Sustainability Studies for Future Linear Colliders & Life-Cycle Assessment

Maxim Titov, CEA Saclay / CERN
**ILC / CLIC: Approaches to Increase Sustainability**

- **Resource optimization traditionally** done for accelerators:
  - Length/complexity -> construction cost
  - Power/energy consumption -> operating costs
  
  Traditionally we **optimize for energy reach and luminosity wrt to cost and power**

- **Sustainability in a wider sense adds new construction and operation optimization criteria:**
  - **Energy use not only costs but also embedded CO$_2$ in construction materials and components, rare earth usage** -> responsible sourcing in general for all parts, landscaping, integration in local communities, life cycle assessments including decommission and many more issues

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<table>
<thead>
<tr>
<th>Overall system design</th>
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<tbody>
<tr>
<td>- Compact accelerator</td>
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<tr>
<td>- high gradient; high field magnets</td>
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<tr>
<td>- Energy efficient</td>
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<tr>
<td>- low losses (wall-plug to beam)</td>
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<td>- Effective</td>
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<td>- nm-beam sizes to maximize luminosity</td>
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<td>- Energy recovery concepts</td>
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<tr>
<td>- Civil engineering including landscaping and « community » integration</td>
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<tr>
<th>Subsystem and component design, e.g.</th>
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<tbody>
<tr>
<td>- High-efficiency cavities and klystrons</td>
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<td>- Permanent magnets, HTS magnets</td>
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<td>- Heat-recovery. e.g. in tunnel linings</td>
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<td>- Responsible sourcing and material choices</td>
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<tr>
<th>Sustainable operation concepts</th>
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<tbody>
<tr>
<td>- Renewables</td>
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<tr>
<td>- Adapt to regenerative power availability</td>
</tr>
<tr>
<td>- Exploit energy buffering potential</td>
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<tr>
<td>- Recover energy (heat recovery)</td>
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Good progress on the **green points** (was also part of the our radiational approach), initial progress/focus on the **yellow / black ones**
ILC / CLIC: Overall Resource Efficiency Considerations

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

- **Optimize resources for construction/operation:**
  - **Compact:** high acceleration gradient
  - **Energy-efficiency:** RF efficiency becomes increasingly important for higher energies
    - ILC: superconducting RF
    - CLIC: high frequency & ultra-short pulses
  - **Effectiveness:** maximize luminosity / beam power → nanobeams technology

- **ILC (250 GeV) and CLIC (380 GeV):**
  - Different solutions to the efficiency problem
  → final power consumption similar (~100 MW)

- **Embodied CO₂:** proportional to facility length
  - Efficient RF systems, luminosities optimization vs. beam power for stability, alignment, instrumentation for nano-beams, etc …
  - Embodied carbon addressed by reducing length of installation and tunnel diameter
On-going CLIC Studies Towards next European Strategy Update

Project Readiness Report as a step toward a TDR
Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030

The X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators

CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

Optimizing the luminosity at 380 GeV – already implemented for Snowmass paper, further work to provide margins will continue:

- Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 10^34 cm^-2 s^-1
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above 2.3 x 10^34 cm^-2 s^-1 (this is the value currently used)

Improving the power efficiency for both the initial phase and at high energies, including more general sustainability studies:

Very large reductions in power estimate (380 GeV) since the CDR: better estimates of nominal settings, much more optimised drive-beam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies

S. Stapnes: https://indico.cern.ch/event/1260648/
A subset of the initial plan for the ILC preparation phase activities (“Pre-lab”) have been identified at the most critical, and the priorities emphasized in the ITN:

→ **European Preparation for the ITN (2023 ->)** distributed on five main activity areas, and foreseen to concentrate for the **accelerator part (ILD-WG2)** & technical activities:

- **A1 SC RF related**: Cavities, Module, Crab-cavities
- **A2 Sources**: Concentrate on undulator positron scheme – fast pulses magnet, consult on conventional one (used by CLIC and FCC-ee)
- **A3 Damping Ring including kickers**: low Emittance Ring community, and also kicker work in CLIC and FCC
- **A4 ATF activities for final focus and nanobeams**: many European groups active in ATF, more support for its operation expected using the fresh funding
- **A5 Implementation including Project Office**: Dump, CE, Cryo, Sustainability, MDI, others (many of these are continuations of on-going collaborative activities)

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S. Stapnes:
https://indico.cern.ch/event/1297278/contributions/5453722/attachments/2675796/4641399/linear-colliders.pptx
ILC / CLIC: Overall System Design & Optimization

Usually, projects optimize – energy reach, luminosity and cost. Power becomes increasingly important; solutions exist compromising ultimate performance for power consumption & savings.

• **Design Optimization for CLIC:**
CLIC designs (drive-beam), including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost, but also focusing on power consumption (in parallel: re-design and optimisation of RF systems, e.g. damping rings and drive-beam).

  E.g. Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum (2015)

• **Design Optimization for ILC:**
ILC design optimization have been, focusing on parameters choices, for example repetition rates, pulse-lengths, cryo and RF systems for various luminosity choices.

  E.g. higher $E_{\text{acc}}$ means lower invest in cavities/cryomodules, but larger invest in RF/cryogenics (losses per length scale as $E_{\text{acc}}^2$)

**For both ILC / CLIC, it would be interesting to repeat studies, focusing more strongly on power consumption, and including exercise with CO$_2$** (e.g. weigh the savings in embodied CO$_2$ vs the expense of CO$_2$ through operation…)

*Updated Baseline for a Staged CLIC: CERN-2016-004*

*Cost Estimation of a 250 GeV ILC LINAC*  

*For Fermilab, D. Baifa @ LCWS2019*
Approaches to Increase Sustainability: Optimization of Subsystems and Components
R&D for Improved ILC SRF Performance & Sustainability

Major progress during past 10 years:

- **Raise Gradient:**
  - Short term goal: 31.5MV/m -> 35MV/m
  - Medium term goal: 45MV/m
  - Lab record: 59MV/m

- **Improve Q₀:** reduce cryogenic losses
  - (1W @ 2K requires ~750W AC power!)
  - Short term goal: 1E10 -> 2E10

- **State-of-the-art surface treatment of bulk Nb:**
  - baking/annealing/doping, plasma processing (possibly reducing aggressive chemicals, required for electropolishing)

- **R&D into replacement of bulk niobium cavities**
  - with Nb or Nb₃Sn coated copper (beyond bulk Nb – thin-film SRF): reduce Nb consumption, increase performance

C. Antoine talk @IPAC2023 | arXiv: 2203.09718
High Efficiency (L-Band, X-Band) Klystron Project at CERN

Accelerators technology could require RF signals in a wide range of the frequencies (few 100 MHz – 12 GHz), peak power levels (few 100 kW – 100 MW) and pulse lengths (CW -100ns). The klystron amplifiers technology is the one that covers almost all RF frequency/power demands of the modern accelerators.

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

Efficiency performance of the selected commercial klystrons and the new HE klystrons.

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 beam power.

High efficiency: 24MW, CLIC TS MBK

L-band klystron CLIC (1 GHz), ILC (1.3 GHz) CW-FCC (600 MHz)
R&D for Permanent Magnets (also important for Higgs Factories)

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 & tested as permanent (two different strengths) magnets, and also dipoles (in drivebeam turn arounds).

Longitudinal gradient dipole magnet for the CLIC DR (CIEMAT)

ZEPTO: comparing carbon footprints

- Electromagnetic quadrupole
  - Main materials: steel, copper
  - Manufacture impacts
    - Operation costs
      - 856W at 100% excitation
      - Another 250W for cooling
      - Assume 251 days / year operation
      - 6.7 MWh / year
      - EU avg intensity 225 gCO₂e/kWh
  - Permanent magnet quadrupole
    - Main materials: steel, NdFeB, aluminium
    - Manufacture impacts (kgCO₂e)
      - NdFeB 1097kg
      - aluminium 210kg
      - steel 9.1kg

(big uncertainties in NdFeB footprint; using recycled magnets could significantly reduce it)

- Operation costs: negligible
- “Carbon payback”: 1 year

HTS magnets might be of interest in Higgs factories to reduce power consumption (CIEAMT/ILC: HTS; N3Ti magnets for ILC main quadrupoles for)

Ben Shepherd, ESSRI Workshop 2022, https://indico.esrf.fr/event/2/contributions/108/
Very large reductions in power estimate (380 GeV) 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

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 of high efficiency klystrons, DR RF redesign or permanent magnets not included at this stage

With standard running scenario every 100MW corresponds to ~ 0.6 TWh (~85 MCHF) annually → CERN MTP assumes 140 MCHF/TWh beyond 2026
CO2-neutrality by 2050 is a goal for Tohoku region → next generation town development when ILC is operational (Green ILC Concept):
- Exhaust heat recovery from the ILC and the creation of business derived from it
- Connecting the ILC with agriculture, forestry, fisheries industries to reduce CO2 emissions and offset by increasing CO2 absorption
- Building an energy recycling society based on the Global Village Vision
- 23% regenerative electricity today – sufficient for ILC operation (ILC is < 1%)

Next generation town development for ILC operation

“Green ILC”: https://green-ilc.in2p3.fr/documents/
Power Modulation - Running on Renewables

Different approaches to reduce impact of large electric power consumption (single pass colliders are well suited):
- Reduce power (by higher efficiency)
- Re-use waste energy (heat)
- Modulate power according to availability (price)
- Use regenerative power

A real implementation of renewable energy supply:
✓ A physical power purchase agreement (PPA) is a long-term contract for the supply of electricity at a defined, fixed price at the start and then indexed every year, and a consumer for a defined period (generally 20 years). Being considered for CERN, initially at limited scale. Advantages: price, price stability, green, renewable.
✓ Must be a goal to run future accelerator at CERN primarily on green and more renewable energy with very low carbon footprint. However, energy costs will remain a concern.

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

FRAUNHOFER STUDY:
- Supply the annual electricity demand of CLIC (380Gev) 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
- Study done for 200 MW, in reality only ~110 MW are needed
- Self-sufficiency during all times can not be reached but 54% of the time CLIC could run independently from public electricity supply with the portfolio simulated.
- Flexibility to adjust the power demand is expected to become increasingly important and in demand by energy companies
Sustainable Construction: Proactivity

- **Operation costs dominated by energy (and personnel)**
  - Reducing power use, and costs of power, will be crucial → huge uncertainty in how the energy market, prices and price variations will be in ~2040 (ILC), ~2050 (CERN projects)
  - Carbon footprint related to energy source, relatively low already for CERN (helped by nuclear power), expected to become significantly lower towards 2050 when future accelerators are foreseen to become operational (in Europe, US and Japan).
  - Align to future energy markets, green and more renewables, make sure we can be flexible customer and deal with grid stability/quality
  - Other consumables (gas, liquids, travels, computing … ) during operation need to be justified (and estimated)

- **For carbon the construction impact might be (more) significant (also rare earths etc) than operational footprint**
  - Construction: CE, materials, processing and assembly – not easy to calculate, very likely a/the dominating carbon source
  - Markets will push for reduced carbon, “responsible purchasing” crucial – construction costs likely to increase
  - Many other factors than a carbon life cycle assessment, rare earths, toxicity, acidity ..
  - Environmental studies, integration in local environment/power grids, very important (CERN generally, Green ILC)

- **Decommissioning – how do we estimate impacts?**
Whole Lifecycle is Important – Lifecycle Assessment (LCA):

✓ **Ultimate Goal:**
  - Quantify the environmental impact of a whole accelerator project, i.e., CLIC / ILC

✓ **Accepted method:**
  - LCA = Life Cycle Assessment

✓ **Define Scope:**
  - System Boundaries
  - Lifecycle Stages

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**Data of carbon intensity of electric power**
(Nuclear energy remains very important, on the timescale of a future CERN facility):

**Power Projections Europe (2040):**
- 50% nuclear at 5g CO₂/kWh;
- 50% renewables at 20g CO₂/kWh  
  (mix sun, wind, hydro, ...)

IEA (2022), World Energy Outlook 2022, IEA, Paris https://www.iea.org/reports/world-energy-outlook-2022, License: CC BY 4.0 (report); CC BY NC SA 4.0 (Annex A)
Sustainable Construction: Life-Cycle Assessment

LCA starting point: Determine the embodied and construction environmental impact of tunnel, caverns and shafts

→ perform a LCA (Lifecycle Assessment) for the construction stage (A1-A5)

System boundaries

Materials
- A0 Preliminary studies
- A1 Raw material supply
- A2 Transport
- A3 Manufacture
- A4 Transport to worksite
- A5 Construction process

Transport & construction activities
- Use stage [B1-B8]
  - B1 Use
  - B2 Maintenance
  - B3 Repair
  - B4 Replacement
  - B5 Refurbishment

End of life stage [C1-C4]
- C1 Deconstruction/Demolition
- C2 Transport for Disposal
- C3 Waste Processing for recovery
- C4 Disposal

Benefits and Loads beyond the system boundary [D]
- Reuse Recycling
- Benefits and loads of additional infrastructure functions

BS EN 17472:2022

✓ Only B6 discussed in all the slides above, now discuss A1-A5 for the CE
✓ Missing A1-A5 for accelerator, some surface installations, all maintenance and upgrades, all EoL activities
Sustainable Construction: Life-Cycle Assessment

Life Cycle Assessment
Comparative environmental footprint for future linear colliders CLIC and ILC

Inherent tension between invest and operation requires a quantitative approach:

Lifecycle Assessment

LCWS2023: ARUP talk –

ARUP: *Suzanne Evans, Ben Castle, Yung Loo, Heleni Pantelidou, Jin Sasaki
CERN: John Osborne, Steinar Stapnes, Benno List, Liam Bromley
KEK: Nobuhiro Terunuma, Akira Yamamoto, Tomoyuki Sanuki
(*presenter: suzanne.evans@arup.com)
Sustainable Construction: Life-Cycle Assessment

Ref: ISO 14040:2006
Linear Collider Options

1. CLIC Drive Beam
   5.6m internal dia. Geneva. (380GeV, 1.5TeV, 3TeV)

2. CLIC Klystron
   10m internal dia. Geneva. (380GeV)

3. ILC
   Arched 9.5m span. Japan. (250GeV)

Full ARUP report: https://edms.cern.ch/document/2917948/1

LCA Methodology
LCA follows the ISO 14040/44 methodology.
LCA has been carried out using the LCA tool Simapro 9.4.0.2 which uses EcoInvent 3.8 database. The ReCiPe Midpoint (H) 2016 method has been used to estimate the environmental impacts across 18 impact categories – see table to the right.

Data for the CLIC and ILC LCA has been gathered from CERN and KEK respectively through drawings and reports, which feeds directly into the Life Cycle Inventory (LCI).

Data quality
Simapro 9.4.0.2 uses EcoInvent 3.8 database, released in September 2021. EcoInvent is widely recognised as the largest and most consistent LCI database. EcoInvent validates the LCI data through ecoEditor software. EcoInvent reviews the data through manual inspection from at least 3 experts prior to the storage of data in EcoInvent database (Data quality guideline for the ecoInvent database version 3.2013).

ReCiPe Midpoint (H) 2016 Impact Categories

<table>
<thead>
<tr>
<th>Impact Category</th>
<th>Abbr.</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Global warming</td>
<td>GWP</td>
<td>kg CO2 eq</td>
</tr>
<tr>
<td>Stratospheric ozone depletion</td>
<td>ODP</td>
<td>kg CFC-11 eq</td>
</tr>
<tr>
<td>Ionizing radiation</td>
<td>IRP</td>
<td>kg Bq Co-60 eq</td>
</tr>
<tr>
<td>Fine particulate matter formation</td>
<td>PMFP</td>
<td>kg PM2.5 eq</td>
</tr>
<tr>
<td>Ozone formation, Human health</td>
<td>HOFP</td>
<td>kg NOx eq</td>
</tr>
<tr>
<td>Ozone formation, Terrestrial ecosystems</td>
<td>EOPF</td>
<td>kg NOx eq</td>
</tr>
<tr>
<td>Terrestrial acidification</td>
<td>TAP</td>
<td>kg SO2 eq</td>
</tr>
<tr>
<td>Freshwater eutrophication</td>
<td>FEP</td>
<td>kg P eq</td>
</tr>
<tr>
<td>Marine eutrophication</td>
<td>MEP</td>
<td>kg N eq</td>
</tr>
<tr>
<td>Terrestrial ecotoxicity</td>
<td>TETP</td>
<td>kg 1,4-DCB</td>
</tr>
<tr>
<td>Freshwater ecotoxicity</td>
<td>FETP</td>
<td>kg 1,4-DCB</td>
</tr>
<tr>
<td>Marine ecotoxicity</td>
<td>METP</td>
<td>kg 1,4-DCB</td>
</tr>
<tr>
<td>Human carcinogenic toxicity</td>
<td>HTPoC</td>
<td>kg 1,4-DCB</td>
</tr>
<tr>
<td>Human non-carcinogenic toxicity</td>
<td>HTPoNC</td>
<td>kg 1,4-DCB</td>
</tr>
<tr>
<td>Land use</td>
<td>LOP</td>
<td>m²a crop eq</td>
</tr>
<tr>
<td>Mineral resource scarcity</td>
<td>SOP</td>
<td>kg Cu eq</td>
</tr>
<tr>
<td>Fossil resource scarcity</td>
<td>FFP</td>
<td>kg oil eq</td>
</tr>
<tr>
<td>Water consumption</td>
<td>WCP</td>
<td>m³</td>
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2030 Baseline assumptions

<table>
<thead>
<tr>
<th>LCA Modules</th>
<th>CLIC Drive Beam</th>
<th>CLIC Klystron</th>
<th>ILC</th>
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</thead>
<tbody>
<tr>
<td>A1-A3 Materials</td>
<td>Concrete (CEM) &amp; Steel (60% recycled)</td>
<td>Concrete: Local by road (500m)</td>
<td>Concrete: Local by road (500m)</td>
</tr>
<tr>
<td>A4 Transport of materials to site</td>
<td>Concrete: Local by road (500m)</td>
<td>Concrete: Local by road (500m)</td>
<td>Steel: National by road (100m)</td>
</tr>
<tr>
<td>A5 Material wasted in construction</td>
<td>Concrete: Local by road (500m)</td>
<td>Concrete: Local by road (500m)</td>
<td>Steel: National by road (100m)</td>
</tr>
<tr>
<td>A6 Transport of disposal materials off site</td>
<td>Concrete: Local by road (500m)</td>
<td>Concrete: Local by road (500m)</td>
<td>Steel: National by road (100m)</td>
</tr>
<tr>
<td>A7 Construction process</td>
<td>Tunnel Boring Machine (TBM)</td>
<td>Off &amp; Steel</td>
<td>Off &amp; Steel</td>
</tr>
<tr>
<td>A8 Electricity mix 2021/2022</td>
<td>Fossil: 12%</td>
<td>Nuclear: 88%</td>
<td>Fossil: 11%</td>
</tr>
</tbody>
</table>

Reference: ReCiPe Midpoint (H) 2016
Comparative environmental footprint for future linear colliders CLIC & ILC

Assuming a small CLIC tunnel (~5.6m diameter) and that the equipment has the same carbon footprint as the tunnel itself, 20 km accelerator (tunnel plus components) correspond to 240 kton CO₂ equivalent.

- A1-A3 material only dominates
- Around 6 kton/km for CLIC DB & ILC

Include all tunnels (access, transfer, damping rings), shafts and caverns. A1-A5

Scaling to main linac tunnel lengths we are now at 11-14 kton/km for the CLIC DB and ILC

Full ARUP report: https://edms.cern.ch/document/2917948/1
The **embedded carbon** due to civil engineering work and material (concrete for example) is a very important contribution, on a level comparable to many years of carbon emission due to energy use during the operational phase.
Many caveats, first of all **this is a very first indication of the scale:**

+ many more components in tunnel (also infrastructure), injectors, shafts, detectors, construction, spoils, etc …
+ **upgrades and decommissioning**, this is not only an initial important contribution

- **improvement and optimisations** (e.g. less and/or better concrete mixes, support structures, steel in tunnels)
- **responsible purchasing** (understanding the impact of supply chain, costs and potential for changes – will be essential for future projects – CERN implementation information from E. Cennini)

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**CLIC Drive Beam 380GeV**

41% possible A1-A5 GWP reduction

If we have energy available at $12.5 \text{ g CO}_2/\text{kWh} = 12.5 \text{ kton CO}_2/\text{TWh}$ (not unlikely in 2050):

- 20km accelerator construction ~ 20 years of operation.
- 1 km accelerator construction ~ 1 TWh annual electricity (annual LC operation 0.6 TWh)
**Europe – America – Japan (EAJADE) Program (2023-2027)**

European Union’s Horizon Europe Marie Sklodowska-Curie Staff Exchanges programme under grant agreement no. 101086276

WP4: Sustainable Technologies for Scientific Facilities

**Task 4.1: High Efficiency & Sustainable SC cavities**

**Task 4.2: High efficiency RF power amplifiers**

**Task 4.3: Energy Recovery Linacs**

**Task 4.4: Power Modulation**

**Task 4.5: Smart Tunneling**

**Task 4.6: “Green ILC”**

Europe – Japan Accelerator Development Exchange Programme

http://www.eajade.eu/
EAJADE Workshop on Sustainability in Future Accelerators

Tohoku, Japan, September 25-27, 2023:
Summary and Outlook

- **Power efficiency, energy consumption and also carbon emission** and other sustainability targets are today important drivers of accelerator development and R&D:
  - Related to designs, new concepts and many technical developments
  - Very large synergy across the entire field of accelerator science (small and large installations)
  - Funding in many cases “encourages” this R&D

- **Optimisation of subsystems and components for energy efficiency**, e.g.:
  - Better accelerator cavities (optimize design for more gradient, reduced losses, etc …)
  - Efficient klystrons
  - Permanent magnets

- **Important to be pro-active, anticipating the changes happening in the energy markets and society with respect to sustainability driven changes:**
  - Power, energy efficiency at all levels
  - Adapting to and using more renewables (increased availability of it, can be increased by contracts)
  - Reducing carbon in construction from civil engineering to technical components
  - Making use of materials, technologies and working with suppliers that are invested in these changes
  - Integration in/with local areas, their infrastructure and development plans (e.g. Green ILC)
Special thanks to:

Benno List, Steinar Stapnes,

Shin Michizono, Takayuki Saeki, John Osborne, Liam Bromiley, Suzanne Evans, Yung Loo, Igor Syratchev, Ben Shepherd, Caterina Vernieri, Emilio Nanni, Sergey Belomestnykh, Masakazu Yoshioka

and many colleagues from the CLIC and ILC collaborations