A prototype RF power source for JLC at X-band
(1 Tev. Ecm)

(Results and perspectives, 1988-1994 R&D in KEK)


KEK, H.Mizuno
### JLC parameters (Ecm=1 Tev)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>500 GeV</td>
</tr>
<tr>
<td>RF frequency</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>No. of particles per bunch</td>
<td>6.9 x 10^9</td>
</tr>
<tr>
<td>Nr of bunches per pulse</td>
<td>85 (120 nsec train)</td>
</tr>
<tr>
<td>Bunch spacing</td>
<td>1.40 nsec</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>150 Hz</td>
</tr>
<tr>
<td>Luminosity</td>
<td>10^34</td>
</tr>
<tr>
<td>Nominal accelerating gradient</td>
<td>76.1 MeV/m</td>
</tr>
<tr>
<td>Effective gradient in cavities</td>
<td>57.1 MeV/m</td>
</tr>
<tr>
<td>Length of a cavity unit</td>
<td>1300 mm</td>
</tr>
<tr>
<td>Nr of cavity units (per beam)</td>
<td>6423</td>
</tr>
<tr>
<td>a/L</td>
<td>0.1576</td>
</tr>
<tr>
<td>Filling time (Tf)</td>
<td>120 nsec</td>
</tr>
<tr>
<td>Attenuation parameter</td>
<td>0.648</td>
</tr>
<tr>
<td>Vg/c</td>
<td>3.64%</td>
</tr>
<tr>
<td>Rf input per a cavity unit</td>
<td>130 MW</td>
</tr>
<tr>
<td>Efficiency (wallplug to RF)</td>
<td>30%</td>
</tr>
<tr>
<td>Total AC power (RF)</td>
<td>194 MW (and some more)</td>
</tr>
</tbody>
</table>

### Problem 1
Find differences between this table and Yokoya Parameters presented this morning.
The prototype RF power source for JLC\((\text{Ec}=1\text{Tev})\)

(1) Klystron (XB72k)
- **RF out**: 130MW
- **Pulse width**: 500ns
- **Efficiency**: 42%
- **Focusing**: Super cond. Mag.

(2) x2 or x3 RF pulse compression system
- **RF input**: 500ns 130MW
- **RF out**: 240ns 250MW
- **Efficiency**: >96%

(3) Blumlein modulator
- **Output pulse**: 600kV 500ns (flat top)
- **Efficiency**: 75%
- **Pulse trans.**: 1:5
- **Rise & Fall time**: 150ns 200ns

\[\sim 28\%\]
### Table-1) XB-72 Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam voltage</td>
<td>550kV</td>
</tr>
<tr>
<td>Beam current</td>
<td>490A</td>
</tr>
<tr>
<td>Max. surface field</td>
<td>273kV/cm</td>
</tr>
<tr>
<td>Beam areal compression</td>
<td>110-l</td>
</tr>
<tr>
<td>Cathode diameter</td>
<td>72 mm</td>
</tr>
<tr>
<td>Current density (Max.)</td>
<td>17A/cm²</td>
</tr>
<tr>
<td>Focusin field (Max.)</td>
<td>6.5kG</td>
</tr>
<tr>
<td>Number of cavities</td>
<td>5</td>
</tr>
<tr>
<td>Frequency</td>
<td>11.424GHz</td>
</tr>
<tr>
<td>RF power</td>
<td>120MW</td>
</tr>
<tr>
<td>Efficiency</td>
<td>47%</td>
</tr>
<tr>
<td>Max. surface Grad.</td>
<td>720kV</td>
</tr>
<tr>
<td>(Output gap) Gain</td>
<td>53-56dB</td>
</tr>
</tbody>
</table>

- **OK?**
  - Beam Voltage: 620 kV
  - Beam Current: 550 A
  - Beam Power: 340 MW
  - Diode is OK.

- **Problems**
  - Efficiency: 35%
  - Output Cavity: Damaged (Discharge) Multi Gap
  - Peak RF Power: 95 MW (96%)

- **OK(?)**
  - Window: TE_{11} \frac{1}{2} \lambda_{g} 600\,\mu m, 70 MW under test Bb OK, to be measured in SLAC (94·Doc)
94-08-30  No.1 & No.2 XB72k RF Station for H87218
94-08-30
XB72x*3, #4 waiting Tests.
XB72K#4

EFFICIENCY (%)

BEAM VOLTAGE (kV)

- ○ Calculated (FCI)
- ● Measured (Nov. '94)
The Field Strength on the Ceramic Surface

<table>
<thead>
<tr>
<th>Type</th>
<th>$E_0^*$</th>
<th>Band Width</th>
<th>Peak RF (100 ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pill Box **</td>
<td>0.87</td>
<td>500 MHz</td>
<td>~200 mV damaged</td>
</tr>
<tr>
<td>$TE_{11}$ (short) ***</td>
<td>0.42</td>
<td>250 MHz</td>
<td>~100 mV OK</td>
</tr>
<tr>
<td>$TE_{11}$ (long)</td>
<td><del>0.3</del>0.4</td>
<td>~300 MHz</td>
<td>?</td>
</tr>
</tbody>
</table>

* Normalized to the WR-90 Rect. W.G.

** Equipped on XB728 #1 -> #4

*** Tested in the Res. Ring up to 100 MW

XB728 #5 will be equipped with this Type.
Ceramic Windows.

TE_{11} Window \( \left( \frac{1}{2} \lambda g \text{ Type } 11.42 \text{ GHz} \right) \)
5\% ceramic \( Y. \) Utake.
X-Band Test 100 MW peak.

T-Wave Window X, S band
S-band 400 MW Tested.
X-Band finished, waiting RF Test.
28\% ceramic.

Design Principle

\[ \text{on the Ceramic Surface} \]
\[ \approx 8 \text{kV/mm} \]
( Y. Saito (KEK))
S-band Experiments

XB72k #1 \( \rightarrow \# 4 \) X-Band Pill Box \( \times 2 \)
XB72k #5 TE_{11} Window \( \times 2 \)
and after
Results of TE11-mode RF Window
High-Power Test

300 ns input to the resonant ring.

Resonant ring input power
200 ns/Div. 14.5 MW

Resonant ring circular power
200 ns/Div. 102 MW

700 ns input to the resonant ring.

Resonant ring input power
200 ns/Div. 8.6 MW

Resonant ring circular power
200 ns/Div. 72 MW
Super Conducting Solenoid (M. Elec.)

- Tested, Sept. 94.

- X372k.

- Independent Refrigerator, water supply, 200V power line, Thermal Conduction Cooling.

- To reduce Heat Loss
  - "High To Super Conductivity Material"
    - for the current lead.

- Total Power Max, 5 kW
  - ~3 kW

- Permanent Current Mode in Future, need some additional "Switch" possible.

- Field Measurement in "SCAC" Jan. 95? effect of "Thermal Cycle"
XB70K Superconducting Solenoid

- Design Value
- Measured

\[ B_z (\text{Gauss}) \]

Position (mm)

- Central Plane \( B_z \)
- \( 72K \) design value
- Measured values

Hall effect used

The field value on the surface is Backing coil compensation is necessary. The target value is 35 Gauss.
XB70K SC Solenoid
Thermal Cycle

Date/Time

10 Days
MODULATORS FOR X-BAND
KLYSTRON(XB-72K)

1) Conventional modulator (1991)

2) Blumlein type PFN
Under design and construction by IHI (Ishikawajima-Harima Heavy Industry) will be completed 1993-Feb.

Design Parameters

(a) PFN (Blumlein Type)

- Rise Time (with Trans.) ~150 ns
- Fall Time (with Trans.) ~230 ns
- Flat Top ~500 ns
- Number of PFN 12
- Output Voltage (=Charging V) 80 kV (1:7 Step-up)
- Impedance 23 Ohm (XB-72K 550 kV)

(b) Pulse Trans. (Primary at 80 kV while charging)

- Step-up ratio 1:7
- Leakage L 830 nH
- Stray Capacitance 4 nF (Primary)
- Primary L 200 micro-H
- Loss at 200 pps 100 W (Hysteresis)
- 1000 W (Eddy Current)
- Rise Time (Trans. only) ~100 ns
- Fall Time (Trans. only) ~200 ns
- Sag. 2.8 % (after 500 ns)
- Core Material Si-Fe (t=25 micron)

- Inductance of Lead Wiring etc

"Maxwell" - OK.? \(\rightarrow\) Very Promising
(Made in USA)

- 1992 Fy Conventional
- 1994 Fy In Oil Tank.

4. \( I_{\text{bias}} = 15\, \text{A} \)

Bias Current

\[ = 15\, \text{A} \]

5. \( I_{\text{bias}} = 20\, \text{A} \)

\[ = 20\, \text{A} \]

6. \( I_{\text{bias}} = 25\, \text{A} \)

\( V_c \sim 450\, \text{kV} \)

\[ = 25\, \text{A} \]

\( \text{Trise} = 250\, \text{ms} \)
A NEW RF POWER DISTRIBUTION SYSTEM FOR X-BAND LINAC EQUIVALENT TO AN RF PULSE COMPRESSION SCHEME OF FACTOR $2^n$

H. Mizuno, Y. Otake, National Laboratory for High Energy Physics (KEK)
1-1 Oho, Tsukuba-shi, Ibaraki-ken 305 JAPAN

ABSTRACT

As an RF power source system for a future X-band linear colliders, some RF pulse compression system is necessary. A new simple scheme which can provide the better efficiency than the present scheme such as SLED or SLED-2, is proposed. This scheme consist of 2-Klystrons, a 3-dB coupler and a TE01 mode delay line one half of the necessary delay time. The output RF pulse of 2-klystrons are combined through 3-dB coupler and the first half of the pulse is transported to the upstream of a linac through the TE01 mode wave guide. Then, by reversing the phase of the one of 2-klystrons, the last half of the RF pulse is directly fed to the linac structure located close to the klystrons. The RF power loss in this system is determined by the loss in the transporting waveguide. In the case of 400nsec pulse, ie 200nsec pulses at the input of 2-different accelerating structures, the estimated efficiency is more than 95%.
図 1 A Schematic Diagram of an RF Power Distribution System

図 2 A Railroad Diagram of RF Distribution
X3 or X4 Delay Line Scheme

4 Klystrons

Diagram showing connections and positions A, B, C, D with a timeline c.
### Table-1)

**Transfer losses in the waveguides***

1) **TE01** mode

<table>
<thead>
<tr>
<th>Waveguide (Diameter)</th>
<th>Loss (dB/m)</th>
<th>$V_g/c$</th>
<th>Line loss (200ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51mm</td>
<td>1.3e-2</td>
<td>0.733</td>
<td>8.02%</td>
</tr>
<tr>
<td>69mm</td>
<td>4.5e-3</td>
<td>0.886</td>
<td>2.82%</td>
</tr>
<tr>
<td>118.1mm</td>
<td>8.3e-4</td>
<td>0.9625</td>
<td>0.56%</td>
</tr>
</tbody>
</table>

2) **TE11** mode

<table>
<thead>
<tr>
<th>Waveguide (Diameter)</th>
<th>Loss (dB/m)</th>
<th>$V_g/c$</th>
<th>Line loss (200ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>51mm</td>
<td>1.22e-2</td>
<td>0.9626</td>
<td>7.93%</td>
</tr>
<tr>
<td>69mm</td>
<td>8.44e-3</td>
<td>0.9748</td>
<td>5.60%</td>
</tr>
<tr>
<td>118.1mm</td>
<td>4.7e-3</td>
<td>0.9951</td>
<td>3.18%</td>
</tr>
</tbody>
</table>

*The loss in the system is 1/2 of these values.
Conclusion

1) A factor $2^n$ RF pulse compression equivalent system can be constructed without any RF power storage devices such as a cavity or cavities.

2) In case of the X-band linear colliders, this system can have very high efficiency. The energy loss in the delay line is less than 2%, while an ordinary RF pulse compression system may suffer energy loss of about 25% or even more.

3) No narrow band component such as an energy storage cavity is necessary. Therefore this system can be as flexible as a conventional electron linac RF power system.

4) Practically, factor x2 or x3 equivalent system are preferable, therefore, the number of klystrons must be 2 or 1.5 times more.

5) A 500nsec class modulator and the pulse transformer system could achieve more than 75% efficiency.
<table>
<thead>
<tr>
<th></th>
<th>500 GeV</th>
<th>1.0 TeV</th>
<th>1.5 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Active Str. Length</strong> (km)</td>
<td>13.5</td>
<td>10.7</td>
<td>16.2</td>
</tr>
<tr>
<td><strong>Accelerating Gradient</strong> (MV/m)</td>
<td>50/37.3</td>
<td>60/44.8</td>
<td>85/63.4</td>
</tr>
<tr>
<td><strong>Unloaded/Loaded</strong> (MV/m)</td>
<td>50</td>
<td>72</td>
<td>145</td>
</tr>
<tr>
<td><strong>Input Power to Str.</strong> (MW/m)</td>
<td>1877</td>
<td>1487</td>
<td>2254</td>
</tr>
<tr>
<td><strong>Particles per Bunch</strong> (10^10)</td>
<td>0.65</td>
<td>0.78</td>
<td>1.10</td>
</tr>
<tr>
<td><strong>Repetition Rate</strong> (Hz)</td>
<td>180</td>
<td>120</td>
<td>120</td>
</tr>
<tr>
<td><strong>Bunches per RF Pulse</strong></td>
<td>90</td>
<td>75</td>
<td>75</td>
</tr>
<tr>
<td><strong>RF Pulse Length</strong> (µs)</td>
<td>240</td>
<td>220</td>
<td>220</td>
</tr>
<tr>
<td><strong>Pulse Compression System</strong></td>
<td></td>
<td>SLED-II (x5)</td>
<td>SLED-II (x5)</td>
</tr>
<tr>
<td><strong>Power Gain/Comp. Efficiency</strong></td>
<td>3.6 / 72%</td>
<td>3.6 / 72%</td>
<td>7.2 / 90%</td>
</tr>
<tr>
<td><strong>Klystron Pulse Length (µs)</strong></td>
<td>1.20</td>
<td>1.10</td>
<td>1.76</td>
</tr>
<tr>
<td><strong>Klystron Efficiency</strong></td>
<td>60%</td>
<td>65%</td>
<td>65%</td>
</tr>
<tr>
<td><strong>Peak Pwr. per RF Station (MW)</strong></td>
<td>100</td>
<td>145</td>
<td>289</td>
</tr>
<tr>
<td><strong>No. Kly. per Station @ Peak Pwr. (MW)</strong></td>
<td>2 @ 50</td>
<td>2 @ 72</td>
<td>4 @ 72</td>
</tr>
<tr>
<td><strong>Total No. Klystrons</strong></td>
<td>3754</td>
<td>2974</td>
<td>9016</td>
</tr>
<tr>
<td><strong>Modulator Efficiency</strong></td>
<td>PFN @ 75%</td>
<td>PFN @ 80%</td>
<td>PFN @ 80%</td>
</tr>
<tr>
<td><strong>Energy per Pulse per Station</strong> (J)</td>
<td>216 / 241</td>
<td>335 / 404</td>
<td>611</td>
</tr>
<tr>
<td><strong>Net RF System Efficiency</strong></td>
<td>32%</td>
<td>37%</td>
<td>47%</td>
</tr>
<tr>
<td><strong>Wall Plug Power</strong> (MW)</td>
<td>90</td>
<td>103</td>
<td>165</td>
</tr>
</tbody>
</table>
Status of Kilogram R&D

XL series: $K_p = 1.2$, $V_0 = 440$ kV

<table>
<thead>
<tr>
<th>Achieved</th>
<th>Jan '95</th>
</tr>
</thead>
<tbody>
<tr>
<td>XL1</td>
<td>XL2</td>
</tr>
<tr>
<td>3 cell</td>
<td>5 cell</td>
</tr>
<tr>
<td>50 (58)</td>
<td>50</td>
</tr>
<tr>
<td>Pulse Length (ps)</td>
<td>1.5 (0.4)</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>52 (42)</td>
</tr>
</tbody>
</table>

* Limited by TE$_{61}$ mode oscillation (3 multimode cavities tuned to same frequency)

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**Windows**

TE$_{01}$ TW windows using isostatic pressed ceramic
Reached **100 MW** in resonant ring at 60 Hz
In progress: 50 MW (and still going up) at 120 Hz

+ 1.5 ns needed for x 6 pulse compression in NLTA 1.2 ns design value for 500 MW NL.
**XL1 Klystron**

- **Input Power (Pin):** 85 W
- **Output Power (Pout):** 51 MW
- **Delay Time (t):** 1.5 μs
- **Peak Voltage (Vp):** 440 kV
- **Peak Current (Ip):** 332 A
- **Center Frequency (fc):** 11.455 GHz
- **Efficiency:** 34.9%

**Specifications:**

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>Saturated Output Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.420</td>
<td>47</td>
</tr>
<tr>
<td>11.4266</td>
<td>50</td>
</tr>
<tr>
<td>11.440</td>
<td>52.5</td>
</tr>
<tr>
<td>11.460</td>
<td>52.7</td>
</tr>
<tr>
<td>11.480</td>
<td>47</td>
</tr>
</tbody>
</table>

**Operational Conditions:** Window at 0-25 °C
PPM - Focused Hyotron for NLC

5 cell TW output circuit
short magnet period
$K_\mu = 0.6$

Simulated results at $V_0 = 470$ kV
- $P_{out} = 55$ MW
- $\eta = 66\%$

Beam stick ready x May '95
will test both immersed + Brillouin flow

video available (K. Eppley)
XL1

SOLENOID POWER: 24 KW

PPM FOCUSED DESCENDANT

NO FOCUSING POWER
## Modulators

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>$T_k$(MeV)</th>
<th>$V_{dc}$(kV)</th>
<th>$V_o$(kV)</th>
<th>$N_E$</th>
<th>$K_+$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5045</td>
<td>15:1</td>
<td>3.6</td>
<td>46</td>
<td>34.5</td>
<td>0.74</td>
<td>—</td>
</tr>
<tr>
<td><strong>DESY Hly.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23:1</td>
<td>2.1</td>
<td>46</td>
<td>52.5</td>
<td>0.60</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td><strong>Xe Hly</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20:1</td>
<td>0.9</td>
<td>46</td>
<td>48.0</td>
<td>0.50</td>
<td>—</td>
<td></td>
</tr>
<tr>
<td><strong>In Progress</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NLC TA(1)</td>
<td>24:1</td>
<td>1.6</td>
<td>48</td>
<td>58.0</td>
<td>0.70</td>
<td>—</td>
</tr>
<tr>
<td>Cassiope (2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6:5:1</td>
<td>1.0</td>
<td>65</td>
<td>60.0</td>
<td>0.80</td>
<td>0.75</td>
<td>—</td>
</tr>
<tr>
<td><strong>Future</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NLC (3)</td>
<td>8:1</td>
<td>1.2</td>
<td>67</td>
<td>53.5</td>
<td>0.80</td>
<td>0.75</td>
</tr>
<tr>
<td>1.0 TeV(4)</td>
<td>6:1</td>
<td>3.5</td>
<td>70</td>
<td>42.0</td>
<td>0.85</td>
<td>0.80</td>
</tr>
</tbody>
</table>

(1) Designed for 2x 100 MW Kilostroms
(2) Ready for high power tests x Feb. '85
(3) For PPM-focused tube: $K_n = 0.6$, $M = 0.6$, $\beta = 75$
(4) For kilostrom matched to a X16 BPC system:
   $K_n = 0.5$, $M = 0.70$, $\beta = 40$ MW
Overmoded $TE_{01}$-mode Components

Based on flower petal mode converter

$\frac{1}{2}$-1% loss $\begin{array}{c}
\begin{array}{c}
\text{[Diagram]}
\end{array}
\end{array}$ narrow wall of rectangular guide

8.7 2 bend = 2 FPs + rectangular bend 1%
3dB coupler = 4 FPs + oct. hybrid 2%

4.75" delay line 1.3%/µs
293 transmission line .06%/meter

WR 90 1%/meter

Flower petal tested to 150 MW in ASTA
## RF Pulse Compression Parameters for ASTA and NLCTA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ASTA</th>
<th>NLCTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klystron peak power</td>
<td>32 MW (Achieved)</td>
<td>50 MW (Planned)</td>
</tr>
<tr>
<td>Klystron pulse length</td>
<td>0.9–1.05 μs</td>
<td>1.5 μs</td>
</tr>
<tr>
<td>Accelerator pulse length</td>
<td>0.15 μs</td>
<td>0.25 μs</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>6–7</td>
<td>6</td>
</tr>
<tr>
<td>Intrinsic SLED-II efficiency</td>
<td>75–70%</td>
<td>75%</td>
</tr>
<tr>
<td>Efficiency due to component losses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Delay line</td>
<td>-3%</td>
<td>-4%</td>
</tr>
<tr>
<td>Mode transducer (R.T. loss)</td>
<td>-2%</td>
<td>-2%</td>
</tr>
<tr>
<td>Magic Tee (R.T. loss)</td>
<td>-7%</td>
<td>-1%</td>
</tr>
<tr>
<td>Non-optimal reflection coeff.</td>
<td>-(8–5)%</td>
<td>—</td>
</tr>
<tr>
<td>Net efficiency due to component losses</td>
<td>80–83%</td>
<td>94%</td>
</tr>
<tr>
<td>Net SLED-II efficiency</td>
<td>60–58%</td>
<td>70–66%</td>
</tr>
<tr>
<td>Power gain</td>
<td>3.6–4.1</td>
<td>4.2–4.6</td>
</tr>
</tbody>
</table>

*Mode conversion losses equal to wall losses (−5%/μs).*

\[ \times 85\% \text{ transmission efficiency} \]

\[ \text{net R.C. efficiency} = 0.6 \]

\[ \text{Power Gain} = 3.6 \]

TLI 7/13/84
Upgrade to 1.0/1.5 TeV

Higher Energy Power
\[ 2 \times 72 = 144 \text{ MW, beam-beam interaction} \]
Low \( \eta \) per port \( \implies \eta > 65\% \)

Grid Switched System
\( \eta \times 90\% \)?

More Pulse Compressions
SLED-II with active switch
(Sami: Tarlami)

\[ 16 \text{ compressions} \]
\[ 10\% \text{ RT loss} \]
\[ \begin{align*}
\eta &= 0.35 & \text{passive} \\
\eta &= 0.8 & \text{active switch}
\end{align*} \]

\[ 16 \text{ BPC with discrete cavities for delay line} \]

\[ Q_0 = \frac{25,880}{y^3 + \frac{1.2}{\eta}} \quad \text{TE}_{01} \text{ cavity} \quad \text{copper} \]
\[ y = 0.617/a \]
\[ \eta = \text{no. wavelengths long} \]
For the Future??

Pulse compression

$x16$ BPC system, with $\eta=80\%$, $P_0=12.8$. Uses 6 TE01 mode cuhites/Stage.

Compact: $x6m$ long $x2m$ high

$\text{Hycrontron}$

$T_k = 16 \times 220 \text{ ns} = 3.5 \mu s$  \hspace{1cm} $\eta_s=0.5$, $\eta_a=0.70$

$P_k = \frac{1}{2} \times \frac{144 \text{ MW/m} \times 7.2 \text{ m}}{12.8} = 40 \text{ MW}$

$\text{Modulator}$

Long pulse (3.5$\mu$s), low output voltage (420kV).
Low turn ratio (6:1), high eff. $\eta_s=80\%$

Net rf system efficiency

$\eta_{\text{rg}} (70\%) \times \eta_{\text{mod}} (80\%) \times \eta_{\text{pc}} (80\%) = 45\%$
JLC X-band Structure

Present design & R&D principle

1. Single bunch emittance growth
   alignment ~10 μm → \( \langle \frac{\sigma}{\lambda} \rangle \sim 0.16 \)

2. Multi bunch emittance growth
   detuned : \( \omega_0 \times \frac{1}{100} \) → 150 cell

→ Start fabrication study
   \( \frac{5f}{f} < 10^{-4} \)
   alignment cell ~ after μm
   precise machining & bonding

3. XB-72k

130MW 500ms × 2 klystrons & power distribution

→ 130MW structure 250ms

\[ T_f \sim 120ms \quad nT_0 \sim 120ms \]

\[ \langle E_{ml} \rangle \sim 73 \text{MV/m} \]

\[ \langle E_{lo} \rangle \geq 50 \text{MV/m} (?), \quad \text{Lee} \sim 20 \text{km for 1TeV} \]

detuned: medium damping ?
choke mode: initial/operational cost ? later
JLC-X parameters

RF pulse: \[ N_b \times t_b + T_f = 20 \times 1.4 \text{ ns} + T_f = 253 \text{ nsec} \]
Field: \[ E_{NL} = 40 \text{ MV/m}, E_{LD} = 20 \text{ MV/m} \]

Detuned structure of \( a/\lambda = 0.16 \) with medium damping

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency ( &lt;a/\lambda&gt; )</td>
<td>11.424 GHz</td>
</tr>
<tr>
<td>Number of cells</td>
<td>150</td>
</tr>
<tr>
<td>Effective length</td>
<td>1.31 m</td>
</tr>
<tr>
<td>Filling time ( \tau )</td>
<td>126.5 nsec</td>
</tr>
<tr>
<td>ENL</td>
<td>40 MV/m</td>
</tr>
<tr>
<td>(ELD)</td>
<td>23.8 MV/m</td>
</tr>
<tr>
<td>PIN</td>
<td>130 MW/structure</td>
</tr>
<tr>
<td>Q0</td>
<td>6550 ~ 6750</td>
</tr>
<tr>
<td>Qex</td>
<td>&lt; 2000</td>
</tr>
<tr>
<td>Iris width</td>
<td>4 mm</td>
</tr>
<tr>
<td>Iris height</td>
<td>2 mm</td>
</tr>
<tr>
<td>( \sigma f_{d_1}/f_{d_4} )</td>
<td>2.44%</td>
</tr>
<tr>
<td>( \Delta f_{d_1}/f_{d_4} )</td>
<td>12.5%</td>
</tr>
<tr>
<td>± 3 ( \sigma f_d/f_d )</td>
<td>&lt;10(^{-4})</td>
</tr>
</tbody>
</table>

To realize the damping of the wake field down to a few % during 126ns, QL should be < 1500 ----> s. ce Q0 = 6600 ----> Qex = 2000.
Iris width \( w = 3.5 \sim 3.8 \) mm to obtain Qex=2000.
If iris width \( w=4 \) mm ----> Qex=1600 in ideal matched case.
----- No degradation of accelerating mode
Qex=1600 ----> 2000 when \( |\Gamma| = 0.45 \) (VSWR = 2.6)
Disk thickness 2mm (K. Bane 1 to 2mm for higher modes > 1st & 2nd)
** artificially cited from JLC-I and should be calculated.

\[ \begin{align*}
1st\, mode & : 15.6 \, \text{GHz} & \Delta f & : 0.35 \, \text{GHz} & \Delta f & : 1.75 \, \text{GHz} \\
6th\, mode & : 36.3 \, \text{GHz} & \Delta f & : 0.26 \, \text{GHz} & \Delta f & : 1.30 \, \text{GHz}
\end{align*} \]
X-band structure studies at KEK

[1] Fabrication of 30cm CZ structure

"Establish reliable fabrication technique"

- IHI: Au 890°C 10g/mm² '93
- NKC: Au 800°C 5g/mm² Apr.'94
- MHI: Ag-plating 800°C 3g/mm² vac leak !!
- MHI: Cu-Cu 800°C 3g/mm² Dec. '94

[2] Fabrication of 1.3m detuned structure

Fabrication of full size structure $< a/\lambda > = 0.166$

---> gaussian detuned in 1st and 6th dipole modes
---> machining of 150 different cells
---> study the frequency controllability
---> high field characteristics

\[ E_{av} = 73 \text{ MV/m at } P_{in} = 130 \text{ MW} \]

- 1.3m [#1] with damping port without load
  ---> fabrication with
daumping / vacuum port milling ~1μm
good alignment of cells < a few μm

- 1.3m [#2] without damping port
  ---> check vacuum $10^{-8}$Torr inside ---> need baking, material?
  ---> wake feild measurement (ASSET) if calculation precise

  -> fab. machining & joining by company

[3] Precision machining of cells for SLAC 1.8m structure

  -> fine machining & brazing
[4] High field experiment

- **20cm-long structure (CERN)**
  
  ---> further conditioning the CERN structure  
  at >100MV/m and >100ns  
  peak accelerating field = **100 MV/m at 30 MW**

- **30cm-long structures**

  ---> high power performance of diffusion bonded structure  
  peak accelerating field = **100 MV/m at 131 MW**

- **1.3m-long structures**

  ---> high field characteristics of full-size structures  
  ---> average accelerating field = **73 MV/m at 130 MW**  
  ---> dark current, amount, emittance, multiplication  
  ---> VAC level inside structure  
  ---> break downs, fault rate
[5] Wake field related studies

--> in order to confirm the idea of "detuned structure"

- Development of wake field calculation
  for practical design
  treatment of rounded beam holes
  coupler cells
  how to damp through medium damping ports

- Trial of electrical measurement
  for checking the calculation

- Measurement using ASSET at SLAC
  1.3m structure
  with medium damping
  or without damping port (pure detuned)

- Estimation of tolerances
  considering beam dynamics with corrections
30cm Cu-Cu bonding structure

\[ \frac{\Delta f}{\Delta \ell} = -0.41 \text{ MHz/\mu m} \]
Summary of MHI 17cell Ag-LTD bonding

MHI 17cell measurement (each cell)
with dummy half cells
or with two plungers

GHz
11.0605
11.0625
11.06
11.05975
11.0595

GHz
11.3305
11.3295
11.329
11.3285
11.328

17cell alignment after diffusion bonding

Mean & Standard deviation
x = -2.5 ± 1.2
y = 0.2 ± 0.6

machined cell OD = ± 0.4 micrometer
V block straightness = 270 better than 1 micrometer in 17cell
Summary of IHI 30cm structure

![Graphs showing data for IHI 30cm structure](image-url)
Results of alignment IHI 30-cm structure bonded by diffusion brazing
Schematic drawing of a regular cell

Schematic drawing of 150-cell detuned structure
Regular cells for 1.5m Detuned Structure with Medium Damping
132. cell into furnace

Aug. '94
Cu-Cu diffusion bonding at 800°C for 1 hr.

**Diagram:**
- X-band Aoo Tube (図1-1)

**Graphs:**
1. **Alignment (A):**
   - Curvature measurement (μm)
   - Before and after comparison
2. **Alignment (B):**
   - Curvature measurement (μm)
   - Before and after comparison
132 cell Cu-Cu diffusion bonding at 100°C for 1 hr.

~10 kg weight, 3 g/mm² pressure

Xband Acc Tube (図2)

(L_after - L_before)

寸法差[mm] / [mm]

常温と拡散接合1回との差

長さの:

注: セルNo.132は1セル数使用せず

表-3のデータ参照
Summary on Precise Fabrication

1. Machining cells

- Face: $f \approx 0.1 \text{ MHz}$
- OD: full $\pm 0.5 \mu m$

2. Alignment of cells

- Assembling:
  - 10-30 cells
  - A few $\mu m$
  - Bonding: kept

3. Shrinkage along Z

- 3 $\mu m$ / junction or 3 $\mu m$ / cell at 890 $^\circ C$, 10 min
- 500 $\mu m$ / 122 cells at 800 $^\circ C$, 1 h

Need understanding of mechanism & perturbation to frag. on dipole modes.

4. Frequency control

- $f_{1\text{st}}$: $\approx 0.1 \text{ MHz}$ at 750 $^\circ C$
- $f_{2\text{nd}}$: $\approx 1 \text{ MHz}$ at 890 $^\circ C$ 10$^\circ$C 1 h 850 $^\circ C$ 1 h

Temp. dep.

Need summary of data.

$S_{1\text{st}}$, $S_{2\text{nd}}$, or others larger?

Need control of how in add. to face.
CERN-made 20cm CZ structure

Eacc_av [MV/m]

Time_Integrated [hrs]

Dark current from CERN-made 20cm structure

Peak_Current [μA]

Eacc_av
Electron Trajectory Simulator (Yamaguchi)

\[ \Phi_L \text{ on } \left\{ a = 3 \text{ m}, t = 2 \text{ m} \right\} \text{ X-band } \frac{2\pi}{3} \text{ structure} \]

M116_data-60cells

Phase at emission of trapped electrons

\[ \text{Eacc [MV/m]} \]

M116_data-29cells

Phase at emission of trapped electrons

\[ \text{Eacc [MV/m]} \]

(\text{dep. on Eacc})
Area where some field emitted electrons come out of structure.
M116_critical gradient

Eacc [MV/m] vs. cells
Geometry of "Open Mode Expansion" Yamamoto (1-32).

図 G.1: 非周期構造の電場の積分経路。点線に沿って $E_z$ の線積分を行う。
Open Mode Expansion
Basic Modes

(a); open 1 (e₁)  (b); open 2 (e₂)  (c); open 3 (e₃)  (d); open 4 (e₄)

(e); open 5 (e₅)  (f); open 6 (e₆)  (g); open 7 (e₇)  (h); open 8 (e₈)

Electric Fields of the open mode. Resonant modes of the detuned structure was calculated by open mode expansion using base function as shown above.
from Maxwell's eq.

\[
\left\{ \left( \frac{\omega}{c} \right)^2 - \left( \frac{\omega_i}{c} \right)^2 \right\} \int V \mathbf{E}_i^* \cdot \mathbf{E} \, dV = \int_S \left( \frac{\omega_i}{c} \mathbf{E} \times \mathbf{h}_i^* \right) \cdot \mathbf{n} \, dS
\]

\[ E = \sum_{j=1}^{\infty} a_j \mathbf{e}_j \quad \text{open mode expansion} \]

\[ \mathbf{e}_i(L) = \mathbf{\dot{e}}_i(R) \]

\[ \mathbf{h}_i^*(L) = -\mathbf{\ddot{h}}_i^*(R) \]

\[
\left\{ \left( \frac{\omega}{c} \right)^2 - \left( \frac{\omega_i}{c} \right)^2 \right\} \int V \mathbf{E}_i^* \cdot \mathbf{E} \, dV = \frac{\omega_i}{2c} \sum_{j=1}^{\infty} a_j (\mathbf{\dot{e}}_i \mathbf{e}^{i\phi} + \mathbf{\dot{\sigma}}_j \mathbf{e}^{-i\phi} + \mathbf{\ddot{\sigma}}_j + 1) \int_R \{ \mathbf{\dot{e}}_j(R) \times \mathbf{h}_i^*(R) \} \cdot \mathbf{n}_R \, dS
\]

\[ v_{ij} = \int_V \mathbf{E}_i^* \cdot \mathbf{\dot{e}}_j \, dV \]

\[ m_{ij} = \int_R \mathbf{\dot{e}}_j(R) \times \mathbf{h}_i^*(R) \cdot \mathbf{n}_R \, dS \]

\[ \mathbf{n} = \begin{pmatrix} a_1 \\ a_2 \\ a_2 \\ \vdots \end{pmatrix} \]

\[ \mathbf{\dot{\Omega}}_{ij} = \mathbf{\ddot{\omega}}_i \delta_{ij} \]

\[ U_{ij} = \frac{\omega_i^2}{\omega_j^2 - \omega_i^2} [\mathbf{\dot{\sigma}}_j \mathbf{\ddot{\sigma}}_i + 1] m_{ij} = \frac{\omega_i}{c} v_{ij} \]

\[ T_{ij} = \frac{1}{2} [\mathbf{\dot{\sigma}}_i \mathbf{e}^{i\phi} + \mathbf{\dot{\sigma}}_j \mathbf{e}^{-i\phi} + \mathbf{\ddot{\sigma}}_i \mathbf{\dot{\sigma}}_j + 1] m_{ij} \]

\[ Xa = \omega^2 a \]

\[ X = U^{-1} \mathbf{\dot{\Omega}}^2 (T + U) \]

216
図 J.3: $VMX$ をエルミート行列にしたときの分散関係 ($a=6.0\text{mm}$)。黒丸はフィールドマッチング、実線はオープンモード展開で計算した結果である。それぞれの図は展開するモード数が異なる。
図 J.6: $VMX$ をエルミート行列にしたときのキック因子 ($\alpha = 6.0 \, [\mu m]$)。黒丸はフィールドマッチング、実線や破線はオープンモード展開の結果を示す。
Basic Parameters of Structure under Fabrication Test

detune 181
図4.14: 周波数分収構造の固有ベクトル。横軸はセルの番号、縦軸はオープンモードの固有ベクトルの成分を示す。各グラフ上の数値は、共振モードの番号と周波数である。

図4.12: 周波数分収構造の固有ベクトル。横軸はセルの番号、縦軸はオープンモードの固有ベクトルの成分を示す。各グラフ上の数値は、共振モードの番号と周波数である。
図 4.11: 周波数分散構造のキック因子
図 4.18: 少しずつ形状の異なる4個の周波数分散構造のウェーク関数の絶対値の包絡線
\[ c \sum_{\ell=1}^{m-1} W_\ell (X_{\ell}) \]

#181

#181, all, wake sum of before

#181 & 2

#181 all
detune 181

average $a / \lambda = 0.165824$ in 150. cell structure

$\tau = 0.578477$

Filling time = 106.404 [ns]

Voltage/structure = 84.3924 [MV] in 100MW input

$E_{av} = 64.3181$ [MV/m] in 100MW input
第4章 非周期構造のオープンモード展開

図4.6: MAFIAとオープンモード展開の共振周波数。横軸は周波数の低い順に並べたモードの番号である。

図4.7: MAFIAとオープンモード展開で計算されたキック因子。横軸は周波数の低い順に並べたモードの番号である。
Frequency in ascending order.

28-all C-Band Detuned Structure
Frequency vs Mode No.

* measured
* calculated

- Higher freq. resonance not yet measured.
- Some in middle freq. range seem missing.
Design for reduction of Long Range Dipole Wake: "remains"

1. Open mode expansion
   - extension to more modes than 8, rounded in to non symmetry

2. Equivalent circuit
   - medium damping
   - coupling to WG & Beam Tube

3. Choke mode cavity

4. Checking Wake field
   - What to check?
   - gross structure of wake
   - fine structure of wake at 0.1
   - necessary information on structure parameter?

5. Design of feedback with beam with BPMs etc.
PROGRESS REPORT
ON STUDIES OF
ACCELERATOR STRUCTURES

Juwen Wang

Accelerator Theory and Special Projects Department

SLAC

December/1994
WORK on ACCELERATOR STRUCTURES

1. Theoretical Calculations
   - Design and RF Parameter Calculation
   - Equivalent Circuit Models
   - Field Matching Technique and Applications
   - Beam Loading Calculations
   - Resonant Phenomenon
   - Multibunch Effects, Misalignment, interleaving, ..... 
   - Numerical Simulations (Couplers, Pumping Holes...)
   - Weak Damping for Detuned Structure
   - Vacuum System Calculations

2. Low-Power Measurements
   - Matching, Tuning and Mode Studies

3. High-Power Tests
   - 7-cavity X-Band SW Section
   - Four Types of X-Band TW Sections

4. Wakefield Measurements
   - Argonne’s AATF for Detuned Structure Models
   - ASSET for 1.8m Detuned Section in SLC

5. Fabrication Technique Studies
   - Design and Machining (75cm and 1.8m Sections)
   - Brazing and Alignment
   - CMM Machine Measurements
Design of First 1.8 m Detuned Section

\[ f_r = f_i (a + t) \]

Lowest Synchronous Dipole Mode Frequency (GHz)

\[
\begin{array}{c|c|c|c|c|c|c|c|c}
0.3 & 0.325 & 0.35 & 0.375 & 0.4 & 0.425 & 0.45 \\
0.04 & 0.05 & 0.06 & 0.07 & 0.08 & 0.09 & 0.1 \\
\end{array}
\]

2a (inches) 2a_i = 0.4464
2b (inches) 2b_i = 0.9010 inches

2a_{06} = 0.3094 inches
2b_{06} = 0.8413 inches

2a = 0.4464 inches
2b_i = 0.9010 inches

2a_{06} = 0.3094 inches
2b_{06} = 0.8413 inches

\[ f_0 (a + b + t) = 11.424 \text{ GHz} \]

YAP: 2-D Finite Element Code
Transverse Wakefield Envelope (V/pC/mm/m)

Distance Behind Driving Bunch (m)

bunch spacing
0.42 m
1.4 ns
ACCELERATING GRADIENT AT 100 MW INPUT POWER

ACCELERATING GRADIENT (MV/M)

Structure
- Detuned
- Constant Gradient
- Constant Impedance

Z (M)
MODEL OF 18m ACCELERATOR STRUCTURE FOR NLCTA
Beam Loading and Compensation for 1.8 m Detuned Structure

Fig. 1. Generator, beam and loaded gradients as a function of cell number n.

Rsh1 = 67.48  Rsh2 = 87.96  Q1 = 7416  Q2 = 6674

Pin = 87.8 MW, Steady Case

Fig. 2. Norm. input field and difference between it and a linear field (dots) vs time

Initial norm. power = 0.3758

Farkas / Wilson
Beam Loading and Compensation for 0.9m Detuned Structure

Electric Field (MV/m)

$P_{in} = 86.5\text{ MW}$, Steady Case 0.92m

RF Electric Field Envelope at Input End (MV/m)

Capture Section needs special consideration.

J.W.
High-Gradient Studies at SLAC

X-Band SW $E_s = 570\text{MV/m}$

<table>
<thead>
<tr>
<th>X-Band</th>
<th>TW</th>
<th>$E_{ave}\text{(MV/m)}$</th>
<th>$E_{a,max}\text{(MV/m)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>26cm CI</td>
<td>101</td>
<td>108 Limited by Power</td>
<td></td>
</tr>
<tr>
<td>75cm CI</td>
<td>79</td>
<td>90 Power</td>
<td></td>
</tr>
<tr>
<td>1.8m Detuned</td>
<td>55</td>
<td>65 Power</td>
<td></td>
</tr>
<tr>
<td>(CERN)</td>
<td>24cm CI</td>
<td>125</td>
<td>152 Time</td>
</tr>
</tbody>
</table>

Learned a Great Deal about

- RF Processing
- Dark Current Due to Field Emission
- RF Breakdown Phenomenon
Acceleration Test in ASTA
1.8 m X-Band TW Section

USA 602 DIGITIZING SIGNAL ANALYZER

date: 4-MAR-94 time: 22:59:35

at $E_{acc} = 53 \text{MV/m}$

![Graph showing signals and waveforms with labels for input and output, peak values, and time scales][1]

[1]: https://example.com/graph.jpg
DARK CURRENT PRODUCED BY TW ACCELERATOR SECTIONS

1.8m Section
March 6, 1994

75cm Section
September 23, 1993

75cm Section
October 9, 1993

PEAK DARK CURRENT (mA)

AVERAGE ACCELERATING GRADIENT (MV/m)
Accelerator Structure SETup (ASSET) in the SLC

MEASUREMENT OF THE BUNCH-TO-BUNCH TRANSVERSE WAKEFIELD COUPLING IN THE TEST STRUCTURE

- Inject a positron bunch into the linac followed by an electron bunch - the positrons serve as the drive bunch and electrons as the witness bunch.
- Vary the vertical drive bunch amplitude and measure the betatron amplitude of the witness bunch in the linac after the drive bunch is dumped - the ratio of these amplitudes is proportional to the wakefield coupling.
- Repeat for different bunch-to-bunch time separations to measure the temporal dependence of the long-range transverse wakefield.
Dipole wakefield measured (a) near the bunch crossing and (b) at a bunch separation of about 92 ns. The solid lines are described in the text.
Dipole wakefield amplitude measurements and prediction
a) without cell frequency errors and b) with $1.5 \times 10^{-4}$ rms fractional frequency errors.
1.8 m NHCTA Structure: Short Stacks

Data direction $\sigma_x = 10 \mu m$

Data direction $\sigma_y = 13 \mu m$

Data direction $\sigma_y = 18 \mu m$

Data direction $\sigma_x = 10 \mu m$. 

Cells 163-200

Cells 44-82

X-BAND STRUCTURE

X-BAND STRUCTURE

X-BAND STRUCTURE
<table>
<thead>
<tr>
<th></th>
<th>Regular Machine</th>
<th>Diamond Machine</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimension Tolerance</strong></td>
<td>±7 μm</td>
<td>Δf₀ &lt; 1.5 MHz</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Δf₀ &lt; 1 x 10⁻⁴</td>
</tr>
<tr>
<td><strong>Surface Finishing</strong></td>
<td>0.2 μm</td>
<td>0.025 μm</td>
</tr>
</tbody>
</table>

**Alignment**

Nesting (40-cavity stack) ±20 μm

Vee-Block (16-cavity stack) ±4 μm
MANIF FREQS, BG LFS, CONST Q = 6500.
Wake envelope for 4 interleaved structures

No freq. errors

\( \sigma_e, \sigma_p = 1 \times 10^{-4} \)
Freq errors (typical seed)

Considerable degradation of wake due to frequency errors
Cutaway View

Cross-section through Center of a Cavity

Beam Hole Iris
Cavity Wall
Slot from Cavity into Manifold
Damping and pumping Manifold
1. Single-mode (TE_0) manifold
2. Double-mode
3. Multi-mode

CELL 70

CELL 196

CELL 10

CELL 122
<SINGLE-MODE MANIFOLD>

<table>
<thead>
<tr>
<th></th>
<th>CELL 10</th>
<th>CELL 70</th>
<th>CELL 122</th>
<th>CELL 196</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>WG</strong></td>
<td>5 x 10.8</td>
<td>5 x 10.2</td>
<td>5 x 9.7</td>
<td>5 x 9.4</td>
</tr>
<tr>
<td><strong>SLOT</strong></td>
<td>5 x (+2.0)</td>
<td>5 x (+1.0)</td>
<td>5 x (-0.5)</td>
<td>5 x (-1.45)</td>
</tr>
<tr>
<td>$\hat{\eta}$</td>
<td>0.083</td>
<td>0.081</td>
<td>0.084</td>
<td>0.068</td>
</tr>
<tr>
<td>$\phi_{cr}$</td>
<td>58°</td>
<td>67°</td>
<td>72°</td>
<td>83°</td>
</tr>
<tr>
<td>$f_c \ (GHz)$</td>
<td>12.208</td>
<td>12.910</td>
<td>13.315</td>
<td>13.706</td>
</tr>
<tr>
<td>$\frac{\Delta R}{R}_{100}$</td>
<td>1.53%</td>
<td>1.38%</td>
<td>3.9%</td>
<td>5.0%</td>
</tr>
</tbody>
</table>
### NLC ACCELERATOR PARAMETERS

(Single Mode DDT)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Section length</td>
<td>1.8 m</td>
</tr>
<tr>
<td>Phase advance per cell</td>
<td>$2\pi/3$</td>
</tr>
<tr>
<td>Iris aperture diameter</td>
<td>1.134-0.786 cm</td>
</tr>
<tr>
<td>Cavity diameter</td>
<td>2.228-2.059 cm</td>
</tr>
<tr>
<td>Group velocity</td>
<td>0.12$c$-0.03$c$</td>
</tr>
<tr>
<td>Filling time</td>
<td>100 ns</td>
</tr>
<tr>
<td>Unloaded time constant</td>
<td>205-177 ns</td>
</tr>
<tr>
<td>Attenuation parameter</td>
<td>0.498 nepers</td>
</tr>
<tr>
<td>Shunt impedance</td>
<td>66.48-83.40 MΩ/m</td>
</tr>
<tr>
<td>Elastance ($\omega R/Q$ per unit length)</td>
<td>849-941 V/pC/m</td>
</tr>
<tr>
<td>Peak input power/(1.8 m) for 50 MV/m</td>
<td>49.9 MW/m</td>
</tr>
<tr>
<td>Peak power per feed for 50 MV/m</td>
<td>89.7 MW</td>
</tr>
<tr>
<td>Structure average power dissipation for 50 MV/m, 250-ns pulse length, 180 pps</td>
<td>1.45 kW/m</td>
</tr>
</tbody>
</table>
SUMMARY

1. Several Short Sections Constructed
   - Manufacture Studies
   - High Power Tested with $E > 100 \text{MV/m}$

2. First 1.8 Detuned Section Constructed
   - Design Studies
   - Cold Test Without Tuning
   - High Power Test with $E > 55 \text{MV/m}$
   - ASSET Wakefield Measurement

3. Second 1.8m Detuned Section
   - Rough Machining at Local Company
   - Diamond Machining at KEK

4. Two 0.9m Detuned Sections for NLCTA Injector
   - Machining Started

5. Third 1.8m Section
   - Detuning with Weak Damping under Study
JLC-I  250 GeV + 250 GeV
Table 3.5: Characteristics of JLC-I

<table>
<thead>
<tr>
<th>$E_{\text{beam}}$ (GeV)</th>
<th>150</th>
<th>150</th>
<th>150</th>
<th>250</th>
<th>250</th>
<th>250</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band</td>
<td>S</td>
<td>C</td>
<td>X</td>
<td>S</td>
<td>C</td>
<td>X</td>
</tr>
<tr>
<td>$L$ (cm$^{-2}$sec$^{-1}$) $\times 10^{33}$</td>
<td>3.5</td>
<td>6.6</td>
<td>3.2</td>
<td>4.8</td>
<td>11.</td>
<td>6.3</td>
</tr>
<tr>
<td>$L$ (cm$^{-2}$bunch$^{-1}$) $\times 10^{20}$</td>
<td>15.3</td>
<td>6.1</td>
<td>2.4</td>
<td>17.5</td>
<td>10.</td>
<td>4.7</td>
</tr>
<tr>
<td>rep. rate (Hz)</td>
<td>50</td>
<td>150</td>
<td>150</td>
<td>50</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>number of bunches</td>
<td>46</td>
<td>72</td>
<td>90</td>
<td>55</td>
<td>72</td>
<td>90</td>
</tr>
<tr>
<td>bunch separation</td>
<td>5.6 ns</td>
<td>2.8 ns</td>
<td>1.4 ns</td>
<td>5.6 ns</td>
<td>2.8 ns</td>
<td>1.4 ns</td>
</tr>
<tr>
<td>$N_e$/bunch $\times 10^{10}$</td>
<td>1.56</td>
<td>1.0</td>
<td>0.63</td>
<td>1.30</td>
<td>1.0</td>
<td>0.63</td>
</tr>
<tr>
<td>$\sigma_x$ (nm)</td>
<td>335.</td>
<td>335.</td>
<td>335.</td>
<td>301.</td>
<td>260.</td>
<td>260.</td>
</tr>
<tr>
<td>$\sigma_y$ (nm)</td>
<td>3.92</td>
<td>3.92</td>
<td>3.92</td>
<td>3.04</td>
<td>3.04</td>
<td>3.04</td>
</tr>
<tr>
<td>$\sigma_z$ (µm)</td>
<td>80.</td>
<td>80.</td>
<td>85.</td>
<td>80.</td>
<td>80.</td>
<td>67.</td>
</tr>
<tr>
<td>$\beta_x$ (mm)</td>
<td>10.</td>
<td>10.</td>
<td>10.</td>
<td>10.</td>
<td>10.</td>
<td>10.</td>
</tr>
<tr>
<td>$\beta_y$ (µm)</td>
<td>100.</td>
<td>100.</td>
<td>100.</td>
<td>100.</td>
<td>100.</td>
<td>100.</td>
</tr>
<tr>
<td>$D_x$</td>
<td>0.21</td>
<td>0.13</td>
<td>0.090</td>
<td>0.13</td>
<td>0.13</td>
<td>0.071</td>
</tr>
<tr>
<td>$D_y$</td>
<td>18.0</td>
<td>11.5</td>
<td>7.7</td>
<td>13.0</td>
<td>11.5</td>
<td>6.1</td>
</tr>
<tr>
<td>disruption angle: $\theta_x$ (mrad)</td>
<td>0.88</td>
<td>0.57</td>
<td>0.35</td>
<td>0.49</td>
<td>0.44</td>
<td>0.27</td>
</tr>
<tr>
<td>crossing angle: $\phi_x$ (mrad)</td>
<td>11.0</td>
<td>10.4</td>
<td>9.0</td>
<td>7.3</td>
<td>8.0</td>
<td>7.2</td>
</tr>
<tr>
<td>$\langle T \rangle$</td>
<td>0.14</td>
<td>0.093</td>
<td>0.059</td>
<td>0.23</td>
<td>0.19</td>
<td>0.15</td>
</tr>
<tr>
<td>$\gamma_{\text{max}}$</td>
<td>0.47</td>
<td>0.32</td>
<td>0.19</td>
<td>0.78</td>
<td>0.70</td>
<td>0.51</td>
</tr>
<tr>
<td>energy loss ($\delta$) (%)</td>
<td>7.0</td>
<td>3.5</td>
<td>1.7</td>
<td>9.0</td>
<td>7.0</td>
<td>4.0</td>
</tr>
<tr>
<td>$n_T$</td>
<td>1.7</td>
<td>1.1</td>
<td>0.74</td>
<td>1.6</td>
<td>1.4</td>
<td>0.91</td>
</tr>
<tr>
<td>$A$</td>
<td>1.3</td>
<td>0.95</td>
<td>0.74</td>
<td>1.0</td>
<td>0.93</td>
<td>0.66</td>
</tr>
<tr>
<td>$1.65 \times P_{\text{max}}$ (MeV) at $\theta = 0.15$</td>
<td>26.9</td>
<td>17.2</td>
<td>10.3</td>
<td>22.9</td>
<td>18.2</td>
<td>13.2</td>
</tr>
<tr>
<td>$R_{\text{mask}}$ (cm)</td>
<td>9.0</td>
<td>5.7</td>
<td>3.5</td>
<td>7.7</td>
<td>6.1</td>
<td>4.4</td>
</tr>
<tr>
<td>$L_{\text{mask}}$ (m)</td>
<td>0.60</td>
<td>0.38</td>
<td>0.23</td>
<td>0.51</td>
<td>0.41</td>
<td>0.29</td>
</tr>
<tr>
<td>$\eta_{\text{mask}}(I_Q = 2.5 m) \times 10^{-4}$</td>
<td>6.0</td>
<td>1.9</td>
<td>0.60</td>
<td>3.9</td>
<td>2.2</td>
<td>1.0</td>
</tr>
<tr>
<td>total energy deposits (GeV) and e's/bunch</td>
<td>429.4</td>
<td>117.8</td>
<td>63.1</td>
<td>350.2</td>
<td>100.4</td>
<td>81.6</td>
</tr>
<tr>
<td>and e's/bunch</td>
<td>(188.5)</td>
<td>(21.1)</td>
<td>(5.8)</td>
<td>(69.8)</td>
<td>(34.4)</td>
<td>(11.1)</td>
</tr>
<tr>
<td>number of hits(e's)/bunch in $</td>
<td>\cos \theta_e</td>
<td>&lt; 0.9$</td>
<td>76.8</td>
<td>7.3</td>
<td>124.</td>
<td>51.7</td>
</tr>
<tr>
<td>$\tau = 2 \text{ cm}$</td>
<td>(14.6)</td>
<td>(4.7)</td>
<td>(2.8)</td>
<td>(10.9)</td>
<td>(6.8)</td>
<td>(2.9)</td>
</tr>
<tr>
<td>$\tau = 5 \text{ cm}$</td>
<td>2.3</td>
<td>1.1</td>
<td>0.</td>
<td>1.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$\tau = 30 \text{ cm}$</td>
<td>(1.0)</td>
<td>(0.5)</td>
<td>(0)</td>
<td>(0.75)</td>
<td>(0.2)</td>
<td>(0.2)</td>
</tr>
</tbody>
</table>
1 Design of Optics

The design concept of the JLC final focus system has its base on the non-interleaved two-family sextupole chromaticity correction scheme [?]. Table 1 lists the main parameters of the final focus system. The parameters are for the beam energy 250 GeV and we can use the same optics for a lower energy only with scaling of the strengths of magnets. In Table 1, the incoming emittances are somewhat larger than those at the damping ring. We design the focusing optics to accept a beam with a certain amount of blow-up and a emittance dilution. The emittances at the interaction point (IP) are larger than the incoming, since they suffer from optical aberrations including the synchrotron radiation. The beta functions at IP are determined considering the chromaticities and the effects of the synchrotron radiation in the final lenses on their focusing. The focusing components including the final lenses are all conventional and possible to be built under existing technologies.

Table 1: Parameters of the JLC final focus system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy</td>
<td>$E_0$</td>
</tr>
<tr>
<td></td>
<td>250</td>
</tr>
<tr>
<td>GeV</td>
<td></td>
</tr>
<tr>
<td>Incoming invariant emittances</td>
<td>$\varepsilon_x/\varepsilon_y$</td>
</tr>
<tr>
<td>Invariant emittances at IP</td>
<td>$\varepsilon_x/\varepsilon_y$</td>
</tr>
<tr>
<td>$\beta$ functions at the IP</td>
<td>$\beta_x^<em>/\beta_y^</em>$</td>
</tr>
<tr>
<td>Spot sizes at the IP</td>
<td>$\sigma_x^<em>/\sigma_y^</em>$</td>
</tr>
<tr>
<td>Free area length</td>
<td>$\ell^*$</td>
</tr>
<tr>
<td>Half aperture of the final quad</td>
<td>$a$</td>
</tr>
<tr>
<td>Pole-tip field</td>
<td>$B_0$</td>
</tr>
<tr>
<td>Length of the final quad</td>
<td>$L_1$</td>
</tr>
<tr>
<td>Chromaticities of final lenses</td>
<td>$\xi_x/\xi_y$</td>
</tr>
<tr>
<td>Momentum bandwidth</td>
<td>$\chi_m$</td>
</tr>
<tr>
<td>Total bend angle</td>
<td>$\theta$</td>
</tr>
<tr>
<td>Length/beam</td>
<td>$L_0$</td>
</tr>
</tbody>
</table>

This optical scheme is essentially same as the FFTB optics[?]. The magnet lattice and the optical functions are show in Fig. 1. We have installed several new characteristics on top of the FFTB design. The first one is the long length of the free area for the detector. We set this length $\ell^*$ to 2.5 m, which is a sufficient length to place the masks for the background,
Beam size at the IP in JLC-FF
with and without orbit correction

\[ \sigma_x, \sigma_y \]

- \( \sigma_x \) - Without Orbit Correction
- \( \sigma_y \) - With orbit correction using 100nm BPM

\( \sigma_{\text{ground}} \) (m)

\( 10^{-4} \) to \( 10^{-8} \)
Chromo-geometric - No aberrations

Displacement

\sigma_x^2 \quad \sigma_y^2 \quad b

Radiation in Quads
Radiation in Bends
Chromo-geometric
Geometric
Chromatic

No aberrations
Δx, Δy (μm) for Δξ/Δη = 0.1
\[ \Delta x, \Delta y \text{ (nm)} \]

\[ \frac{\Delta y}{\Delta x} \]

\[ \text{for } \Delta x, \Delta y = 0.1 \]

\[ \text{and } \Delta x, \Delta y = 0.1 \]

- QA1
- QA2
- QA3
- QA4
- SF
- QN2
- QN1
- QN2.2
- SF.5
- QT1
- QT2
- QT3
- SD
- QM2
- QM1
- QM2.2
- SD.5
- QB2
- QB1
- QC4
- QC3
- QC2
- QC1

268
Spot size at IP (m)

Initial spot

Beam-based alignment

Global knobs 1

Global knobs 2

Global knobs 3

Global knobs 4

$\sigma_y^*$ (ave.)

$\sigma_x^*$ (ave.)

$\sigma_y^*$ (max.)

$\sigma_x^*$ (max.)

design values
Table 3: Parameters of the JLC collimation section

<table>
<thead>
<tr>
<th>Bending section 1 &amp; 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending angle</td>
<td>20 &amp; -16 mrad</td>
</tr>
<tr>
<td>Bending radius</td>
<td>4200 m</td>
</tr>
<tr>
<td>Tune $\nu_x = \nu_y$</td>
<td>3.5 &amp; 2.75</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy collimator</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance $\Delta p/p$</td>
<td>±1.5 %</td>
</tr>
<tr>
<td>Collimator half aperture</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Beta at col. $\beta_x/\beta_y$</td>
<td>100/300 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nonlinear transverse collimator</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance $x/y = x'/y'$</td>
<td>$\pm 6\sigma_x/\pm 35\sigma_y$</td>
</tr>
<tr>
<td>Collimator half aperture</td>
<td>0.3 mm</td>
</tr>
<tr>
<td>Beta at sextupoles $\beta_x/\beta_y$</td>
<td>67/134 m</td>
</tr>
<tr>
<td>Sextupole pole tip field</td>
<td>1 T</td>
</tr>
<tr>
<td>Sextupole aperture</td>
<td>5 mm</td>
</tr>
<tr>
<td>Sextupole length</td>
<td>4 m</td>
</tr>
</tbody>
</table>
horizontal and vertical directions, which correspond to $22\sigma_x$ and $264\sigma_y$, respectively, there is emittance growth due to a wake field by the mask. There is no secondary particles ($e^\pm$'s or $\mu^\pm$'s) created at the mask because no beam tail can hit it. With this mask the synchrotron radiation is well collimated to 1 cm at IP.

**Quadrupole Magnets**

There are only 4 quadrupole magnets, QC1 - QC4, in a straight section between the last magnet and IP. Among them QC2 is the largest radiation source. Here we do not need any mask since a doublet of final quadrupole magnets (QC1 and QC2) is so near IP that there is no way to stop back-scattered synchrotron radiations from the mask. The control of synchrotron radiations from the quadrupole magnets is uniquely provided by the optics of focus system. The optics is carefully determined in order to have a large bore (1.34 cm), which is enough for the synchrotron radiations to go through without scattering for collimated at $\pm 6\sigma_x$, $\pm 35\sigma_y$. The tail of the synchrotron radiations is also produced by off-axis profiles discussed in the previous section; there must be tails up to $10^4$ photons beyond sharp lateral spreads in Fig.3.20. We show Fig.3.21 to see how the radiations go through the off-axis profiles; those of the radiations with exit beam (after collision) since angle is 8 mrad at $E_{\text{beam}}=250$GeV and QC1 is 2.4 m long, whereas the profile at the exit of focusing beam (before collision). Therefore there is no serious background synchrotron radiations.

---

Figure 3.20: Profile of synchrotron radiation per train crossing from QC4-QC1 at the front face QC1 seen from IP, i.e. 2.5 m upstream from IP for $E_{\text{beam}}=250$GeV.
3.7.5 Masking System

Our masking system is schematically shown in Fig.3.24. A mask is employed in order to shield against the large amount of the secondary photons. The probability for the $O(10^7)$ photons/train (see Tab.3.5) to escape from the mask, $\eta_{\text{mask}}$, should be less than $10^{-3}$, which is geometrically determined by the front aperture of the mask. Most of the escaped photons hit the mask surface on the opposite side, then they enter the detector region. In addition the mask must have enough thickness to absorb the photons, that is, its attenuation coefficient should be less than $10^{-3}$ for 0.5MeV photons which corresponds to a 5cm thick tungsten. We require that the acceptable number of photons in the detector region is $O(10^2)$ per train crossing. As we fix the angular region of the mask as $0.15 < \theta_{\text{mask}} < 0.2$, it remains to determine only one parameter to fully specify the geometry of the mask. We take the half aperture of the mask, $\theta_{\text{mask}}$ in Fig.3.24, for this parameter. $R_{\text{mask}}$ can be linearly related to a diameter of circular trajectory of a charged track in a solenoidal magnetic field ($B$), i.e. $R_{\text{mask}} = p_{\text{max}}/0.15B$ and $B=2$Telsa. We determine $R_{\text{mask}}$ for the pairs, which comprise a shoulder in Fig.3.23, to loop inside the mask. There is another important constraint from the solid angle seen by the photons back-scattered at QC1, i.e. $\eta_{\text{mask}} = R_{\text{mask}}^2/4(L_Q - L_{\text{mask}})^2 < 1 \times 10^{-3}$, where $L_{\text{mask}}$ and $L_Q$ are the distances of the mask and the final focus quadrupole magnet from the interaction point(IP), respectively(Fig.3.24). The location of the final focus quadrupole magnet has been set to be 2.5 m from IP for the synchrotron radiations to go through QC1 without scattering as mentioned in the previous section. The optimized values of $R_{\text{mask}}$, $L_{\text{mask}}$ and $\eta_{\text{mask}}$ are also listed in Tab.3.5. With this masking system, the total number of charged particles hitting the outer surface of the mask is less than $10^3$/train(72 bunches) as shown in Fig.3.23.
Figure 3.23: Pair yield/bunch crossing as a function of $P_t^o$ for $\theta_\phi > 0.15$ at JLC-I(c-band).

Figure 3.24: A masking system at the interaction region.
Figure 3.25: background hits by the pairs in B=2 Tesla as a function of radius ($R_{\text{vtx}}$).
Figure 3.21: Cross sectional views of incoming and outgoing synchrotron radiations, which are shown as ellipses, at the entrance and exit of QC1, for $E_{\text{beam}} = 250 \text{GeV}$, where the crossing angle of two beams is 8 mrad. QC1 is located at 2.5m upstream from IP, and its half aperture and length are 6.7mm and 2.4m, respectively. Its coils are indicated by crosses boxes. Disrupted beams after collision are also plotted by dots.