Lecture 13 -
Radiofrequency Cavities III

Professor Emmanuel Tsesmelis
Directorate-General Unit, CERN
Department of Physics, University of Oxford

Accelerator Physics Graduate Course
John Adams Institute for Accelerator Science
18 November 2015
Table of Contents III

- Synchronizing Particles with Cavities
- Operation of Linac Structure
- Power Generators for Accelerators
  - Triode Amplifier, Tetrode Amplifier, Klystron
- Accelerator RF Examples
  - Large Hadron Collider (LHC)
  - Linear Colliders (ILC, CLIC)
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

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

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 $2\pi$

- 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.
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 $\text{TE}_{10}$ wave in rectangular waveguide which is connected perpendicular to cylindrical $\text{TM}_{01}$ cavity.
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 $d$:
  $$\lambda_z = pd \quad \text{with} \quad p = 1, 2, 3, ...$$
  resulting in
  $$\frac{2\pi}{p} = \frac{2\pi}{\lambda_z} = k_z d \quad \text{with} \quad p = 1, 2, 3, ...$$
- 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.
  $$k_z d = \begin{cases} \pi & (\pi \text{ mode } \ i.e. \lambda_z = 2d) \quad \text{if } p = 2 \\ \frac{2\pi}{3} & (2\pi / 3 \text{ mode } \ i.e. \lambda_z = 3d) \quad \text{if } p = 3 \\ \frac{\pi}{2} & (\pi / 2 \text{ mode } \ i.e. \lambda_z = 4d) \quad \text{if } p = 4 \end{cases}$$
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.

- **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.
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
- \( \mu \) = 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
- \( \mu_a \) = anode amplification factor
- \( \mu_s \) = 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 $\text{TM}_{011}$ 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 $\lambda$ 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

\[ P_{\text{klystron}} = \eta U_0 I_{\text{beam}} \]

- \( U_0 \) = klystron supply voltage (e.g. 45 kV)
- \( I_{\text{beam}} \) = beam current (e.g. 12.5 A)
- \( \eta \) = 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 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

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

Energy: 250 GeV x 250 GeV
# of RF units: 560
# of cryomodules: 1680
# of 9-cell cavities: 14560
2 Detectors push-pull
peak luminosity: $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
5 Hz rep rate, 1000 -> 6000 bunches
IP: $\sigma_x$ 350 – 620 nm; $\sigma_y$ 3.5 – 9.0 nm
Total power: $\sim 230 \text{ MW}$
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

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

Not to scale!
CLIC Accelerating Module

- VACUUM MANIFOLDS
- COOLING CIRCUITS
- RF DISTRIBUTION
- ACCELER. STRUCTURE (BRAZED DISKS)
- BEAM INSTRUMENTATION
- CRADLES
- MAIN BEAM
- DRIVE BEAM
- GIRDERS
- INTERCONNECTIONS
- PETS (MINI-TANK)
- PETS (OCTANT)

Transfer lines:
- Drive Beam
- Main Beam

CLIC TUNNEL TYPICAL CROSS SECTION
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

*PETS structure*

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

*Accelerating structure*

*Decelerating structure*

Large boats on the water

Surfer riding the wave

Arno Candel, SLAC
Accelerating Cavities

CERN PS 19 MHz Cavity (prototype 1966)

35 MV/m

ILC 1.3 GHz Cavity (prototype 2005)

0MV/m

CERN PS 19 MHz Cavity (prototype 1966)

CLIC 30 GHz Cavity (prototype 2006)

CLIC 12 GHz Cavity (prototype 2009)
Acknowledgments and References

- Klaus Wille, *The Physics of Particle Accelerators*, Oxford University Press, 2005
- Edmund Wilson, *An Introduction to Particle Accelerators*, Oxford University Press, 2006