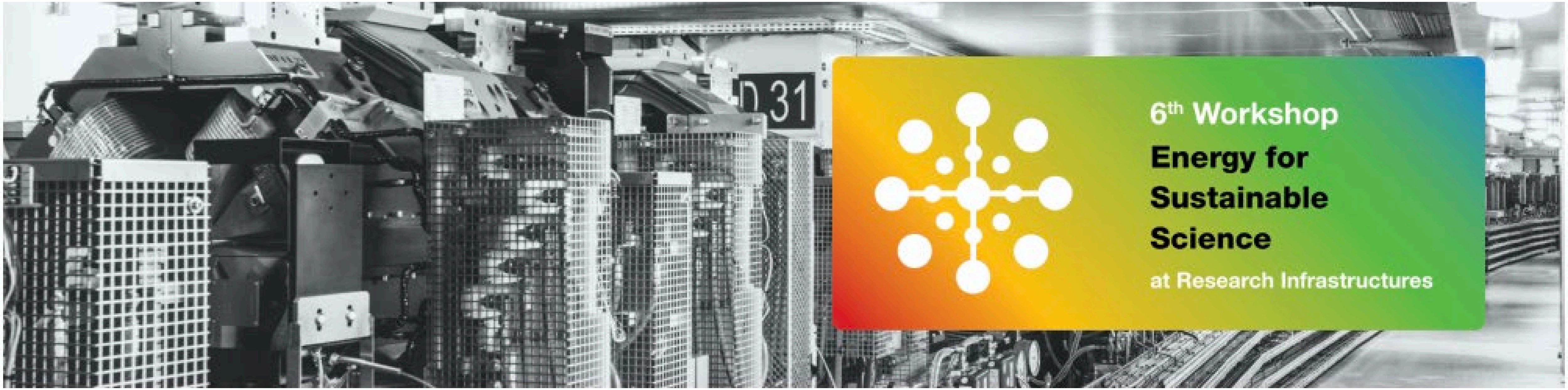


29–30 Sep 2022
ESRF, Grenoble
Europe/Paris timezone

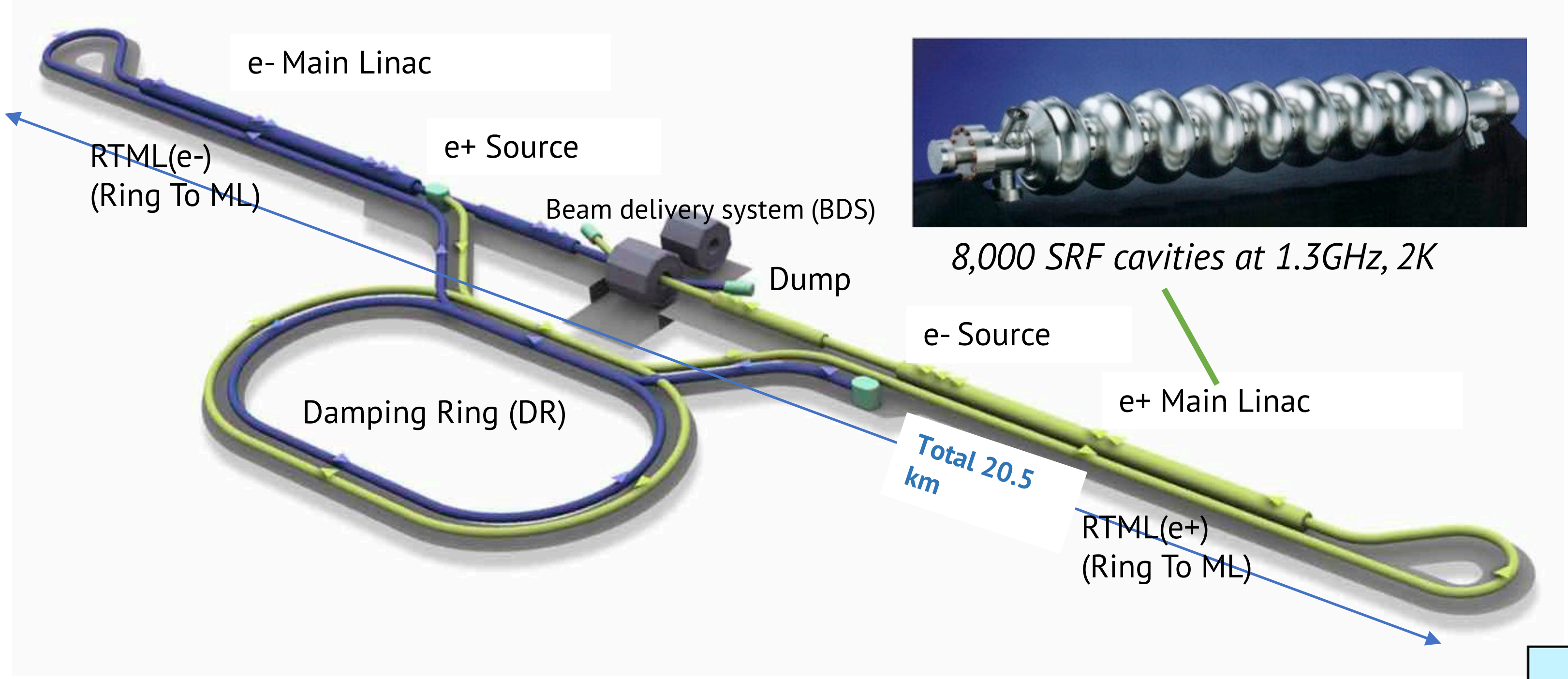
Sustainability Studies for Linear Colliders

Benno List, Shinichiro Michizono, Takayuki Saeki, Steinar Stapnes*, Maxim Titov

DESY, CEA, CERN, KEK

(*presenter: steinar.stapnes@cern.ch)

The International Linear Collider (ILC)

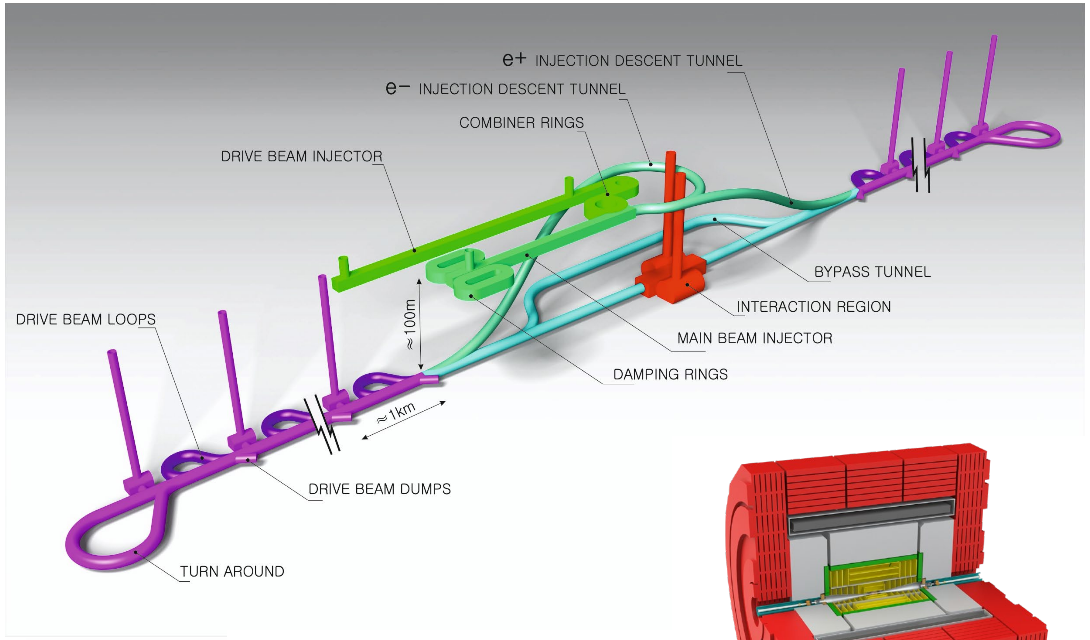


8,000 SRF cavities at 1.3GHz, 2K

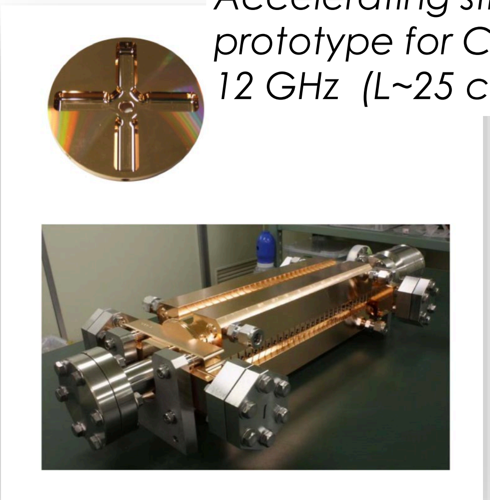
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	**7.7** nm@250GeV
SRF Cavity G. Q_0	**31.5** MV/m (**35** MV/m) Q_0 = 1x10^{10}

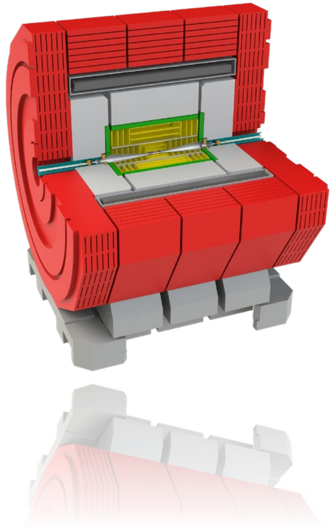
- Proposed Higgs factory in Tohoku (Japan), 250GeV initial energy
- Superconducting Main Linac for energy efficiency
- Timeline: 4 year preparation + 10 years construction -> operation 2037
- Expandable to 1TeV
- Cost: 6.3 – 7.0 B$, including human resources
- Power: 111 MW at 250GeV

The Compact Linear Collider (CLIC)



Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)





- Timeline: Electron-positron linear collider at CERN for the era beyond HL-LHC
- Compact: Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- Expandable: Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

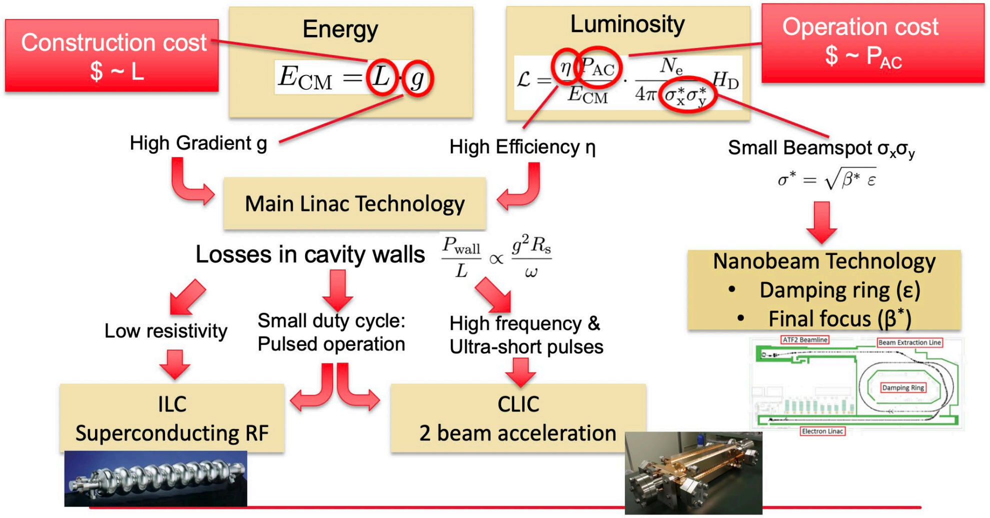
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

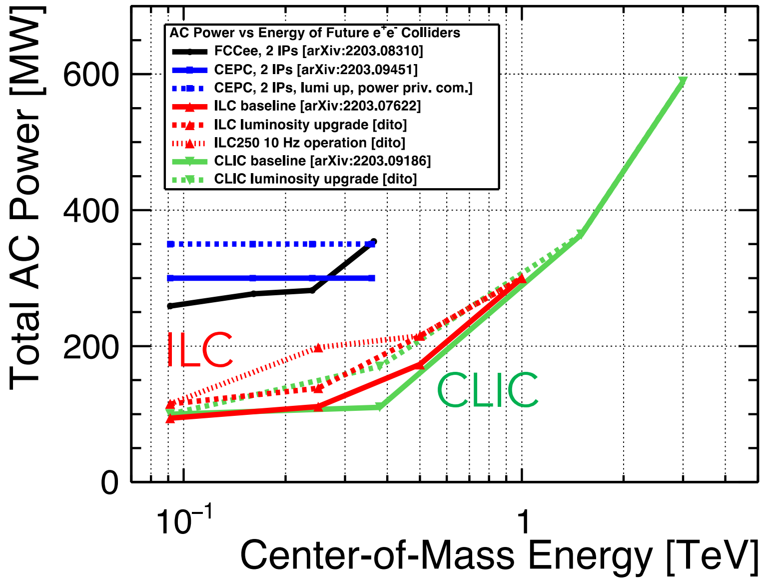
- Cost: 5.9 BCHF for 380 GeV
- Power/Energy: 110 MW at 380 GeV (~0.6 TWh annually), corresponding to 50% of CERN’s energy consumption today

- Comprehensive Detector and Physics studies

Overall resource efficiency considerations

BL: https://indico.cern.ch/event/981823/contributions/4328846/





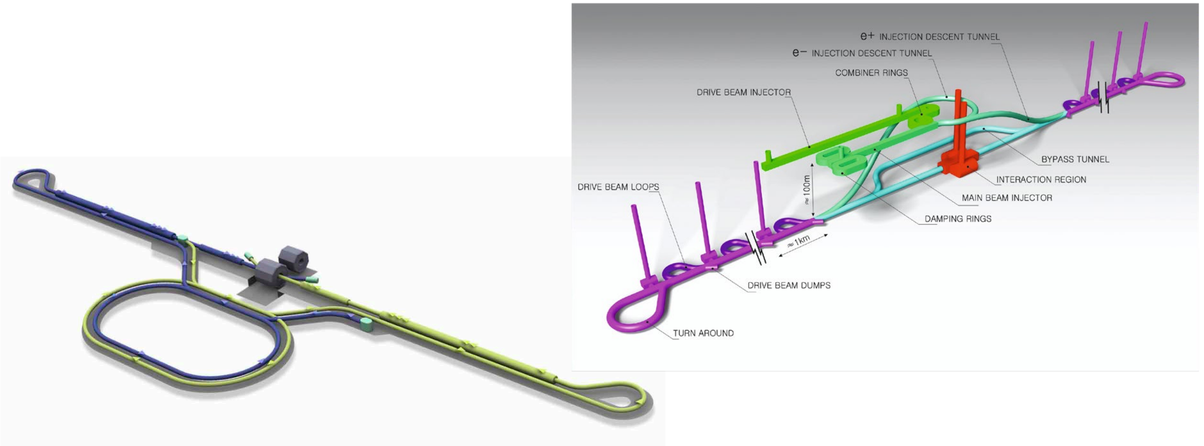
arxiv:2203.07622

- Challenge: Achieve target **energy** and **luminosity** with least possible amount of **resources**
- Conserve ressources for construction:
  - Compact -> high acceleration gradient
- Conserve ressources in operation:
  - Energy-efficiency (limit losses in cavity walls): superconducting RF – ILC high frequency & ultra-short pulses: CLIC
  - Effectiveness: maximum luminosity per charge -> nanobeam technology
- ILC and CLIC:
  - Different solutions to the efficiency problem, final power consumption similar

- Figure on the left, two main features
  - LC at high energy by-passes current energy use (e.g. CERN at ~1.2 TWh annually, for example at 3 TeV one gets to ~2.5 TWh) – this motivated initial work to reduce power
  - The circular machines suffer from the synchrotron losses in the 60-100 MW range (the LC beams are in few MW range - as Higgs factories)
- However, with current energy prices, ANY energy use is problematic and design drivers to reduce operation costs
- Huge uncertainty in how the energy market, prices and price variations will be in ~2040 (ILC), ~2050 (CERN projects)

Sustainability Considerations

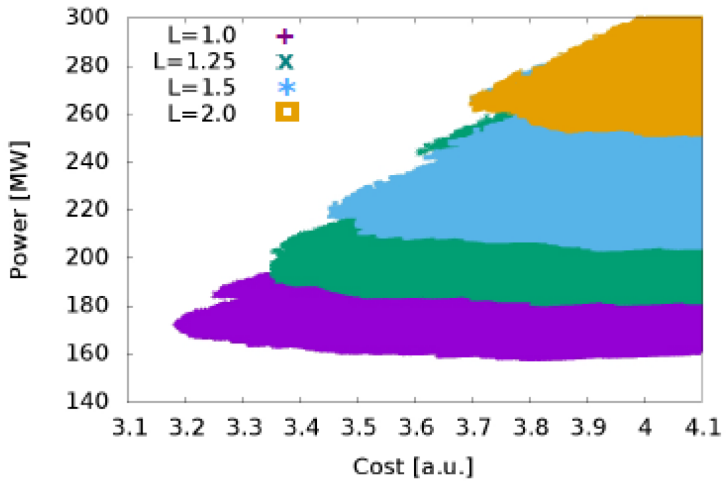
- Ressource planning as traditionally is done for accelerators is paramount:
  - Length/complexity -> construction cost
  - Power/energy consumption -> operating costs
- Sustainability in a wider sense adds new implementation and operation guidelines
  - e.g. energy use critical, CO_2, rare earth usage, sourcing in general, landscaping, decommission



Approaches to increase sustainability

- Overall system design
  - Compact (short) accelerator -> high gradient
  - Energy efficient -> low losses
  - Effective -> small beam sizes
- Subsystem and component design, e.g.
  - High-efficiency cavities and klystrons
  - Permanent magnets
  - Heat-recovery. e.g. in tunnel linings
  - Responsible sourcing and material choices
- Sustainable operation concepts
  - Renewables
  - Adapt to power availability
  - Exploit energy buffering potential
  - Recover energy

Examples of LC system optimization



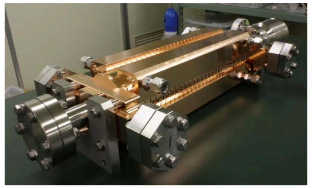
Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum

Design Optimisation for CLIC

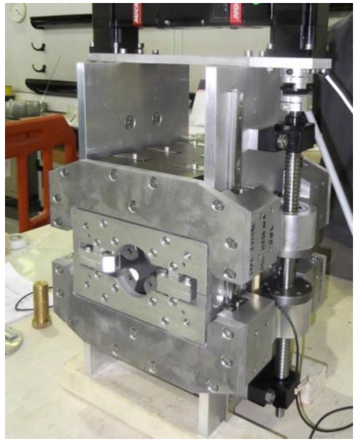
- The designs of CLIC, including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost but also increasingly focussing on reducing power consumption.
- This was done in 2015 optimising the 380 GeV machine (selected to cover top and Higgs)
- In parallel: Re-design and optimisation of RF systems (e.g. damping rings and drivebeam)

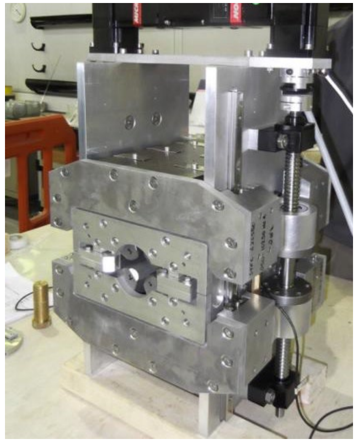
For ILC design optimisations have been and are being done, also focussing on parameters choices, for example repetition rates, pulse-lengths, cryo and RF systems for various luminosity choices

In both cases it would be interesting to repeat these studies now, focussing more strongly on power consumption (and including a lot of progress in technical developments)



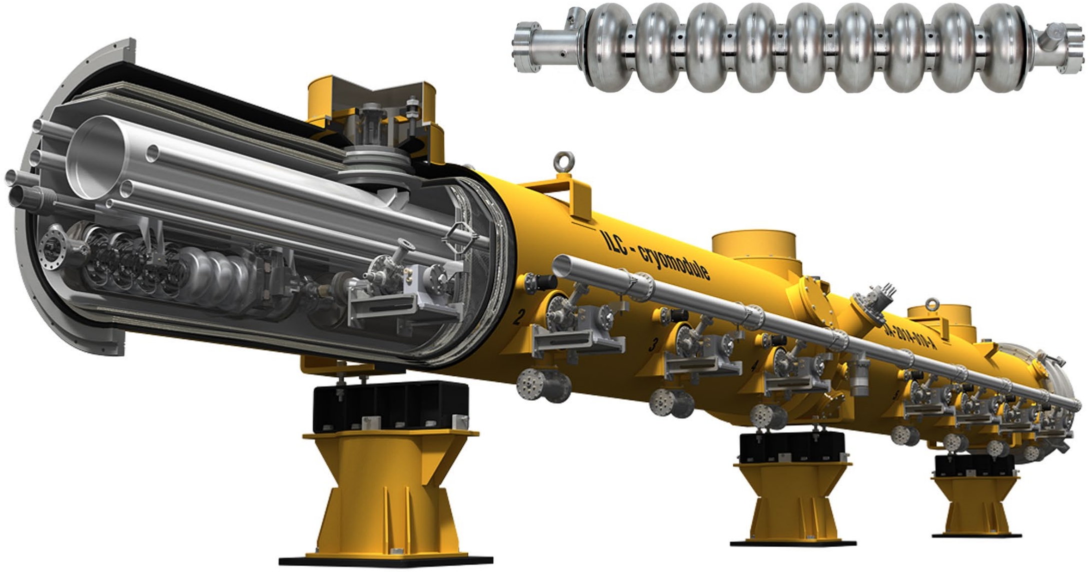
Optimization of Components and Subsystems





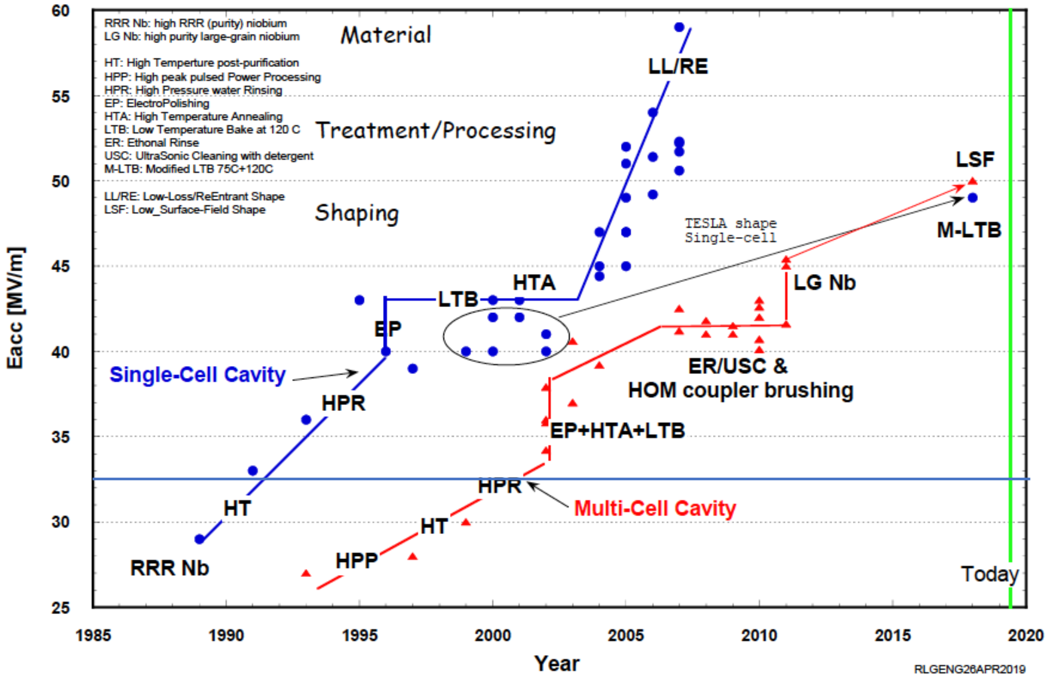
TESLA SRF Technology for the ILC Main Linac

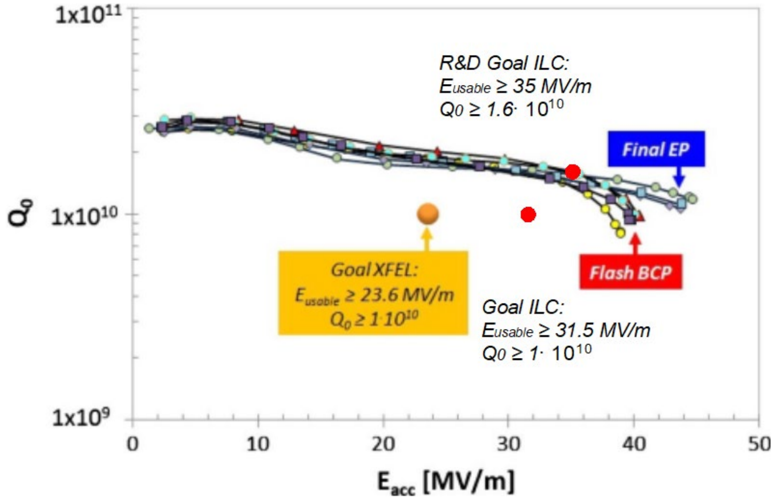
- ~8000 superconducting niobium 9-cell cavities:
  1.3 GHz, 1.038m long, 31.5MV/m
- 9 cavities per 12m long cryomodule
- 2K operating temperature
  -> 4-6 cryo plants 19kW@4.5K
- Pulsed operation, 5Hz x 0.73ms (1312 bunch)
- European XFEL in operation
  100 cryomodules, 800 cavities



R&D for Improved SRF Performance & Sustainability

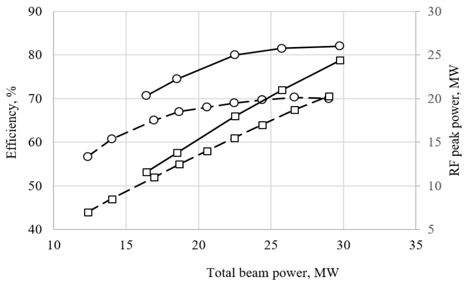
- Better surface treatments and cavity shapes improve cavity performance. Lots of progress in last 10 years
- Raise gradient: fewer cavities for same beam energy.
  Short term goal: 31.5MV/m -> 35MV/m
  Medium term goal: 45MV/m
  Lab record: 59MV/m
- Improve Q_0: reduce cryogenic losses
  (1W @ 2K requires ~750W AC power!)
  Short term goal: 1E10 -> 2E10
- New treatments reduce / avoid need for electropolishing treatments (involving aggressive chemicals)
- R&D into replacement of bulk niobium cavities with Nb or Nb_3Sn coated copper:
  reduce niobium consumption,
  increase performance (arXiv:2203.09718)





High Eff. Klystrons

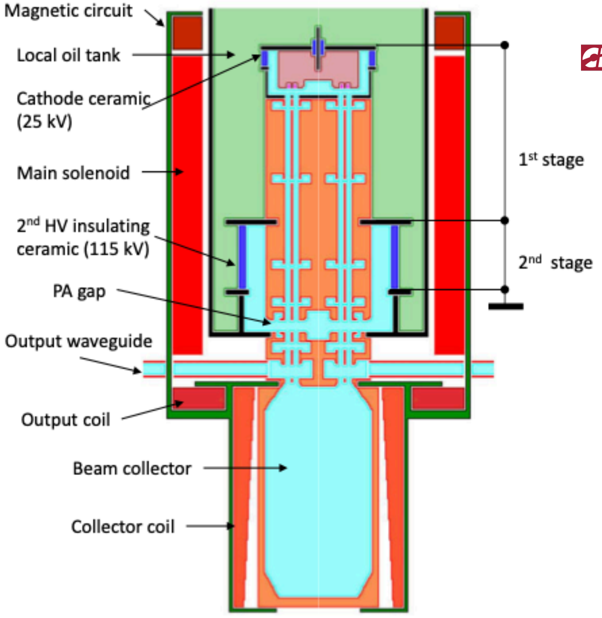
L-band, X-band (for applications/collaborators and test-stands

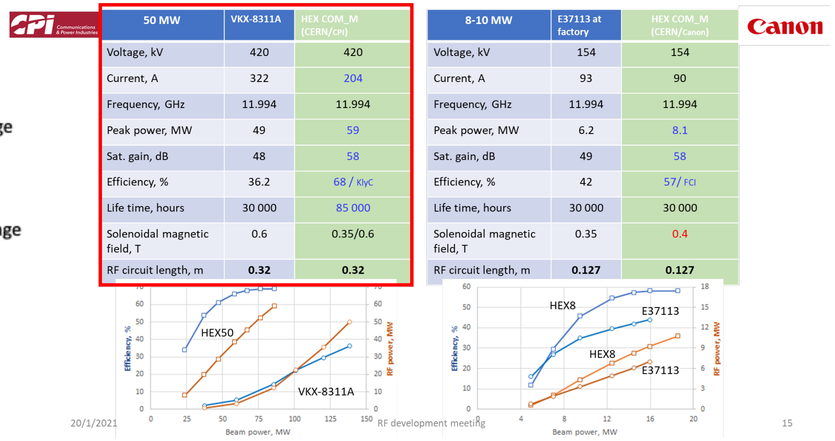


Location: CERN Bldg: 112

Drivebeam klystron: The klystron efficiency (circles) and the peak RF power (squares) simulated for the CLIC TS MBK (solid lines) and measured for the Canon MBK E37503 (dashed lines) vs total beam power. See more later.

Publication: https://ieeexplore.ieee.org/document/9115885





High Efficiency X-band klystrons retrofit upgrades (in collaboration with CPI and Canon).

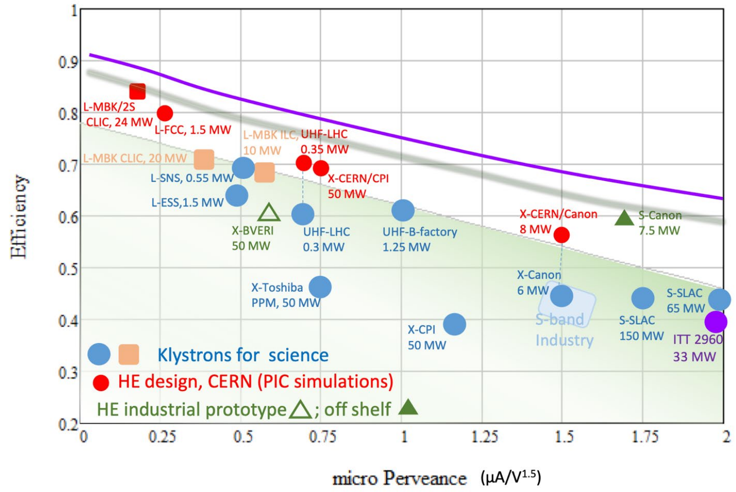
50 MW	VKX-8311A	HEX COM_M (CERN/CPI)
Voltage, kV	420	420
Current, A	322	204
Frequency, GHz	11.994	11.994
Peak power, MW	49	59
Sat. gain, dB	48	58
Efficiency, %	36.2	68 / KlyC
Life time, hours	30 000	85 000
Solenoidal magnetic field, T	0.6	0.35/0.6
RF circuit length, m	0.32	0.32

8-10 MW	E37113 at factory	HEX COM_M (CERN/Canon)
Voltage, kV	154	154
Current, A	93	90
Frequency, GHz	11.994	11.994
Peak power, MW	6.2	8.1
Sat. gain, dB	49	58
Efficiency, %	42	57/ FCI
Life time, hours	30 000	30 000
Solenoidal magnetic field, T	0.35	0.4
RF circuit length, m	0.127	0.127

High Efficiency implementations:

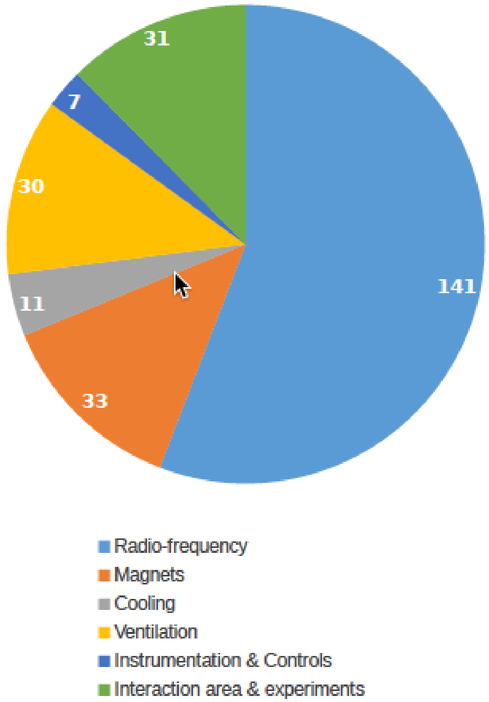
- New small X-band klystron – recent successful prototype
- Large X-band with CPI
- L-band two stage, design done, prototype desirable

Also important, redesign of damping ring RF system – no klystron development foreseen



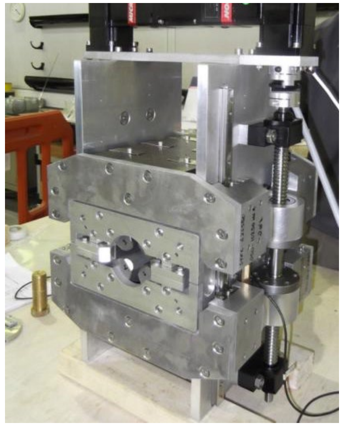
Magnets also important

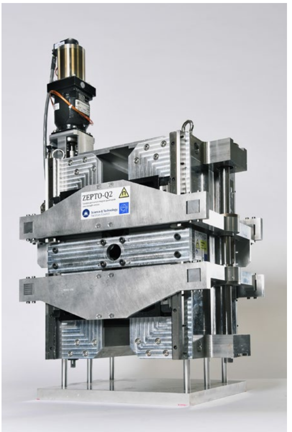
1.5 TeV CLIC power
Magnets second largest



ZEPTO (Zero Power Tuneable Optics) project is a collaboration between CERN and STFC Daresbury Laboratory to save power and costs by switching from resistive electromagnets to permanent magnets.

For CLIC the dominant power is in the drive-beam quadrupoles, successfully prototyped and tested as permanent (two different strengths) magnets, and also dipoles (in drivebeam turn arounds)





Left: Longitudinal gradient dipole magnet for the CLIC DR (CIEMAT)

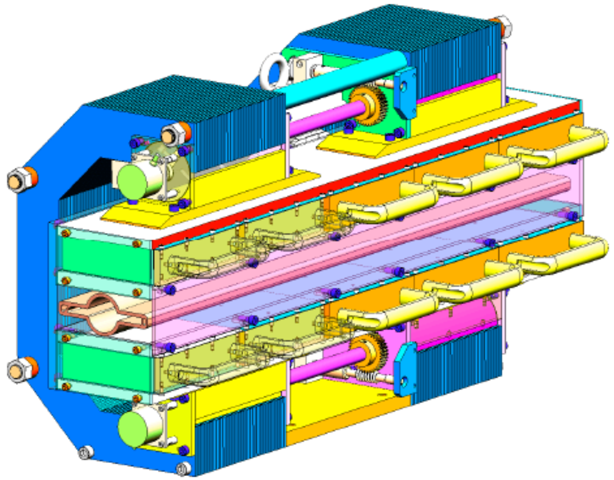


Figure 3: Overview of possible design of PM dipole for ILC damping ring.

doi:10.18429/JACoW-IPAC2018-MOPML048

CLIC: Power and Energy

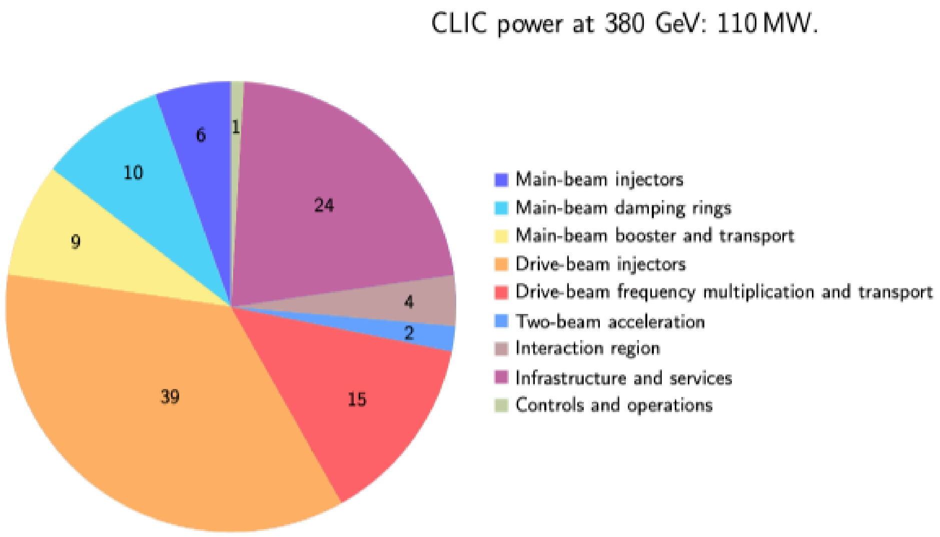


Fig. 4.8: Breakdown of power consumption between different domains of the CLIC accelerator in MW at a centre-of-mass energy of 380 GeV. The contributions add up to a total of 110 MW. (image credit: CLIC)

Table 4.2: Estimated power consumption of CLIC at the three centre-of-mass energy stages and for different operation modes. The 380 GeV numbers are for the drive-beam option and have been updated as described in Section 4.4, whereas the estimates for the higher energy stages are from [57].

Collision energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	110	25	9
1500	364	38	13
3000	589	46	17

Power estimate bottom up (concentrating on 380 GeV systems)

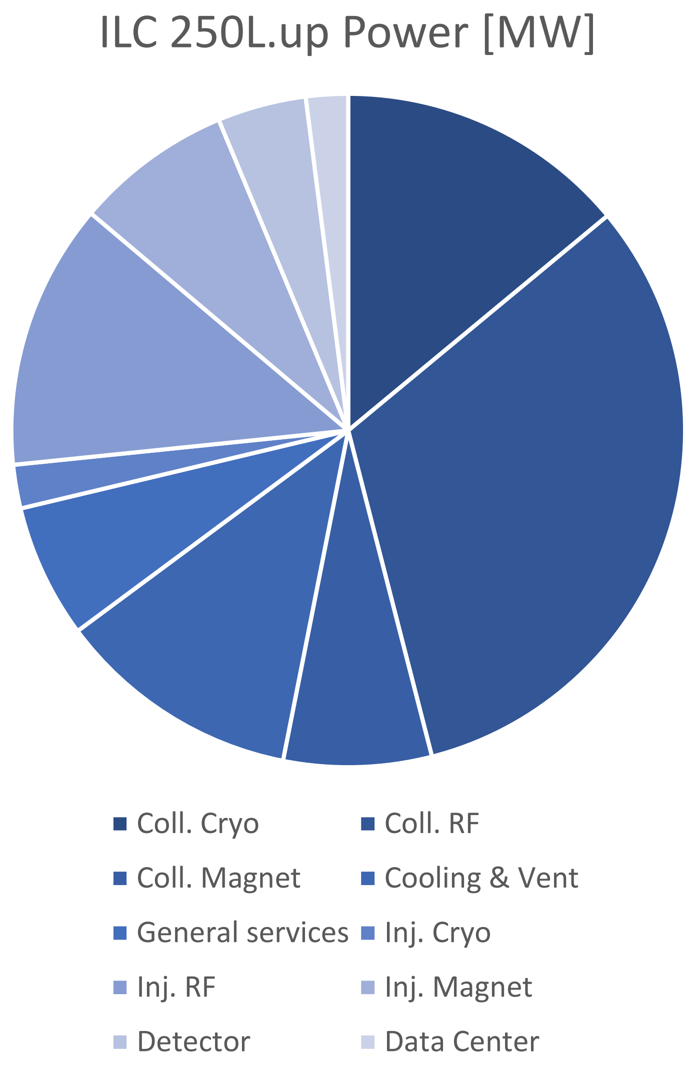
- Very large reductions since the CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies Note than permanent magnets are not yet included in the estimate.

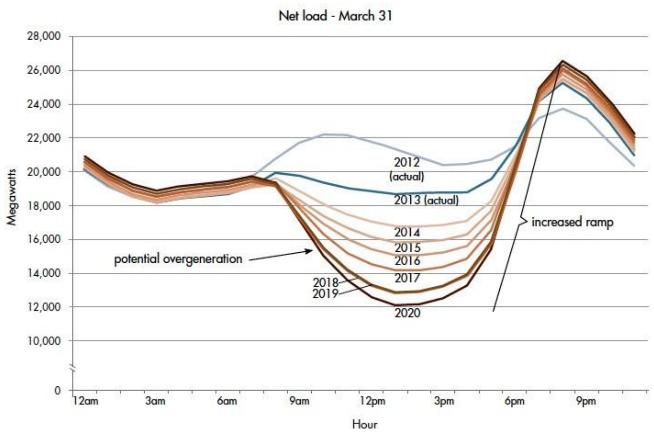
Energy consumption ~0.6 TWh yearly, CERN is currently (when running) at 1.2 TWh (~90% in accelerators). Includes energy use in long shutdowns (off) and short shutdown & MDs (power estimated to 50/50 standby/running for the two latter periods)

1.5 TeV and 3 TeV numbers still from the CDR (but included in the reports), to be re-done the next ~2 years
Savings due to high efficiency klystrons, DR RF redesign or permanent magnets not included at this stage, so numbers will be reduced.

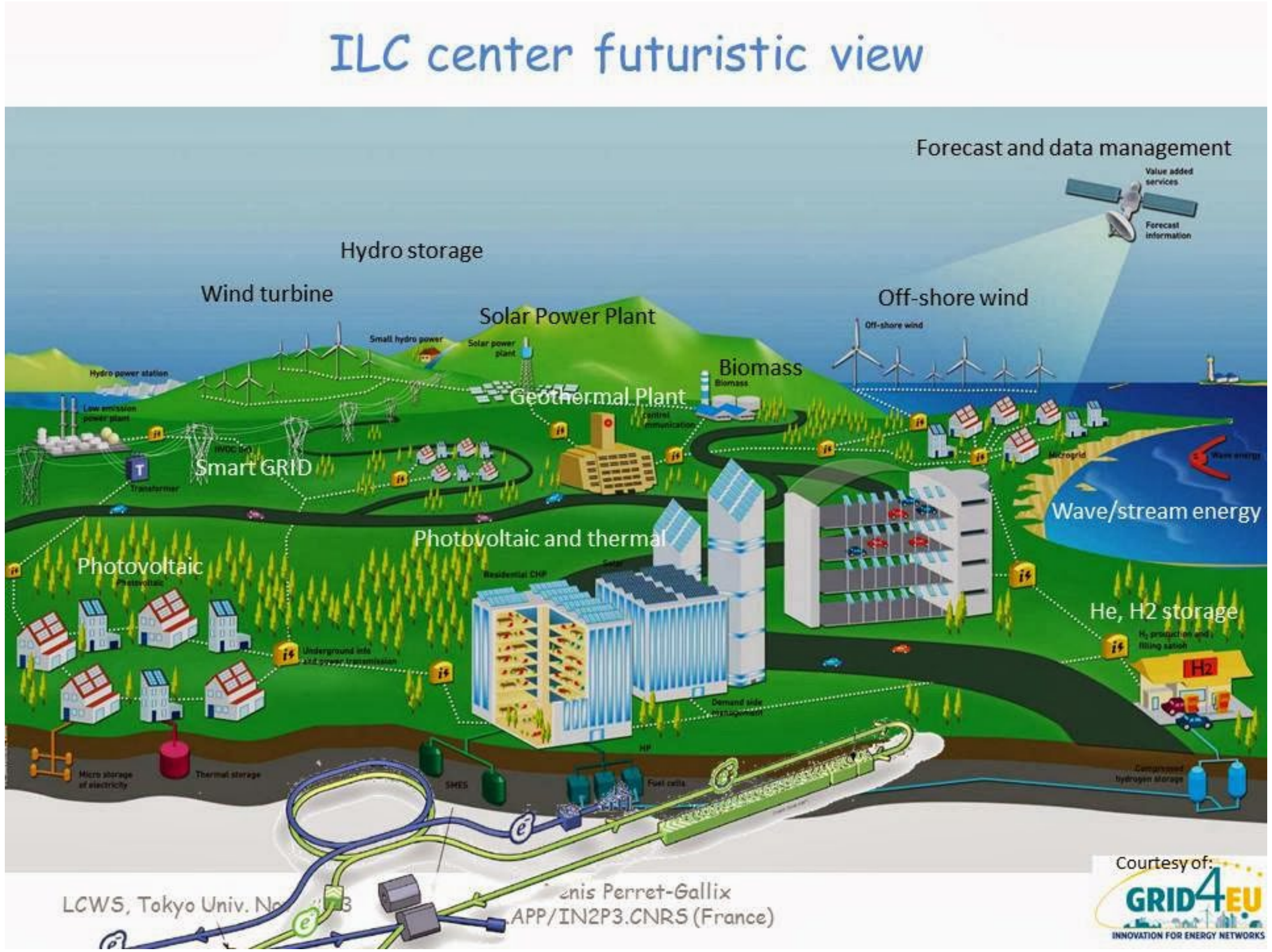
Result for ILC250 (Lumi upgrade)

	ILC 250L.up	(ILC250)	(TDR)
Coll. Cryo	**18.7**	17.8	32.4
Coll. RF	**42.8**	29.2	56.9
Coll. Magnet	**9.5**	9.5	12.6
Cooling & Vent	**15.7**	13.1	19.9
General services	**8.6**	8.8	13.4
Inj. Cryo	**2.8**	2.8	2.8
Inj. RF	**17.1**	10.0	11.3
Inj. Magnet	**10.1**	8.6	8.6
Detector	**5.7**	5.7	5.7
Data Center	**2.7**	2.7	-
Margin (3%)	**4.0**	3.3	-
Total [MW]	**138**	111	164





Sustainable Operation



Approaches to increase sustainability

- Different approaches to reduce impact of large electric power consumption
  - Reduce power (by higher efficiency) – discussed above
  - Re-use waste energy (heat)
  - Modulate power according to availability (price)
  - Use regenerative power
- Regenerative energy sources (esp. solar, wind) vary seasonally and daily
- Public electricity demand also varies
  -> daily "duck curve", seasonal variation
- Use of regenerative energy sources (RES) should be combined with power modulation
- **Single pass colliders well suited** -> Study power consumption in different operating states of the linear colliders
- Two ways to modulate power usage
  - Change performance
  - Buffer energy

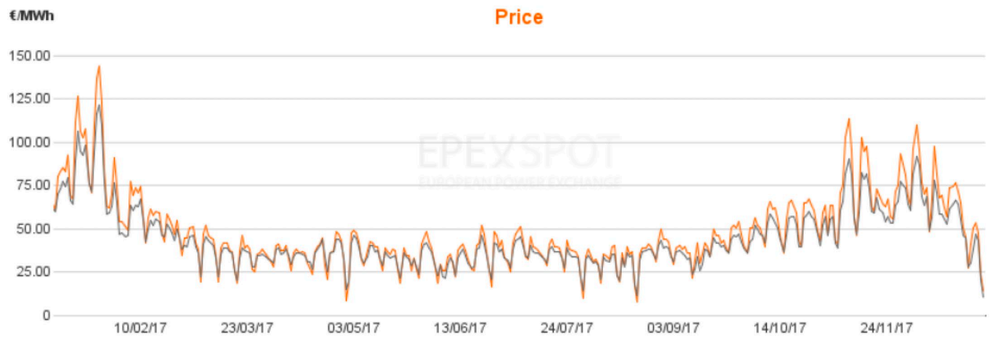
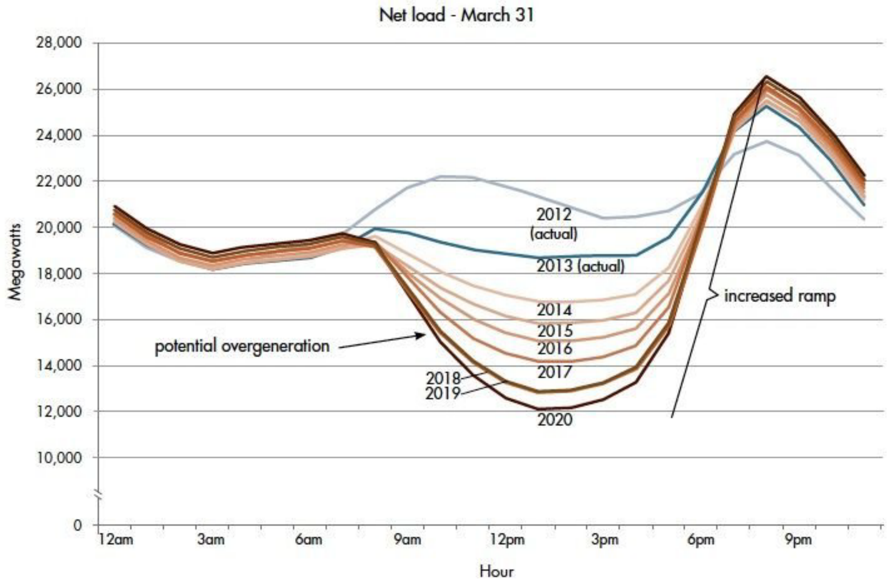


Figure 2-3: Day-Ahead auction results at EPEXSPOT for trading area France and year 2017 (orange: price peakload, black: price baseload)[7]

https://edms.cern.ch/document/2065162/1



https://www.energy.gov/eere/articles/confronting-duck-curve-how-address-over-generation-solar-energy

Running on renewables

- It is possible to supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators, at a cost of slightly more than 10% of the CLIC 380 GeV cost)
  - At the time of the study 200 MW was conservatively used, in reality only ~110 MW is needed
- Self-sufficiency during all times can not be reached and 54% of the time CLIC could run independently from public electricity supply with the portfolio simulated.
- About 1/3 of the generated PV and wind energy will be available to export to the public grid even after adjusting the load schedule of CLIC.
- However, the renewables are most efficient in summer, when prices **(until recently)** are low
- A similar approach is applicable to ILC

More information about the study carried out by Fraunhofer (link)

Study on energy use modulations

- CLIC Study - Consider 5 operating modes and transition times between them:
  - Off (shutdown)
  - Standby and intervention – scheduled or unscheduled
  - Low power running (50% lumi)
  - Full operation (note at that time assumed to need 200 MW, now reduced)
- Study assumes target of 130 days of full operation equivalent running
- Considers impact of various running strategies on energy costs

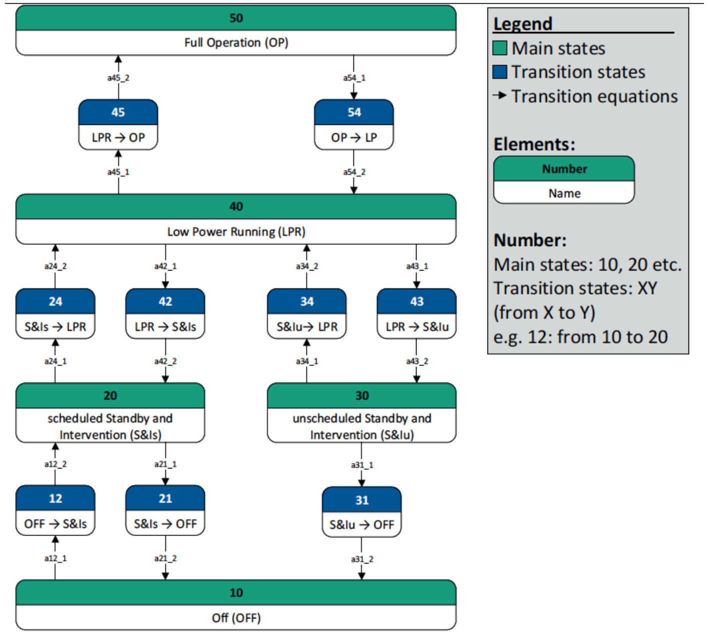


Figure 1-1: Schematic representation of the finite state machine

https://edms.cern.ch/document/2065162/1

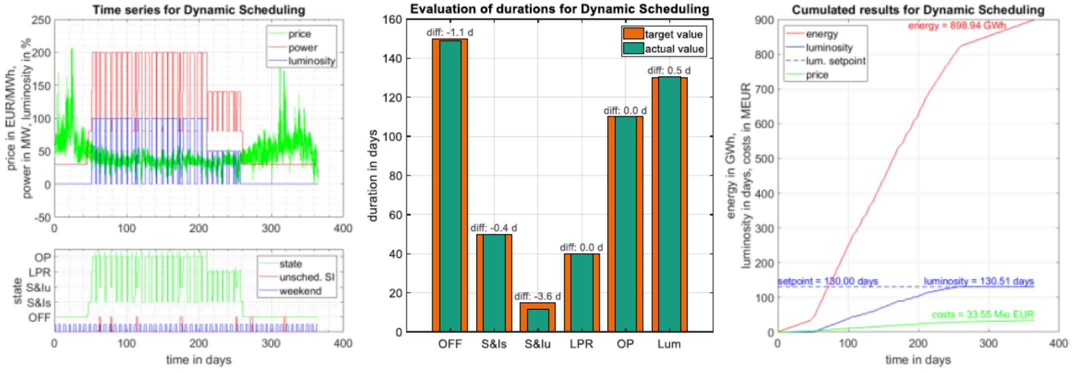


Figure 1-18: Example plots of a simulation run (left: time series, middle: bar graph with durations, right: cumulated times)

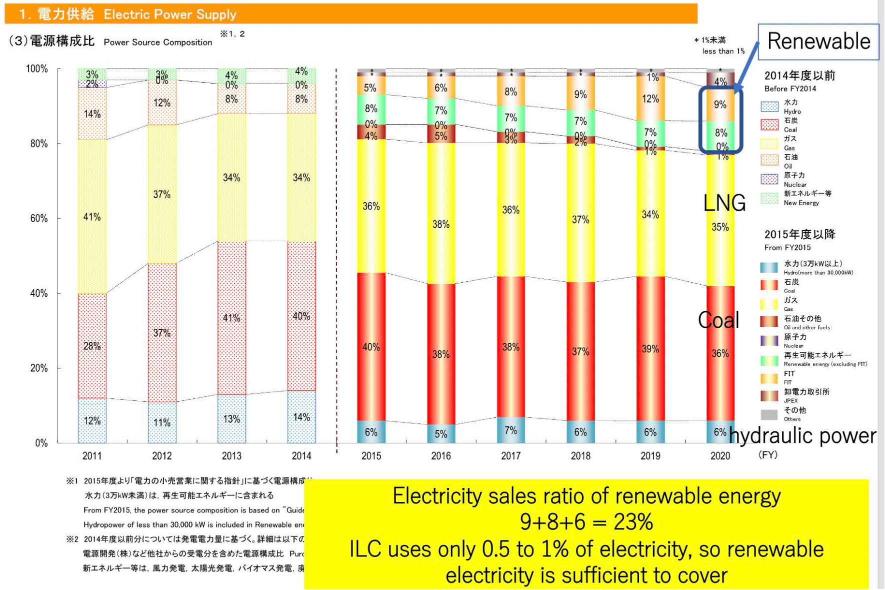
Shows that most of the saving is by not running in winter (as already implemented at CERN)
Some further saving (but significantly less) making use of other periods with energy surplus

Note: This study was done in 2018, the results today might be very different, and what will the results be in ~2050 (more renewable energy, improved buffering) ?

Considerations for ILC Operation

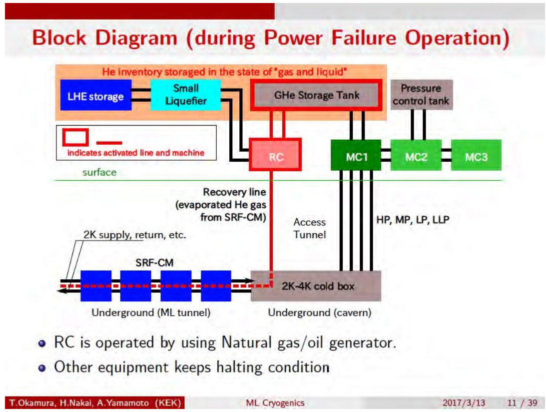
- CO_2-neutrality by 2050 is a goal for Tohoku region – ILC needs to contribute to this goal
- 23% regenerative electricity today – sufficient for ILC operation (ILC is less than 1%)
- First studies to evaluate potential to modulate power consumption according to RES availability (analogous to CLIC study):
  - Reduce repetition rate by 50% -> save 20MW
  - Interrupt beam operation -> save further 20MW
- Look for accelerator-specific energy buffers
  - Cryogenic plants a candidate: Liquid helium as energy buffer

Fact book (2020) by Tohoku Electric Power Co. Breakdown of electricity sales



Electricity sales ratio of renewable energy
9+8+6 = 23%
ILC uses only 0.5 to 1% of electricity, so renewable electricity is sufficient to cover

M. Yoshioka: https://agenda.linearcollider.org/event/9211/contributions/49408/



A very first estimate for 2.5Hz operation

	500 TDR	250-A	250-A' w/R&D	250 2.5 Hz	250 2.5 Hz w/R&D	Standby (RF off)
Rep-Rate / Hz	5	5	5	2.5	2.5	0
Bunches / Pulse	1312	1312	1312	1312	1312	0
Lumi / 10^{34}	1.8	1.35	1.35	0.68	0.68	0
Gradient / MV/m	31.5	31.5	35	31.5	35	
Q_0/1E10	1.0	1.0	1.6	1.0	1.6	
ML E-gain / GeV	470	220	220	220	220	
ML Power / MW	107.1	50.1	49.3	30.1	29.1	10.0
e- Src / MW	4.9	4.9	4.9	4.9	4.9	4.9
e+ Src / MW	9.3	9.3	9.3	9.3	9.3	9.3
DR / MW	14.2	14.2	14.2	14.2	14.2	14.2
RTML / MW	10.4	10.4	10.4	10.4	10.4	10.4
BDS / MW	12.4	9.3	9.3	9.3	9.3	9.3
Dumps / MW	1.2	1.2	1.2	1.2	1.2	1.2
IR / MW	5.8	5.8	5.8	5.8	5.8	5.8
Campus / MW	2.7	2.7	2.7	2.7	2.7	2.7
Gen. Margin/MW	5.1	3.3	3.2	2.7	2.6	2.1
Total	**173**	**111**	**110**	**91**	**90**	**70**

Based on ILC-CR-0018

Simple estimate Based on scaling RF and dynamic part of cryo power

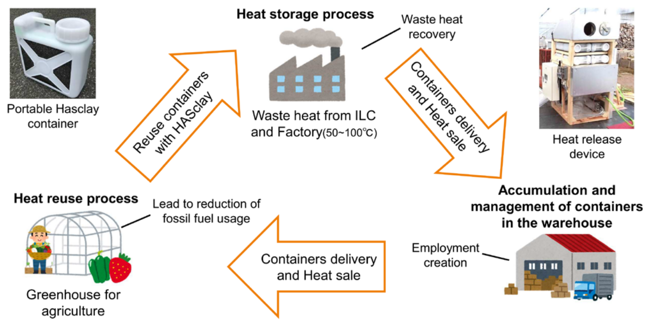
Not updated

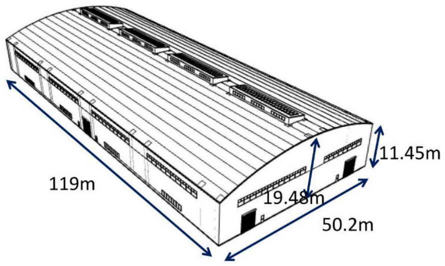
BL: https://agenda.linearcollider.org/event/9211/contributions/49518/

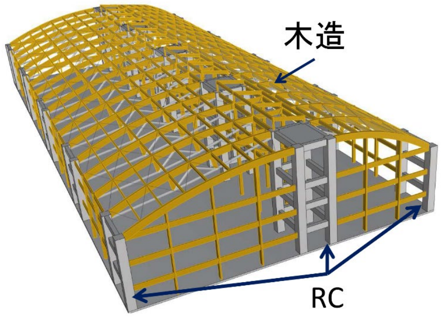
Green ILC Studies in Tohoku Area

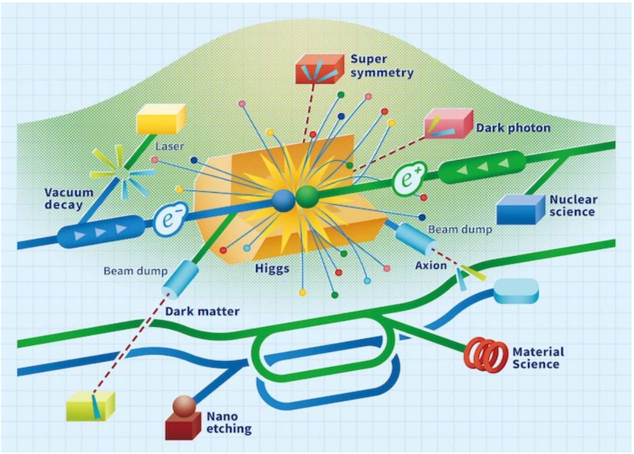
- Studies conducted on
  - Exhaust heat recovery from the ILC and the creation of business derived from it
  - Connecting the ILC with the local forestry industry
  - Utilization of solar heat
  - The ”Green ILC” concept and community development and planning - building an energy recycling society based on the Global Village Vision

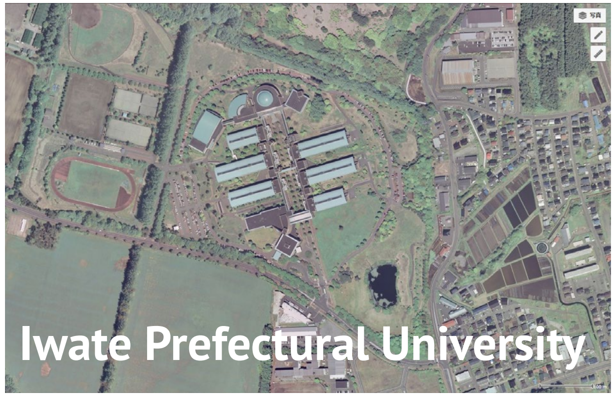
Utilization of heat circulation in Iwate prefecture by using HASClay®.











M. Yoshioka: https://agenda.linearcollider.org/event/9211/contributions/49408/
M. Yoshioka et al.: https://www.pasj.jp/web_publish/pasj2020/proceedings/PDF/WEPP/WEPP57.pdf

Being worked on – for both ILC and CLIC

More technical studies, e.g CLIC at higher energies and to some extent also ILC with SRF improvements folded in, magnets (permanent, HTS) and future klystron experimental results

Repeat some of the accelerator and system studies - system costs and power estimates (and prices) have changed signficantly

Repeat Fraunhofer like study, also for ILC in Japan, covering use of renewables and daily/weekly fluctations – but very volatile prices currently.

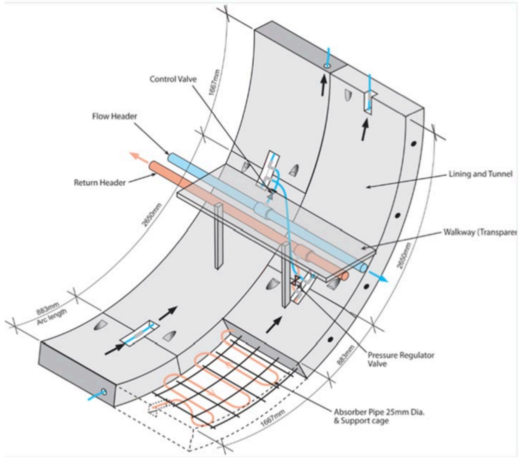
Tunnel heat recovery study, initial study done by ARUP (see panels)

Dealing with the spoil from CE

Carbon estimates:

- Towards 2040-50 the energy for operation is likely to come from carbon neutral sources
- However, CE, accelerator construction and later decommissiong – will have very imporant carbon footprint
- Need to study many systems, many materials, different processing of materials (even concrete), what is done to them and where, removal and decommissioning – not an easy task

At some point feed back into cost estimates



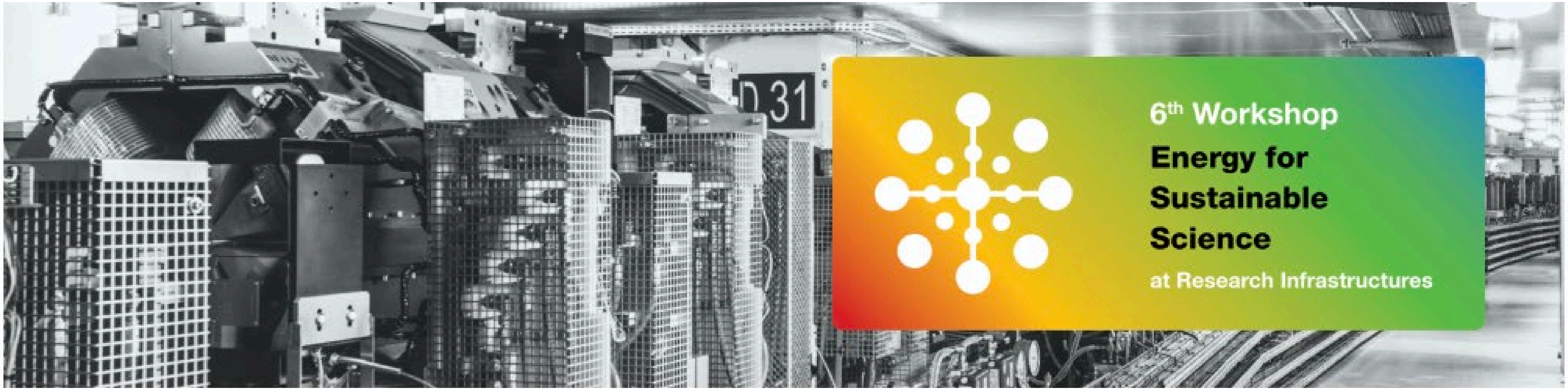
The lower bound of energy output of the thermal tunnel is 10W/m2, this is likely to be an underestimate as tunnel air or heat ejection is not considered.

A 600m thermally activated tunnel is similar to that of 35 100m borehole in term of ground heat exchange rate.

For like-to-like comparison, i.e. the tunnel is to run with a balanced load, the tunnel can produce 20-30W/m2, which is similar to 70 or more GSHP boreholes.

Summary

- Sustainable accelerator design starts with choice of fundamental design and technology:
  - Selection of least resource-hungry designs compatible with the long-term scientific objective – linear accelerators well suited
- Optimisation of subsystems and components for energy efficiency and material conservation, e.g.
  - Better accelerator cavities (optimize design for more gradient, reduced losses, reduced waste during fabrication)
  - Efficient klystrons
  - Permanent magnets
- Optimize operation strategies
  - Re-cycling of waste heat
  - Power modulation to follow "low cost" power availability
  - Identify & utilize accelerator-specific energy buffers



Thank you

and to many contributors to these studies

In particular Benno List, DESY – this talk is based on his presentation to IAEA in May 2022