IAEA-CN301-054

Sustainability Studies for Linear Colliders

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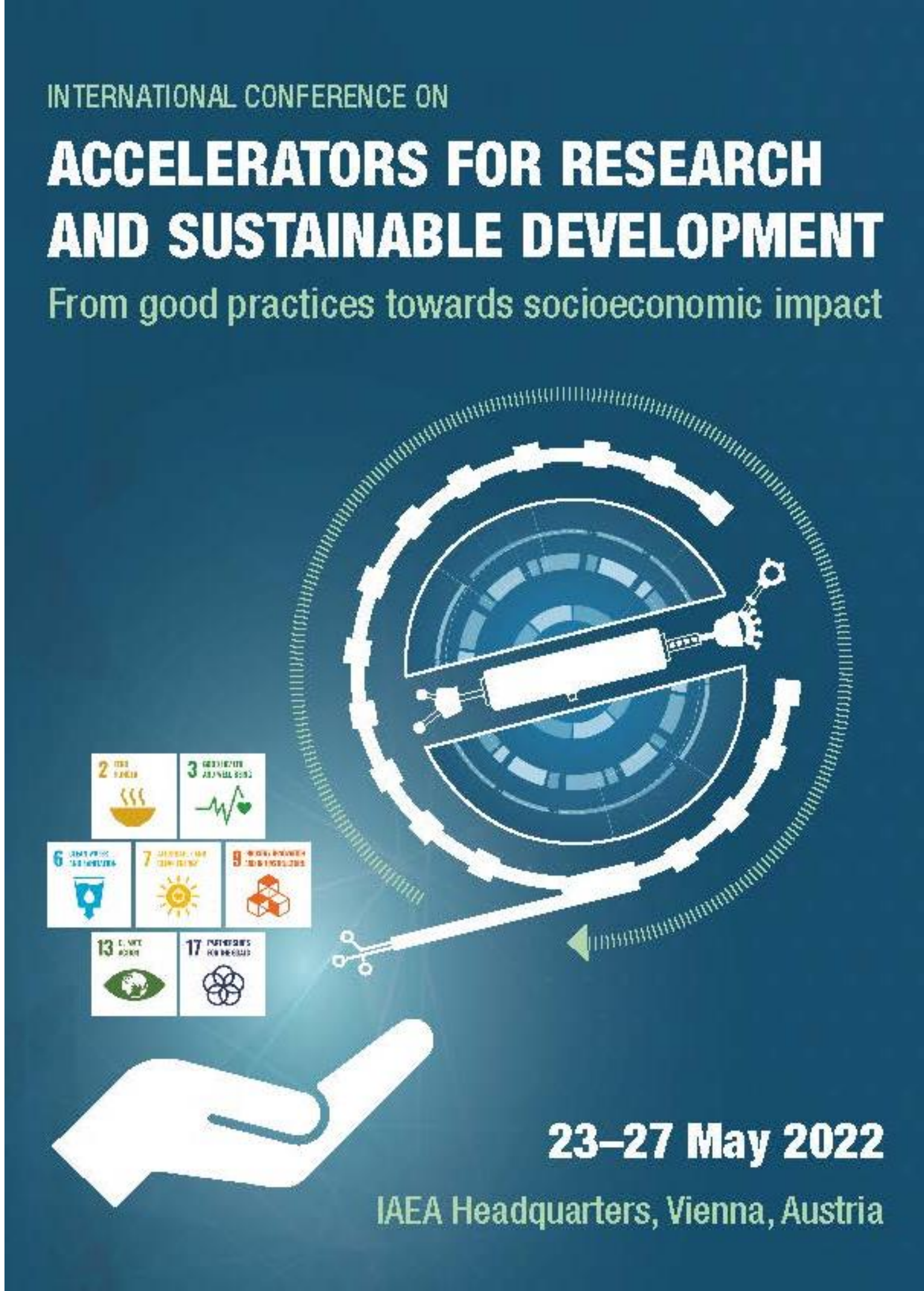
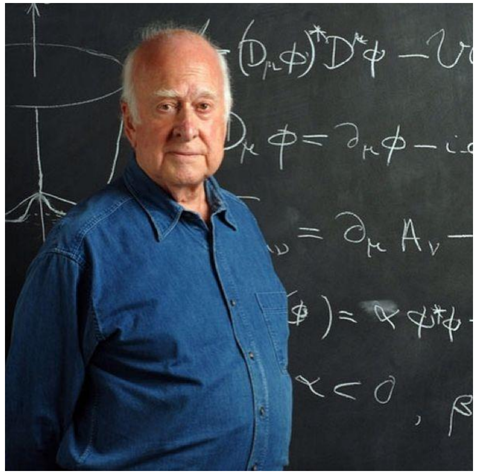


Linear Colliders as Higgs Factories

Higgs Boson
- The most mysterious particle yet discovered
- gives mass to elementary particles
- Discovered in 2012 at CERN, Mass: 125 GeV
- -> Nobel Prize in 2013 for Englert and Higgs

Higgs Factory
- Highest priority as next project in high energy physics
- Produces Higgs+Z^0 bosons in e^+e^- collisions
- Centre-of mass energy 250GeV
  -> beam energy 2 x 125GeV
- Beyond only the Higgs:
  - Top-quark pairs: require 350-380GeV
  - Top pair + Higgs, Z^0+Higgs pair: require ≥500 GeV

A New Linear Collider
- Synchrotron radiation limits circular storage rings
- 11-21km linear accelerator instead of 100km ring
- 5MW beam power instead of 100MW synchrotron radiation
- Two concepts for linear collider presented here: ILC and CLIC



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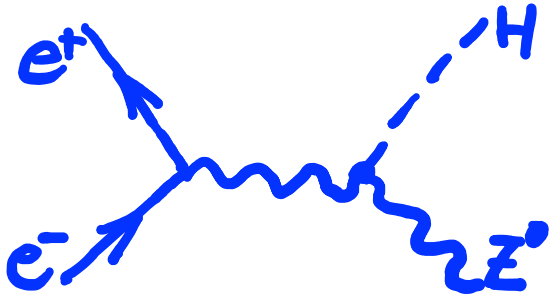
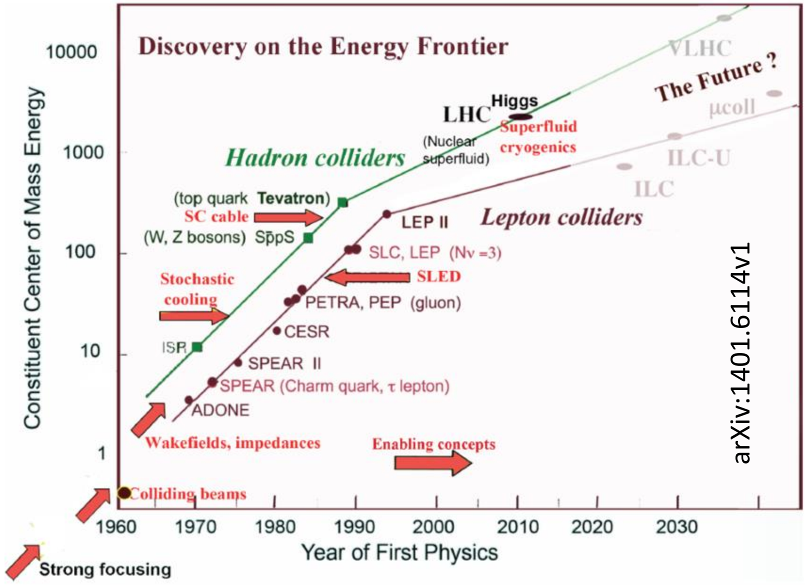


$e^+e^- \rightarrow ZH$ production

SLAC linear collider, Stanford, CA

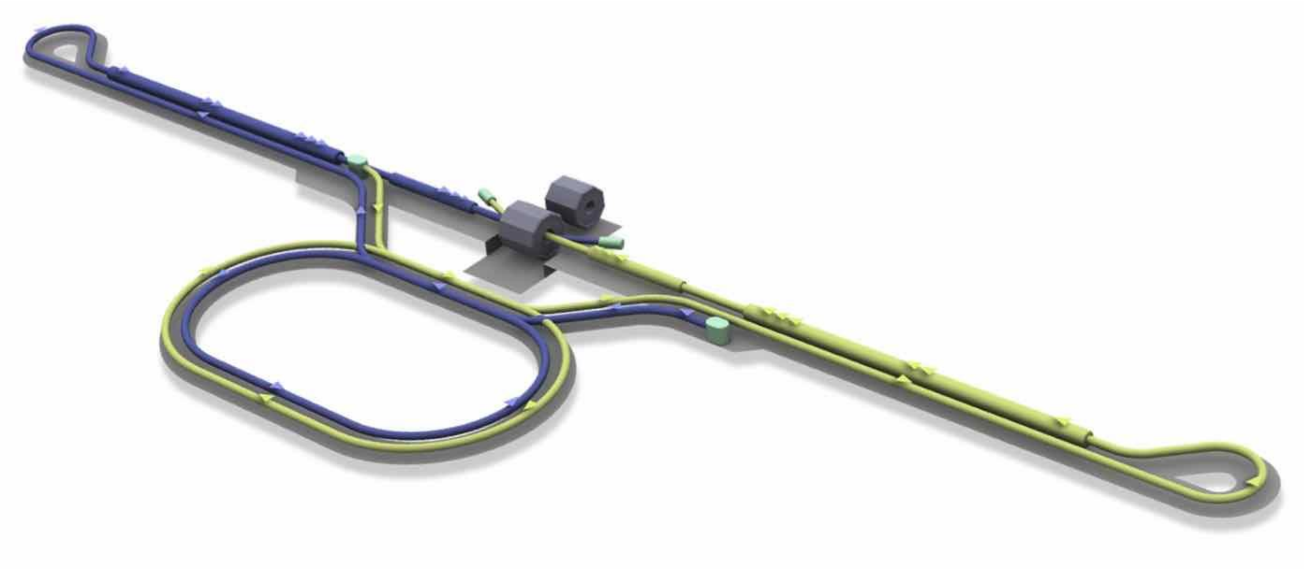
Sustainability Considerations

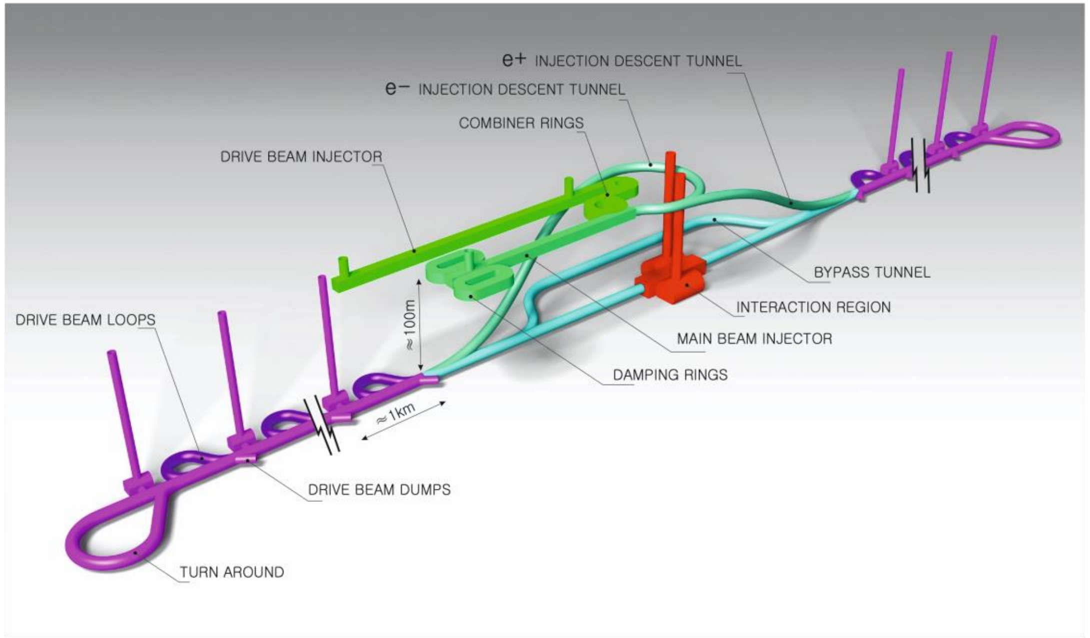
- Accelerators for High Energy Physics are at the leading edge of technology:
  beam energy, intensity, luminosity…
- Ressource conservation is paramount:
  - Tunnel length -> construction cost
  - Power consumption -> operating costs
- Sustainability adds new cost measures:
  e.g. CO_2, rare earth usage



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 in tunnel linings
- Sustainable operation concepts
  - Recycle energy (heat recovery)
  - Adapt to regenerative power availability
  - Exploit energy buffering potential

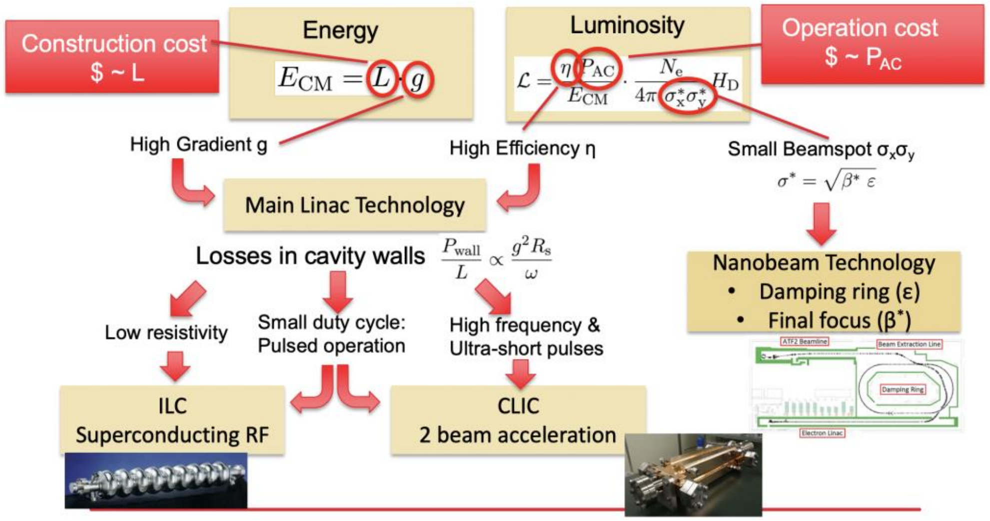


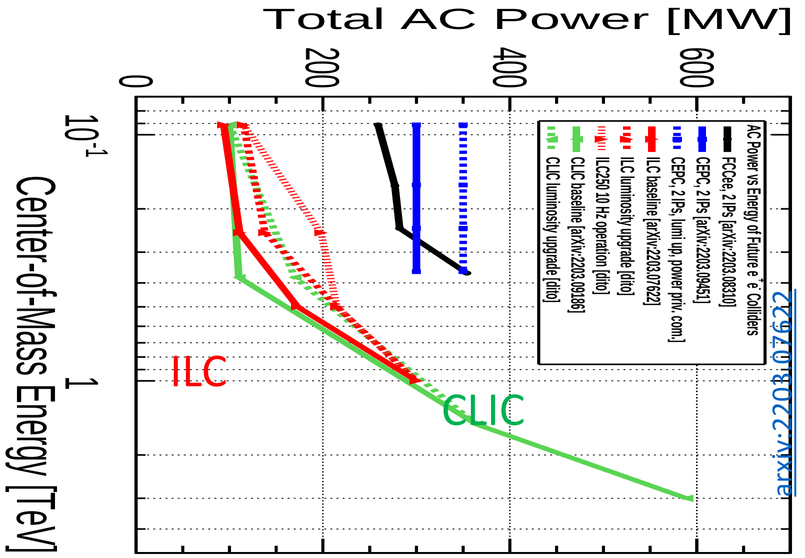


Overall System Design

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

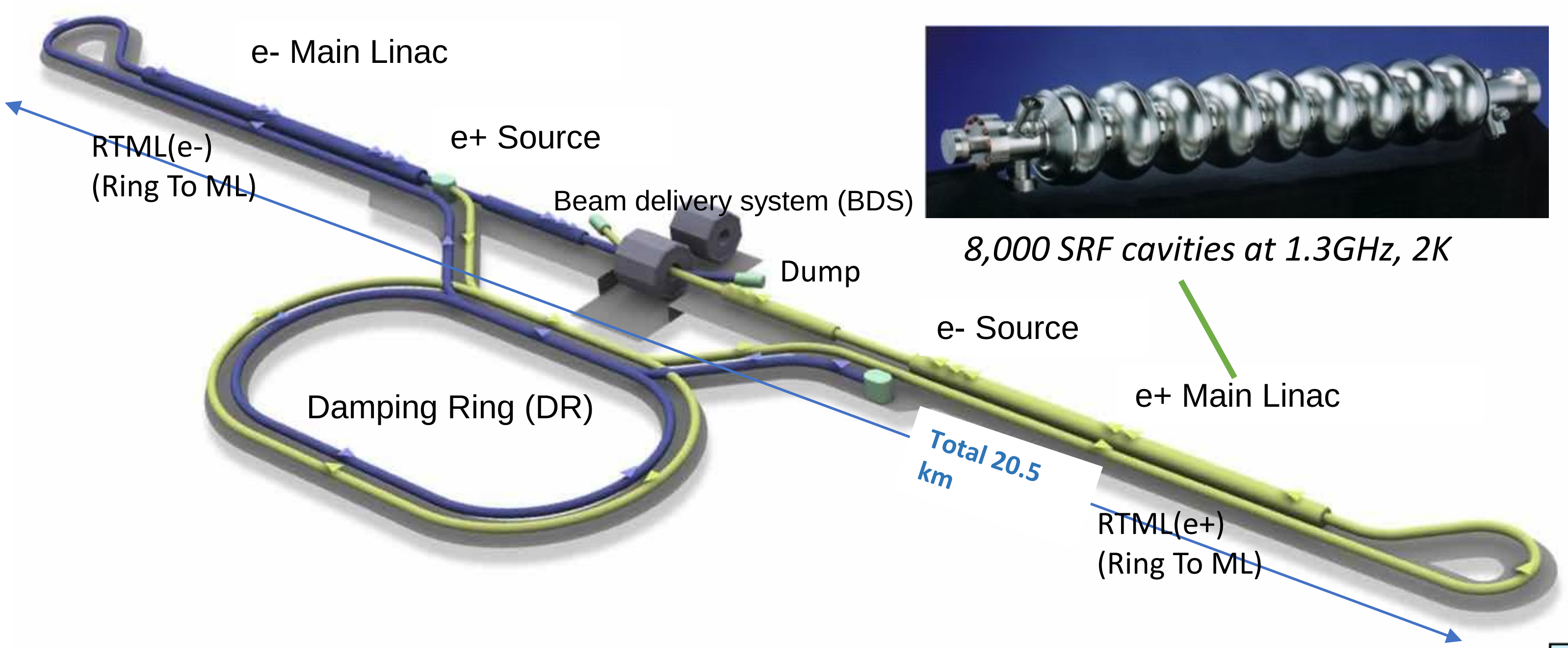
Overall System Design





- Challenge: Achieve target **energy** and **luminosity** with least possible amount of **ressources**
- 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

The International Linear Collider (ILC)

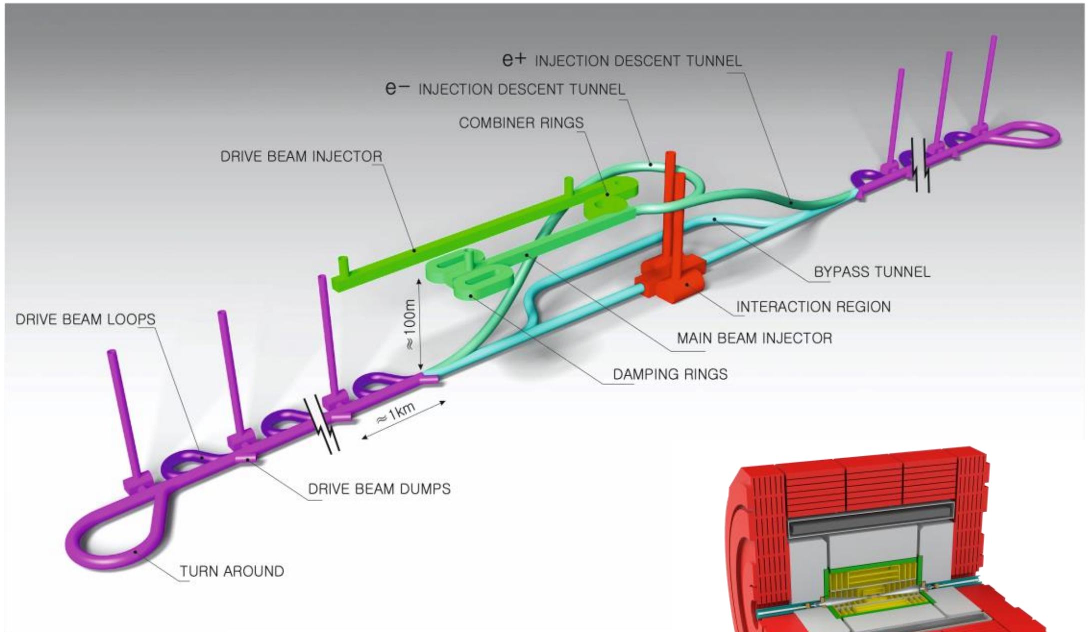


8,000 SRF cavities at 1.3GHz, 2K

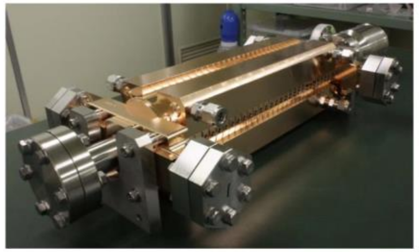
Item	Parameters
C.M. Energy	250 GeV
Length	20km
Luminosity	1.35 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA (in pulse)
Beam size (y) at FF	7.7 nm@250GeV
SRF Cavity G. Q_0	31.5 MV/m (35 MV/m) Q_0 = 1x10^{10}

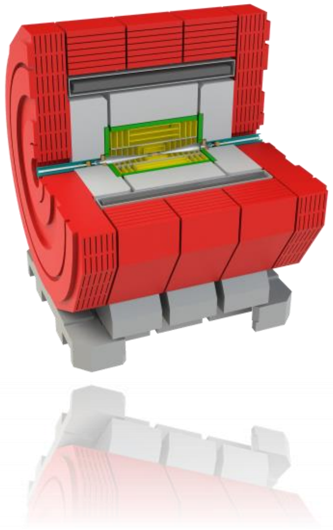
- Proposed Higgs factory in Tohoku (Japan), 250GeV initial energy
- Superconducting Main Linac for energy efficiency
- Timeline: 4 year preparation + 10 years construction -> operation 2037
- Expandable to 1TeV
- Cost: 6.3 – 7.0 B$, including human ressources
- Power: 111 MW at 250GeV

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:** 110 MW at 380 GeV corresponding to ~50% of CERN’s energy consumption today

- Comprehensive **Detector and Physics** studies

From power to energy for CLIC - as an example

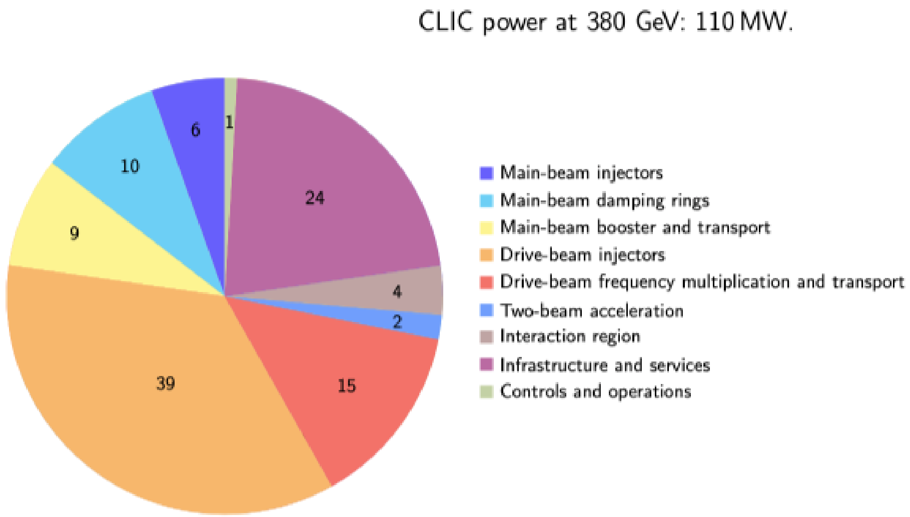


Fig. 4.8: Breakdown of power consumption between different domains of the CLIC accelerator in MW at a centre-of-mass energy of 380 GeV. The contributions add up to a total of 110 MW. (image credit: CLIC)

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].

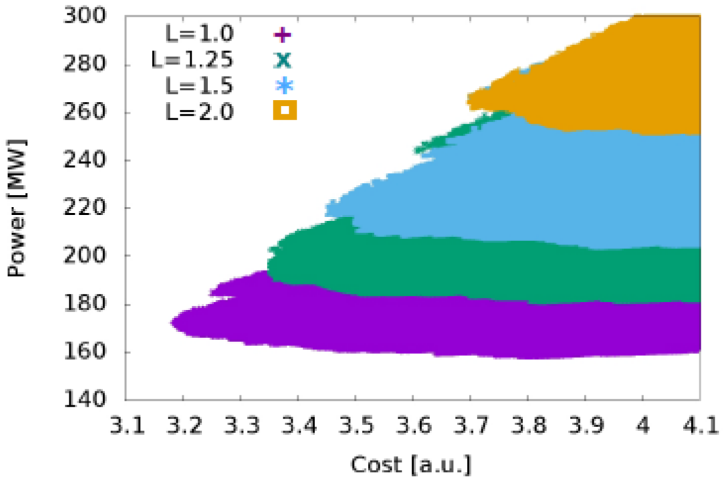
Collision energy [GeV]	Running [MW]	Standby [MW]	Off [MW]
380	110	25	9
1500	364	38	13
3000	589	46	17

Power estimate bottom up (concentrating on 380 GeV systems). Very large reductions achieved by systematic studies:

- better estimates of nominal settings
- much more optimized system design
- more efficient klystrons
- damping ring RF, injectors significantly reduced by redesign
- permanent magnets (become more important for 1.5 and 3 TeV)

Energy consumption ~0.6 TWh yearly, CERN is currently (when running) at 1.2 TWh (~90% in accelerators)

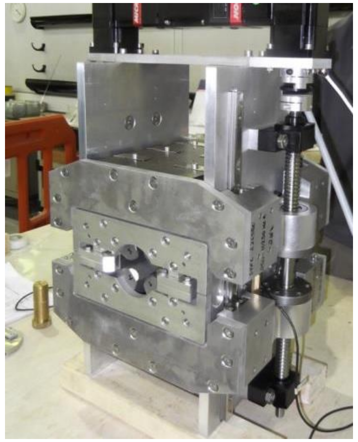
1.5 TeV and 3 TeV numbers still from the CDR in 2012, to be re-done the next ~2 years

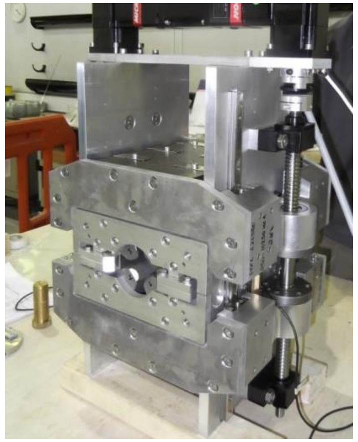


Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum*

* this work was done before all other reductions were implemented

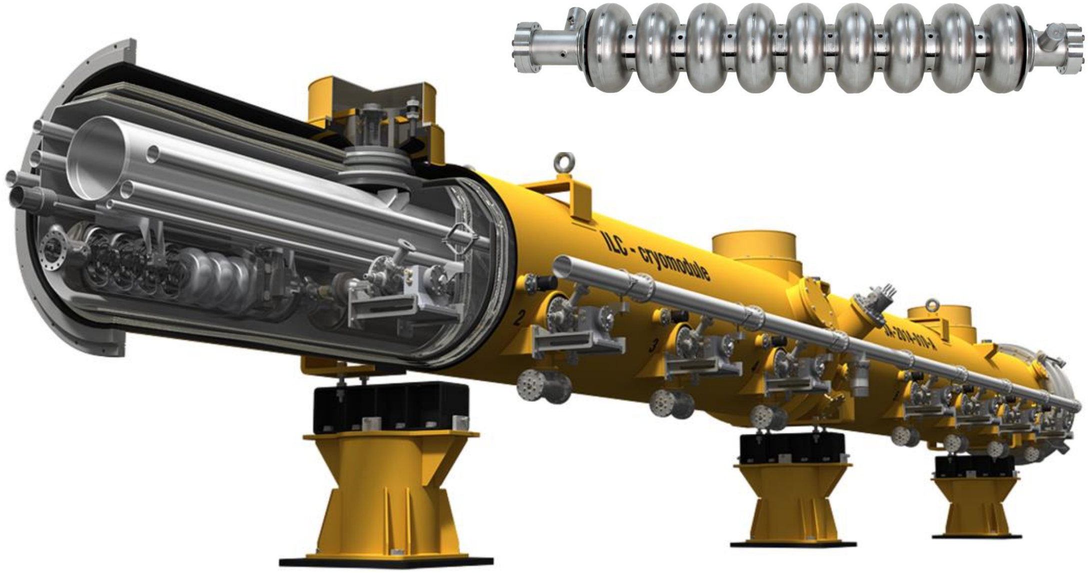
Optimization of Components and Subsystems

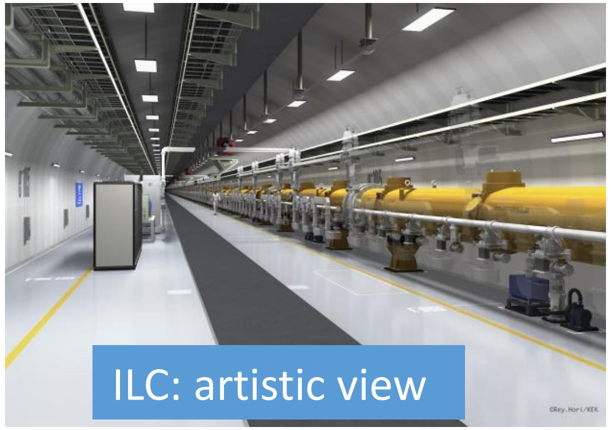




TESLA SRF Technology for the ILC Main Linac

- ~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

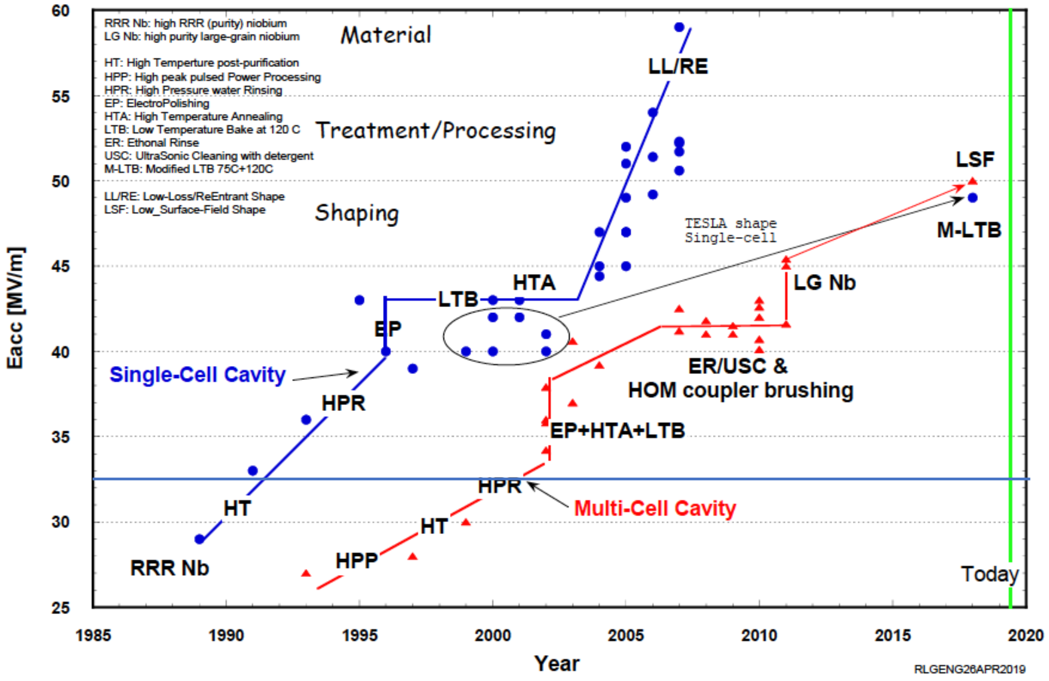


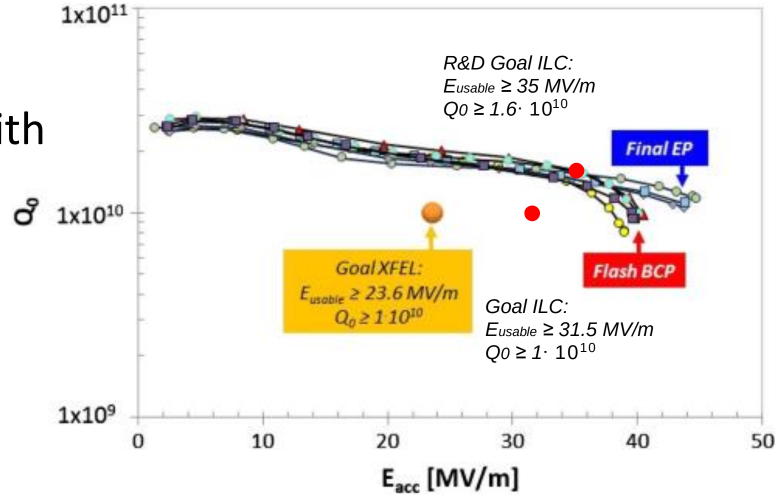

ILC: artistic view


E-XFEL: Reality

R&D for Improved SRF Performance & Sustainability

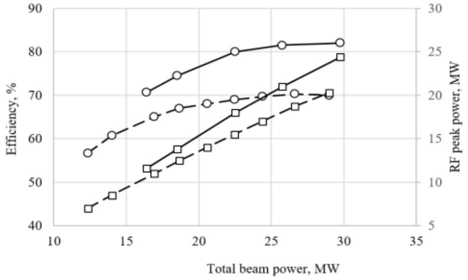
- Better surface treatments and cavity shapes improve cavity performance. Lots of progress in last 10 years
- Raise gradient: fewer cavities for same beam energy.
  Short term goal: 31.5MV/m -> 35MV/m
  Medium term goal: 45MV/m
  Lab record: 59MV/m
- Improve Q_0: reduce cryogenic losses
  (1W @ 2K requires ~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 (CLIC)

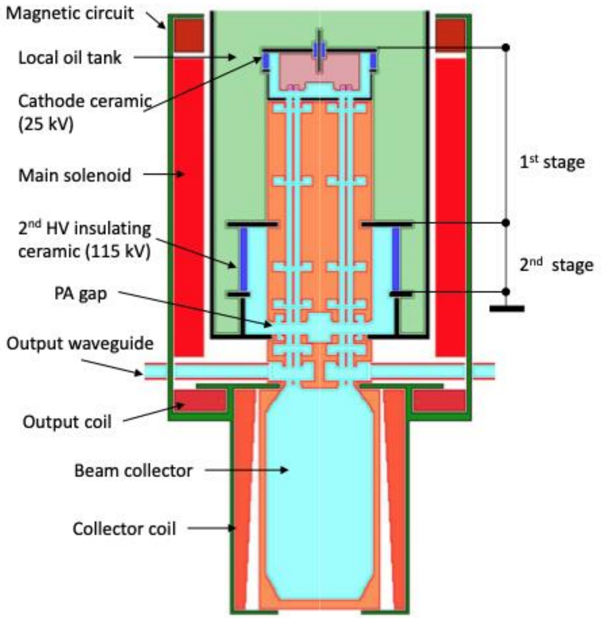
L-band, X-band (for applications/collaborators and test-stands)

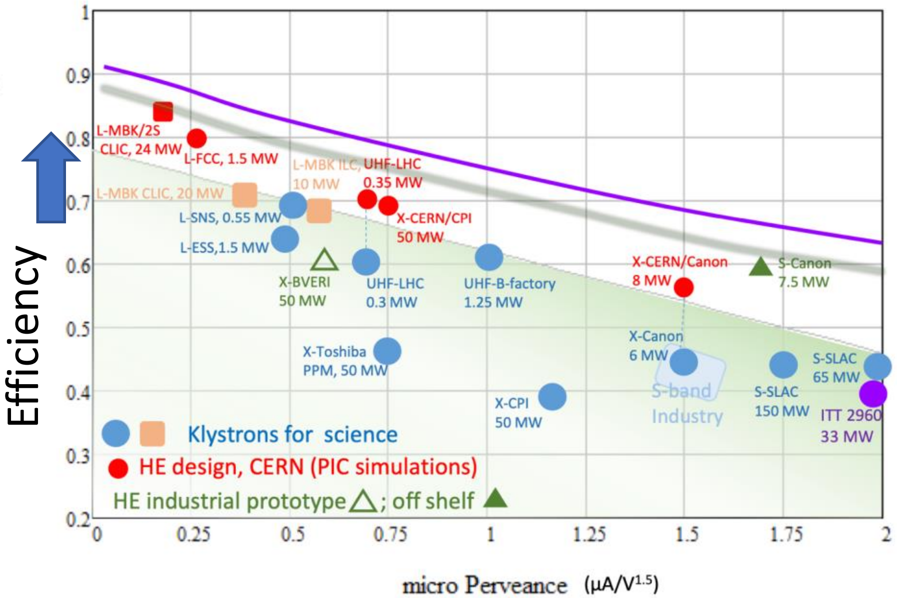


Location: CERN Bldg: 112

Drive-beam 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.

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





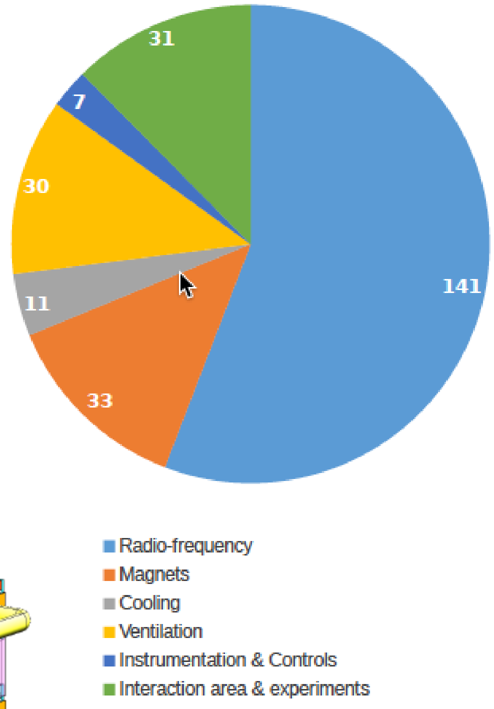
High Efficiency implementations:

- New small X-band klystron, ordered
- Large with CPI, work with INFN
- L-band two stage for CLIC drivebeam, design done, prototyping for FCC, also suitable for ILC
- Aim: ~80% efficiency (up from 65-70%)

All of these have a substantial impact on power and energy use (see recent progress below)

Magnets also important

1.5 TeV CLIC power
Magnets second largest



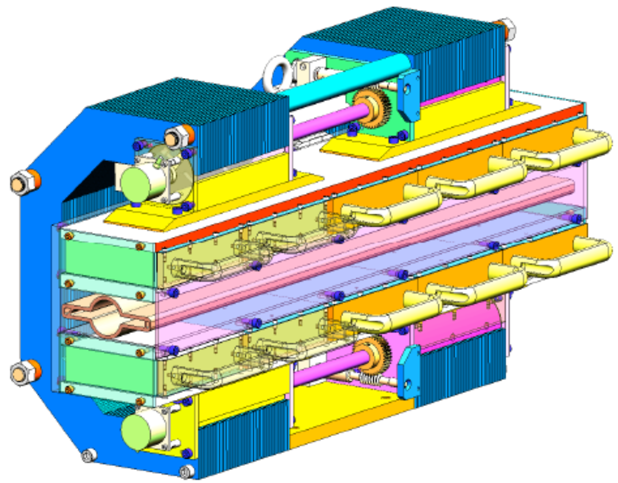
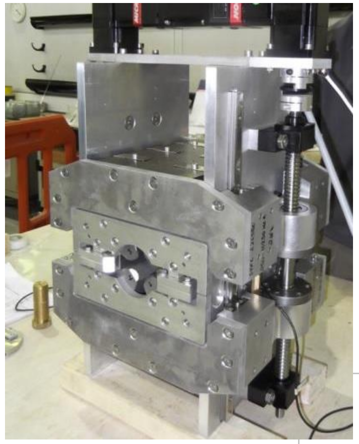


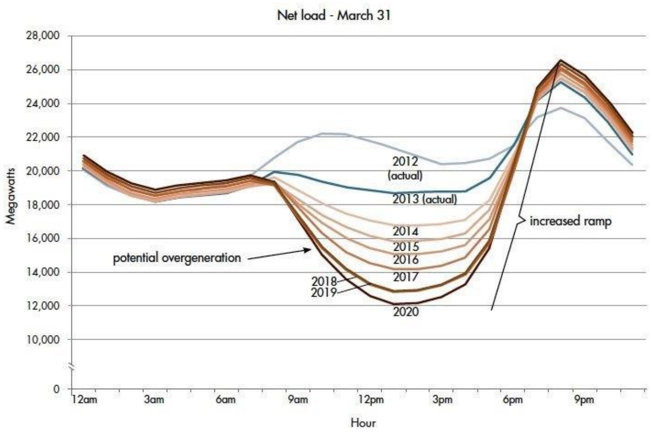
Figure 3: Overview of possible design of PM dipole for ILC damping ring.

doi:10.18429/JACoW-IPAC2018-MOPML048 CC-BY-3.0

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.

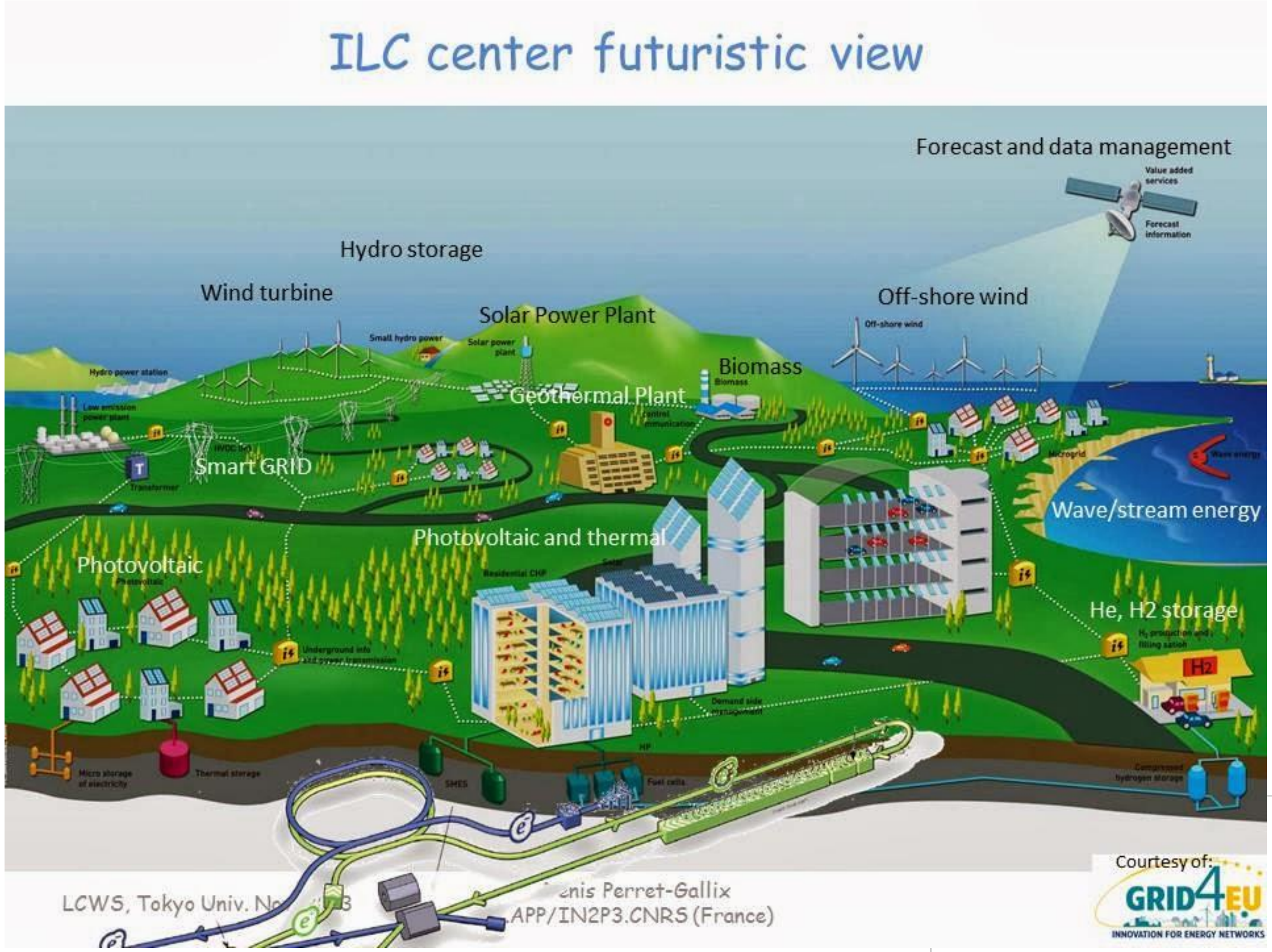
For CLIC the dominant power is in the drive-beam quadrupoles, successfully prototyped and tested as permanent (two different strengths) magnets





Sustainable Operation


Asurnipal CC-BY-SA-4.0

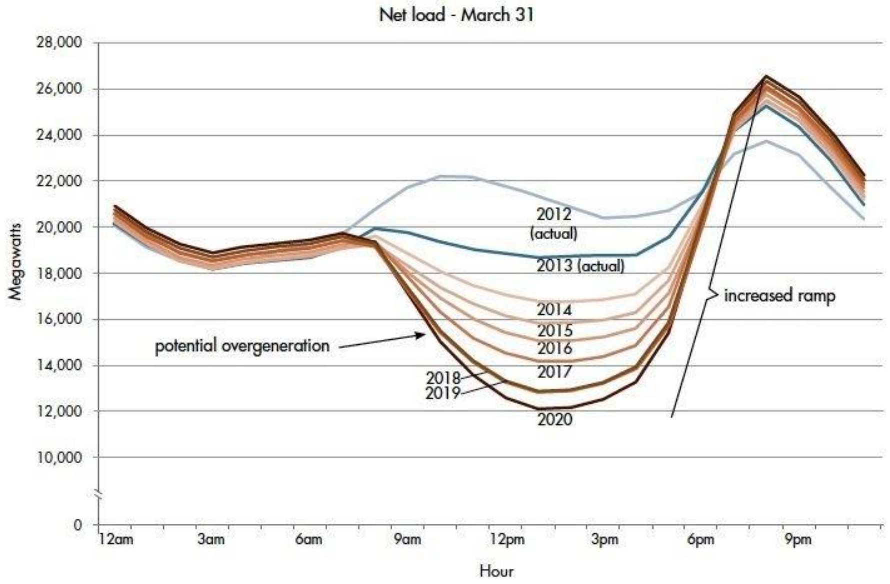


Approaches to increase sustainability

- 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
- -> 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

CLIC: Study on Regenerative Energy Use

- CLIC Study: consider 5 operating modes:
  - Off (shutdown)
  - Standby and intervention – scheduler 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

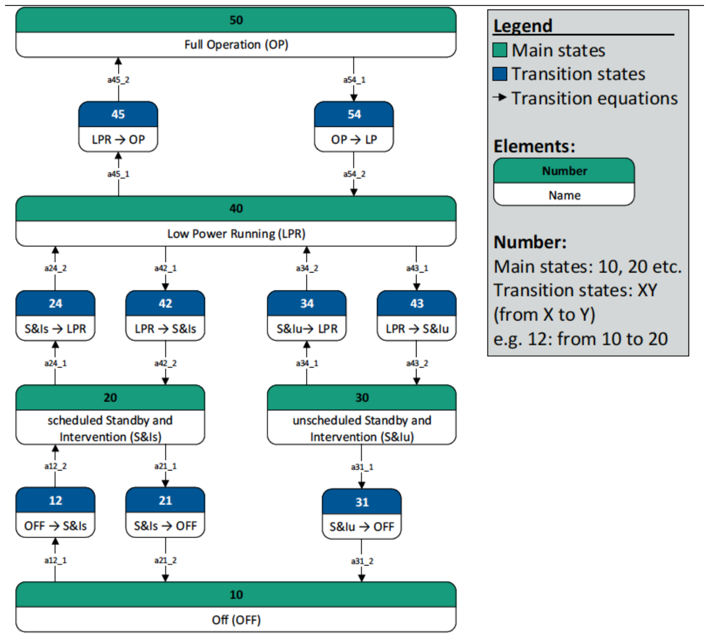


Figure 1-1: Schematic representation of the finite state machine

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

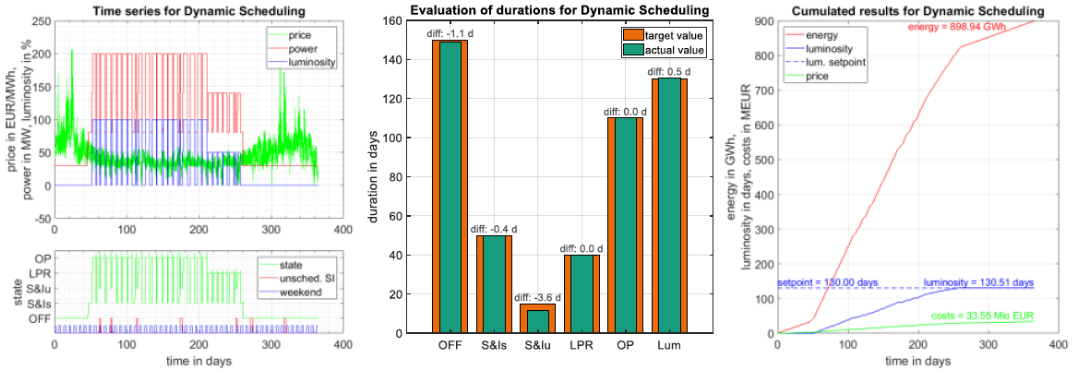


Figure 1-18: Example plots of a simulation run (left: time series, middle: bar graph with durations, right: cumulated times)

Running on renewables

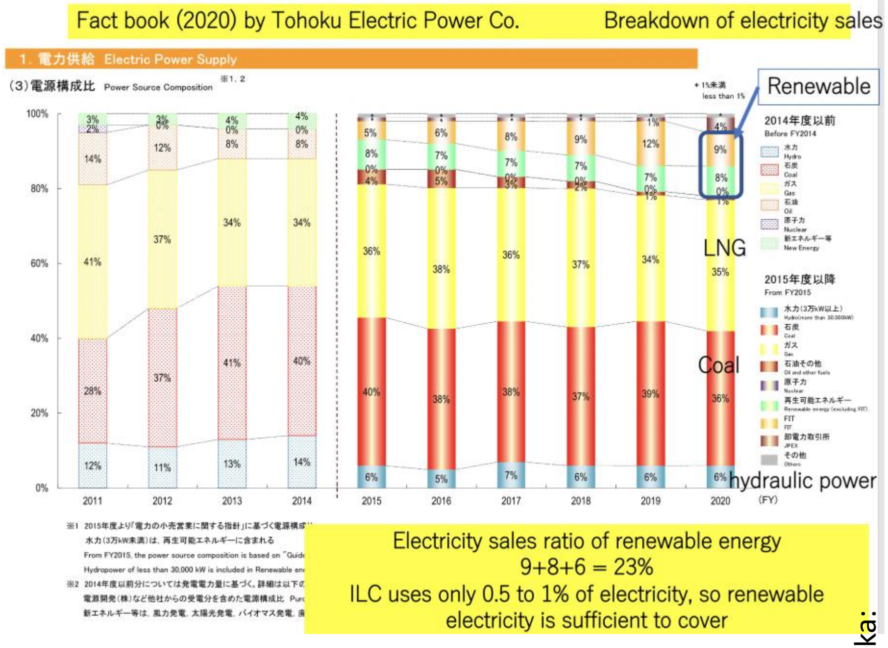
- It is possible to supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators, at a cost of slightly more than 10% of the CLIC 380 GeV cost)
  - At the time of the study 200 MW was conservatively used, in reality only ~110 MW are 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 are low anyway

- A similar approach will also work well for ILC

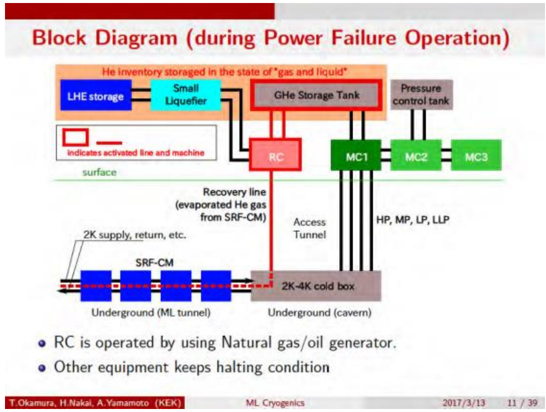
More information (link)

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
- 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



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

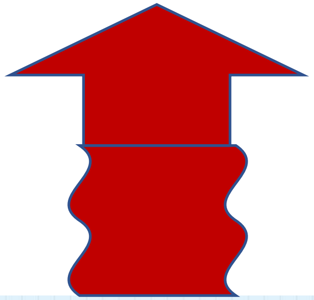
Simple estimate
Based on scaling
RF and dynamic part
of cryo power

Not updated

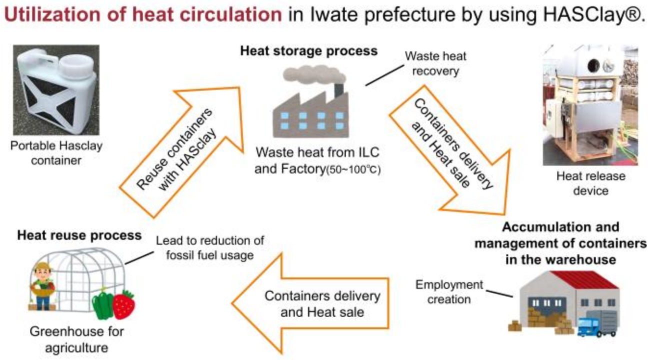
BL: https://agenda.linearcollider.org/event/9211/contributions/49518/

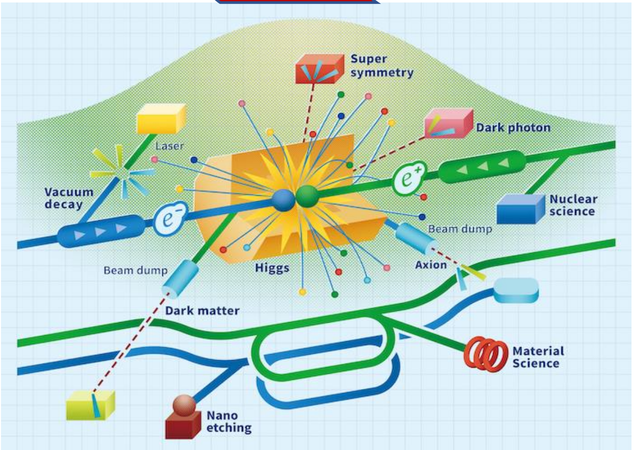
Green ILC Studies in Tohoku Area

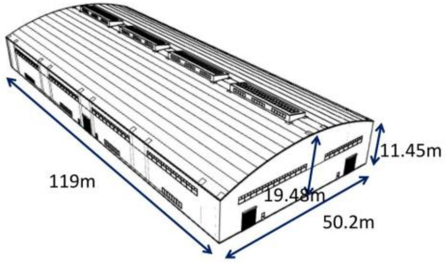
320ktonCO2/year

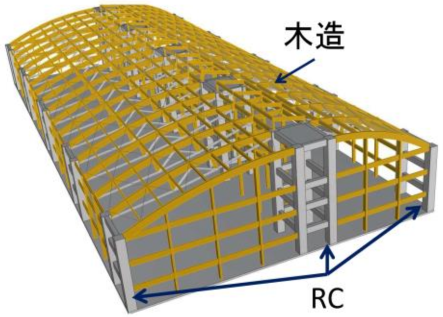


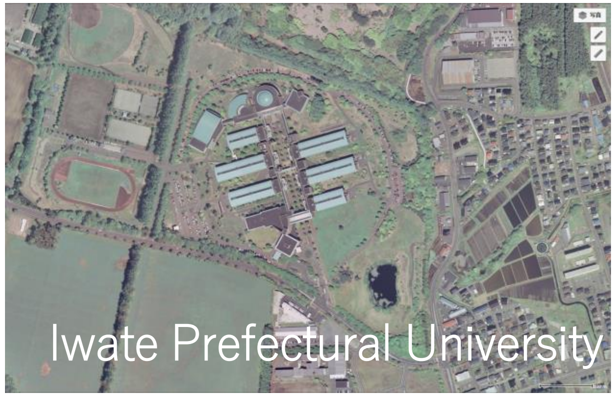
- Studies conducted on
  - Exhaust heat recovery from the ILC and the creation of business derived from it
  - Connecting the ILC with the local forestry industry
  - Utilization of solar heat
  - The ”Green ILC” concept and community development and planning - building an energy recycling society based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







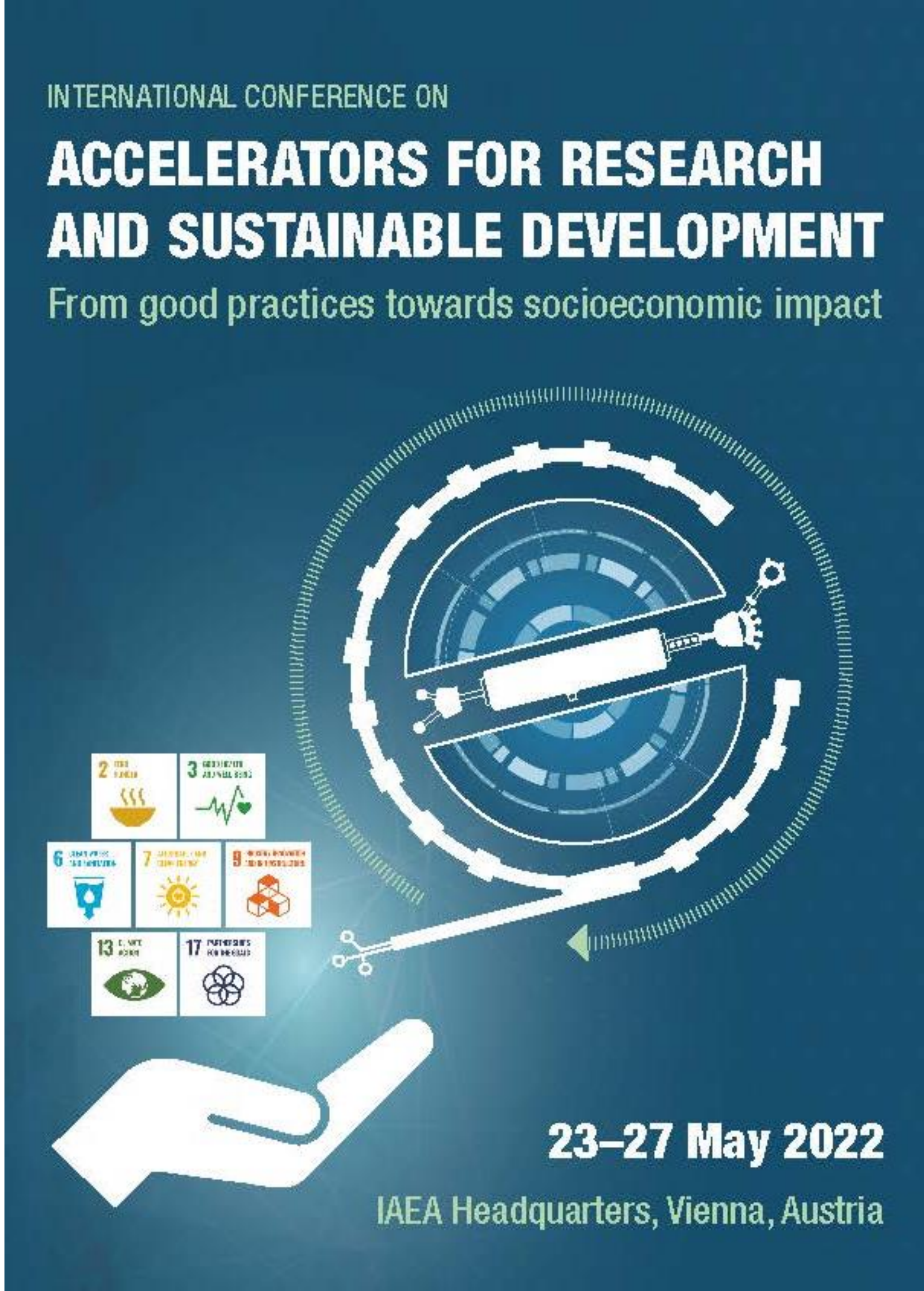




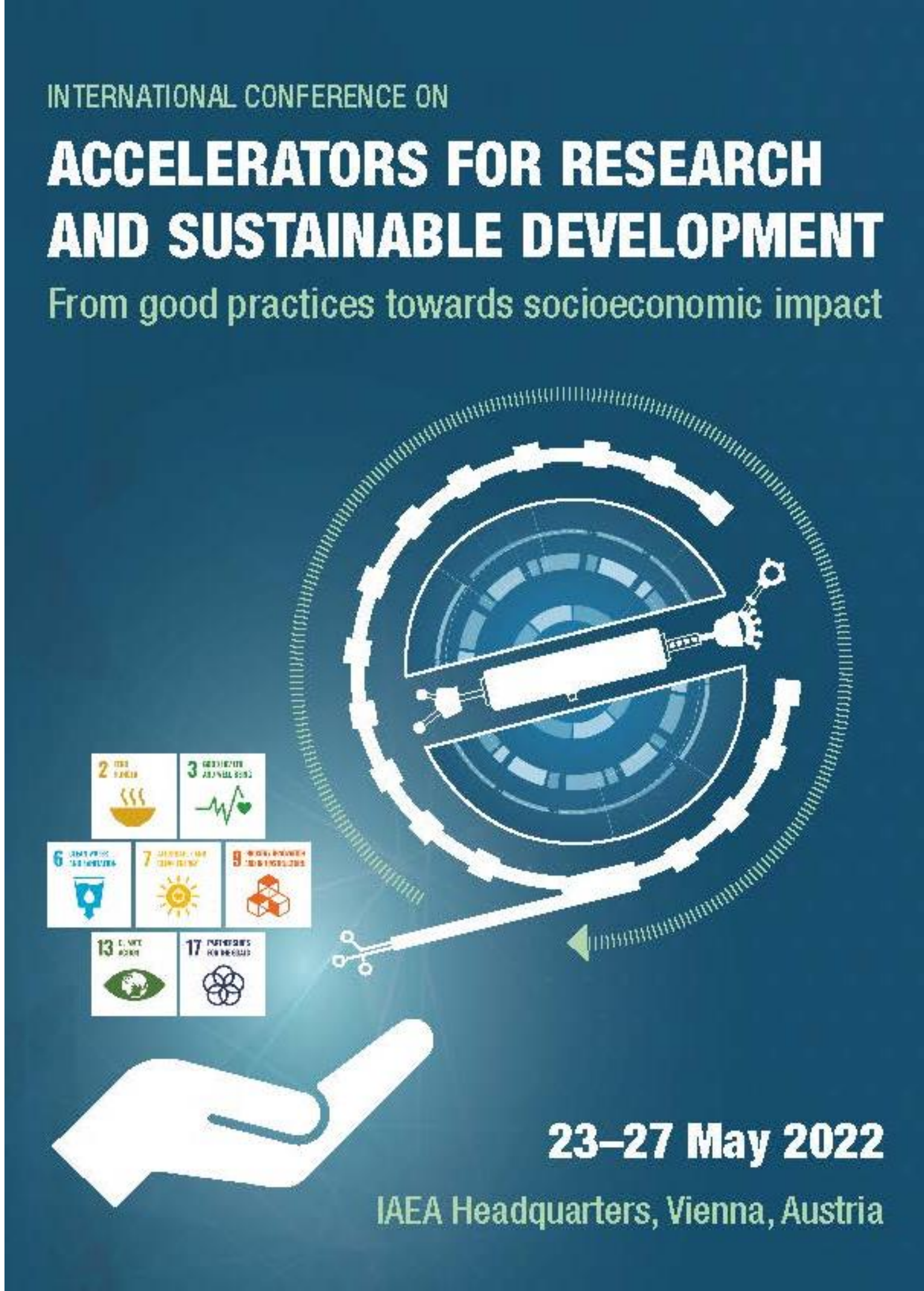
M. Yoshioka: https://agenda.linearcollider.org/event/9211/contributions/49408/
M. Yoshioka et al.: https://www.pasj.jp/web_publish/pasj2020/proceedings/PDF/WEPP/WEPP57.pdf

Summary

- Sustainable accelerator design starts with choice of fundamental design and technology:
  - selection of least resource-hungry design compatible with the long-term scientific objective – linear accelerator
- 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 RES availability
  - Identify & utilize accelerator-specific energy buffers



Thank you


INTERNATIONAL CONFERENCE ON
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