A Brief Introduction of Radio Frequency Cavity in Particle Accelerator

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Accelerator Physicist

July 30, 2014

ATD seminar
SLRI, Nakhon Ratchasima, Thailand
• A brief history of DC and RF acceleration
• Principle of RF cavity
• RF cavity classification
• RF cavity properties
• RF cavity design criterion
• Effects of RF cavity to particle beam and suppression method
• RF cavity fabrication
• 2\textsuperscript{nd} RF cavity at SLRI
Lorentz Force

- Force that keeps a charged particle circulate in a ring or travel along a line.

\[ \vec{F} = q \vec{E} + q (\vec{v} \times \vec{B}) \]

- In the presence of E-field, a charged particle will experience a force in direction of E-field.

- In the presence of B-field, a charged particle will experience a force in a perpendicular direction of B-field.
DC Acceleration

- Use high DC voltage to accelerate a charged particle.

- Limitations:
  - High energy = High voltage DC source \((1 \text{ MeV} = 1 \text{ MV DC source})\)
  - Impossible for circular machine \(\oint \vec{E} \cdot d\vec{s} = 0\)
  - Breakdown limit of material

Protons were accelerated and hit the lithium target producing helium and energy

Cockcroft-Walton’s electrostatic accelerator (1932)

![Electrostatic Accelerator Diagram](image)
• **Energy calculation**

Electrostatic potential energy

\[ U_E = - \int q \mathbf{E} \cdot d\mathbf{s} = qV \]

Special relativity theory

\[ E = E_0 + E_k = mc^2 = \sqrt{(pc)^2 + E_0^2} = \gamma E_0 \]

\[ \gamma = \sqrt{\frac{1}{1 - \beta^2}} , \quad \beta = \frac{\nu}{c} \]

40 MeV -> \( \nu = 0.99992c \)

\[ \beta = \sqrt{1 - (E_0/(E_0+E_k))^2} , E_0 = 0.511 \text{ MeV} \]

\[ \beta = 0.548 \]

\[ \nu = 0.548c \]

V = 100 kV

\( U_E = 100 \text{ keV} , 1 \text{ eV} = 1.602 \times 10^{-19} \text{ J} \)

\( U_E = 1.6 \times 10^{-14} \text{ J} \)

Kinetic energy

\[ U_E = E_k = \frac{mv^2}{2} = 1.6 \times 10^{-14} \text{ J} \]

\( \nu = \sqrt{2U_E/m} , m_e = 9.1 \times 10^{-31} \text{ kg} \)

\( \nu = 1.8 \times 10^8 \text{ m/s} \)

\( \nu = 0.6c , c = 2.998 \times 10^8 \text{ m/s} \)
RF Acceleration (time-varying field)

- Rolf Wideroe applied a 25-kV, 1 MHz AC voltage to the drift tube between two grounded electrodes. The beam experienced an accelerating voltage in both gaps.

- He accelerated Na and K beams to 50 keV kinetic energy equal to twice the applied voltage.

- This is not possible using electrostatic voltages

1928 - World’s first RF accelerator

Drift tube linac (DTL)

For slow particles
- Proton @ few MeV

Drift tube length vary according to the velocity of particle and the frequency of a source
RF Acceleration (time-varying field)

This is not the RF cavity

1 2 ... n

---

This is the RF cavity

- The length of the drift tubes become too long for higher velocities.
- The drift tube become antennas when operation at higher frequencies (> 10MHz) - very poor efficiency

Energy gain

\[ \Delta E = q N_{\text{gap}} V_{RF} \]

synchronism condition

\[ l_n = \frac{v}{2f} \]

- Put Wideroe linac in a conducting cylinder.
- Each gap has the same resonant frequency, which is now determined by the diameter of the cylinder, the distance between the drift tubes, and their diameter.
- Frequency up to 200MHz

Wideroe linac (1928)

Louis Alvarez linac (1946)

Yes, we can accelerate without cavities, but reaching higher energies becomes very inefficient
**Maxwell’s equations**

\[
\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} \\
\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \\
\n\nabla \cdot \vec{D} = \rho \\
\n\nabla \cdot \vec{B} = 0
\]

- The magnetic field \( H \) integrated around a closed loop equals the total current passing through that loop.
- A time-dependent magnetic field generates an electric field.
- The total flux of electric displacement crossing a closed surface equals the total electric charge enclosed by that surface.
- The total flux entering a bounded region equals the total flux leaving the same region.

\[
\vec{D} = \varepsilon \vec{E}, \quad \vec{B} = \mu \vec{H}
\]

**Maxwell’s equations are linear**
- This means that if two fields satisfy Maxwell’s equations, so does their sum.
- As a result, we can apply the *principle of superposition* to construct complicated electric and magnetic fields just by adding together sets of simpler fields.

Maxwell’s equations are of fundamental importance in electromagnetism, because they tell us the fields that exist in the presence of various charges and materials.

In accelerator physics (and many other branches of applied physics), there are two basic problems:

- Find the electric and magnetic fields in a system of charges and materials of specified size, shape and electromagnetic characteristics.
- Find a system of charges and materials to generate electric and magnetic fields with specified properties.

- Andy WOLSKI
**Principle of RF cavity**

**Pill-box cavity**

Solving in cylindrical coordinates \((r, \phi, z)\)

\[
E_r = j \frac{k_z}{k_c} E_0 J_1(k_c r)e^{-jk_z z} e^{j \omega t}
\]

\[
E_z = E_0 J_0(k_c r)e^{-jk_z z} e^{j \omega t}
\]

\[
B_\phi = j \frac{k}{Z_0 k_c} E_0 J_1(k_c r)e^{-jk_z z} e^{j \omega t}
\]

\[
k = \frac{2\pi}{\lambda} = \frac{\omega}{c} \quad Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377 \Omega
\]

\[
E_z = 0 \text{ at } r = a \quad \text{cut off wave length } \lambda_c \quad \lambda_c \approx 2.61 a
\]

Only waves with shorter wavelength, or a frequency above the cut off frequency \(\omega_c\) can propagate in the cavity undamped

\[
k_z^2 = \frac{\omega^2}{v_{ph}^2} = \left(\frac{\omega}{c}\right)^2 - \left(\frac{\omega_c}{c}\right)^2
\]

\(J_0\) and \(J_1\) are Bessel functions of the first kind of zeroth and first order

\(\omega = 2\pi f\) is the angular frequency

\(k\) is the wave number

\(k_z\) is the wave propagation constant

\(Z_0\) is the wave-impedance in free space

\(E_0\) is the amplitude of the electric field

\(j\) indicates imaginary parts

**Dispersion relation (Brioullin diagram)**

\[k_c = \frac{2\pi}{\lambda_c} = \frac{\omega_c}{c}\]

\[k_z^2 = k^2 - k_c^2\]
Principle of RF cavity

- Each frequency corresponds to a certain phase velocity
- The phase velocity is always larger than the speed of light
- At $\omega = \omega_c$ the propagation constant $k_z$ goes to zero and the phase velocity becomes infinite
- It is impossible to accelerate particles in a circular waveguide because synchronism between the particles and the RF is impossible (particles would have to travel faster than light to be synchronous with the RF)
- Information and therefore energy travels at the speed of the group velocity $v_g = d\omega/dk_z$, and is always slower than the speed of light
**Principle of RF cavity (TW)**

Slowing down phase velocity, in order to accelerate particles
- Put obstacles into waveguide, i.e. discs.

\[ \omega = \frac{2.405c}{b} \sqrt{1 + \kappa (1 - \cos(k_z L) e^{-\alpha h})} \]

\[ \kappa = \frac{4a^3}{3\pi f_1^2 (2.405)b^2 L} \ll 1, \alpha \approx \frac{2.405}{a} \]

When a structure operates in the $2\pi/3$ mode it means that the RF phase shifts by $2\pi/3$ per cell, or in other words one RF period stretches over three cells. The particles then move in synchronism with the RF phase from cell to cell.

**Constant impedance** each cell’s bore radii are kept constant, i.e. uniform structure. The electromagnetic wave becomes more and more damped along the structure.

**Constant gradient** bore radius are changing from cell to cell. The maximum possible accelerating gradient in each cell.
Principle of RF cavity (SW)

Closing both ends of a circular wave guide with electric walls. This will yield multiple reflections on the end walls until a standing wave pattern is established.

Only with discrete frequencies and discrete phase changes can exist in the cavity. If one feeds RF power at a different frequency, then the excited fields will be damped exponentially.

\[ \omega_n = \frac{\omega_0}{\sqrt{1 + k \cos(n\pi/N)}} \]

\[ k = \frac{\omega_\pi - \omega_0}{\omega_0} \]

The frequency bandwidth \(|\omega_n - \omega_0|\) is independent of the number of cells, which means that we can determine the cell-to-cell coupling constant by measuring the complete structure.

For electric coupling the 0-mode has the lowest frequency and the \(\pi\)-mode has the highest frequency. In case of magnetic coupling this behavior is reversed.

Dispersion curve of half-cell terminated SW structure, magnetic coupling

Image courtesy of F. Gerigk

Thomas P. Wangler, RF Linear Accelerator

RF cavity classification

Application

<table>
<thead>
<tr>
<th>Constant velocity, constant RF frequency</th>
<th>Changing velocity, constant RF frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-accelerating cavities</td>
<td>Changing velocity, variable RF frequency</td>
</tr>
</tbody>
</table>

EM wave

<table>
<thead>
<tr>
<th>Travelling wave (TW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant impedance</td>
</tr>
<tr>
<td>Constant gradient</td>
</tr>
</tbody>
</table>

| Standing wave (SW) |

Material

<table>
<thead>
<tr>
<th>Normal conducting (NC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting (SC)</td>
</tr>
</tbody>
</table>
### RF cavity classification

#### Application

<table>
<thead>
<tr>
<th>Constant velocity, constant RF frequency</th>
<th>Changing velocity, constant RF frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Relativistic particles ( (\beta = v/c &gt; 0.99) )</td>
<td>- The velocity of the particles is increased along the acceleration cycle but where the RF frequency can be kept constant</td>
</tr>
<tr>
<td>- <strong>Synchrotron</strong>, no need to adapt RF frequency to the revolution frequency of the particles</td>
<td>- <strong>Cyclotrons</strong>, use single-cell cavities to avoid any problems with synchronicity between subsequent gaps of multi-cell structures</td>
</tr>
<tr>
<td>- <strong>Linac</strong>, no need to change the distance between accelerating gaps</td>
<td>- <strong>Low-( \beta ) ion and proton linacs</strong>, use multi-cell structures in order to keep the overall linac length compact, it is necessary to adapt the gap distance to the velocity of the particles</td>
</tr>
<tr>
<td>- <strong>Electron accelerators</strong> energy ( &gt; 1 \text{ MeV} )</td>
<td></td>
</tr>
<tr>
<td>- <strong>High energy proton accelerators</strong> (GeV)</td>
<td></td>
</tr>
<tr>
<td>- <strong>Ion accelerators</strong> 10s-100s of GeV (depending on ion species)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Non-accelerating cavities</th>
<th>Changing velocity, variable RF frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Mainly used with relativistic particles</td>
<td>- These are the most demanding operating conditions for RF cavities, in</td>
</tr>
<tr>
<td>- <strong>RF deflection</strong></td>
<td>- <strong>Low-( \beta ) (ion/proton) synchrotrons and FFAGs</strong></td>
</tr>
<tr>
<td>- Chopper cavities, Low energy beam chopping systems, JPARC</td>
<td>- A change in RF frequency can be achieved by putting a material with an adjustable permeability (typically ferrites) into a cavity</td>
</tr>
<tr>
<td>- CRAB cavities, to maximize the collision rate of colliding particle beams, which are brought to collision under a certain angle</td>
<td>- Small accelerating voltages ( (10s \text{ of keV}) ) can be achieved in these cavities at rather poor efficiencies</td>
</tr>
<tr>
<td>- Funneling cavities, combination of two beams arriving at a certain angle into one common beam line, if interleaved one by one the bunch repetition frequency will doubles during this process</td>
<td></td>
</tr>
<tr>
<td>- <strong>RF bunching</strong></td>
<td></td>
</tr>
<tr>
<td>- Used to keep bunches longitudinally confined during beam transport</td>
<td></td>
</tr>
<tr>
<td>- Form bunches out of CW beams coming from a particle source</td>
<td></td>
</tr>
<tr>
<td>- <strong>Beam monitoring cavities</strong></td>
<td></td>
</tr>
</tbody>
</table>
RF cavity examples

Constant velocity, constant RF frequency

- MAX-IV cavity
  - http://www.lightsources.org/
- ESRF cavity
  - http://www.esrf.eu/
- ILC cavity
  - http://wwwold.jlab.org/
- CEBAF cavity
  - http://www.hep.phys.sfu.ca/
- LHC cavity
  - http://anim3d.web.cern.ch/
RF cavity examples

Changing velocity, constant RF frequency

- PSI, RIKEN, RCNP: separate higher harmonic resonator
- CAS, RF for cyclotron (materials)

Sytze Brandenburg (KVI), P. K. Sigg (PSI)
RF cavity examples

Changing velocity, variable RF frequency

Application

http://www.hep.manchester.ac.uk/g/accelerators/conform/news/guide/
RF cavity examples

Non-accelerating cavities

Deflecting cavity

Elmar Vogel's Website

Third harmonic Systems

Application

Crab Cavities for Colliders

Head-on collision
Maximum luminosity

Crossing angle introduced
Reduced luminosity due to crossing angle

Crossing angle with crab rotation
Effective head-on collision

Harmonic cavity can be operated in ACTIVE mode (RF external power supply) or in PASSIVE mode (voltage induced by beam current). The choice of several Synchrotron Light Sources nowadays has been the Passive Mode.

Hans-H. Braun / PSI

4.9 GHz Phase and Position Resonators in MAMI double sided Microtron (at Mainz University)

Courtesy H. Euteneuer and O. Chubarov

Deflecting cavity

http://pbpl.physics.ucla.edu/
RF cavity classification

**Travelling wave (TW)**
- Cavities are filled in space (cell after cell) – sub- μs
- Constant impedance
  - Each cell has the same shape (iris radius)
- Constant gradient
  - Each cell has different iris radius

**Standing wave (SW)**
- Cavities are filled in time (Slowly build up SW pattern at desired amplitude) - 10s μs to ms

**EM wave**

Example of a 2/3 travelling wave structure

synchronism condition: $d = \frac{(\beta)\lambda}{3}$ with $\beta \approx 1$

NLC cavity

MAX-IV linac cavity

MAX-IV cavity

F. Gerigk (CERN/BE/RF)
RF cavity classification

Material

Normal conducting (NC)
- Need water cooling
- Higher gradient < 150 MV/m

Superconducting (SC)
- Need Cryogenic plant
- Low gradient < 45 MV/m

Toshiba
Hitachi

ILC cavity

MAX-IV cavity

Niobium Superconducting Cavities
1.3 GHz 9-Cell ILC/TESLA

Contact us to discuss your needs.

N. Juntong (nawin@slri.or.th)
February 7, 2014

Siam Photon Laboratory
### RF cavity classification

**EM Mode**

<table>
<thead>
<tr>
<th>TM</th>
<th>Transverse Magnetic field on beam path</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mainly use for accelerating particle</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TE</th>
<th>Transverse Electric field on beam path</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low surface losses</td>
</tr>
<tr>
<td></td>
<td>Can be adapted by adding drift tube to make axial E field on beam path for acceleration (H-mode cavity)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TEM</th>
<th>Low frequency &lt; 100 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Frequency determined by the length</td>
</tr>
<tr>
<td></td>
<td>QWR (Quarter wave resonator)</td>
</tr>
<tr>
<td></td>
<td>HWR (Half wave resonator)</td>
</tr>
<tr>
<td></td>
<td>Spoke cavity</td>
</tr>
</tbody>
</table>

**Fig. 12:** Commonly used TE mode cavities, left: TE$_{110}$ (interdigital TE mode), right: TE$_{210}$ (crossbar TE mode) [15]

**Fig. 16:** Left: coaxial 1/2 wave cavity, right: 1/4 wave cavity

**Fig. 18:** Triple-spoke cavity developed at FZJ [24]
RF cavity classification

EM Mode

EXAMPLES OF QWRS

A. Facco, Low and intermediate β cavity design, SRF 2009

TRIUMF

INFN LNL-MSU

New Dehli

MSU

ANL

INFN LNL

INFN LNL (sputtered)

Saclay

IPNO
3.2 Nomenclature of electromagnetic modes

The definition of modes is generally done according to the following rules:

**TM\(_{mnp}\) or E\(_{mnp}\) modes**

- magnetic field components only in transverse direction (TM — transverse magnetic),
  - no longitudinal magnetic field component (\(B_z = 0\)),
  - non-vanishing longitudinal electric field component (\(E_z \neq 0\));

**TE\(_{mnp}\) or H\(_{mnp}\) modes**

- electric field components only in transverse direction (TE — transverse electric),
  - no longitudinal electric field component (\(E_z = 0\)),
  - non-vanishing longitudinal magnetic field component (\(B_z \neq 0\)).

In cylindrical coordinates the indices \(m, n, p\) are:

\(m\) number of full-period variations of the field components in the azimuthal direction, in cylindrical resonators this means: \(E, B \propto \cos(m\varphi)\) or \(\sin(m\varphi)\);

\(n\) number of zero-crossings of the longitudinal field components in the radial direction, in cylindrical resonators this means: \(E_z, B_z \propto J_m(x_{mn}r/R_c)\), \(x_{mn}\) are the zeros of the \(J_m\);

\(p\) number of half-period variations of the field components in the longitudinal direction, in cylindrical resonators this means: \(E, B \propto \cos(p\pi z/l)\) or \(\sin(p\pi z/l)\).
RF cavity classification

EM Mode

SuperFISH Results

Microwave Studio Results
RF cavity properties

- Accelerating voltage ($V_a$)
  \[- V_a = |\int E_z e^{i\omega z/c} \, dz|\]

- Accelerating gradient ($E_a$)
  \[- E_a = \frac{V_a}{L}, \, L \text{ – effective length of cavity} \]

- Store Energy ($U$)
  \[- U = \frac{1}{2} \mu_0 \int_V |\vec{H}|^2 \, dV = \frac{1}{2} \varepsilon_0 \int_V |\vec{E}|^2 \, dV \]

- Power dissipate on cavity wall ($P_c$)
  \[- P_c = \frac{1}{2} R_s \int_S |\vec{H}|^2 \, dS, \, R_s \text{ – Surface resistance} \]

- Unloaded Quality factor ($Q_0$)
  \[- Q_0 = \frac{\omega U}{P_c} \]

- Shunt impedance ($R_a$)
  \[- R_a = \frac{V_a^2}{P_c} \]

- R/Q
  \[- \frac{R}{Q} = \frac{V_a^2}{\omega U} \]

- External Q ($Q_{ex}$), Loaded Q ($Q_L$)
  \[- Q_{ex} = \frac{\omega U}{P_{ex}}, \, Q_L = \frac{\omega U}{P_c} \]
  \[- \frac{1}{Q_L} = \frac{1}{Q_0} + \frac{1}{Q_{ex}} \]
RF cavity design criterion

• Efficiency of cavity

\[ \eta = \frac{P_{\text{beam}}}{P_{\text{gen}}} = \frac{P_{\text{beam}}}{P_{\text{beam}} + P_c} \]

NC – increase peak fields in the area of nose to maximize shunt impedance, but it’s limit by Kilpatrick (maximum achievable field in vacuum as a function of frequency)

• Kilpatrick limit (1957)

\[ f [\text{MHz}] = 1.64E_k^2 e^{\frac{8.5}{E_k}} , \quad E_k \text{ in MV/m} \]

Modern cavities, \( E_{\text{surf}} = bE_k \), \( b \) is the bravery factor, 1<\( b < 2 \).
- Better vacuum and cleaner inner surfaces

SC – \( P_b \gg P_c \), no longer limit by losses
- Optimize shape for a low ratios of \( E_{\text{peak,surf}}/E_a \) and \( B_{\text{peak,surf}}/E_a \), \( E_p/E_a \sim 2 \)
- Nose cone is not suitable, elliptical shape is basically used

F= 118 MHz, \( E_k = 12 \text{ MV/m}, E_{\text{sm}} = 24 \text{ MV/m} \)
F= 500 MHz, \( E_k = 21 \text{ MV/m}, E_{\text{sm}} = 42 \text{ MV/m} \)
**RF cavity design criterion**

**Cost** - Cost of building cavity, cost of RF station, cost of Cooling system, etc..

**Figure 2.6** Costs versus accelerating field. The structure power cost, the beam power cost, structure length cost, and the total cost are shown.
## RF cavity design criterion

### LC 500 GeV Main parameters

http://clic-meeting.web.cern.ch/clic-meeting/ComparisonTable.html

<table>
<thead>
<tr>
<th>Parameter</th>
<th>NLC 500 GeV</th>
<th>ILC 500 GeV</th>
<th>CLIC 500 G Conservativ</th>
<th>CLIC 500 G Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center-of-mass energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total (Peak 1%) luminosity</td>
<td>2.0(1.3)(\times)10^{34}</td>
<td>2.0(1.5)(\times)10^{34}</td>
<td>0.9(0.6)(\times)10^{34}</td>
<td>2.3(1.4)(\times)10^{34}</td>
</tr>
<tr>
<td>Repetition rate (Hz)</td>
<td>120</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loaded accel. gradient MV/m</td>
<td>50</td>
<td>33.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main linac RF frequency GHz</td>
<td>11.4</td>
<td>1.3 (SC)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch charge10^9</td>
<td>7.5</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bunch separation ns</td>
<td>1.4</td>
<td>176</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Beam pulse duration (ns)</td>
<td>400</td>
<td>1000</td>
<td></td>
<td>177</td>
</tr>
<tr>
<td>Beam power/linac (MWatts)</td>
<td>6.9</td>
<td>10.2</td>
<td></td>
<td>4.9</td>
</tr>
<tr>
<td>Hor./vert. norm. emitt (10^{-6}/10^{-9})</td>
<td>3.6/40</td>
<td>10/40</td>
<td>3 / 40</td>
<td>2.4 / 25</td>
</tr>
<tr>
<td>Hor/Vert FF focusing (mm)</td>
<td>8/0.11</td>
<td>20/0.4</td>
<td>10/0.4</td>
<td>8/0.1</td>
</tr>
<tr>
<td>Hor./vert. IP beam size (nm)</td>
<td>243/3</td>
<td>640/5.7</td>
<td>248 / 5.7</td>
<td>202/2.3</td>
</tr>
<tr>
<td>Soft Hadronic event at IP</td>
<td>0.10</td>
<td>0.12</td>
<td>0.07</td>
<td>0.19</td>
</tr>
<tr>
<td>Coherent pairs/crossing at IP</td>
<td>10?</td>
<td>10?</td>
<td>10</td>
<td>100</td>
</tr>
<tr>
<td>BDS length (km)</td>
<td>3.5 (1 TeV)</td>
<td>2.23 (1 TeV)</td>
<td></td>
<td>1.87</td>
</tr>
<tr>
<td>Total site length (km)</td>
<td>18</td>
<td>31</td>
<td></td>
<td>13.0</td>
</tr>
<tr>
<td>Wall plug to beam transfer eff.</td>
<td>7.1%</td>
<td>9.4%</td>
<td></td>
<td>7.5%</td>
</tr>
<tr>
<td>Total power consumption MW</td>
<td>195</td>
<td>216</td>
<td></td>
<td>129.4</td>
</tr>
</tbody>
</table>
Effects to particle beam

1. Wakefields Fundamentals

Roger JONES (Manchester University), CAS 2010

dipole modes $\rightarrow$ lowest order contribution to transverse momentum

integrated transv. momentum: $\Delta P_t = \frac{q_1 q_2}{c_0} w_D(s) r_{1f}$
linear accelerators: $w'_D(s) = \frac{w_D(s)}{\text{length}}$

dimension: $\sqrt{\text{v/(Cm}^2\text{)}}$

R.M. Jones, HOM Mitigation Part II, CAS RF for Accelerators, Ebeltoft, Denmark, 15th June 2010
Effects to particle beam

1. Mode Multipoles

-Focus mainly on dipole long-range transverse wakes

monopole \((m = 0)\)

- \(TM_{01}\)-like
- high losses, no kick

dipole \((m = 1)\)

- \(TM_{11}\)-like
- kick and losses when beam is not centered

quadrupole \((m = 2)\)

- \(TM_{21}\)-like
- kick, coupling and losses when beam is not centered

Roger JONES (Manchester University), CAS 2010
2.1 C-Band Wakefield HOM Suppression

SPring-8 (Super Photon ring-8 GeV)
- Synchrotron radiation facility, including compact SASE Source in Japan
- High peak-brilliance soft X-ray FEL project for R&D A
- Angstrom X-ray laser facility.
- SCSS (SPring-8 Compact SASE Source) will provide six order of magnitude peak-brilliance enhancement compared to the current third-generation sources at 3 ~ 20 nm
- C-Band (5.712 GHz) linacs provided with choke mode damping
- HOMs flow out through radial channels
- Fundamental mode trapped within the structure (λ/4)
- 35-40 MeV/m, why not higher?

2. http://www-xfel.spring8.or.jp
2.2 CLIC Baseline Accelerating Structure

- HOM damping waveguides
  - HOM damping waveguides
  - Alignment
  - High electric field and power flow region - breakdown
  - Magnetic field concentration – pulsed surface heating
  - Vacuum pumping
  - Beam and rf
  - Short range wakefields

- Heavy Damping, Q=10. Dielectric materials impinge into structure

2.2 Alternate Design CLICDDS

- DDS structure illustrates the essential features of the conceptual design
- Each of the cells is tapered - iris reduces with an Er-like distribution
- HOM manifold running alongside main structure remove dipole radiation and damp at remote location (4 in total)
- Each of the HOM manifolds can be instrumented to allow:
  1) Beam Position Monitoring
  2) Cell alignments to be inferred

5. HOMs in LHC Crab Cavity

- Waveguides are directly coupled to the cavities to provide significant damping.
- The coupling slots are placed at the field nulls of the crabbing mode to avoid high fields.

3. HOMs in SCRF Cavities

- F-probe couplers are a type of co-axial coupler, commonly used to damp HOM’s in superconducting cavities.
- These complex shapes are designed to provide the coupler with additional capacitances and inductances.
- These additional capacitances and inductances form resonances which preferentially couple at specific frequencies.

The LCR circuit can be used to reduce coupling to the operating mode (which we do not wish to damp) or to increase coupling at dangerous HOMs.

4. HOMs in Energy Recovery Linacs

- Total # loads: 3 @ 76mm + 3 @ 106mm
- Power per load: 26 W (200 W max)
- HOM frequency range: 1.4 – 100 GHz
- Operating temperature: 80 K
- Coolant: He Gas
- RF absorbing tiles: TT2, Co2Z, Cerabid

Ref: S. Belomestnykh, ERL09 Workshop, Cornell Univ.

Roger JONES (Manchester University), CAS 2010
**HOM suppression**

352.2 MHz Single cell NC HOM damped cavity

[ESRF project leader: Vincent Serrière]

- 9 MV with 12 to 18 cavities (4.7 ± 0.4 MΩ)
- Planned operation at 300 mA
- Power capability to sustain up to 500 mA

**E-beam welding of HOM coupling sections to the body**
- to avoid the gap between ridges and cavity body
- to suppress residual HOM and flange overheating (observed on BESSY/ALBA cavity)

**3 power prototypes in fabrication:**
- validate the design
- validate 2 different manufacturing procedures
- qualify 3 companies: RI, SDMS, CINEL
- obtain 3 operational cavities for cell 23 according to initial upgrade concept

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**Copper prototype – design aspect**

- No gap between the ridges and the cavity body, coupling section e-beam welded to the cavity.
- In the ridge zones, the electrical continuity will be established by means of RF fingers.
Cavity fabrication (ESRF cavity)

Initially specified mechanical design & manufacturing procedure
applied by RI Research Instruments

- e-beam welding of HOM coupling sections
- Brazing:
  - cooling circuits
  - outlets
  - flanges
- Frequency tuning
- Brazing end plates

RI Research Instruments cavity

Cavity after e-beam welding & before machining of the beam stop

Alternative design proposed by SDMS
applied by SDMS and CINEL

- e-beam welding

Then the cavity body is cut in three parts.

V. Serrière, ESRF
Cavity fabrication (SCRF cavity)

- From Sheets to Fields

Hanspeter Vogel, RI

Some important properties of Niobium

- Niobium is a rare, soft, malleable, ductile, gray-white metal.
- The metal is inert to acids.
- It tends to react with oxygen, carbon, the halogens, nitrogen, and sulfur at low temperatures (<200°C).
- Melting point: 2410 °C
- Critical temperature: 9.2 K (at atmospheric pressure, the highest critical temperature of the elemental superconductors)

General Use:
- Niobium is used for the production of high-temperature acid resistant alloys and special stainless steels. Small amounts of niobium impart greater strength to other metals.
- Niobium-tin and niobium-titanium alloys are used as wires for superconducting magnets.

Special Use:
- For accelerator cavities is its highest purity form

Nb mines worldwide

- Tantalite (Fe, Mn)(Nb, Ta)₂O₆
- Columbite (Fe, Mn)(Nb, Ta)₂O₆
- Pyrochlore (Ca₂Na)₃Nb₂O₇F

Pyrochlore is mostly used for the generation of high purity niobium due to its low Ta-content


Forming of single parts for cavities (1)

7-cell cavity for Jefferson Laboratory
Cavity cells and waveguide coupler parts and flanges are made from Nb sheet

 Nb ingot after refining by multiple electron beam welding in vacumm

 Nb sheets ready for cavity production

 two half of a waveguide coupler

 Half cells (cups)
SLRI 2nd RF Cavity

Based on MAX-IV Cavity

Source: Ake Andersson, MAX-Lab

Source: Soren Pape Moller, ASTRID2

Source: Ake Andersson, MAX-Lab
Proposed Cavity 3D shape

Cavity shape 3D

1, 2 Pump
3 Input coupler
4, 5 HOM coupler
6, 7 Vacuum gauges
8 RGA
9 View port
10, 11 Beam
12, 13 Pickup
Accelerating mode fields (118 MHz)
Higher Order Modes (HOM) in RF Cavity

- Monopole
- Dipole
- Quadrupole
- Sextupole
- Tenth-pole
- Twelfth-pole
Thank you

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