A few hundred femto-second soft X-ray source by several meter facility

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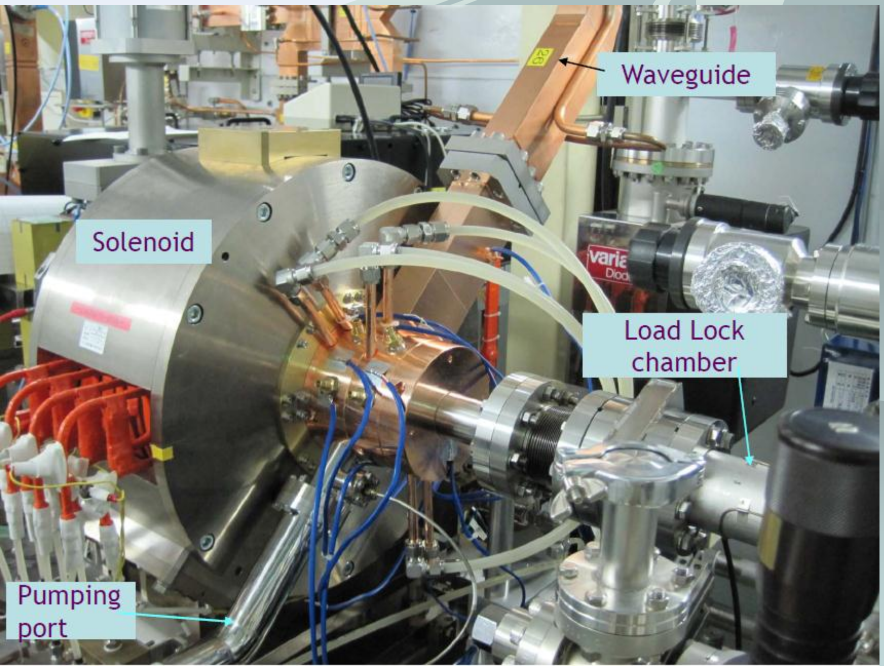
Contents :

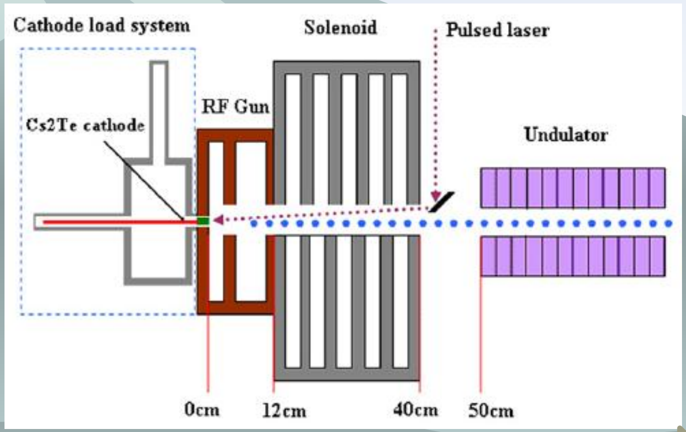
1. Introduction
2. Basic Technologies
   - 2-1. High Gradient S-band RF Gun
   - 2-2. Multi f-second Laser Pulse Train
3. Rough Evaluation by ASTRA and Genesis
4. Development Plan
5. From THz microwave to soft X-ray

1. Introduction

This presentation was stimulated by the papers of Shengguang Liu and Yen-Chieh Huang (NIM A, doi:10.1016/j.nima.2010.02.050 and APL, doi:10.1063/1.3447928)

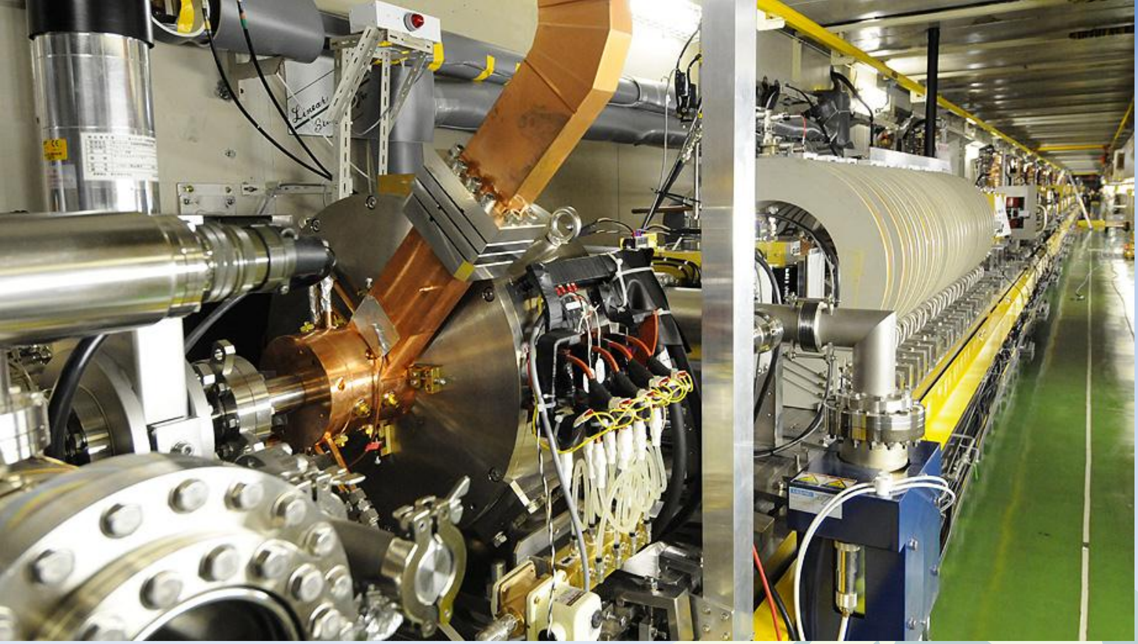
Terahertz radiation is an electromagnetic wave in the frequency interval from 0.3 to 10THz, which is a scientifically rich, but technologically limited frequency band.
A THz-FEL is a good candidate due to its characteristics of high peak brightness, short duration, and tunable wave length.
However, the need for a huge facility and substantial funds limit THz-FEL development.
Two important goals are to make the THz-FEL facility compact and to increase its output radiation power. **Then, I propose several hundred femto-s soft X-ray source facility.**





Less than 2m

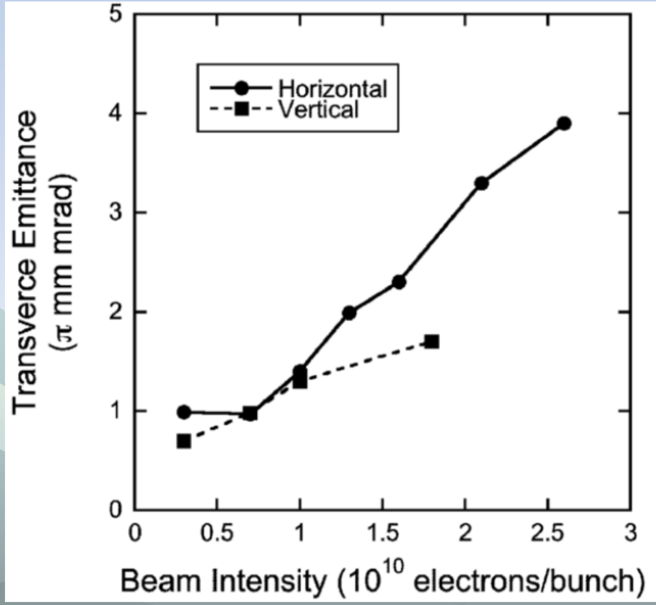
THz Peak power :10MW to 100MW



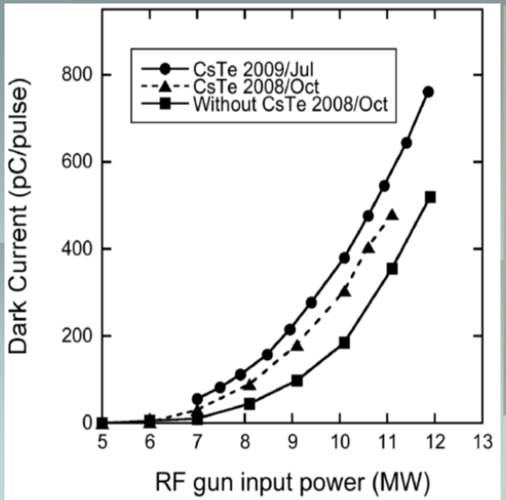
2. Basic Technologies

2-1. High Gradient S-band RF Gun

1.3GeV ATF Linac, results at 80MeV beam.



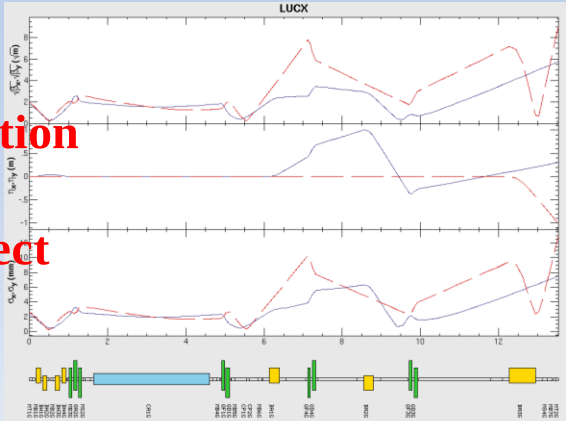
A laser-driven RF gun with a **Cs_2Te photocathode** has been developed at KEK **since 2002**. This gun has been operated as an electron source for the ATF and generates a beam with an operational intensity of up to **2×10^{10} electrons per bunch**. In 2008, a new gun incorporating all of the earlier modifications was produced for the ATF. Tests have confirmed a significant improvement of the Q value of the latest model. A typical transverse emittance of **1.3 π mm·mrad at 80 MeV** has been obtained under the following conditions: solenoid field of 0.18 T, beam intensity of **1×10^{10} electrons per bunch**, and **RF power of 9 MW**.



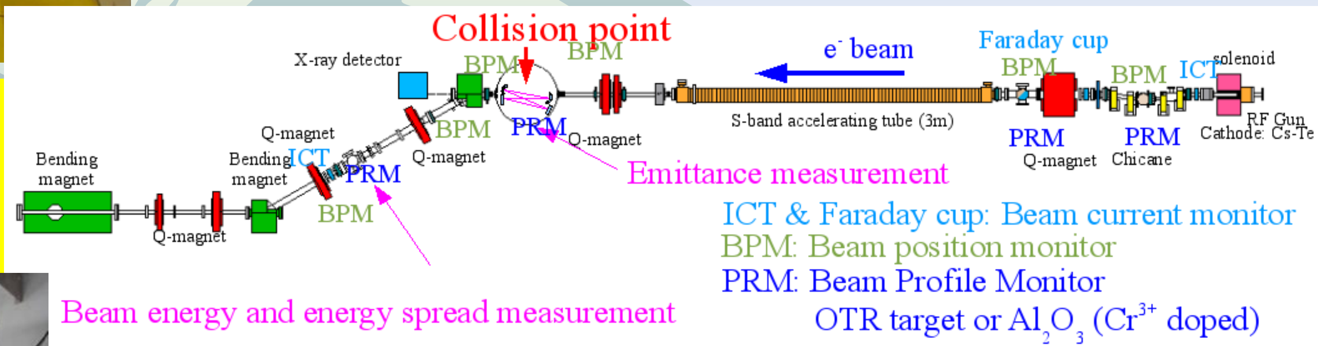
Advanced Accelerator Facility from 2008 to 2012 for Quantum Beam R&D

Multi-bunch electron beam generation, pulse laser accumulation system Upgrade, R&D of precise multi-collision control will be done using this normal conducting facility by end of March 2012.

Imaging for X-ray Application Experiments will be taken and possibility of this project will be confirmed soon.

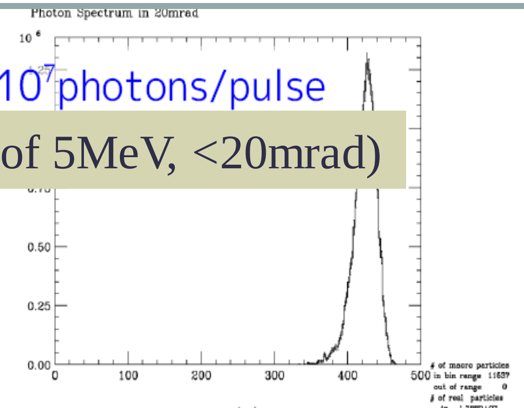


Maximum Energy 50MeV
Maximum Beam Power
156.26MeV μA



Laser parameter

wavelength	1064nm
Intensity	10mJ/pluse
Pulse width	7ps
Beam size (σ_x, σ_y)	8μm, 8μm

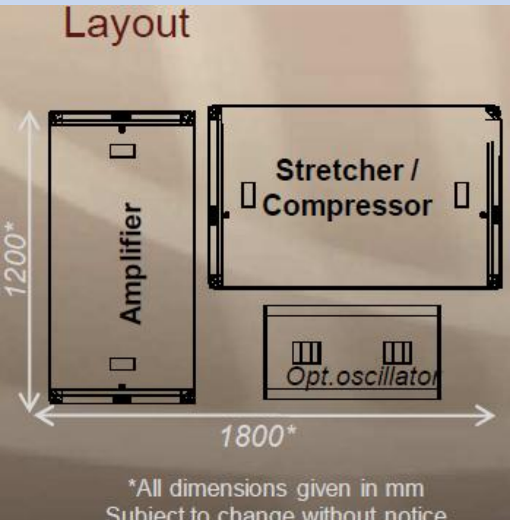


Nx=1.8x10^7 photons/pulse

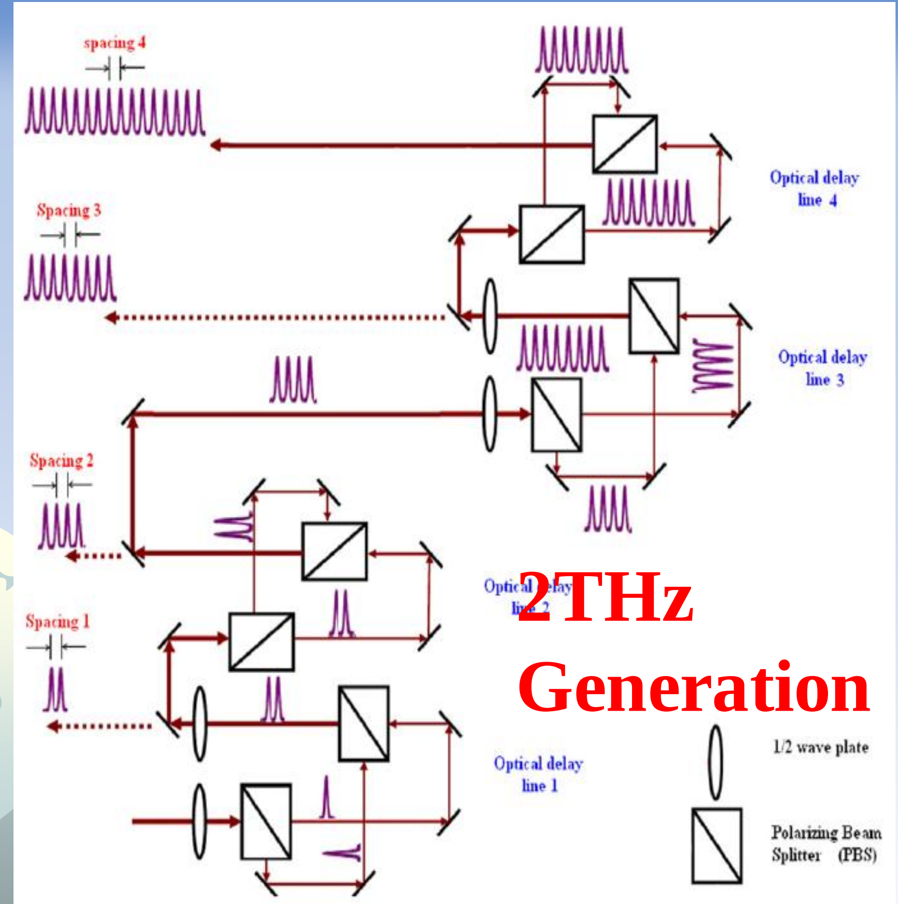
(In the case of 5MeV, <20mrad)

2-2. Multi f-second Laser Pulse Train

CPA Titanium-Sapphire laser system to generate 1 μJ/pulse at 800nm in the range from 20 to 100fs: Aurora(1mJ) or Trident laser system of Amplitude Technologies, multi-bunch beam generation is possible due to enough laser power.



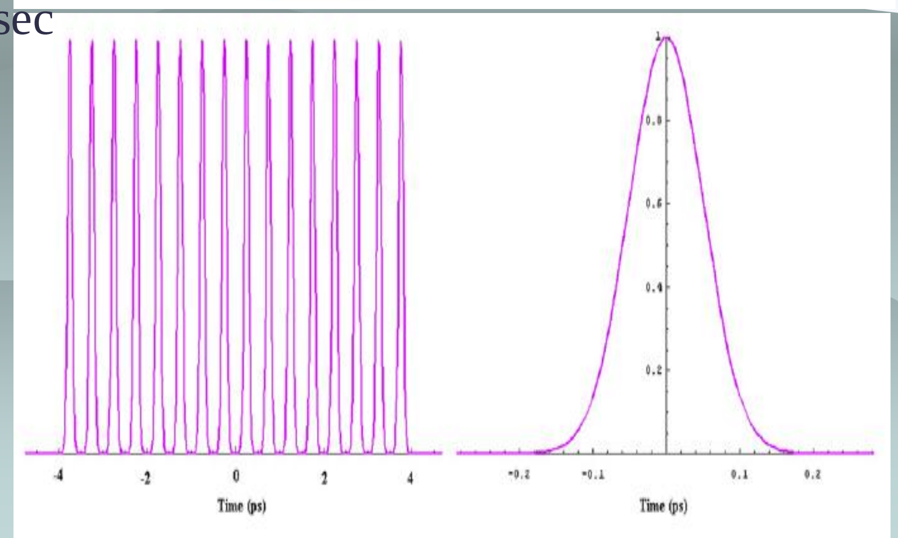
½ plate rotates S-wave by 45 degrees. PBS makes S-wave and P-wave by reflection and transmission. Repeated 4 times with delay of about 500 fs. Then, we got 16 micro-bunched laser within 8 psec



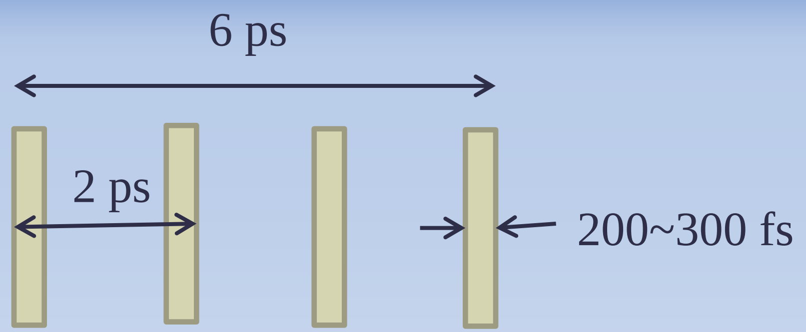
2THz Generation

Performances

Model	Trident X	Trident C	Trident M
Rep. rate	10 Hz	100 Hz	multi-kHz
Energy	Up to 25 mJ	Up to 4 mJ	Up to 3 mJ
Pulse duration		Down to 30fs**	
ASE contrast		$> 10^5$:1	
M^2		< 1,3	
Stability (% rms)	< 1,5% rms	< 1,2% rms	< 0,8% rms



Essential points :
Pre-bunched FEL,
Dynamical bunching in RF gun cavity which means faster laser injection phase less than 20 deg.,
Micro-bunch spacing should be matched to wavelength,
Late micro-bunch makes the bunching of former micro-bunches in resonated Undulator.



Time structure of 4 micro laser train for 500GHz super radiation from Undulator

500GHz microwave generation

Problem: beam loading effect due to multi micro-bunch and tuning on undulator field by pole-gap which makes the FEL resonance.

If we accept low micro-bunch charge, say 100pC or less, and not many micro-bunch, say 10 or less, above problems can be overcame.

We assume the time response of Cs_2Te cathode is same as Cu cathode and 0.2% QE at least.

We try to generate total single bunch charge 50pC and conversion efficiency from 800nm to 266nm by nonlinear crystal:10% may be possible.

Necessary number of photons: 7E11/pulse
Laser pulse energy:0.5μJ

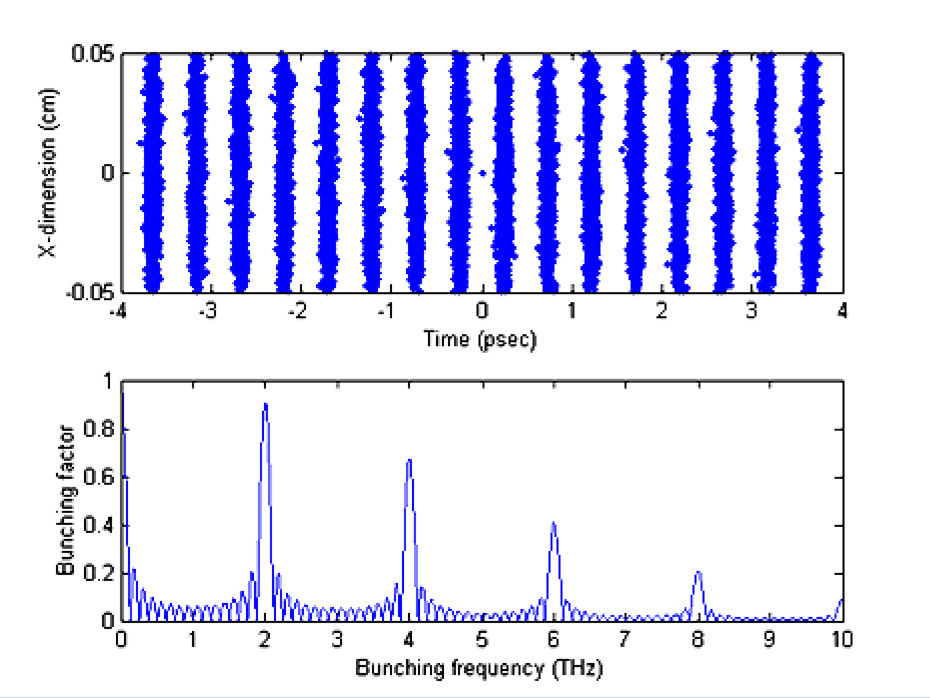
3. Rough Evaluation by ASTRA and Genesis

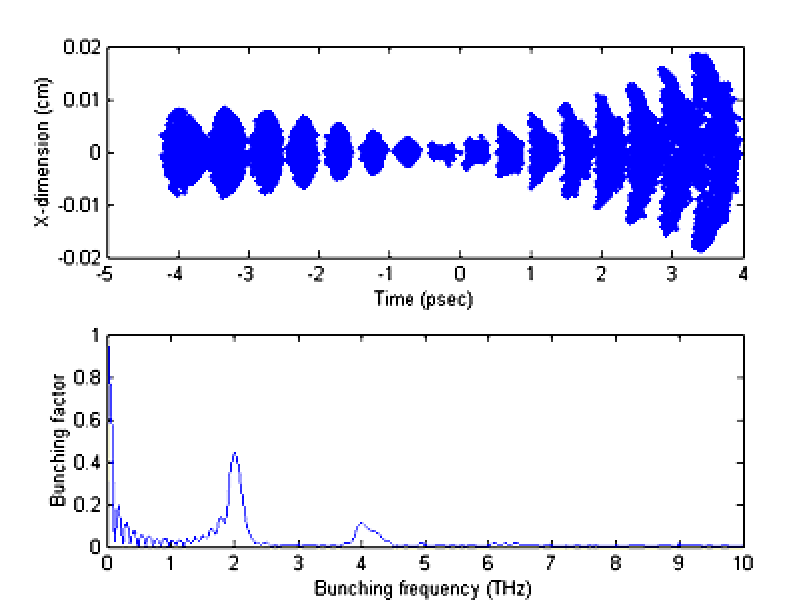
Astra (**A** **S**pace Charge **Tr**acking **A**lgorithm) by K. Flottmann (DESY)
Genesis by Sven Reiche (PSI)

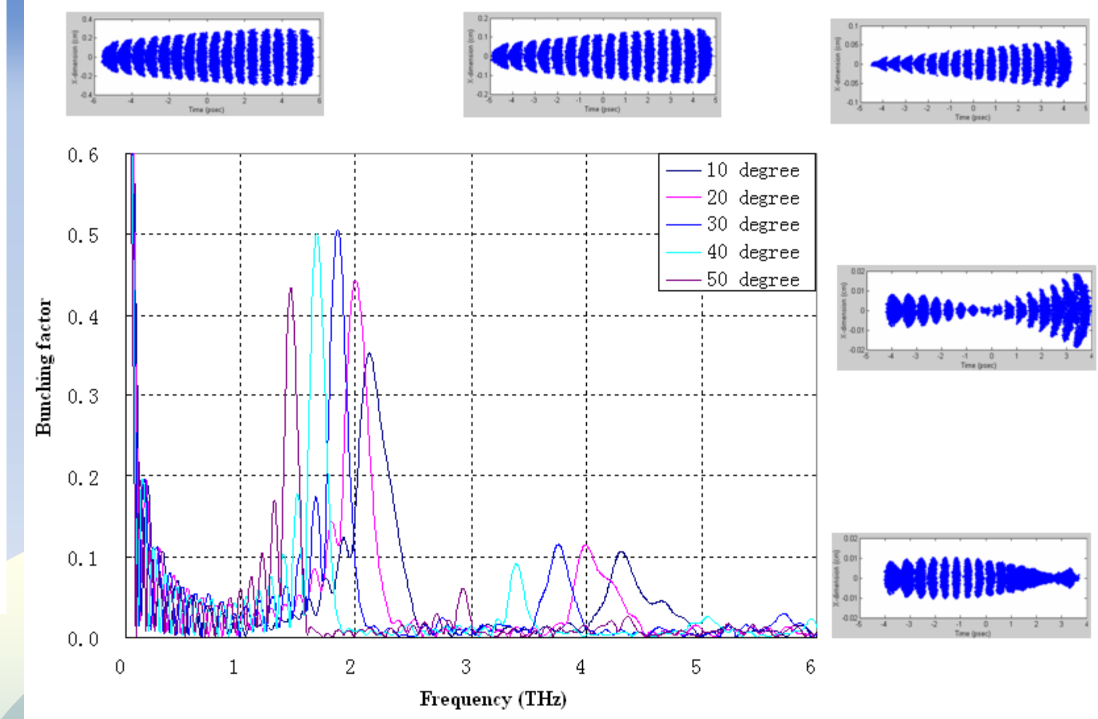
We assume the peak RF field gradient at the cathode surface is 100MV/m, 200pC and the laser injection phase is 20 degree.

The bunching factor at 2THz is still high ,0.446 at the wiggler entrance, see next figure.

$P=P_1[N_e + N_e(N_e-1)B(f)]$,
$B(f)=\sum \exp(i2\pi f z_j/c)/N_e$,
$\lambda_r=\lambda_w(1+K^2)/(2\gamma^2)$



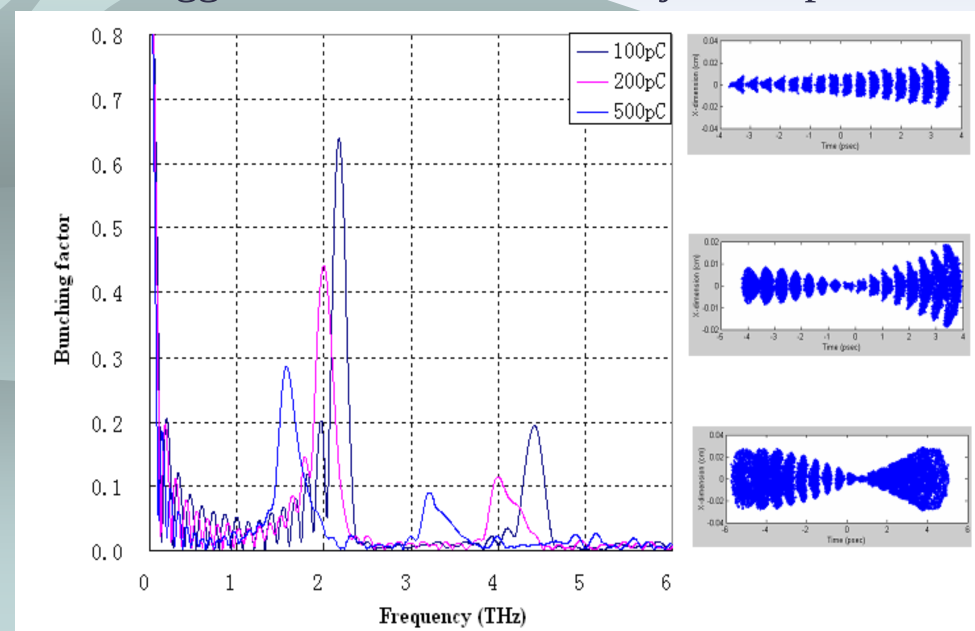




Above shows bunching factor dependence at the wiggler entrance on laser injection phase.

Right figure shows bunching factor dependence on total charge assuming Micro-bunch charge is uniform.

We need higher gradient acceleration, lower total charge and about 20 degree laser injection phase to keep a high bunching factor.

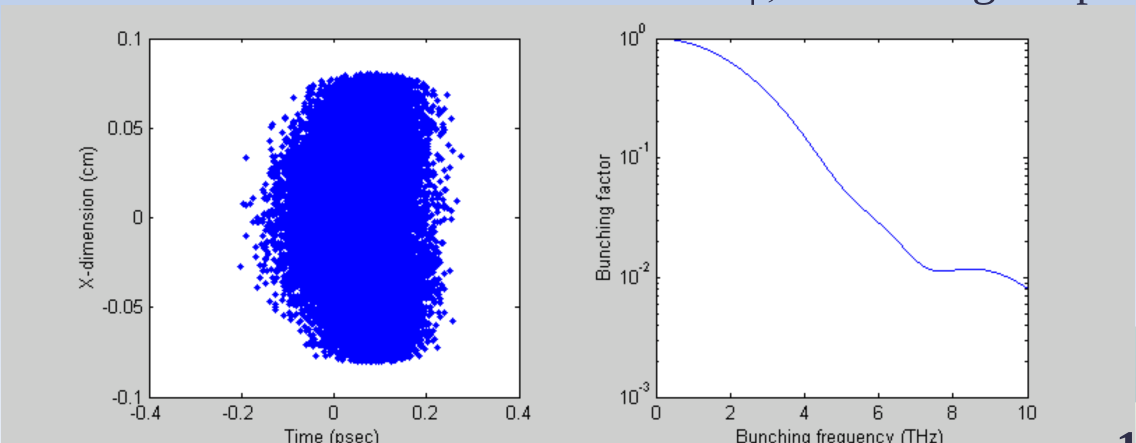


For example, we assume the peak field gradient at the cathode surface is 120MV/m and laser injection phase 20 degree. Then, electron beam energy is 5.68MeV.

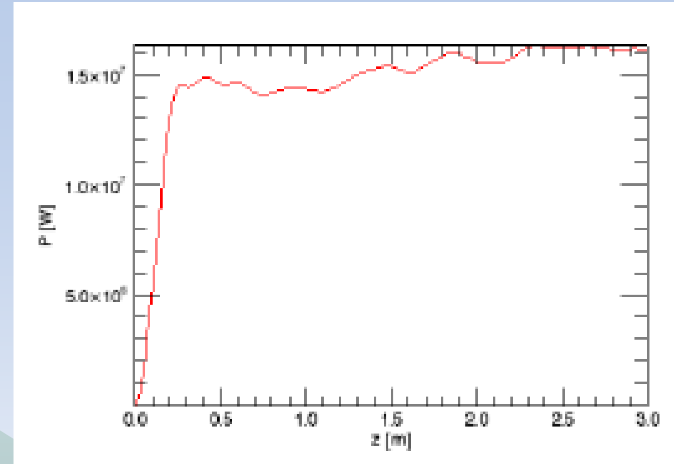
Also, we consider the wiggler period length 30mm and 2THz radiation (wave length 150μm).

g=12, K=0.873

Uniform laser size on cathode 1.0mmϕ, total charge 25pC



170 fs (FWHM), peak current=147A



14 MW peak power at 0.3m position

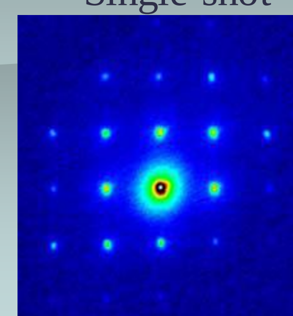
My colleague, Prof. Yan of Osaka University, demonstrated the generation of 100fs single electron bunched beam and obtained the single-shot Ultrafast Electron Diffraction (UED) using our RF gun cavity. In this experiment, the time resolution was 20fs in sigma.

Electron beam:
3 pC, 3 MeV,
10 Hz operation

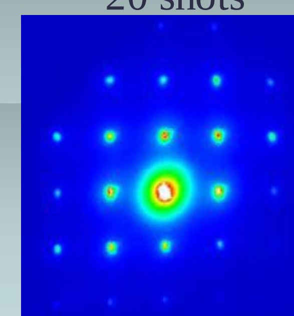
Sample:
~180nm-thick
single-crystal Si

The single-shot measurement was succeeded

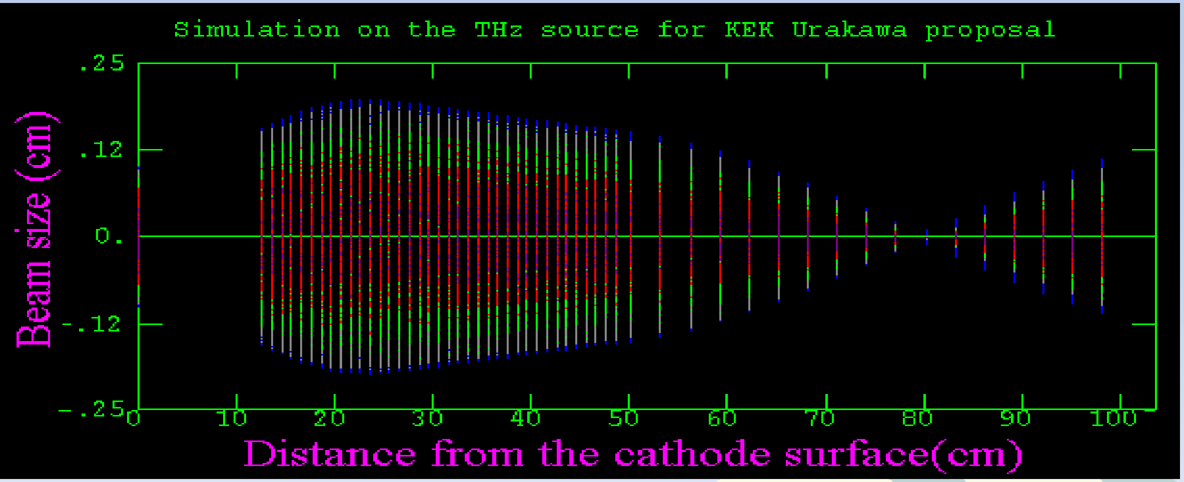
Single-shot

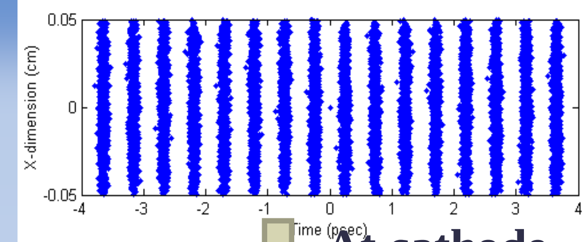


20 shots



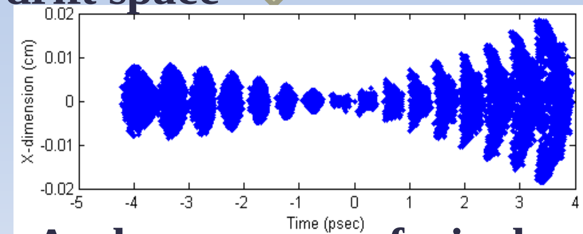
Simulation results



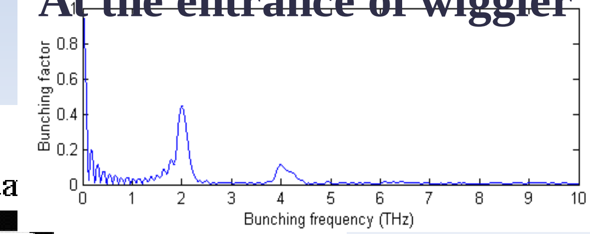


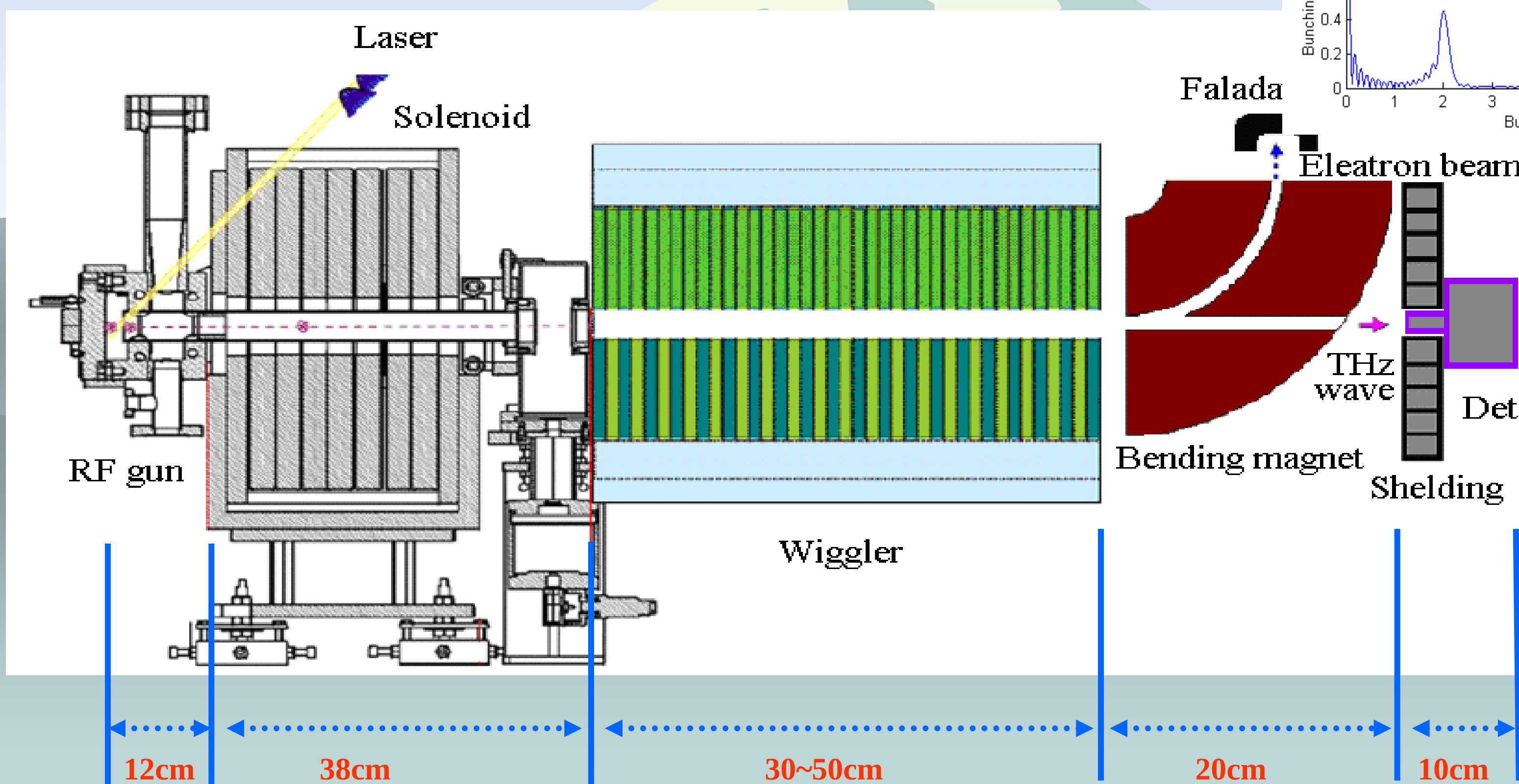
At cathode

38cm drift space

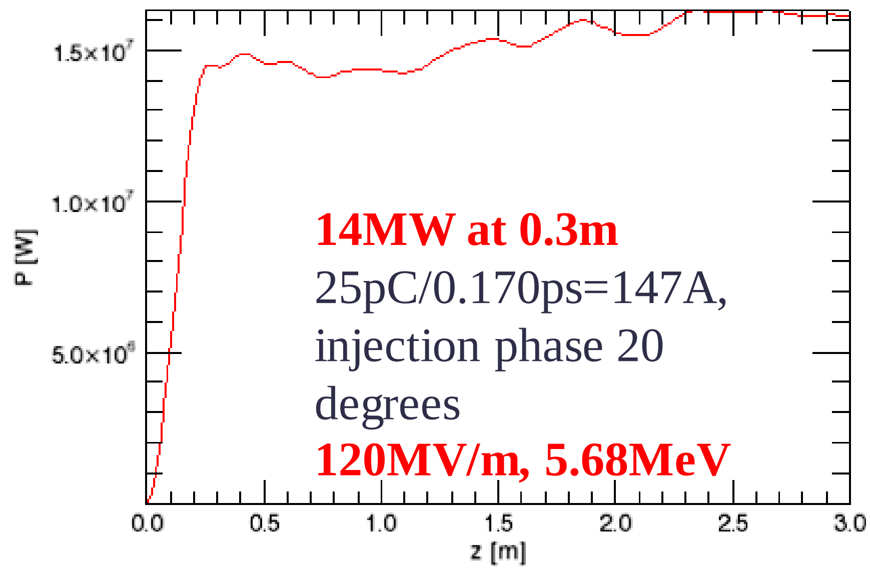


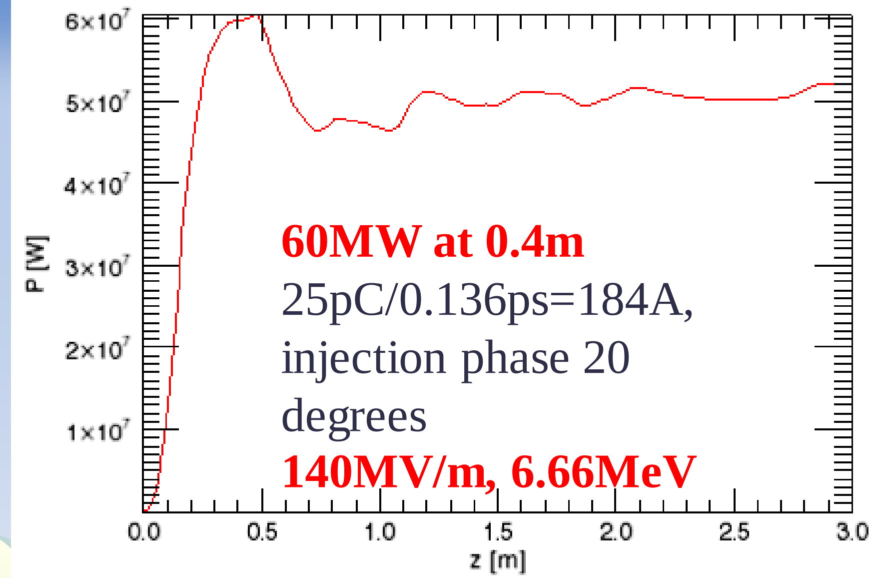
At the entrance of wiggler





0.68MW at 0.4m 12.5pC/0.214 ps=58A, injection phase 20 degrees, **100MV/m, 4.7MeV**





$P=P_1[N_e + N_e(N_e-1)B(f)]$, $B(f)=\sum \exp(i2\pi f z_j/c)/N_e$,

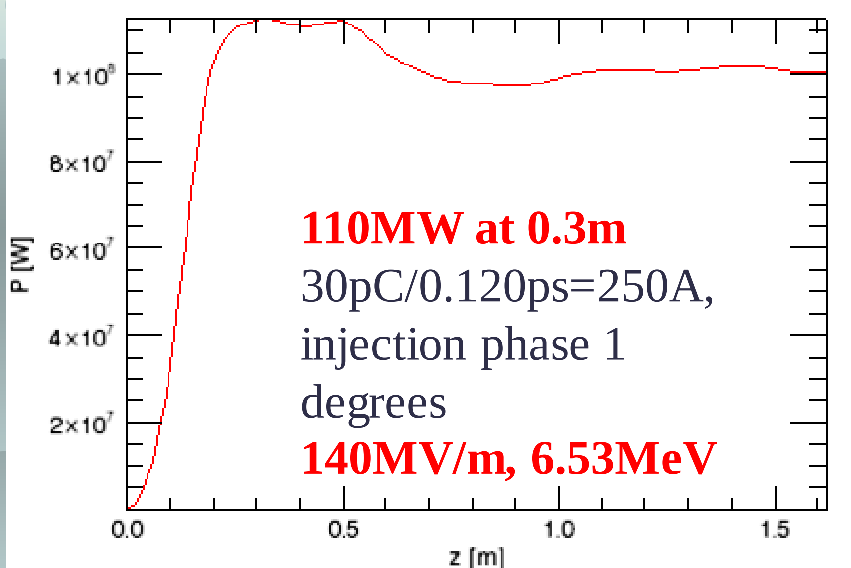
$\lambda_r=\lambda_w(1+K^2)/(2\gamma^2)$, K: tune the gap to make the resonance.

High gradient acceleration: shorter bunch length

(100MV/m-→140MV/m)

earlier laser injection phase: high bunching factor

High Peak Power radiation(20-→10-→1)



THz peak power 100MW generation will be possible.

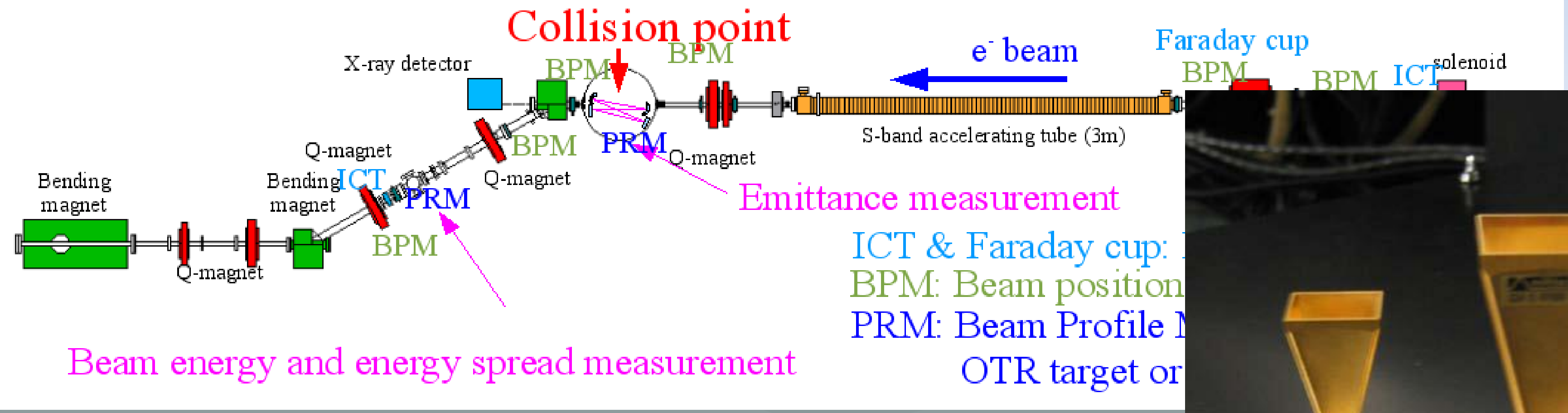
High gradient acceleration gun is essential.

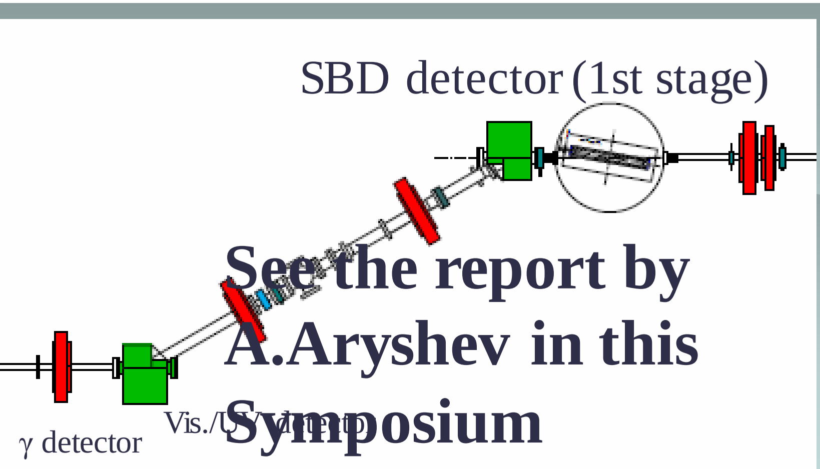
100μJ/pulse THz source will be 1mJ-fs laser

We have to take care the shielding effect to CSR, maybe.

4. Development Plan

I want to demonstrate the generation of ~500fs electron beam by measuring THz CDR in JFY2012. Anyway, we are developing micro-wave detector for sub-THz power measurement. Generation of multi-trains of 500fs THz wave is very useful for life science.

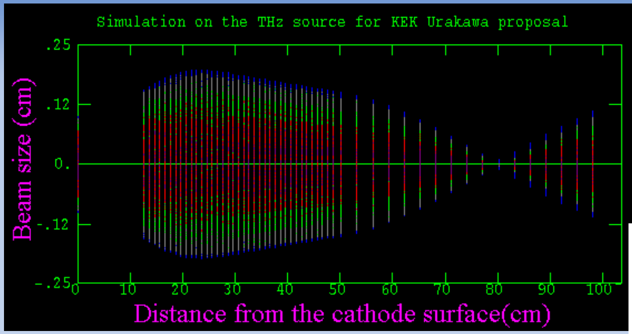


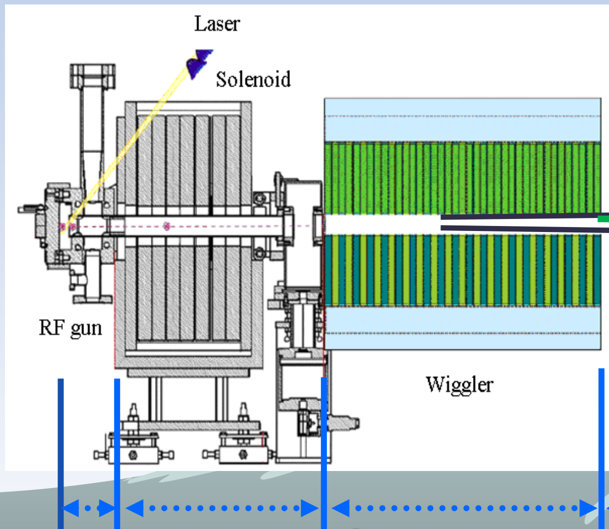


See the report by A.Aryshev in this Symposium

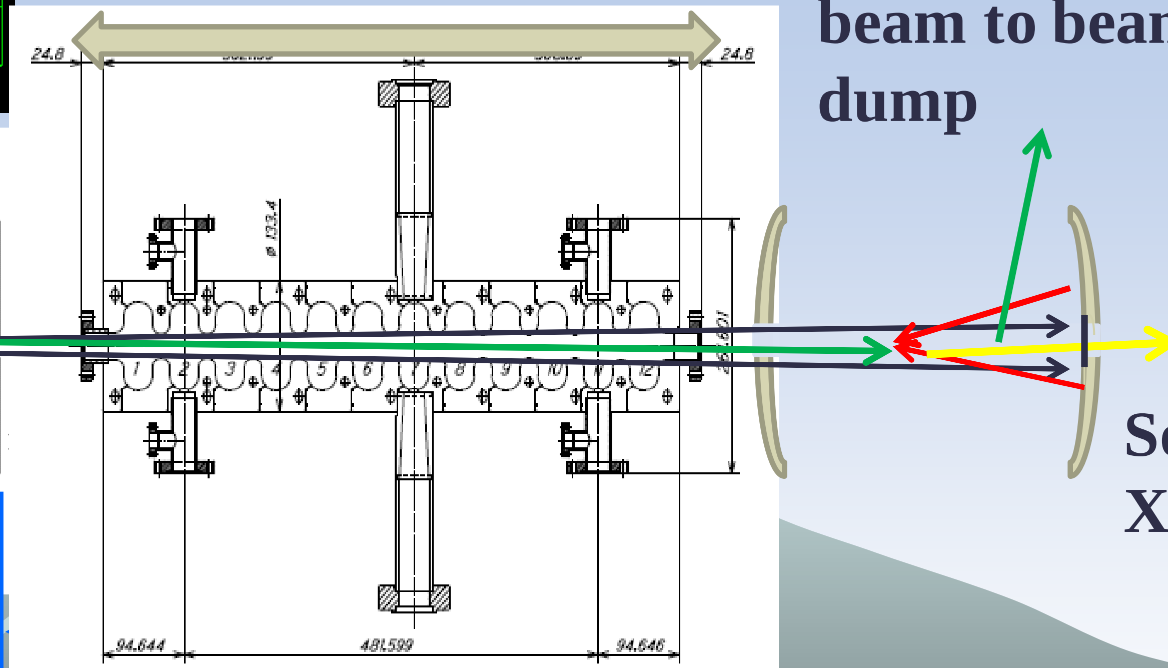
SBD detector development at LUCX : Measuring micro-wave around 100GHz

5. From THz microwave to soft X-ray





72cm

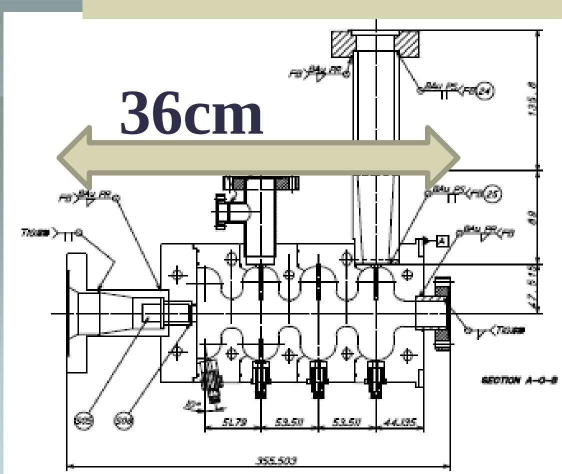


50MeV electron beam to beam dump

Soft X-ray

S-band 12 cell booster linac to get 50MeV.

36cm

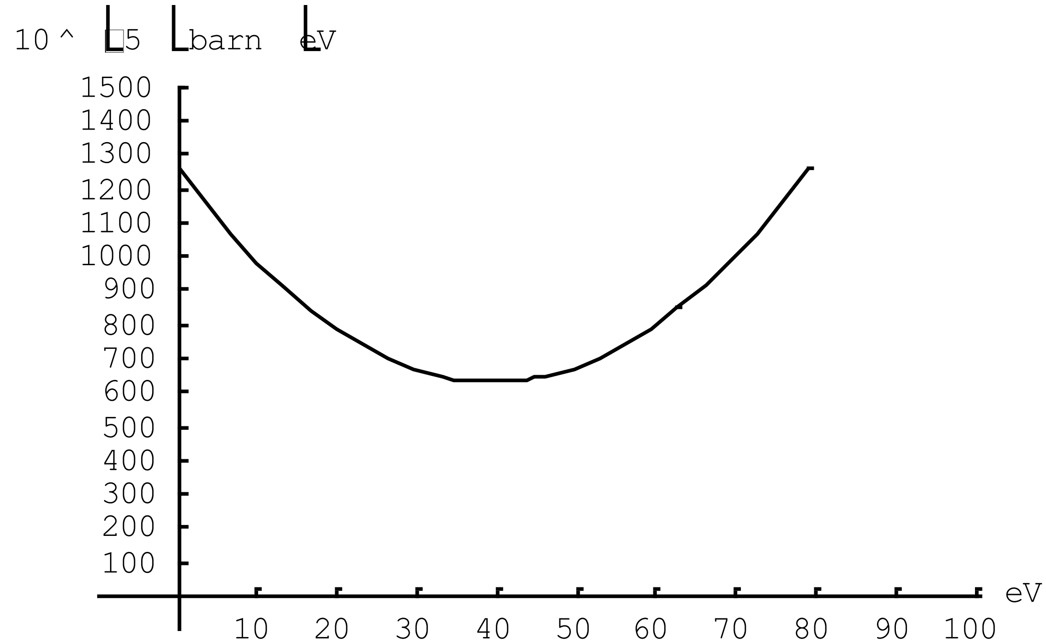


S-band 3.5 cell RF Gun ~ 10MeV

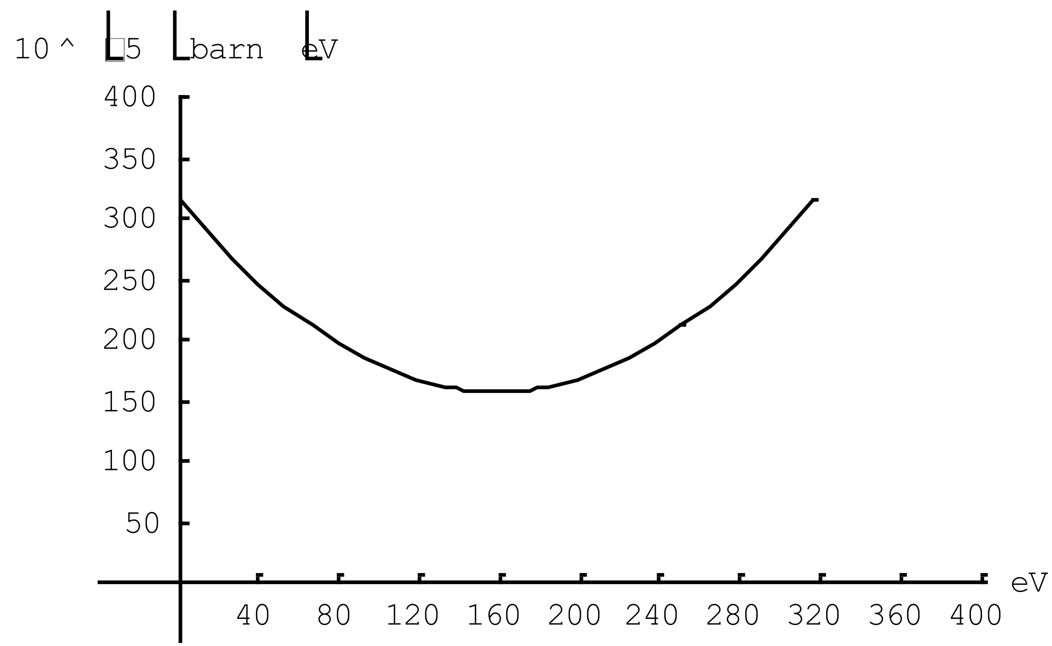
Total length is less than several meters including other necessary devices.

Rough estimation of Soft X-ray yield.

10THz microwave Generation is very Interesting but very Challenging.



3.5x10^{6} photons/sec·10% b.w. at 0.5THz



7.5x10^{6} photons/sec·10% b.w. at 2THz

Medical linear accelerator for Intensity Modulation Radiotherapy (IMRT)

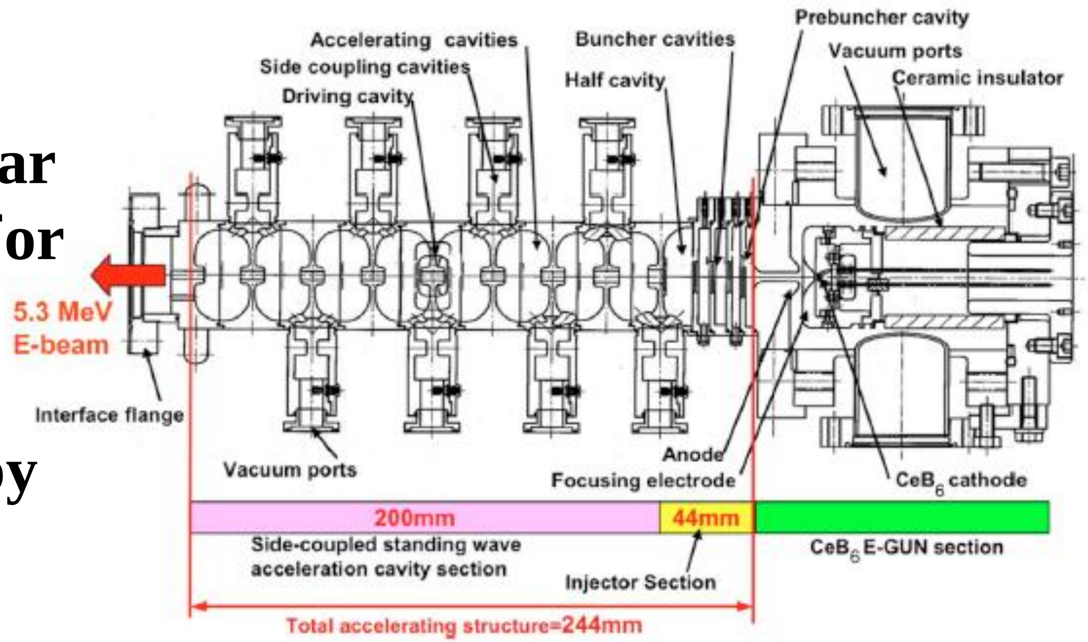
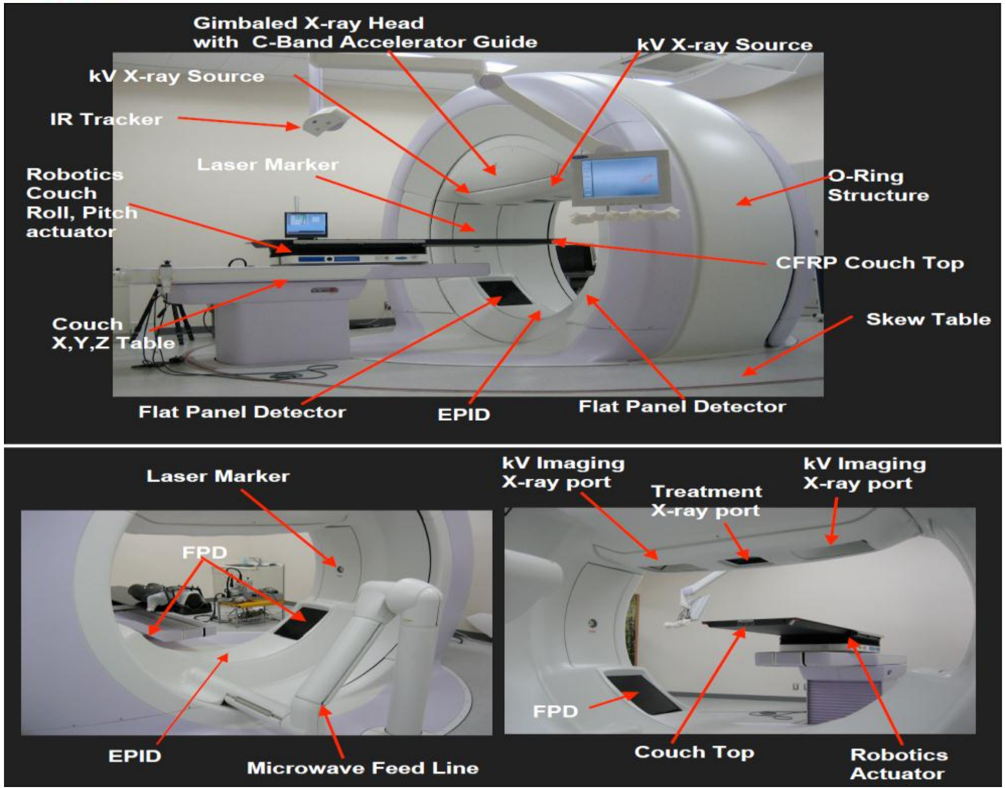


FIG. 3. The accelerator guide is composed of the electron gun section with a CeB_6 cathode, an injector section, and a side-coupled standing wave acceleration cavity section.

Commercial available medical linac produced by Mitsubishi heavy Industry Co., which is a four-dimensional image-guided radiotherapy System (4D IGRT).

Total length of 5.3MeV linac is less than 50cm.



Electron beam	Laser pulse	Collision condition	10% bandwidth X-ray rate [Hz] (Calc.)	Detected X-ray rate
40MeV, 100bunches/pulse, 12.5Hzoperation, bunch charge=0.4nC, 2.8nsec bunch spacing, σ_{ez}=6psec	0.112mJ/pulse, 357MHz burst mode operation in cavity, σ_{lz}=3psec	σ_{ex}/σ_{ey}=200/40μm , σ_{1x}/σ_{1y}=30/30μm, Crossing angle 20deg.	$1.34x10^5$	$1.2x10^5$Hz/10%b.w.~ 10^6Hz/10%b w.
500bunches/pulse, bunch charge=0.5nC、etc. Same above	1.12mJ/pulse, 357MHz burst mode operation in cavity	σ_{ex}/σ_{ey}=60/30μm, σ_{lx}/σ_{ly}=30/30μm,etc. same above	$6.6x10^{6\sim7}$	By 2011.11.30
Same above	Same above	Crossing angle 10deg.	$1.2x10^7$	cancelled
8000bunches/pulse, etc. Same above	Same above	Same above	$3.3x10^8$	
Same above	Same above	Head-on	$9.4x10^8$	From 2011.12
Same above	Same above	σ_{ex}/σ_{ey}=10/10μm, σ_{1x}/σ_{1y}=20/20μm	$8.5x10^9$	
Same above	10.2mJ/pulse, 357MHz burst mode operation in cavity	Same above	$8.5x10^{10}$	By 2012.3