
Lecture 19

Radiofrequency Cavities III

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Synchronising Particles with Cavities

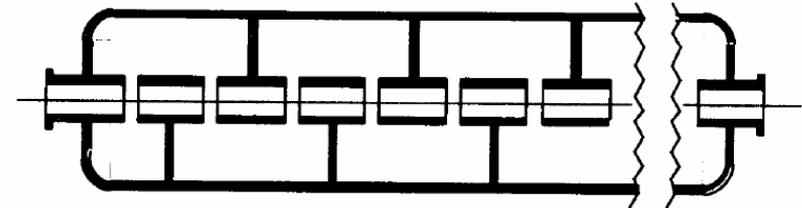
- If accelerator has more than single cavity, particles should be bunched to arrive at the same phase with respect to the voltage at each cavity.
- Space cavities by distance L that a particle travels in one RF period

$$L = \beta\lambda \text{ (Alvarez, } 2\pi) \text{ or } L = \beta\lambda / 2 \text{ (Wideroe, } \pi)$$

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

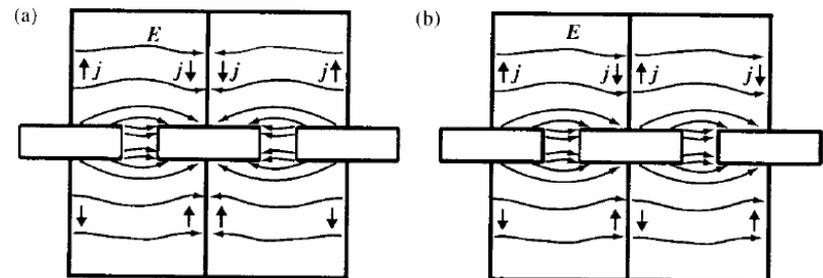
Synchronising Particles with Cavities

- 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

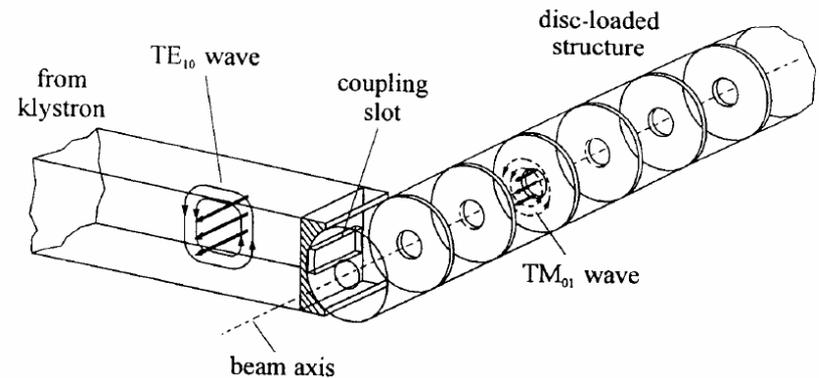
Wideröe Cavity



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

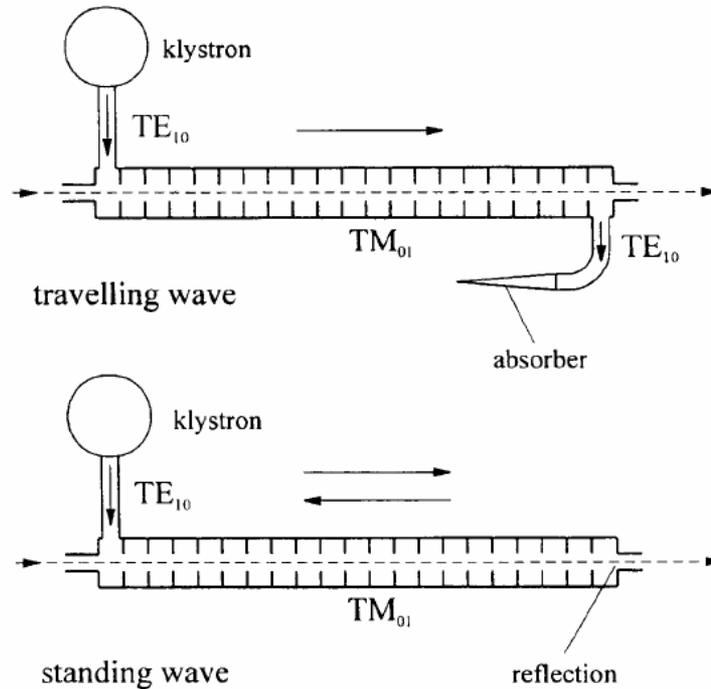
Operation of LINAC Structure

- Standard operation of linac structure is in the S-band.
 - $\lambda=0.100\text{m}$ ($f_{RF}=3\text{ GHz}$)
- 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 :

$$\lambda_z = pd \quad \text{with} \quad p = 1, 2, 3, \dots$$

resulting in

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

- 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.

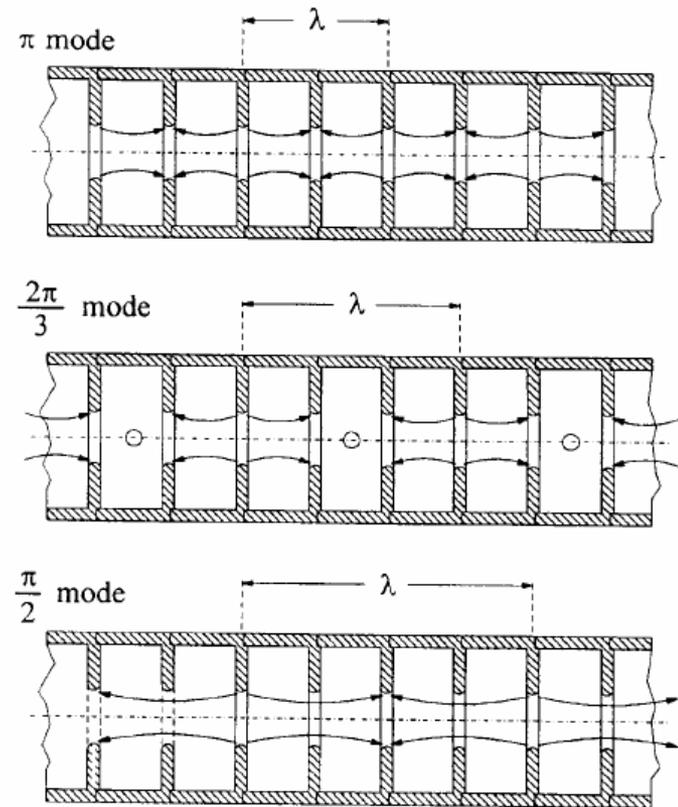
$$k_z d = \begin{cases} \pi & (\pi \text{ mode} \quad \text{i.e. } \lambda_z = 2d) & \text{if } p = 2 \end{cases}$$

$$k_z d = \begin{cases} \frac{2\pi}{3} & (2\pi/3 \text{ mode} \quad \text{i.e. } \lambda_z = 3d) & \text{if } p = 3 \end{cases}$$

$$k_z d = \begin{cases} \frac{\pi}{2} & (\pi/2 \text{ mode} \quad \text{i.e. } \lambda_z = 4d) & \text{if } p = 4 \end{cases}$$

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.
- $\pi/2$ -mode
 - Low shunt impedance so for fixed RF power energy gain per structure is small.
- $2\pi/3$ -mode
 - Best compromise between π -mode & $\pi/2$ -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
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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

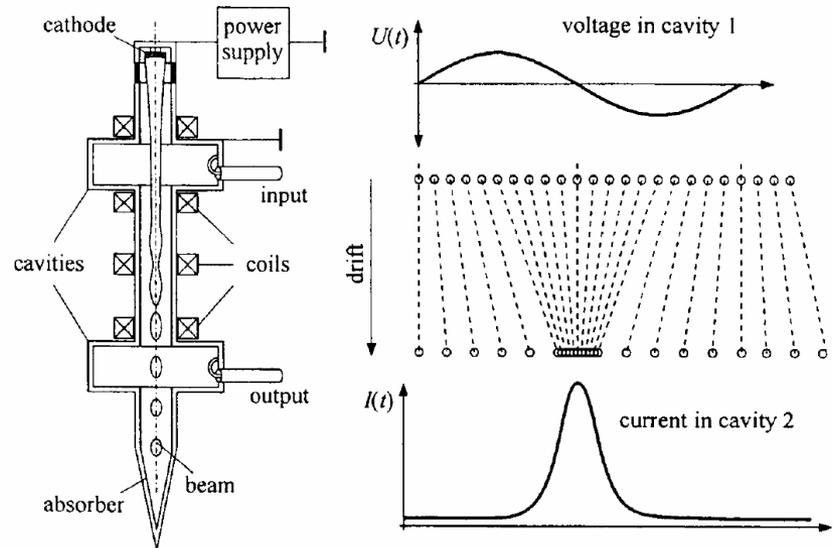
$$I_a = k \left(V_{cg} + \mu_s V_{sg} + \mu_a V_a \right)^{3/2}$$

- ❑ 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.
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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.
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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 cavity has 2 MV accelerating voltage, corresponding to a field strength of 5.5 MV/m
 - ❑ $R/Q = 45 \Omega$
- ❑ 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

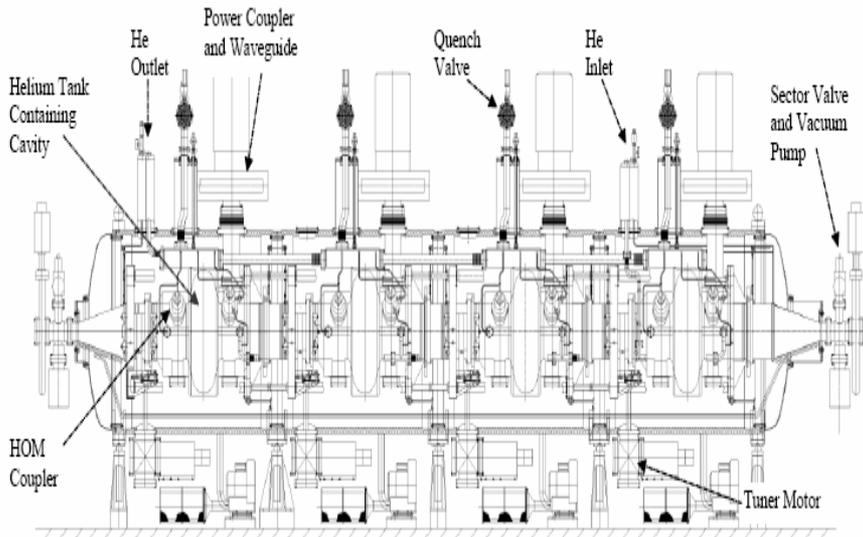
	Unit	Injection 450 GeV	Collision 7 TeV
Bunch area (2σ)*	eVs	1.0	2.5
Bunch length (4σ)*	ns	1.71	1.06
Energy spread (2σ)*	10^{-3}	0.88	0.22
Intensity per bunch	10^{11} p	1.15	1.15
Number of bunches		2808	2808
Transverse emittance V/H	μm	3.75	3.75
Intensity per beam	A	0.582	0.582
Synchrotron radiation loss/turn	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

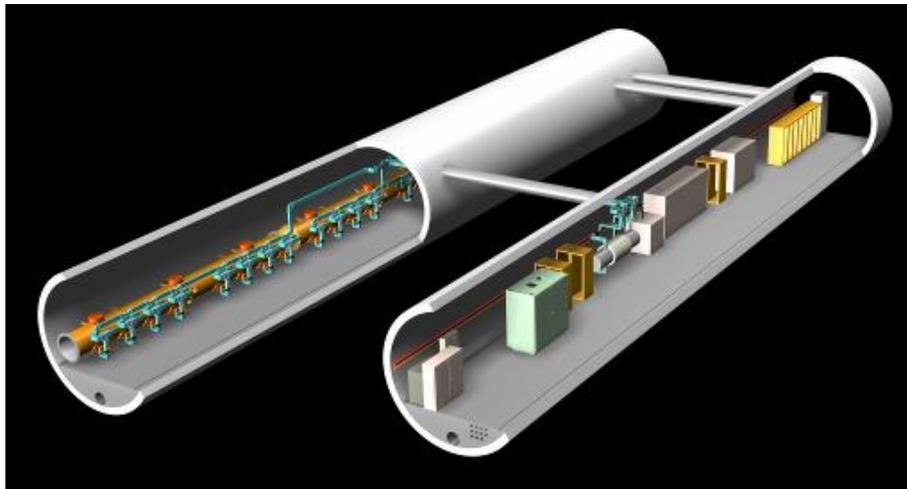
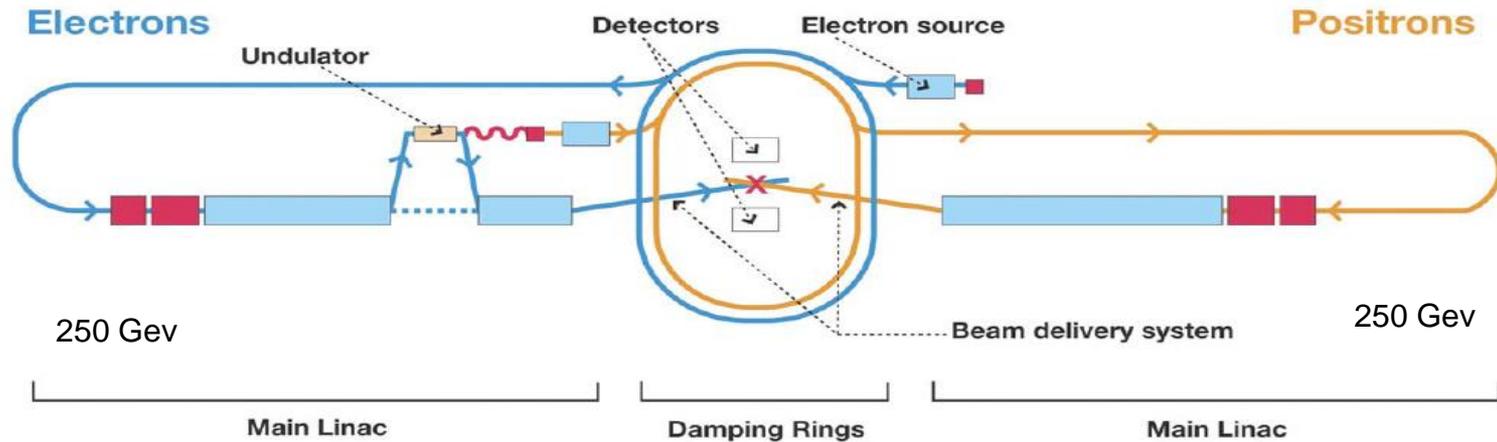


- Four cavities, each equipped with their He tank and power coupler, are grouped together in a single cryomodule.
- Reduces overall static thermal losses and requires less total space for installation than a single cavity configuration.

Linear Colliders

International Linear Collider Baseline Design

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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	$2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
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
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Cavity Design Parameters

ILC 9-cell superconducting cavity design parameters

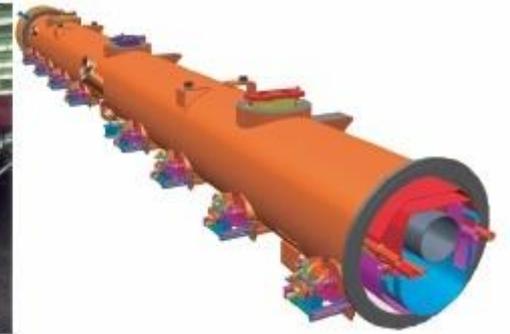
Parameter	Value
Type of accelerating structure	Standing Wave
Accelerating Mode	TM ₀₁₀ , π mode
Fundamental Frequency	1.300 GHz
Average installed gradient	31.5 MV/m
Qualification gradient	35.0 MV/m
Installed quality factor	$\geq 1 \times 10^{10}$
Quality factor during qualification	$\geq 0.8 \times 10^{10}$
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
$E_{\text{peak}}/E_{\text{acc}}$	2.0
$B_{\text{peak}}/E_{\text{acc}}$	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.



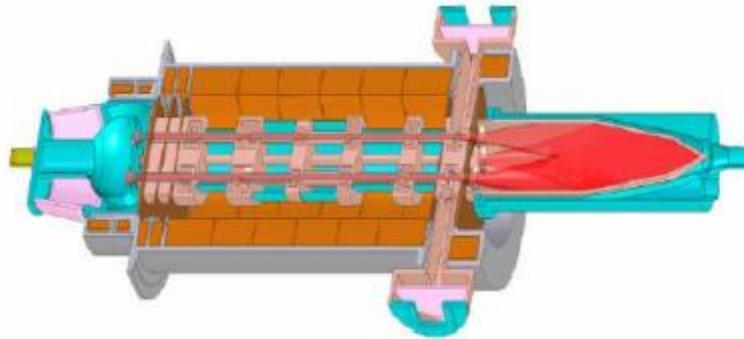
ILC prototype cryomodules.



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



Multi-Beam Klystrons

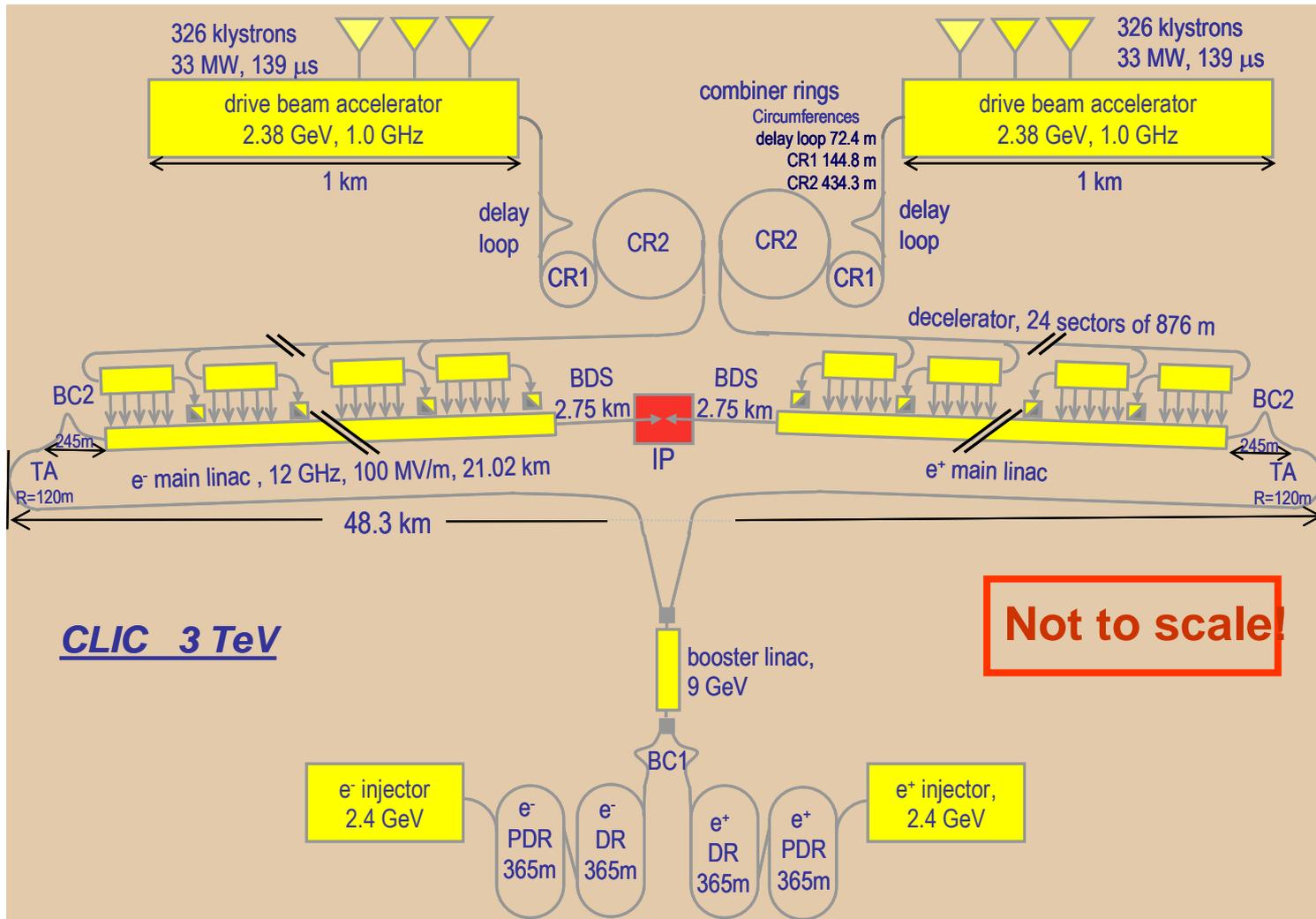


Toshiba E3736

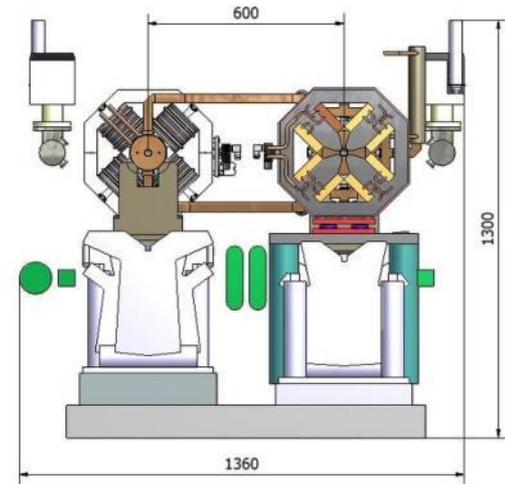
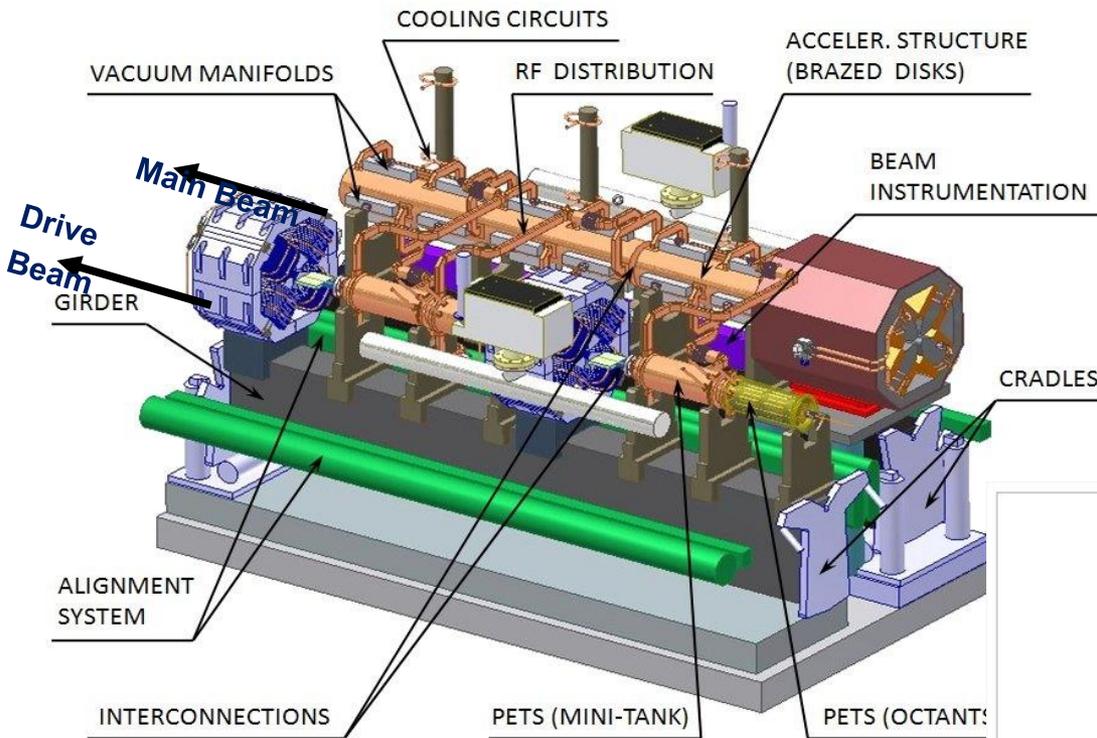


10 MW L-band source

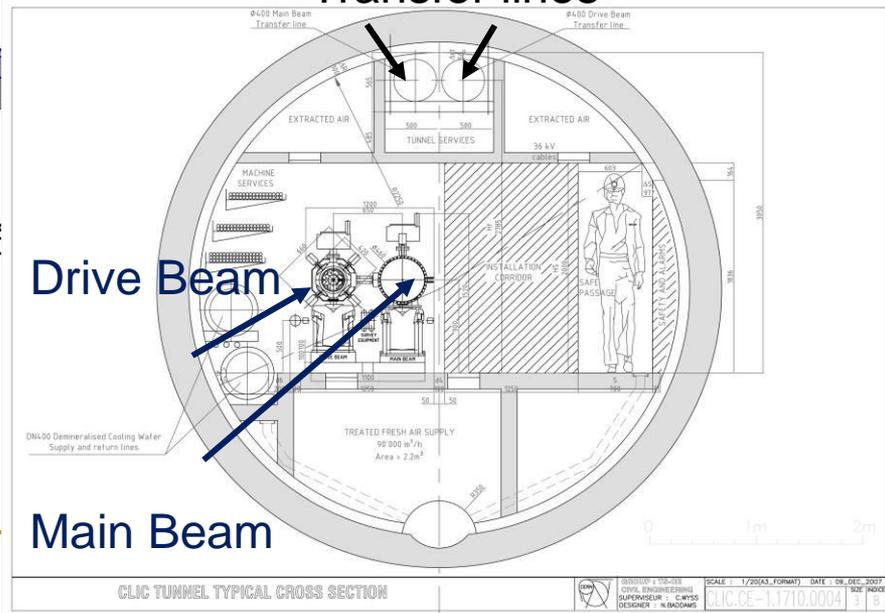
The Full CLIC scheme



CLIC Accelerating Module



Transfer lines



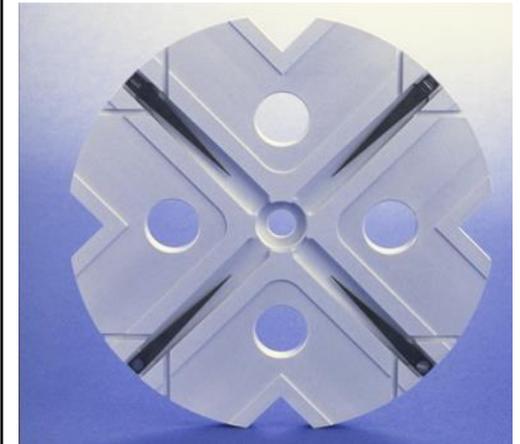
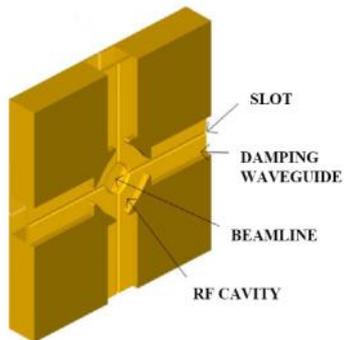
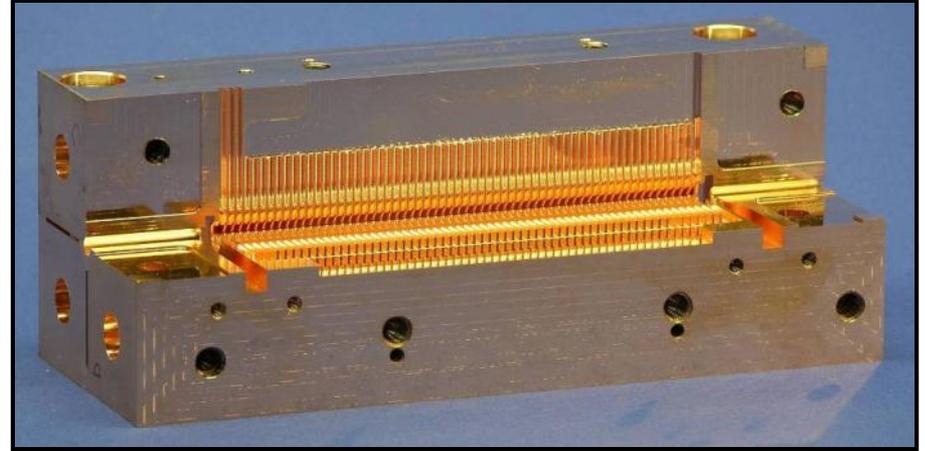
Accelerating Structures

Objective:

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

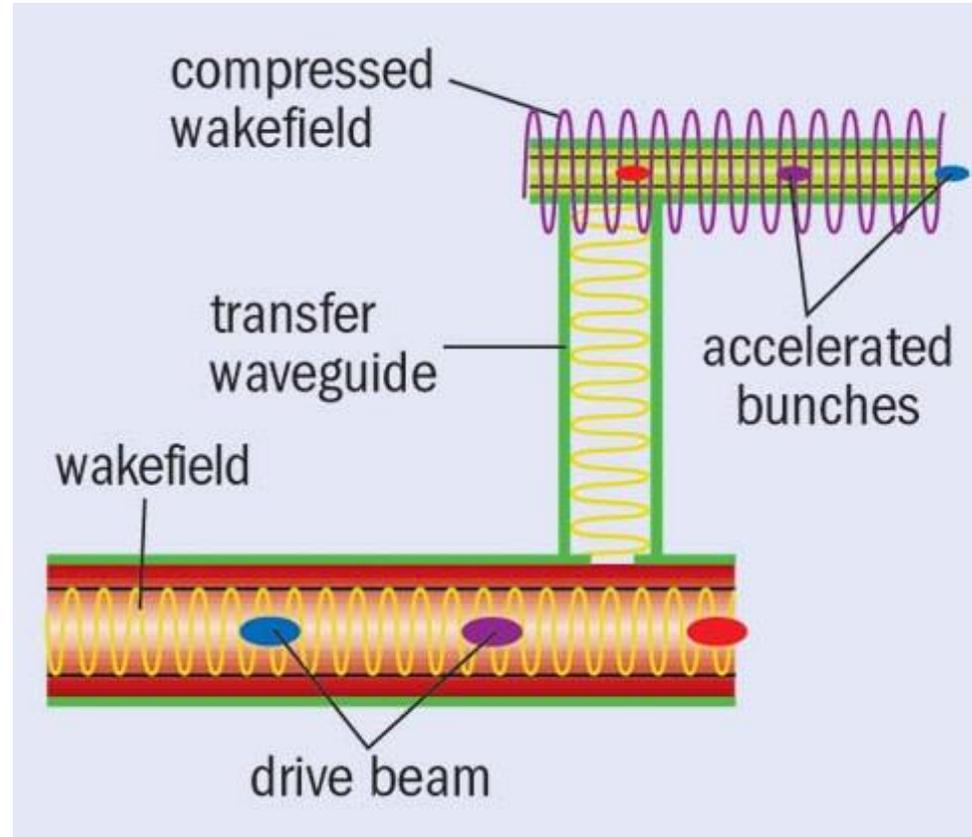
Technologies:

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

time: 0 0 . 0 ns

Accelerating structure

Surfer riding the wave

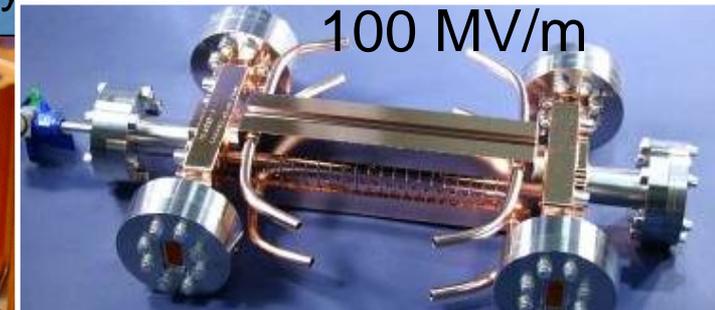
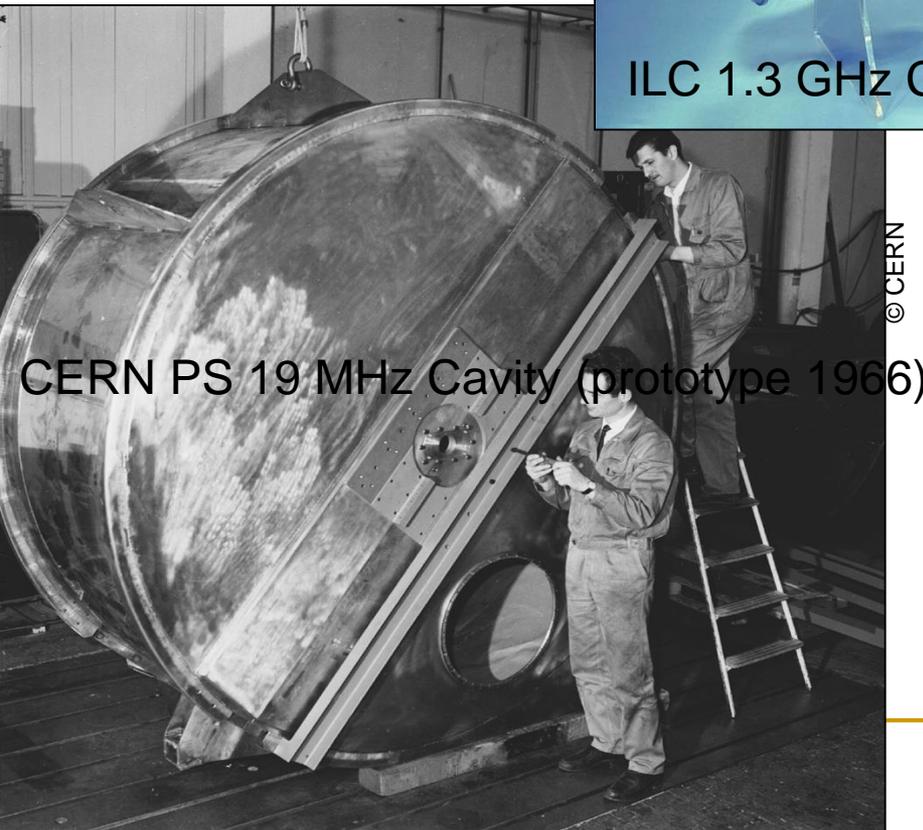
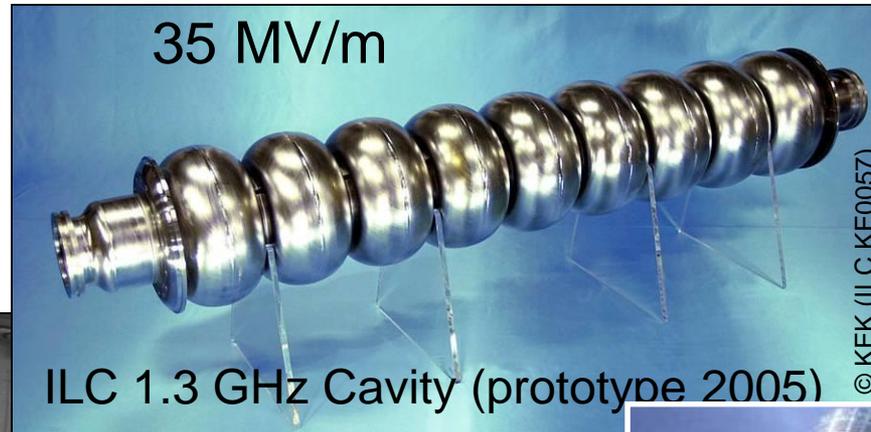
PETS structure

The induced fields travel along the PETS structure and build up resonantly

Decelerating structure



Accelerating Cavities



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
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