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Transient modes and their impacts on the cryoplant size and operation margins

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- AC losses during magnet current ramp
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AC-losses: input for 16 T magnets

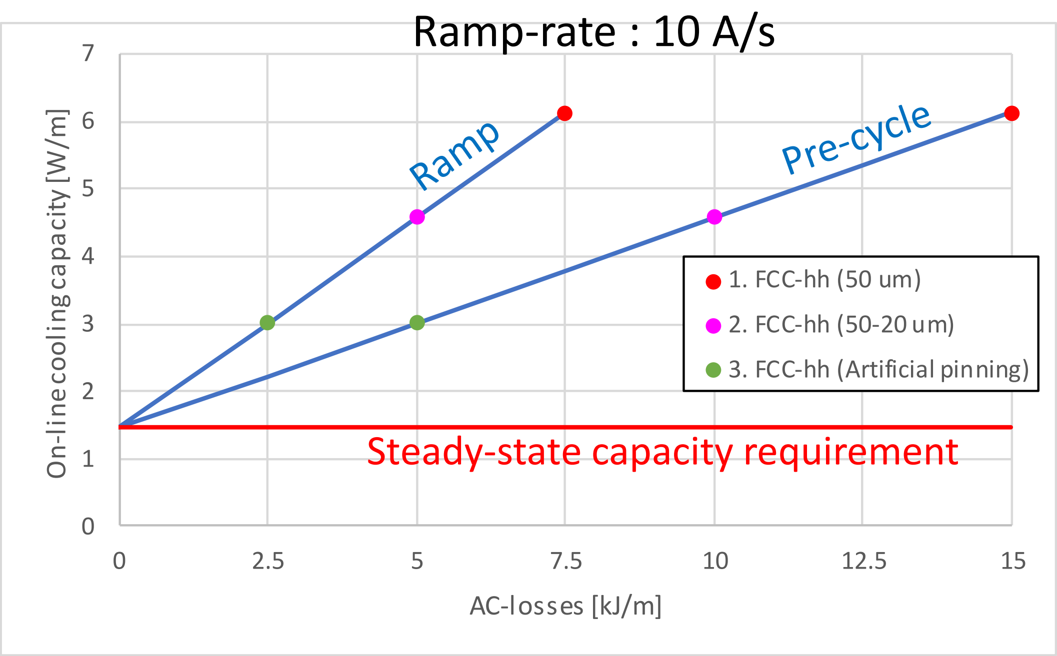
	AC-losses during ramp-up [kJ/m]	AC-losses during ramp-down [kJ/m]	AC-losses during pre-cycle [kJ/m]
Case 1: present state-of-the-art of NB3Sn conductor (D_{eff} of 50 μm)	7.5	7.5	15
Case 2: Reduced D_{eff} on low-field external layers (D_{eff} of 20 μm)	5	5	10
Case 3: Reduced D_{eff} on low-field external layers (D_{eff} of 20 μm) and implementation of new concepts (artificial pinning)	2.5	2.5	5

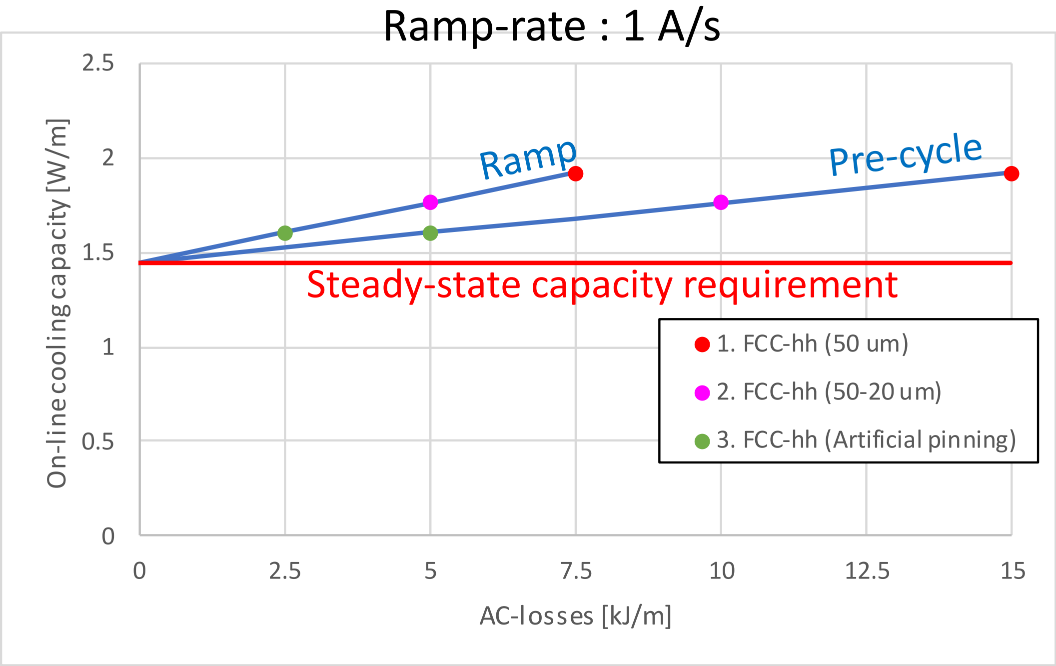
LHC as comparison	0.5	0.5 (10 A/s) 3 (fast discharge)	1

Remark : For FCC cable, AC-losses dominated by magnetization losses, i.e. no strong dependence on ramp rate

AC-losses: On-line extraction ?

- The nominal current ramp rate is about 10 A/s, i.e.:
  - A ramp-up time of 1600 s (~27 min)
  - A pre-cycle time of 3200 s (~53 min)





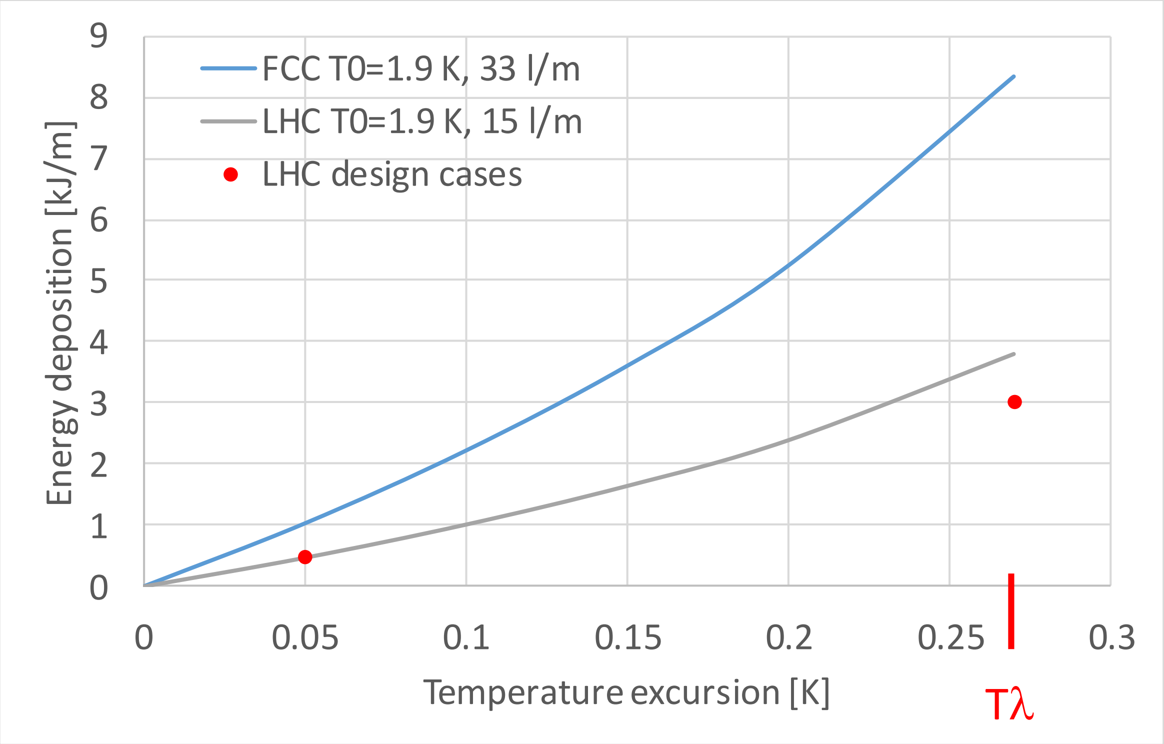
Capacity increase by a factor 2 to 4
w/r to steady-state requirement

Capacity increase by up to 33 %
w/r to steady-state requirement…
…but ramp-up time of 4.5 h (9 h per pre-cycle) !!

On-line extraction not possible → AC-loss energy must be buffered in the cold-mass helium inventory

AC-losses: Buffering in magnet cold-masses

- At 1.9 K, the specific heat of materials is negligible → only helium is taken into account.
- The specific helium inventory required for steady-state operation is 33 l/m
  - 50 % required by the longitudinal free area
  - 50 % required by the laminations void-fraction and end volumes



With the present helium inventory (33 l/m) and an initial temperature of 1.9 K, it is possible to buffer:

- ~ 5 kJ/m if we accept a temperature excursion of 0.2 K (OK for Nb_3Sn)
- ~ 8 kJ/m if we want to stay below Tλ.

AC-losses: Impact on He inventory

- Cryo requirement 1: Remain in LHeII after a pre-cycle (temperature excursion of 0.27 K)
- Cryo requirement 2: Remain below 2.1 K after a ramp-up (temperature excursion of 0.2 K)
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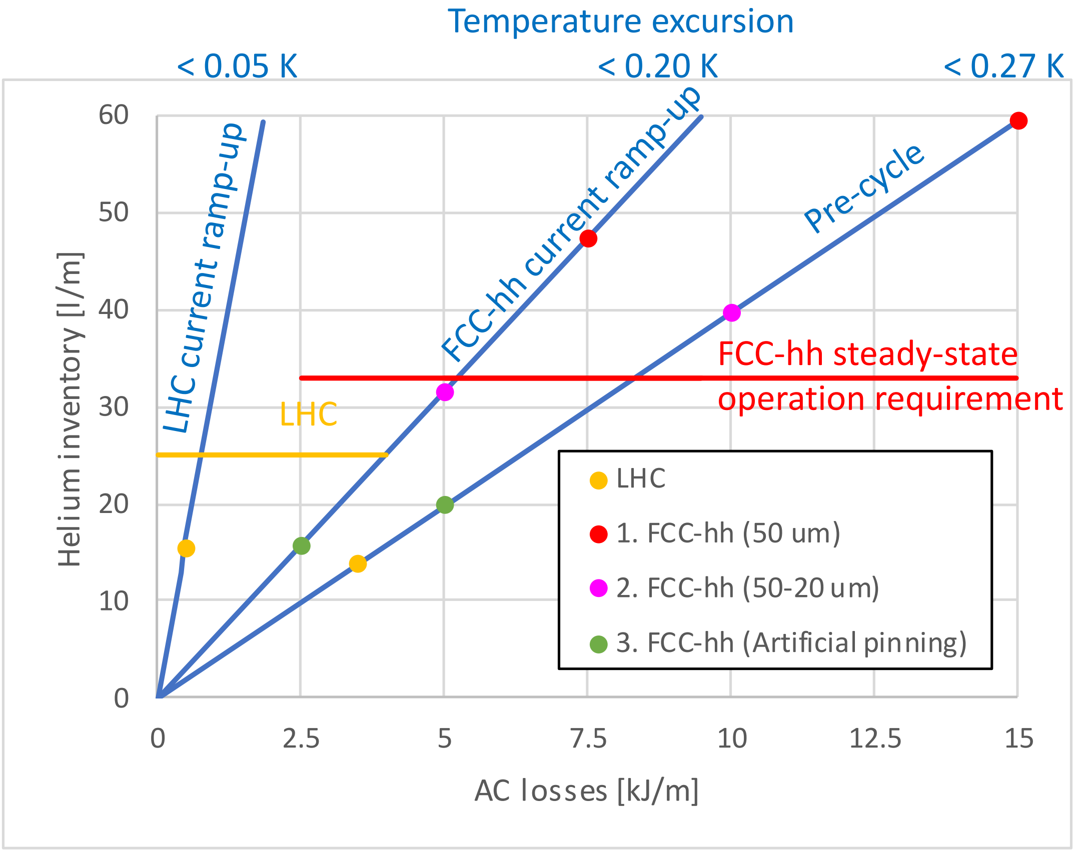
→ Both requirements have impacts on He inventory and on the quench recovery line diameter (Line D)

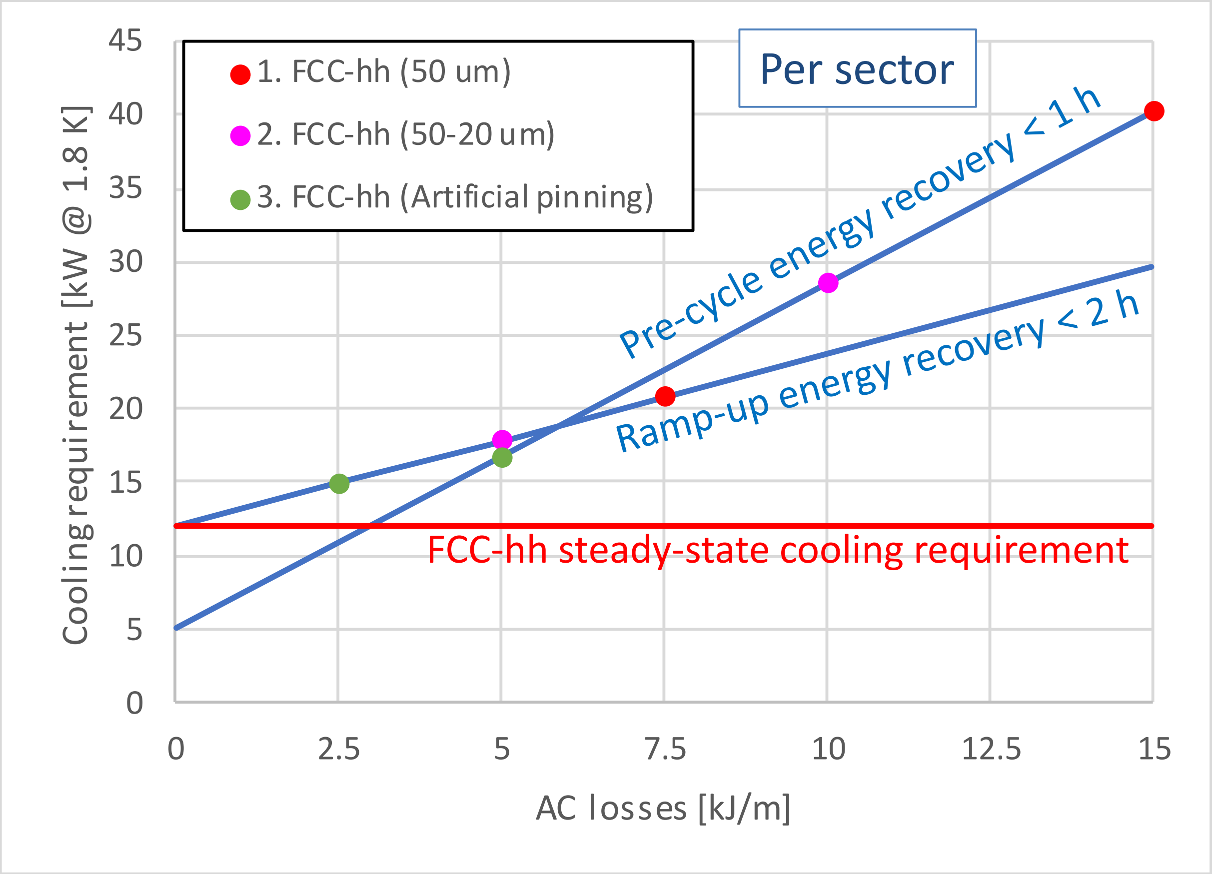


- Requirement 1 is the design case
- Case 1: + 80 % of cold mass He inventory (+ 300 t for FCC total inventory)
- Case 2: + 20 % of cold mass He inventory (+ 80 t for FCC total inventory)
- Case 3: no impact on He inventory (covered by steady-state need).

AC-losses: Impact on 1.8 K cooling capacity

- Cryo requirement 3: Extract deposited energy during ramp-up in less than 2 hours (half-time of a high-luminosity stable-beam plateau)
- Cryo requirement 4: Recovery of a pre-cycle in less than 1 hour (time to wait before Cryo OK for injection)

→ Both requirements have impacts on installed capacity @ 1.8 K



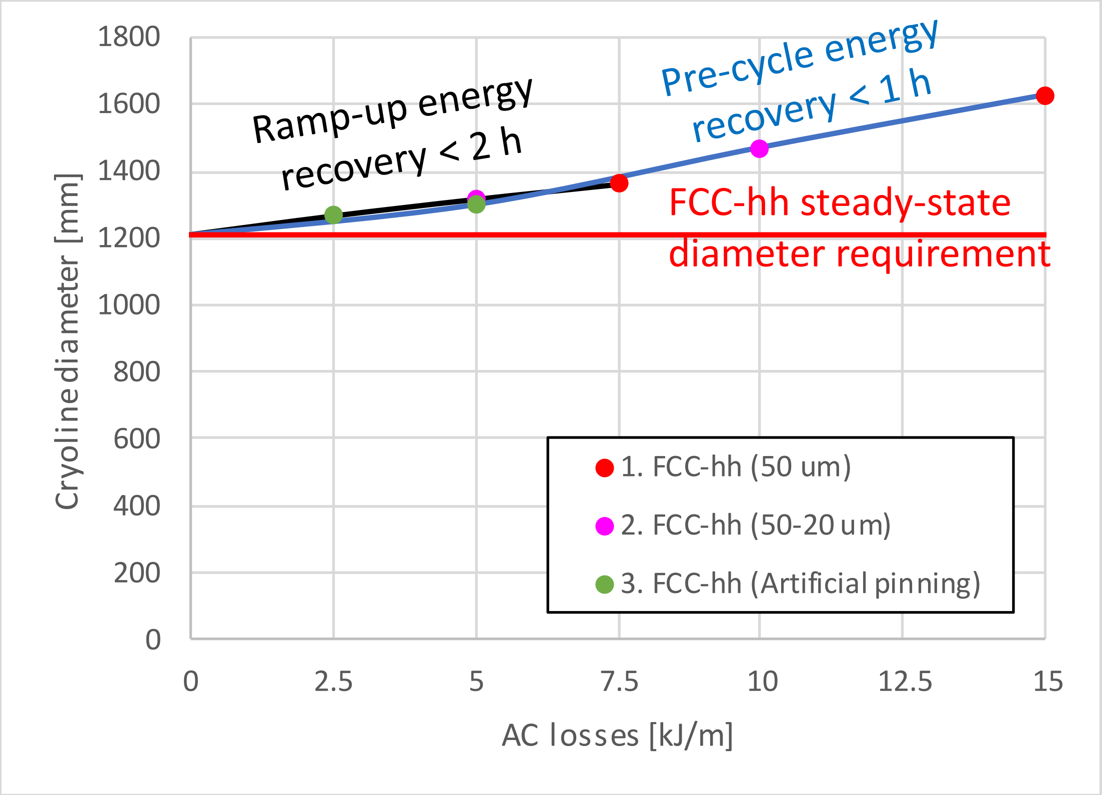
- Requirement 4 is the design case
- Additional 1.8 K cooling capacity:

Case	Requirement 3	Requirement 4
Case 1	+ 75 %	+ 230 %
Case 2	+ 50 %	+ 140 %
Case 3	+ 25 %	+ 40 %

AC-losses: Impact on cryogenic distribution

- Increase of cold-mass helium inventory will impact the size of the cold quench buffer (Line D)
- Increase of the 1.8 K cooling capacity will impact the diameter of the pumping line (Line B)

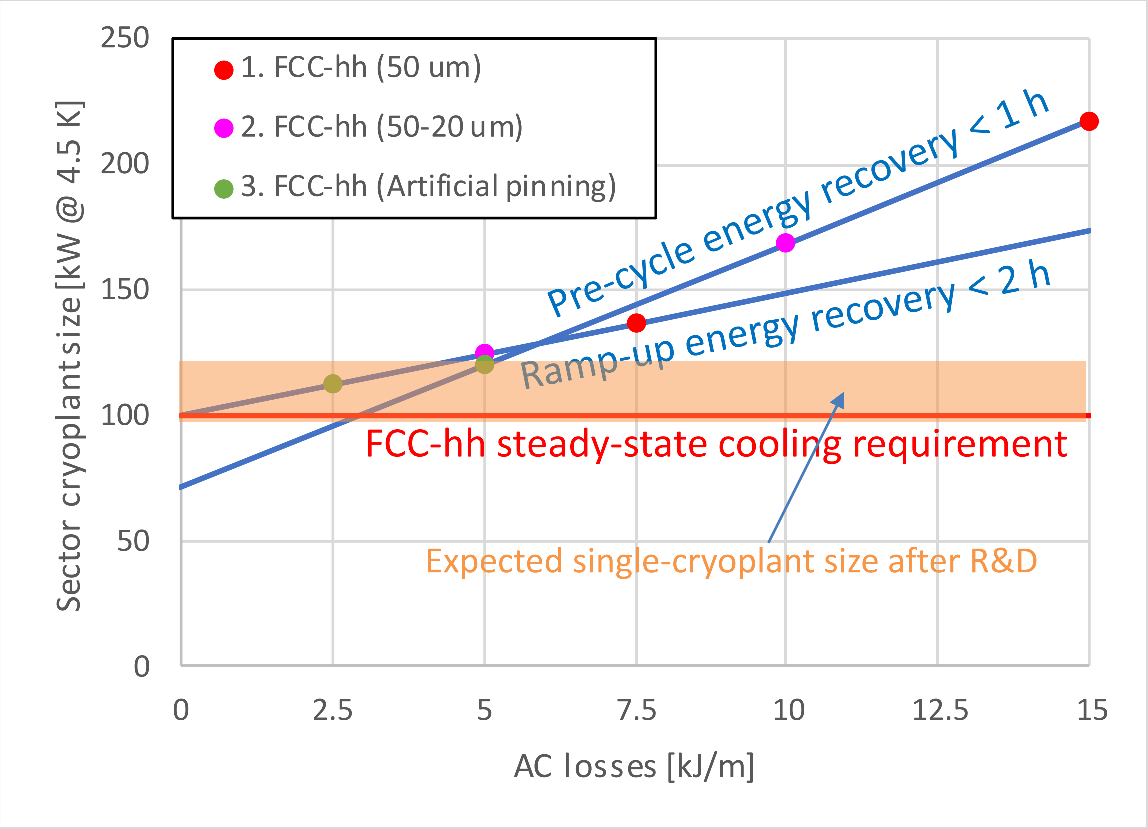
→ i.e. an increase of the diameter of the cryogenic distribution line

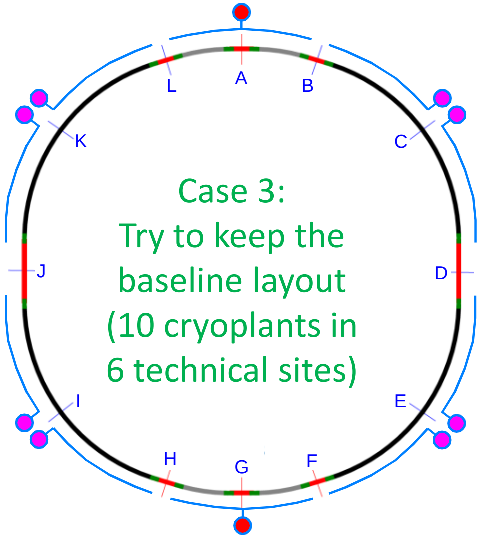


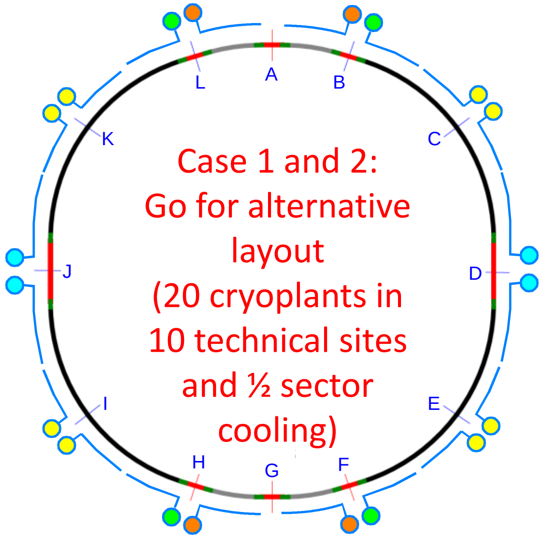
For Case 1 and 2 the cryoline is becoming larger than the magnet cryostats
→ first signs of a design showstopper
→ 10-km sector cooling has to be questioned

AC-losses: Impact on sector cryoplant size and cryogenic layout

- Increase of 1.8 K cooling capacity will impact the sector cryo-plant size and the cryogenic layout.







…but:
- Point J and D with extended LSS (~2 km)
- Point F with a very deep shaft (~600 m)
- Point B in a difficult urban area

AC-losses: Conclusion and baseline input

- Main project decisions:
→ The Case 3 (SC conductor with artificial pinning) is taken as the baseline input for cryogenics.
→ Maximum recovery time of 2 hours after a magnet ramp-up is endorsed.
→ Maximum recovery time after a pre-cycle is not required (could be longer than 1 h).

- Main consequences:
→ No impact on the helium inventory requirement (remain at 33 l/m)
→ Increase of the sector cooling capacity at 1.8 K from 12 kW at 15 kW (+25 %). This 3 kW extra-capacity is also an operational margin for steady-state operation.
→ Recovery time after a pre-cycle will be 1.2 h
→ The VLP pumping line diameter will increase from 630 to 690 mm; the corresponding vacuum jacket of cryogenic distribution line diameter will increase from 1200 to 1300 mm, i.e.:
- 1400 mm at the position of local flanges and bellows
- 1550 mm at the position of service modules (valves, heat exchanger and jumper connection)
→ The unit cryogenic plant size will increase from 100 to 110 kW @ 4.5 K, still compatible with a single-plant per 10-km long sector.
→ The cryogenic layout baseline remains with 10 cryogenic plants in 6 technical sites (PA, PC, PE, PG, PI & PK).

Operational margins

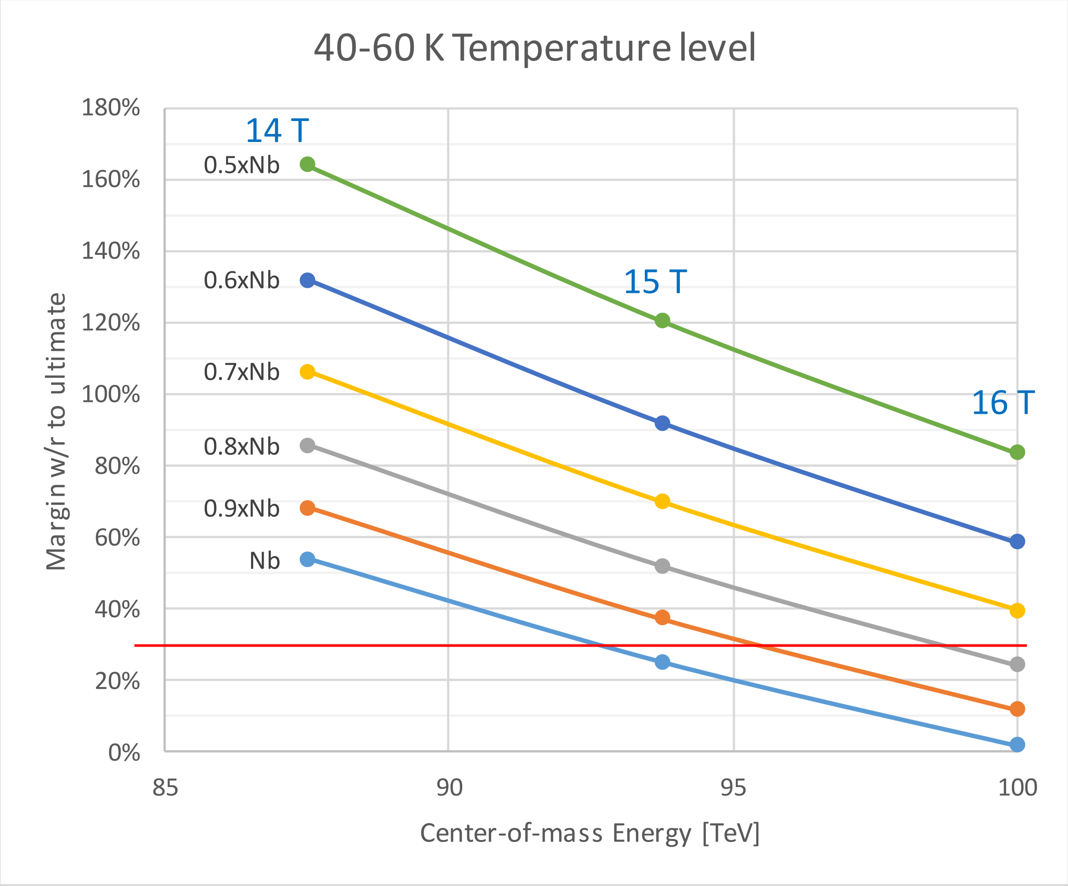
- Main project decisions:
  - The FCC-hh beam energy (100 TeV c.m.) and bunch current (1E11 ppb) has to be considered as ultimate conditions, i.e. they could be reached without operational margins.
- However, a cryogenic system requires a minimum operational margin of 1.3 to guarantee its availability.
  → What are the beam parameters which give an operational margin of 1.3 with respect to the ultimate conditions?

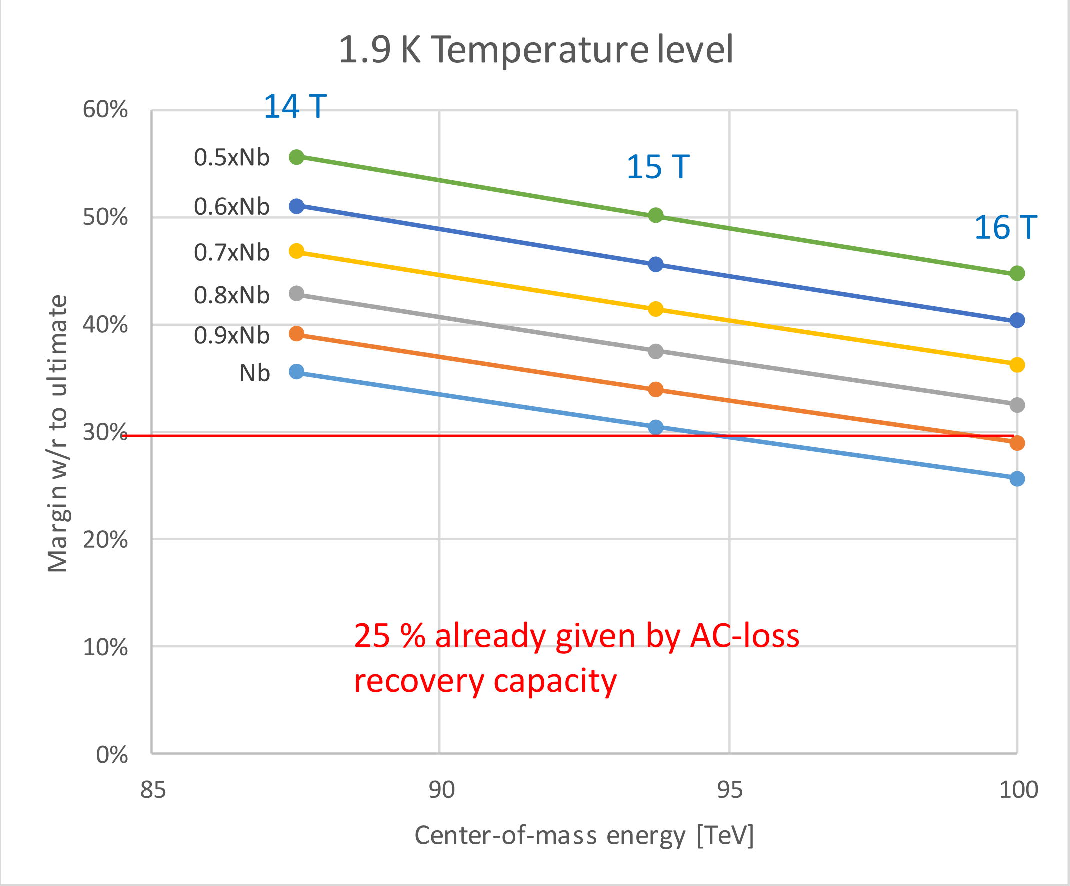
Scaling laws

- Scaling laws for beam induced heating:

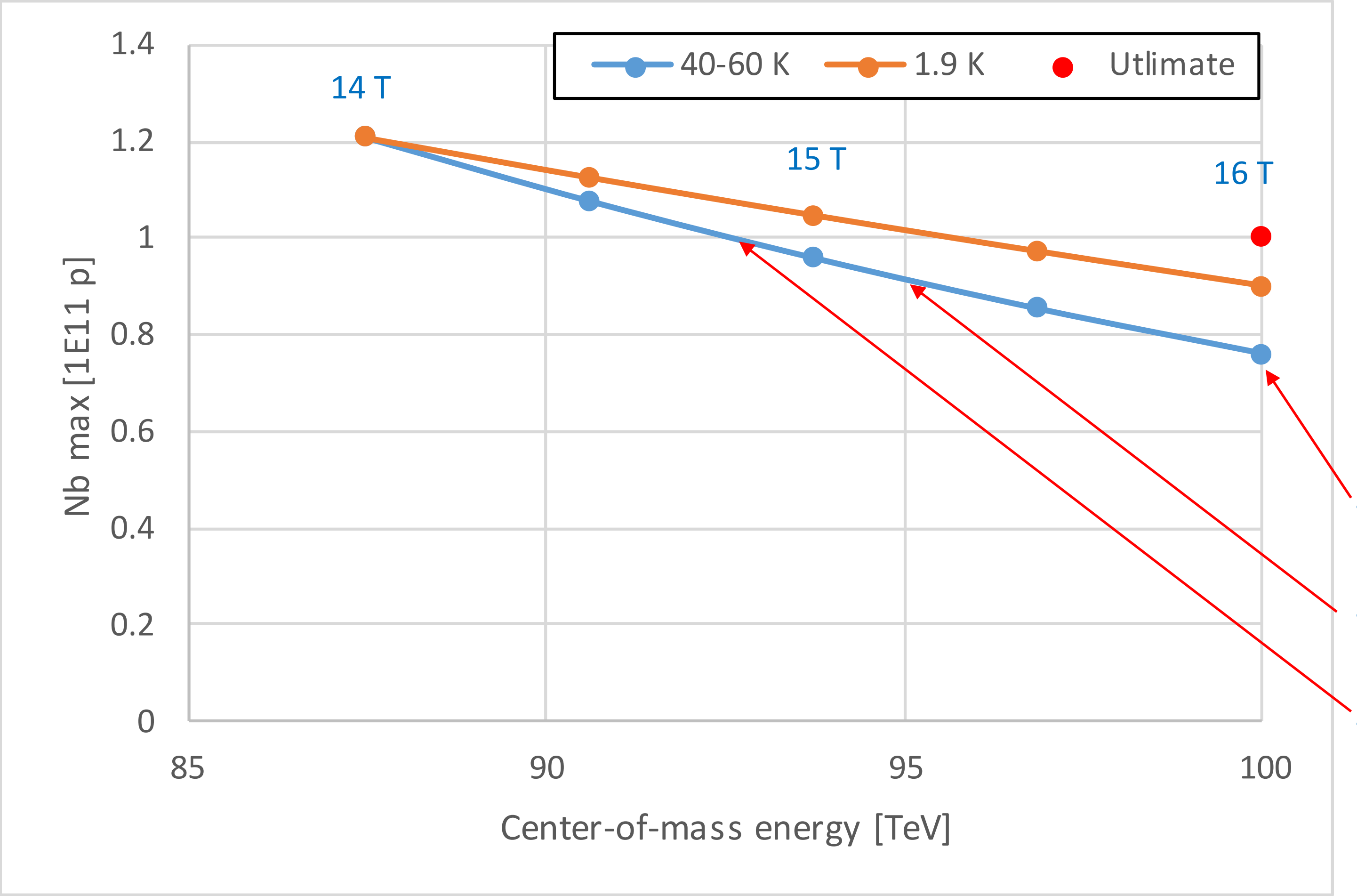
Beam parameter	Energy E	Bunch population N_b	Bunch number n_b	Temperature level
Resistive heating	E^2	-	-	@ 1.9 K
Synchrotron radiation	E^4	N_b	n_b	@ 40-60 K
Image current	-	N_b^2	n_b	@ 40-60 K
Beam gas scattering	E	N_b	n_b	@ 1.9 K

Operational margins vs beam energy and bunch population





Operational margins: Beam parameters giving an operational margin of 1.3



Operational margin of 1.3 obtained :

- For ultimate beam energy (100 TeV) by reducing the bunch population by 25 %
- For a beam energy of 95 TeV (- 5 %) and a bunch population of 0.9Nb (-10 %).
- For ultimate bunch population by reducing the beam energy by 7.5 %

Conclusion

- AC-losses:
  - AC-losses during magnet current transient are strongly impacting the cryogenic system design.
  - Impacts are limited by the introduction of new concepts in Nb3Sn conductor (artificial pinning), which are now part of the baseline for cryogenic design.
  - The remaining impacts are:
    - the increase of the 1.8 K capacity by 25 % (from 12 to 15 kW per sector)
    - The increase of the pumping line diameter and of the cryogenic distribution line (from 1200 to 1300 mm).
- Operational margins:
  - Present design beam parameter has to be considered as ultimate conditions (without margin)
  - However, a minimum operation margin factor of 1.3 is required to guarantee the cryogenic system availability.
    - A factor 1.25 already is existing at 1.8 K (thanks to AC-losses)
    - With the proposed installed capacity, the cryogenic system can guarantee the following “Nominal Conditions”:
      - 100 Tev & 0.75E11 ppb
      - 95 TeV & 0.9E11 ppb
      - 92.5 TeV & 1E11 ppb

Thank you!