

# Photo-cathode RF Gun Development for Quantum Beam Program

小型高輝度光子ビーム発生装置

第10回 高輝度・高周波電子銃研究会

SPring-8放射光普及棟

KEK 浦川順治 2013.1.10

High Energy Accelerator Research Organization, KEK

1. QB program以前のPhoto-cathode RF Gun開発  
先進小型加速器開発事業前とこの計画下での開発
2. KEK共同開発と加速器支援事業及びJSPSアジア協力事業
3. QB programの為の高周波電子源開発
4. 今後の開発
5. 利用の為の光子ビーム生成

日米科学協力事業に基づいたBNL-ATFとのnon-linear QED実験でのPhoto-cathode RF Gun開発検討及びその重要性をSLACと検討した。1998年

X.J. Wangと住友重機械工業(鷺尾、遠藤等)の協力及びKEK工作センター(高富、工藤、肥後等)参加により高周波空洞製作を開始した。2000年  
上坂研も参加、最初の3台製作分は東大、早稲田、KEK-ATF用でBNL Gun-IVとほぼ同じものである。

放医研幹事機関の下で普及型(先進)小型加速器開発事業が電源特会予算でスタートした。関係者は延長を望んだが5年間で終了した。  
「サイクル機構から野村、平野、山崎の3名が先進小型加速器計画でKEK小型試験加速器実験に参加。

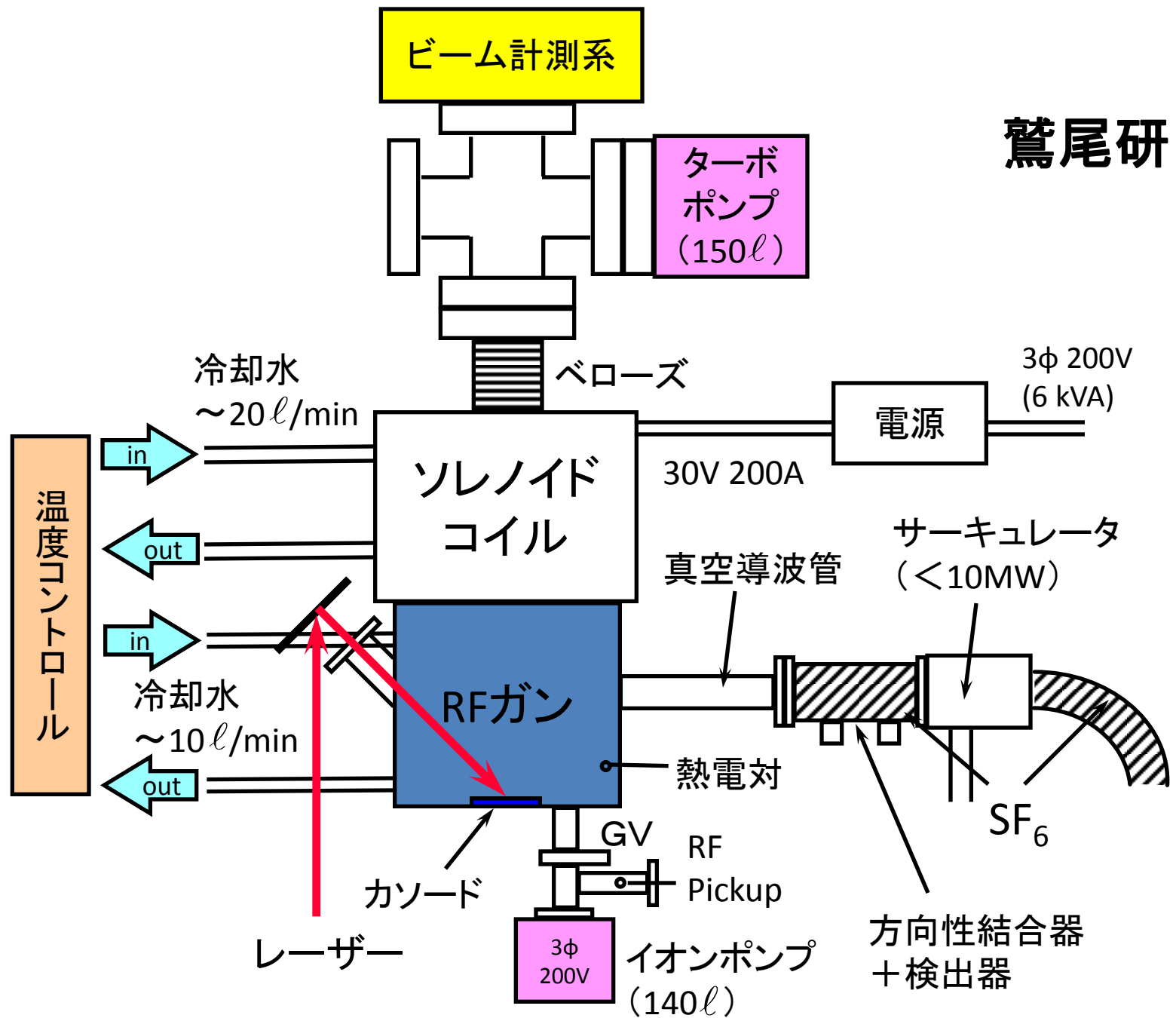
先進小型加速器計画で良かったこと:

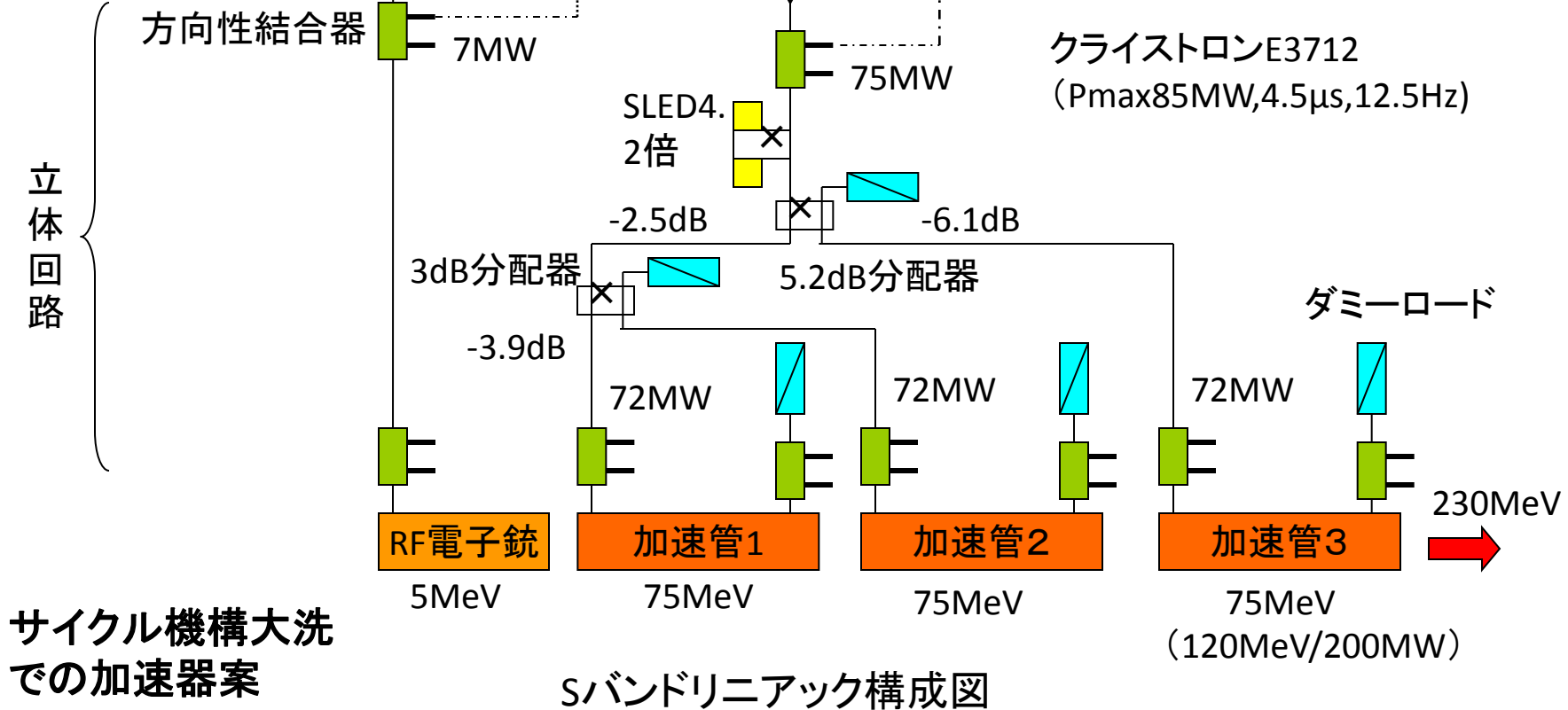
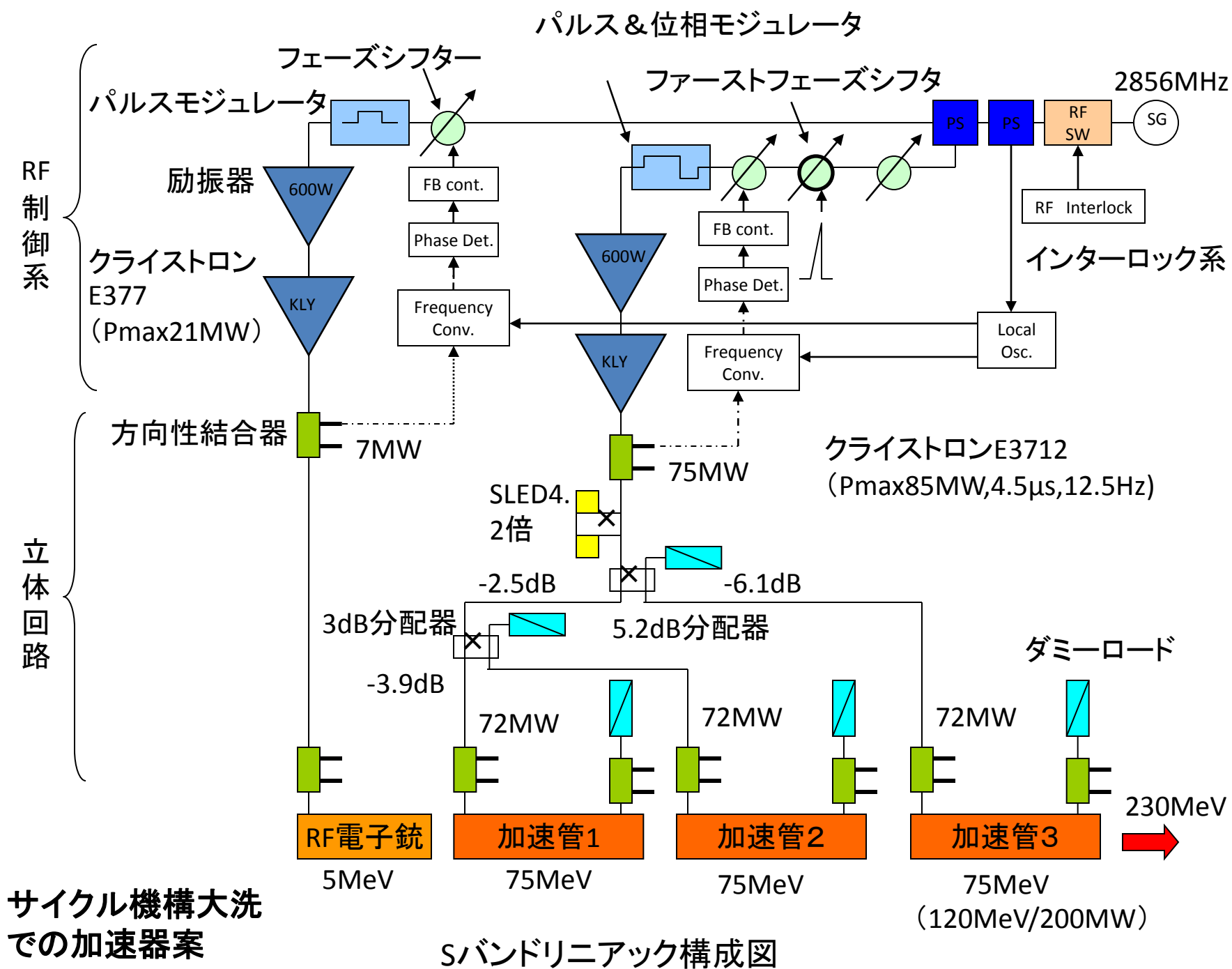
1. KEK-ATFの電子源を熱電子銃からPhoto-cathode RF Gunに変え、ビーム輸送系でのビームロス(エネルギーテール部の50%近いビームロス)が完全に無くなり100%入射を達成できた。
2. 野村、平野、山崎の3名がJPARCの加速器部に所属できた。
3. KEKに小型加速器が完成した。(平尾先生、上坂先生等に感謝!)

KEKの共同開発、加速器支援事業及びJSPSアジア協力事業に高周波電子銃開発をテーマにして、大学等との連携で10台以上のPhoto-cathode RF Gunを製作した。

大阪大学(楊研)、早稲田大学(鷺尾研)、産総研(黒田研)、京都大学(大垣研)との協力で1.6 cell RF Cavity数台の製作を行った。

鷲尾研

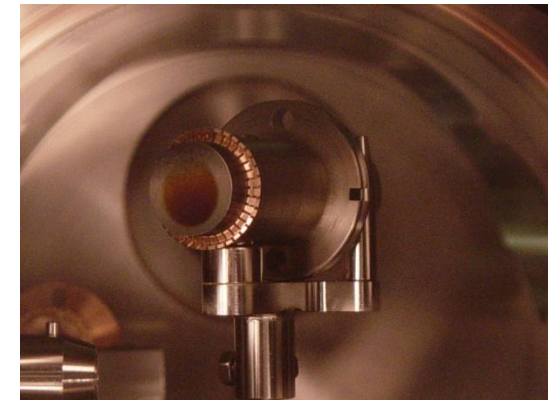
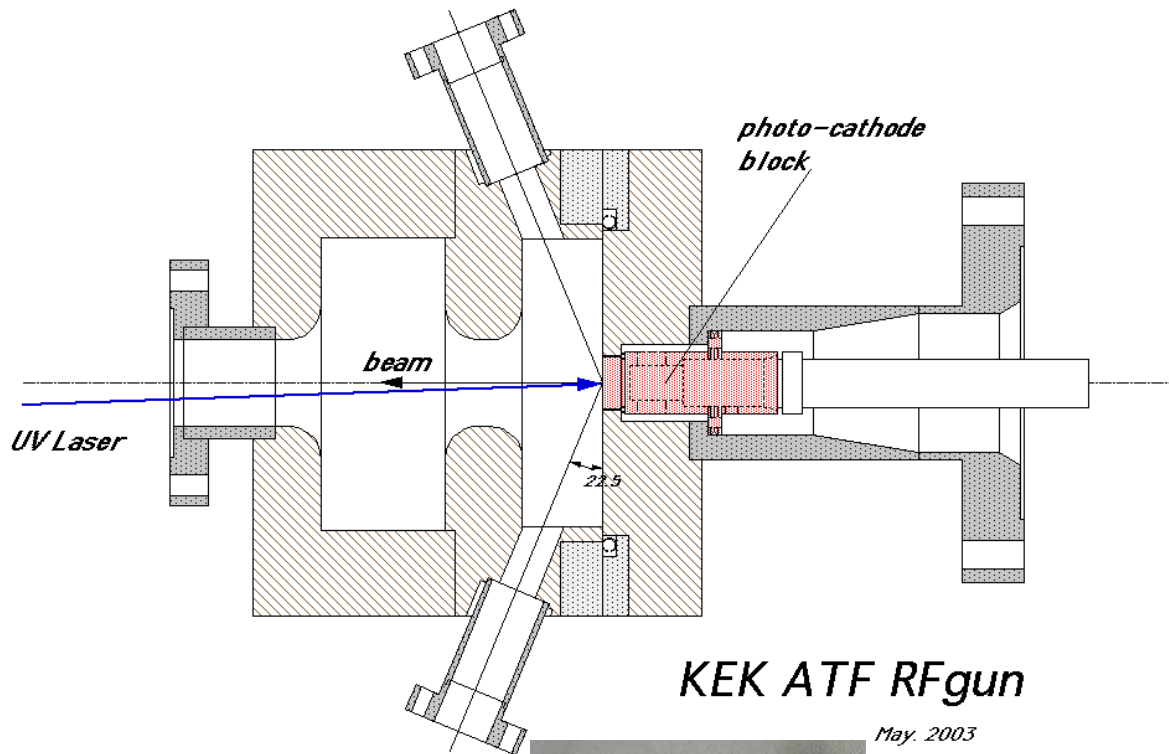




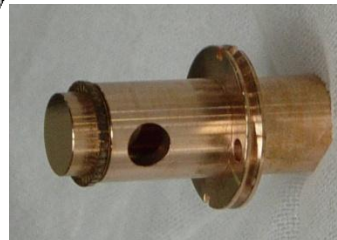
サイクル機構大洗  
での加速器案

Sバンドリニアック構成図

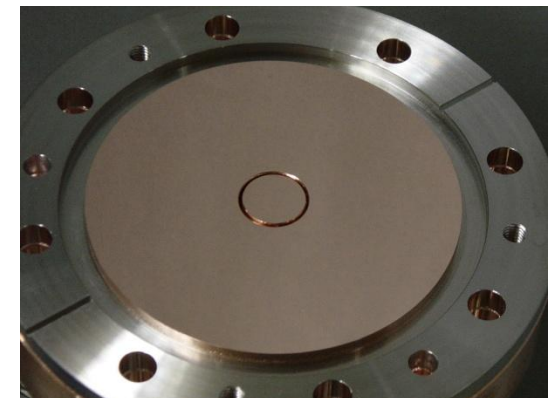
# *RF-gun cavity & cathode block*



**Cathode block with CsTe coating**



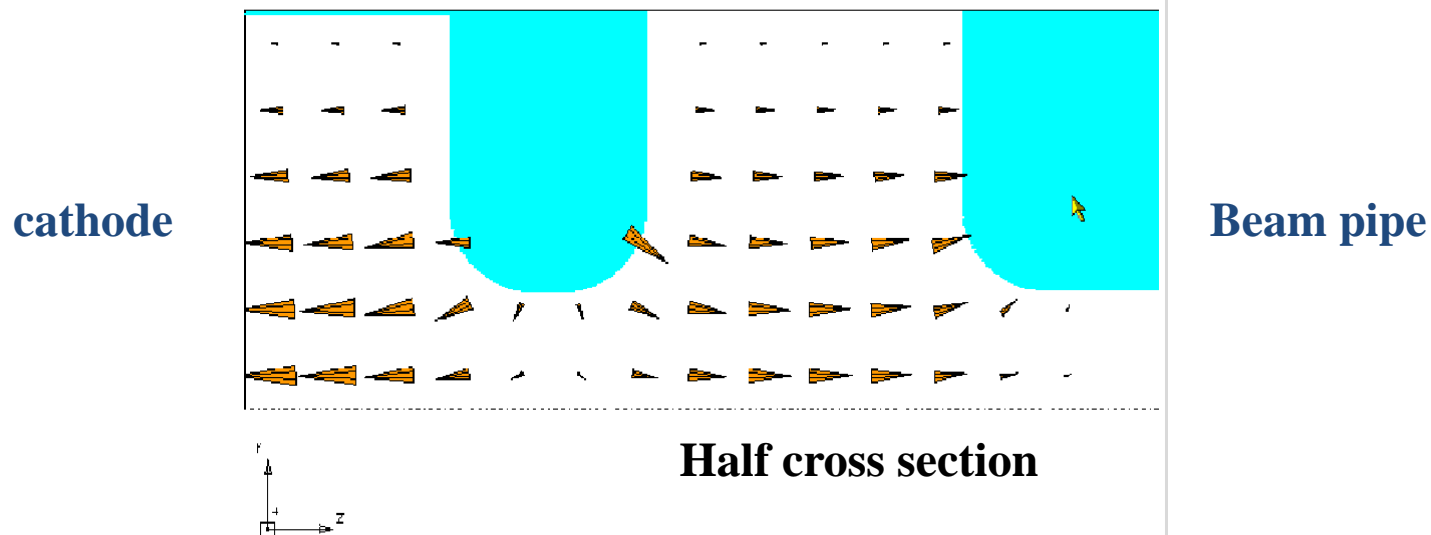
**Cathode block**



**End plate with cathode block**

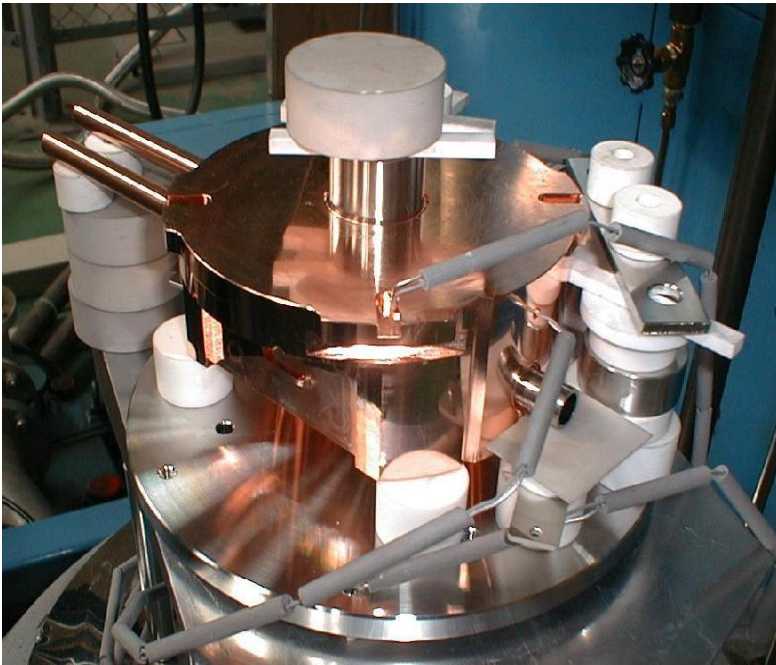
# *BNL Gun IV in KEK*

- 1. 1.6 cells standing wave RF gun with laser photo-cathode.*
- 2. Driving RF (2856 MHz) is fed to the second cell ( full cell).*
- 3. The cavity and the conventional cathode are made from Cu.*
- 4. The cathode plate was modified for the load-lock system that makes Cs<sub>2</sub>Te cathode possible.*



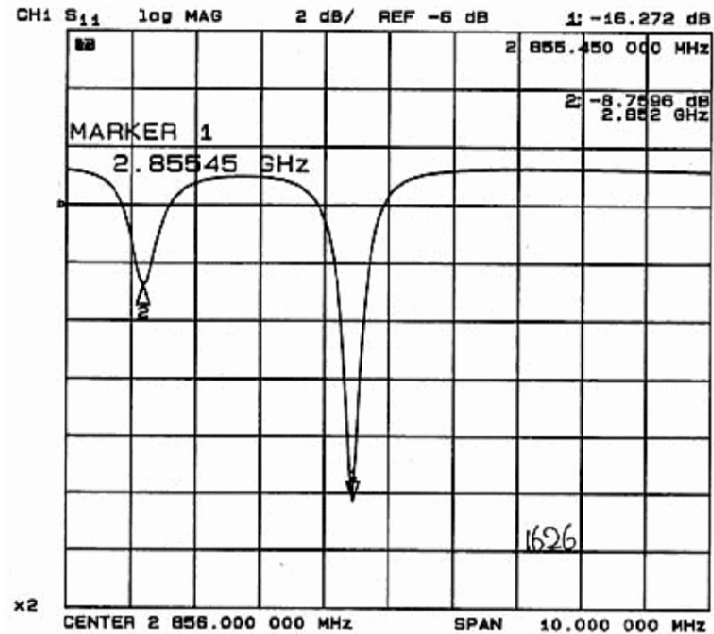
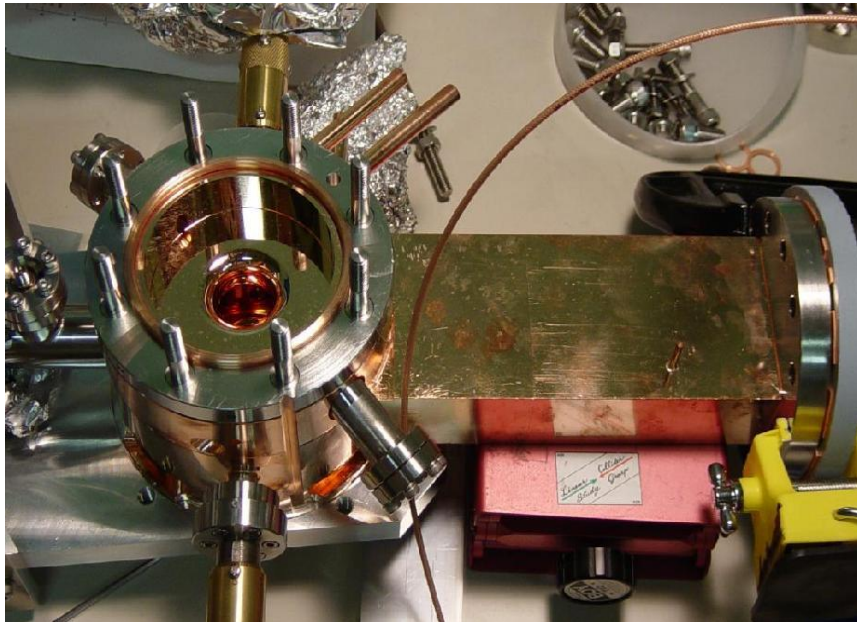
# *Blazing in KEK*

- 1. It is a hydrogen atmosphere blazing oven.*
- 2. Blazing was performed in four steps.*
- 3. RF power was fed without any de-hydrogen process. No difficulty.*



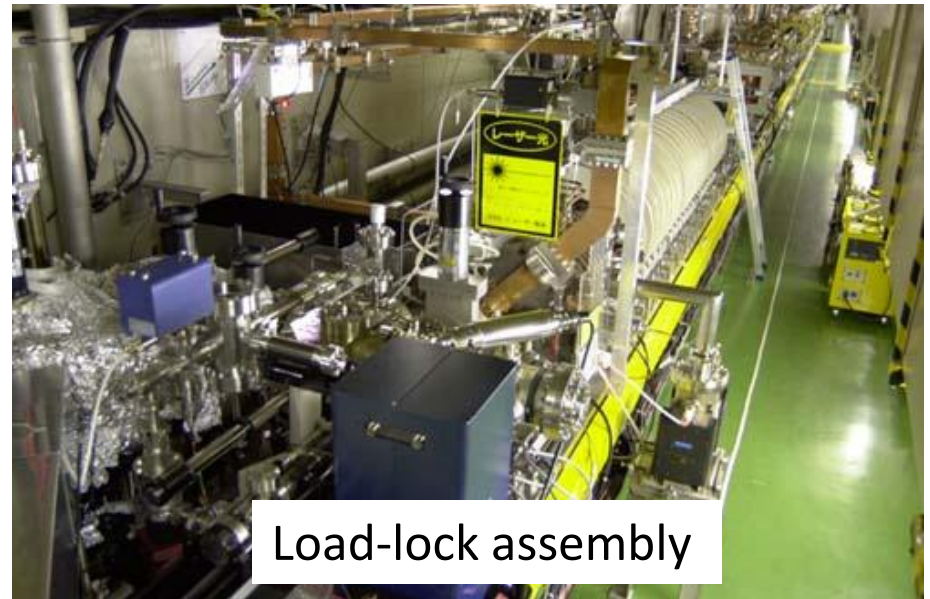
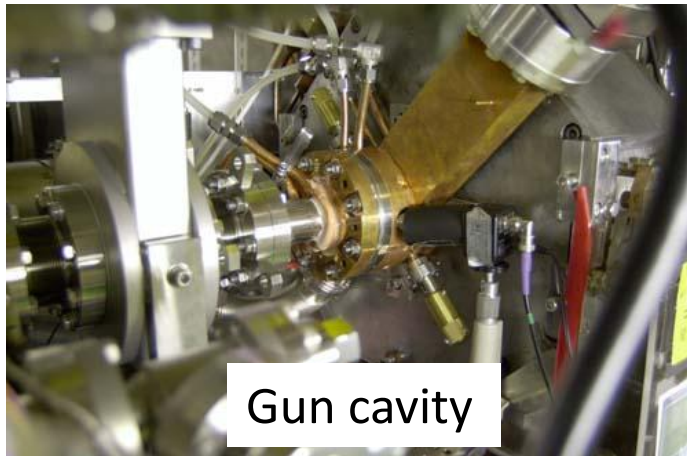
# Final check

- Newly purchased HELICOFLEX<sup>(R)</sup> did not fit to the cavity. We then used the old spare instead of the new one.
- Finally, the cavity was tuned succesfully at  $f\pi \sim 2855.4$  MHz that corresponds to 2856 MHz in 30deg. C, vacuum.





# *Gun cavity, Load-lock & Laser system*



# Requirements for the laser system

野村

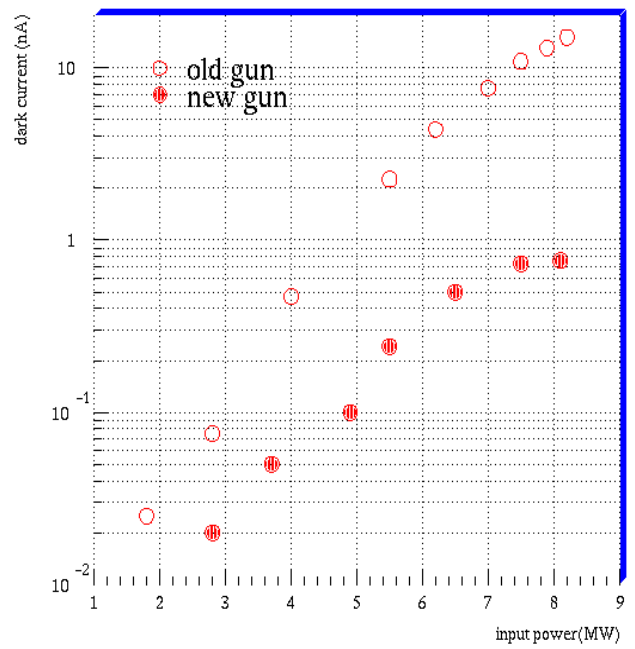
Photo cathode	Cs <sub>2</sub> Te
Laser wavelength	266nm (Nd:YAG (4 $\omega$ ))
Pulse duration	10ps
Time between pulses	2.8ns
Pulse train duration	56ns (20 pulses in the 1 train)
Repetition rate	6.25Hz
UV energy per micro pulse	>1 $\mu$ J
Quantum efficiency of photo cathode	>1%
Electron bunch charge	1 $\times$ 10 <sup>10</sup>



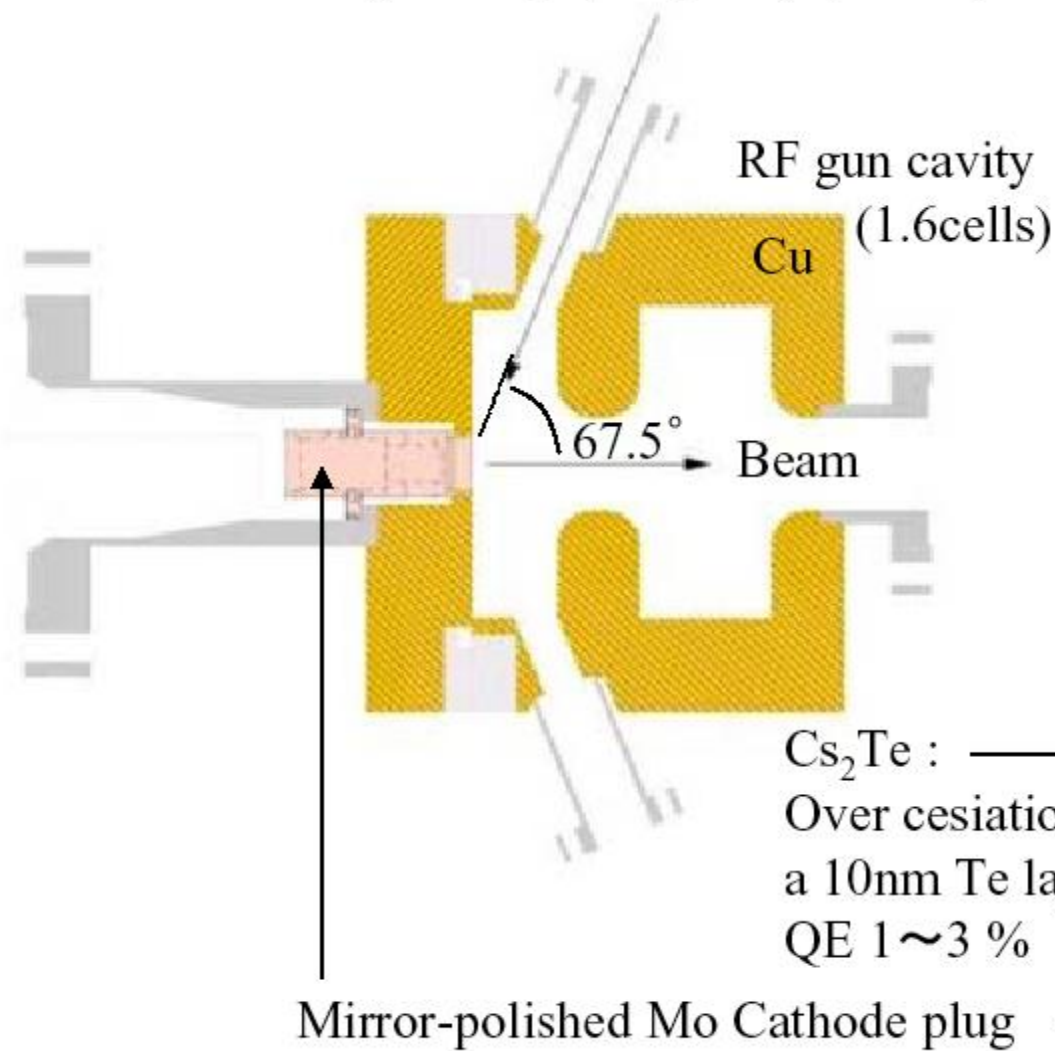
Your institution  
logo here

# Performance

The dark current was much lower than that of the old gun which was 3 years old, made by SHI (commercial company) with a conventional machining.

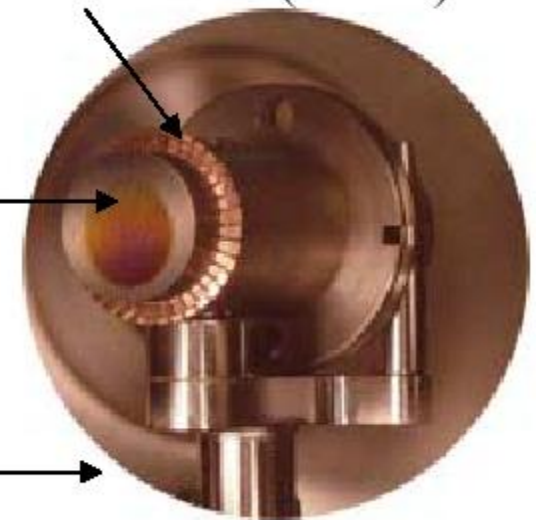


UV laser (266nm, 1  $\mu$ J/pulse,  $\phi$  2mm)



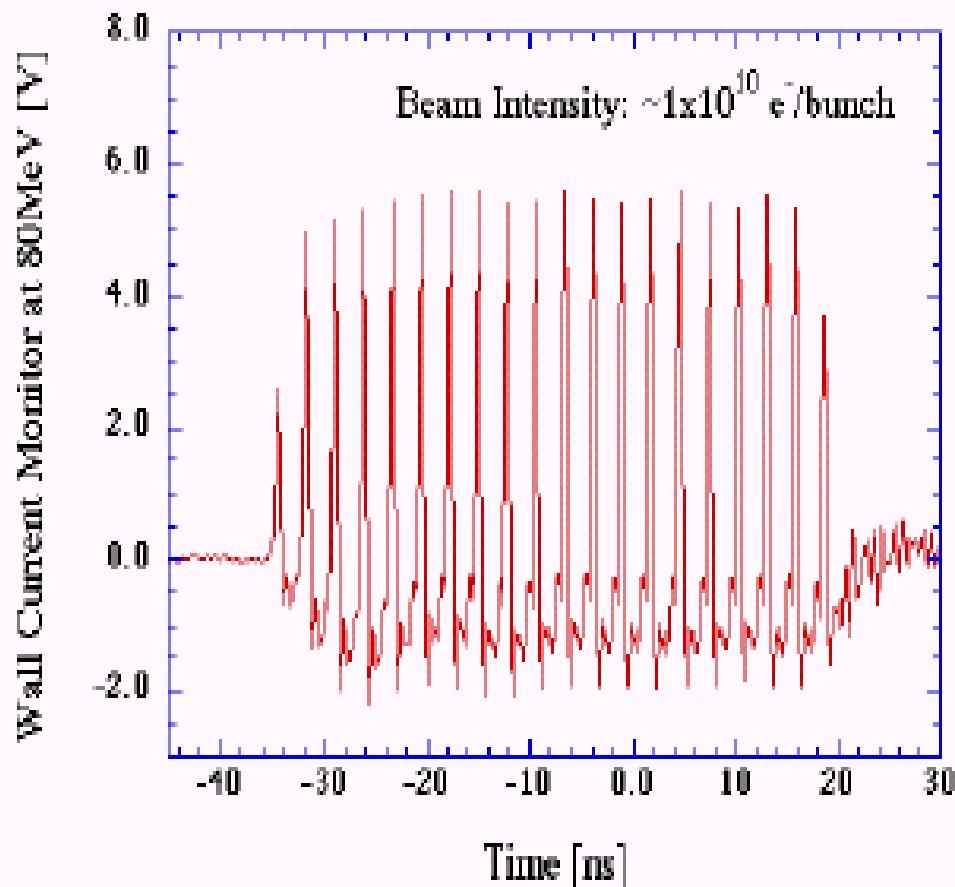
Contactor (Cu-Be)

Cs<sub>2</sub>Te :  
Over cesiation on  
a 10nm Te layer.  
QE 1~3 %



# 2003年1月に得られた結果

Multibunch waveform from RF gun



ビーム強度

$\sim 19 \times 10^{10}$  electrons/pulse

$\sim 1 \times 10^{10}$  electrons/bunch

規格化エミッタンス

水平  $\sim 25 \times 10^{-6}$  m · rad

垂直  $\sim 78 \times 10^{-6}$  m · rad

バンチ長

13~16psec(FWHM)

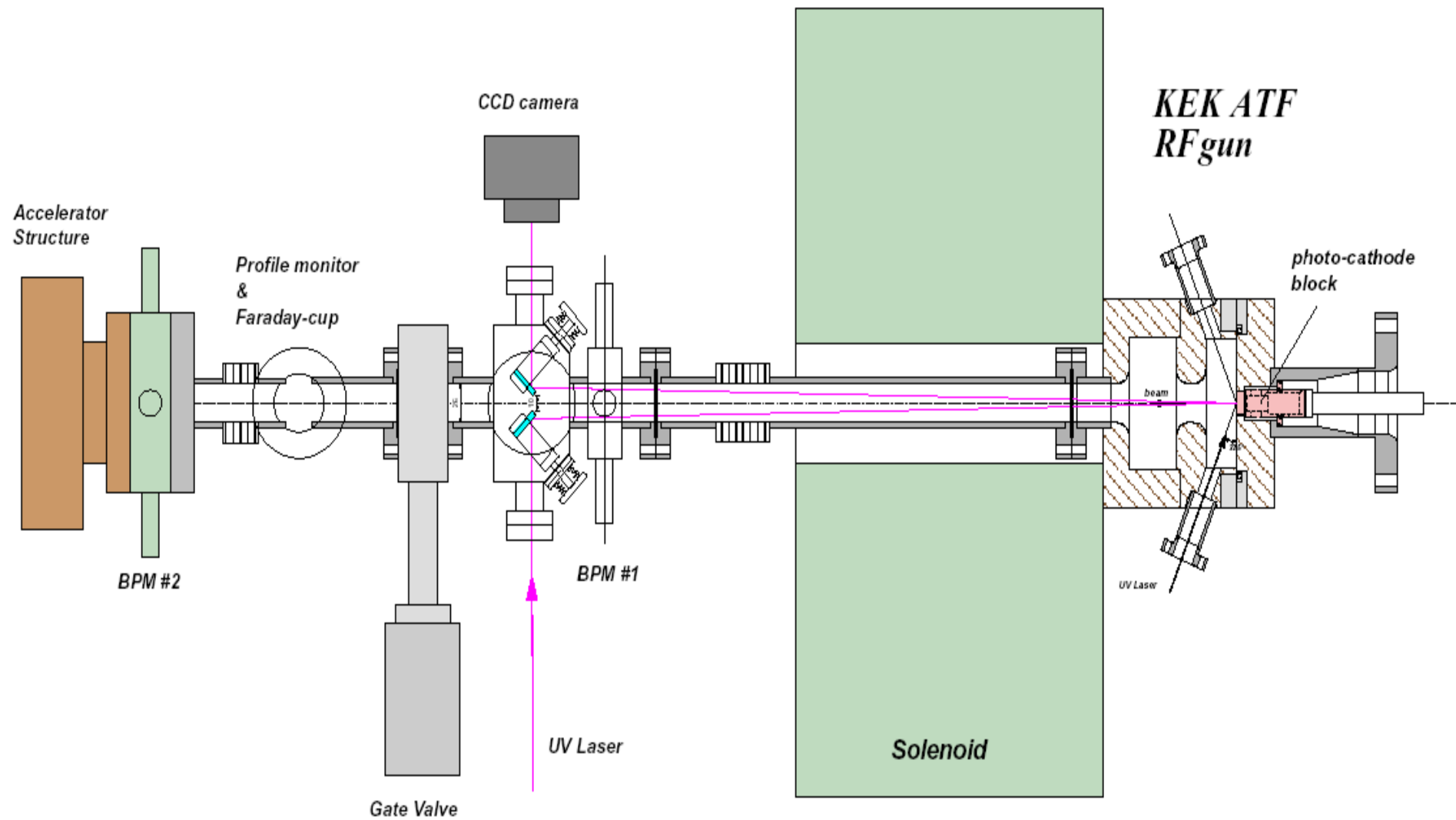
エネルギー広がり

$\sim 7.6\%$ (FWHM)

ビーム強度変動

10%(rms)以内

# Head-on Laser Injection scheme



Plan view Jan. 2003

3.2nC/bunch, 20 bunches/pulse, 12.5Hz beam operation

$< 10\pi$  radm normalized emittance at 1.3GeV

100 bunches/pulse can be generated but it can not be accelerated at ATF.

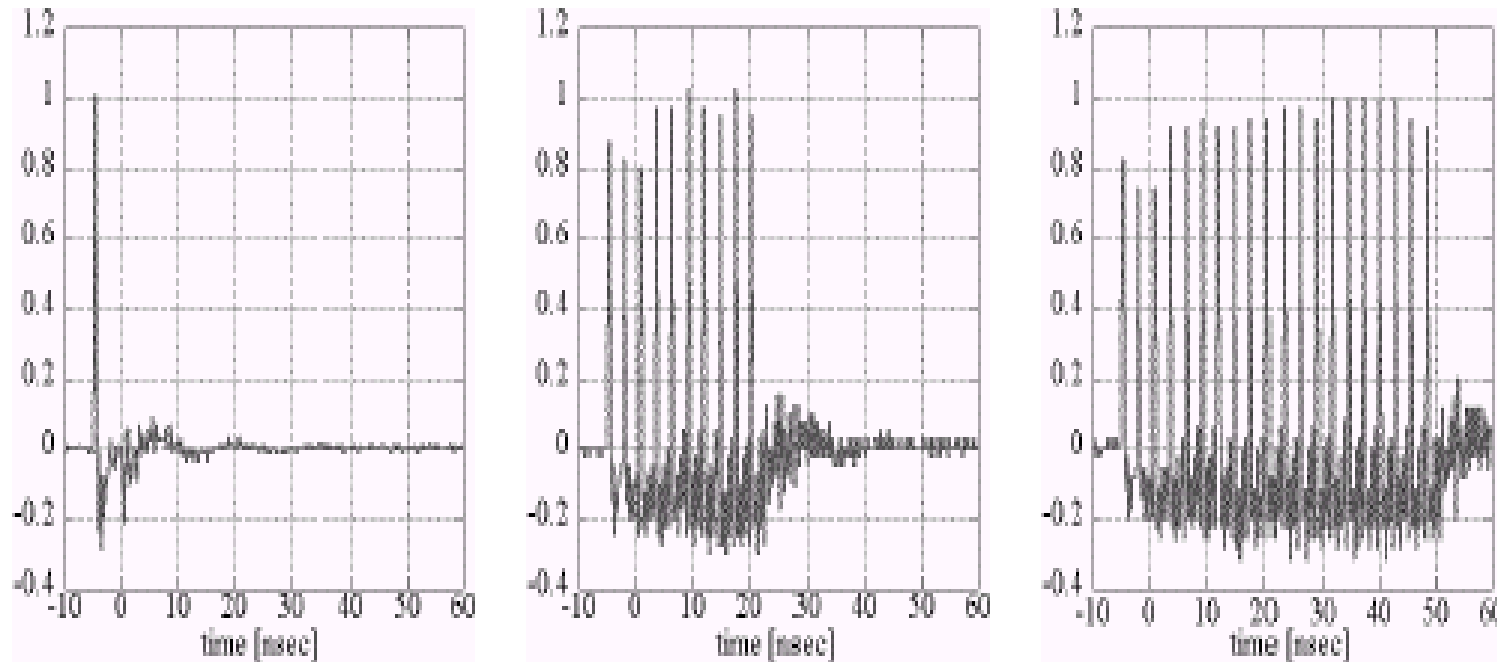
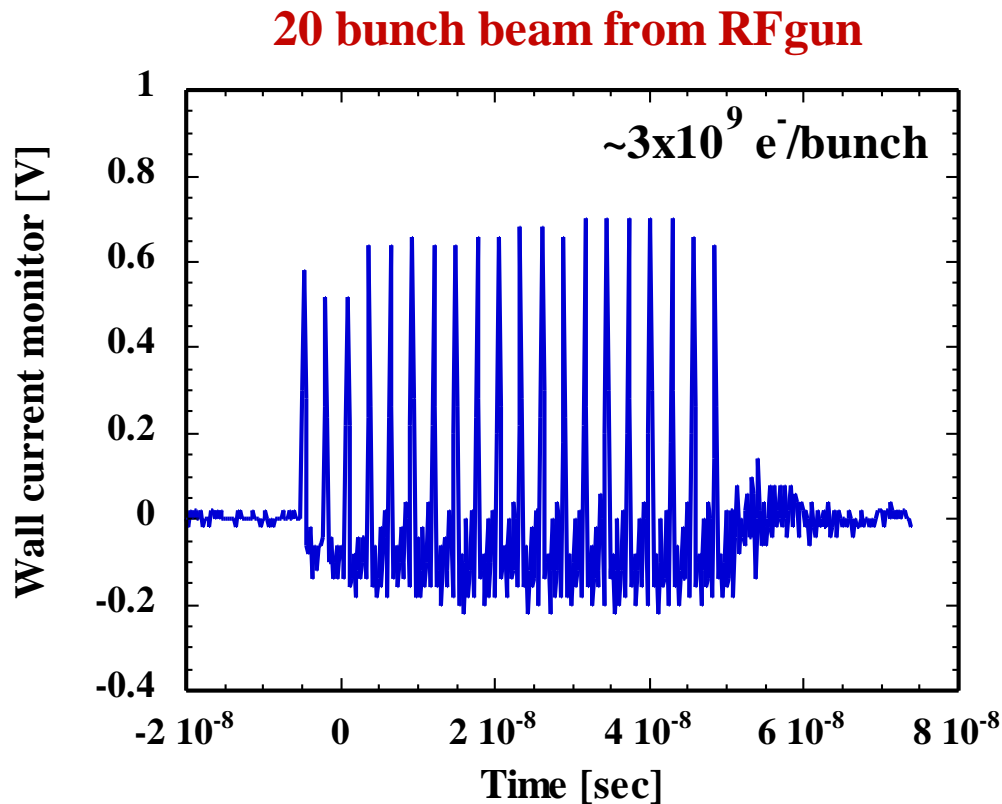


Figure 3: Beam profile in time measured by Wall current monitor. From left, the bunch numbers are set to 1, 10, and 20.

# *RF gun beam at 80MeV*

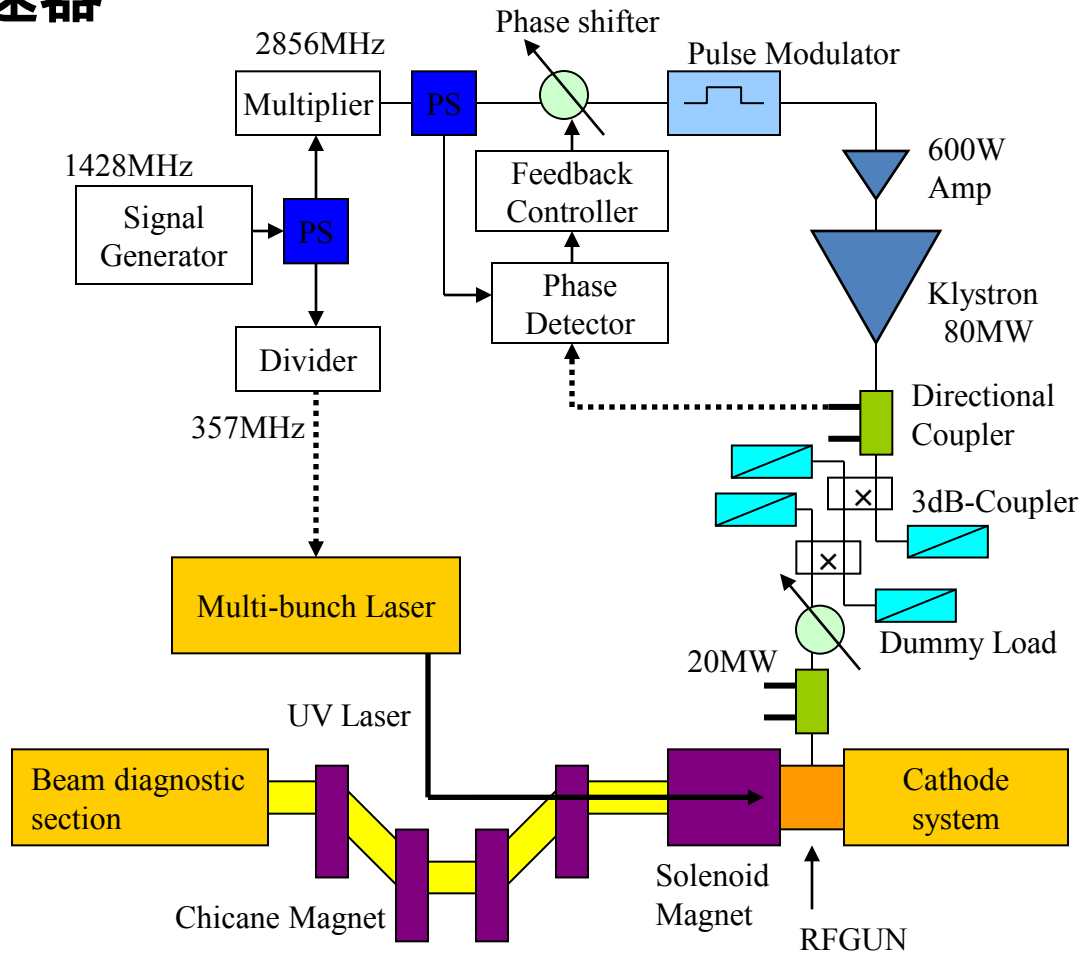


1. Beam Intensity  
~ $1 \times 10^{10}$ /bunch
2. Normalized Emittance  
 $\epsilon_y = 4 \sim 7 \times 10^{-6}$  rad.m
3. Bunch length  
 $\sigma_z = 3 \sim 6$  ps
4. Energy spread  
 $dE/E = 2 \sim 3$  % full-width
5. Q.E. of CsTe cathode  
16% initial, ~ 1% with RF ON  
& keep constant over several weeks

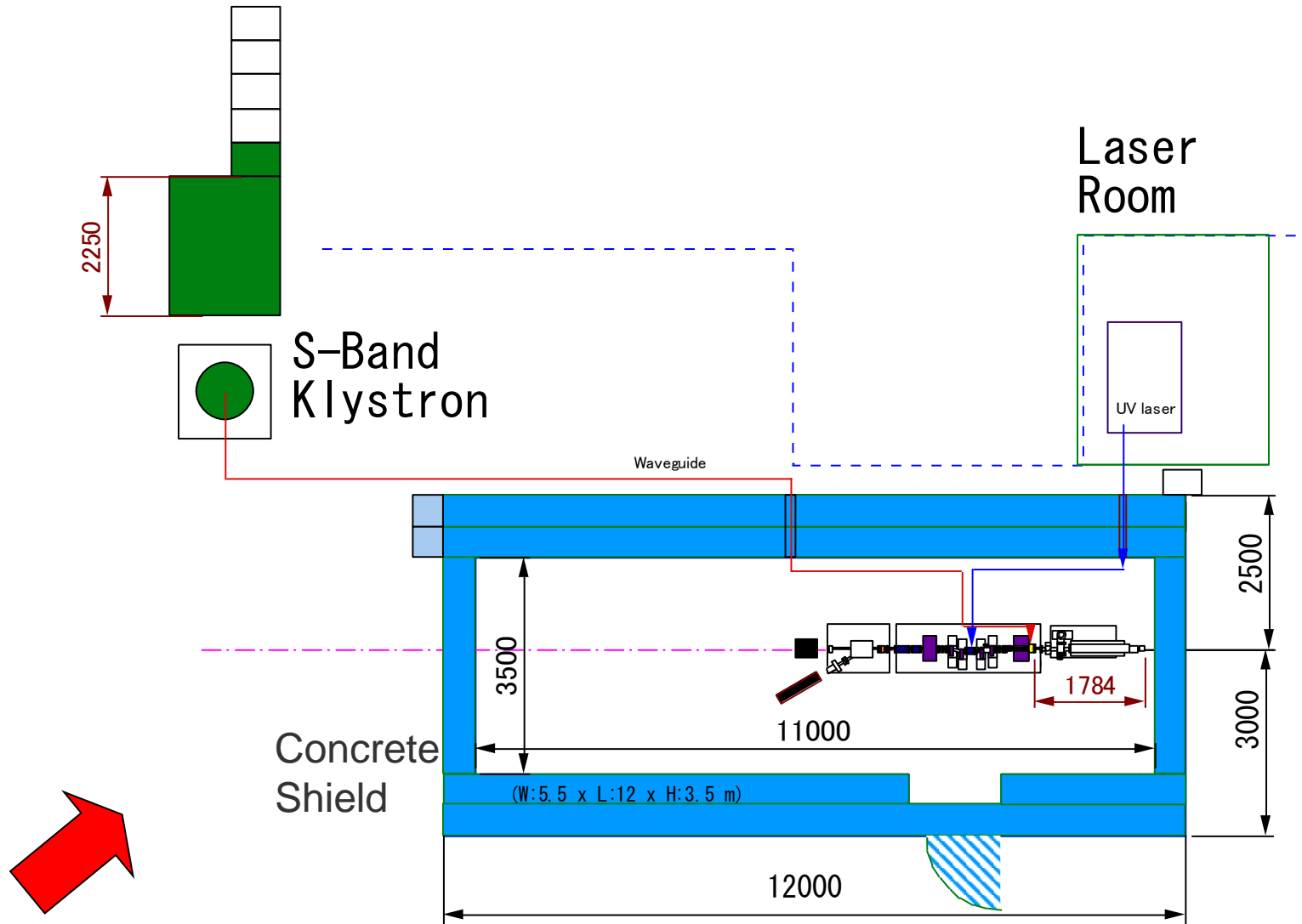


# *Schematic of the RFGUN Test Bench*

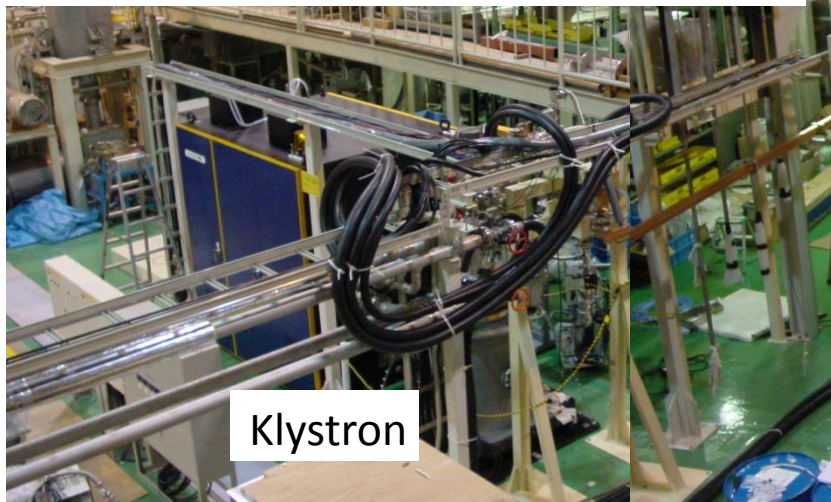
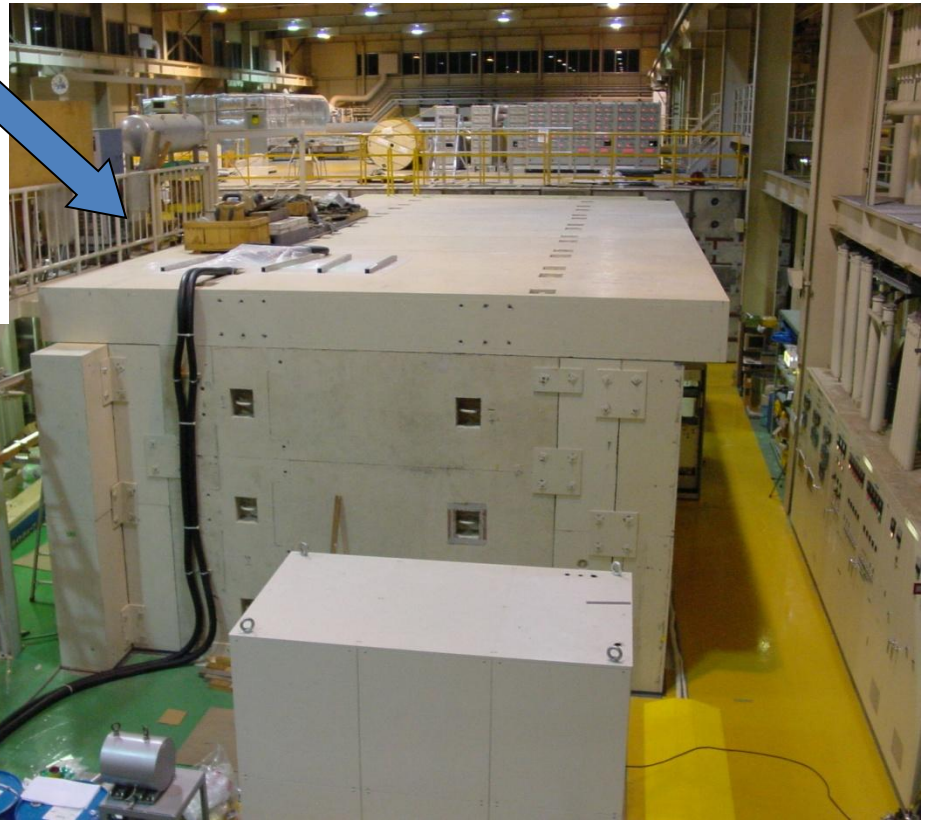
## 小型試験加速器



# Top View of RF GUN Test Bench



# *Photo of RFGUN Test Bench*



Klystron

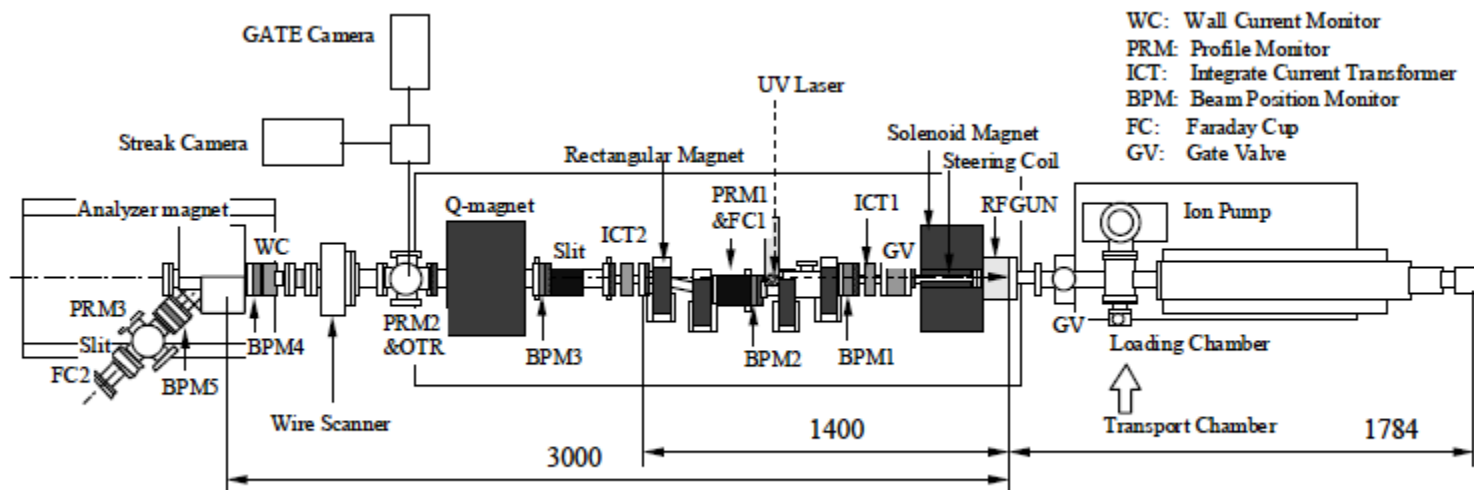


Figure 4: Schematic view of experimental setup

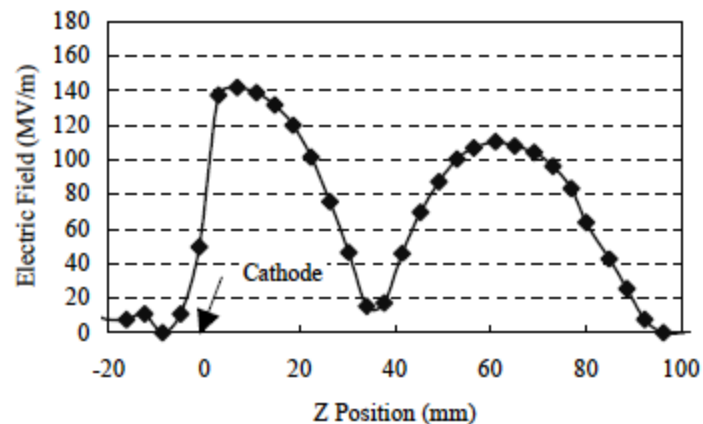


Figure 3: Electric field distribution in the RF gun cavity at the RF cavity power 15MW.

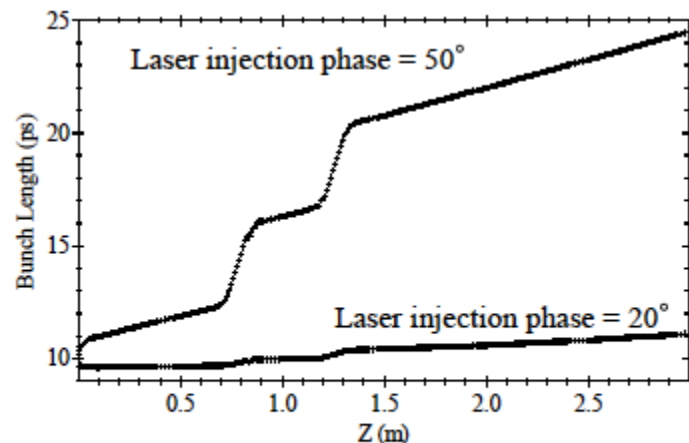


Figure 7: Electron beam bunch length as a function of a position from the cathode.

Beam energy (max.)	7MeV
Bunch charge(max.)	5nC/bunch
Number of bunches(max.)	100/pulse
Repetition rate (max.)	12.5Hz
RF frequency	2856MHz
Bunch frequency	357MHz
Bunch separation	2.8ns
Photo-cathode	Cs <sub>2</sub> Te
QE (aim)	>3%
Laser energy (aim)	>3μJ/bunch
Laser wavelength	266nm
Laser width (FWHM)	10ps
RF pulse width (max.)	4μs
RFGUN input power (max.)	20MW
Solenoid magnetic field (max.)	3.2kGauss
Chicane magnetic field	500Gauss

Table 1: Beam parameters.

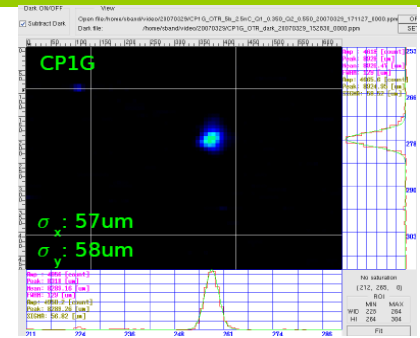
# Pulse laser storage in optical cavity and X-ray measurement in 2009

## X-ray generation with 1000 enhancement by optical cavity

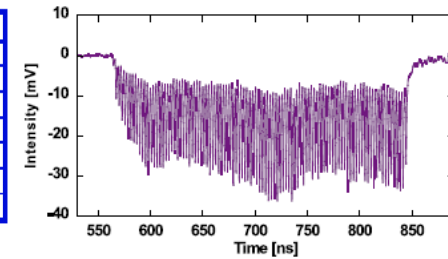
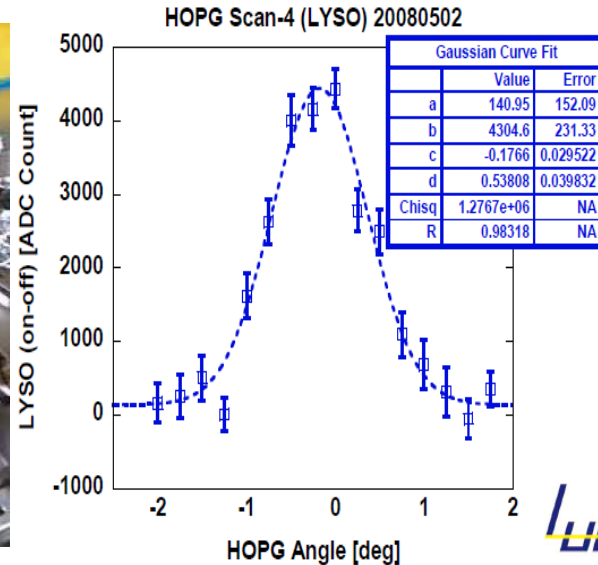
Average power in burst period :40kW, 7psec(FWHM)

Status : 0.2mJ/pulse, target : 10mJ/pulse

## X-ray measurement



Electron beam size 60 $\mu$ m in  $\sigma$

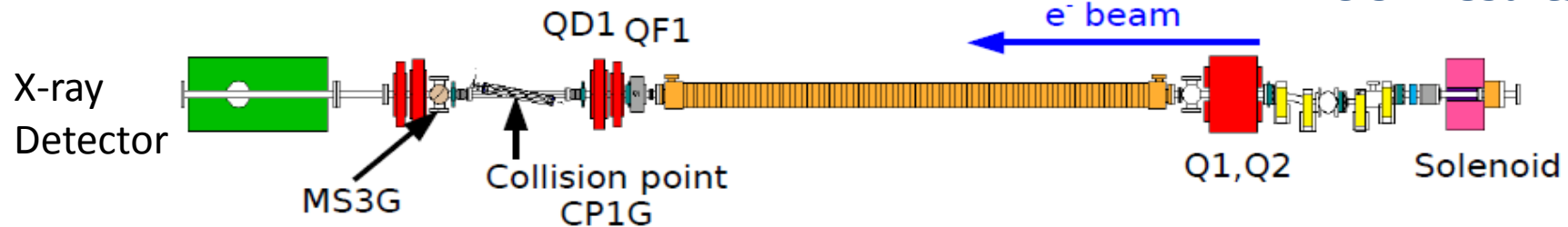


MCP waveform background subtracted. Detected X-ray flux 1.2x10<sup>5</sup> Hz/~10%b.w.



## Beam collision technique

43MeV Multi-bunch beam+ Super-Cavity = 33keV X-ray.



## LUCX results

Laser size:30 $\mu$ m in  $\sigma$ , target:electron beam size:10 $\mu$ m in  $\sigma$ , laser waist size:8 $\mu$ m in  $\sigma$

# Simple comparison of main parameters

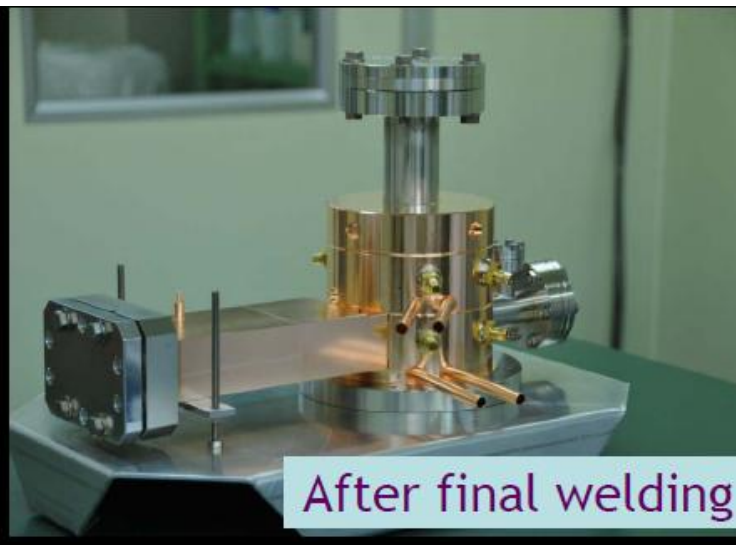
## New 1.6 cell RF Cavity

	Simulated	Measured	
	New Gun	New Gun	Old Gun
Frequency MHz	2855.64	2855.61	2855.74
Mode Separation MHz	8.67	8.63	3.52
Field Balance	1.0	0.98	1.3
Q	18000	14,700	7900
Coupling $\beta$	1.0	1.0	0.6

RF Gun	Q
BNL (original)	7900
LUCX (original)	7900
ATF ( modified)	12600
BNL (modified)	12780
LUCX New (Curved Profile)	14,700
LCLS (modified)	13,900



After 1<sup>st</sup> Brazing

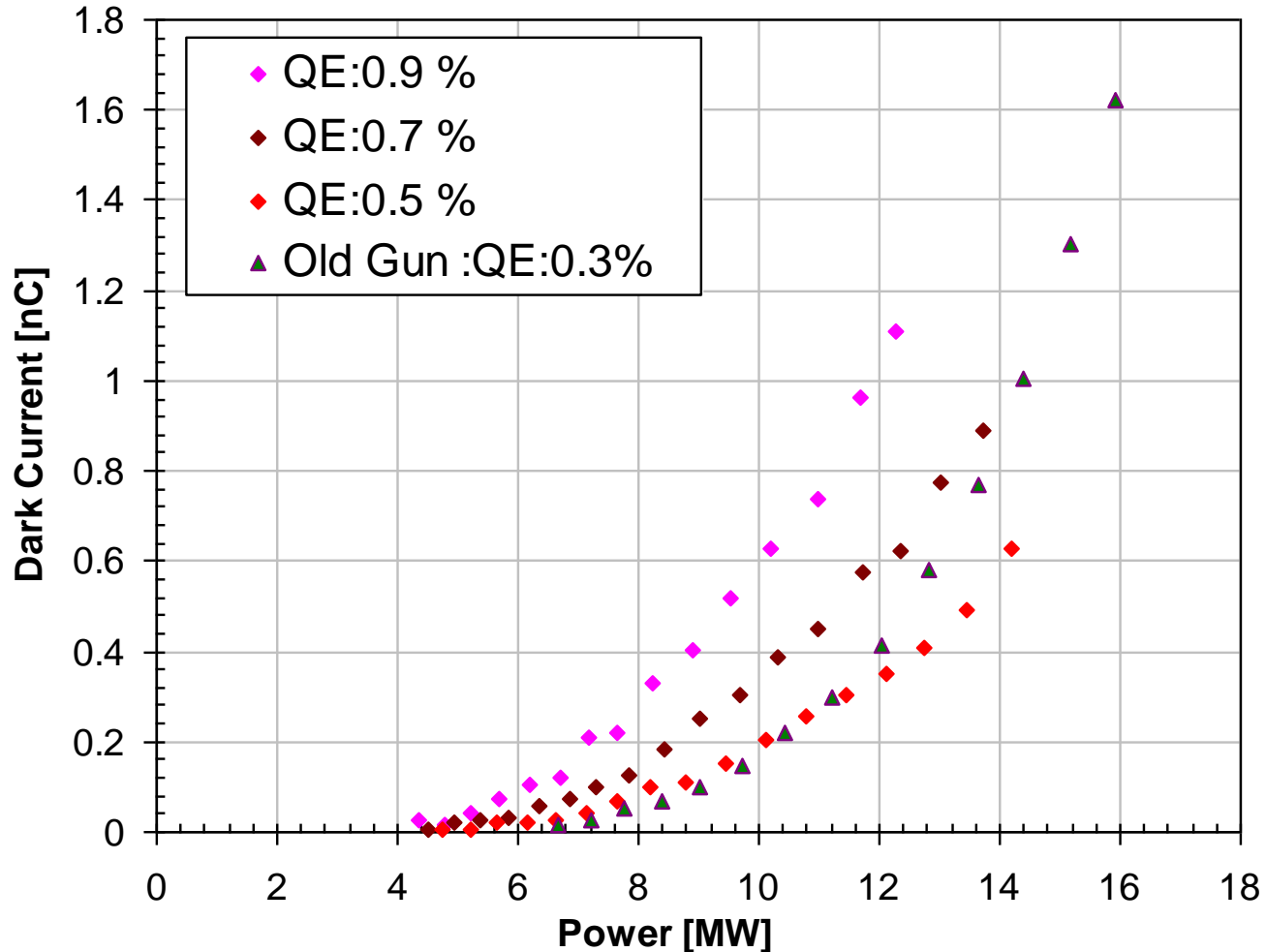


After final welding

Stable operation  
at 130MV/m.

140MV/m  
Operation possible.

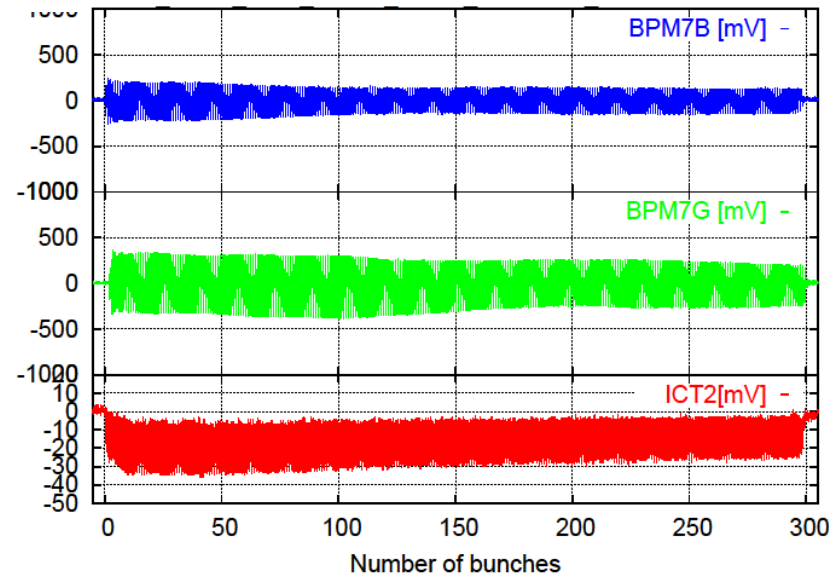
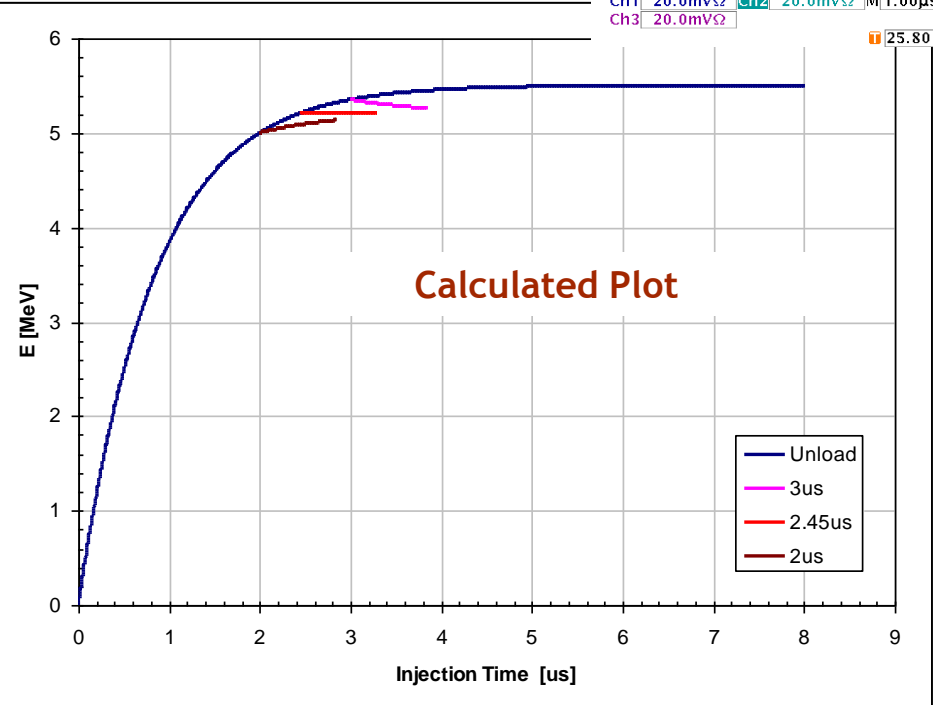
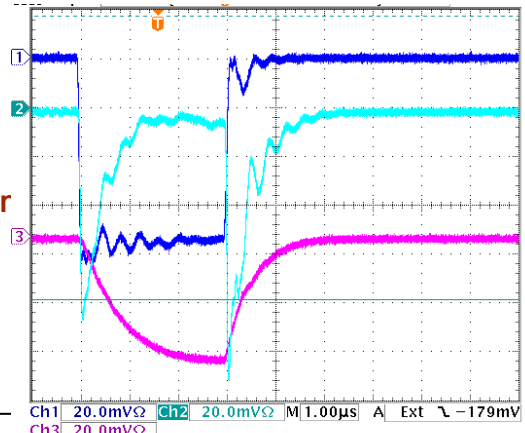
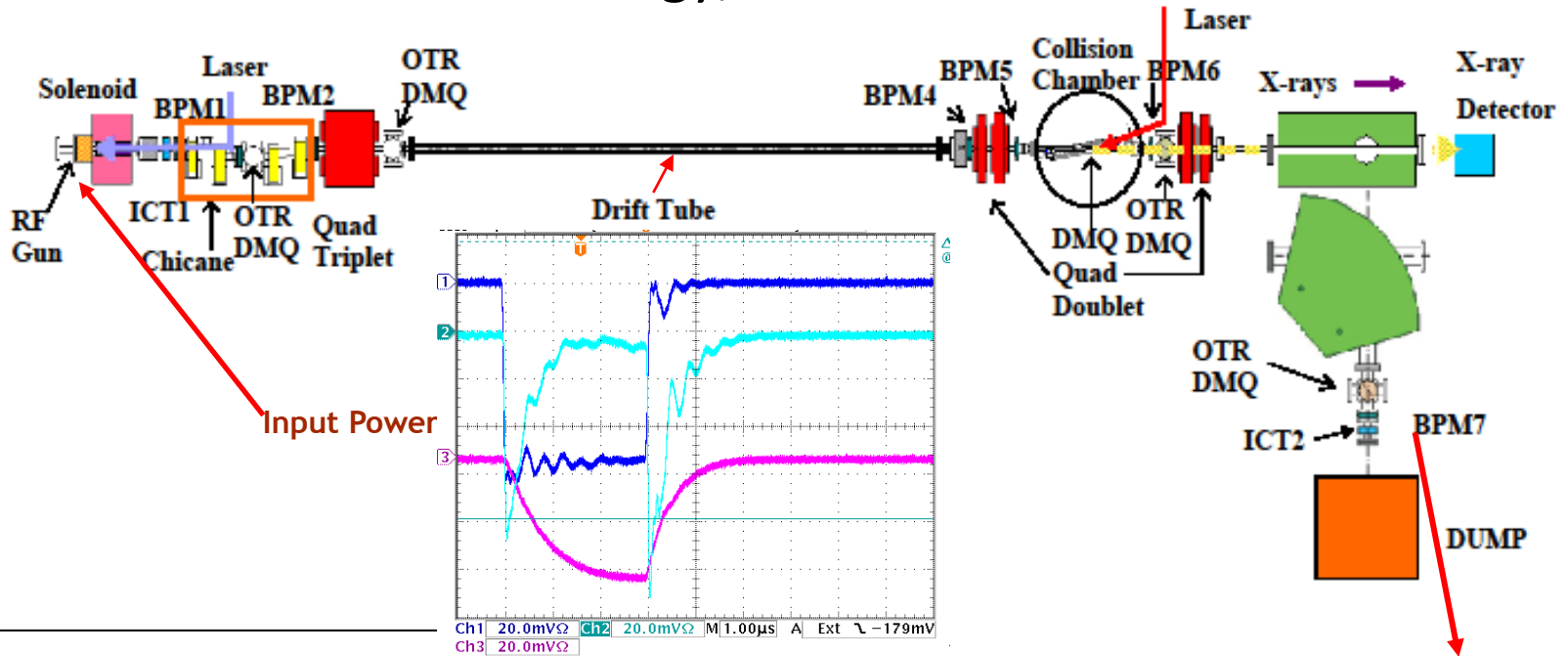
# Dark current measurement



- The Dark current was measured using ICT 1 downstream of solenoid.
- The pulse width was 2  $\mu$ s
- Old gun readings were taken in 2006 with quantum efficiency  $\sim$  0.3%



# Low energy; 300 bunch train



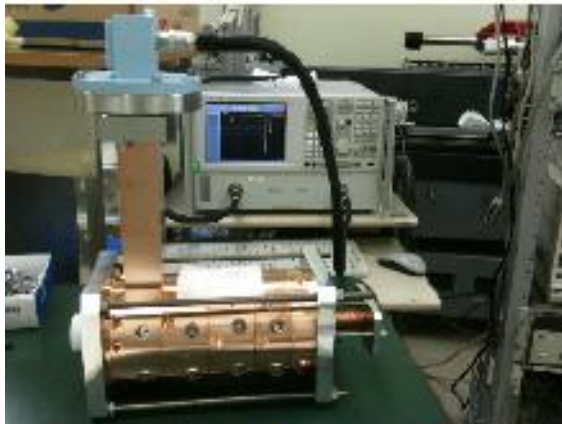
Measured BPM and ICT Signal

# Fabrication

## 空洞製作



Rough to fine machining



Mode frequency meas.

SUPERFISHでField BalanceがなるべくフラットになるようにCut幅を決める。

July 1st

1st 精密加工

1st 共振周波数測定 7/8

2nd 精密加工

2nd 共振周波数測定 7/15

Bead測定 7/20

3rd 精密加工

3rd 共振周波数測定 + Bead測定 8/2

導波管ロウ付け 8/6

リークテスト 8/9

共振周波数測定 + チューニングピン調整 8/10

最終ロウ付け 8/12

共振周波数測定 8/23

溶接 8/24 27

共振周波数測定 8/31

完成

End of Aug.



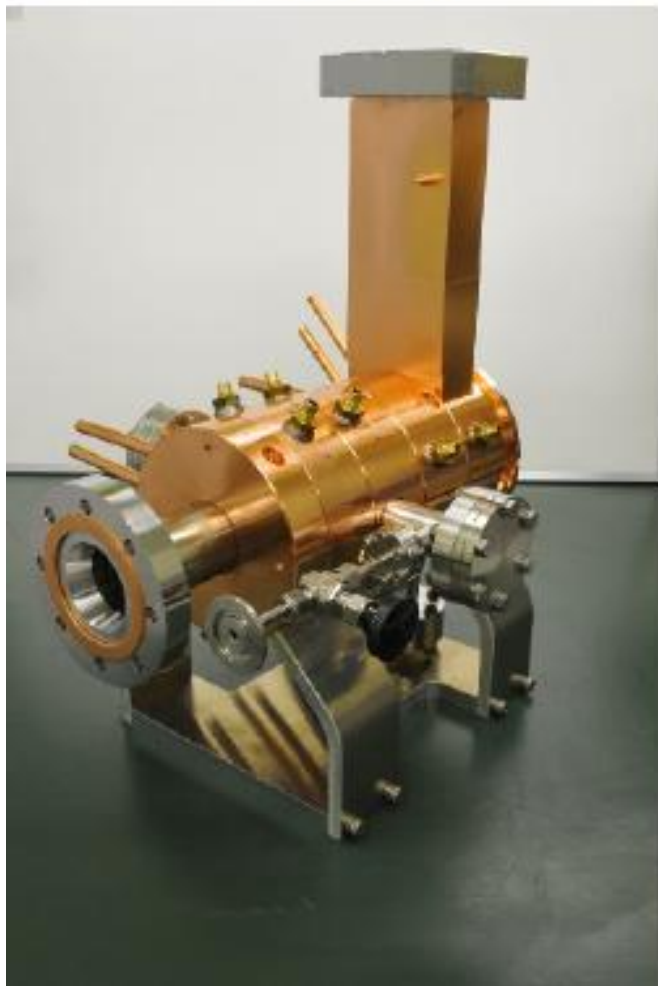
Res. freq. meas. of each cell



Field pattern meas.

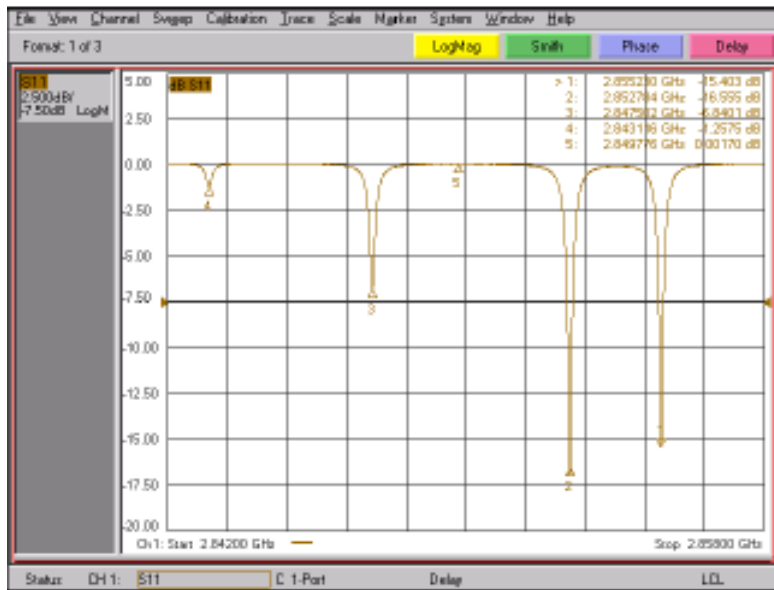
## 3.6 cell RF Gun Installation レ

RF-Gun 完成



ATF インストールの様子

# After installation



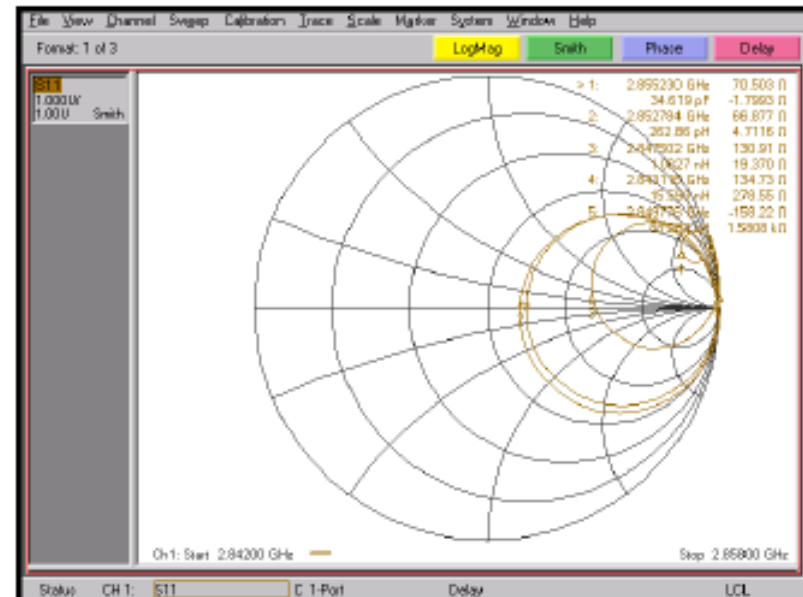
## Res. Frequency

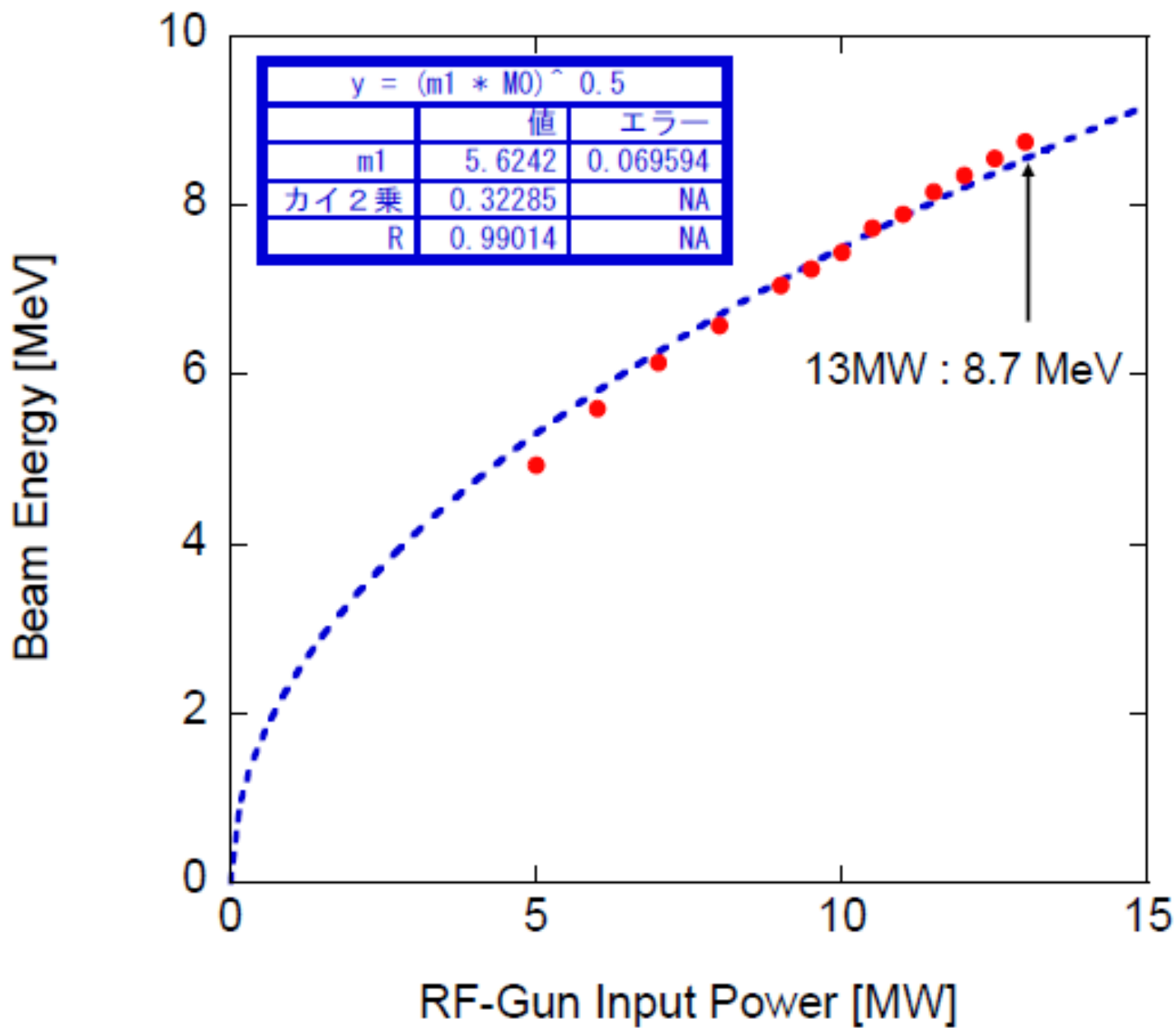
$\pi$	2855.230 MHz
$2/3 \pi$	2852.784 MHz
$1/3 \pi$	2847.502 MHz
0	2843.116 MHz

Mode separation : 12.114 MHz

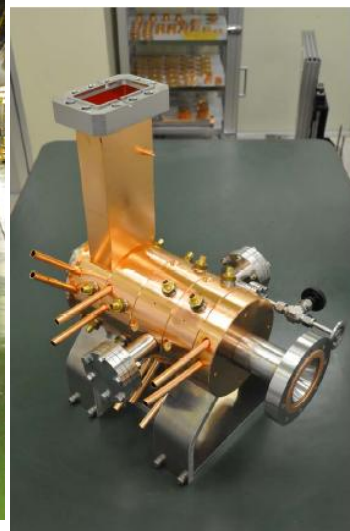
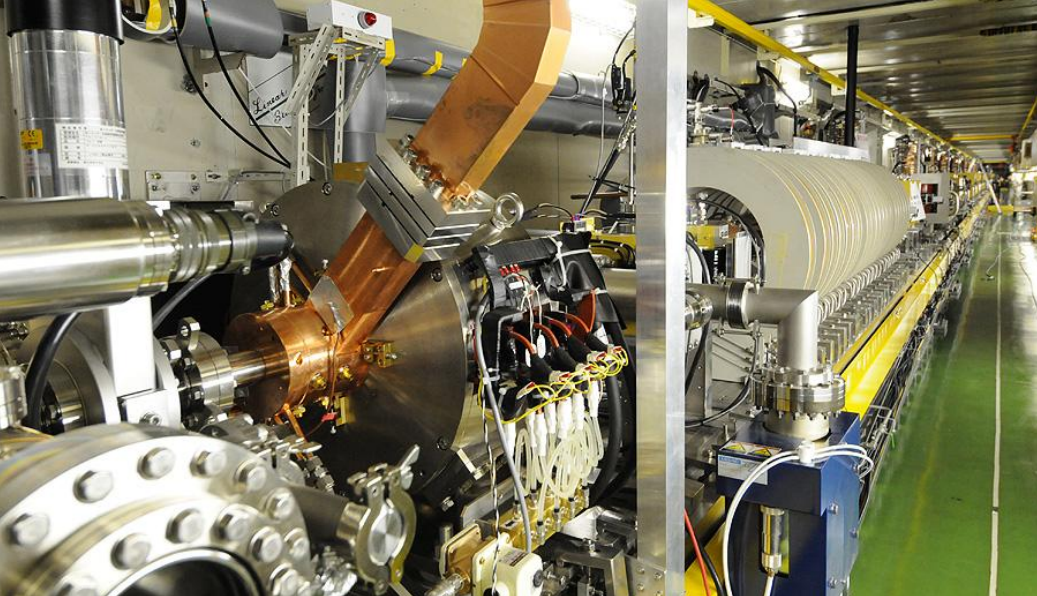
## Analysis of $\pi$ mode

共振周波数 : 2855.230 MHz  
(真空中で2856 MHz , 34.7°C)  
Coupling : 0.71  
Q値 : 15456





# Photo-cathode RF Gun

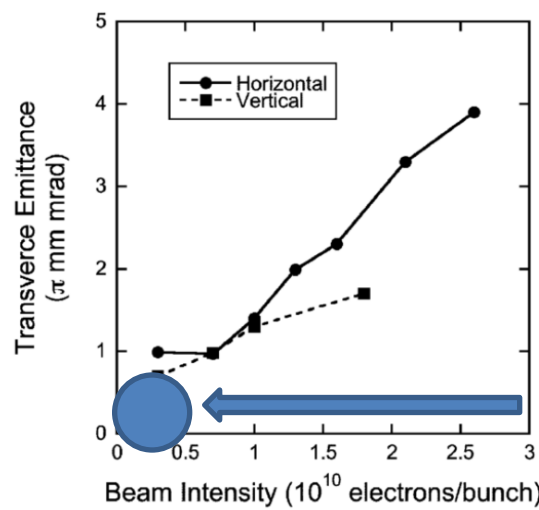
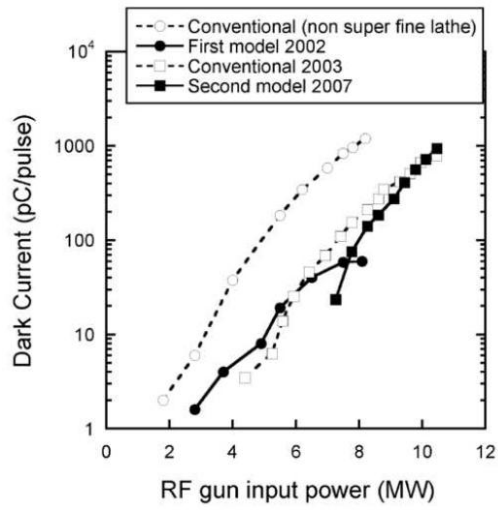
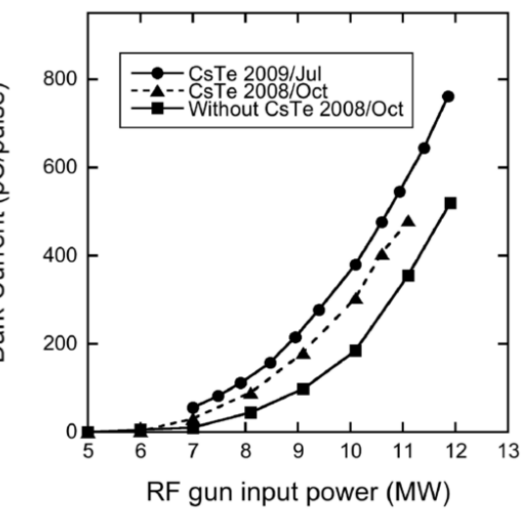


1.3 GeV ATF Linac, results by 80 MeV beam.

10 MeV 3.6 cell gun

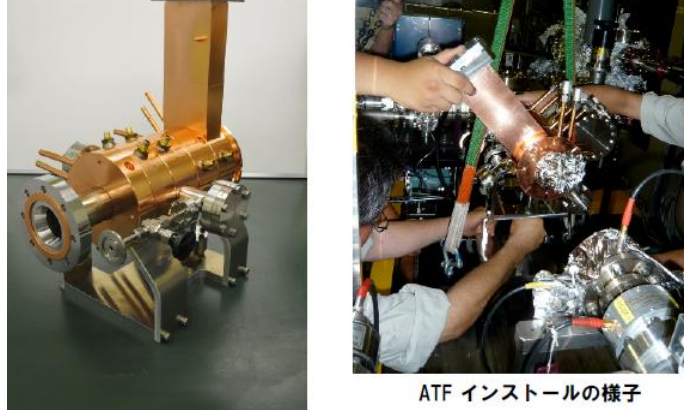
6 MeV 1.6 cell gun

From 2002 onward, successive improvements have been incorporated into newer models of the RF gun. In 2008, a new gun incorporating all of the earlier modifications was produced for the ATF. A typical transverse emittance of **1.3  $\pi$  mm·mrad** has been obtained under solenoid field of 0.18 T, beam intensity of **1.6 nC/bunch**, and **RF power of 9 MW**.

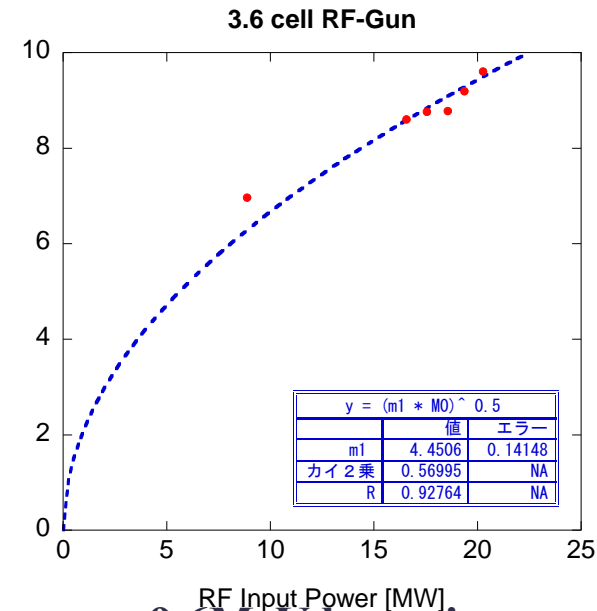


Study to reduce normalized emittance.  
**0.3  $\pi$ mm·mrad**  
 at 0.1 nC/bunch

# 3.6 cell RF Gun Installation

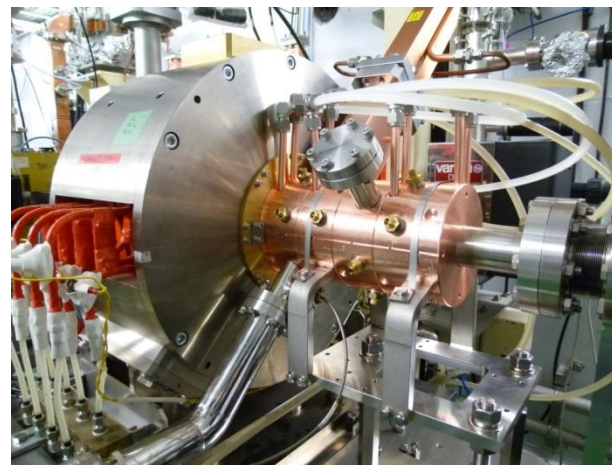
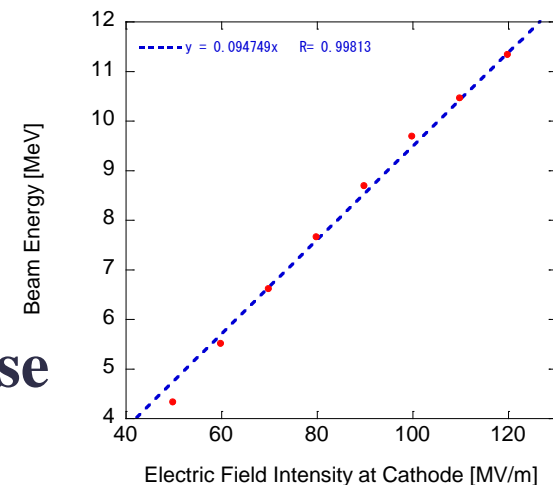


ATF インストールの様子

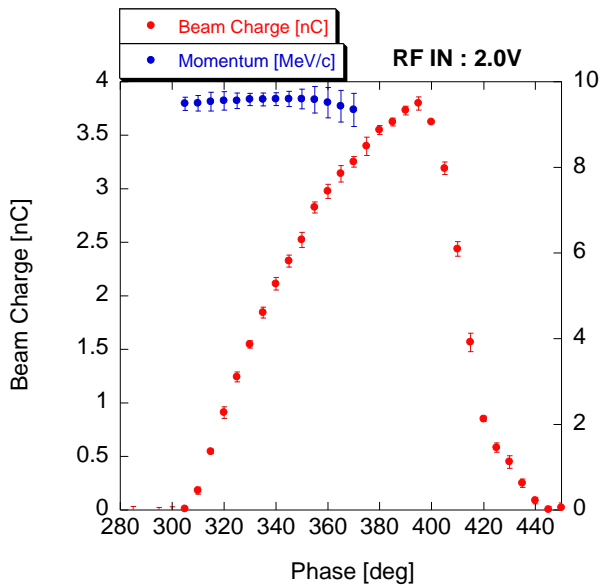
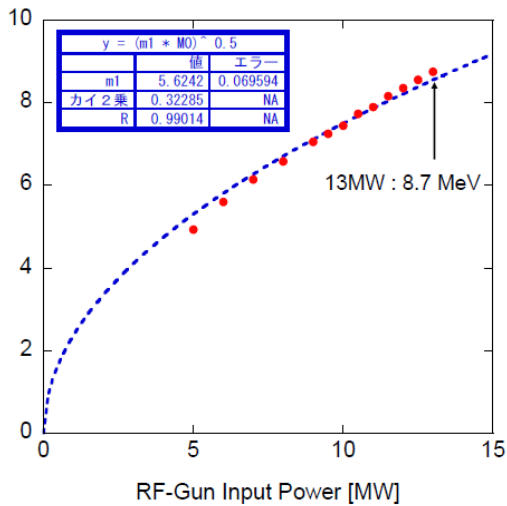


RF Input Power [MW]  
**9.6MeV beam in a week RF aging with ~22MW RF input power**

## PARMELA SIMULATION



**3.6 cell RF-Gun**  
**Start of beam acceleration test from 1/11,2012.**



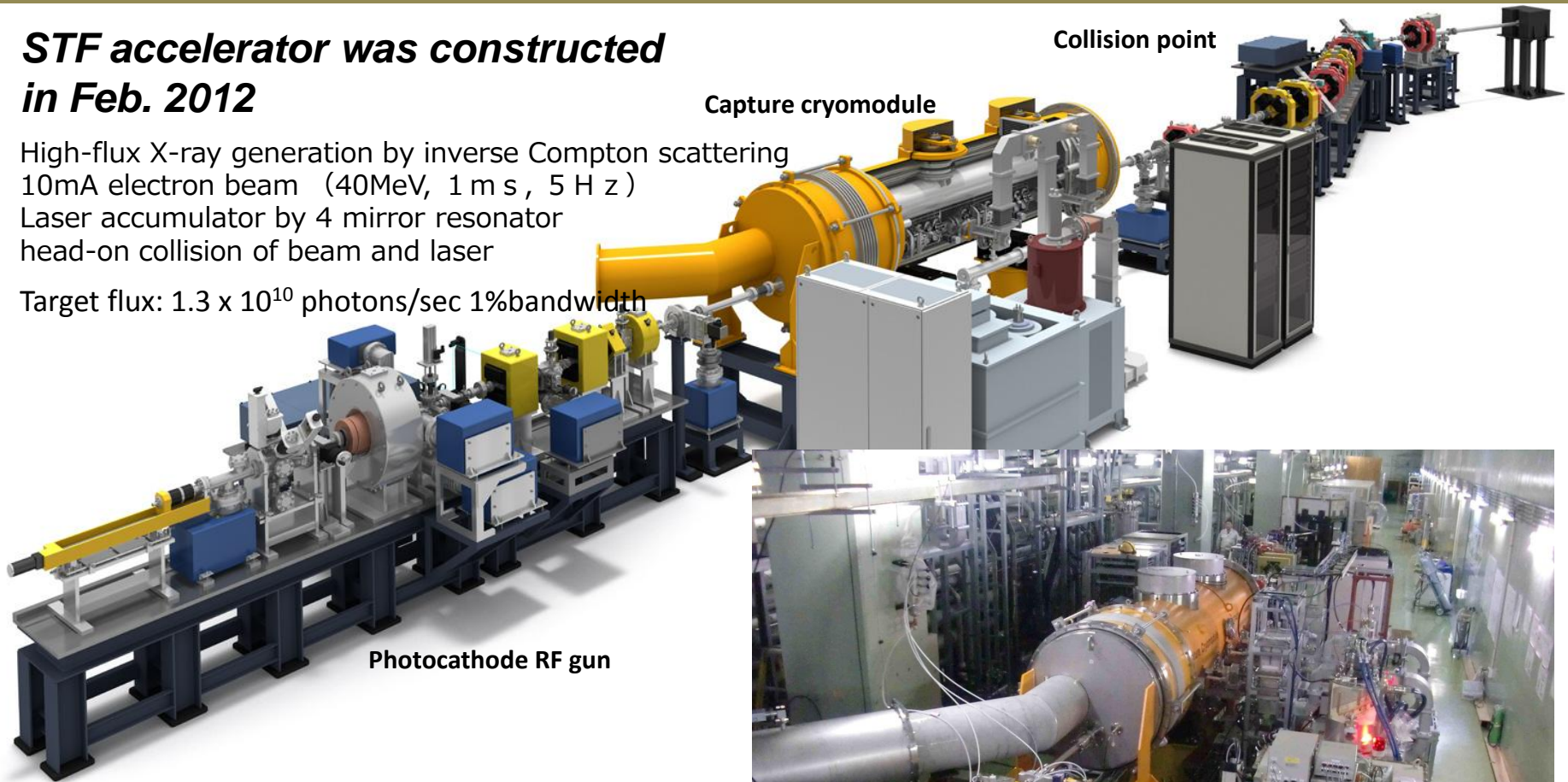
**10MeV beam at 120MV/m, from 100bunches/pulse to 1000bunches/pulse beam generation**

# STF加速器 (量子ビーム実験)

## STF accelerator was constructed in Feb. 2012

High-flux X-ray generation by inverse Compton scattering  
10mA electron beam (40MeV, 1 m s, 5 H z)  
Laser accumulator by 4 mirror resonator  
head-on collision of beam and laser

Target flux:  $1.3 \times 10^{10}$  photons/sec 1%bandwidth



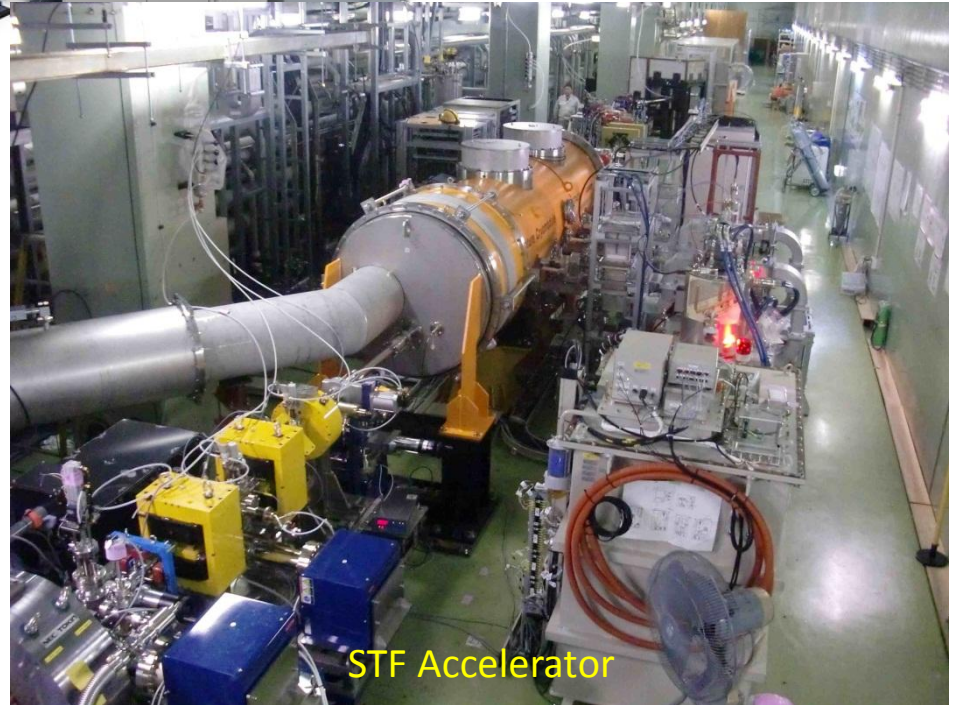
Photocathode RF gun

Capture cryomodule

Collision point

2012.9~2013.3

目標: 高輝度X線生成、各種加速器Study



STF Accelerator

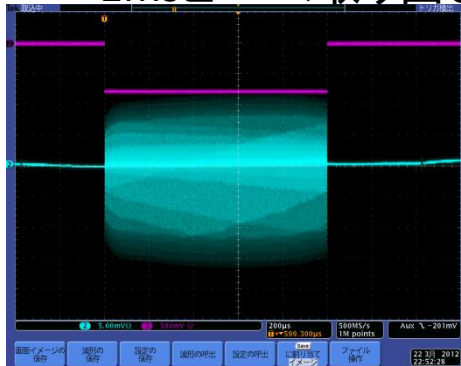


# 量子ビーム「STF加速器」 現在までに達成されているビーム

07132012 Hayano

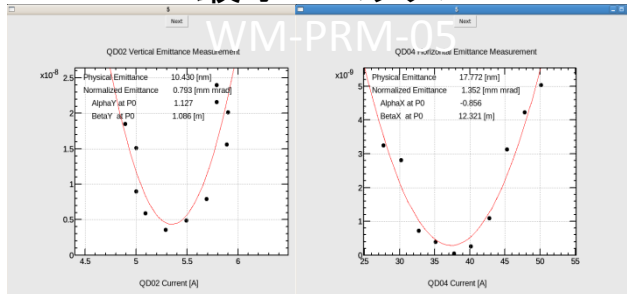
V1.0

## 1msビーム取り出し



RF電子銃からの1msフラットビーム取り出し (RF feedback ON) 03.22.2012 50pC/bunch

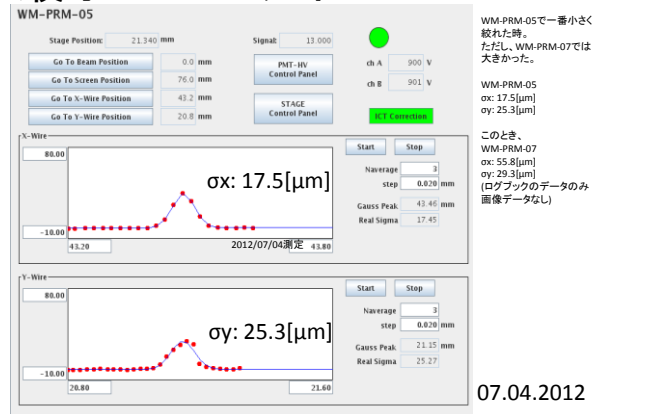
## 最小エミッタンス



Date	Normalized Emittance [mm mrad]	RF gun [MW]	SC cav. [MV/m]	Main Solenoid : Main/Backlog	UV Laser	Charge [pC]	Energy [MeV/C]
13/June	Vertical 0.79 Horizontal 1.3	1.3	3.5 14.5, 24.0	306.23 / 100.73	φ1mm	15-25	39.1

ワイヤースキャナーによるビームのエミッタンス計測 06.13.2012

## 最小ビームサイズ@WM-PRM-05

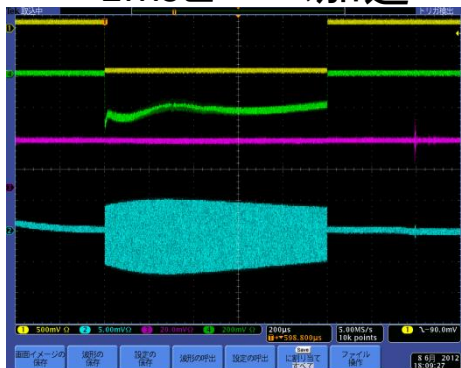


WM-PRM-05で一番小さく  
れた時。  
ただし、WM-PRM-07では  
大きかった。

このとき、  
WM-PRM-07  
σx: 55.8 [μm]  
σy: 29.3 [μm]  
(ログブックのデータのみ  
画像データなし)

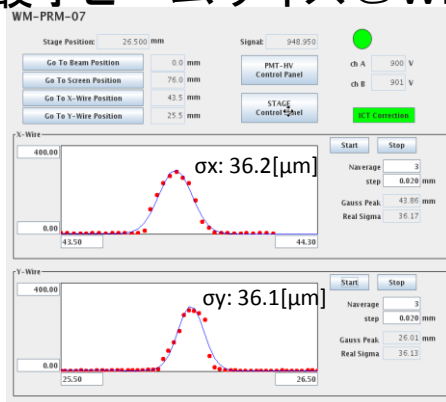
07.04.2012

## 1msビーム加速



1msビーム加速(15pC/bunch)  
(Gun/SCRF RF feedback ON) 06.08.2012

## 最小ビームサイズ@WM-PRM-07



07.04.2012

目標: 衝突点で10μm

## Dispersion測定

07.04.2012

超伝導空洞のRF位相を変えてエネルギーを振り、WM-PRM-05、-07のDispersionを測定

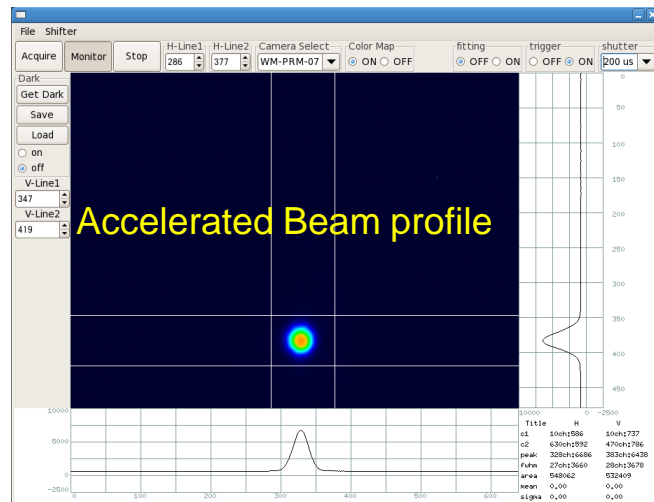
SC phase	240deg	40.58 MeV/c (B1)
SC phase	250deg	40.02 MeV/c (B1)

この2点でのビーム位置のずれからDispersionを計算した。  
ビーム位置はワイヤースキャナーで測定。

	$\Delta x$	$\Delta y$	$\Delta x$	$\Delta y$
WS-PRM-05	85um	14um	6.2mm	1.0mm
WS-PRM-07	42um	14um	3.1mm	1.0mm

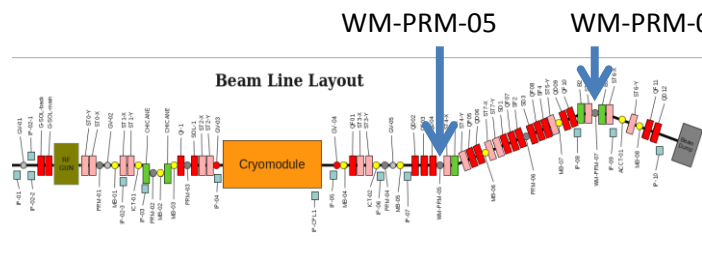
測定されたサイズ $\sigma_x = 35\mu m$ ,  $\sigma_y/P_{e0.002} = 0.2\%$ ,  $r_x = 6mm$ と仮定すると、  
Dispersionの影響を引いたサイズは $S_{\sigma_x} = S_{\sigma_x} \sqrt{1 - (r_x/P_{e0.002})^2} = 32.8\mu m$ になる。  
ほとんど影響はない。測定値が20umの場合でも、16um  
10umに較ぶらうという場合はDispersionを1-2mmに減らす必要がある。

Momentum spreadが測定できていないので、  
これを測定する場所を作る必要がある。  
(07.04.2012測定)

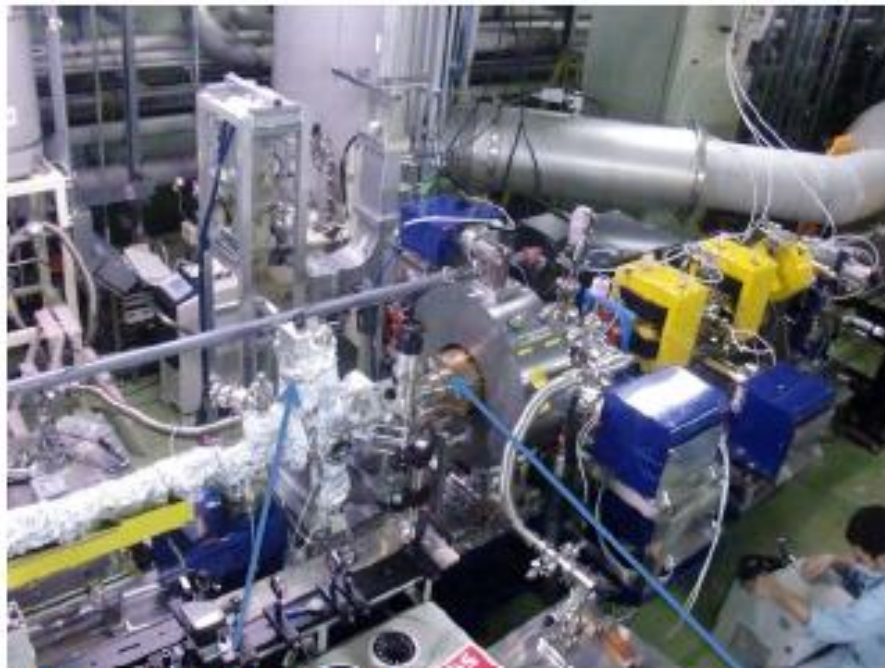


Accelerated Beam profile

## Beam Line Layout



# STF Photo-cathode RF-gun



Cs<sub>2</sub>Te photocathode  
Preparation chamber

RFgun cavity



Cs<sub>2</sub>Te  
Photocathode  
Preparation  
Chamber



Molybdenum cathode-block

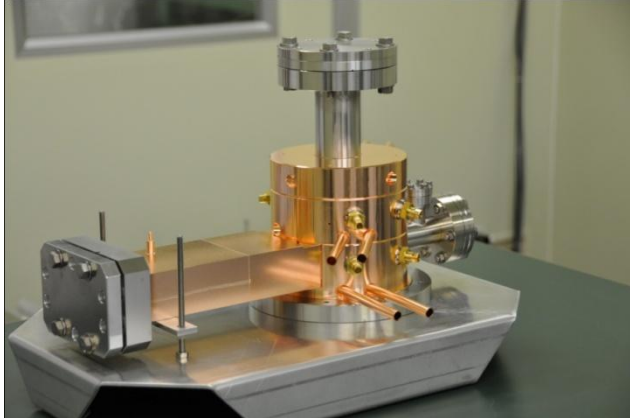


1ms beam was extracted  
from Gun

Quantum efficiency of photo-cathode  
0.5 – 1.5%

dark-current (peak)  
~300 $\mu$ A

emittance:  
reliable measurement was not yet done



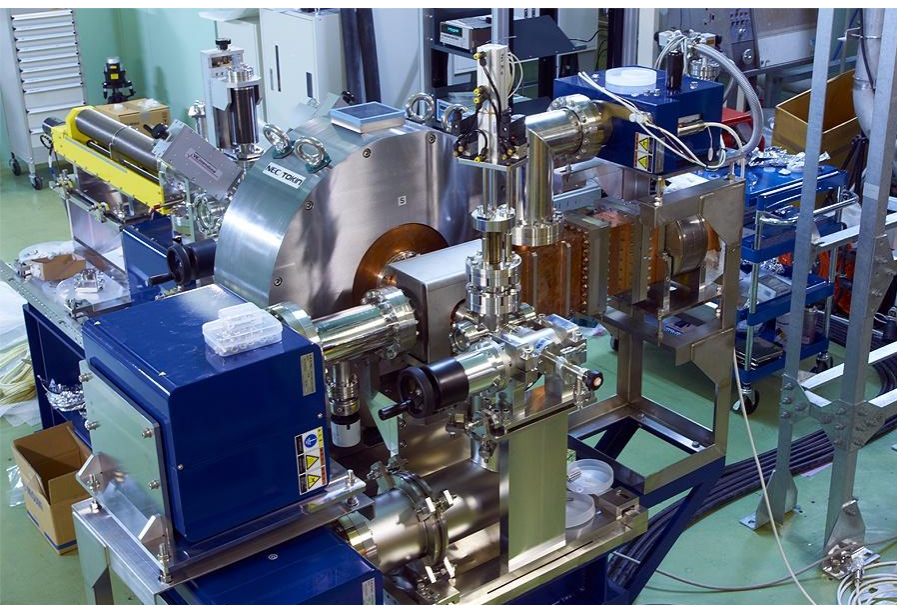
130MV/m , 6MeV S-band  
Photo-cathode RF Gun

**Duty 0.03-0.5%,  
10-100mA beam  
Av. beam power 3kW  
and 6kW**

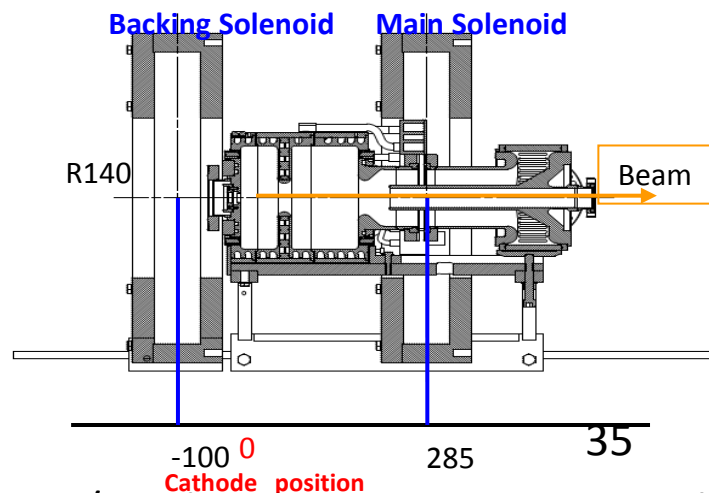


120MV/m, 10MeV S-band  
Photo-cathode RF Gun

L-band RF Gun: 大阪大学(磯山研)、広島大学(栗木研)、柏木  
及びDESY, FNALとの協力で開発している。



L-band photo-cathode RF Gun



60MV/m L-band RF Gun structure with 5MW

## 4. 今後の開発

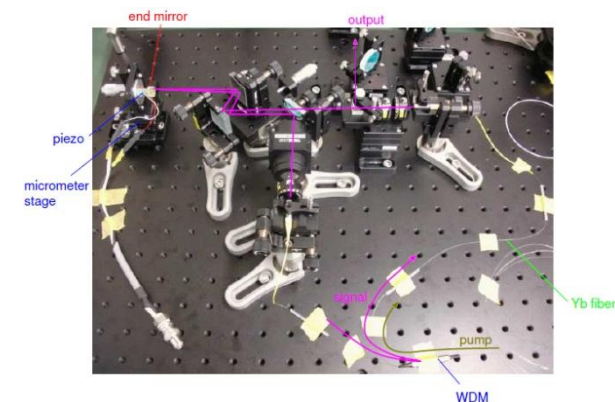
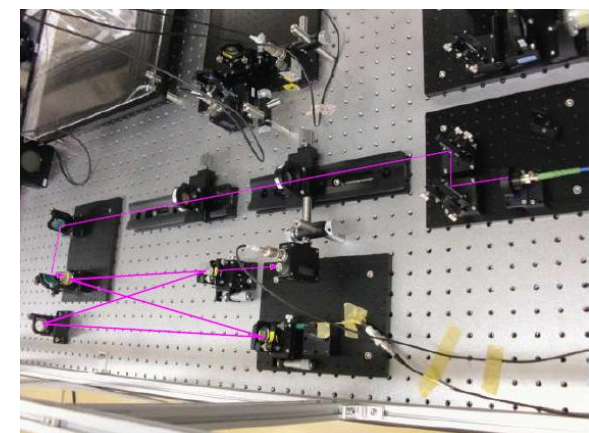
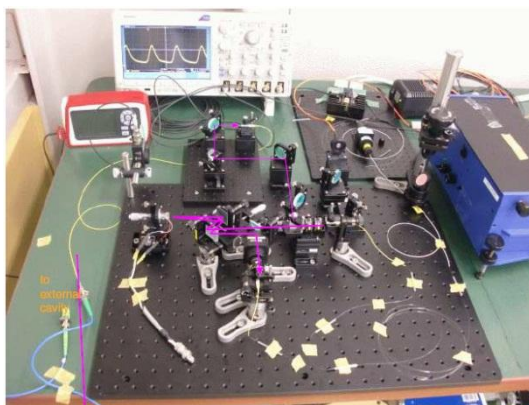
Photo-cathode用レーザーシステムを製作する。まず、Yb Fiber を使った小型試験装置を製作して、性能を確認する。

目標スペック: 繰り返しを2856MHzへ (714MHz, 1428MHz) 光共振器を導入したレーザー発信器を製作する。

Bunch chargeは50pC以下。  
(規格化エミッタンスを小さくしたい。)

Beam Loadingをある程度 Heavy にする。電子パルス内平均電流を100mA以上を想定して開発する。

電子パルス幅 $\sim 3\mu\text{sec}$ 程度  
(高効率なRF Aging、RF Sourceおよび電源サイズ等を考慮した場合、パルス幅を広げることは難しく得られる結果の意義少ない。)



## 5. 利用の為の光子ビーム生成

大学共同

1. コヒーレントパルスTHz生成とその利用
  2. 軟X線生成とその利用
  3. 硬X線生成とその利用
  4. ガンマ線生成とその利用
- 数MeV: 核燃料廃棄物診断  
数十MeV: 核変換、偏極陽電子生成  
ガンマ・ガンマ-コライダー

木米を照らす新しい光  
小型高輝度光子



最近の小型加速器

X. J. Wang 用RF Gun、上海へ。  
製作: 高富  
測定: 坂上(鷺尾研)