超伝導加速による次世代小型高輝度光子ビーム源の開発

「Development for X-ray Source based on Compton Scattering using 1.3GHz Super Conducting RF Accelerating Linac and New Laser Storage Cavity」

2010.2.25「量子ビーム基盤技術開発プログラム」シンポジウム

Junji Urakawa (KEK, Japan)

Under development of Quantum Beam Technology Program(QBTP) supported by MEXT
-Development for Next Generation Compact High Brightness X-ray Source-
5 years project from 2008

Contents :

1. Introduction
2. Status of basic technologies
3. New Laser Storage Scheme using picosecond mode-locking 1μm laser with super-cavity
4. Plans and schedule

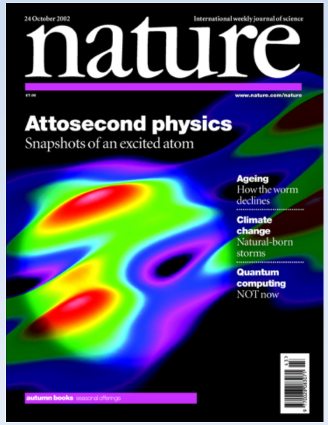
1. Introduction

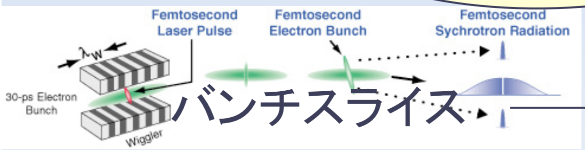
光源の進化：　加速器X線光源とレーザー

次世代放射光

コヒーレンス
超短パルス
小型化

SLAC-XFEL —— 2010





バンチスライス ——

アト秒の科学

2000

ERLの提案 ——

第3世代放射光 ——

超高強度場の科学

プラズマX線源

XFELの提案 ——

1990 —— 高次高調波＝コヒーレント軟X線

フェムト秒の科学

第2世代放射光 ——

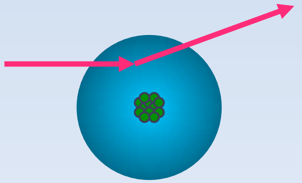
チャープパルス増幅法（1985）

1980

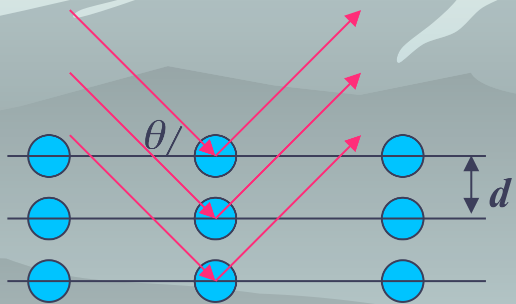
その光源は、何の役に立つんですか？

例１：X線によるタンパクの構造解析
新薬の開発に欠かせない技術

X線は電子で散乱される

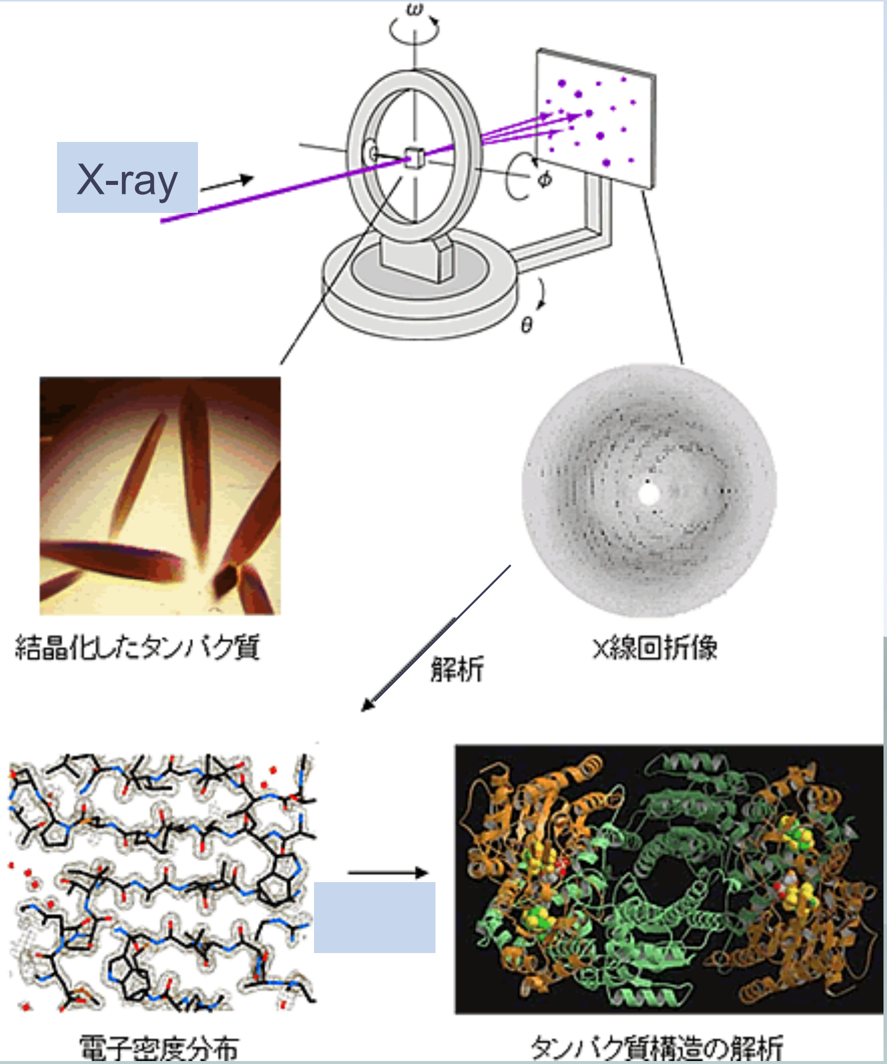


結晶によるX線の散乱
＝　X線回折



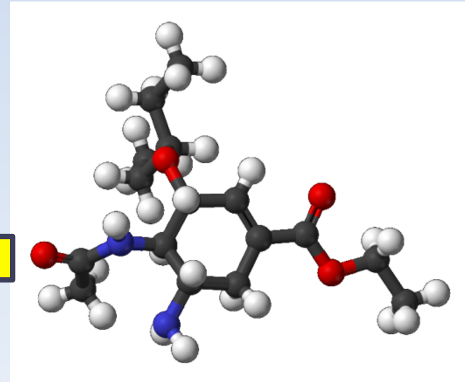
Bragg's law

$$n\lambda = 2d\sin\theta$$



http://www.ap.eng.osaka-u.ac.jp/

新薬の例： インフルエンザ薬、タミフル



ノイラミニダーゼ

インフルエンザウイルスの
感染、増殖に作用する酵素

ノイラミニダーゼ阻害薬

タミフル、ロシェ社
2009年、売上2300億円

例2:X線放射光が3兆円の税金節約に貢献

Physics Today, Sep. 2006.

核兵器工場の廃止措置

feature article

Science-based cleanup of Rocky Flats

David L. Clark, David R. Janecky, and Leonard J. Lane

The chemical and physical interactions of radioactive compounds are key to understanding how they can contaminate the environment and, more importantly, how best to remove them.

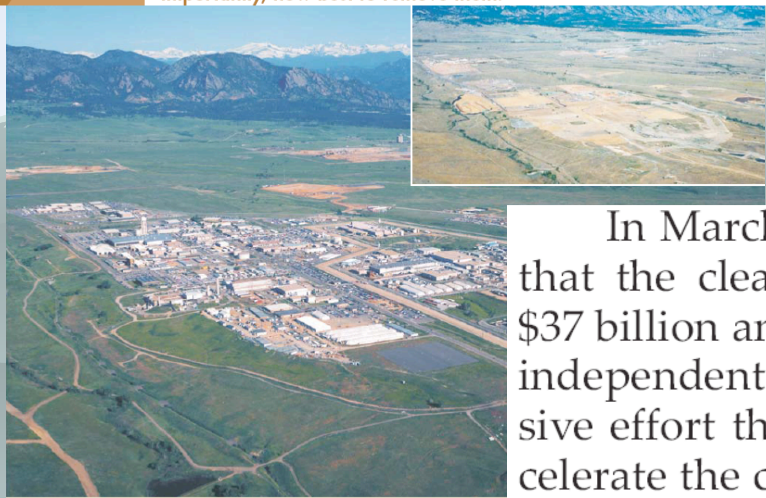
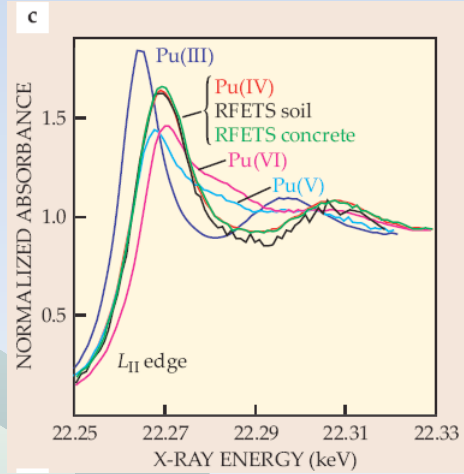


Figure 1. A 1995 photograph of the Rocky Flats Environmental Technology Site s
become as a nuclear production facility, with more than 800 structures built on 1.6
square kilometers of open space. The inset shows the same area in October 2005,

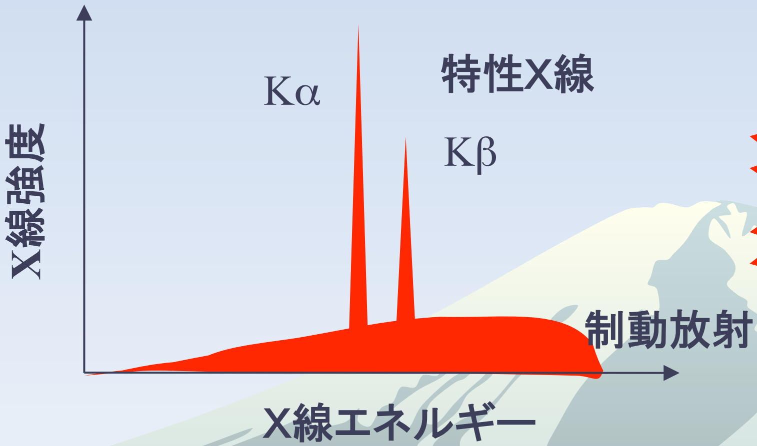


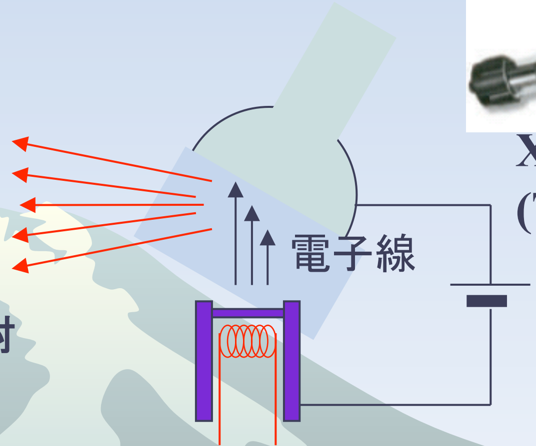
放射光を使ったXANES 実験
Puの環境中移動の精密評価

In March 1995 the US Department of Energy estimated that the cleanup for Rocky Flats would cost in excess of $37 billion and take 70 years to complete. By 1996, DOE and independent contractor Kaiser-Hill Co had initiated a massive effort that eventually resulted in a credible plan to accelerate the closure of Rocky Flats by 31 December 2006 at a contracted cost of $7 billion. After a troubled start, Kaiser-Hill completed the task nearly a year ahead of schedule.

$37B（70年計画）→ $7B（10年で完了）　3兆円の節約

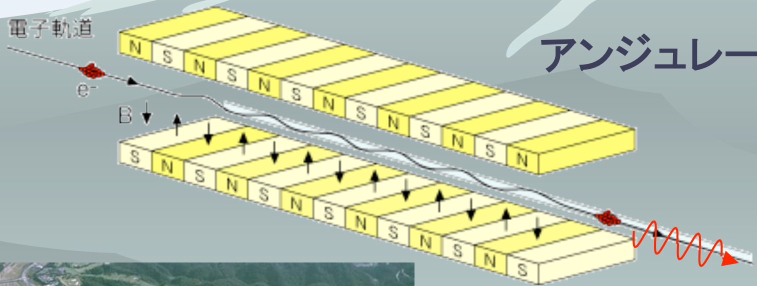
高エネルギー電子による光の発生

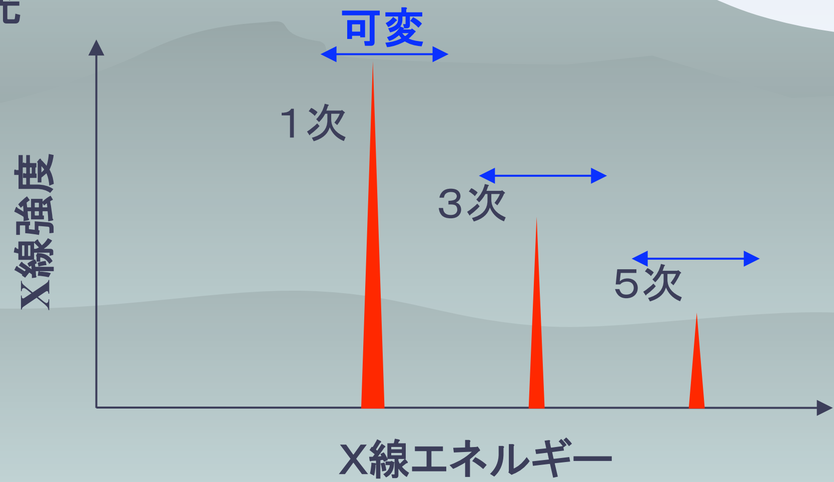




X-ray tube
(TOSHIBA, 1938)

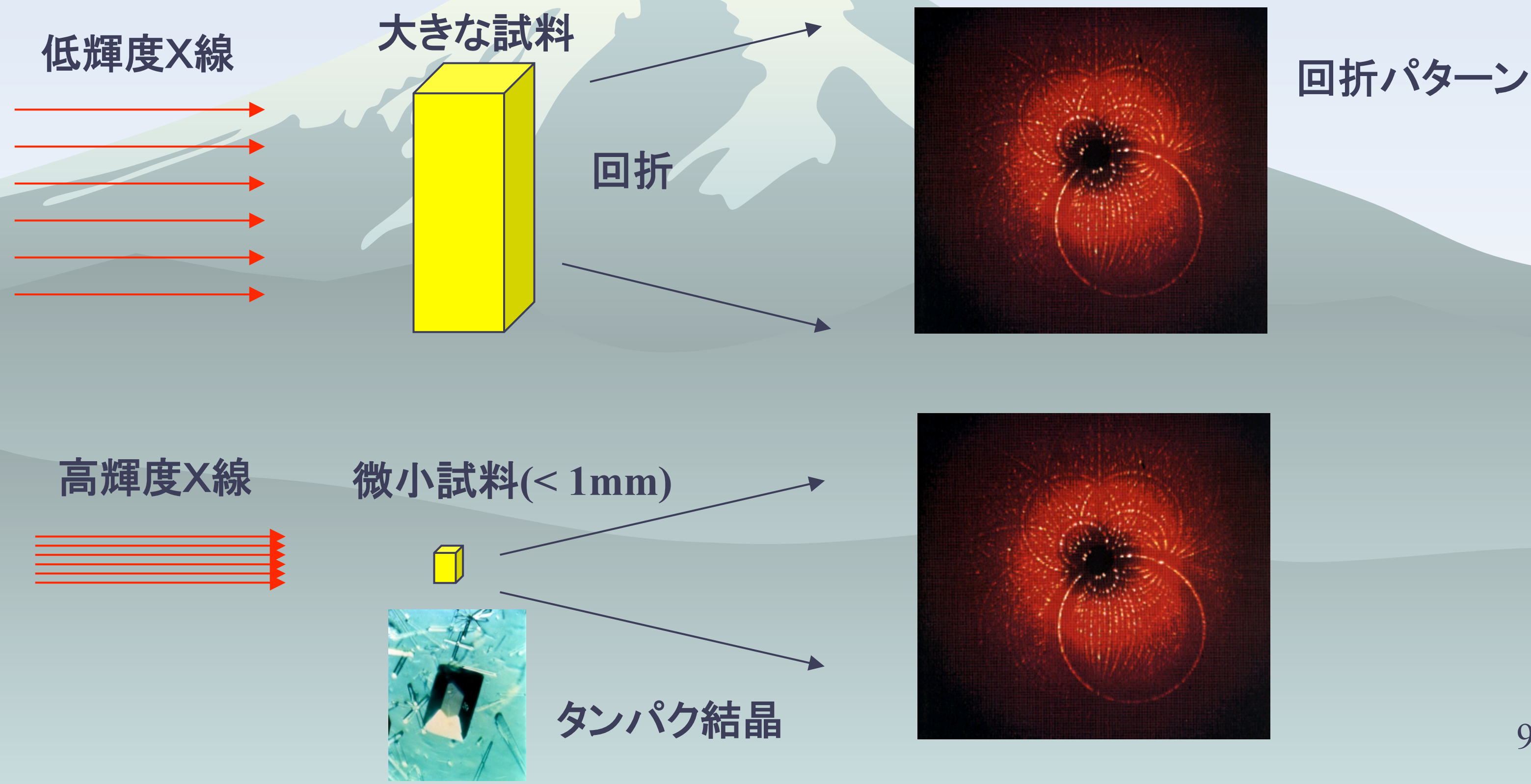
アンジュレータ放射光





より強い光、明るい光を求めて

$$\text{X線輝度} = \frac{\text{光子数}/\text{秒}}{(\text{mrad})^2(\text{mm}^2\ \text{光源面積})(0.1\%\ \text{スペクトル幅})}$$



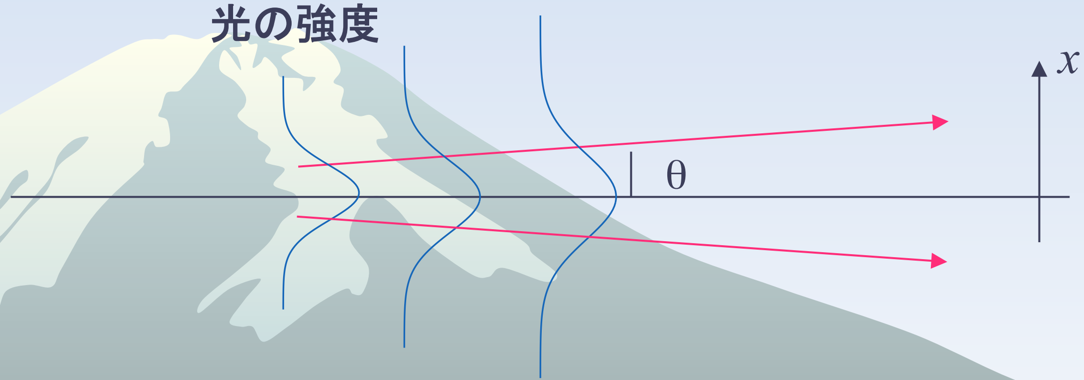
X線の高輝度化
X線ビームはどこまで細く絞れるのか？

"光子" のもつ不確定性　→ 光の広がり＝回折

$$\Delta x \Delta p_x \geq \hbar / 2$$

Δx　位置

Δp_x　運動量



$$\theta = p_x / p$$

$$p = \hbar\omega / c$$

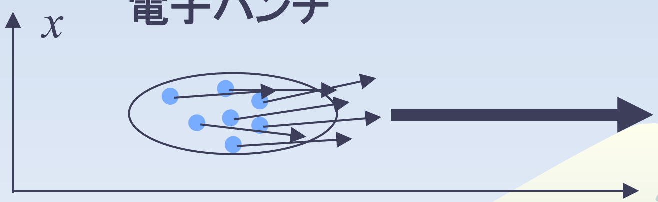
$\longrightarrow$　$\Delta x \Delta\theta \geq \lambda / 4\pi$

$\Delta x \Delta\theta = \lambda / 4\pi$ $\longrightarrow$ コヒーレント光　＝　最小不確定性

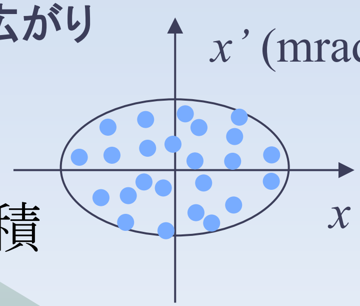
＝　単一横モード

回折限界

電子ビームはどこまで細く絞れるのか？



電子ビームの広がり



エミッタンス

$$\varepsilon = A/\pi$$

蓄積リング放射光源のエミッタンス

emittance = 3 nm-rad

3桁の相違

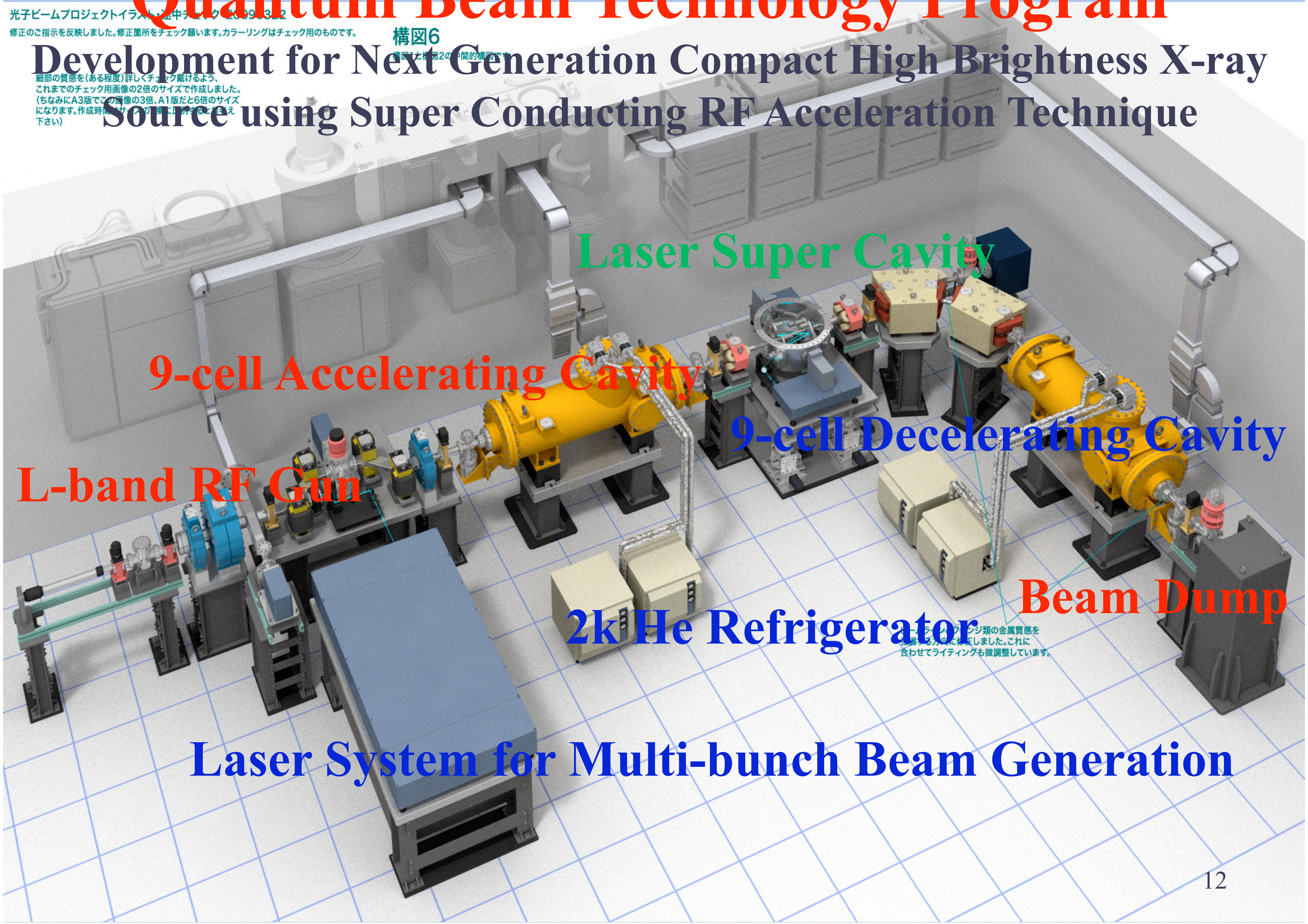
X線回折限界の値

$$\Delta x \Delta \theta = \lambda / 4\pi$$

8 pm-rad for λ=0.1nm

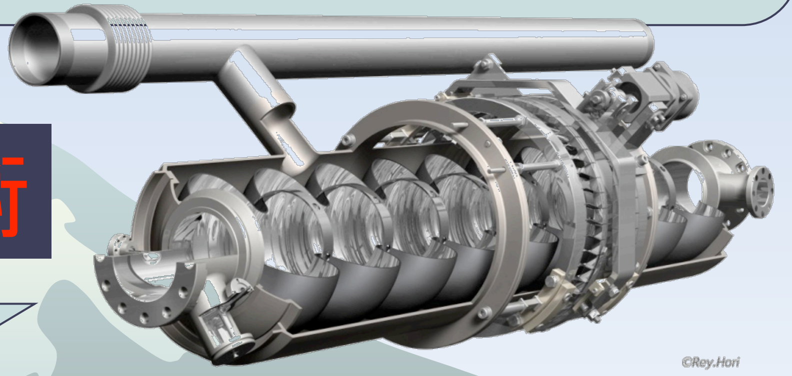
Quantum Beam Technology Program

Development for Next Generation Compact High Brightness X-ray Source using Super Conducting RF Acceleration Technique



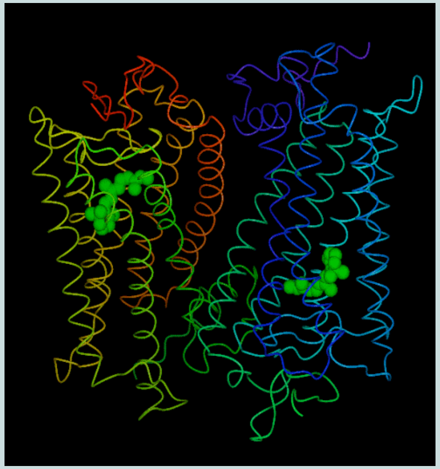
この装置の特長は、

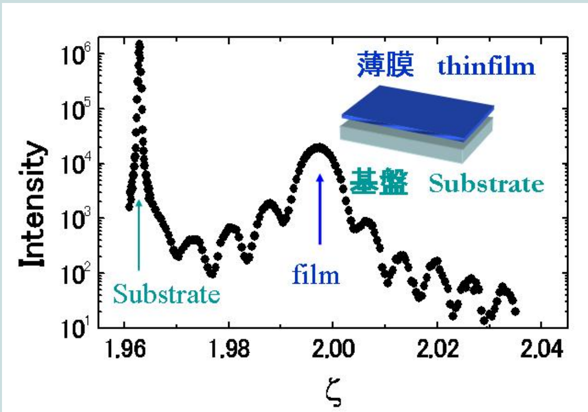
小型（全長 10 m 以下） 準単色（エネルギー幅1%以下）
高フラックス（小型常伝導X線源の100倍：10^{11} photons/sec 1% b.w.）
高輝度（2.5世代放射光施設級の輝度：10^{17} photons/sec mrad^2 mm^2 0.1% b.w.）
極短パルス（40 fs ~）

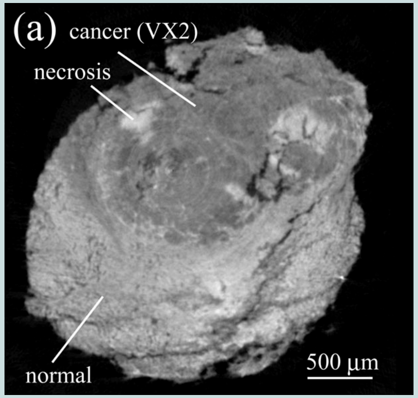


超伝導高周波加速技術

構造ゲノム解析、ナノマテリアル評価、高精細X線イメージング



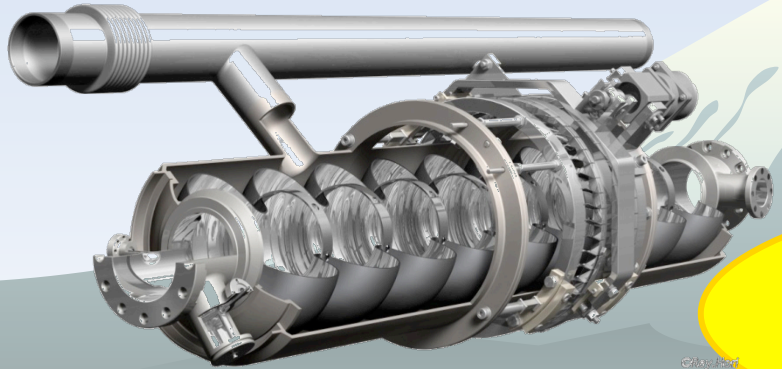




http://mml.k.u-tokyo.ac.jp/

超伝導加速空洞

超低損失（10 nΩ）
➡長いパルスが可能
➡低エミッタンスかつ大電流



レーザーパルス蓄積

蓄積エネルギー 100倍
ビームサイズ: < 8 μm

レーザー逆コンプトン散乱

大強度・高品質の単色光が手軽に

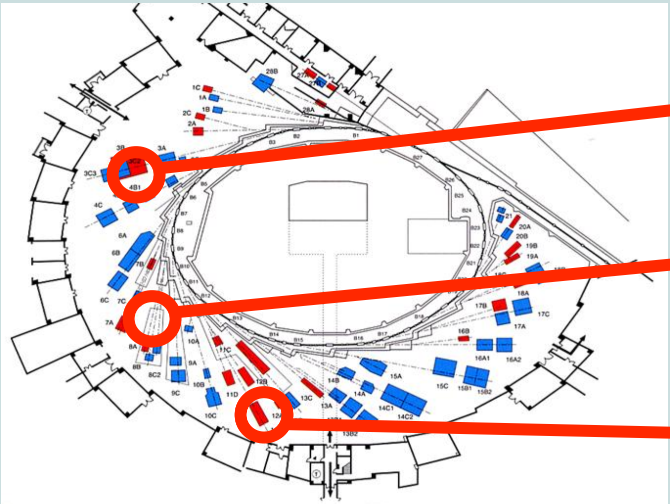
フォトカソードRF電子銃

1/100のエミッタンス
短パルス、速い繰り返し

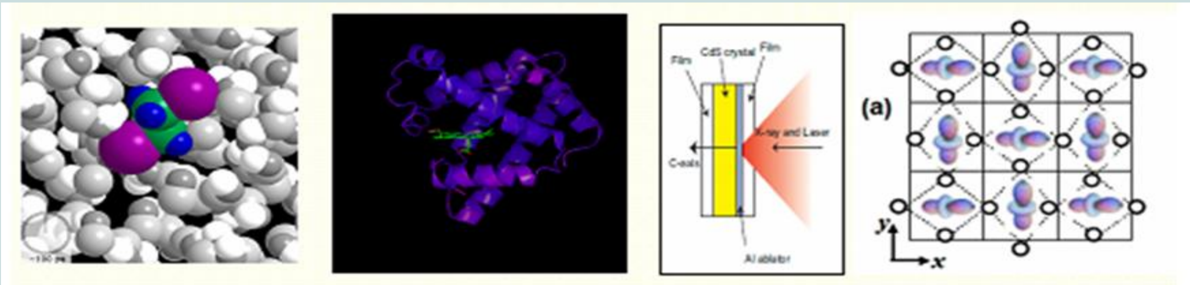
CWにするとフラックスはさらに400倍

小型高輝度光子ビーム源の波及効果

1) *第2世代放射光源の性能が* ***実験室へ！***



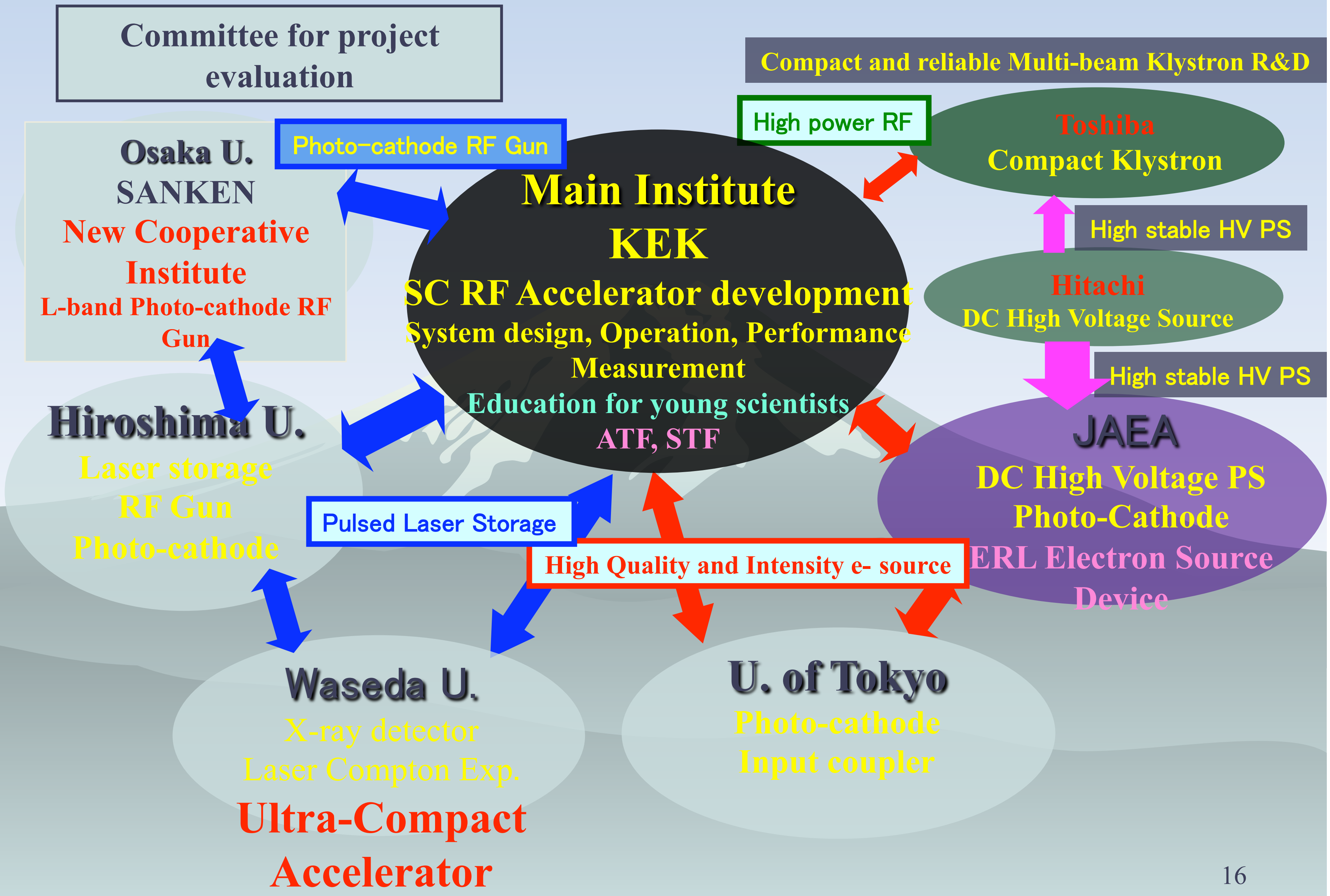
2) *サブピコ秒X線源を* ***実験室へ！*** *→ 高速過渡現象の研究*



溶液中の化学反応、 タンパク質の機能、 衝撃破壊、 光誘起相転移

3) *放射性廃棄物中の同位体検出 （エネルギー･環境問題解決へ）*

Organization and Responsibility



2. Status of basic technologies

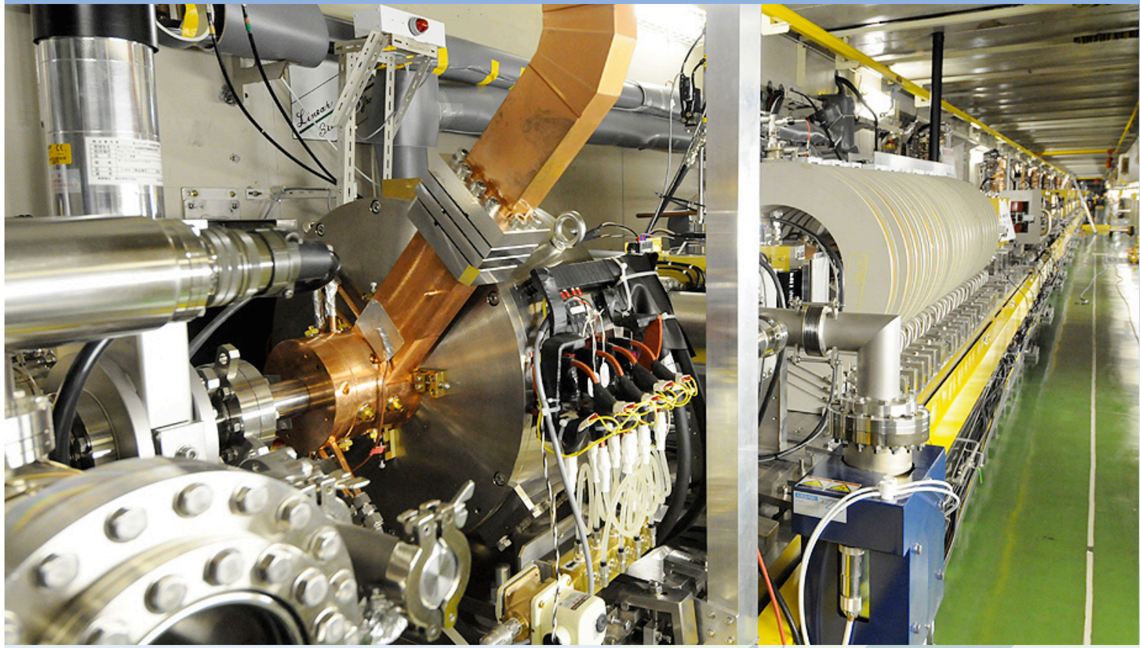
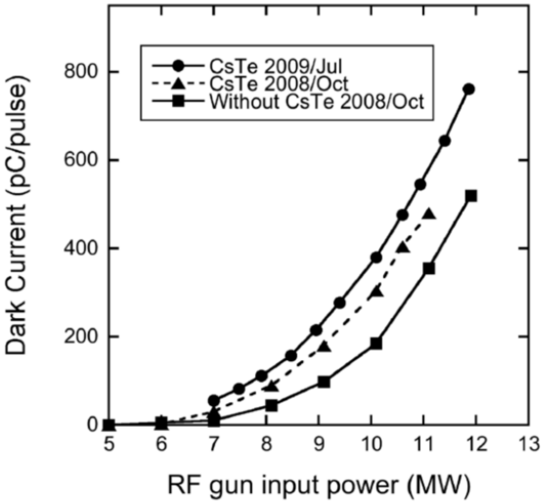
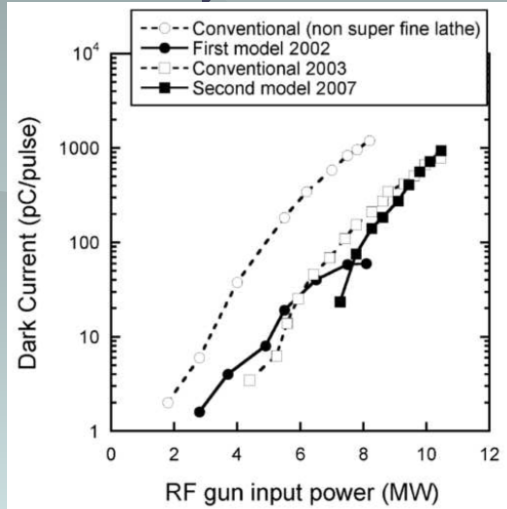


Photo-cathode RF Gun for 1.3GeV ATF Linac

From 2002 onward, successive improvements have been incorporated into newer models of the RF gun. Most recently, 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**.





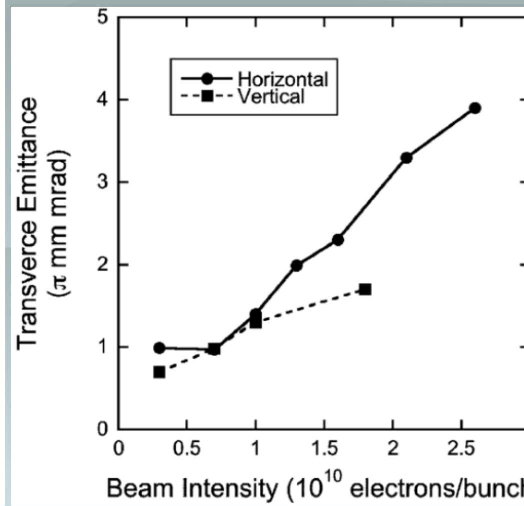
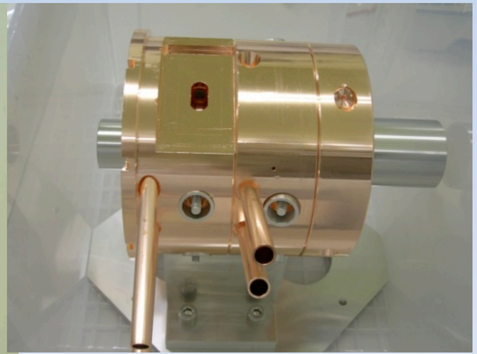


Photo-cathode RF Gun Development

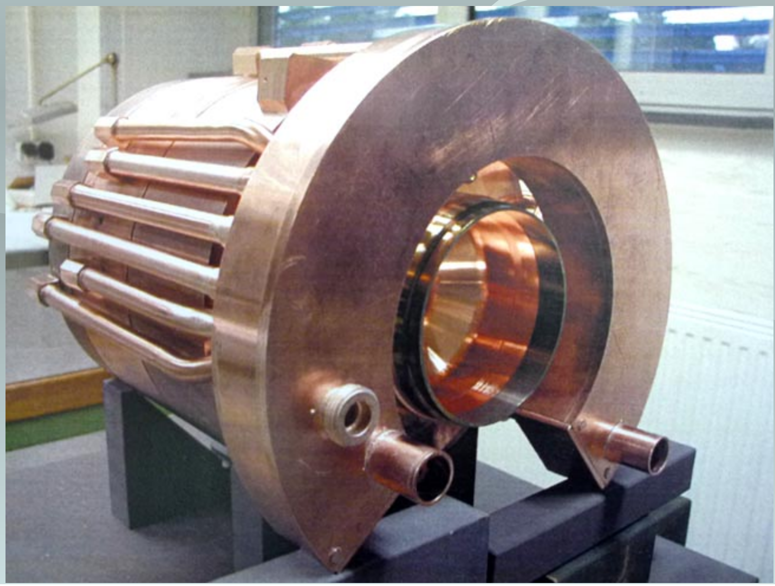
S-band RF Gun: 120MV/m
JFY2004
300nC/pulse achieved.

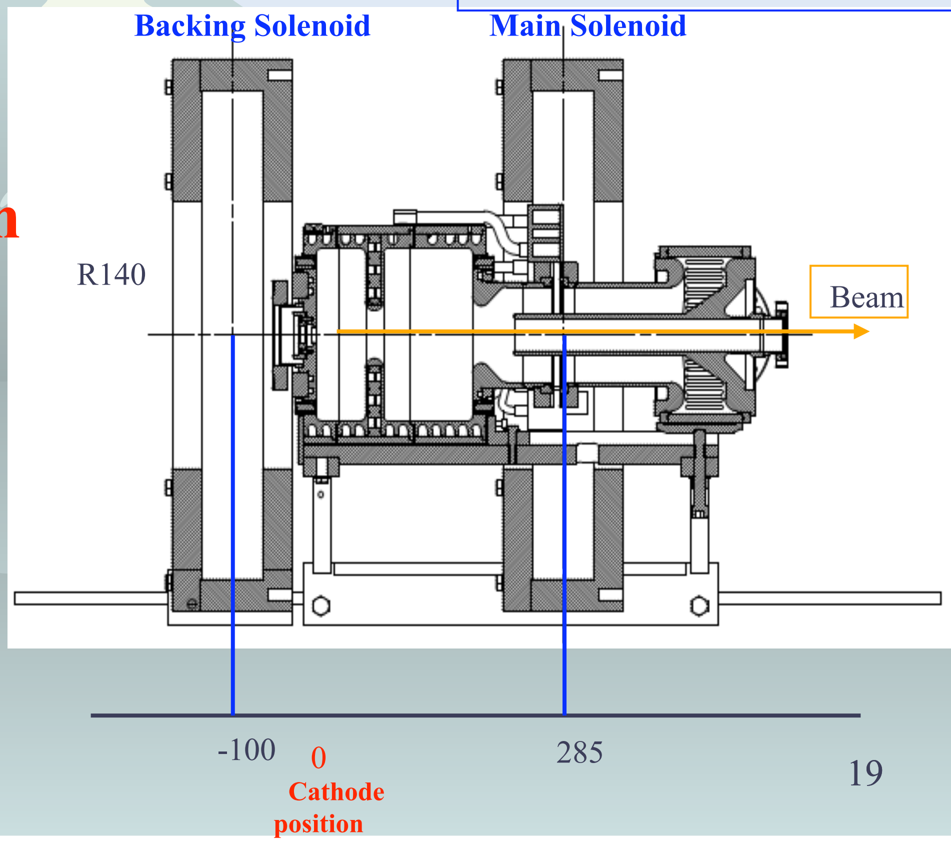
Schedule
JFY2009 – JFY2010
1000nC-5000nC/pulse



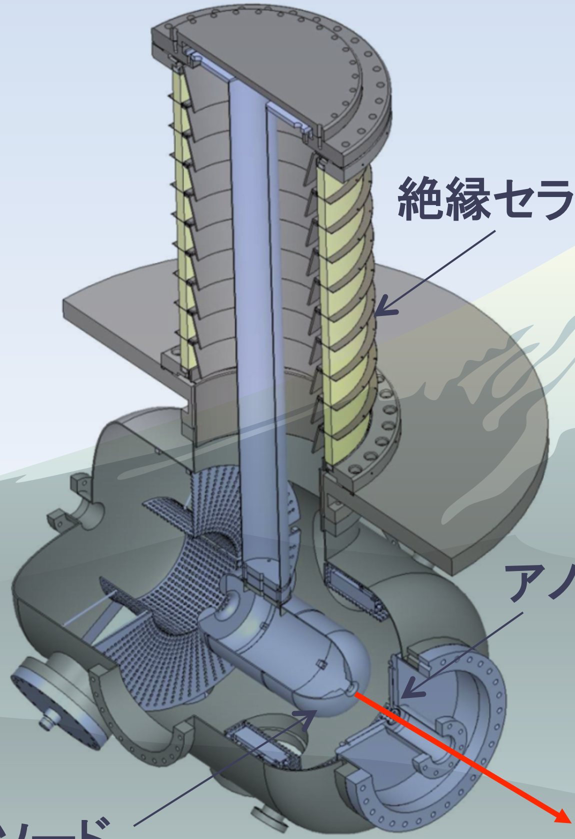
L-band RF Gun: 40MV/m
Half cell: 55mm
Full cell: 100mm
Disk thickness: 20.1mm
Disk iris(2a): ~54mm
Cavity diameter(2b): ~180mm

JFY2010 – JFY2011
Soft X-ray Generation :
1.3x10^{11}photons/sec1%bandwidth

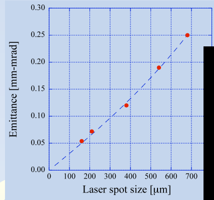


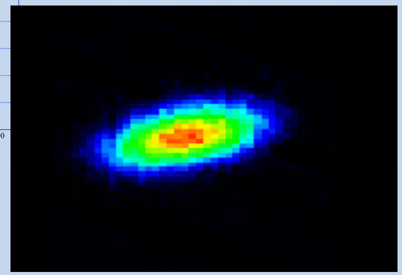


フォトカソードDC電子銃による
低エミッタンス電子ビームの発生



500kV-DC Gun





規格化エミッタンス
＝0.054mm-mrad

原子力機構におけるフォトカソード電子銃の開発
（KEK、広島大学、名古屋大学との共同研究）

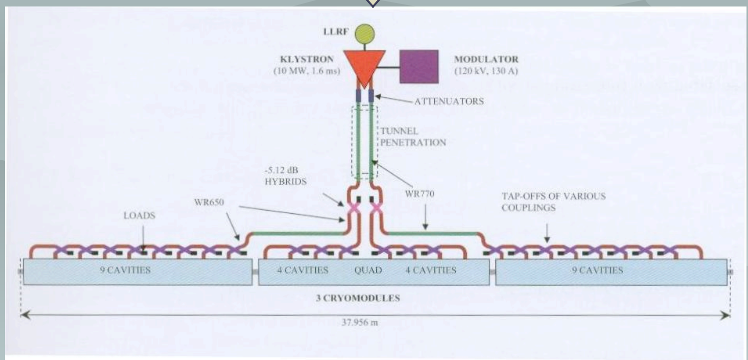
Compact RF Source

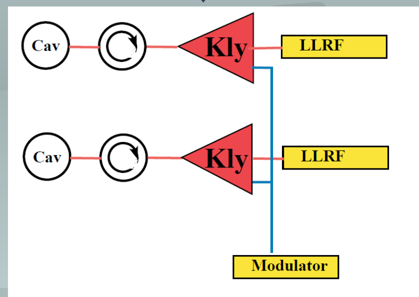
Distributed RF Source（DRFS） for ILC application

ILC Baseline RF unit consists of one Modulator, 10MW Klystron, PDS, three Cryo-modules which include 26 9-cell SC Cavities. New proposed RF unit consists of one small Modulator, 350kW Klystron and one 9-cell SC Cavity.

RF Source ~\$500k
Modulator ~\$800k
PDS ~\$600k
Total ~\$1900k

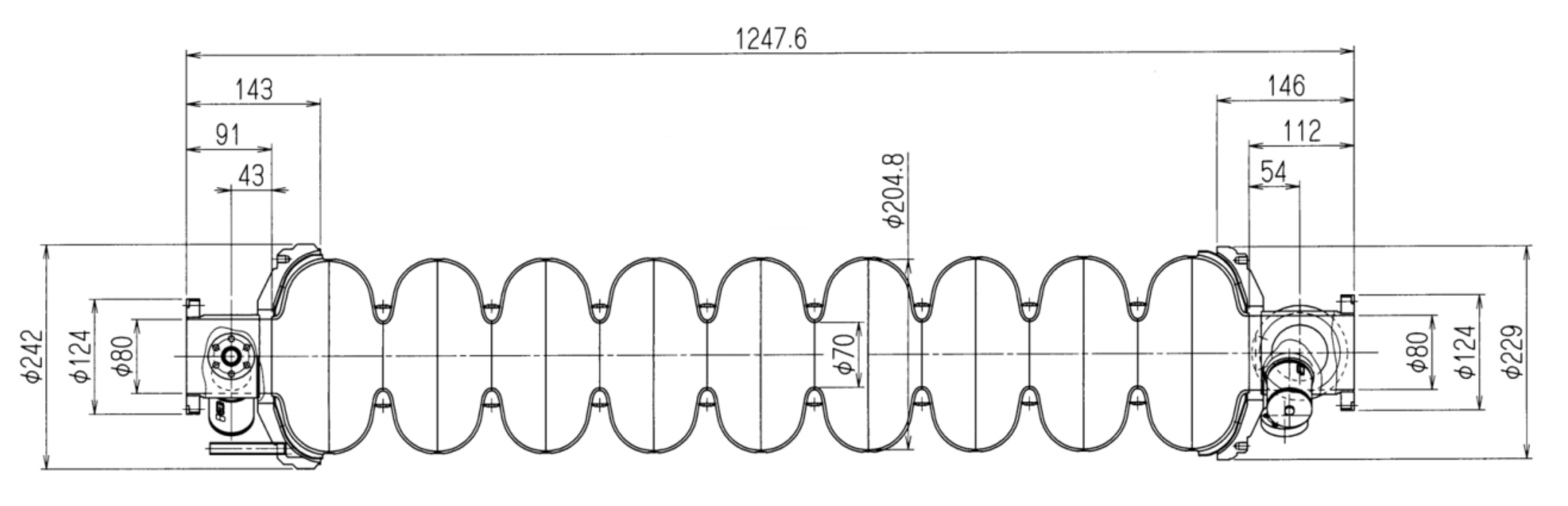
~\$200k for Tow RF unit

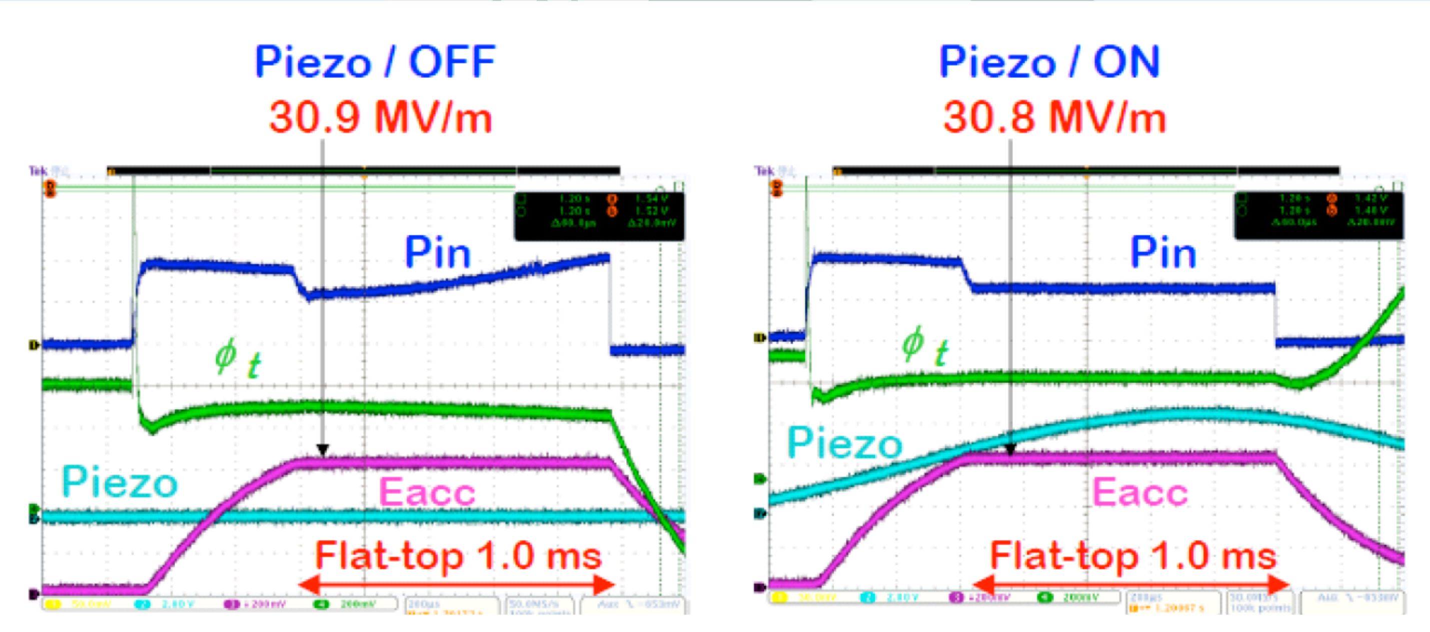




高周波源の小型化、
高信頼性化にILC
Groupの協力を得る。

Manufactured and Tested three 9-cell super conducting cavities



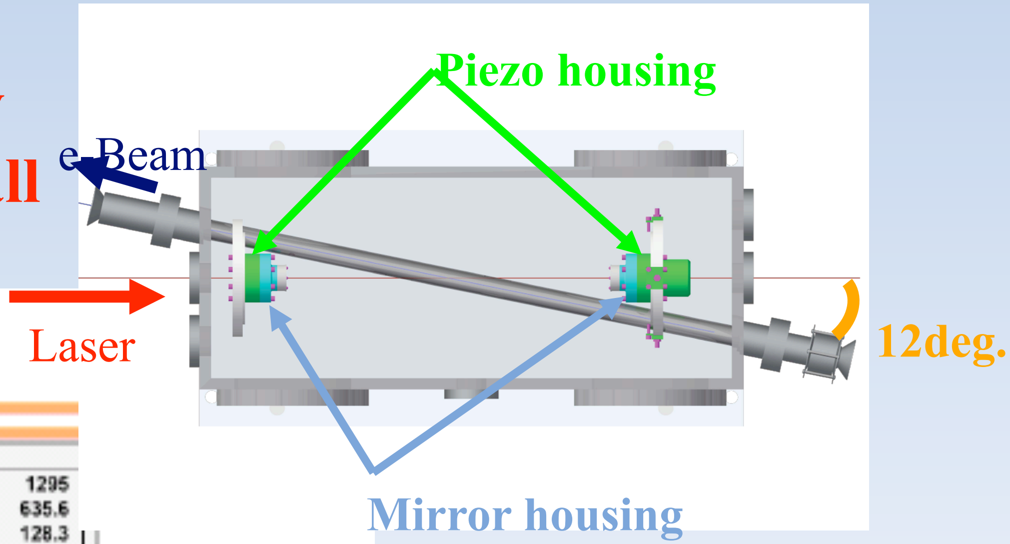


最近、37MV/mの超伝導空洞が試験できるようになってきた。

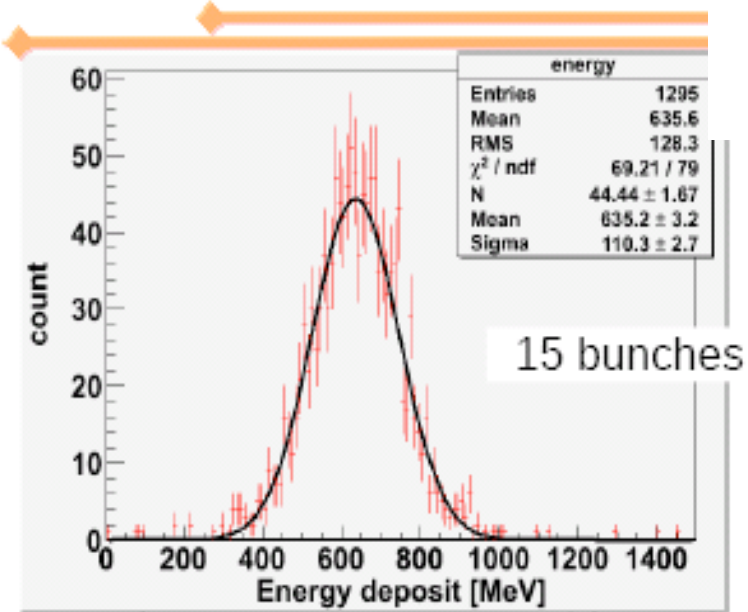

超伝導空洞開発のインフラと
半導体グレードの品質管理
1 m² の内面から 1 μm 級の欠陥を除去
徹底した表面管理
清浄表面の実現
充実した開発設備
空洞組立
測設備
高度化中の電
内面検査
ュールの
設備
©Rey.Hori
溶接ビード欠陥
専用冷凍設備

R/D Status for Compton Scheme

We established two important techniques which are slow cavity length control method and overall fast feedback method.

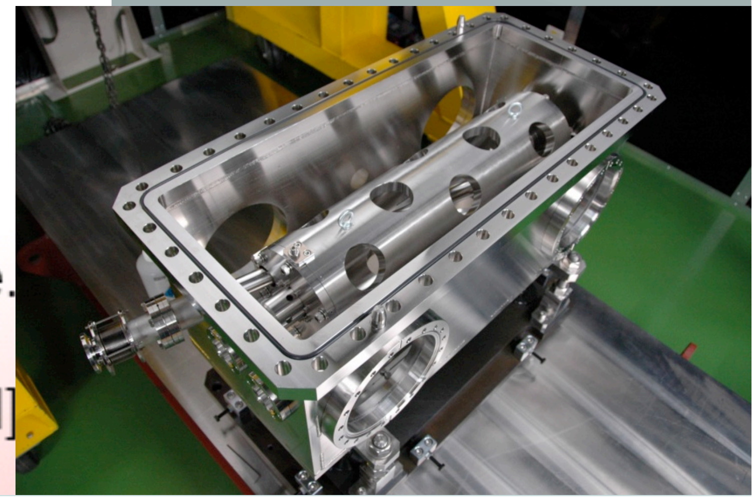


Result



We detected 27 gamma-rays / bunch train.
generation 60 gamma-rays / train to all angle.

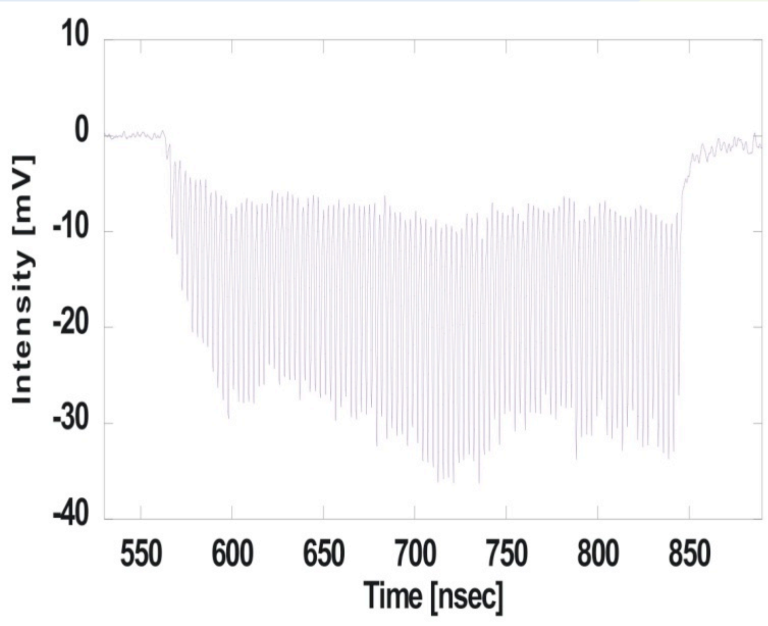
60×2.16MHz ~ 1.2×10^8 [gamma / second]
Revolution



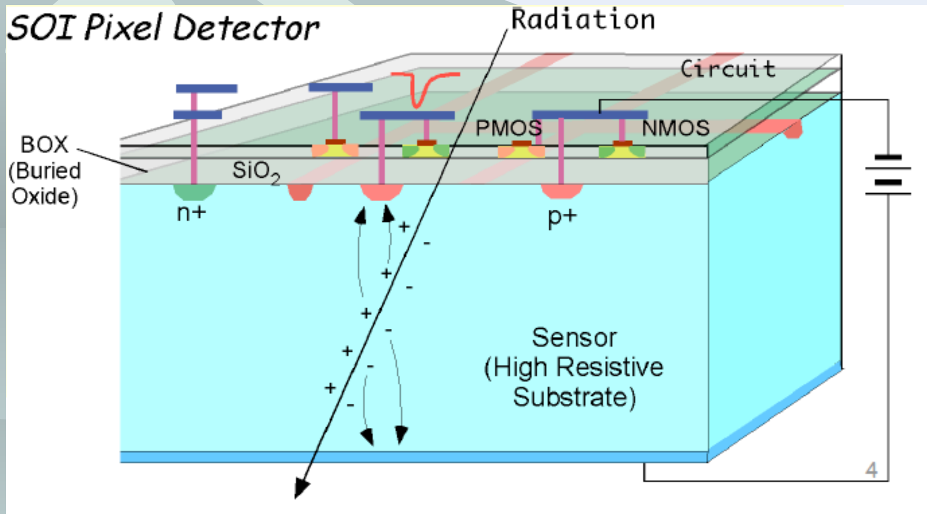
X-ray Detector Development

Measured S/N ratios of several detectors

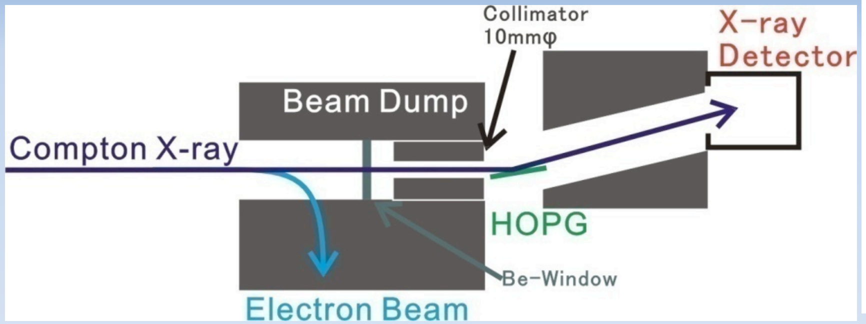
	S/N	Average laser power
Direct scintillation detector	1/4	40.6kW
Scintillation detector after Bragg Reflection	1.98	32kW
MCP detector	1/1.3	30kW
Si-PIN photo diode after Bragg Reflection	1/3	24.2kW

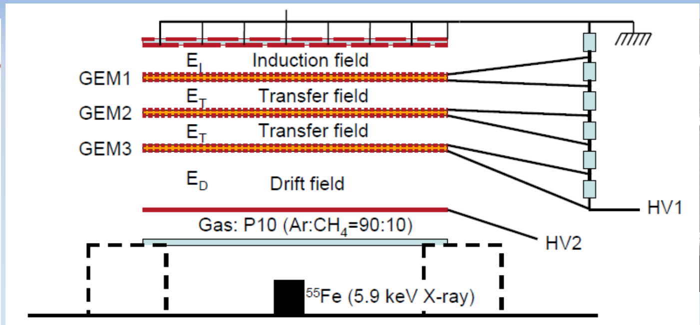


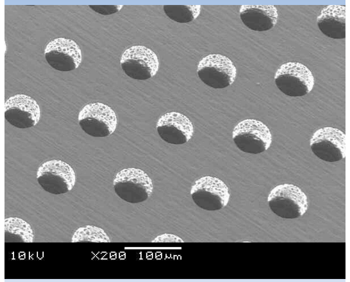
MCP detected 100 pulses X-ray train.



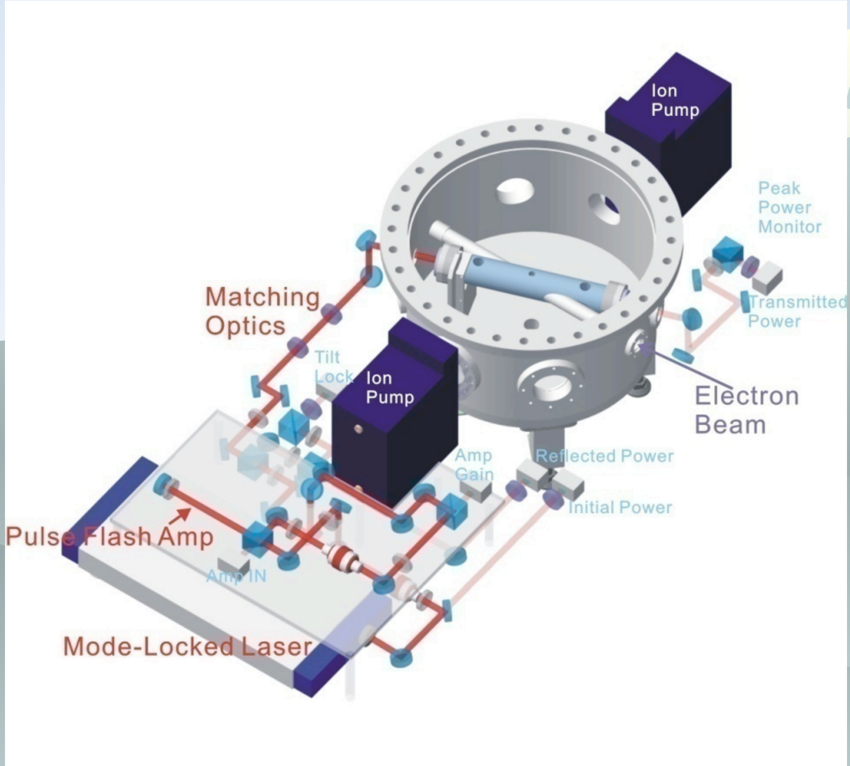
SOI(Silicon On Insulator) technology

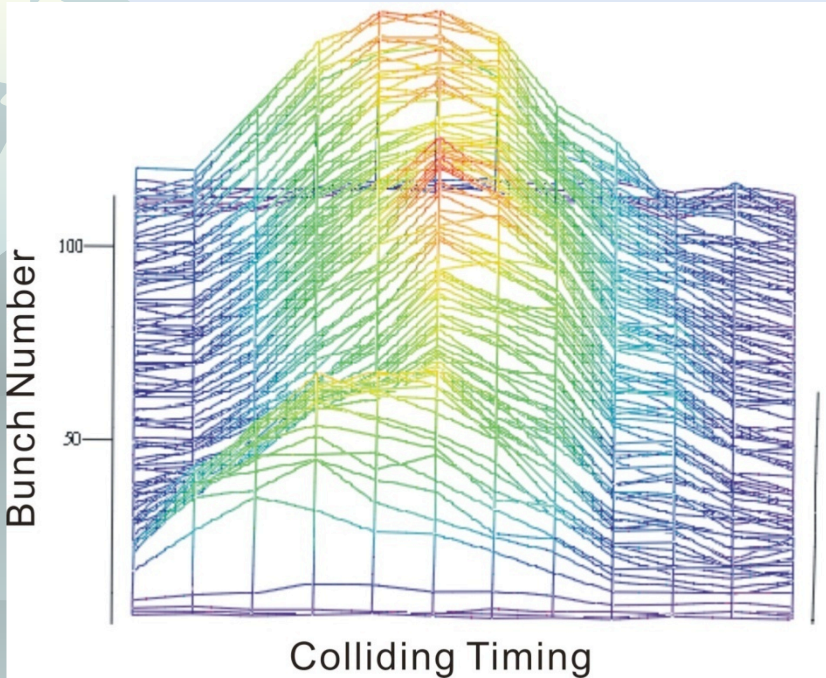






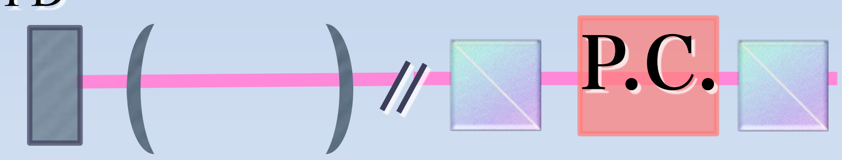
HOPG: Highly Oriented Pyrolytic Graphite GEM (Gas Electron Multiplier)X線検出器





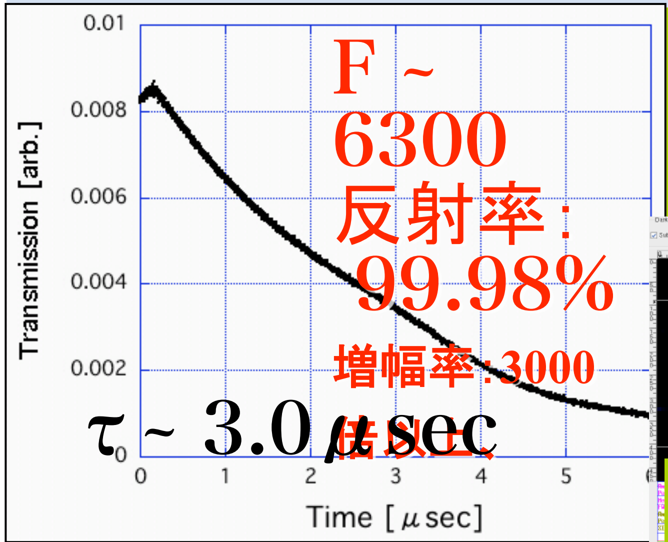
30keV X-ray Intensity : 2.0x10^3 photons/sec1%bandwidth(2008)

パルスレーザー蓄積

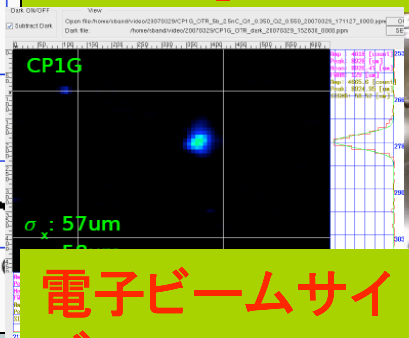


現状1000倍程度でX線生成。

現状：0.5mJ/pulse,目標：50mJ/pulse



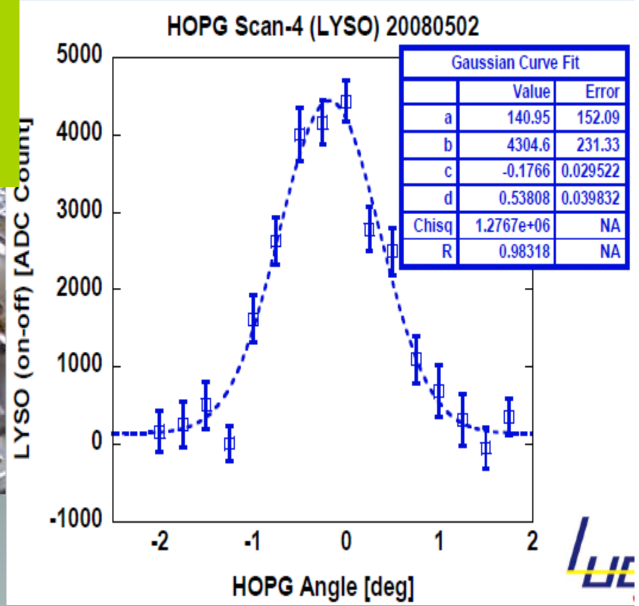
平均レーザーパワー40kW, 7psec(FWHM), next step :2MW



電子ビームサイズ 60μm in σ

ビーム衝突技術

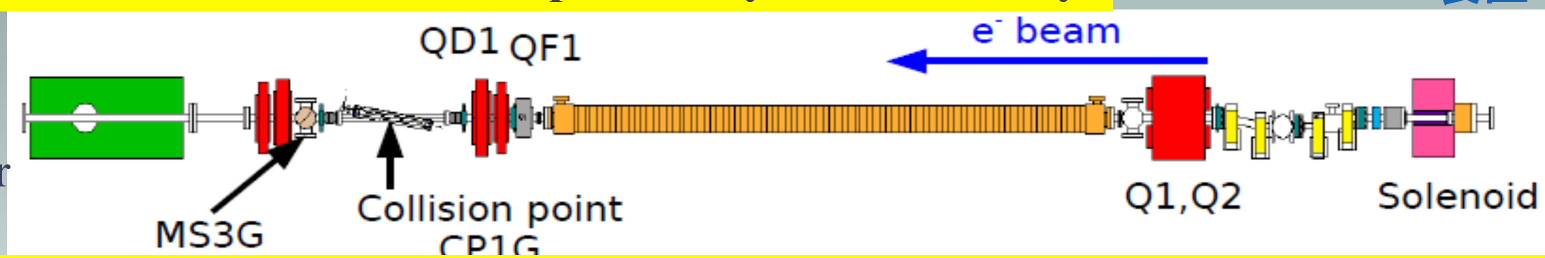
X線測定



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

LUCX装置

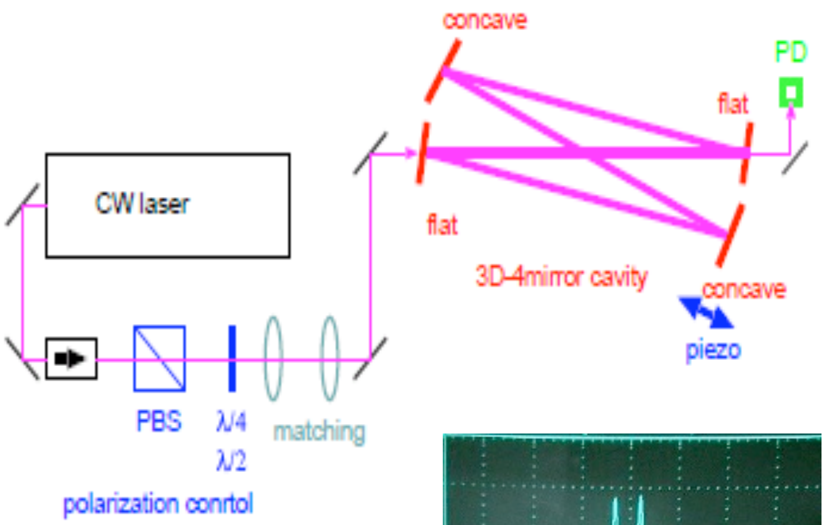
X-ray Detector

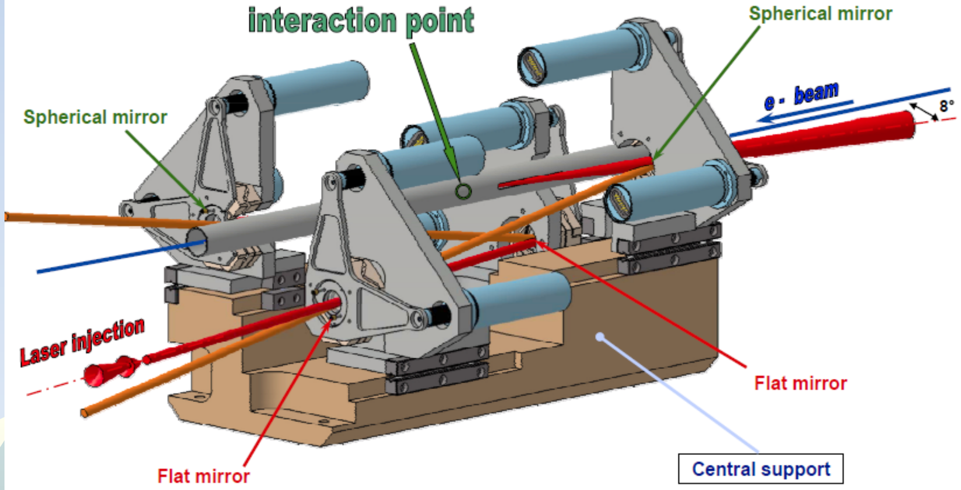


レーザーサイズ 30μm in σ,目標：電子ビームサイズ 10μm,レーザーウエストサイズ 8μm

3. New Laser Storage Scheme using picosecond mode-locking 1μm laser with super-cavity

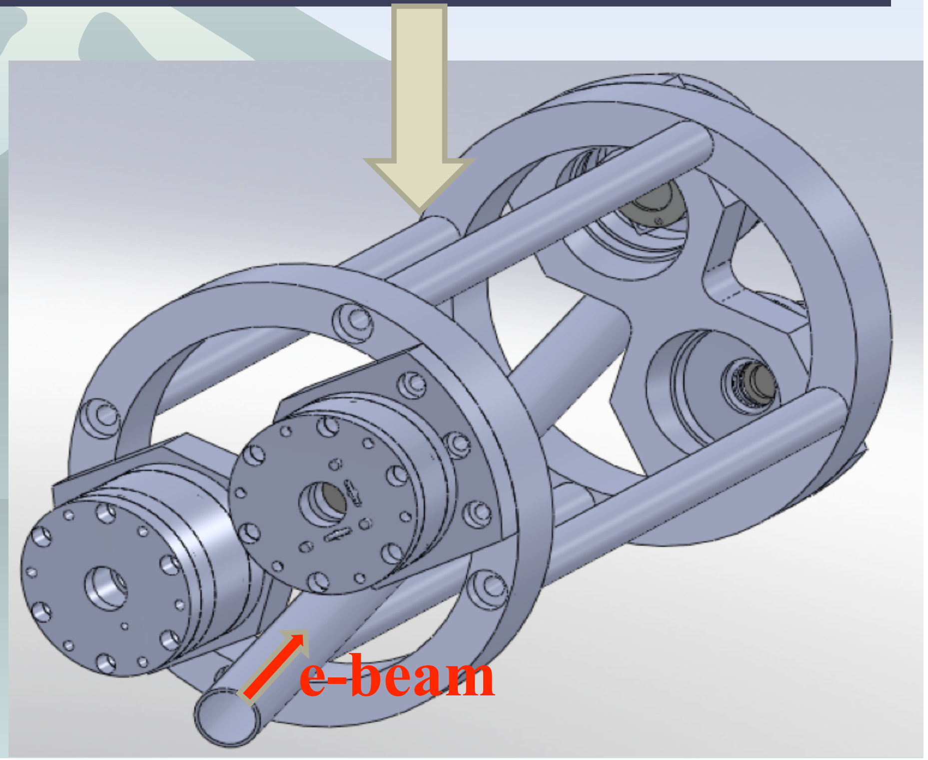
Development for Polarized Optical Cavity (3D-4mirror)

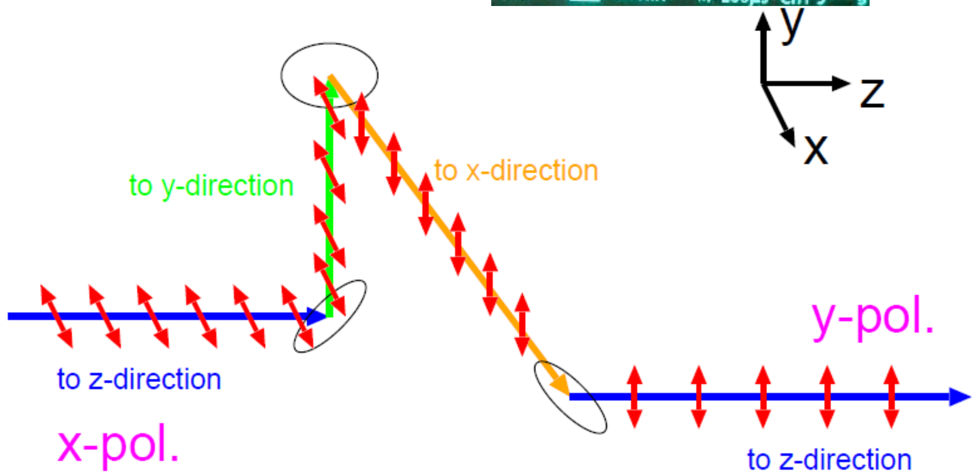




50 mJ / pulse, waist = 8 μm

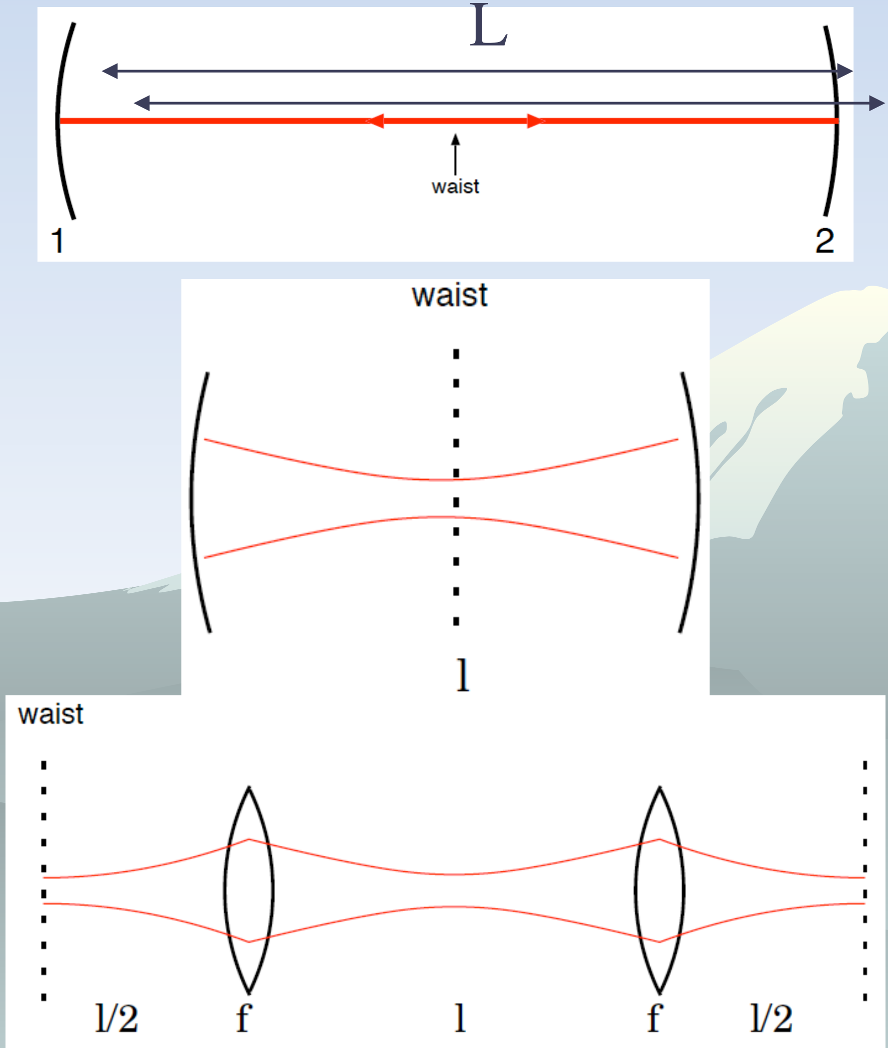
Circular Polarization Control by Piezo.





2-mirror cavity

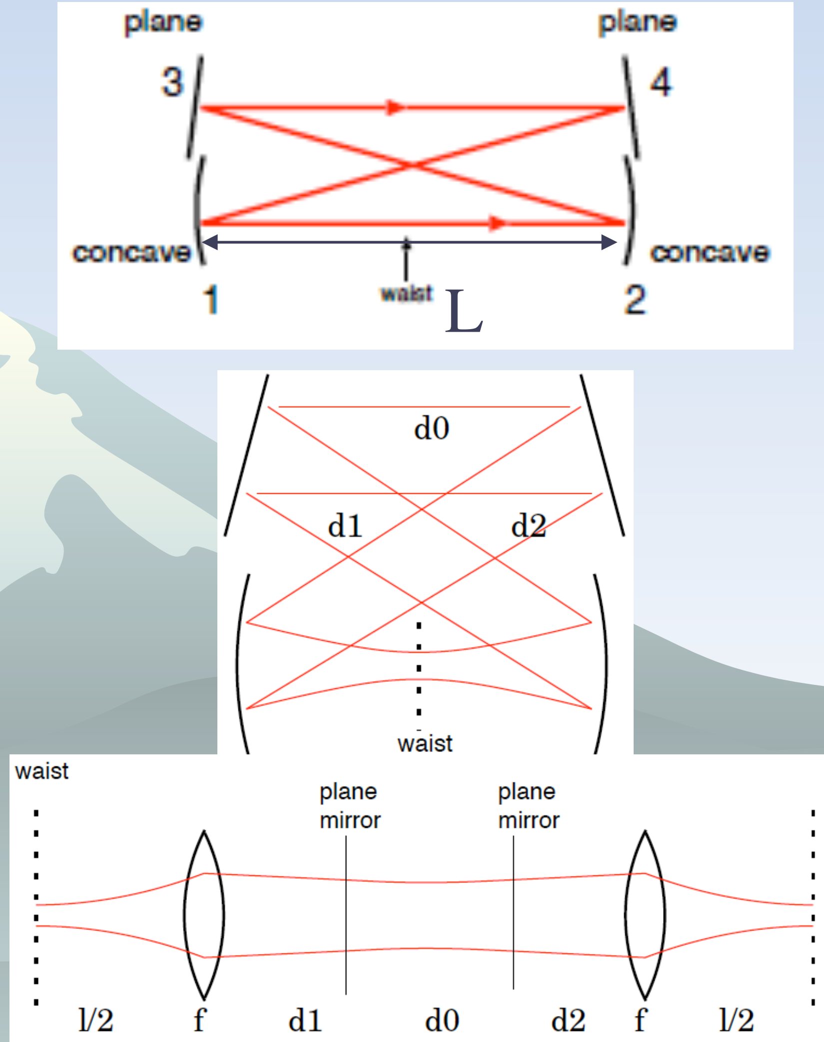
R1=R2=L/2



concentric

4-mirror cavity

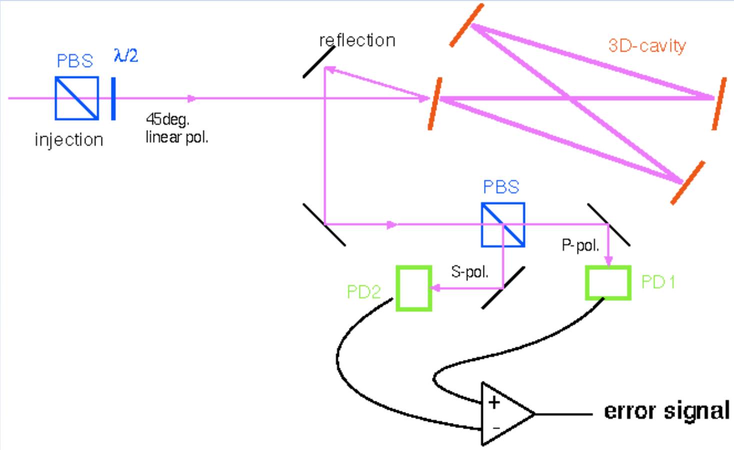
R1=R2=L



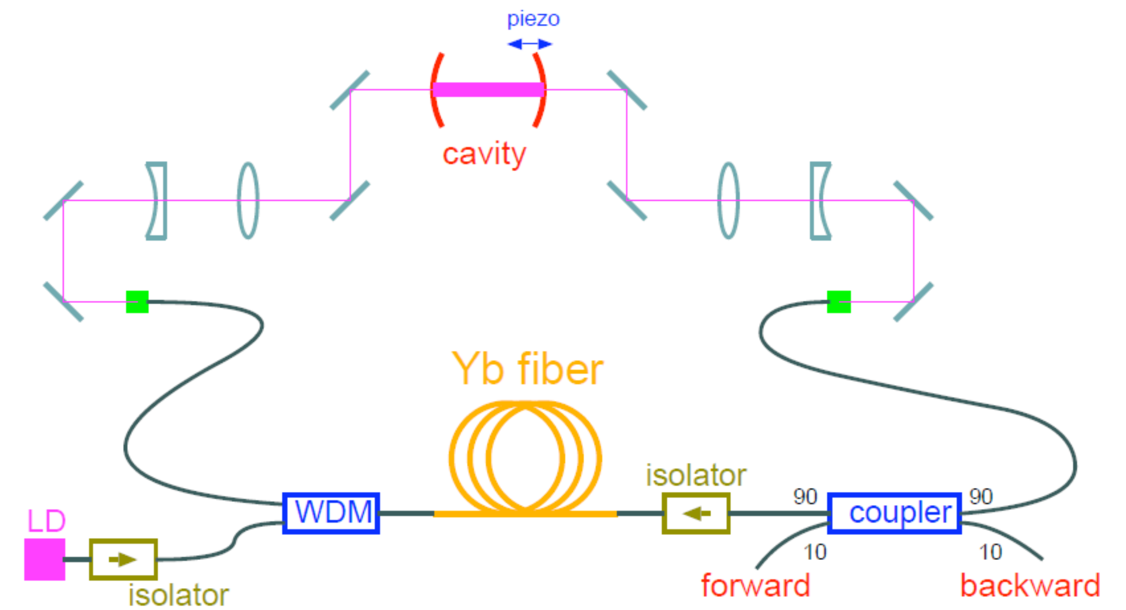
confocal

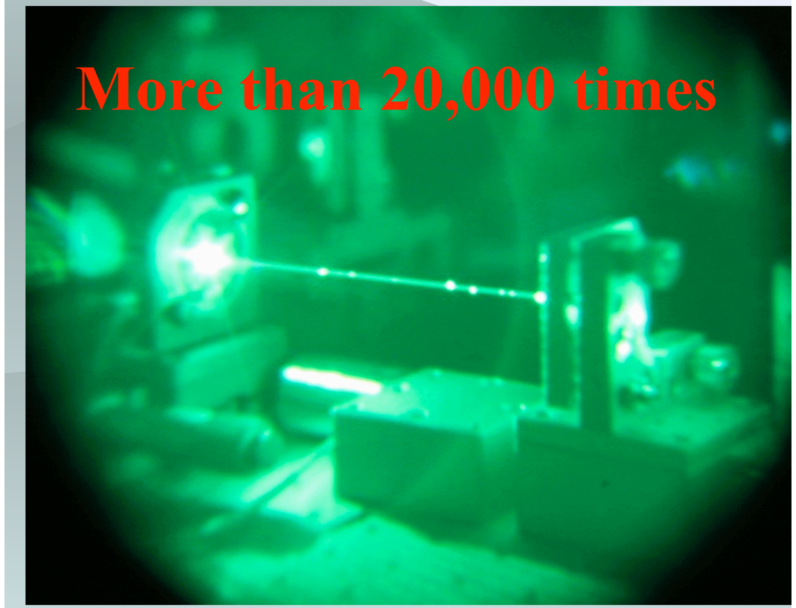
New fast switching for circular polarization X-ray

Development for laser accumulation



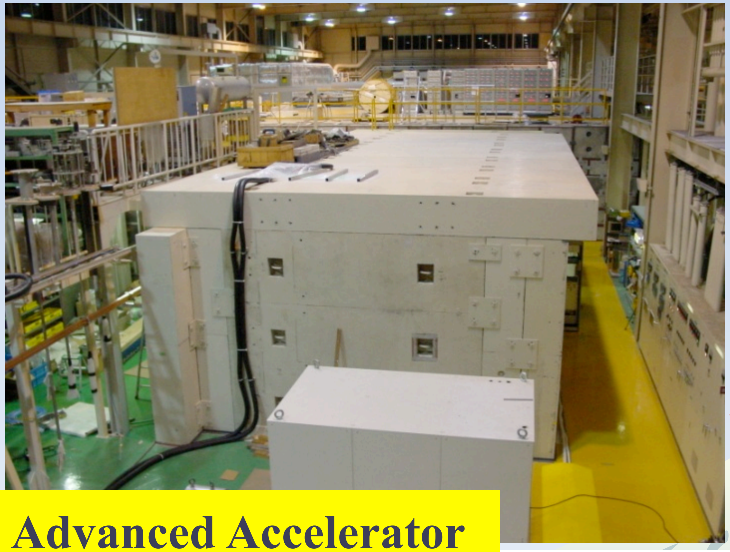
New laser storage scheme, so called ‘self-starting oscillator scheme‘





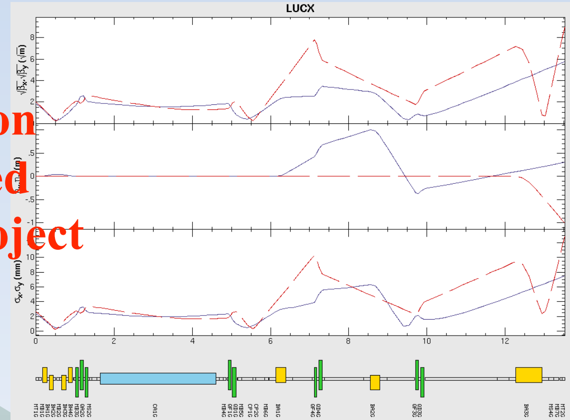
4. Plans and schedule

S-band Linac with photo-cathode RF gun

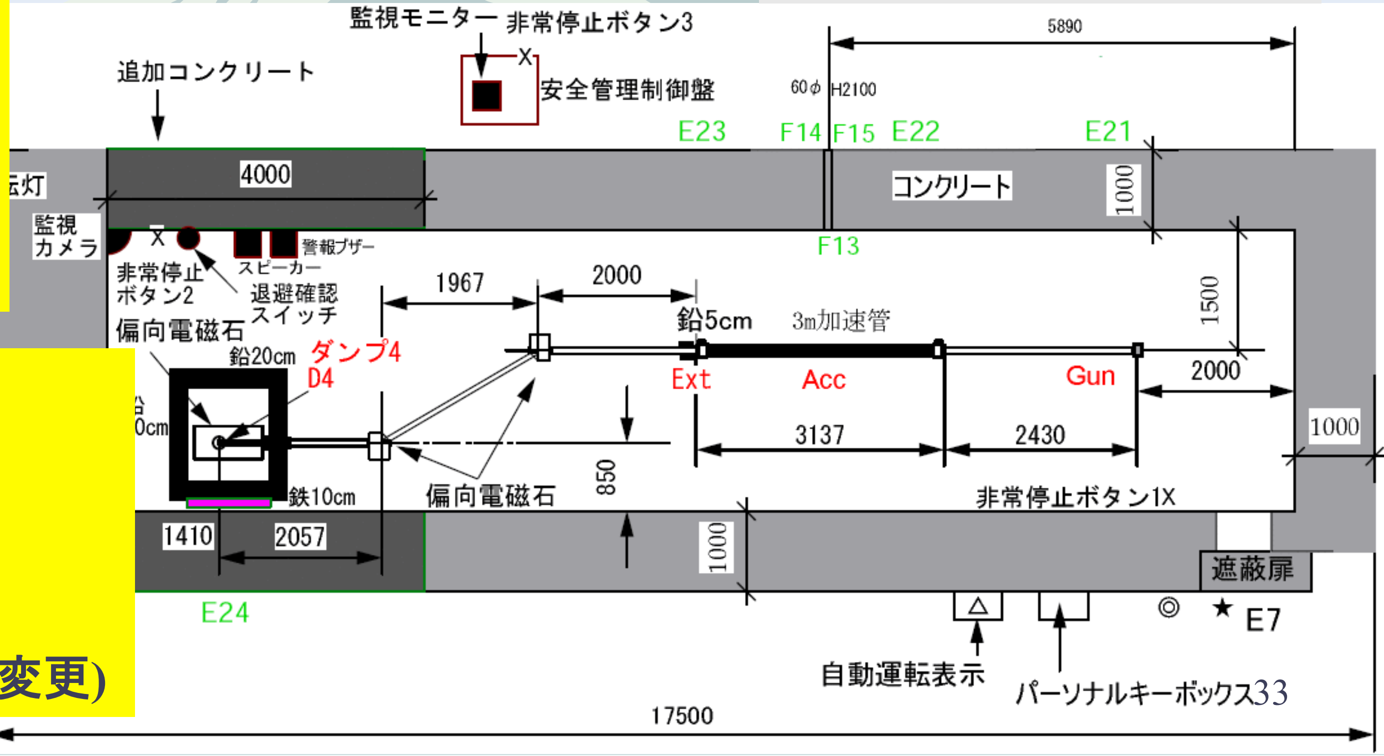


Multi-bunch electron beam generation, pulse laser accumulation system Upgrade, R&D of precise multi-collision control will be done using this normal conducting facility by 2011.

Plan for X-ray Application Experiments will be tested and possibility of this project will be confirmed.

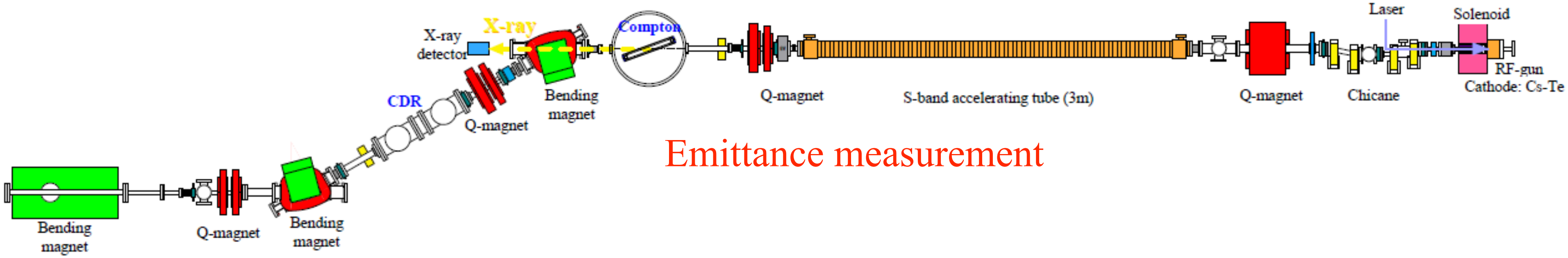


Advanced Accelerator Facility from 2008 to 2012 for Quantum Beam Technology Program R&D



Maximum Energy
50MeV
Maximum Beam Power
156.26MeV μA-→ 500MeVμA(放射線申請変更)

要素技術開発用逆コンプトン散乱高輝度X線生成装置 LUCX （2010年5月から衝突技術及びX線検出技術開発再開）

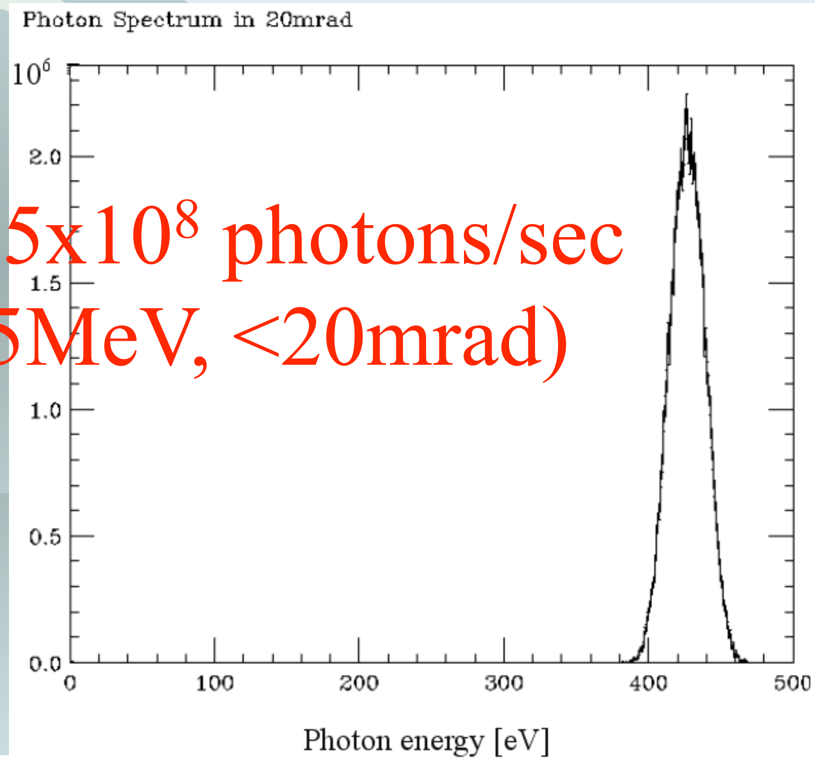


Emittance measurement

Beam energy and energy spread measurements

Energy	5MeV	50MeV
Intensity	0.5nC/bunch	2nC/bunch
Num. of Bunches	8000 bunches	100bunches
Bunch spacing	2.8ns	2.8ns
Bunch length	10ps	10ps
Repetition Rate	12.5 train/sec	12.5 train/sec
Normalized Emittance	0.5 πmm・mrad	2 πmm・mrad
Beam size(σ_x, σ_y) at C.P.	60μm, 20μm	50μm, 25μm

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

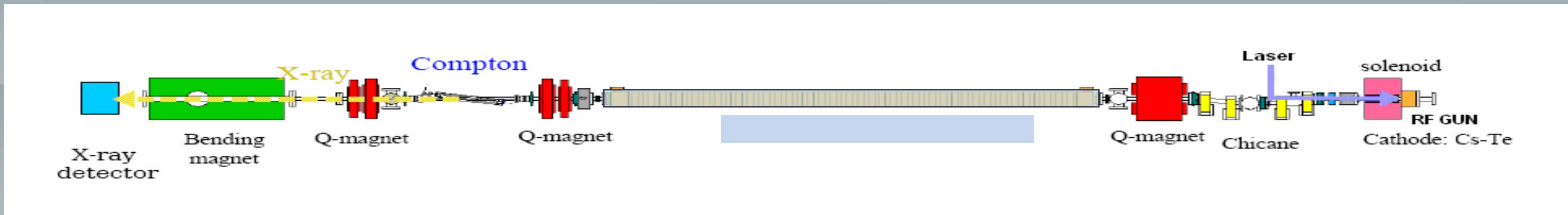


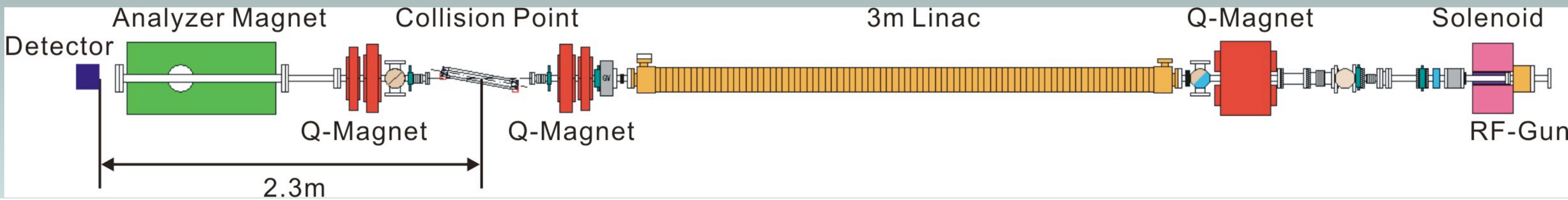
$2.25\text{x}10^8$ photons/sec (5MeV, <20mrad)

8000 bunches/pulse beam at Compact S-band Linac will be used to generate following soft X-ray by the collision with laser pulse.

Bunch charge	0.5nC
Repetition rate	12.5Hz
Bunch spacing	2.8 nsec
Number of bunches/pulse	8000
Total charge/pulse	4000nC
Current	178.57mA
Maximum beam energy	5MeV
Beam power	250.0W (250.0MeVμA)
RF Pulse width	24μsec

Soft X-ray Target Flux: $1.3\times10^{7} \sim 1.3\times10^{9}$ photons/sec1%bandwidth





R&D for Pulsed SC acceleration system

5 years schedule

2008: R&D for 30MV/m 9-cell SC Cavity

2009: R&D for stable operation of the SC Cavity and Compact RF Source System

2010: Establishment of 30MV/m 9-cell SC Cavity
Final Fabrication for two 9-cell SC Cavities System

2011: Final Gradient Test and Installation to Cryomodule for Beam Acceleration Test at STF

(Experiment for Proof of Performance will start from the autumn of 2011.)

2012: Stable pulsed beam operation at following facility
Generation of high brightness X-ray at STF

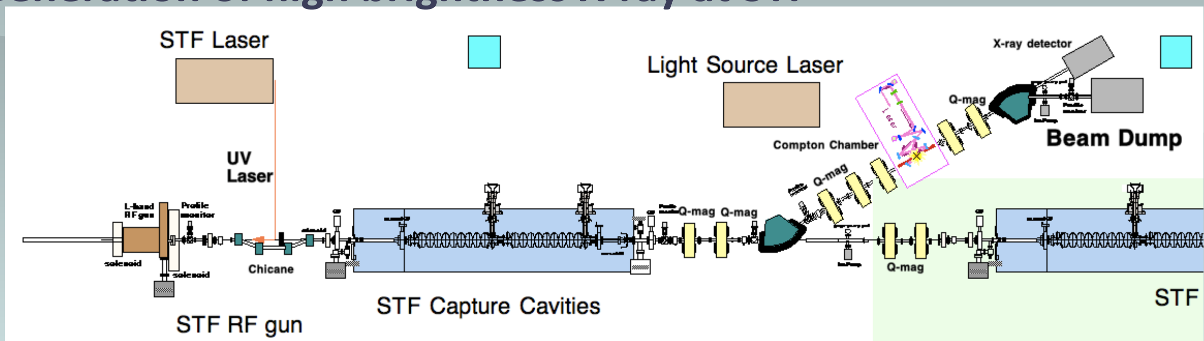
Manufacturing of SC Cavity and Test

Research of the surface condition and modified manufacturing of the Cavity, and Test

Final Cavity Manufacturing

Test of the Cavity

Beam operation of Facility



Target Value of Quantum Beam Program on Development for Next Generation Compact High Brightness X-ray Source using Super Conducting RF Acceleration Technique

Pulsed SC operation:1.3×10^{11} photons/sec1%bandwidth
(CW SC operation:5.4×10^{13} photons/sec1%bandwidth)

Photon Beam Generation

Establishment of Advanced Technology for Compact X-ray with 1.3×10^{10} photons/sec1%bandwidth or more by 2012.

5Hz Operation, 2.6×10^{9} photons/sec1%bandwidth every 200msec should be detected at STF.

30MeV,10mA, 162.5MHz bunch train

Laser pulse energy:50mJ/pulse, 10psec pulse width

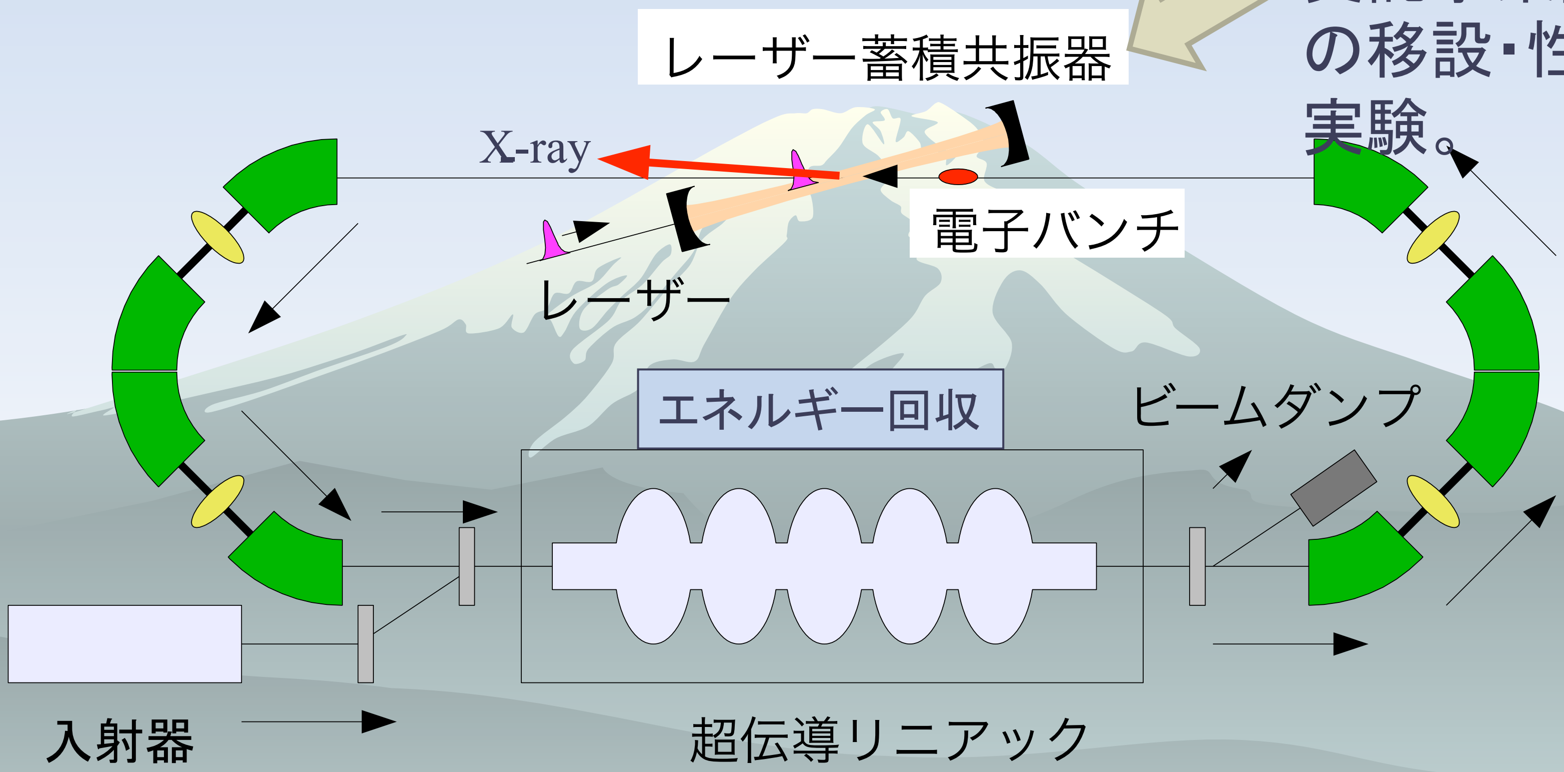
Junji Urakawa on Nov. 28, 2008

コンパクトERLの概要（2012運転開始時）

2012年度にミニマムバージョンである35MeV, 10mAのERL運転開始を目指す。
その後、順次性能向上。 ⇒ 2014年度までに65MeV, 10mA
2015-6年度までに2ループによる加速エネルギーアップ等

超伝導加速(ERL)による高輝度X線生成実証実験

cERL運転が間に合えば、2012年本受託事業開発装置の移設・性能実証実験。



35 MeV 電子 × 1μm レーザ ＝ 23 keV X線

まとめ

１．高周波電子銃、DC高圧電子源開発は世界最高性能を達成できる状況になっている。大強度高輝度電子ビーム運転を行い、本要素技術を確立する。

２．Super-Cavityを使ったレーザー高強度化と収束技術開発は進展している。逆コンプトン散乱X-ray測定によって、先端要素技術を実証する。

３．超伝導加速器技術の要素技術は2011年の実証実験に向けて順調に進んでいる。