The KEK C-band RF System for Linear Collider

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Collaborating with
- Pohang Accelerator Laboratory
- RIKEN at SPring8
- Univ. of Tokyo
- Shanghai Light Source

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Why we developed C-band technology

(1) **With a minimum R&D** to construct the 1st stage LC and to start the physics program as early as possible.

(2) **Many devices/ideas developed for C-band can be used for other LC technologies.**

(3) **To bring spin-off of the C-band LC technology to other fields of science and also to industry.**

X-ray and infrared-red free electron lasers (e.g. SCSS at SPring8) Compact electron linacs for medical use and for sterilization.
1) Conservative design based on the S-band experiences. S-band linac was established ½ century ago. It is a global-standard of the high energy electron linacs.

SLAC 2-mile linac, B-factory (TRISTAN/Photon Factory), Pohang Light Source Injector, etc. etc.

C-band frequency is only two times higher than S-band
Size of the structures: ½ of S-band

>>The accelerating structure fabrication and alignment with well-established technologies of 90's.
Advantages of C-band

**Simplicity**

The design of a RF unit is simple

⇒ Construction and operation are easy.

(2) **Relaxed Tolerance**

- Voltage of the klystron gun (~350 kV) same as SLAC5045.
- The modulator HV-pulse length (3.5 μsec).
  
  Filling time = 0.25 μsec, RF pulse=2.5 μsec
- The maximum electrical field on the surface of copper cavity is low (~80 MV/m).
- The structure straightness is relaxed (~50 μm).
  
  ⇒ Reliability, Long term stability can be insured.

(3) **Capability of the mass production / repair**

From the beginning of the design mass production is considered.

⇒ Availability

**Obvious trade-off : Lower acceleration gradient than X-band.**
The design is not just conservative, but

(2) Many novel ideas are invented and used

| (a) | Accelerator structure with choke-mode cavities. |
| (b) | Short-size pulse compressor (SLED-III). |
| (c) | Smart Modulator driven by an inverter HV power supply. |
| (d) | Double-feed type Coupler. |
| (e) | Beam position monitor with TM$_{010}$ mode suppression. |
| (f) | Unisex type waveguide & vacuum flange. |
| (g) | Beam size monitor with a Compton laser interferometer. |
| (h) | Stable support stand using new concrete with high compressive strength. @RIKEN |

The C-band physicists worked out these ideas. Many of these inventions are materialized by collaborations with industries. Many of them can be used for other LC technologies.
RF unit of the GLC C-band Main Linac

AC POWER LINE

SMART MODULATOR

HV INVERTER POWER SUPPLY

50 MW KLYSTRON

RF-PULSE COMPRESSOR

WAVEGUIDE

ACCELERATOR

Beam

ACTIVE MOVER

1.8 m

WR-187 Rectangular LOSS ~5%
C-band in the GLC Main Linac Tunnel

Active Length: 15.3 km for two linacs at 500 GeV C.M.

Granite: stable ground

Can be installed in the same tunnel as X-band

Accelerator tunnel

Klystron gallery

RF Pulse compressors (~1m-long)

50 MW x 2 Klystron
## Main R&D Items

<table>
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<tr>
<th>C-band Klystron</th>
<th>Klystron Modulator</th>
<th>RF Pulse Compressor</th>
<th>Accelerating Structure</th>
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<td>50 MW, 2.5 µsec, 47 %</td>
<td>110 MW 100 pps</td>
<td>Flat Pulse Gain: 3</td>
<td>1.8 m Choke-Mode</td>
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- **Life test >8000 hours.**
  - **OK**

- Smart modulator-I using inverter HV charger.
  - Running for klystron life test. **OK**

- High power test at KEK.
  - RF repetition rate: 50 pps (limited by HV charging power supply)

- Beam acceleration at 50 MV/m was done at ATF-KEK, with S-band model.
  - HOM damping performance was proved by ASSET-SLAC test, 1998.
C-band 50 MW Klystron

TOSHIBA: MODEL-E3746

Measured data
- Output power: 55 MW
- Beam voltage: 365 kV
- Beam current: 331 A
- Beam perveance: $1.5 \mu A/V^{1.5}$
- Efficiency: $>45\%$

Stable Operation with the Modulator for >6400h at C-band.

KEKB injector linac use a C-band accelerating structure run with 40 MV/m.

KEK
C-band Smart Modulator I

Advantages:
- Compact
- Use Inverter type charging power supply
- Low EMI noise level

Peak power output: 111 MW
Average power output: 39 kW
Charging voltage: 47 kV
Flat top pulse width: 2.5 µsec

Daily use at C-band for >10,000h
Shanghai Light Source

Smart modulator (I)
Circuit Diagram for Oil Filed Modulator

Charging Voltage: 47 kV
Average power: 30 kW

Stored energy: 475 J

In insulating oil

-22 kV (114 MW)

-350 kV

18 cell PFN

Klystron (Cathode): -350 kV

Pulse transformer 1:16
New Oil-filled Compact Modulator
(Smart Modulator II)

Specifications
- Peak power: 111 MW
- Charging voltage: 50 kV
- 25 kV, 4-μsec pulsed power
- 60-pps (for SCSS)
- $\eta$: 60%
- 1.5 (W) x 1 (H) x 1 (D) [m³]

Advantages:
- Very compact
- Low EMI noise level
- Free from the atmosphere condition (dusts, humidity)
- Low cost (model-I × 2/3)

NICHICON modulator #1

Measured waveformes for beam voltage and current.
**50 kV Inverter Power Supply**

**TOSHIBA: Inverter power supply #1**

**SPECIFICATIONS**
- Output voltage: 0~50 kV
- Average current: 1.5 A
- Charge rate: 30 kJ/sec (average)
  - Peak: 37.5 kJ/sec
- Power factor: >85% (50 pps, full load)
- Power efficiency: >85% (full load)

- Output voltage: 50 kV
- Charge rate average: 30 kJ/s
  - Peak: 37.5 kJ/s
- Average current: 1.5 A
- Output voltage regulation: < ±0.5%
- 48 (W) × 45 (H) × 63 (D) [cm³]

**Very good voltage regulation: 0.14% (p-p)**
PFN Adjustment Safe & Easy

Coil (adjustable inductance)
\[ L \text{ (coil)} = 290 \sim 580 \text{ nH} \]

HV capacitor: Maxwell (General Atomic)
\[ C = 22.3 \text{ nF} \times 18 \]
\[ V_{\text{max}} = 50 \text{ kV} \]
In the case of maintenance...
(10 minutes)

HV input

HV output
41\Omega \text{ coaxial } \times 9 \text{ parallel}

EOL clipper
Return protection
Diode & resistor

Thyratron tube
(Inside)

Pulse Forming Network
(PFN)

Cooling water pipe
High Gradient Test at Spring-8

We will test in July, 2004

Structure Length: 1.8 long
Accelerating Gradient: 56 MV/m
Dark Current Energy: 100 MeV (MAX.)
Monitors:
- Faraday Cup & Pico-Ampere-Meter
- Current Monitor
- X-Ray Survey Meter
- Scintillator & Photo-Multiplier
- Profile Monitor & Video-Camera
Enhancement of Field Emission Dark Current

(1) Primary field emission

(2) Desorption of ions and molecules by electron bombardment

(3) Ionization by electron impact

(4) Back bombardment

(5) Emission of secondary ions and electrons

Dark current = (1) Primary field emission + (2) Enhanced emission

Enhancement effect of dark current by electron and ion impact on electrode
(1) Mo exhibits low primary field emission current

(2) The enhancement effect due to bombardments is weak for Ti
(1) We have been developing C-band main linac to construct and start physics program at the 1st stage LC with a minimum R&D, so as to be as concurrent as possible with LHC operation.

(2) The basic components (klystron, modulator, pulse compressor, accelerator structure) are in principle ready for the 500 GeV LC.
   - Industrial models ready for the klystron and the modulator.
   - First high power test of rf compressor successful.
   - 40 MV/m conventional C-band accelerating structure is being used at KEKB injector. High power test of Choke-mode cavity will be done at SPring8 in 2004.
   - High power test of the full RF unit in 2006.

(3) Many novel devices based on new ideas have been developed, and many of them can be used also for other LC technologies.

Since the Main Linac is a huge periodic system, Simplicity and Reliability of a RF unit must be the key for easy construction and stable operation.
Possible Realistic Application
C-band Tests at SPring8 Compact SASE Source (SCSS)

From... http://www.spring8.or.jp

- e⁻ beam energy: 8 GeV
- Storage ring: 1436 m
- Photon beam line: 62
Low Emittance Injector
500-kV plus DC gun

High Gradient Accelerator
C-band 35 MV/m x 30 m = 1 GeV (4 units)
35 MV/m x 180 m = 6 GeV (24 units)

Short Period Undulator
In-vacuum undulator

The first step, we will be to generate 60-nm FEL from a 250-MeV beam energy by November 2005.
CeB₆ Cathode & Heater Assembly

- CeB₆ Cathode 3 mm Diameter
- Emittance 0.4 π.mm.mrad
  (thermal emittance, theoretical)
- Beam Current 3 Amp. at 1450 deg.C
  (using graphite heater)
- Current Density > 40 A/cm²
**Compact Infrared FEL**

- **Modulator Power Supply**: 20 MW, 10 µsec, 100 pps

- **RF Gun**: 20 MW, 10 µsec, 100 pps

- **Accelerator**: 1.5 m long, 20 MV/m

- **RF Undulator using Ridge shape wave-guide**: ~2 m

- **De-accelerator**: < 5 MeV

- **Wavelength**: λ > 4 µm
Spare Slides
Possible Scenario for Hybrid Scheme

The C-band can be used for the same rf technologies as the S-band accelerator.

The hybrid scheme will provide the flexibility for the energy expendabilities with the minimum R&D.

Early start up, and TeV in the future.
Simulations of RF Compression Cavity

Cavity 1

- TE$_{01, 15}$
- Q = 190k

Coupling cavity

- TE$_{01, 5}$
- Q = 90k

Cavity 2

- TE$_{01, 15}$
- Q = 190k

Input

Output

TETE01, 1501, 15
Q = 190k

TETE01, 501, 5
Q = 90k

1m
Applicability of Invar metal to RF cavity

### Application of Invar metal to RF cavity

<table>
<thead>
<tr>
<th>Property</th>
<th>Copper</th>
<th>Super-Invar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal expansion coefficient</td>
<td>$16 \times 10^{-6}^\circ\text{C}$</td>
<td>$0.42 \times 10^{-6}^\circ\text{C}$</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>$394 \text{ W/(m} \cdot ^\circ\text{C)}$</td>
<td>$13.5 \text{ W/(m} \cdot ^\circ\text{C)}$</td>
</tr>
<tr>
<td>Electric conductivity</td>
<td>$1.7 \times 10^{-8} \text{ \Omega m}$</td>
<td>no good</td>
</tr>
</tbody>
</table>

Super-Invar is preferred due to lower thermal frequency drift at C-band.

Thermal expansion coefficient:
- Copper: $16 \times 10^{-6}^\circ\text{C}$
- Super-Invar: $0.42 \times 10^{-6}^\circ\text{C}$

Thermal conductivity:
- Copper: $394 \text{ W/(m} \cdot ^\circ\text{C)}$
- Super-Invar: $13.5 \text{ W/(m} \cdot ^\circ\text{C)}$

Electric conductivity:
- Copper: $1.7 \times 10^{-8} \text{ \Omega m}$
- Super-Invar: no good

**Thermal frequency drift at C-band**
- Copper: $96 \text{ kHz/}^\circ\text{C}$
- Super-Invar: $9 \text{ kHz/}^\circ\text{C}$

96 kHz/°C measured data
High Power Test

High power test done at KEK in 2003.

Power multiple factor: 3

RF repetition rate: 50 pps (limited by HV charging power supply)

Full test (350 MW) will be done at SPring8 in 2006.
Possible improvements and solutions

1) Upgrade of power multiplication factor 3 → 3.5
   - Precise frequency tuning of 1st cavity.
   - Increase the mechanical strength for cavity end plates at 1st cavities.
   - Precise phase adjustment to reduce the reflection rf power from the cavities.

2) Full power operation 135 → 350 MW
   - The maximum surface electrical field gradients at the coupling irises designed within 80 MV/m at rf output power of 350 MW and 0.5 µs.
   - For the S-band SLED-I cavity at KEKB and ATF, it was designed within 120 MV/m of surface gradient at 450 MW and 1.0 µs, and it is routinely in use in both facilities.

   - We believe there will be no problem at 350 MW.
Accelerator Structures
Choke-Mode Accelerating Structure

Rotationally symmetric design
⇒ easy fabrication with a turning machine
C-band Accelerating Structure

- Choke-Mode Cavity
- Full Scale Structure 1.8 m long
- SiC Loads
- RF-BPM
- Dual arises input coupler
Beam Acceleration at KEKB Injector Linac

- The first C-band accelerating structure (1-m long) with a conventional disk-loaded type successfully accelerated the beam in the KEKB injector linac at the gradient of 40 MV/m in October 2003.

- It is routinely in use at KEKB injector since after the first operation.

![Graph showing energy gain by C-band unit with field gradient of 41.2 MV/m.](image)
Roller Cam Mover and Support Stand
Precise Roller Cam type Mover

This mechanism is designed to support a load of up to 500 kg, while providing smooth motion, free of hysteresis at the micron level. The new roller cam mover unit is comprised of two roller cams, their stepping motors drivers, two linear sliders and support frames. We used 72 mm diameter roller cams to provide ±1 mm of positioning area.

Two roller cam units were used to manipulate the dummy weight. Each roller cam mover unit can be controlled individually to adjust for any axis. A position repeatability of around ±0.1 µm within ±1 mm of the adjustable area was obtained.
High-strength Concrete for Support Table

New

- Low dry shrinking
- Flexible shape
- Massive (damp the vibration)
- Low cost

**High-strength concrete**

Diameter: 500 mm
Length: 680 mm
Flatness at top: $\pm 20 \, \mu m$
Klystron and Modulator
RF $\lambda$ & Bunch Length $\sigma_z$

$\sigma_z \sim 110\mu m$

$\sigma_z \sim 200\mu m$

$\lambda_c = 2\lambda_x$ Optimum Bunch Length? In C+X

Changing $\Phi$ -> Controlling $\gamma\varepsilon$, $\Delta E/E$

T. Sanuki, ITRF/Meeting Four KEK
C+X hybrid optics (SAD)
## Main Machine Parameters

<table>
<thead>
<tr>
<th>Overall Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C.M. Energy</td>
<td>500 GeV</td>
</tr>
<tr>
<td>Nominal Luminosity</td>
<td>$1.4 \times 10^{33}$</td>
</tr>
<tr>
<td>Beam Current</td>
<td>$1.4 \times 192 \times 100$</td>
</tr>
<tr>
<td>Spot Size at IP (rms)</td>
<td>$243 \times 4.0$ nm</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Bunch Separation</td>
<td>1.4 nsec</td>
</tr>
<tr>
<td>Main Linac Length</td>
<td>15.3 km</td>
</tr>
<tr>
<td>Number of RF Unit</td>
<td>2125 Units</td>
</tr>
<tr>
<td>Linac AC Power</td>
<td>240 MW</td>
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<tr>
<td>Klystron Power</td>
<td>50 MW, 2.5 μsec</td>
</tr>
<tr>
<td>Modulator</td>
<td>110 MW, 25 kV</td>
</tr>
<tr>
<td>Efficiency</td>
<td>50%</td>
</tr>
<tr>
<td>RF Pulse Compressor</td>
<td></td>
</tr>
<tr>
<td>Compression Gain</td>
<td>$\times 3.3$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>70%</td>
</tr>
<tr>
<td>Accelerating Structure</td>
<td></td>
</tr>
<tr>
<td>Accelerating Gradient</td>
<td>31 MV/m (with beam), 42 MV/m (no load)</td>
</tr>
<tr>
<td>Shunt-Impedance</td>
<td>54 MΩ/m</td>
</tr>
<tr>
<td>Alignment Tolerance</td>
<td>50 μm</td>
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**ECEP/POSTECH**
## Main R&D items

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<td>Life test &gt;6500 hours, OK.</td>
<td>Smart modulator-I using inverter HV charger, Running for klystron life test. OK</td>
<td>1m long cold model Three-cell cavity.</td>
<td>Beam acceleration at 50 MV/m was done at ATF-KEK, with S-band model. HOM damping performance was proved by ASSET-SLAC test, 1998.</td>
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RF Pulse Compressor (low power model)

Mode Converter

Circular Waveguide (400 mm)

Input Cell (No. 1)

Coupling Cell (No. 2)

Main Energy Storage (No. 3)

Ø 153

TE0,1,15

TE0,1,5

TE0,1,15

Q: 190k

Q: 90k

Q: 190k

~1 m
NOTE: we used only one klystron for the high power test, because of limited the resource.
From 1987 to 1994 extensive high gradient tests were performed at KEK using S-band structures. We learned that

1. The magnitude of dark current depends on the cleanliness of the surface inside the structure.

2. The maximum electric field gradient depends on the shape of the structures (especially the couplers).

3. Microscopic voids in the structure is one of the reasons of the dark current.

4. Empirical threshold of surface discharge at S-band: around 120 MV/m.

⇒ The C-band structure design is based on these experimental facts.
R2: The klystrons and modulators should be tested successfully at the nominal 100 Hz repetition rate.

This should lead to the full test of the linac subunit, with beam. This will include klystrons, modulators, pulse compression system, LLRF control and several structures in their future environment.

- A new modulator for SCSS already tested at 60 Hz.
- A beam test of a RF-unit will be done at SCSS in SPring-8 in 2006.
1) Accelerating structure

- For single wake filed: 25 µm (rms)
- Mechanical tolerance: 50 µm (max)
C-band Accelerating Structure

- HOM Damping by Choke-Mode Cavity
- 1.8 m long, 91 Cells, CG-structure
- $3\pi/4$-mode
- Brazing Bonding
- SiC by Tungsten wire-spring
- Double-feed Coupler
- High-power test will be July 2004
High Gradient Test

Klystron: 50 MW
Pulse compressor
Gradient: 56 MV/m (max)
Traveling-wave Output Structure

- Reduced surface field
  - 29 MV/m
- Stable beam envelop
- Lowered focusing solenoid power
  - (4.6 kW)
- Lowered X-ray emission
- Enhanced efficiency
  - 47%
Beam Emittance Measurement on SCSS

Beam Energy: 200 keV
Peak Current: 0.5 A
Pulse Width: 3 μs
Repetition Rate: 10 Hz

Emittance ($\varepsilon_{n,\text{RMS}}$)

- Requirement: 2 $\pi$.mm.mrad @Undulator
- Experiment: 0.9 $\pi$.mm.mrad @Gun (preliminary)
Currently RF-gun is promising for the unpolarized electron gun, but DC-gun can also be used for unpolarized electron gun.

- **Thermionic gun is stable and long life.**
  - High temperature single-crystal cathode operates quite stably and long life ( > 10,000 hours)

- **Uniform Electron Density.**
  - Single crystal CeB6 cathode provide uniform emission density ( very low slice remittance)

- **Wide Range of Tuneability.**
  - Sub-harmonic buncher + buncher configuration enable one-by-one tuning of beam parameter.
What makes C-band system simple & reliable

Parameters are for the 500 GeV C.M. Energy case. In 1 TeV upgrade case, we use 100 MW klystron and longer linacs by 3.5 km for each beams.

Smart Modulator
High reliability, good efficiency, simple
- Compact modular design
- No de-Q’ing (simple)
- Inverter HV supply

50 MW C-band Klystron High Reliability
- Large Beam Drift Tube Diameter: 16 mm
- Lower Gun Voltage: 350 kV

Pulse Transformer Good efficiency
- HV-Pulse length of 3 μsec is best fit to conventional pulse-transformer and PFN.

Pulse Compressor High efficiency, compact
- Small Size Ø 160 x L1000 mm
- High Efficiency > 80 %

Standard Rectangular Waveguide Simple
- Small Loss 0.03 dB/m
- Loss = 5 % for 8 meter

Beam Line
- 3 1 MV/m

Acc. Structure

Low emittance dilution
- Iris aperture <2a>=16 mm
- Alignment tolerance 50 μm /structure

Mover
Girder
8 m
1.8 m
Measured Wakefield

- Energy: 1.2 GeV
- Drive $e^+$: 1 nC
- Witness $e^-$: 1 nC
- Offset $\Delta y$: 2 mm
- Used BPMs: 20 units
- Averaging: 16 shots/point
- Active Str. Length: 1.791 m

2nd Bunch

(distance(m))