High-Gradient Acceleration and Applications
Part 1

Overall objectives

The main objective of these two hours of lectures are to give you an taste of high-gradient accelerators. Some of the points we will address include:

- The CLIC project - features, performance demands
- High-gradient acceleration – introduction, vacuum arcing
- Compact applications – Technology spin-out to fields beyond high-energy physics, in particular compact facilities, with a focus on FLASH therapy

Part of the lectures are seminar-like but I've tried to put in theory appetizers.

Please feel free to interrupt with questions!

Introduction to CLIC
Physics requirements drive accelerator technology development

Linear colliders

Among the possible paths forward for accelerator-based high-energy physics are e^+e^- linear colliders.

- High-energy physics has historically advanced through the complementarity of lepton and hadron machines.
- An intrinsic advantage of a linear e^+e^- collider is that the collision energy is not limited by synchrotron radiation as in a ring. Synchrotron radiation power α E^4.
- Technology challenge different from hadron collider – rf (radio frequency) systems rather than magnets.

Based on these considerations, e^+e^- linear collider designs and technology have been developed worldwide since the late 1980s.

Two main linear collider projects have emerged and survived:

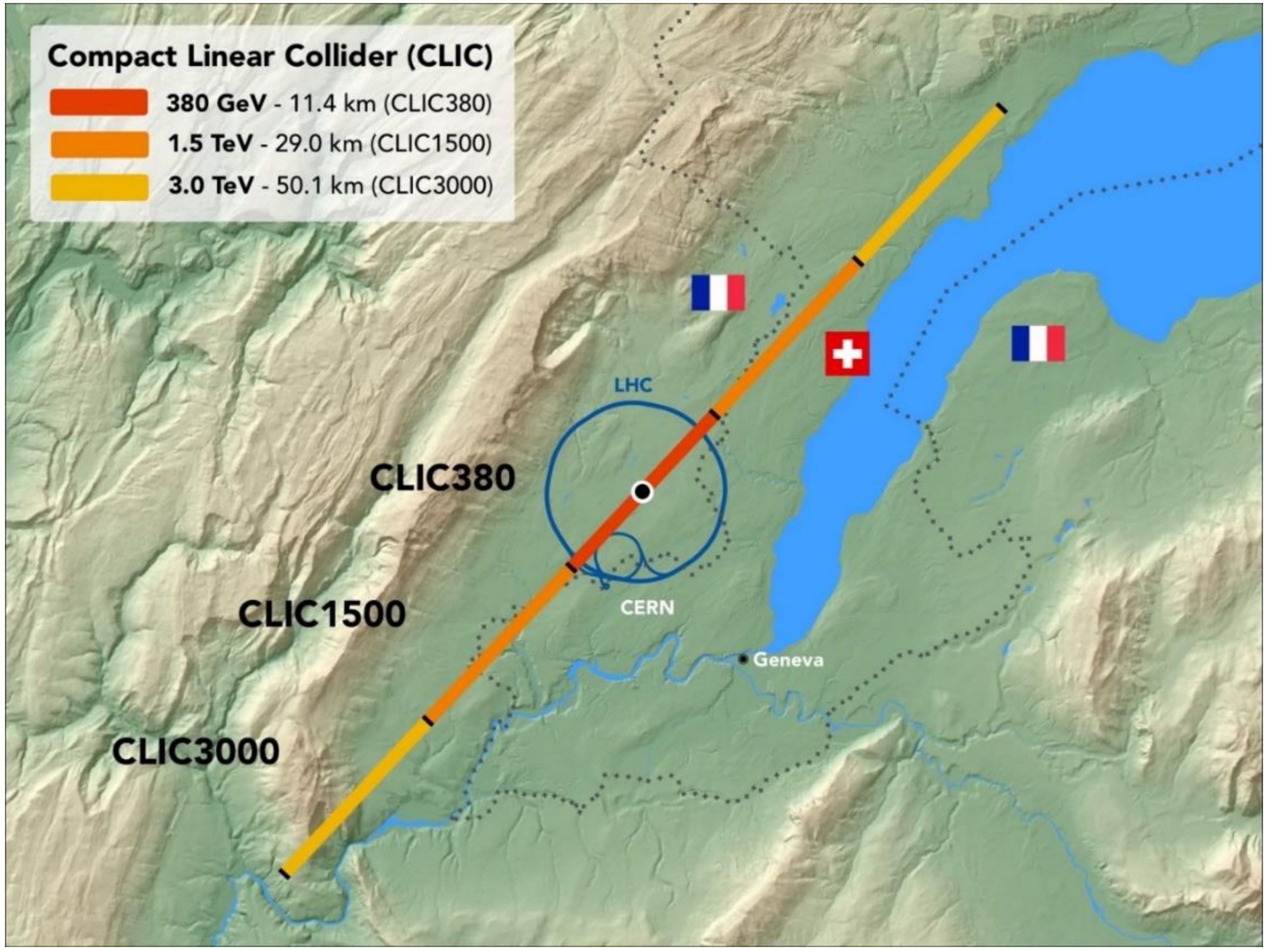
- ILC – Based on superconducting rf (radio frequency) cavity acceleration. 250 GeV center of mass. International project with Japan as host. Long-standing effort to obtain approval. https://linearcollider.org/
- CLIC – Based on normal conducting high-gradient rf. 380 GeV first stage, extendable up to 3 TeV. International collaboration led by CERN. Now so-called plan B for CERN… http://clic.cern/

CLIC

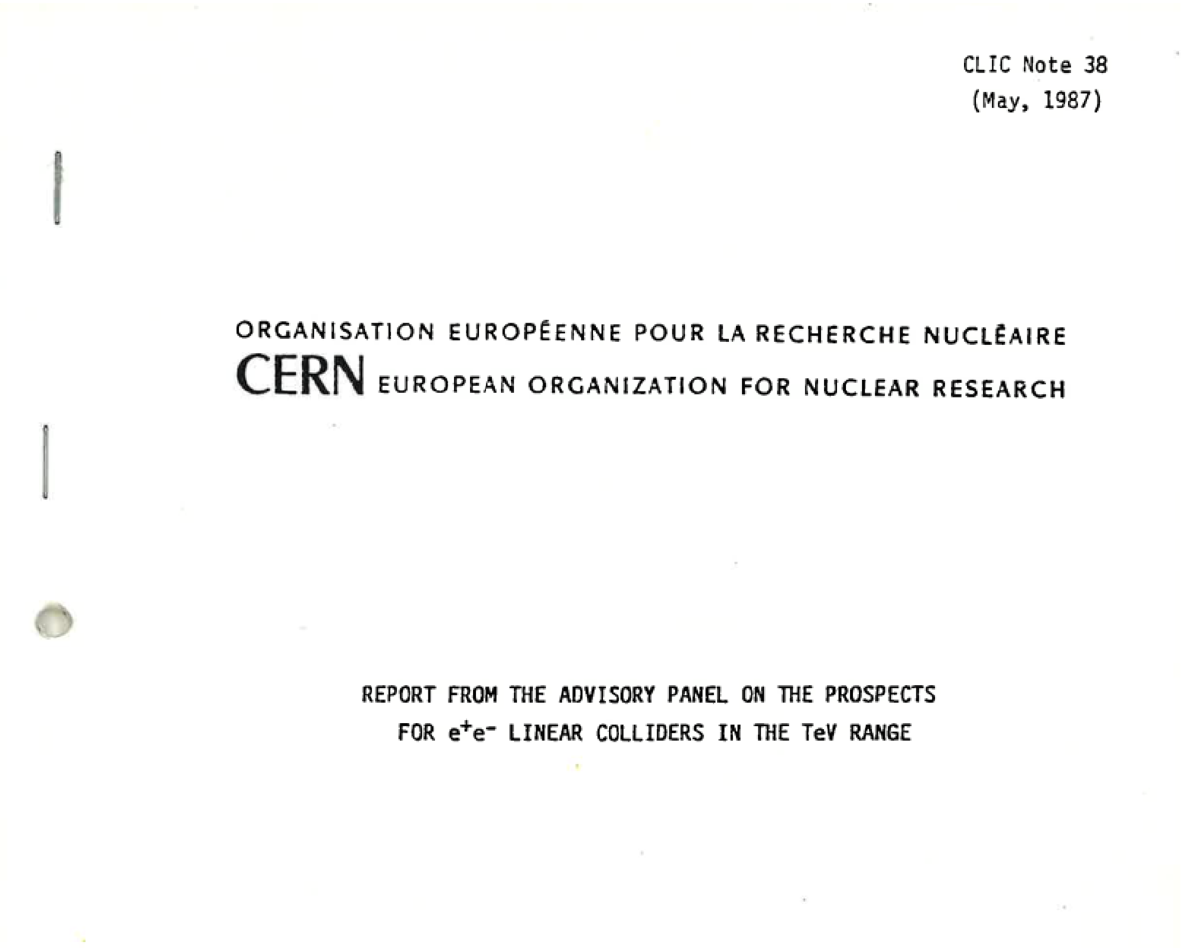
Initial energy of 380 GeV to cover Higgs and top physics.

The highest energy stage is 3 TeV in order to complement the physics reach of the LHC, for example directly producing new particles discovered there (!). Roughly 14 TeV/6.

The higher energy stages also provide a strong probe for beyond standard model physics.



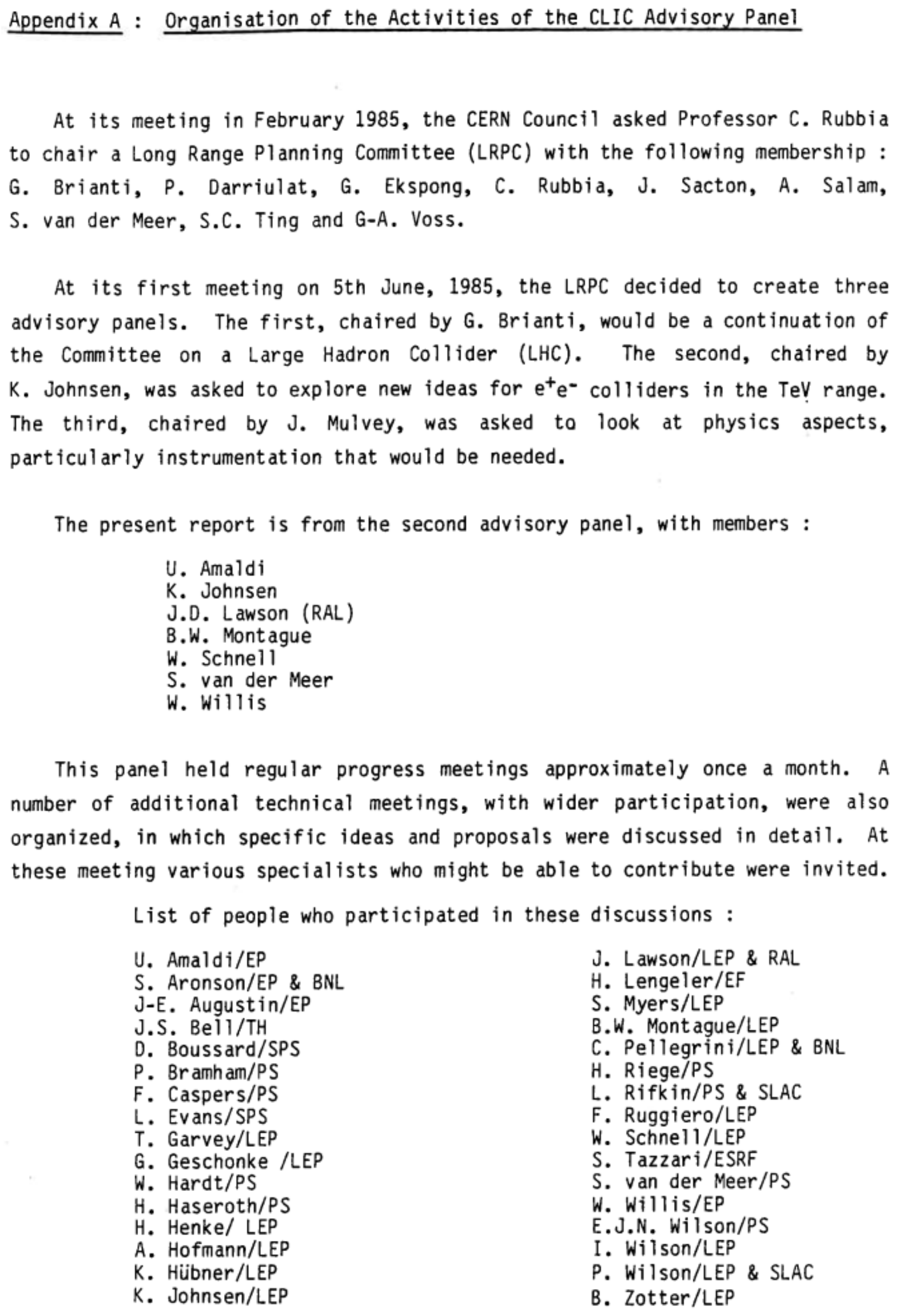
A bit of history



CLIC Note 38
(May, 1987)

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

REPORT FROM THE ADVISORY PANEL ON THE PROSPECTS
FOR e^+e^- LINEAR COLLIDERS IN THE TeV RANGE



Appendix A : Organisation of the Activities of the CLIC Advisory Panel

At its meeting in February 1985, the CERN Council asked Professor C. Rubbia to chair a Long Range Planning Committee (LRPC) with the following membership : G. Brianti, P. Darriulat, G. Ekspong, C. Rubbia, J. Sacton, A. Salam, S. van der Meer, S.C. Ting and G-A. Voss.

At its first meeting on 5th June, 1985, the LRPC decided to create three advisory panels. The first, chaired by G. Brianti, would be a continuation of the Committee on a Large Hadron Collider (LHC). The second, chaired by K. Johnsen, was asked to explore new ideas for e^+e^- colliders in the TeV range. The third, chaired by J. Mulvey, was asked to look at physics aspects, particularly instrumentation that would be needed.

The present report is from the second advisory panel, with members :

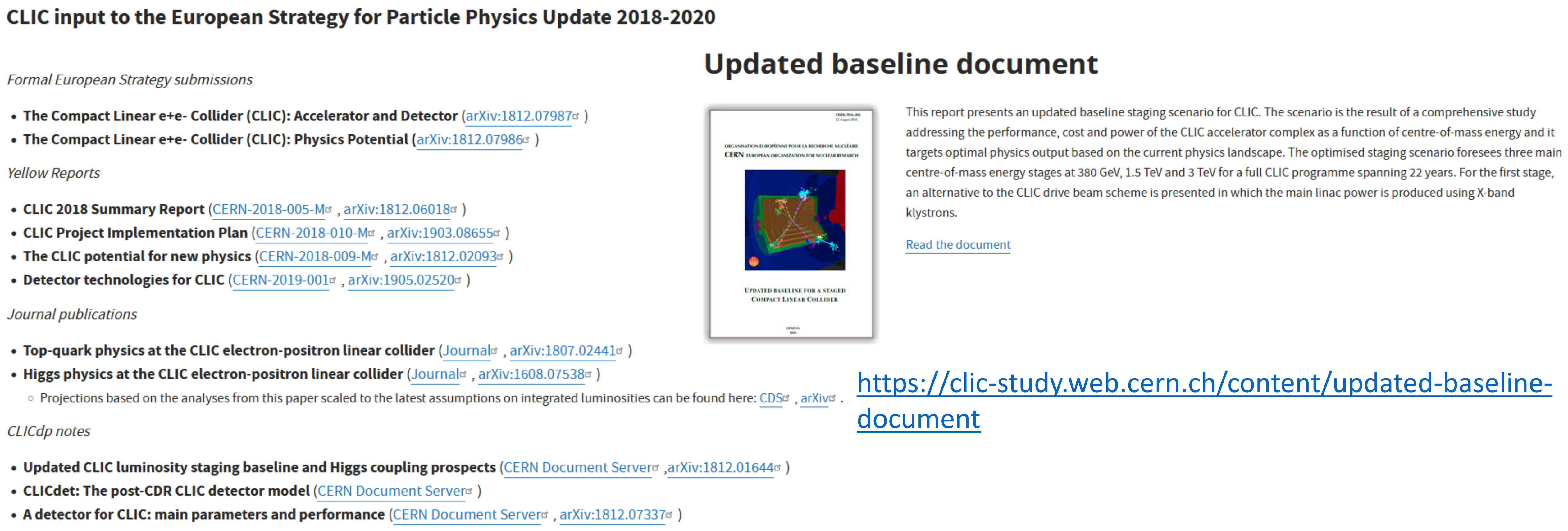
U. Amaldi
K. Johnsen
J.D. Lawson (RAL)
B.W. Montague
W. Schnell
S. van der Meer
W. Willis

This panel held regular progress meetings approximately once a month. A number of additional technical meetings, with wider participation, were also organized, in which specific ideas and proposals were discussed in detail. At these meeting various specialists who might be able to contribute were invited.

List of people who participated in these discussions :

U. Amaldi/EP
S. Aronson/EP & BNL
J-E. Augustin/EP
J.S. Bell/TH
D. Boussard/SPS
P. Bramham/PS
F. Caspers/PS
L. Evans/SPS
T. Garvey/LEP
G. Geschonke /LEP
W. Hardt/PS
H. Haseroth/PS
H. Henke/ LEP
A. Hofmann/LEP
K. Hübner/LEP
K. Johnsen/LEP
J. Lawson/LEP & RAL
H. Lengeler/EF
S. Myers/LEP
B.W. Montague/LEP
C. Pellegrini/LEP & BNL
H. Riege/PS
L. Rifkin/PS & SLAC
F. Ruggiero/LEP
W. Schnell/LEP
S. Tazzari/ESRF
S. van der Meer/PS
W. Willis/EP
E.J.N. Wilson/PS
I. Wilson/LEP
P. Wilson/LEP & SLAC
B. Zotter/LEP

Back to the Future



CLIC input to the European Strategy for Particle Physics Update 2018-2020

Formal European Strategy submissions

- **The Compact Linear e+e- Collider (CLIC): Accelerator and Detector** (arXiv:1812.07987)
- **The Compact Linear e+e- Collider (CLIC): Physics Potential** (arXiv:1812.07986)

Yellow Reports

- **CLIC 2018 Summary Report** (CERN-2018-005-M , arXiv:1812.06018)
- **CLIC Project Implementation Plan** (CERN-2018-010-M , arXiv:1903.08655)
- **The CLIC potential for new physics** (CERN-2018-009-M , arXiv:1812.02093)
- **Detector technologies for CLIC** (CERN-2019-001 , arXiv:1905.02520)

Journal publications

- **Top-quark physics at the CLIC electron-positron linear collider** (Journal , arXiv:1807.02441)
- **Higgs physics at the CLIC electron-positron linear collider** (Journal , arXiv:1608.07538)
  - Projections based on the analyses from this paper scaled to the latest assumptions on integrated luminosities can be found here: CDS , arXiv .

CLICdp notes

- **Updated CLIC luminosity staging baseline and Higgs coupling prospects** (CERN Document Server ,arXiv:1812.01644)
- **CLICdet: The post-CDR CLIC detector model** (CERN Document Server)
- **A detector for CLIC: main parameters and performance** (CERN Document Server , arXiv:1812.07337)

Updated baseline document

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

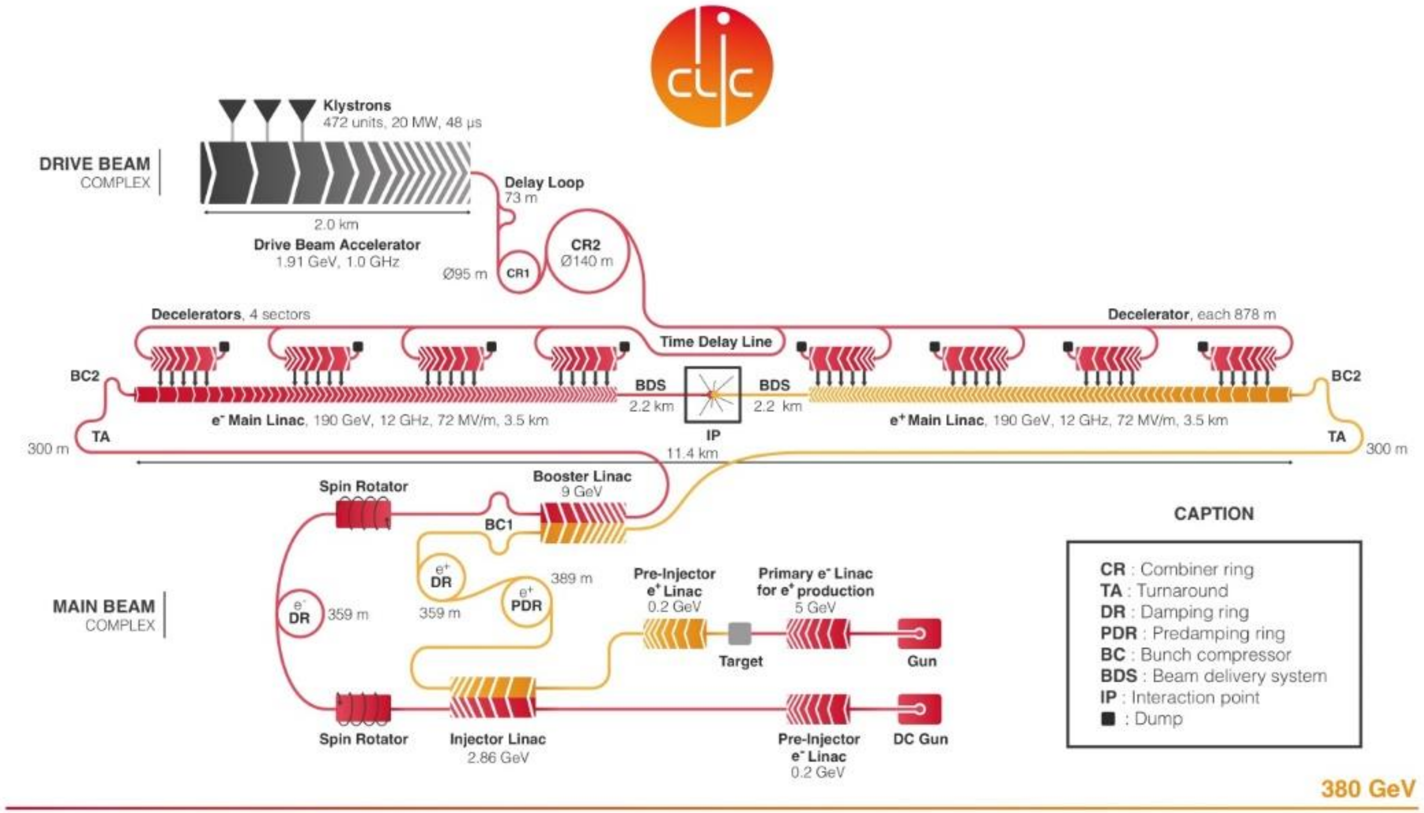
This report presents an updated baseline staging scenario for CLIC. The scenario is the result of a comprehensive study addressing the performance, cost and power of the CLIC accelerator complex as a function of centre-of-mass energy and it targets optimal physics output based on the current physics landscape. The optimised staging scenario foresees three main centre-of-mass energy stages at 380 GeV, 1.5 TeV and 3 TeV for a full CLIC programme spanning 22 years. For the first stage, an alternative to the CLIC drive beam scheme is presented in which the main linac power is produced using X-band klystrons.

Read the document

https://clic-study.web.cern.ch/content/updated-baseline-document

https://clic.cern/european-strategy

Linear collider features



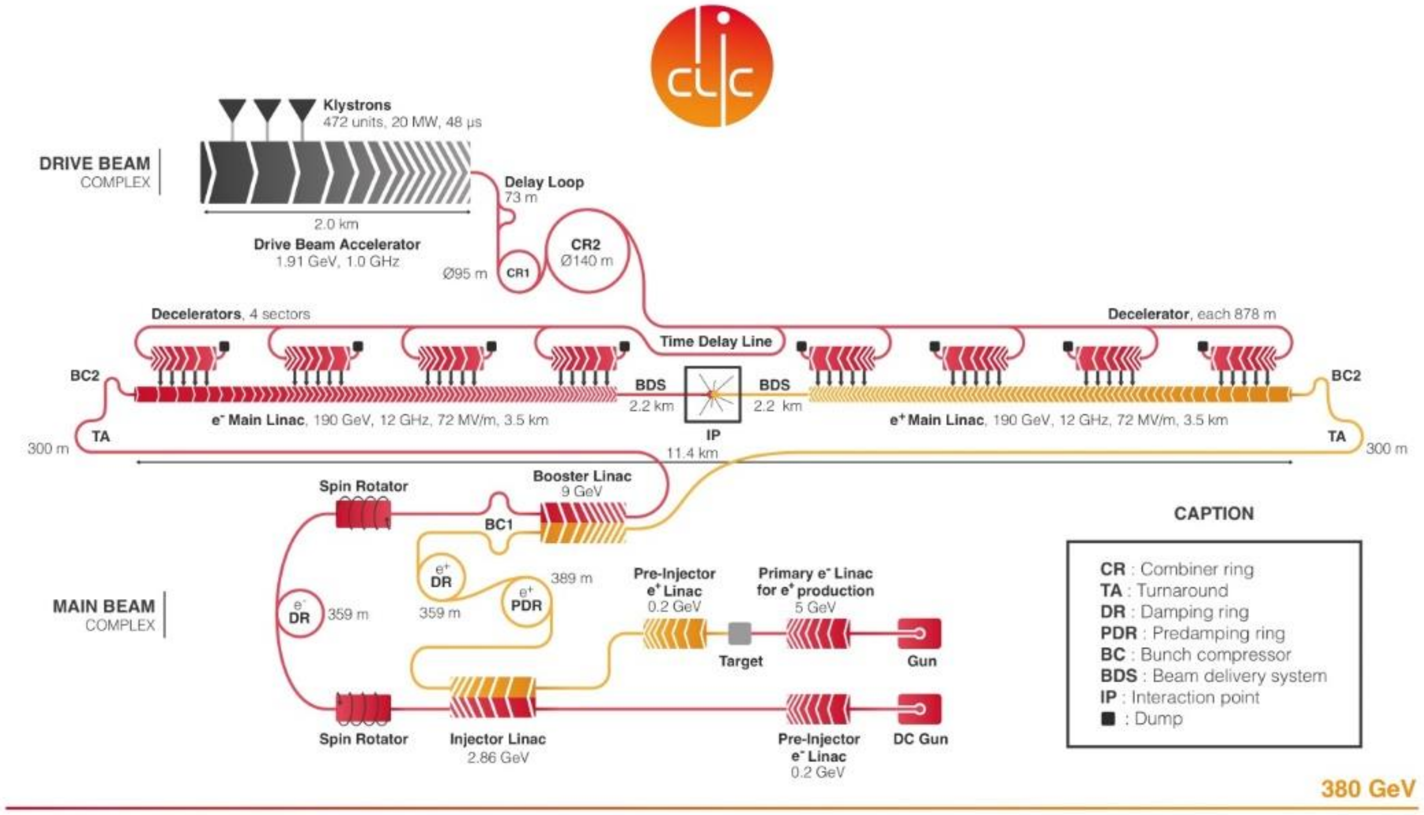
CLIC - Scheme of the Compact Linear Collider (CLIC)

Beam energy:

- Beams take single pass through machine, so collision energy is length times gradient.
- High-gradient becomes a key performance parameter.
- CLIC uses 72 MV/m for 380 GeV stage and 100 MV/m for 3 TeV stage.
- Normal conducting rf
- These gradients used to be beyond state-of-the-art consequently CLIC invested significant resources in finding ways to increase gradient.
- Plasma enthusiast aim to go even higher.

No upper limit on energy due to synchrotron radiation energy loss – but –rf system must proved full energy in one pass.

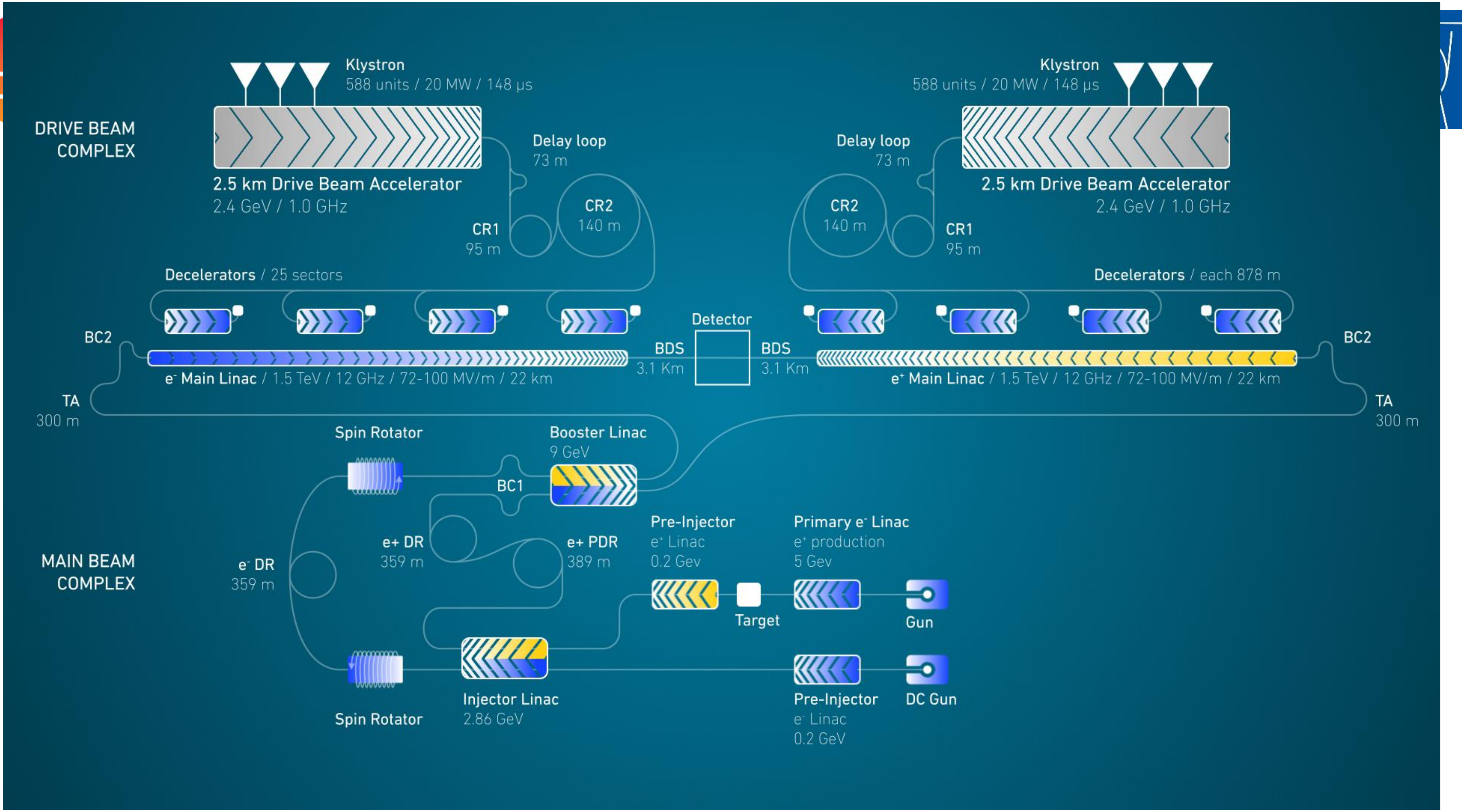
Linear collider features



CLIC - Scheme of the Compact Linear Collider (CLIC)

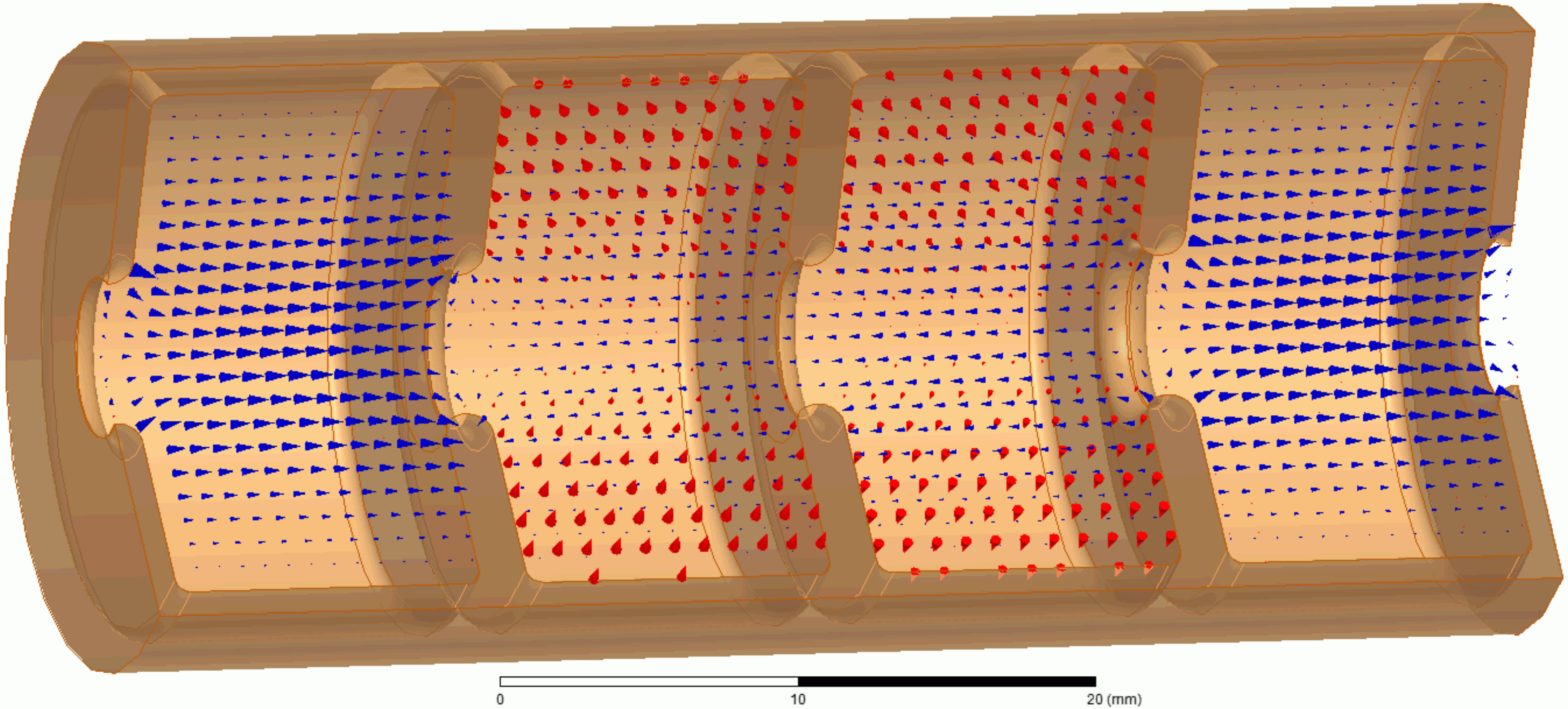
Luminosity:

- Beams collide only once.
- Aim for high current and very small beam at interaction region.
- CLIC beam current is approximately 1 A during pulse, 7.3 μA average per beam so a total of 5.5 MW average beam power – developed extremely efficient acceleration with strong beam loading.
- The beam size at the interaction region 150 x 3 nm – damping rings to produce very low emittance beams plus very precise alignment to maintain low emittance in linac.


DRIVE BEAM COMPLEX
Klystron
588 units / 20 MW / 148 μs
2.5 km Drive Beam Accelerator
2.4 GeV / 1.0 GHz
Delay loop
73 m
CR1
95 m
CR2
140 m
Klystron
588 units / 20 MW / 148 μs
Delay loop
73 m
2.5 km Drive Beam Accelerator
2.4 GeV / 1.0 GHz
CR2
140 m
CR1
95 m
Decelerators / 25 sectors
Decelerators / each 878 m
Detector
BC2
BDS
3.1 Km
BDS
3.1 Km
BC2
e^- Main Linac / 1.5 TeV / 12 GHz / 72-100 MV/m / 22 km
e^+ Main Linac / 1.5 TeV / 12 GHz / 72-100 MV/m / 22 km
TA
300 m
TA
300 m
Spin Rotator
Booster Linac
9 GeV
BC1
MAIN BEAM COMPLEX
e^- DR
359 m
e+ DR
359 m
e+ PDR
389 m
Pre-Injector
e^+ Linac
0.2 Gev
Primary e^- Linac
e^+ production
5 Gev
Target
Gun
Spin Rotator
Injector Linac
2.86 GeV
Pre-Injector
e^- Linac
0.2 GeV
DC Gun

A very brief introduction to radio frequency acceleration

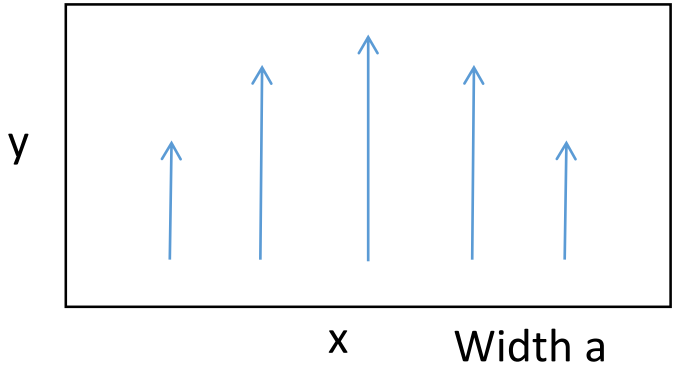
Electric field
Magnetic field



Beam propagation direction. Beam and phase velocity must be the same – synchronism.
How can this be arranged?

Uniform (rectangular) waveguide

The lines are electric field



Field solution

$$E_y = E_0 \sin\left(\frac{\pi}{a}x\right)e^{i(\omega t - k_z z)}$$

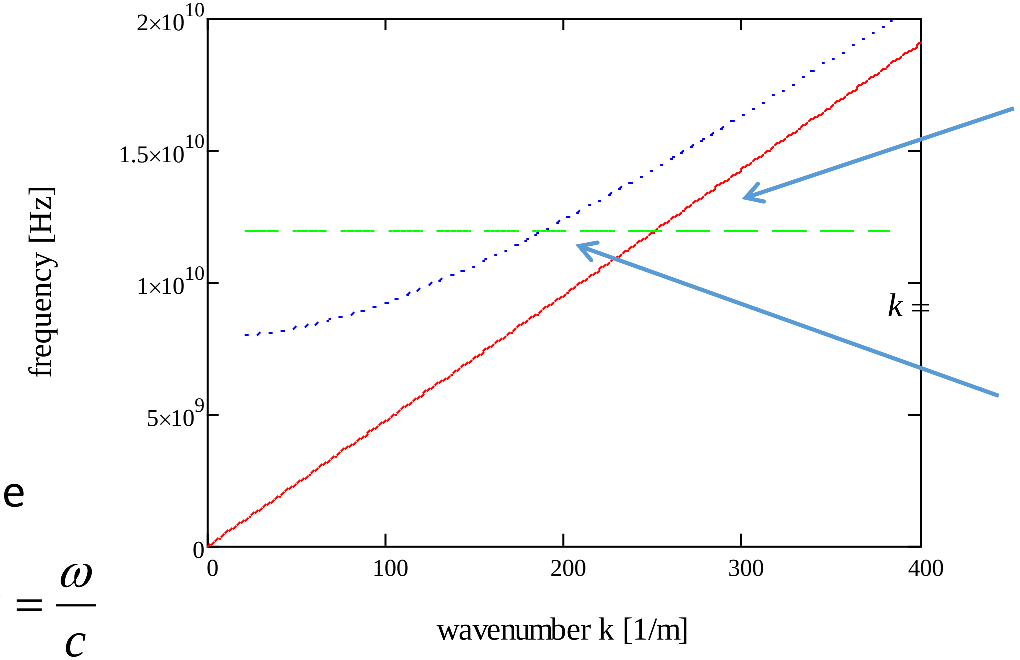
$$k_z = \sqrt{\left(\frac{\omega}{c}\right)^2 - \left(\frac{\pi}{a}\right)^2}$$

Gives cutoff frequency

The dispersion curve

$$v_{phase} = \frac{\omega}{k}$$

$$k = \frac{\omega}{c}\sqrt{1-\left(\frac{\omega_0}{\omega}\right)^2}$$

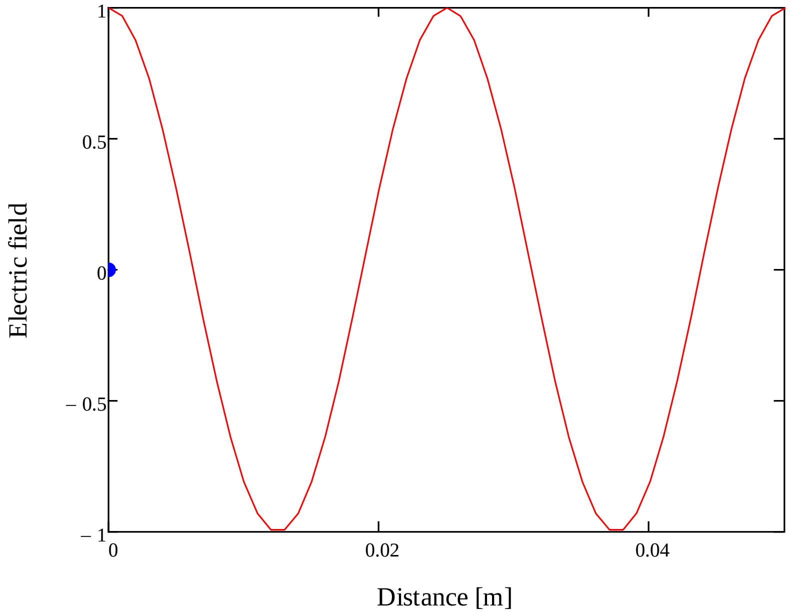


Speed of light line

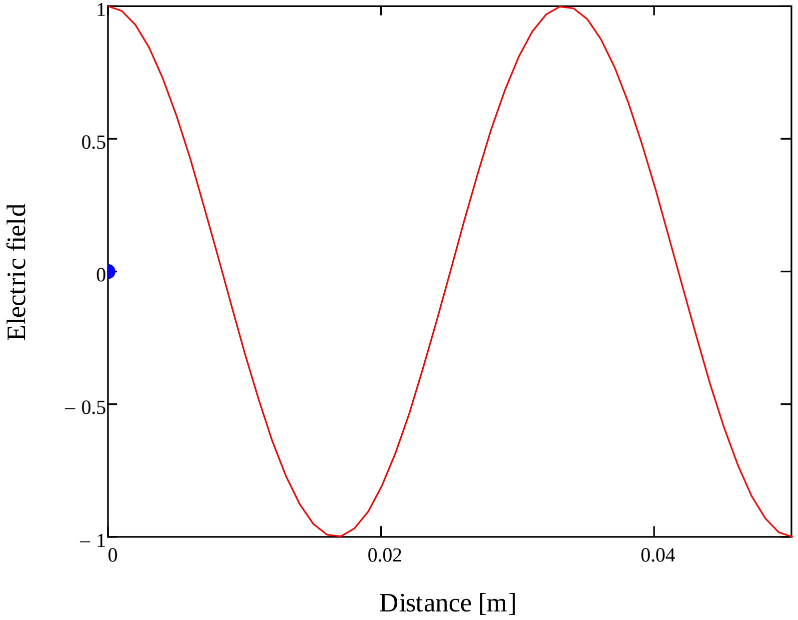
$$k = \frac{\omega}{c}$$

$$e^{i(\omega t - kz)}$$

Horizontal green line: waveguide k is 0.75 of free space k at 11.994 GHz

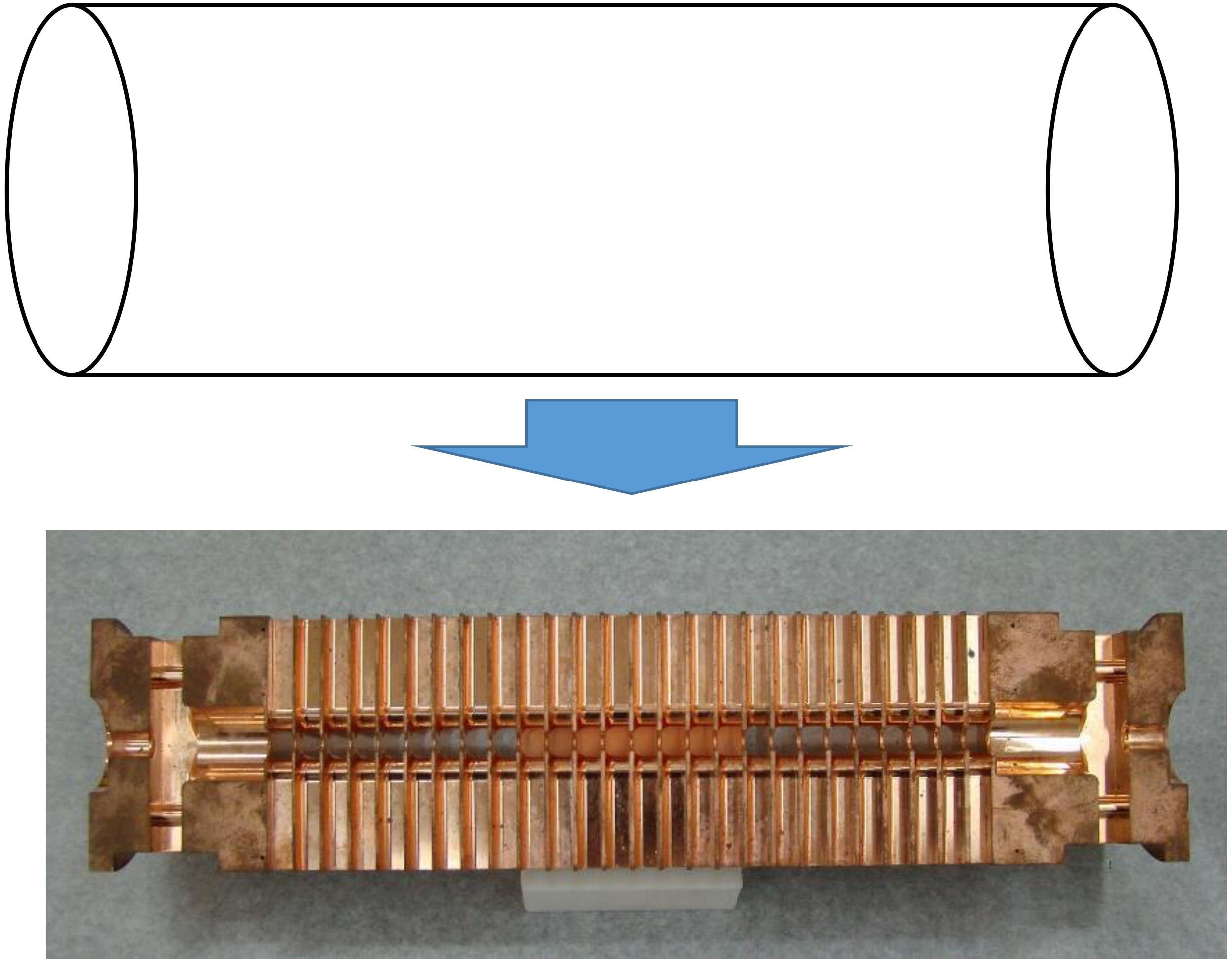


case 1



case 2

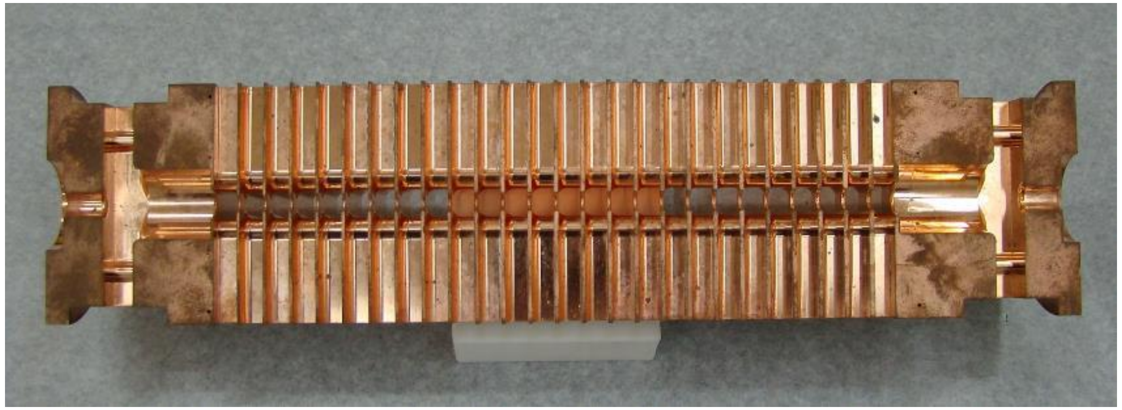
How do we slow down phase velocity to c?



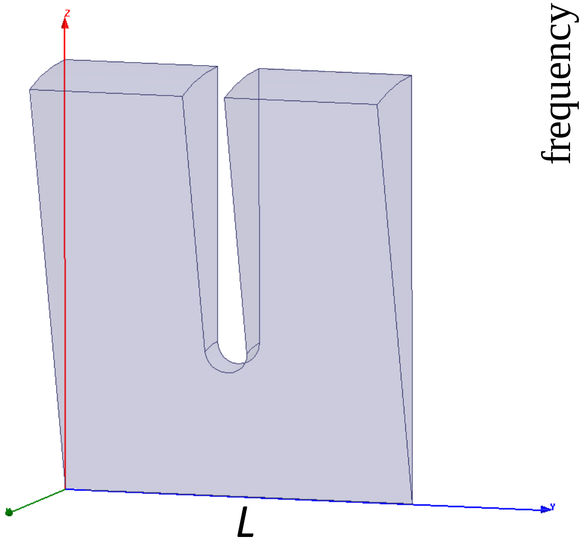
Uniform waveguide

Periodic loading

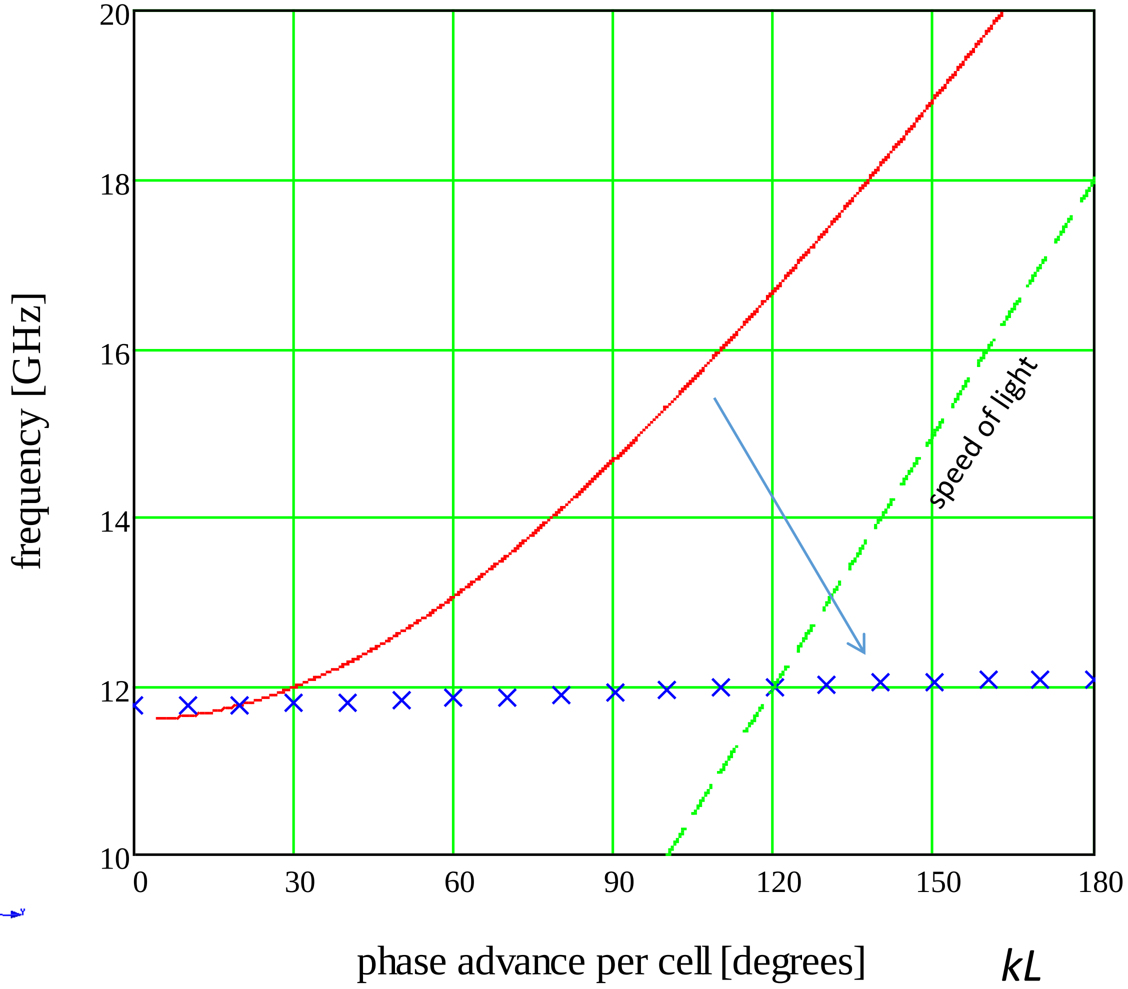
Solve the problem that phase velocity is too high (wavelength is too long) with periodic loading by putting “irises” in the uniform waveguide



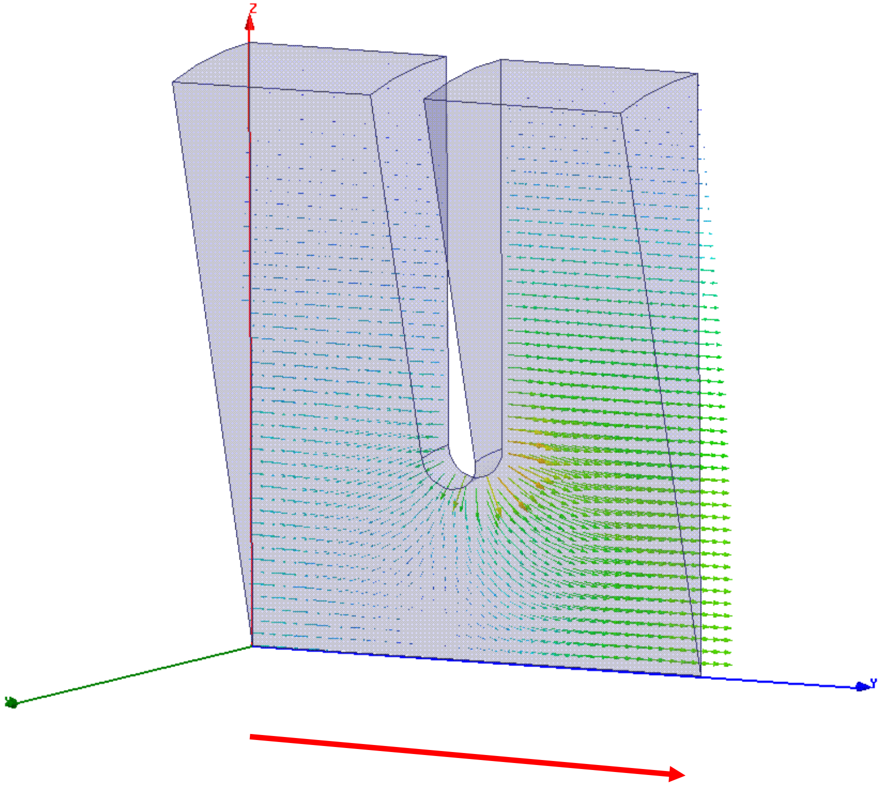
Floquet’s theorem states, translated to rf language, that periodic boundary conditions give solution with same field in every cell, just differing by a complex phase advance.

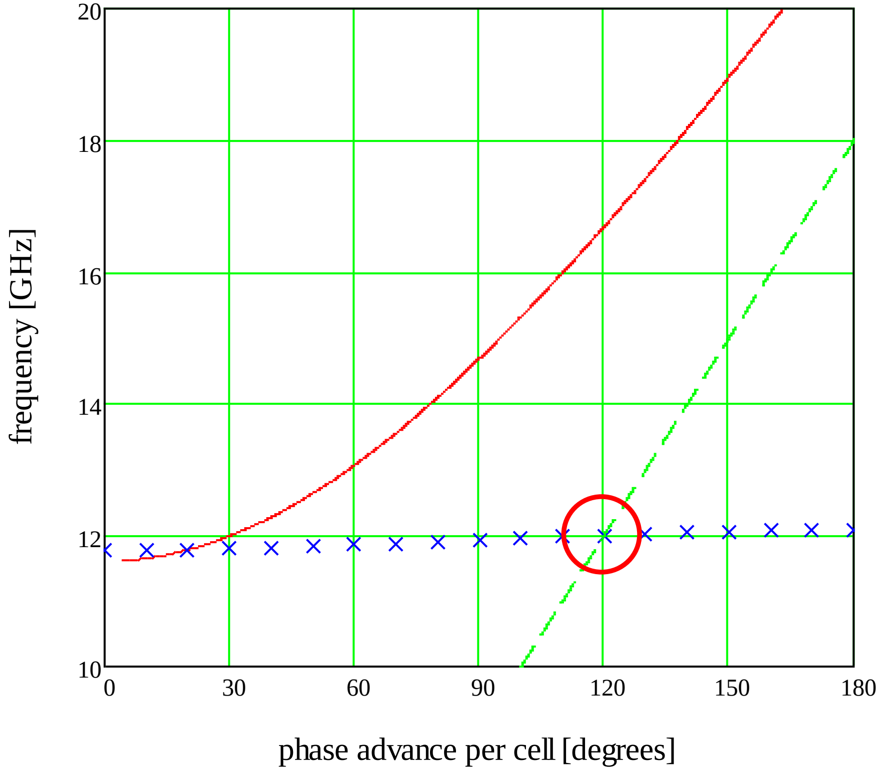


periodic loading



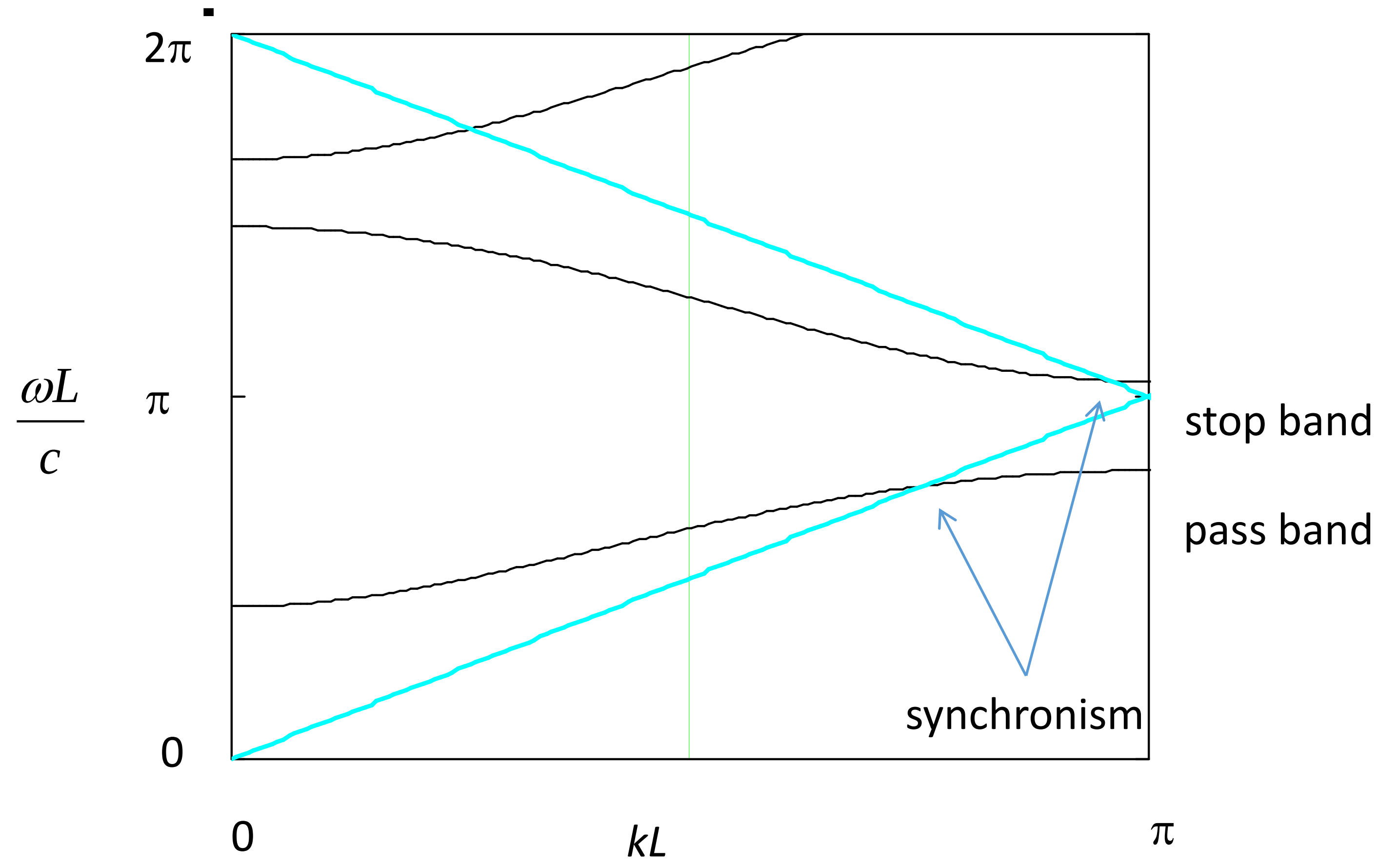
Single cell electric field pattern 2π/3 phase advance

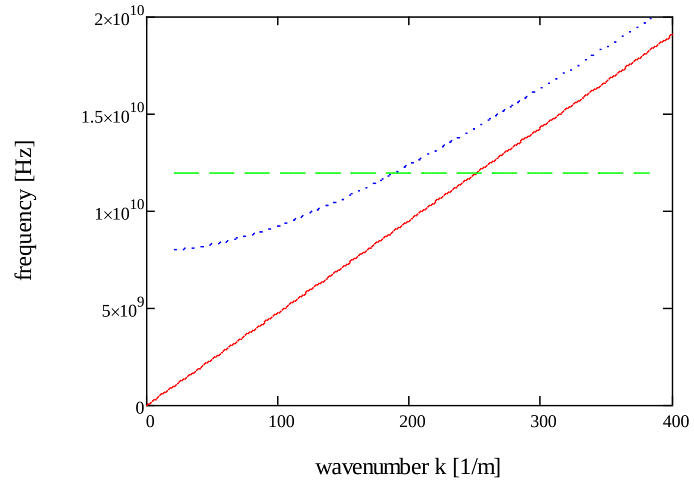


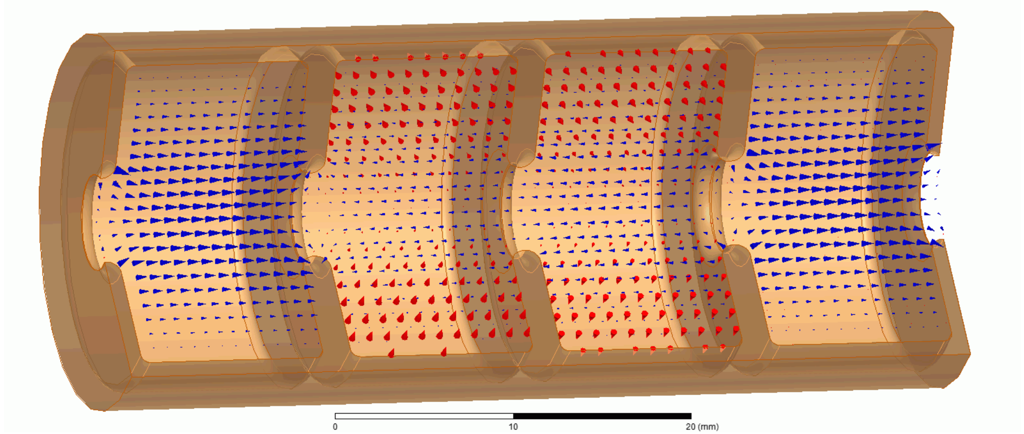


Phase synchronism means time for beam to get across cell is the same as accelerating phase to get across cell.

The Brillouin diagram. Frequency vs phase advance per period, which is *kL.*







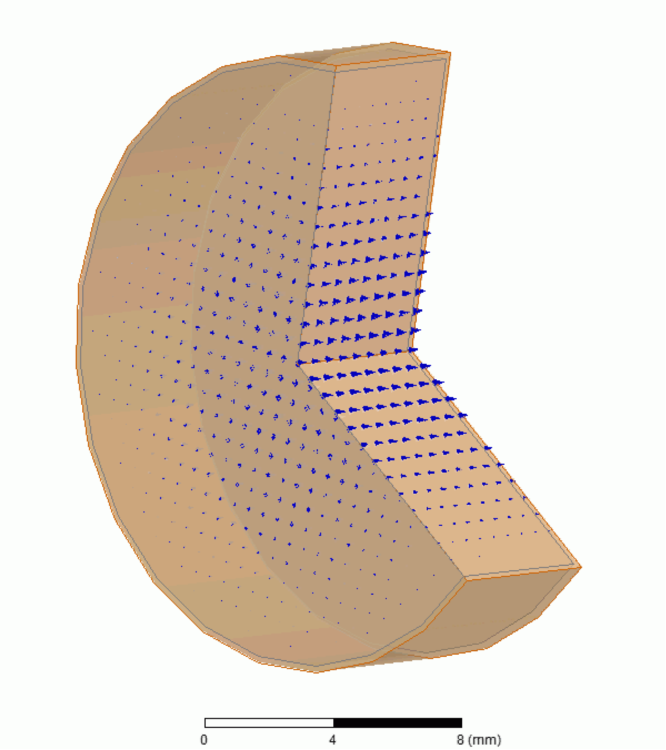
Quantities people use

$$Q = \frac{\omega W}{P_{loss}}$$

Quality factor

$$\frac{R}{Q} = \frac{|V_{acc}|^2}{\omega W}$$

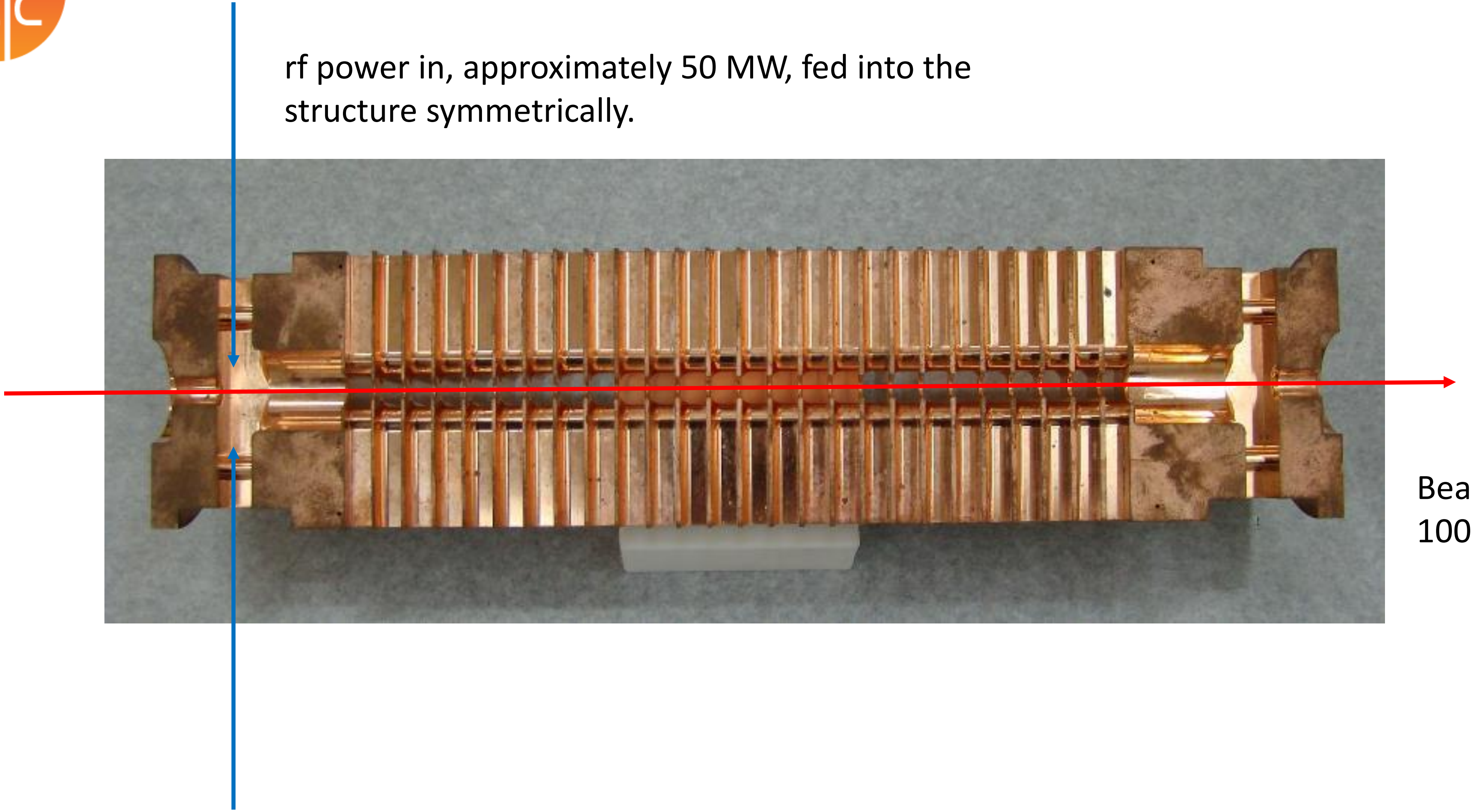
Ratio of acceleration to stored energy



$$R = \frac{|V_{acc}|^2}{P_{loss}}$$

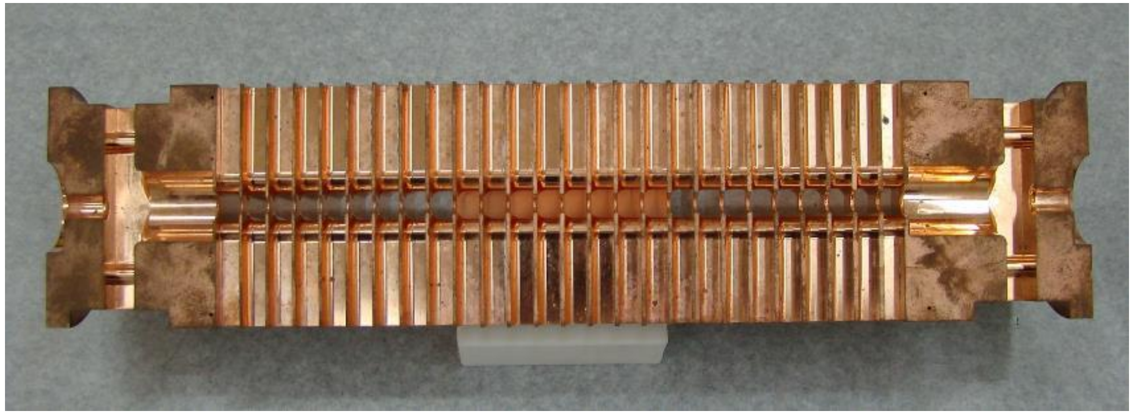
Shunt impedance [MΩ]
Often the quantity used to optimize cavity design

rf power in, approximately 50 MW, fed into the structure symmetrically.



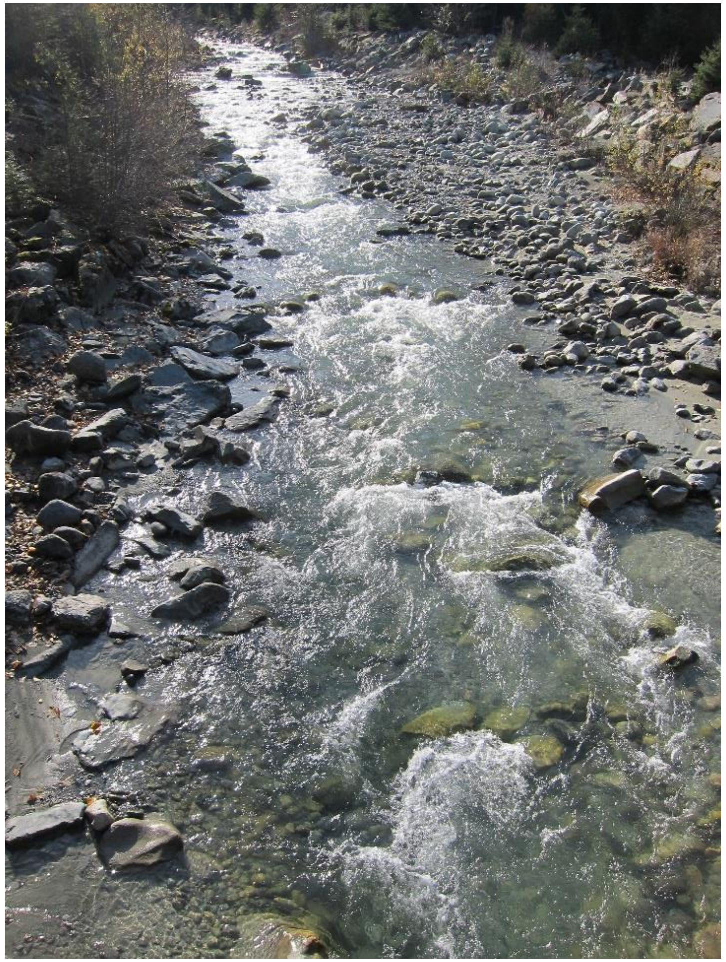
Beam accelerated by 100 MV/m

Group velocity



We now go from stored energy to power via group velocity:

$$P = v_g W'$$



Quantities people use with group velocity mixed in

$$\frac{R}{Q} = \frac{\left|V_{acc}\right|^2}{\omega W}$$

Ratio of acceleration to stored energy

$$Q = \frac{\omega W}{P_{loss}}$$

Quality factor

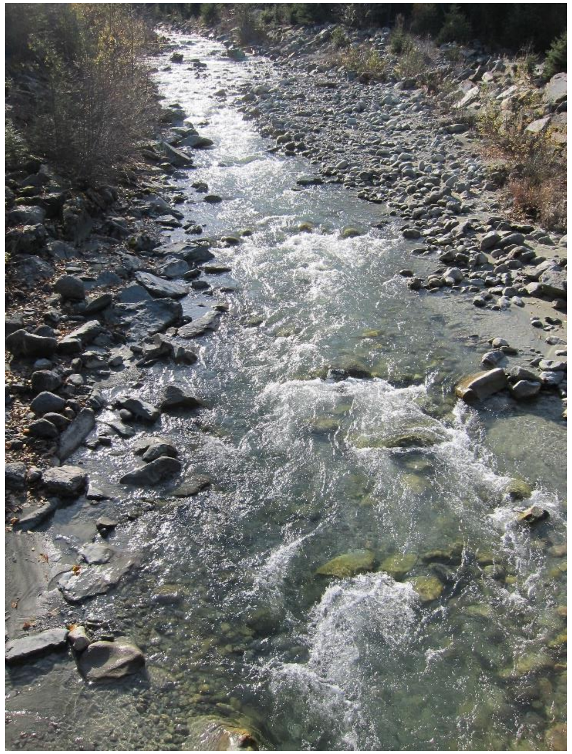
$$R = \frac{\left|V_{acc}\right|^2}{P_{loss}}$$

Shunt impedance [MΩ]
Often the quantity used to optimize cavity design

We now go from stored energy to power via group velocity:

$$P = v_g W'$$

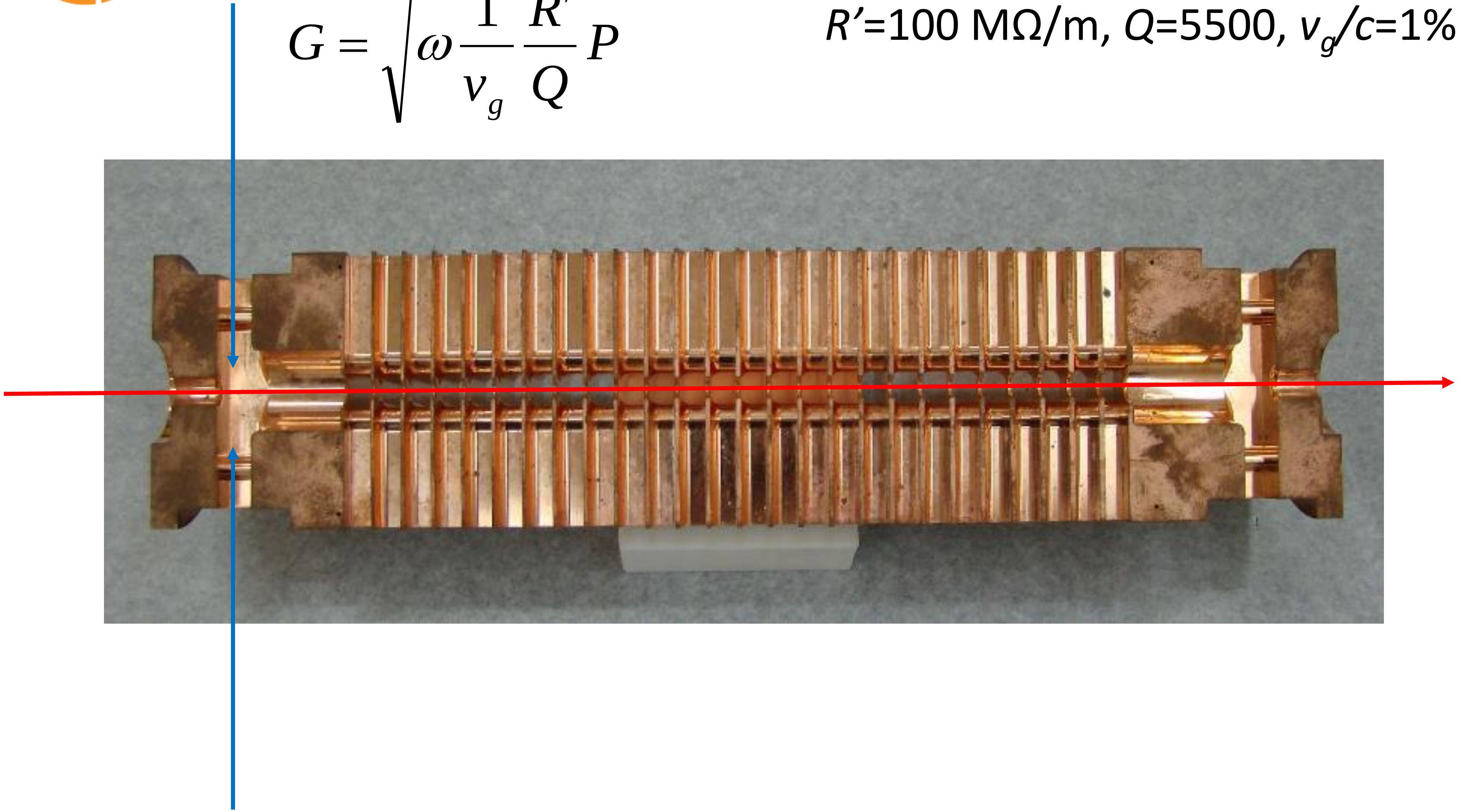
$$G = \frac{|V_{acc}|}{l}$$

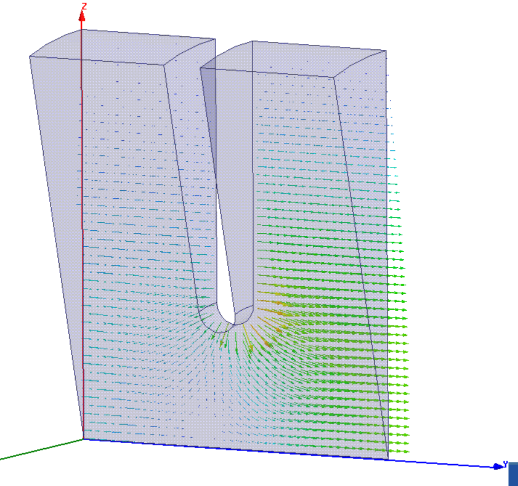


$$G = \sqrt{\omega \frac{1}{v_g} \frac{R'}{Q} P}$$

$$G = \sqrt{\omega \frac{1}{v_g} \frac{R'}{Q} P}$$

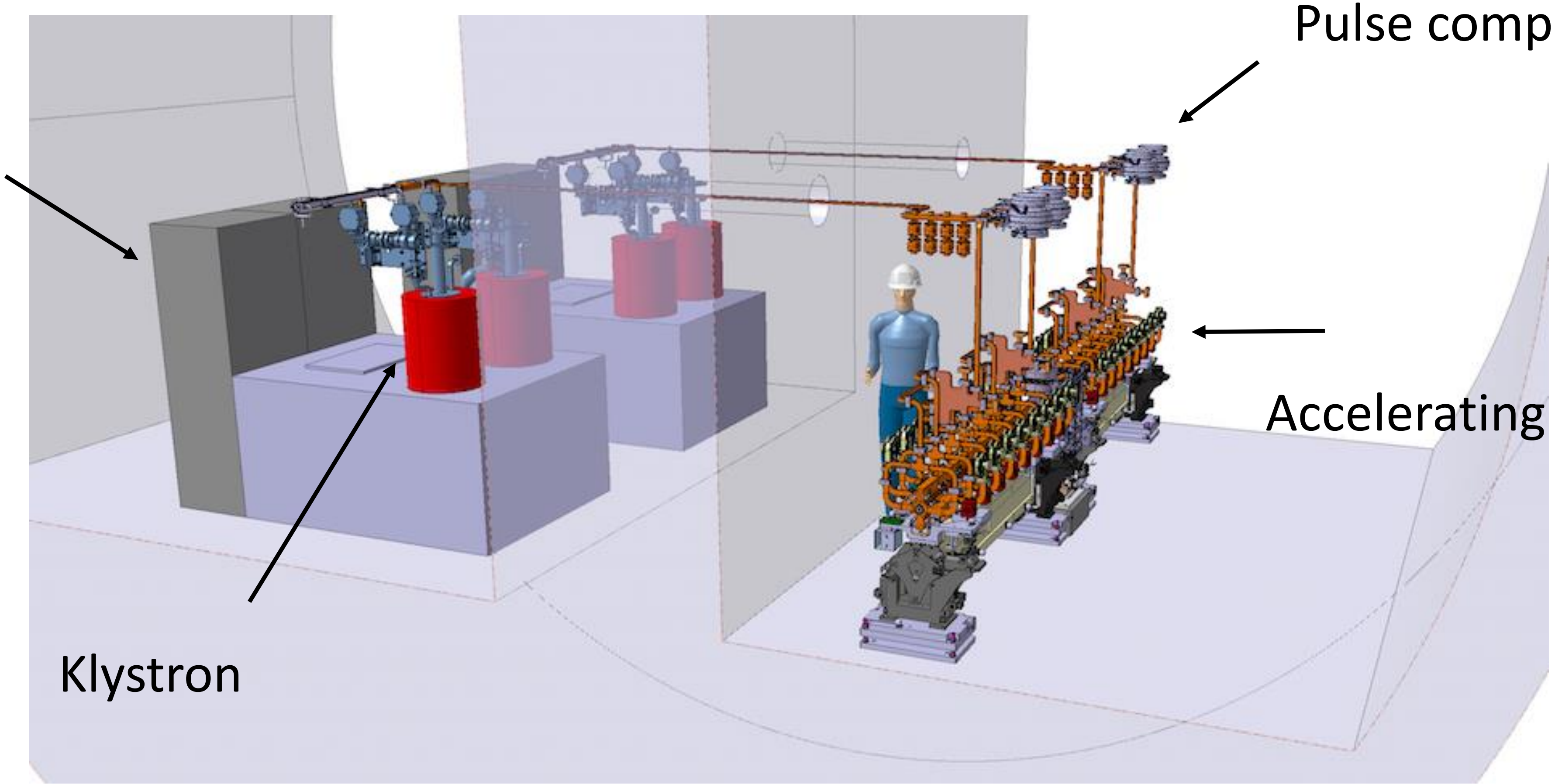
CLIC structure (approximate values):
R'=100 MΩ/m, *Q*=5500, v_g/c=1%





The layout of a linac radio frequency unit

Linear accelerator, linac, overview



Modulator

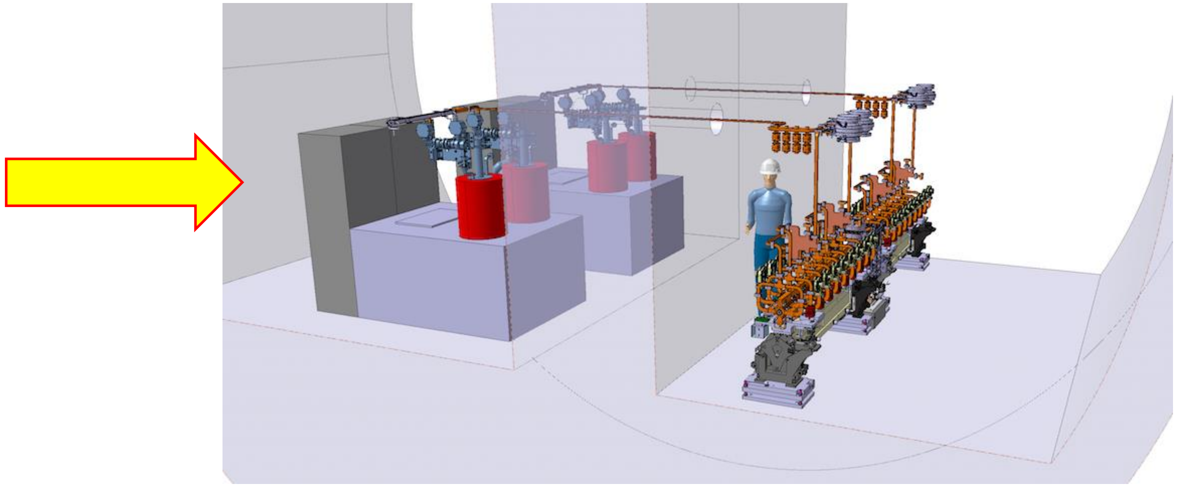
Pulse compressor

Accelerating structures

Klystron

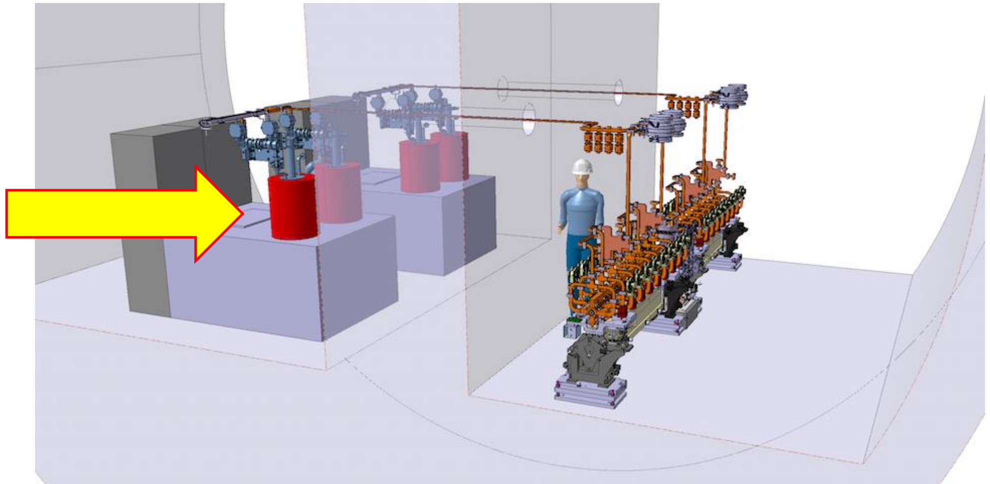
Solid-state modulator

Prototype modulator used in high-gradient test stands.



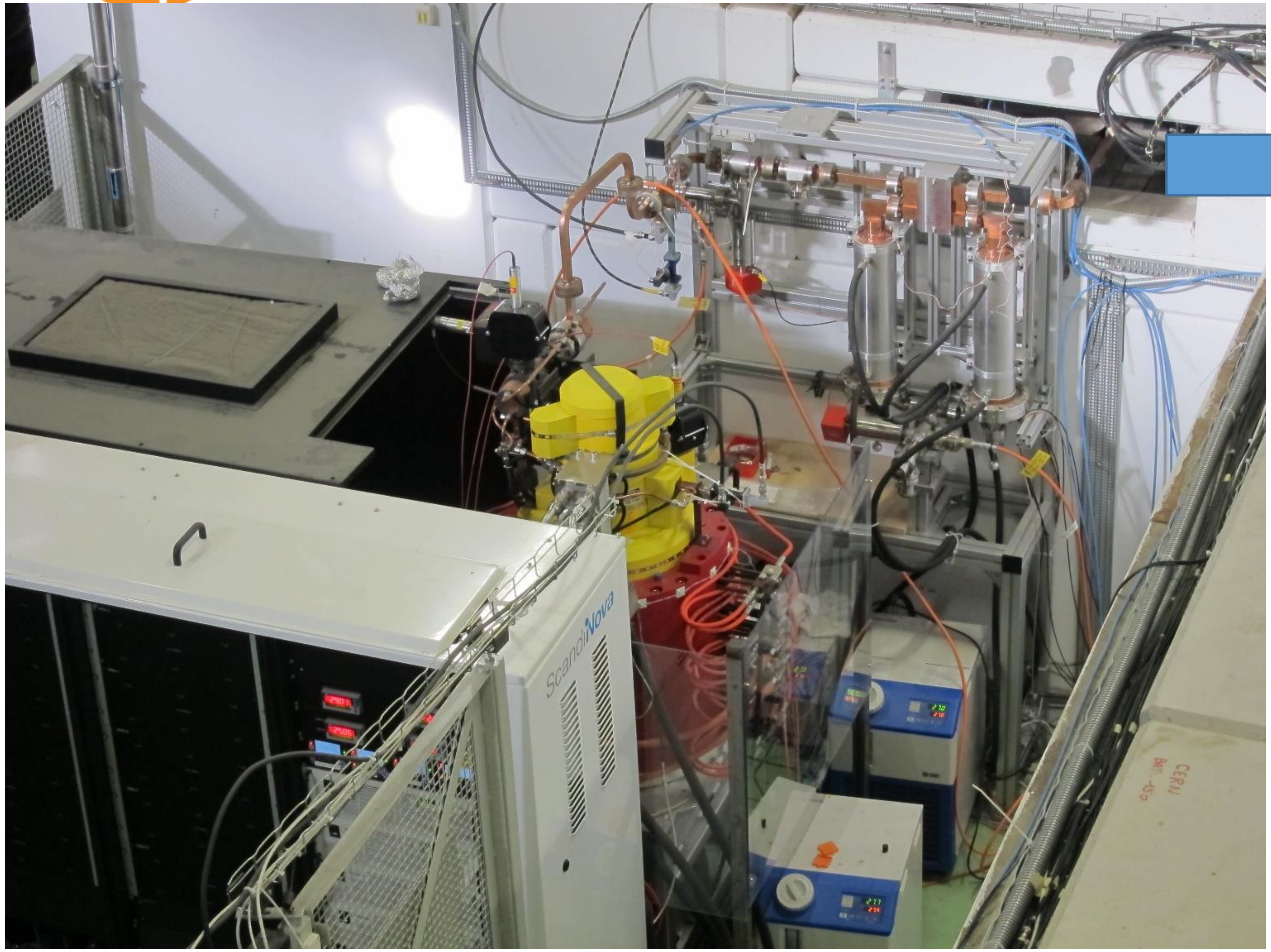
- Converts mains to 1.5 kV and stores energy in capacitors.
- Switches IGBTs which feed split core transformer
- Secondary on transformer produces (approximate numbers) 400 kV, 200 A pulse, which is 80 MW. Pulse duration is 1.5 µs.
- Note pulse is longer than we need for accelerator.

Klystron

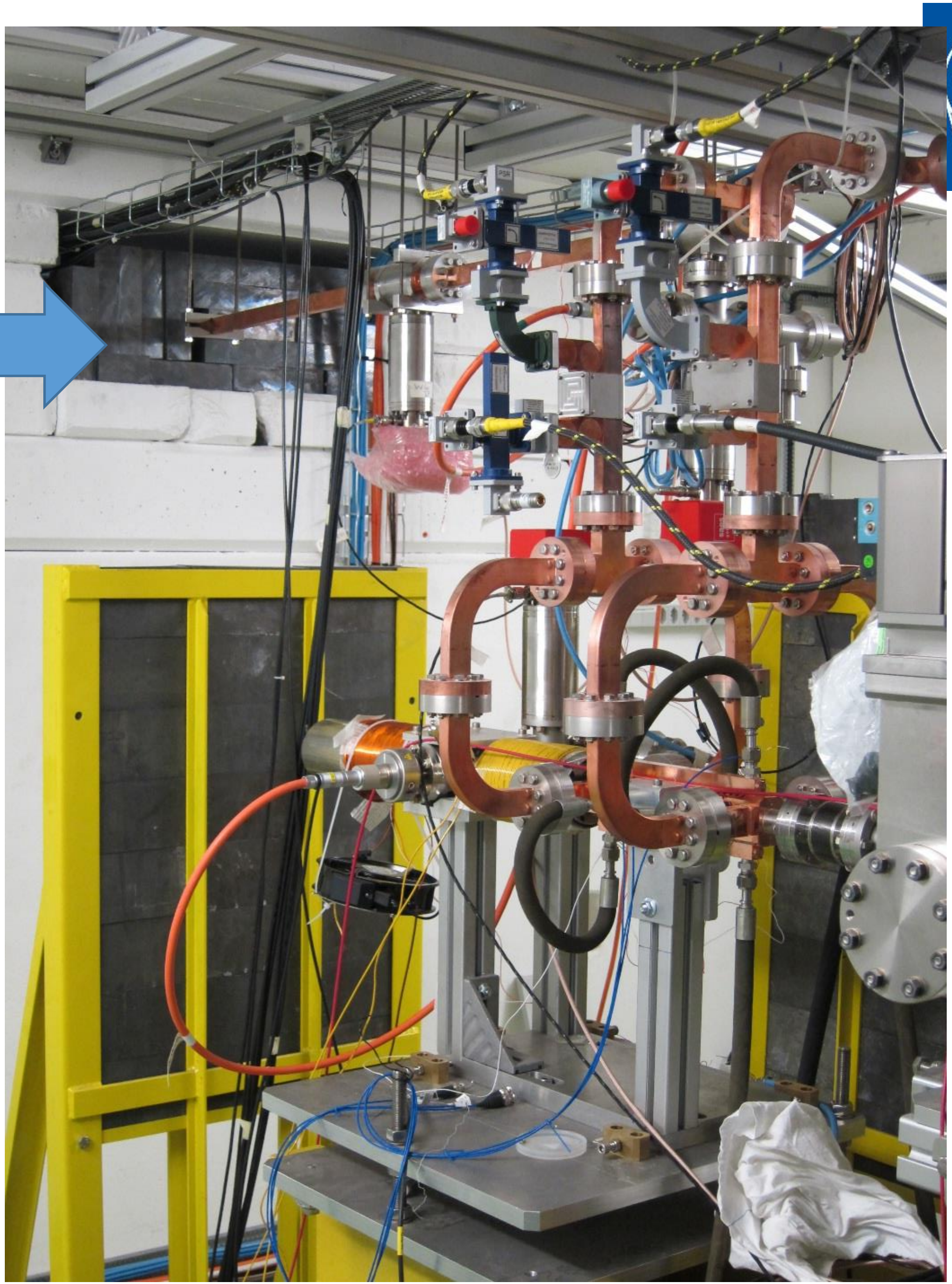


- Pulse from modulator is converted to a current in vacuum inside the klystron, approximately 400 keV and 200 A.
- This is done by emitting electrons from a cathode, making a vacuum diode.
- 400 keV is sub-relativistic. This allows the beam to be bunched through a velocity modulation.
- Power is extracted by cavity which decelerates the bunched beam.

This klystron modulator unit feeds…

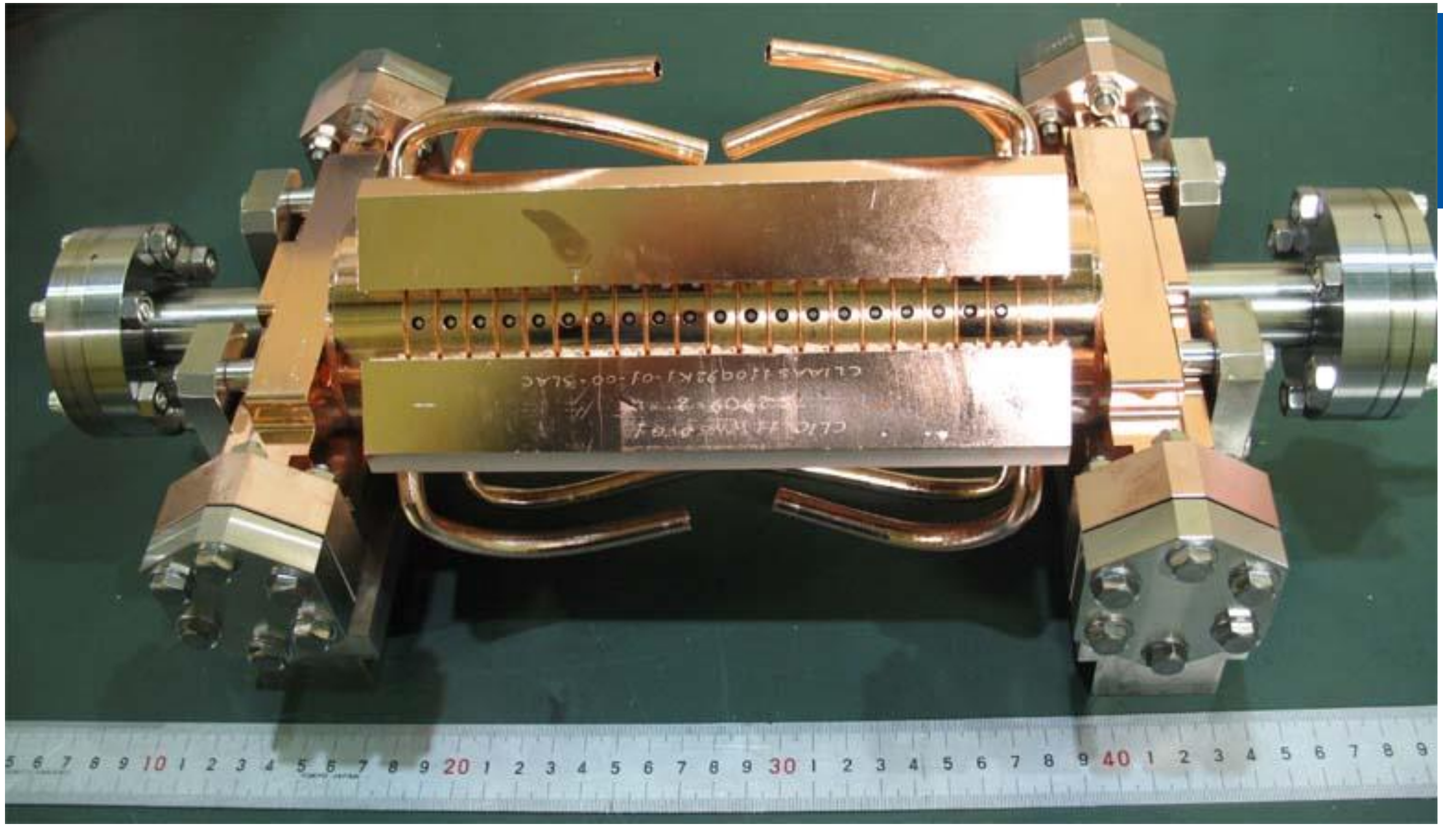


this accelerating structure.

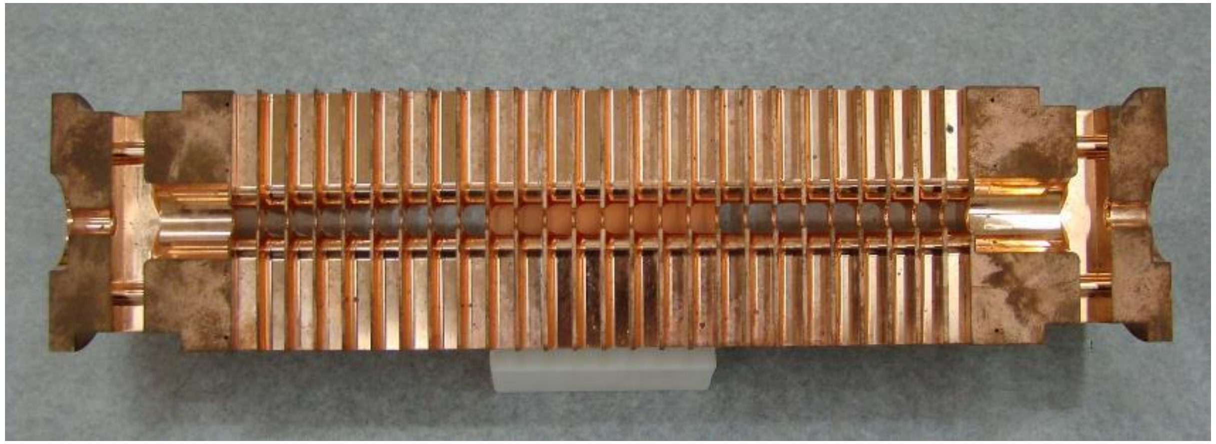


A CLIC prototype accelerating structure.

11.994 GHz X-band
100 MV/m acceleration
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz

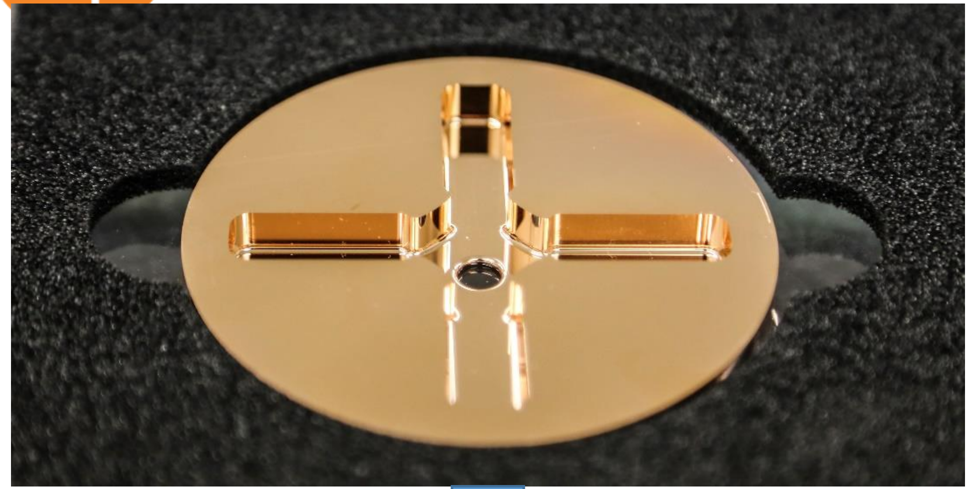


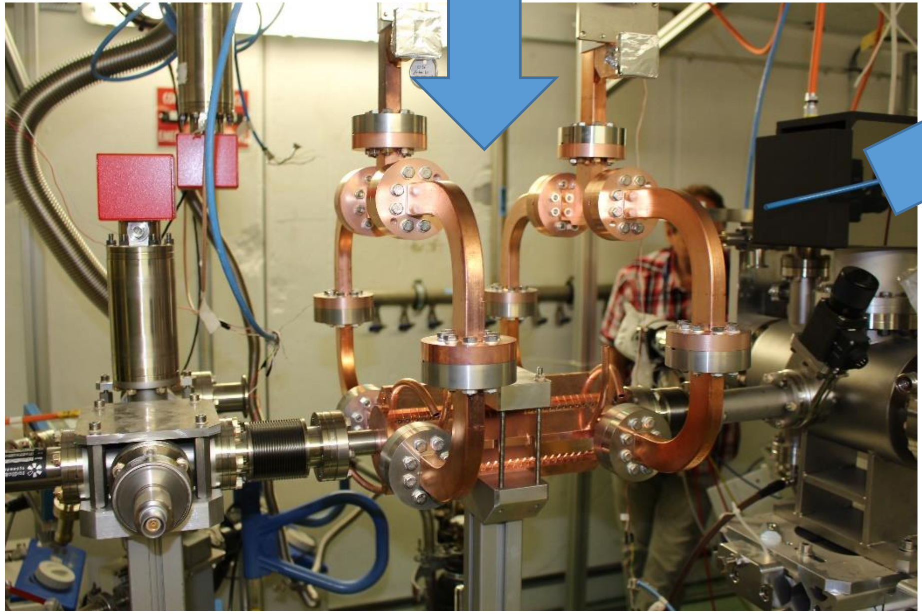
outside

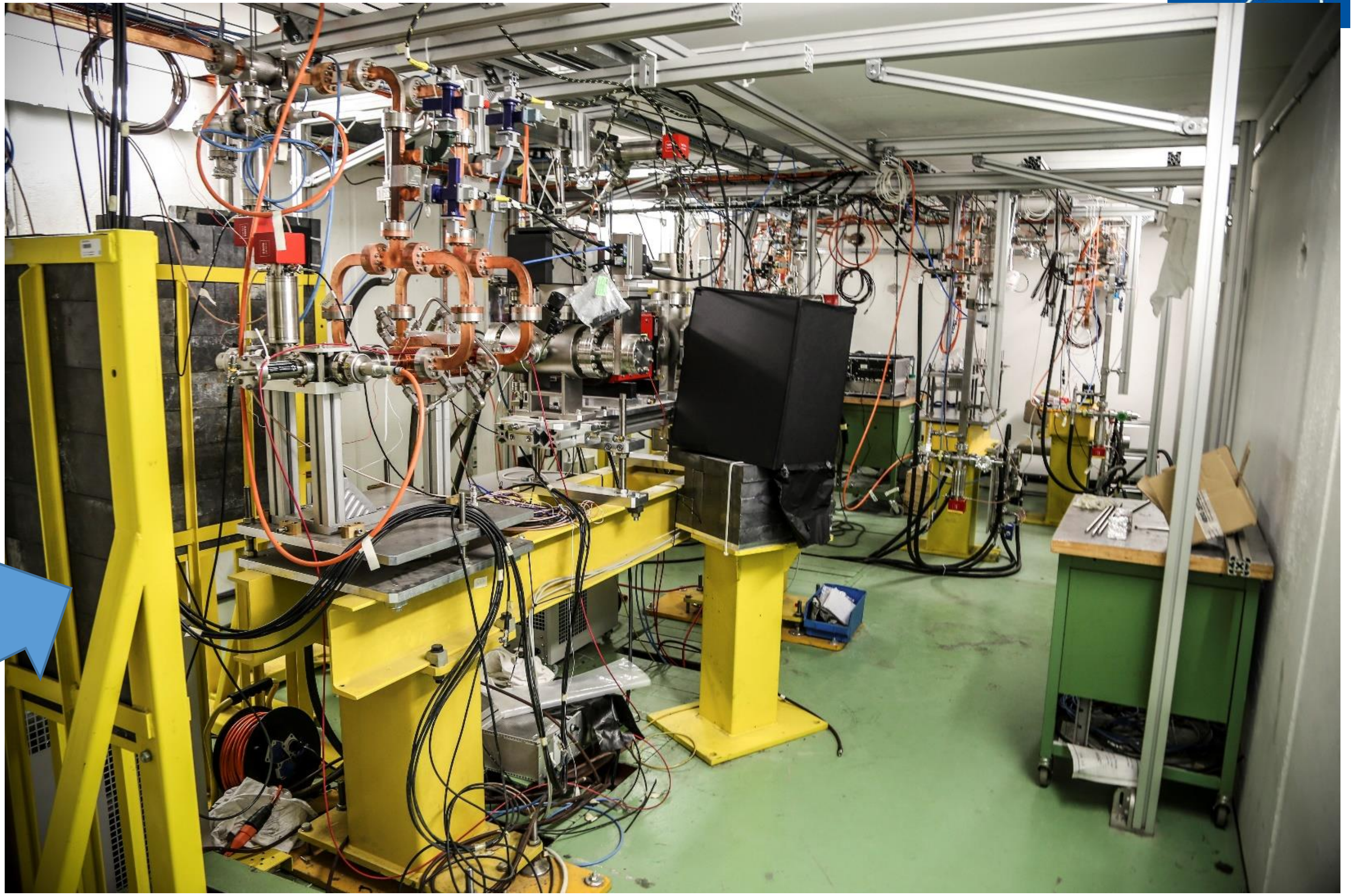


inside

Introduction to CLIC linac technology







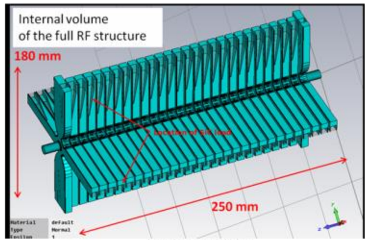
Very strong involvement of University of Tartu and University of Helsinki in understanding high-gradient phenomena!

High current beam stability

High-current beam requires Higher-Order-Mode suppression for beam stability, just like CLIC

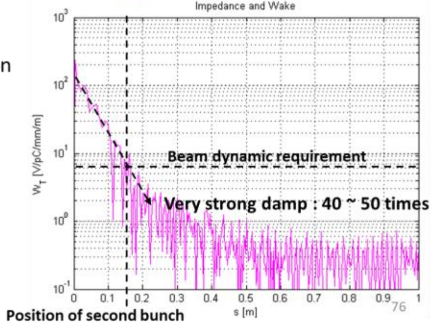
Transverse long-range Wakefield in CLIC-G structure

Structure name	CLIG-G TD26cc
Work frequency	11.994GHz
Cell	26 regular cells+ 2 couplers
Length (active)	230mm
Iris aperture	2.35mm - 3.15mm



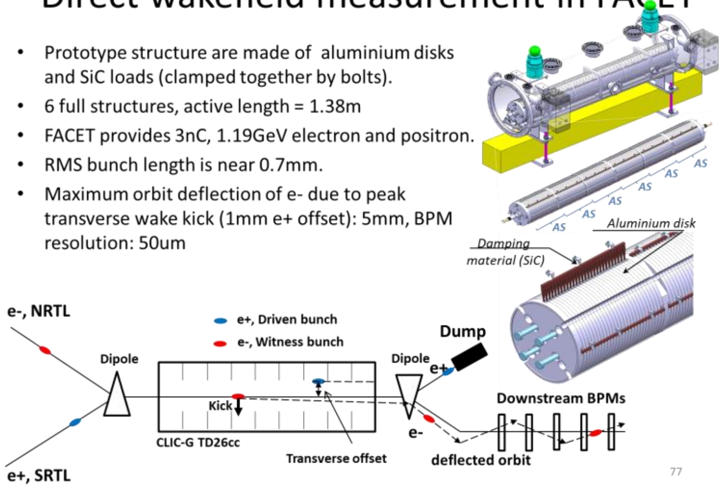
transverse long-range wakefield calculation using Gdfidl code:

Peak value :
250 V/pC/m/mm
At position of second bunch (0.15m):
5~6 V/pC/m/mm
Beam dynamic requirement:
< 6.6 V/pC/m/mm

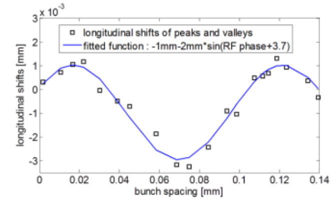


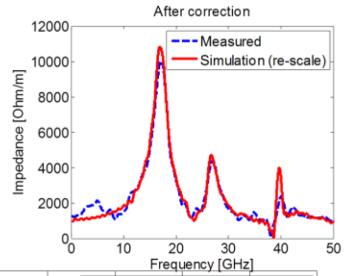
Direct wakefield measurement in FACET

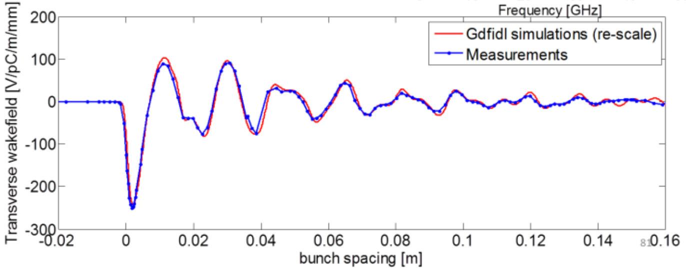
- Prototype structure are made of aluminium disks and SiC loads (clamped together by bolts).
- 6 full structures, active length = 1.38m
- FACET provides 3nC, 1.19GeV electron and positron.
- RMS bunch length is near 0.7mm.
- Maximum orbit deflection of e- due to peak transverse wake kick (1mm e+ offset): 5mm, BPM resolution: 50um

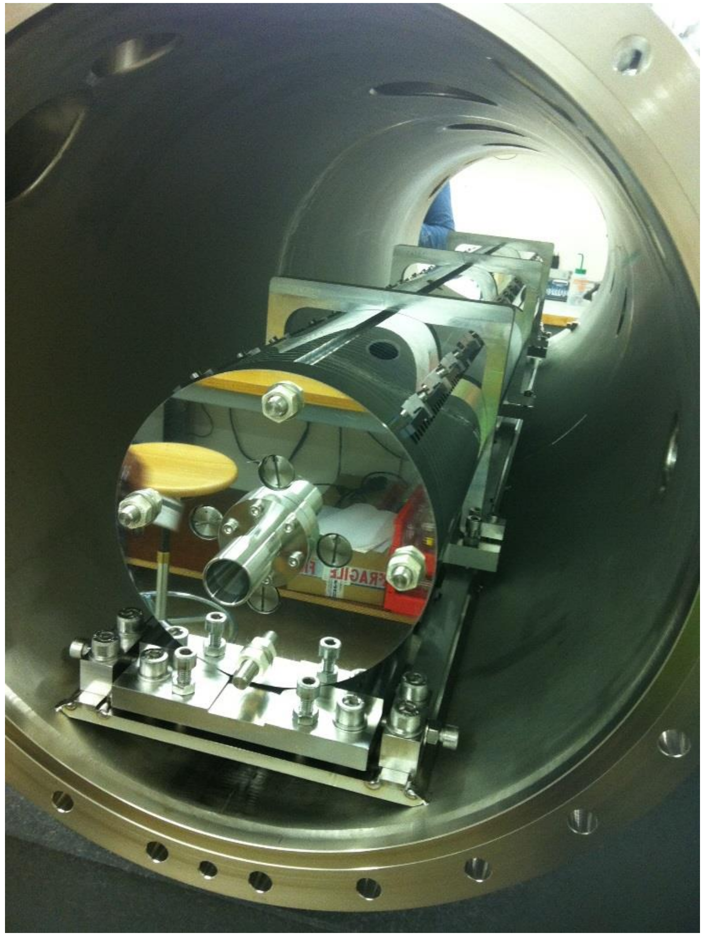


Timing correction









https://doi.org/10.1103/PhysRevAccelBeams.19.011001

Now – The thrilling world of high gradients!

"Mavericks and surfer" by Brocken Inaglory. Licensed under CC BY-SA 3.0 via Commons - https://commons.wikimedia.org/wiki/File:Mavericks_and_surfer.jpg#/media/File:Mavericks_and_surfer.jpg

Motivation

We have seen that CLIC (and tomorrow see other applications) requires a high collision energy. This makes a high accelerating gradient an extremely important parameter to reduce the length and cost of the facility.

But going to high gradient requires:

- High peak rf power
- Facing high field phenomena, especially vacuum breakdown (sparking)

$$G = \sqrt{\omega \frac{1}{v_g} \frac{R'}{Q} P}$$

Vacuum breakdown has been known about for a long time, but with limited quantitative understanding. The CLIC project has invested significant resources in extending the quantitative understanding of vacuum arcing in order to improve the performance of CLIC structures and so reducing the cost of CLIC and extending its energy reach.

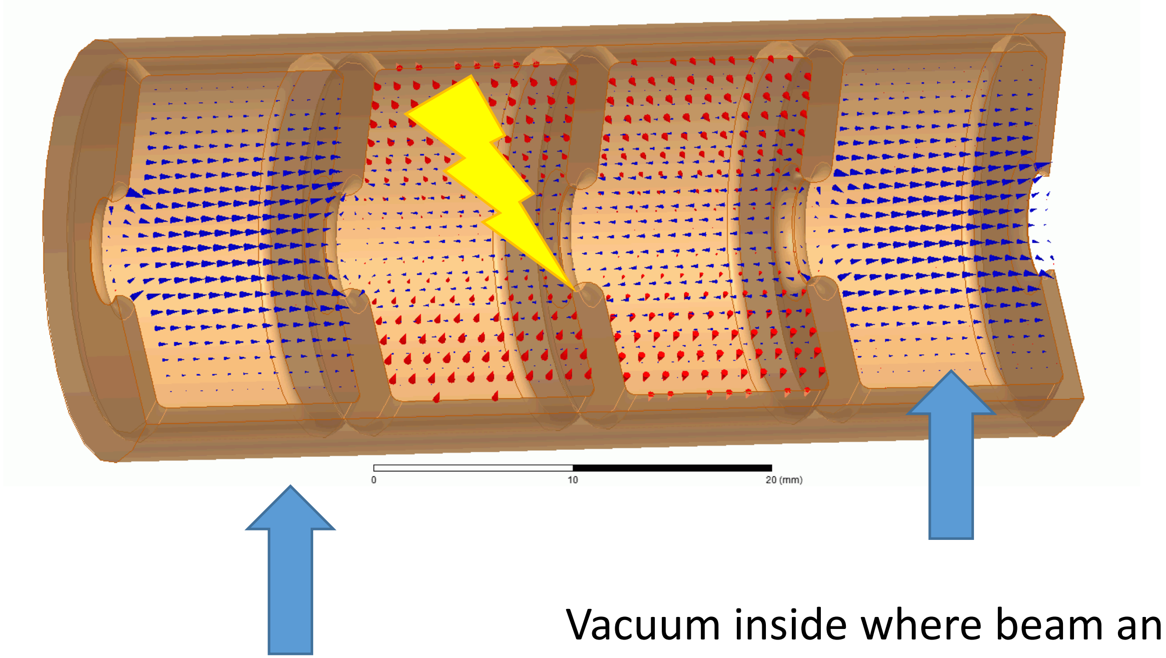
Also vacuum arcing is a fascinating and extremely challenging problem of applied physics!

Connection point - You've already had an extensive introduction to breakdown in Flyura's lectures.

Complexity

- The underlying equations for the acceleration equations we have seen are Maxwell’s equations and the Lorentz force – linear equations!
- When we raise the power we put in a structure, increasing the surface fields, we encounter a whole range of new phenomena.
- These phenomena include field emission and vacuum arcing and pulsed surface heating which, in various combinations, affect the beam and can damage a structure.
- We need to consider:
  - Electromagnetism
  - Material science
  - Plasma physics
  - Quantum mechanics - field and photo emission

Vacuum arc, a.k.a. breakdown



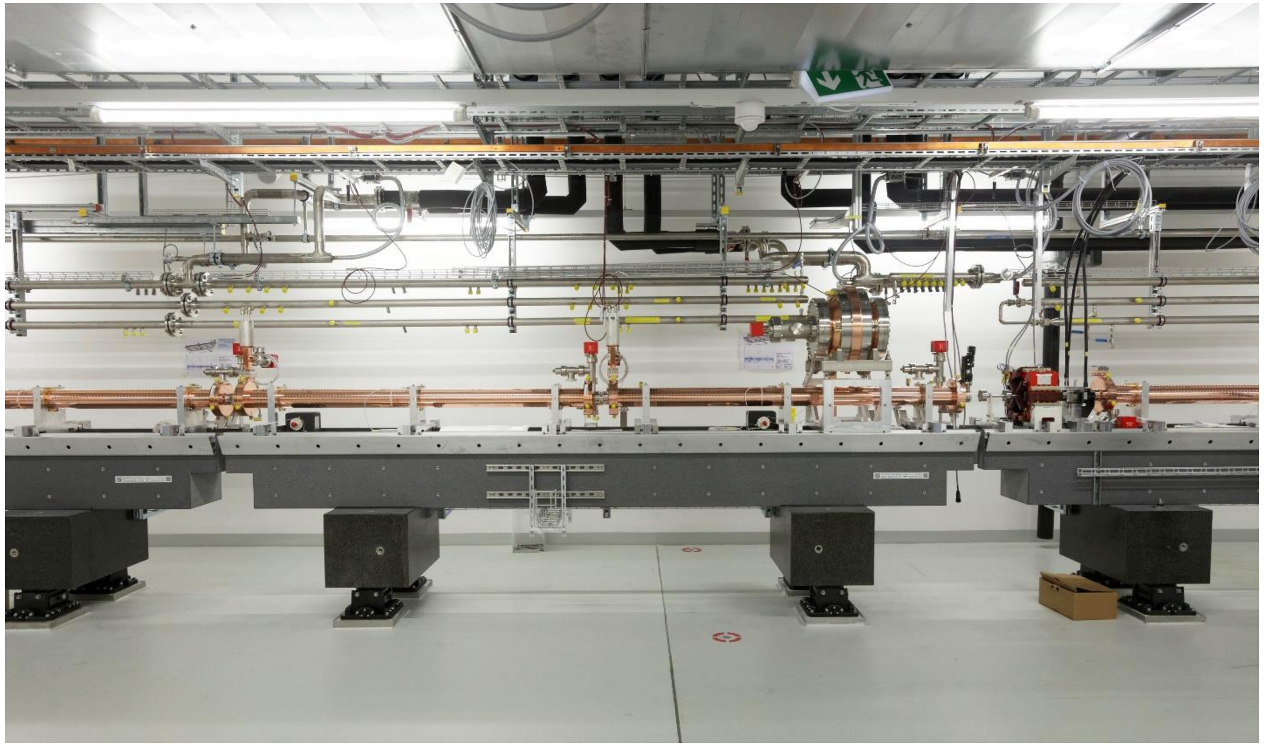
Vacuum inside where beam and fields are

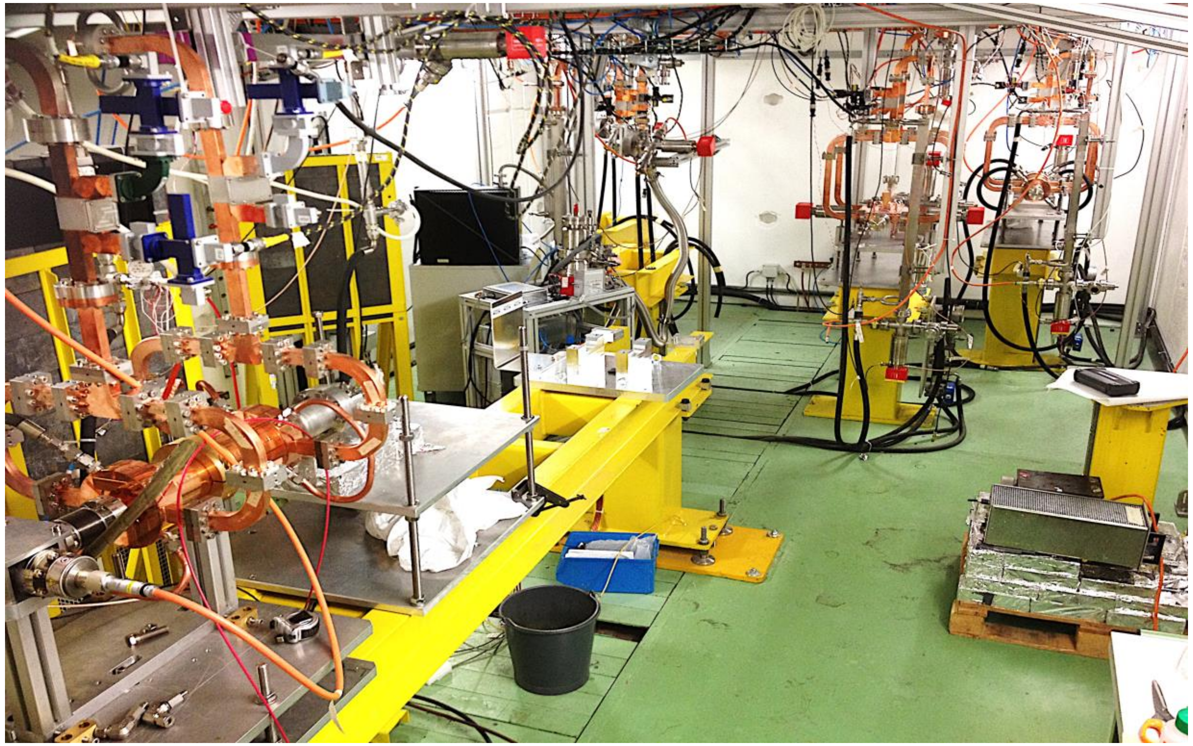
Usually copper walls

Some (round) numbers to keep in mind:

Average accelerating gradient - 100 MV/m
Peak surface electric field – 220 MV/m
Input power - 50 MW
Pulse length - 180 ns
Pulse energy of 12 J.

Operational and state-of-the-art





SwissFEL C-band linac:
Just under 30 MV/m

CLIC prototypes:
Over 100 MV/m