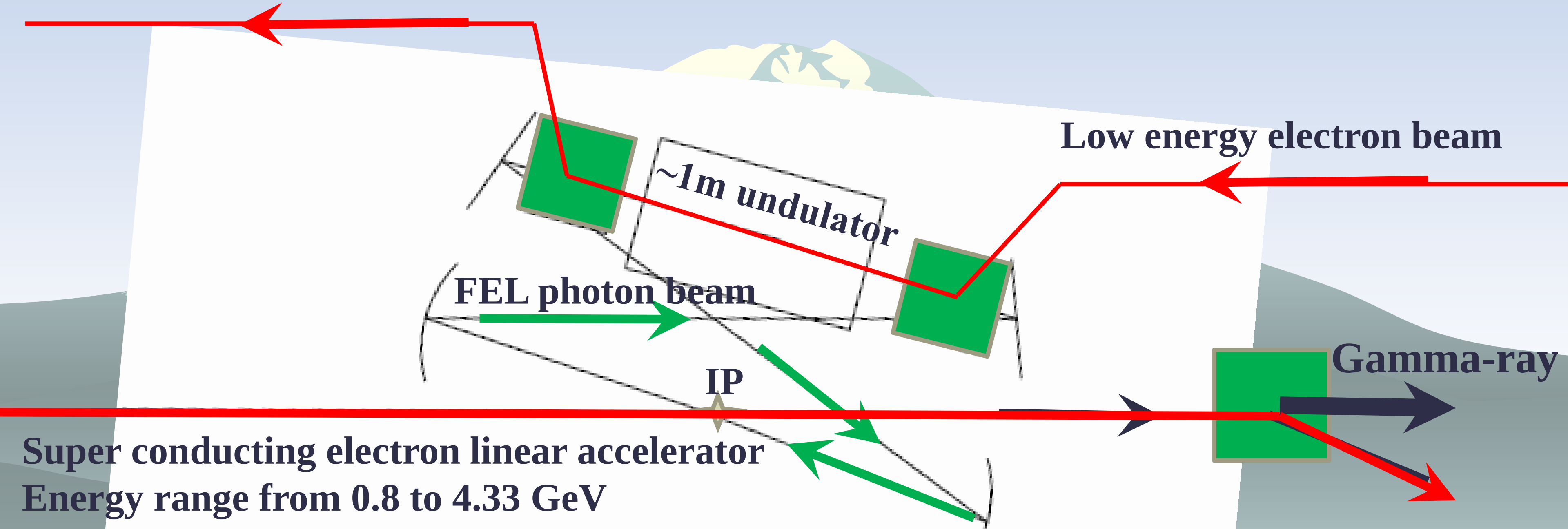
Pol. e+ source based on Compton scattering with FEL & 4 mirror cavity

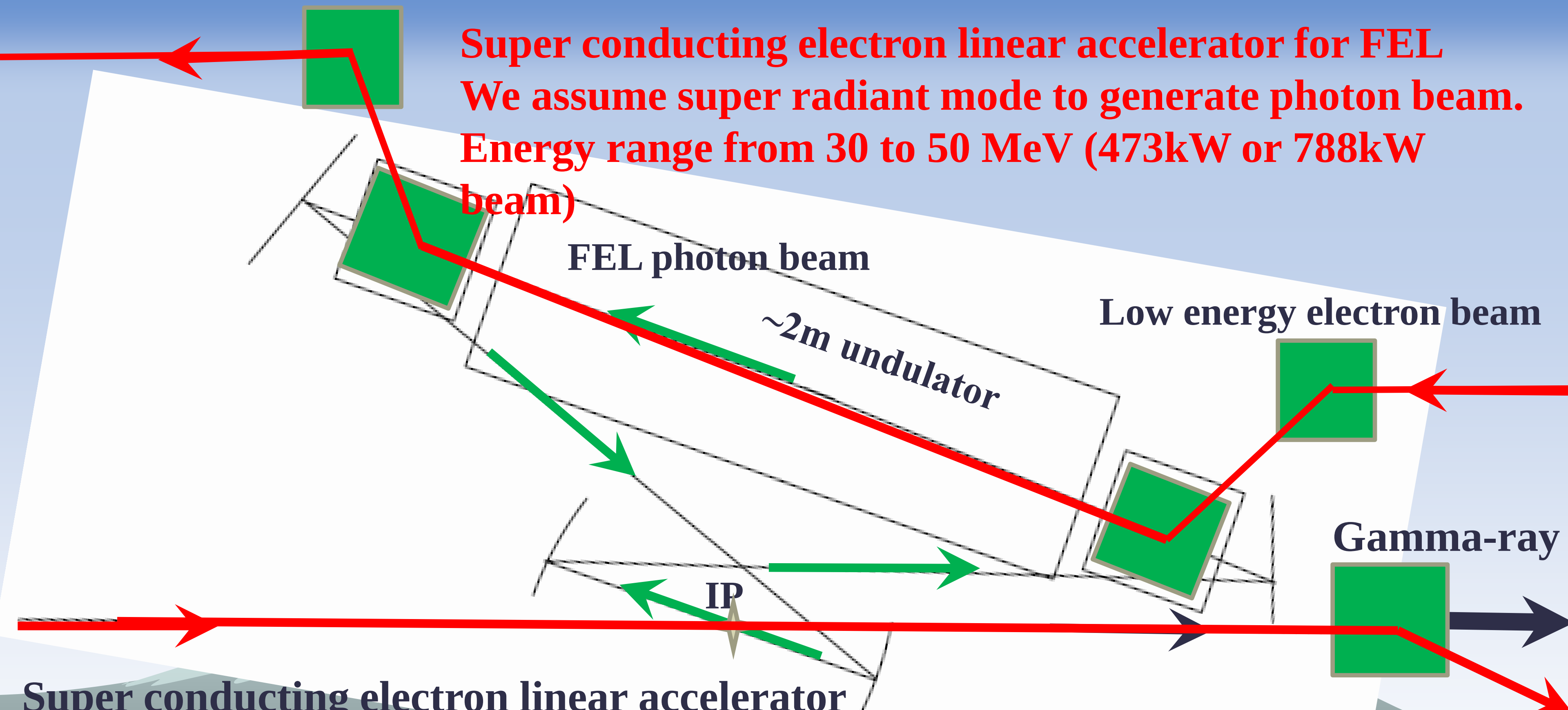
LCWS2014 in Belgrade, 8 Oct. 2014
KEK, Junji Urakawa and TPU, Alexander Potylitsyn

Super conducting electron linear accelerator for FEL
We assume super radiant mode to generate photon beam.
Energy range from 31 to 200 MeV



We survey the possibility of ILC positron source based on inverse Compton scattering with super conducting linear accelerator including advanced technologies which will be confirmed within 3 or 4 years. Consider LCLS-II and recent EUV project.

Super conducting electron linear accelerator for FEL
We assume super radiant mode to generate photon beam.
Energy range from 30 to 50 MeV (473kW or 788kW beam)



Super conducting electron linear accelerator
Energy range from 1.4 to 1.96 GeV (2.3MW or 3.1MW beam)

Wavelength [um]	1	2
Both beam size in sigma at IP [um]	10	16
Enhancement factor	5000	3000
FEL electron beam energy [MeV]	50	30
High energy electron beam energy [GeV]	1.4	1.96
Energy of Fundamental Compton Edge [MeV]	36	36
Collimated Gamma yield on target [x 10^7]	4.27	5.76[2]

“Pol. Positron source based on inverse Compton scattering with super-radiant FEL and 4 mirror optical cavity”

We assume 50mA 5Hz-63msec super-conducting linear accelerator to generate high intensity FEL photon beam and gamma-ray based on inverse Compton scattering.

I am also assuming 100% beam injection efficiency to accumulate positron beam into 5GeV damping ring.

63msec and 5Hz super-conducting linear accelerator has 162.5MHz bunch repetition rate which means 63 x 162.5k bunches with bunch spacing 6.15nsec per beam pulse.

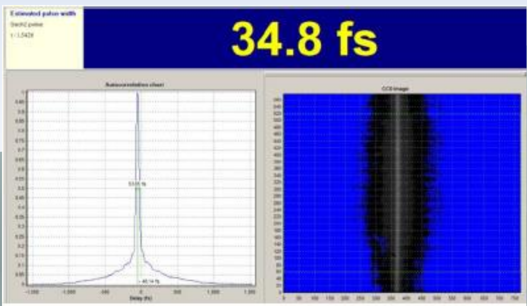
So, we will accelerate 307.5pC/bunch with 6.15ns bunch spacing to generate the gamma-ray beam and to stack positron beam 7802 times for each bunch into the 5GeV damping ring.

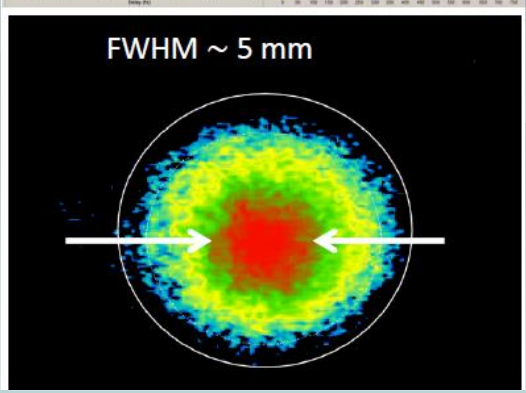
The conversion efficiency from gamma-ray to accumulated positron is assumed to be 10%.

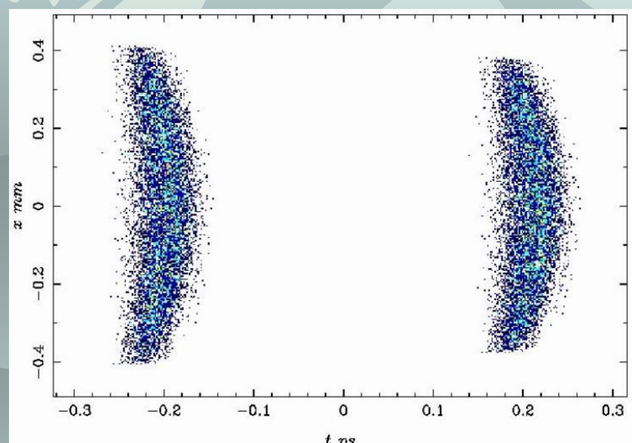
Necessary yield of the gamma-ray from single Compton collision is 3.7 x 10^7 gamma-ray.

Wavelength [um]	1	2
Laser pulse energy from ~2.0m wiggler [mJ]	0.240	0.433
FEL efficiency from beam energy to photon energy, k_{eff} [%]	1.5	4.7
FEL photon number per bunch [x 10^{16}]	0.13	0.47
Resulting photon number per pulse (with taking into account the enhancement factor) [x 10^{19}]	0.65	1.4
Pulse energy in the cavity [J]	1.2	1.3
Stored laser average power [MW]	61	66
Rayleigh length [mm]	1.2	1.6
Number of Pol. Positron/bunch in DR [x 10^{10}]	3.3	4.5

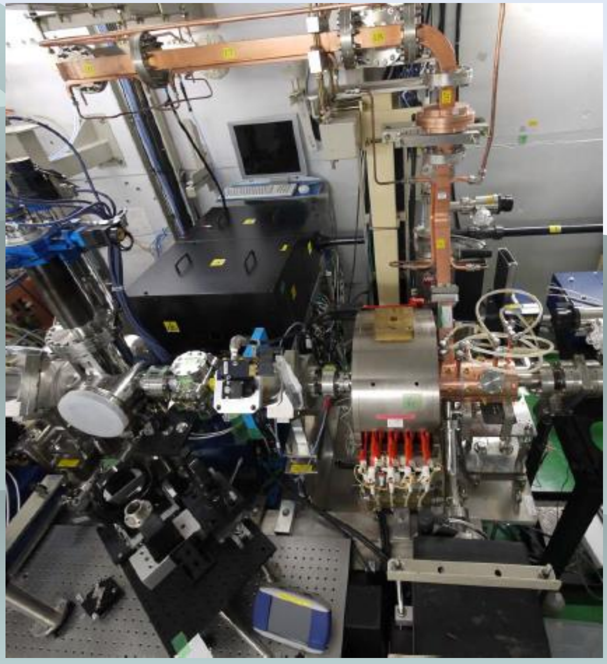
What is super radiant mode? Ideal micro-bunch train with same micro-bunch spacing as main radiation wavelength can radiate coherently ,which is narrow bandwidth radiation.
We are seriously considering the generation of micro-bunch train in single RF acceleration period, say in 10ps. How to generate it 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.





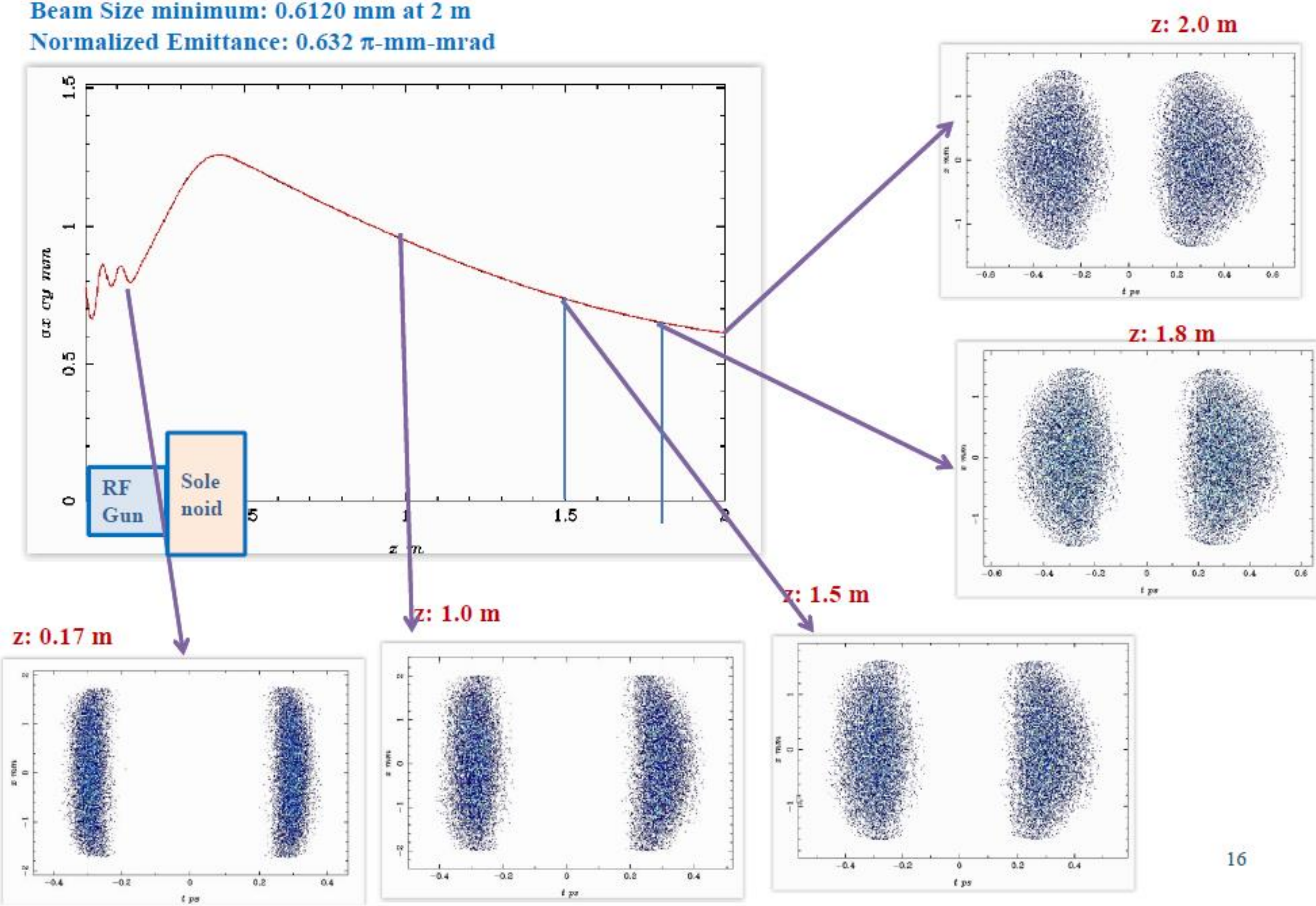


Micro-bunch spacing : 500fs
25pC/micro-bunch at cathode



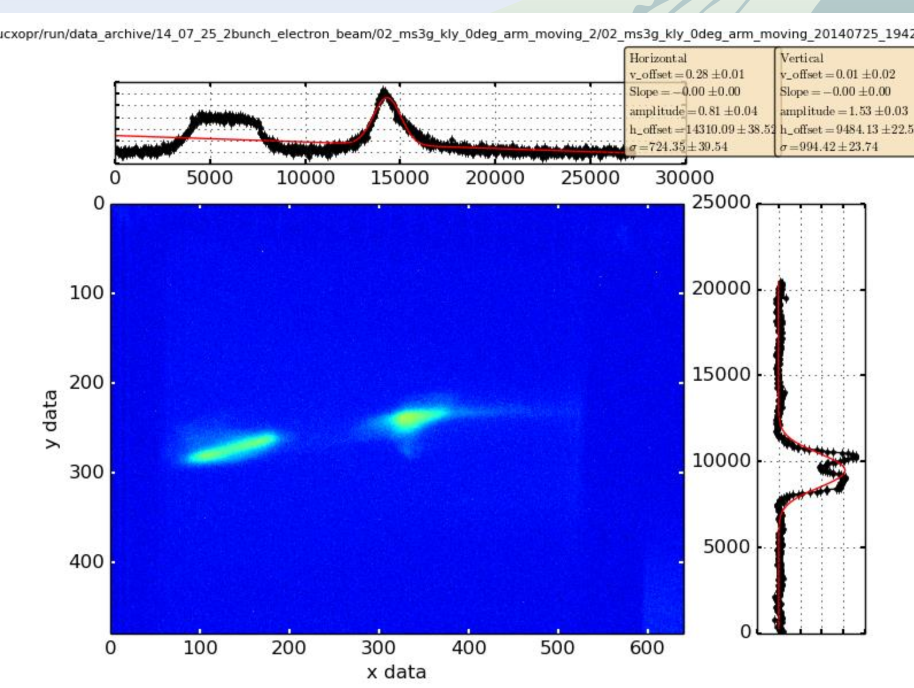
Simulation result by ASTRA with 1.6 cell photo-cathode RF gun

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

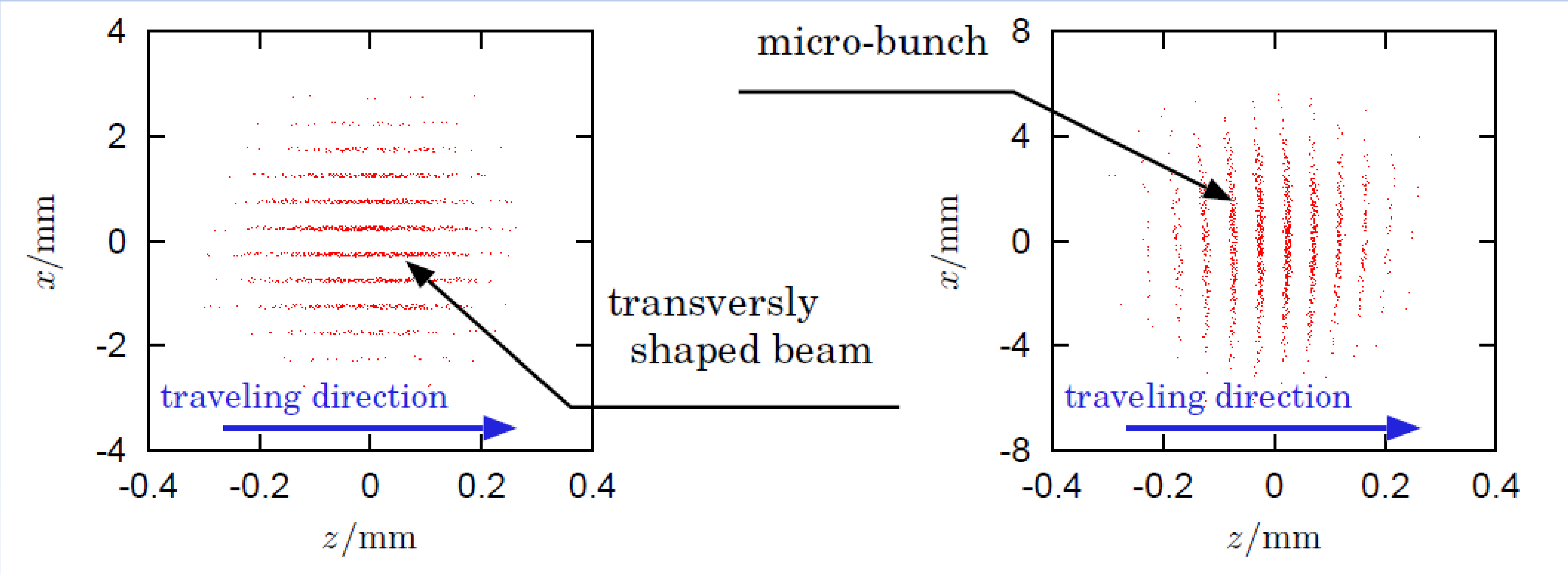


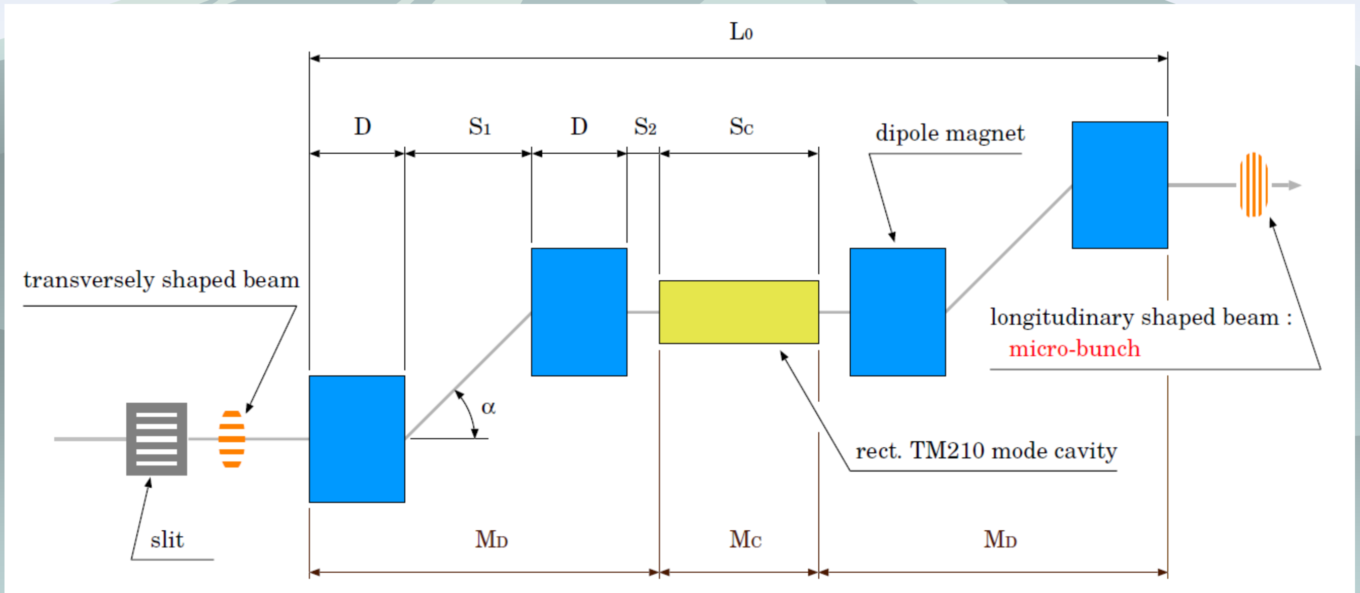
One example of measurement result using zero cross acceleration technique to convert time structure to energy.
Generation of two micro-bunch train was confirmed using Ti-Sa laser and photo-cathode RF gun.
4 micro-bunch train generation is not difficult.
We will generate THz and confirm the super radiation using appropriate Smith-Purcell gratings.

Next step; we will install 30cm wiggler to confirm the super radiation also.



For shorter wavelength radiation, we use phase-space rotation.





I copy parts of the slide from M. Kuriki's talk at PFWS 2013.

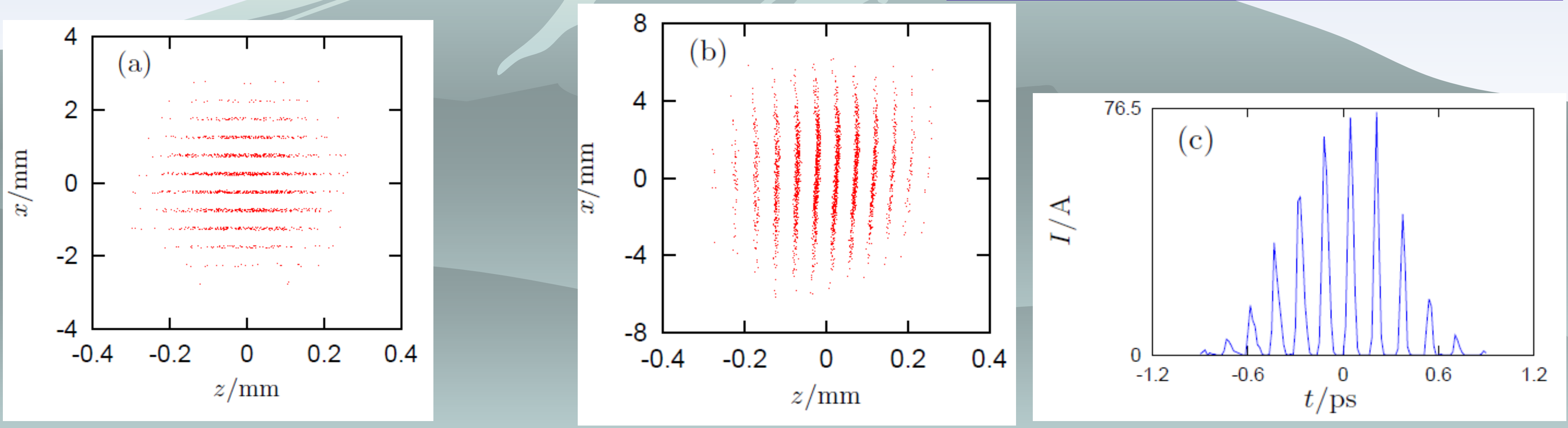
Simulation result from Kuriki's slide.

We have to demonstrate this method using existing accelerator in the range from 150μm to 1μm as wavelength.

For more shorter wavelength, Grave of MIT gave an idea and the simulation results in 2012.

Precise beam instrumentation and new cathode idea are necessary for this study.

Parmeter	Sym	Value
Beam Energy	E	15 MeV
Bunch charge	Q	100 pC
N. emittance	ε_{nx}	1.0 πμm
rms radius	σ_0	2mm
slit width	Δ_{slit}	0.08mm
slit interval	Δ_{int}	0.34mm
Max. slitted charge	q_{max}	3.8pC
μbunch freq.	$f_{\mu b}$	6.25THz
μB width FWHM	Δt	34fs
Peak current	I_{max}	77A



Bunch repetition rate is 162.5MHz and 1312 bunches are needed in 3238 m damping ring. In the damping ring, we can expect the stacking by factor 7802 based on top-up injection using non-linear kicker or very fast kicker.
If we assume 10% conversion efficiency from gamma-ray to positron and 100% positron injection efficiency into the damping ring, 3.0 x 10^{10} positron/bunch is obtainable during 63msec every 5Hz. In this case single FEL target system is enough in order to obtain ILC pol. positron beam in the damping ring.

Wavelength [um]	1	2
Rayleigh length [mm]	1.2	1.6
Pulse energy in the cavity [J]	1.2	1.3
Stored laser average power [MW]	61	66
No. of Gamma photons on rotating target per beam pulse in the period of 63ms [x 10^{14}]	4.4	5.9
No. of generated Pol. positron just after the target in the period of 63ms [x 10^{13}]	4.4	5.9
Number of Pol. Positron/bunch in DR [x 10^{10}]	3.3	4.5

Bunch charge is 307.5pC/bunch.
Pre-Summary: 50mA beam acceleration and 63msec RF source are relatively difficult at present. However, ERL should be establish following technologies: 100mA, CW operation with 15MV/m accelerating gradient in the future. ILC target problem requests longer gamma-ray pulse and 63msec for the generation of gamma-ray is attractive, so we are considering 15MV/m acceleration gradient operation with 63msec RF pulse length. Therefore, precise FEL radiation evaluation is necessary including the effect of super-radiation with normalized emittance 1μrad.

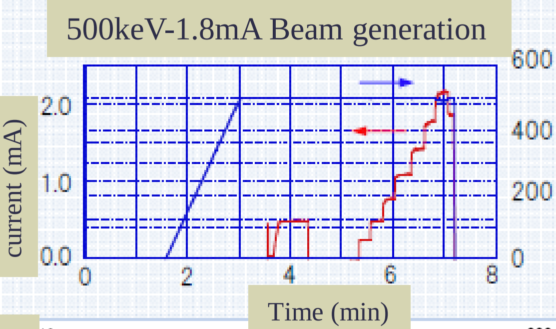
From IPAC14 I thought 148k Cryogenic undulator was good candidate for FEL because of cooling ability.
The period of permanent magnet at 148k will be 5cm with gap more than 2cm and we can reduce the beam energy, also we can increase the stored energy in the optical cavity using 148k cooling system.

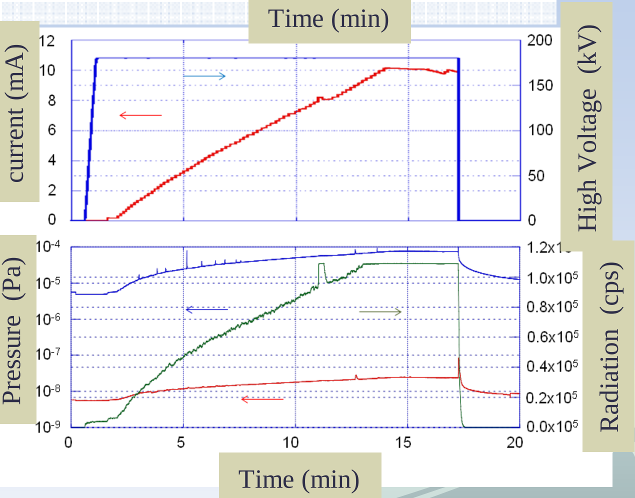
Cooling system for cryogenic undulator should be applied to optical cavity because heating due to circulating laser power is very high.

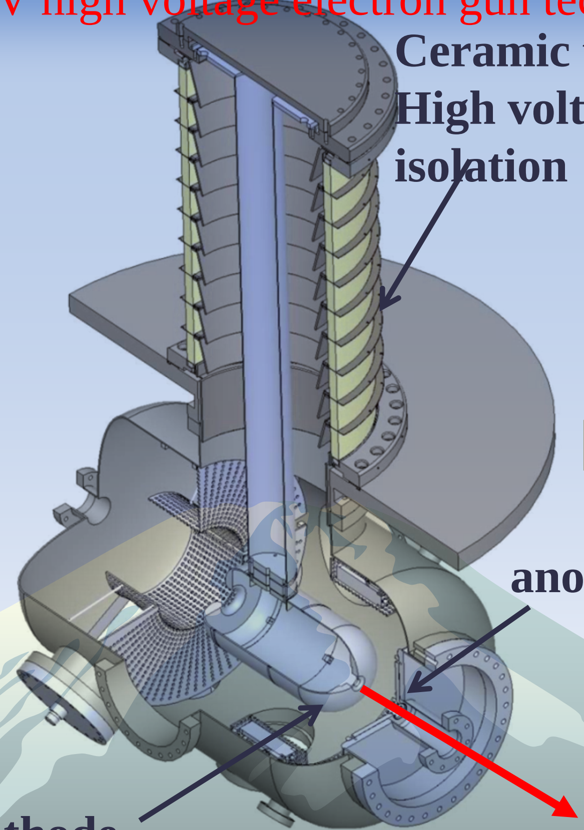
Concept of new scheme

1. 5Hz long electron pulse acceleration technology using super conducting linear accelerator like ILC and ERL.
2. Positron beam stacking into main damping ring within 63msec period.
3. FEL coherent radiation photons are coherently accumulated in 4 mirror planar optical cavity.
4. High energy gamma-ray is generated based on inverse Compton scattering with 5Hz super conducting linear accelerator.
5. Efficiency of positron injection into damping ring is 100% using fast kicker into longitudinal & transverse phase space.

500kV high voltage electron gun technology





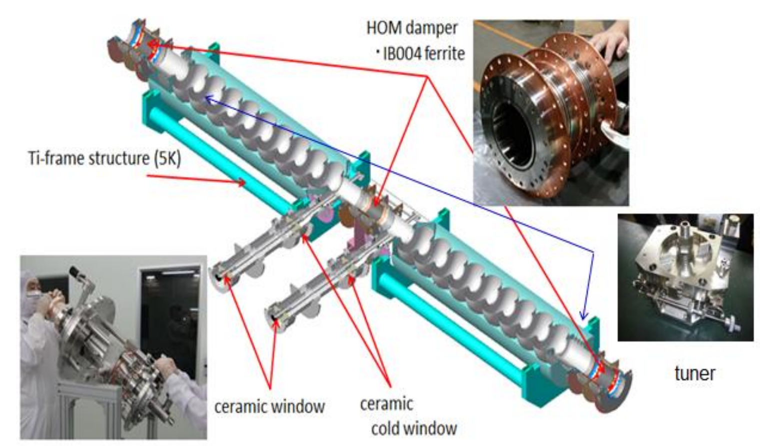


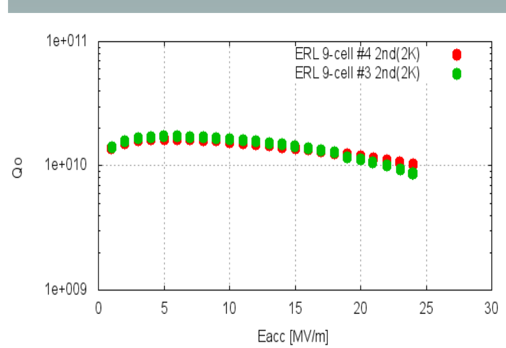
500kV-DC Gun

From Negative Electron Affinity (NEA)-GaAs Photocathode to Multi-Alkali photocathode Development

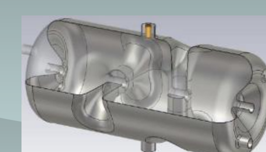
From DC gun to Cryogenic RF gun Development

Reason: to long lifetime and Compact





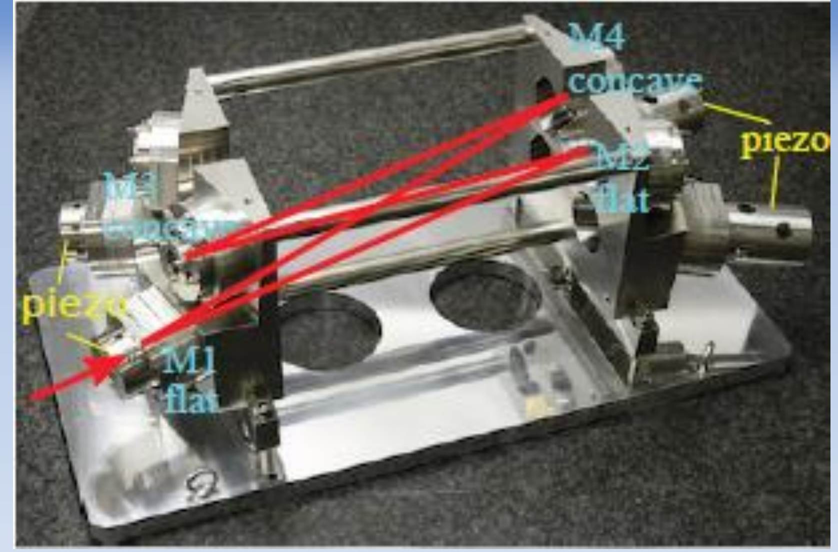
4K 325MHz super Conducting Spoke cavity

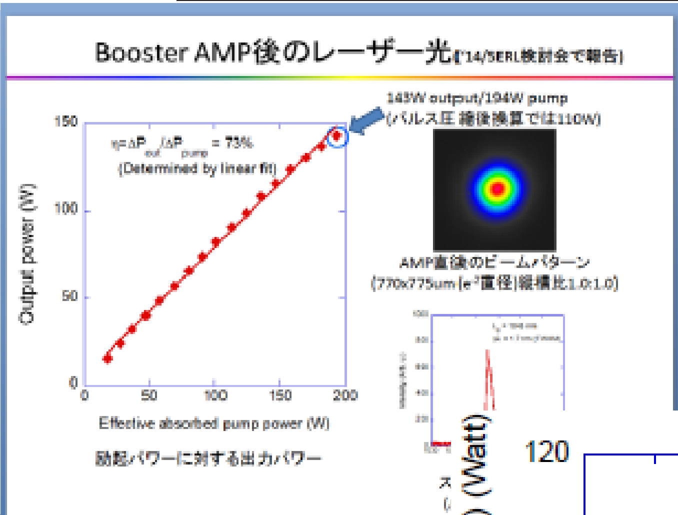


Compact semi-conductor amplifier is commercial available..

Table 1: Design parameters of the mode-locked fiber laser.

Average power	100 W
Center wavelength	1040 nm
Bandwidth (FWHM)	2 nm
Pulse duration	1 ps
Repetition rate	162.5 MHz





JAEA almost established the specification which we requested. Laser system will be installed in this year at KEK-cERL.

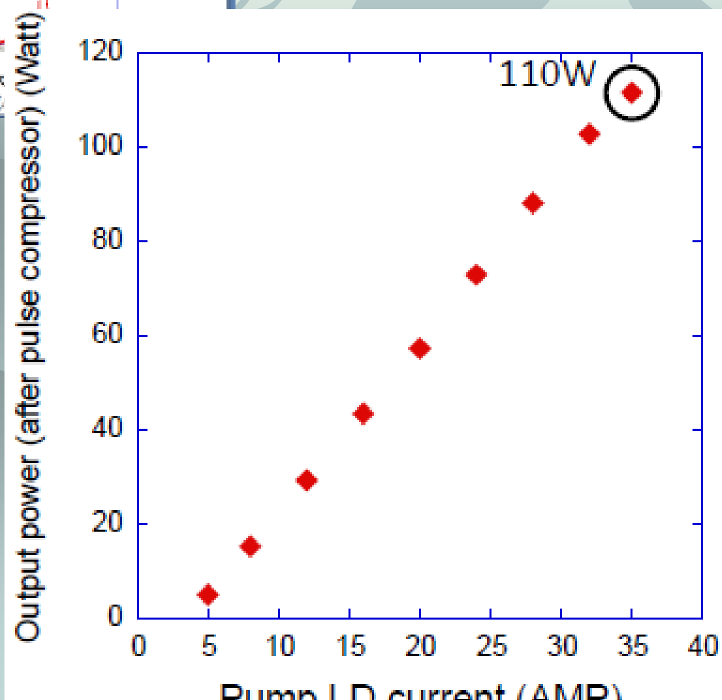


Table 2: Design parameters of the optical cavity

Repetition rate	162.5 MHz
Finesse	5600
Collision angle	18 degree
Spot size at IP (σ_x/σ_y)	20/30 μm
Specification of mirrors	
Substrate material	Fused silica
Diameter	25.4 mm
Reflectivity	
M1	99.9%
M2	99.99%
M3 and M4	99.999%

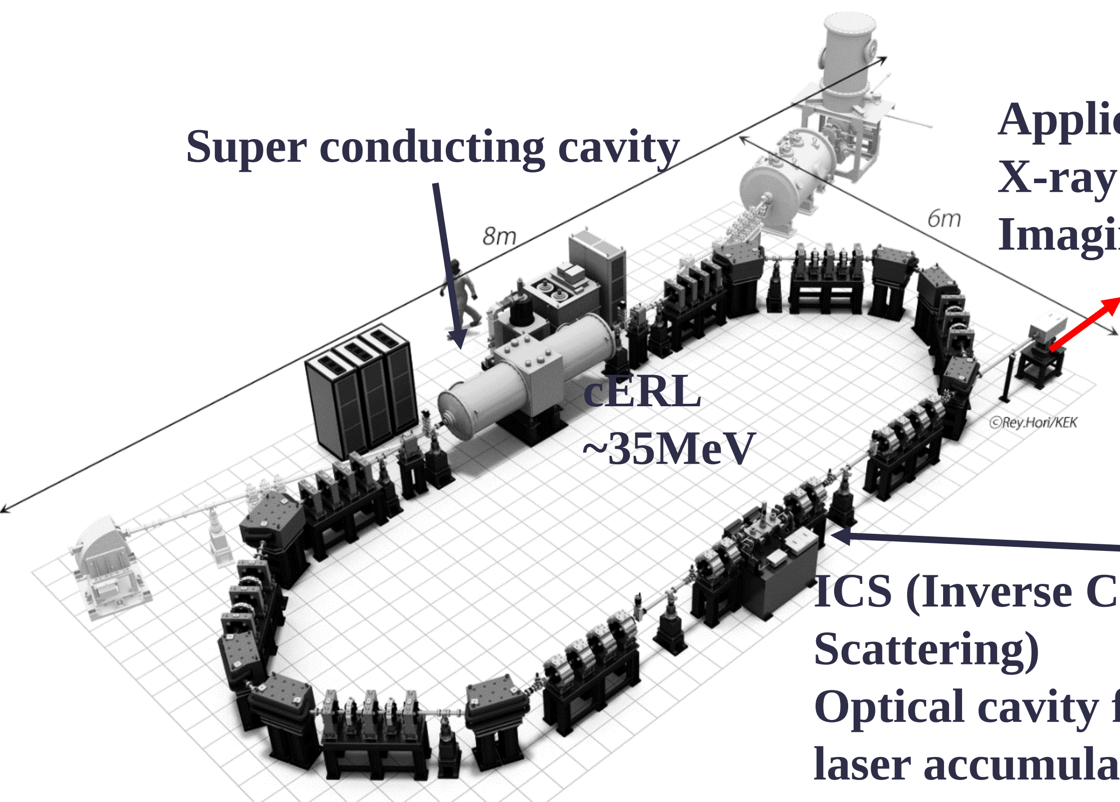
Total system will be tested in this year.

X-ray generation will start on March 2015.

New QB Program (Fundamental Technology Development for High Brightness X-ray Source and the Imaging by Compact Accelerator under Photon and Quantum Basic Research Coordinated Development Program)

2013 – 2017 research program

Compact X-ray Source (Peak Brightness 10^{19})
~keV-100keV tunable X-ray generation



Super conducting cavity

cERL
~35MeV

Application of X-ray: Imaging etc.

ICS (Inverse Compton Scattering)
Optical cavity for pulse laser accumulation, collision point

Development of Basic Technologies

1. Multi-alkali photocathode for high average current
2. 20k Cryogenic rf-gun
3. ERL
~1MW electron beam
4. ~1MW high-average power laser
5. ~10μm precise collision technique
6. X-ray imaging
7. 4K 325MHz spoke cavity

Summary

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. 650MHz or 325MHz SRF technologies should be developed for future ILC beam source.)

3. Control of 4 mirror optical cavity is almost mature with enhancement of ~3000.

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

5. Generation of micro-bunch train with wavelength 2μm as micro-bunch spacing which is corresponding 6.64fs. It is relatively challenging.

6. Problem which should be solved is only heating due to power loss on mirrors. Stored laser power with about 50 times higher comparing usual case is serious problem.

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

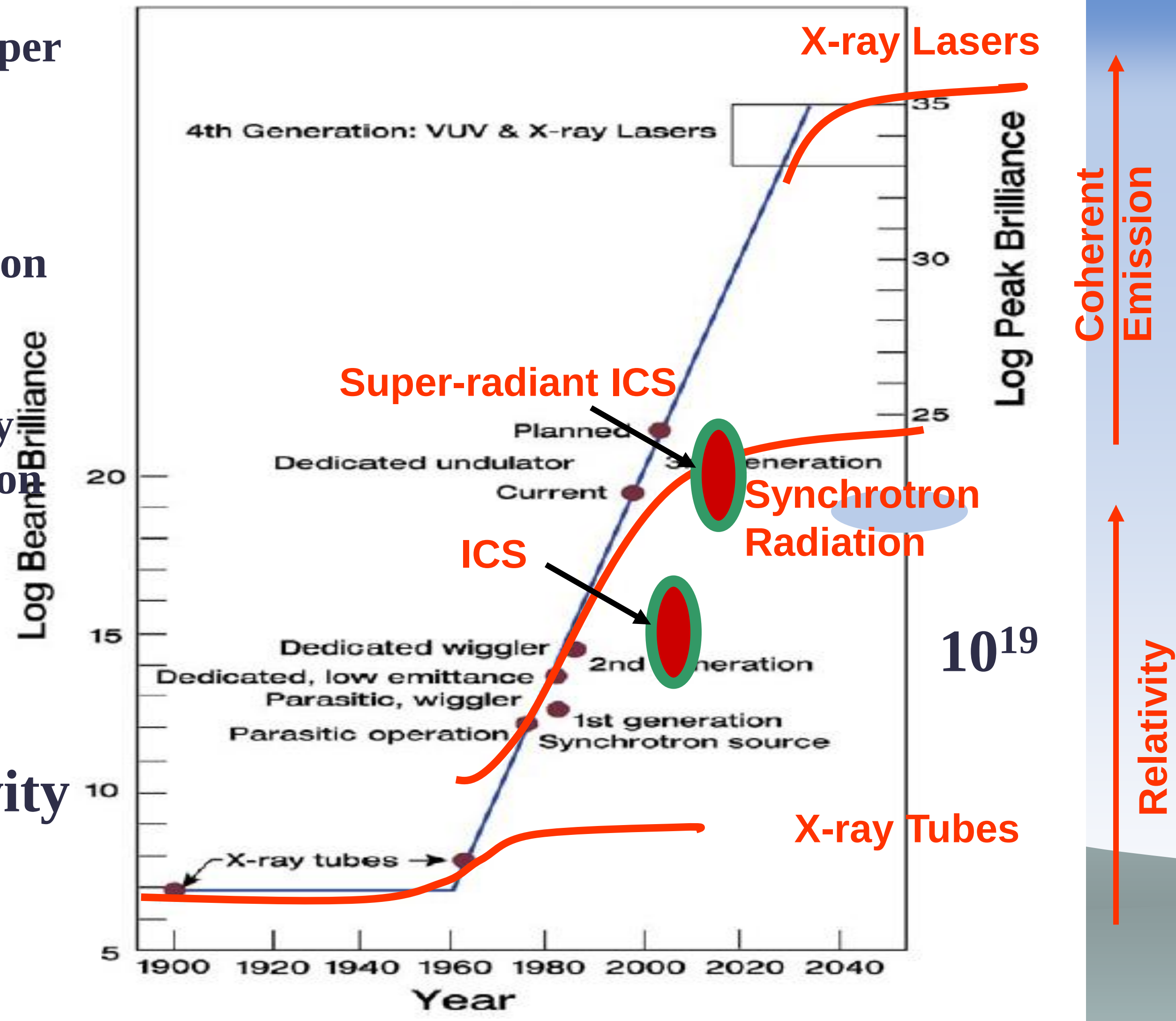
There are many interesting and bright research items for many young researchers.

Key-tech. for stimulated and super radiation

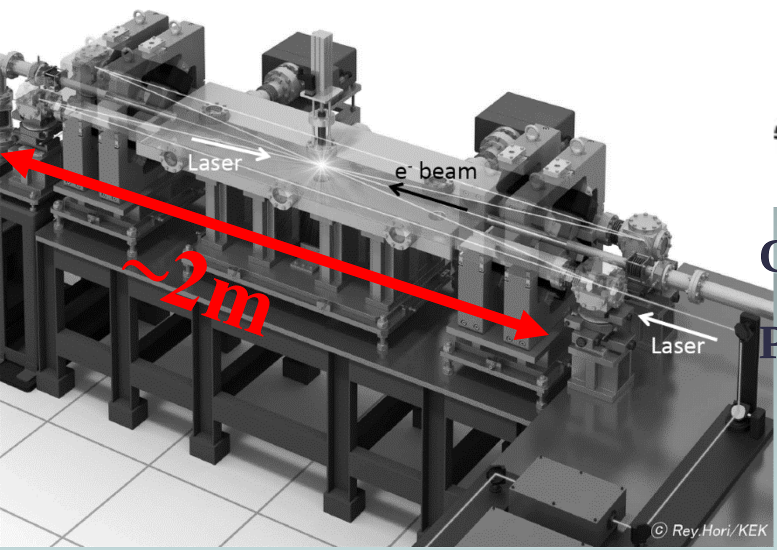
Efficient pre-bunched FEL and micro-bunch train generation

Energy or velocity modulation to make intensity modulation by laser field or intensity modulation by other tech..

and coherent radiation



2D 4-mirror optical cavity

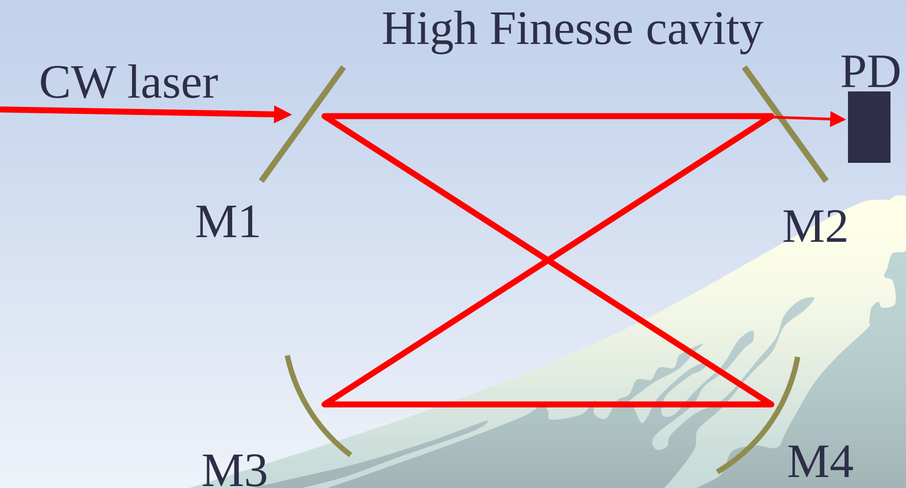


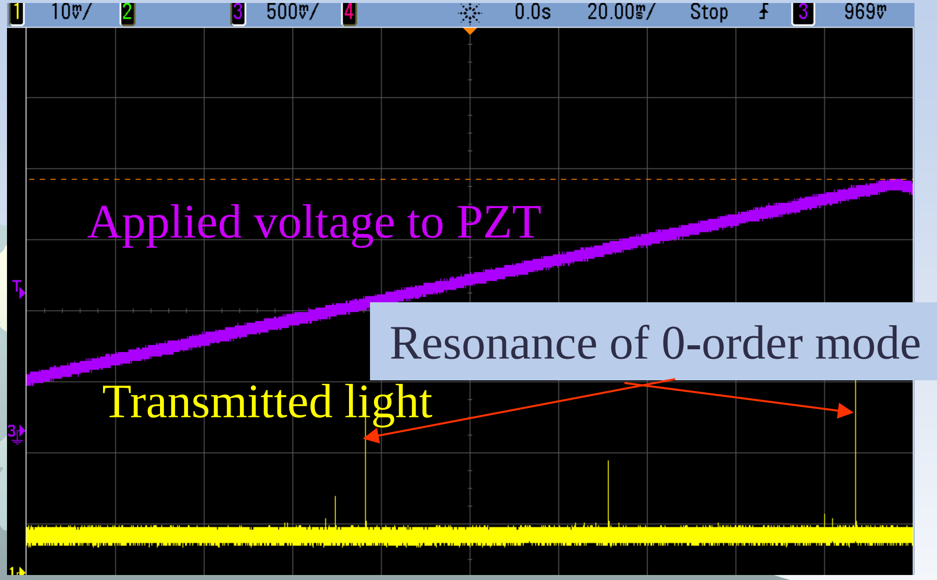
Copy of presentation by W.S. Graves, MIT, March, 2012

Presented at the ICFA Future Light Sources Workshop

Thank you for your attention!

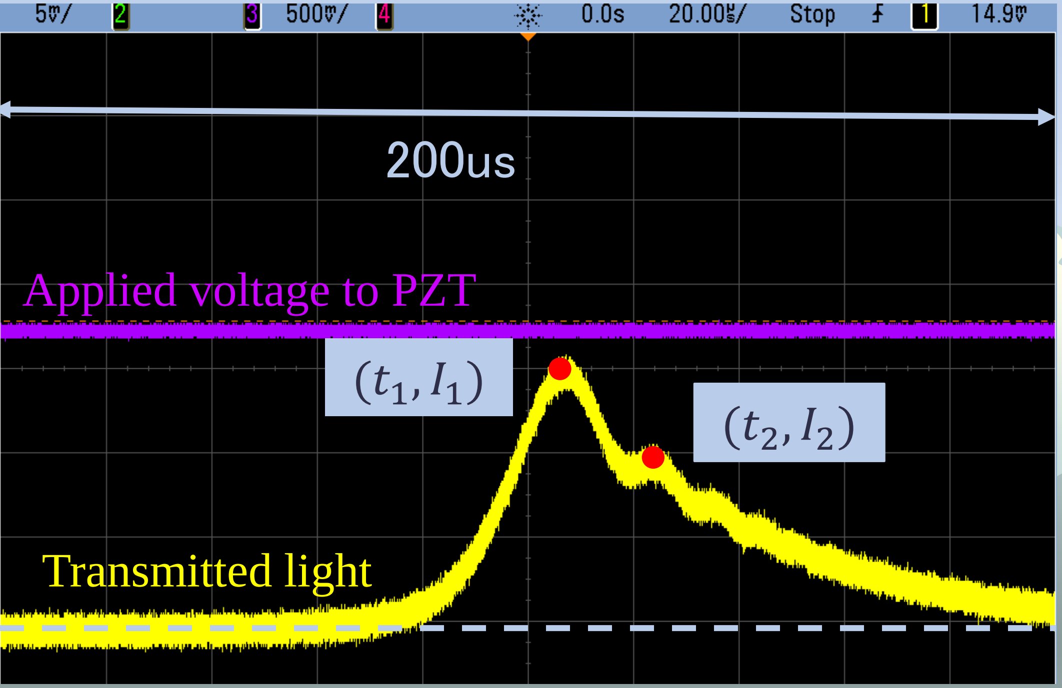
High Finesse 4 mirror optical cavity development





Mirror	Co.	Reflectivity(spec.) [%]	Transmission(meas.) [ppm]
M1(flat)	REO	99.99	70±7
M2(flat)	LMA	99.999	10±3
M3(concave)	LMA	99.999	10±3
M4(concave)	LMA	99.999	10±3

Evaluation of high finesse cavity



Finesse ∝ lifetime of photon in the cavity

$$\tau = -\frac{t_1 - t_2}{\ln(I_1) - \ln(I_2)}$$

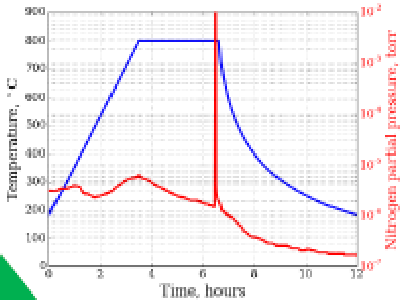
Measurements: τ = 40 ± 1us
⇒Finesse = $4.5 \times 10^4 \pm 0.1 \times 10^4$
enhancement factor = 1.5×10^4
Calc. value from mirror spec.
Finesse = 4.8×10^4
Enhancement factor = 1.66×10^4

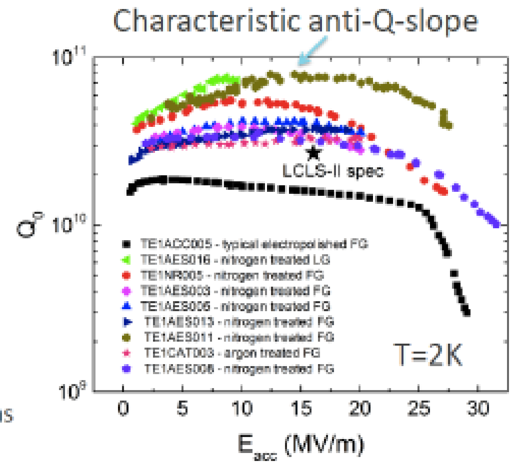
attenuation rate within one turn in the optical cavity:140ppm
=transmission of 4 mirrors(100ppm)+scattering rate + absorption rate
⇒total scattering of 4 mirrors + total absorption =40ppm

Old optical cavity had 600ppm ↔ new optical cavity has 40ppm

Nitrogen doping

Breakthrough in quality factor: nitrogen doping



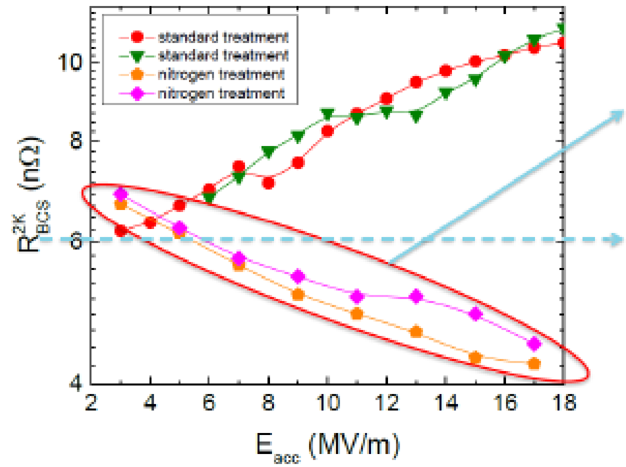


- Injection of small nitrogen partial pressure at the end of 800C degassing followed by several ums of EP-> drastic increase in Q
- Reproduced on tens of 1- and 9-cell cavities at FNAL

A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)

Physics – origin of the effect

$R_s(T) = R_{BCS}(T) + R_{residual}$



Anti-Q-slope emerges from the BCS surface resistance decreasing with field

This is what Mattis-Bardeen theory predicted to be the lowest possible surface resistance for Nb -> we breached it!

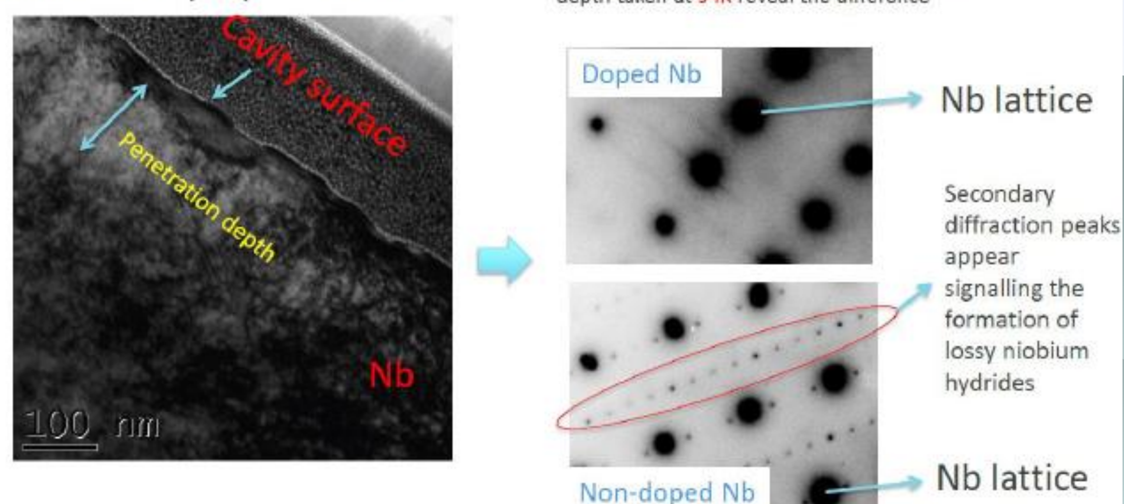
A. Grassellino et al, 2013 Supercond. Sci. Technol. **26** 102001 (Rapid Communication)
A. Romanenko and A. Grassellino, Appl. Phys. Lett. **102**, 252603 (2013)

Nanostructural studies provide first clues

Y. Trenikhina (IIT/FNAL), A. Romanenko – to be published

TEM on FIB-prepared cutouts

Electron diffraction patterns from the penetration depth taken at 94K reveal the difference



- Hydrides may be the cause of the medium and high field Q slopes [see A. Romanenko, F. Barkov, L. D. Cooley, A. Grassellino, 2013 Supercond. Sci. Technol. 26 035003]
- Nitrogen doping may fully trap hydrogen => only intrinsic Nb behavior is then manifested?

Nb_3Sn SRF possibility

To higher gradient (100MV/m?)