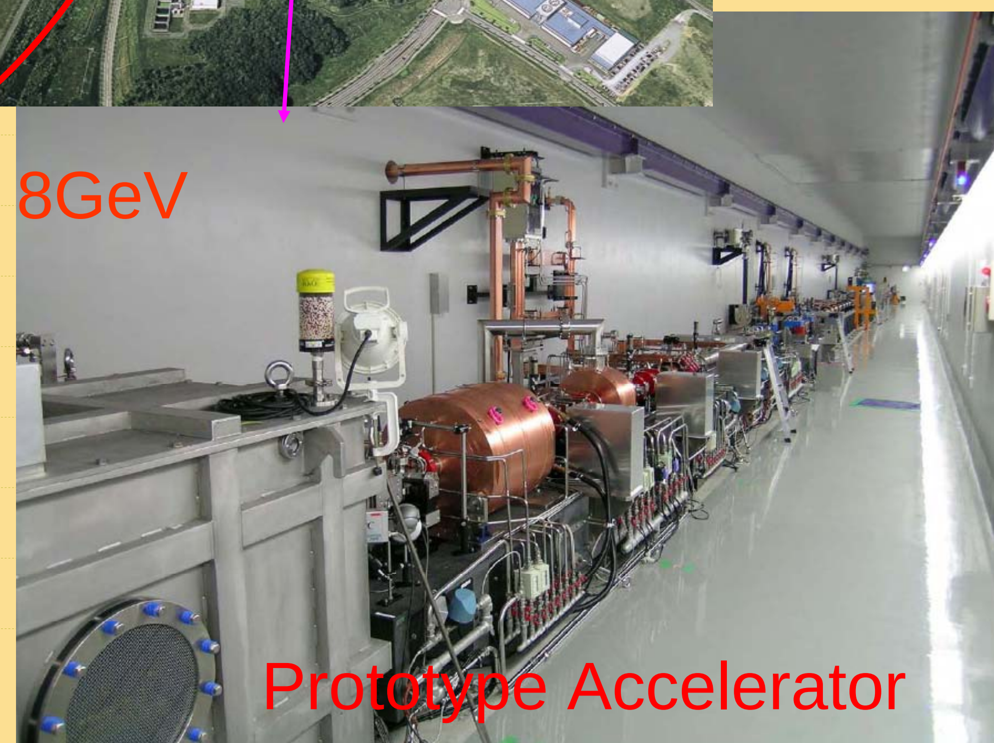
Introduction of Japanese X-FEL

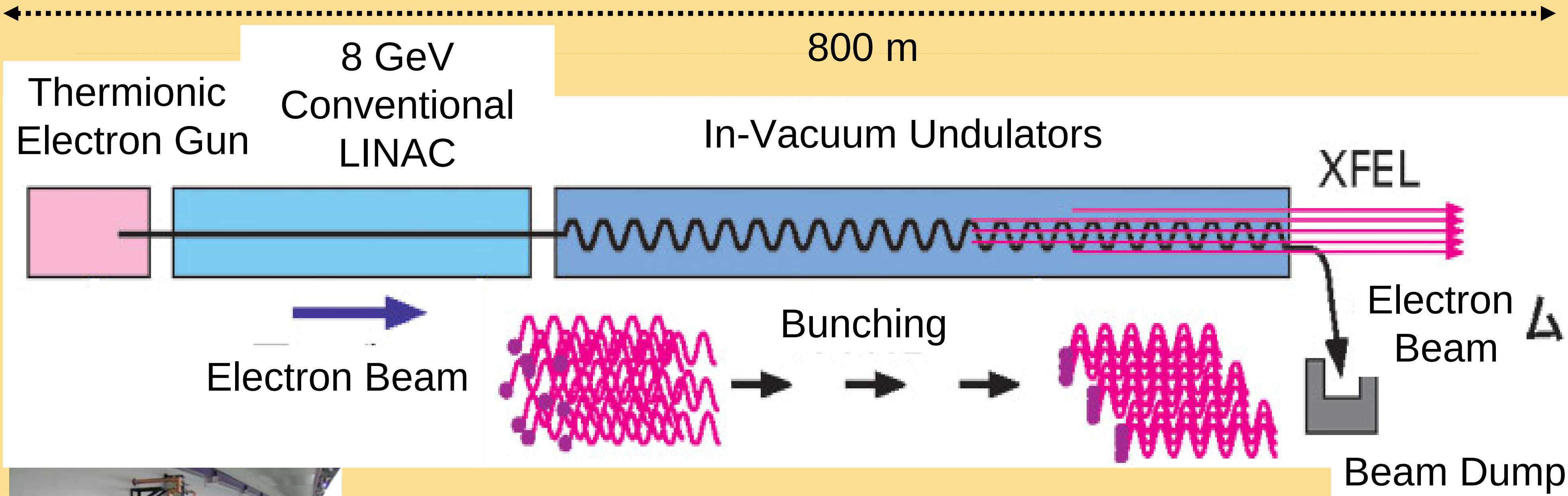
Yuji Otake, RIKEN, XFEL project

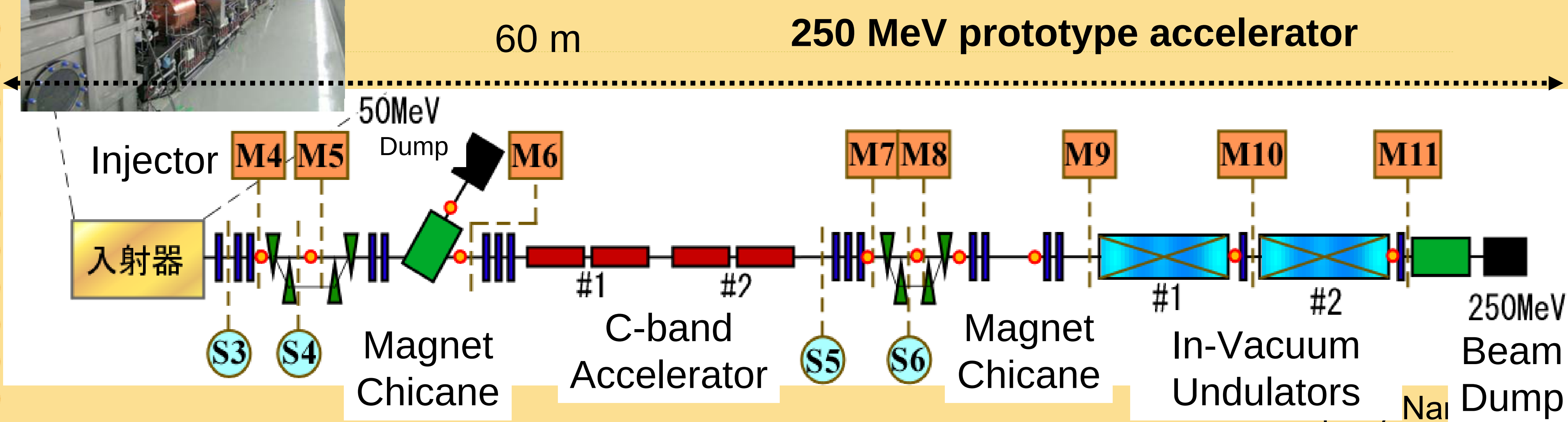
Location, Where is X-FEL (RIKEN, HARIMA)

X-FEL 8GeV



Configuration of Japanese X-FEL





In the case of the prototype accelerator

- **We have confirm feasibility of**

  1. 500 kV CeB6 Thermionic Electron Gun

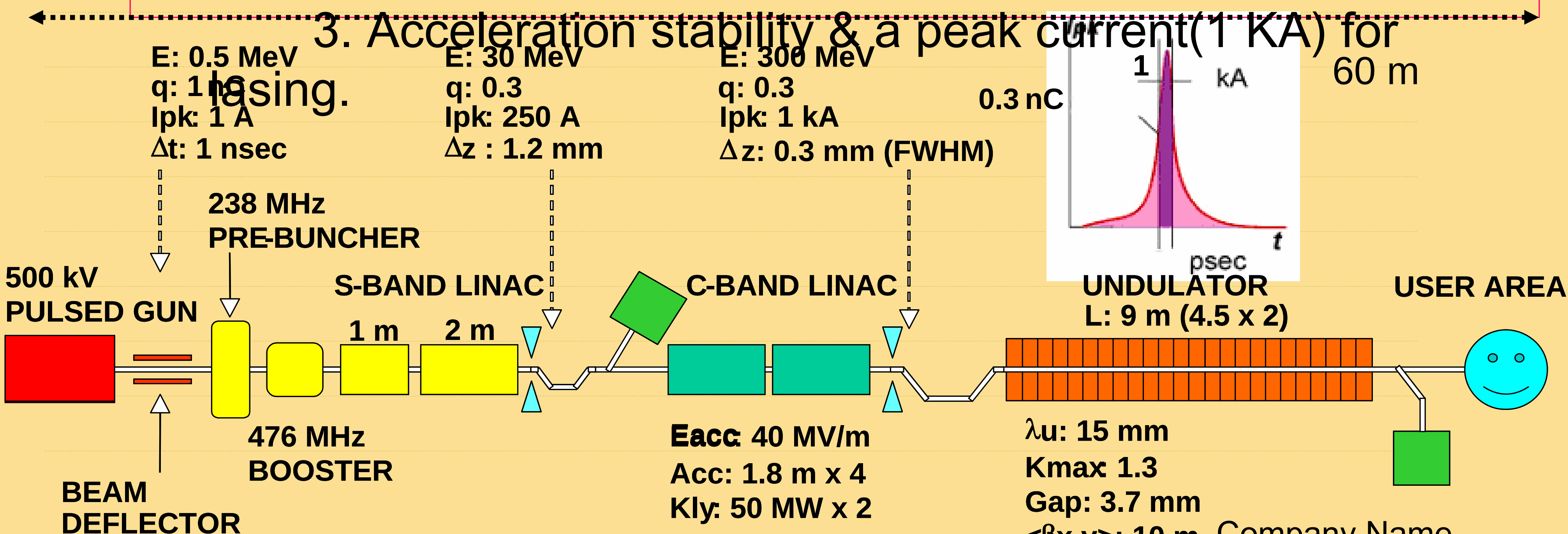
  (Small Emittance (less than 2π mm mrad) and Dark

rent),

  2. C-band high gradient acceleration

  (High Gradient Acceleration (more than 35 MV/m)),

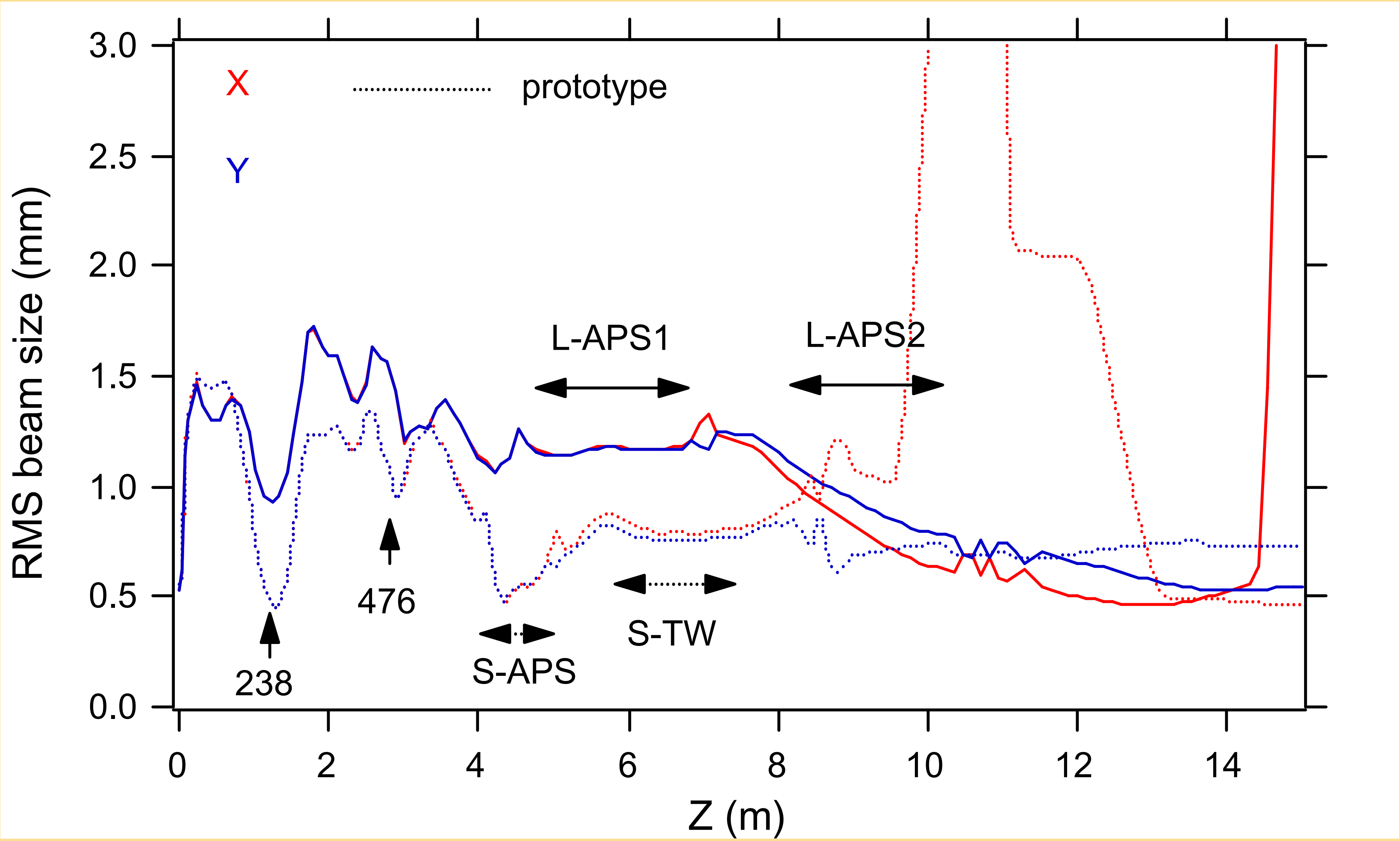
  3. Acceleration stability & a peak current(1 KA) for lasing.



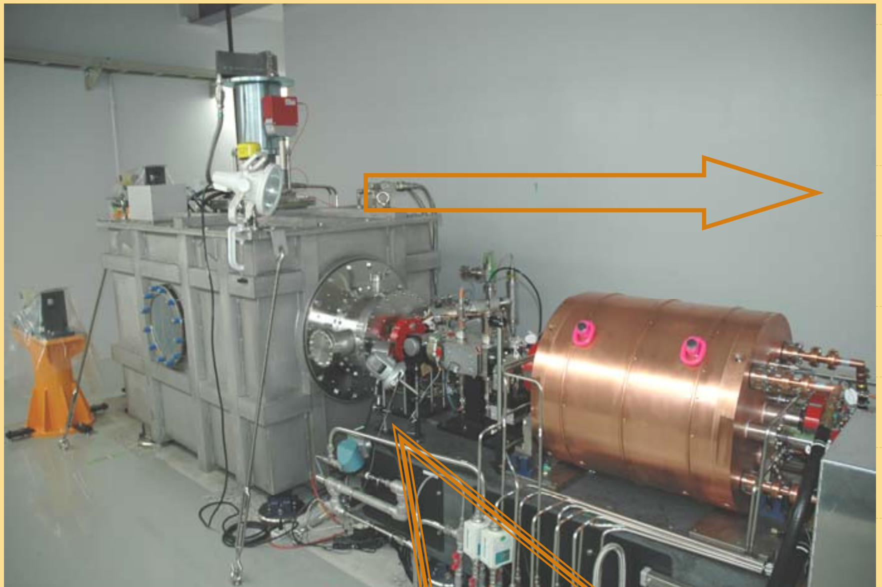
Summary of Machines

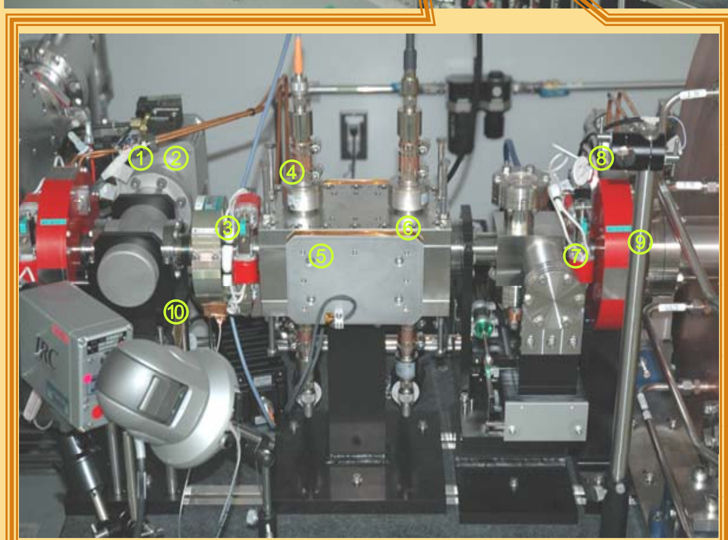
	Prototype	X-FEL
Beam Energy (MeV)	250	8000
Peak Current [A]	800	3000
Normalized Emittance (πmm.mrad)	2	1
Electron Beam Brightness ($A/\pi^2 mm^2.mrad^2$)	200	3000
総電荷量 (nc)	0.2~0.3	0.2~1

Beam Transport of the SCSS Prototype & 8GeV Injector Accelerator

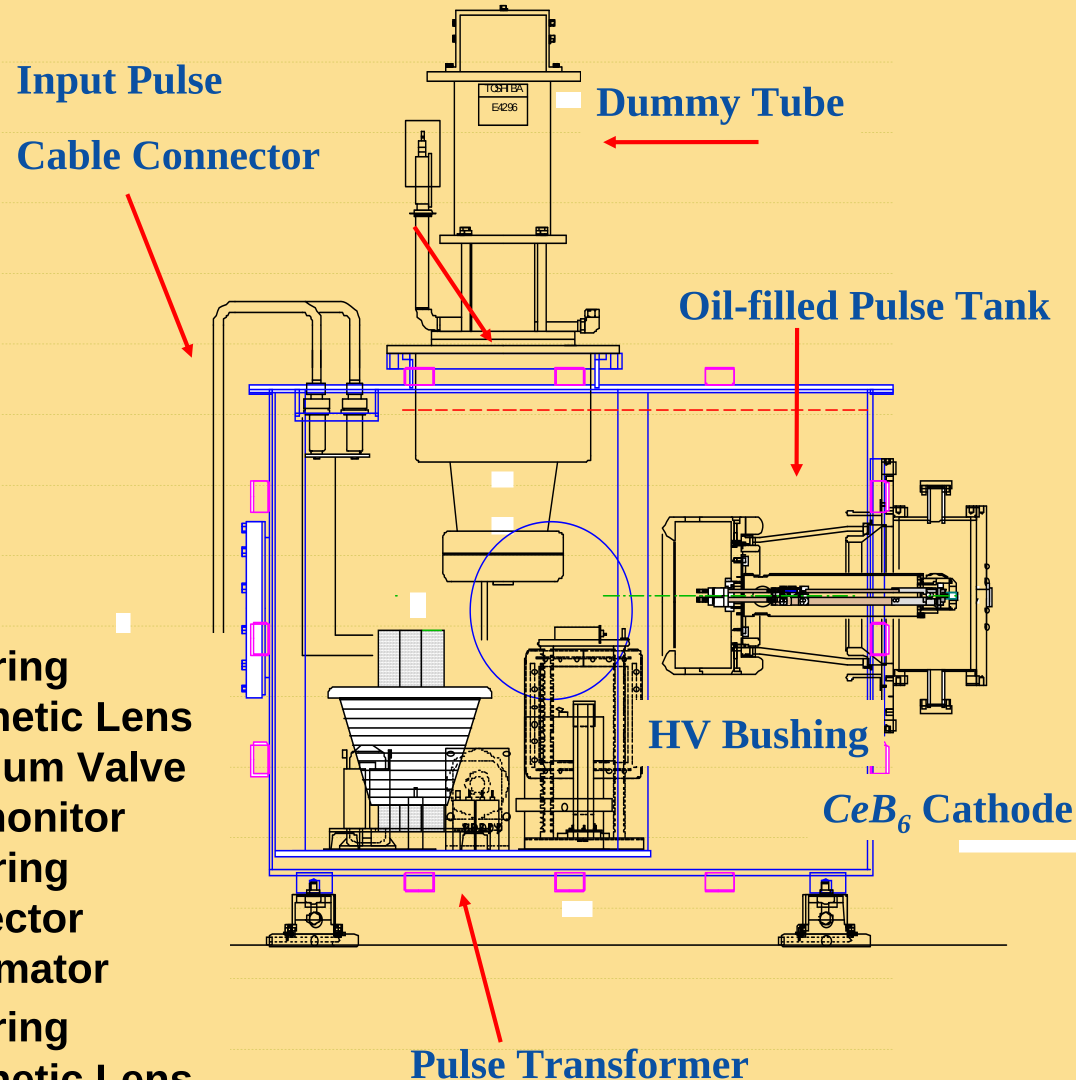


Thermionic Electron Gun

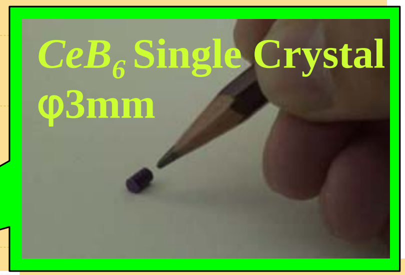


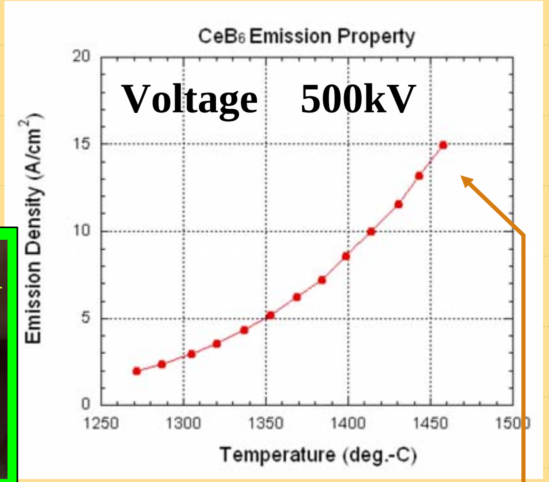


①Steering
②Magnetic Lens
③Vacuum Valve
④CT monitor
⑤Steering
⑥Deflector
⑦Collimator
⑧Steering
⑨Magnetic Lens
⑩Temp. Meter



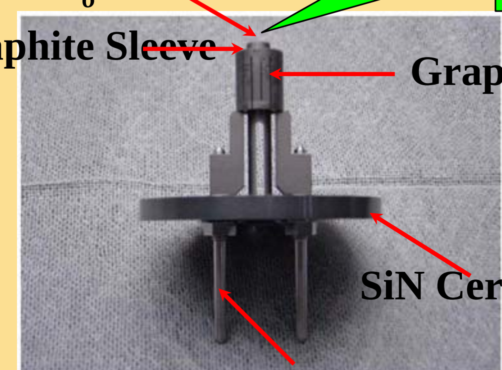
Electron Gun Detail





CeB_6 **cathode**

Graphite Sleeve

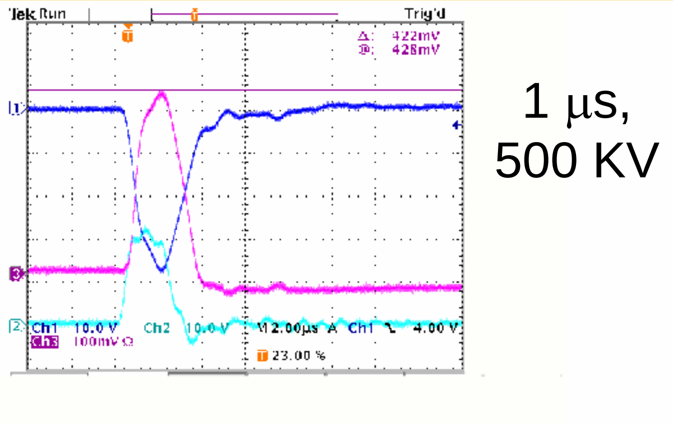


Graphite Heater

SiN Ceramic Base

Molybdenum Current Lead

High Voltage Pulse Wave Form



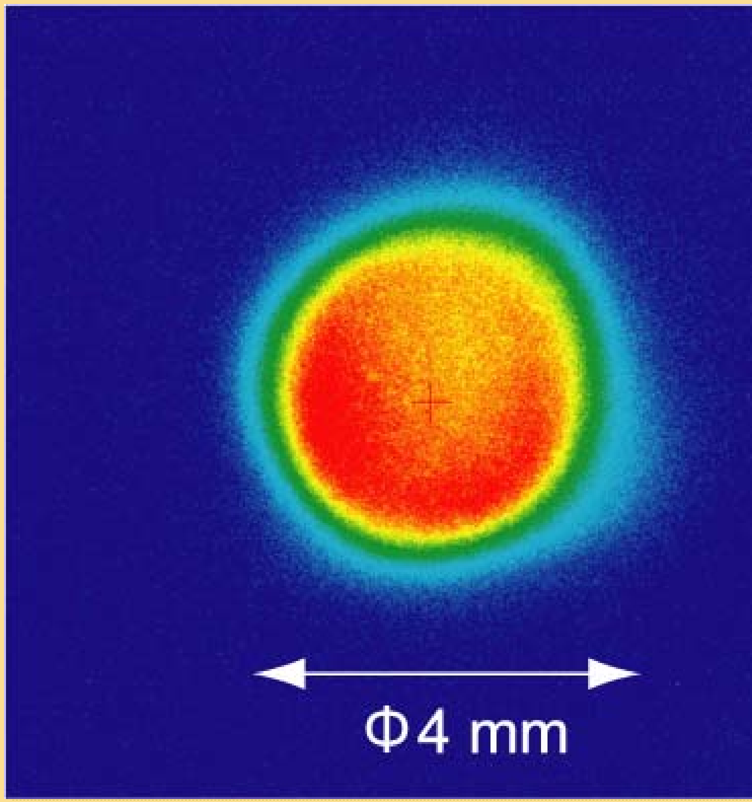
1 μs,
500 KV

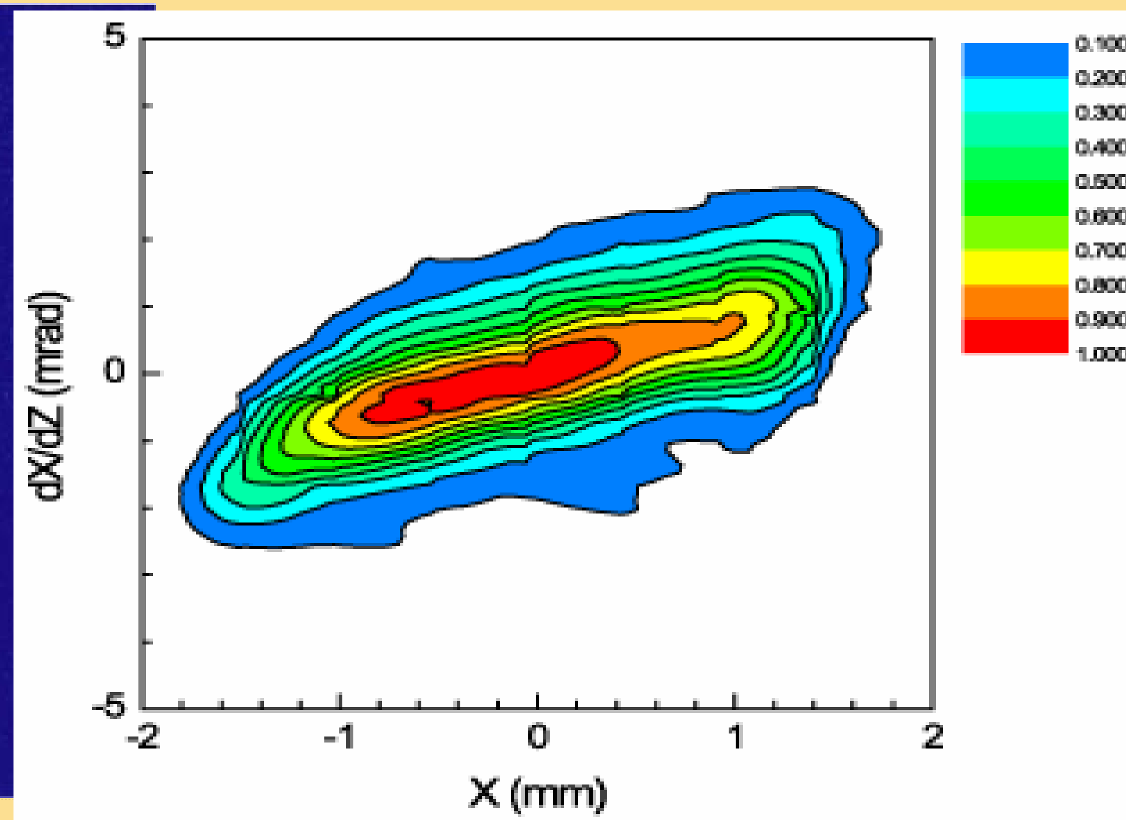
Measured with the Radiation Thermometer graphite sleeve

Beam from Electron Gun

Beam Profile

Phase Space Distribution





Screen (100μm^t) at 3.5 m from the electron gun (Fluorescence)

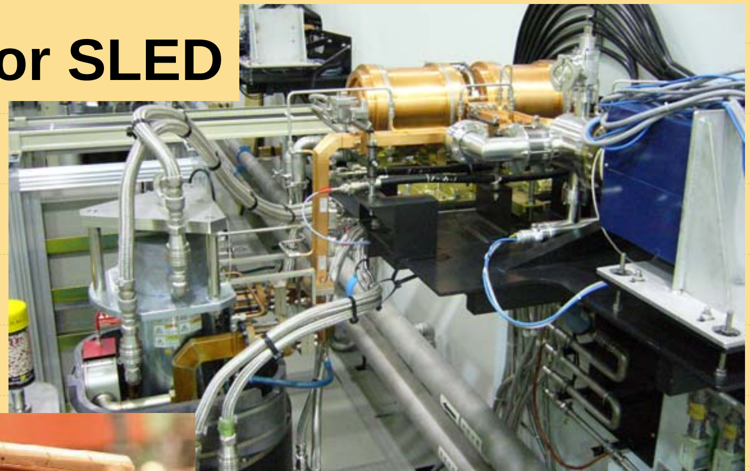
Projected Emittance : 1.1π mm mrad

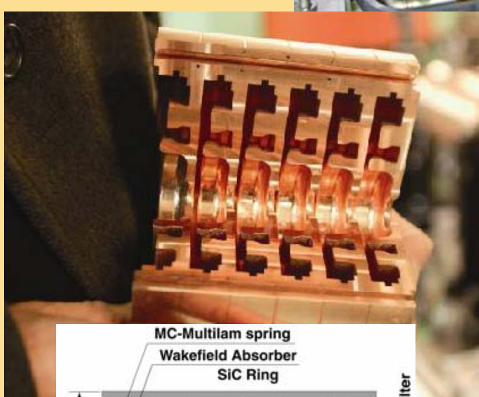
2 ns beam width produced with the high voltage deflector

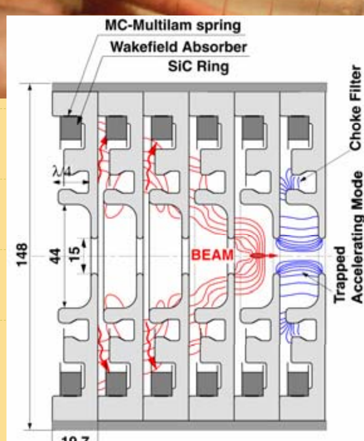
C-band (5712MHz) Accelerator

RF Pulse Compressor SLED

150 MW peak more







Cross-section of the accelerator guide

Total Length : 1,8m

Weight : 200kg

Cell Number :89

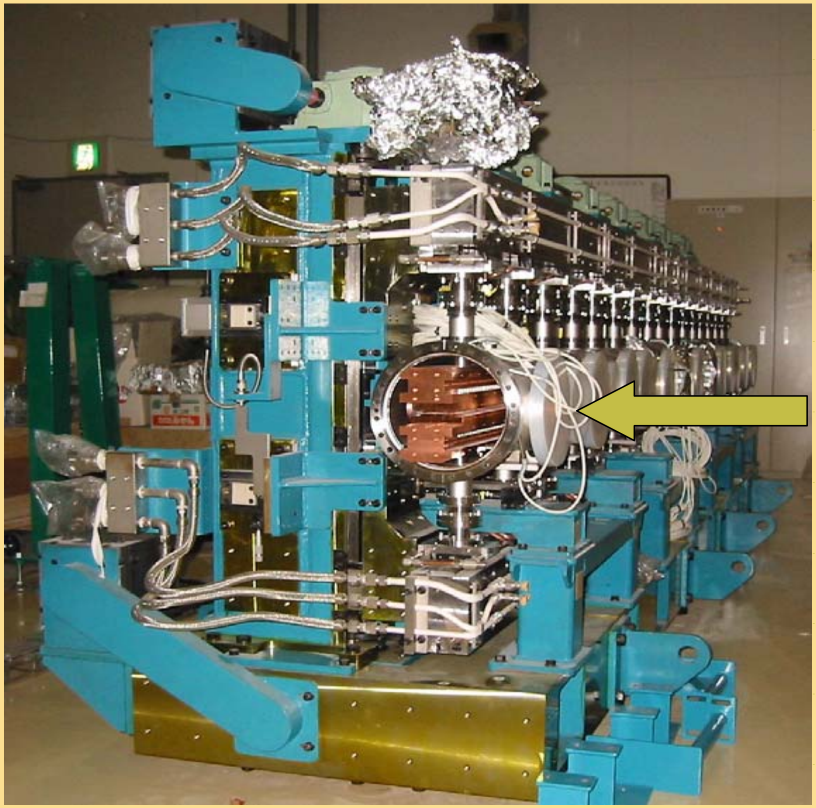
+2 coupler cell

Acceleration Mode : 3π/4

C-band Choke Mode Accelerator Guide

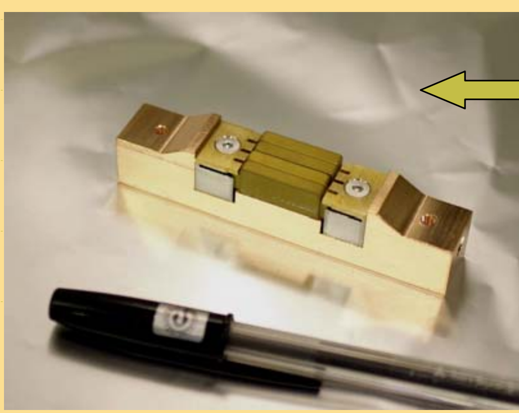
37 MV/m Achieved

In-Vacuum NdFeB Undulator



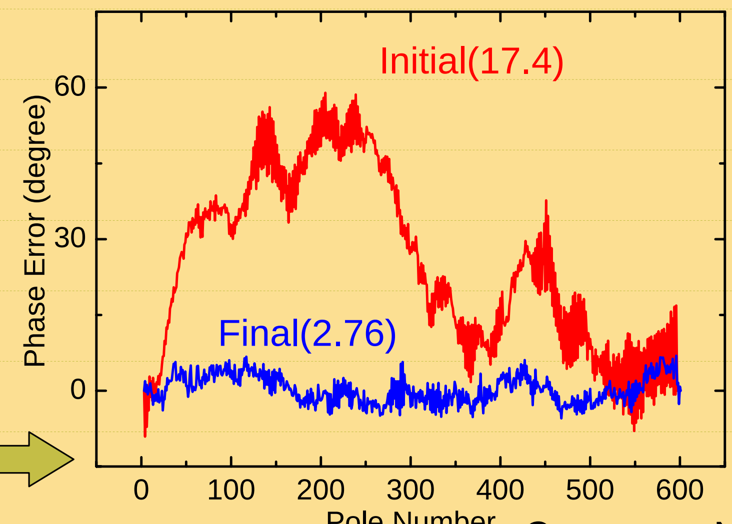
Movable Gap

λu : 15 mm
Length/Segment : 4.5 m
Number of Periods : 300
Gap : Max. 35 mm
Min. 2mm
Nominal 3.5 mm
K Value : Max. 1.8
Min. 1.3



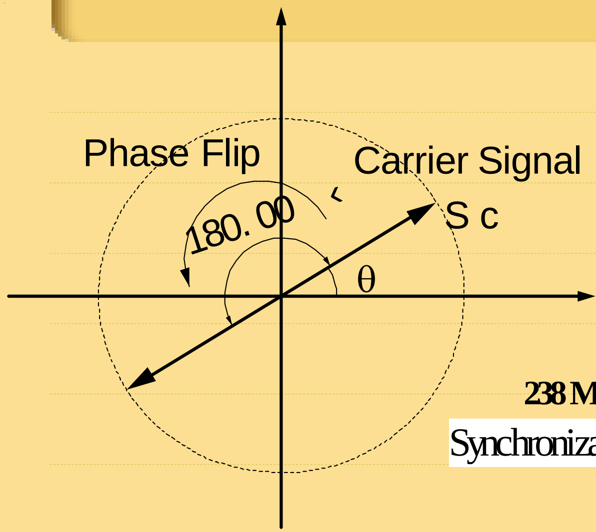
Magnet Unit (period, about 15 mm)

Magnetic field alignment (Phase)

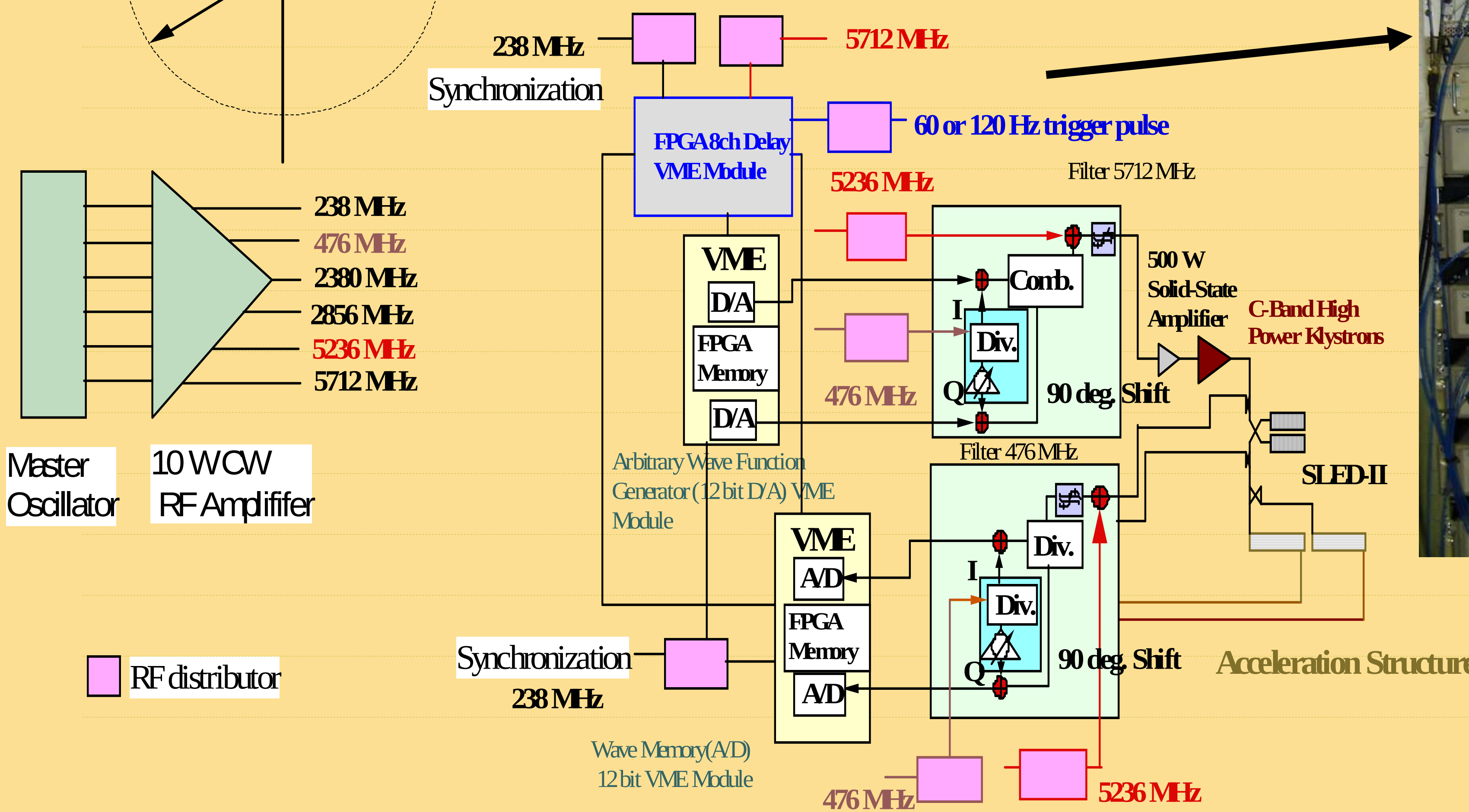


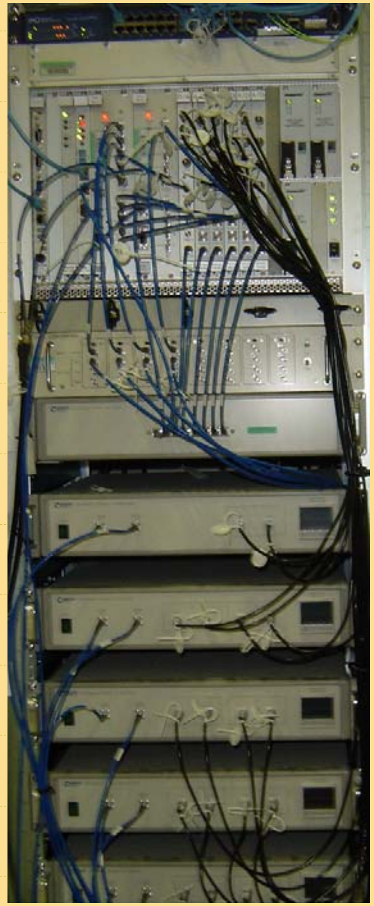
Company Name

Low-Level RF System of SCSS Prototype Accelerator



PSK Operation for SLED



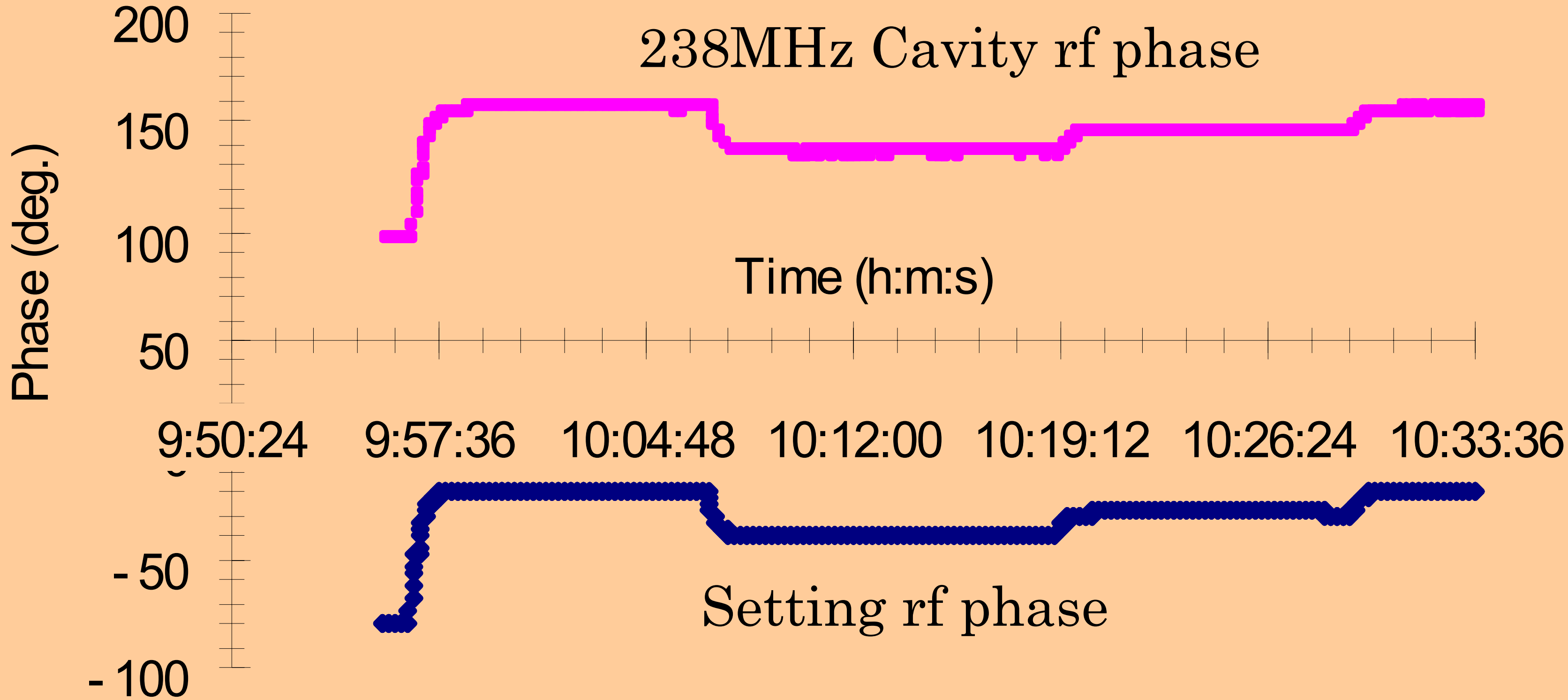


PID Control of RF Phase & Amplitude

PID Quantized Equation

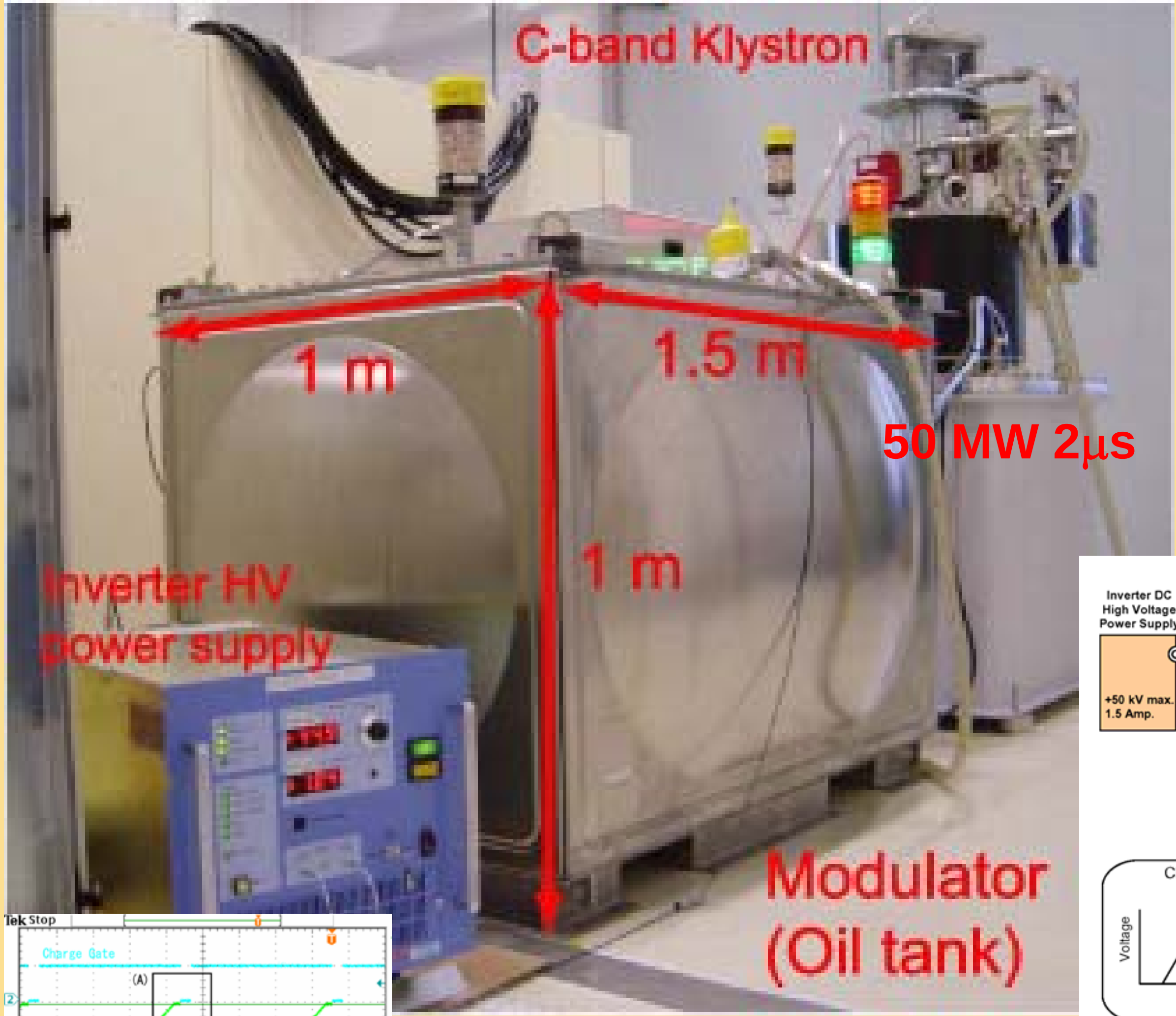
$$y = K\left(e_n + \frac{\theta}{T_i}\Sigma e_n + T_d\left(e_n - e_{n-1}\right)\right)$$

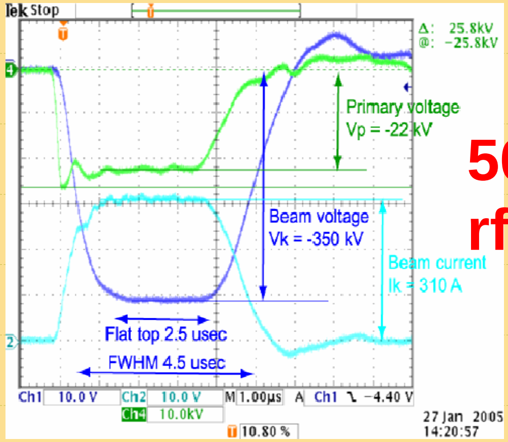
The control parameters of *K*, *Ti*, *Td*, and *Q* are , 0.1, 0.001, 0, and 1 s.



The 238 MHz cavity phase is controlled within 0.5 deg.
In the case of 5712 MHz, the phase stability is almost same.
Phase difference between the cavity and setting phases is artificial.

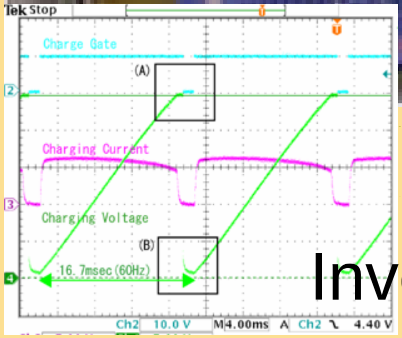
Inverter & Modulator



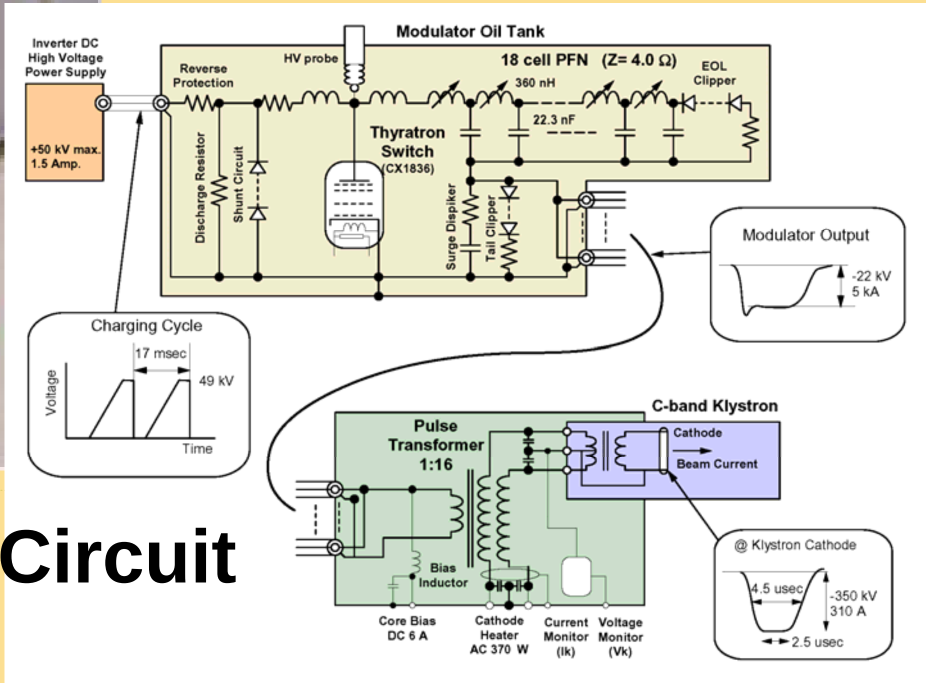


50 MW 2μs rf pulse

Modulator pulse



Inverter charging pattern

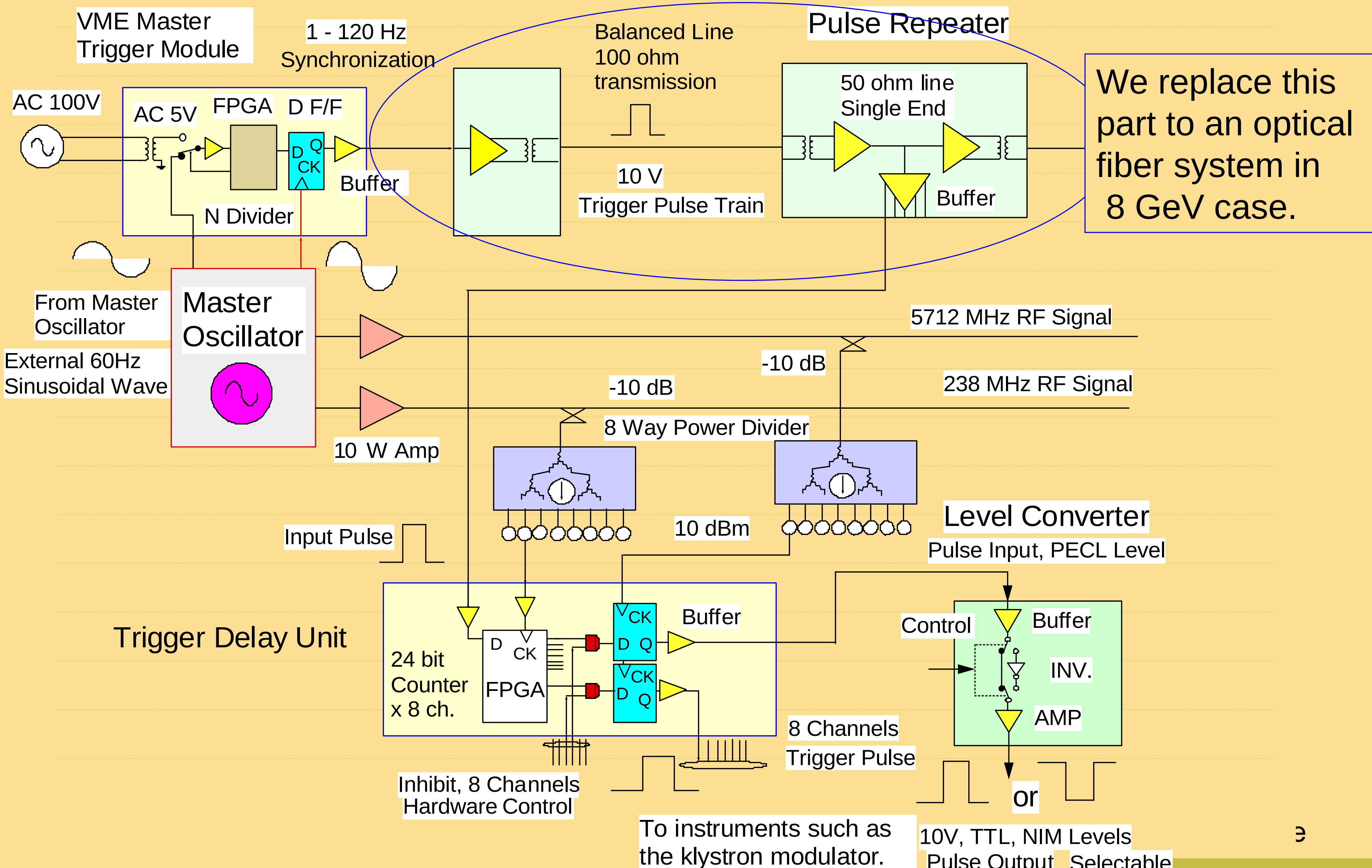


Circuit

Major Specification of Inverter Power Supply

Output voltage range:	**0 - 50**	**kV**
Average current:	**1.5**	**A**
Charge rate average:	**>30**	**kJ/sec**
peak:	**>37.5**	**kJ/sec**
Output voltage regulation (p-p):	**<0.2** **<0.04** **(Under development)**	**%** **%**
Power factor at full load:	**>85**	**%**
Power efficiency at full load:	**>85**	**%**

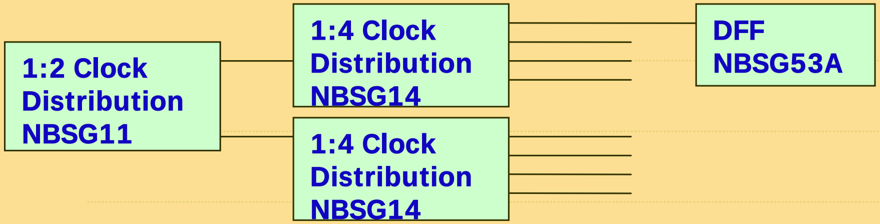
The trigger system of the SCSS prototype accelerator

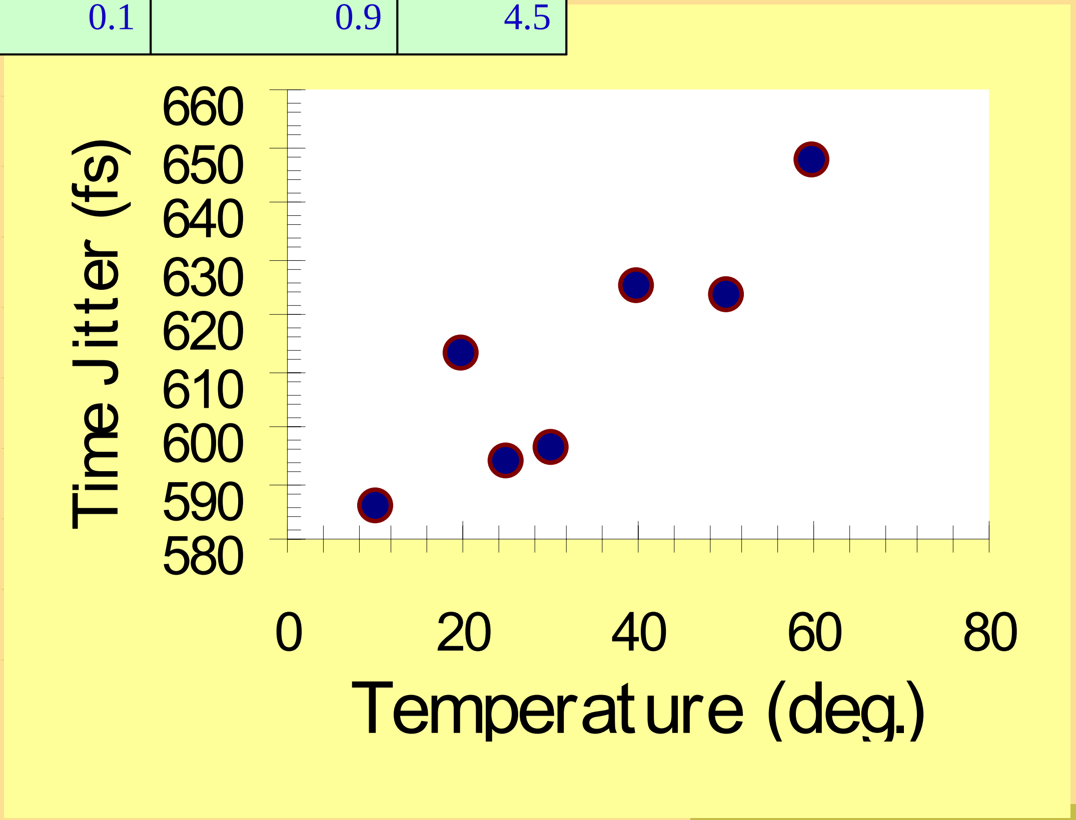


The measurement result of the time jitters of the trigger delay unit. The jitters are less than 1ps that satisfies our requirement. The temperature dependence of the jitter is very low.

IC Devices		NBSG 11	NBSG 14	NBSG 53A	Wire	Risk Margin	Total
Skew [ps]	TYP	6	25	5	5	0	41
	MAX	15	50	20	12	13	110
Jitter(RMS) [ps]	TYP	0.2	0.2	0.5	0.02	0	0.92
	MAX	1	1	1.5	0.1	0.9	4.5

Calculated data

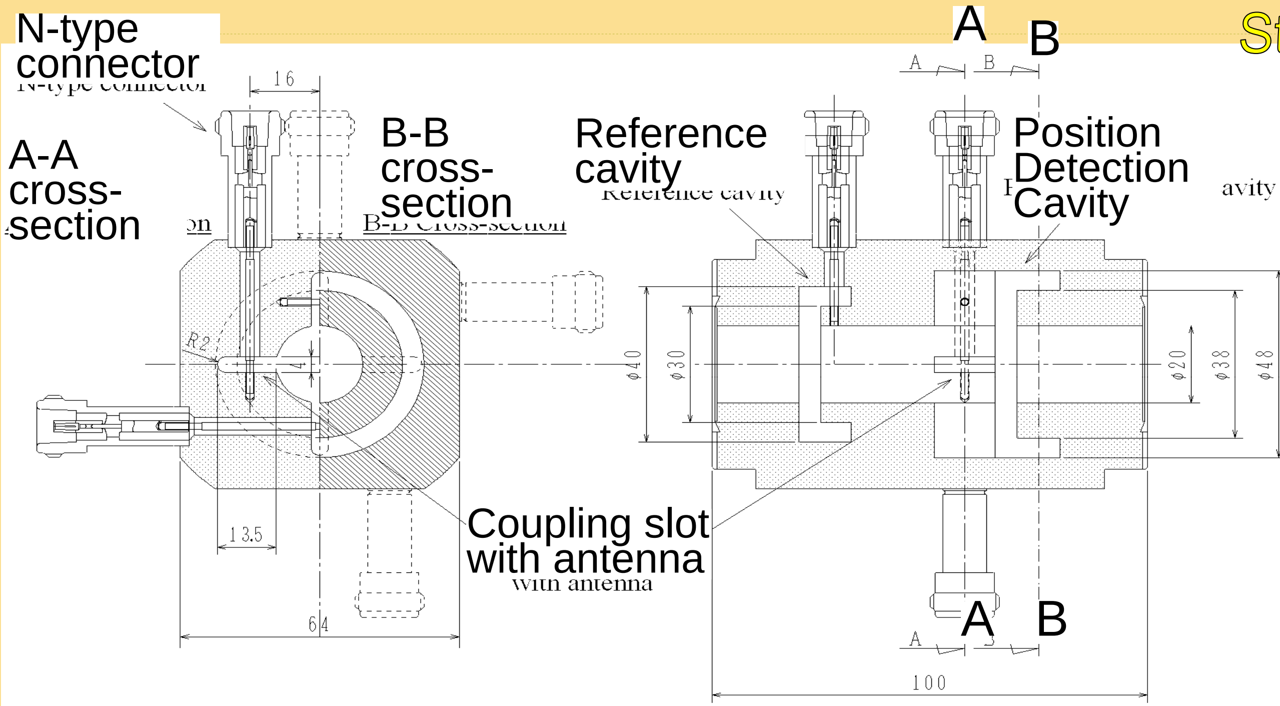


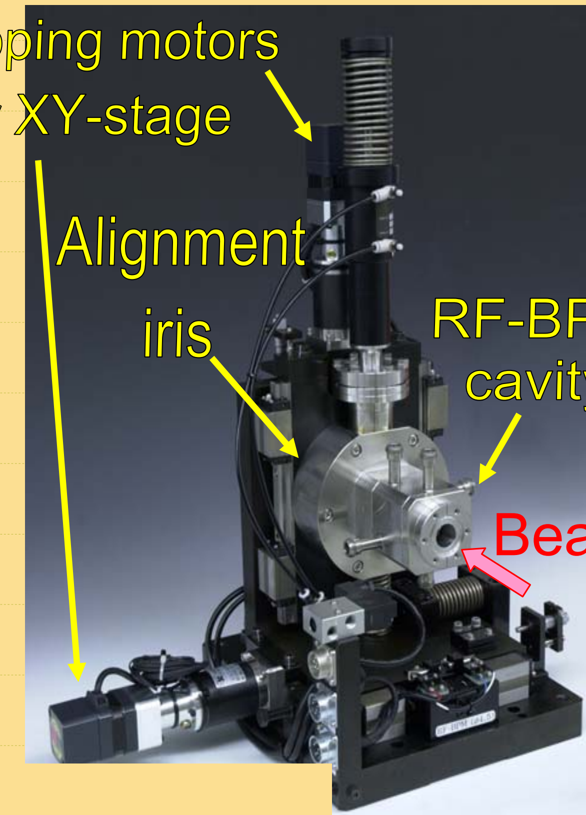


A delay time change of the unit dependent on the temperature was about 400 fs/ ^{o}K.

A temperature controller using a heater to stabilize the temperature of the flip/flips circuit within +/- 0.1 ^{o}K.

Cavity Beam Position Monitor





Cavity

RF-BPM consists of a position detection cavity (TM110) and a reference cavity (TM010).

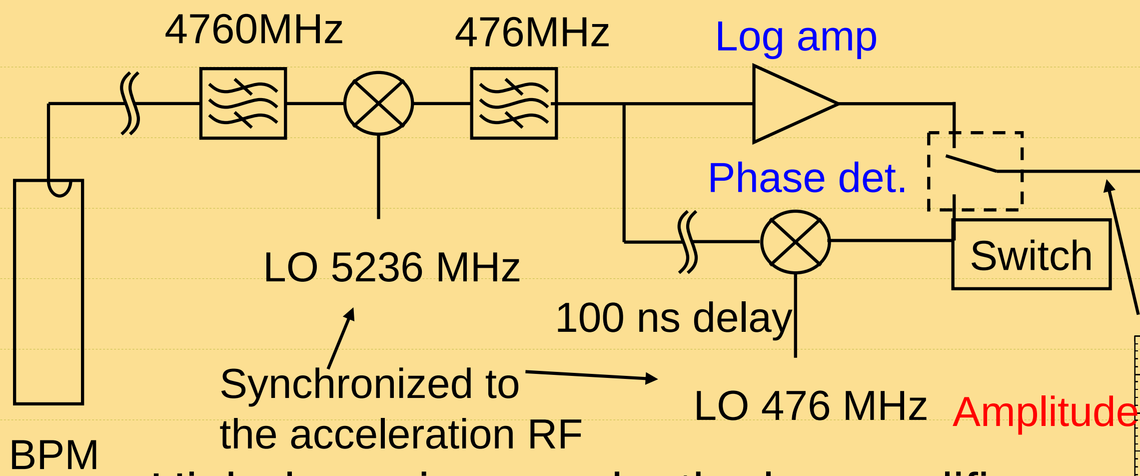
Resonant frequency: 4760 MHz.

- The frequency is intentionally shifted from the acceleration RF (5712 MHz) to suppress any background from the dark current.

Coupling slots of the position detection cavity are designed to couple with the TM110 mode selectively, and to be insensitive to the TM010.

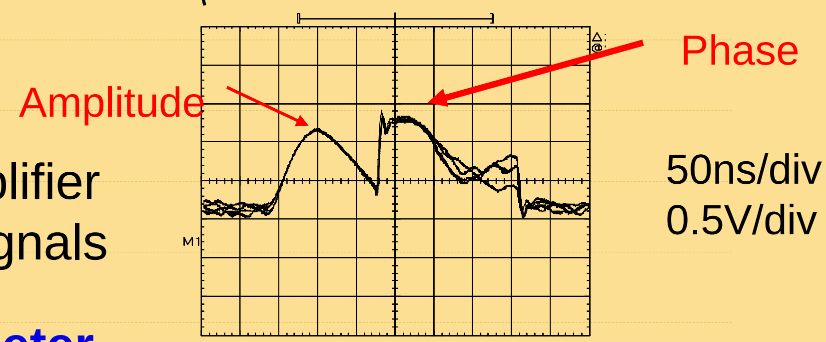
Loaded Q factor: ~90, Signal amplitude: 16 mV/nC/mm

BPM Circuit



Present Circuit

Res. 5 μm

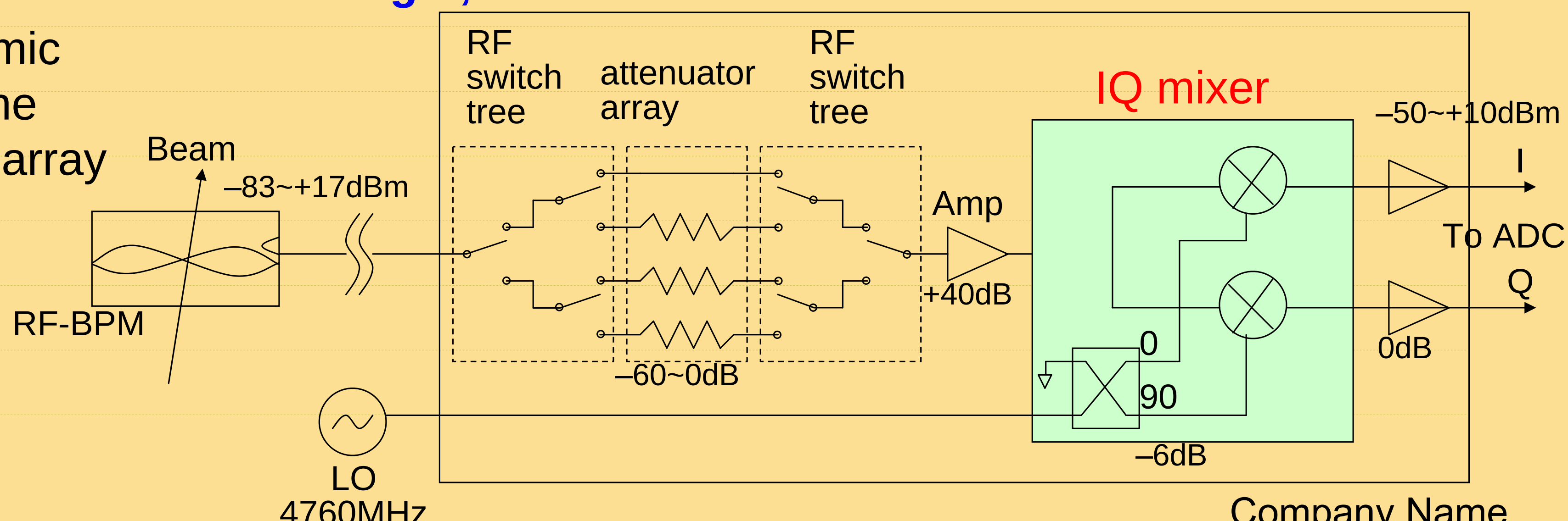


High dynamic range by the log amplifier

Can not distinguish tilt & position signals

Next Version. Target, Sub-micron meter

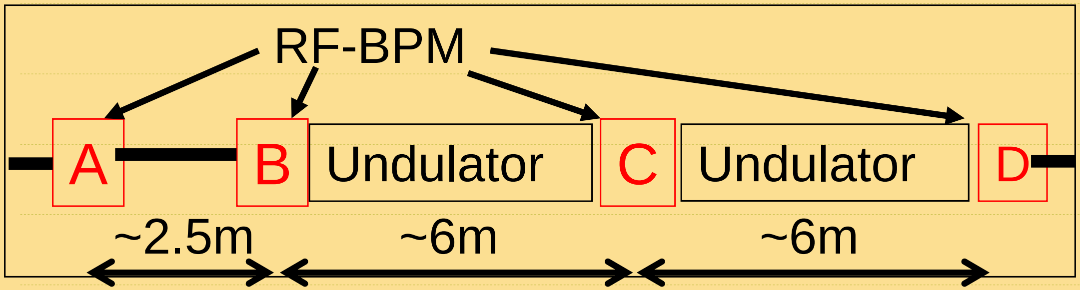
High dynamic range by the attenuator array



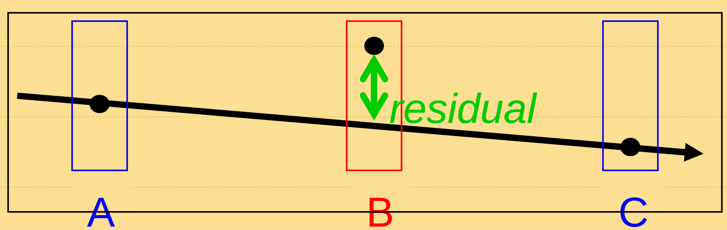
Company Name

Position Resolution Measurement

- Four BPMs in the undulator line were used.



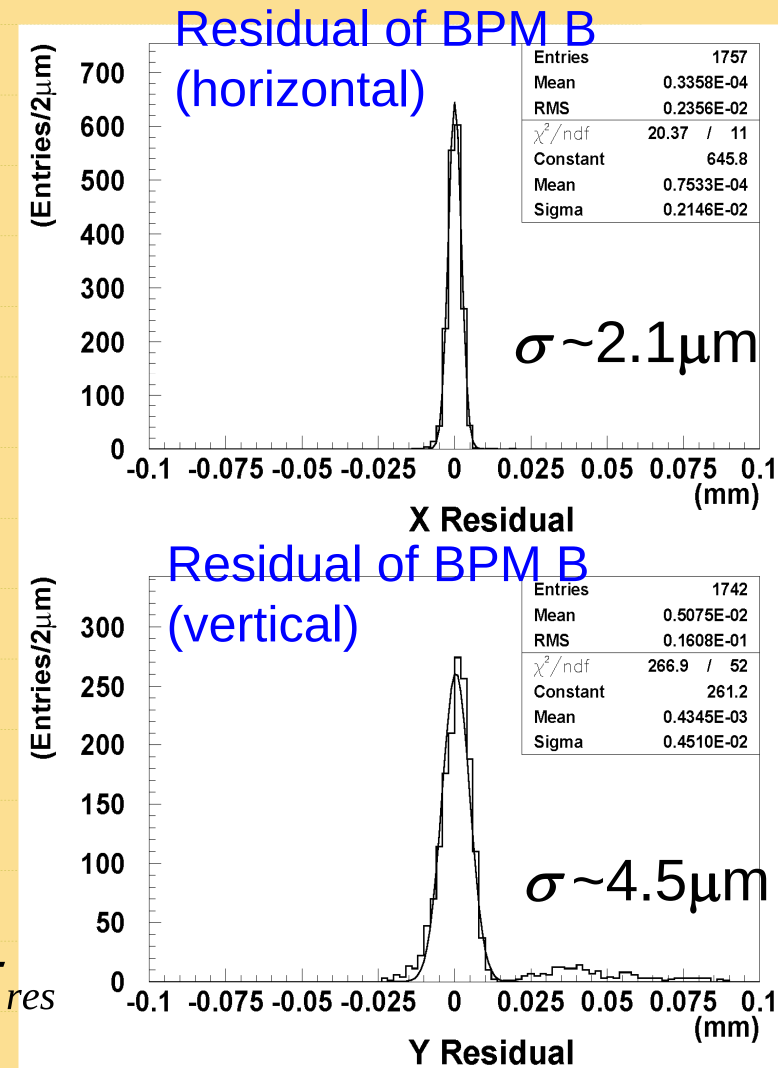
- Position resolution can be measured by three adjacent BPMs.
- The 1st and 3rd BPMs determine the expected position at the 2nd BPM.
- The *residual*, which is the difference between the detected position of the 2nd BPM and the expectation, is calculated on a shot-by-shot basis.



BPM-B Res. X 1.7 μm, Y 3.6 μm

BPM-C Res. X 5.3 μm, Y 4.9 μm

$$\sigma_{BPM} = \sqrt{2/3} \cdot \sigma_{res}$$



Position resolution was 5 μm, or better.

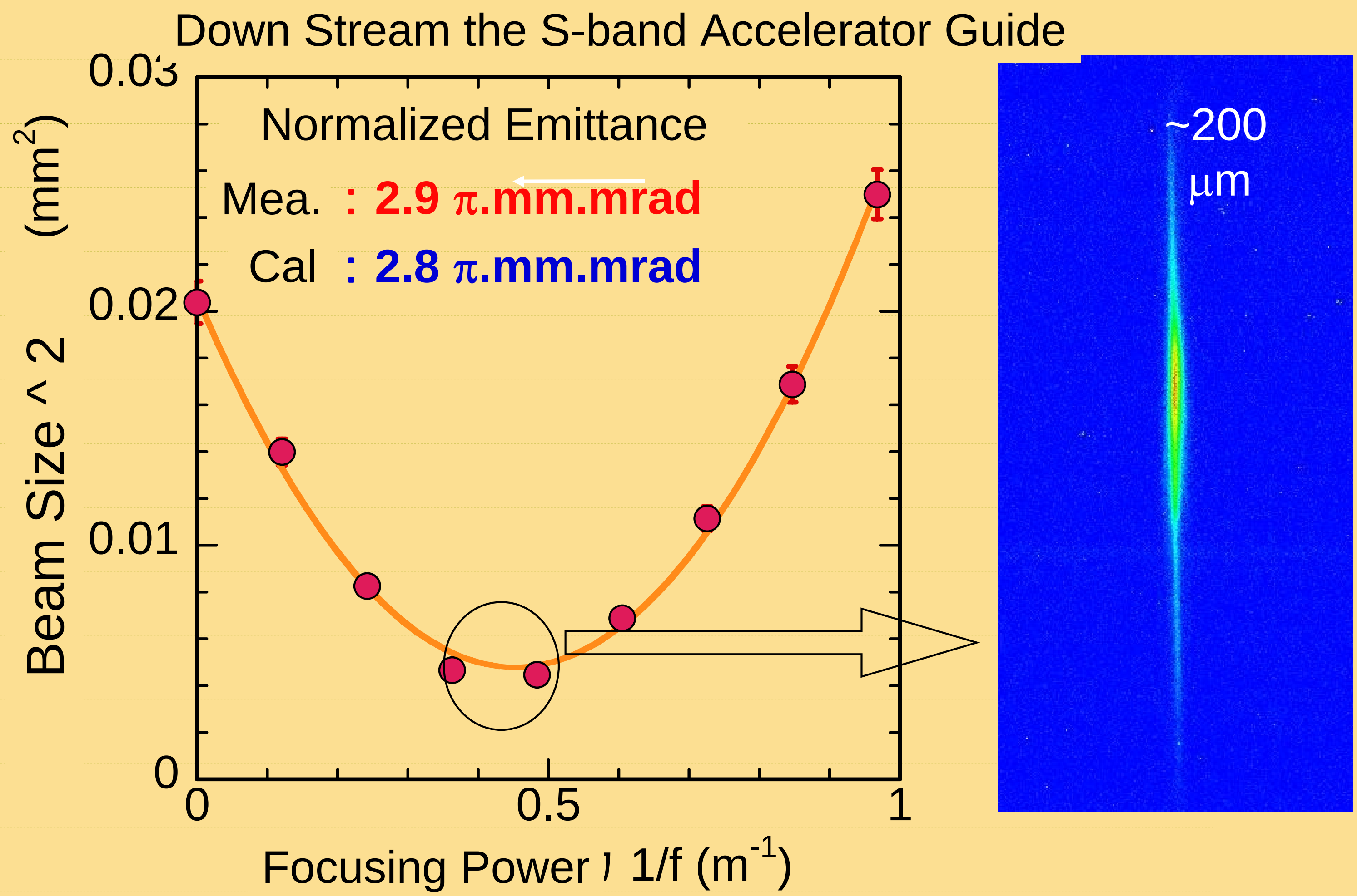
Milestone of the Prototype Accelerator

Commissioning detail

- 05/12 Confirmed spontaneous light at125MeV.
- 06/1~4 Improved the accelerator system, and finish the construction.
- 06/5/8 Restart the tuning of the accelerator to aim SASE Amplification at 250MeV.
- 06/6/20 First Lasing (49nm, confirm)
- 06/8~11 Preparation of RF feedback control to obtain the stable amplification.
- 06/11 Reproduce SASE light (177nm) at150MeV.

Emittance Measuremènt by Q scan method

Good agreement between
the measured beam profile and the calculated profile

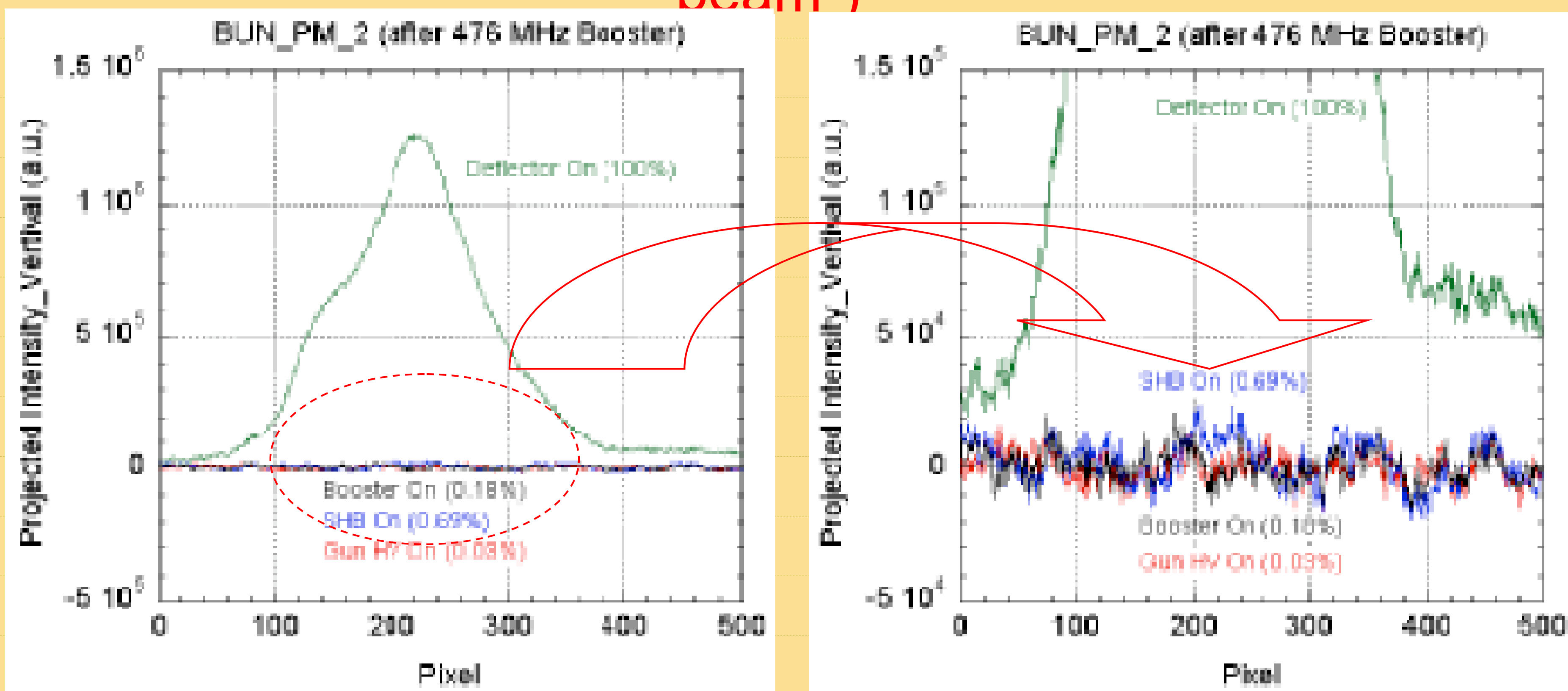


Dark Current of the electron gun

Horizontal data projected from the screen monitor intensity.

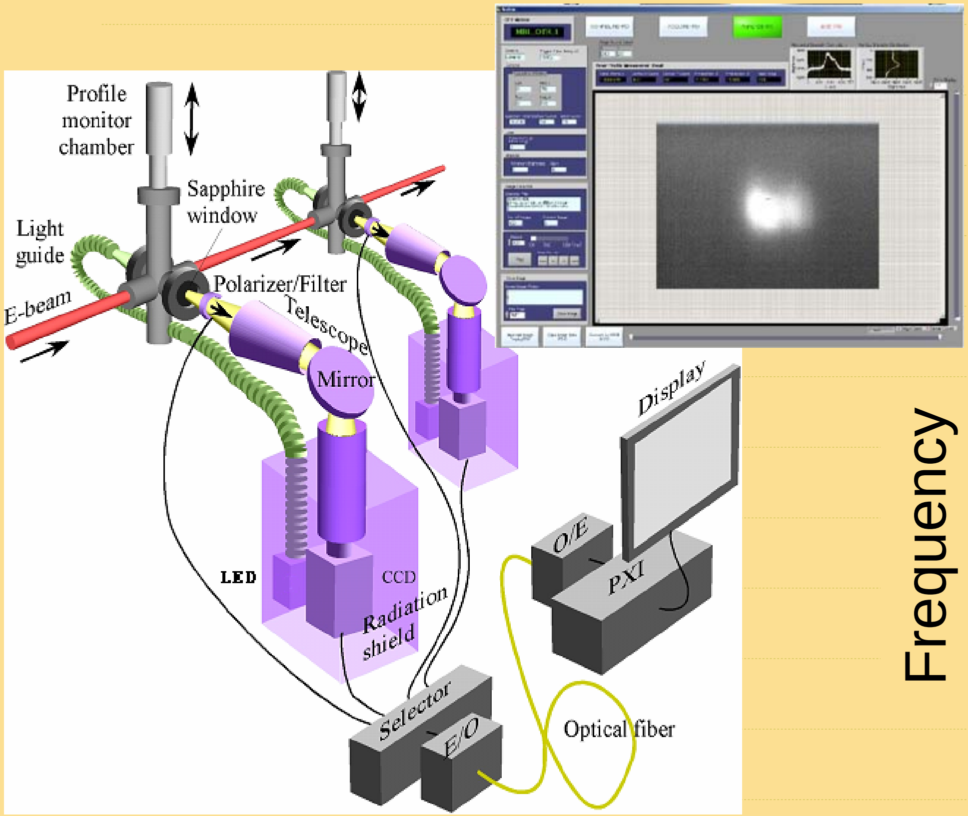
PRM, down stream of the 238 MHz SHB

Small Dark Current (<0.2% of the core beam)

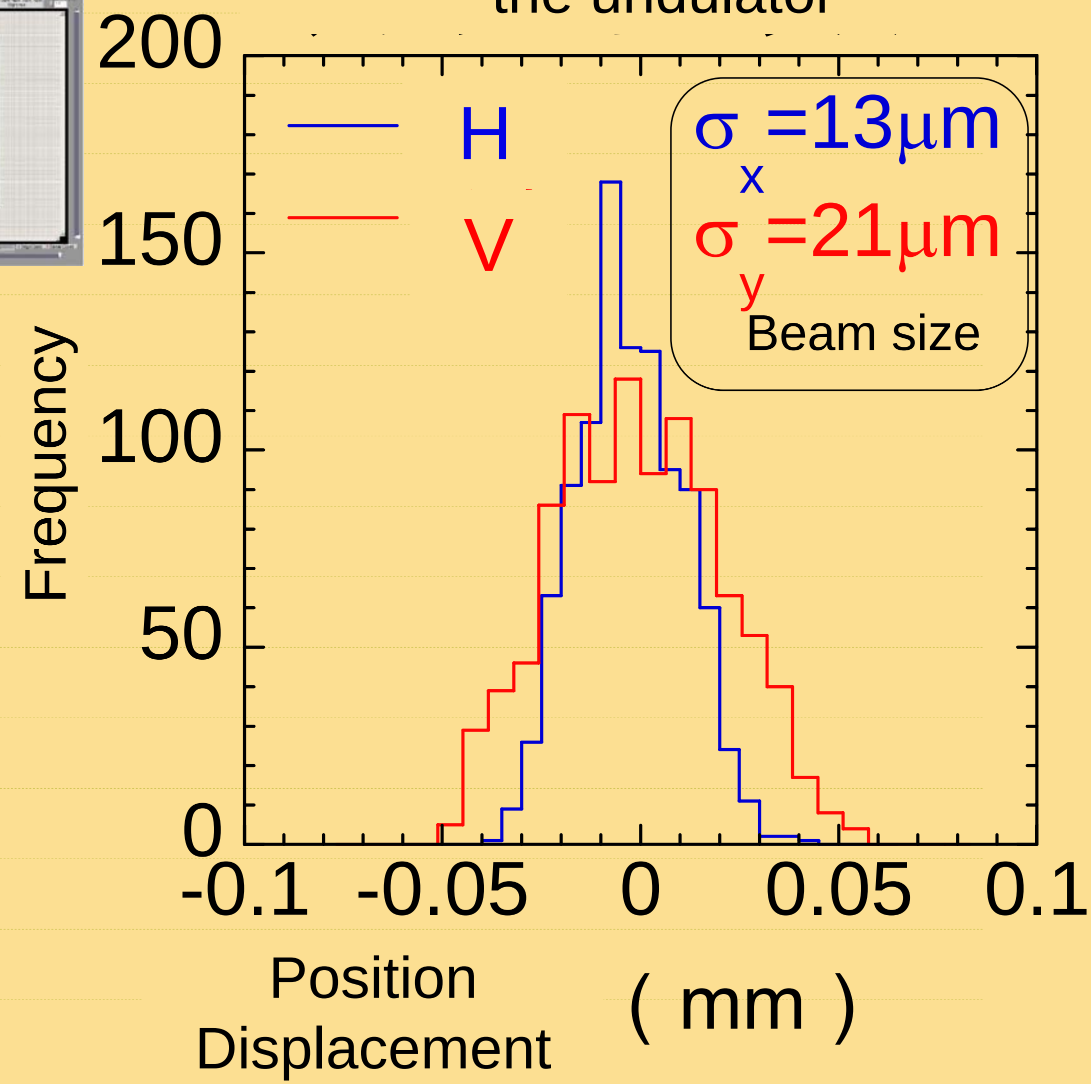


Black Line : Noise level, Red Line : Usual operation current level + deflector off

Stability of Beam Trajectory



Beam position displacement at the undulator



- Trajectory stability (1σ):

1/5~1/10 of the beam pulse width at the undulator

- Energy stability (1σ):

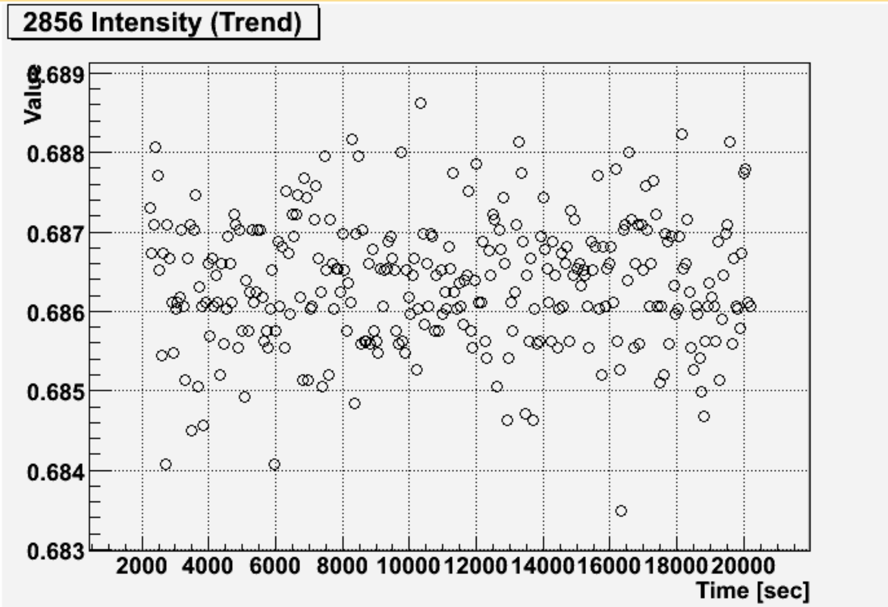
0.06% at 250MeV

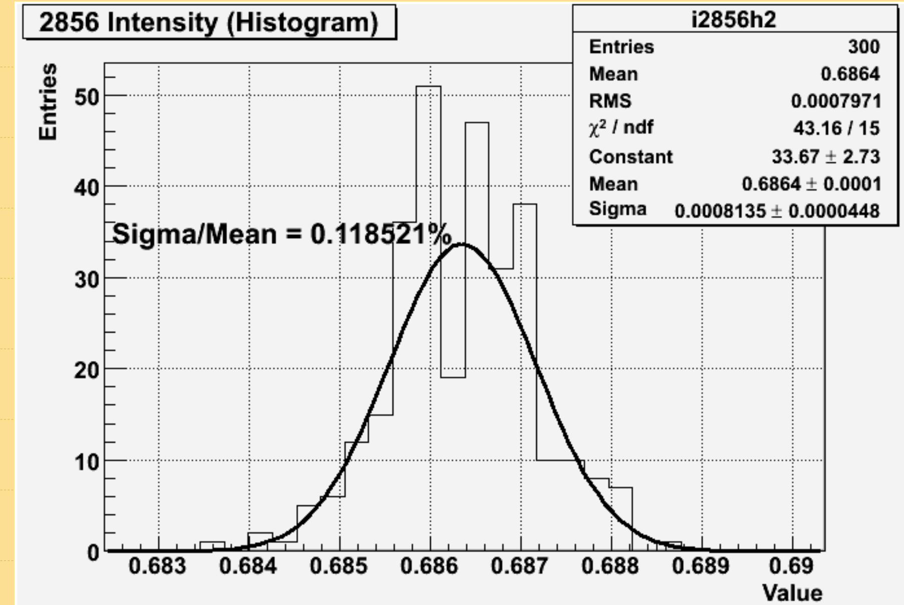
RF stability

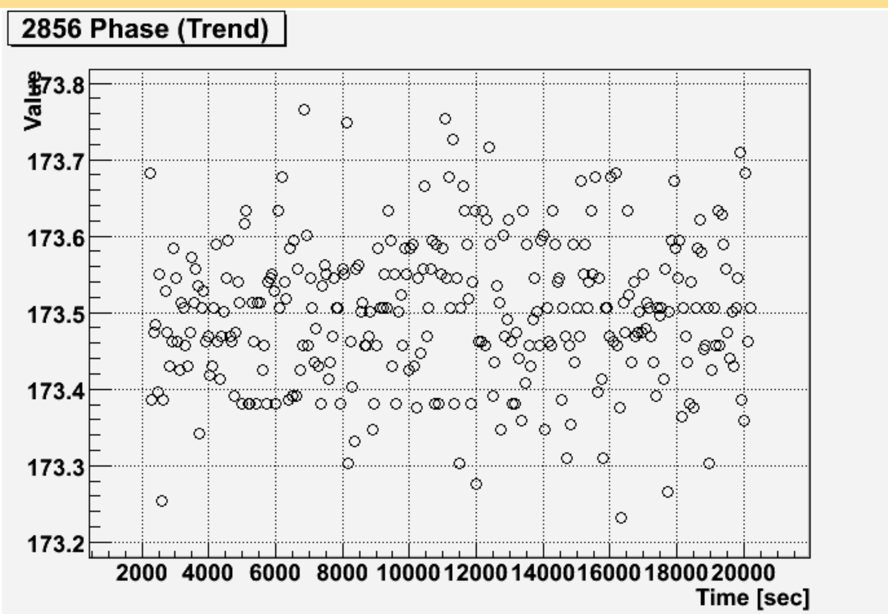
With PID feedback control, 1 σ of phase and amplitude data.

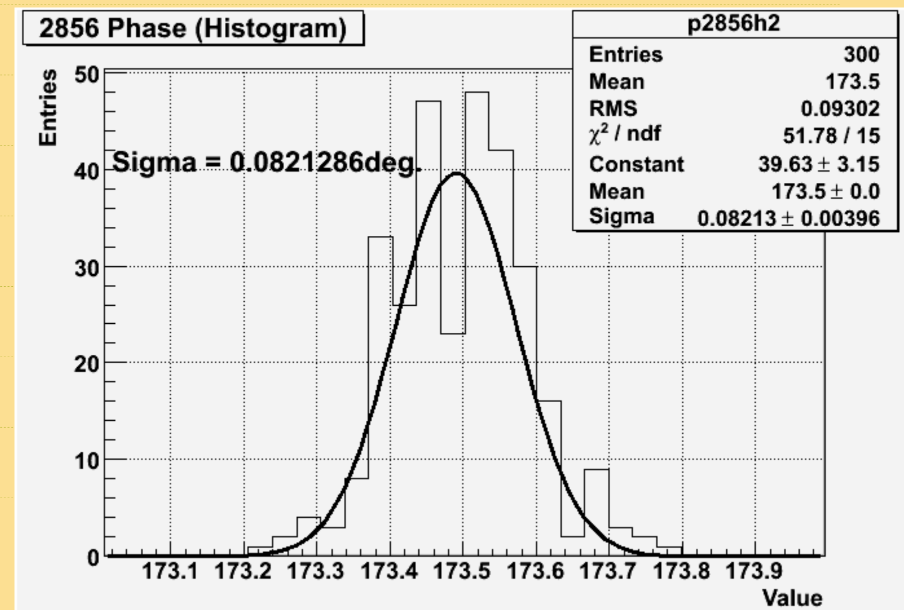
Source	Amplitude	Phase	Time
Gun Vk	0.07%		
238MHz pickup	0.17%	0.10 deg	1.2 ps
476MHz pickup	0.10%	0.07 deg	0.41 ps
2856MHz Kly fwd	0.12%	0.08 deg	0.078 ps
5712MHz SLED fwd	0.14%	0.42 deg	0.20 ps

Amplitude & Phase Data (2856MHz)



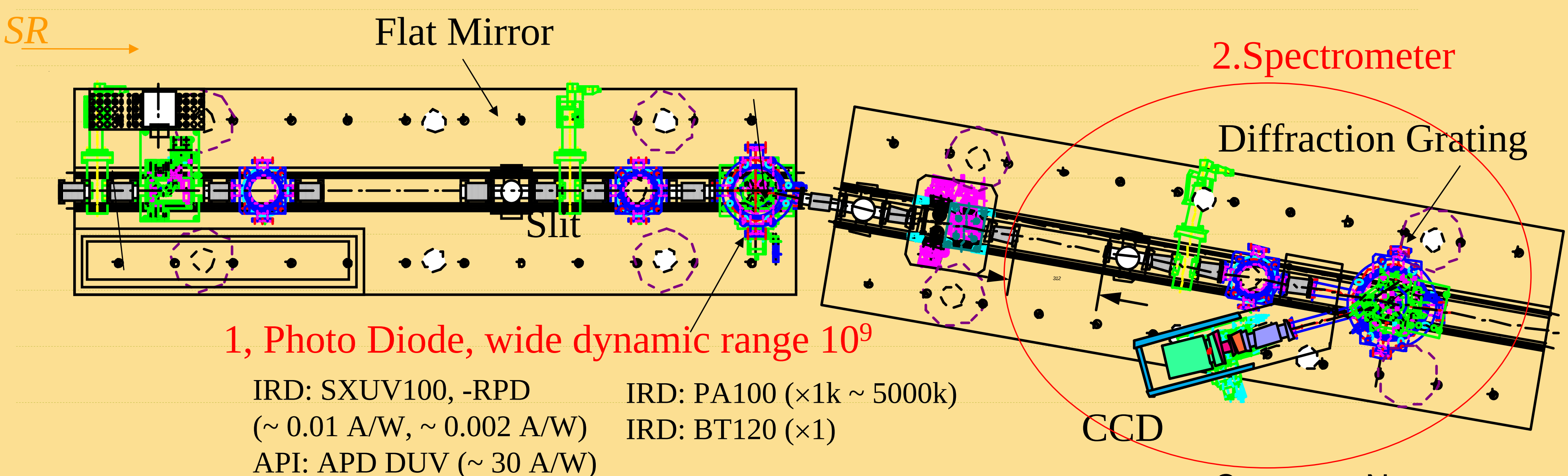




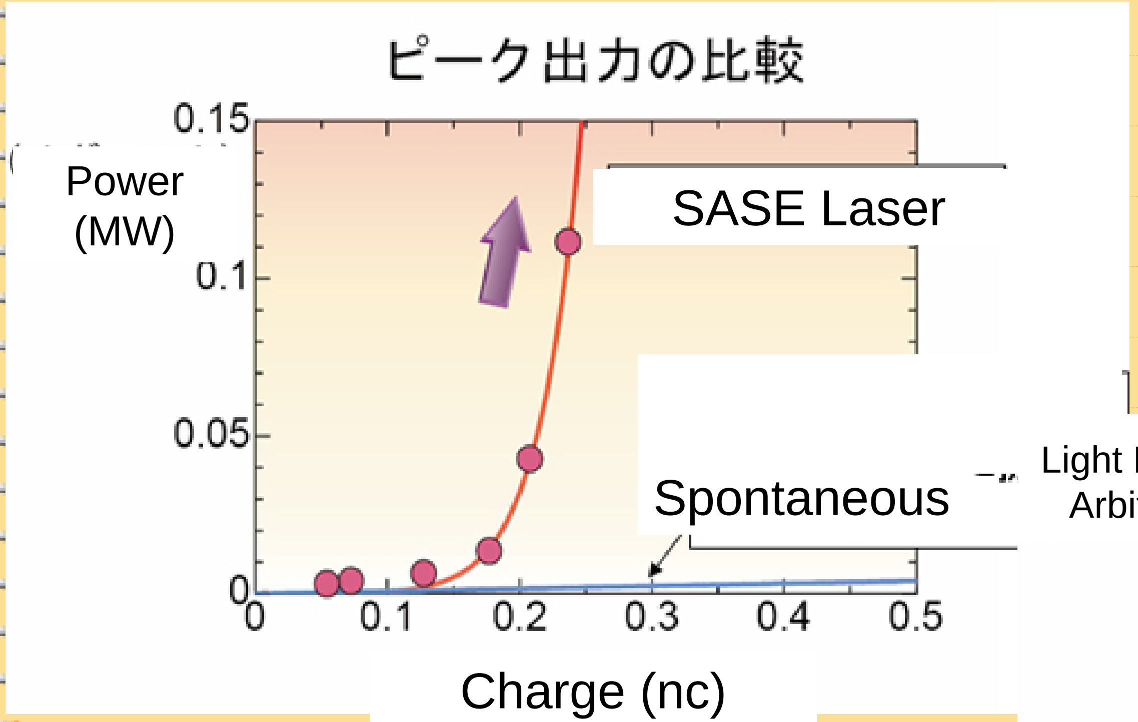


VUV計測系

Measurement Items	Method
1.Optical intensity (0.1 pJ ~ 0.1 mJ/pulse)	Photo Diode, Gas chamber
2. VUV Spectrum (l=60 nm ~ 700 nm, l/Dl>1000)	Spectrometer
3. Pulse width	CSR spectrum (Beam dump BM)
4. Spatial profile	0^{th} order diffraction light (Slit position

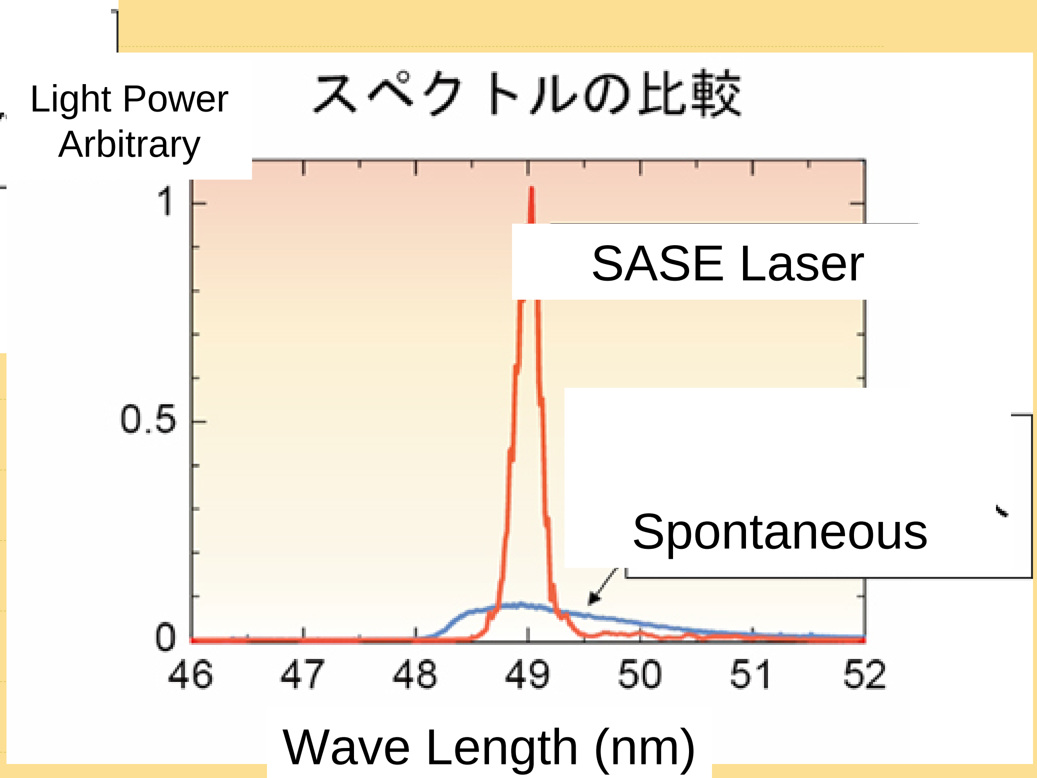


SASE Amplification

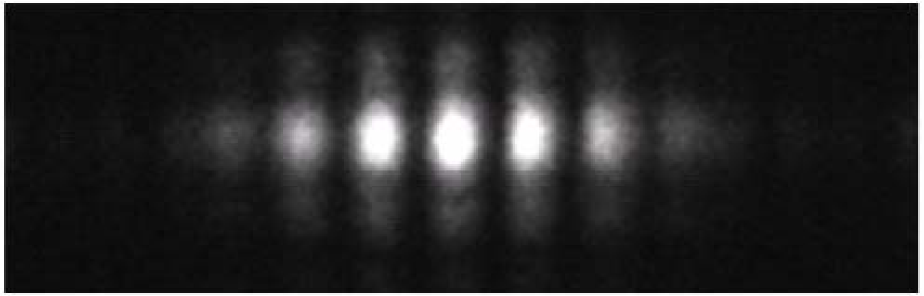


Power

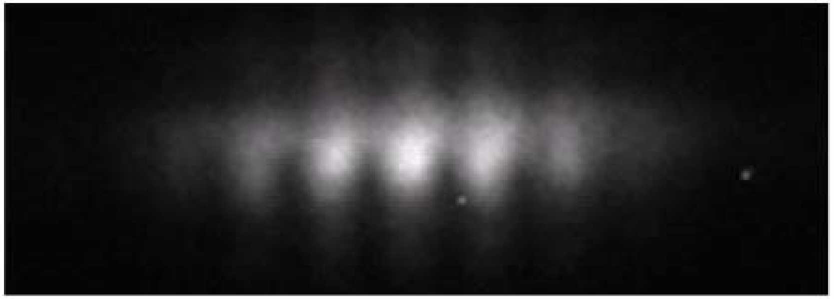
Spectrum



Double Slit Image



SASE
(1 shot, bunching condition)



Spontaneous radiation
(debunching condition, 100 shots)

Evaluation of Beam and Laser Light Quality

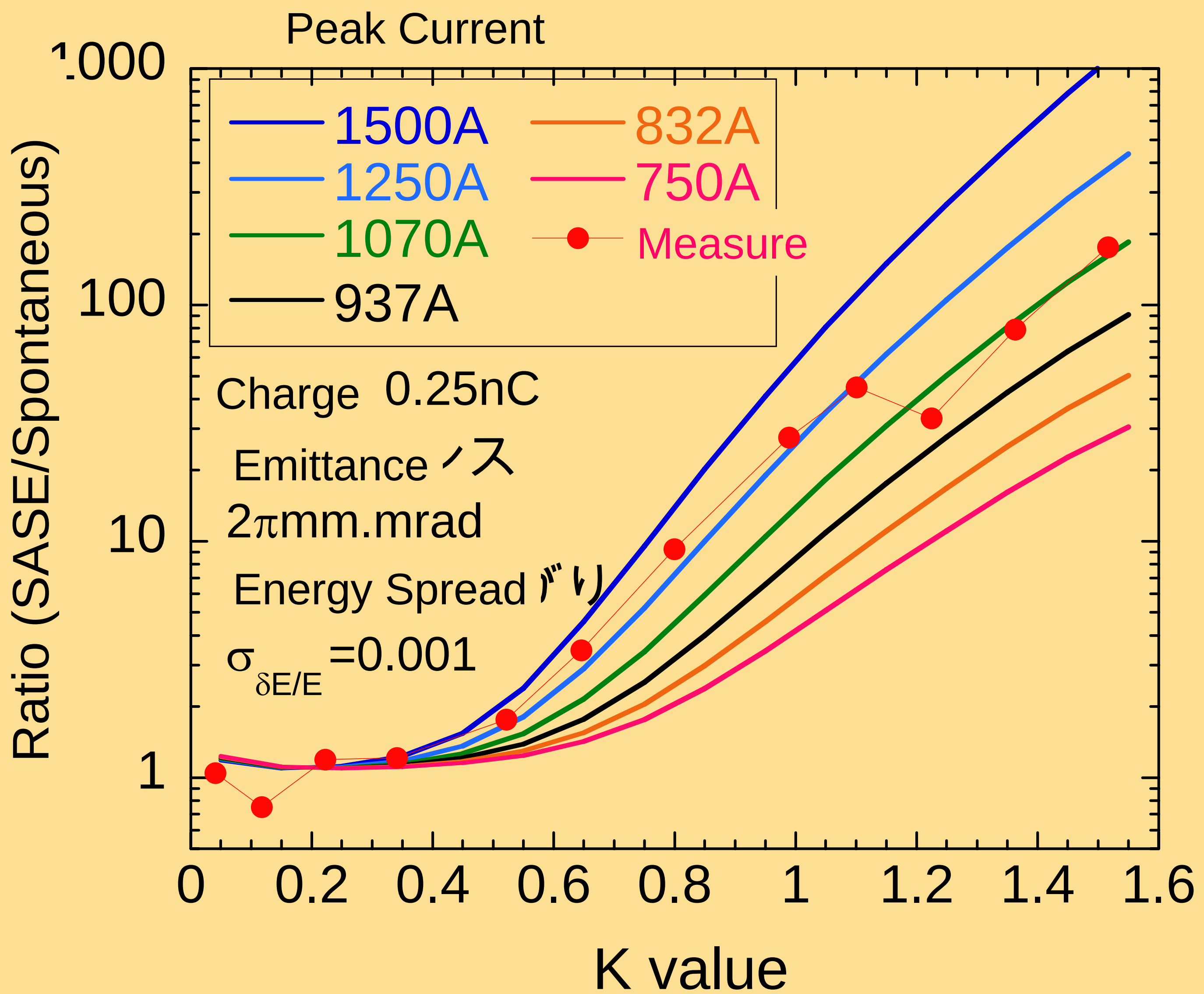
Amplification factor dependent on the K values.

Simulated by 3 dimensional FEL simulation in one undulator(5m)

-> Electron beam brightness

270~315

A/π^2mm^2·mrad^2



Evaluation of Beam and Laser Light Quality

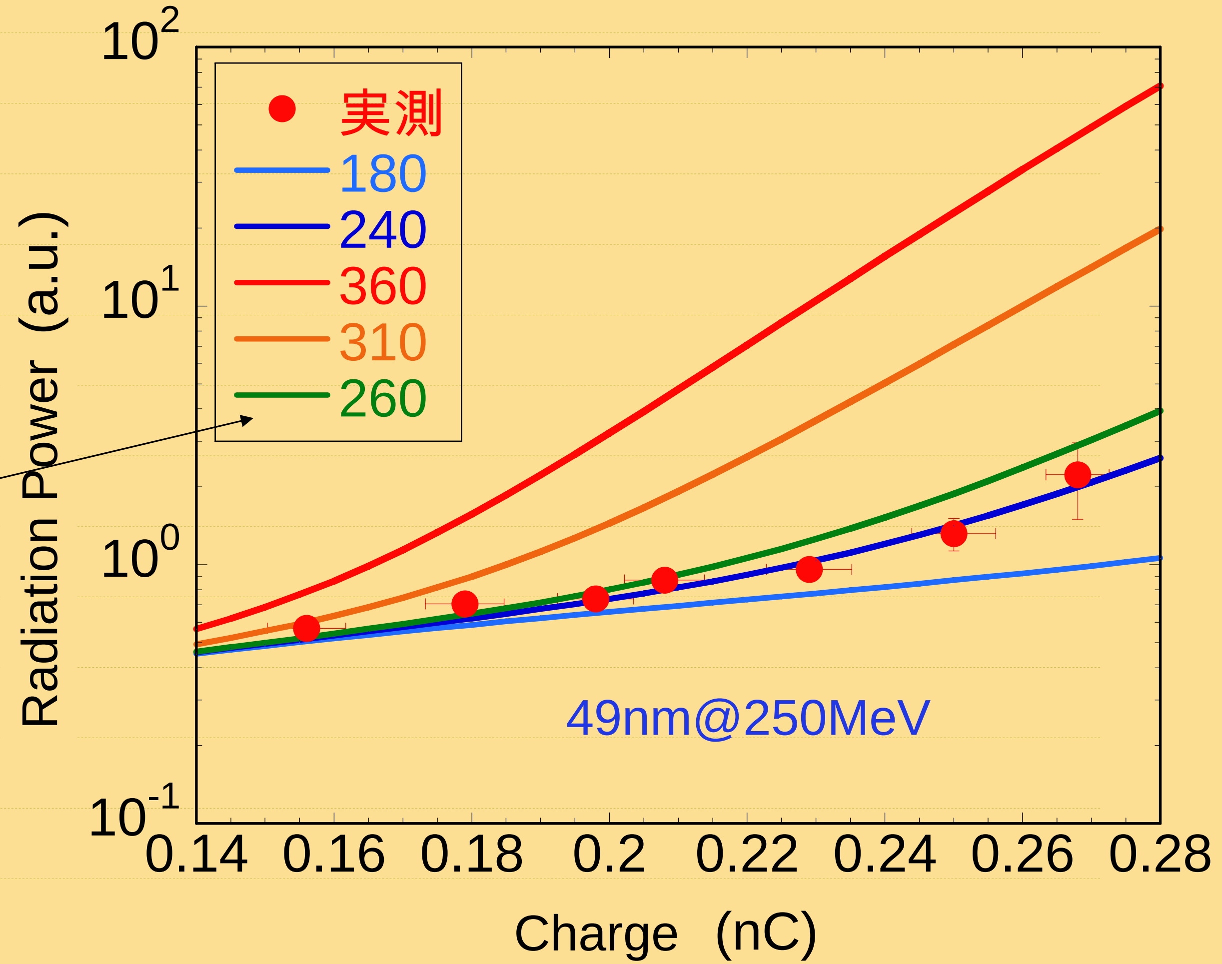
Beam quality evaluated form the laser amplification condition
(using 3 dimensional FEL simulation)

Radiation Intensity vs. Charge amount

Evaluated by 1 D FEL model

-> Electron beam brightness

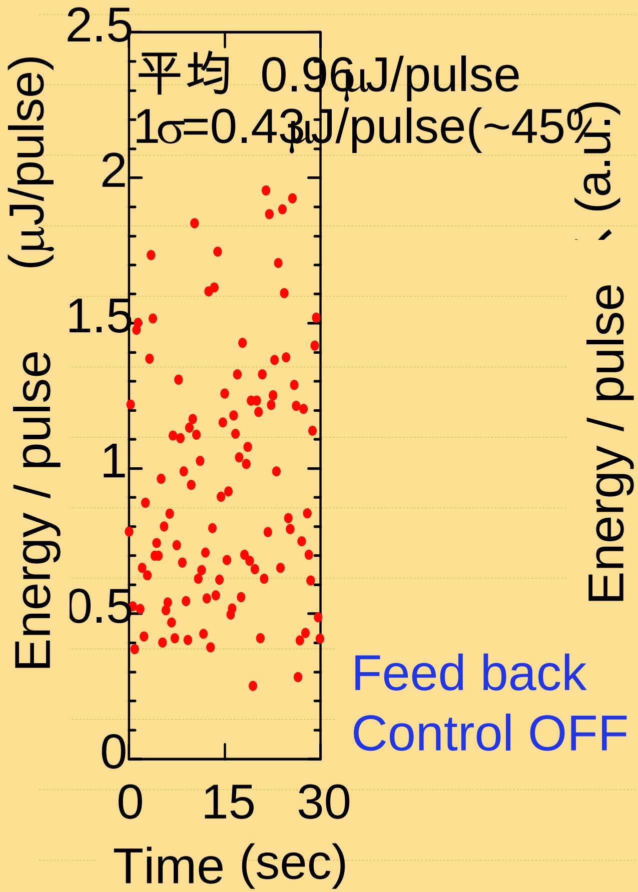
240 A/π^2mm^2·mrad^2



Continuous high power Amplification

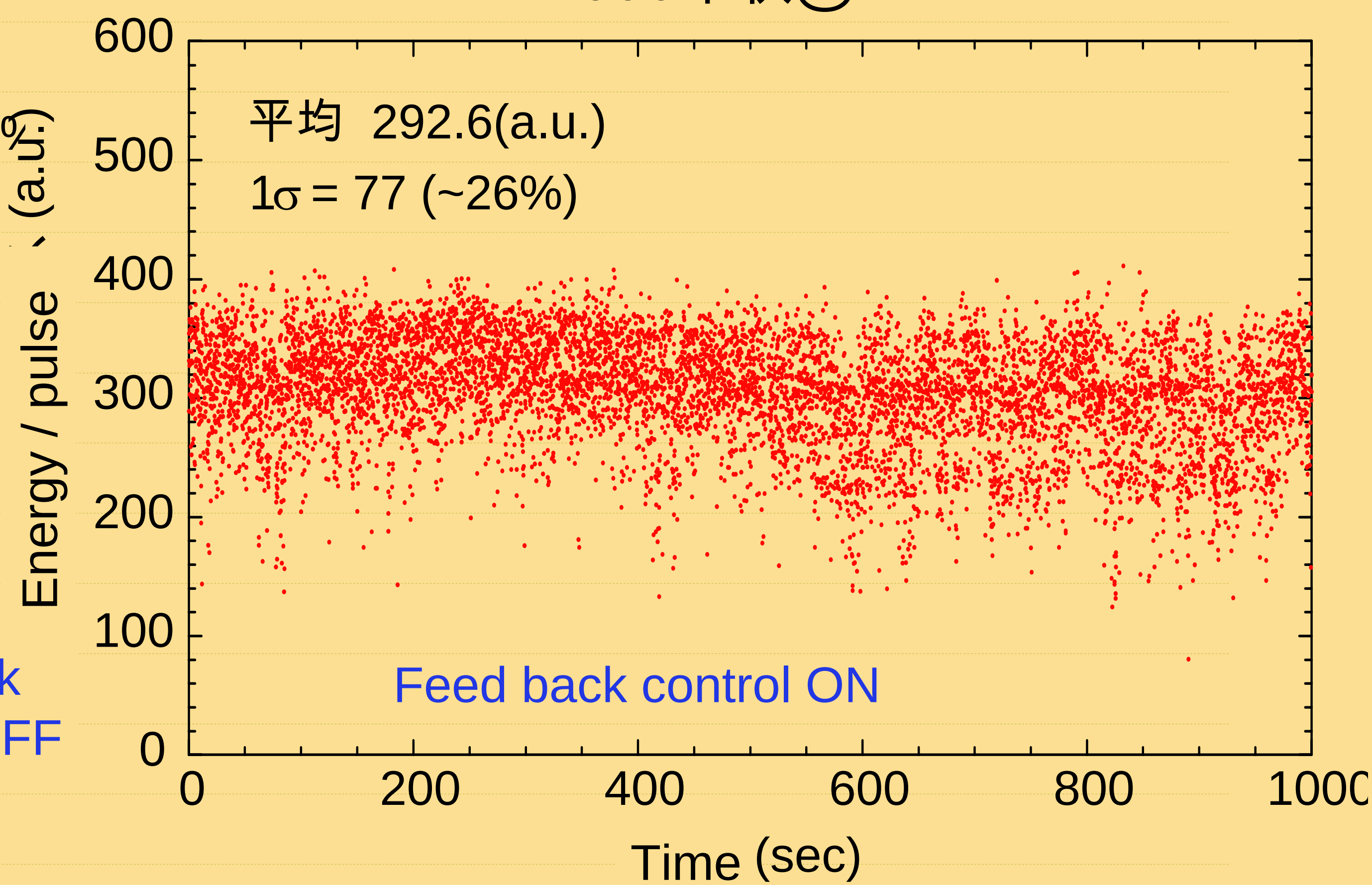
Summer

2006年夏@60nm



Autumn

2006年秋@177nm



Before and after the rf phase and amplitude feedback control
at the 238, 476,2856 MHz rf cavity,

Summary

1. Evaluated the beam quality by the 1D & 3D simulation using the laser amplification condition.
2. We almost realized the target specification of the beam that is 800 A peak current and a normalized emittance of 2 π mm.mrad.
3. 0.2 % dark current of the core beam from the gun.

We confirmed feasibility of

- OK 1. 500 kV CeB6 Thermionic Electron Gun (Small Emittance and Dark Current) ,
- OK 2. C-band high gradient acceleration (High Gradient Acceleration 37 MeV/m),
- OK 3. Acceleration stability. (dE = 0.06% at 250MeV)