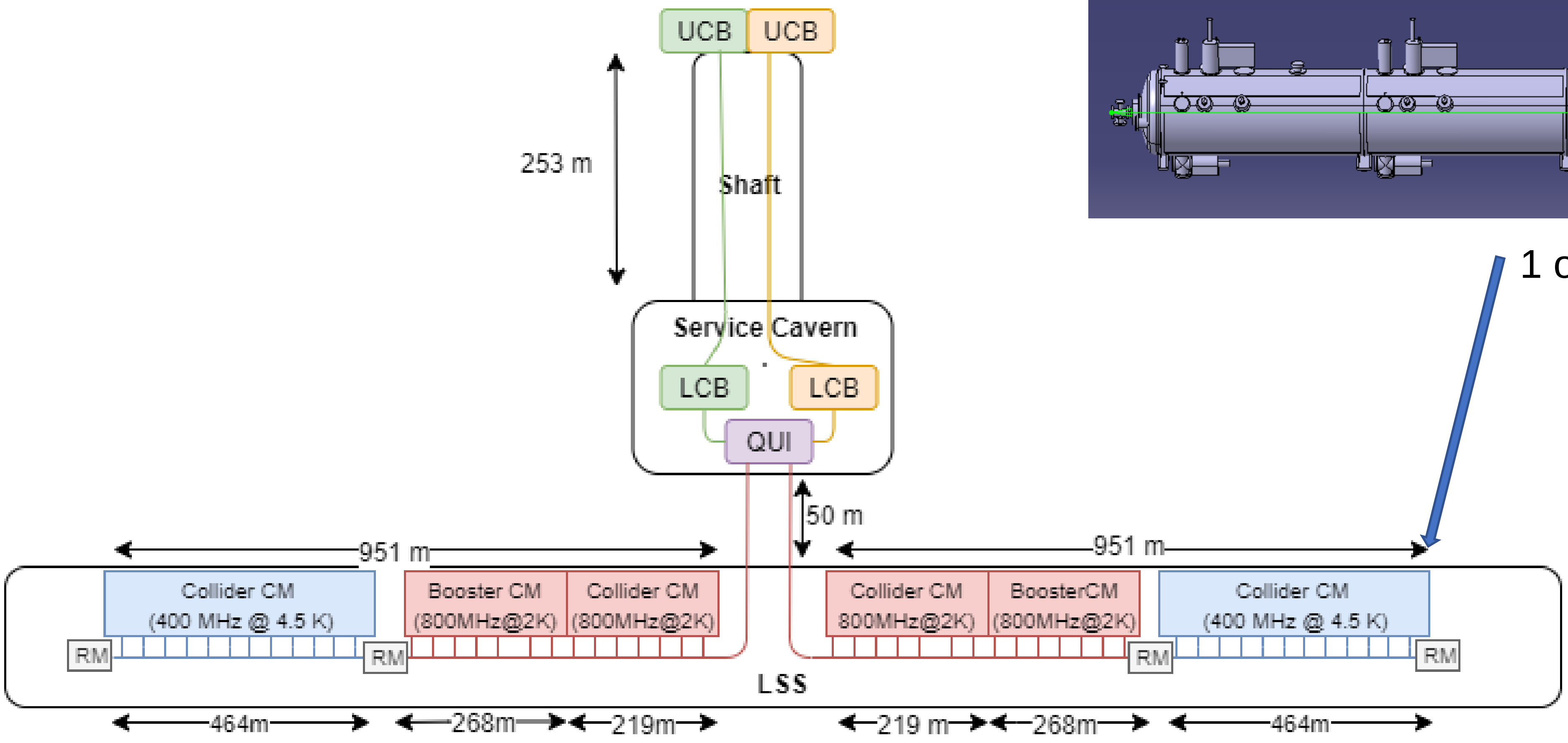
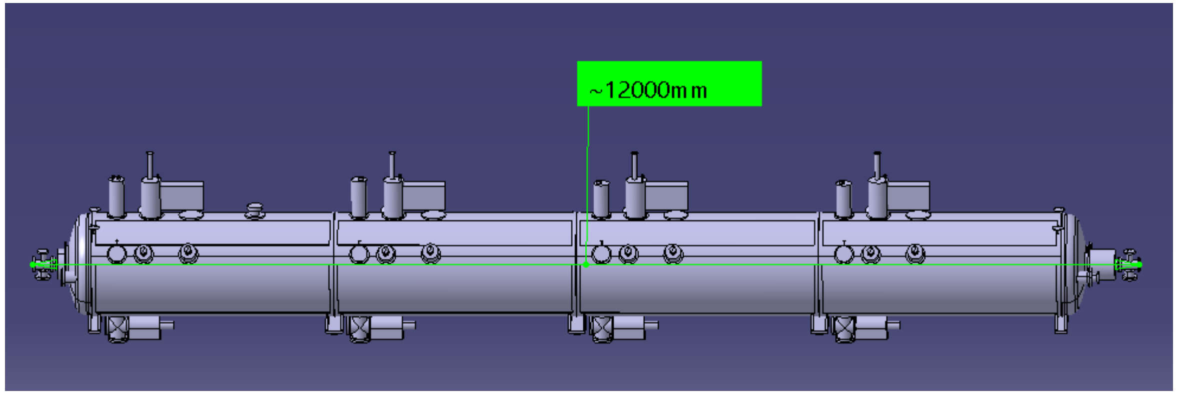
Tutorial

Technical Training: Cryostat Engineering for SC devices
CERN, 7-9 November 2022

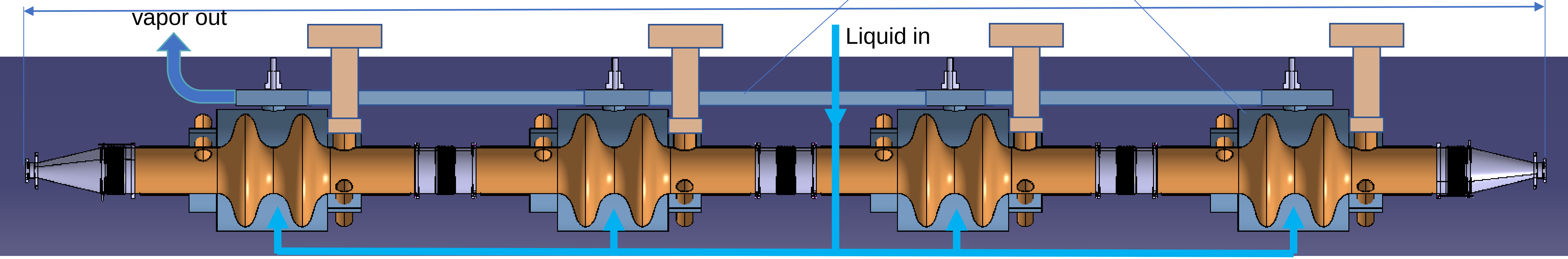
FCCee, RF cryogenic layout, 400 MHz Cryomodule



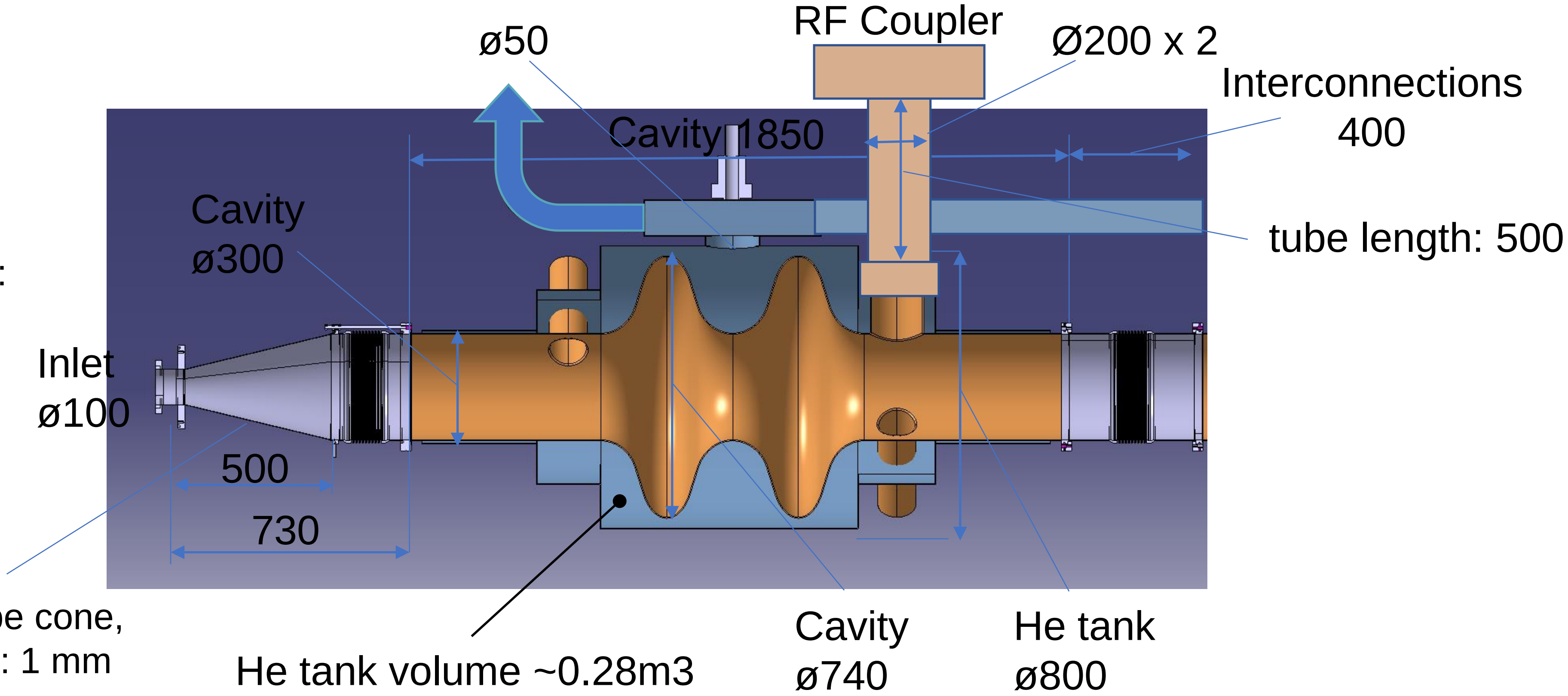


1 of 35 cryomodules per side

400 MHz cavities, 2-cell



- Cavity: copper, 3-mm thick
- Cavity mass: 150 kg
- Helium vessel: thickness TBD, st.steel (304L grade)
- Helium vessel mass: (304L): 200 kg
- Beam tube cone (304L)
- RF coupler tube (304L)
- Approximate mass of cavity/helium tank/RF coupler assembly: 500 kg



Task 1. Cryostat design

1. Conceptual design of a cryostats for the 400 MHz cryomodule containing 4 cavities. Make a schematic design (simplified sketch, use ppt or any other S/W tool), and make a preliminary engineering design as follows:
    a. Calculate helium tank thickness, for a maximum allowable pressure of 4 bar
    b. Calculate vacuum vessel: material, diameter and thickness
    c. Calculate thermal shielding: material, diameter, thickness. Propose a possible supporting principle.
    d. Design of the supporting system. Choose type (column, tie rods, etc.), make a conceptual design (materials and sizing for mechanical and thermal requirements). Consider maximum loads from road transport: vertical: 7 m/s^2; lateral: 4 m/s^2; longitudinal: 6 m/s^2 and a minimum Safety Factor on 2 on $\sigma_{0.2}$.
    e. Propose a possible assembly method of the cavities string inside the vacuum vessel
2. Calculate the static thermal performance (Heat Loads) and total cooling mass flow needs, for the following :
    a. Supporting system (no heat intercept)
    b. RF couplers (with active vapor cooling or not)
    c. Beam tubes cold to warm transitions (cones between 300 K and 4.2 K, no heat intercept). (neglect conduction path of bellows)
    d. Thermal radiation from vacuum vessel and thermal shielding (flat plate approximation). Calculate the radiation load in the absence of a thermal shield.
    e. Calculate liquid boil-off mass flows, liquefaction load for ideal vapor cooling of couplers, and thermal shield mass flow assuming T_{in}=50 K and T_{out}= 55 K.

Task 1.1. Table of design parameters

Item	Description	Value	Comments
1 a.			
1 b.			
1 c.			
1 d.			
1 e.			

Task 1.2. Table of Static Heat Loads and mass flows

<table>
<tr><th>Source of HL</th><th colspan="2">HL (W) @ 4.2 K</th><th>HL (W) @ 50 K</th><th>4.2 K liquid boil-off (g/s)</th><th>Liquefaction load (g/s)</th><th>Thermal shield mass flow (g/s) (with T_{in}=50K, T_{out}=55 K)</th></tr>
<tr><td>Supports conduction</td><td colspan="2"></td><td>-</td><td></td><td>-</td><td>-</td></tr>
<tr><td>Beam tube cones conduction</td><td colspan="2"></td><td>-</td><td></td><td>-</td><td>-</td></tr>
<tr><td>RF Couplers conduction (uncooled)</td><td></td><td>-</td><td rowspan="2">-</td><td></td><td>-</td><td rowspan="2">-</td></tr>
<tr><td>RF Couplers conduction (ideal vapor cooling)</td><td>-</td><td></td><td></td><td></td></tr>
<tr><td>Radiation, with thermal shield @ 50 K</td><td colspan="2"></td><td></td><td></td><td>-</td><td></td></tr>
<tr><td>Radiation, without thermal shield</td><td colspan="2"></td><td>-</td><td></td><td>-</td><td>-</td></tr>
<tr><td>Radiation from beam tube cones</td><td colspan="2"></td><td>-</td><td></td><td>-</td><td>-</td></tr>
<tr><td>Totals</td><td colspan="2"></td><td></td><td></td><td></td><td></td></tr>
</table>

Task 2. Cool-Down

The cool down from 293 K is obtained by boil-off of liquid helium at 4.2 K (1 bar) entered from the bottom of the helium vessels.

a. Calculate the liquid helium need (mass in kg) for cooling down to 4.2 K helium the mass of cavity+helium tank. Consider, during the CD process, an average effectiveness in the use of the sensible heat of helium vapor between 4.2 K and 100 K (exhaust temperature at the exit of the cavity). How correct is this assumption? (Neglect, in the calculation, the contribution from static heat loads to the power balance).

b. Calculate the average cooling power for a cool down from 293 K to 100 K in 12 h, assuming that cavity/helium vessel are isothermal in the cooling process

Task 2 Results

Item	Value	Comments
a.	10 kg	Using Cryostat Toolbax, the heat capacity of 500 kg of st.steel between 4.2 K and 100 K is 5.25 MJ (and 5.31 MJ for Cu). The mass of liquid helium to cool down is the sum of the Lv plus the sensible heat up to 100K. The latter is calculated by Cryostats Toolbox (fluids) as the heat capacity of helium: 503 kJ/kg. The latent heat is 21 kJ/kg. So 1 kg of liquid has an ideal cooling energy up to 100 K of 524 kJ/kg. The helium mass is therefore: 5250 kJ/524kJ/kg = ~10 kg of liquid helium.
b.		To cool down to 100 kg in 12 h requires an average power of 5250 kJ * 1/(12*3600s) = 121 W

Task 3. RF operation, helium boil-off and pumping

During RF operation of a cryomodule, a dynamic heat load 175 W is added to the static heat load calculated previously. Vapours are pumped back to the refrigerator through a 1’000 m long, DN200 smooth pipe, routed in a shielded and vacuum insulated transfer line.

a. Calculate the total boil-off rate in saturated helium at 4.2 K and 1 bar (g/s) for one cryomodule

b. Calculate the pumping pressure drop along the line, neglecting static heat loads along the line

c. Calculate the total pressure drop for 35 cryomodules all operating with the same dynamic load

d. If the cavities operate at 2K, 30 mbar, calculate the pressure drop along the line

Task 3 Results

Item	Value	Comments
a.	15.4 g/s	Assuming steady state operation (T_{op} 4.2 K and p_{op} =1 bar), the boil-off liquid is replenished by refilling. The liquid is therefore constant and the vapor boil-off mass rate is q=m*Lv, where q=qstat+qdynam= 150 (assumption)+175 =325 W. → m=325W/21000J/kg = 15.4 g/s
b.	0.001 mbar	Using Cryostat Toolbax (fluid) one can calculate the Re=3.1^{E}+04 → turbulent flow. Velocity is 4 mm/s. Linear pressure drop calculated for 1000m DN200 smooth pipe results: 0.001 mbar
c.	0.824 mbar (0.08% of p_{op})	T_{op}=2 K, p_{op}=30 mbar. For 35 cryomodules at same operation: 35*15.4 = 539 g/s. For the same tube geometry: pressure drop = 0.824 mbar (0.08%). If the pipe size is reduced to DN100 → Δp = 29 mbar
d.	0.982 mbar (3.2% of p_{op})	For operation at 2K, 30 mbar, the latent heat is 23 kJ/kg, so m=35*325W/23000J/kg= 590 g/s. At a pressure of 30 mbar, using Cryostat Toolbox, Re=1.2^{E}+6 (turbulent), velocity is 0.15 m/s, and pressure drop is Δp = 0.982 mbar (3.2 %)