CLIC CDR
Power & Energy

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Contents

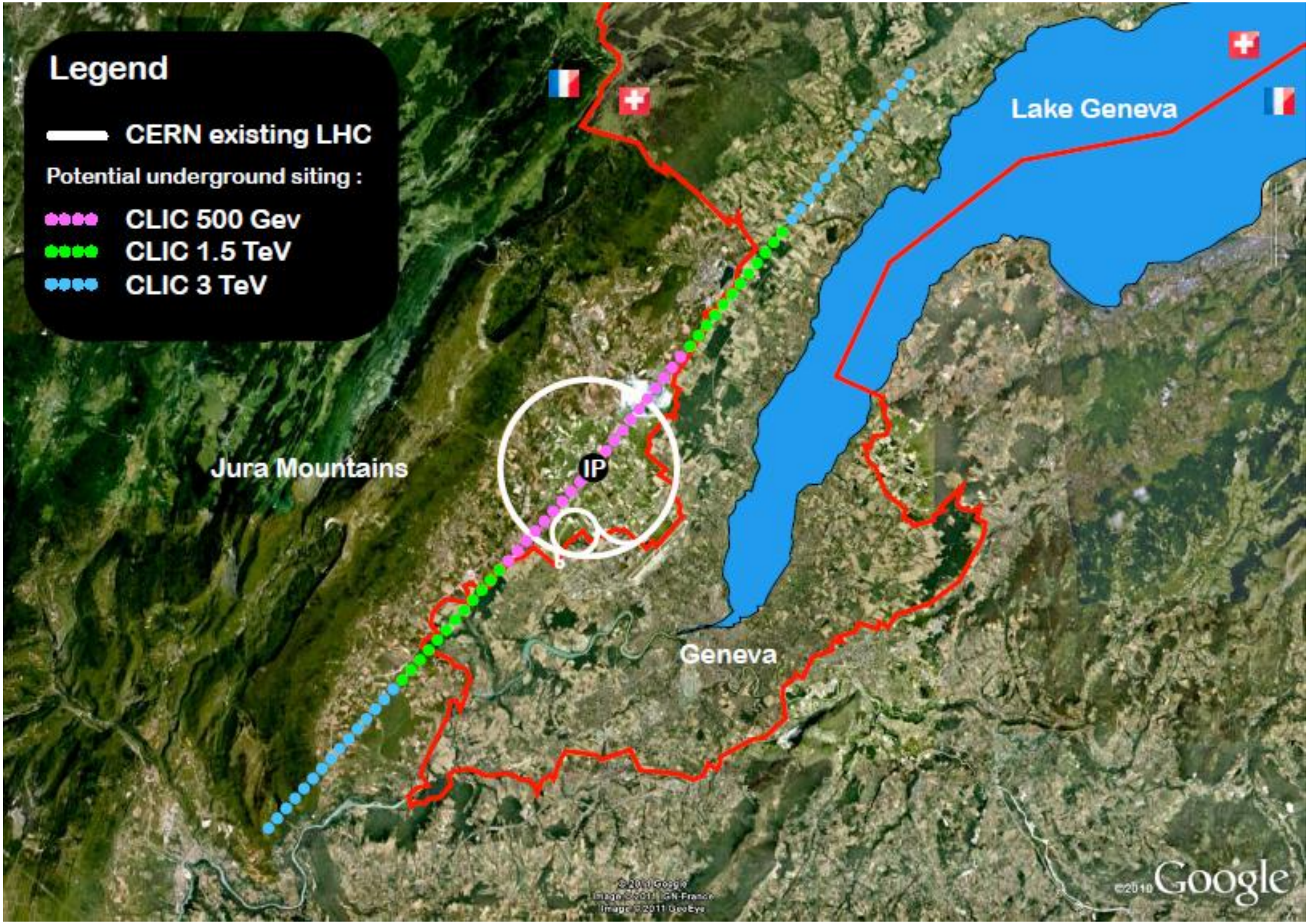
- Scope of the CLIC CDR study
- Power, energy and efficiency estimates
- Electrical power distribution
- Cooling and HVAC
- Paths to power and energy savings
- Conclusion

Contents

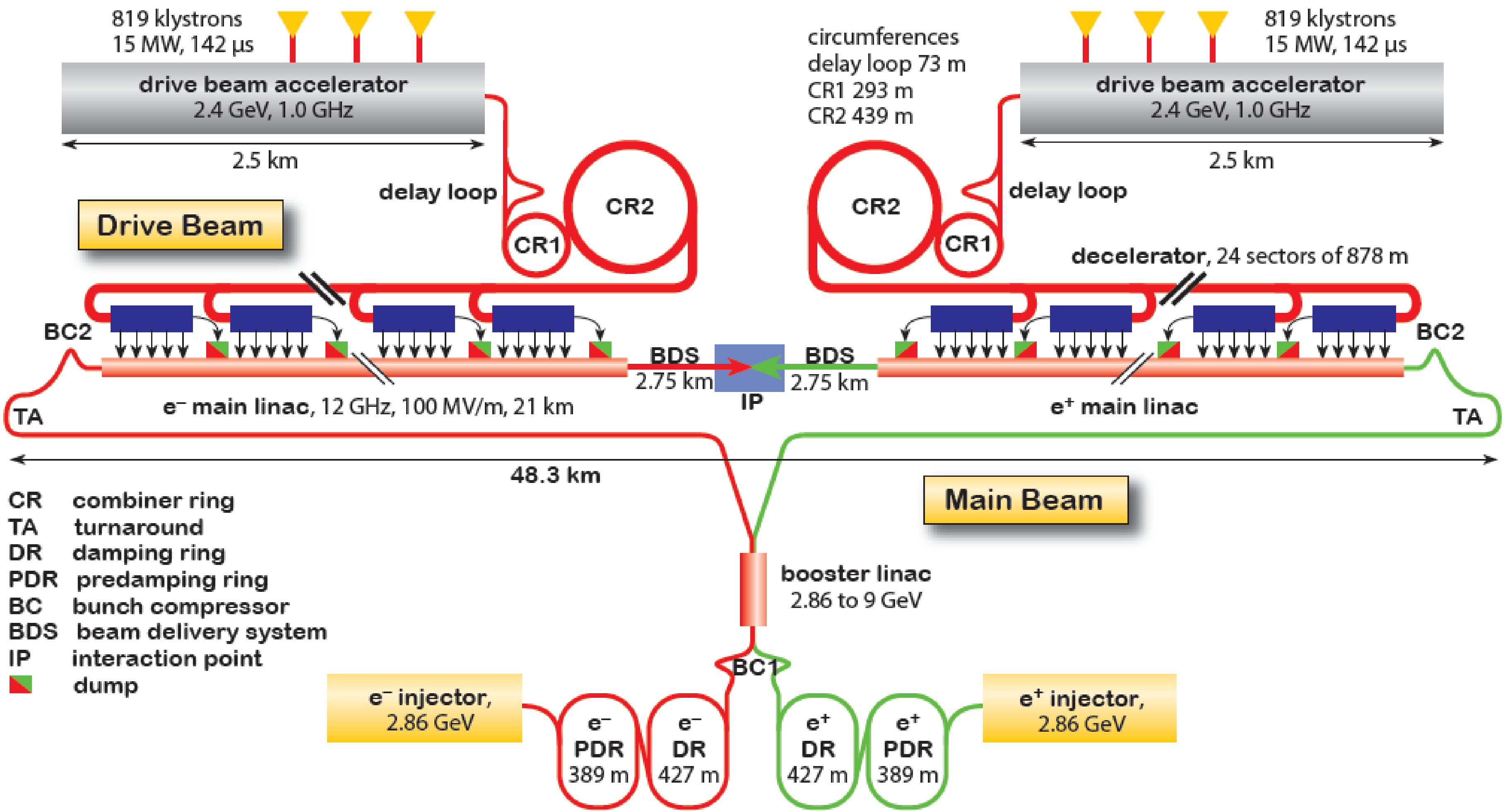
Scope of the CLIC CDR study
CDR Volume 1

- The basic parameters for the CLIC CDR study are optimized for a collision energy of 3 TeV and a peak luminosity of 2 E34 cm^{-2} s^{-1}
- The study includes a first stage at 500 GeV and a second stage at ~1.5 TeV, for which a single drive-beam production complex is sufficient to power both main linacs
- The bunch charge must be almost doubled to preserve luminosity at 500 GeV. This results in
  - Main linac accelerating structures with larger iris and lower gradient (80 MV/m)
  - Longer main linacs (2 x 5 sectors)
  - Increased RF power in the drive-beam and main-beam production complexes
- Accelerator and technical systems are built as far as possible in a modular way, so as to follow the staged construction. Part of the infrastructure is however defined by the 3 TeV horizon
- A possible operation schedule based on physics requirements and expected machine performance enables to estimate energy consumption
  - Integrated luminosity of 500 fb^{-1} at 500 GeV, 1.5 ab^{-1} at ~1.5 TeV, and 2 ab^{-1} at 3 TeV
  - Operational efficiency (collider & detectors) taken at 0.5 for 200 days/year, with ramp-up in initial years

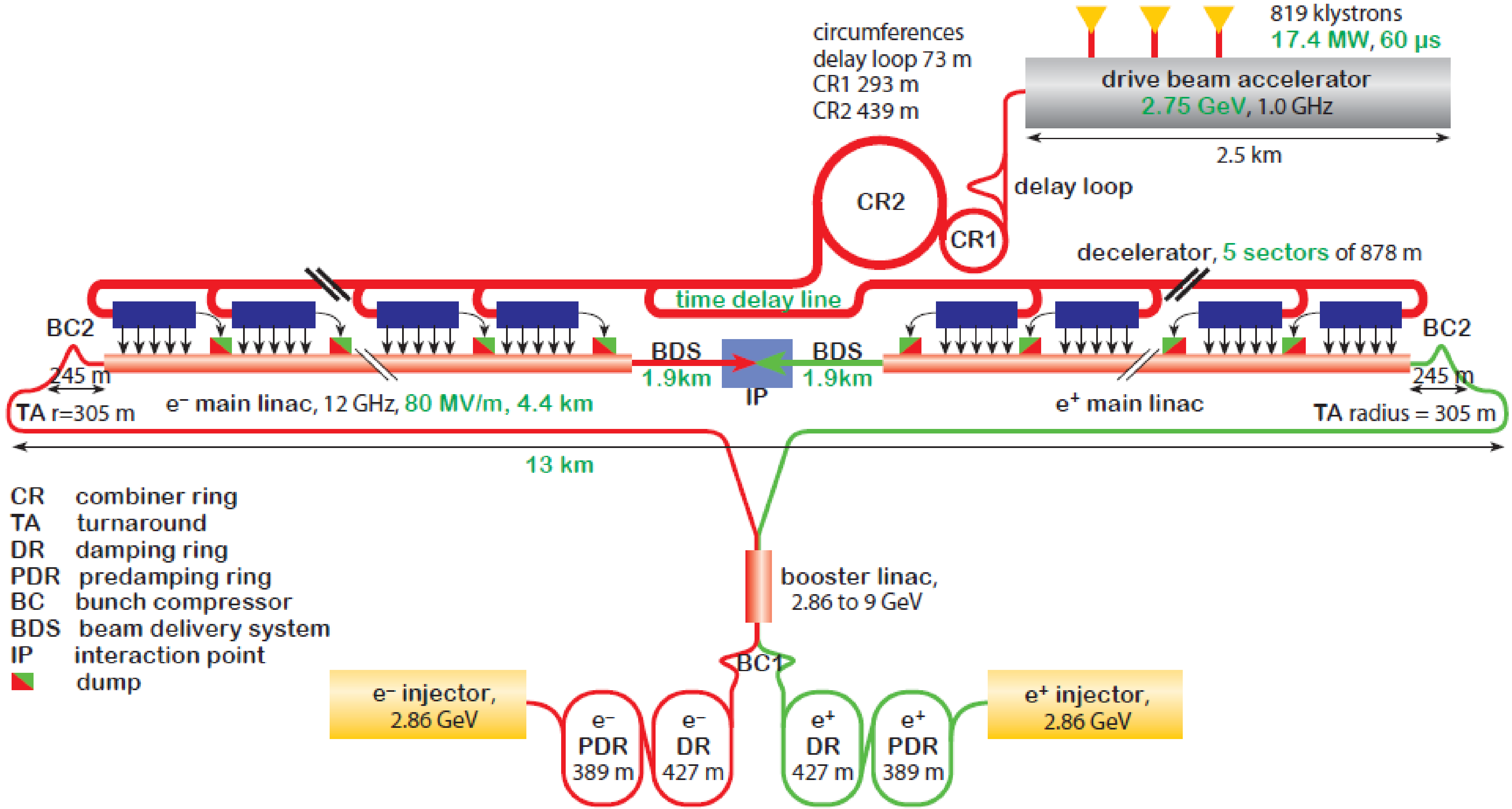
CLIC footprints near CERN



CLIC layout at 3 TeV



CLIC layout at 500 GeV



CR combiner ring
TA turnaround
DR damping ring
PDR predamping ring
BC bunch compressor
BDS beam delivery system
IP interaction point
dump

Scope of the CLIC CDR study
Changes in CDR Volume 3

- Two alternative staging scenarios
  - Each with three stages: 500 GeV, ~1.5 TeV and 3 TeV
  - Scenario A: « optimized for luminosity in the first stage »
  - Scenario B: « optimized for lower entry cost »
  - First and last stages of scenario A are identical to CDR Volume 1
  - Reuse of 80 MV/m structures in scenario A limits the energy of the second stage to 1.4 TeV
  - Scenario B has nominal bunch charge at all stages, resulting in
    - Use of final (100 MV/m) gradient structures already at 500 GeV
    - Shorter main linacs (2 x 4 sectors)
    - Lower installed RF power in the main-beam and drive-beam production complexes

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

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

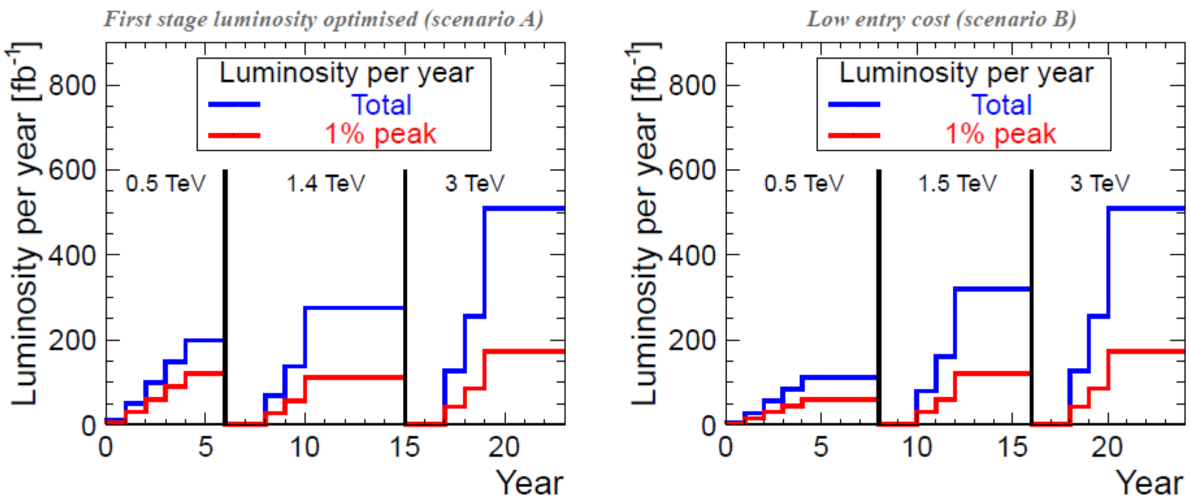


Fig. 5.1: Luminosity per year in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right).

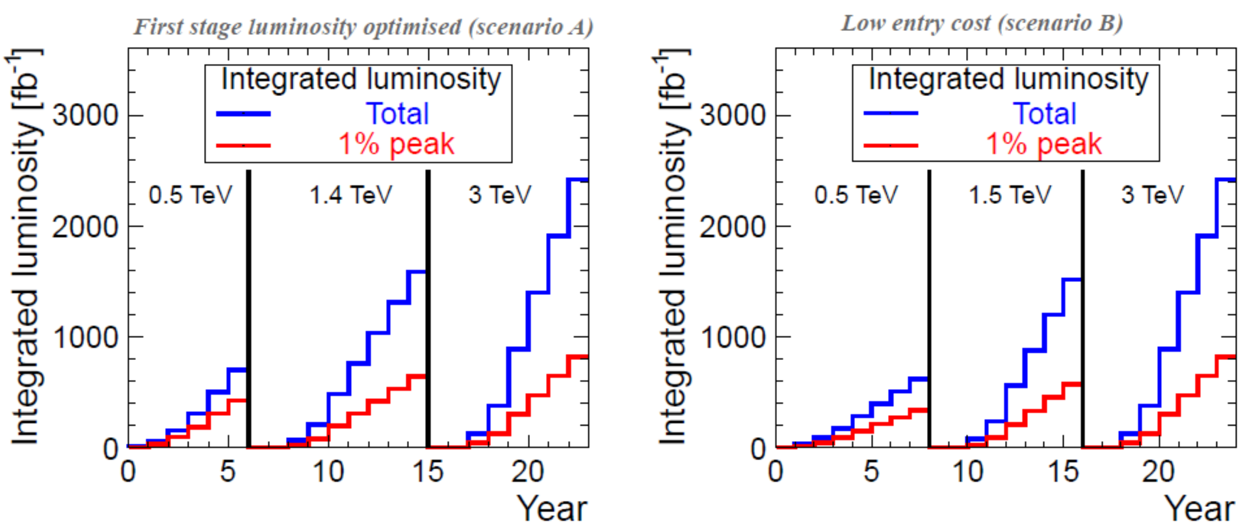


Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two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

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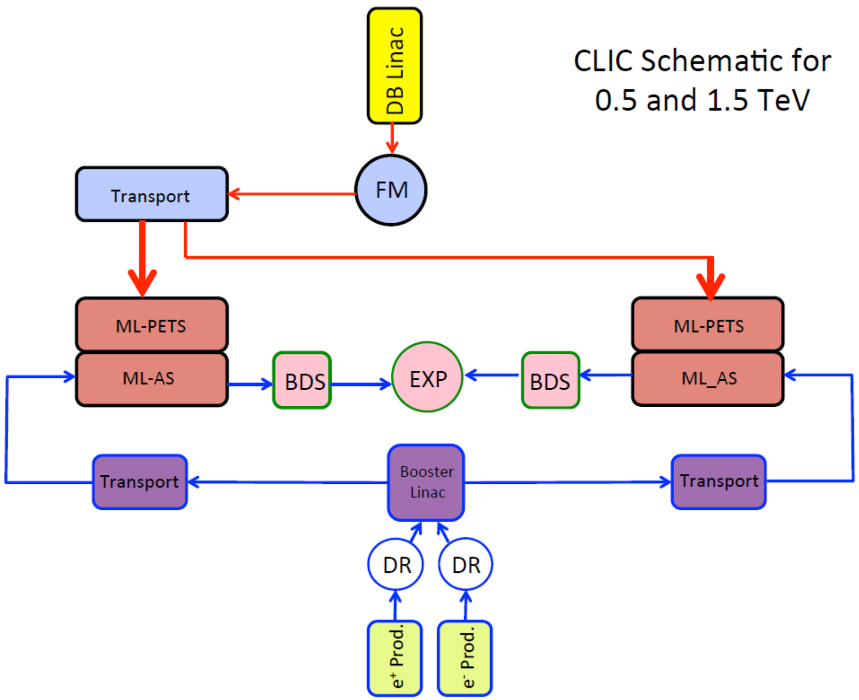
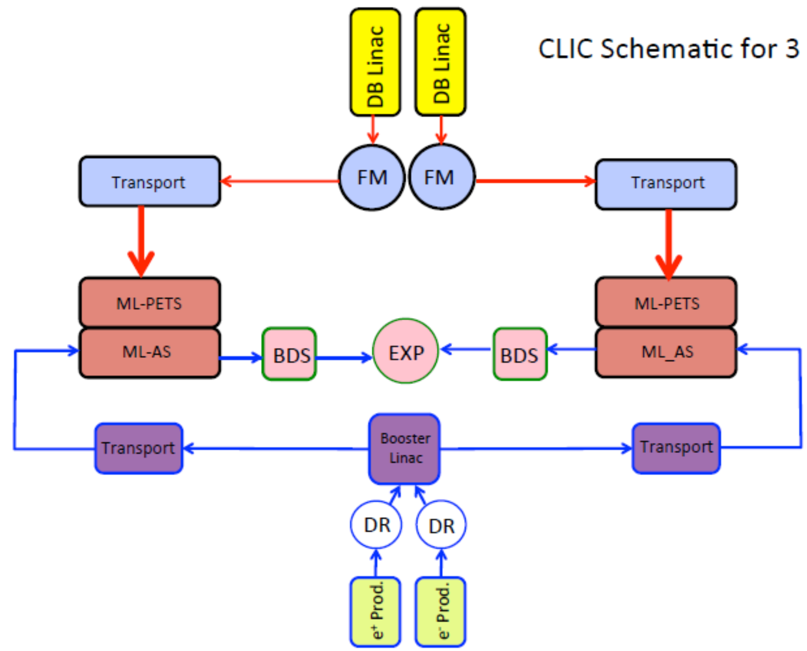
CLIC functional schematics



CLIC Schematic for 0.5 and 1.5 TeV



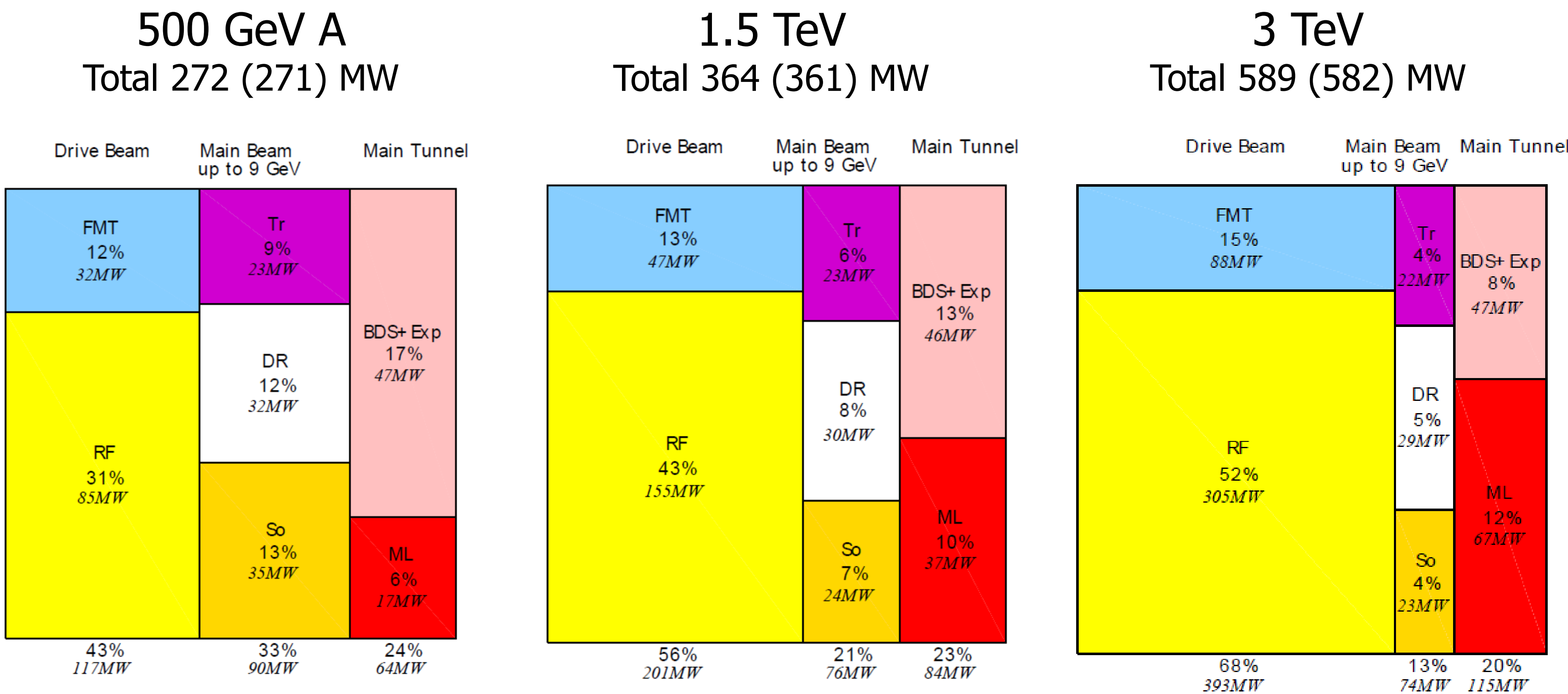
CLIC Schematic for 3 TeV

Assumptions & boundary conditions for power estimates

- Power & energy consumption are consistent with the technical definition of the CLIC accelerator project as per the CDR
  - Minor adjustments have been made to the numbers between CDR Volume 1 and Volume 3
  - In addition, Volume 3 includes numbers for scenario 500 GeV B
- Assumptions for RF-to-beam efficiencies
  - Modulators 0.89 (0.95 flat-top, 3 μs rise time, 5 μs setting time)
  - Klystrons 0.7 (R&D goal, best achieved today 0.68)
  - Drive beam acceleration 0.89 (low-gradient structures)
  - PETS (fully loaded) 0.98
  - Residual drive beam power after deceleration 17 % $\Rightarrow$ effective power extraction from drive beam 0.81
  - Main beam acceleration 0.25 (compromise between gradient, efficiency and minimization of wake fields)
- A number of technical alternatives aiming at mitigation of power and energy consumption have been identified, and will be studied in the post-CDR phase

Power consumption by WBS domain

Minor changes between CDR Volume 1 and Volume 3
Numbers in parentheses refer to CDR Volume 1
Power consumption of ancillary systems ventilated pro rata and included in numbers by WBS domain

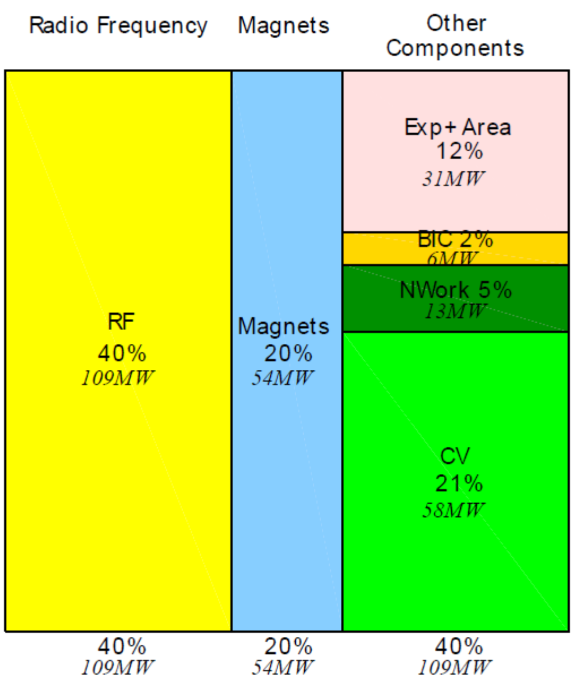


RF: drive beam linac, FMT: frequency multiplication & transport, So: sources & acceleration up to 2.5 GeV, DR: damping rings, Tr: booster linac up to 9 GeV & transport, ML: main linacs, BDS: beam delivery system, main dump & experimental area

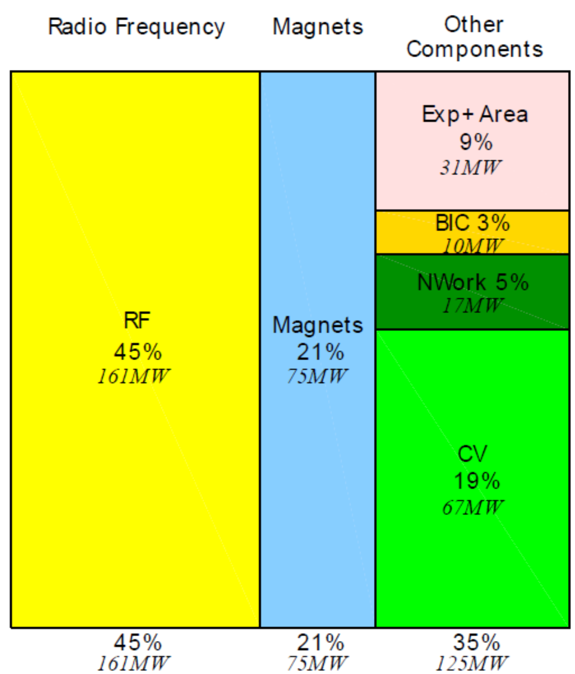
Power consumption by technical system

Minor changes between CDR Volume 1 and Volume 3
Numbers in parentheses refer to CDR Volume 1

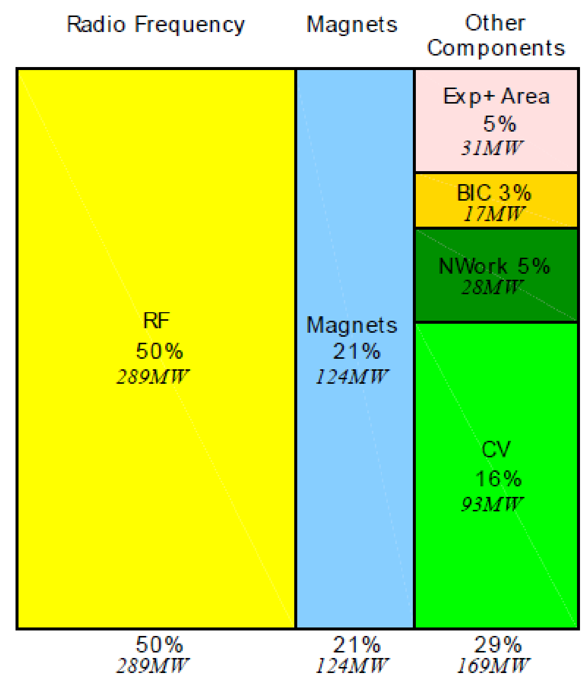
500 GeV A
Total 272 (271) MW



1.5 TeV
Total 364 (361) MW



3 TeV
Total 589 (582) MW



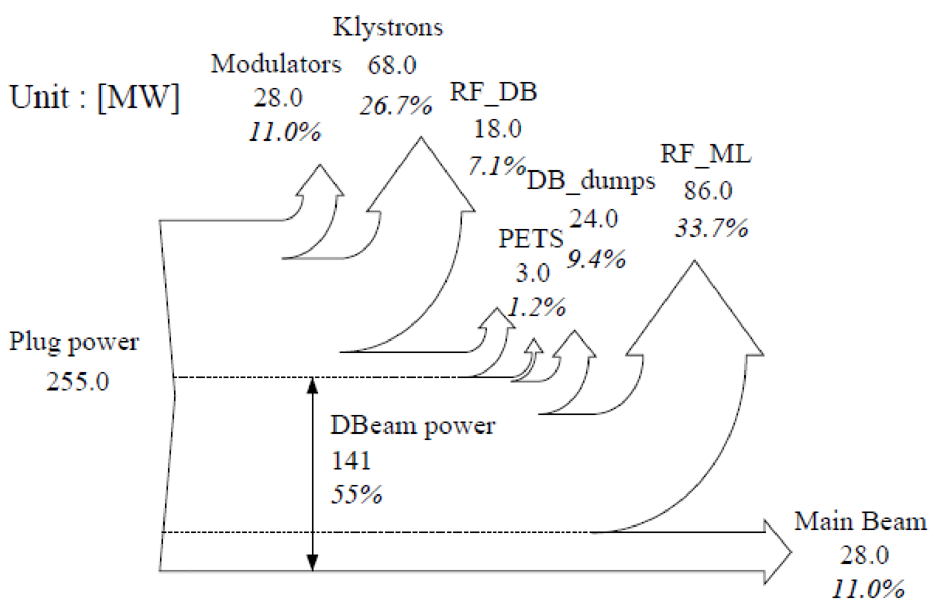
CV: cooling & ventilation, NW: electrical network losses, BIC: beam instrumentation & control

Scenario A

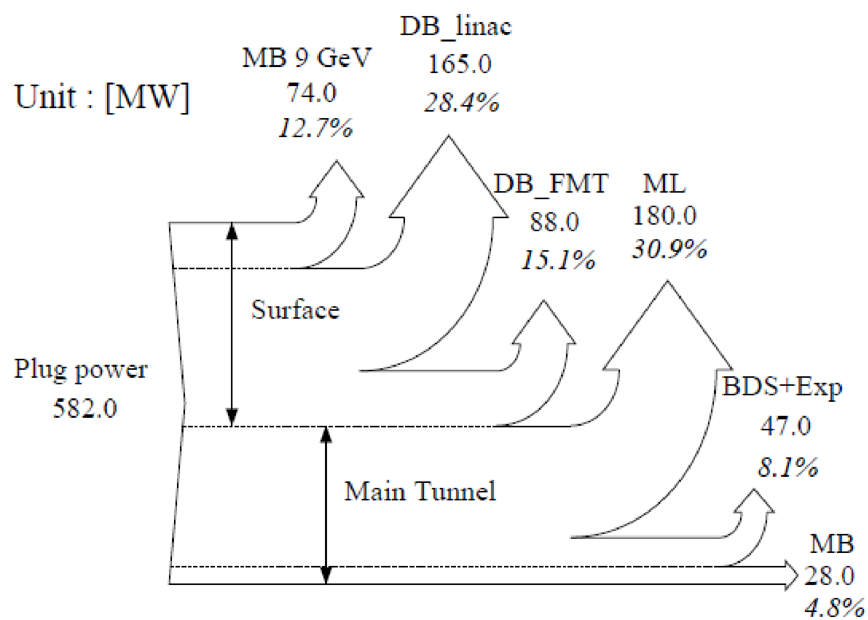
Item nb.	System	Power [MW] 0.5 TeV	1.5 TeV	3 TeV
1	MB injectors magnets	1.0	1.0	1.0
2	MB injectors RF	24.3	16.5	16.5
3	MB PDR+DR magnets	5.1	5.1	5.1
4	MB PDR+DR RF	17.6	17.2	17.2
5	MB Transport	16.5	16.5	16.5
6	MB Long Transport Line	0.1	0.3	0.5
7	DB injectors Sol+Mag	3.4	3.4	6.8
8	DB injectors RF	66.8	127.6	255.2
9	DB FM	9.3	9.3	18.5
10	DB transport to tunnel	0.1	0.1	3.0
11	DB transport in tunnel	8.1	19.6	39.1
12	DB Long Delay Line	2.0	2.3	0.0
13	TBM MB	1.0	2.5	4.9
14	TBM DB	2.8	6.7	13.3
15	Post Decel	2.2	5.3	10.6
16	BDS	0.9	1.2	1.6
17	Interaction area	16.3	16.3	16.3
18	Dump Line	1.1	1.7	3.3
19	Instrum. Main tunnel	2.1	5.0	10.0
20	Instrum. other	3.0	3.0	4.0
21	Control Main tunnel	0.4	1.0	2.0
22	Control other	0.8	0.8	1.0
23	Experiment	15.0	15.0	15.0
Sub-total		200	277	462
24	Cooling + Ventilation	58	67	93
25	network losses	13	17	28
TOTAL [MW]		**271**	**361**	**582**
TOTAL [MVA]		284	379	609

Power flow at 3 TeV

RF chain only



All systems



	A	A	B	B
	LUM_opt		Low_entry	
E_CM [TeV]	0.5	1.4	0.5	1.5
POWER [MW]				
MB injectors magnets	1	1	1	1
MB injectors RF	**24.3**	16.5	**16.5**	16.5
MB PDR+DR magnets	5.1	5.1	5.1	5.1
MB PDR+DR RF	17.6	17.2	17.2	17.2
MB Transport	16.5	16.5	16.5	16.5
MB Long Transport Line	0.1	0.3	0.1	0.3
DB injectors Sol+Mag	3.4	3.4	3.4	3.4
DB injectors RF	**66.8**	127.6	**49.0**	127.6
DB FM	9.3	9.3	9.3	9.3
DB transport to tunnel	0.1	0.1	0.1	0.1
DB transport in tunnel	8.1	19.6	6.5	19.6
DB Long Delay Line	2.0	2.3	2.0	2.3
TBM MB	2.0	4.9	1.6	4.9
TBM DB	2.8	6.7	2.2	6.7
Post Decel	2.2	5.3	2.0	5.3
BDS	0.9	1.2	0.9	1.2
Interaction area	16.3	16.3	16.3	16.3
Dump Line	1.1	1.7	1.1	1.7
Experiment	15.0	15.0	15.0	15.0
Instrum. Main tunnel	2.1	5.0	2.0	5.0
Instrum. other	3.0	3.0	3.0	3.0
Control Main tunnel	0.4	1.0	0.4	1.0
Control other	0.8	0.8	0.8	0.8
Cooling & Ventilation	58.0	67.0	52.2	67.0
Network Losses	13.0	17.0	11.3	17.0
TOTAL POWER [MW]	**272**	**364**	**235**	**364**

MB injectors RF: Twice fewer e^+

DB injectors RF: 26% gain
16% on beam
10% on klystrons at optimum yield

Cooling & Ventilation, Network Losses: Proportional reduction with the above

From power to energy

For each value of CM energy

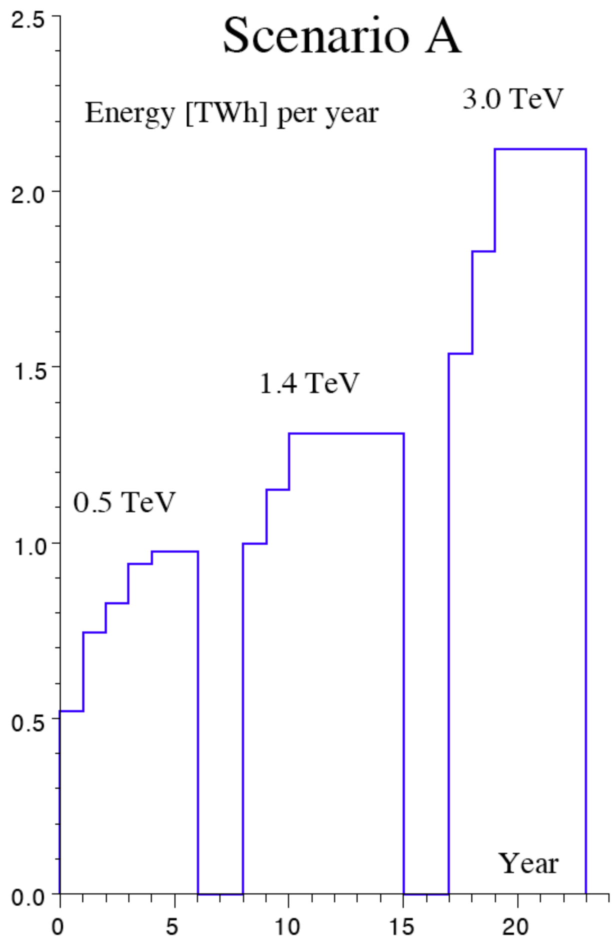
- 177 days/year of beam time
- 188 days/year of scheduled and fault stops
- First year
  - 59 days of injector and one-by-one sector commissioning
  - 59 days of main linac commissioning, one linac at a time
  - 59 days of luminosity operation
  - All along : 50% of downtime
- Second year
  - 88 days 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, fault, downtime

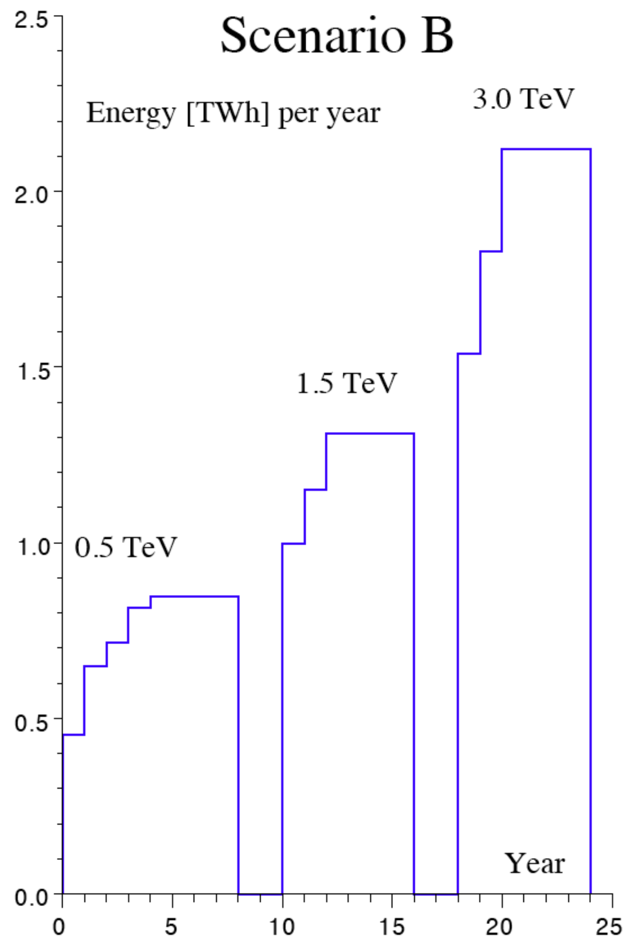
Staging Scenario	E_{CM} [TeV]	$P_{nominal}$ [MW]	$P_{waiting\ for\ beam}$ [MW]	$P_{shutdown}$ [MW]
	0.5	272	168	37
A	1.4	364	190	42
	3.0	589	268	58
	0.5	235	167	35
B	1.5	364	190	42
	3.0	589	268	58

Yearly energy consumption

Integral over the whole programme

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





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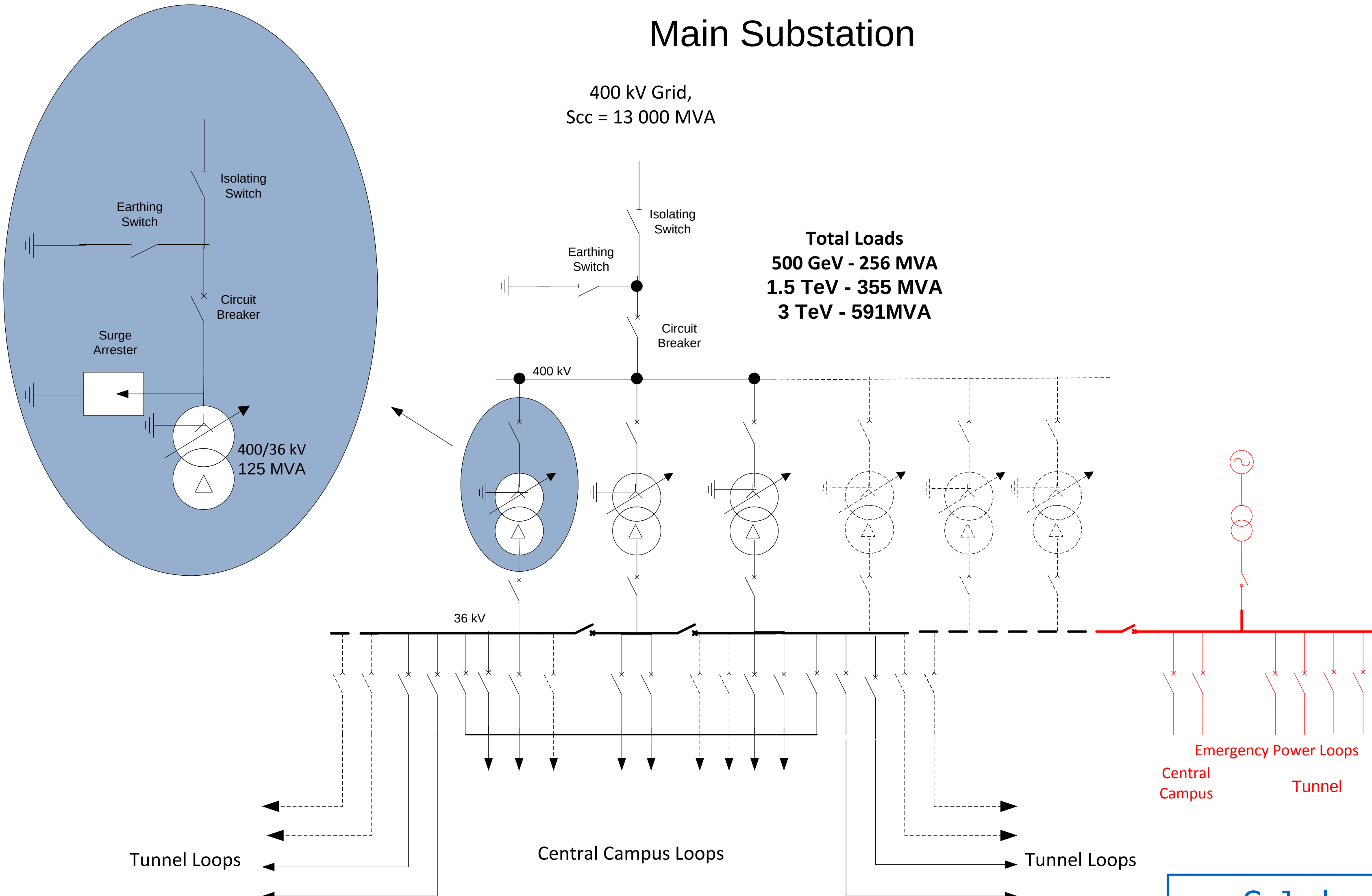
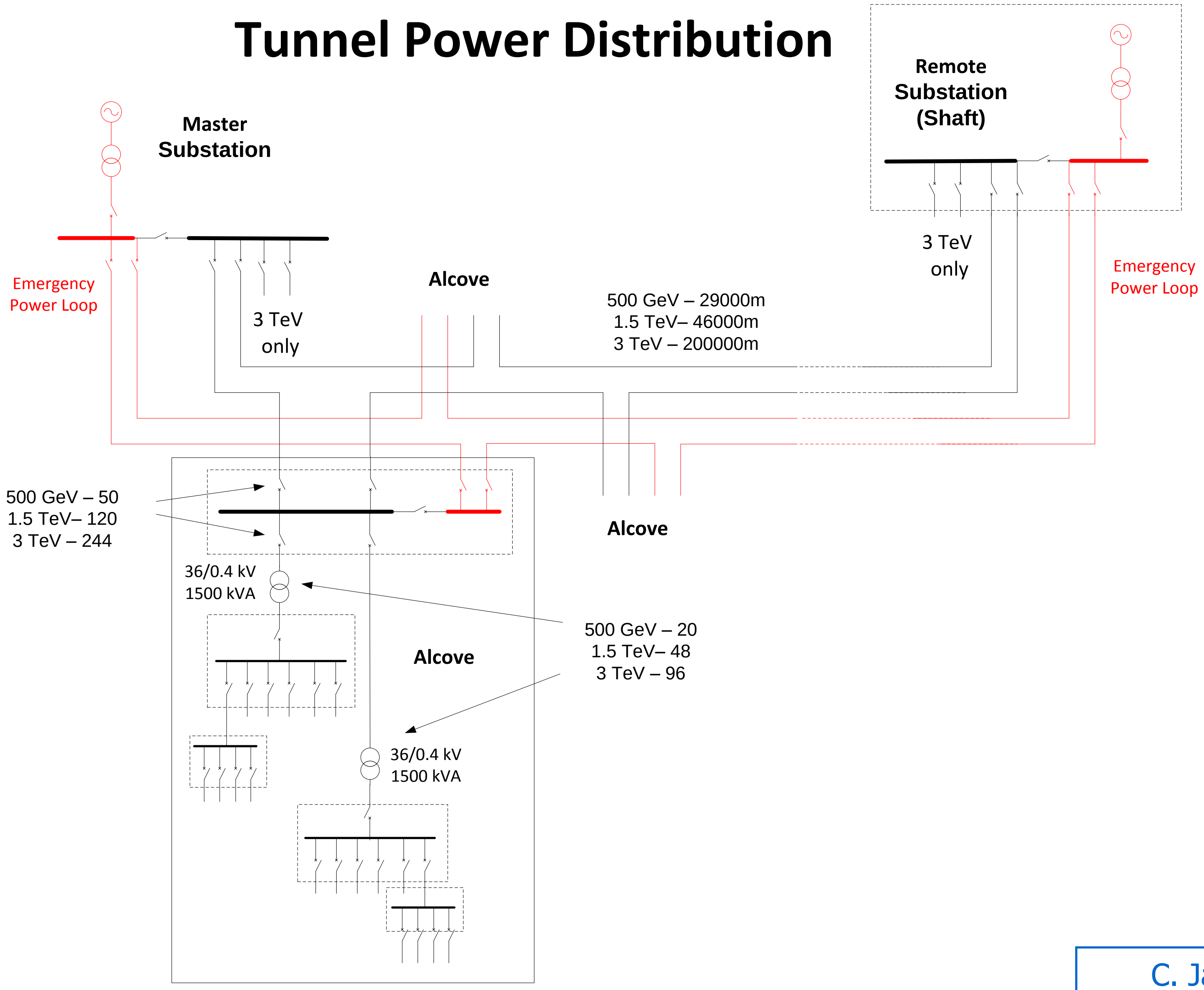
Electrical power distribution, main substation



C. Jach

Tunnel Power Distribution



C. Jach

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Cooling

- Primary circuits
  - Raw industrial water, make-up of drinking water
  - Treatment against scaling and algae
  - Evaporative cooling towers on main campus
- Secondary circuits
  - Demineralized water $\sigma < 0.1\ \mu S/cm$
  - Make-up from independent central station
- Chilled water
  - For cooling of ventilation plants

Location	Temperature at inlet [°C]	Temperature at outlet [°C]
Primary circuit: cooling towers	45	25
Secondary circuit: heat exchanger	27	47

M. Nonis

Sizing of cooling water circuits
3 TeV

Circuit	Cooling power [kW]	Q [m^3/h]	Nominal diameter [mm]
Drive Beam injector – surface	155 000	6670	900
Drive Beam injector – tunnel	17 000	730	400
Frequency multiplication	17 000	730	400
Transfer lines	9000	390	300
Chilled water production	19 000	2043	500
Total sector 1	217 000	13 360	1300
Main Beam injector – surface	16 000	690	300
Main Beam injector – tunnel	1700	70	150
Damping rings – surface	24 000	1030	350
Damping rings – tunnel	19 000	820	350
Booster LINAC – tunnel	1180	50	100
Booster LINAC – surface	5900	250	200
Chilled water production	3000	325	250
Total sector 2	70 780	3235	650
Main tunnel e^-- circuit A	69 000	3000	600
Main tunnel e^+- circuit A	69 000	3000	600
Total sector 3	138 000	6000	900
Main tunnel e^- - circuit B	56 500	2450	500
Main tunnel e^+ - circuit B	56 500	2450	500
Total sector 4	113 000	4900	800
Detector areas	18 700	800	350
BDS	46 000	1980	500
Chilled water production	7500	800	350
Total sector 5	72 200	3580	700

Total capacity 611 MW

M. Nonis

Ventilation

- Functions
  - Supply fresh air for people
  - Provide heating & ventilation
  - Maintain suitable temperature at surface of equipment
  - Dehumidify to prevent condensation (dewpoint kept below 12 °C)
  - Perform smoke extraction

Indoor conditions

Location	Summer temperature [°C]	Winter temperature [°C]
Tunnels, underground caverns (at equipment level)	21±1	21±1
Surface buildings with controlled temperature	25±1	18±1

Outdoor conditions Geneva

Period	Dry bulb temperature [°C]	Relative humidity [%]
Summer	32	40
Winter	12	90

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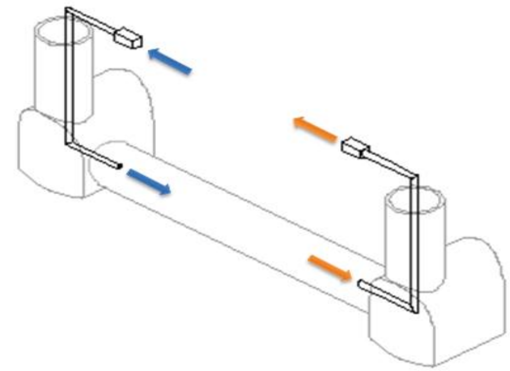
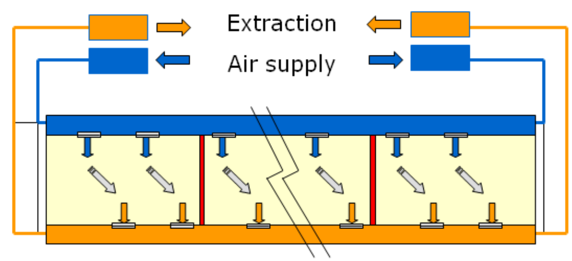
Ventilation schemes

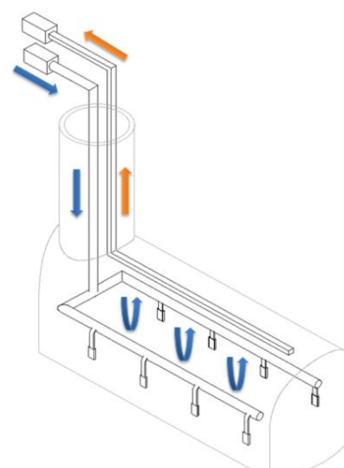
- Longitudinal
  - Access or equipment tunnels



- Semi-transverse
  - Main tunnel



- Standard
  - Caverns



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Ventilation, underground premises
3 TeV

Underground premises	Total number of units	Flow rate run mode [m³/h]	Flow rate shutdown mode [m³/h]	Flow rate purge [m³/h]	Equipment heat load [kW]
Tunnel Drive Beam injector	4	63 000	63 000	120 000	1760
Tunnel Main Beam injector	1	55 000	55 000	80 000	380
Damping rings	5	30 000	15 000	30 000	950
Tunnel booster LINAC	1	15 000	6000	20 000	100
Transfer line to JP, SP	1	65 000	40 000	100 000	450
Loop	1	35 000	20 000	60 000	230
Transfer line e^-	1	30 000	16 000	50 000	0
Transfer line e^+	1	50 000	25 000	75 000	0
Frequency multiplication	4	15 000	10 000	30 000	405
Main tunnel* e^+	10	45 000	45 000	90 000	528
Main tunnel* e^-	10	45 000	45 000	90 000	528
Turnaround e^- - end tunnel	1	30 000	30 000	60 000	35
Bunch compressor e^-	1	15 000	15 000	30 000	35
Turnaround e^+	1	30 000	30 000	60 000	35
Bunch compressor e^+	1	15 000	15 000	30 000	35
UTRC	10	16 000	32 000	60 000	95
UTRA	40	16 000	32 000	60 000	95
Drive Beam dump caverns/ post decelerators	48	1000	2000	3000	5
Loop	48	2000	2000	4000	10
BDS - intersection point	4	60 000	35 000	120 000	1560
Detector halls	2	45 000	45 000	9000	650
Main beam dump cavern	2	20 000	10 000	20 000	140
Service halls cavern (pt 2.2 and 3.2)	1	22 000	22 000	45 000	150
BC2 caverns	4	3000	10 000	10 000	20
Bypass tunnel	1	25 000	25 000	50 000	0
Escape tunnel	2	2500	5000	5000	0
Pressurized area shaft	2	15 000	45 000	45 000	0

* per sector, between two surface points

Total capacity 39 MW

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Ventilation, surface buildings
3 TeV

Surface building	Number of units	Flow rate per unit [m^3/h]	Equipment heat load [kW]
Drive beam Linac	50	70 000	15 840
Main Beam Linac Hall	9	10 000	608
Linac 1 and 2 target halls	2	5000	0
Compton ring	1	22 500	0
Damping rings area (5 buildings)	5	22 500	0
Booster linac	5	10 000	0
Injection hall	1	34 000	170
Combiner ring 1 & 2	2	55 000	380
Cryo building	1	12 000	n.a.
Gas building	1	8000	n.a.

Total capacity 17 MW

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power & energy economy
waste heat recovery
sobriety
energy management
efficiency

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 HVAC 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

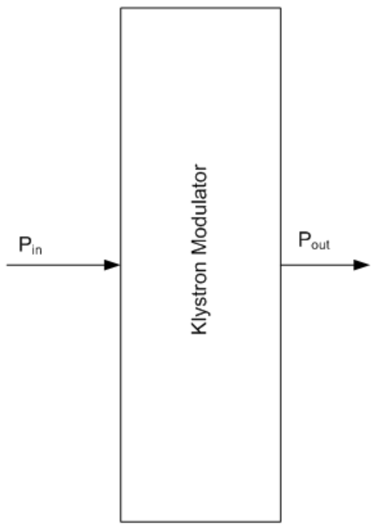
- Grid-to-RF power conversion
  - R&D on klystrons
  - R&D on modulators, powering from the grid at HV
- RF-to-beam power conversion
  - Re-optimization of accelerating structures and gradient with different objective function (present value 0.25)
- Permanent or super-ferric superconducting magnets
  - 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

⇒ Potential for power savings at 3 TeV

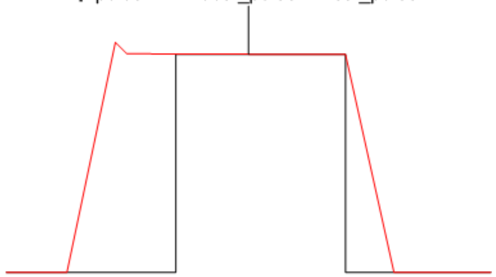
- magnets ~ 86 MW
- cooling & ventilation ~24 MW

Development of high-efficiency modulators

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

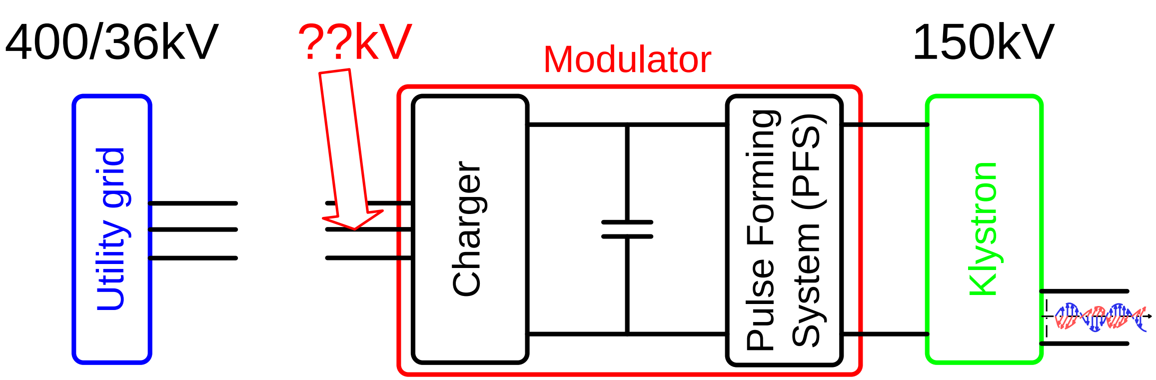


$\rho_{pulse} = E_{ideal\_pulse}/E_{real\_pulse}$



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%**

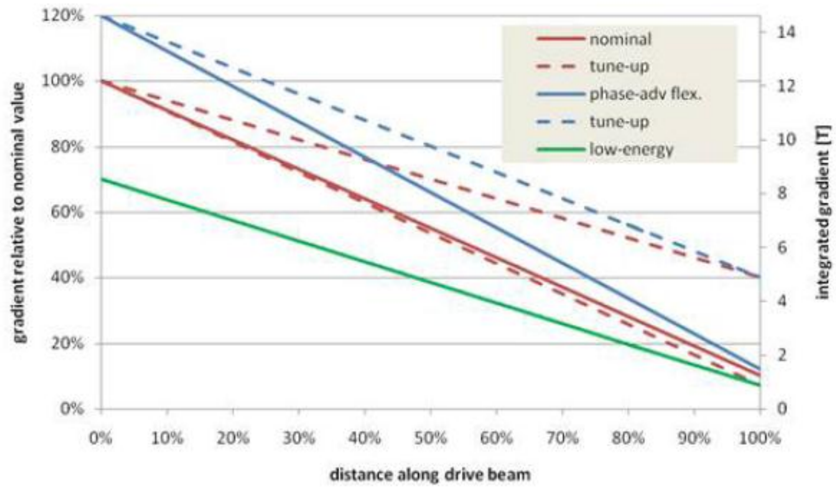
$$\rho_{modulator} = \rho_{power} * \rho_{pulse}$$



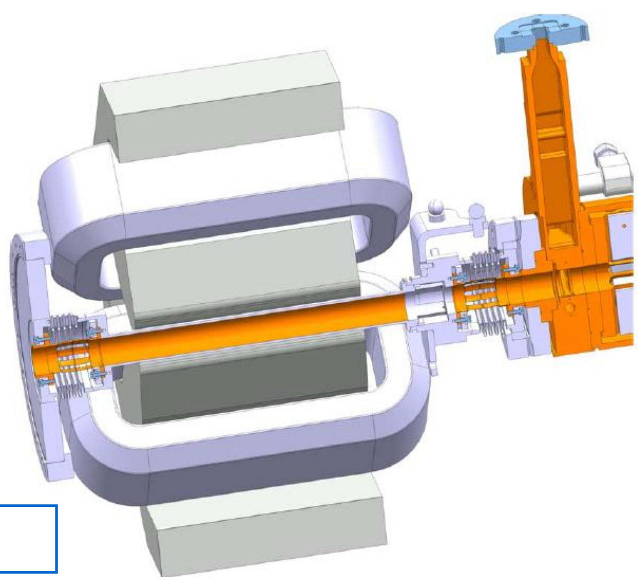
D. Nisbet & D. Aguglia

Main linac DB quadrupoles

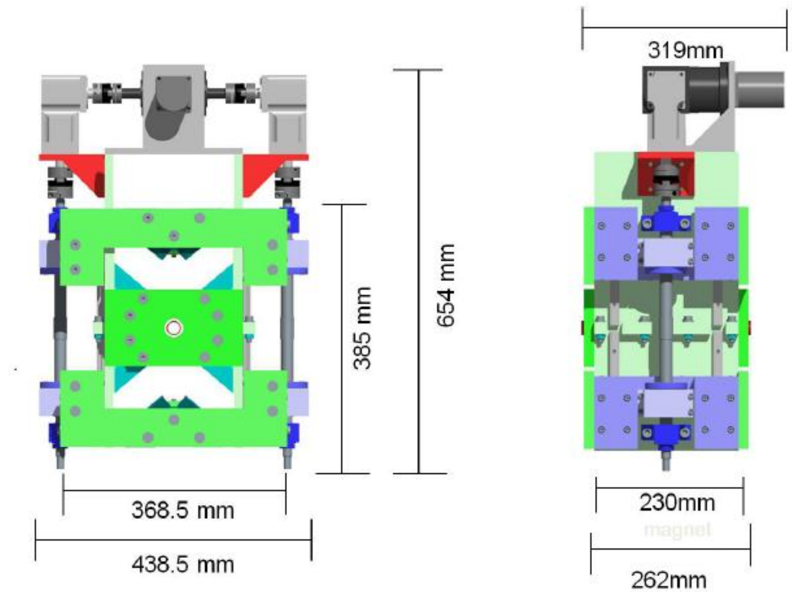
Parameter	High-energy side	Low-energy side
Number of magnets	41 400	
Nominal maximum strength [T] (integrated gradient)	12.2	1.22
Stability	5×10^{-4}	
Integrated gradient quality	0.1%	
Good field region [mm]	11	
Bore radius [mm]	13	
Available width [mm]	391	
Available height [mm]	391	
Available length [mm]	270	



Conventional electromagnet

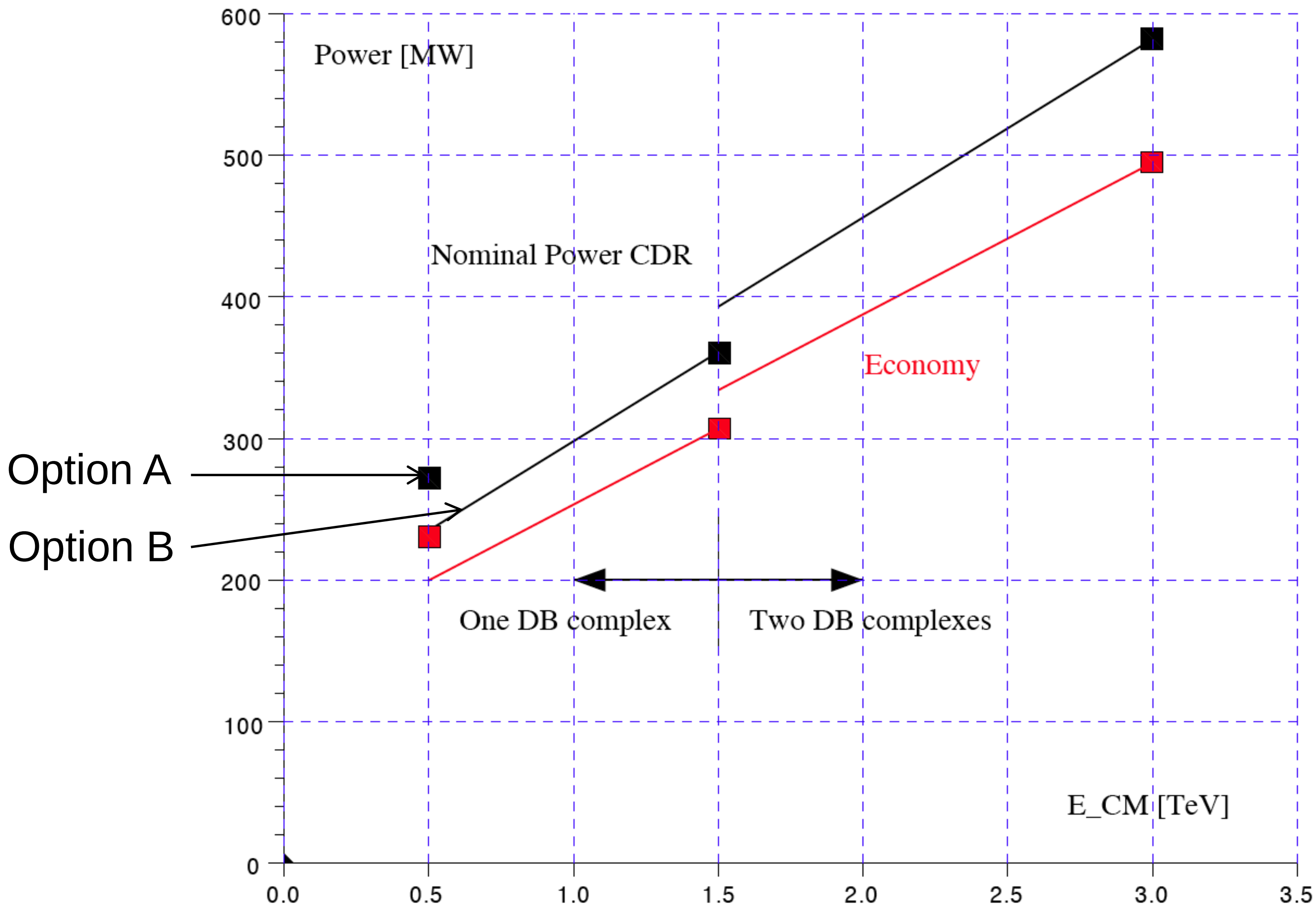


Tunable permanent magnet



M. Modena

Power consumption versus cm energy



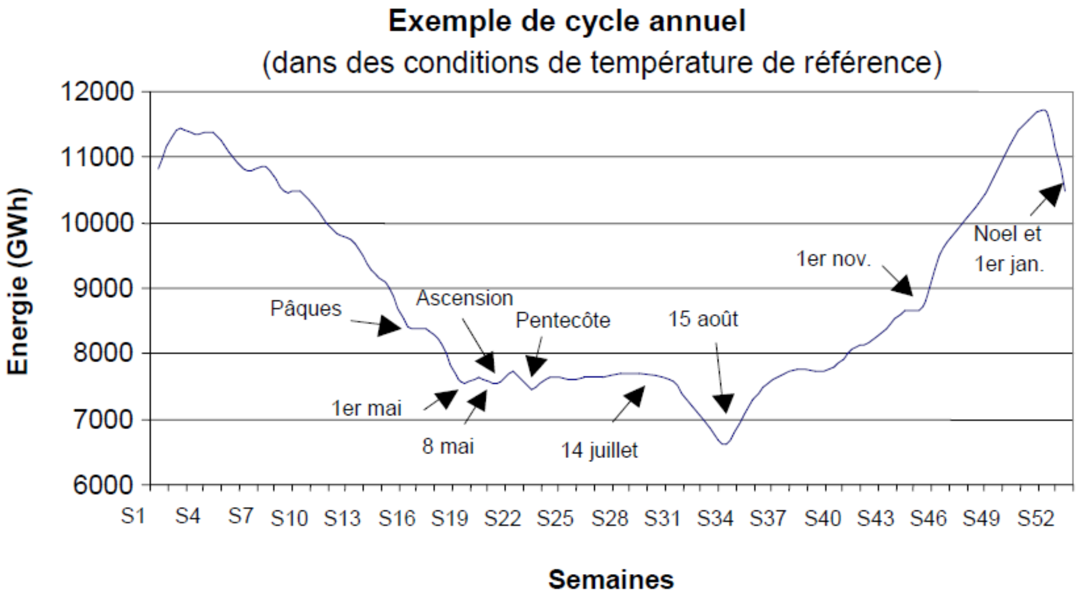
Paths to power & energy savings
Energy management

- Low-power configurations in case of beam interruption

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

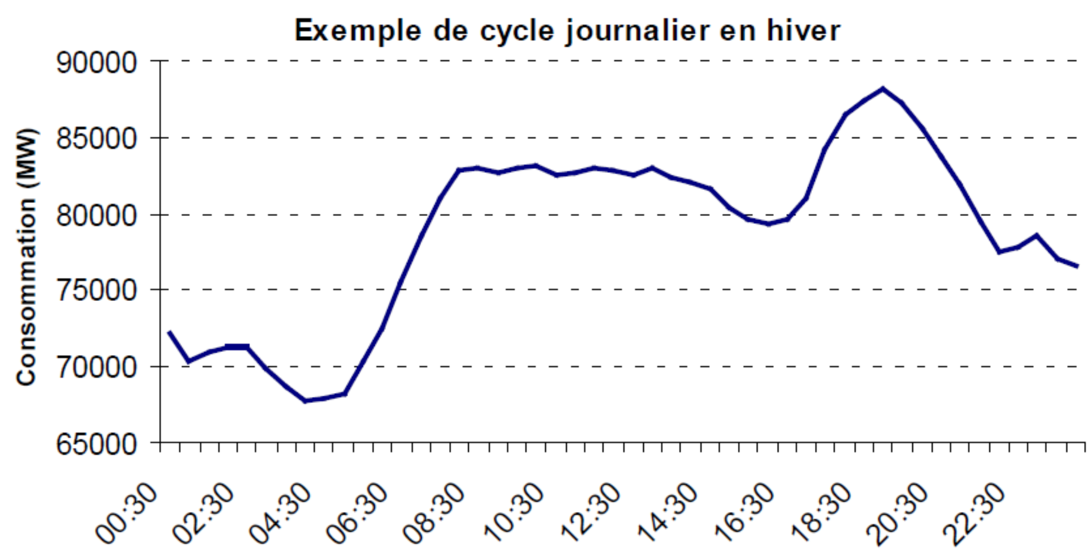
- Modulation of scheduled operation to match electricity demand
  - Seasonal load shedding
  - Diurnal peak shaving

Variations of electricity demand in France
(source: RTE)



Annual variations of power consumption (integrated weekly)

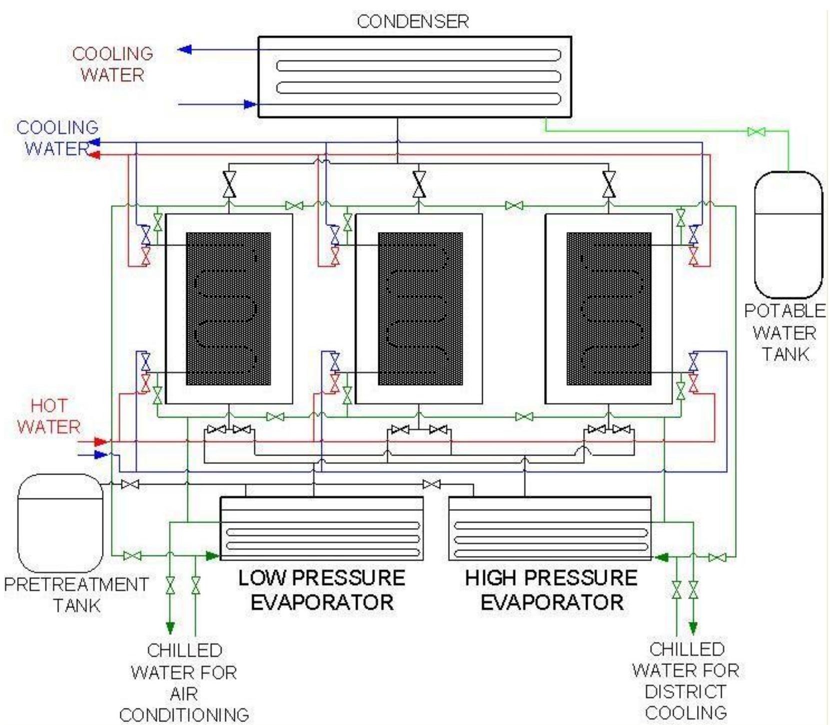
Diurnal variations of power consumption (winter day)



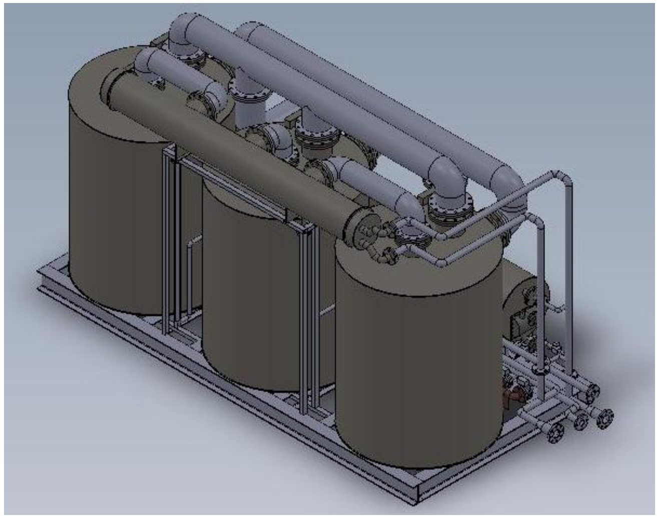
Paths to power & energy savings
Waste heat recovery

- 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



Conclusions

- Linear colliders are single-pass machines and thus unavoidably show low energy efficiency
- Optimization of the RF chain is therefore an essential issue, from power grid to RF and from RF to beam. Well identified by CLIC (and ILC), this has driven design choices and triggered specific R&D. The RF system however uses only about half of the total power consumed
- CLIC is a large complex of accelerators and beam lines, resulting in significant power being used in magnet systems (21 % of total). Several approaches to mitigating this demand are being explored
- In view of the large size and installed power of the CLIC complex, conventional services such as electrical distribution and cooling & HVAC are also large power consumers (21 % of total)
- Re-optimizing machine parameters for 500 GeV collision energy (or below) with comprehensive accounting of power consumption constitutes the main path of power savings
- Significant and swift decrease of power consumption in standby modes opens the way for running CLIC as peak-shaving facility
- Recovery and valorization of low-grade waste heat appears feasible in specific cases and requires further study