Energy consumption and savings potential of CLIC

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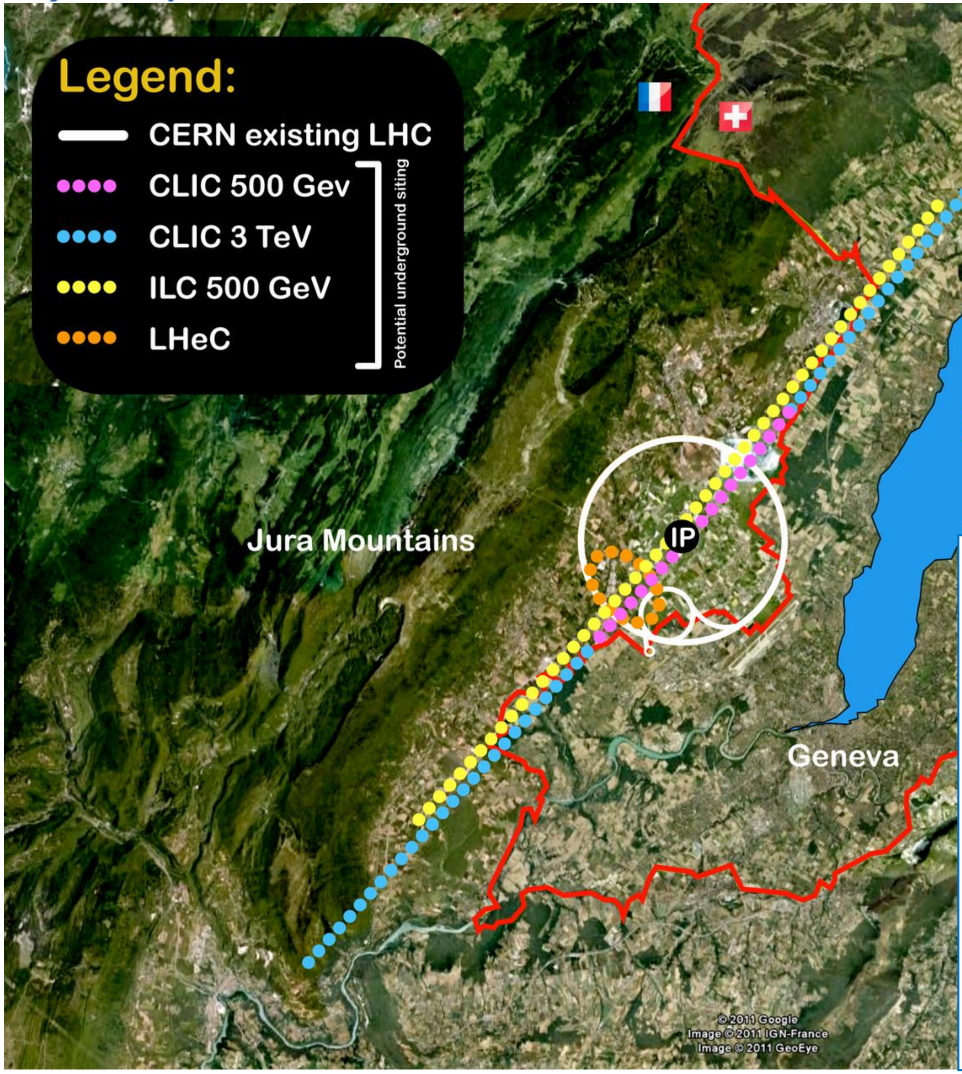
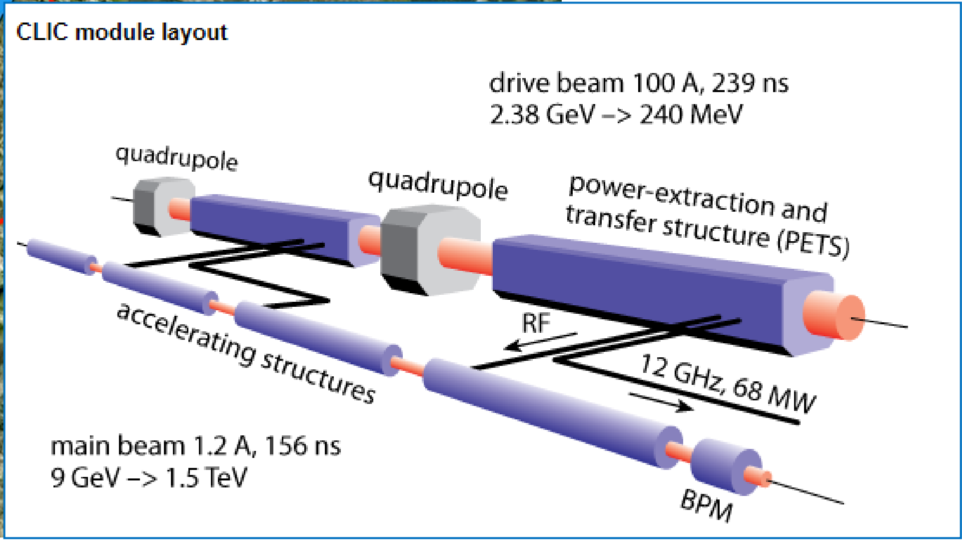
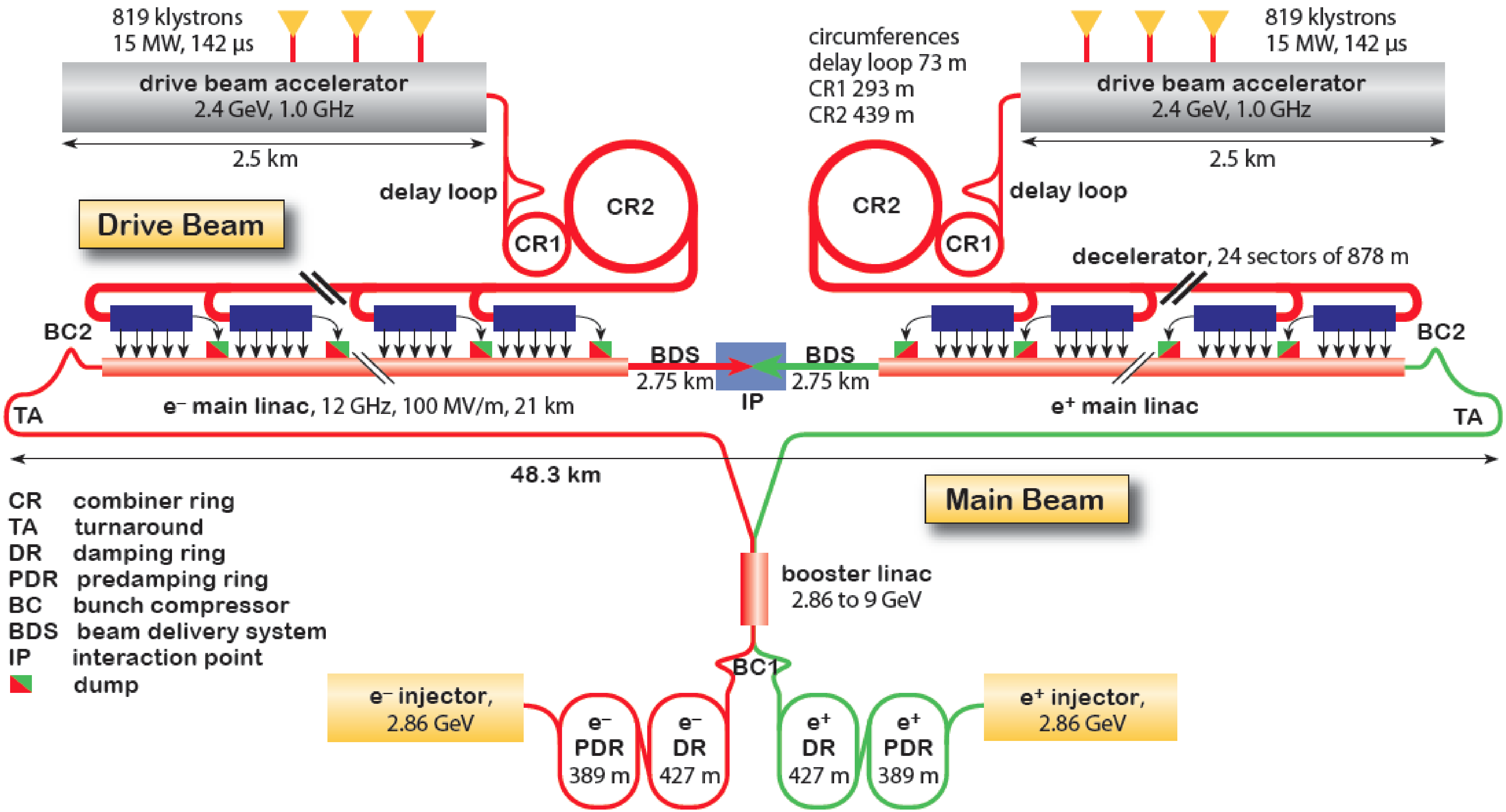
CLIC linear $e^+ e^-$ collider study





CLIC complex schematic



Energy, luminosity and power consumption of linear colliders

- Lower-energy regime (small beamstrahlung)

$$\mathcal{L} \sim \frac{1}{\sqrt{\beta_y \varepsilon_y}} \eta \frac{P}{E}$$

Grid power

Beam energy

Grid-to-beam efficiency

Vertical beta at collision

Vertical emittance

- High-energy regime (large beamstrahlung)

$$\mathcal{L} \sim \frac{1}{\sqrt{\sigma_z}} \frac{1}{\sqrt{\varepsilon_y}} \eta \frac{P}{E}$$

Bunch length

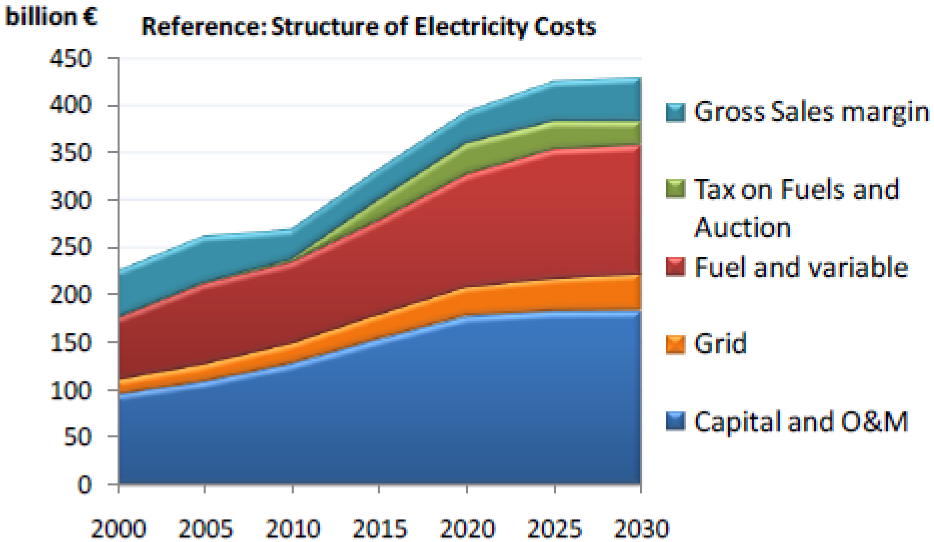
CLIC

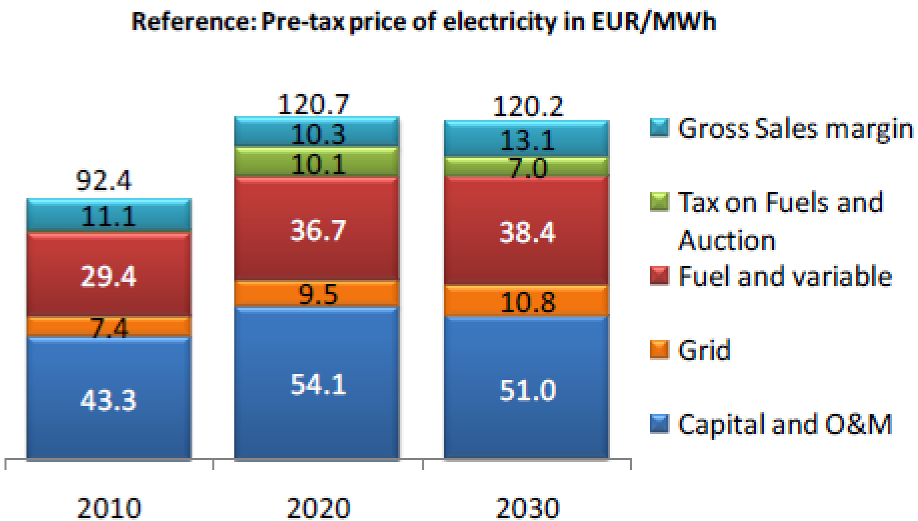
Particles per bunch	3.7×10^9	bunches per pulse	312
bunch spacing	$15\,cm$	bunch length	$44\,\mu m$
initial r.m.s. energy spread	$\leq 2\,\%$	final r.m.s. energy spread	$0.35\,\%$
initial horizontal emittance	$\leq 600\,nm$	final horizontal emittance	$\leq 660\,nm$
initial vertical emittance	$\leq 10\,nm$	final vertical emittance	$\leq 20\,nm$

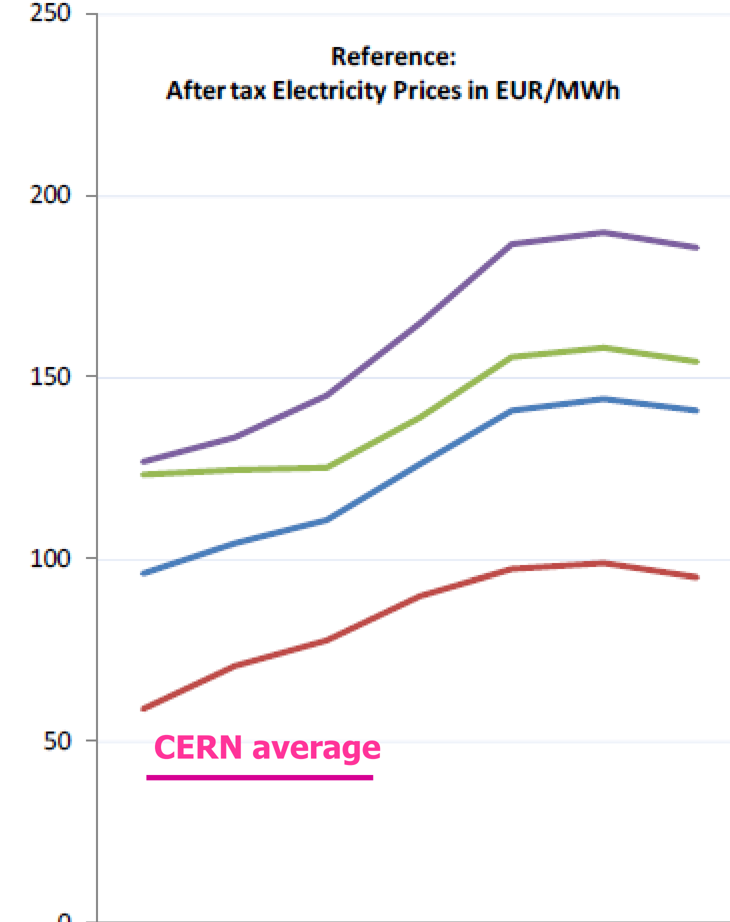
Electricity price projections

European Commission, Directorate-General for Energy

EU energy trends to 2030, Reference Scenario 2010







	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

CLIC CDR parameters for Scenario A

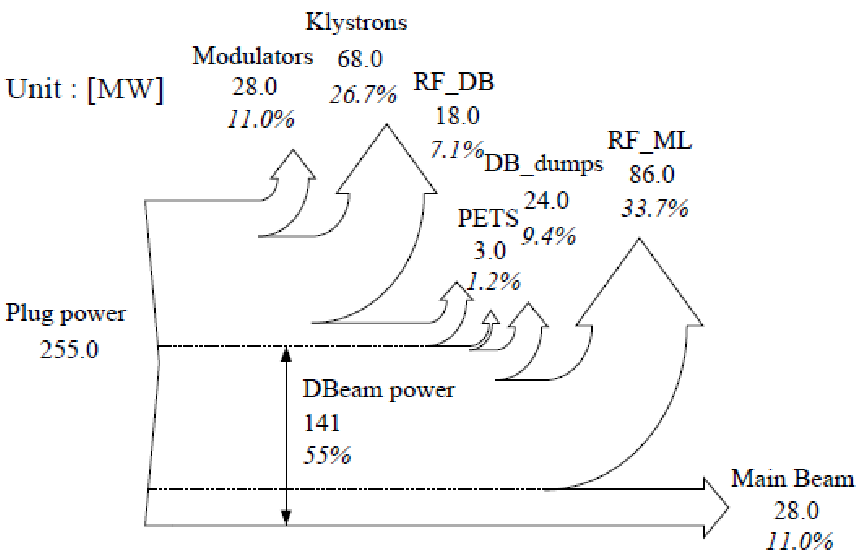
« optimized for luminosity at 500 GeV »

Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1400	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		354	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	80	80/100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	2.3	3.2	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	1.4	1.3	2
Main tunnel length		km	13.2	27.2	48.3
Charge per bunch	N	10^9	6.8	3.7	3.7
Bunch length	σ_z	µm	72	44	44
IP beam size	σ_x/σ_y	nm	200/2.6	≈ 60/1.5	≈ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	2350/20	660/20	660/20
Normalised emittance (IP)	$\varepsilon_x/\varepsilon_y$	nm	2400/25	—	—
Estimated power consumption	P_{wall}	MW	272	364	589

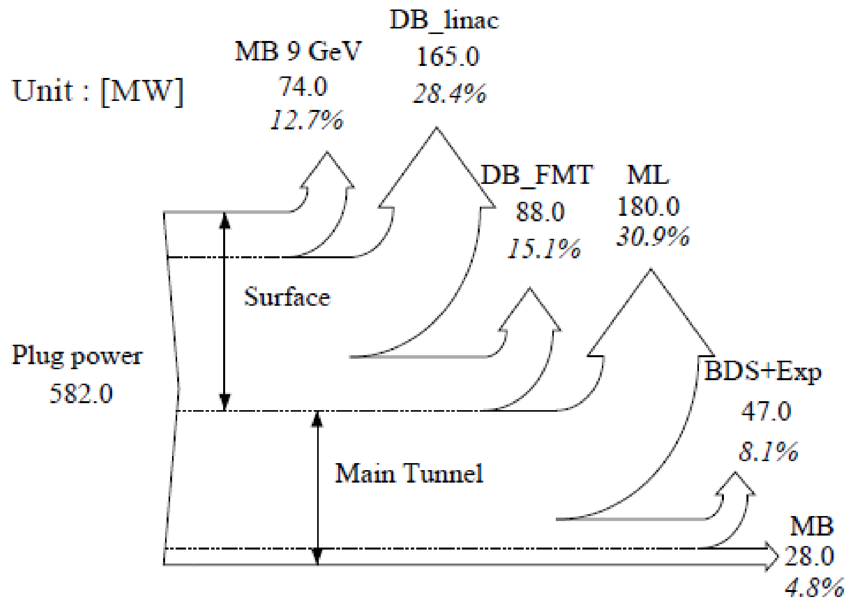
CLIC CDR parameters for Scenario B

« lower entry cost »

Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	≈ 60/1.5	≈ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589



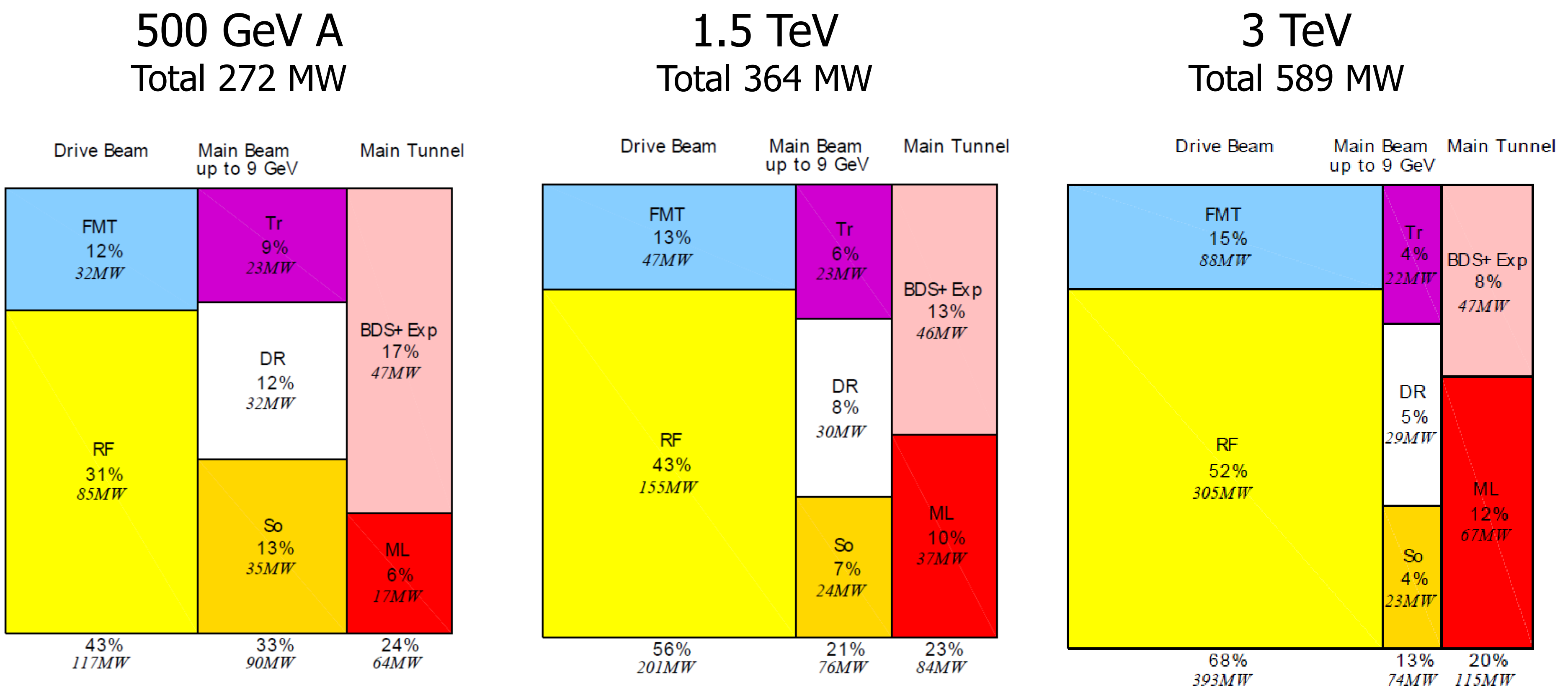
Power flow for the main RF system of CLIC at 3 TeV



Overall power flow for CLIC at 3 TeV

CLIC power consumption by WBS domain

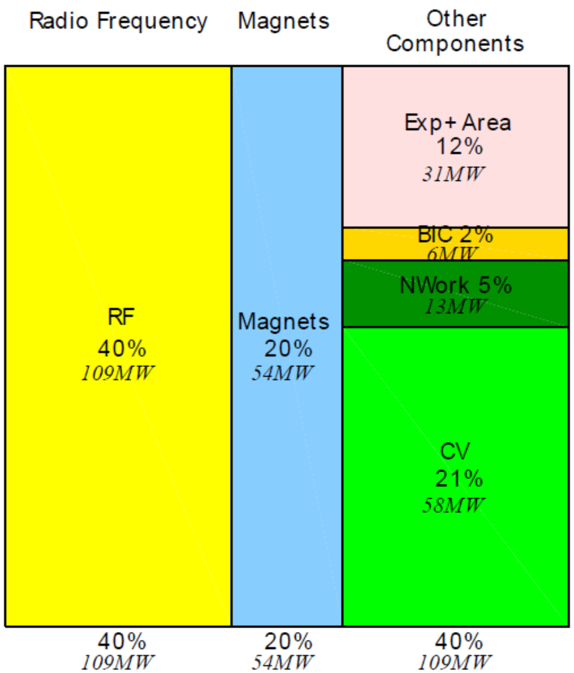
Power consumption of ancillary systems ventilated pro rata of and included in numbers by WBS domain



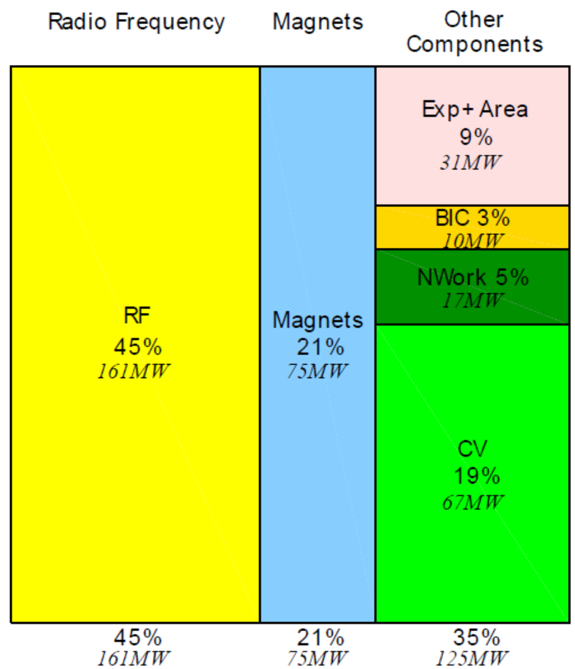
RF: drive beam linac, FMT: frequency multiplication & transport, So: sources & acceleration up to 2.5 GeV, DR: damping rings, Tr: booster linac up to 9 GeV & transport, ML: main linacs, BDS: beam delivery system, main dump & experimental area

CLIC power consumption by technical system

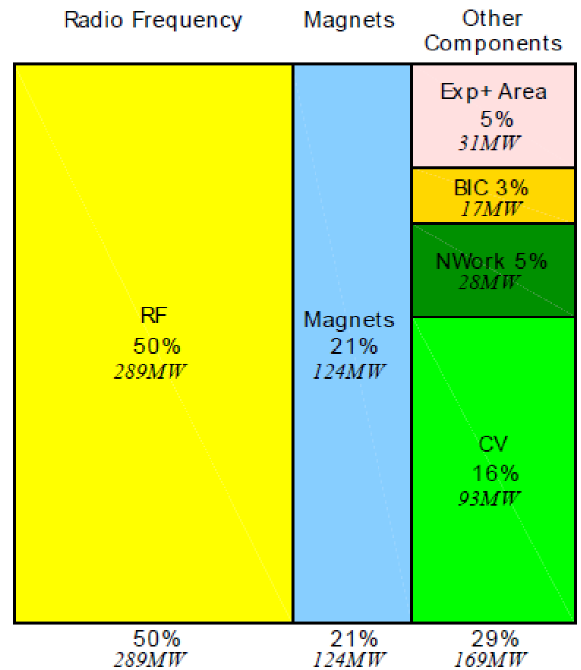
500 GeV A
Total 272 MW



1.5 TeV
Total 364 MW



3 TeV
Total 589 MW



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

CLIC CDR
Integrated luminosity/Collision energy scenarios

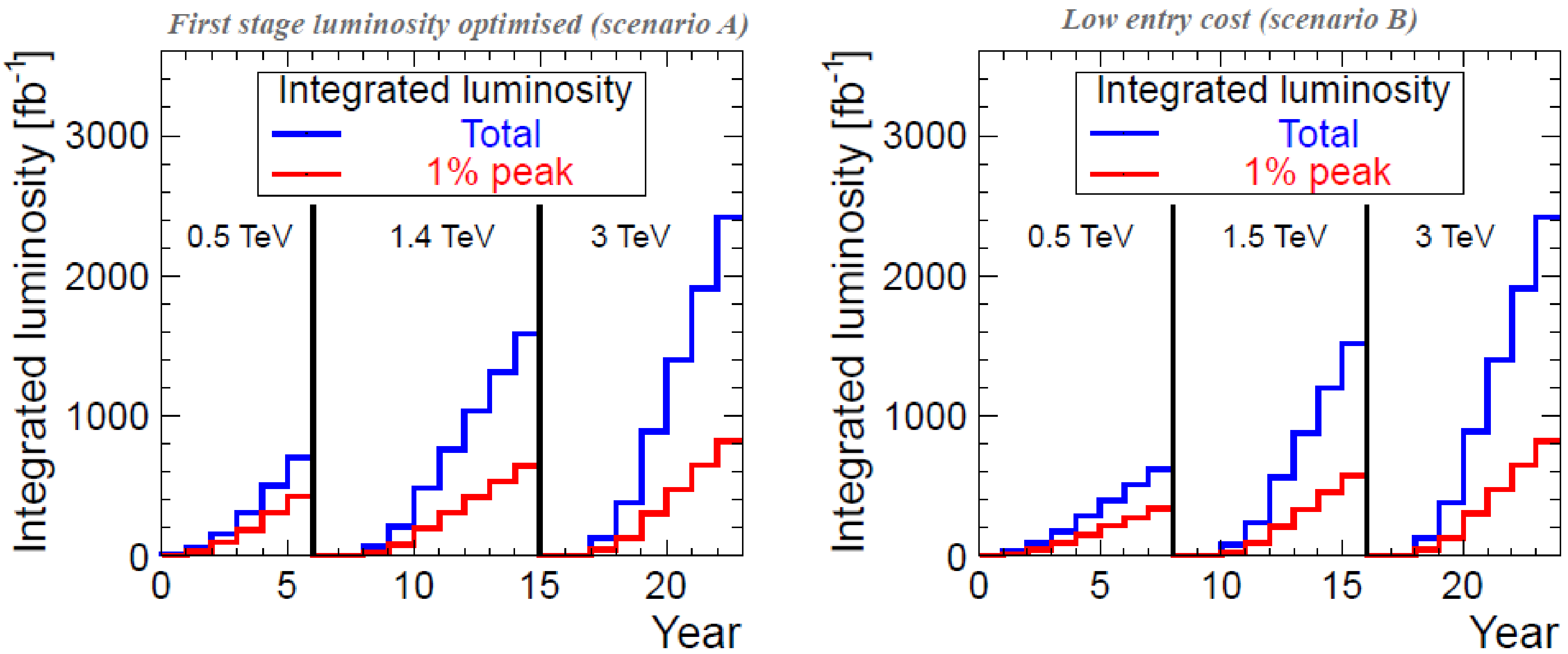


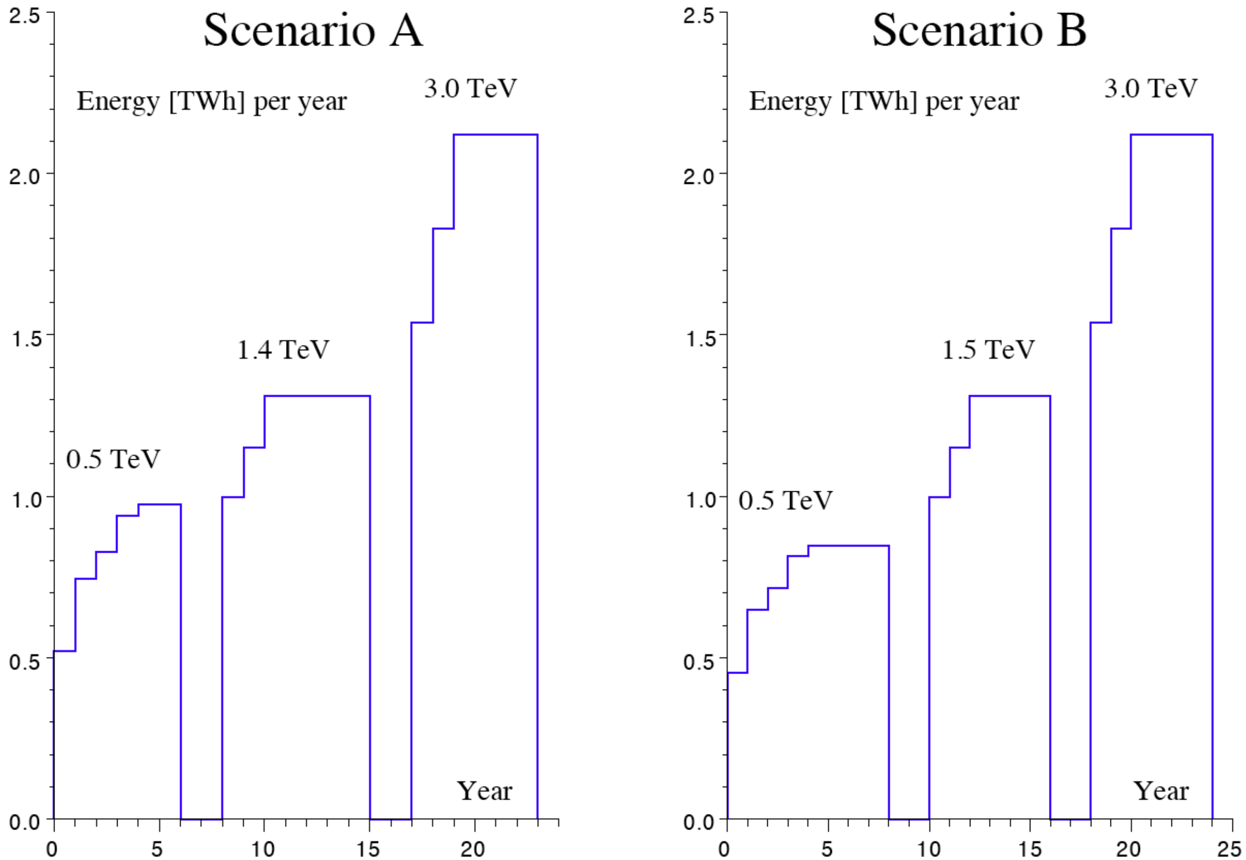
Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two years (25%, 50%) in subsequent stages.

From power to energy
CLIC CDR assumptions

For each value of CM energy

- 177 days/year of beam time
- 188 days/year of scheduled and fault stops
- First year
  - 59 days of injector and one-by-one sector commissioning
  - 59 days of main linac commissioning, one linac at a time
  - 59 days of luminosity operation
  - All along : 50% of downtime
- Second year
  - 88 days with one linac at a time and 30 % of downtime
  - 88 days without downtime
- Third year
  - Still only one e+ target at 0.5 TeV, like for years 1 & 2
  - Nominal at 1.5 and 3 TeV
- Power during stops: scheduled (shutdown), unscheduled (fault), downtime

CLIC CDR
Yearly energy consumption



Integral over the whole programme

- Scenario A : 25.6 TWh
- Scenario B : 25.3 TWh

The four pillars of energy economy

Paths to power & energy savings
Sobriety

- Reduced current density in normal-conducting magnets
  - Magnets & overheads (electrical network losses, cooling & ventilation) represent 27 % of overall power at 3 TeV
  - For given magnet size and field, power scales with current density
  - Compromise between capital & real estate costs on one hand, and operation costs on the other hand
- Reduction of ventilation duty
  - Most heat loads already taken by water cooling
  - Possible further reduction in main tunnel by thermal shielding of cables
  - Possible reduction in surface buildings by improved thermal insulation, natural ventilation, relaxation of temperature limits

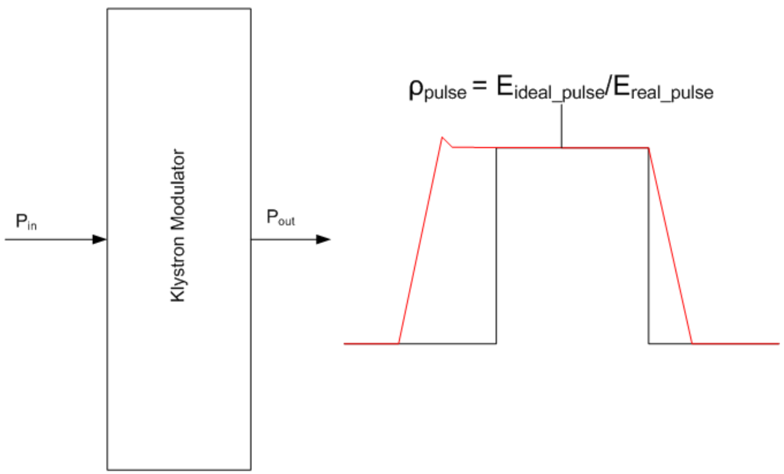
Paths to power & energy savings
Efficiency

- Grid-to-RF power conversion
  - R&D on klystrons
  - R&D on modulators, powering from the grid at HV
- RF-to-beam power conversion
  - Re-optimization of accelerating structures and gradient
- Permanent or super-ferric superconducting magnets
  - Permanent magnets
    - distributed uses, e.g. main linac DB quads
    - fixed-field/gradient or mechanical tuning
  - Super-ferric superconducting magnets
    - « grouped » and DC uses, e.g. combiner rings, DB return loops in main linacs

Total potential for further power savings at 3 TeV
- RF already taken at high efficiency
- magnets ~ 86 MW
- cooling & ventilation ~24 MW

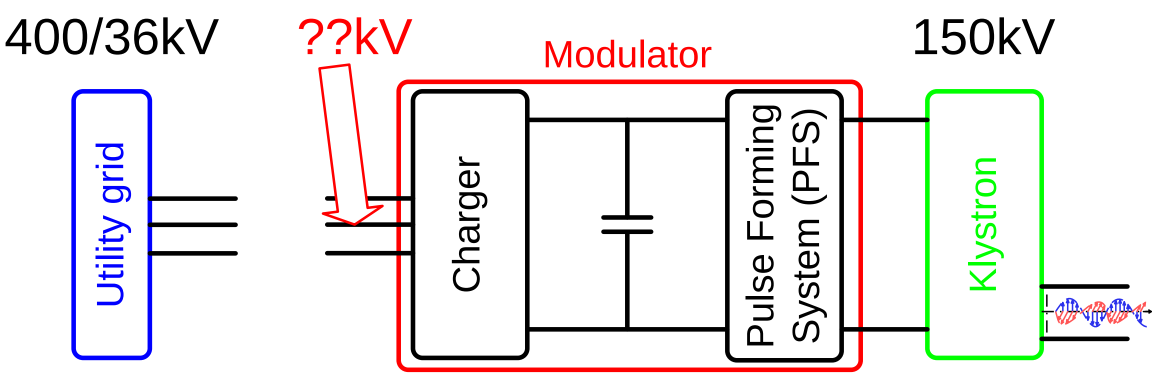
Development of high-efficiency modulators

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



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

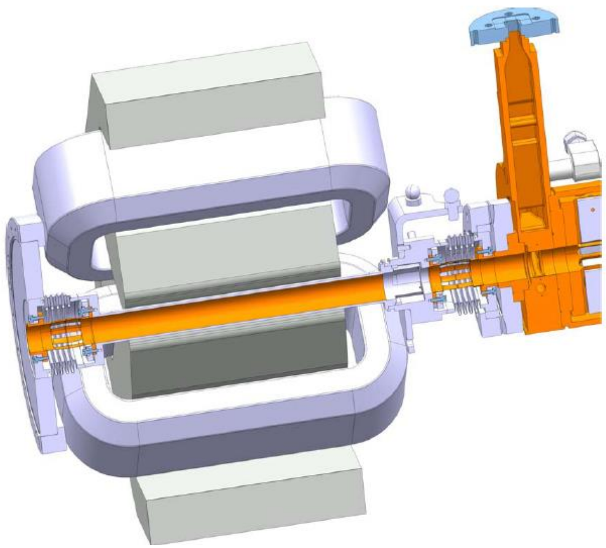
Useful flat-top Energy	22MW*140μs = 3.08kJ
Rise/fall time energy	22MW*5μs*2/3= 0.07kJ
Set-up time energy	22MW*5μs = 0.09kJ
Pulse efficiency	**0.95**
Pulse forming system efficiency	0.98
Charger efficiency	0.96
Power efficiency	**0.94**
Overall Modulator efficiency	**89%**



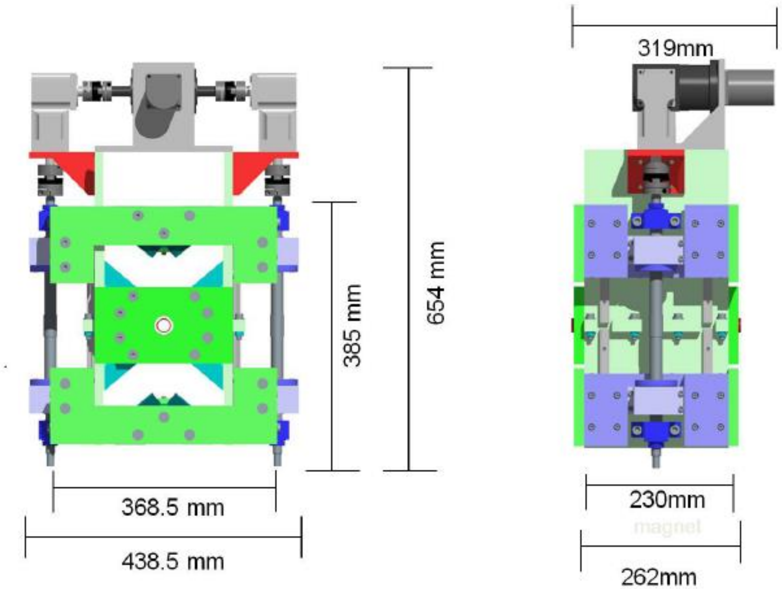
D. Nisbet & D. Aguglia

Main linac DB quadrupoles

Conventional electromagnet



Tunable permanent magnet



M. Modena, B. Shepherd

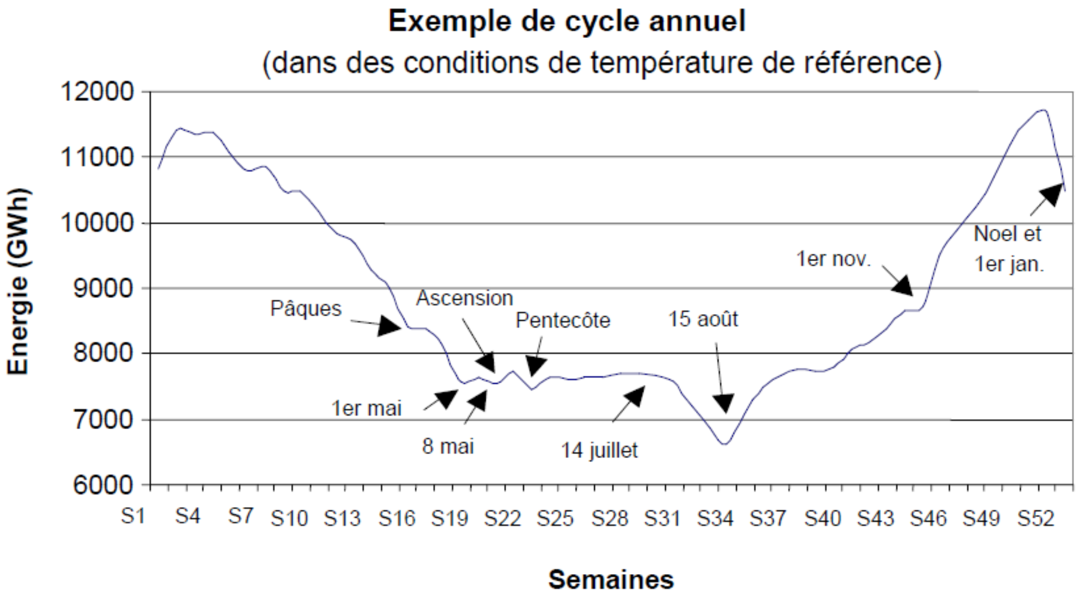
Paths to power & energy savings
Energy management

- Low-power configurations in case of beam interruption

Staging Scenario	E_{CM} [TeV]	$P_{nominal}$ [MW]	$P_{waiting\ for\ beam}$ [MW]	$P_{shutdown}$ [MW]
	0.5	272	168	37
A	1.4	364	190	42
	3.0	589	268	58
	0.5	235	167	35
B	1.5	364	190	42
	3.0	589	268	58

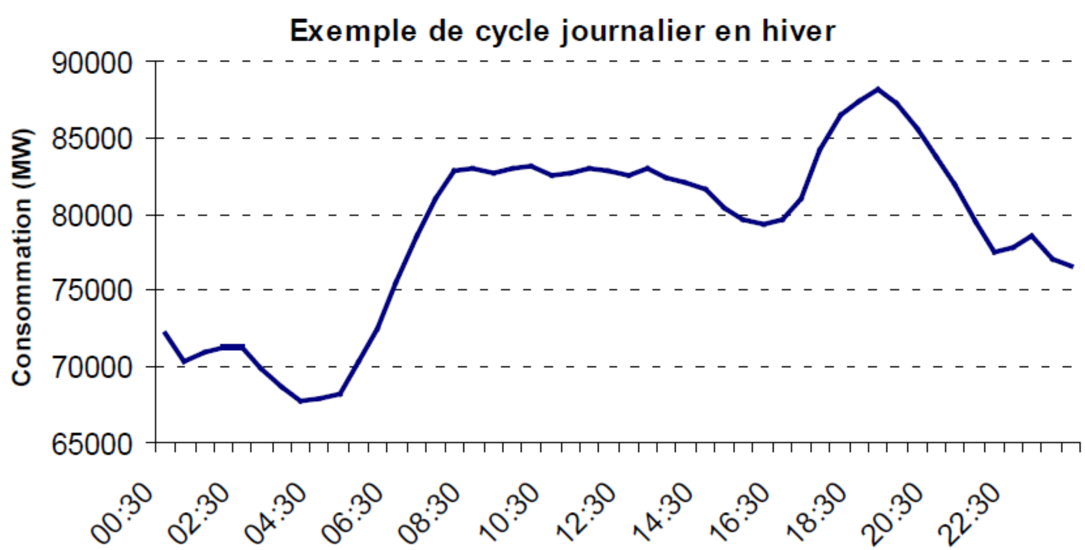
- Modulation of scheduled operation to match electricity demand
  - Seasonal load shedding
  - Diurnal peak shaving

Variations of electricity demand in France
(source: RTE)



Annual variations of power consumption (integrated weekly)

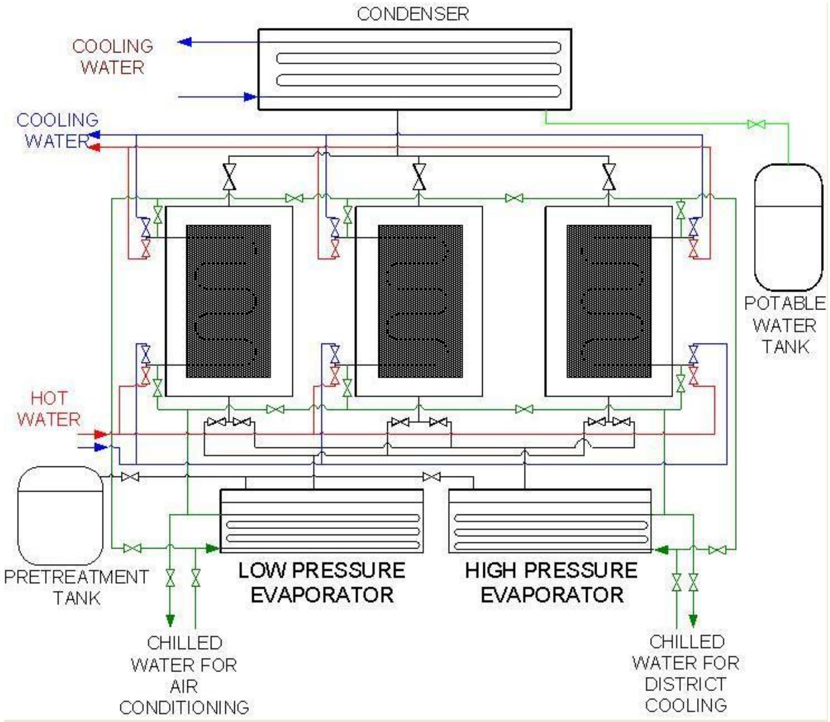
Diurnal variations of power consumption (winter day)



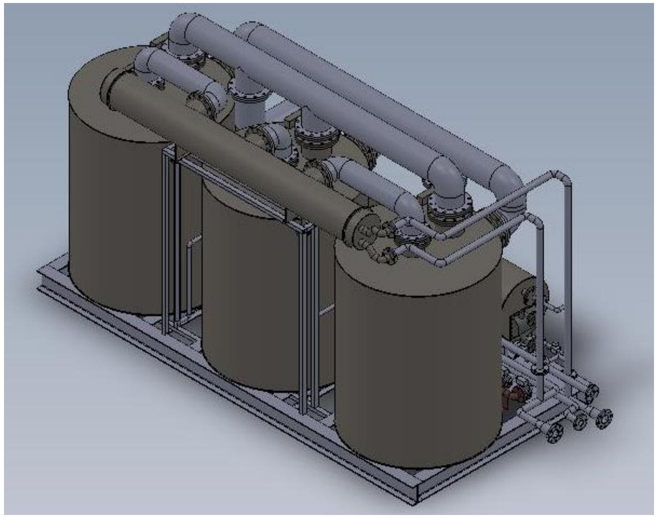
Paths to power & energy savings
Waste heat recovery

- Possibilities of heat rejection at higher temperature, e.g. beam dumps
- Valorization of low-grade waste heat for concomitant needs, e.g. residential heating or absorption cooling

Three-bed, two evaporator adsorption chiller (Wroclaw Technology Park)



$T_{hot\ water}$	60°C
$T_{cooling\ water}$	25°C
$T_{chilled\ water\ LP}$	9°C
$T_{chilled\ water\ HP}$	15°C
Capacity	12.5 Rton ~ 45 kW
Mode	3-bed, 2-evaporator



Is waste heat worth recovering?

- Consider heat rejection Q at temperature T with environment at T_0
- What are the recovery options?
  1) use as such
     - Is there a concomitant need for heat Q at $T=T_{use}$?
  2) use as heat at higher temperature $T_{use}>T$
     - Minimum work required for heat pump $W_{min} = Q\,(T_{use}/T - 1)$
     - Example: for raising waste heat from 40 °C to 80 °C, $W_{min} = 0.13\,Q$
     - In practice, W_{real} may be 2 to 3 times higher
     - May still be an interesting option
  3) use to produce work
     - Maximum work produced (Carnot machine) $W_{max} = Q\,(1 - T_0/T)$
     - This can also be written $W_{max} = Q - T_0\,\Delta S$ = Exergy
     - Example: with T = 40 °C and T_0 = 15 °C, $W_{max} = 0.08\,Q$
     - In practice, W_{real} is only a fraction of this
     - Very inefficient unless one operates at higher T

⇒ *Investigate all options, using both energy and exergy as f.o.m.*

Energy & exergy in CLIC magnet systems
T cooling water = 40 °C

Tenvironment = Tair = 15 C = 288 K						
Twater = 40 C = 313 K						
Assume 0.9 of magnet energy in water, 0.1 in air						
	Electrical efficiency	Electrical energy	Heat rejected in water	Heat rejected in air	Electrical exergy	Exergy in water
Network	NA	100.0			100.0	
AC distribution	0.97	97.0		3.0	97.0	
Power converter	0.9	87.3	9.7		87.3	0.8
DC cables	0.95	82.9		4.4	82.9	
Magnet	0	0.0	74.6	8.3	0.0	6.0
Environment	NA		84.3	15.7		6.7

- 100 drawn from network produces only 82.9 used in magnet
- Waste heat in water contains 84.3% of consumed energy, but only 6.7% of consumed exergy: waste heat recovery is therefore interesting for final use as heat, not as source of electrical/mechanical energy
- Exergy economy should target improvement of electrical efficiency upstream the magnets, rather than waste heat recovery

Energy & exergy in CLIC magnet systems
T cooling water = 60 °C

Tenvironment = Tair = 15 C = 288 K						
Twater = 60 C = 333 K						
Assume 0.9 of magnet energy in water, 0.1 in air						
	Electrical efficiency	Electrical energy	Heat rejected in water	Heat rejected in air	Electrical exergy	Exergy in water
Network	NA	100.0			100.0	
AC distribution	0.97	97.0		3.0	97.0	
Power converter	0.9	87.3	9.7		87.3	1.3
DC cables	0.95	82.9		4.4	82.9	
Magnet	0	0.0	74.6	8.3	0.0	10.1
Environment	NA		84.3	15.7		11.4

- Increasing cooling water temperature to 60 °C raises its exergy content to 11.4%

Energy & exergy in CLIC RF systems
T cooling water = 40 °C

Tenvironment = Tair = 15 C = 288 K								
Twater1 = 40 C = 313 K								
Twater2 = 40 C = 313 K								
Assume 0.25 of AS energy in beam, 0.65 in water, 0.1 in air								
	Electrical efficiency	Electrical energy	Heat rejected in water1	Heat rejected in water2	Heat rejected in air	Electrical exergy	Exergy in water1	Exergy in water2
Network	NA	100.0				100.0		
AC distribution	0.97	97.0			3.0	97.0		
Modulator	0.89	86.3	10.7			86.3	0.9	
Klystron	0.7	60.4		25.9		60.4		2.1
RF distr & DB cavity	0.89	53.8	6.6			53.8	0.5	
PETS	0.98	52.7	1.1			52.7	0.1	
DB deceleration	0.83	43.7		9.0		43.7		0.7
AS	0.25	10.9	28.4		4.4	10.9	2.3	
MB dump	0	0.0		10.9		0.0		0.9
Environment	NA		46.8	45.8	7.4		3.7	3.7

- 100 drawn from network produces only 53.8 in PETS, 43.7 in AS, of which 10.9 goes into the main beam
- Waste heat in water contains 92.6% of consumed energy, but only 7.4% of consumed exergy: waste heat should rather be valorized as heat
- Exergy economy should target improvement of electrical efficiency upstream the magnets, rather than waste heat recovery

Energy & exergy in CLIC RF systems
T cooling water = 40 °C & 80 °C (klystrons & b. dumps)

Tenvironment = Tair = 15 C = 288 K								
Twater1 = 40 C = 313 K								
Twater2 = 80 C = 353 K								
Assume 0.25 of AS energy in beam, 0.65 in water, 0.1 in air								
	Electrical efficiency	Electrical energy	Heat rejected in water1	Heat rejected in water2	Heat rejected in air	Electrical exergy	Exergy in water1	Exergy in water2
Network	NA	100.0				100.0		
AC distribution	0.97	97.0			3.0	97.0		
Modulator	0.89	86.3	10.7			86.3	0.9	
Klystron	0.7	60.4		25.9		60.4		4.8
RF distr & DB cavity	0.89	53.8	6.6			53.8	0.5	
PETS	0.98	52.7	1.1			52.7	0.1	
DB deceleration	0.83	43.7		9.0		43.7		1.6
AS	0.25	10.9	28.4		4.4	10.9	2.3	
MB dump	0	0.0		10.9		0.0		2.0
Environment	NA		46.8	45.8	7.4		3.7	8.4

- Increasing klystron and beam dump cooling water temperature to 80 °C raises its exergy content to 8.4%, i.e. 12.1% in total (water1 and water2)

Conclusions

- Power consumption of CLIC and other large accelerator projects at the energy frontier has become a major issue in their technical feasibility, economic affordability and social acceptance
- Power and energy savings are therefore essential aspects of the study of such machines from the conceptual design phase
- Paths towards this goal must combine sobriety, efficiency, optimal energy management and waste heat recovery and valorisation
- Exergy content of CLIC waste heat remains low at acceptable recovery temperatures
  - Conversion to mechanical work is inefficient
  - Use for heating/cooling may be economical, provided one finds concomitant needs

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