Lecture 13 - Radiofrequency Cavities III

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Synchronising Particles with Cavities

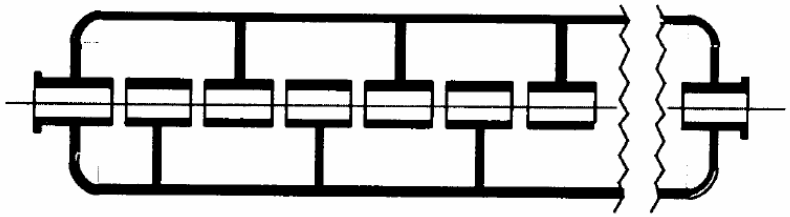
- If accelerator has more than single cavity, particles should be bunched to arrive at the same phase with respect to the voltage at each cavity.
- Space cavities by distance *L* that a particle travels in one RF period

$$L = \beta\lambda\ (Alvaez, 2\pi)\ or\ L = \beta\lambda / 2 (Wideroe, \pi)$$

$$with\ \beta = v / c\ and\ \lambda = 2\pi c / \omega$$

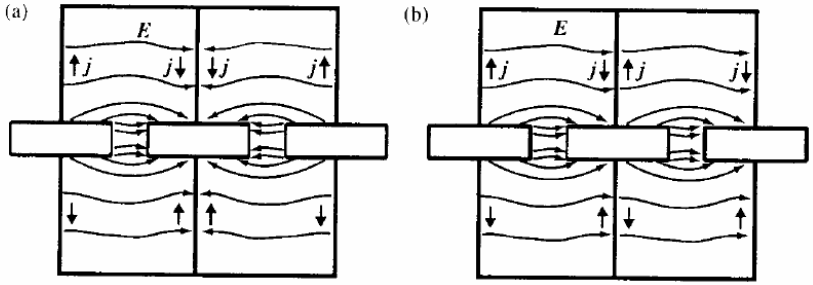
Synchronising Particles with Cavities

- Alvarez Structure
  - Increasing L between accelerating gaps along structure.
  - Snapshot of fields across each gap shows them all exactly in phase.
  - Particle‘s phase advance between cells is 2π
- Wideröe Structure
  - Alternate drift tubes grounded.
  - Snapshot shows vector alternating in sign from gap to gap.
- In these cases, cells oscillate either in phase or in antiphase.
  - Difficult for power to propagate along the waveguide and small errors produce serious distortions.



Alvarez Cavity

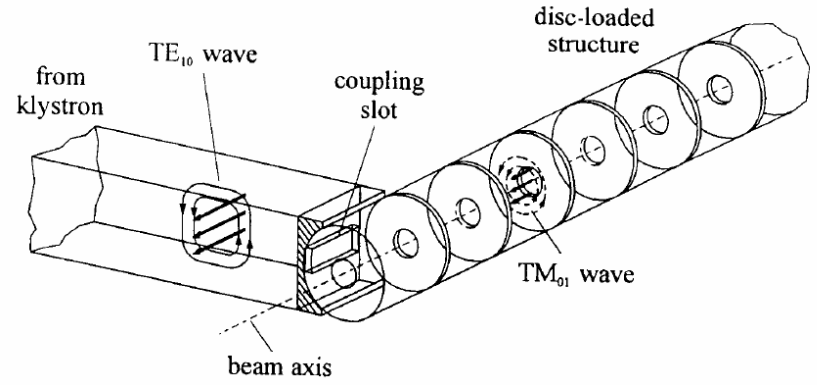
Wideröe Cavity



Adjacent single-gap cavities in (a) π mode and b) 2π mode

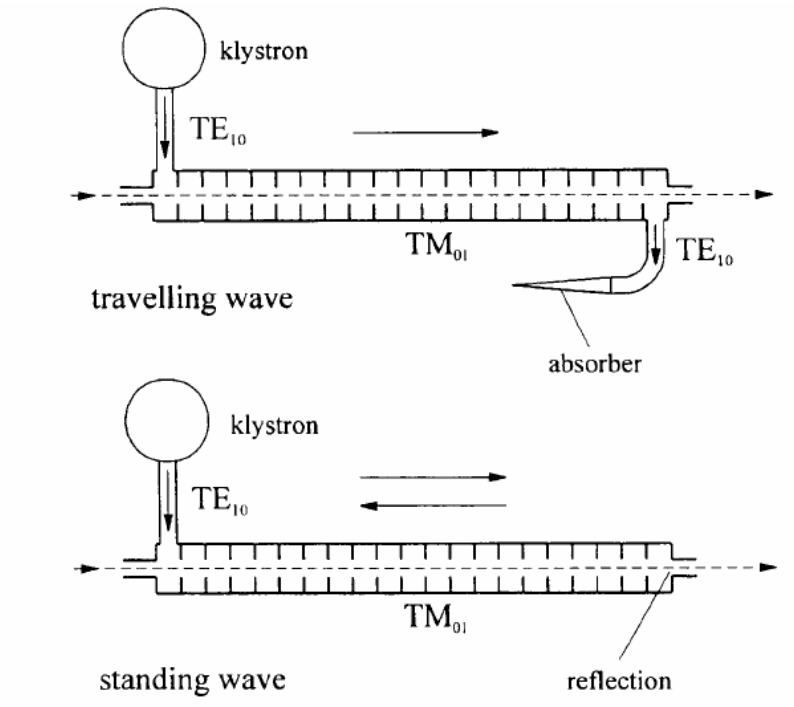
Operation of LINAC Structure

- Standard operation of linac structure is in the S-band.
  - λ=0.100m (f_{RF}=3 GHz)
- As in radar technology, RF power supplied by pulsed power tubes – klystrons.
  - Power fed into linac structure by TE_{10} wave in rectangular waveguide which is connected perpendicular to cylindrical TM_{01} cavity.



Operation of LINAC Structure

The two modes of operation of a linac structure.



Travelling wave mode, in which an absorber is installed at the end of the structure to prevent reflections, is more commonly used.

In a standing wave mode, the energy is reflected virtually without loss.

Operation of LINAC Structure

- Irises form a periodic structure within cavity, reflecting the wave as it passes through and causing interference.
- Loss-free propagation only if wavelength is integer multiple of iris separation *d:*

$$\lambda_z = pd \quad with \quad p = 1,2,3,...$$

resulting in

$$\frac{2\pi}{p} = \frac{2\pi}{\lambda_z} d = k_z d \quad with \quad p = 1,2,3,...$$

- Irises only allow certain wavelengths, characterised by number p, to travel in longitudinal direction.

- These fixed wave configurations are termed modes.

- In principle there are arbitrary such modes but only three used for acceleration.

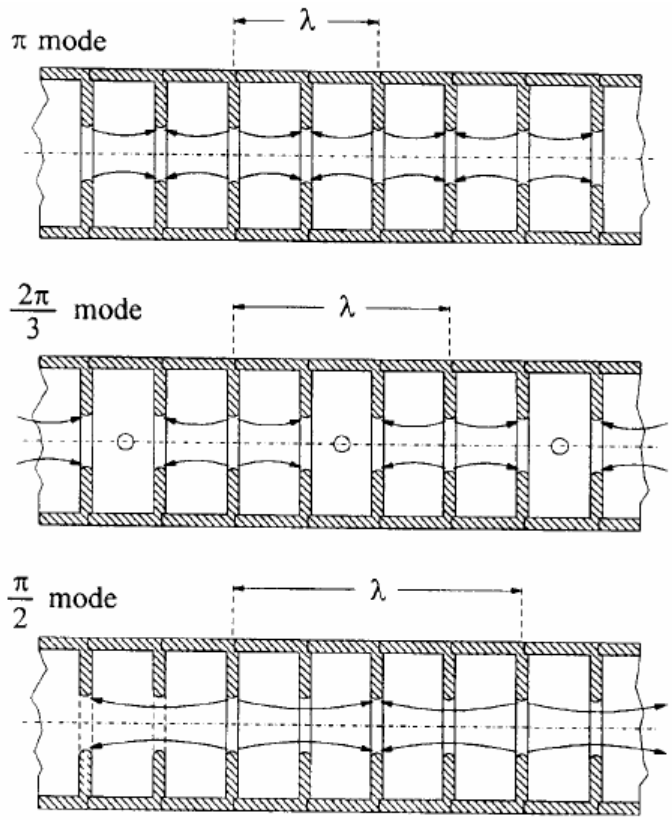
$$k_z d = \{\pi \quad (\pi \text{ mode} \quad \text{i.e. } \lambda_z = 2d) \qquad if \;\; p = 2$$

$$k_z d = \left\{\frac{2\pi}{3} \quad (2\pi/3 \text{ mode} \quad \text{i.e. } \lambda_z = 3d) \right. \quad if \;\; p = 3$$

$$k_z d = \left\{\frac{\pi}{2} \quad (\pi/2 \text{ mode} \quad \text{i.e. } \lambda_z = 4d) \right. \qquad if \;\; p = 4$$

Operation of LINAC Structure

- π-mode
  - Takes long time for transient oscillations to die away and a stationary state to be used.
  - Not suitable for fast-pulsed operation.
- π/2-mode
  - Low shunt impedance so for fixed RF power energy gain per structure is small.
- 2π/3-mode
  - Best compromise between π-mode & π/2-mode



Field configurations of three most important modes in linac structures.

Power Generators for Accelerators

- The sinusoidal power needed to drive the accelerating structures ranges between a few kW to a few MW.
- RF power amplifiers
  - Triodes & tetrodes: few MHz to few hundred MHz
  - Klystrons: above a few hundred MHz
    - Proven to be the most effective power generator for accelerator applications

Triode Amplifier

- Three active electrodes
  - Cathode (filament)
  - Grid
  - Anode (plate)
- Anode current obeys Langmuir-Child Law

$$I_a = k(V_a + \mu V_g)^{3/2}$$

  - k = perveance of tube
  - μ = amplification factor
  - V_a = anode voltage
  - V_g = grid voltage

Tetrode Amplifier

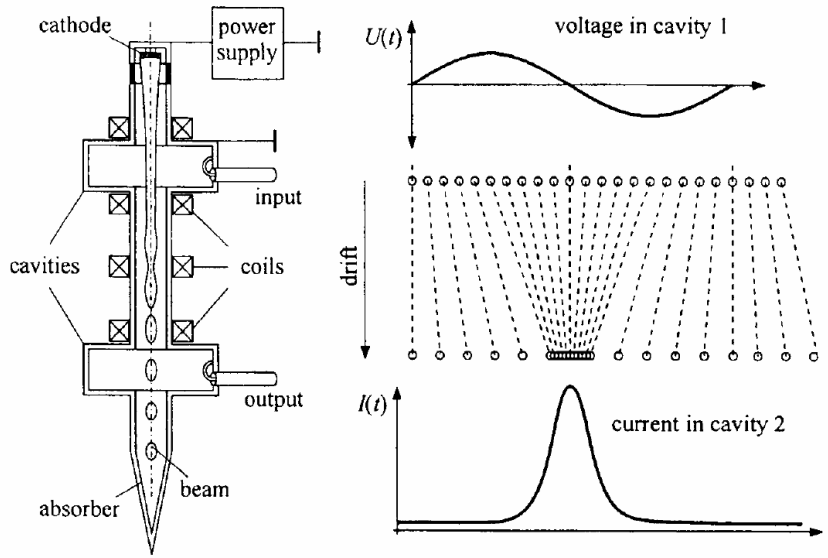
- Four active electrodes
  - Cathode (filament)
  - Control Grid
  - Screen Grid – reduce space charge between cathode and Control Grid
  - Anode (plate)
- Anode current obeys Langmuir-Child Law

$$I_a = k\left(V_{cg} + \mu_s V_{sg} + \mu_a V_a\right)^{3/2}$$

  - k = perveance of tube
  - μ_a = anode amplification factor
  - μ_s = screen grid amplification factor
  - V_a = anode voltage
  - V_{cg} = control grid voltage
  - V_{sg}= screen grid voltage

Klystrons

- Principle of operation
  - Electrons emitted from round cathode with large surface area.
  - Accelerated by voltage of a few tens of kV.
  - Yields a round beam with a current of between a few amperes and tens of amperes.
  - Electrodes close to the cathode focus the beam and solenoid along the tube ensure good beam collimation.
  - Outgoing particles from cathode have a well-defined velocity and pass through cavities operated in TM_{011} mode.
  - Wave excited in this resonator by external pre-amplifier.



Klystrons are similar to a small linear accelerator.

Klystrons

- Depending on phase, will modulate velocity with resonant frequency of particles (accelerate, decelerate, or have no influence).
- In subsequent zero-field drift, faster particles move ahead, while slower ones lag behind.
- Changes hitherto uniform particle density distribution and bunches of particles are formed with separation given by λ of driving wave.

Klystrons

- Continuous current from cathode becomes pulsed current with frequency of coupled pulsed current.
- A second cavity mounted at this location is resonantly excited by pulsed current and the RF wave generated in this second cavity is then coupled out.
- A better coupling of beam to output cavity achieved by inserting additional cavity resonators, each tuned to frequencies close to operating frequency.

Klystrons

- Klystron output power

$$P_{klystron} = \eta U_0 I_{beam}$$

  - U_0 = klystron supply voltage (e.g. 45 kV)
  - I_{beam} = beam current (e.g. 12.5 A)
  - η = klystron efficiency (45% - 65%)

Large Hadron Collider (LHC)

Superconducting Cavities (SC)

- The use of superconducting material (Nb) at low temperature (2-4 K) reduces considerably the ohmic losses and almost all the RF power from the source is made available to the beam (i.e. ~100% efficiency).
- In contrast to normal conducting cavities, SC cavities favour the use of lower frequencies.
  - Offers a larger opening to the beam.
  - Reduces the interaction of the beam with the cavity that is responsible for beam instability.

Superconducting Cavities

- Characteristics
  - Q_0 as high as 10^9 – 10^{10} are achievable.
    - Leads to much longer filling times.
  - Higher electric field gradients are reached for acceleration – 25-30 MV/m.
    - Reduces number of cavities or a higher energy can be reached with a given number of cavities.
    - Single-cell or multi-cell.
    - Used for both lepton and hadron machines.

Parameter Specification

- Two independent RF systems.
  - One per each beam cooled with 4.5 K saturated He gas
- Each RF system has eight single-cell cavities
  - Each cavitiy has 2 MV accelerating voltage, corresponding to a field strength of 5.5 MV/m
  - R/Q = 45 Ω
- RF Power System
  - Each cavity is driven by individual RF system with a single klystron, circulator and load.
  - Maximum of 4800 kW of RF power will be generated by the 16 (300 kW) 400 MHz klystrons.
  - Each klystron will feed via a Y-junction circulator and a WR2300 waveguide line, a single-cell SC cavity.
  - High Voltage Interface
    - Each of the 4 main 100 kV power converters, re-used from LEP, will power 4 klystrons.

Large Hadron Collider

The Main Beam and RF Parameters

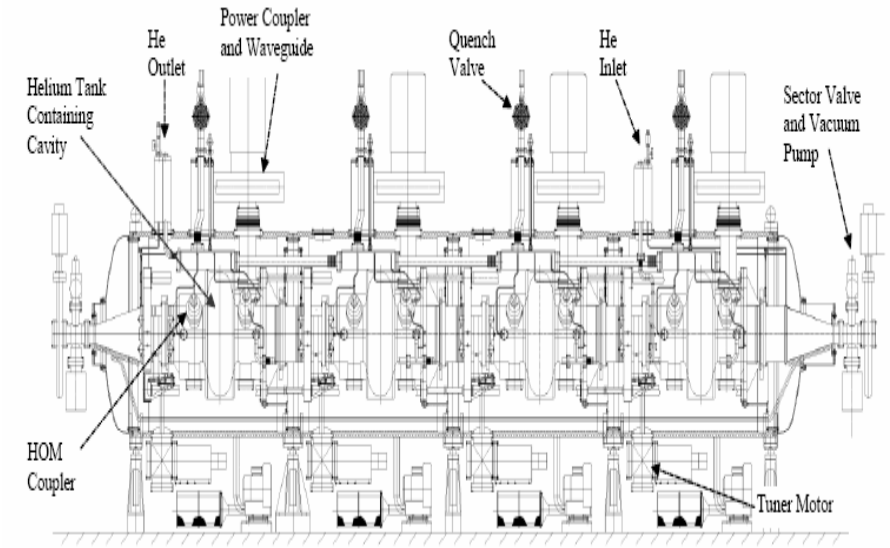
	Unit	Injection 450 GeV	Collision 7 TeV
Bunch area (2σ)*	eVs	1.0	2.5
Bunch length (4σ)*	ns	1.71	1.06
Energy spread (2σ)*	10^{-3}	0.88	0.22
Intensity per bunch	10^{11} p	1.15	1.15
Number of bunches		2808	2808
Transverse emittance V/H	μm	3.75	3.75
Intensity per beam	A	0.582	0.582
Synchrotron radiation loss/turn	keV	-	7
Longitudinal damping time	h	-	13
Intrabeam scattering growth time - H	h	38	80
- L	h	30	61
Frequency	MHz	400.789	400.790
Harmonic number		35640	35640
RF voltage/beam	MV	8	16
Energy gain/turn (20 min. ramp)	keV	485	
RF power supplied during acceleration/ beam	kW	~275	
Synchrotron frequency	Hz	63.7	23.0
Bucket area	eVs	1.43	7.91
RF (400 MHz) component of beam current	A	0.87	1.05

Cavity Material

- As frequency of 400 MHz is close to that of LEP (352 MHz), the same proven LEP technology of Nb sputtered cavities is applied to the LHC.
- Nb Sputtering on Cu
  - Advantage over solid Nb in that susceptibility to quenching is very much reduced.
    - Local heat generated by small surface defects or impurities is quickly conducted away by the Cu.
    - Nb-sputtered cavities are insensitive to the Earth´s B-field

Large Hadron Collider

Design of a four-cavity cryomodule



A four-cavity module during assembly

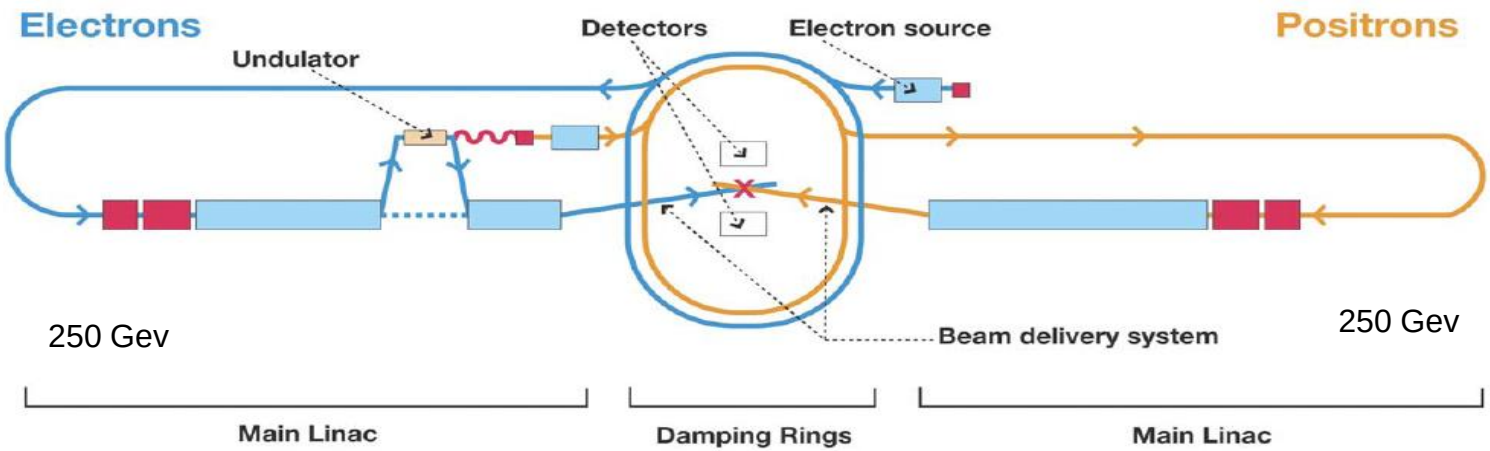
- Four cavities, each equipped with their He tank and power coupler, are grouped together in a single cryomodule.

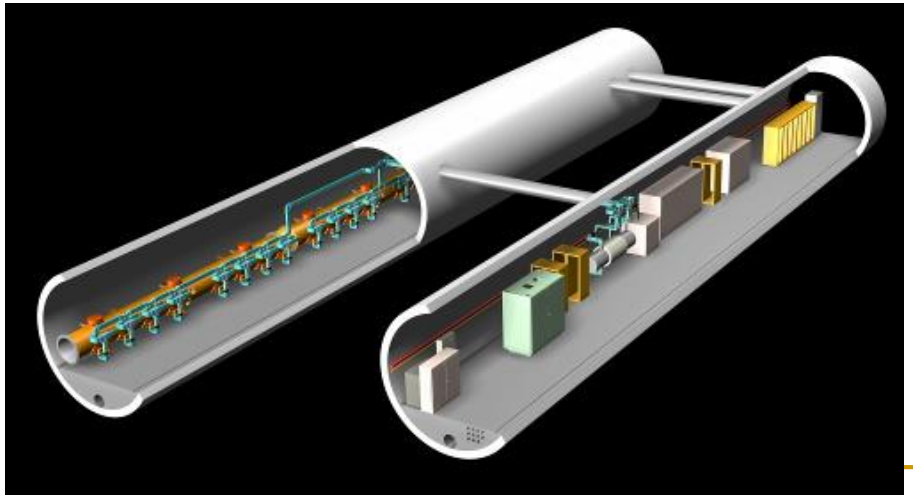
- Reduces overall static thermal losses and requires less total space for installation than a single cavity configuration.

Linear Colliders

International Linear Collider Baseline Design

2





e+ e- Linear Collider

Energy	**250 GeV x 250 GeV**
# of RF units	**560**
# of cryomodules	**1680**
# of 9-cell cavities	**14560**
2 Detectors push-pull	
peak luminosity	**2 10^{34} $cm^{-2}s^{-1}$**
5 Hz rep rate, 1000 -> 6000 bunches	
IP : σ_x 350 – 620 nm; σ_y 3.5 – 9.0 nm	
Total power	**~230 MW**
Accelerating Gradient	**31.5 MeV/m**

Cavities

- Basic element of the superconducting RF is a nine-cell 1.3 GHz niobium cavity
  - Each cavity is about 1 m. long
  - Operated at 2K
  - Nine cavities are mounted together in a string and assembled in a common low-temperature cryostat (cryomodule)
  - About 17 000 cavities are needed for the ILC
- Key to high-gradient performance is ultra-clean and defect-free inner surface of cavity consisting of Nb material and electron beam welds
  - Use of electropolishing in clean-room environment

Cavity Design Parameters

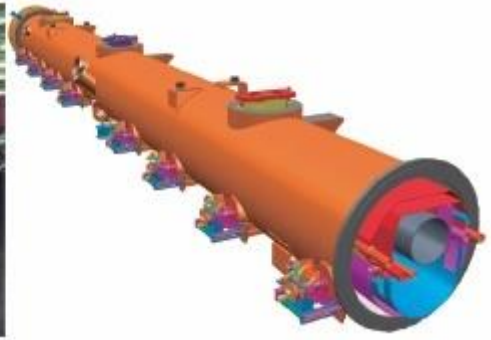
ILC 9-cell superconducting cavity design parameters

Parameter	Value
Type of accelerating structure	Standing Wave
Accelerating Mode	TM_{010}, π mode
Fundamental Frequency	1.300 GHz
Average installed gradient	31.5 MV/m
Qualification gradient	35.0 MV/m
Installed quality factor	$\geq 1\times10^{10}$
Quality factor during qualification	$\geq 0.8\times10^{10}$
Active length	1.038 m
Number of cells	9
Cell to cell coupling	1.87%
Iris diameter	70 mm
R/Q	1036 Ω
Geometry factor	270 Ω
E_{peak}/E_{acc}	2.0
B_{peak}/E_{acc}	4.26 mT $MV^{-1}m^{-1}$
Tuning range	±300 kHz
$\Delta f/\Delta L$	315 kHz/mm
Number of HOM couplers	2

Superconducting RF Structures

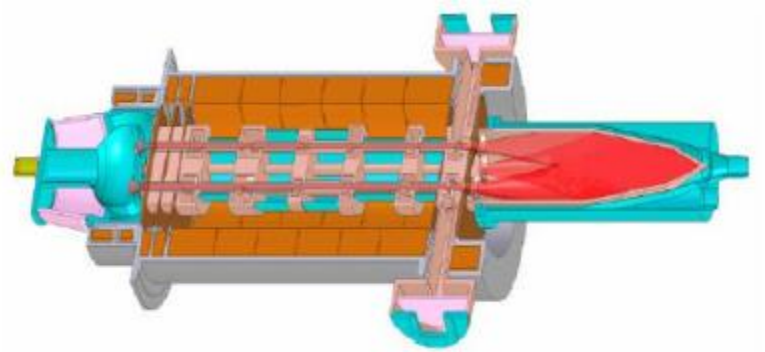
A TESLA nine-cell 1.3 GHz superconducting niobium cavity.

ILC prototype cryomodules.



Clean room environments are mandatory for the cavity preparation and assembly.

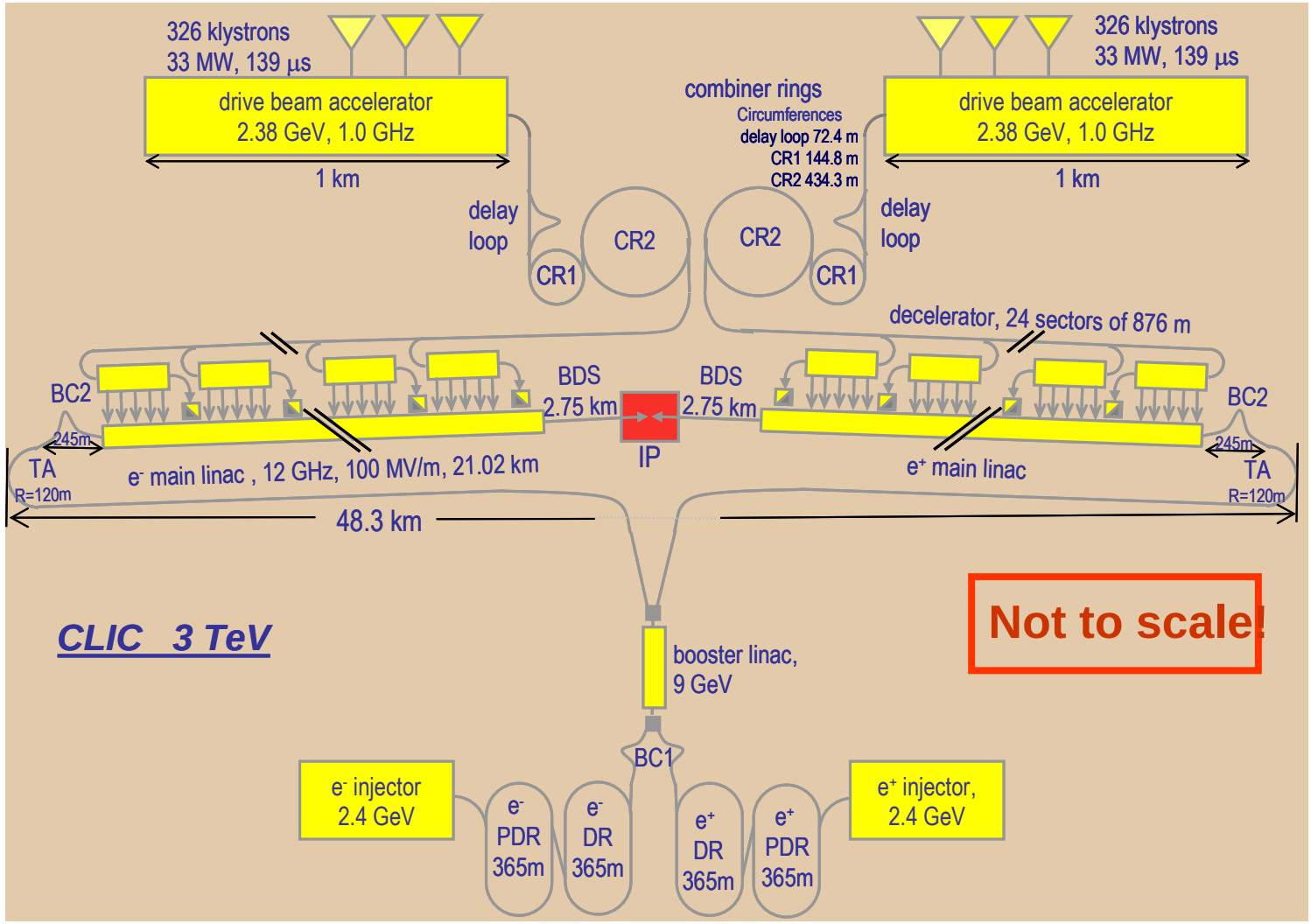
Multi-Beam Klystrons



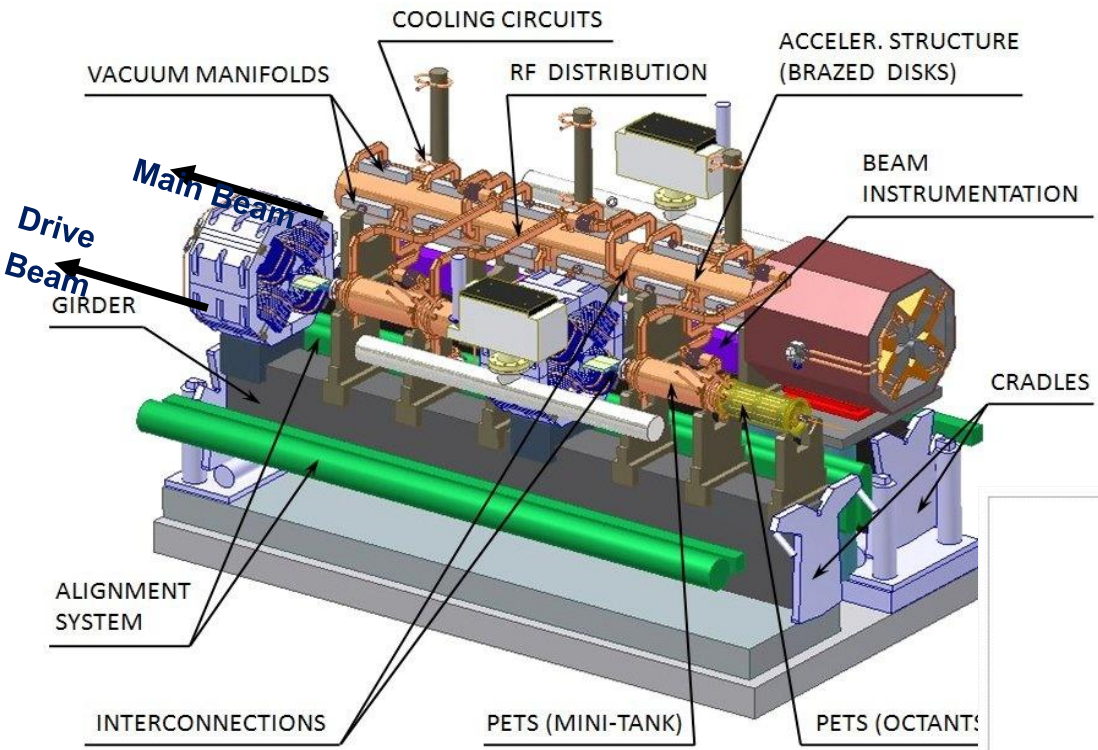
Toshiba E3736

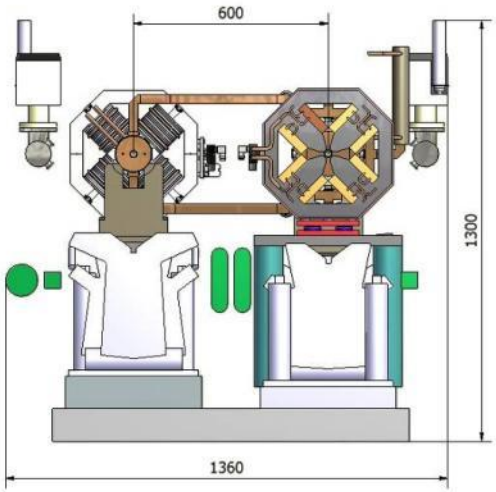
10 MW L-band source

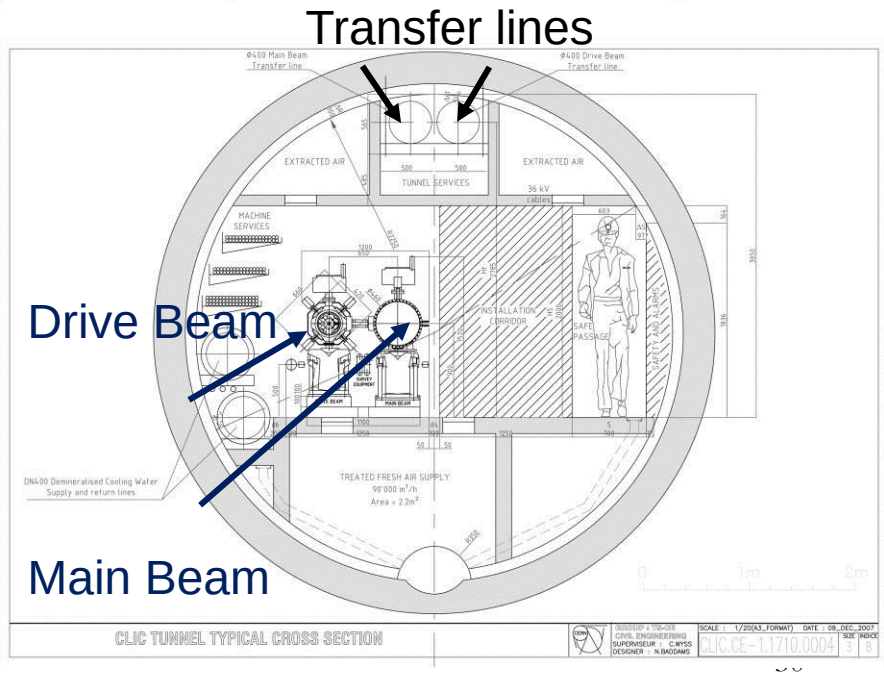
The Full CLIC scheme



CLIC Accelerating Module







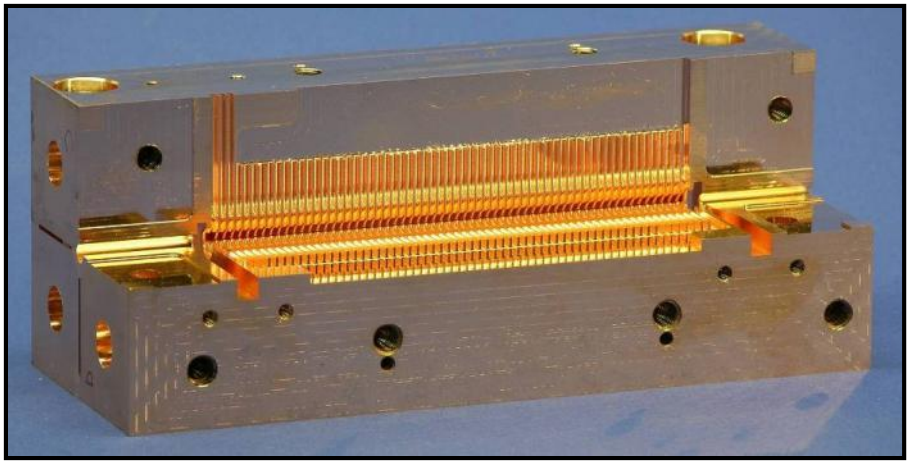
Accelerating Structures

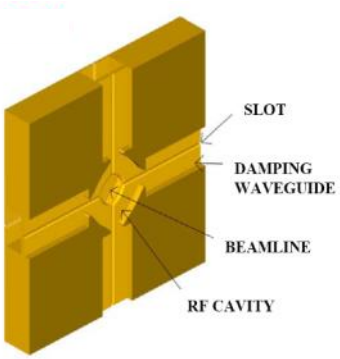
Objective:

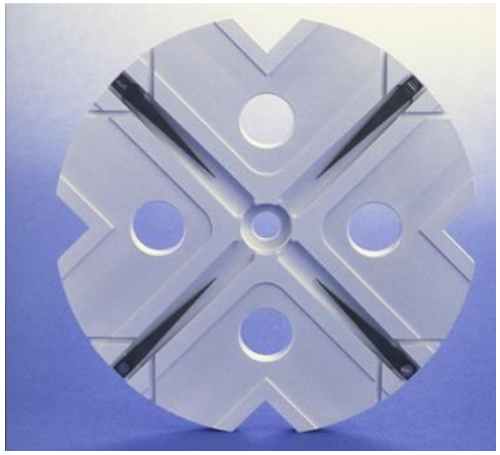
- Withstand of 100 MV/m without damage
- breakdown rate < 10^{-7}
- Strong damping of HOMs

Technologies:

Brazed disks - milled quadrants

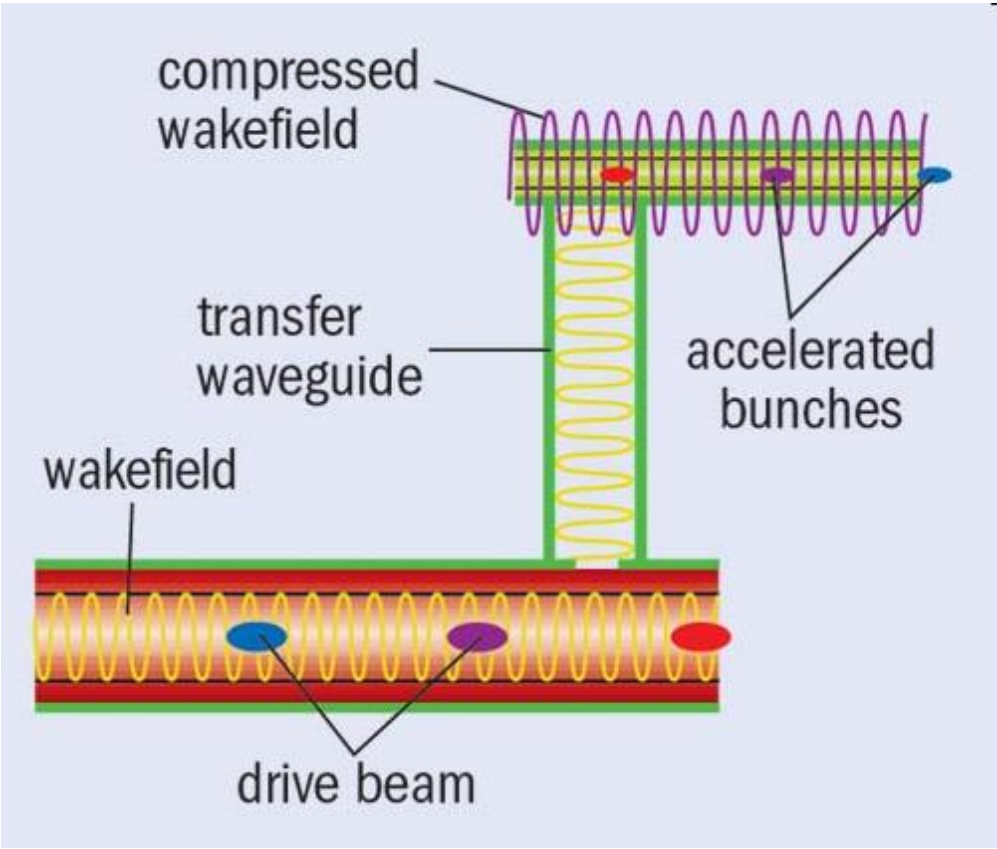


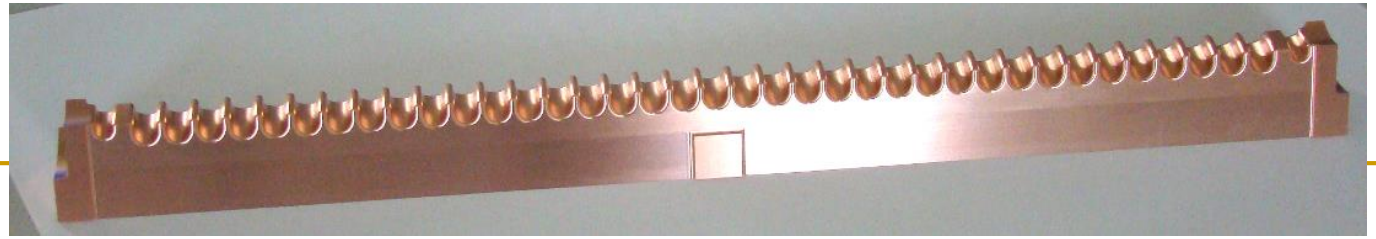




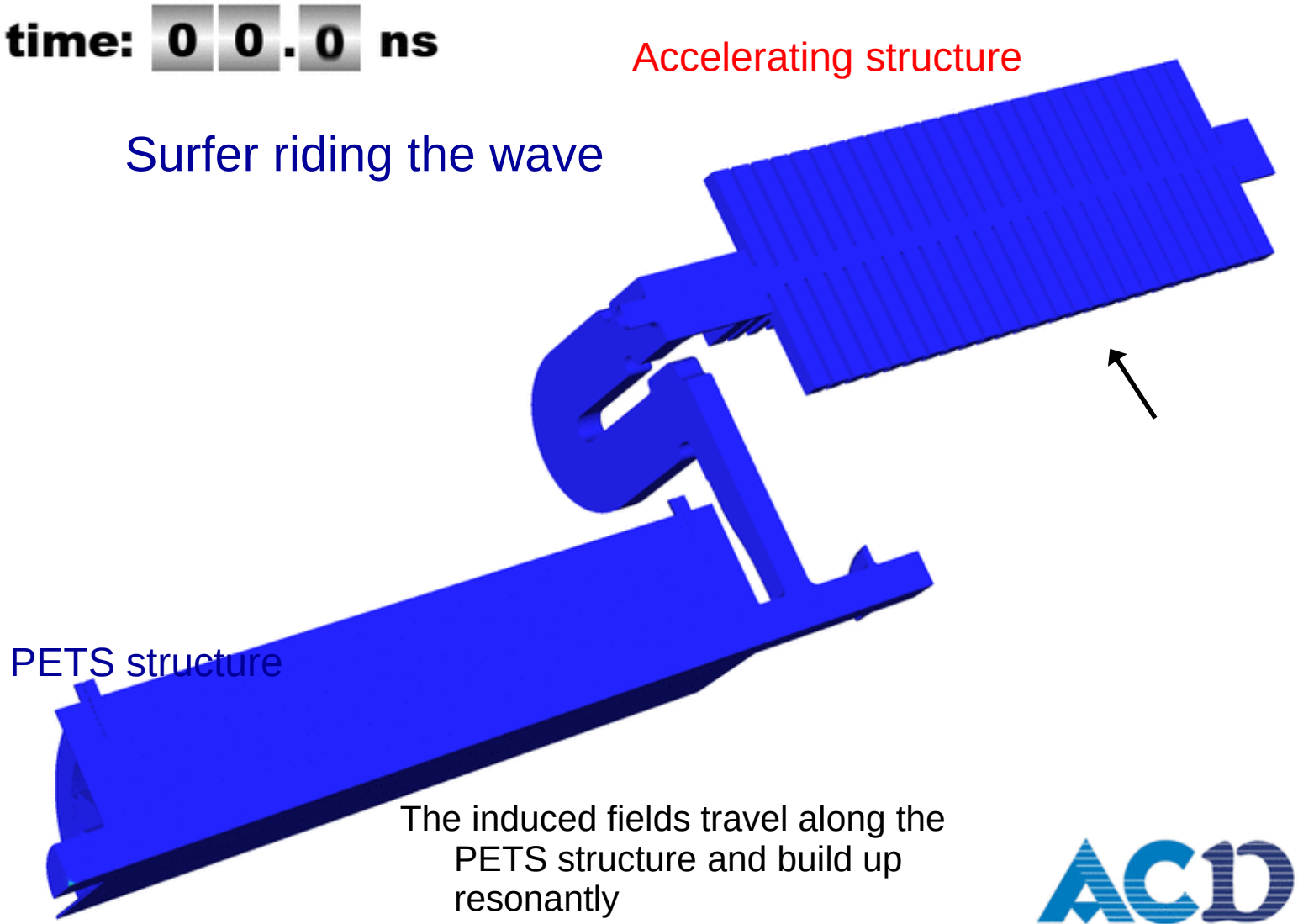
CLIC Two-beam Acceleration Concept

- 12 GHz modulated and high power drive beam
- RF power extraction in a special structure (PETS)
- Use RF power to accelerate main beam



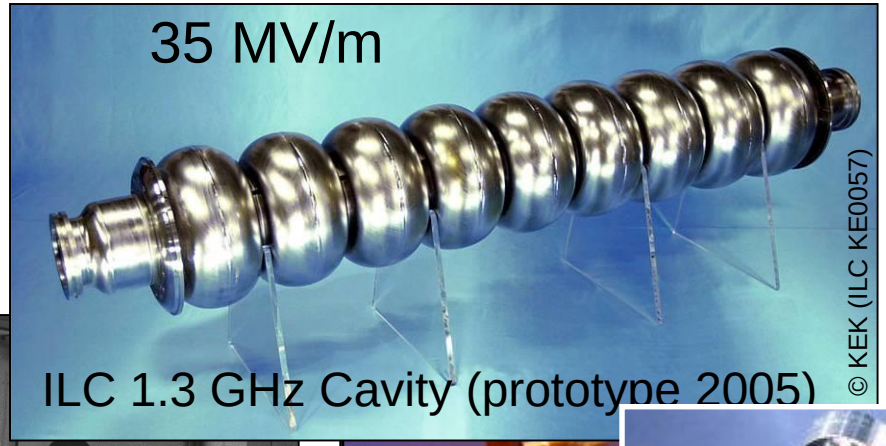


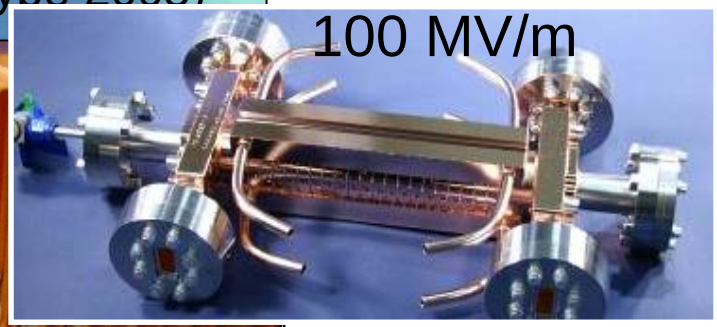
Simulation of RF Power Transfer



ACD ADVANCED COMPUTATIONS

Accelerating Cavities





CLIC 12 GHz Cavity
(prototype 2009)

Acknowledgments and References

- John David Jackson, *Classical Electrodynamics*, John David Jackson, 1998
- Klaus Wille, *The Physics of Particle Accelerators*, Oxford University Press, 2005
- Edmund Wilson, *An Introduction to Particle Accelerators*, Oxford University Press, 2006