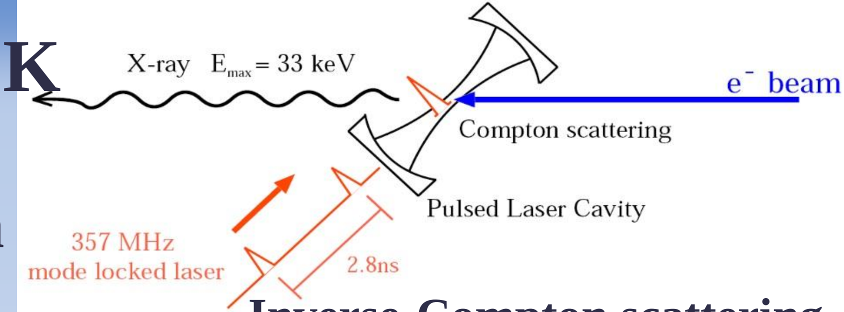
Recent Activities for photon beam generation at KEK based on Inverse Compton

Indo-Japan school on Advanced Accelerators for Ions and Electrons,
16-18 February 2015, at IUAC

KEK, Junji Urakawa

1. Laser-Compton activities at KEK
2. Development for enhancement optical cavity
3. Future Plan and Schedule

1.Laser-Compton activities at KEK



Inverse-Compton scattering

To stronger and brighter photon beam

$$Brightness = \frac{photons/\sec}{(\mathrm{mrad})^2(\mathrm{mm}^2(source-area))(0.1\%\ spectrum-width)}$$

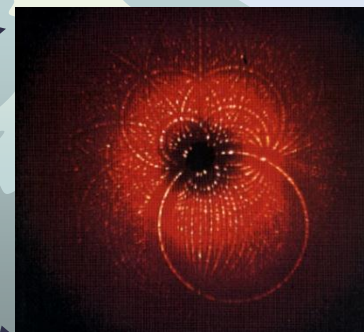
10μm photon source is considered, which means **0.3 mmmrad normalized e-beam emittance**.
1mrad angular spread collimation means small energy spread.

Diffraction pattern

Low brightness X-ray

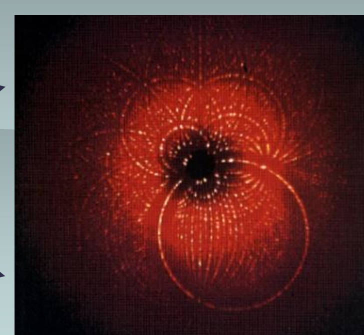
Large sample

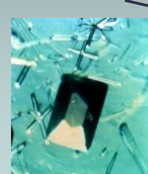
Diffraction



High brightness X-ray

Small sample (< 1mm)





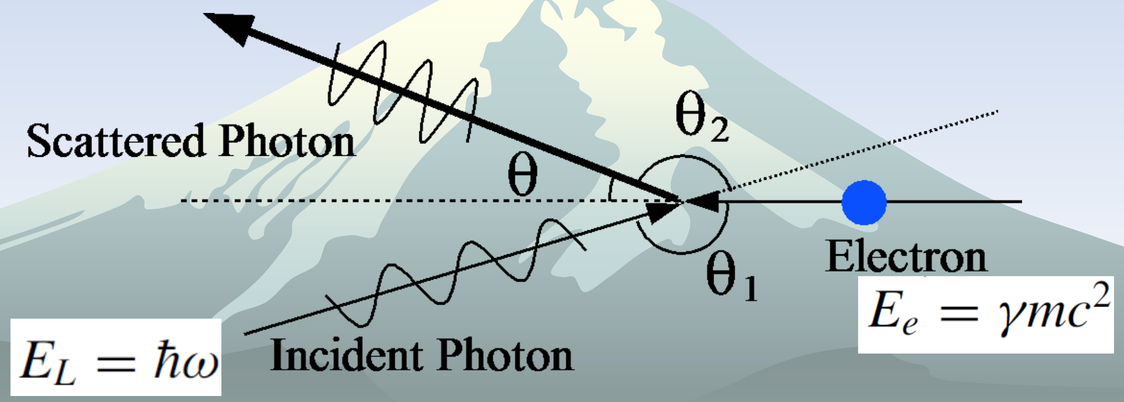
Protein crystal

Smaller source is realized by focusing laser beam and electron beam at IP.
We have to supply low emittance and high intensity electron beam.
Our target is Average Brightness 10^{16} Photons/sec/mm^{2}/mrad^{2} in 0.1%b.w.

Quantum beam : particle beam = electron, proton, ion, neutron

electro-magnetic wave = THz ~ x-ray → γ-ray

γ beam generation based on laser Compton scattering



Details : Klein-Nishina Formula

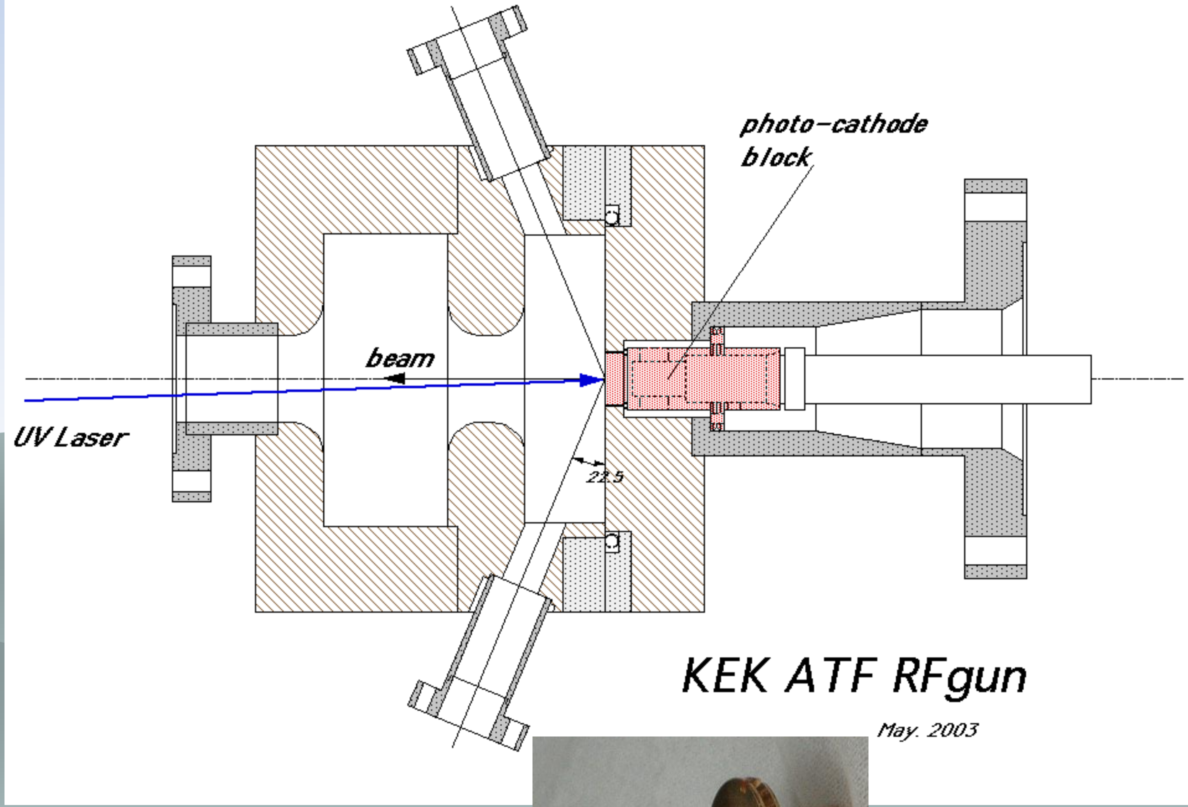
$$E_\gamma \simeq \frac{4\gamma^2 E_L}{1 + (\gamma\theta)^2 + 4\gamma E_L/(mc^2)}$$

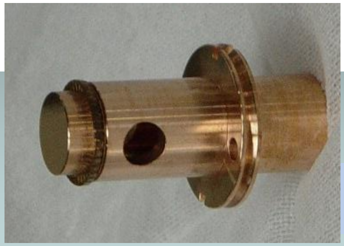
Approximated formula in the case of head on collision.

- monochromatic
- energy tunable
- cone beam
- short pulse

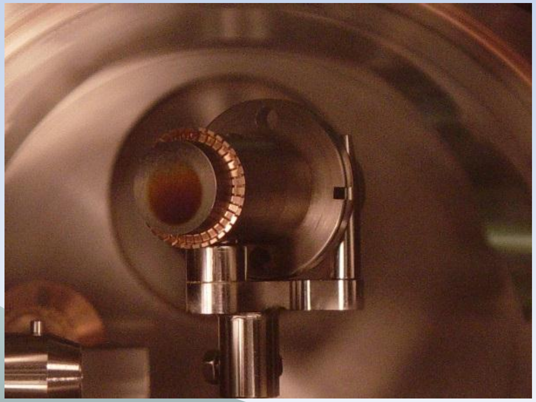
Since we consider the generation of short bunched electron beam and high RF gradient acceleration, short pulse laser to generate photo-electron bunch in the cavity is necessary for the generation of high quality electron beam.
It is a photo-cathode RF gun.

RF-gun cavity & cathode block

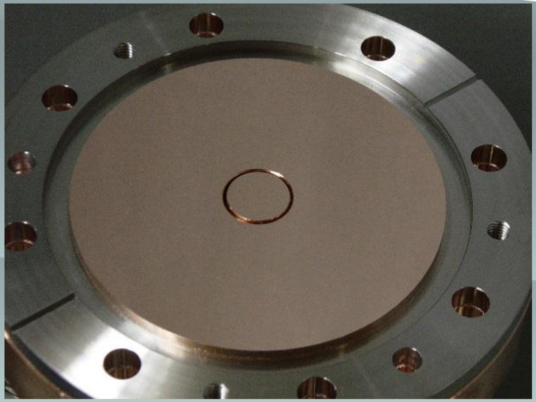




Cathode block

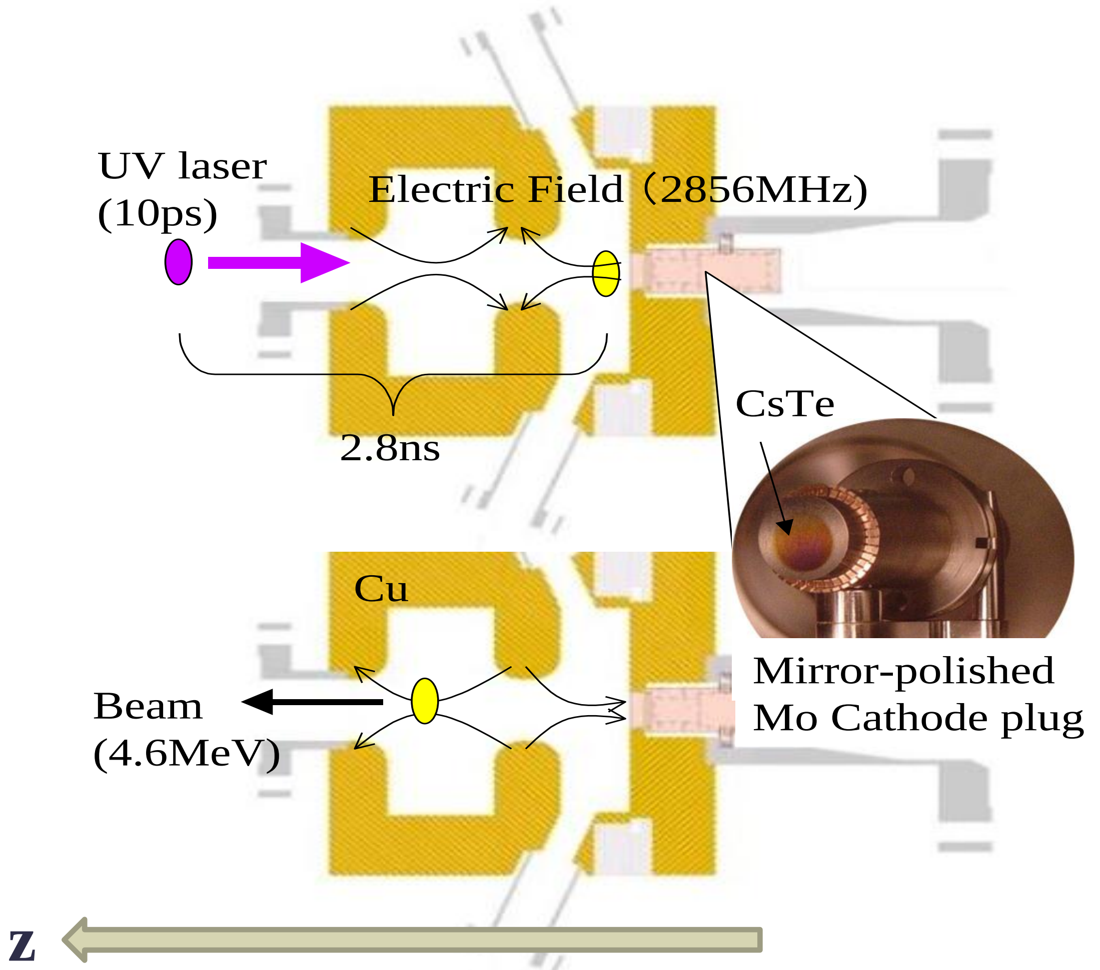


Cathode block with Cs_2Te coating



End plate with cathode block

Photo-cathode RF Gun



Laser pulse with the pulse duration of 10psec(FWHM) is irradiated on Cs_2Te thin film photo-cathode. Figures show 1.6cell-2856MHz RF cavity and an electron bunch accelerated in the cavity.

Ignore z dependence of ϕ : γ is beam energy. ϕ is relative phase.

$$\frac{d\gamma}{dz} = k\alpha[\sin\phi + \sin(\phi + 2kz)]$$

$$\gamma = 1 + \alpha[kz\sin\phi + \frac{1}{2}(\cos\phi - \cos(\phi + 2kz))]$$

Highest accelerating field : 130MV/m
Laser pulse injection phase : 30 degree
Horizontal axis is beam direction in the cavity [m].
Vertical axis is gamma factor.

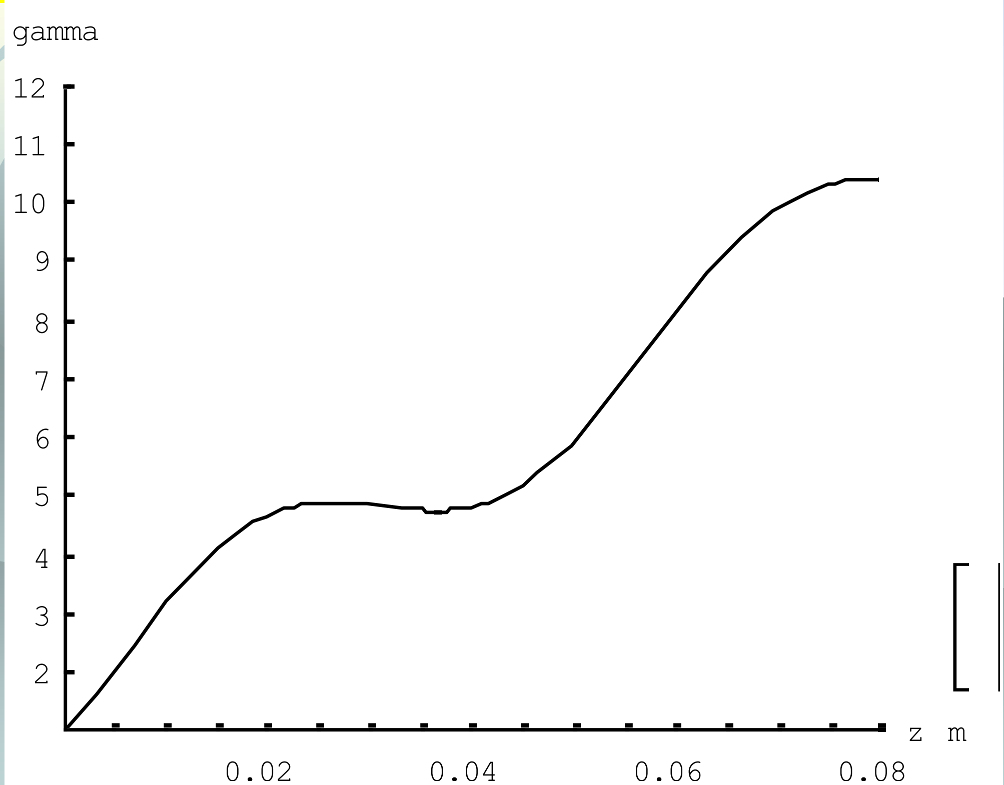
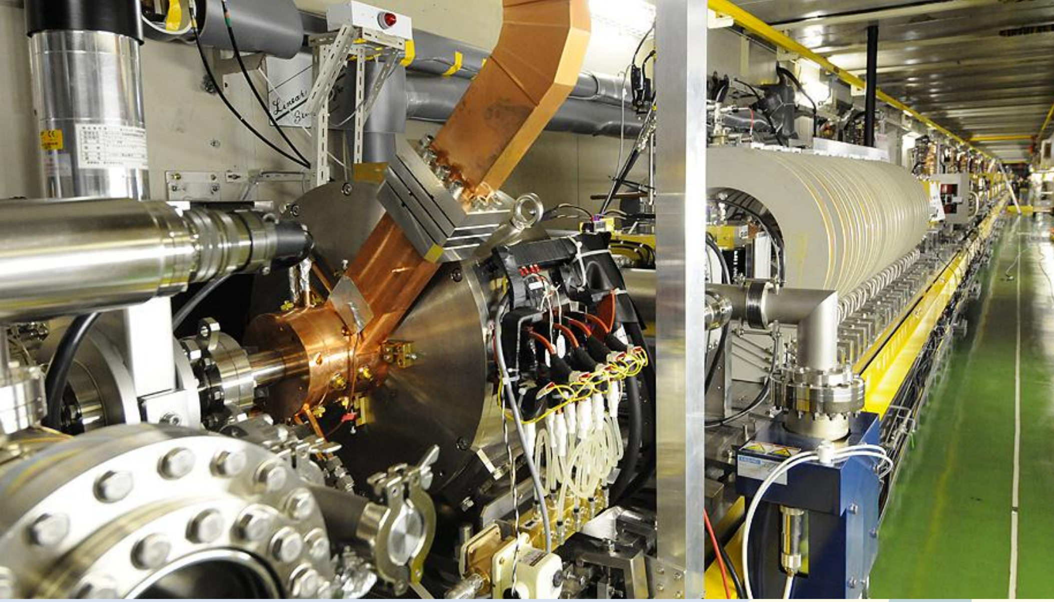
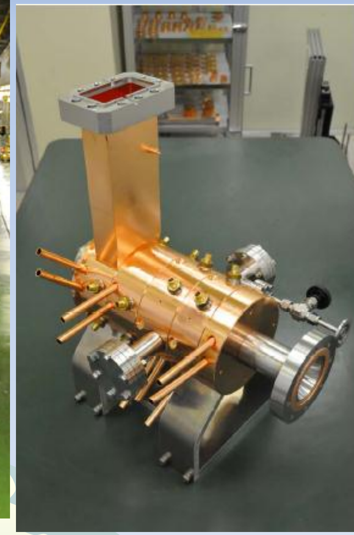


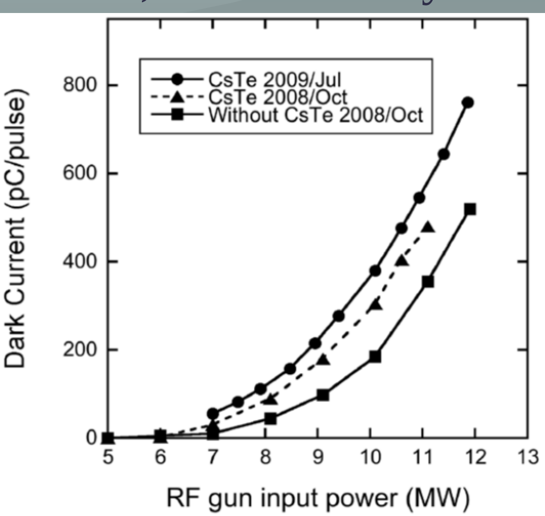
Photo-cathode RF Gun

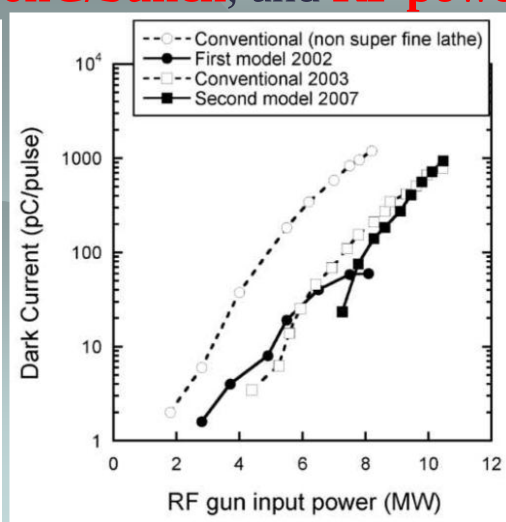


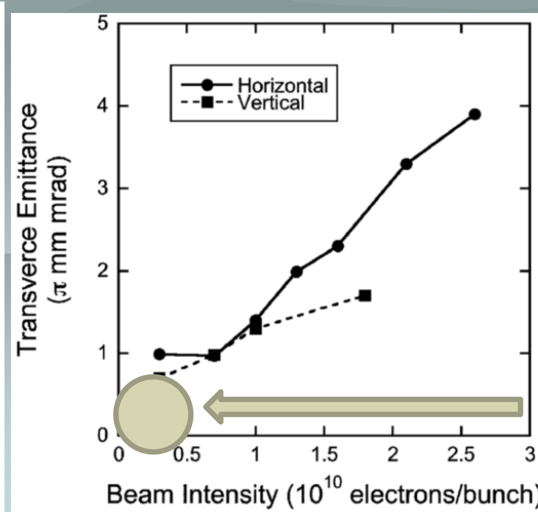


1.3GeV ATF Linac, results by 80MeV beam. **10MeV 3.6 cell gun** **6MeV 1.6 cell gun**

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 π mm·mrad** has been obtained under solenoid field of 0.18 T, beam intensity of **1.6nC/bunch**, and **RF power of 9 MW**.

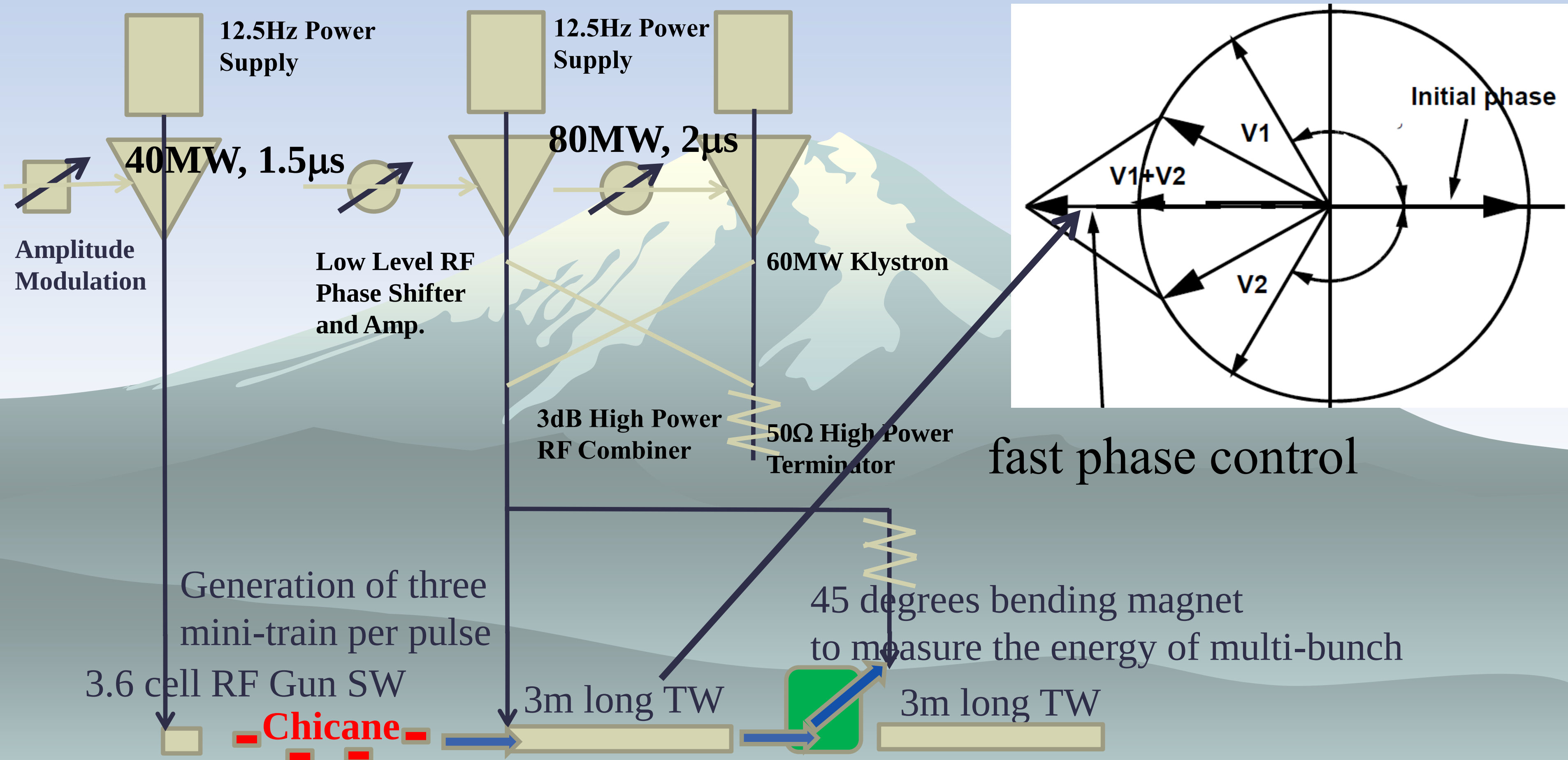




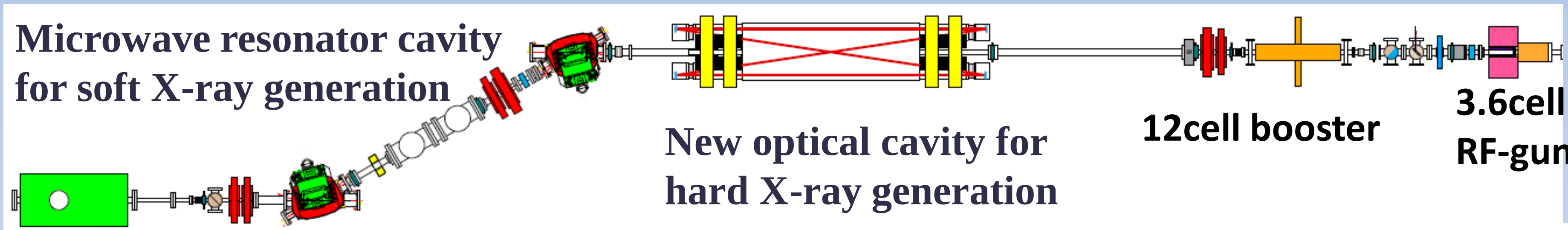


Study to reduce normalized emittance.
0.3 πmm-mrad at 0.1nC/bunch

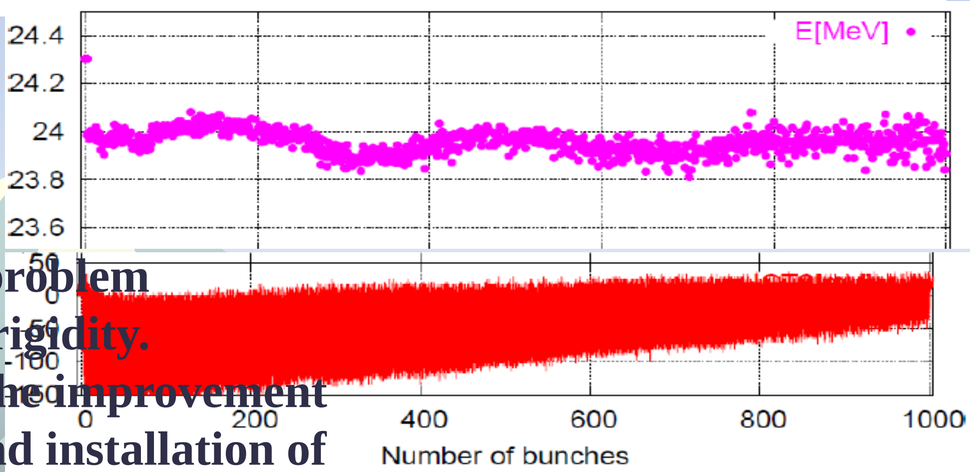
Beam loading compensation by phase amplitude modulation



1000 bunches/pulse operation with 0.6nC/bunch at LUCX



Energy	30MeV
Intensity	0.4nC/bunch
Number of bunch	1000
Beam size at the collision point (1σ)	33μm ×33μm
Bunch length	10ps
Bunch spacing	2.8ns
Energy	1.17eV(1064nm)
Intensity	8mJ/pulse
Waist size(1σ)	55μm ×25μm
Pulse length	7ps



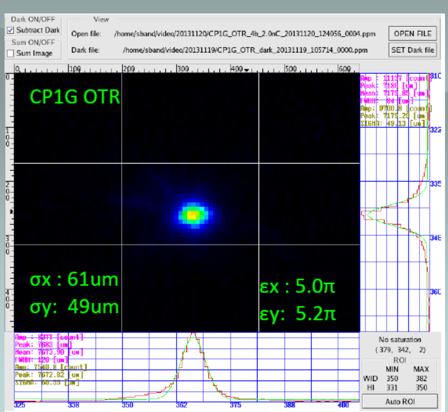
We have problem on cavity rigidity.
We need the improvement of table and installation of high reflectivity mirrors.

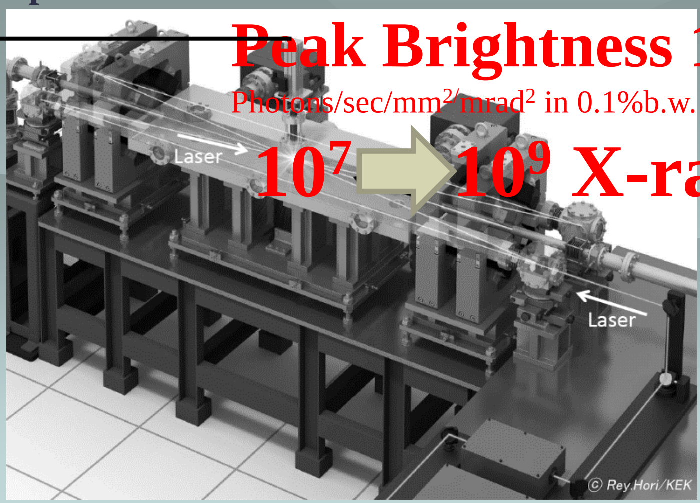
Photon flux more than 10^8 per second

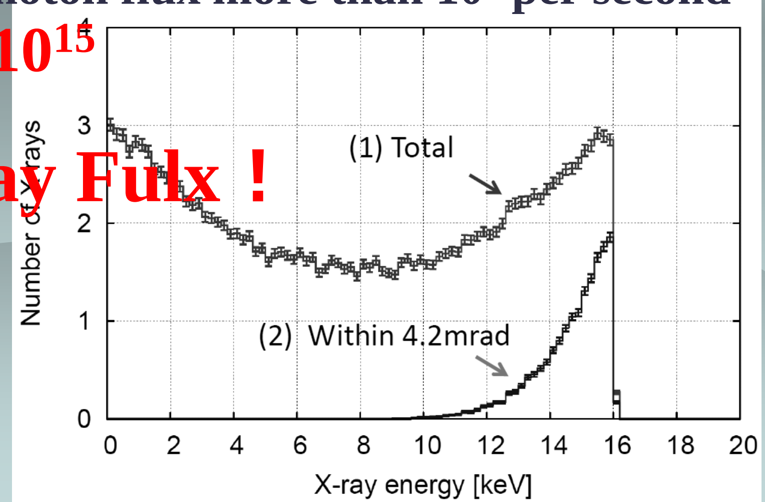
Peak Brightness 10^{15}

Photons/sec/mm²/mrad² in 0.1%b.w.

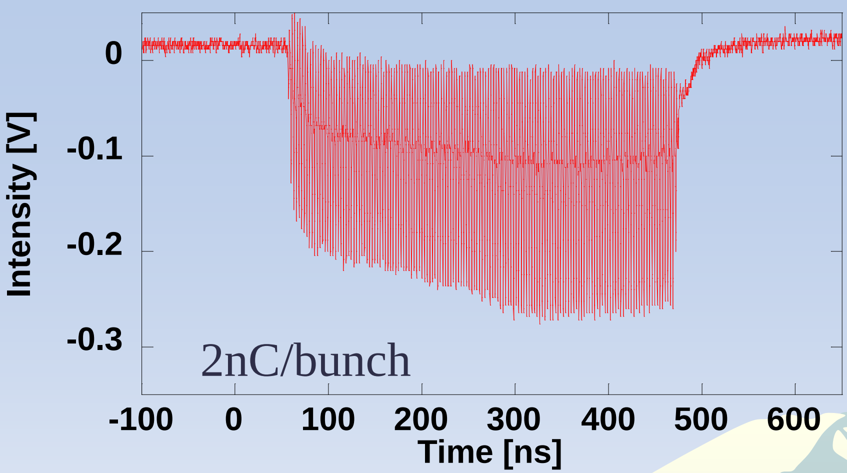
10^7 → 10^9 X-ray Fulx！

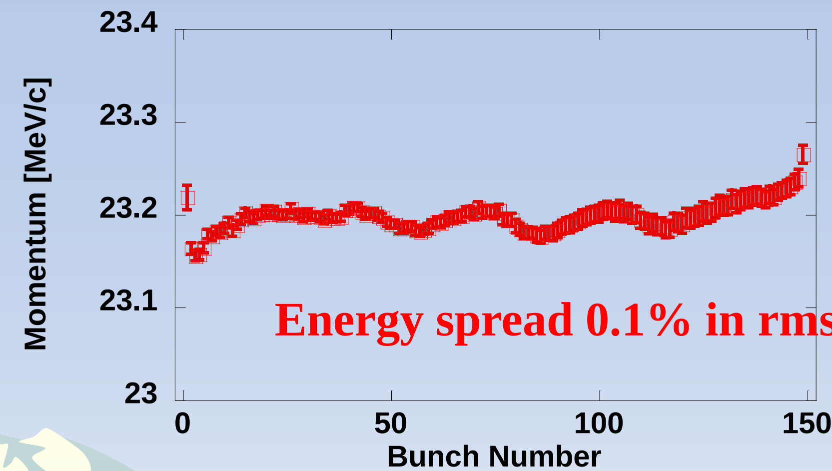




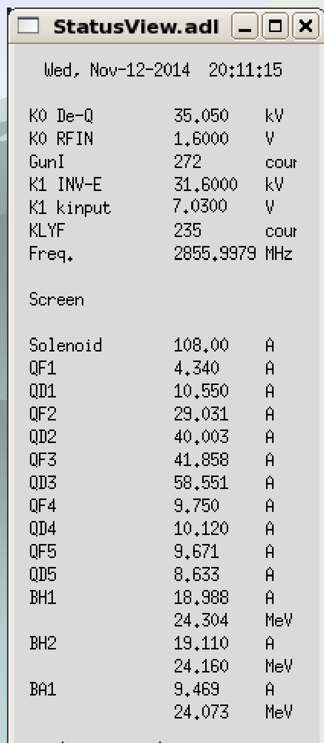


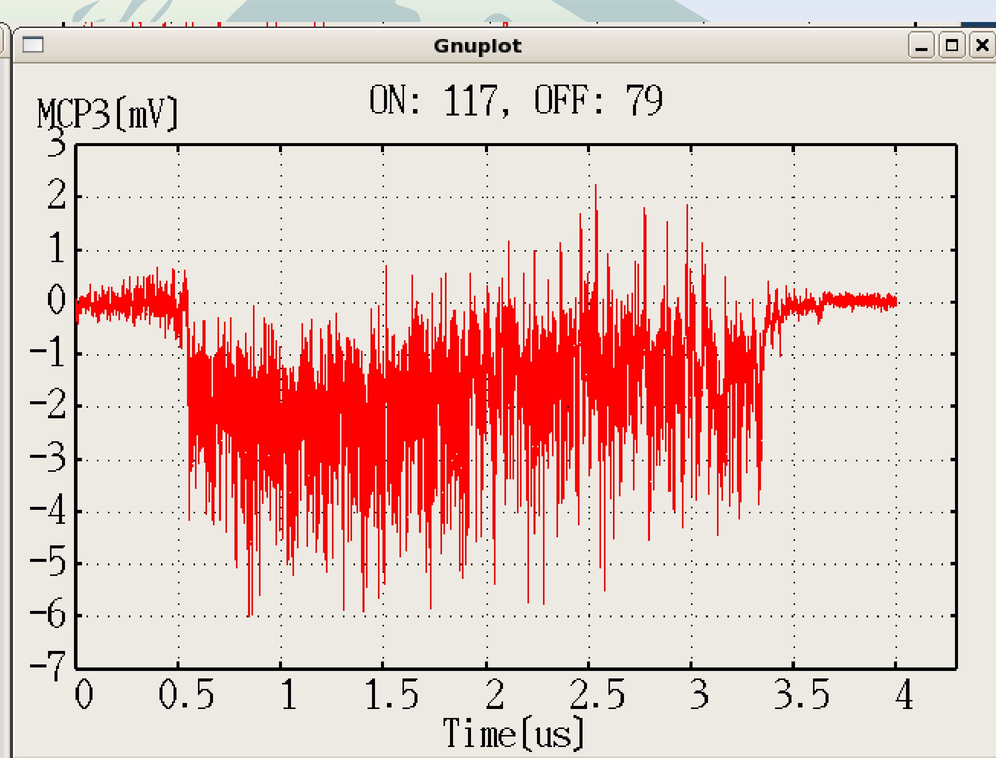
Beam loading Compensation achievement





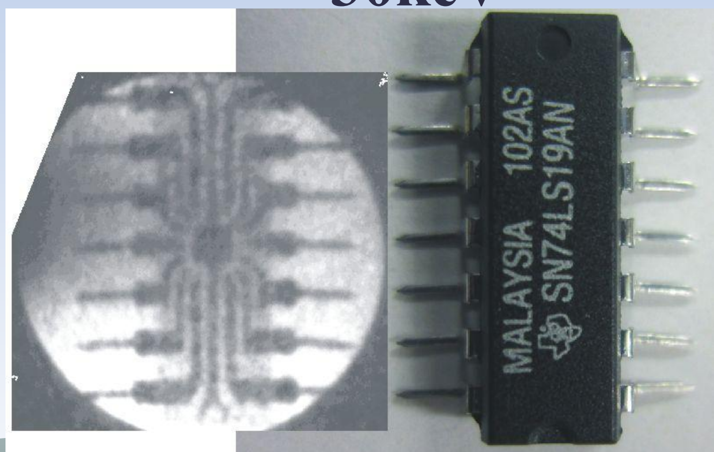
We detected 1000 X-ray pulses with X-ray pulse spacing 2.8ns.



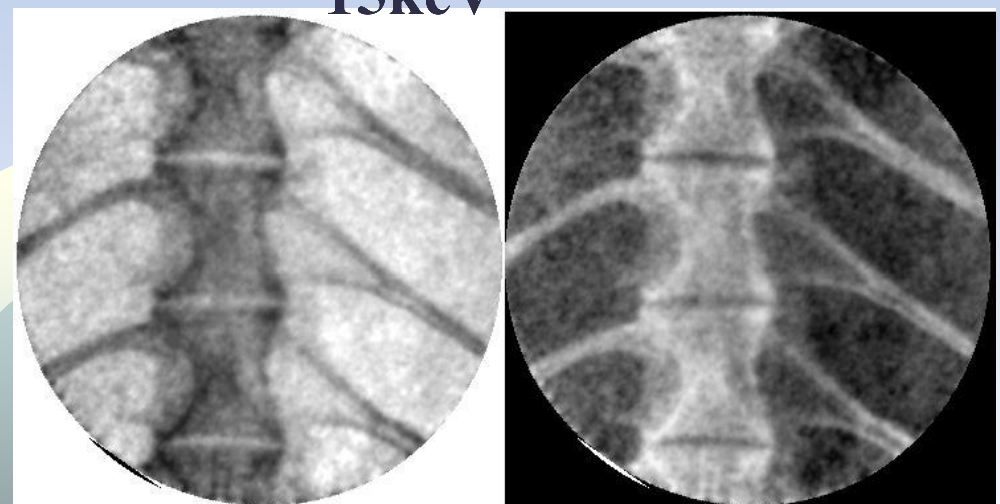


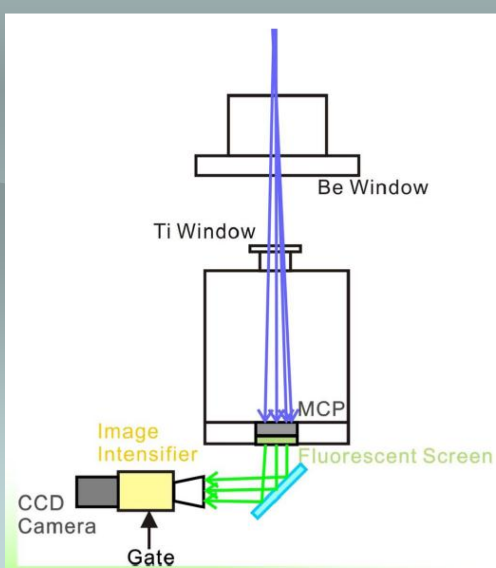
X-ray Imaging by I-MCP+I.I. and SOI
Phase contrast X-ray imaging is next step for imaging technique R&D.

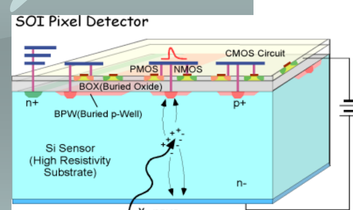
～30keV

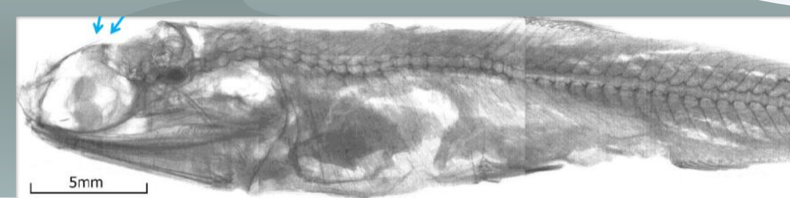


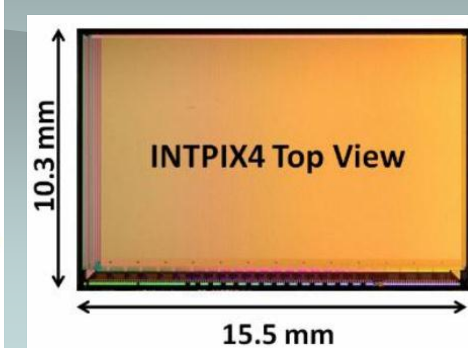
～15keV

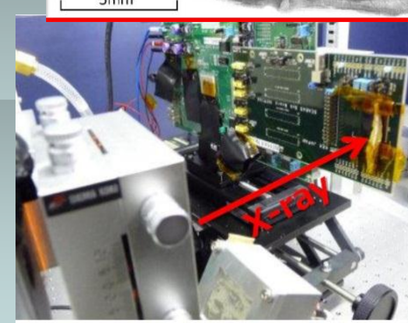










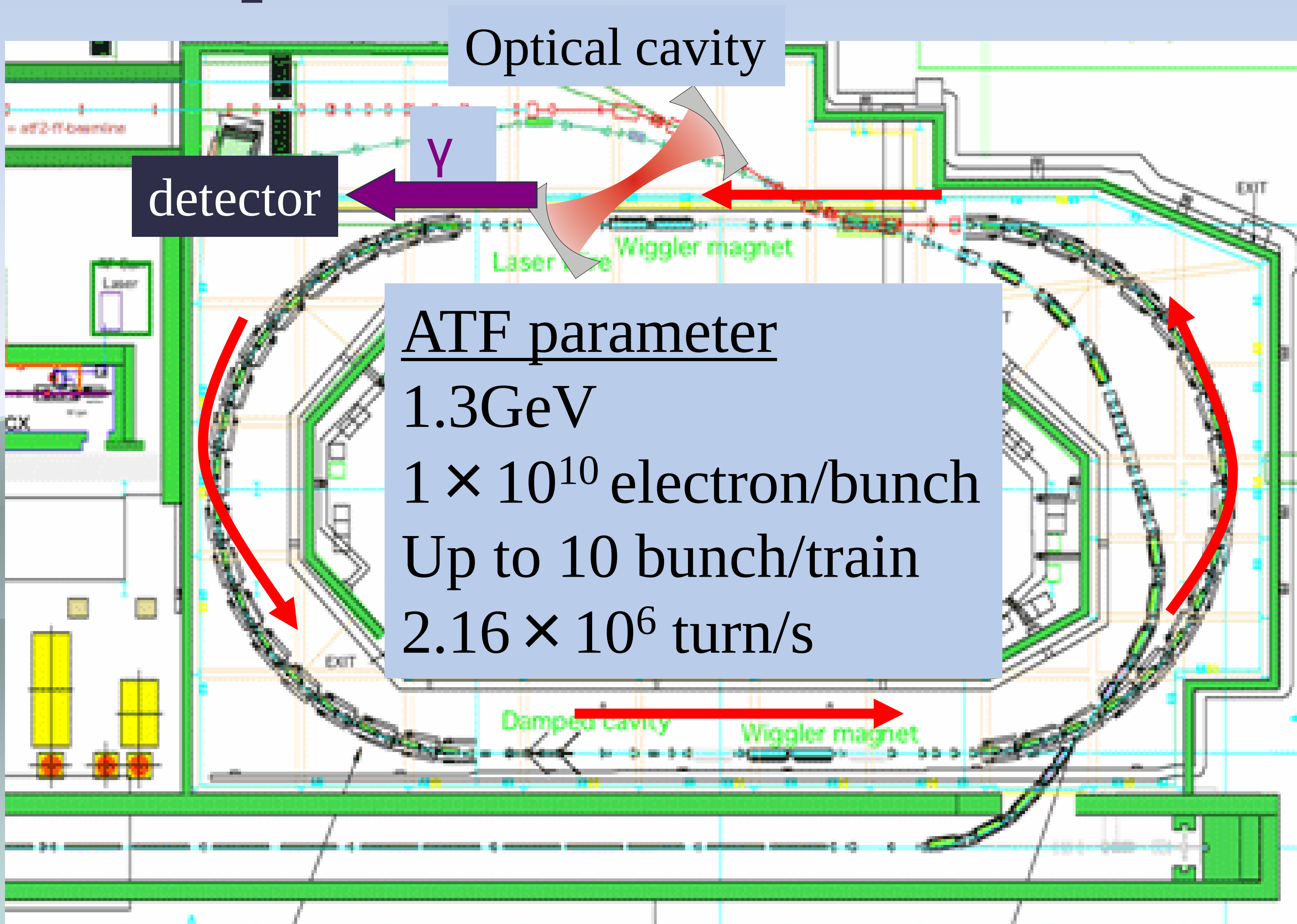


X-ray Imaging by SOI Pixel Detector

2. Development for enhancement optical cavity

γ-ray generation based on ICS with 3D Optical Cavities

Experiments at the KEK ATF



<u>ATF parameter</u>

1.3GeV

1×10^{10} electron/bunch

Up to 10 bunch/train

2.16×10^{6} turn/s

4 mirror 3D cavities were at the ATF

KEK-Hiroshima
installed 2011.

relatively simple control system and employs new feed back scheme.

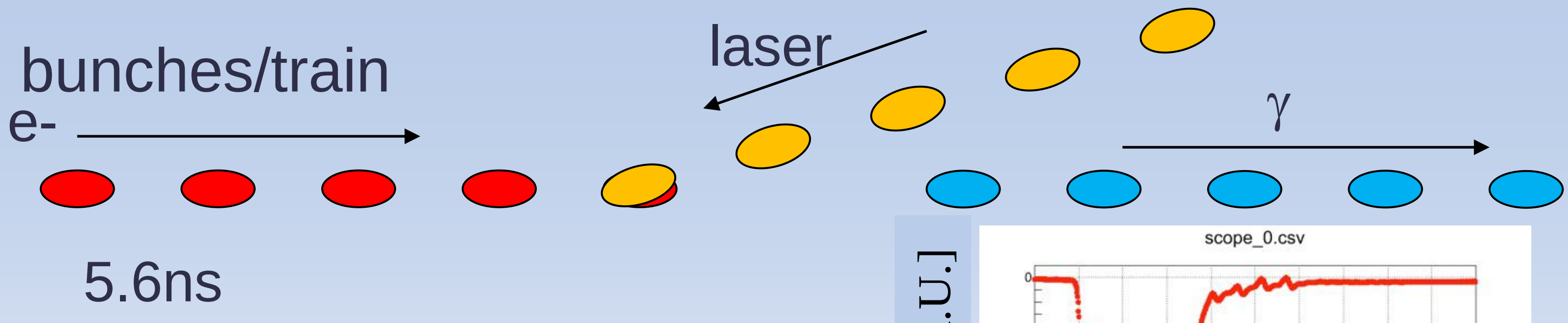
LAL-Orsay
installed summer 2010.

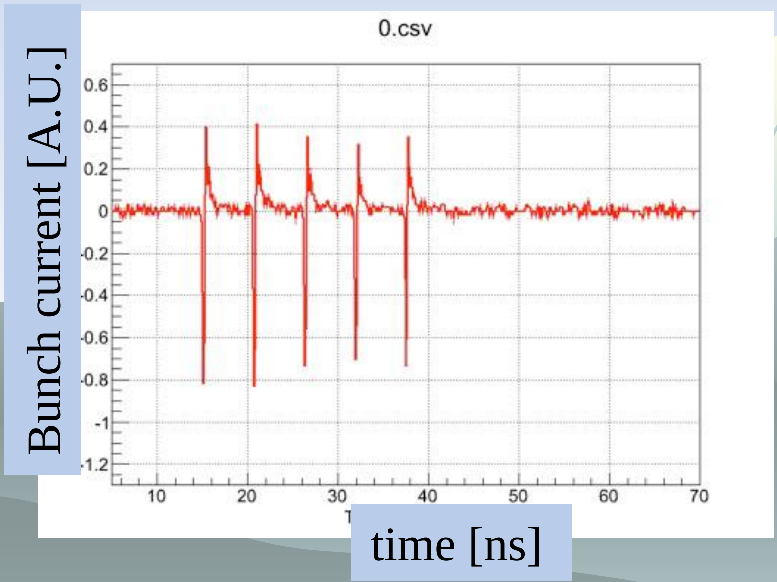
sophisticated control and digital PDH feedback

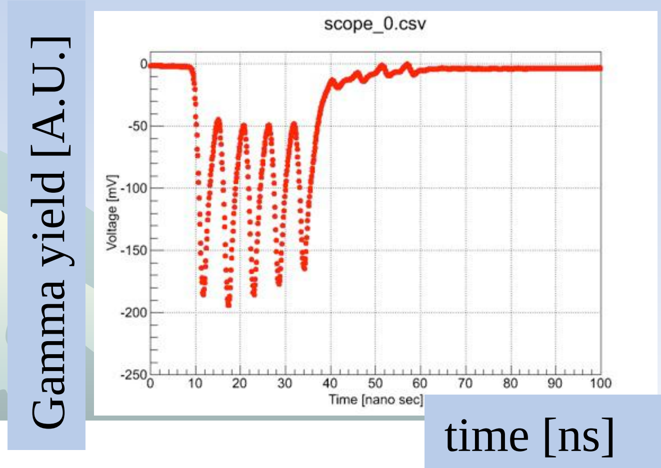
LAL 3D cavity and laser system were reinstalled in 2013.
LAL achieved 101kW accumulation in the cavity. They confirmed 100% laser pulse injection coupling also.
When 30kW was accumulated in the cavity at the ATF damping ring, ~500γ/bunch were generated, which was corresponding to 10^9γ/sec.

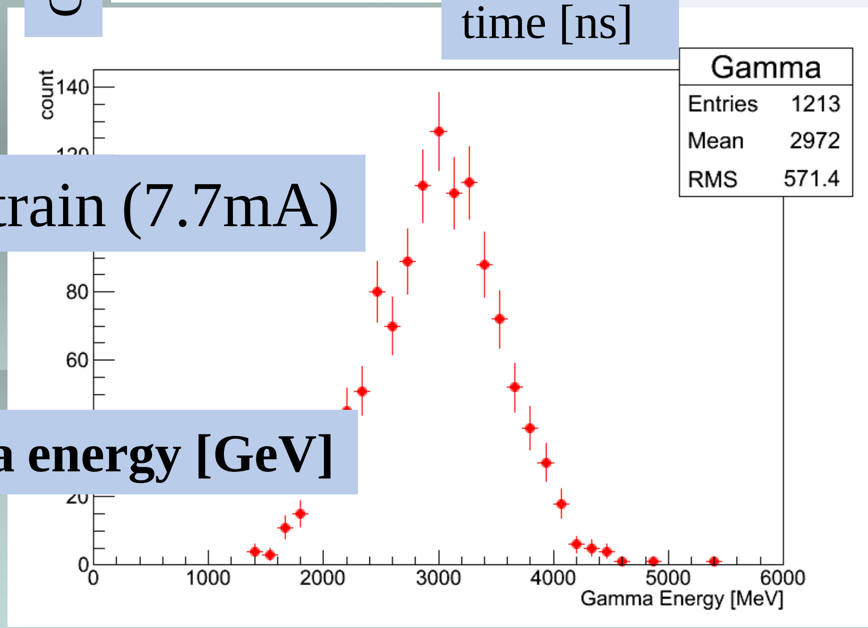
KEK-Hiroshima

γ-ray Generation









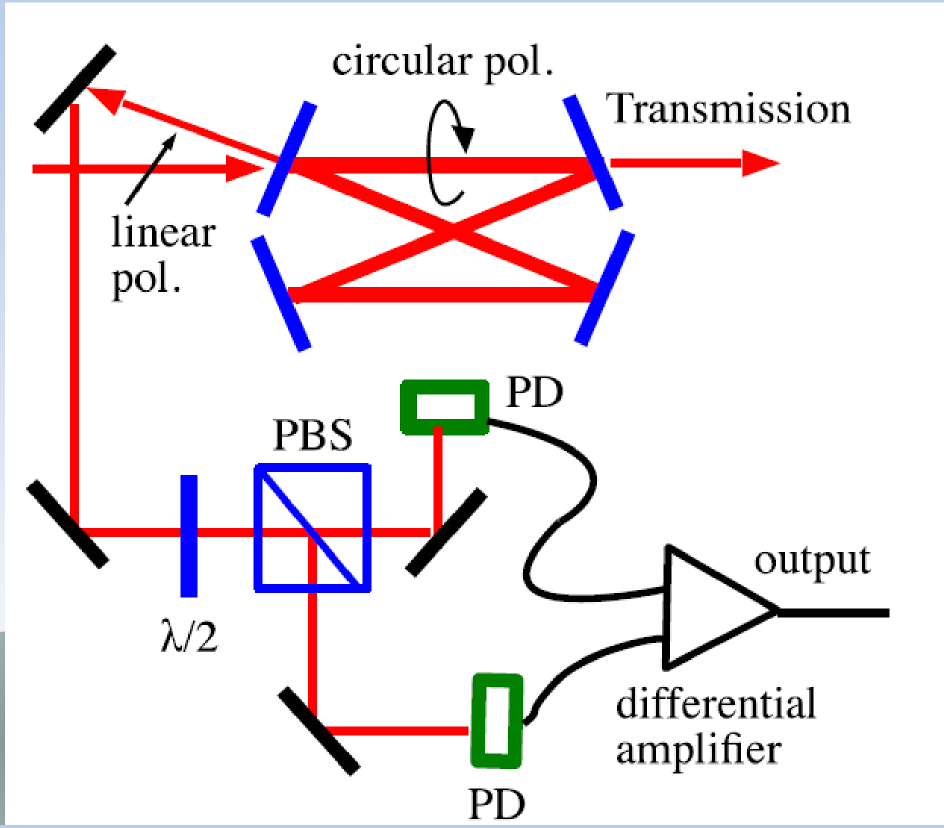
2970±20 MeV

⇒ ~120γs / train

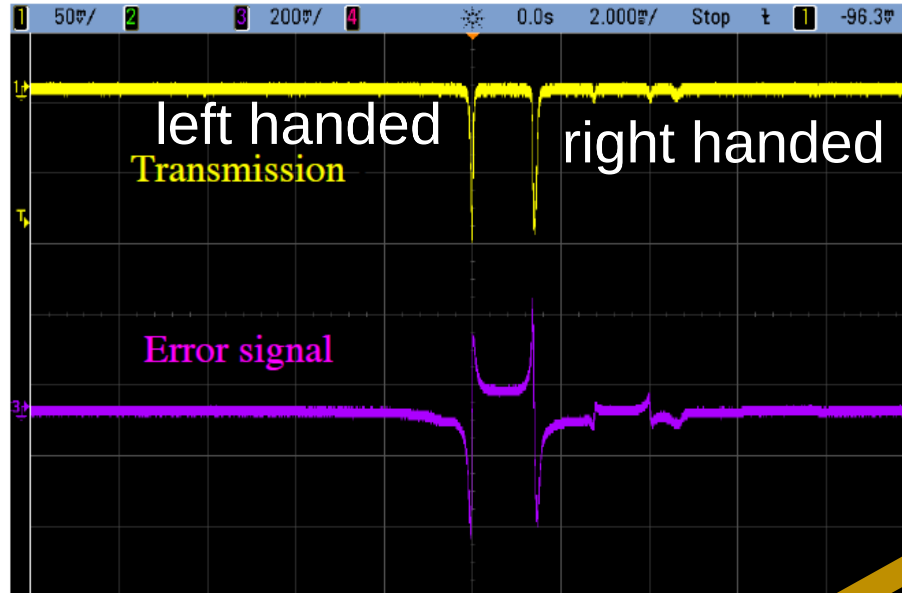
ATF 2.16MHz

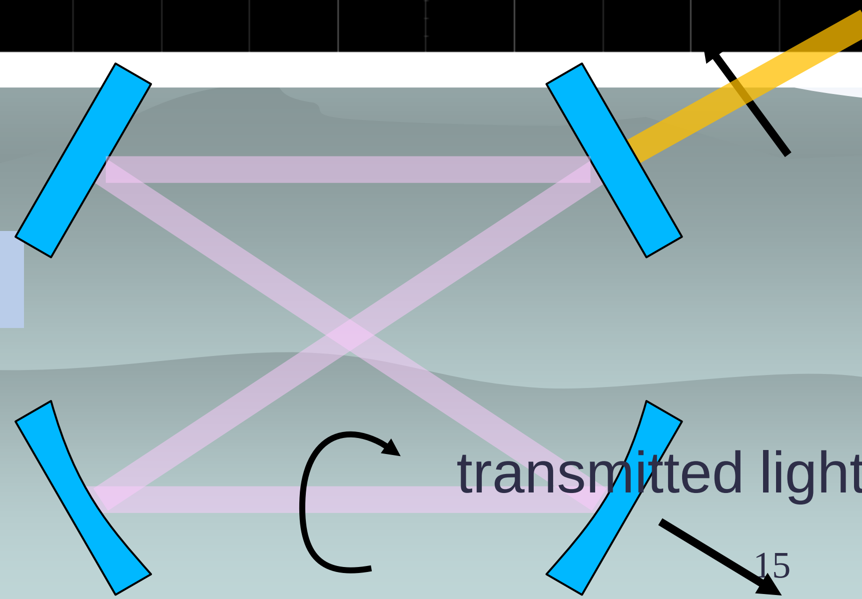
~2.6×10^8/sec

New feedback control using polarization resonance characteristics.



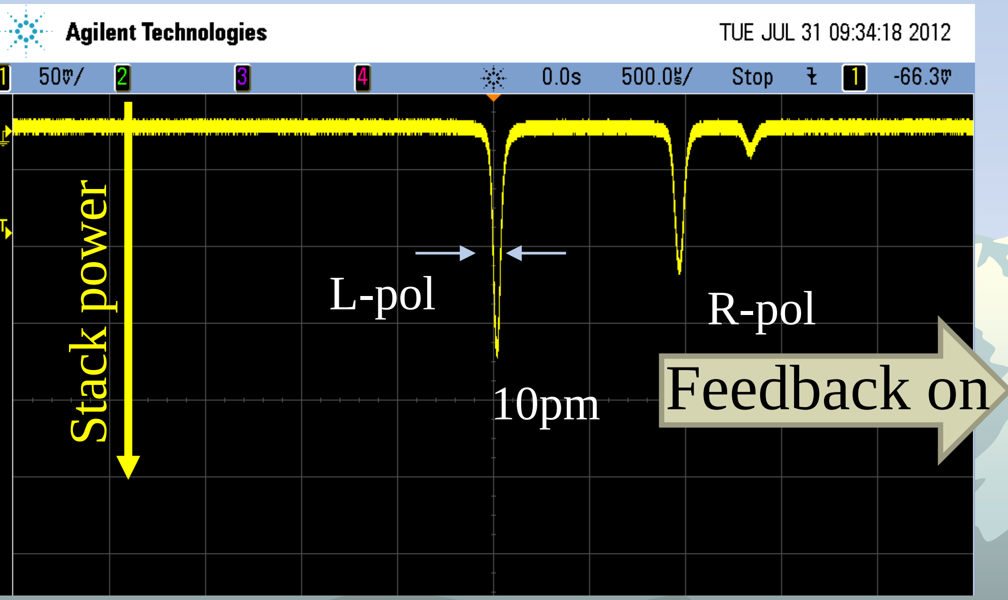
circumference of the cavity

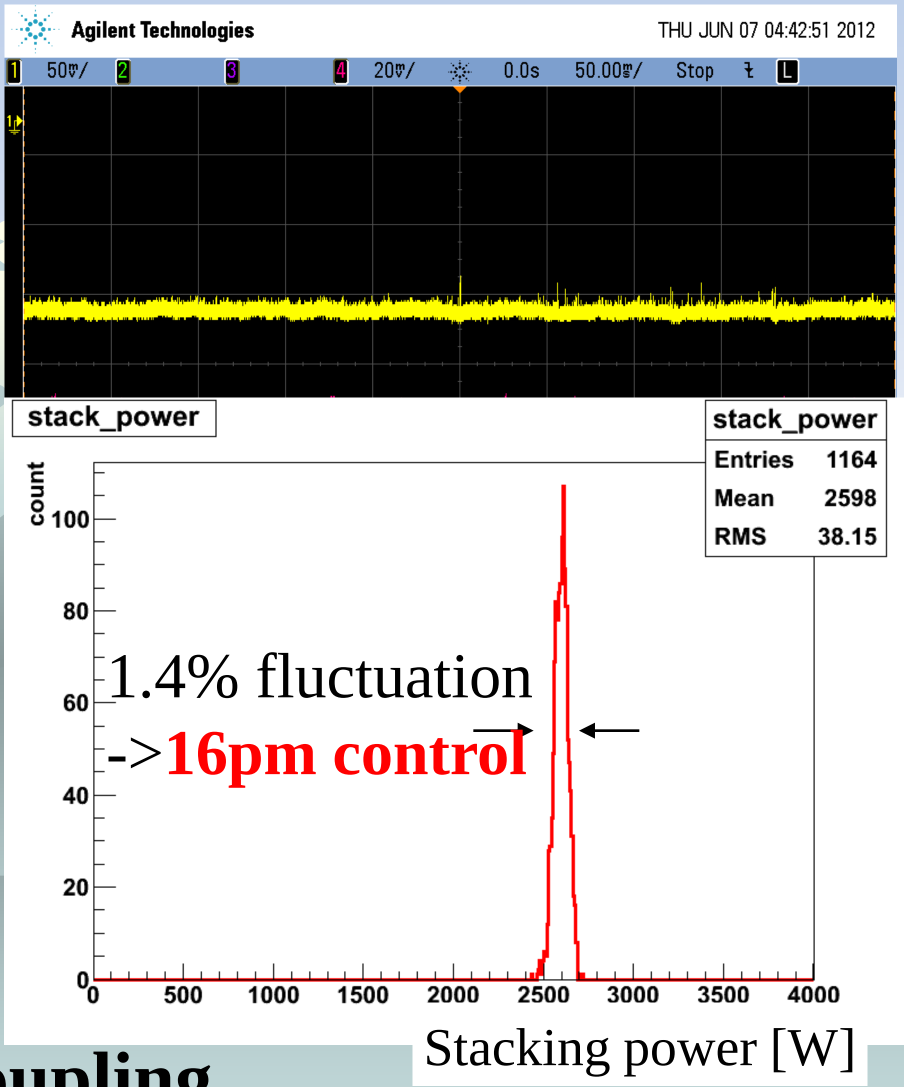




Different slope in left and right pol.

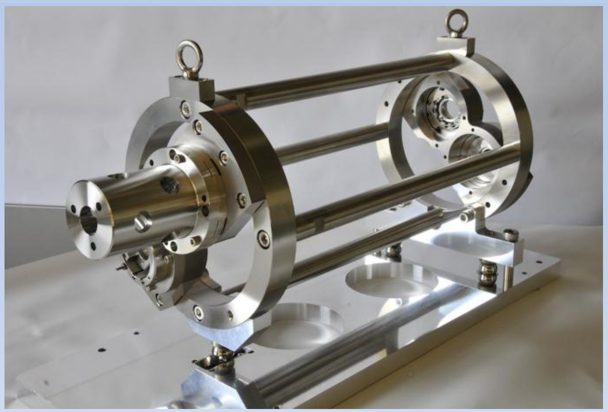
Cavity control accuracy

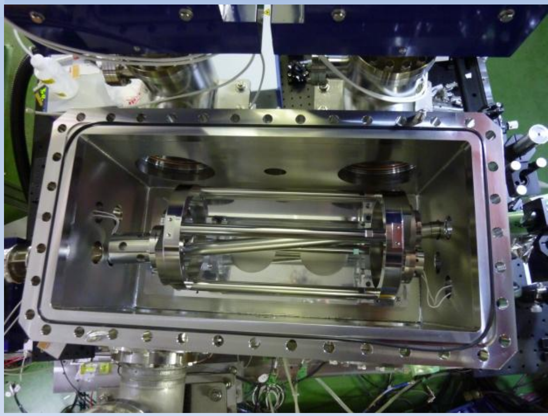




Laser power = 2.6kW
Timing jitter = 8ps
Enhancement 1230
due to mirror
contamination and injection coupling.

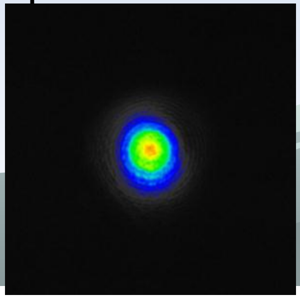
2-Mirror Cavity --> 4-Mirror Cavity





σ_{spot} ~ 15 micron F ~ 5000

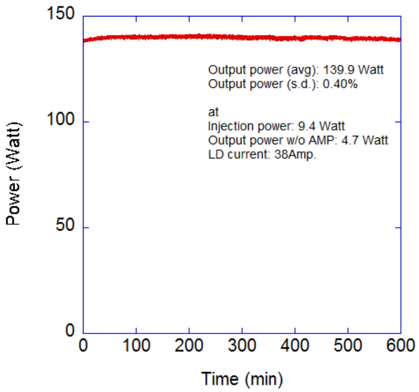
σ_{spot} ~ 30 micron F ~ 2000

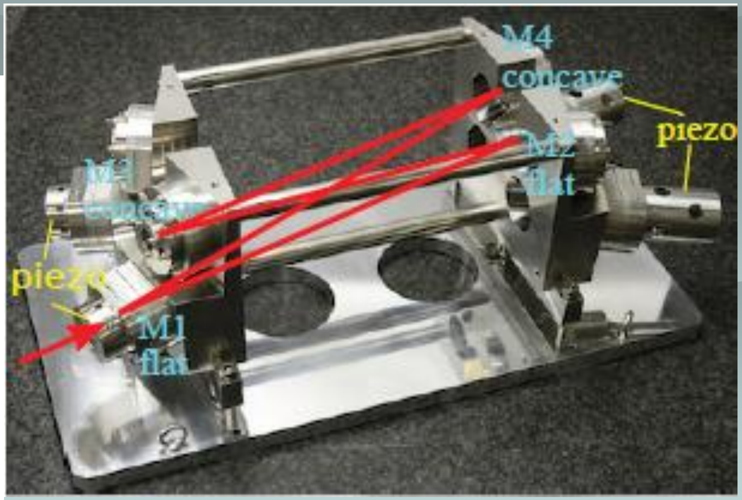


162.5MHz mode-lock
Laser system
Spatial laser profile

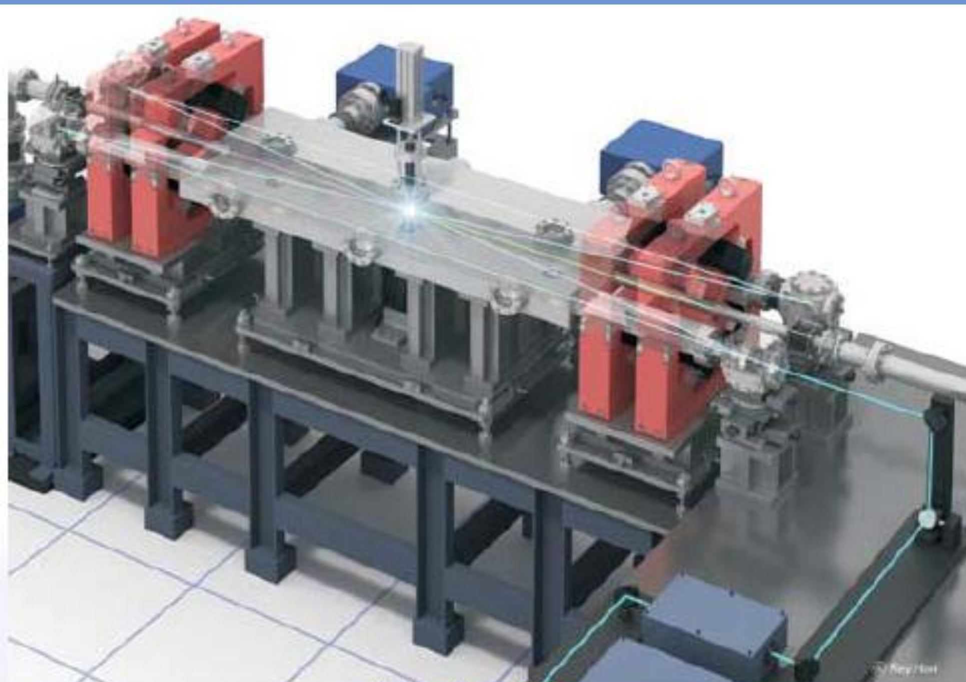
4-Mirror Cavity can storage the power more than 1MW, which is our future target.

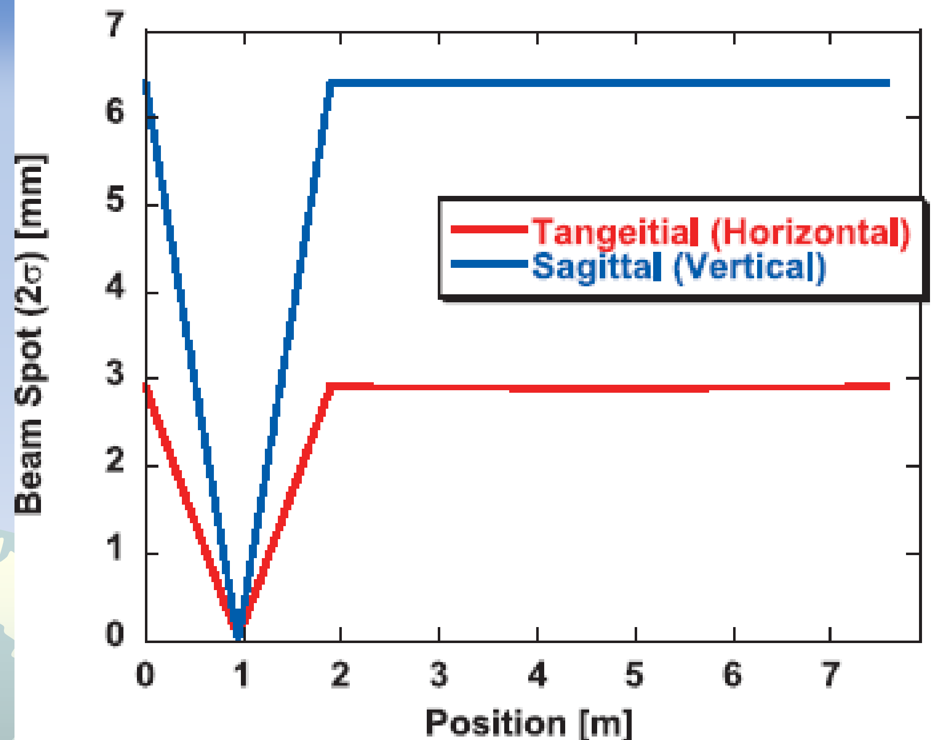
Output laser 140W





Storage power more than 2MW is possible due to recent study. See H. Carstens et al., “Large-mode enhancement cavities,“ *Opt. Express*, 21, 11606-11617 (2013).
They demonstrated the storage of 400kW with pulse duration 250-fs and 2000 enhancement.

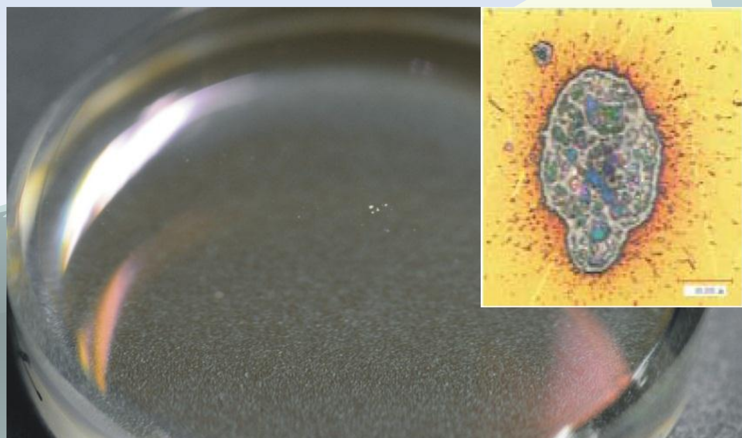




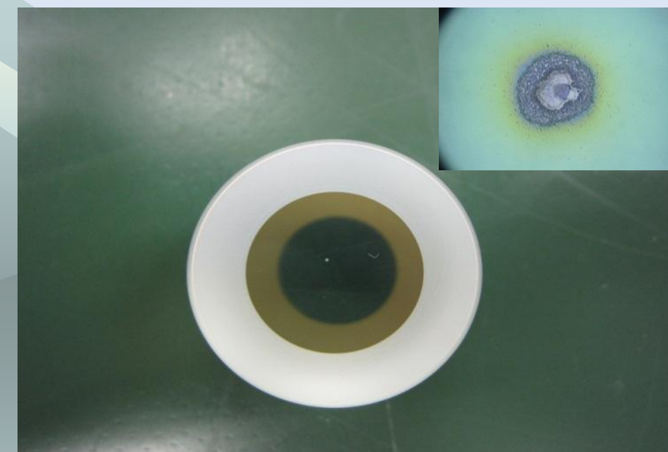
One turn length : 7.56m, horizontal laser waist size : ~100μm in 2σ,
Crossing angle : **7.5 degrees**, vertical laser waist size : **~50μm in 2σ,**
Horizontal laser size on laser injection plane mirror : 2.92mm,
Vertical laser size on laser injection plane mirror : 6.4mm
Laser pulse energy in cavity : 8mJ, distance between concave mirrors : 1.89m, **7.56m means this cavity has 9 laser pulses.**
Use two inch mirrors and increase the threshold damage energy.
Completed this device in September 2012 and started the generation of X-ray from mid. of Feb. 2013. Confirmed 250kW storage of laser pulse.

We destroyed the mirror coating many times. First occurred when the waist size was ~100μm with burst amplification and 42cm two mirror cavity. Second occurred when the waist size was 30μm with the burst amplification and the 42cm two mirror cavity. Now we are using 4 mirror cavity with smaller waist size at IP. From our experience, we have to reduce the waist size to increase the laser size on the mirror and need precise power control for the burst amplification. I guess about storage laser pulse energy from 2mJ to 4mJ destroyed the mirror coating with the waist size of 30μm. Also, we found the damaged position was not at the center.

2008



2011

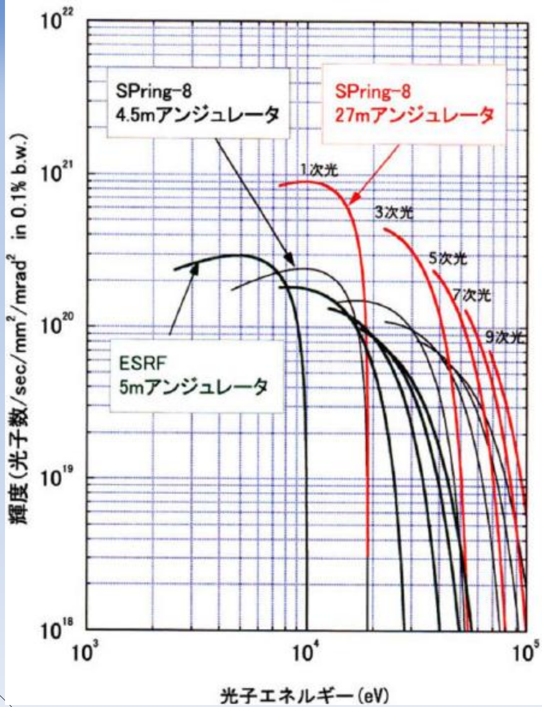


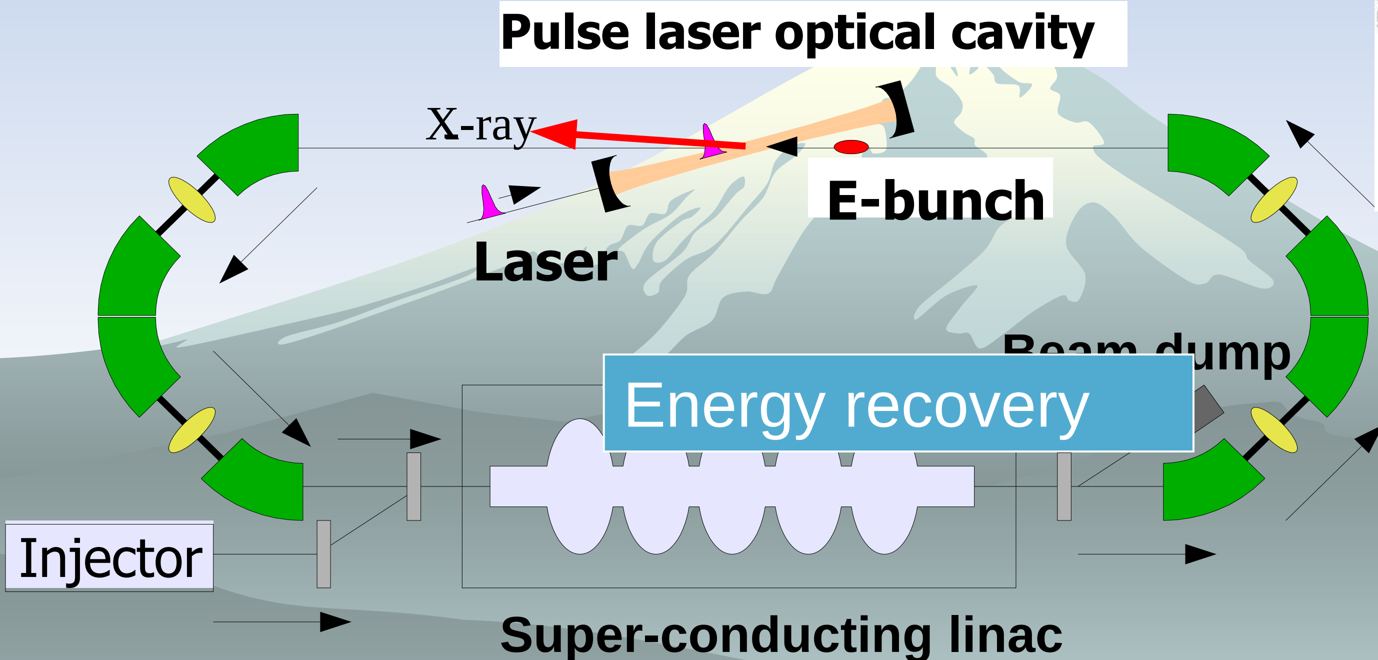
Recent examples also showed same things at 0.7mJ which is 260kW peak. (2013 and 2014, we destroyed 2 inches concave mirror 2 times.)

3. Future plans and schedule

High brightness X-ray generation at c-ERL as a demonstration through beam experiment

By end of 2017: high brightness X-ray generation experiment at cERL.





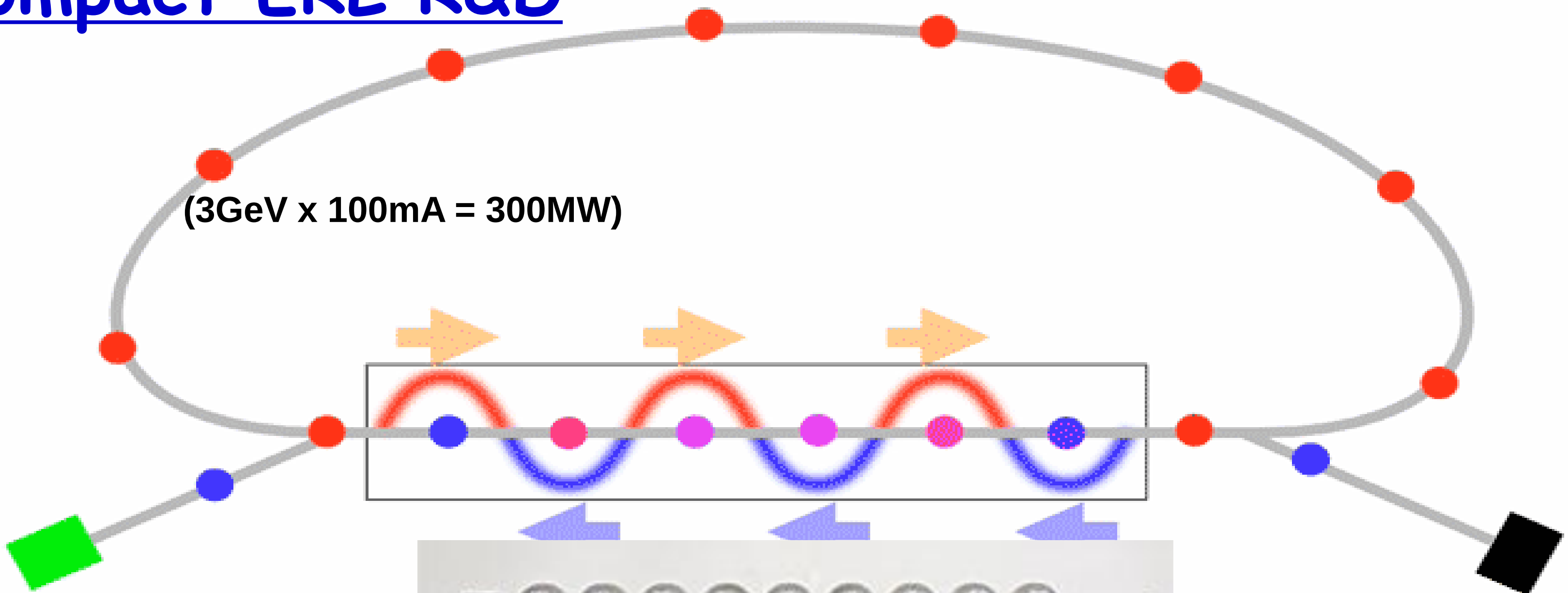
SPring-8
World highest
Av. Brightness 10^{21}
Photons/sec/mm²/mrad² in 0.1%b.w.
from 27m undulator at SPring8

10^{13} photons/(sec･1%b.w.)

Realize the Peak Brightness 10^{19} Photons/sec/mm²/mrad² in 0.1%b.w.

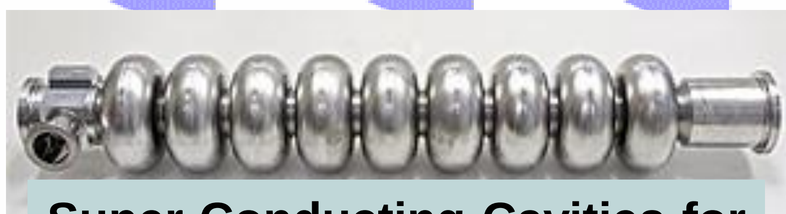
35MeV electron beam x 1μm laser = 23keV X-ray

Compact ERL R&D

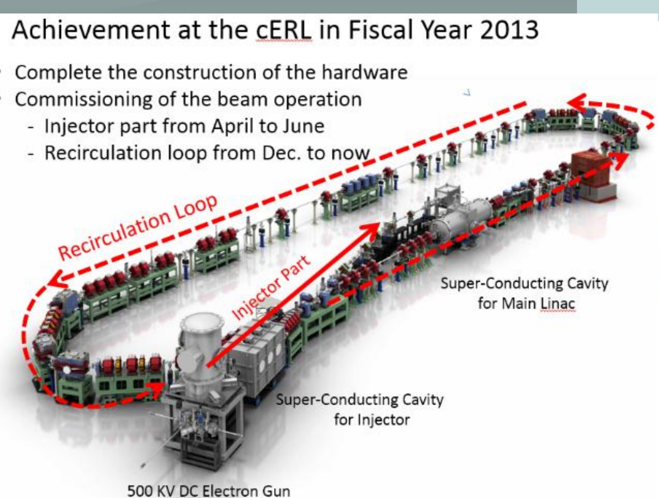


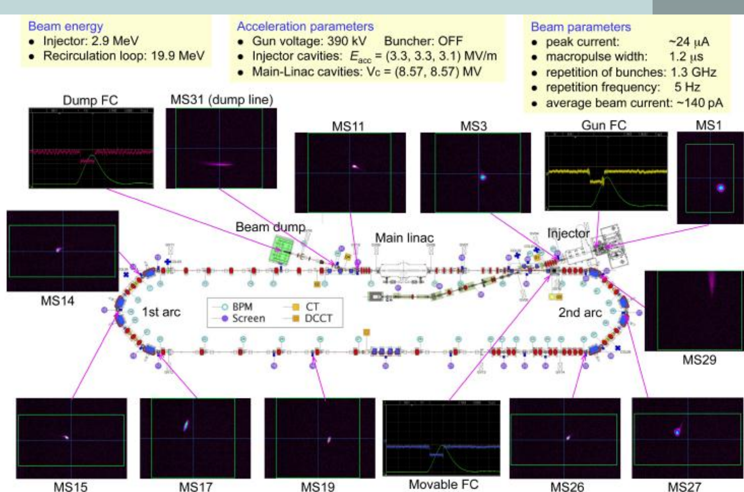
High Brilliant Electron Gun

Beam Dump
(10MeV x 100mA = 1MW)

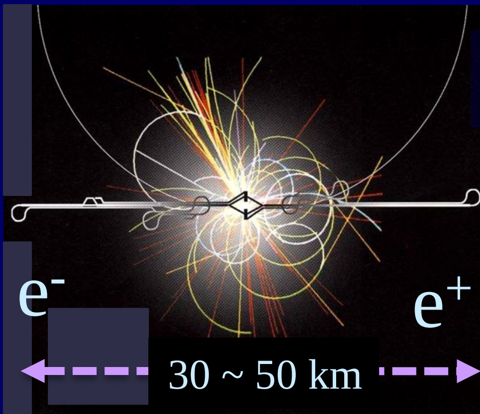


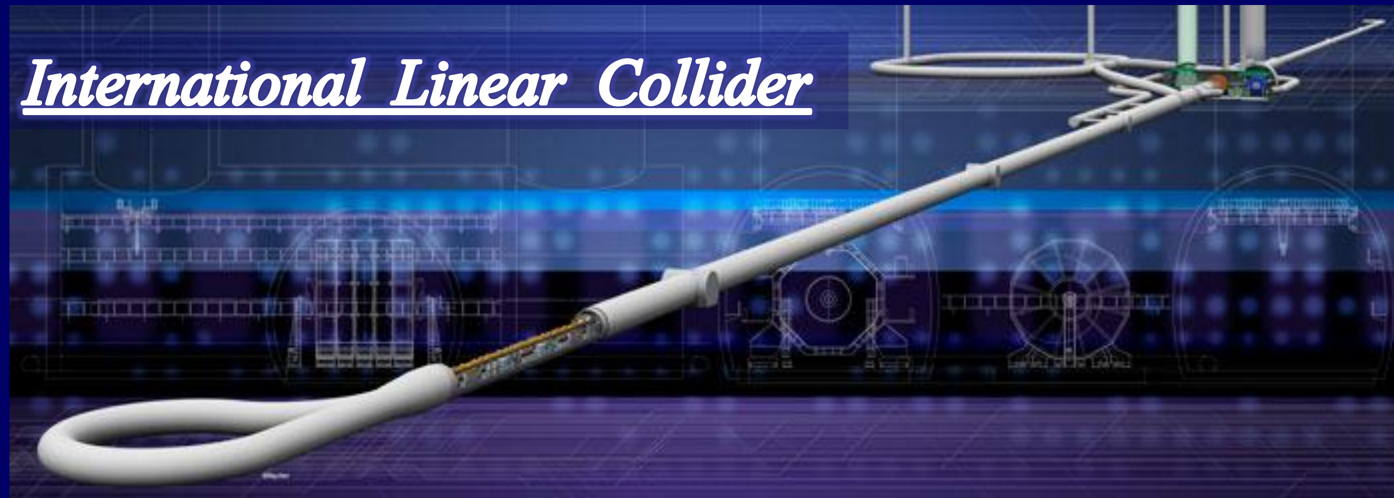
Super Conducting Cavities for Acceleration and Deceleration

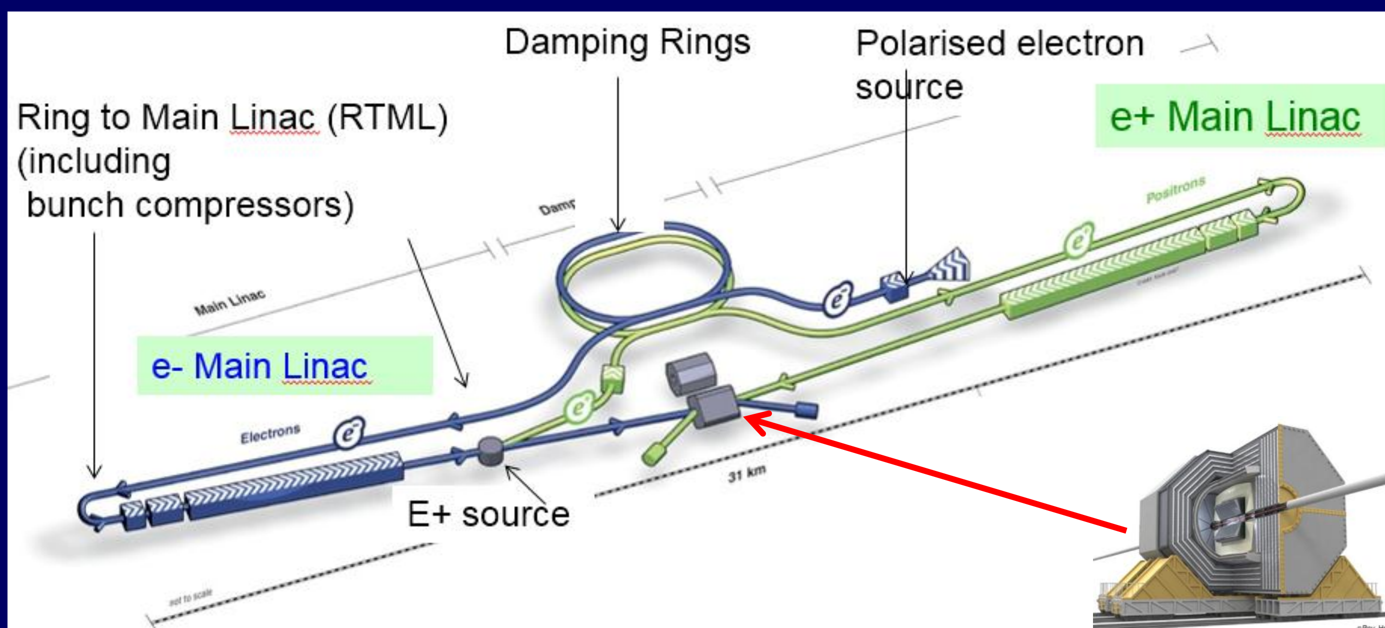




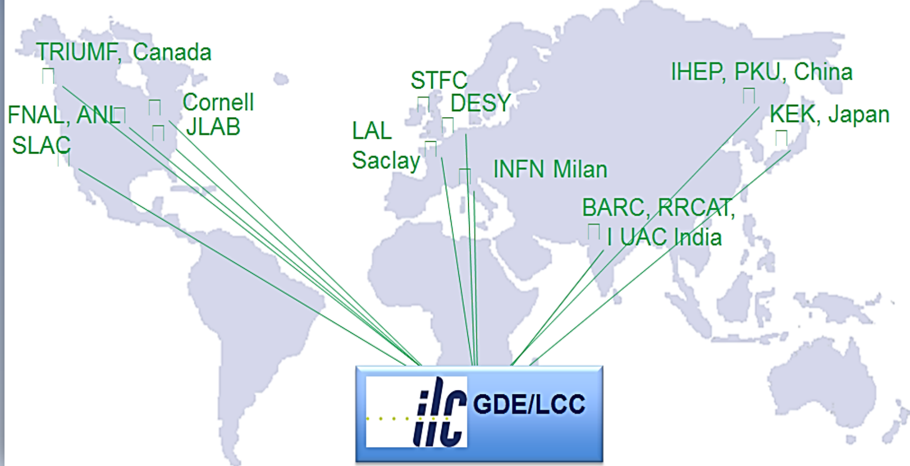
ILC : Next Energy Frontier Project





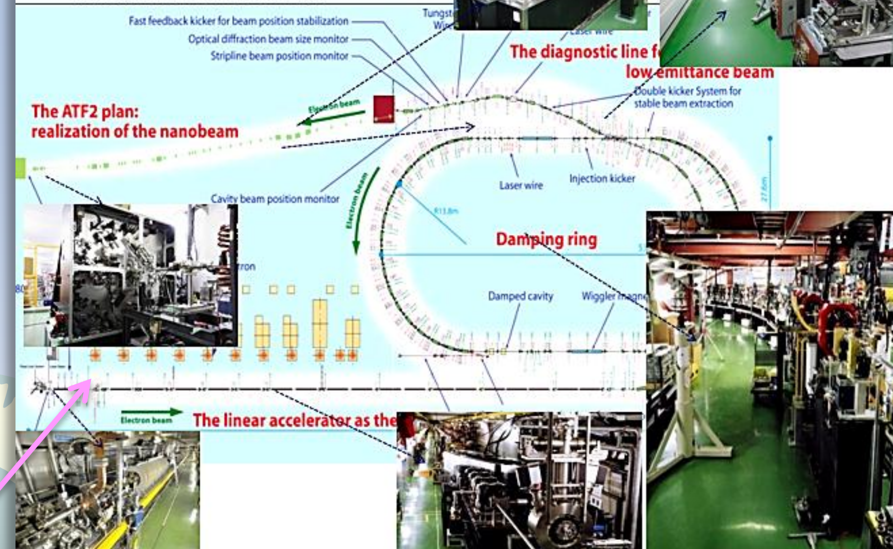


ILC R&D: Global Collaboration



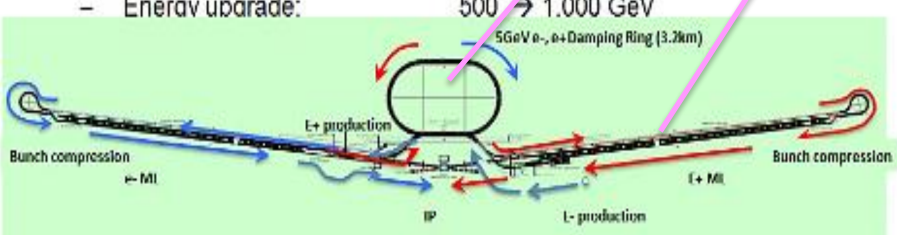
ATF: Accelerator Test Facility for ILC

- Generate Low Emittance Beams
- Handle Nano-Size Beams



Requirements from Physics Exp.

- Basic requirements:
  - Luminosity : $\int Ldt$ = 500 fb^{-1} in 4 years
  - E_{cm} : 200 – 500 GeV and the ability to scan
  - E stability and precision: < 0.1%
  - Electron polarization: > 80%
- Extension capability:
  - Energy upgrade: 500 → 1,000 GeV

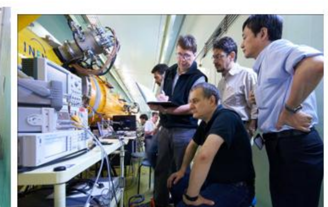


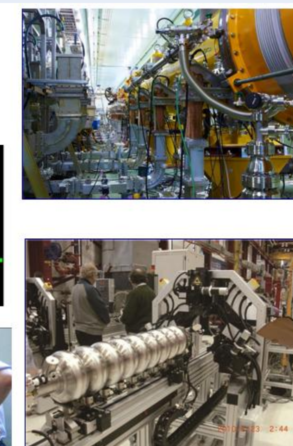
Superconducting Test Facility (STF)

S1-Global

The first step of ILC

2009 ~ 2011.2.25



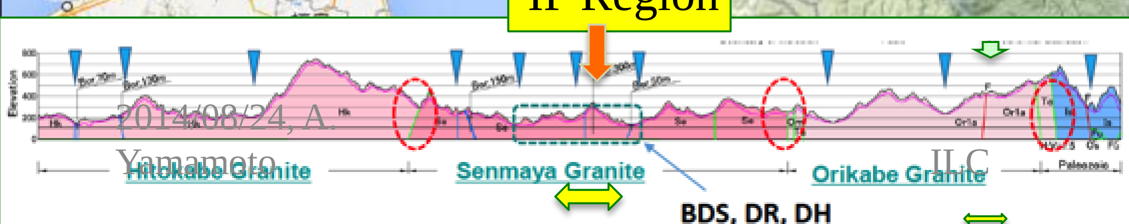


Plug compatibility of SCRF system was successfully demonstrated by international collaboration.

ILC Site Candidate Location in Japan: Kitakami Area

unity

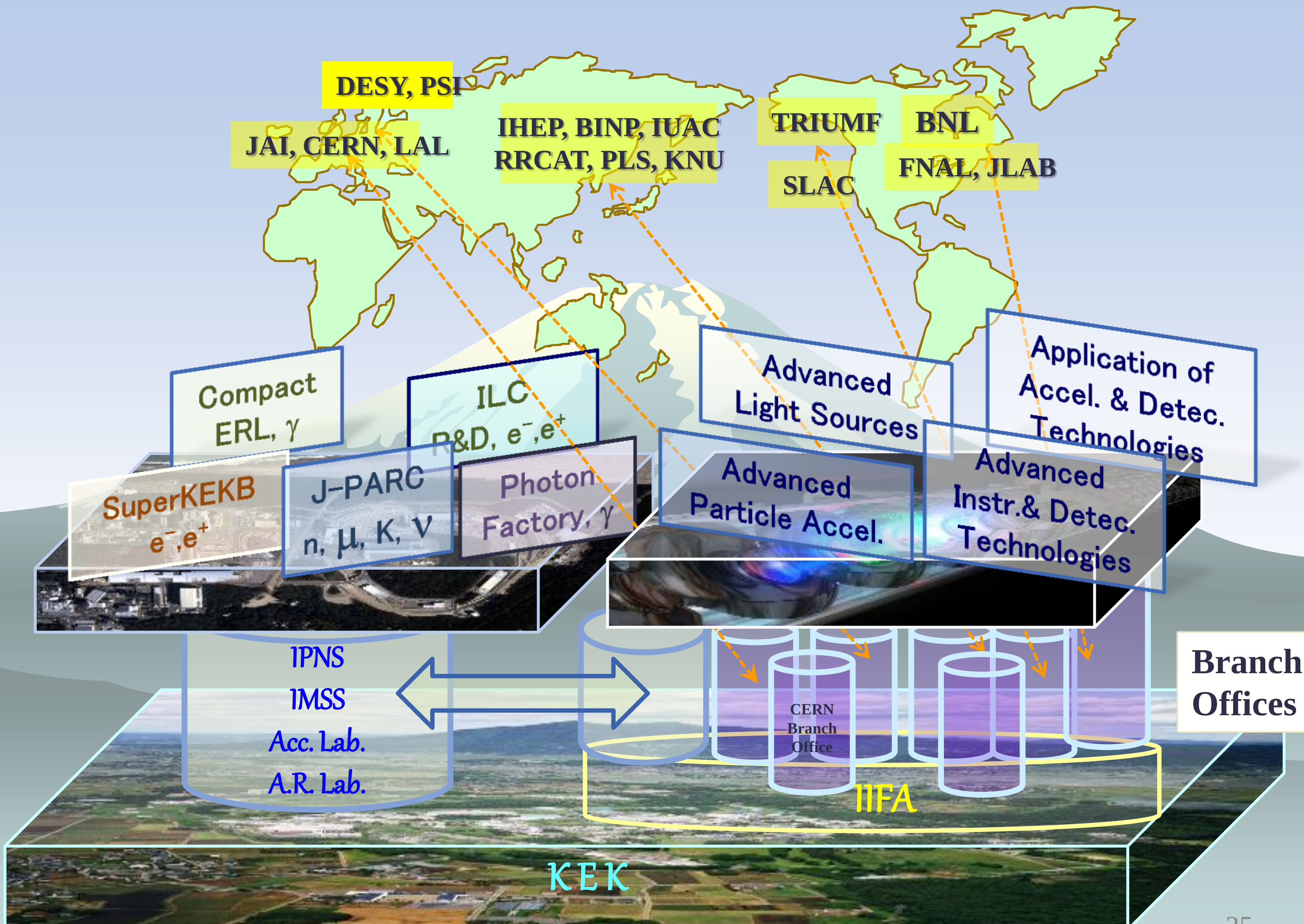
ese Government



Need to finalize:

- IP / Linac orientation and length
- Access points and IR infrastructure
- Conventional Facilities and Siting (CFS)
- …

International Institute for Future Accelerators (IIFA)



Accelerator Science
India-KEK Consortium

Accelerator R&D	Detector R&D	Materials Science	Particle Physics	Medical Application	School
I: J:	I: J:	I: J:	I: J:	I: J:	I: J:
FEL@IUAC		Energy materials	Belle II	Ion therapy	Accelerato r
Light source		Nano-materials	Neutrino	BNCT	Physics
ILC			Muon	Protein crystallography	

https://www.youtube.com/watch?v=ajWgKslzDZQ

http://newsline.linearcollider.org/2014/10/02/take-part-in-the-mylinearcollider-campaign/

Take part in the *#mylinearcollider* campaign!

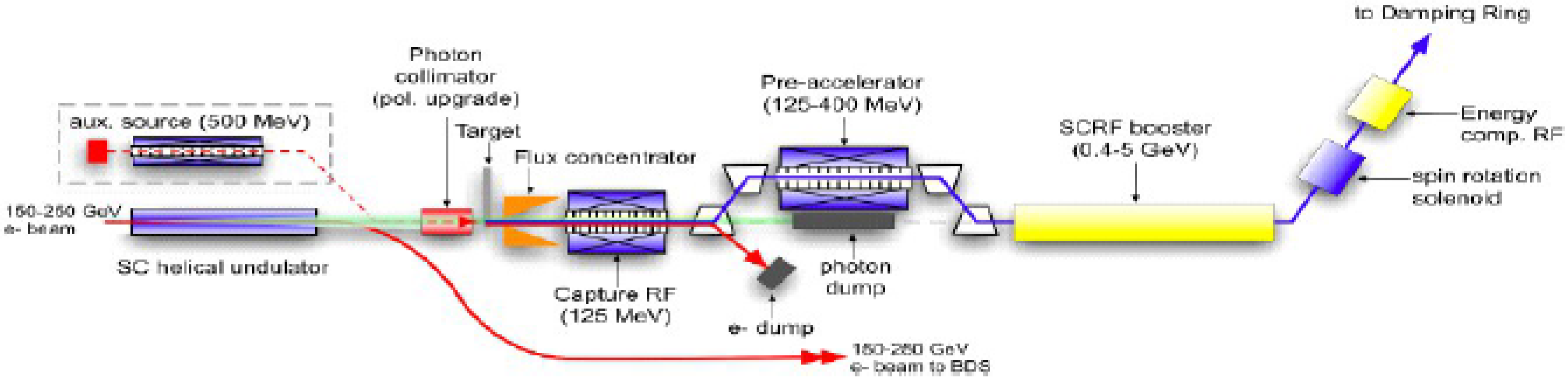
- Linear Collider Collaboration is producing a collection of #mylinearcollider video messages from all over the world to support the ILC.
- Now is the time to show our ambition to realise the ILC.
- It counted 500+. LCC is aiming to collect 1000 messages from scientists.
- Your messages really make difference. Please join and give the ILC project a final push!

Take part in the *#mylinearcollider* campaign!

- How to join:
  1. Take a short video using any video recording devices, **cameras, iPhone, or your PC**.
  - Your message can contain following statements:
    - **Your name and name of institution/university (essential)**
    - **Why you think you need the ILC**
    - **What you want to do when the ILC is built**
    - **Your will to come to the ILC site**
    - **Any message to back up the realisation of the ILC**
  2. Or Simply write a **message "I want the ILC" with your name, hang in front of you, and take a photo.**
  3. **Send the file to** communicators@linearcollider.org

Undulator Positron Source (Baseline)

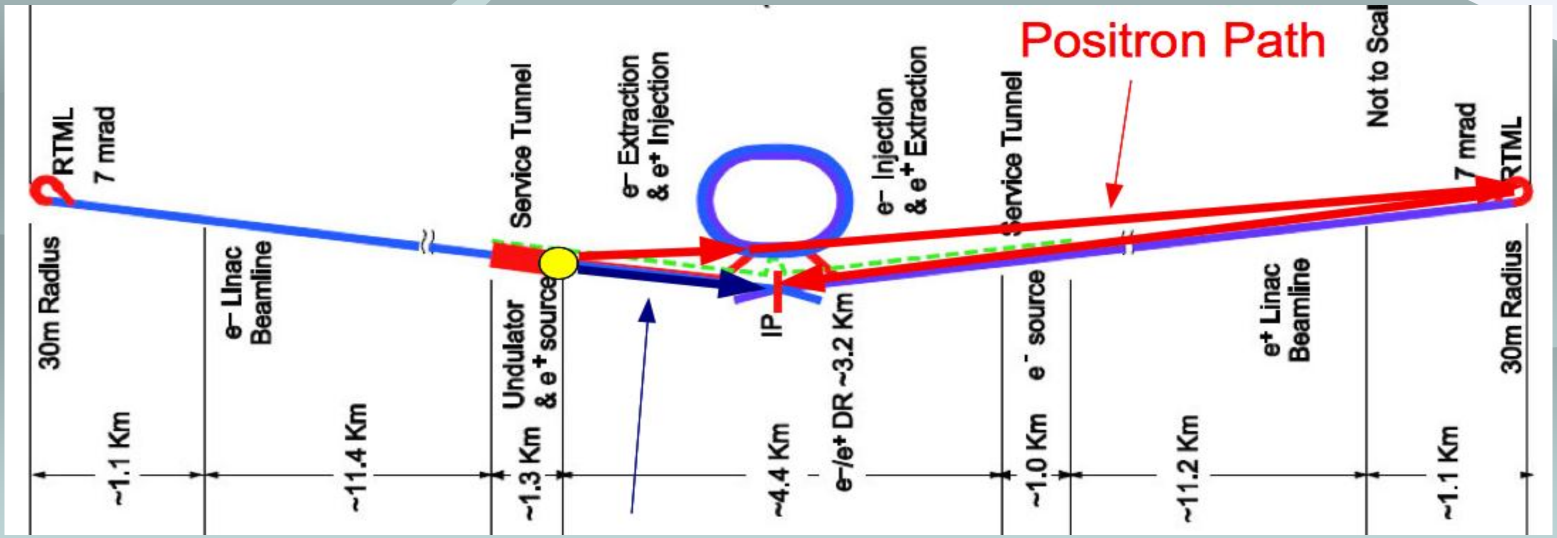
- Gamma rays from undulator radiation is converted to positron.
- 30% polarization (up to 60% optionally).
- The system design is almost completed.
- The design for the target rotating with 100 m/s tangential speed is not yet fully established.



Masao Kuriki

Machine Footprint – Timing constraints

- Positron bunches are produced from their "partner" electron bunches
- -> new positron bunches are injected into DR while old (damped) positrons are still in
- Simplest solution: each e+ bunch goes into exactly the same bucket that was occupied by colliding e+ bunch
  - e+ bunch is ejected from DR, travels down RTML and Main Linac, while
  - empty bucket left by e+ bunch rotates around DR several times
  - Partner e- bunch creates new e+ bunch
  - e+ arrives exactly at DR in time to fill rotating void bucket, while
  - e- and e+ bunches collide at IP

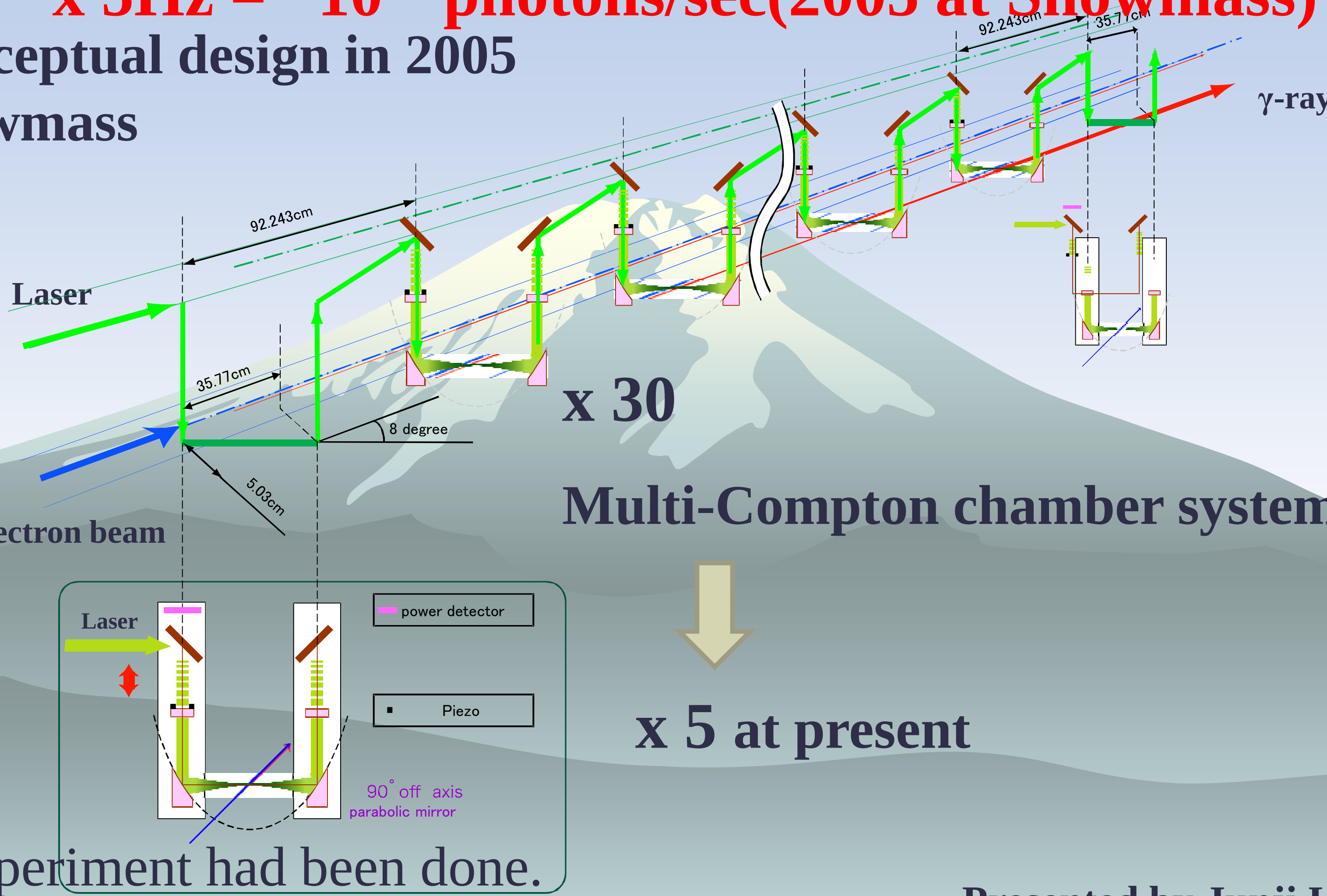


~33km

ILC polarized positron source

~10^{12} photons with 6.16ns spacing x ~3000 bunches x 5Hz = ~10^{16} photons/sec(2005 at Snowmass)

Conceptual design in 2005 Snowmass



x 30

Multi-Compton chamber system

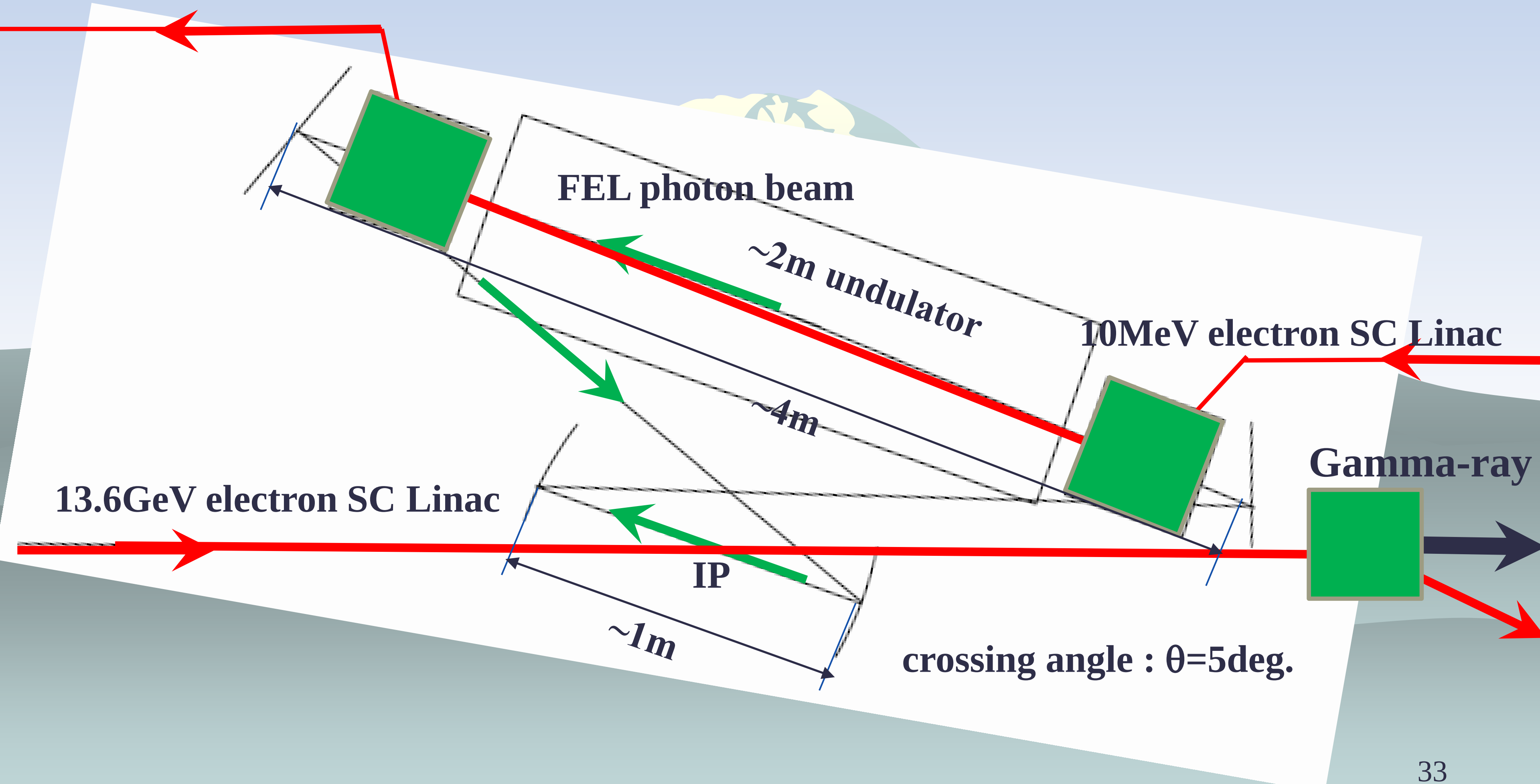
x 5 at present

PoP Experiment had been done.

M. Fukuda *et al*. Physical Review Letter, 91, 164801(2003)
T. Omori *et al*. Physical Review Letter, 96, 114801(2006)

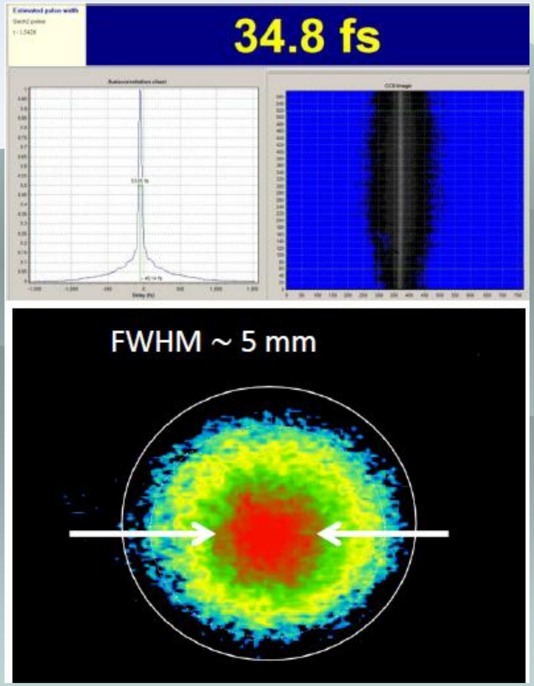
Presented by Junji Urakawa
At KILC12, Daegu, Korea

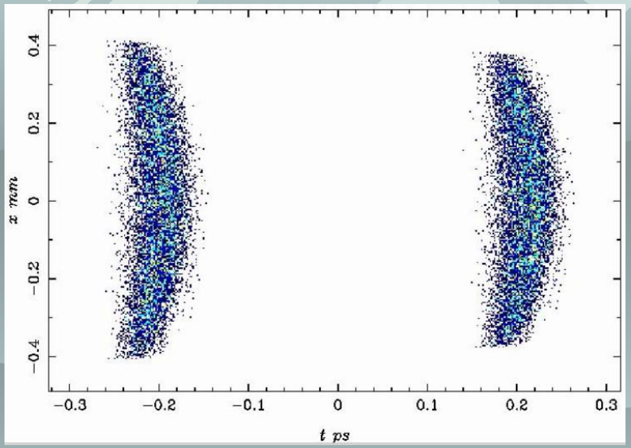
1mJ laser pulse generated by SC FEL is relatively easy.
Smaller laser waist size in σ at IP requests to reduce the distance of two concave mirrors.



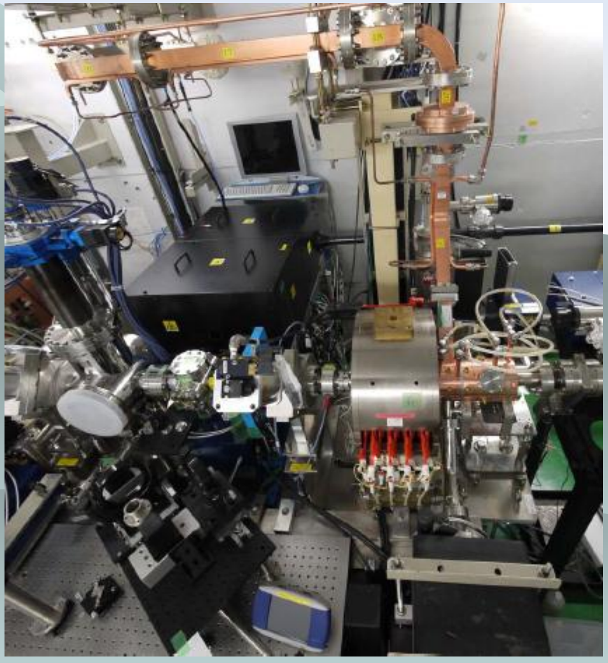
What is super radiant mode? Ideal micro-bunch train with same micro-bunch spacing as main radiation wavelength can radiate coherently ,which is narrow bandwidth radiation.

We are seriously considering the generation of micro-bunch train in single RF acceleration period, say in 20ps. How to generate it and keep time structure of such micro-bunch train during acceleration? Use fs laser (Ti-Sa laser) and photo-cathode gun or phase rotation from transverse to longitudinal direction.



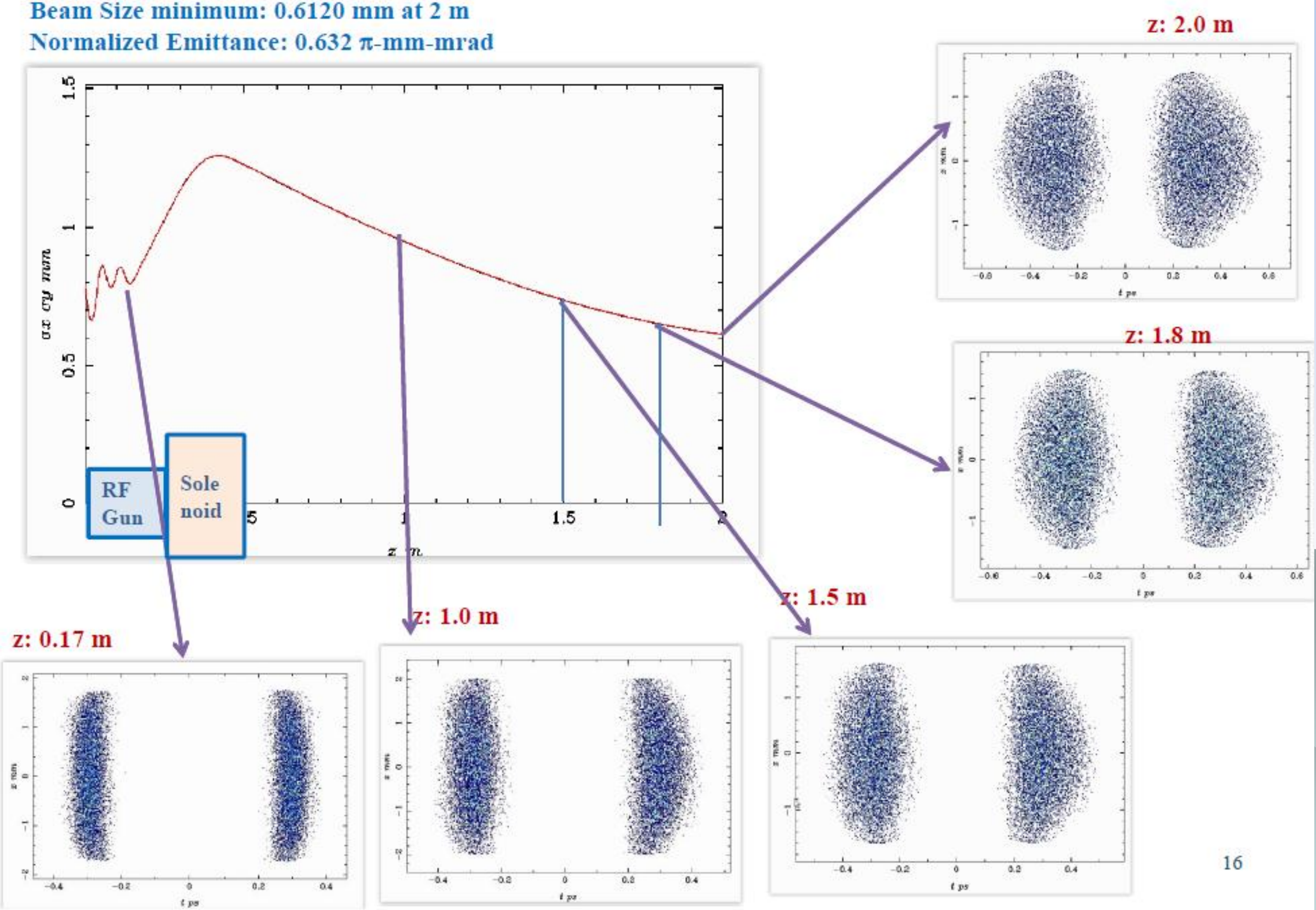


Micro-bunch spacing : 500fs
25pC/micro-bunch at cathode



Simulation result by ASTRA with 1.6 cell photo-cathode RF gun at 5MeV

Beam Size minimum: 0.6120 mm at 2 m
Normalized Emittance: 0.632 π-mm-mrad



Wavelength [μm]	50	100
Both beam size in sigma at IP [μm]	100	200
Enhancement factor	200	300
FEL electron beam energy [MeV]	20	10
High energy electron beam energy [GeV]	9.6	13.6
Energy of Fundamental Compton Edge [MeV]	35	35
Relative Gamma yield [x 10^7]	7.8	6.1
Laser pulse energy generated by ~2.0m wiggler [mJ]	2.5	2.0
FEL efficiency from beam energy to photon energy, k_{eff} [%]	41	65
FEL photon number generated by electron bunch [x 10^{17}]	6.3	10.1
Pulse energy in the cavity during 63msec [J]	0.50	0.60
Stored laser average power [MW]	25.6	31.3
Rayleigh length [mm]	2.5	5.0
Number of Pol. Positron/bunch in DR [x 10^{10}]	3.1	3.0

Cu or good conducting metal with Au coating to deflect the electromagnetic wave and to cool the mirrors.

Summary for new ILC pol. positron source

1. The technologies for electron beam generation are almost mature.

2. 50mA beam acceleration is relatively challenging.
(CW 1.3GHz RF source : 80kW and 300kW exist.)

3. Control of 4 mirror optical cavity is almost mature with enhancement of ~300 .

4. Stable collision is almost OK with timing accuracy of 1psec.

5. Generation of micro-bunch train with wavelength 50μm as micro-bunch spacing which is corresponding 166fs. It is relatively challenging.

6. Problem which should be solved is only heating due to power loss on mirrors. Stored laser power with about 10 times higher comparing usual case is serious problem.

Hopeful solution : Cryomodule for optical cavity is necessary like **148k Cryogenic permanent magnet undulators**.

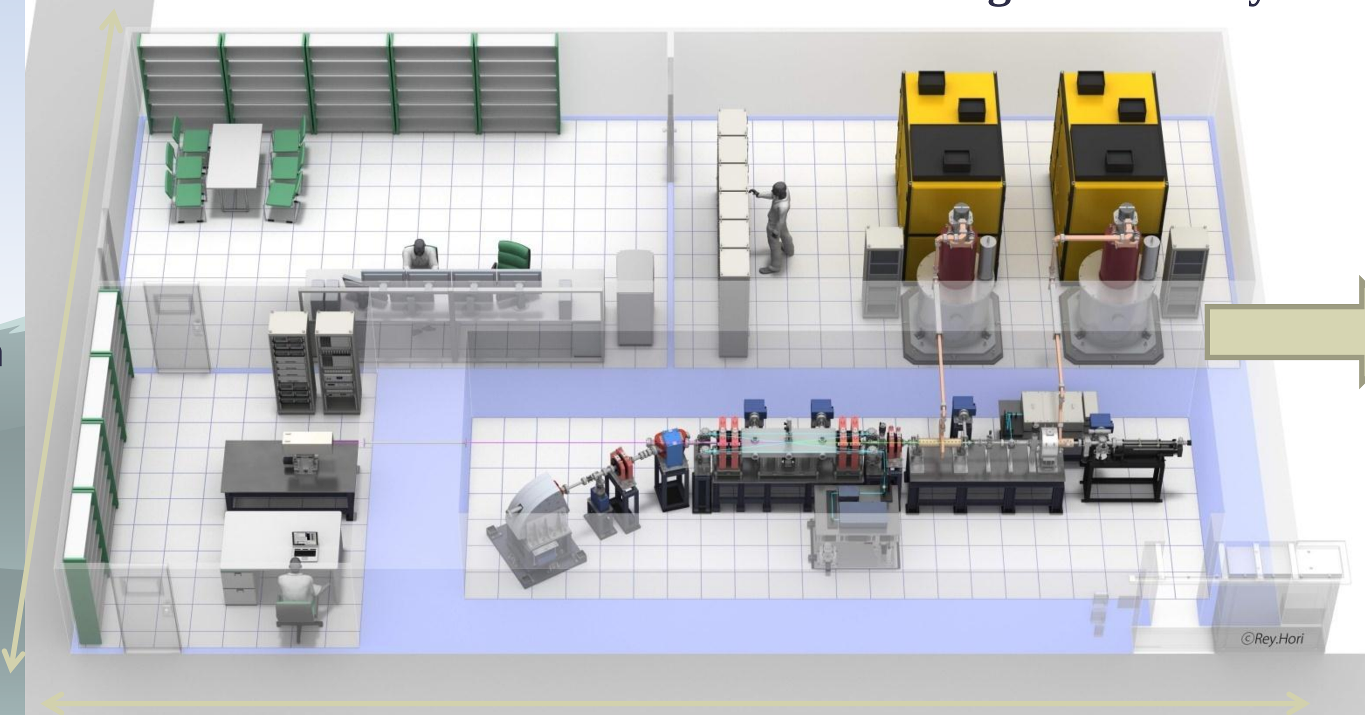
There are many interesting and bright research items for many young researchers.

New Quantum Beam Technology Program(NQBTP) is supported by MEXT from 2013.8 to 2018.3 (~5 years project).

Approved project included two Japanese Companies at least and the development for CW super conducting acceleration technologies. Normal conducting accelerator system and super conducting accelerator system for compact high brightness X-ray source should be realized by joint research with companies.

Normal conducting accelerator system for compact high brightness X-ray

～8m



～12m

Downsizing to 6m x 8m

Welcome your contribution and future collaboration.

Thank you for your attention!