Many slides courtesy of Daniel Schulte (CERN) and Frank Tecker (CERN)
Outline

• Overview future (and past) high energy colliders
• CLIC := Compact Linear (e+e-) Collider
  - Why e+e-? → precision physics
  - Why linear? → no synchrotron radiation
  - how compact? → 100 MV/m with NC RF
• Basic Parameters of CLIC...Comparison with ILC
• Focus on two aspects:
  - Nanometer Size Beams at IP: Why and how?
  - RF Powering through a second particle beam: Why and how?
Past/Existing High Energy Frontier Colliders

Only referring to the highest energy

Lepton colliders:

• **LEP** (Large Electron Positron Colliders)
  • $Z_0$ factory at 90GeV electron-positron cms energy
  • $W^+W^-$ factory at 160GeV
  • Maximum 209 GeV cms energy for higgs search
    (bad luck: $e^+e^- \rightarrow Z^0H$ needs about 250 GeV)
  • Closed in the year 2000

• **SLC** (Stanford Linear Collider)
  • $Z_0$ factory at 90GeV electron-positron cms energy

Hadron colliders

• **LHC** (Large Hadron Collider):
  • Proton-proton with 13TeV
  • Ion-ion operation
Considered Future High Energy Frontier Colliders

Circular colliders:
- **FCC** (Future Circular Collider)
  - FCC-hh: 100TeV proton-proton cms energy, ion operation possible
  - FCC-ee: Potential intermediate step 90-350 GeV lepton collider
  - FCC-he: Lepton-hadron option
- **CEPC / SppC** (Circular Electron-positron Collider/Super Proton-proton Collider)
  - CepC : e^+e^- 240GeV cms
  - SppC : pp 70TeV cms

Linear colliders
- **ILC** (International Linear Collider): e^+e^-, 500 GeV cms energy, Japan considers hosting project
- **CLIC** (Compact Linear Collider): e^+e^-, 380GeV-3TeV cms energy, CERN hosts collaboration

Others
- Muon collider, has been supported mainly in the US but effort has stopped
- Plasma wakefield acceleration in linear collider...not yet ready
- Photon-photon collider
- LHeC
LEP (at CERN)

27km circumference
Electron-positron collider
4 experiments: ALEPH, DELPHI, L3, OPAL
CMS energy: 90GeV (LEP I) - 209GeV (LEP II)
Peak Luminosity: $10^{32}\text{cm}^{-2}\text{s}^{-1}$

Highest particle speed in any accelerator
SLC (at SLAC)

Electron-positron linear collider
2 experiments: first MARK II, then SLD
CMS energy: 92GeV
Peak Luminosity: $2 \times 10^{30} \text{cm}^{-2}\text{s}^{-1}$

The only linear collider so far
The LHC (at CERN)

27km circumference (well, the LEP tunnel)

4 main experiments

Nominal CMS energy: 14TeV
Peak Luminosity: $10^{34}$ cm$^{-2}$s$^{-1}$
Operation: 2009-today

Highest particle energy in any accelerator
Other Colliders

PEP-II, SLAC, Palo Alto, USA

KEKb, KEK, Tsukuba, Japan

HERA, DESY, Hamburg, Germany

Tevatron, Fermilab, Chicago, USA
Collider Choices

- Hadron collisions: compound particles
  - Mix of quarks, anti-quarks and gluons: variety of processes
  - Parton energy spread
  - QCD processes large background sources
    - total cross section increases with log s;
      “interesting cross sections” decrease with s
  - Hadron collisions $\Rightarrow$ large discovery range

- Lepton collisions: elementary particles
  - Collision process known
  - Well defined energy
  - Other physics background limited
  - Lepton collisions $\Rightarrow$ precision measurements
  - All cross sections decrease with s

- Lepton-hadron is also possible
Higgs Physics in e+e- Collisions

- **Precision Higgs measurements**
- **Model-independent**
  - Higgs couplings
  - Higgs mass
- Large energy span of linear colliders allows to collect a maximum of information:
  - ILC: 500 GeV (1 TeV)
  - CLIC: ~350 GeV – 3 TeV
The LHC: signals much smaller than “bkg”

- General event properties
- Heavy flavor physics
- Standard Model physics
  - QCD jets
  - EWK physics
  - Top quark
- Higgs physics
- Searches for SUSY
- Searches for ‘exotica’
All quarks

These & other methods → whole set of quarks & antiquarks

- valence quarks ($u_V = u - \bar{u}$) are hard
  \[ x \to 1 : xq_V(x) \sim (1 - x)^3 \]
  - quark counting rules
  \[ x \to 0 : xq_V(x) \sim x^{0.5} \]
  - Regge theory

- sea quarks ($u_S = 2\bar{u}, \ldots$) fairly soft (low-momentum)
  \[ x \to 1 : xq_S(x) \sim (1 - x)^7 \]
  \[ x \to 0 : xq_S(x) \sim x^{-0.2} \]
Physics Beyond the Standard Model (BSM) Example: Dark Matter

The outer region of galaxies rotate faster than expected from visible matter. This can be explained by dark matter, as

\[
v_{\text{circ}} = \sqrt{\frac{GM(r)}{r}}
\]

Dark matter would explain this. Other observations exist:
• But all through gravity

What is it?

One explanation is supersymmetry.
Supersymmetry

Supersymmetric Partner

Spin 1/2 Spin 1 Spin 0

Spin 0 Spin 1/2

\[ u \ 
\[ c \ 
\[ t \ 
\[ d \ 
\[ s \ 
\[ b \ 
\[ \nu_e \ 
\[ \nu_\mu \ 
\[ \nu_\tau \ 
\[ e \ 
\[ \mu \ 
\[ \tau \ 
\[ \gamma \ 
\[ \nu \ 
\[ \mu \ 
\[ \tau \ 
\[ \sim \nu_e \ 
\[ \sim \nu_\mu \ 
\[ \sim \nu_\tau \ 
\[ \sim e \ 
\[ \sim \mu \ 
\[ \sim \tau \ 
\[ \sim W \ 
\[ \sim Z \ 
\[ \sim \gamma \ 
\[ \sim \mu \ 
\[ \sim \tau \]
Example of Potential SUSY Scenario

Consistent with current LHC results
A “real” story from the past ...

Barcelona, 15 March 1493 ..... 

*CristofoRolf Columbus:

Your Majesty, the fleet needs an upgrade, we need to go back to the Indies with 10 times more ships

*King Ferdinand and Queen IsAgnieszka:

You discovered the Indies, your theory is right, why do you need more?

*CristofoRolf Columbus:

Theorists* say these may not be the standard Indies. They calculated the Earth radius, and the standard Indies cannot be so close: these are likely to be beyond the standard Indies (moving eastward ...)

* If the King had listened to theorists to start with, he would have never authorized the mission: everyone would have died of starvation well before reaching the “standard” Indies ...
Lepton Collider Options

Three main approaches

• Big LEP-type collider ring
  – FCC-ee, CepC
  – Later a proton collider in the same tunnel

• Linear collider
  – ILC, CLIC
  – The focus of this course

• Muon collider
Ring Collider Energy Limitation

Beam can be used many times

Lepton beam energy is below LHC
- magnets are not a problem

But synchrotron radiation is:

\[ \Delta E \propto \left( \frac{E}{m} \right)^4 \frac{1}{R} \]

At LEP2 lost 2.75GeV/turn for E=105GeV

Pay for installed voltage (\( \Delta E \)) and size (R), so scale as:

- use heavier particles, e.g. muons
- or linear collider
- or try to push a bit harder on cost
Linear Collider Energy Limitation

Hardly any synchrotron radiation

Beam can only be used only once
-> strong beam-beam effects

Acceleration gradient is an important issue

\[ C_L = a_L E + b_L \]
Simplified Cost Scaling Comparison

Linac: 
\[ C_L = a_L E + b_L \]

Ring: 
\[ C_R = a_R E^2 + b_R \]

Power consumption behaves similar to cost for constant luminosity.

There will always be an energy where linear colliders are better.
Circular vs. Linear Colliders

China prepares a project similar to FCC-ee

Circular, adding four experiments

The main linac provides the energy of the beam

Issue 1: the gradient
Generic Linear Collider

$$\mathcal{L} = H_D \frac{N^2}{4\pi \sigma_x \sigma_y} n_b f_r$$

But little luminosity, since beams collider only once

Need very small $\sigma_x$ and $\sigma_y$
Generic Linear Collider

\[ \sigma_{x,y} = \sqrt{\frac{\beta_{x,y} \varepsilon_{x,y}}{\gamma}} \]

The damping rings reduce the phase space (emittance \( \varepsilon_{x,y} \)) of the beam. The RTML (ring-to-main linac transport) reduces the bunch length.

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- Energy loss
- Re-acceleration

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The beam delivery system (BDS) squeezes the beam as much as possible, i.e. reduces $\beta_{x,y}$
ILC Layout

- Damping Rings
- IR & detectors
- e- source
- e+ source
- e- bunch compressor
- e+ bunch compressor
- electron main linac 11 km
- positron main linac 11 km
- central region 5 km
- 2 km

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only one DB complex (with 2x RF pulse length compared to 2 DB complexes)

drive beam time delay line (1\textsuperscript{st} half of pulse sent there)

shorter main linac
CLIC Staged Design

Staged design for CLIC to optimise physics and funding profile:

- **First stage:** $E_{\text{cms}} = 380 \text{ GeV}$, $L = 1.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, $L_{0.01}/L > 0.6$
- **Second stage:** $E_{\text{cms}} = O(1.5 \text{ TeV})$
- **Final stage:** $E_{\text{cms}} = 3 \text{ TeV}$, $L_{0.01} = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, $L_{0.01}/L > 0.3$
Cavity/Accelerating Structure

ILC cavity
1.3 GHz, superconducting
Target effective operational 31.5MV/m
Target gradient 35MV/m
$Q_0 \approx 10^{10}$

CLIC accelerating structure
12 GHz, normal conducting
Target loaded gradient 100MV/m
Target unloaded gradient 120MV/m
$Q_0 \approx 6 \times 10^3$
Warm vs Cold RF Collider

**Normal Conducting**
- High gradient $\Rightarrow$ short linac 😊
- High rep. rate $\Rightarrow$ ground motion suppression 😊
- Small structures $\Rightarrow$ strong wakefields 😯
- Generation of high peak RF power 😯

**Superconducting**
- long pulse $\Rightarrow$ low peak power 😊
- large structure dimensions $\Rightarrow$ low WF 😊
- very long pulse train $\Rightarrow$ feedback within train 😊
- SC structures $\Rightarrow$ high efficiency 😊
- Gradient limited $<$40 MV/m $\Rightarrow$ longer linac 😯
  (SC material limit ~ 55 MV/m)
- Large number of e+ per pulse 😯
- very large DR 😯
ILC and CLIC Main Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol [unit]</th>
<th>SLC</th>
<th>ILC</th>
<th>CLIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre of mass energy</td>
<td>$E_{cm}$ [GeV]</td>
<td>92</td>
<td>500</td>
<td>3000</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$L$ [$10^{34}cm^{-2}s^{-1}$]</td>
<td>0.0003</td>
<td>1.8</td>
<td>6</td>
</tr>
<tr>
<td>Luminosity in peak</td>
<td>$L_{0.01}$ [$10^{34}cm^{-2}s^{-1}$]</td>
<td>0.0003</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Gradient</td>
<td>$G$ [MV/m]</td>
<td>20</td>
<td>31.5</td>
<td>100</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>$N$ [$10^9$]</td>
<td>37</td>
<td>20</td>
<td>3.72</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z$ [μm]</td>
<td>1000</td>
<td>300</td>
<td>44</td>
</tr>
<tr>
<td>Collision beam size</td>
<td>$\sigma_{x,y}$ [nm/nm]</td>
<td>1700/600</td>
<td>474/5.9</td>
<td>40/1</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>$\varepsilon_{x,y}$ [nm]</td>
<td>3000</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>Bunches per pulse</td>
<td>$n_b$</td>
<td>1</td>
<td>1312</td>
<td>312</td>
</tr>
<tr>
<td>Distance between bunches</td>
<td>$\Delta z$ [mm]</td>
<td>-</td>
<td>554</td>
<td>0.5</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>$f_r$ [Hz]</td>
<td>120</td>
<td>5</td>
<td>50</td>
</tr>
</tbody>
</table>

ILC has parameter sets from 250 GeV to 1 TeV
CLIC has parameter sets from 250 GeV to 3 TeV
Let us look at two main aspects:

• Why does CLIC need so small vertical beam sizes? (6 times smaller than ILC)
  → and what does this imply for the technical systems

• Why “two beam acceleration”?  
  - usually we have already problems enough with one beam....
Luminosity and Parameter Drivers

Can re-write normal luminosity formula

\[ \mathcal{L} = H_D \frac{N^2}{4\pi \sigma_x \sigma_y} n_b f_r \]

\[ \mathcal{L} \propto H_D \frac{N}{\sigma_x} \frac{N n_b f_r}{\sigma_y} \frac{1}{\sigma_y} \]

Need to ensure that we can achieve each parameter
Small (vertical) beam sizes

Only Normal conducting RF enables accelerating gradients of 100 MV/m

In the present CLIC RF structure (23 cm long) some 50 MW peak power are needed to produce a 100 MV/m accelerating field

With 50 Hz repetition rate beam pulse is as short as 156 ns; i.e. duty cycle 8 * 10^-6!!! Still 300 MW electrical power only for the RF acceleration in case of the 3 TeV accelerator

Max. Rf frequency in damping rings: 2 GHz (presently 1 GHz): 312 bunches/pulse ← wake fields in accelerating structure

4 * 10^9 particles/bunch

Flat beams for minimum energy spread in luminosity spectrum; need to get high luminosity from small vertical beam size
Like firing bullets to hit in middle ...
Except that ...
Whole list of requirements for colliding small beams

• Generate small vertical emittance in high performance damping rings
• Extract from damping rings with low ripple kickers (10-4)
• Transport beams over 24 km without emittance growth
  - through hundreds of quadrupoles
    → active stabilisation against ground motion
  - through thousands of acceleration cavities
    → 10 um alignment to avoid wakefields
• Beam delivery system with highest gradient quadrupoles
• Feedbacks....feedbacks....feedbacks
Let us look at two main aspects:

• Why does CLIC need so small vertical beam sizes? (6 times smaller than ILC)
  ➔ and what does this imply for the technical systems

• Why “two beam acceleration”? - usually we have already problems enough with one beam....
  ➔ Mainly a consequence of the very short beam pulse
Why not using klystrons as RF powersource?

• Reminder: **Klystron**
  – narrow-band vacuum-tube amplifier at microwave frequencies (an electron-beam device).
  – low-power signal at the design frequency excites input cavity
  – Velocity modulation becomes time modulation in the drift tube
  – Bunched beam excites output cavity

• We need:
  - **high power** for high fields
  - **very short pulses** (remember: 200 ns!)

• We need also: Many klystrons
  – ILC: 560 10 MW, 1.6 ms
  – NLC: 4000 75 MW, 1.6 µs
  – CLIC: would need many more klystrons with extremely short pulses
  – Avoid another critical set of components: RF pulse compression schemes

• ➔**Drive beam like beam of a gigantic klystron**
only one DB complex (with 2x RF pulse length compared to 2 DB complexes)

drive beam time delay line
(1\textsuperscript{st} half of pulse sent there)

shorter main linac
Two-beam acceleration

Instead of using a single drive beam pulse for the whole main linac, several ($N_S = 24$) short drive beam pulses are used. Each one feeds a ~880 m long sector of two-beam acceleration (TBA).

Counter flow distribution allows to power different sectors of the main linac with different time bins of a single long electron drive beam pulse. The distance between the pulses is $2L_s = \frac{2L_{main}}{N_S}$ ($L_{main}$ = single side linac length).

The initial drive beam pulse length $t_{DB}$ is given by twice the time of flight through one single linac:

$$t_{DB} = \frac{2L_{main}}{c},$$

140 µs for the 3 TeV CLIC.

This is the required RF pulse length of the drive beam klystrons.
Drive beam time structure

Bunch charge: 8.4 nC, Current in train: 100 A
CLIC Drive Beam Scheme

- Very high gradients possible with NC accelerating structures at high RF frequencies (12 GHz)
- Extract required high RF power from an intense e- “drive beam”
- Generate efficiently long beam pulse and compress it (in power + frequency)

\[
\begin{align*}
\text{Long RF Pulses} & : P_0, \nu_0, \tau_0 \\
\text{Electron beam manipulation} & : \\
& \text{Power compression} \\
& \text{Frequency multiplication} \\
\text{Short RF Pulses} & : P_A = P_0 \times N_1 \\
& \tau_A = \tau_0 / N_2 \\
& \nu_A = \nu_0 \times N_3
\end{align*}
\]
More on drive beam generation

Again a big transformer:
  ➔ But now in time domain

Input: Long beam pulse train
  low current
  low bunch frequency

Output: Short beam pulse trains
  high current
  high bunch frequency

=> high beam power

---

**Drive beam time structure - initial**

- Train length: 140 μs
- 24 x 24 sub-pulses
- Current: 4.2 A
- Energy: 2.4 GeV
- Distance between bunches: 60 cm

**Drive beam time structure - final**

- Train length: 5.8 μs
- 24 pulses
- Current: 101 A
- Distance between bunches: 2.5 cm

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Lemmings Drive Beam

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• Goal: transport particles of all energies through the decelerator sector: in the presence of huge energy spread (90%)
• Tight FODO focusing (large energy acceptance, low beta)
• Lowest energy particles ideally see constant FODO phase-advance $\mu \sim 90^\circ$, higher energy particles see phase-advance varying from $\mu \sim 90^\circ$ to $\mu \sim 10^\circ$

• Good quad alignment needed (20\(\mu\)m)
• Good BPM accuracy (20\(\mu\)m)
• Orbit correction essential
  – 1-to-1 steering to BPM centres
  – DFS (Dispersion Free Steering) gives almost ideal case
Power extraction structure PETS

- must extract efficiently >100 MW power from high current drive beam
- passive microwave device in which bunches of the drive beam interact with the impedance of the periodically loaded waveguide and generate RF power
- periodically corrugated structure with low impedance (big a/λ)
- ON/OFF mechanism

The power produced by the bunched (ω₀) beam in a constant impedance structure:

\[ P = \frac{I^2 L^2 F_b^2}{4 v_g R/Q} \]

Design input parameters
- P - RF power, determined by the accelerating structure needs and the module layout.
- I - Drive beam current
- L - Active length of the PETS
- F_b - single bunch form factor (≈ 1)
Present PETS status (12 GHz)

- achieved 150 MW @ 266ns in RF driven test at SLAC
- up to >250 MW peak power beam driven at CTF3 (recirculation)
- model well understood
CLIC two-beam Module layout

Standard module

**Total per module**
- 8 accelerating structures
- 8 wakefield monitors
- 4 PETS
- 2 DB quadrupoles
- 2 DB BPM

**Total per linac**
- 8374 standard modules

- Other modules have 2, 4, 6 or 8 acc. structures replaced by a quadrupole (depending on main beam optics)
- Total 10462 modules, 71406 acc. structures, 35703 PETS
CLIC two-beam Module

Alignment system, beam instrumentation, cooling integrated in design

G. Riddone
CLIC - Future Milestones

2013-18 Development Phase
Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.

4-5 year Preparation Phase
Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement. Prepare detailed Technical Proposals for the detector-systems.

2018-19 Decisions
On the basis of LHC data and Project Plans (for CLIC and other potential projects as FCC), take decisions about next project(s) at the Energy Frontier.

Construction Phase
Stage 1 construction of CLIC, in parallel with detector construction. Preparation for implementation of further stages.

2024-25 Construction Start
Ready for full construction and main tunnel excavation.

Commissioning
Becoming ready for data-taking as the LHC programme reaches completion.
Tunnel implementations (laser straight)

Central MDI & Interaction Region
Vol 1: The CLIC accelerator and site facilities (H. Schmickler)
- CLIC concept with exploration over multi-TeV energy range up to 3 TeV
- Feasibility study of CLIC parameters optimized at 3 TeV (most demanding)
- Consider also 500 GeV, and intermediate energy range

Vol 2: Physics and detectors at CLIC (L. Linssen)
- Complete, presented in SPC in March 2011, in print.
- Physics at a multi-TeV CLIC machine can be measured with high precision, despite challenging background conditions
- External review procedure in October 2011

Vol 3: "CLIC study summary" (S. Stapnes)
- Summary and available for the European Strategy process, including possible implementation stages for a CLIC machine as well as costing and cost-drives
- Proposing objectives and work plan of post CDR phase (2012-16)
- Completed and printed, submitted for the European Strategy Open Meeting in September

In addition a shorter overview document was submitted as input to the European Strategy update, available at: http://arxiv.org/pdf/1208.1402v1
Slides for detailed explanation of small vertical emittances

all slides get called from within the talk
Bunch structure

- SC allows long pulse, NC needs short pulse with smaller bunch charge

The different RF technologies used by ILC, NLC/JLC and CLIC require different packaging for the beam power.
Beam-beam Effect

Bunches are squeezed strongly to maximise luminosity

Electron magnetic fields are very strong

Beam particles travel on curved trajectories

They emit photons ($O(1)$) (beamstrahlung)

They collide with less than nominal energy
Beamstrahlung Optimisation

For low energies (classical regime) number of emitted photons

\[ n_{\gamma} \propto E_{\gamma} \propto \frac{N}{\sigma_x + \sigma_y} \]

\[ \mathcal{L} \propto \frac{N}{\sigma_x \sigma_y} \]

Hence use \( \sigma_x \gg \sigma_y \)

\[ \sigma_x + \sigma_y \approx \sigma_x \]

\[ \mathcal{L} \propto H_D \left( \frac{N}{\sigma_x} \right) N n_b f_r \frac{1}{\sigma_y} \]

For CLIC at 3TeV (quantum regime)

Total luminosity grows for smaller beams

Luminosity in peak starts to decrease again

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Breakdown-rate vs gradient

- Higher breakdown rate for higher gradient
- Strong function of the field (~E^-30)
  => small decrease of field lowers BDR significantly
Breakdown-rate vs pulse length

Higher breakdown rate for longer RF pulses

Experimental scaling: $\text{BDR} \sim (\text{pulselength})^6 \times (\text{gradient})^{30}$
Accelerating structure developments

- Structures built from discs
- Each cell damped by 4 radial WGs
- terminated by SiC RF loads
- Higher order modes (HOM) enter WG
- Long-range wakefields efficiently damped
Limitations of NC Gradient $E_{\text{acc}}$

- **Surface magnetic field**
  - Pulsed surface heating $\Rightarrow$ material fatigue $\Rightarrow$ cracks

- **Field emission due to surface electric field**
  - RF break downs
  - Break down rate $\Rightarrow$ Operation efficiency
  - Local plasma triggered by field emission $\Rightarrow$ Erosion of surface
  - Dark current capture
    $\Rightarrow$ Efficiency reduction, activation, detector backgrounds

- **RF power flow**
  - RF power flow and/or iris aperture apparently have a strong impact on achievable $E_{\text{acc}}$ and on surface erosion. Mechanism not fully understood
Pulsed surface heating - Fatigue

Magnetic RF field heats up cavity wall
Extension causes compressive stress
Can lead to fatigue

High number of cycles limits to smaller stresses
20 years operation $\Rightarrow$ $\sim 10^{10}$ cycles!
Limits maximum $\Delta T$ and peak magnetic field

Stress Amplitude, $S$

Cycles to Failure, $N$

Failure

No Failure

Failure Strength at $N_1$ Cycles

Endurance Limit

Cu, Al, ...

Steads, Mo, Ti, ...

$S_0$

$H_{\text{peak}}\uparrow\downarrow\Delta T\uparrow\downarrow\sigma$
Pulsed surface heating

- Pulsed surface heating proportional to
- Square root of pulse length
- Square of peak magnetic field
- Field reduced only by geometry, but high field needed for high gradient
- Limits the maximum pulse length
  => short pulses (~few 100ns)

\[
\Delta T = \sqrt{\frac{\mu_0}{2\pi} \frac{\omega t_p}{\sigma \lambda \rho c_H}} \hat{H}^2
\]

\(\Delta T\) temperature rise, \(\sigma\) electric conductivity
\(\lambda\) heat conductivity, \(\rho\) mass density
\(c_H\) specific heat, \(t_p\) pulse length
\(\hat{H}\) peak magnetic field

\(\hat{H} = \frac{g_H}{377 \Omega} E_{acc}\)

\(g_H\) geometry factor of structure design
  typical value \(g_H \approx 1.2\)

Numerical values for copper

\[\Delta T \approx 4 \cdot 10^{-17} \left[ \frac{\text{K}}{\text{m}^2/\text{V}^2} \right] \sqrt{t_p \ f \ E_{acc}^2}\]

\[\Delta T_{\text{max}} \approx 50 \text{ K}\]

\[t_p < \left( \frac{\Delta T_{\text{max}}}{4 \cdot 10^{-17}} \right)^2 \frac{1}{f \ E_{acc}^4}\]