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.

Design Principle of C-band

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

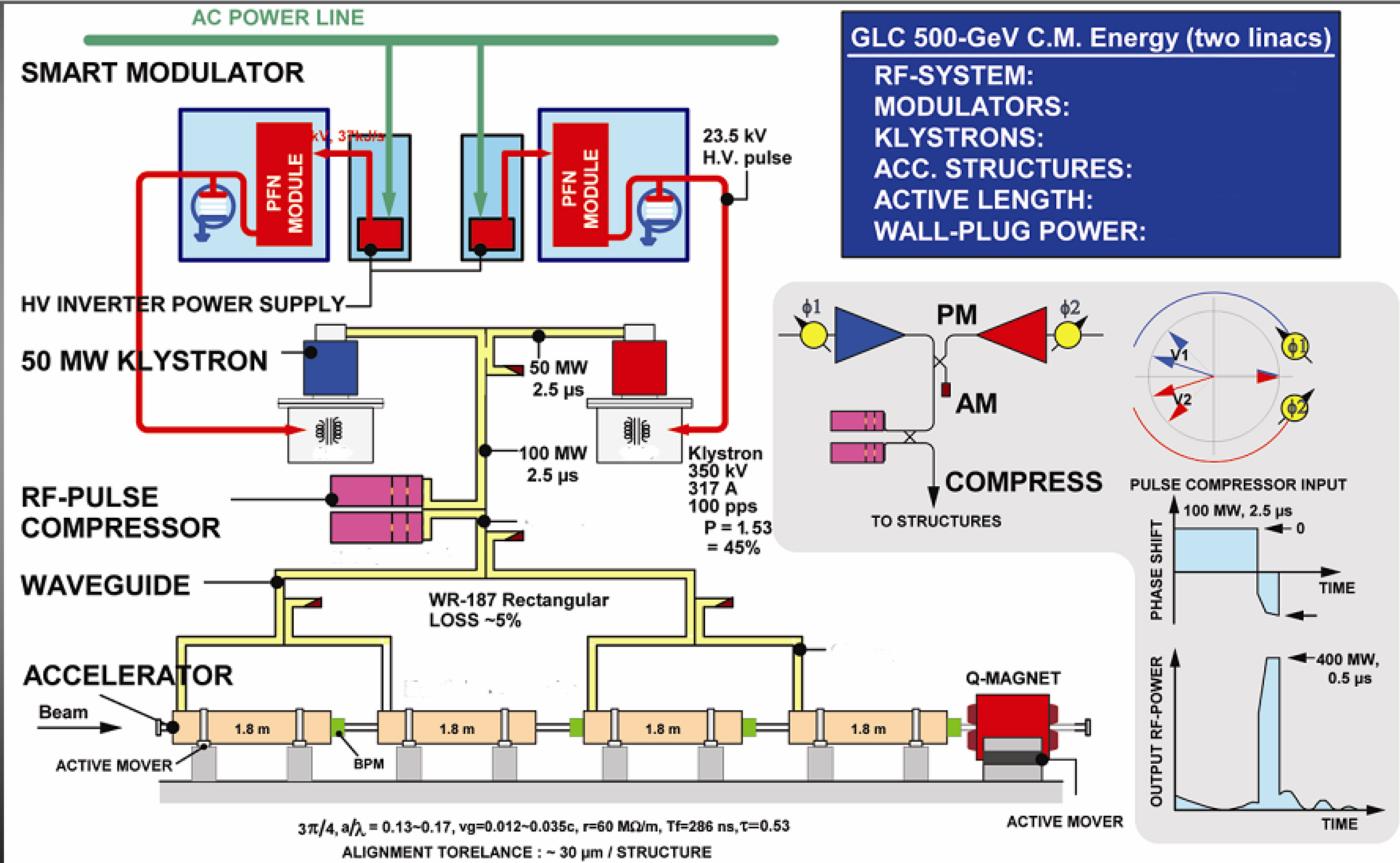
(a) Accelerator structure with choke-mode cavities.
(b) Short-size pulse compressor (SLED-III).
(c) Smart Modulator driven by an inverter HV power supply.
(d) Double-feed type Coupler.
(e) Beam position monitor with TM_{010} mode suppression.
(f) Unisex type waveguide & vacuum flange.
(g) Beam size monitor 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



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C-band in the GLC Main Linac Tunnel

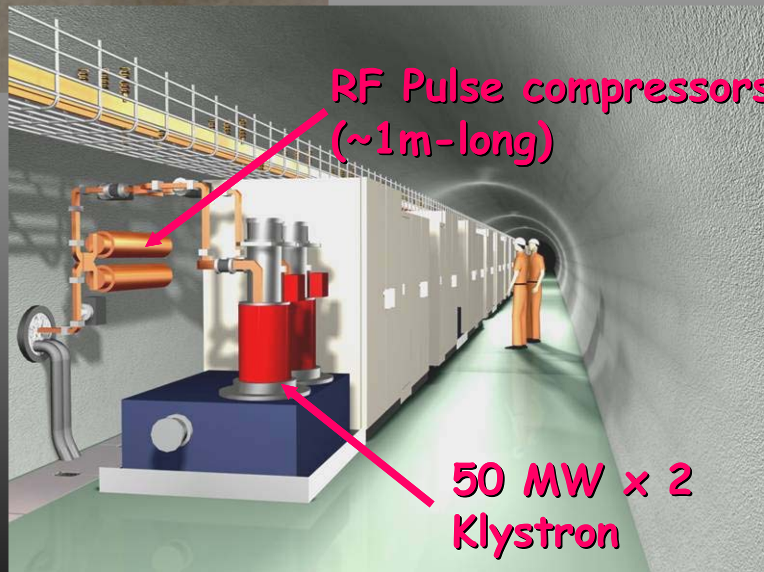
Active Length:

15.3 km for two linacs at 500 GeV C.M.

Can be installed in the same tunnel as X-band

Accelerator tunnel

Klystron gallery



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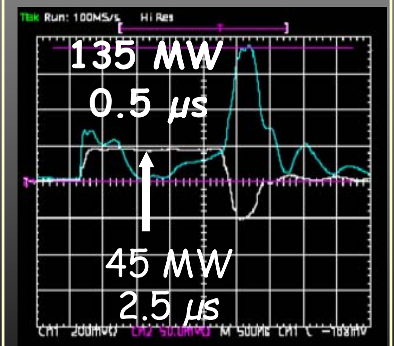
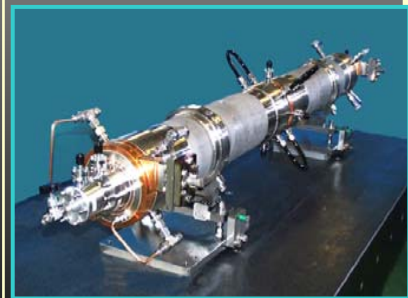
Main R&D items

C-band Klystron	Klystron Modulator	RF Pulse Compressor	Accelerating Structure
50 MW, 2.5 μsec, 47 %	110 MW 100 pps	Flat Pulse Gain: 3	1.8 m Choke-Mode
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.





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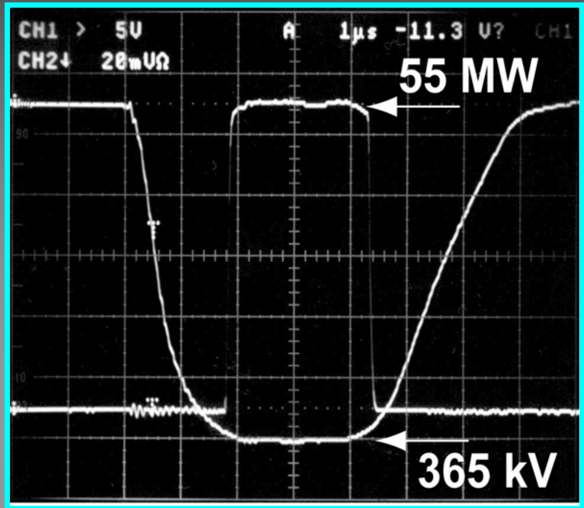
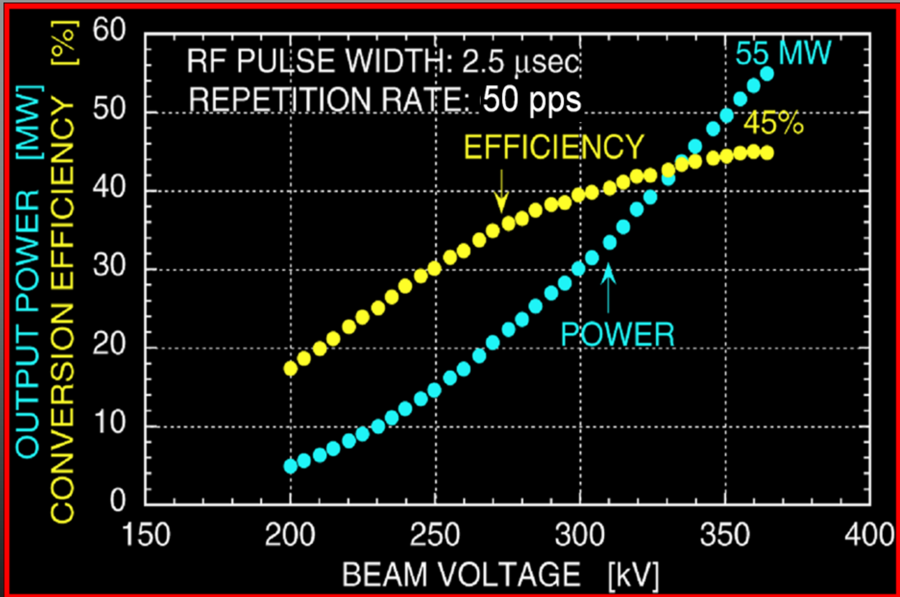
C-band 50 MW Klystron

OK

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.

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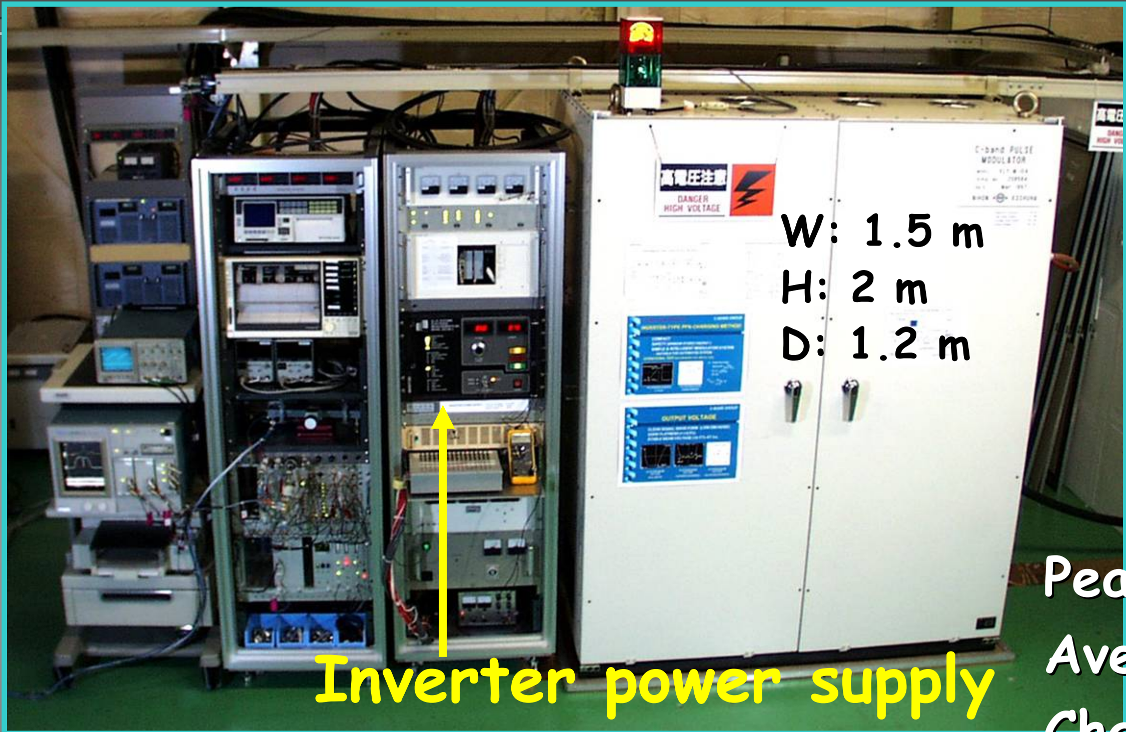
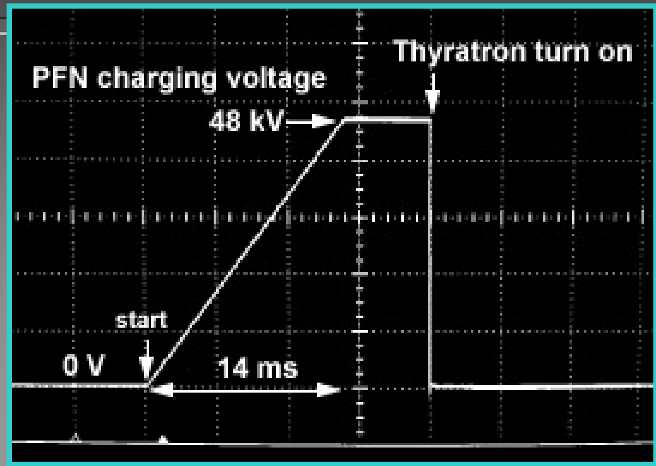
C-band Smart Modulator I

OK





Charging voltage

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

Advantages:

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

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

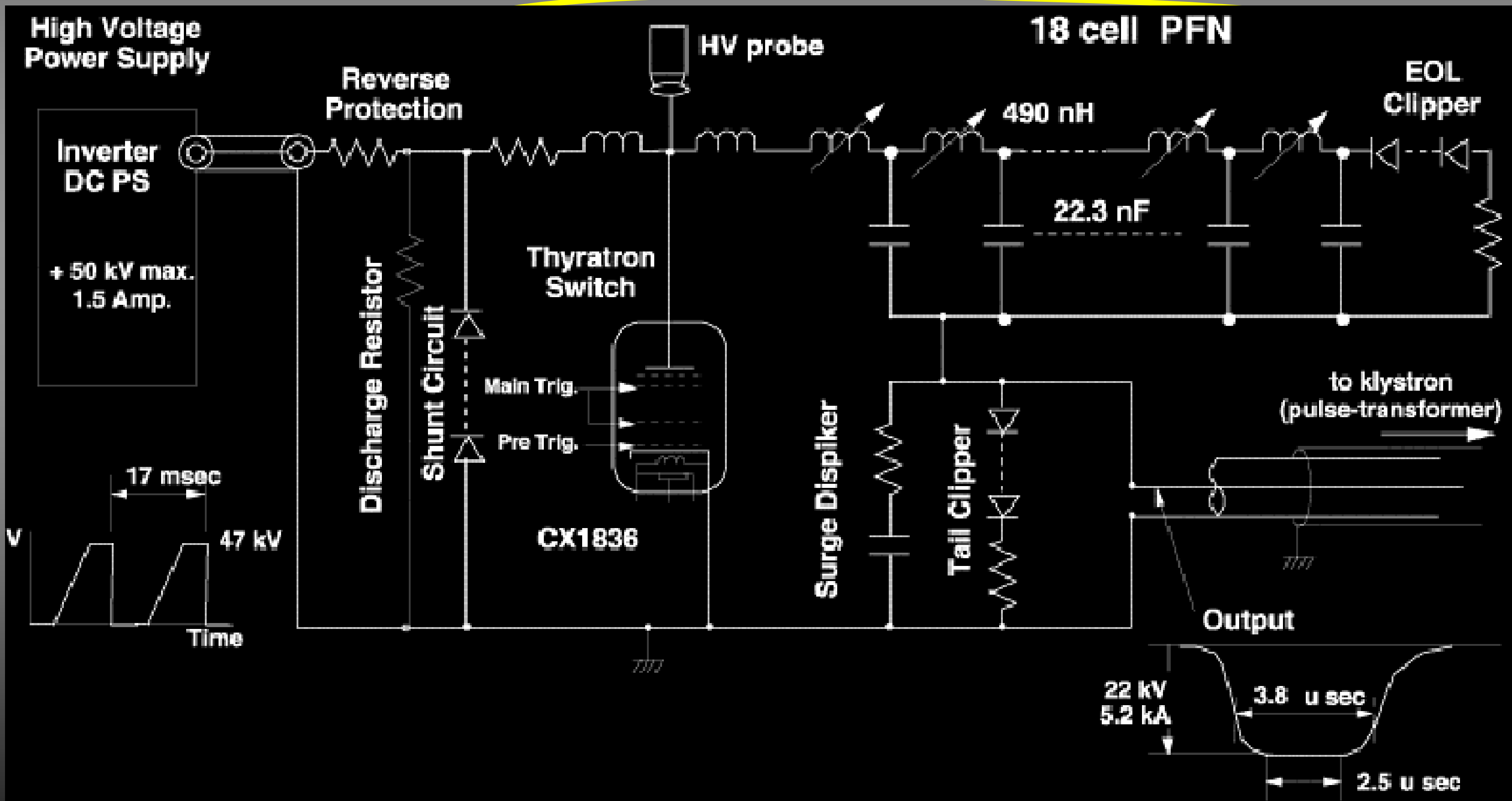
Shanghai Light Source

Circuit Diagram for Oil Filed Modulator

Charging Voltage : 47 kV
Average power: 30 kW

Stored energy : 475 J

In insulating oil



tput:
2 kV
4 MW)
r
tron
ode):
-350 kV

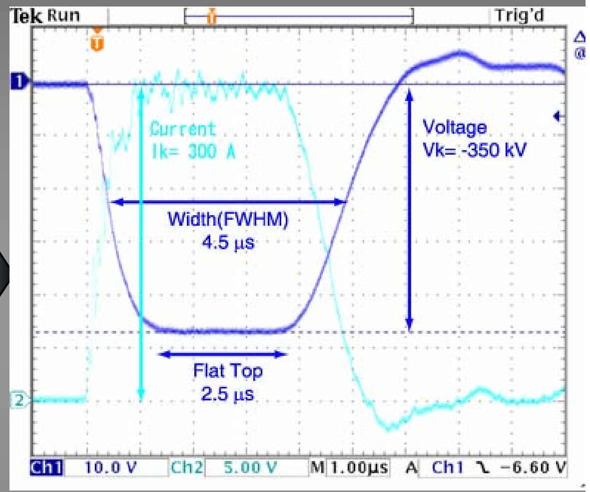
New Oil-filled Compact Modulator (Smart Modulator II)

New

Specifications

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

NICHICON modulator #1



Measured waveformes for beam voltage and current.

Advantages:

-Very compact

-Low EMI noise level

- Free from the atmosphere condition (dusts, humidity)

-Low cost (model-I x 2/3)

50 kV Inverter Power Supply

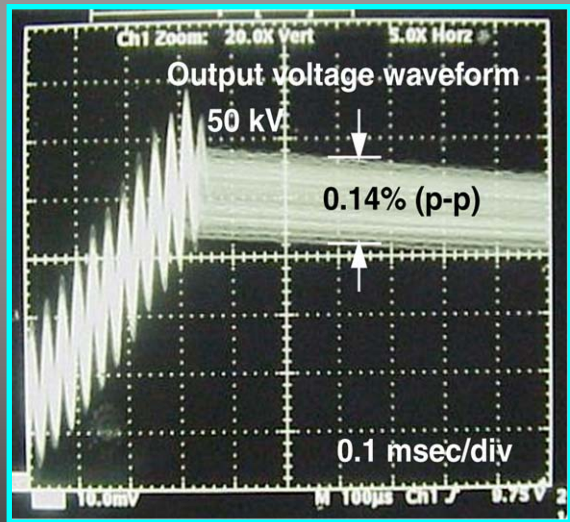
New

TOSHIBA: Inverter power supply #1

- 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) x 45 (H) x 63 (D) [cm^3]

SPECIFICATIONS

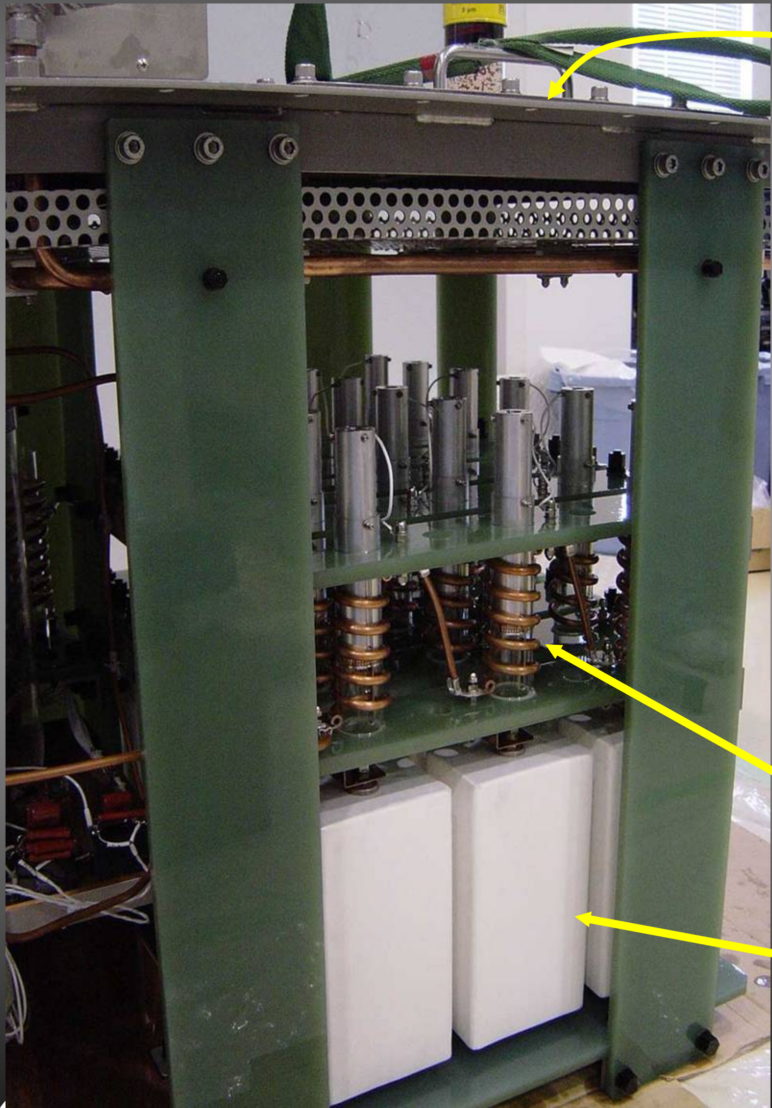
Output voltage: 0~50 kV
Average current: 1.5 A
Charge rate: 30 kJ/sec (average)
37.5 kJ/sec (peak)
Power factor: >85% (50 pps, full load)
Power efficiency: >85% (full load)

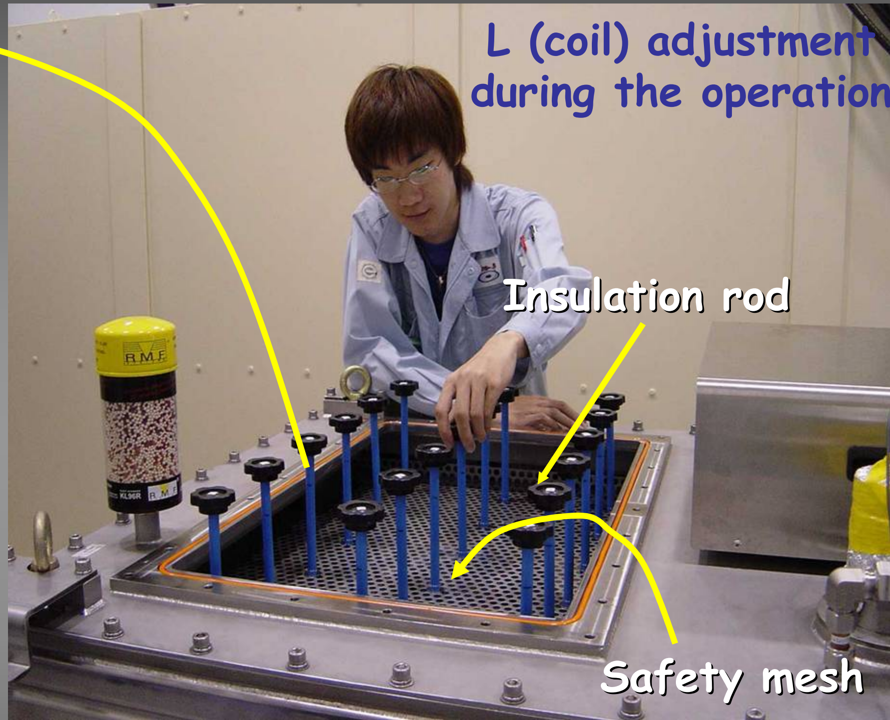


Measured output voltage regulation

Very good voltage regulation: 0.14% (p-p)

PFN Adjustment Safe & Easy





Coil (adjustable inductance)
L (coil) = 290 ~ 580 nH

HV capacitor : Maxwell (General Atomic)
C = 22.3 nF x 18
V_{max} = 50 kV

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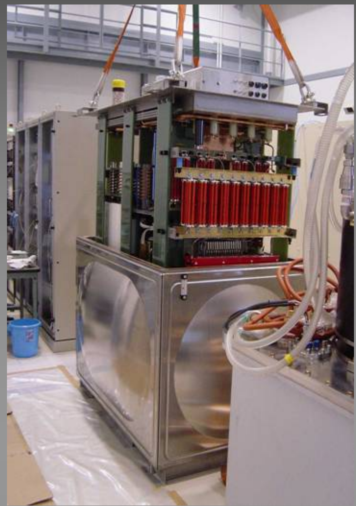
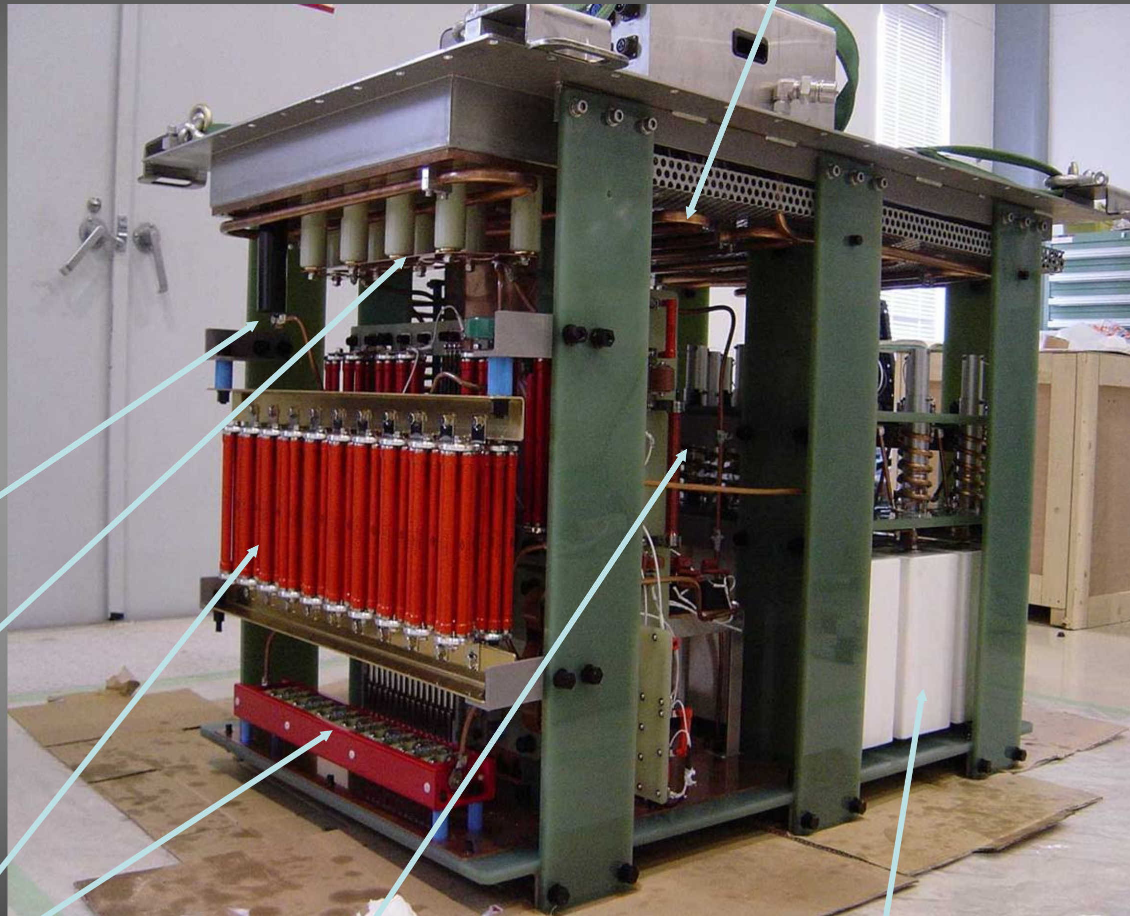
Maintenance Easy

In the case of maintenance…
(10 minutes)





Cooling water pipe

HV input

HV output
41Ω coaxial x 9 parallel

EOL clipper
Return protection diode & resister

Thyratron tube
(Inside)

Pulse Forming Network
(PFN)

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High Gradient Test at Spring-8 New

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
- SCINTILATOR & PHOTO-MULTIPLIER
- PROFILE MONITOR & VIDEO-CAMERA

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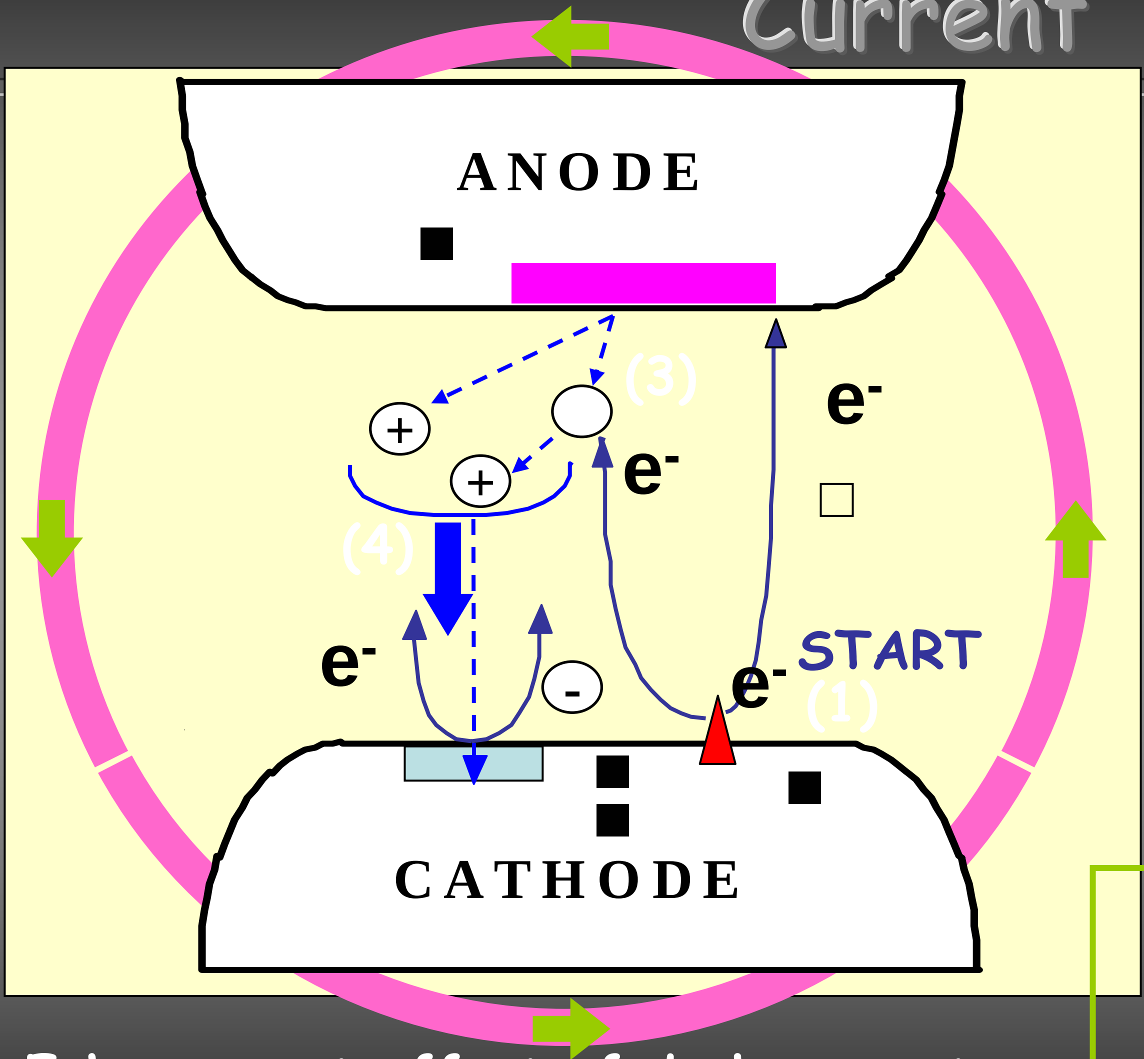
Enhancement of Field Emission Dark Current



(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

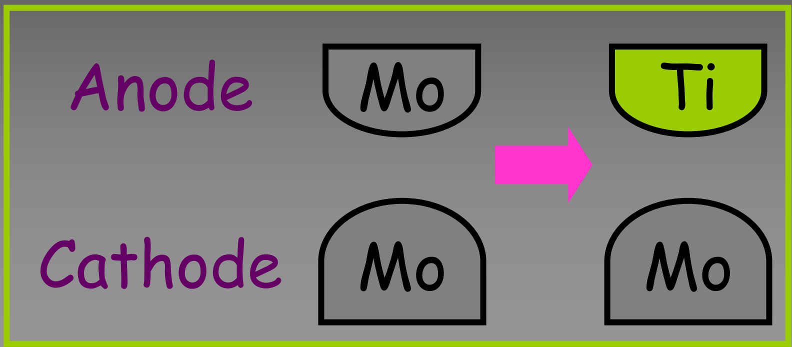
Enhancement effect of dark current by electron and ion impact on electrode

Dark current =

(1) Primary field emission

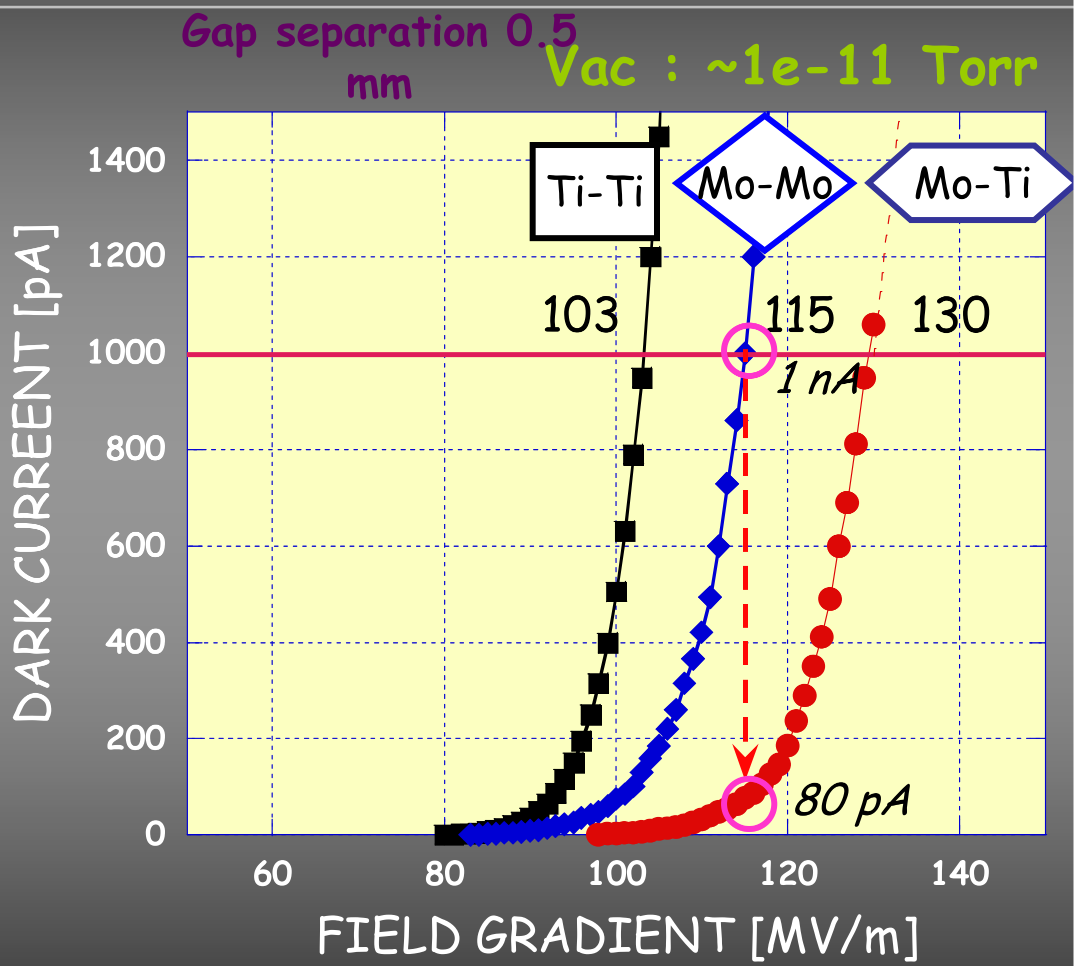
\+ (2) Enhanced emission

Reduction of Dark Current



(1) Mo exhibits low primary field emission current

(2) The enhancement effect due to bombardments is weak for Ti



Reduction of dark current

Summary of R&D for Linear Collider

(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.

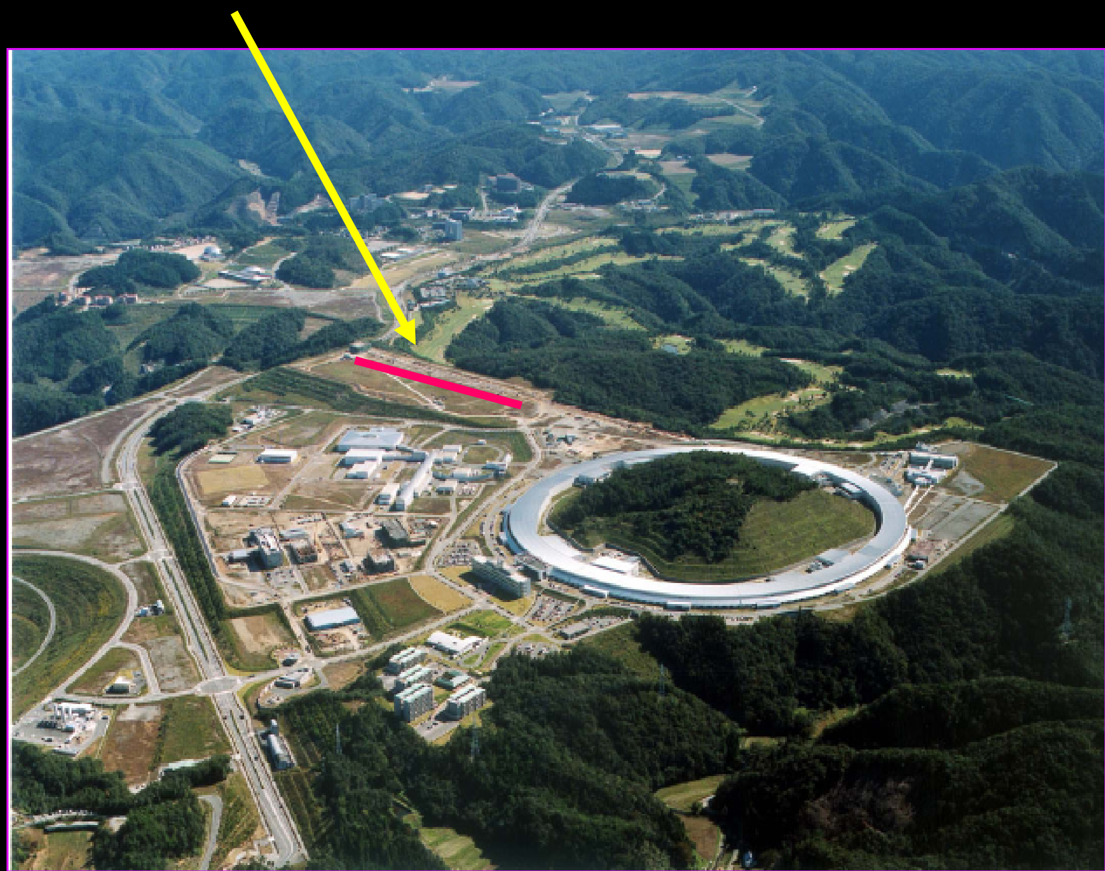
(2) The basic components (klystron, modulator, pulse compressor, accelerator structure) are in principle ready for the 500 GeV LC.
- Industrial models ready for the klystron and the modulator.
- First high power test of rf compressor successful.
- 40 MV/m conventional C-band accelerating structure is 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)

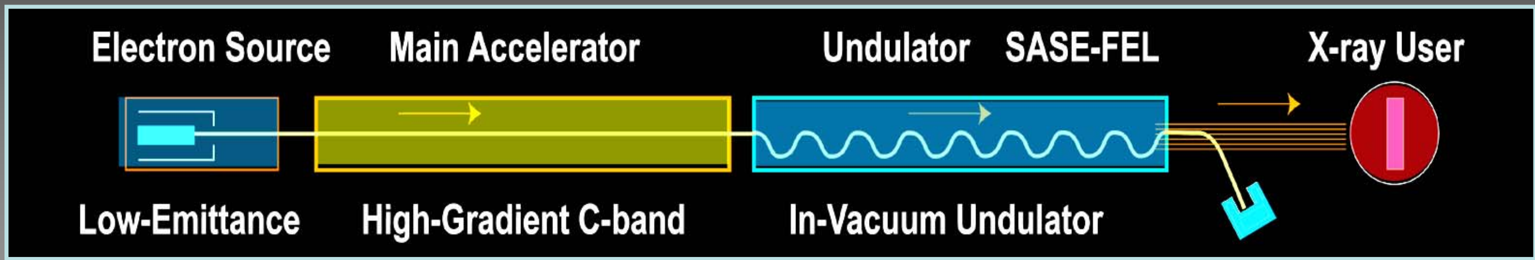


e⁻ beam energy:	8 GeV
Storage ring:	1436 m
Photon beam line:	62

From… http://www.spring8.or.jp

SCSS : SPring-8 Compact SASE Source

10-nm with 1-GeV in 2006-2007



- Low Emittance Injector ⟹ Short Saturation Length

  500-kV pluses DC gun

- High Gradient Accelerator ⟹ Short Accelerator Length

  C-band 35 MV/m x 30 m = 1 GeV (4 units)

  35 MV/m x 180 m = 6 GeV (24 units)

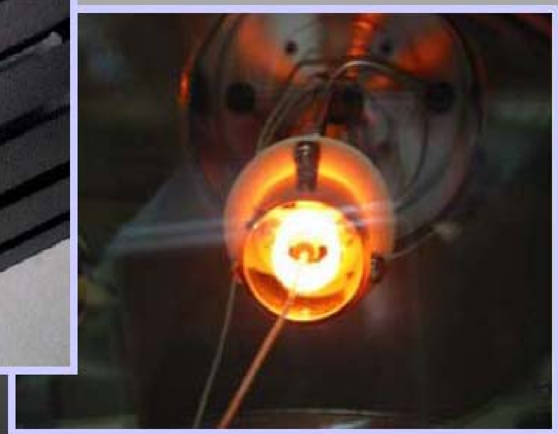
- Short Period Undulator ⟹ Lower Beam Energy and Short Saturation Length

  In-vacuum undulator

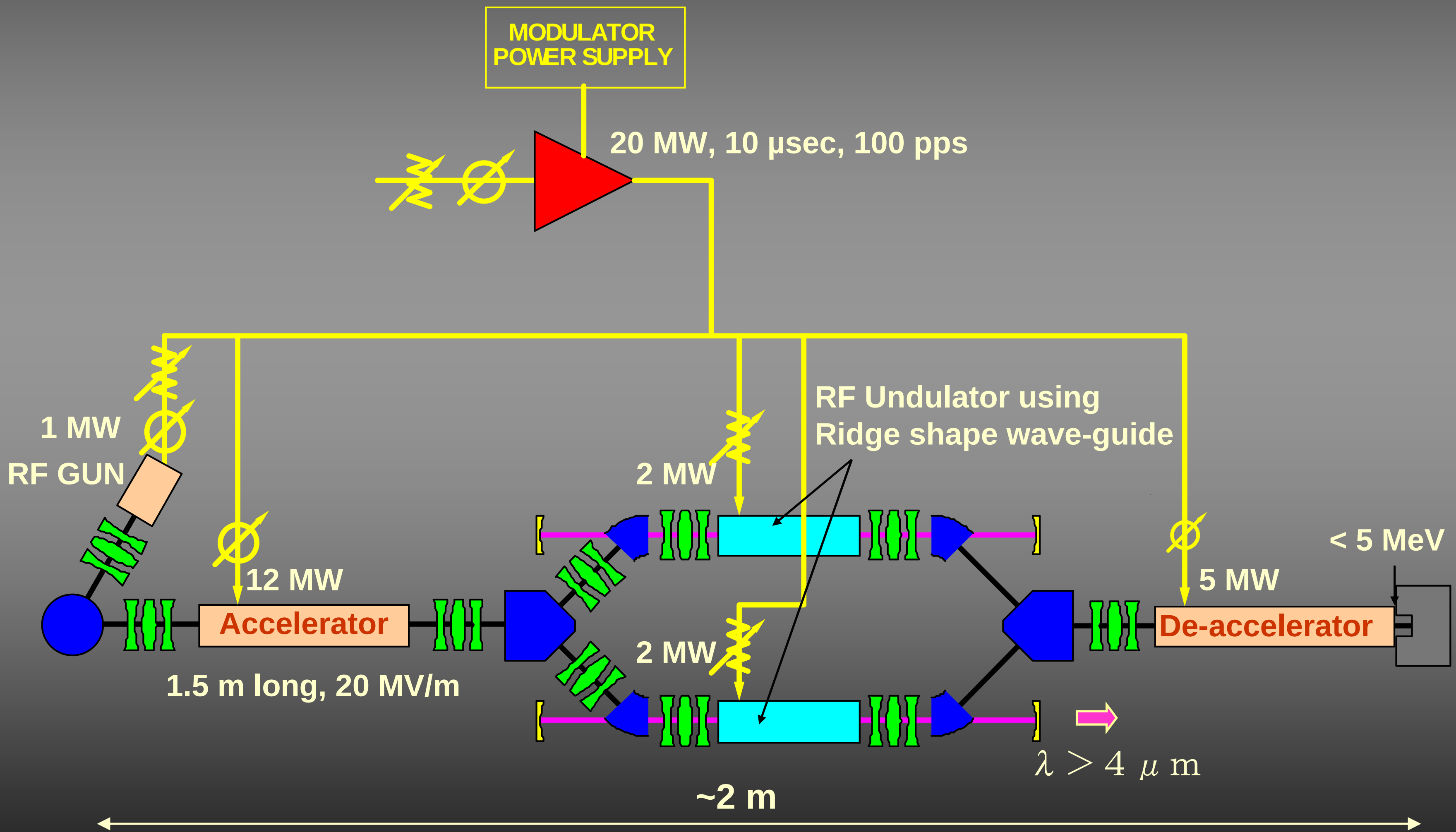
The first step, we will be to generate 60-nm FEL from a 250-MeV beam energy by November 2005.

CeB6 Cathode & Heater Assembly

- CeB_6 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/cm^2



Compact Infrared FEL



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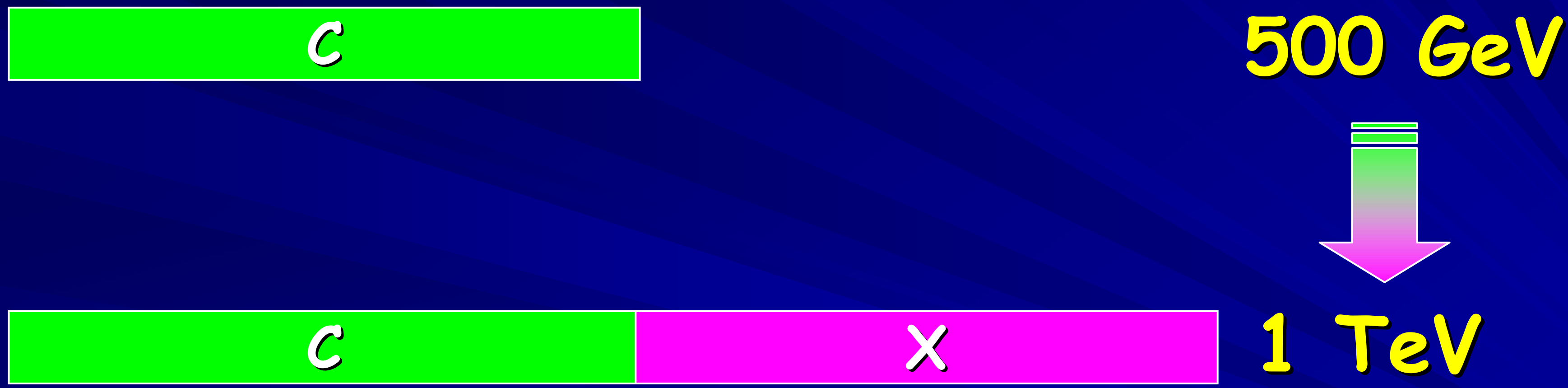
Spare Slides

Possible Scenario for Hybrid Scheme

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

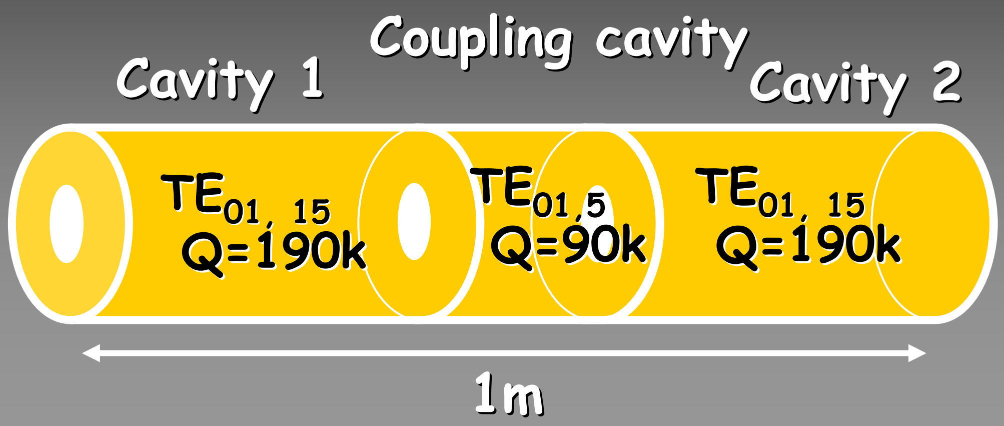


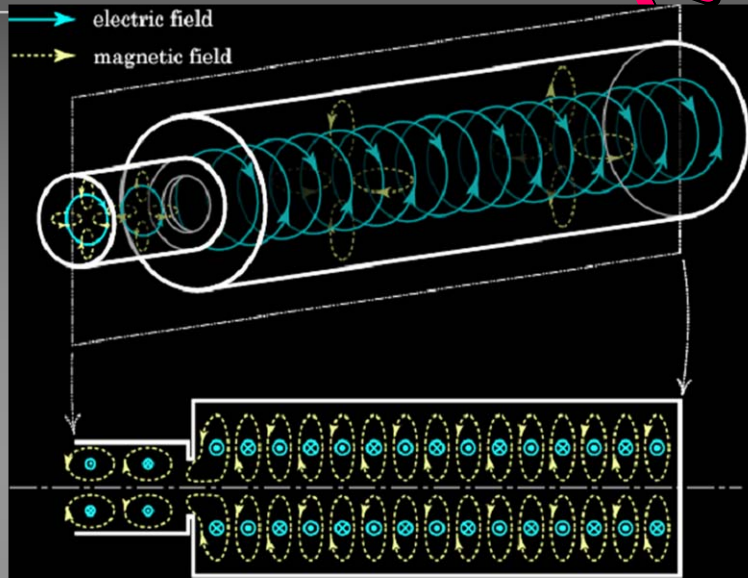
The hybrid scheme will provide the flexibility for the energy expendabilities with the minimum R&D.

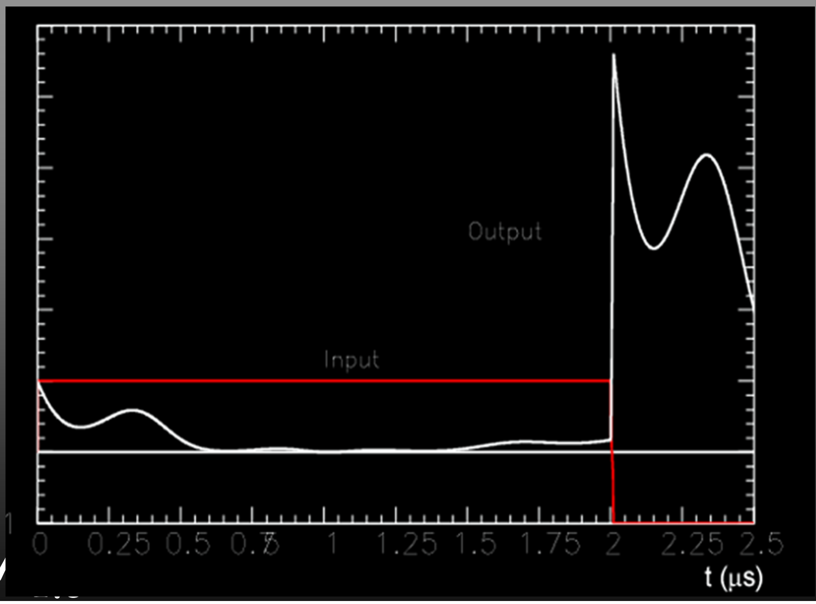
Early start up, and TeV in the future.

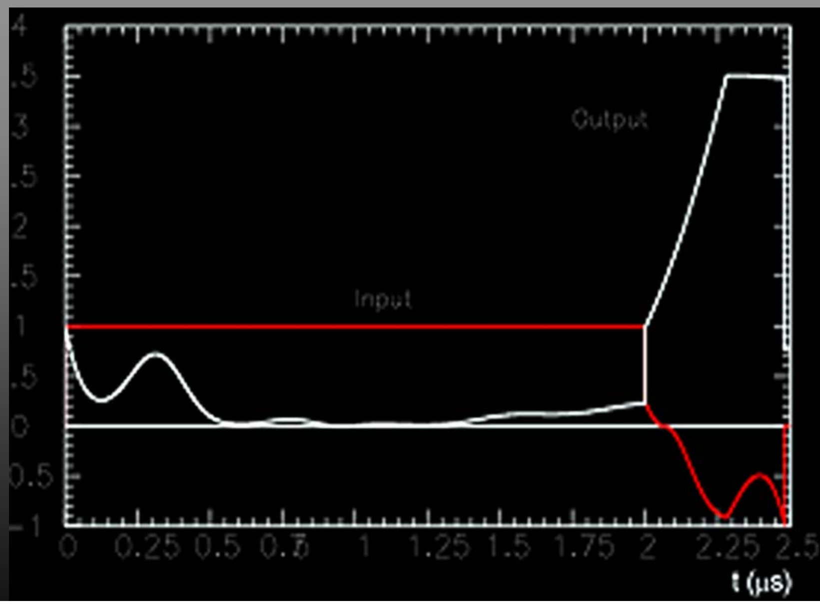
Simulations of RF Compression Cavity

New





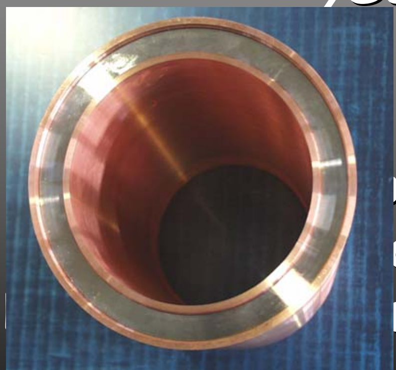




Application of Invar metal to RF cavity

	Copper	Super-Invar
Thermal expansion coefficient:	16 x 10^{-6}/℃	**0.42 x 10^{-6}/℃**
Thermal conductivity	394 W/(m·℃)	13.5 W/(m·℃)
Electric conductivity	1.7x10^{-8} Ωm	no good

Super-Inver



plating

or

ng using HIP

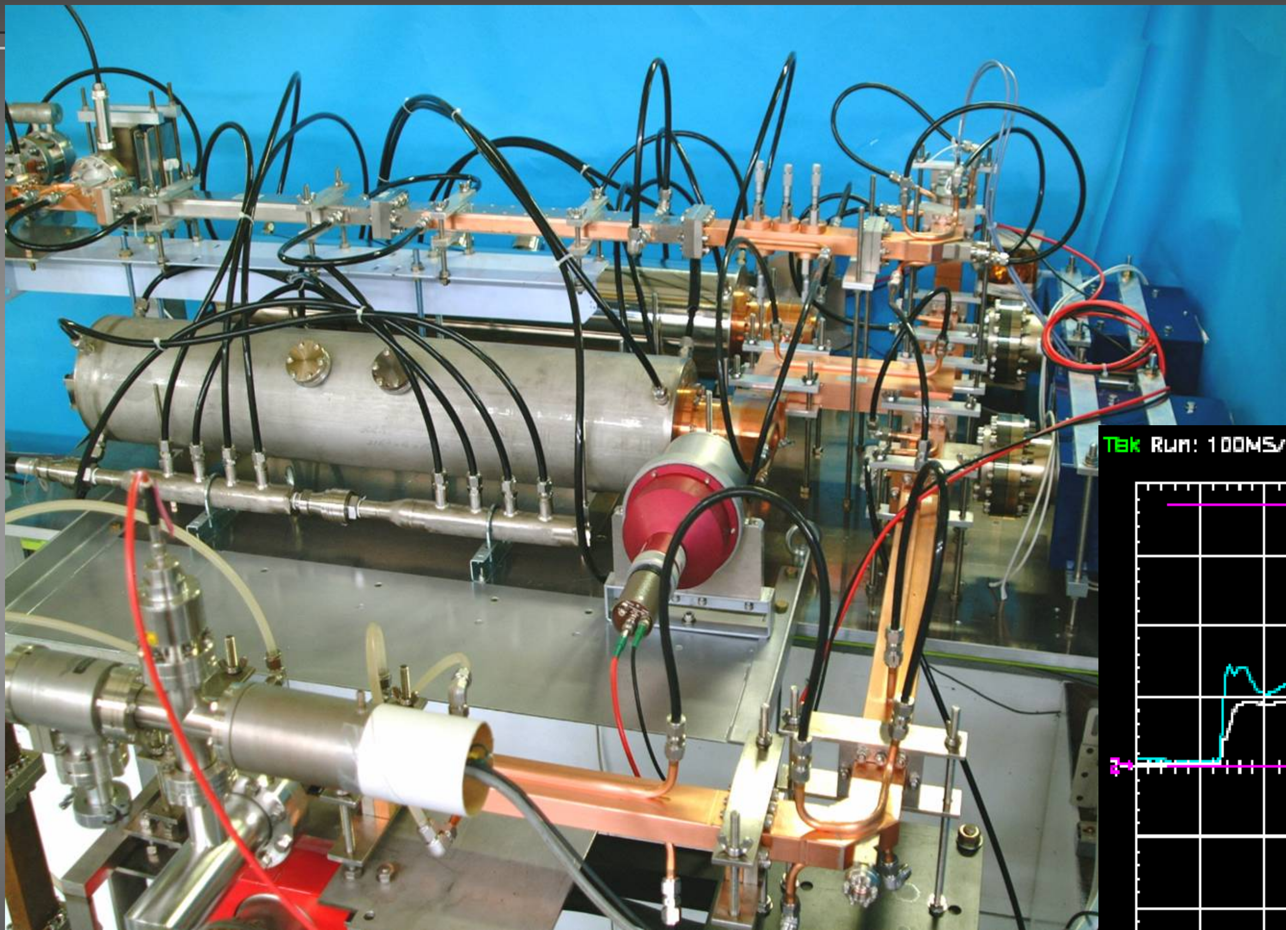
Thermal frequency drift at C-band

96 kHz/°C (Cooper cavity) → **9 kHz**/°C

measured data

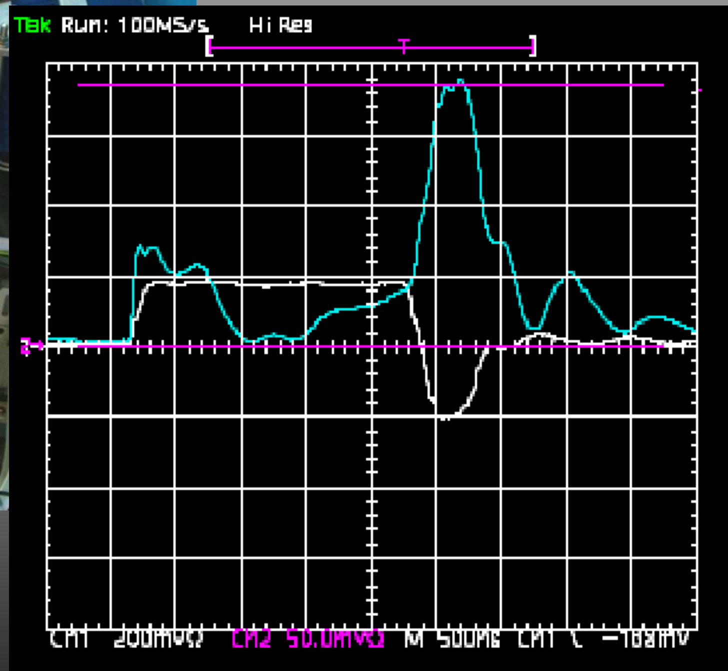
High Power Test

New



igh power test done
t KEK in 2003.

ower 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.

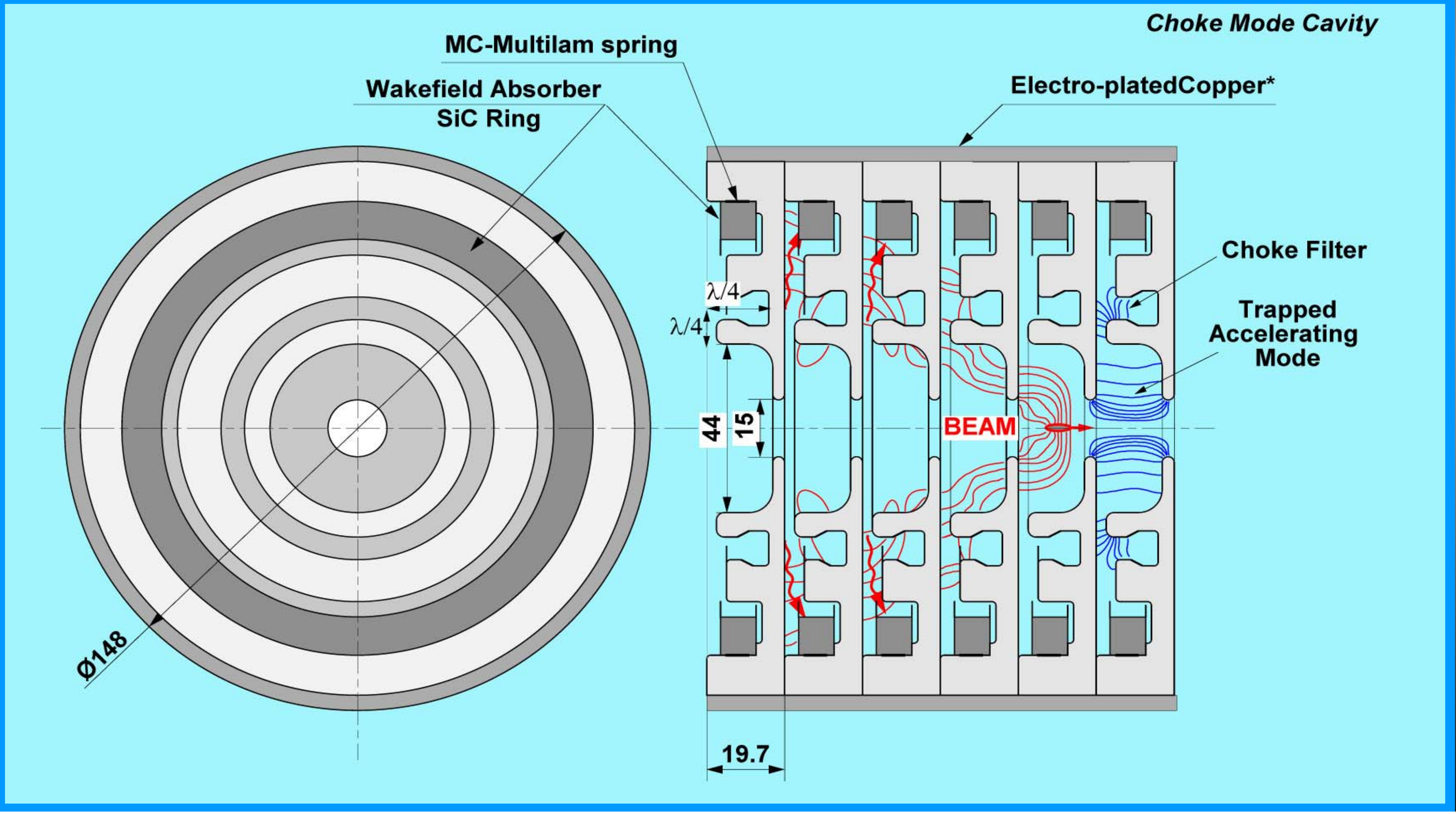
- We believe there will be no problem at 350 MW.

Accelerator Structures

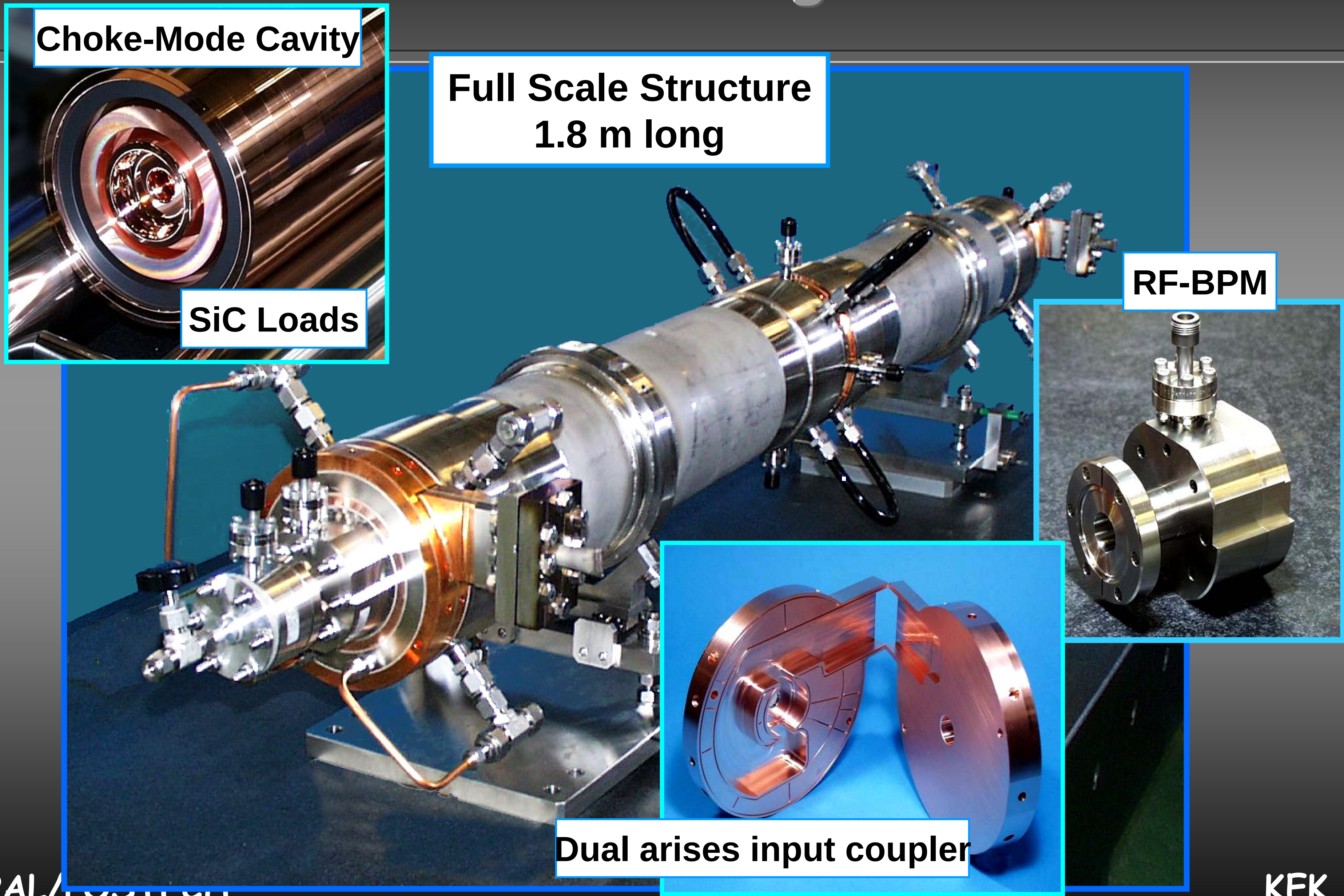
Choke-Mode Accelerating Structure

Rotationally symmetric design

⇒ easy fabrication with a turning machine

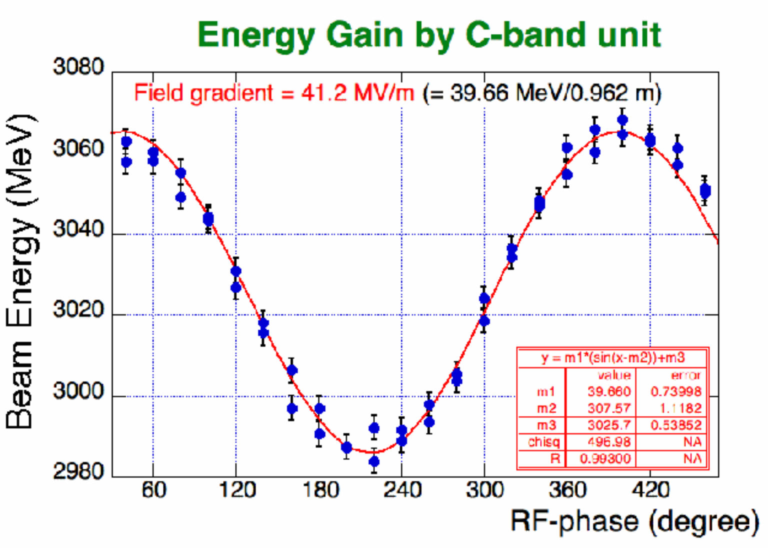


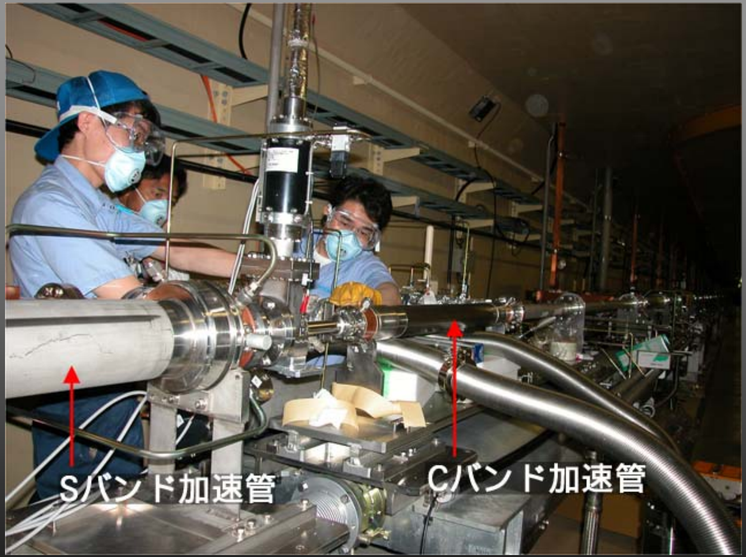
C-band Accelerating Structure



Beam Acceleration at KEKB Injector Linac

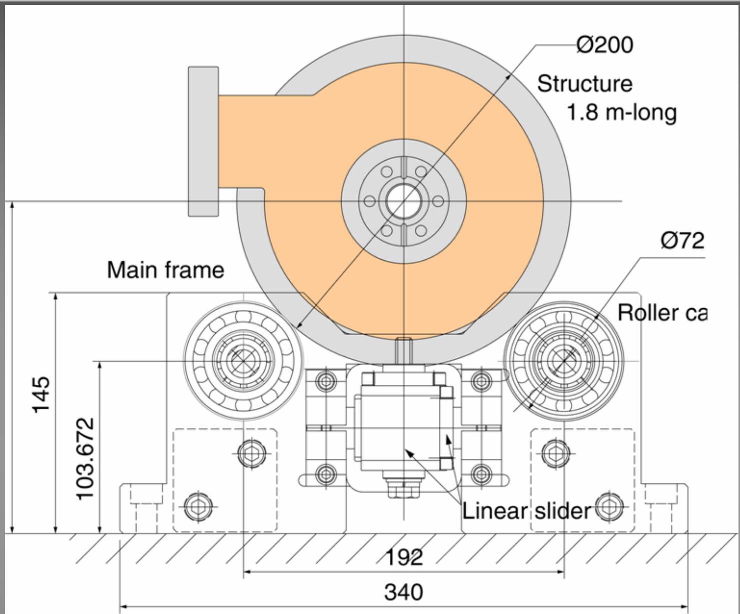
- The first C-band accelerating structure (1-m long) with a conventional disk-loaded type successfully accelerated the beam in the KEKB injector linac at the gradient of **40 MV/m** in October 2003.
- It is **routinely in use** at KEKB injector since after the first operation.



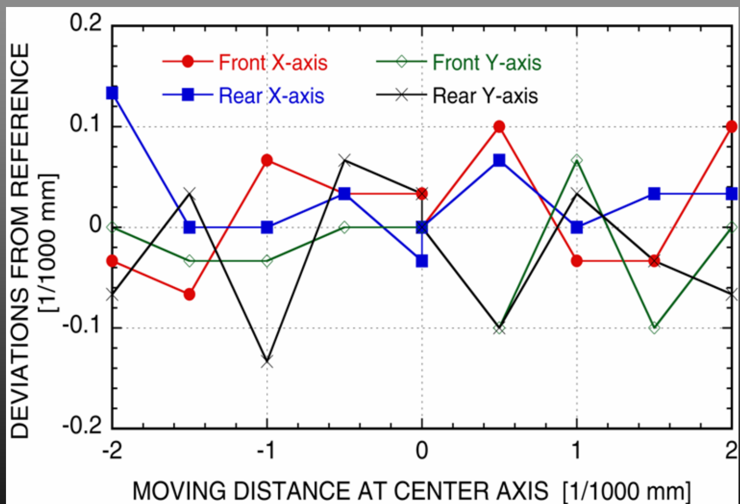


Roller Cam Mover and Support Stand

Precise Roller Cam type Mover New



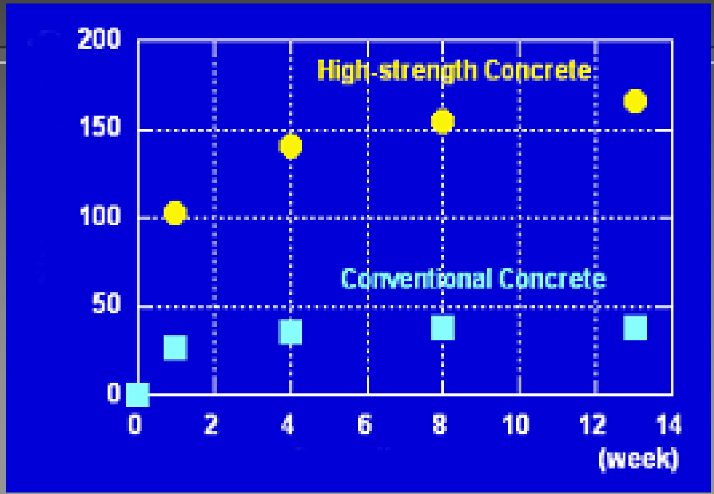
This mechanism is designed to support a load of up to 500 kg, while providing smooth motion, free of hysteresis at the micron level. The new roller cams mover unit is comprised of two roller cams, their stepping motors drivers, two linear sliders and support frames. We used 72 mm diameter roller cams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

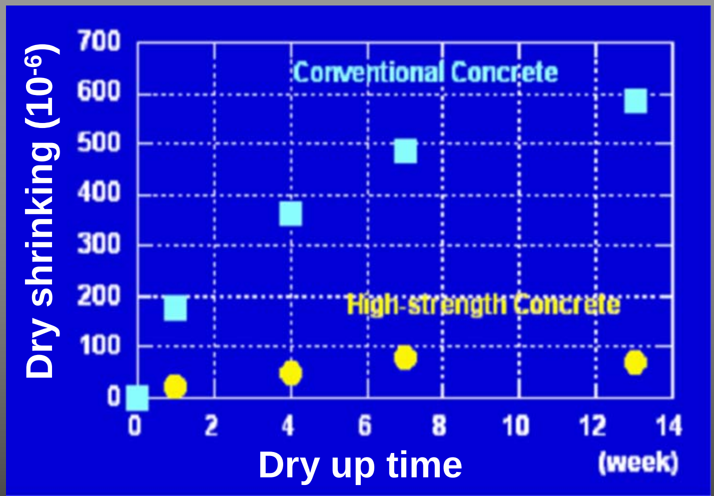


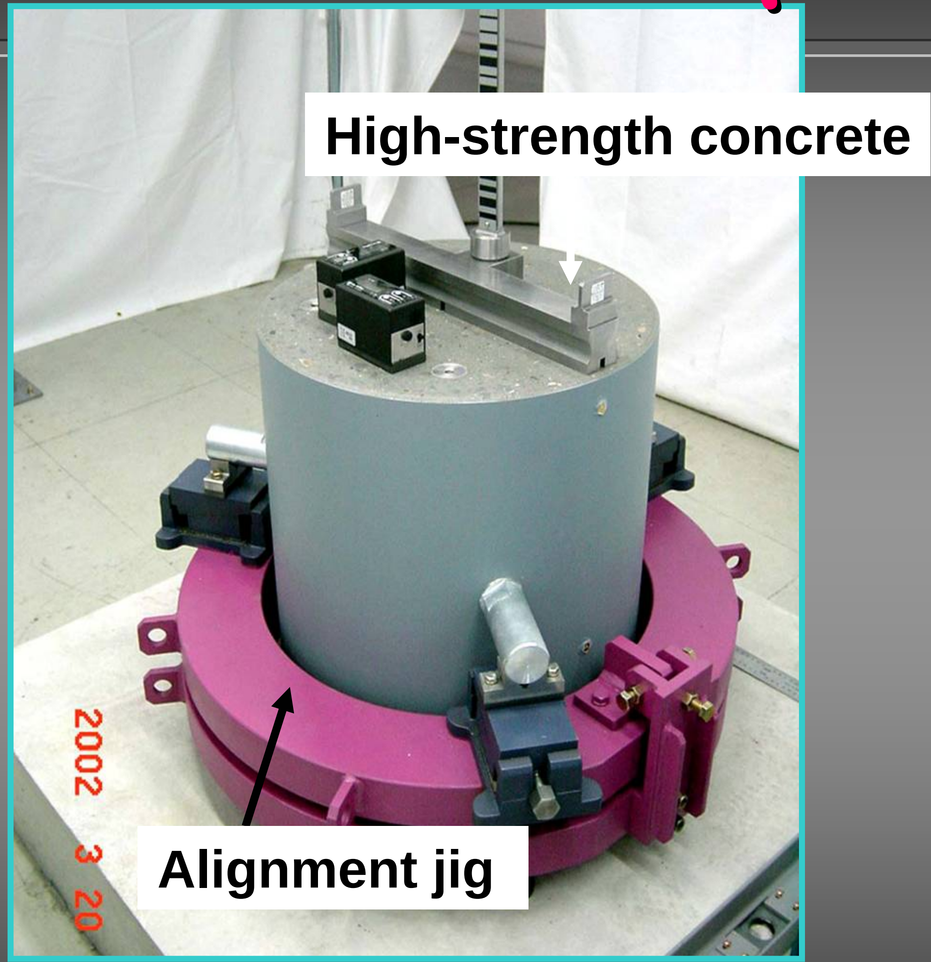
Two roller cams units were used to manipulate the dummy weight. Each roller cams mover unit can be controlled individually to adjust for any axis. A position repeatability of around ±0.1 μm within ± 1 mm of the adjustable area was obtained.

High-strength Concrete for Support Table

New





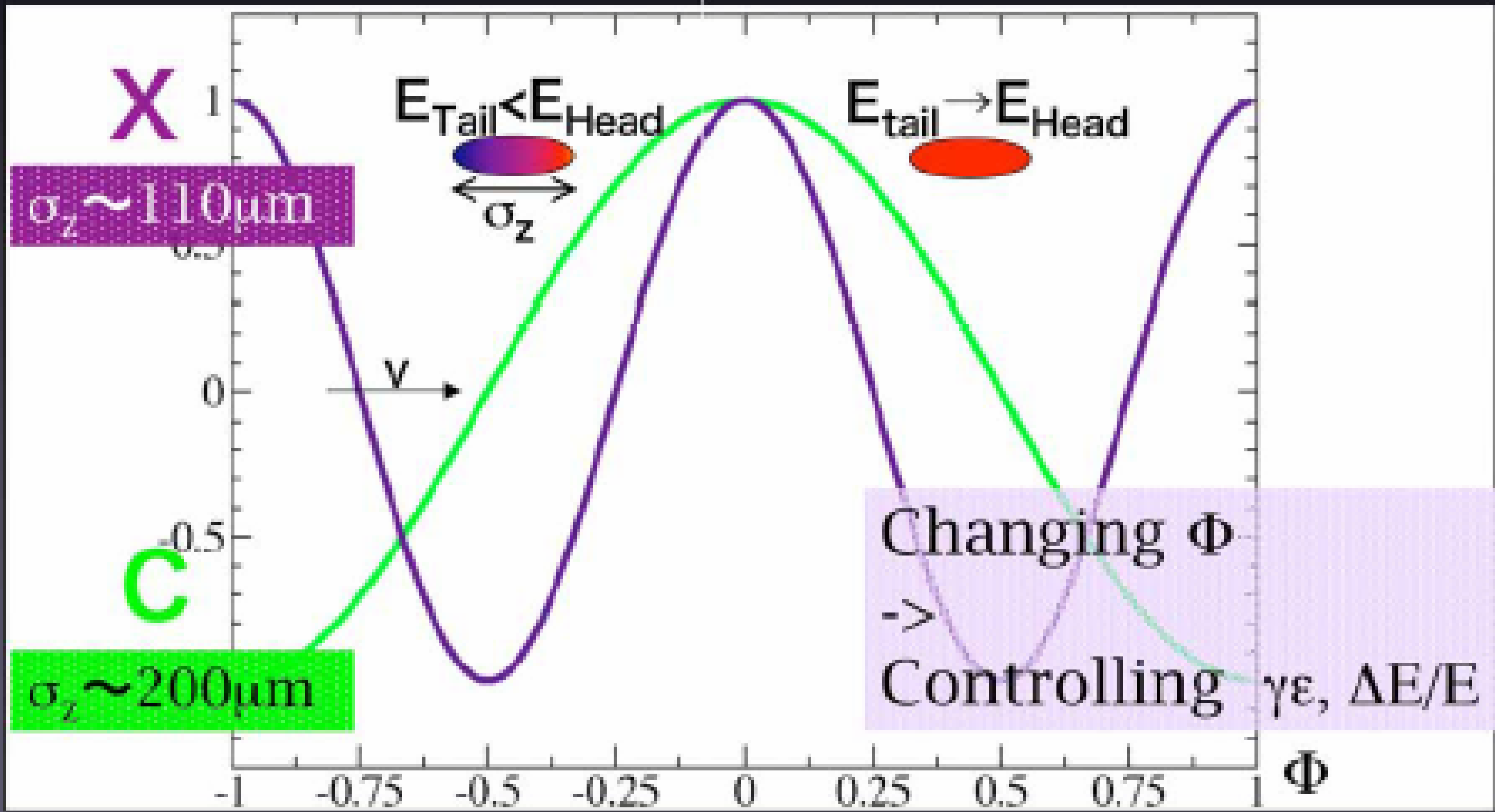


- Low dray shrinking
- Flexible shape
- Massive (damp the vibration)
- Low cost

Diameter: 500 mm
Length: 680 mm
Flatness at top: ±20 μm

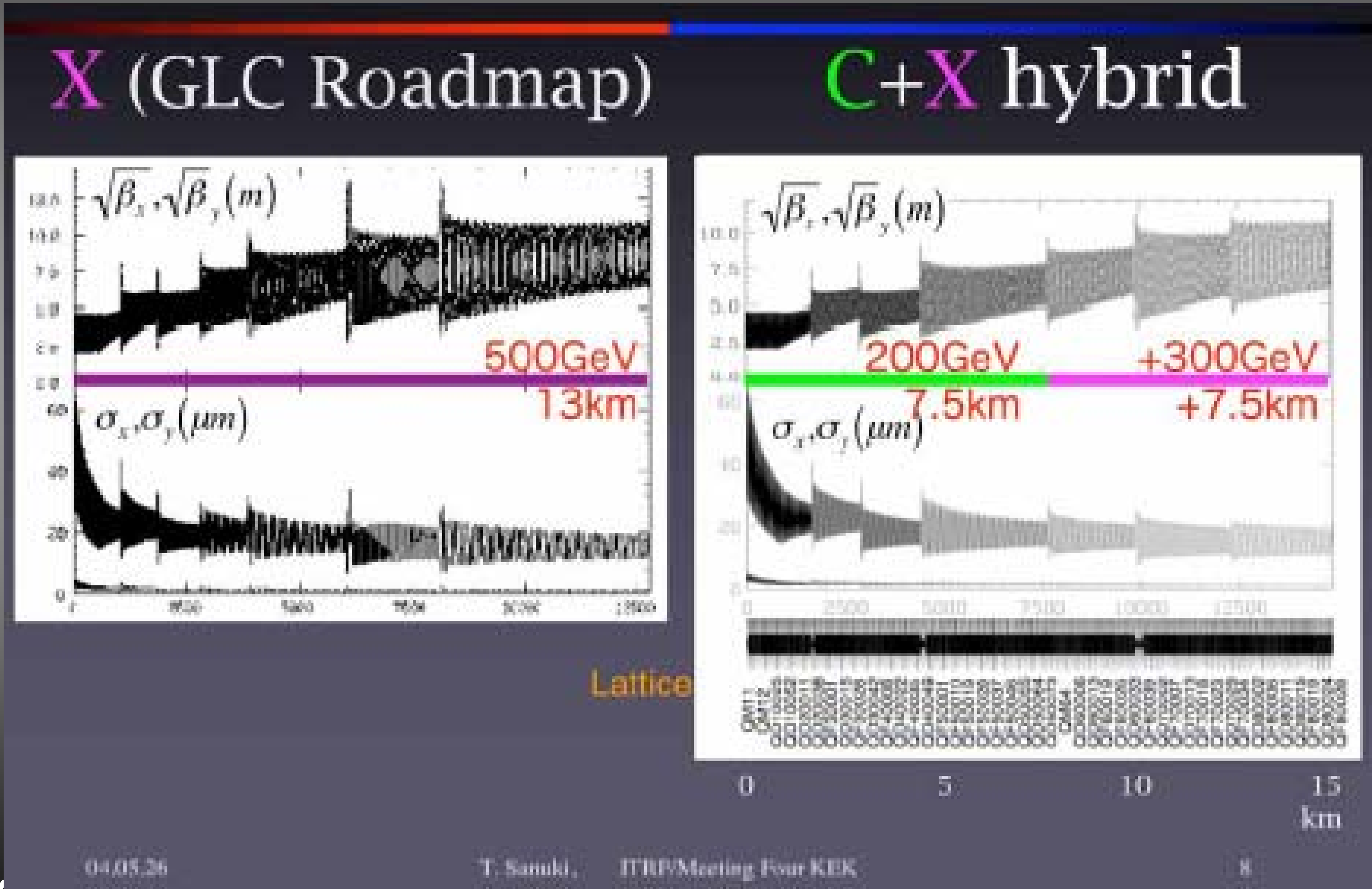
Klystron and Modulator

RF λ & Bunch Length σ_z



$\lambda_C = 2\lambda_X$ Optimum Bunch Length? In C+X

C+X hybrid optics (SAD)

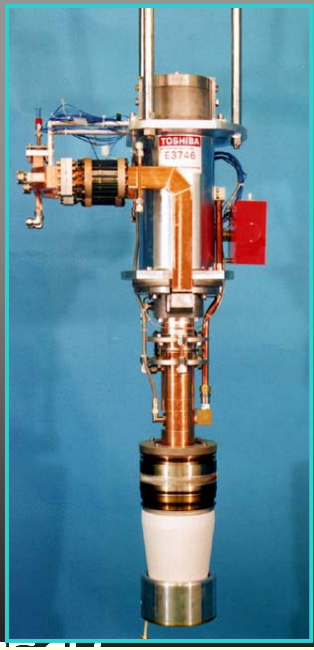
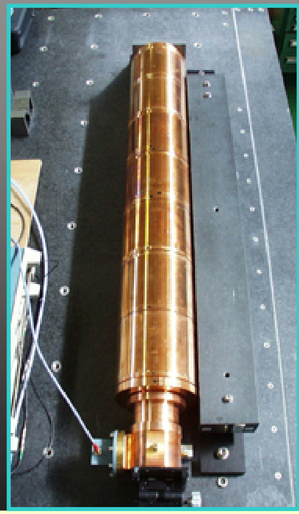
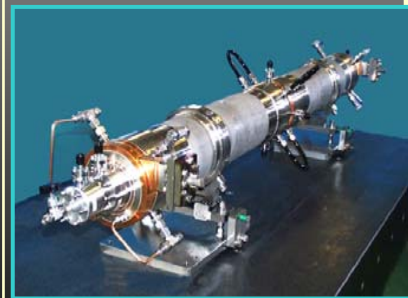


Main Machine Parameters

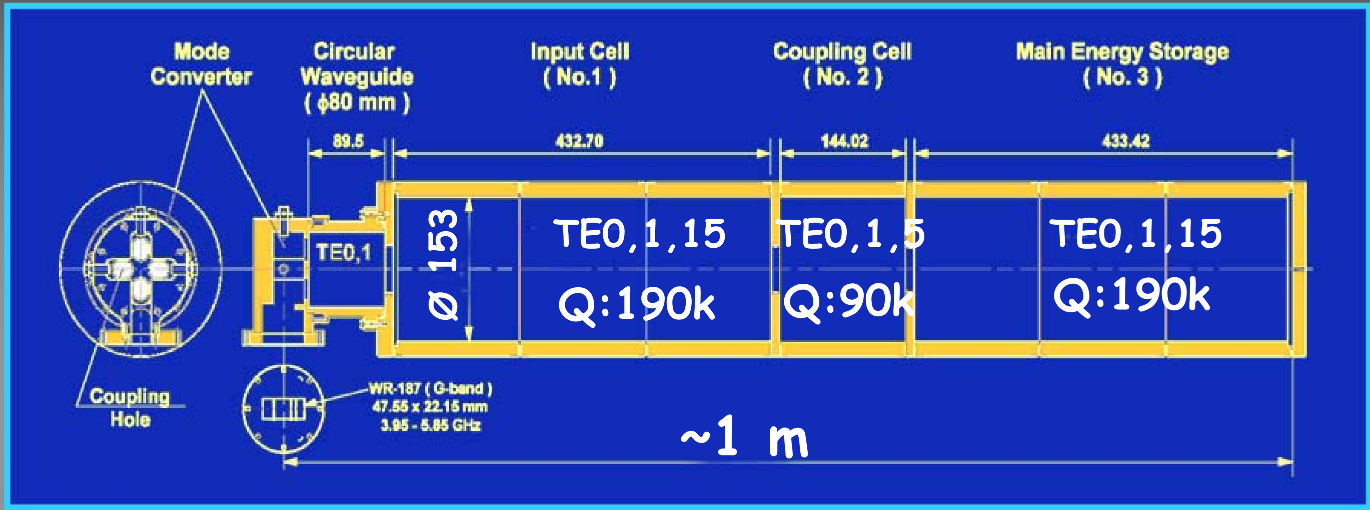
Overall Parameter		
C.M. Energy	500	GeV
Nominal Luminosity	14.1×10^{33}	
Beam Current nC x bunches x pps	1.4 x 192 x 100	
Spot Size at IP (rms)	243 x 4.0	nm
Bunch Length	0.2	mm
Bunch Separation	1.4	nsec
Main Linac Parameter		
Main Linac Length	15.3	km
Number of RF Unit	2125	Units
Linac AC Power	240	MW

Klystron	
Klystron Power	50 MW, 2.5 μsec
Modulator	110 MW, 25 kV
Efficiency	50%
RF Pulse Compressor	
Compression Gain	x 3.3
Efficiency	70%
Accelerating Structure	
Accelerating Gradient	31MV/m (with beam), 42 MV/m (no load)
Shunt-Impedance	54 MΩ/m
Alignment Tolerance	50 μm

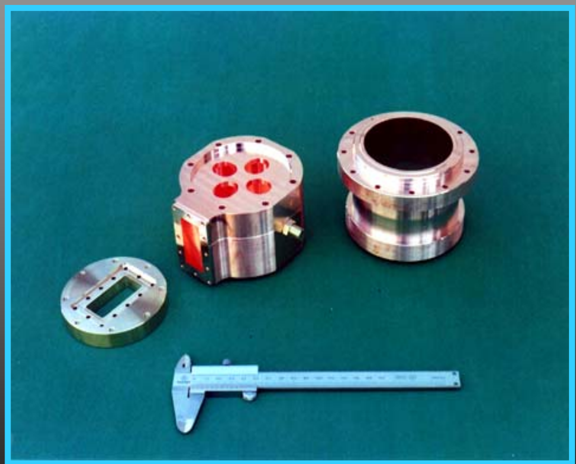
Main R&D items

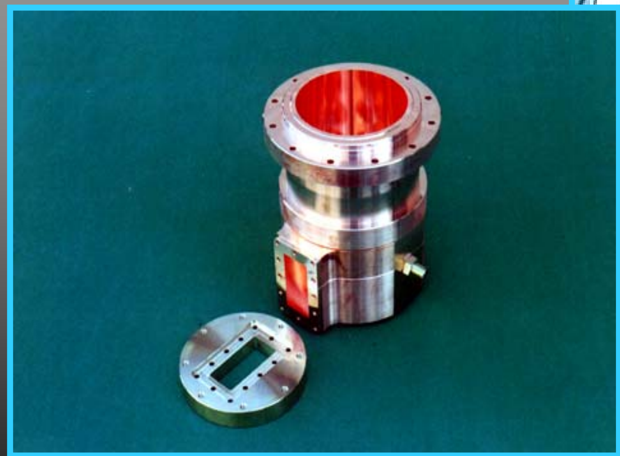
C-band Klystron	Klystron Modulator	RF Pulse Compressor	Accelerating Structure
50 MW, 2.5 μsec, 47 %	110 MW 100 pps	Flat Pulse Gain: 3	1.8 m Choke-Mode
Life test >6500 hours, OK. 	Smart modulator-I using inverter HV charger. Running for klystron life test. OK 	1m long cold model Three-cell cavity. 	Beam acceleration at 50 MV/m was done at ATF-KEK, with S-band model. HOM damping performance was proved by ASSET-SLAC test, 1998. 

RF Pulse Compressor (low power model)



Cold-Model Cavity



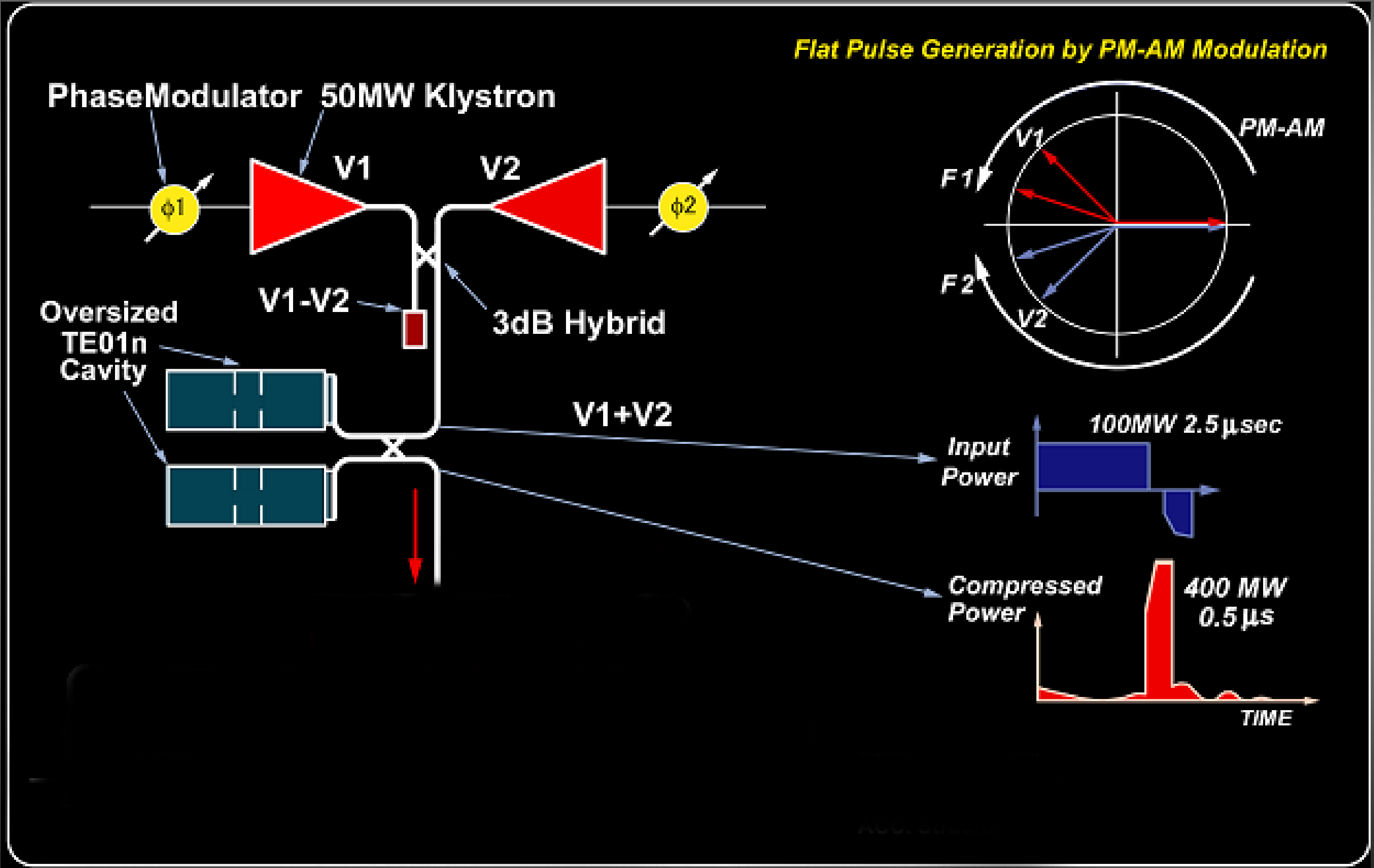


PAL/POSTECH

Mode Converter

KEK

PM-AM Modulation



From 1987 to 1994 extensive high gradient tests were performed at KEK using S-band structures. We learned that

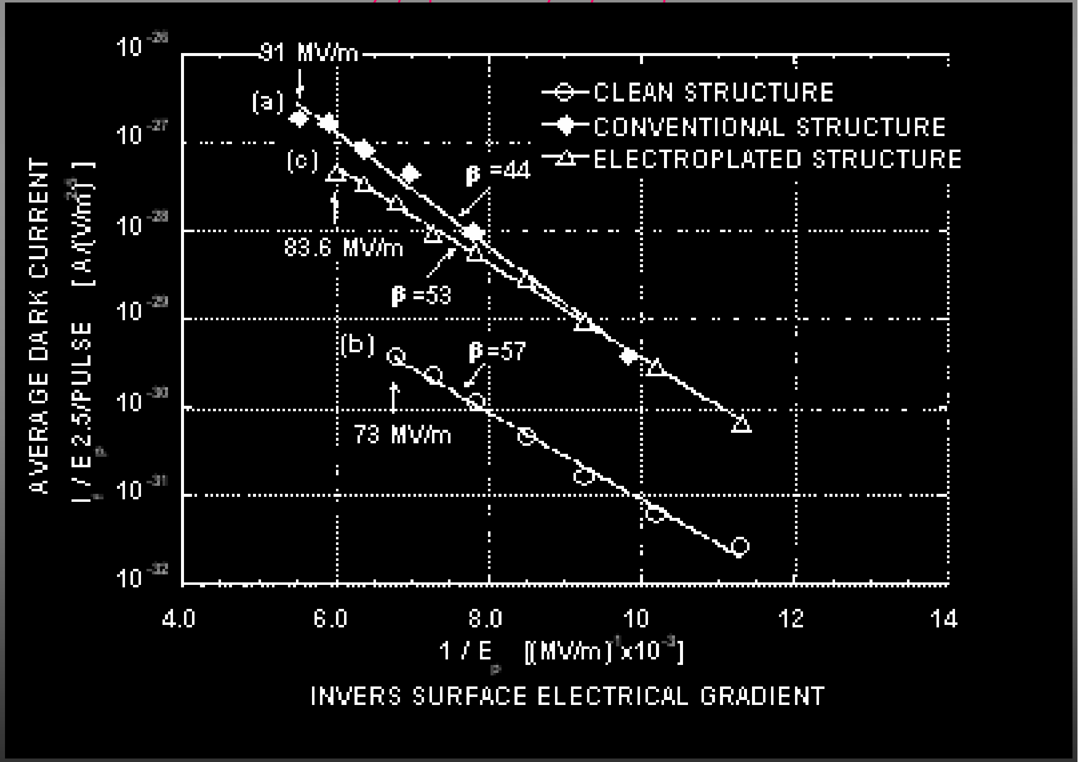
(1) The magnitude of dark current depends on the cleanliness of the surface inside the structure.

(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.



High Power RF unit Test

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.

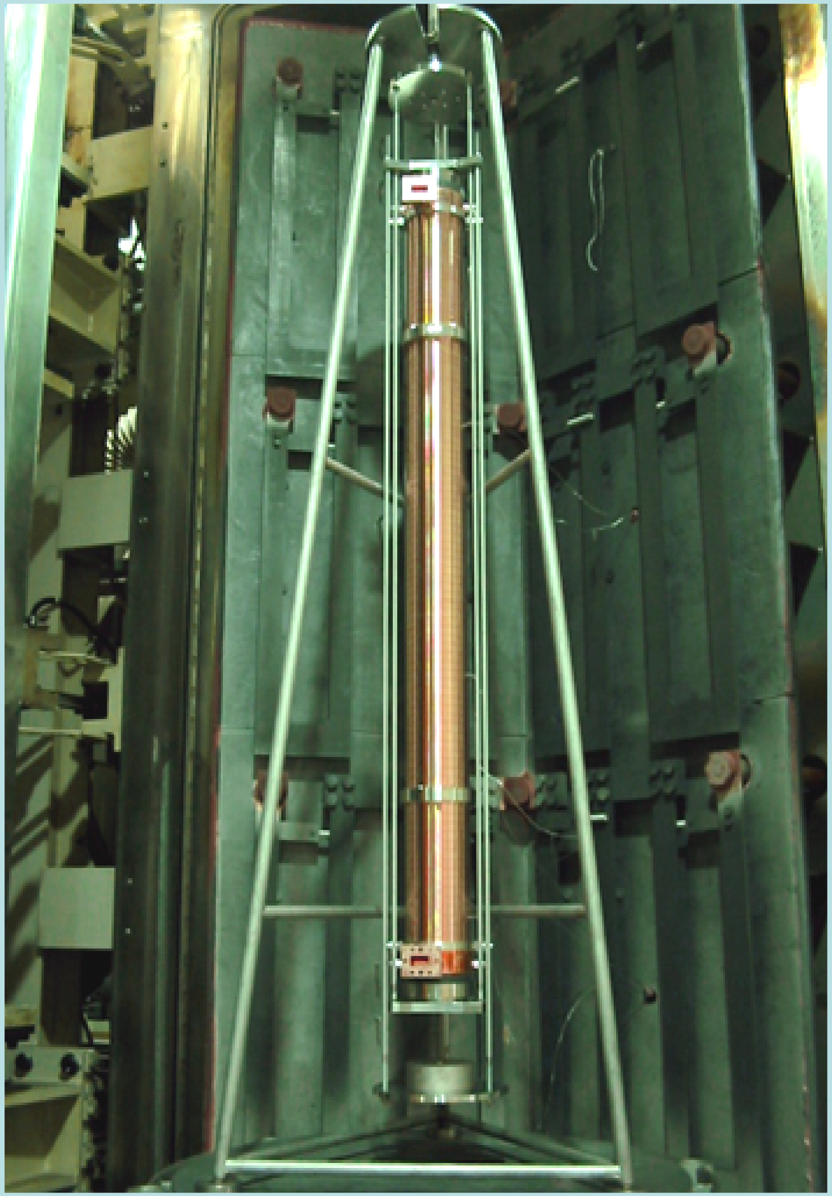
- A beam test of a RF-unit will be done at SCSS in SPring-8 in 2006.

Requirements of Alignment

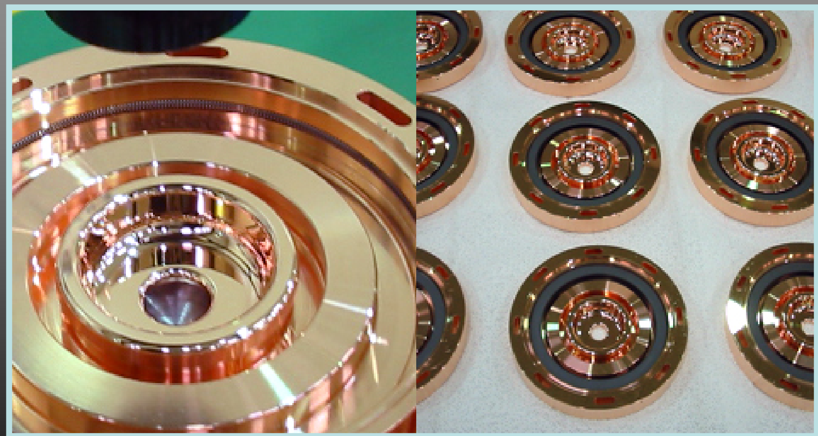
1) Accelerating structure

- For single wake filed: 25 μm (rms)
- Mechanical tolerance: 50 μm (max)

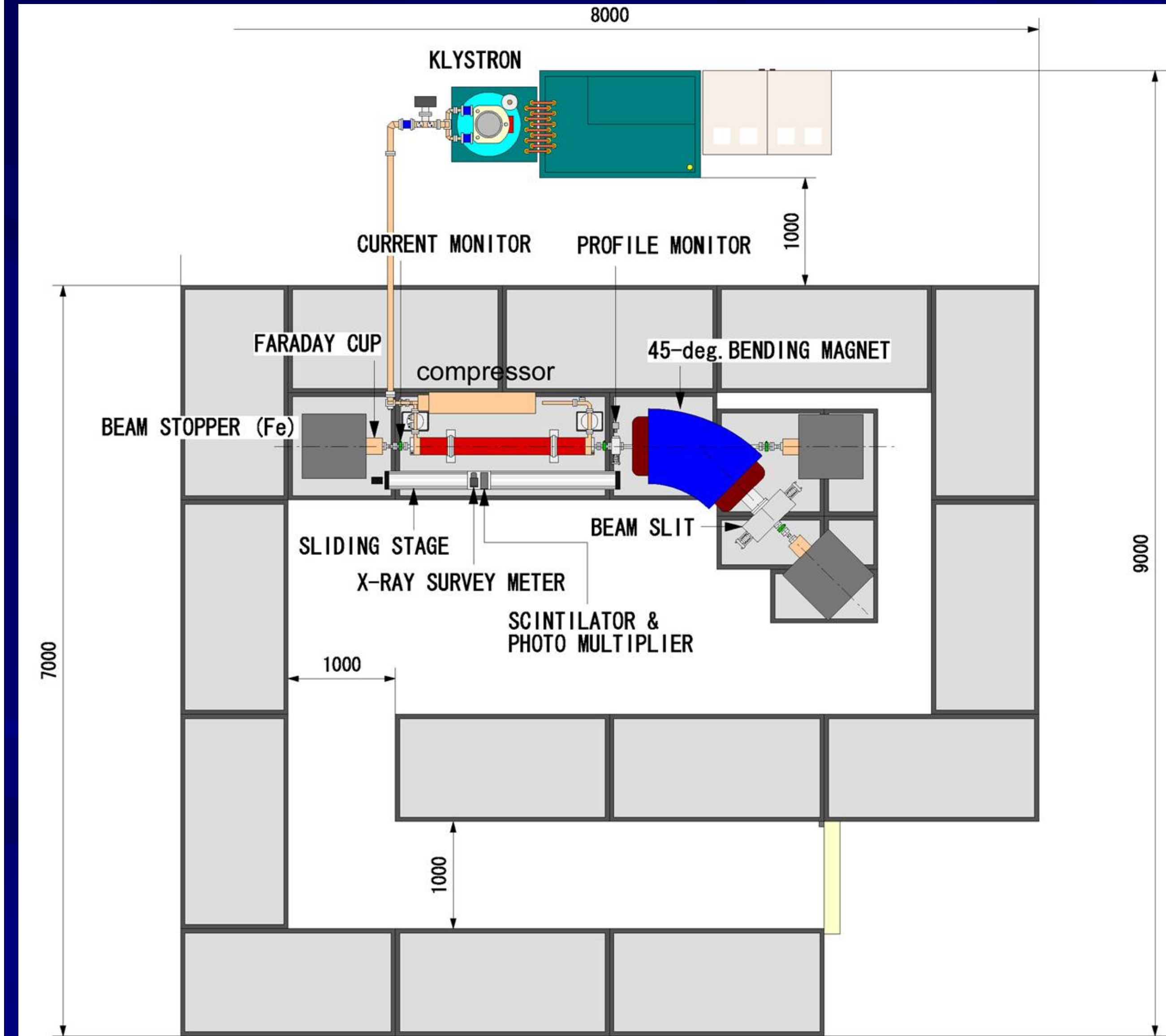
C-band Accelerating Structure



- 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

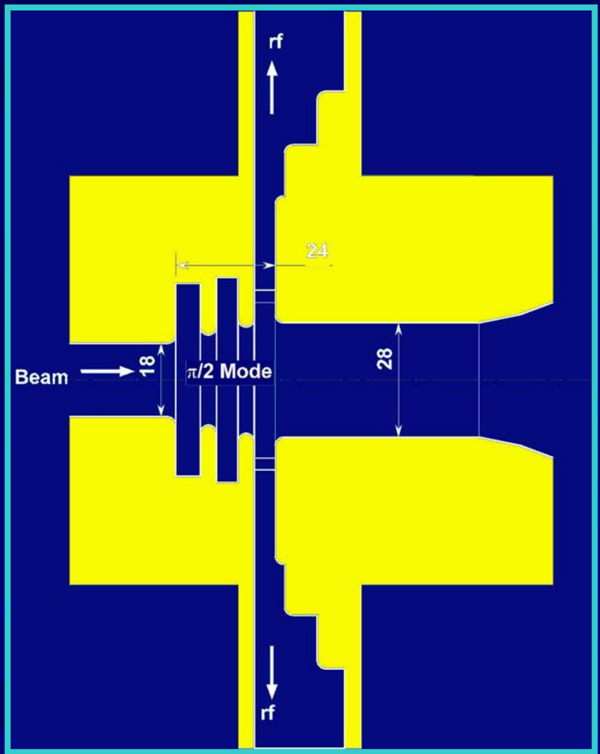
Pulse compressor

Gradient:

56 MV/m(max)

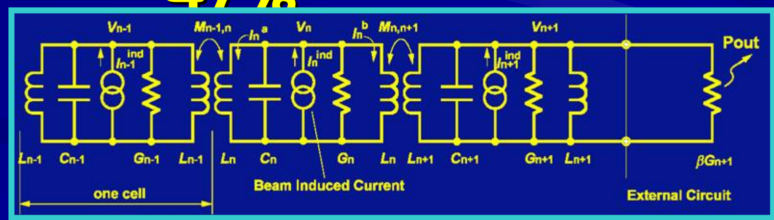
Traveling-wave Output Structure

3 - cell traveling π/2 - mode



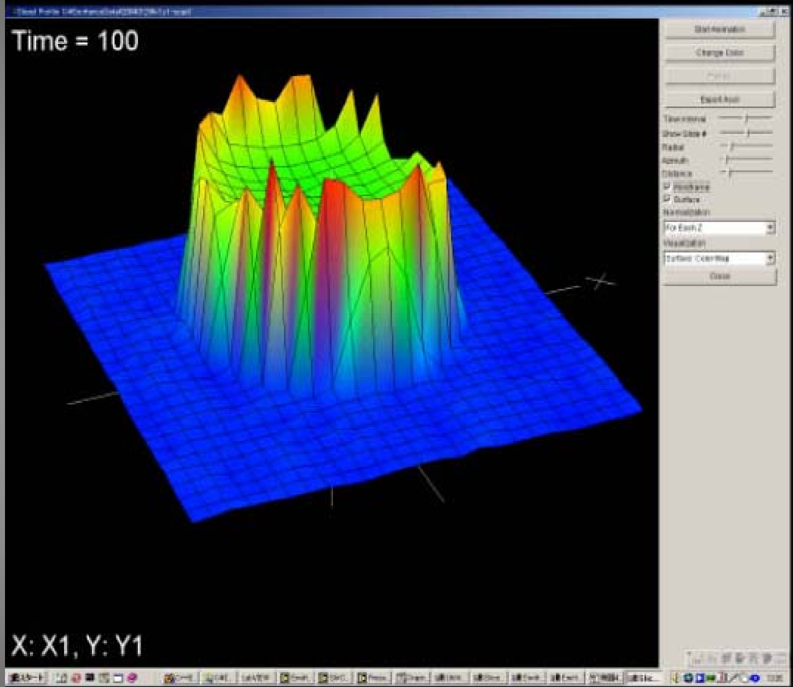
- Reduced surface field
  45 → 29 MV/m
- Stable beam envelop
- Lowered focusing solenoid power (4.6 kW)
- Lowered X-ray emission
- Enhanced efficiency
  41 → 47%

Coupled Resonator Model

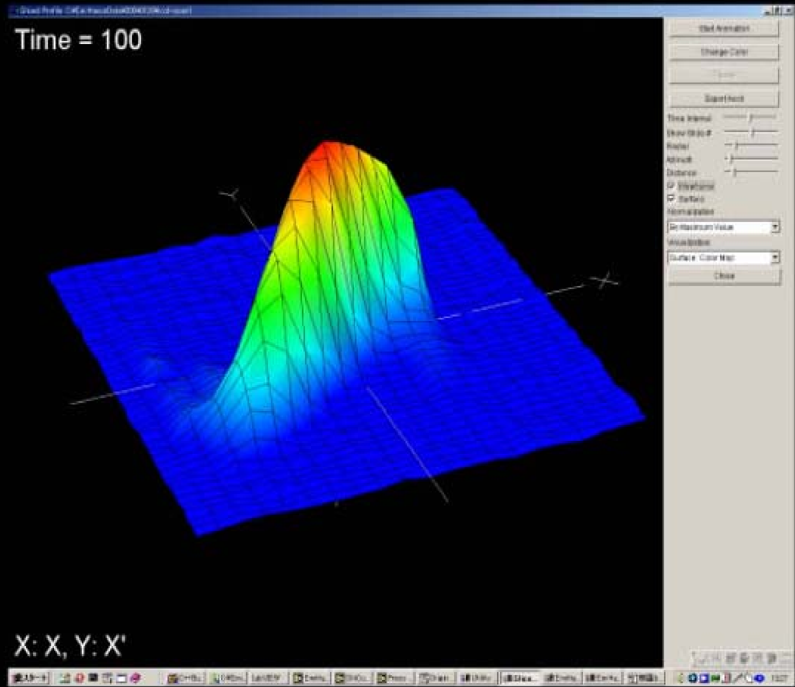


Beam Emittance Measurement on SCSS

Beam Profile



Emittance Profile



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

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

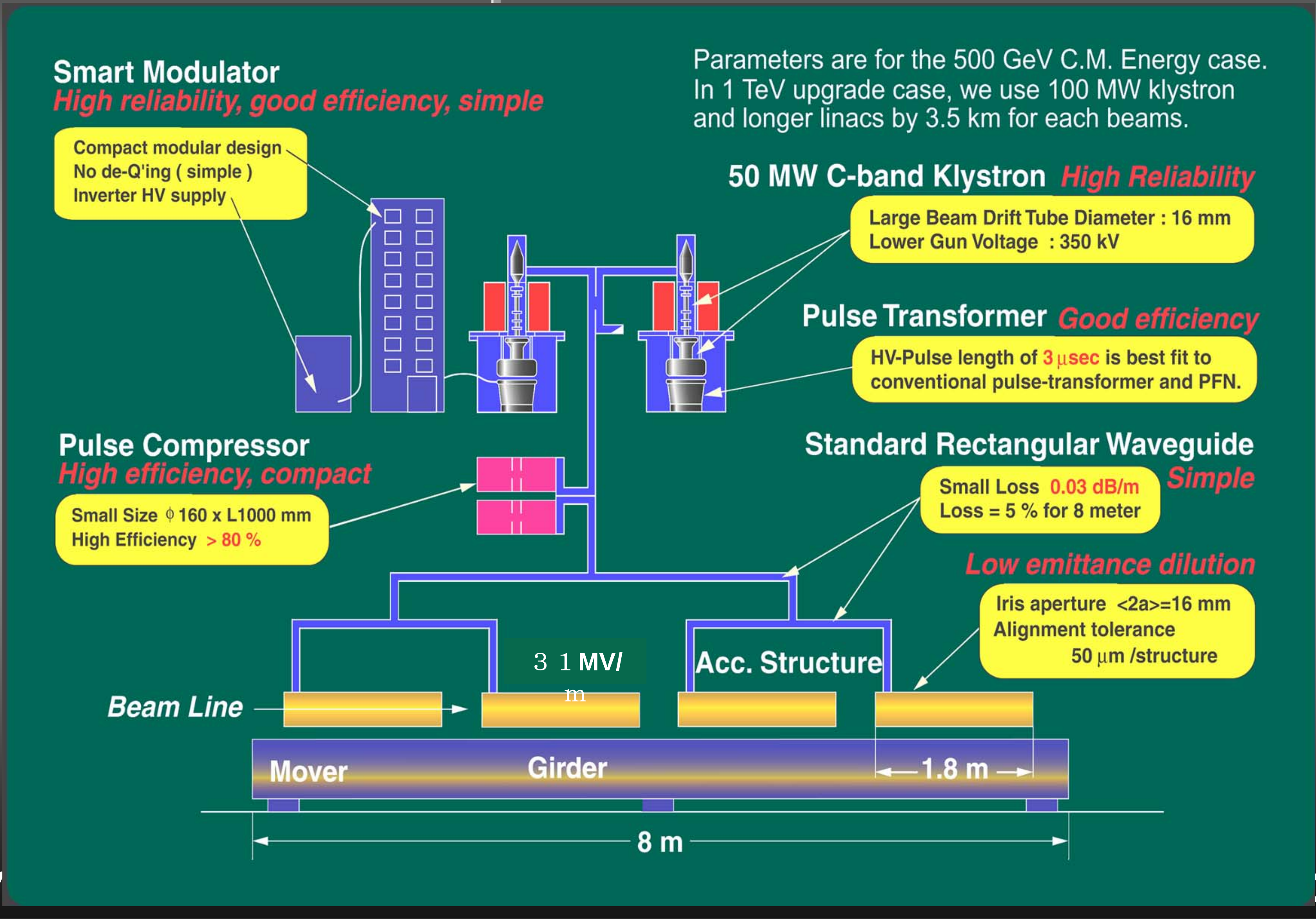
Requirement : 2 π.mm.mrad @Undulator
Experiment : 0.9 π.mm.mrad @Gun (preliminary)

Pulsed High Voltage DC GUN

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



Measured Wakefield