Beam screen cooling: scaling from LHC to FHC

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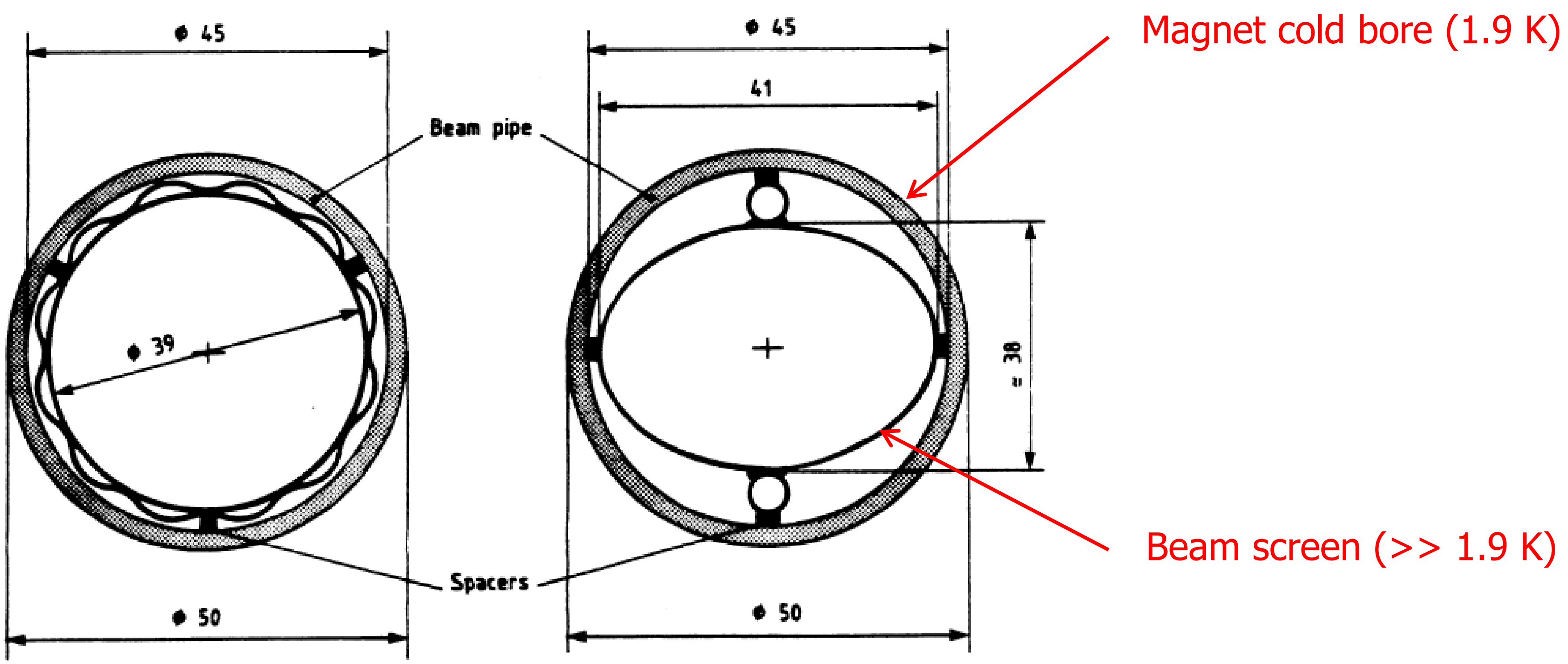
FHC meeting on beam pipe design, CERN
20 December 2013

The beam screen concept



G. Claudet, F. Disdier, Ph. Lebrun, M. Morpurgo, P. Weymuth, Preliminary Study of a superfluid helium cryogenic system for the Large Hadron Collider, LHC Note 26 (1985)

Rationale for beam screen temperature
1) Thermodynamics

- Exergy load ΔE = measure of (ideal) refrigeration duty

$$\Delta E = \Delta E_{cm} + \Delta E_{bs}$$

$$\Delta E = Q_{cm} \,.\, (T_a/T_{cm} - 1) + (Q_{bs} - Q_{cm}) \,.\, (T_a/T_{bs} - 1)$$

- With Q_{bs} = heat load to beam screen

  T_{bs} = beam screen (average) temperature

  Q_{cm} = residual heat load to cold mass

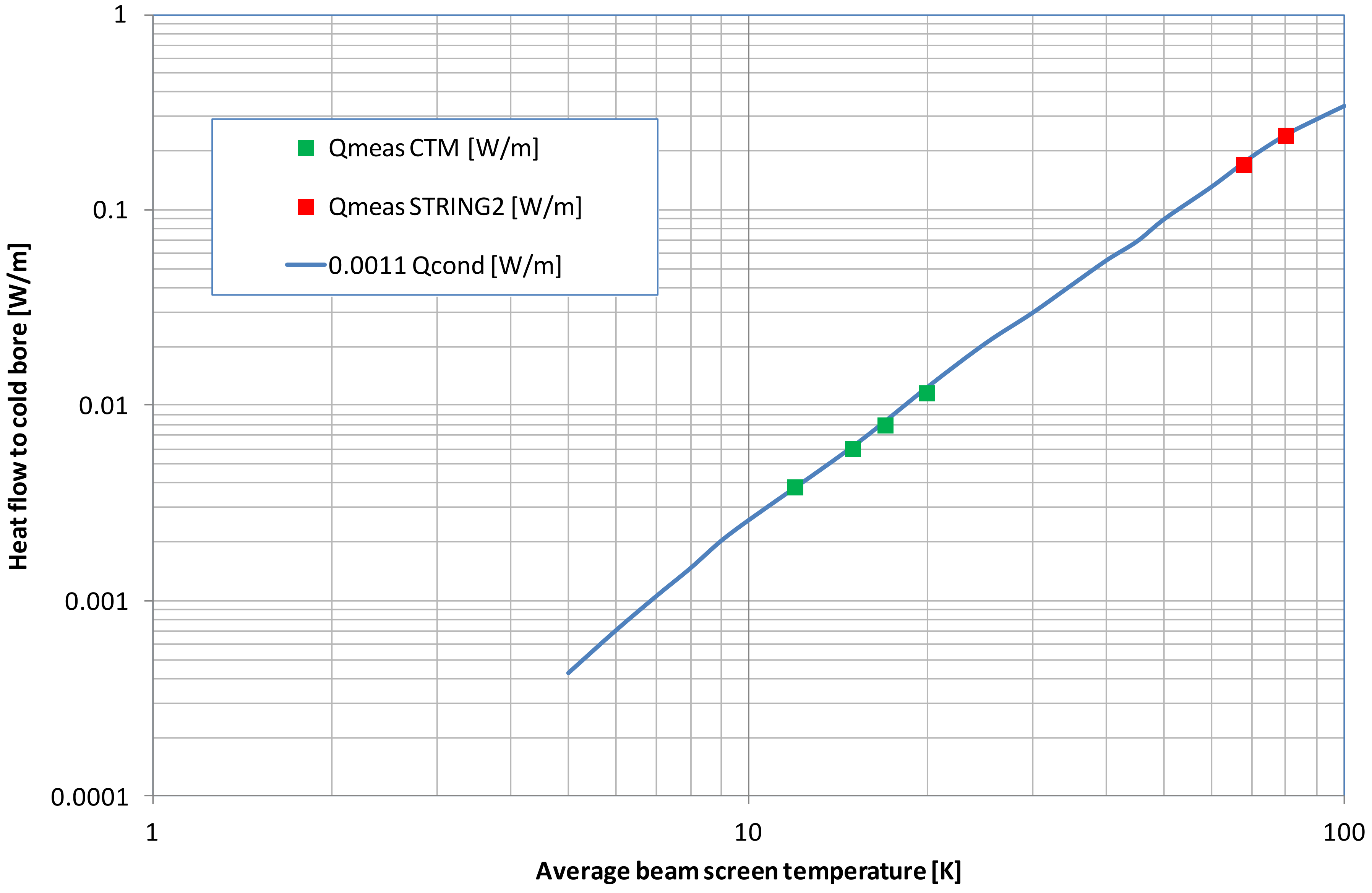
  T_{cm} = cold mass temperature (1.9 K for LHC)

  T_a = ambient temperature (290 K)

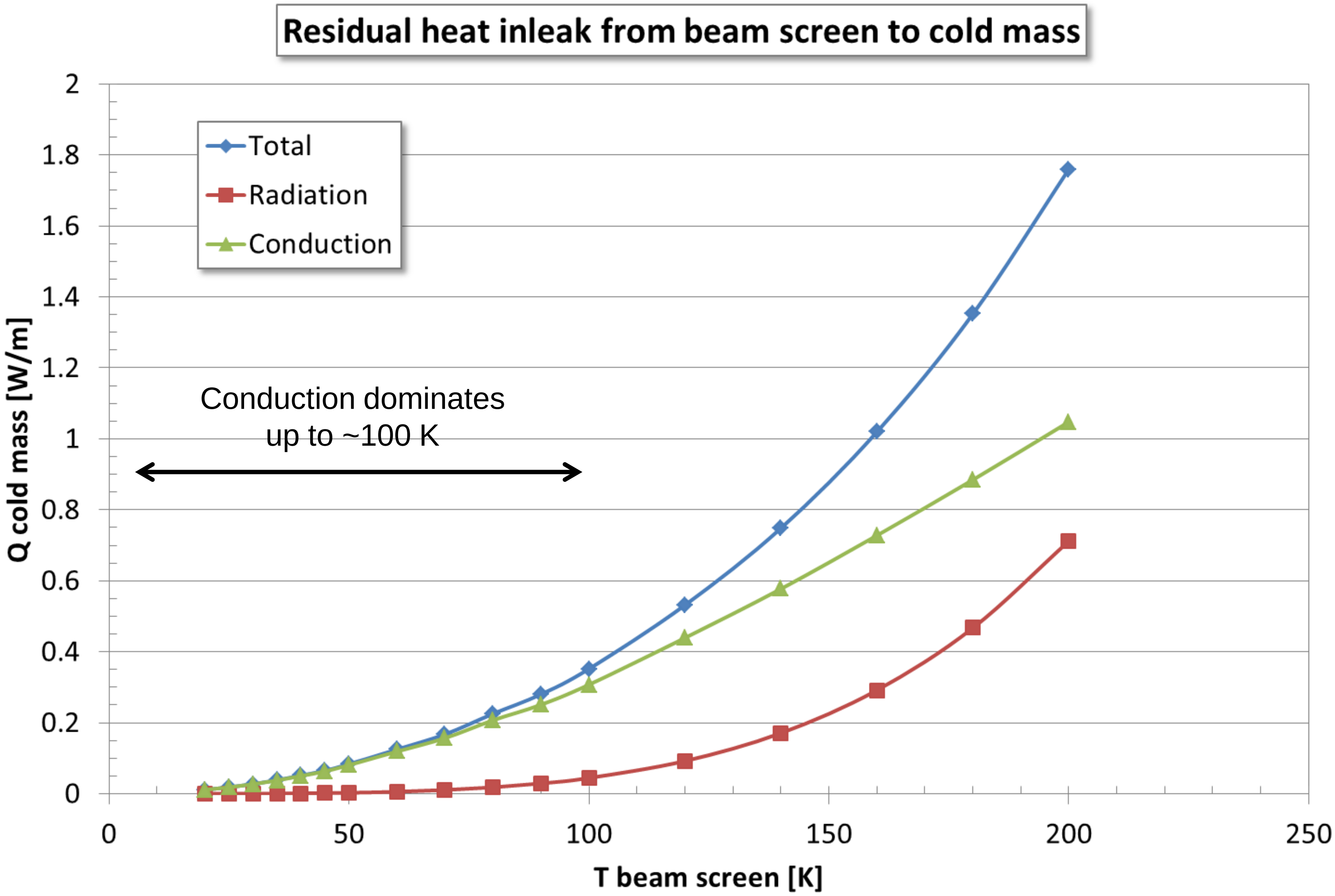
- Minimize total exergy load

- Estimate $Q_{cm} = f\,(T_{bs})$
  - Calculation: radiation + conduction along supports with contact resistance
  - Measurements on full-scale thermal models

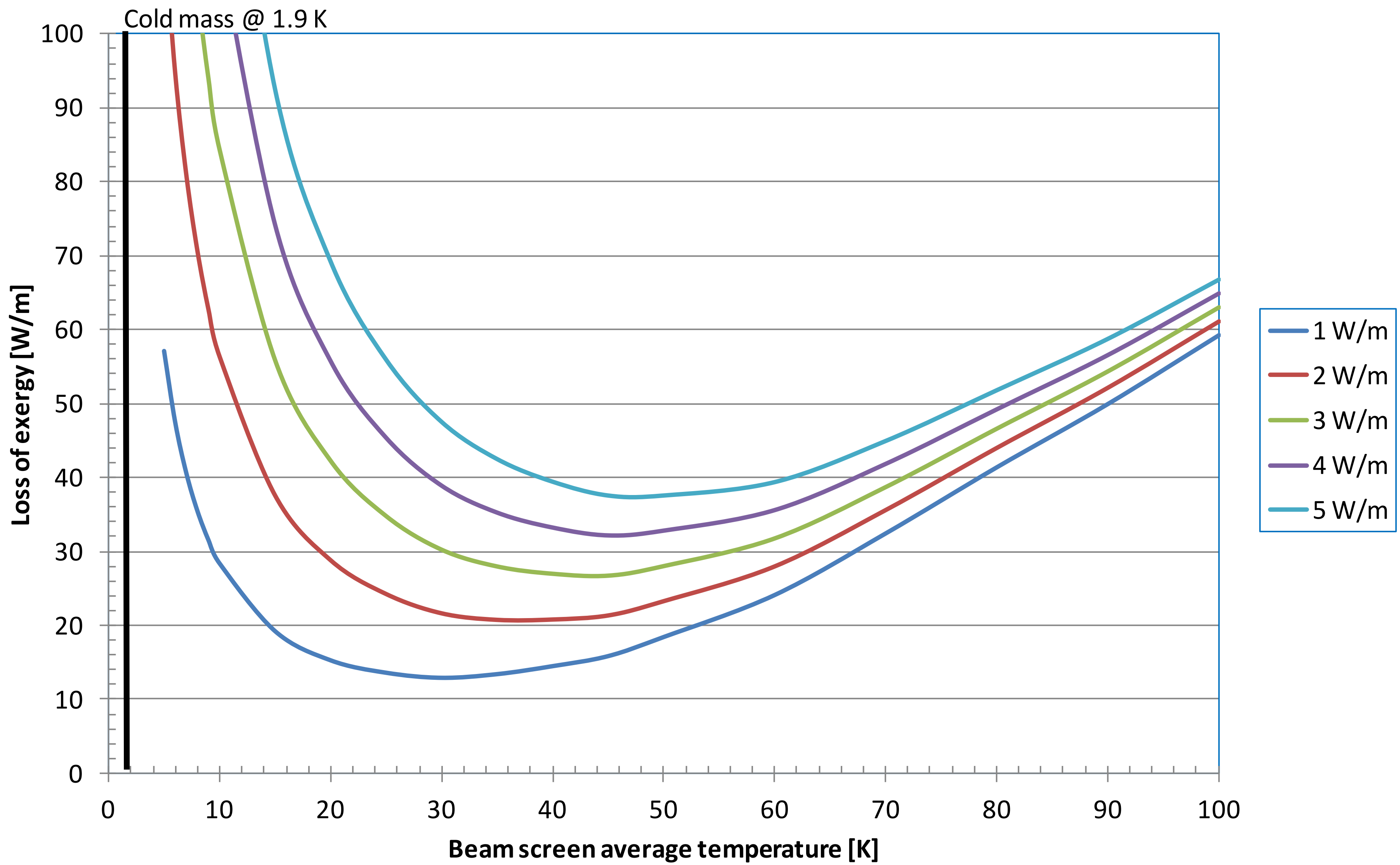
Measured residual heat load from beam screen to cold mass



Residual heat load model from beam screen to cold mass



Total exergy loss vs beam screen temperature
Parameter: beam screen heat load



LHC beam vacuum requirements

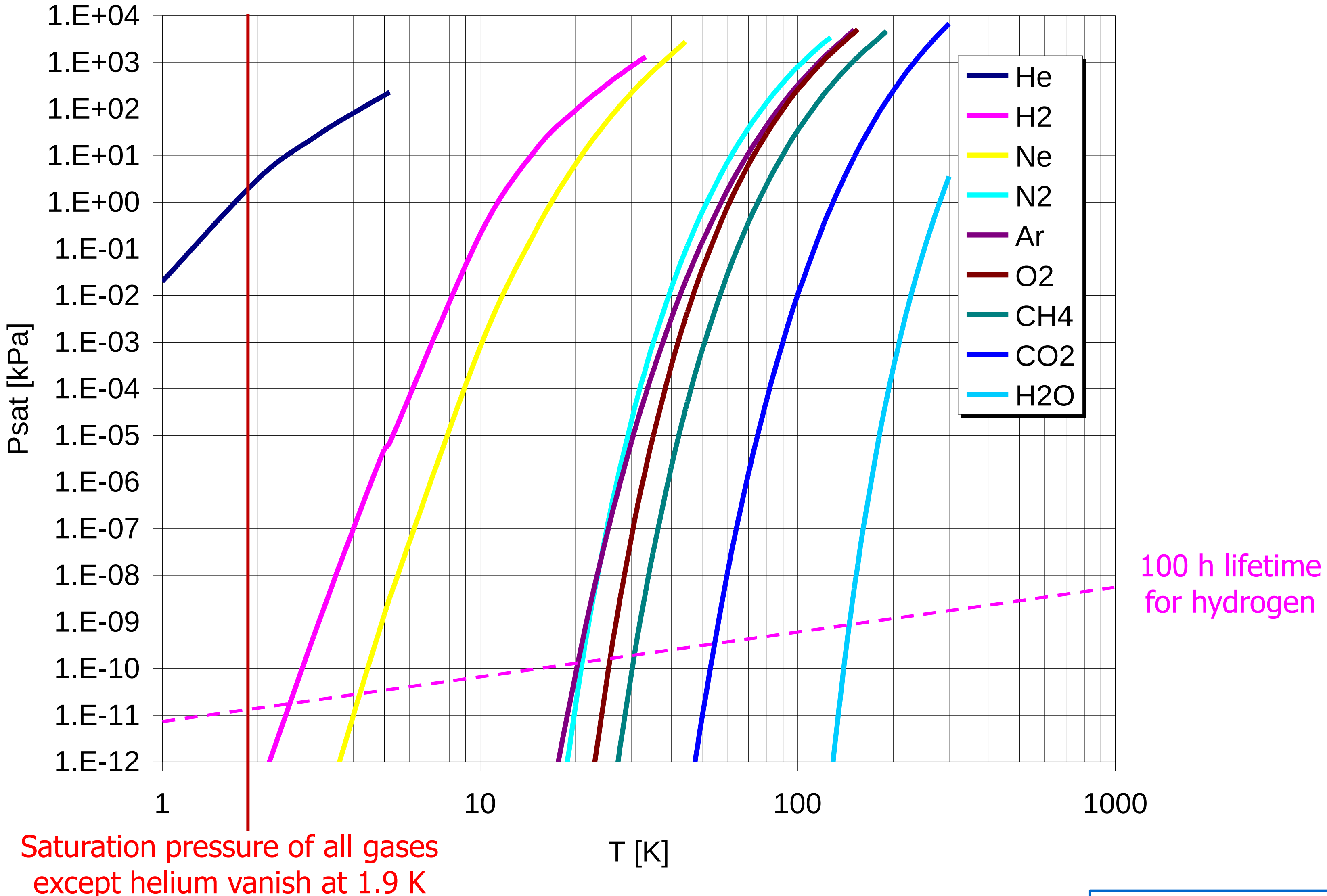
- Beam vacuum lifetime dominated by nuclear scattering of protons on residual gas
- Beam vacuum lifetime of ~100 h required to
  - Limit decay of beam intensity
  - Reduce energy deposited by scattered protons to ~ 30 mW/m

$\Rightarrow$ residual gas density in the 10^{14} m^{-3} range

$\Rightarrow$ residual pressure in the 10^{-9} to 10^{-8} Pa range

- Cryopumping on cold bore at 1.9 K meets these requirements
- This would be sufficient in absence of beam-induced desorption

Cryopumping of beam vacuum at 1.9 K



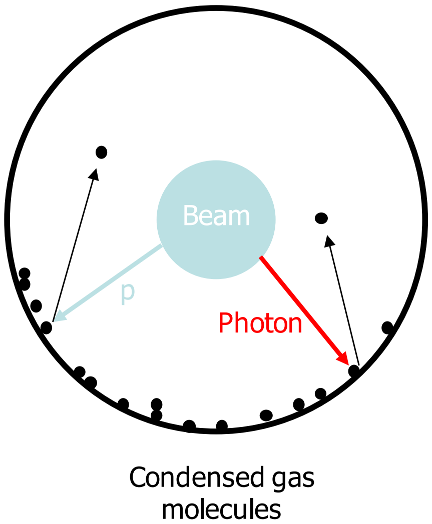
M. Jimenez

Rationale for beam screen temperature
2) Dynamic vacuum

- Beam-induced desorption of cryopumped gas molecules degrades vacuum

⇒ beam screen shelters 1.9 K cryopumping surface from proton/ion/photon induced desorption

⇒ pumping holes for desorbed molecules (4%)



- Avoid beam screen temperatures where vapor pressure of condensed species (H_2, H_2O, CH_4, CO, CO_2) are in the 10^{-7} to 10^{-4} Pa range: insufficient pumping speed to the cold bore at 1.9 K

⇒ allowed ranges 5 – 20 K, 40 – 60 K, 100 – 120 K, > 190 K

V. Baglin

Rationale for beam screen temperature
3) Transverse wall impedance

- Beam stability requires low transverse impedance
- Transverse impedance

  $Z_T(\omega) \sim \rho R / \omega b^3$

  ρ wall electrical resistivity

  R average machine radius

  b half-aperture of beam pipe
- Transverse resistive-wall instability
  - dominant in large machines with small aperture
  - must be compensated by beam feedback, provided growth of instability is slow enough (~ 100 turns)
  - maximize growth time $\tau \sim 1/Z_T(\omega)$ i.e. reduce $Z_T(\omega)$

  ⇒ for a large machine with small aperture, low transverse impedance is achieved through low ρ, i.e. low-temperature wall coated with >50 μm copper (typically < 50 K for RRR=100)

Heat loads to beam screen
1) Synchrotron radiation from bending magnets

- Charged particle beams bent in a magnetic field undergo centripetal acceleration and emit electromagnetic radiation
- When beams are relativistic, radiation is emitted in a narrow cone
- Median of spectrum $E_c \sim \gamma^3/R$
- Power radiated per m $P_{syn} \sim \gamma^4/R^2$

with γ = relativistic factor of beam, R = radius of curvature

parameter	450 GeV	7 TeV	
total power / beam	0.066 W	3886 W	0.17 W/m per aperture
energy loss per turn	0.11 eV	6.7 keV	
average photon flux per metre and second	0.4×10^{16}	6.8×10^{16}	
photon critical energy	0.01 eV	43.13 eV	UV, easy to screen
longit. emittance damping time	5.5 yr	12.9 h	
transv. emittance damping time	11 yr	26 h	

Heat loads to beam screen
2) Beam image currents in the resistive wall

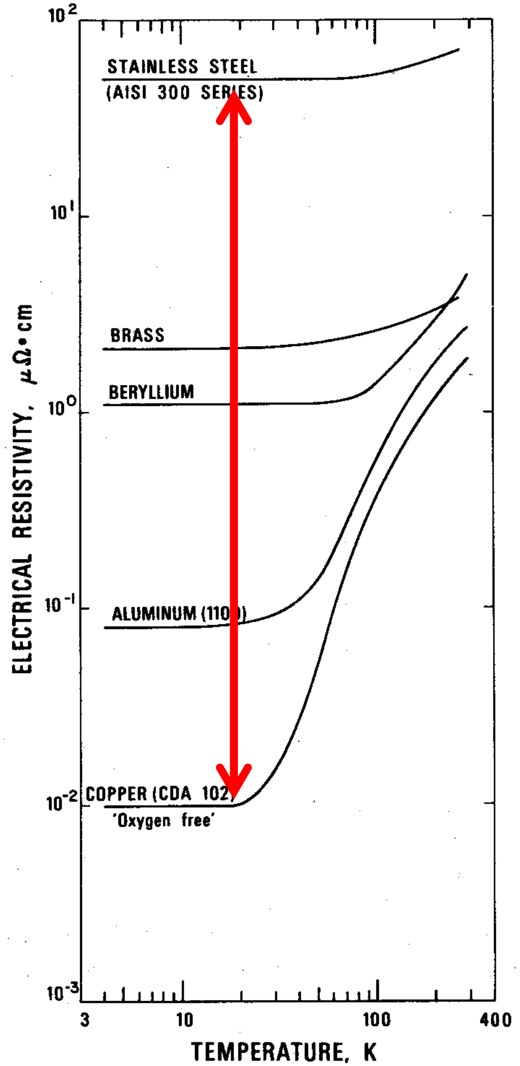
- Beam of charged particles = electrical current
- « Image currents » are induced in the (resistive) wall of the vacuum chamber, producing ohmic dissipation
- Power per m $P_{rw} \sim N^2 \rho^{1/2}$

with N = particle bunch charge

ρ = electrical resistivity of wall

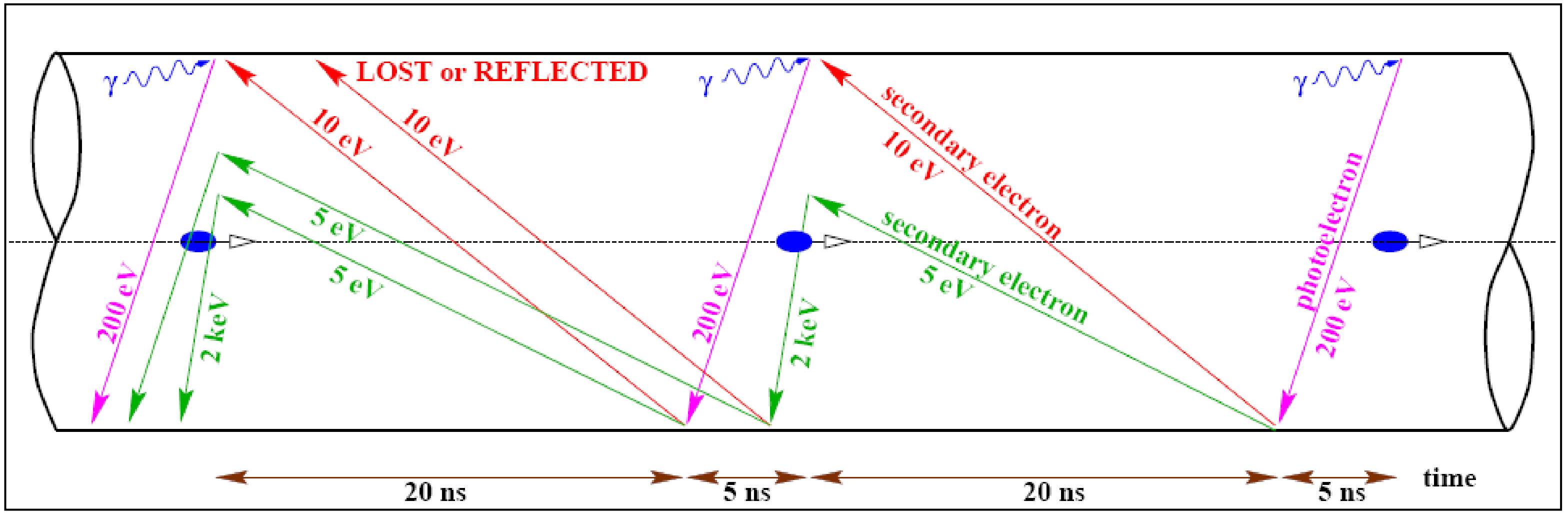
- Low-resistivity
  - Copper vs stainless steel
  - Low temperature
  - Magneto-resistance
  - Eddy currents at magnet resistive transition

=> 75 μm Cu (RRR = 100) on 1 mm austenitic steel

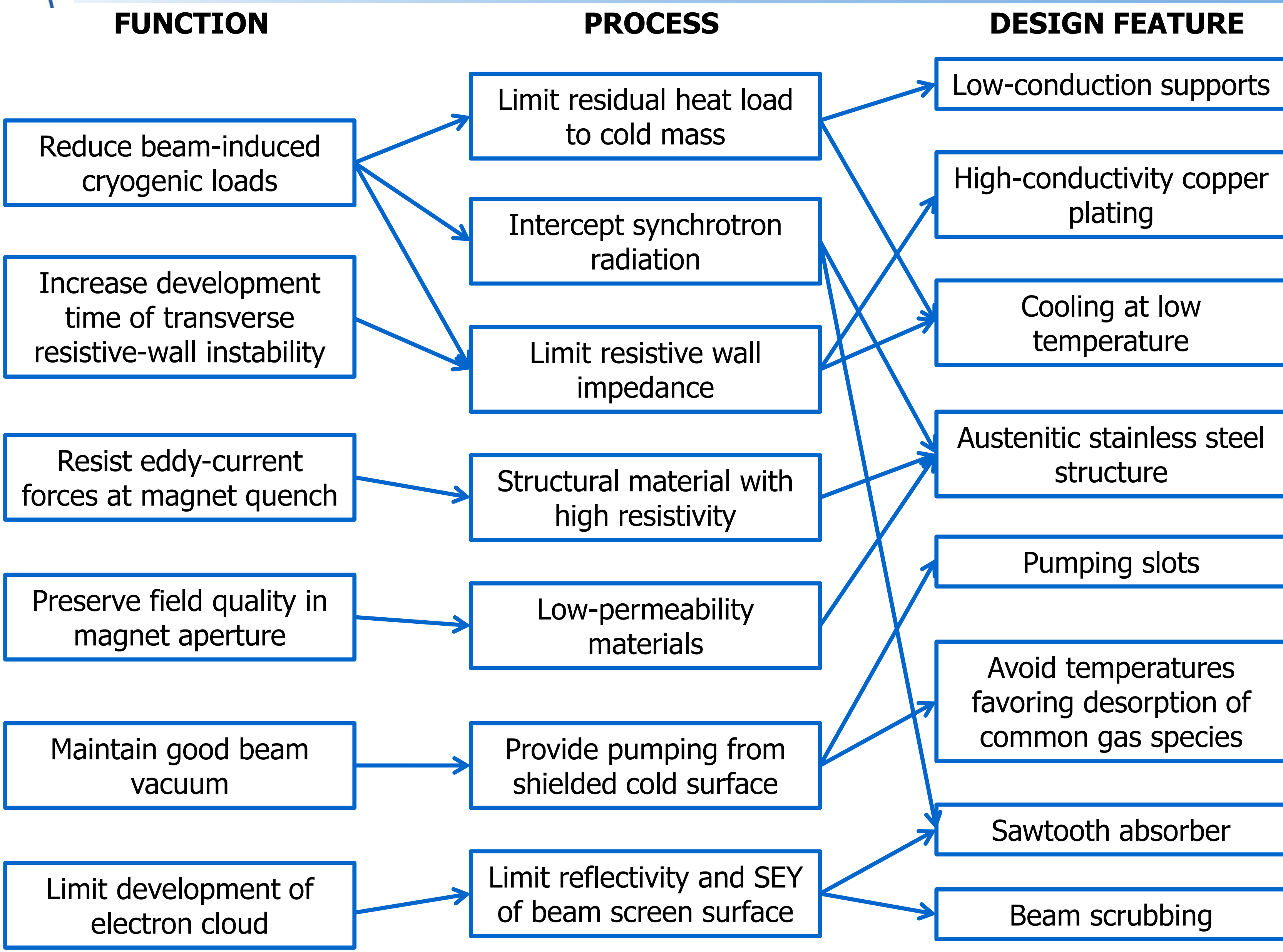


Heat loads to beam screen
3) Electron cloud

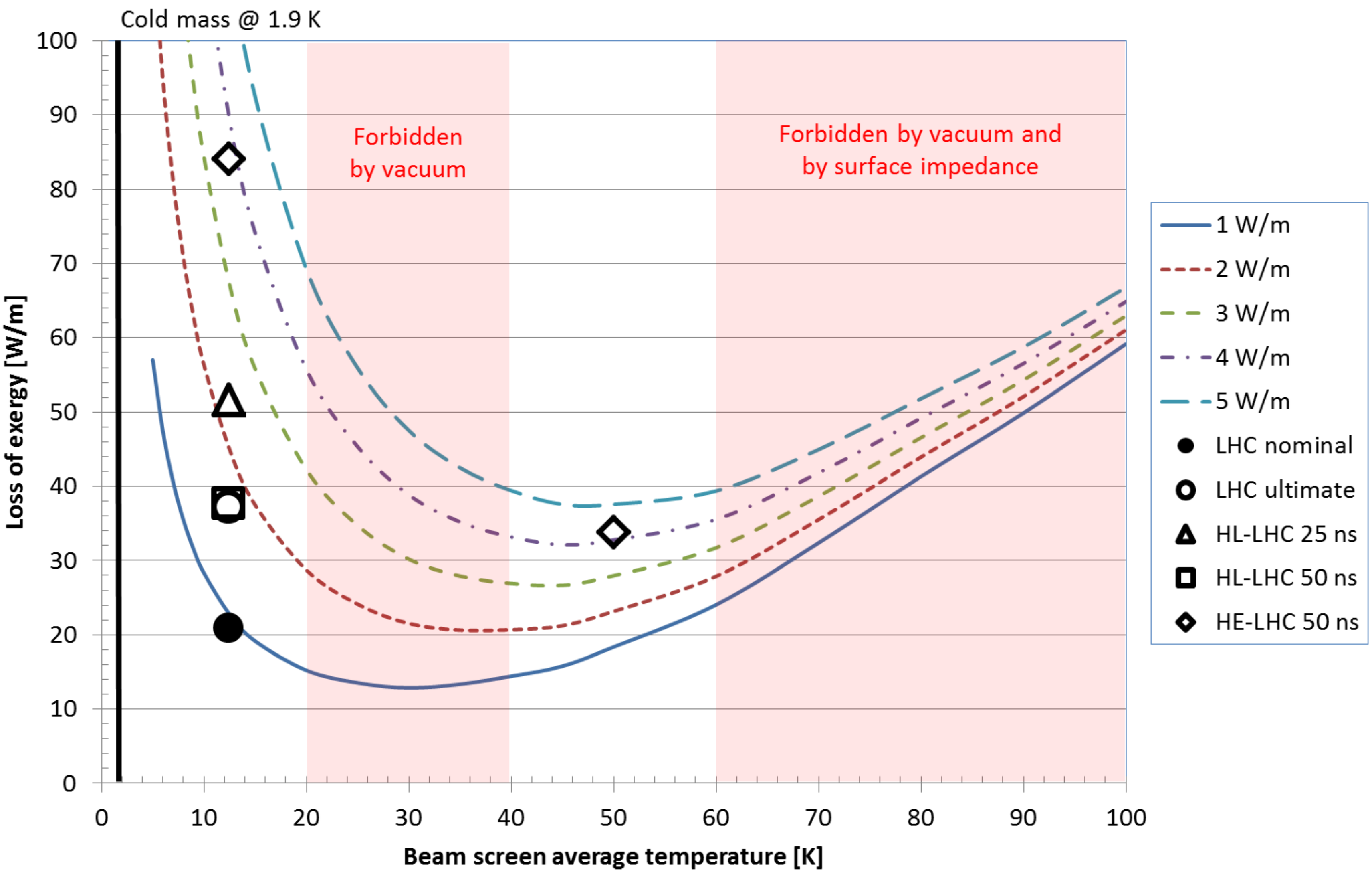
- Photo-electrons extracted from the wall by synchrotron radiation, can be resonantly accelerated by the successive particle bunches => multipacting => buildup of electron cloud
- Energy deposition by electons hitting the wall
- Intensity of electron cloud governed by
  - photon irradiation of the wall ⇒ low reflectivity surface
  - bunch repetition rate ⇒ increase bunch spacing
  - secondary electron yield ⇒ low-SEY surface and beam "scrubbing"



Functional design map of beam screen



Design space for LHC beam screen
Parameter: beam screen heat load



Beam screen heat loads
[W/m per aperture]

Case	Temperature	Synchrotron radiation	Image currents	Electron cloud	Total
LHC nominal	5 – 20 K	0.17	0.18	0.45	0.79
LHC ultimate	5 – 20 K	0.24	0.39	0.79	1.40
HL-LHC 25 ns	5 – 20 K	0.32	0.66	1.00	2.00
HL-LHC 50 ns	5 – 20 K	0.25	0.83	0.36	1.40
HE-LHC 50 ns	5 – 20 K	2.90	0.22	0.12	3.20
HE-LHC 50 ns	40 – 60 K	2.90	1.20	0.12	4.20

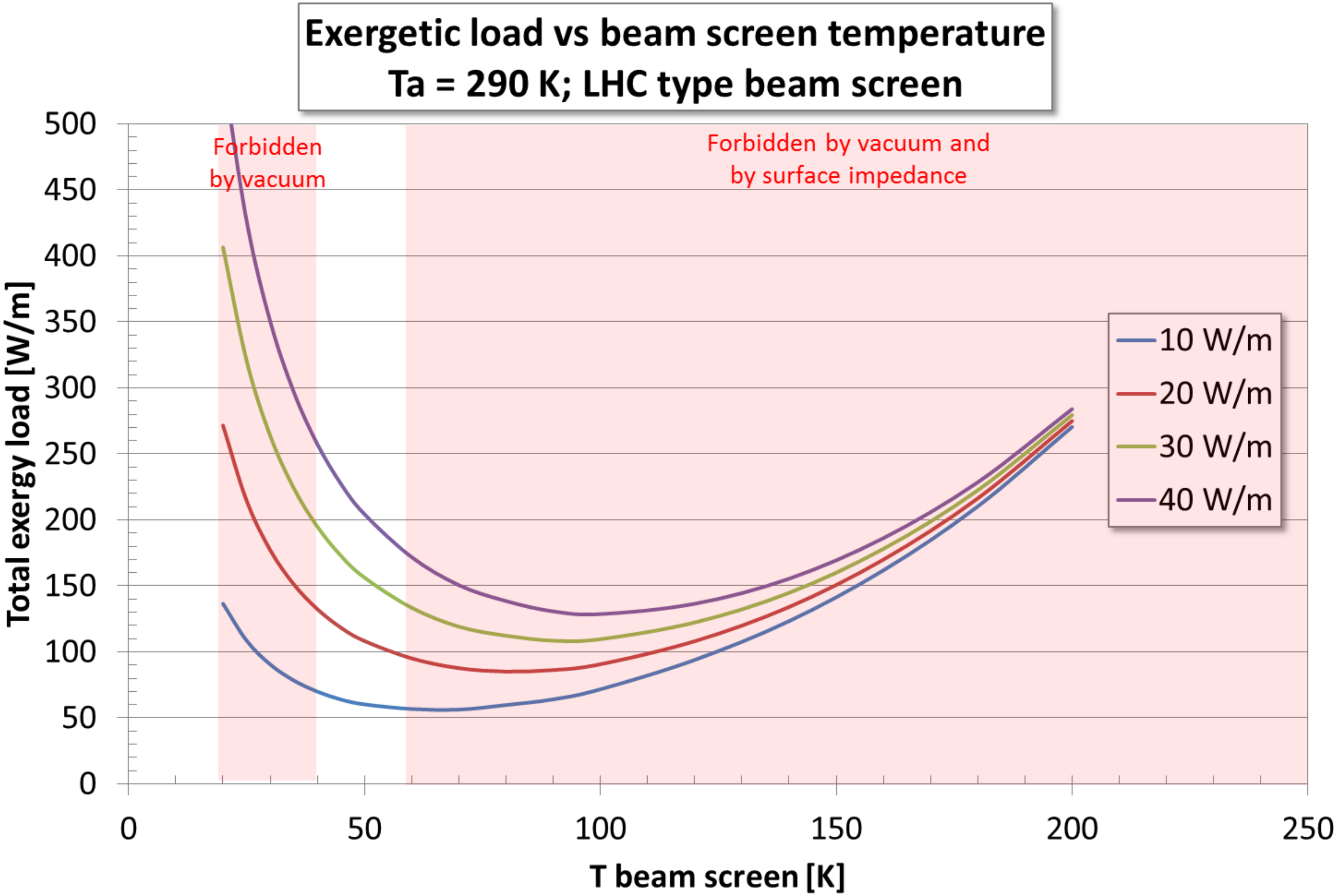
HL-LHC: high-luminosity upgrade (14 TeV center-of mass energy, ~10^{35} $cm^{-2}.s^{-1}$ luminosity)
HE-LHC: high-energy upgrade (33 TeV center-of-mass energy, ~2.10^{34} $cm^{-2}.s^{-1}$ luminosity)
25 ns and 50 ns refer to spacing of particle bunches

V. Baglin, Ph. Lebrun, L. Tavian, R. van Weelderen, Cryogenic beam screens for high-energy particle accelerators, Proc. ICEC24 Fukuoka, Cryogenics and Superconductivity Society of Japan (2013) 629-634

Compared parameters of hadron colliders

	LHC	HE-LHC	FHC
C.M. energy [TeV]	14	33	100
Circumference [km]	26.7	26.7	80 (100)
Dipole field [T]	8.33	20	20 (15)
Inner coil diameter [mm]	56	40	40
Injection energy [TeV]	0.45	>1	3
Beam current [A]	0.58	0.48	0.49
Beam stored energy [MJ]	362	701	6610 (8364)
SR power per ring [kW]	3.6	96.2	2900 (2130)
Arc SR heat load per aperture [W/m]	0.17	4.35	43.3 (25.7)
Events per crossing (at 25 ns spacing)	27	147	171
Luminosity [E+34 cm-2.s-1]	1.0	5.0	5.0
Beam luminosity lifetime [h]	45	5.7	14.8 (18.6)

LHC-type beam screen for FHC
Assumption T_{cm} = 1.9 K



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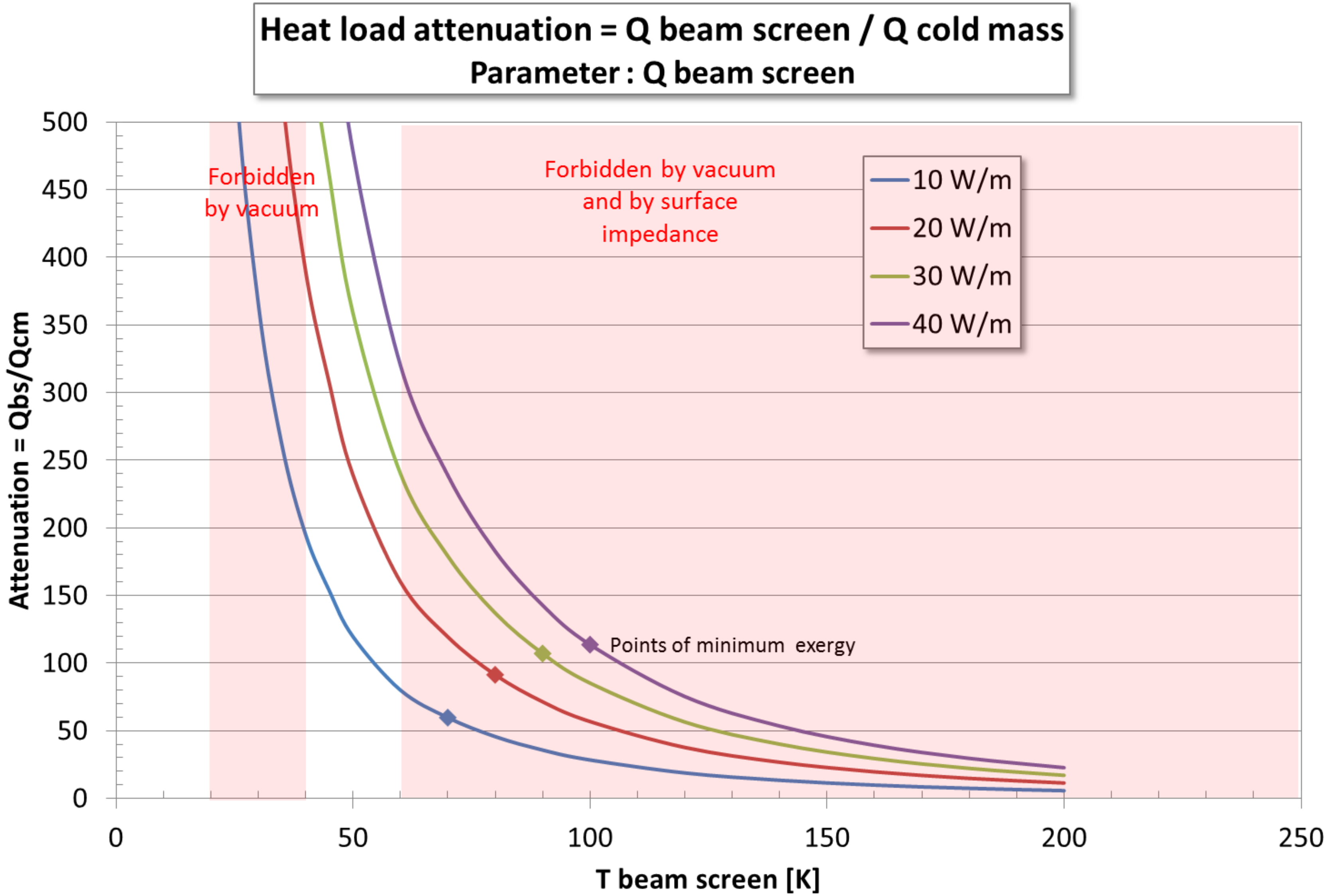


From exergy to power consumption

- Real electrical power to refrigerator P_{ref}

  $P_{ref} = \Delta E / \eta(T)$

  with $\eta(T)$ = efficiency w.r. to Carnot = COP_{Carnot}/COP_{Real}

  $$P_{ref} = Q_{cm} \cdot (T_a/T_{cm} - 1)/\eta(T_{cm}) + (Q_{bs} - Q_{cm}) \cdot (T_a/T_{bs} - 1)/\eta(T_{bs})$$

- With Q_{bs} = heat load to beam screen

  T_{bs} = beam screen (average) temperature

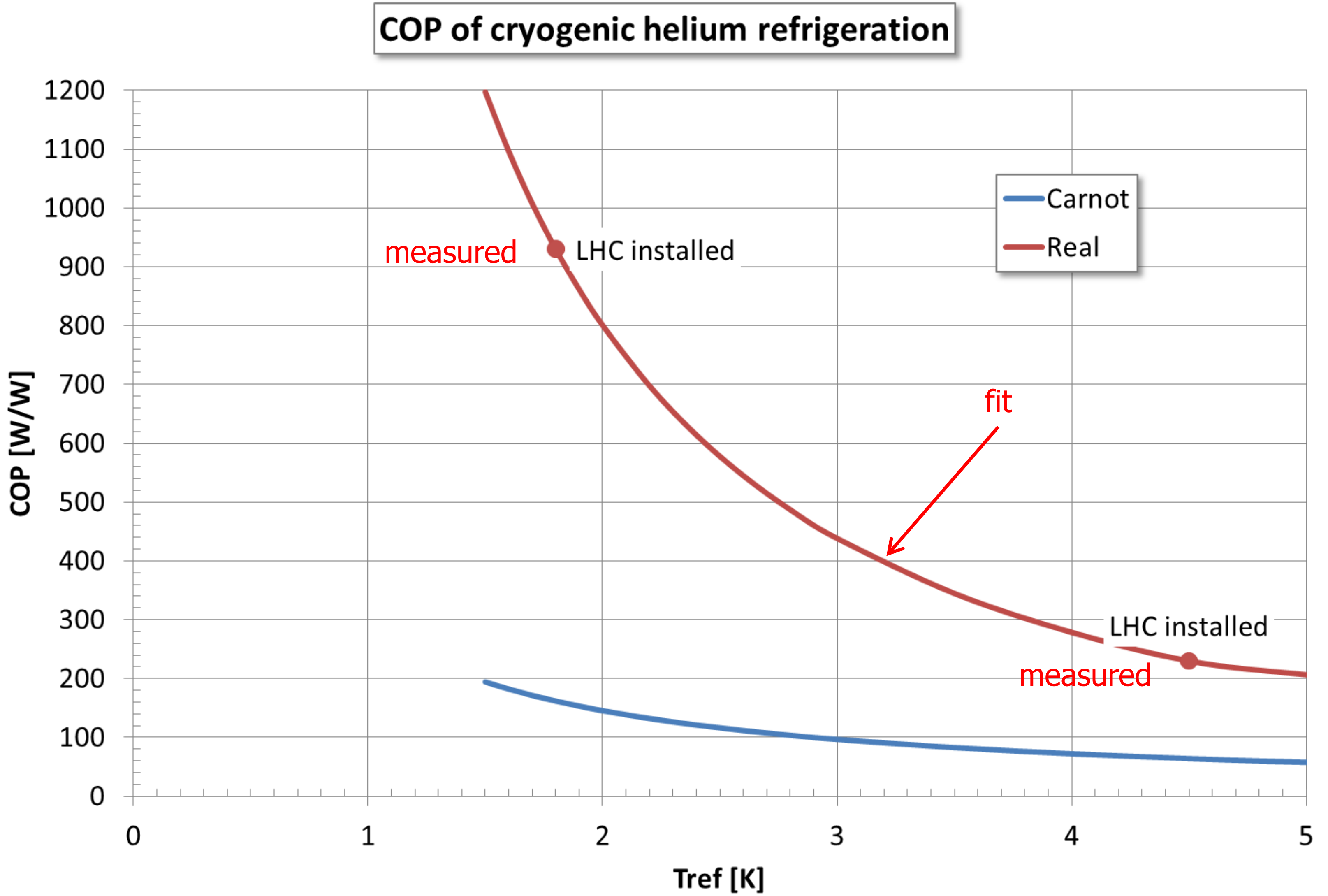
  Q_{cm} = residual heat load to cold mass

  T_{cm} = cold mass temperature (1.9 K for LHC)

  T_a = ambient temperature (290 K)

- Minimize total electrical power to refrigerator

$\eta(T) = COP_{Carnot}/COP_{Real}$



LHC-type beam screen for FHC

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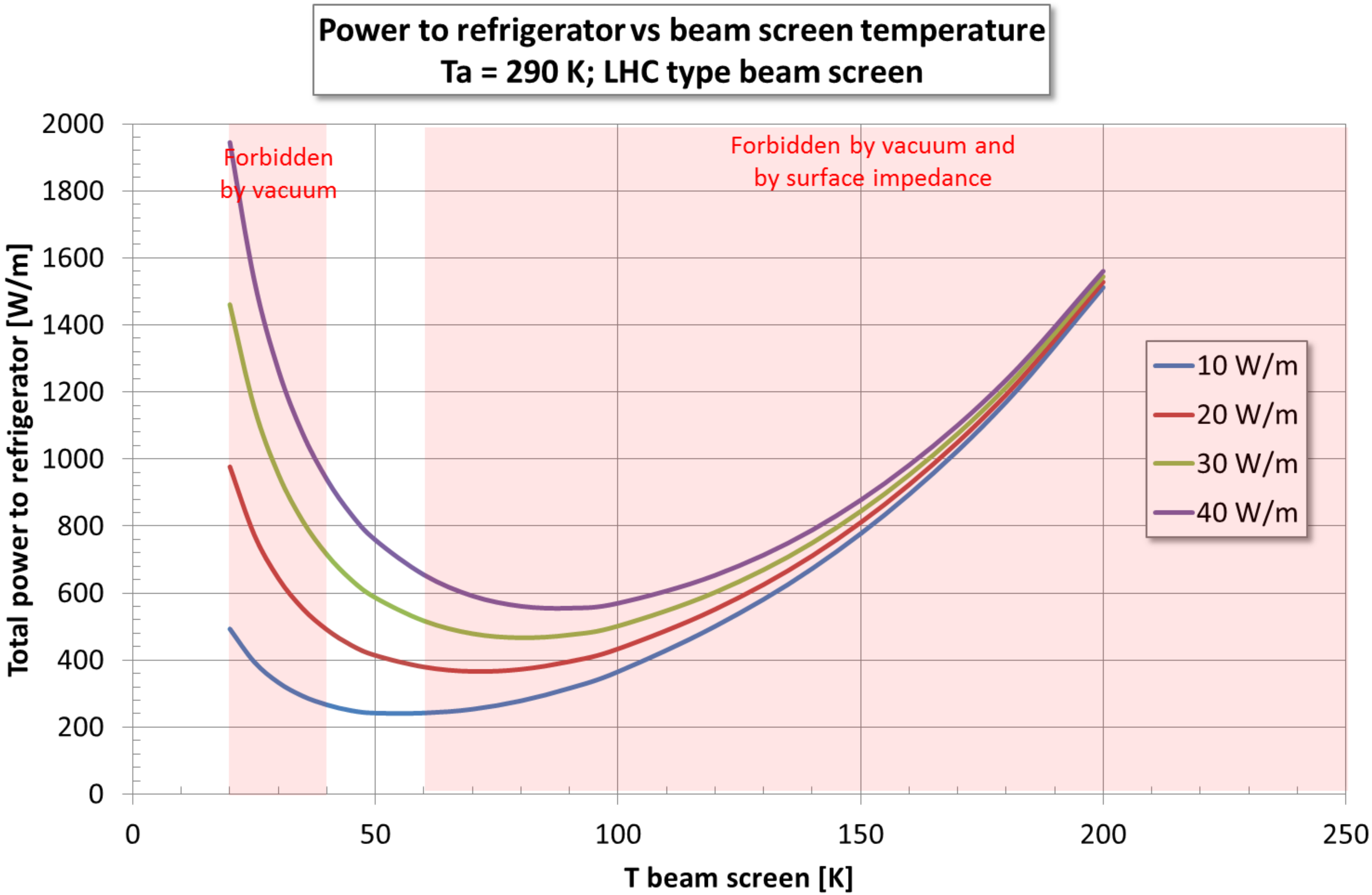
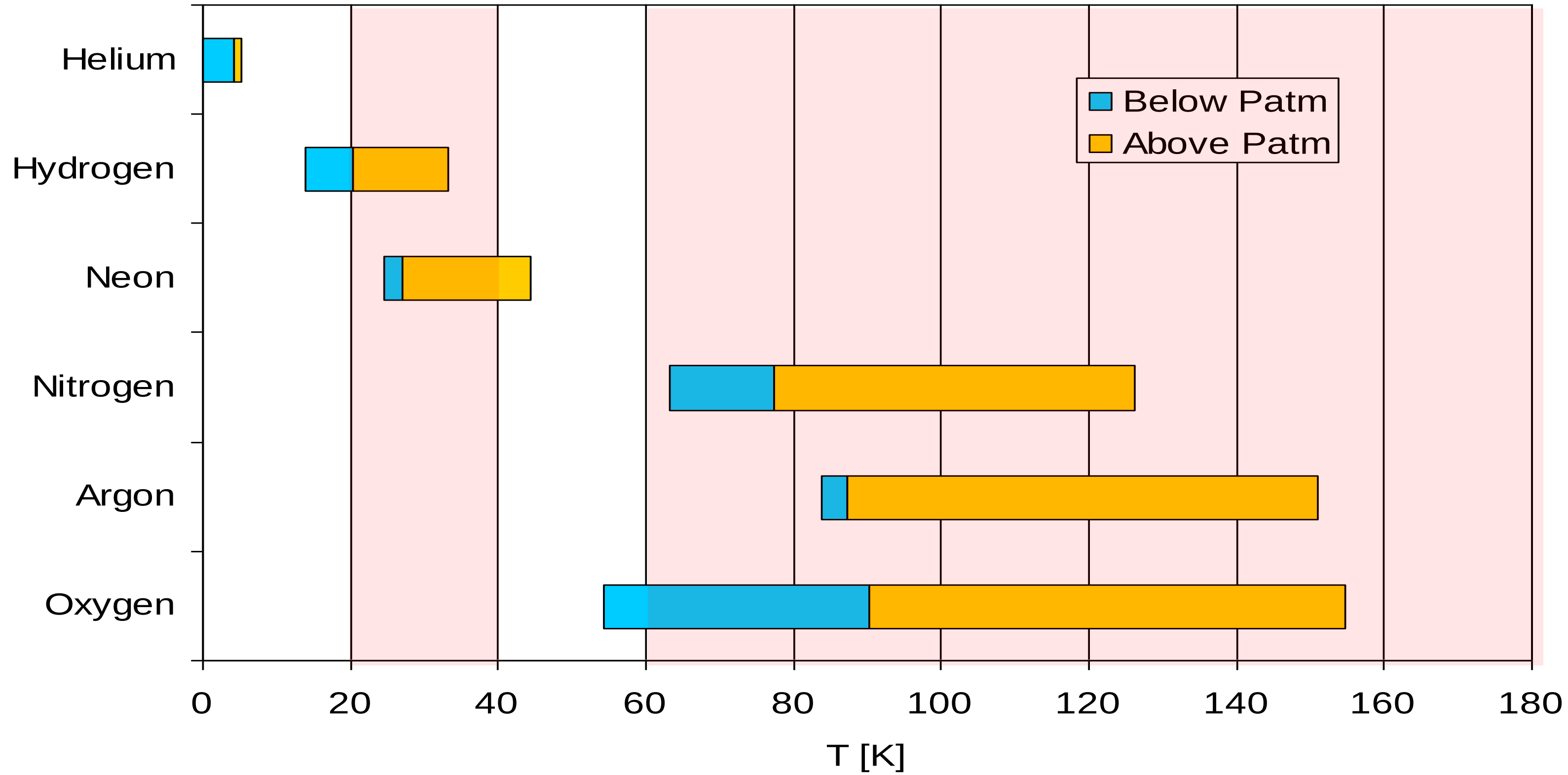


Cooling potential of cryogens for beam screen



Cryogen	Temperature range	Per unit mass [J/g]	Per unit volume* [J/cm^3]
He 3 bar	5-20 K	103	0.74
He 20 bar	5-20 K	89.3	4.20
He 20 bar	40-60 K	107	1.64
Ne 30 bar	40-60 K	79.1	11.3

** at exit conditions*

Operating the beam screen at higher temperature would allow other cooling fluids

Summary

- Original motivation for LHC beam screen: thermodynamics
  - Reduce exergy load to the cryogenic system, and therefore power to refrigerator
- Also essential for
  - Ensuring good (dynamic) vacuum for circulating beams
  - Limit development of beam collective effects and instabilities
- Beam screen design space constrained by multi-physics
  - Thermodynamics
  - Electromagnetism
  - Material properties
  - Vacuum
  - Thermohydraulics
- Assume FHC has same cold mass temperature and similar beam screen as LHC
- FHC higher linear heat loads push thermodynamic optimum towards higher beam screen temperatures (~ 80-100 K for 80 km ring): is this acceptable?
- Power to refrigerator needed to compensate for synchrotron radiation load of ~ 40 W/m per aperture for 80 km ring would be ~ 600 W/m per aperture with thermodynamically optimized beam screen, i.e. ~ 100 MW for complete FHC
- In absence of beam screen, it would be > 5 GW!