Why are particle accelerators so inefficient?

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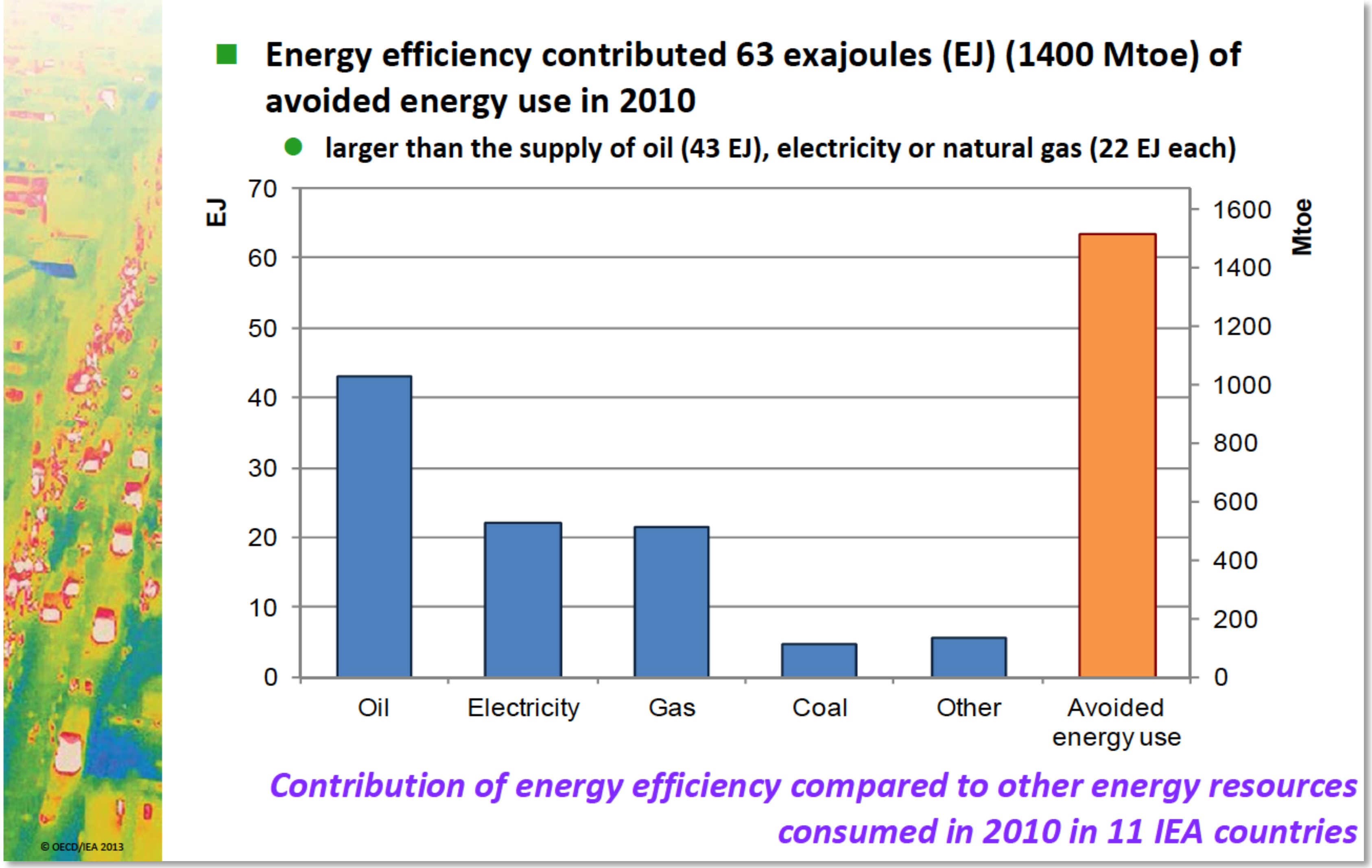
CERN, Geneva, Switzerland

Workshop on Compact and Low-Consumption Magnet Design for Future Linear and Circular Colliders
CERN, 9-12 October 2014

Why bother about efficiency?

M. van der Hoeven, *Energy efficiency report 2013*, IEA



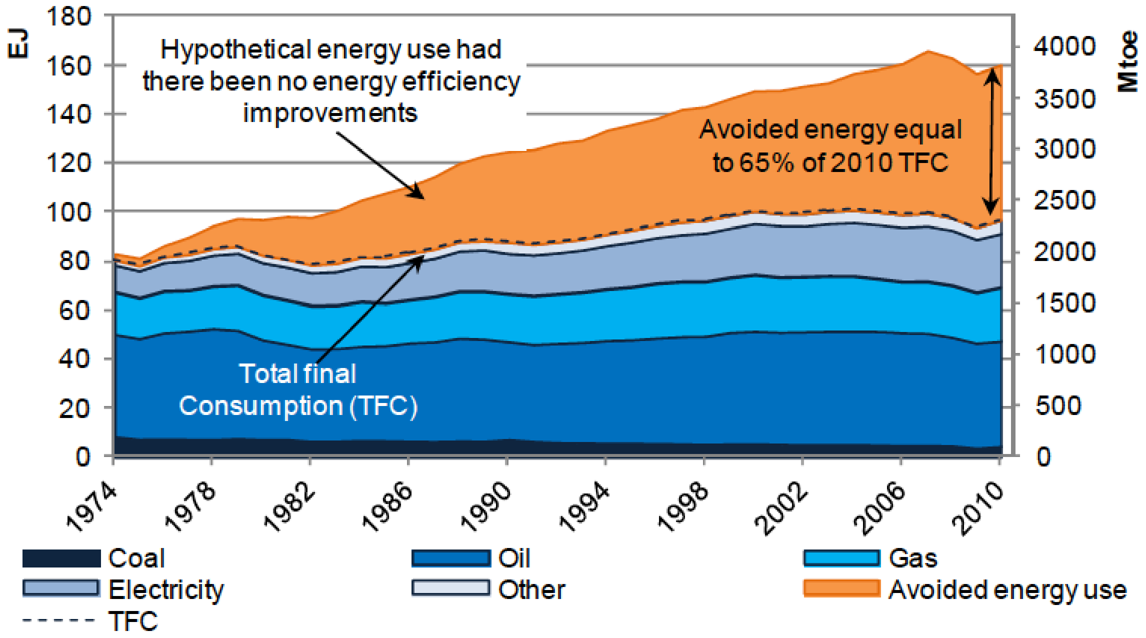
- **Energy efficiency contributed 63 exajoules (EJ) (1400 Mtoe) of avoided energy use in 2010**
  - larger than the supply of oil (43 EJ), electricity or natural gas (22 EJ each)

Contribution of energy efficiency compared to other energy resources consumed in 2010 in 11 IEA countries

The largest energy resource

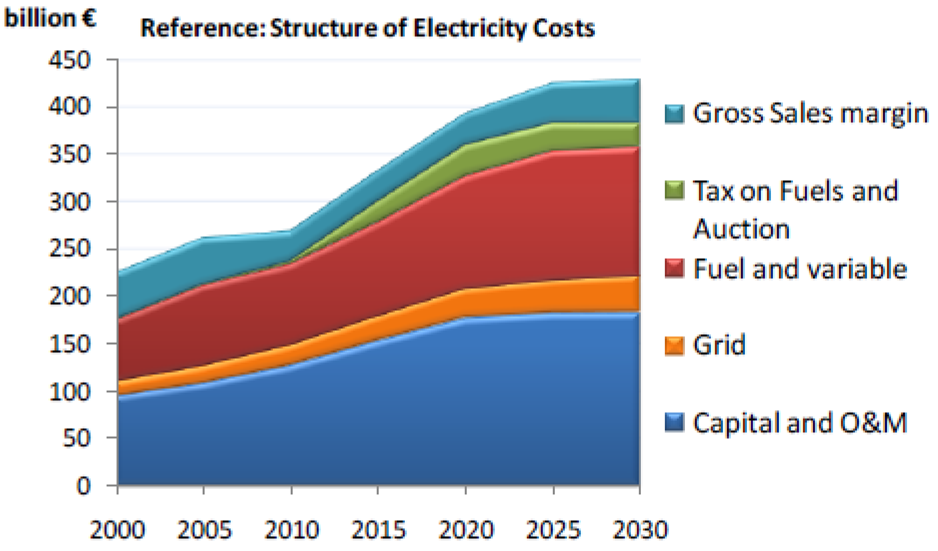
M. van der Hoeven, *Energy efficiency report 2013*, IEA

- **Between 1974 and 2010, energy efficiency was the largest energy resource**
- **Cumulative avoided energy consumption due to energy efficiency in these IEA countries amounted to over 1 350 EJ (32 billion toe)**

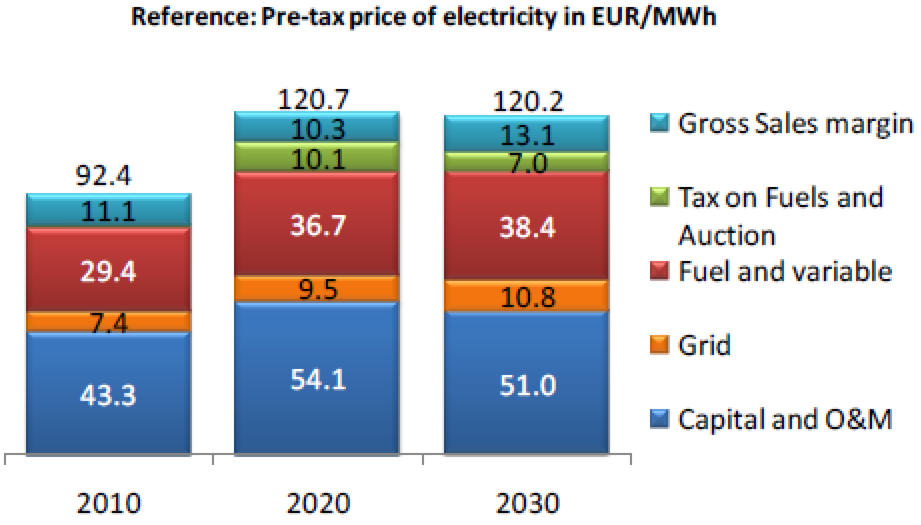


Long-term improvements in energy efficiency in 11 IEA countries

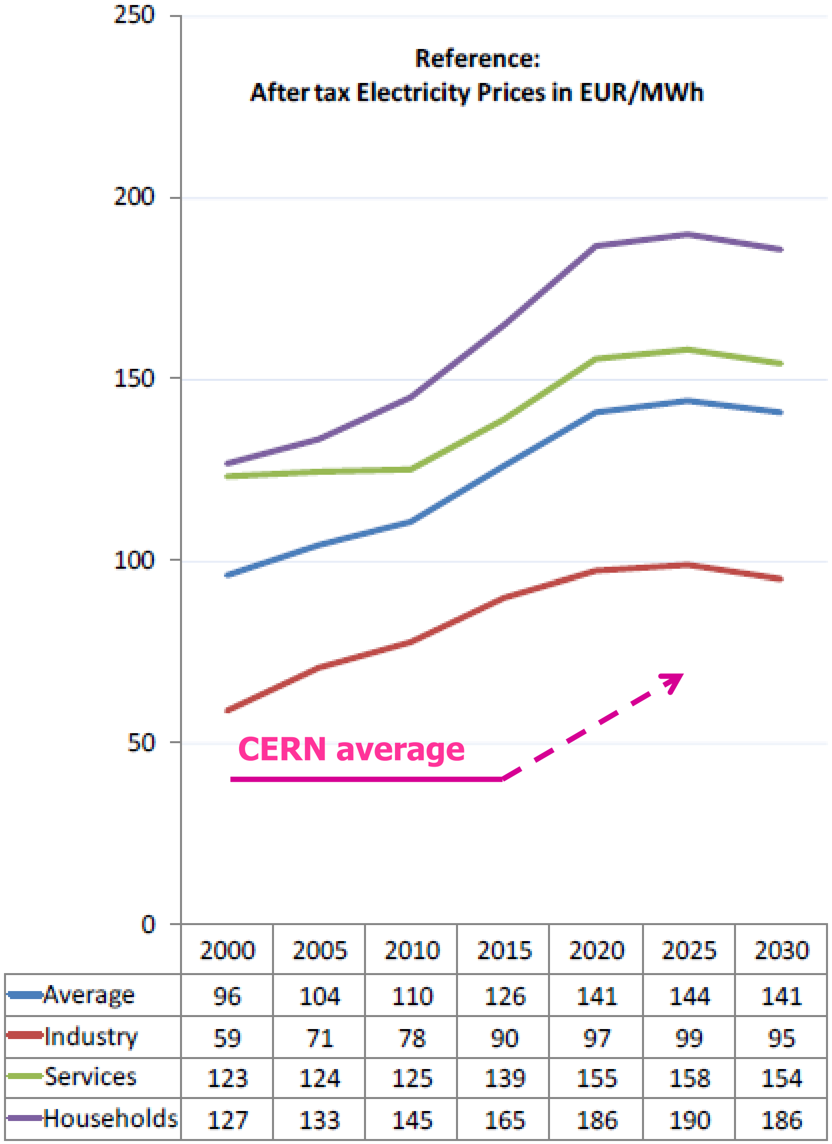
Electricity price projections
European Commission, Directorate-General for Energy
EU energy trends to 2030, Reference Scenario 2010



Reference: Structure of Electricity Costs



Reference: Pre-tax price of electricity in EUR/MWh

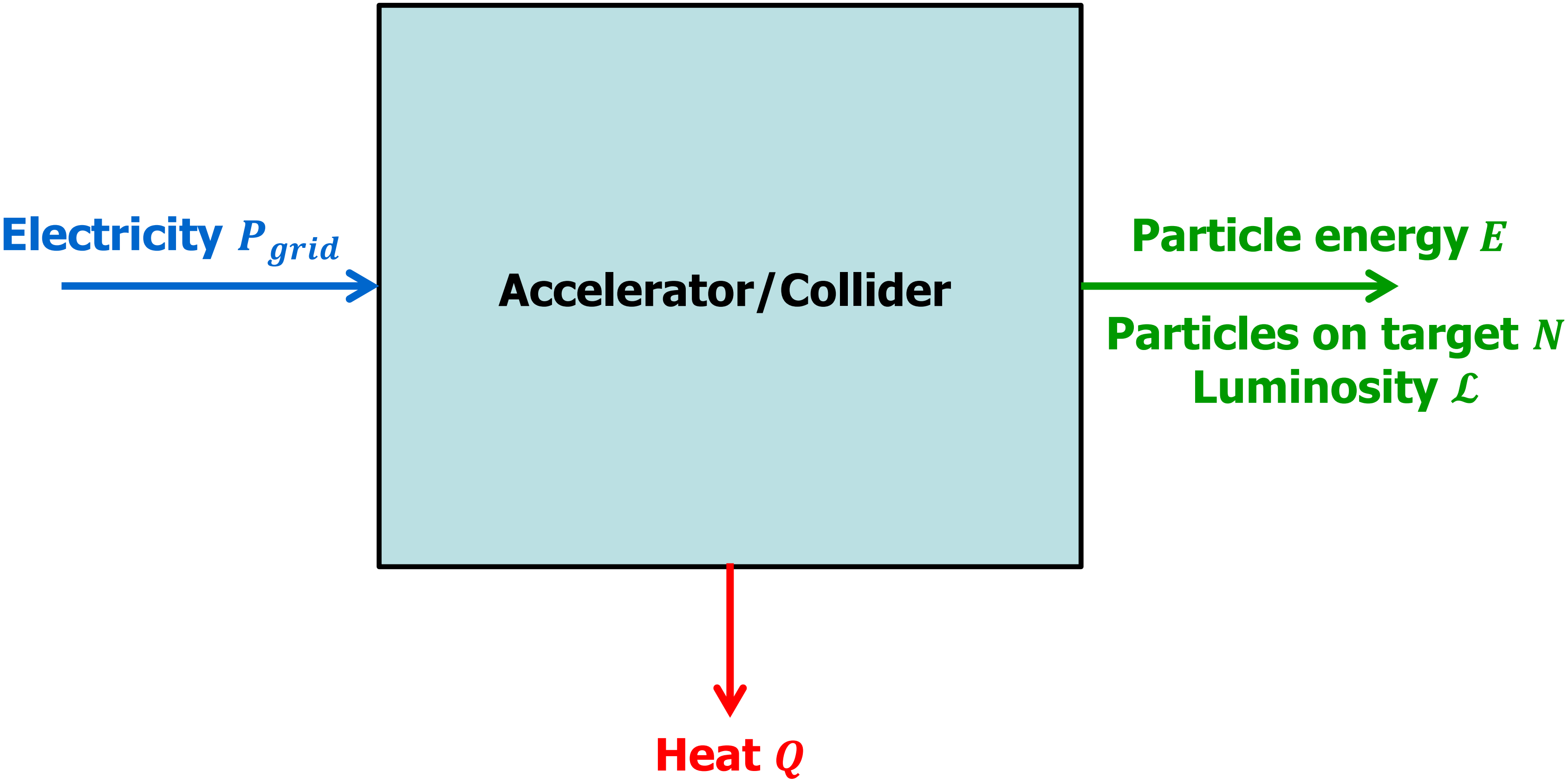


Reference: After tax Electricity Prices in EUR/MWh

CERN average

	2000	2005	2010	2015	2020	2025	2030
Average	96	104	110	126	141	144	141
Industry	59	71	78	90	97	99	95
Services	123	124	125	139	155	158	154
Households	127	133	145	165	186	190	186

Accelerator "black box" model



Electricity P_{grid}

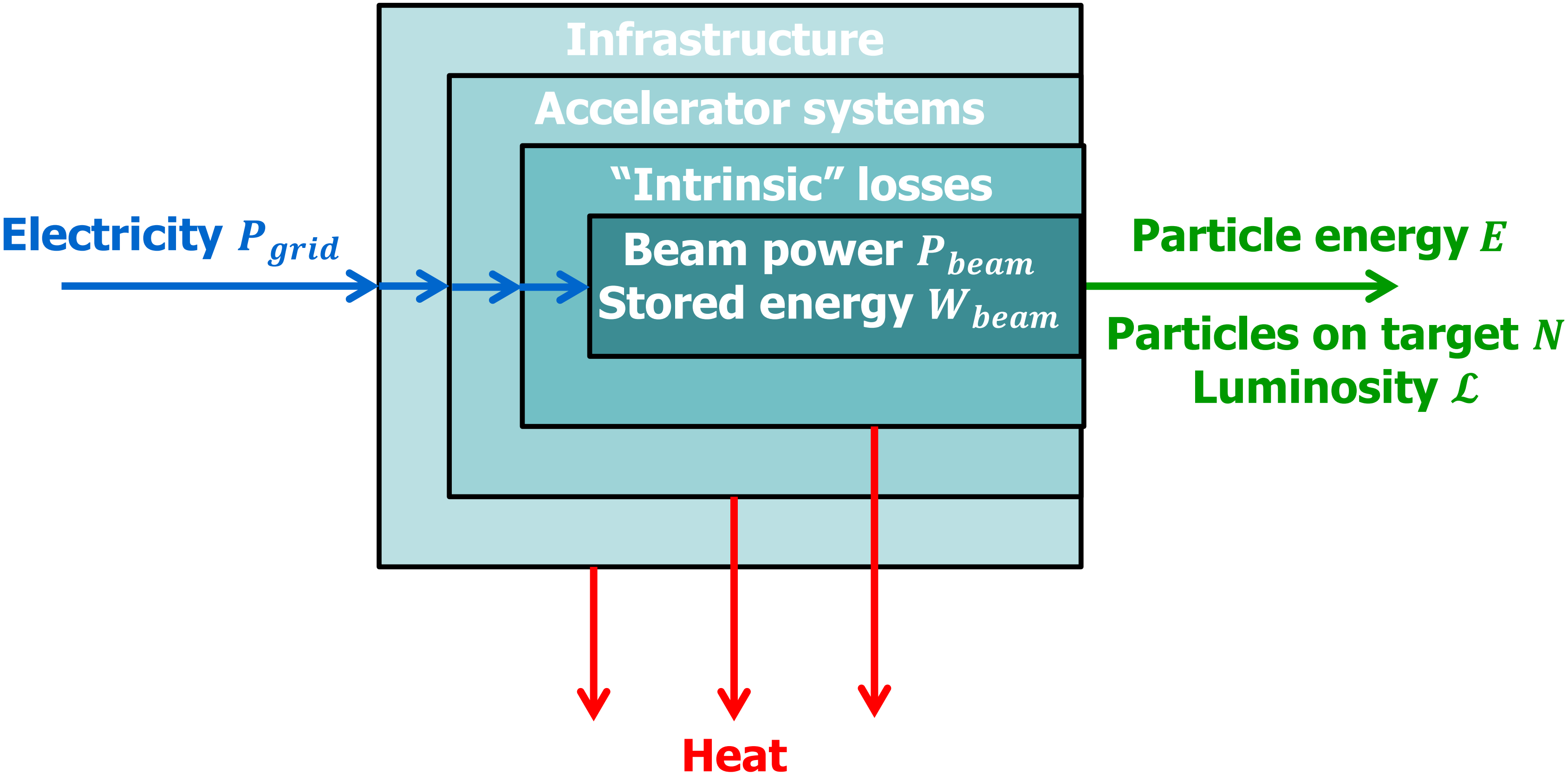
Accelerator/Collider

Particle energy E

Particles on target N
Luminosity $\mathcal{L}$

Heat Q

Accelerator “multi black box” model



Infrastructure

Accelerator systems

“Intrinsic” losses

Beam power P_{beam}

Stored energy W_{beam}

Electricity P_{grid}

Particle energy E

Particles on target N

Luminosity $\mathcal{L}$

Heat

A two-step approach

- Understand relations between
  - Performance parameters
    - Particle energy E
    - Luminosity $\mathcal{L}$
  - Beam parameters
    - Beam power P_{beam}
    - Beam stored energy W_{beam}

- Analyse sources of losses
  - "Intrinsic" losses
    - Synchrotron radiation
    - Beam image currents
    - Electron cloud
  - Accelerator systems
    - RF
    - Magnets
    - Vacuum
    - Beam instrumentation
    - …
  - Infrastructure
    - Electrical distribution
    - Cooling & ventilation
    - Cryogenics
    - …

A two-step approach
[1/2]

- Understand relations between
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Beam power, particle energy, intensity
Linear accelerators

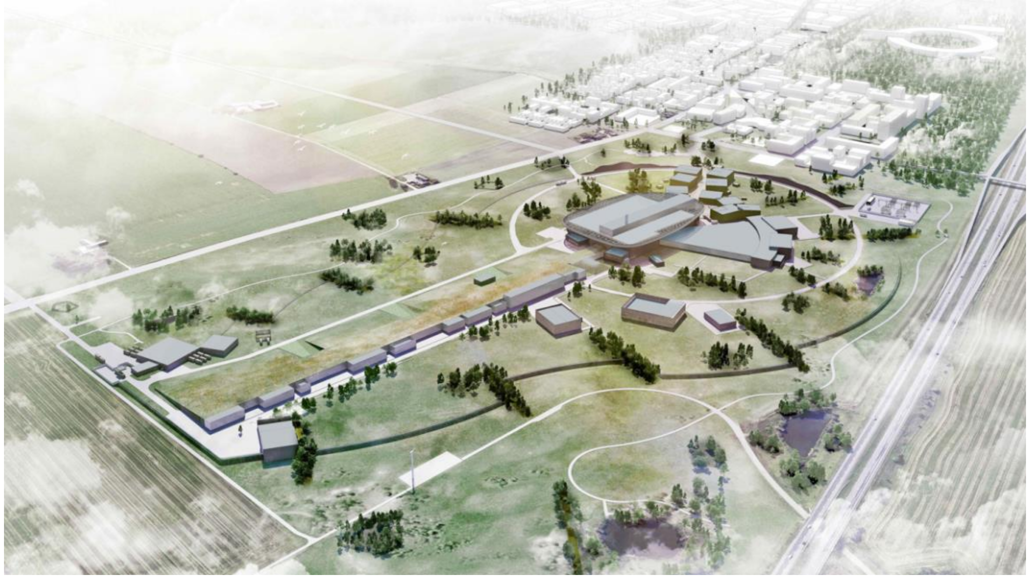
- Average beam power

Beam current Particle energy

$$P_{beam} = \delta I \frac{E}{e} = f_{rep}\boxed{N_{pulse}E}$$

Duty factor Repetition frequency Particles per pulse

- Example: ESS proton linac
  - $E = 2\ \mathrm{GeV}$
  - $I = 62.5\ \mathrm{mA}$
  - $\delta = 4\ \%$
  - $P_{beam} = 5\ \mathrm{MW}$ average



Beam power, particle energy, luminosity
Linear colliders

- Lower-energy regime (small beamstrahlung)

$$\mathcal{L} \sim \frac{1}{\sqrt{\beta_y \varepsilon_y}} \boxed{\frac{P_{beam}}{E}}$$

Beam power

Particle energy

Vertical beta at collision

Vertical emittance

- High-energy regime (large beamstrahlung)

$$\mathcal{L} \sim \frac{1}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\varepsilon_y}} \boxed{\frac{P_{beam}}{E}}$$

Bunch length

- Example: CLIC

Centre-of-mass energy E_{CM} [TeV]	Luminosity $\mathscr{L}_{1\%}$ [$\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	Electrical power P [MW]	Main Beam power (2 beams) P_{MB} [MW]	Overall efficiency $\eta = P_{\mathrm{MB}}/P$ [%]
0.5	1.40×10^{34}	271	9.4	3.5
1.5	1.45×10^{34}	361	14	3.9
3	2.00×10^{34}	582	28	4.8

Beam power, particle energy, intensity
Circular accelerators

- Beam energy

$$W_{beam} = N_{pulse} E$$

Particles per pulse

Particle energy [eV]

- Average beam power

$$P_{beam} = \frac{\boxed{N_{pulse} E}}{T_{cycle}}$$

Accelerator cycle period

- Example: SPS (design)
  - $E = 400 \text{ GeV}$
  - $N_{pulse} = 10^{13}$
  - $T_{cycle} = 5.8 \text{ s}$
  - $W_{beam} = 640 \text{ kJ}$
  - $P_{beam} = 110 \text{ kW}$

Stored energy, particle energy, luminosity

Circular colliders [1/2]

- For round beams with crossing angle

Number of bunches

Particles per bunch

Revolution frequency

$$\mathcal{L} = \frac{{N_b}^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F$$

Geometrical factor

Normalized emittance

Beta function at collision

- Noting that $W_{beam} = m_0 c^2 \gamma N_b n_b = E N_b n_b$

- Then

$$\mathcal{L} = \frac{1}{4\pi m_0 c^2} \underbrace{f_{rev}}_{\text{Circumference}} \underbrace{\frac{N_b}{\varepsilon_n}}_{\text{Injector chain}} \underbrace{\frac{F}{\beta^*}}_{\text{Collision optics}} W_{beam} = \frac{\gamma}{4\pi} f_{rev} \frac{N_b}{\varepsilon_n} \frac{F}{\beta^*} \boxed{\frac{W_{beam}}{E}}$$

Circumference

Injector chain

Collision optics

Avg. beam power, particle energy, luminosity

Circular colliders [2/2]

- Introducing “average” beam power, i.e. beam stored energy divided by beam lifetime

$$P_{avg\ beam} = \frac{W_{beam}}{\tau_{beam}} \sim \boxed{\frac{E\mathcal{L}}{\tau_{beam}}}$$

- Example: LHC nominal
  - $E = 7\ \mathrm{TeV}$
  - $I = 0.58\ \mathrm{A}$
  - $\mathcal{L} = 1.0\mathrm{E}34\ \mathrm{cm}^{-2}.\mathrm{s}^{-1}$
  - $W_{beam} = 362\ \mathrm{MJ}$
  - taking $\tau_{beam} \approx 10\ \mathrm{h}$,
  - then $P_{avg\ beam} \approx 10\ \mathrm{kW}$
  - i.e. about 20 kW for two beams

Collider COP

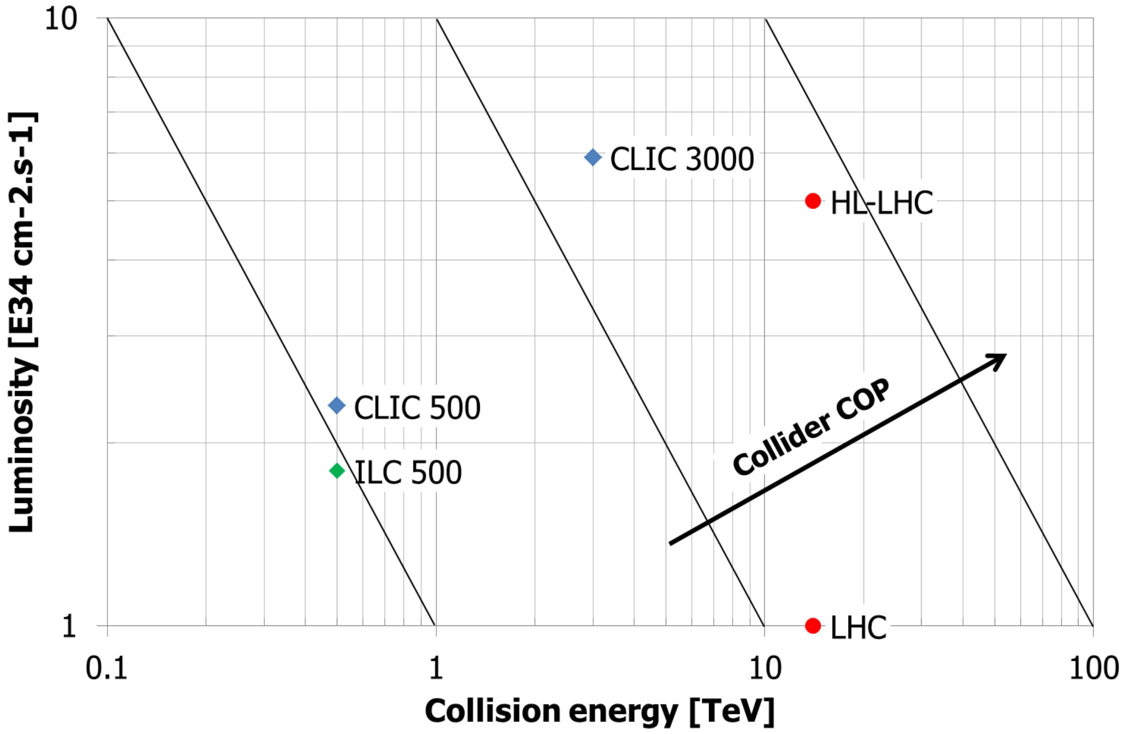
- For all types of colliders , the average beam power is proportional to the product of particle energy and luminosity
- We can then define a “collider coefficient of performance” (CoCOP) as the product of collision energy and luminosity

$$CoCOP = 2\,E\,\mathcal{L} \quad [\mathrm{E34\ TeV.cm^{-2}.s^{-1}}]$$

- The CoCOP can then be compared to the beam power for different machines, and the ratio $CoCOP/P_{beam}$ [E34 TeV.cm^{-2}.s^{-1}/MW] used to quantify the relation between beam power and collider performance
- Notes
  - The CoCOP has the dimension of an inverse cross-section
  - The CoCOP may be seen as an attempt to quantify the “physics reach” of the collider. However, it gives the same weight to energy and luminosity, which are both important but not equivalent. A “physics coefficient of performance” (PhyCOP) could be defined by a Cobb-Douglas function

$$PhyCOP = 2\,E\,\mathcal{L}^n \qquad \text{with} \quad n < 1$$

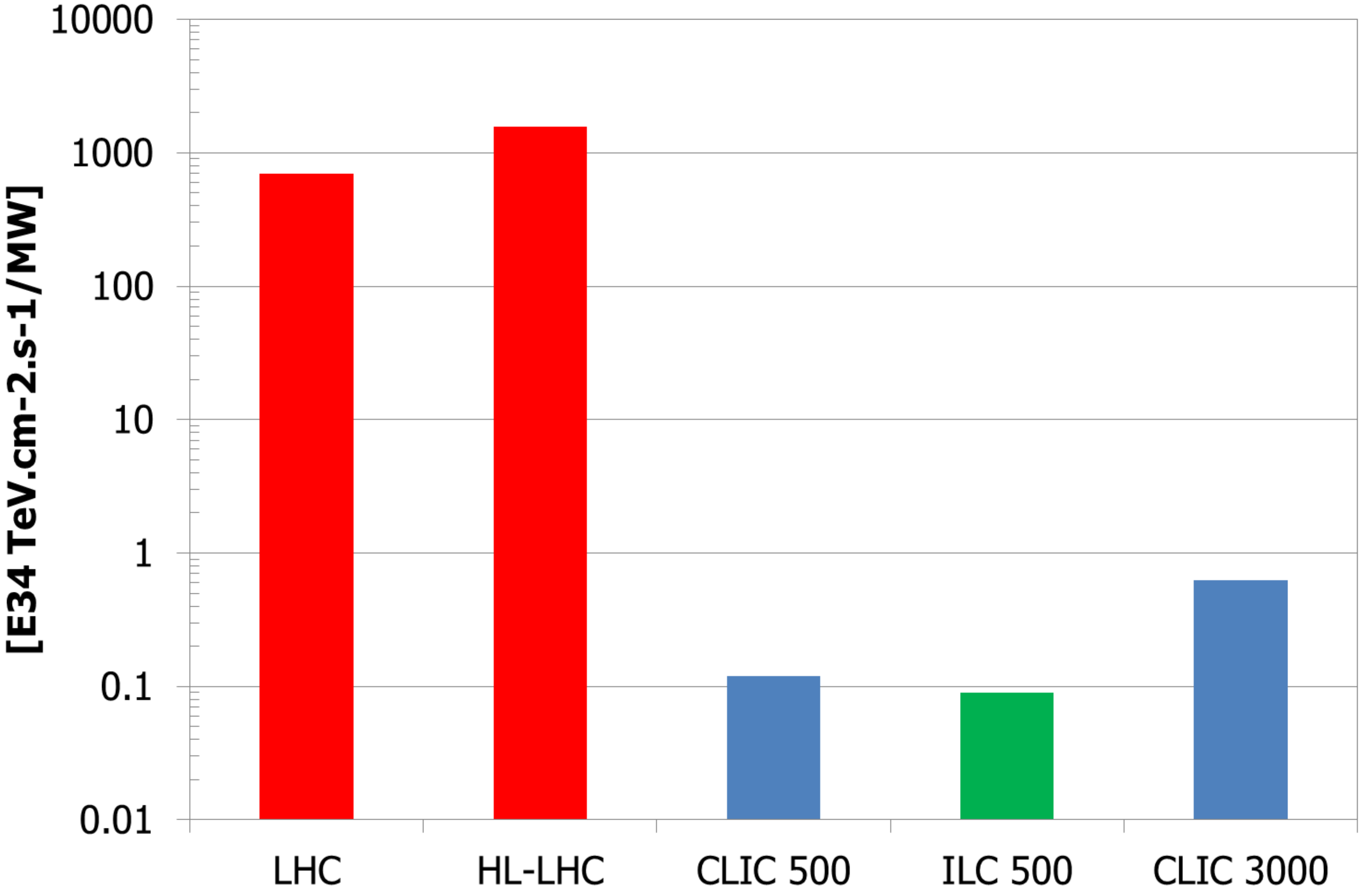
Collider COP



	LHC	HL-LHC	CLIC 500	ILC 500	CLIC 3000
Collision energy [TeV]	14	14	0.5	0.5	3
Luminosity [E34 cm-2.s-1]	1	5	2.3	1.8	5.9
Collider COP [E34 TeV.cm-2.s-1]	14	70	1.15	0.9	17.7
Beam power (2 beams) [MW]	0.02	0.045	9.8	10.5	28
Collider COP/beam power	700	1556	0.12	0.09	0.63

Collider COP/beam power

Note logarithmic scale



A two-step approach
[2/2]

- Understand relations between
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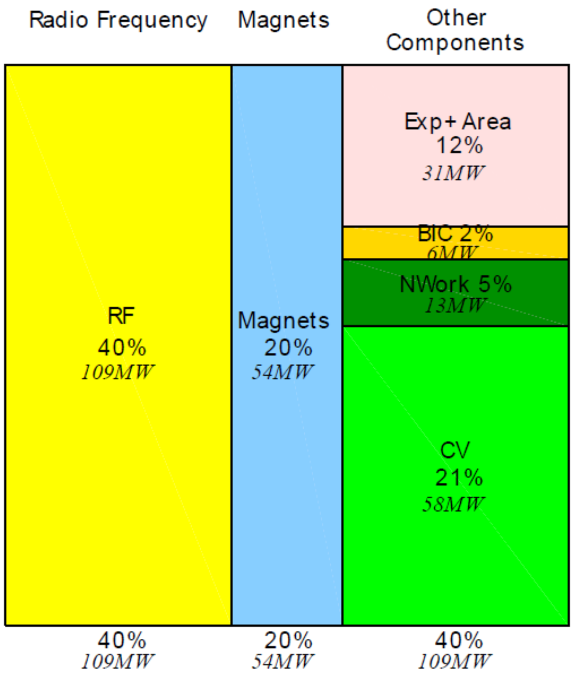
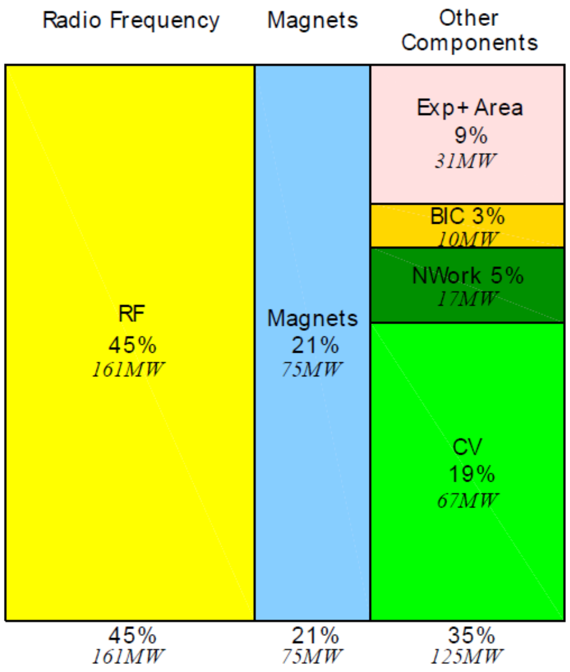
- Analyse sources of losses
  - “Intrinsic” losses
    - Synchrotron radiation
    - Beam image currents
    - Electron cloud
  - Accelerator systems
    - RF
    - Magnets
    - Vacuum
    - Beam instrumentation
    - …
  - Infrastructure
    - Electrical distribution
    - Cooling & ventilation
    - Cryogenics
    - …

Example of analysis
CLIC power consumption by technical system

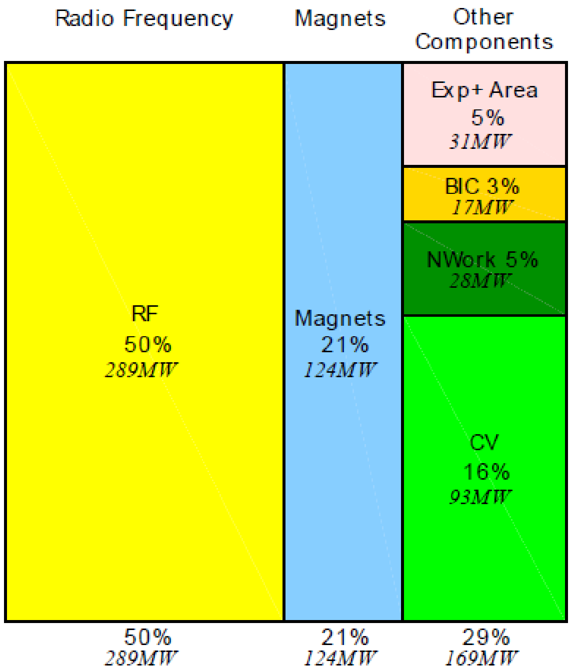
500 GeV A
Total 272 MW



1.5 TeV
Total 364 MW



3 TeV
Total 589 MW



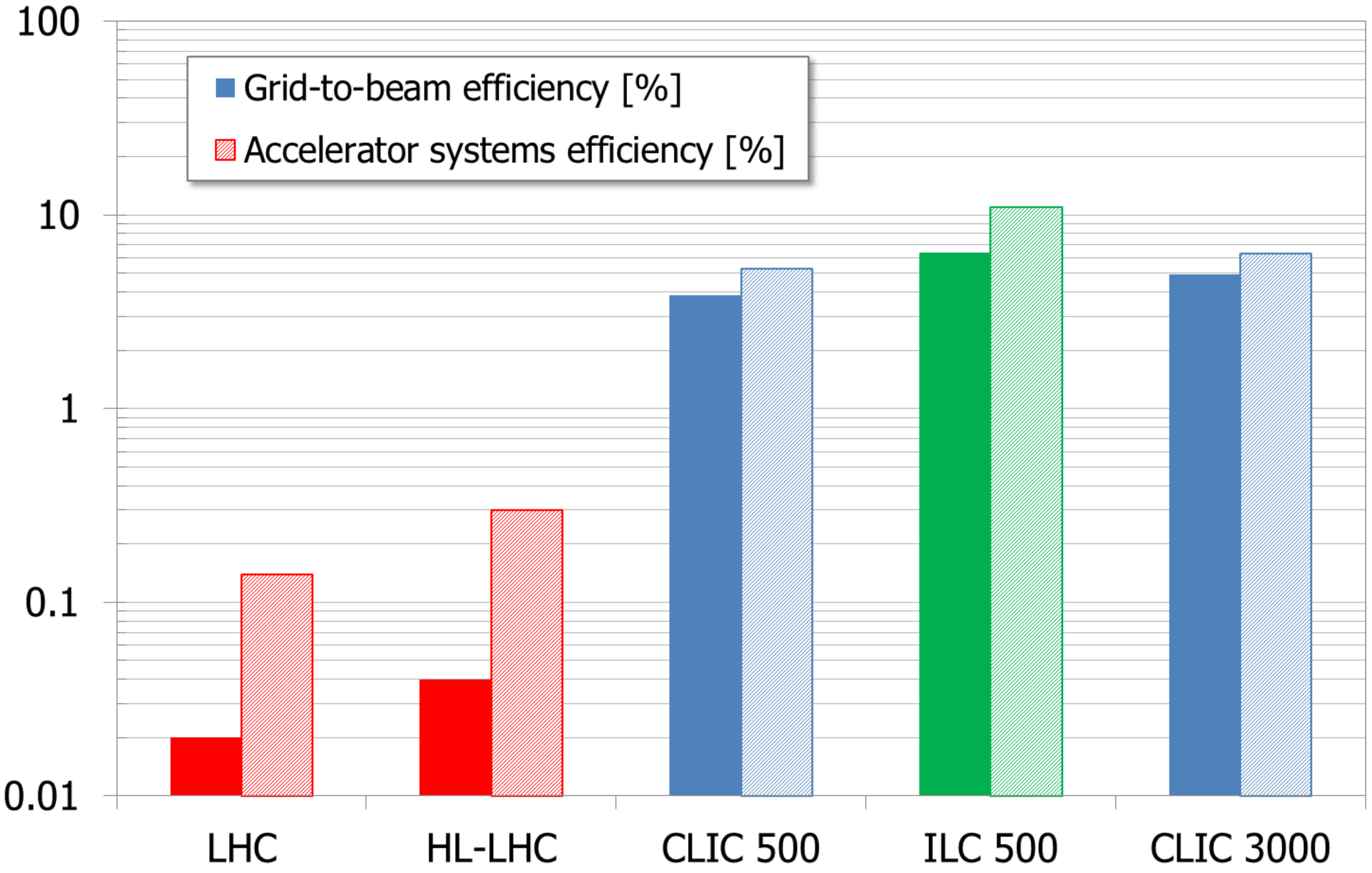
CV: cooling & ventilation, NW: electrical network losses, BIC: beam instrumentation & control

Collider power and efficiency

	LHC*	**HL-LHC***	**CLIC 500**	**ILC 500**	**CLIC 3000**
Beams [MW]	0.02	0.045	9.8	10.5	28
Intrinsic [MW]	0.025	0.036			
Accelerator systems** [MW]	14.8	14.8	185	96	446
Accelerator efficiency [%]	**0.14**	**0.30**	**5.30**	**10.94**	**6.28**
Infrastructure***[MW]	72.4	85.5	71	68	121
Total grid power [MW]	**87**	**101**	**261**	**175**	**573**
Grid-to-beam efficiency [%]	**0.02**	**0.04**	**3.75**	**6.00**	**4.88**
* excluding injectors					
** including beam power					
*** including cryogenics					

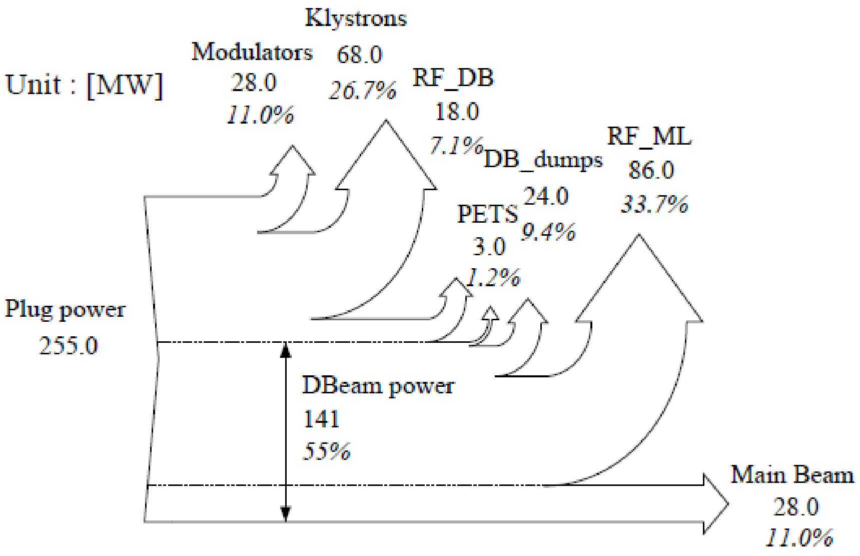
Collider efficiencies

Note logarithmic scale

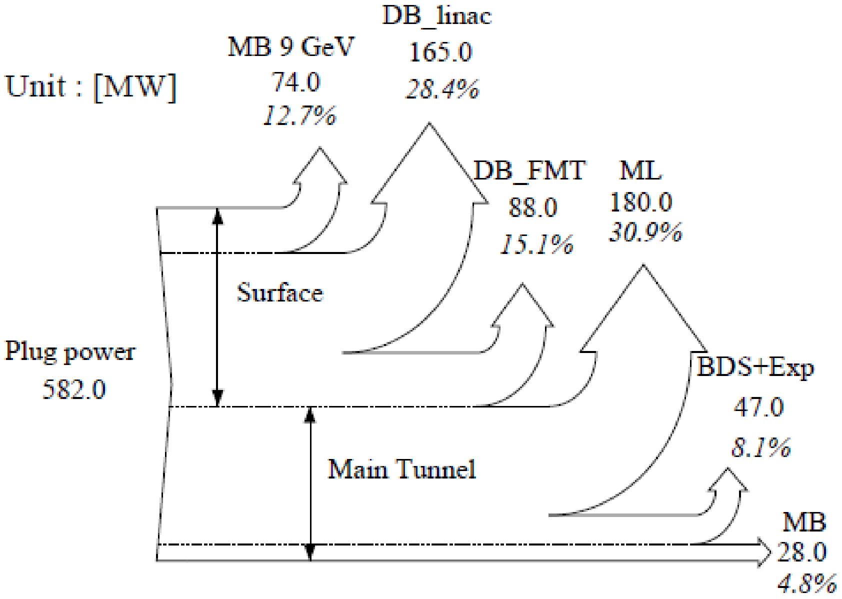


Sankey diagrams are useful tools

CLIC power flow



Power flow for the main RF system of CLIC at 3 TeV



Overall power flow for CLIC at 3 TeV

Accelerator systems: magnets

Power consumption

- Normal conducting (copper)
  - Power dissipation per unit length $P/L \sim \rho_{Cu}\, jB$
  - Total power dissipation $P \sim \rho_{Cu}\, jBR \sim \rho_{Cu}\, jE_{beam}$

-> power dissipation can be reduced by choosing a low current density

- Superconducting
  - Total power (refrigeration) $P \sim L \sim R$

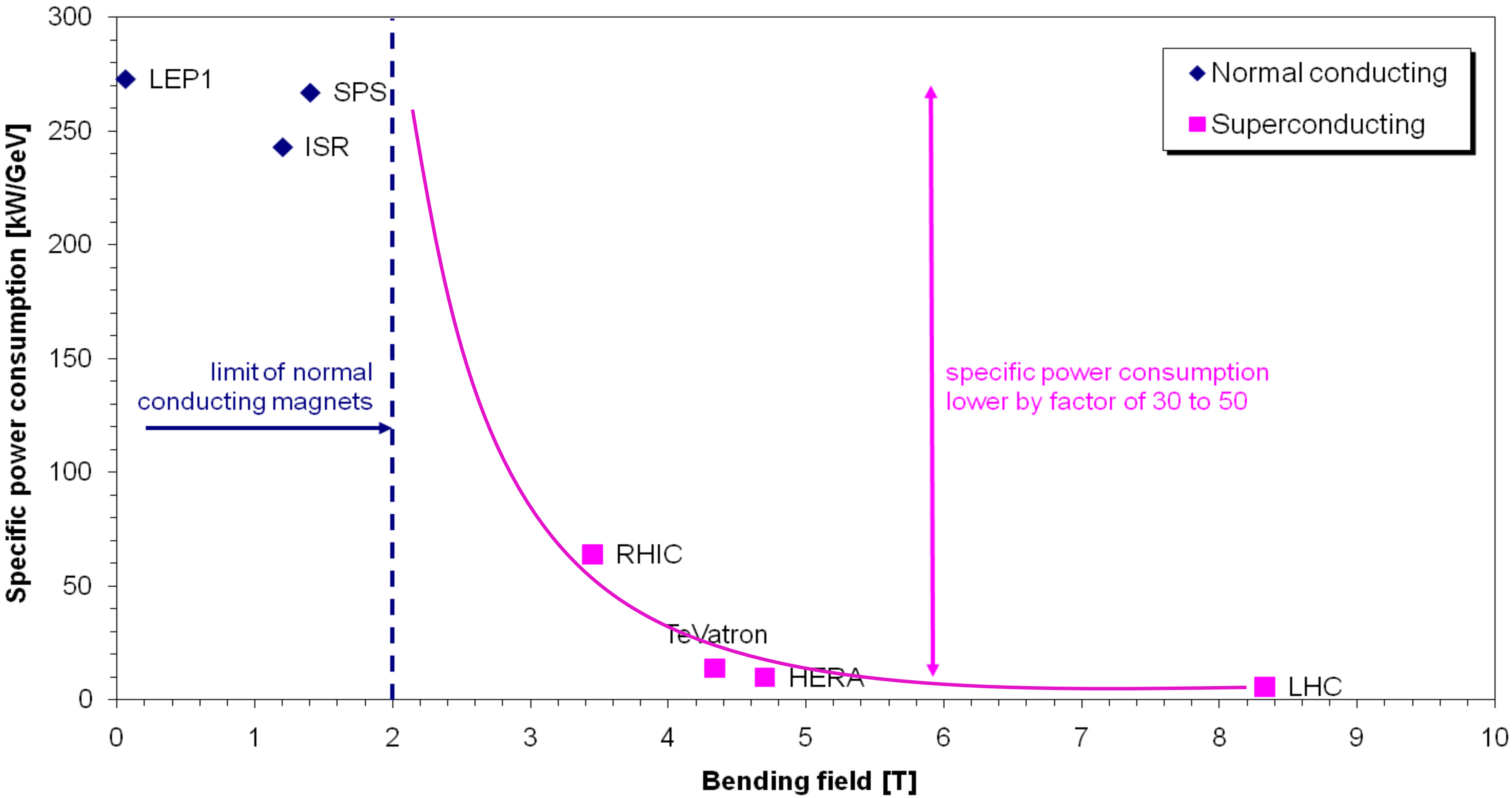
-> independent of magnetic field

	Normal conducting	**Superconducting (LHC)**
Magnetic field	1.8 T (limited by iron saturation)	8.3 T (limited by critical surface of Nb-Ti)
Field geometry	Defined by pole pieces	Defined by windings
Current density in windings	10 A/mm^2	400 A/mm^2
Electromagnetic forcess	20 kN/m	3400 kN/m
Electrical power from grid	10 kW/m	2 kW/m

Magnet systems for circular accelerators

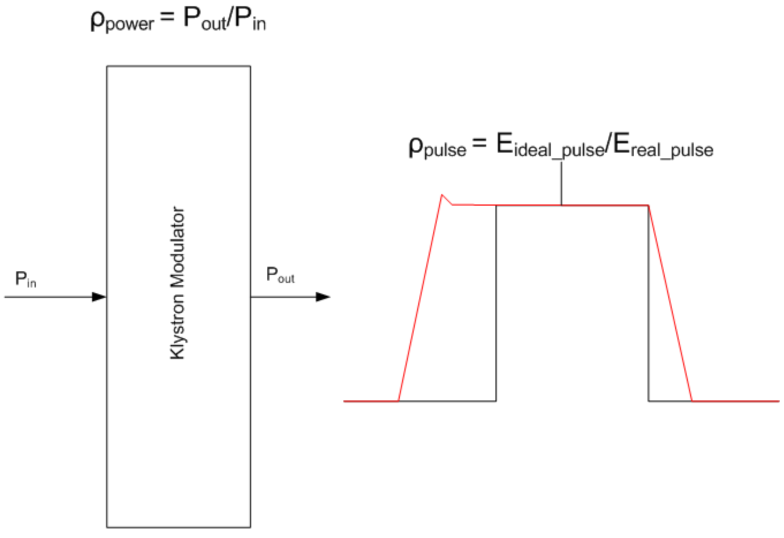
Specific power consumption

Superconductivity and higher fields break the canonical
~ 250 kW/GeV specific power consumption of conventional synchrotron magnets



Accelerator systems: RF

Development of high-efficiency modulators

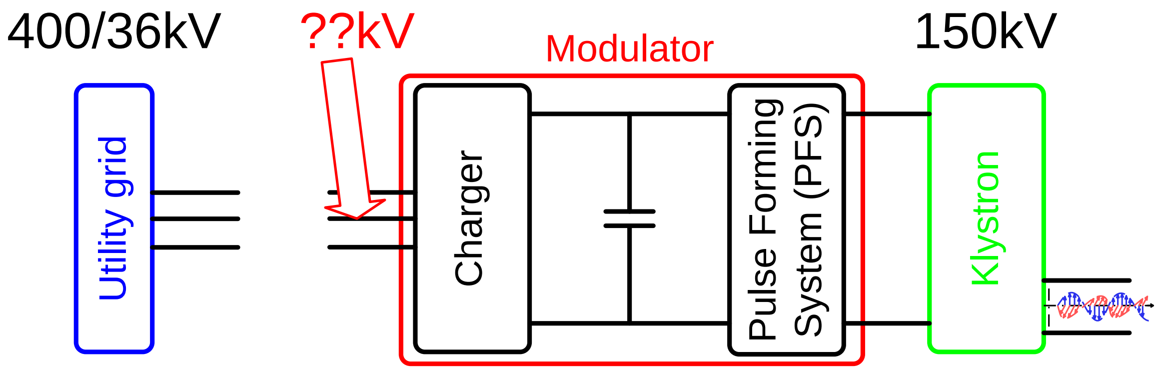


$\rho_{power} = P_{out}/P_{in}$

$\rho_{pulse} = E_{ideal\_pulse}/E_{real\_pulse}$

$$\rho_{modulator} = \rho_{power} * \rho_{pulse}$$

Useful flat-top Energy	22MW*140µs = 3.08kJ
Rise/fall time energy	22MW*5µs*2/3= 0.07kJ
Set-up time energy	22MW*5µs = 0.09kJ
Pulse efficiency	**0.95**
Pulse forming system efficiency	0.98
Charger efficiency	0.96
Power efficiency	**0.94**
Overall Modulator efficiency	**89%**



400/36kV

??kV

Modulator

150kV

Utility grid

Charger

Pulse Forming System (PFS)

Klystron

D. Nisbet & D. Aguglia

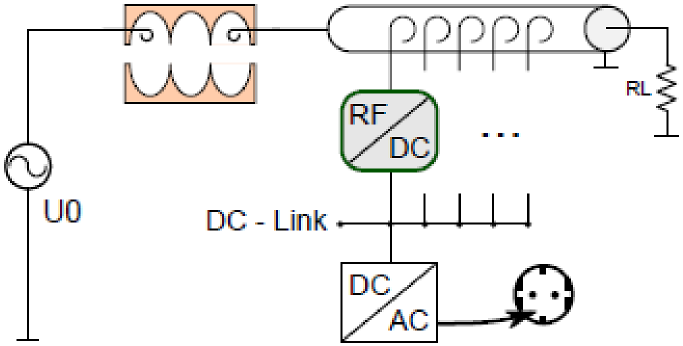
Accelerator systems: RF
"Smart" RF loads

- RF-to-DC power conversion

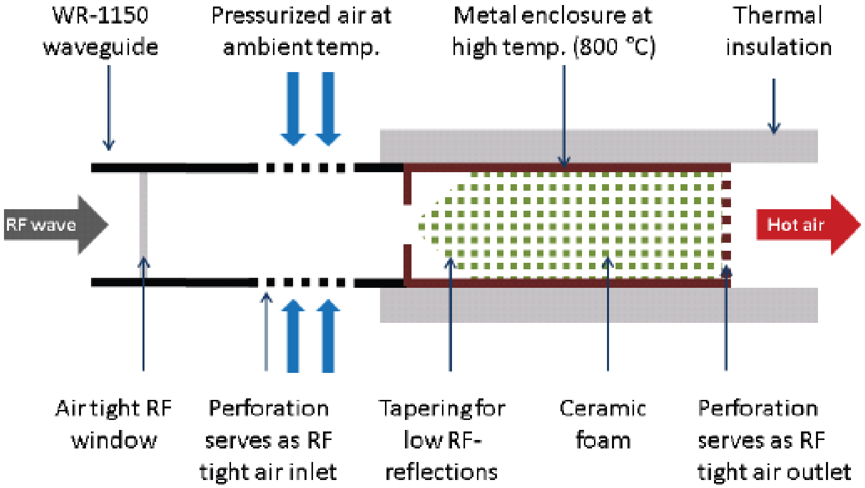
  F.Caspers, M. Betz, A. Grudiev & H. Sapotta, *Design concepts for RF-DC conversion in particle accelerator systems*, IPAC10

- High-temperature heat recovery

  S. Federmann, M. Betz, F.Caspers, *RF loads for energy recovery,* IPAC12

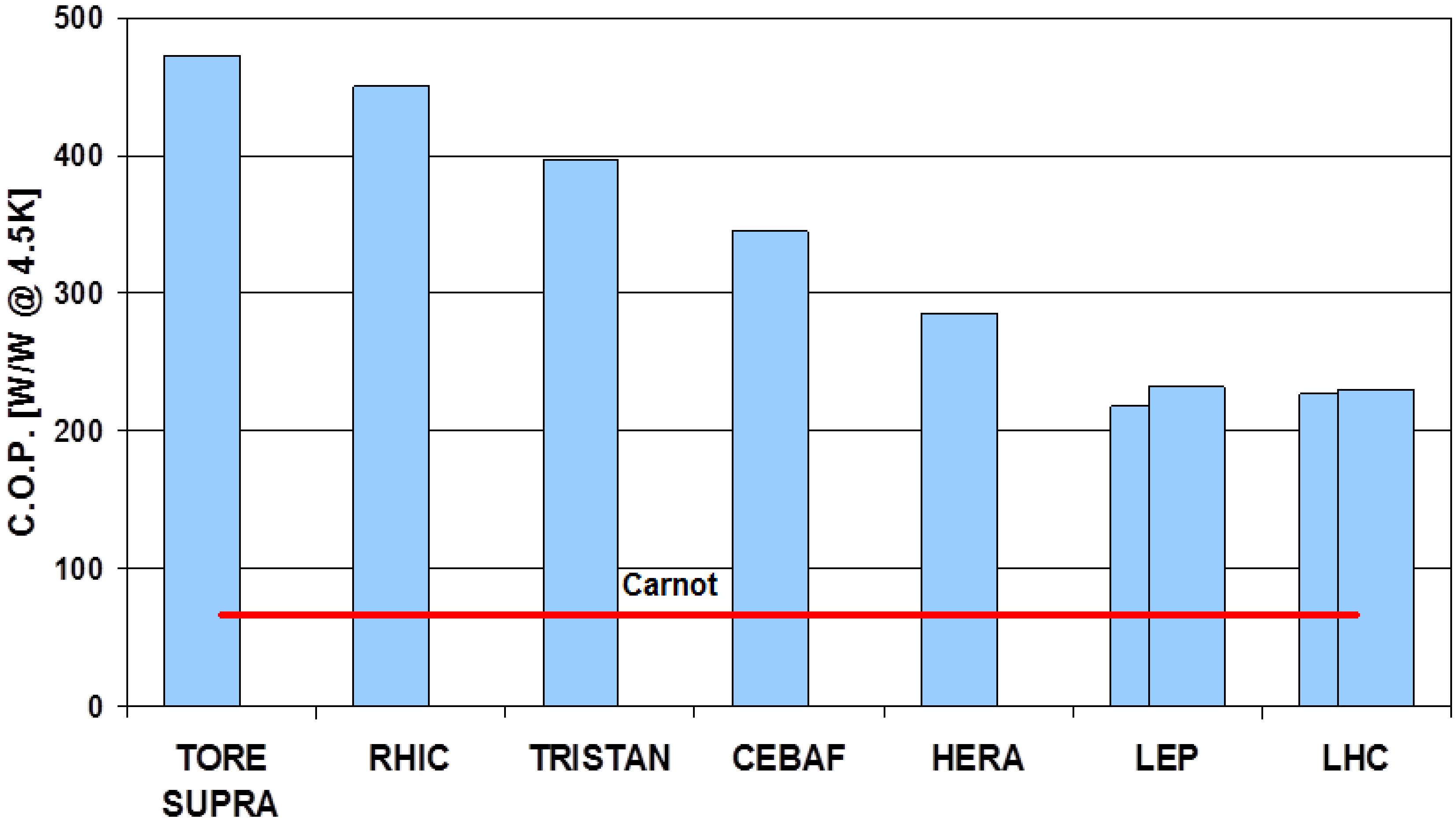


AC 50 Hz, to distribution grid

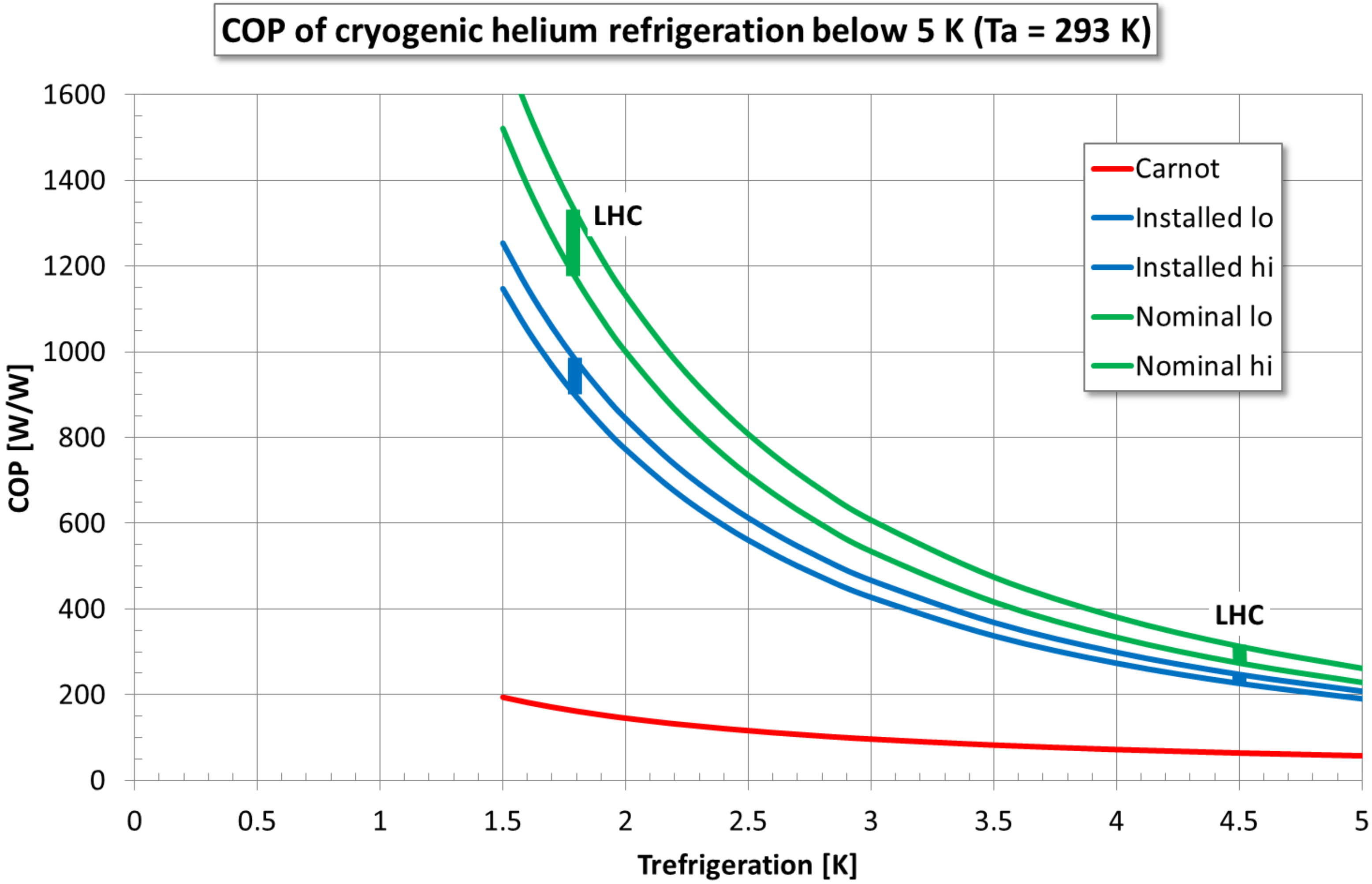


Infrastructure systems: cryogenics

COP of cryogenic helium refrigerators (installed)



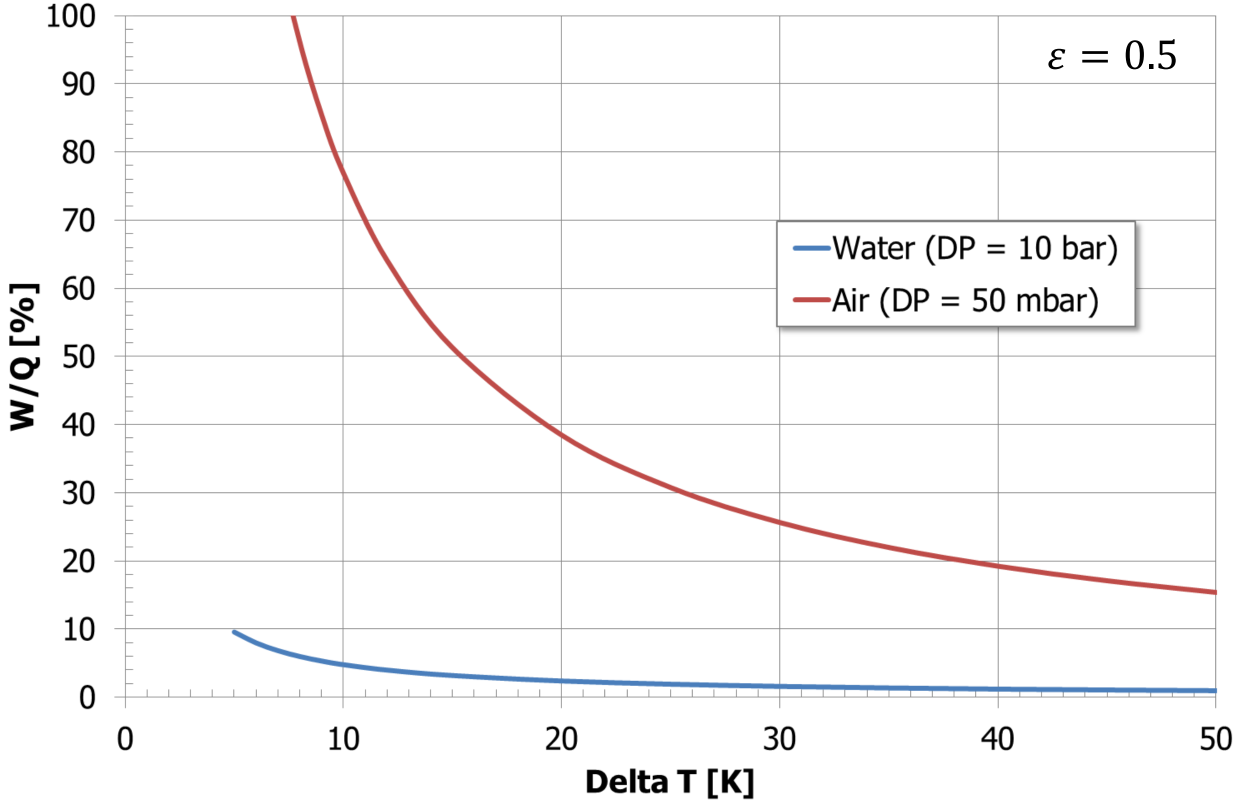
Cryogenic refrigeration
Efficiency degrades at reduced capacity



Infrastructure systems: cooling & ventilation

Efficiency of heat transport in water vs. air

- Heat to be extracted $Q = \dot{m}\, C\, \Delta T$
- Mechanical power on coolant $W = \dfrac{\dot{m}\, \Delta P}{\varepsilon\, \rho}$ with ε = circulator efficiency
- Specific power $W/Q = \dfrac{\Delta P}{\varepsilon\, \rho\, C\, \Delta T}$



Summary

Reasons for low efficiency

- For all types of machines, the average beam power is proportional to the product of particle energy and luminosity or delivered particle flux
- The energy-luminosity performance, and possibly the physics reach of a collider can be represented by a single "coefficient of performance"
- The ratio of "coefficient of performance" to beam power quantifies the relation between collider performance and beam parameters: it is lower for single-pass machines than for circular colliders
- "Intrinsic" losses due to basic physics processes add up to the beam power and often exceed it (synchrotron radiation)
- Accelerator systems and infrastructure represent the bulk of electrical power consumption
- Comparing total power consumption and average beam power yields very low values for overall "grid-to-beam" efficiency
- Linear colliders show higher overall "grid-to beam" efficiencies than circular colliders. This partly compensates for their much lower COP/beam power ratio

Outlook
Strategies for better efficiency

- Maximize energy-luminosity performance per unit of beam power
  - Minimize circumference for a given energy (high-field magnets)
  - Operate at beam-beam limit
  - Low-emittance, high-brilliance beams
  - Low-beta insertions, small crossing angle ("crabbing")
  - Short bunches (beamstrahlung)
- Contain "intrinsic" losses
  - Synchrotron radiation
  - Beam image currents
  - Electron-cloud
- Optimize accelerator systems
  - RF power generation and acceleration (deceleration)
  - Low-dissipation magnets (low current density, pulsed, superconducting, permanent)
- Optimize infrastructure systems
  - Efficient cryogenics (heat loads, refrigeration cycles & machinery, distribution)
  - Limit electrical distribution losses (cables, transformers)
  - Absorb heat loads preferably in water rather than air
  - Recover and valorise waste heat

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