電子加速器と新量子放射源

失敗に学ぶ

山嵜 鉄夫

2008年9月3日

夜話 OHO’08 @KEK

山嵜 鉄夫履歴書

学 歴

1971年　京都大学大学院工学専攻科原子核工学専攻博士課程修了

職 歴

1971年　電子技術総合研究所入所

26年 6ヶ月

1998年　京都大学エネルギー理工学研究所に異動

9年 3ヶ月

単身赴任を楽しむ！！

2007年　京都大学退職

京都大学原子核工学教室

コッククロフト型加速器
ヴァンデグラーフ型イオン加速器

イオンビームの多重散乱

電子技術総合研究所田無分室

40 - MeV電子リニアック

加速器の性能向上
高エネルギー放射線標準
放射線遮蔽
新電子加速器施設の設計

電子技術総合研究所（つくば）

600 - MeV電子リニアック
800 - MeV電子蓄積リング
電子蓄積リングNIJI I – IV
小型蓄積リングNIJIシリーズ

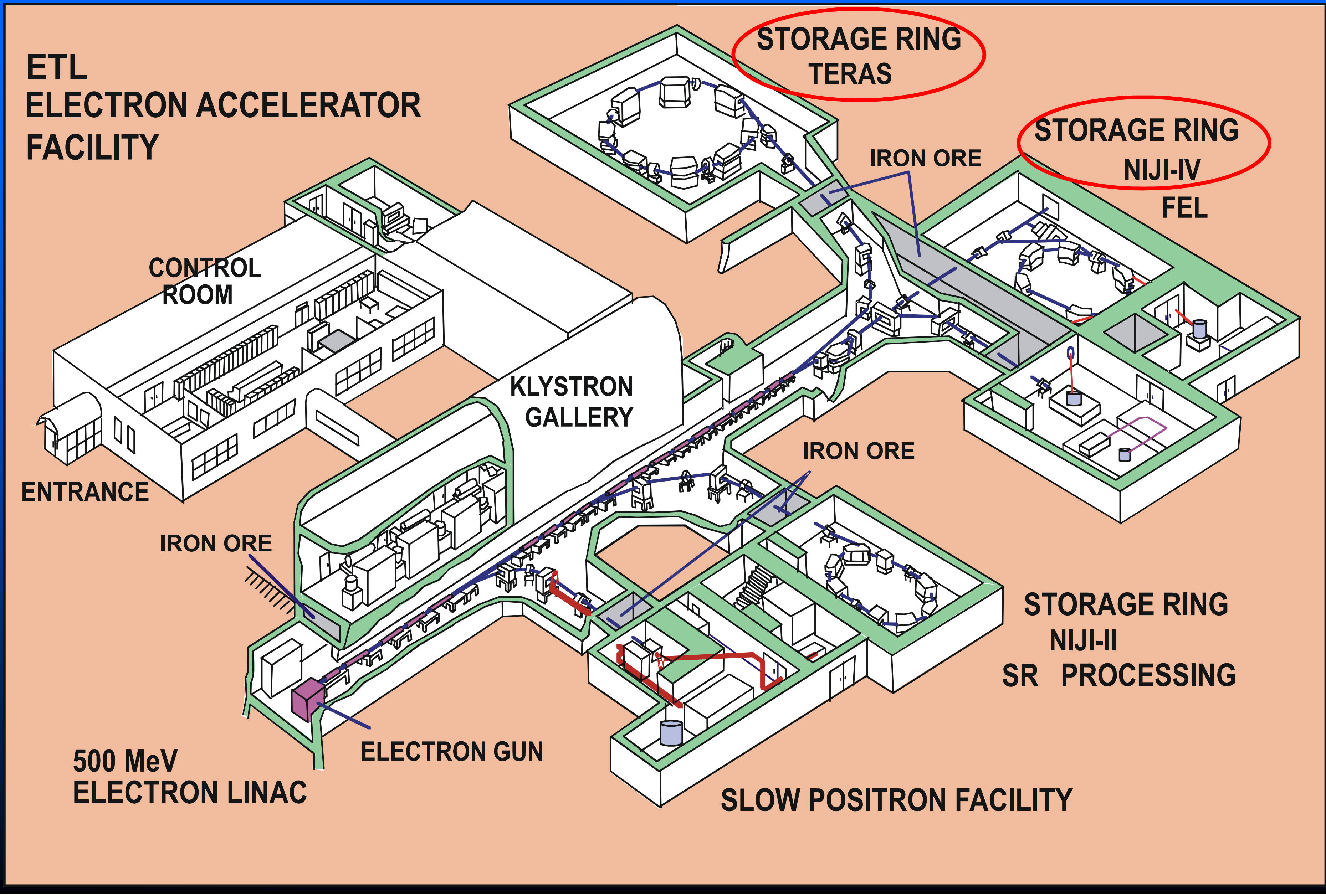
電子加速器施設の建設
加速器の性能向上
レーザー・コンプトン散乱
自由電子レーザー
・・・・・・・・・・

京都大学エネルギー理工学研究所

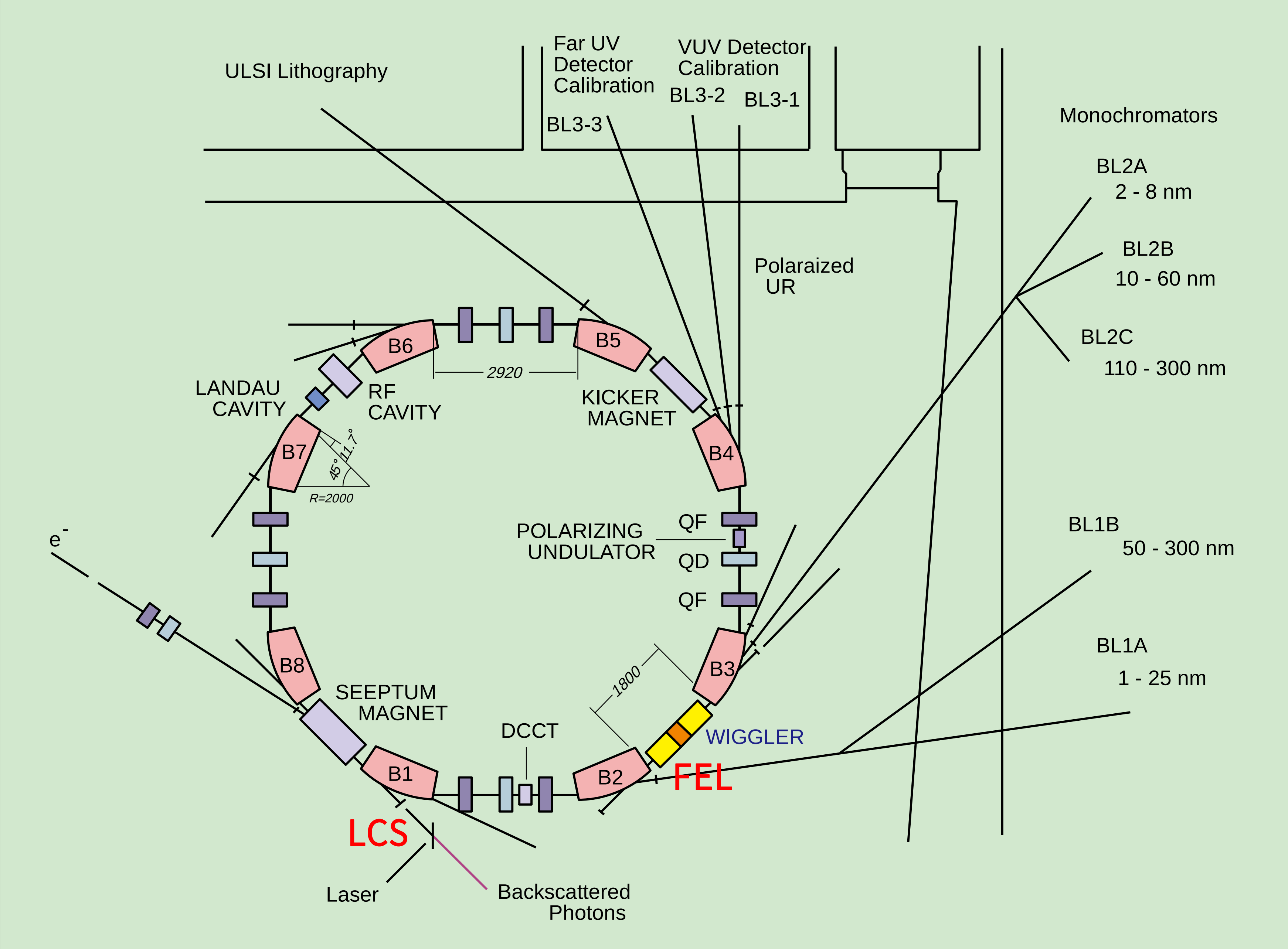
40 - MeV電子リニアック

新量子放射エネルギー

AIST ELECTRON ACCELERATOR FACILITY

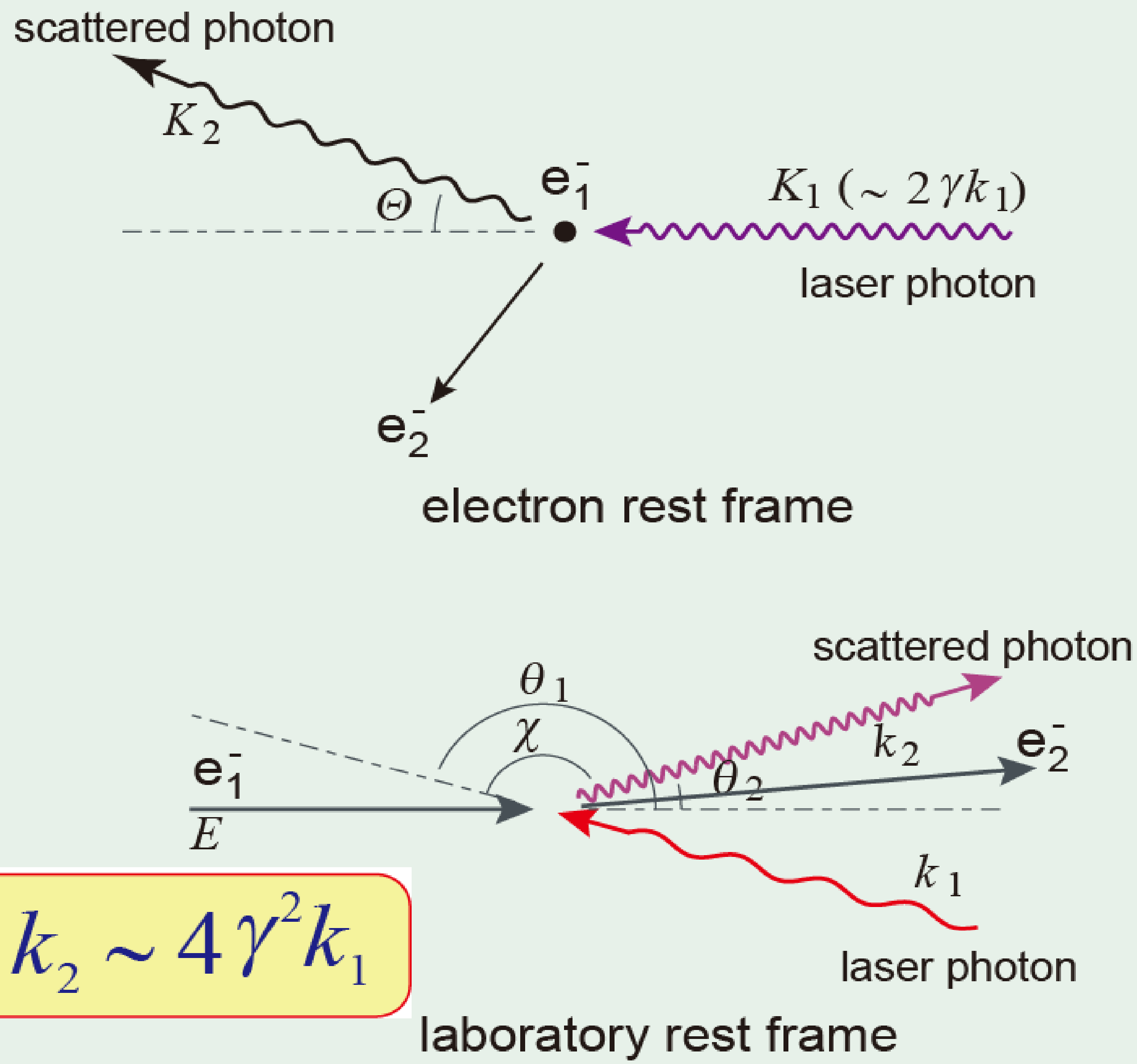


STORAGE RING TERAS



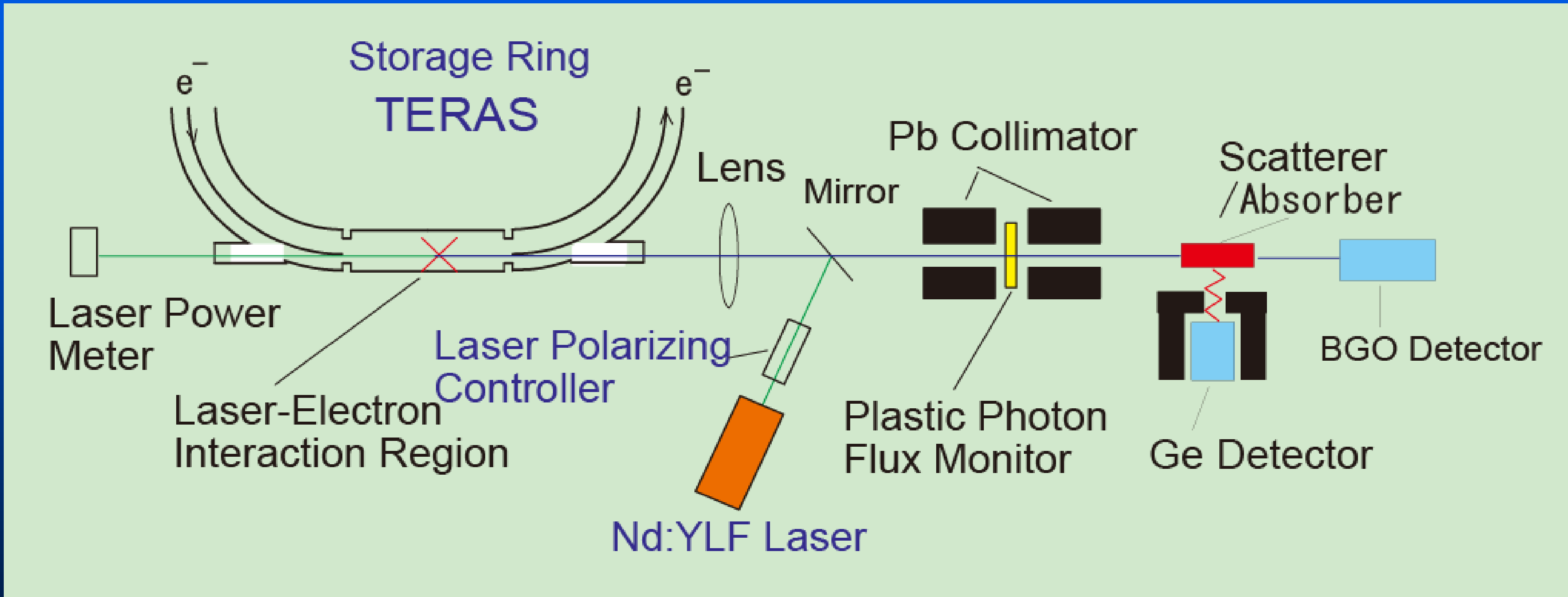
STORAGE RING TERAS

Laser Induced Compton Backscattering



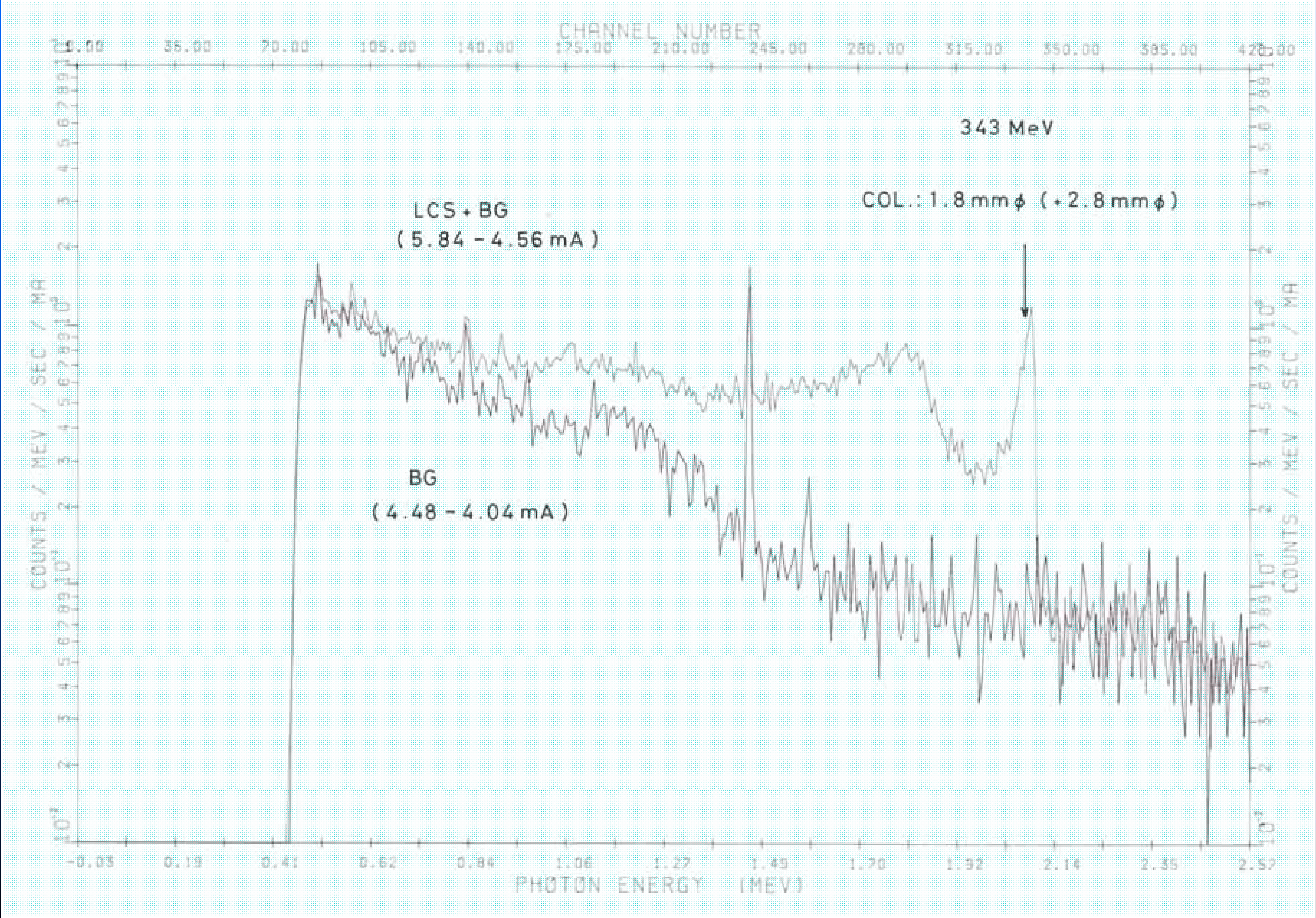
$$k_2 \sim 4\gamma^2 k_1$$

AIST LCS FACILITY

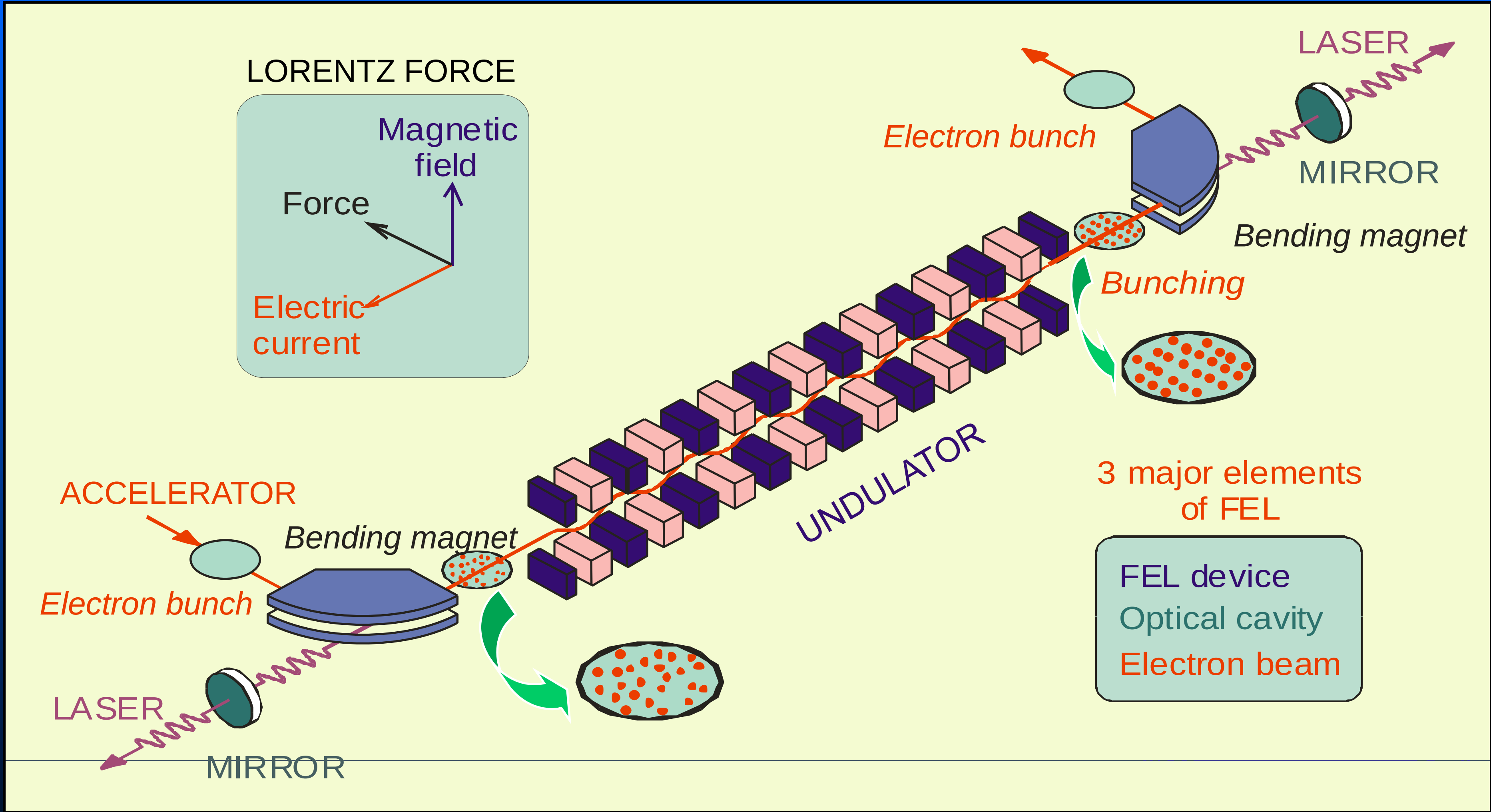


by H. Ohgaki

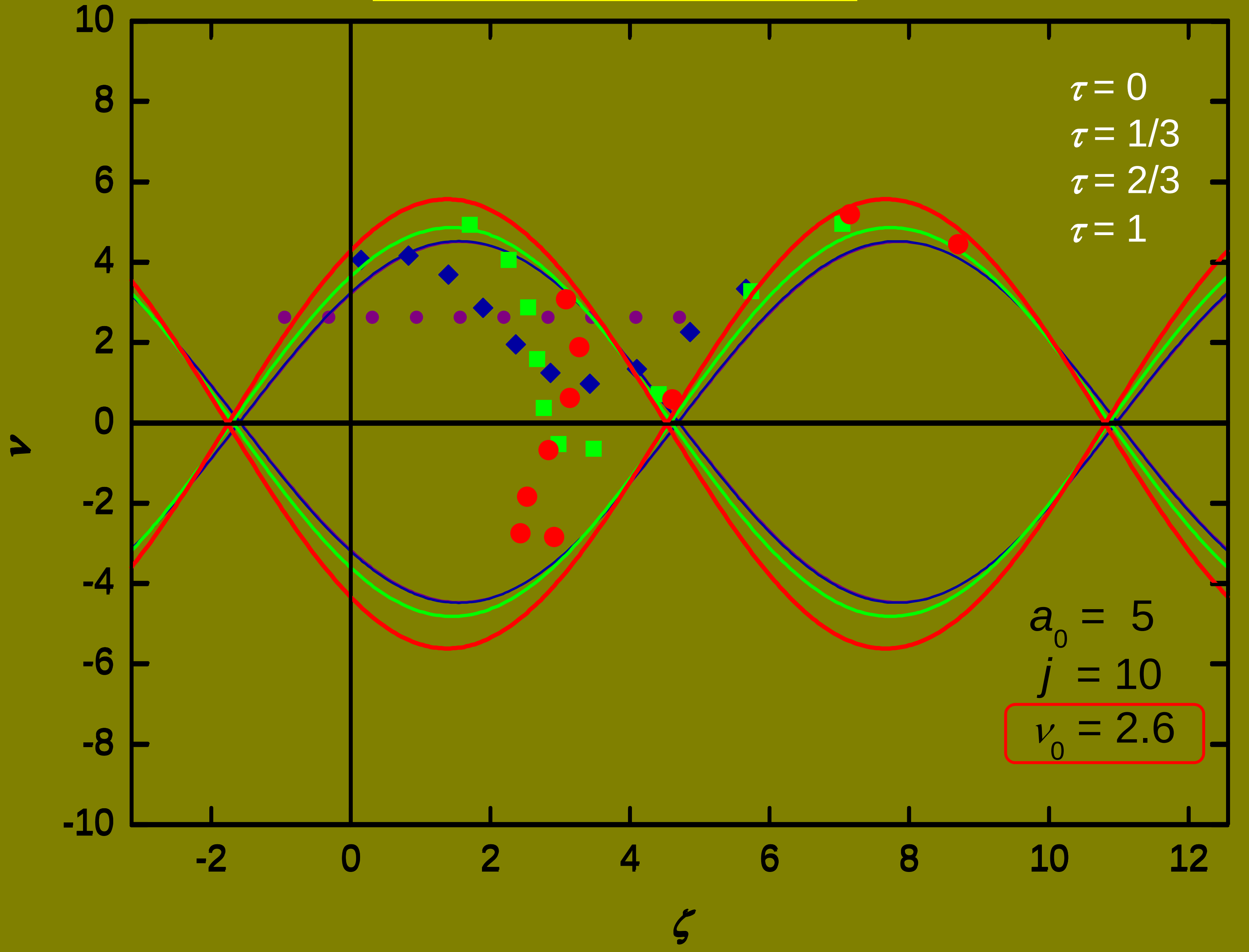
example of LCS spectrum



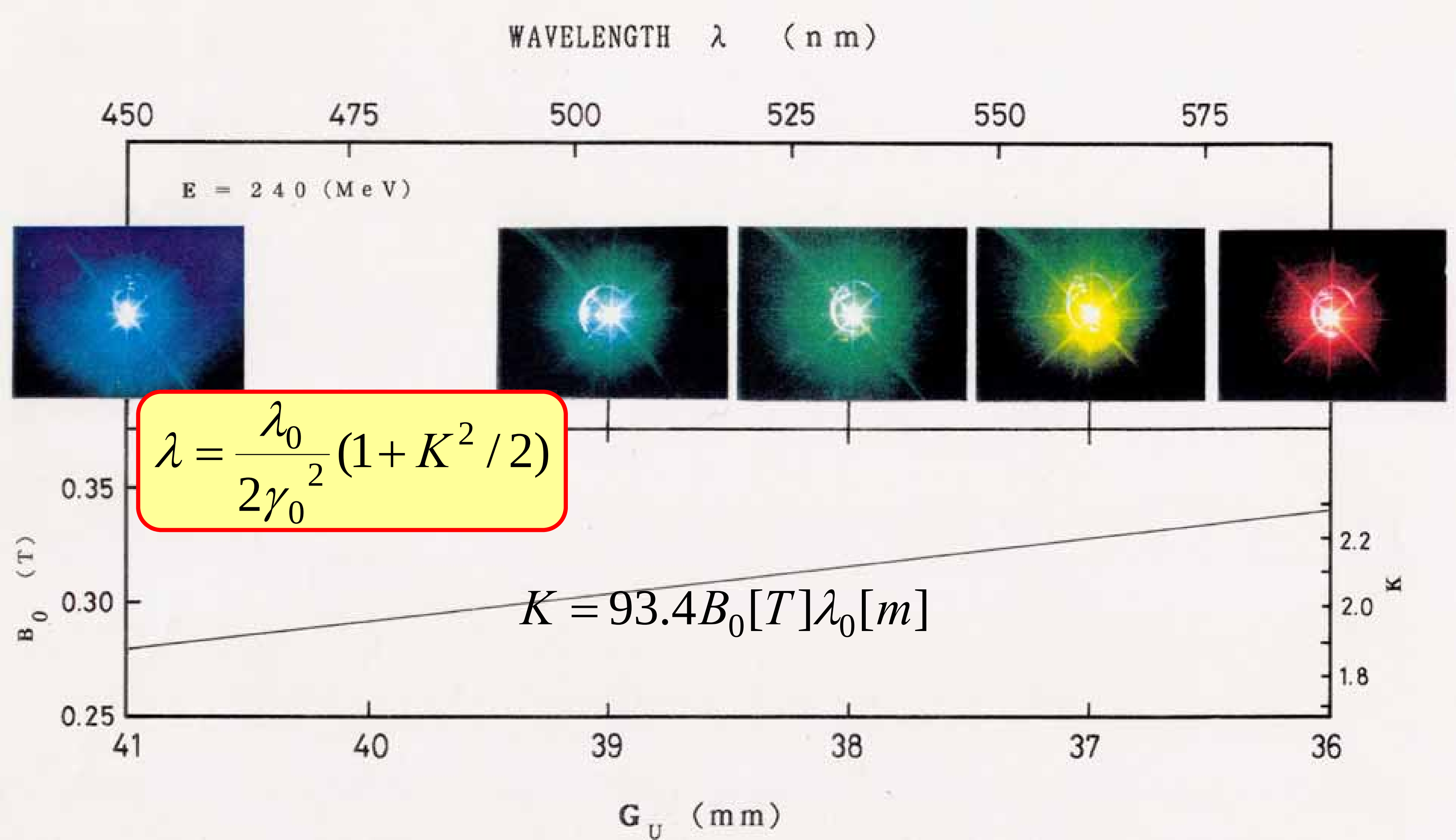
CONCEPTUAL SCHEME OF FEL



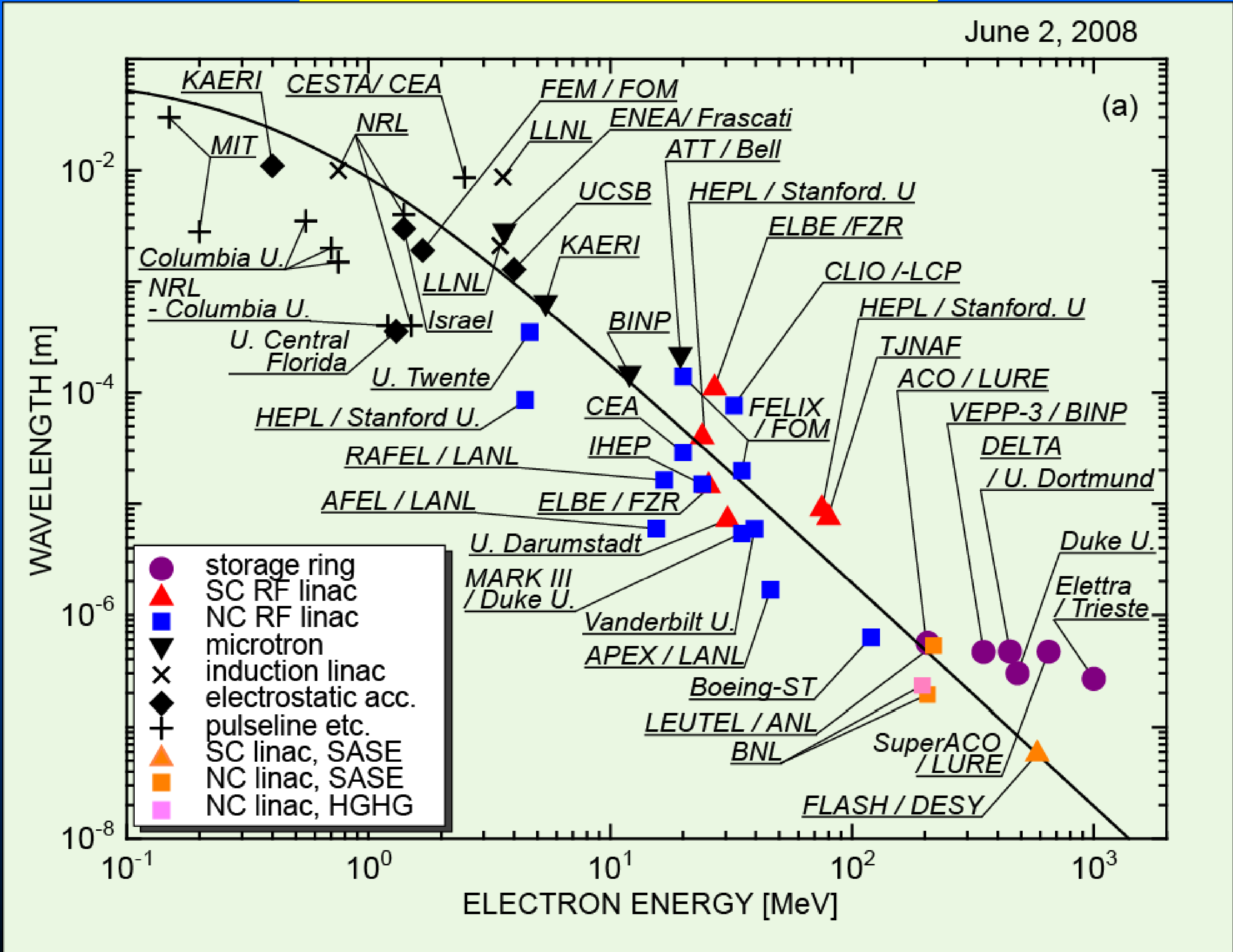
FEL EVOLUTION



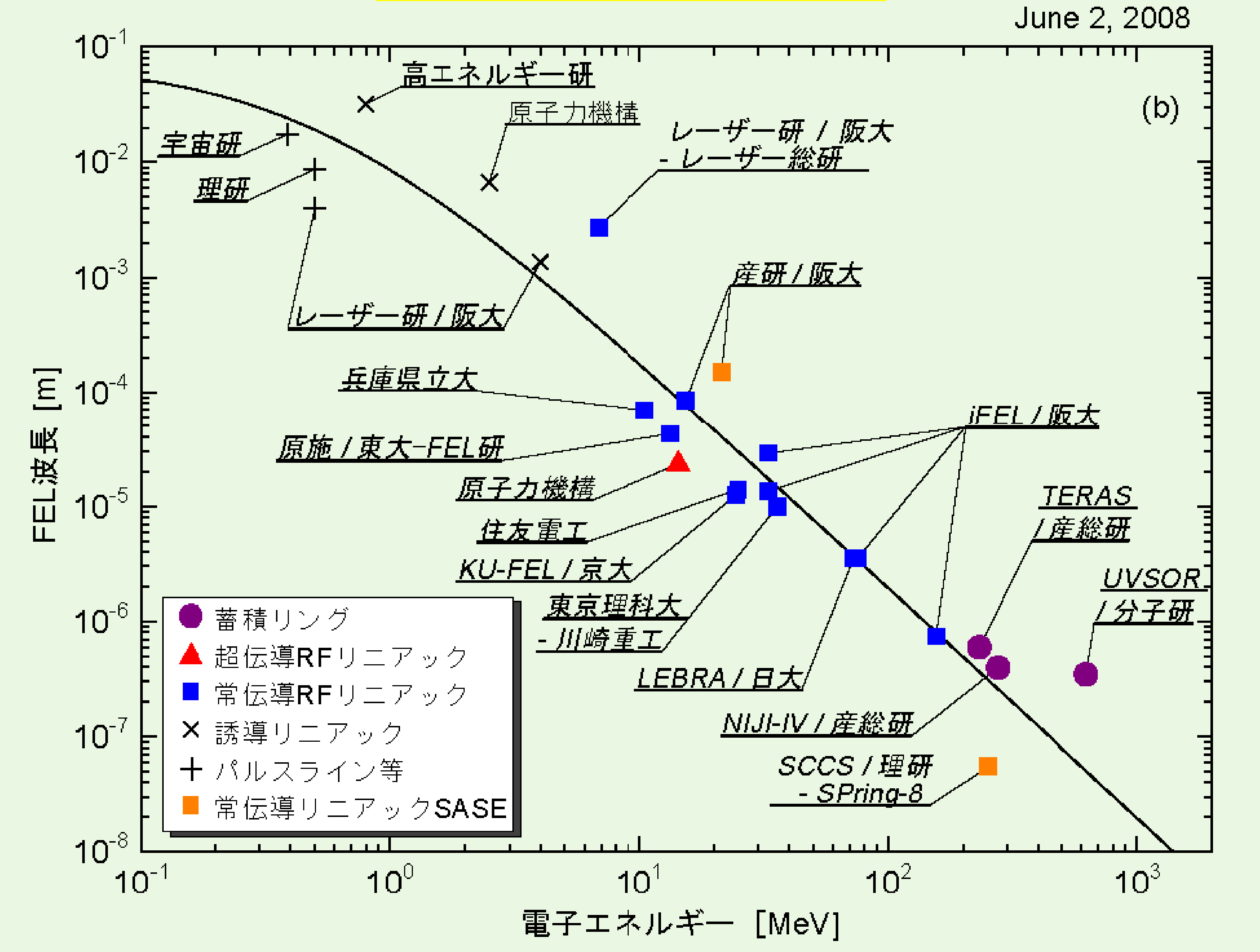
Wavelength Tunability of FEL



FEL PRJECTS IN THE WORLD

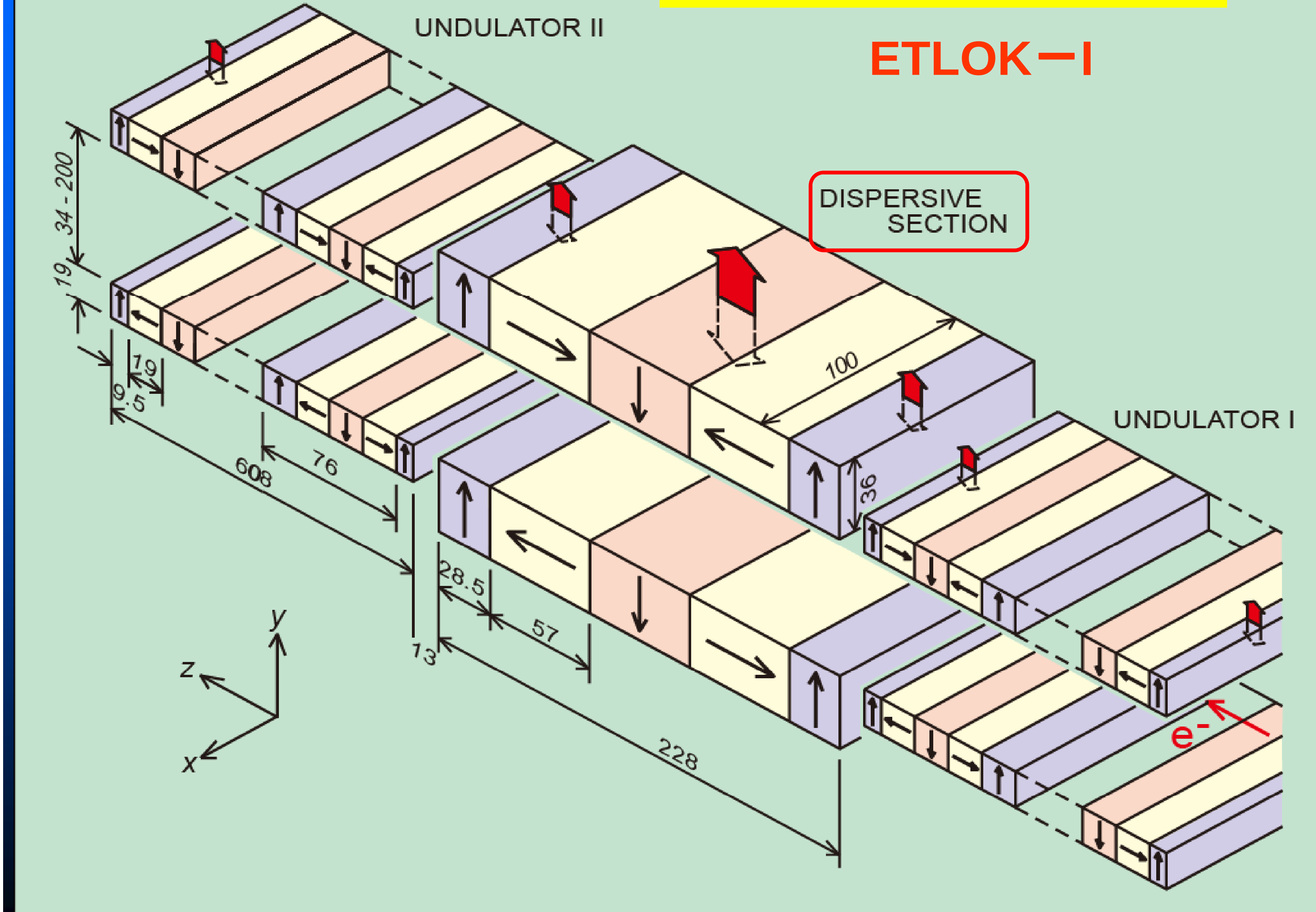


FEL PRJECTS IN JAPAN



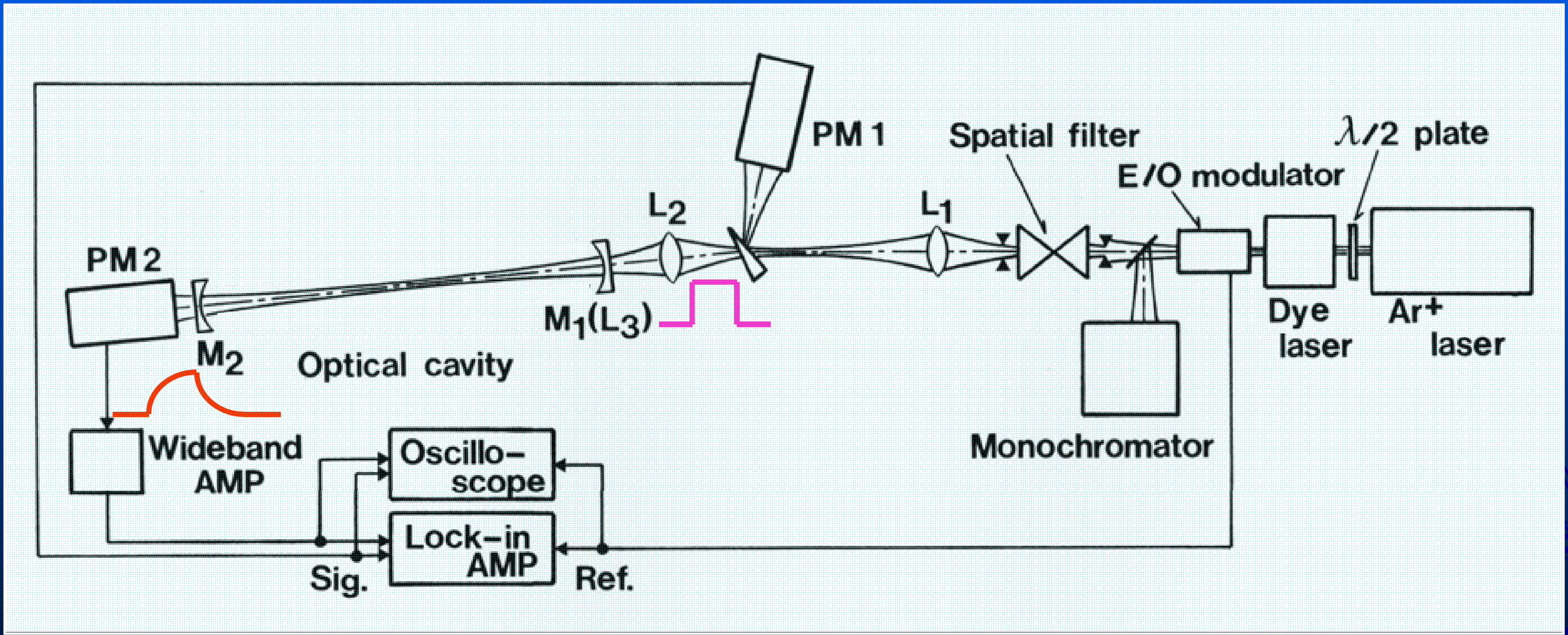
OPTICAL KLYSTRON

ETLOK－I

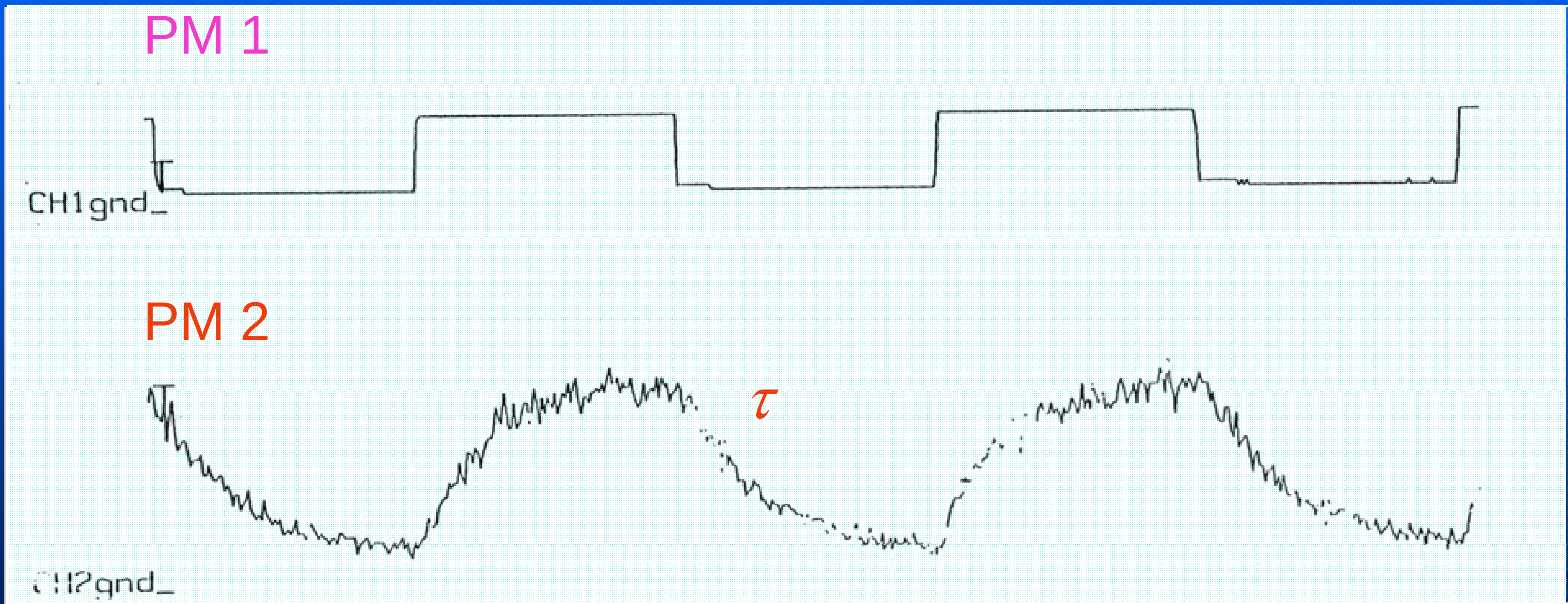


CAVITY-LOSS MEASUREMENT

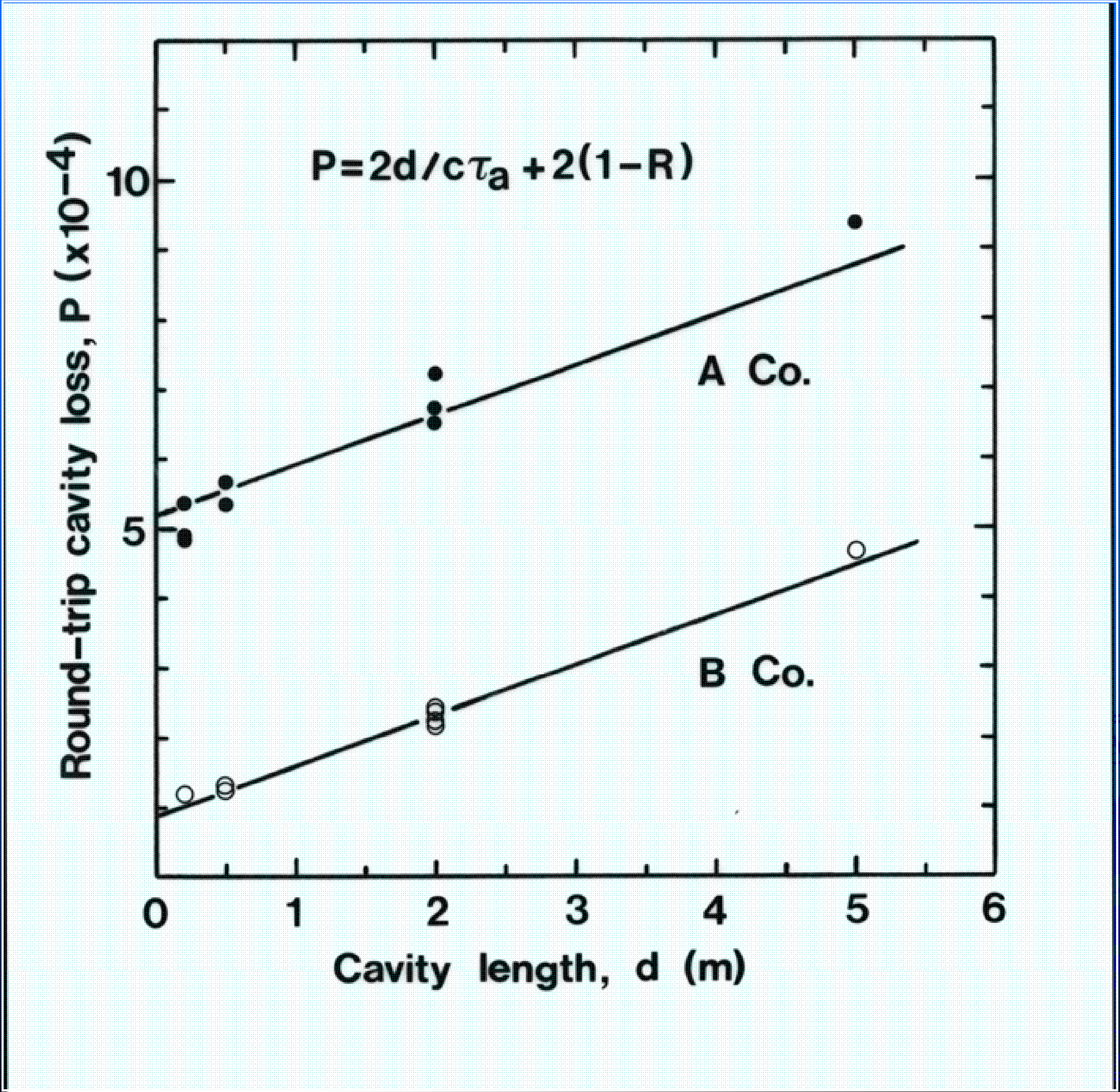
Decay-Time Method



Measured Waveform



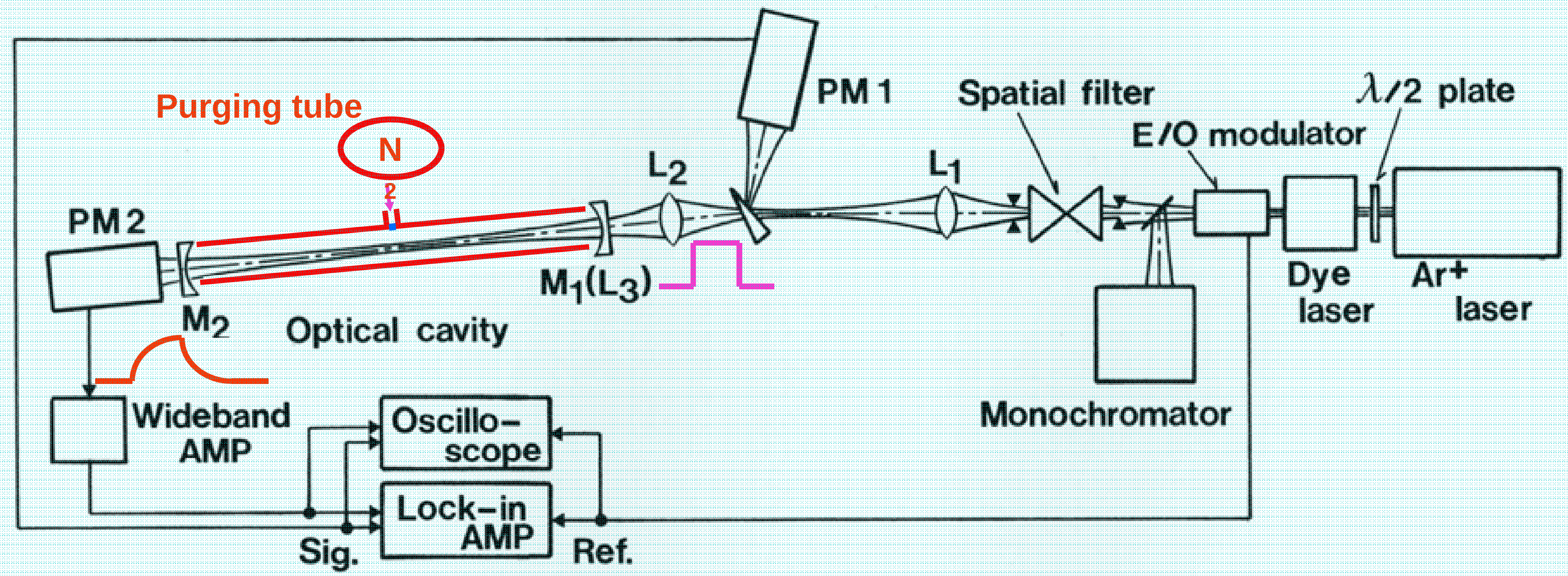
with averaging



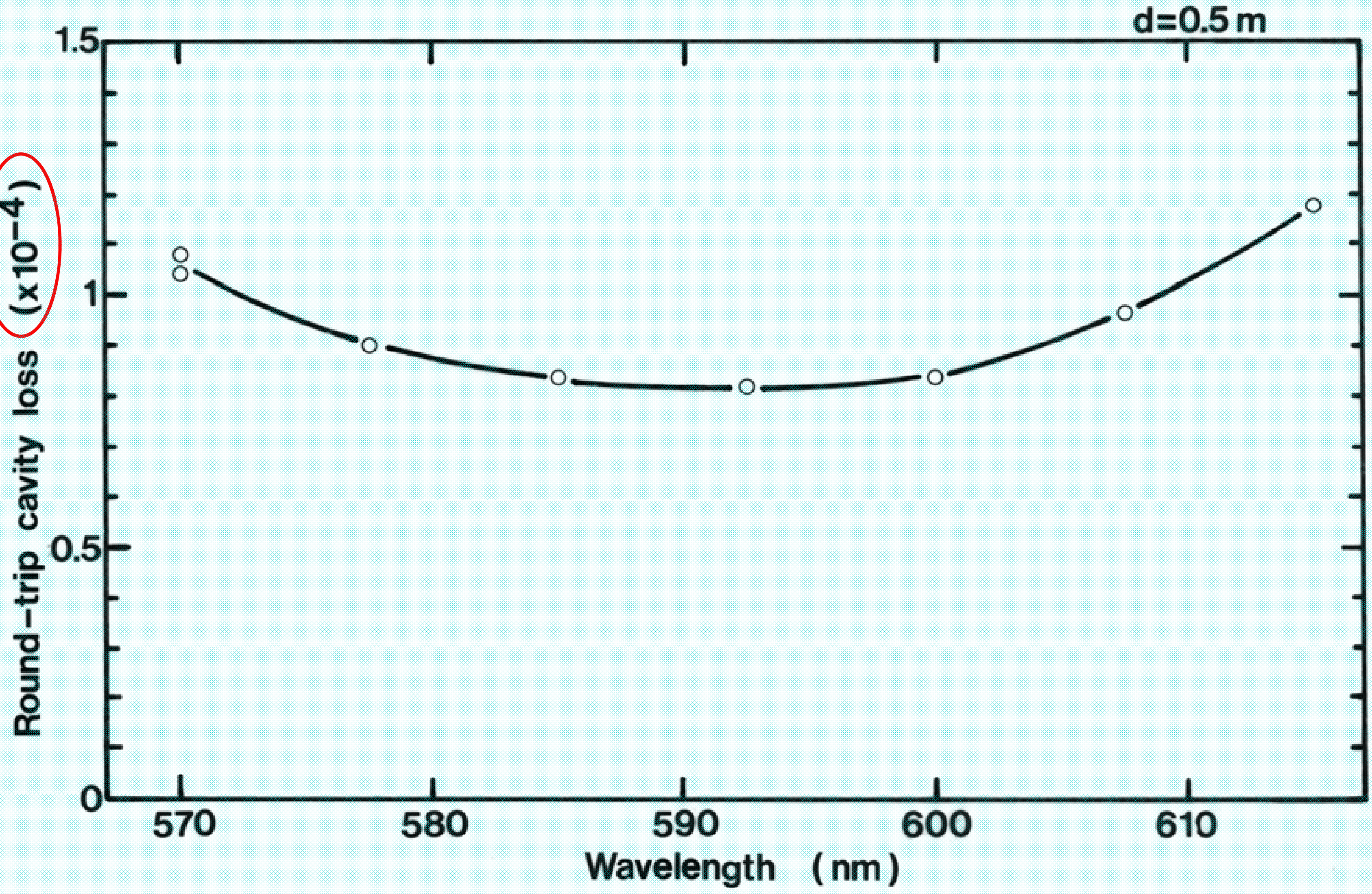
P=2d/cτa +2(1−R)
10
5
A Co.
B Co.
0
1
2
3
4
5
6
Round-trip cavity loss, P (x10−4)
Cavity length, d (m)

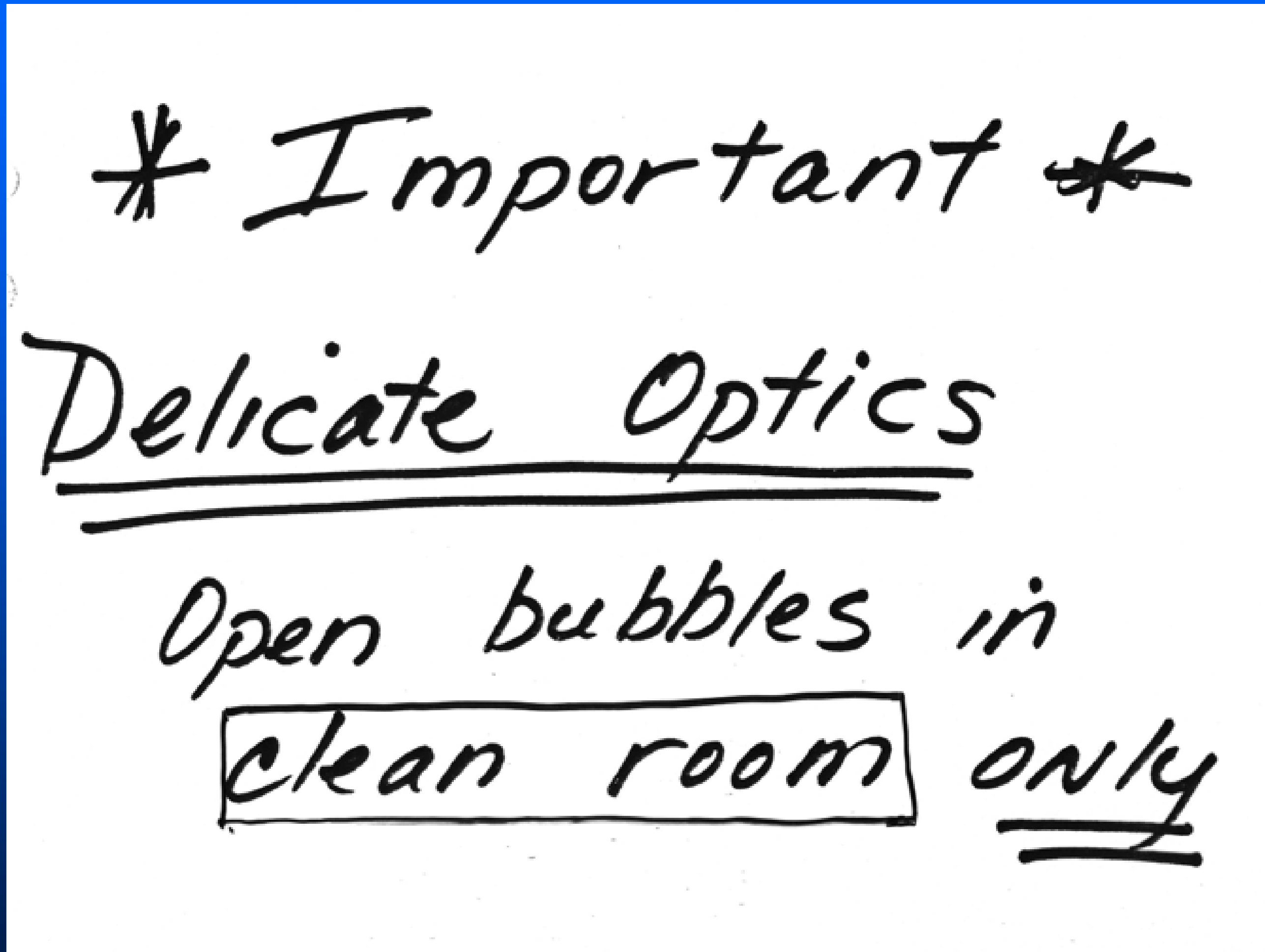
CAVITY-LOSS MEASUREMENT

Decay-Time Method

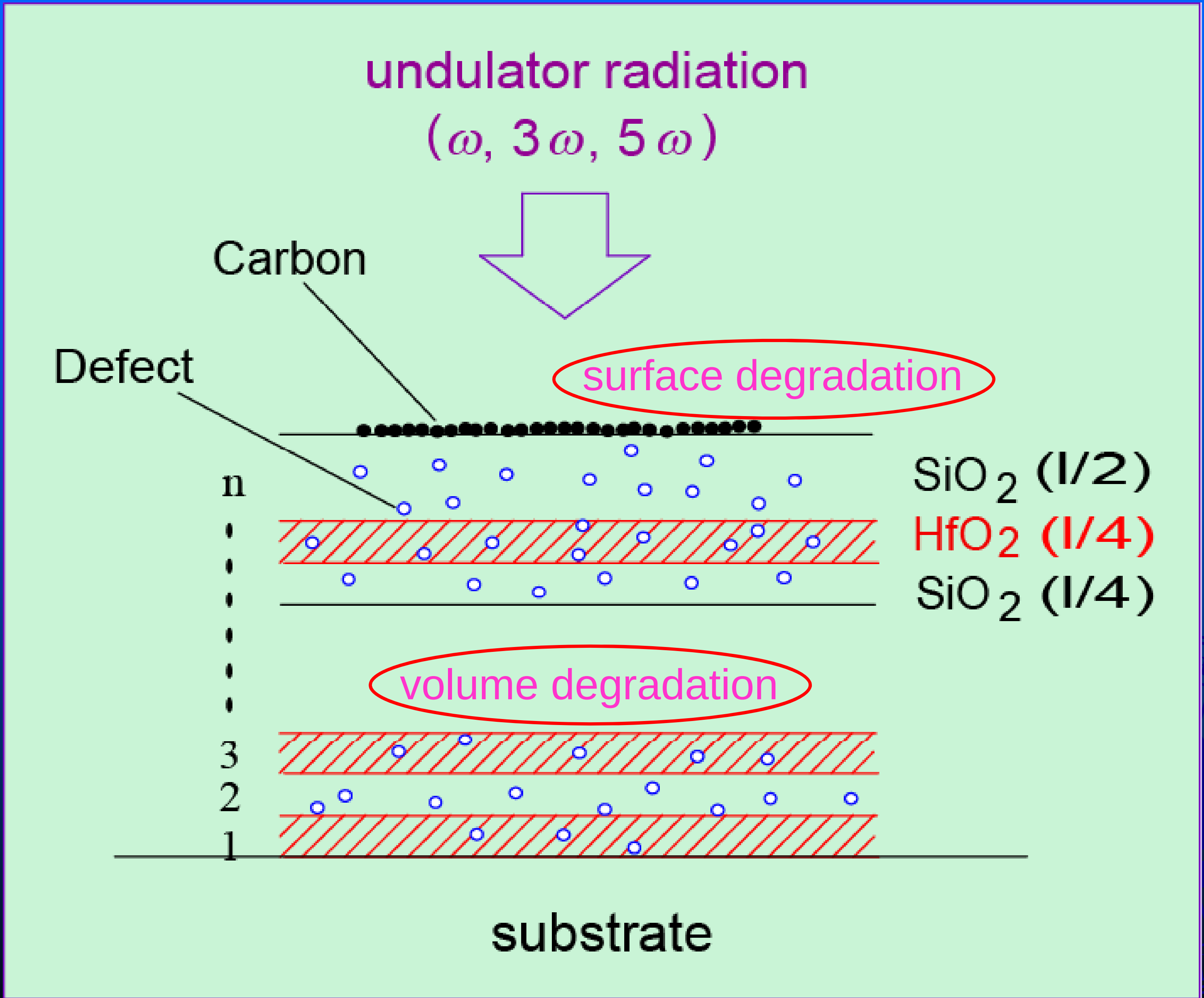


ROUND-TRIP CAVITY-LOSS

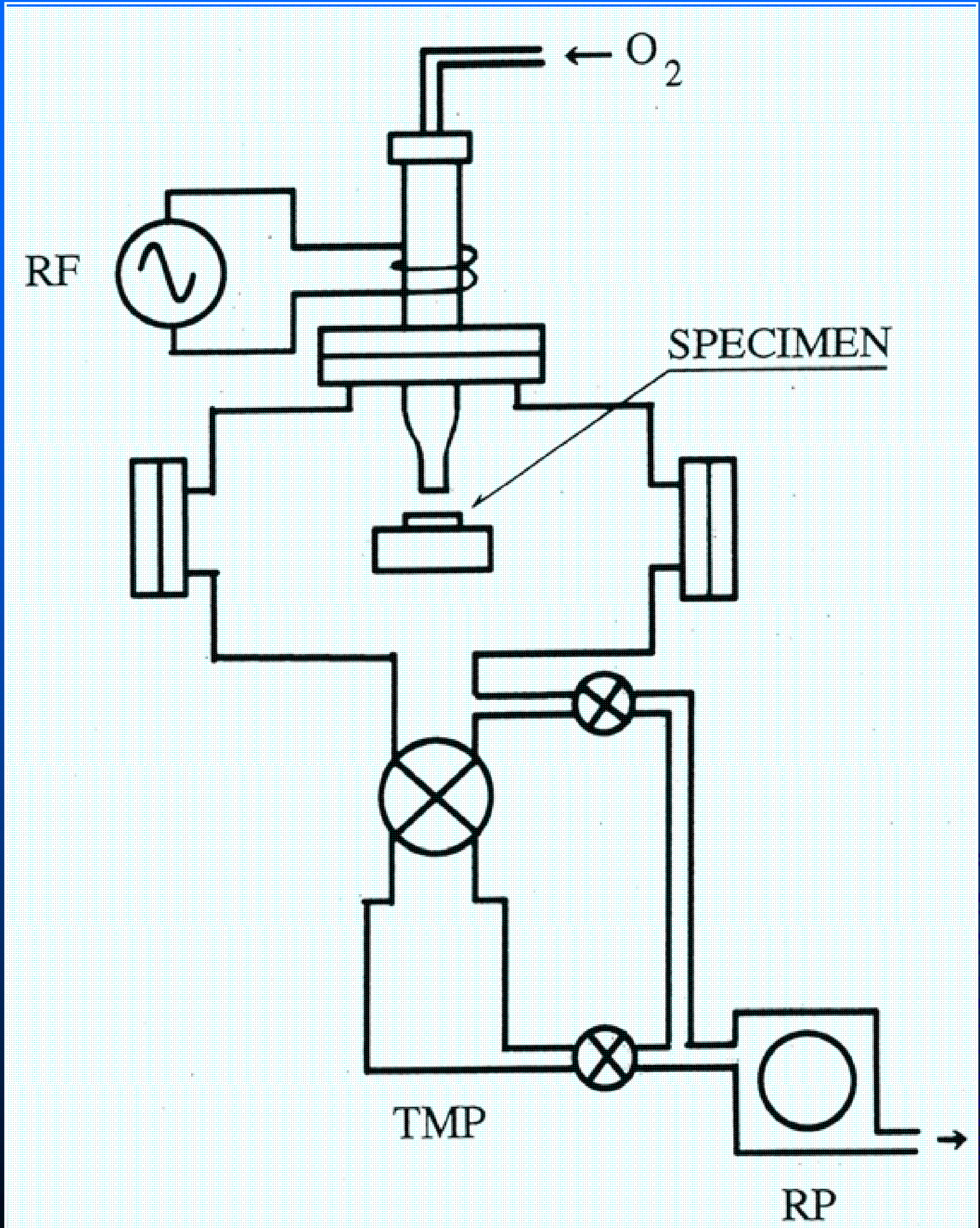



* Important *
Delicate Optics
Open bubbles in
clean room only

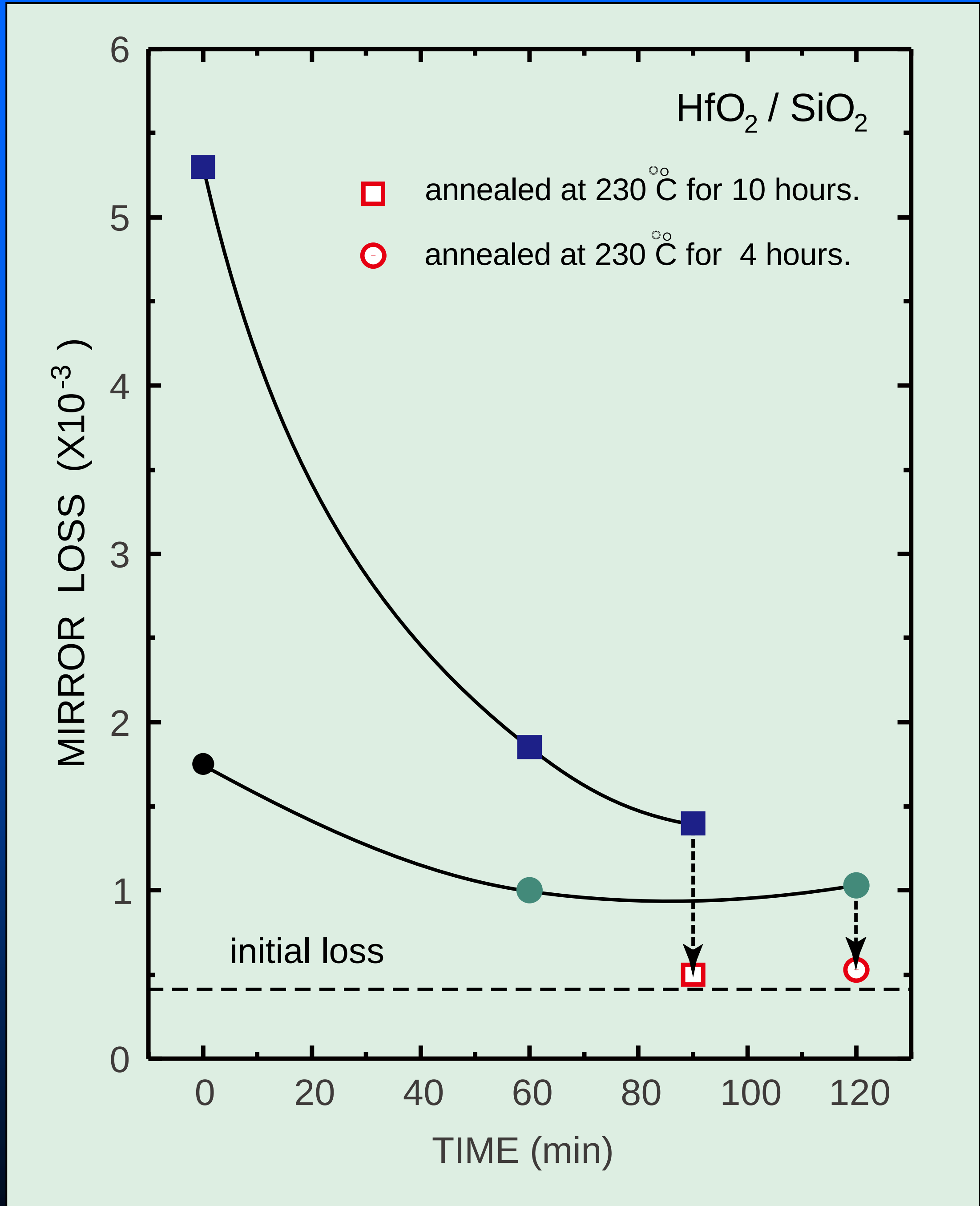
Mechanism of Mirror Degradation



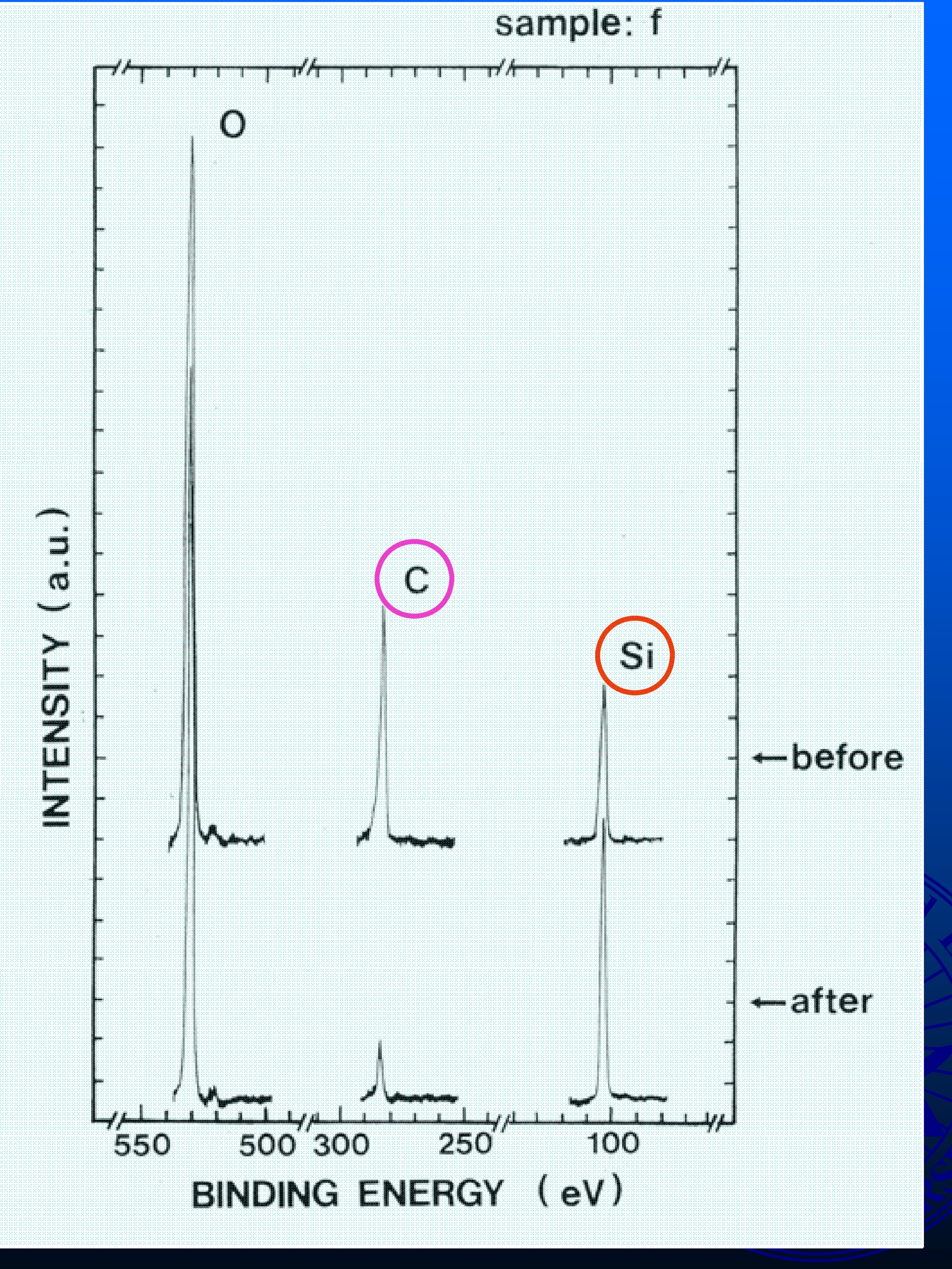
OXYGEN PLASMA TREATMENT



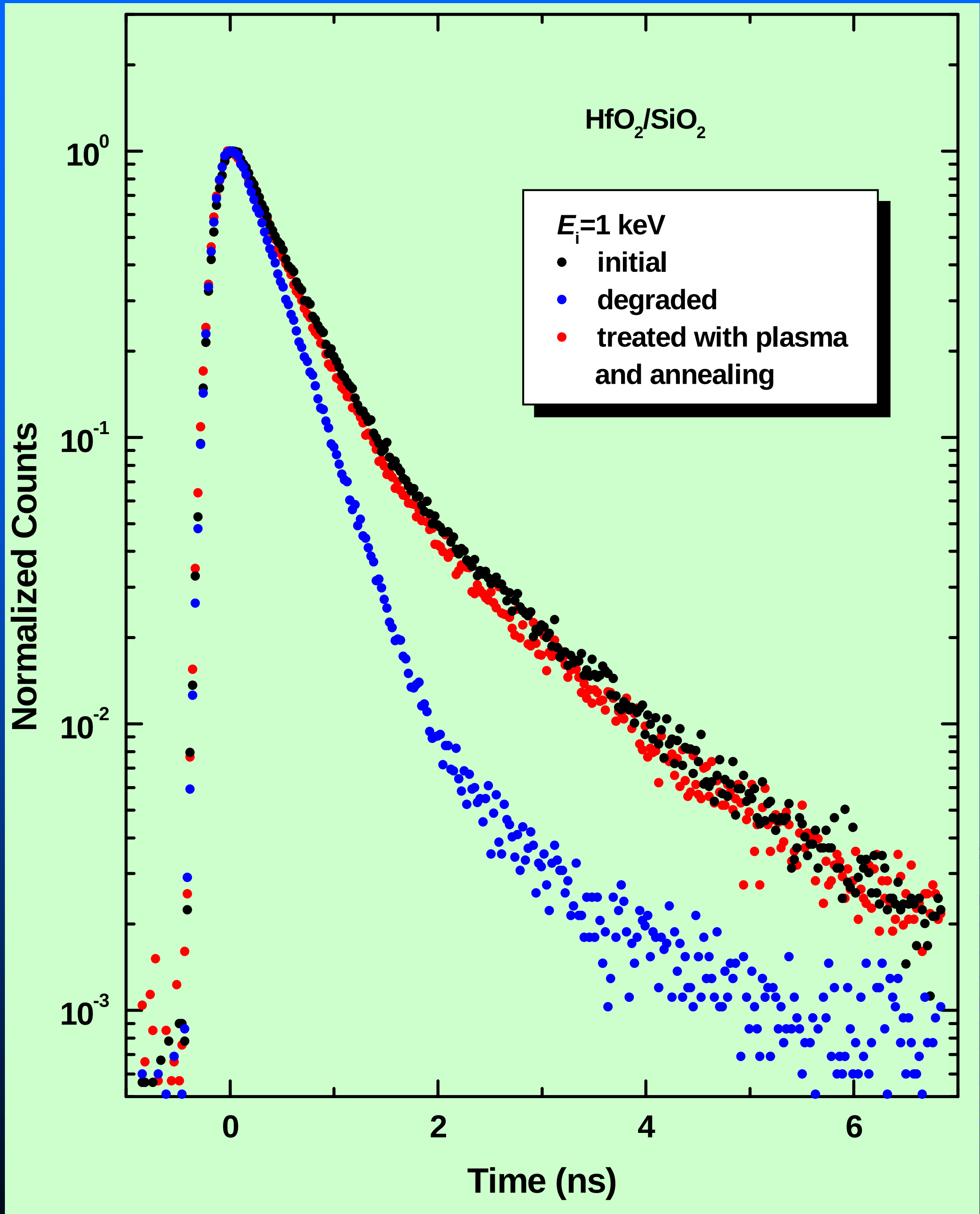
RESTORATION OF MIRROR DEGRADATION



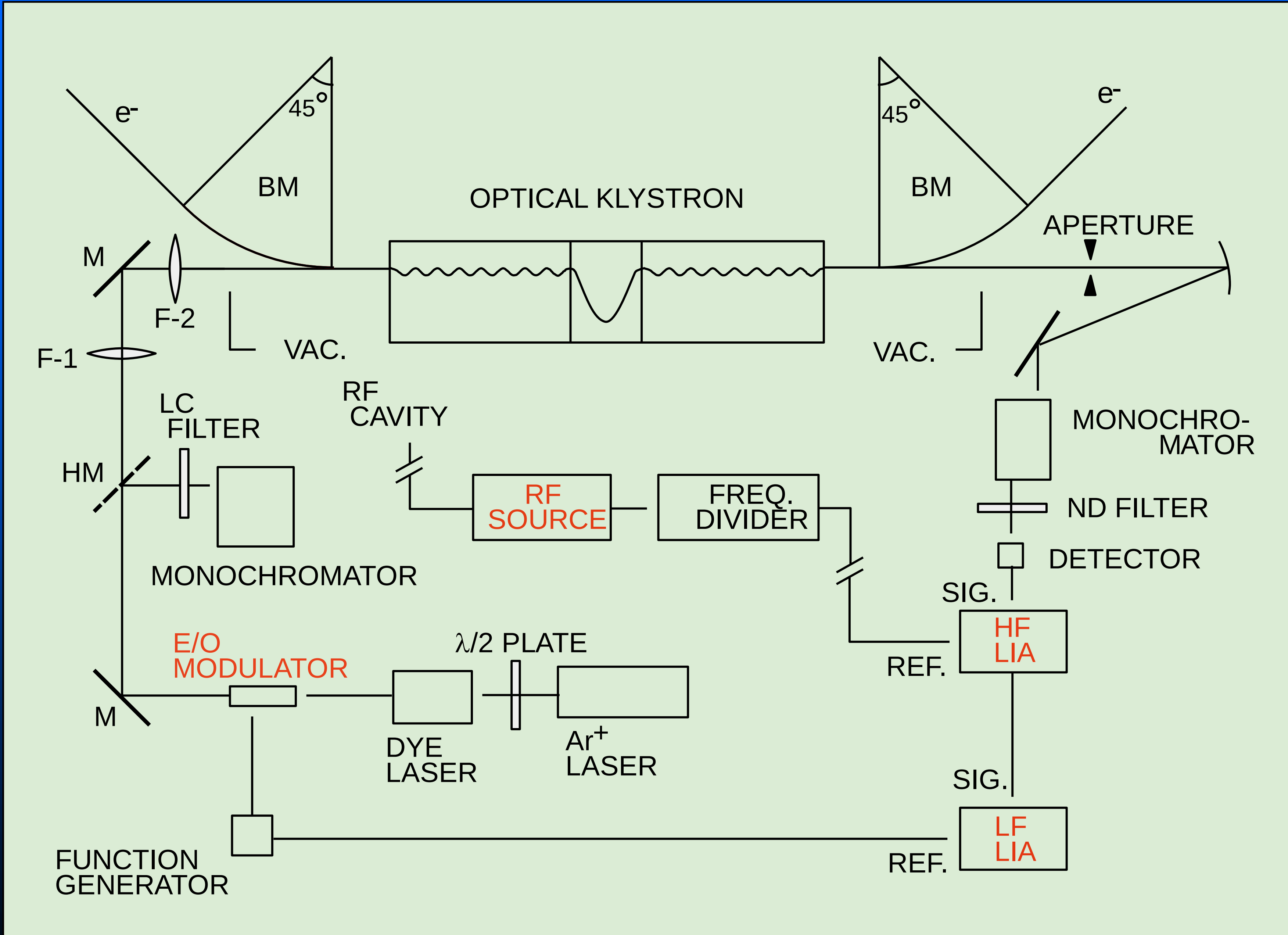
X-RAY PHOTOELECTRON SPECTRA FROM MIRROR SURFACE



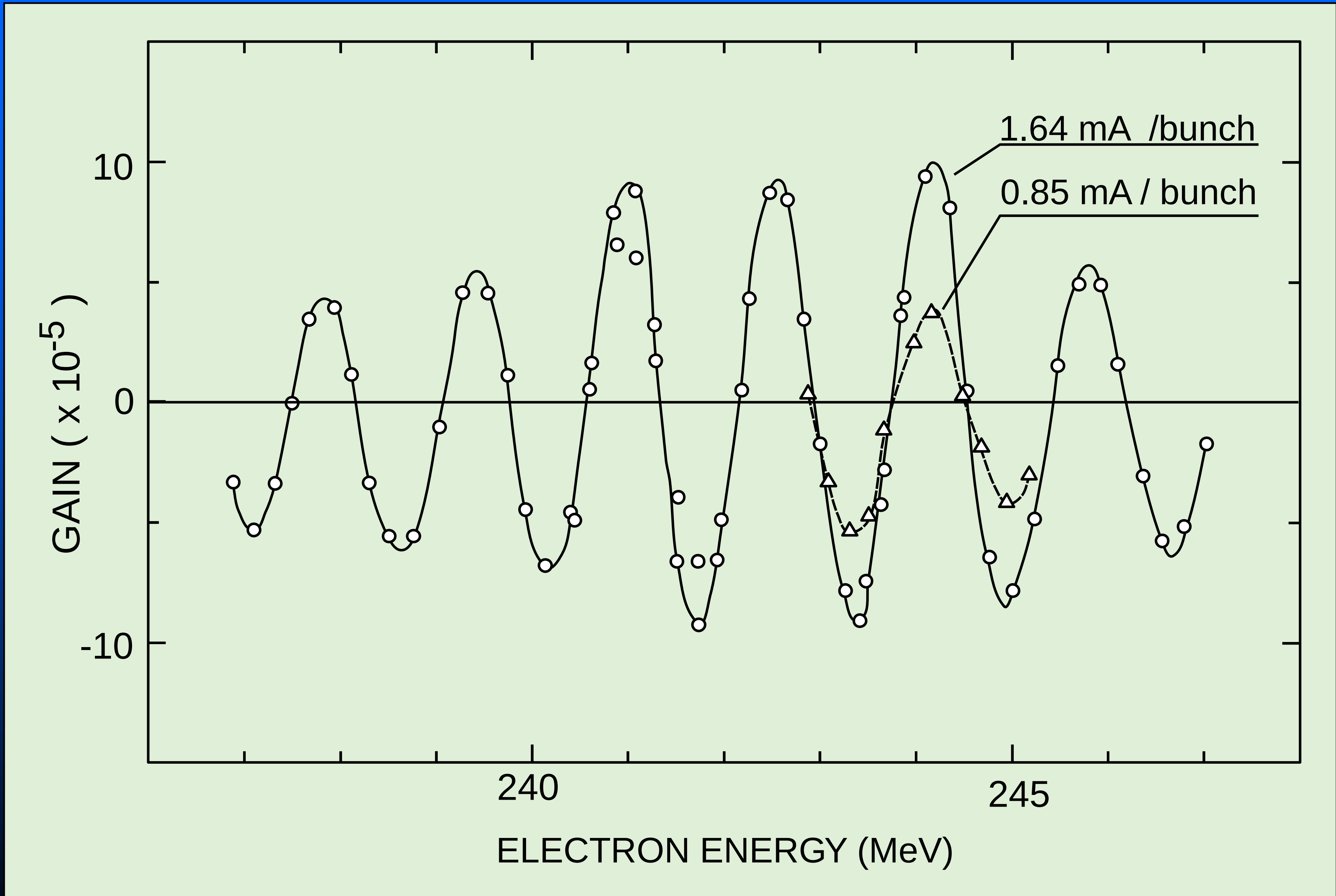
Positron lifetime spectra of a dielectric multilayer cavity mirror for FEL



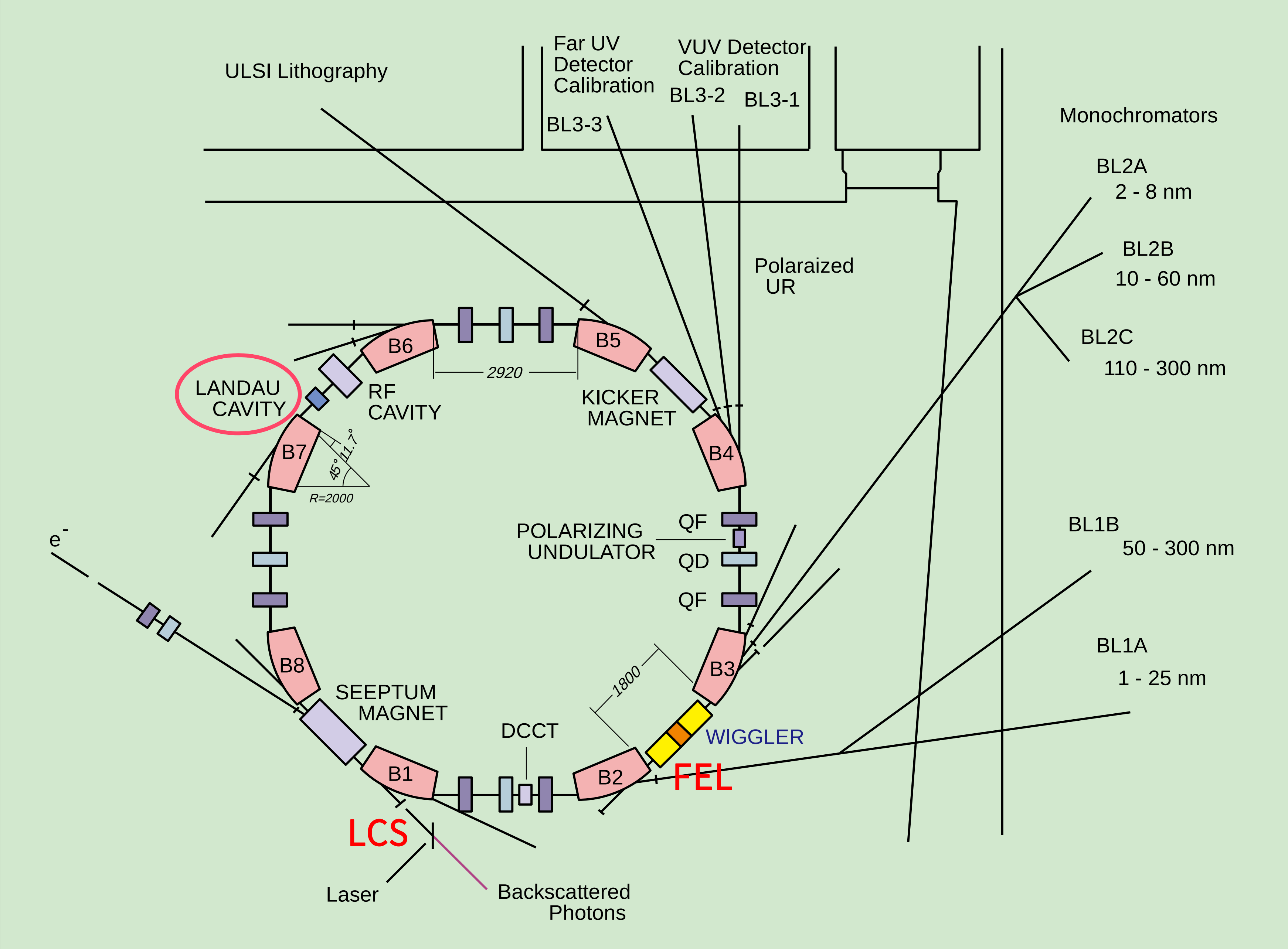
FEL GAIN MEASUREMENT



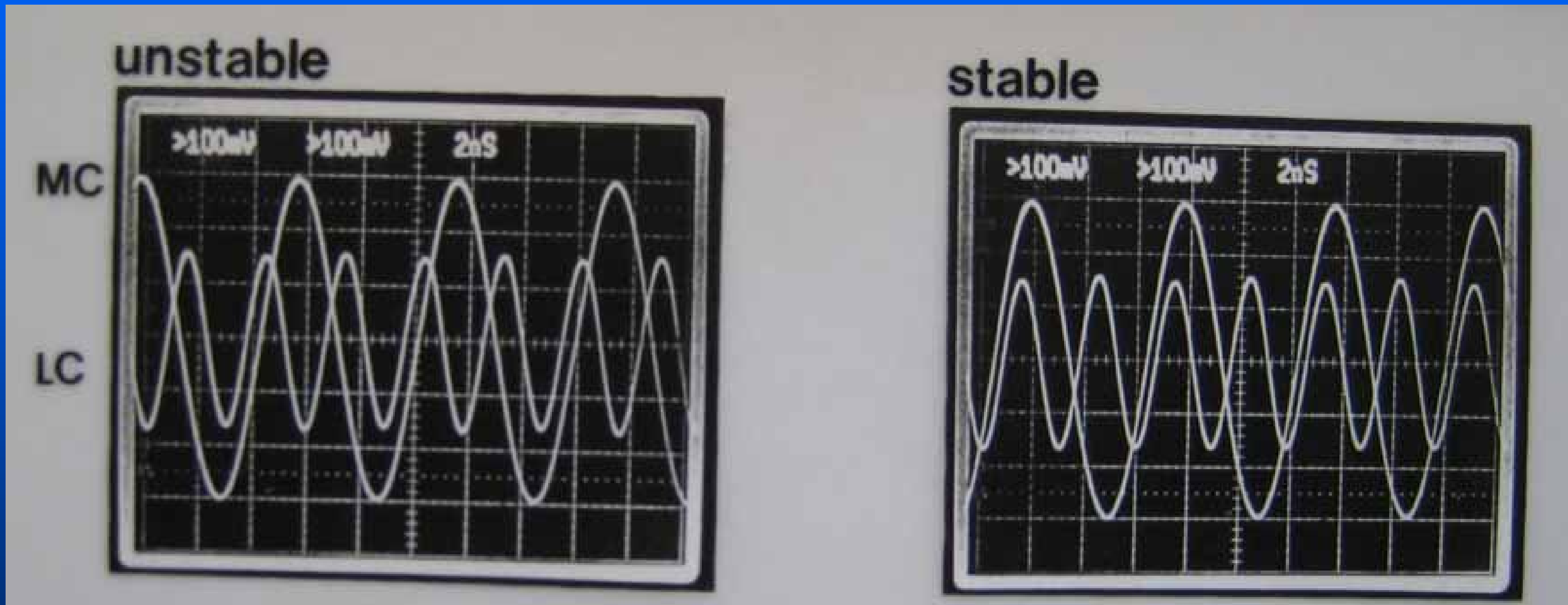
GAIN OF TERAS FEL



STORAGE RING TERAS

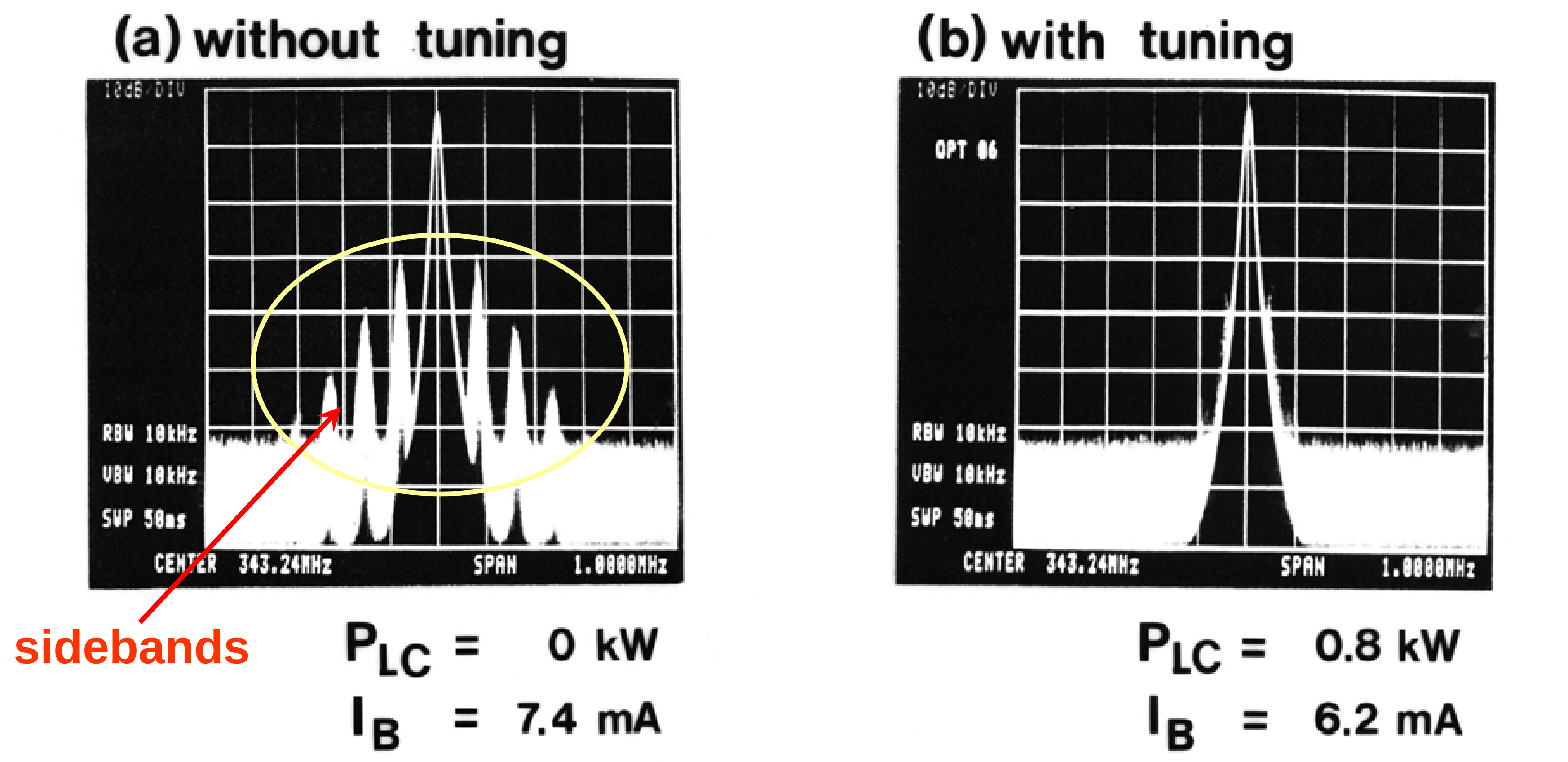


main RF cavity and Landau cavity



P_{LC}= 0.53 kW

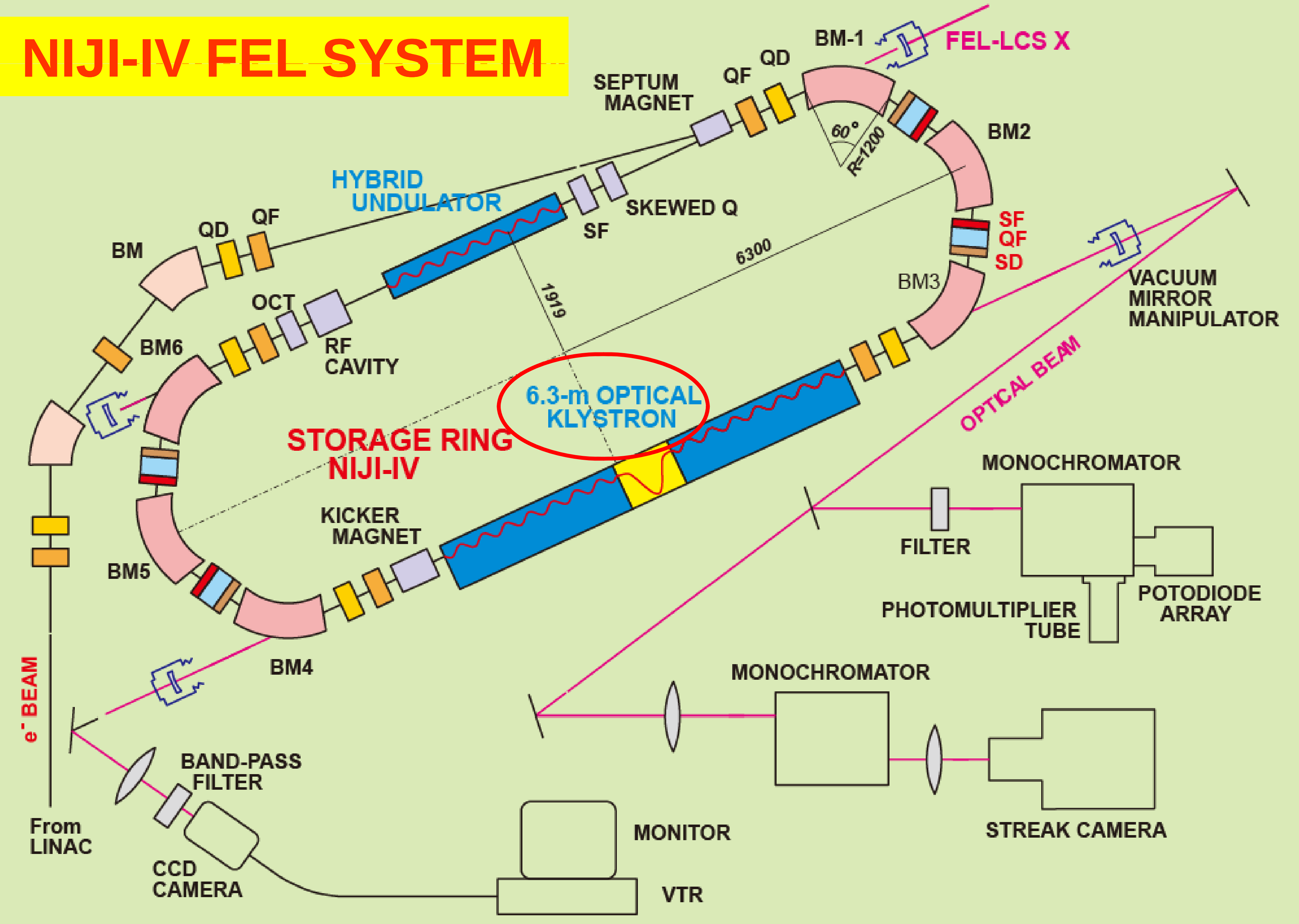
SUPPRESSION OF
COHERENT SYNCROTRON OSCILLATION



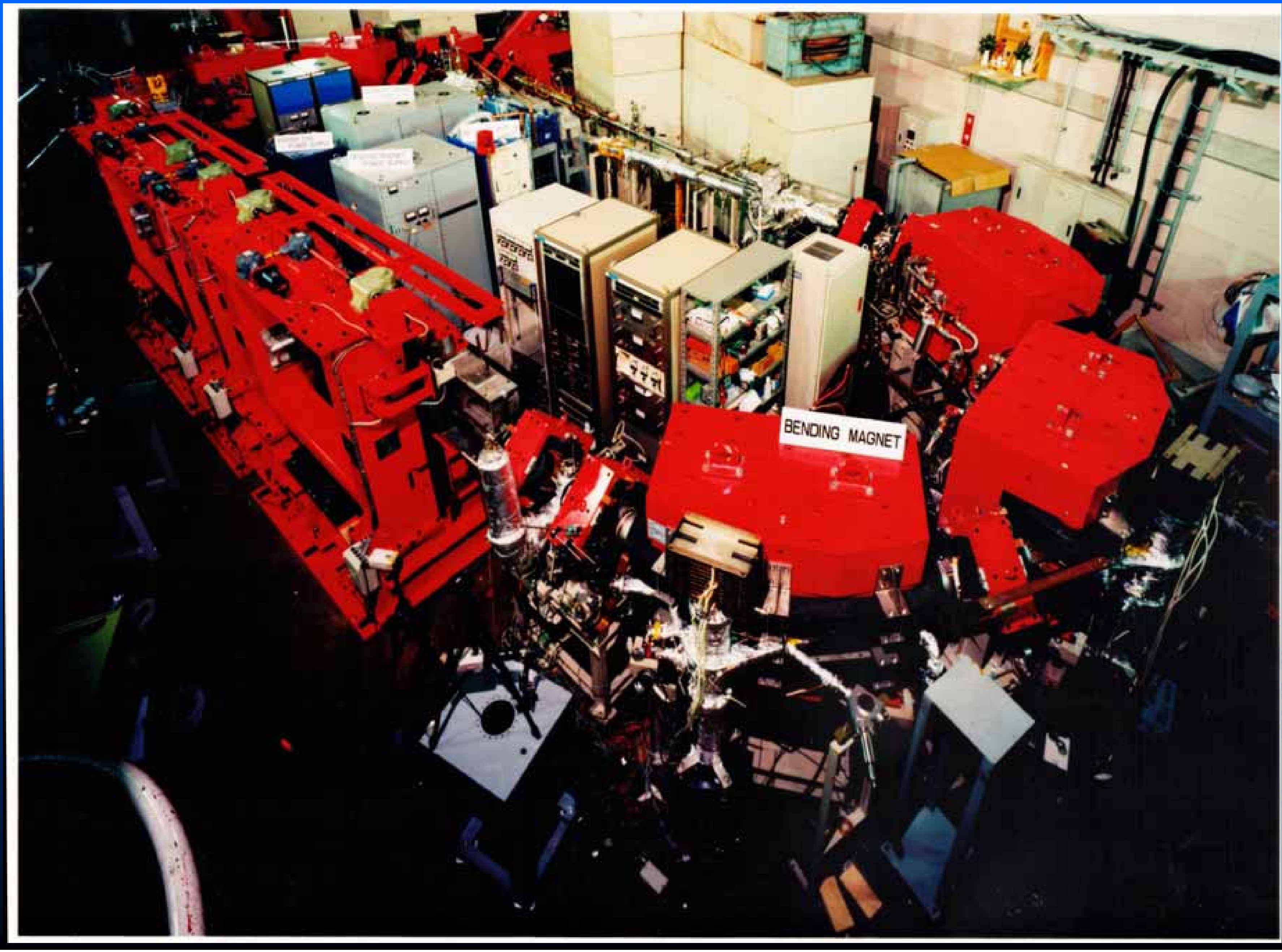
Lasing pattern of FEL on storage ring TERAS

spatial coherence

NIJI-IV FEL SYSTEM

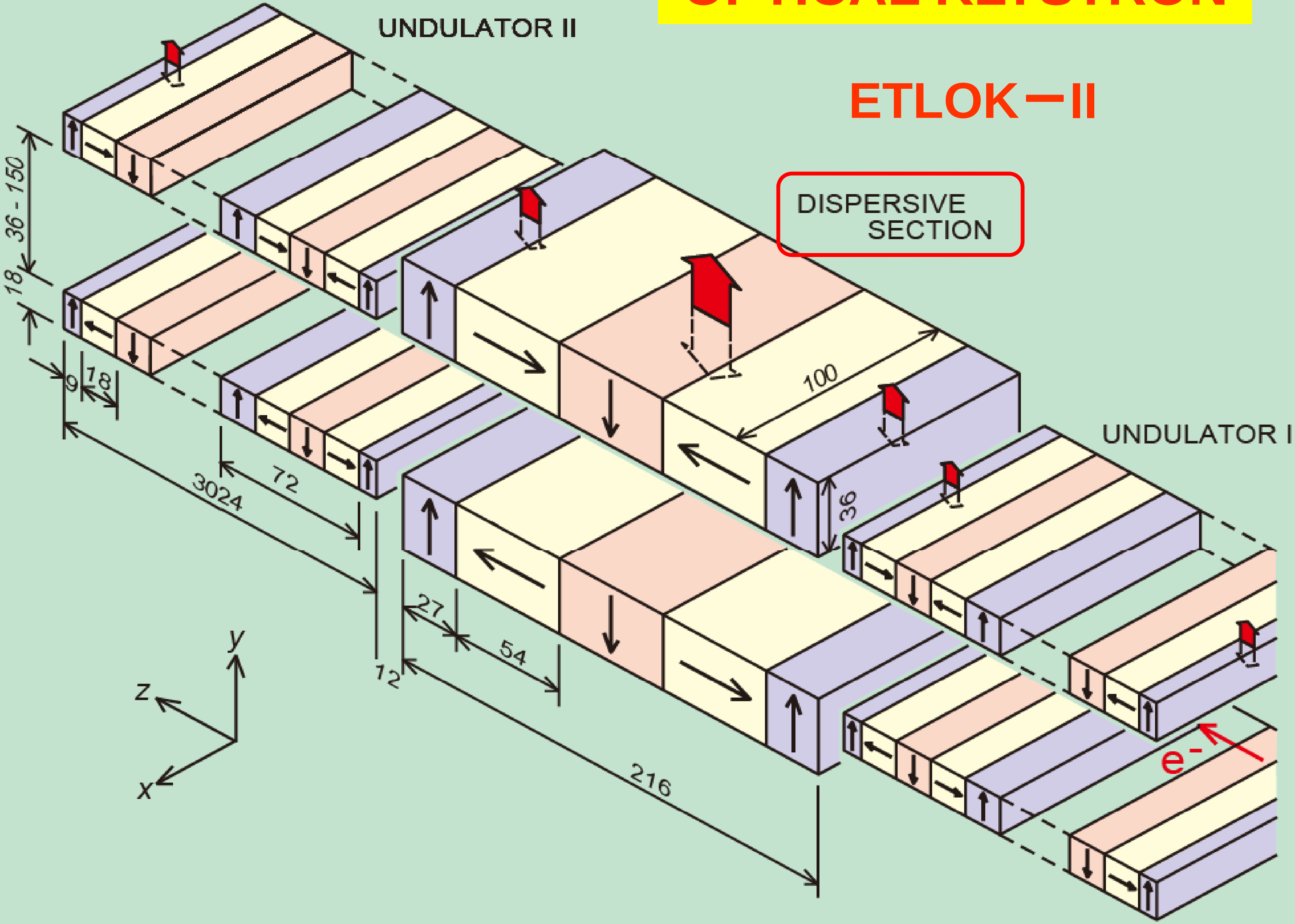


STORAGE RING NIJI-IV

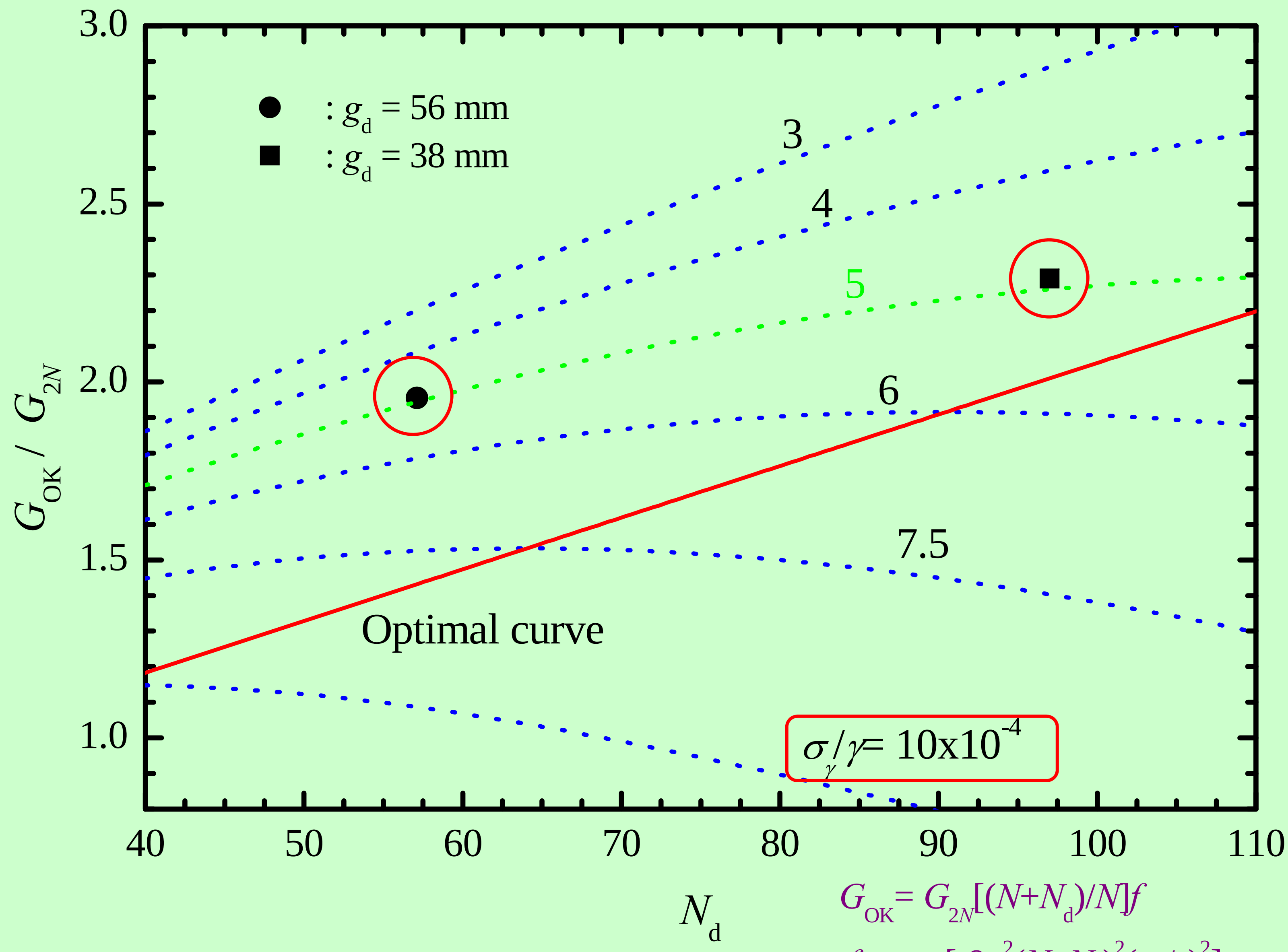


OPTICAL KLYSTRON

ETLOK－II



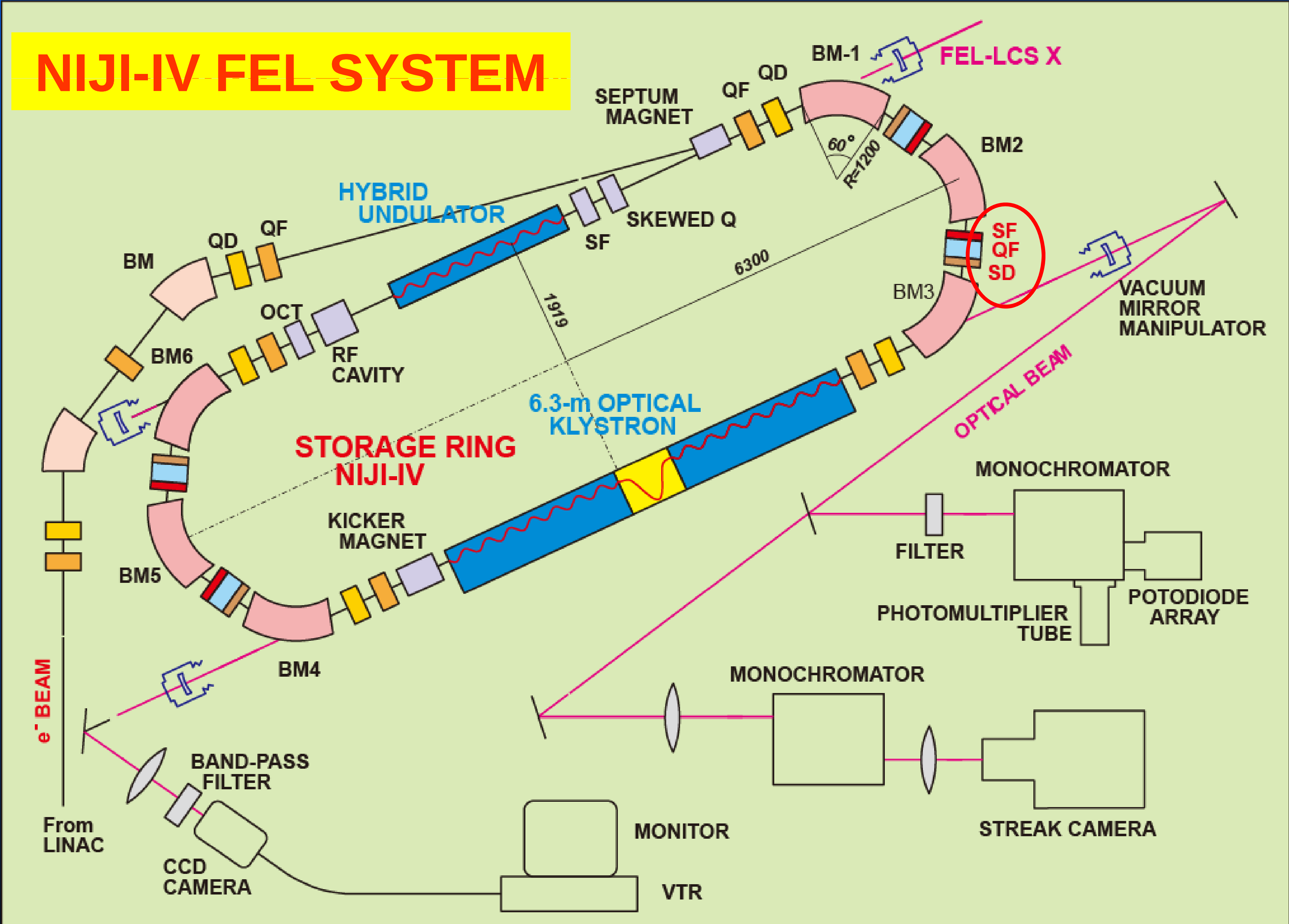
GAIN OF NORMAL UNDULATOR & OK



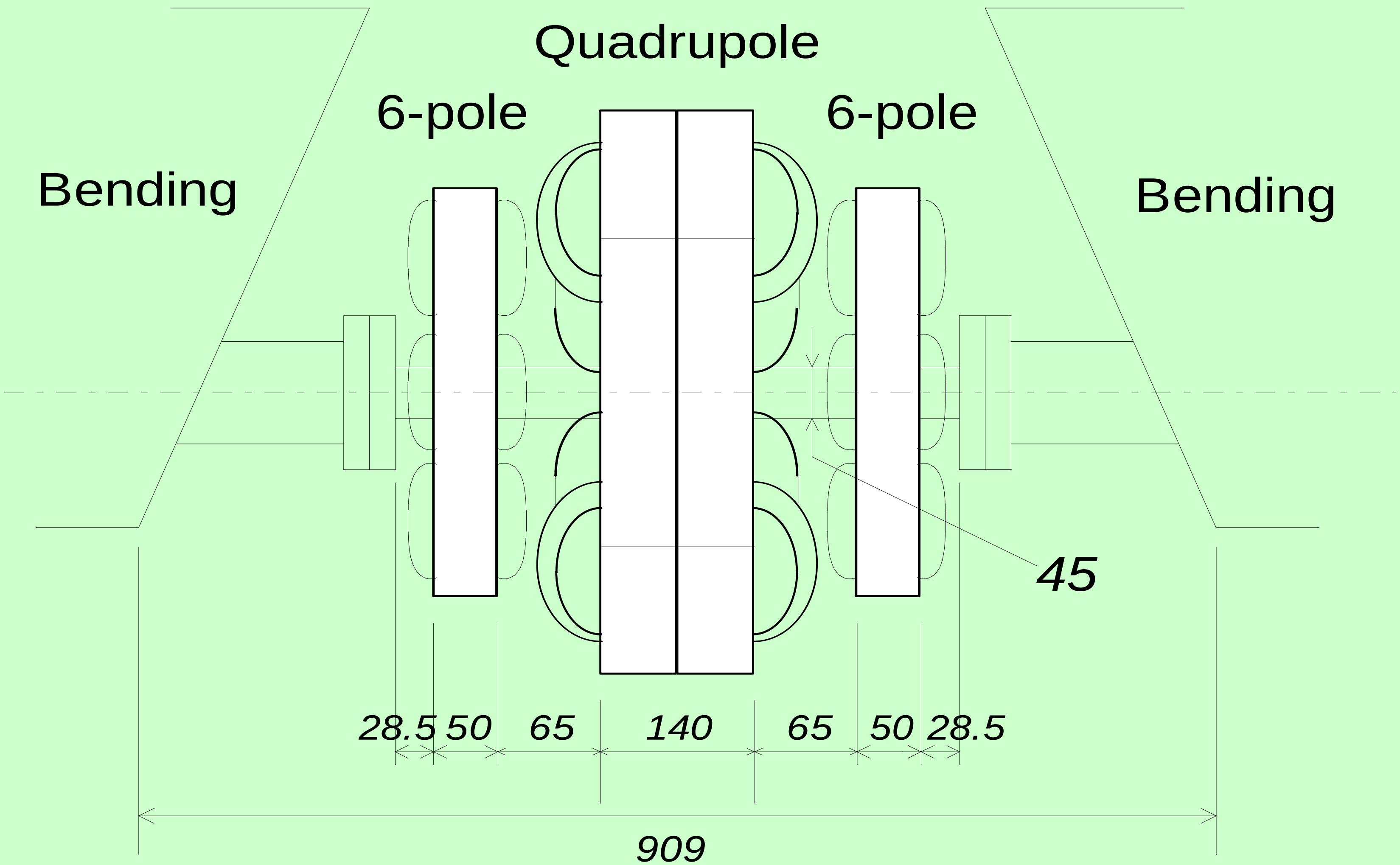
$G_{OK} = G_{2N}[(N+N_d)/N]f$

$f = \exp[-8\pi^2(N+N_d)^2(\sigma_\gamma/\gamma)^2]$

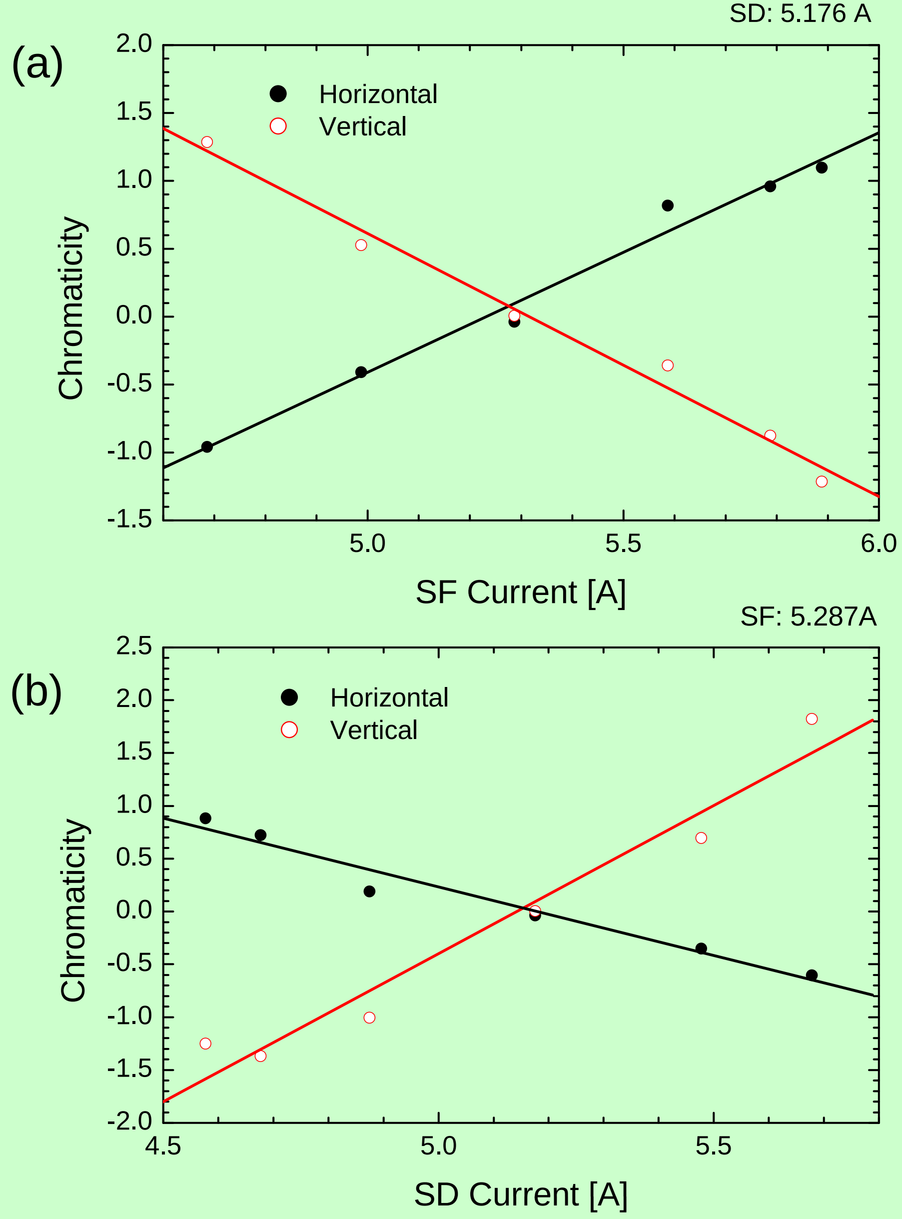
NIJI-IV FEL SYSTEM



SQS SYSTEM OF NIJI-IV



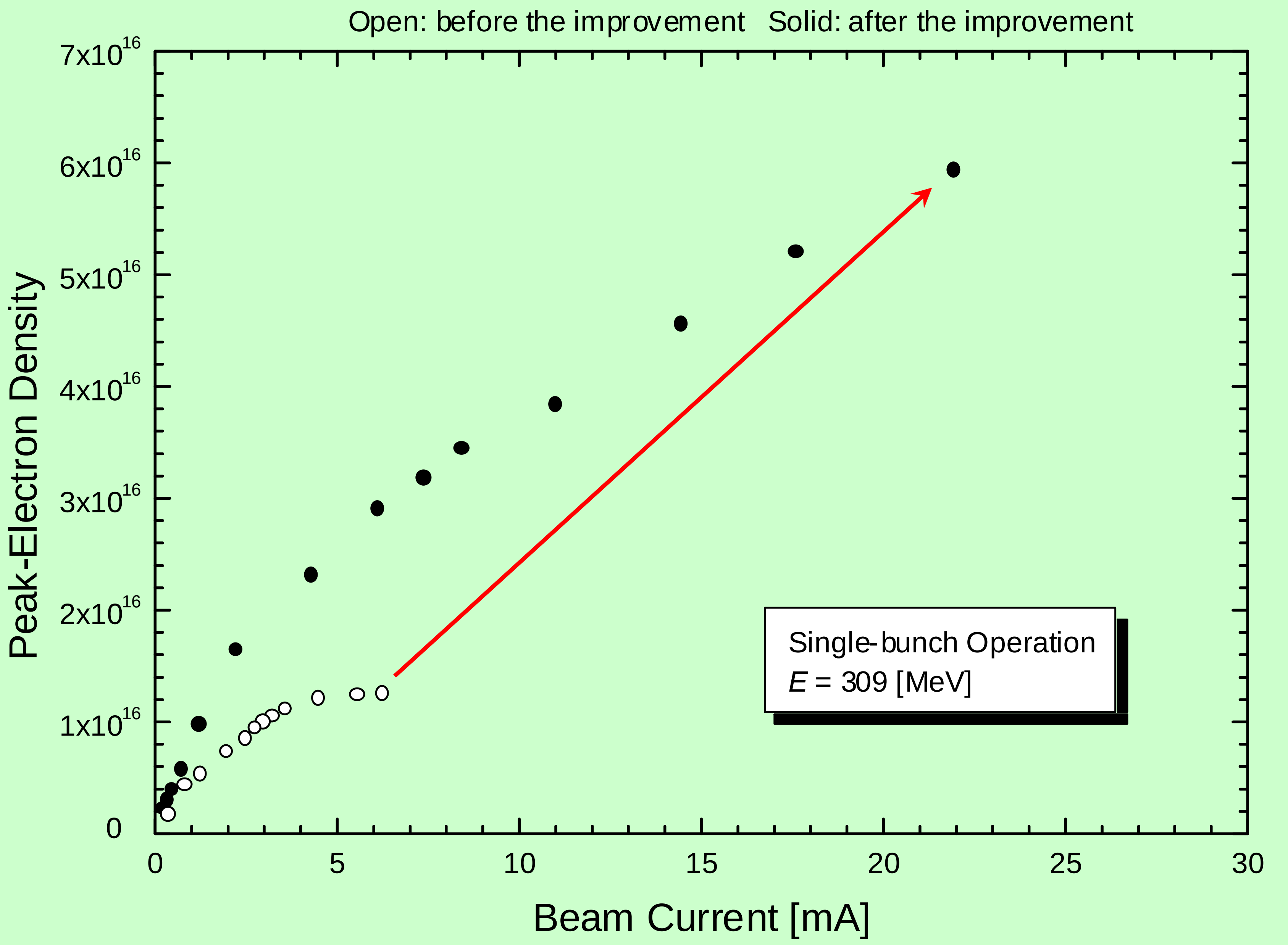
CHROMATICITY CORRECTION WITH 6-POLE MAGNETS

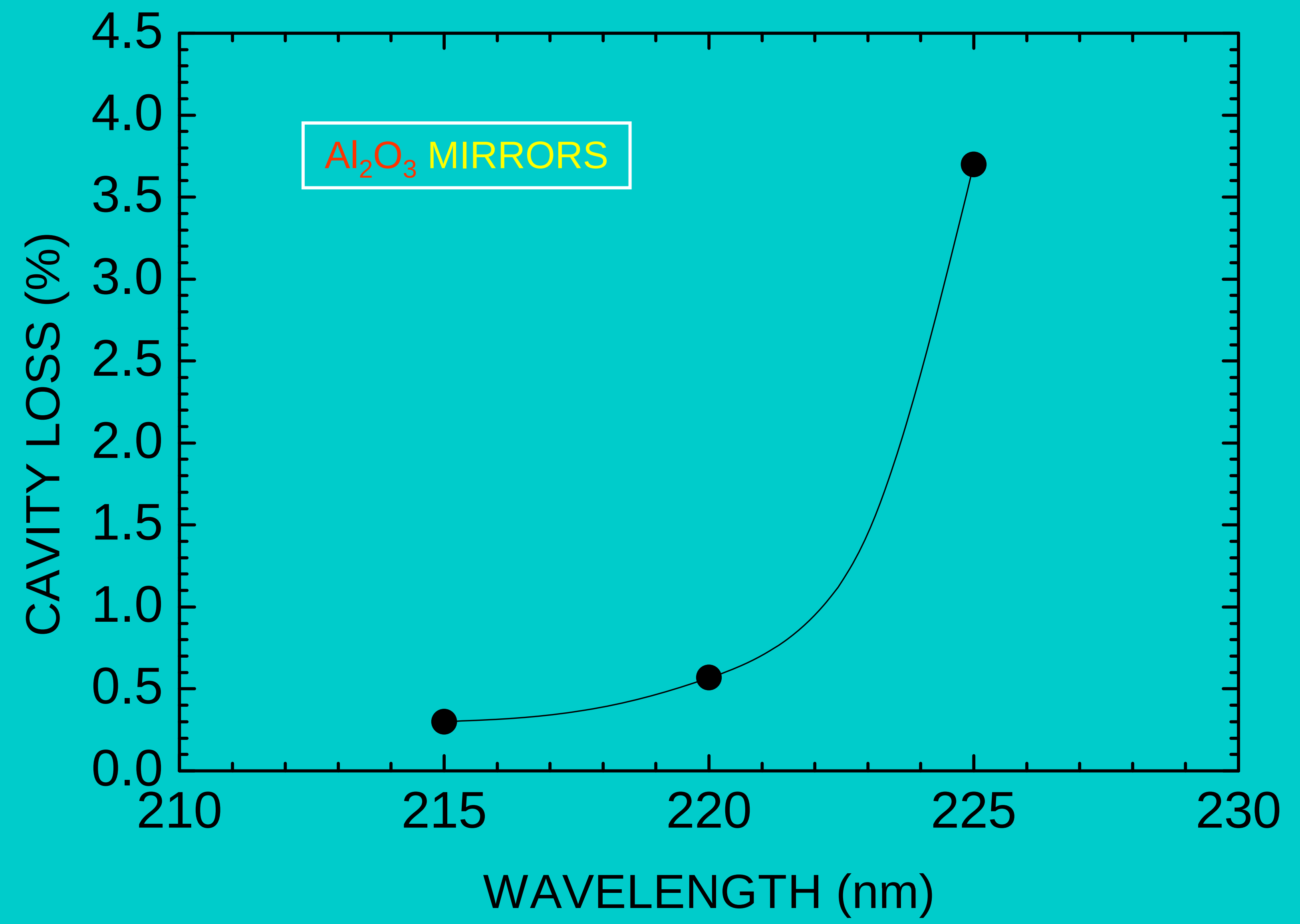


SF = 5.09 A, SD = 4.99 A, for x = 0

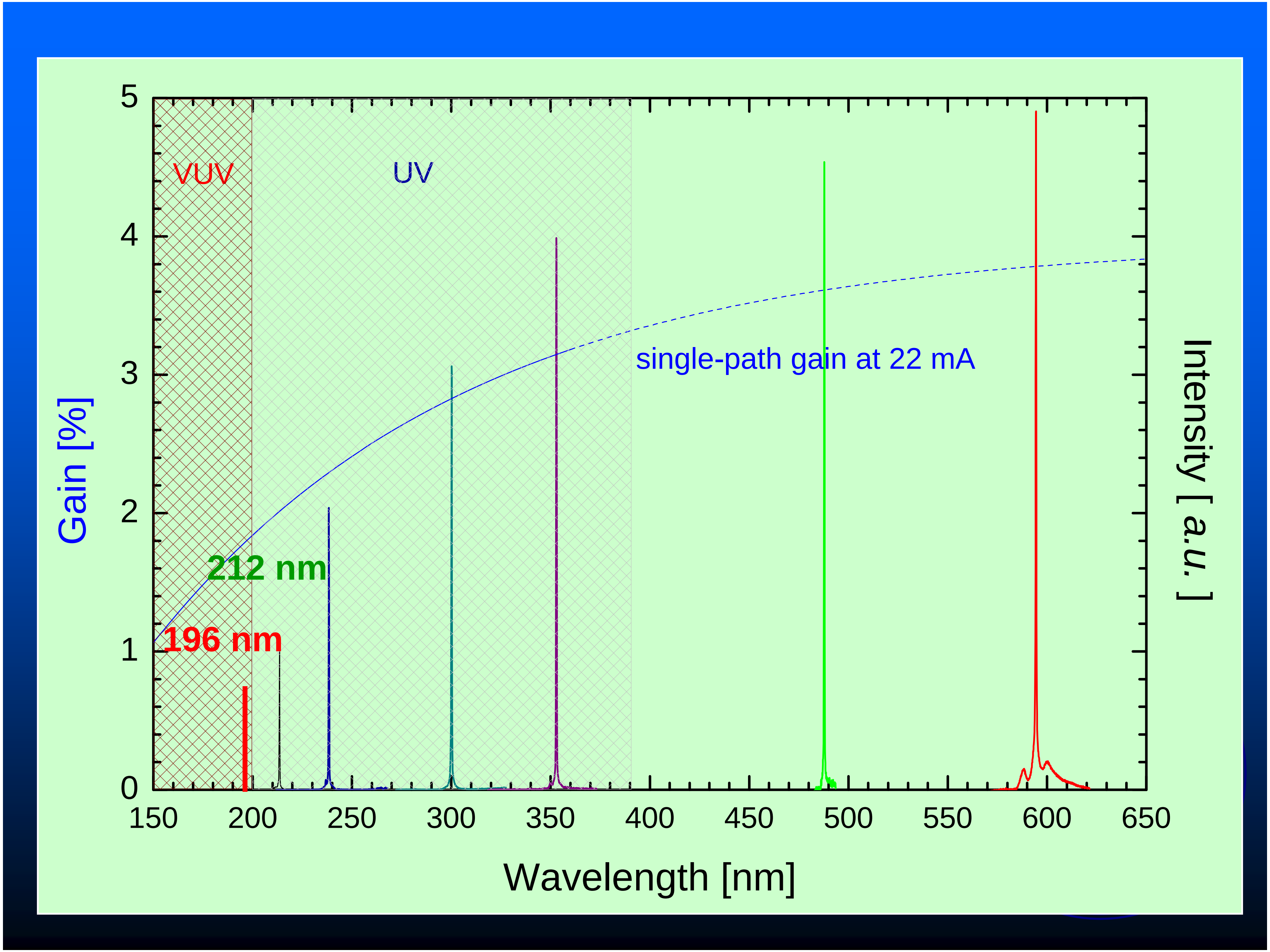
SF = 5.29 A, SD = 5.18 A, for ξ_x = 0.15, ξ_y = 0.08

EFFECT OF CHROMATICITY CORRECTION





Al_2O_3 MIRRORS
CAVITY LOSS (%)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
210
215
220
225
230
WAVELENGTH (nm)



VUV
UV
single-path gain at 22 mA
212 nm
196 nm
Gain [%]
Intensity [a.u.]
Wavelength [nm]
0
1
2
3
4
5
150
200
250
300
350
400
450
500
550
600
650

MAIN FEATURES OF FEL

Wavelength Tunability

Polarization Tunability

High Efficiency

High Power

Can we use FELs ?

with such excellent features

PRESENT STATUS OF FEL

Large Scale

Expensive

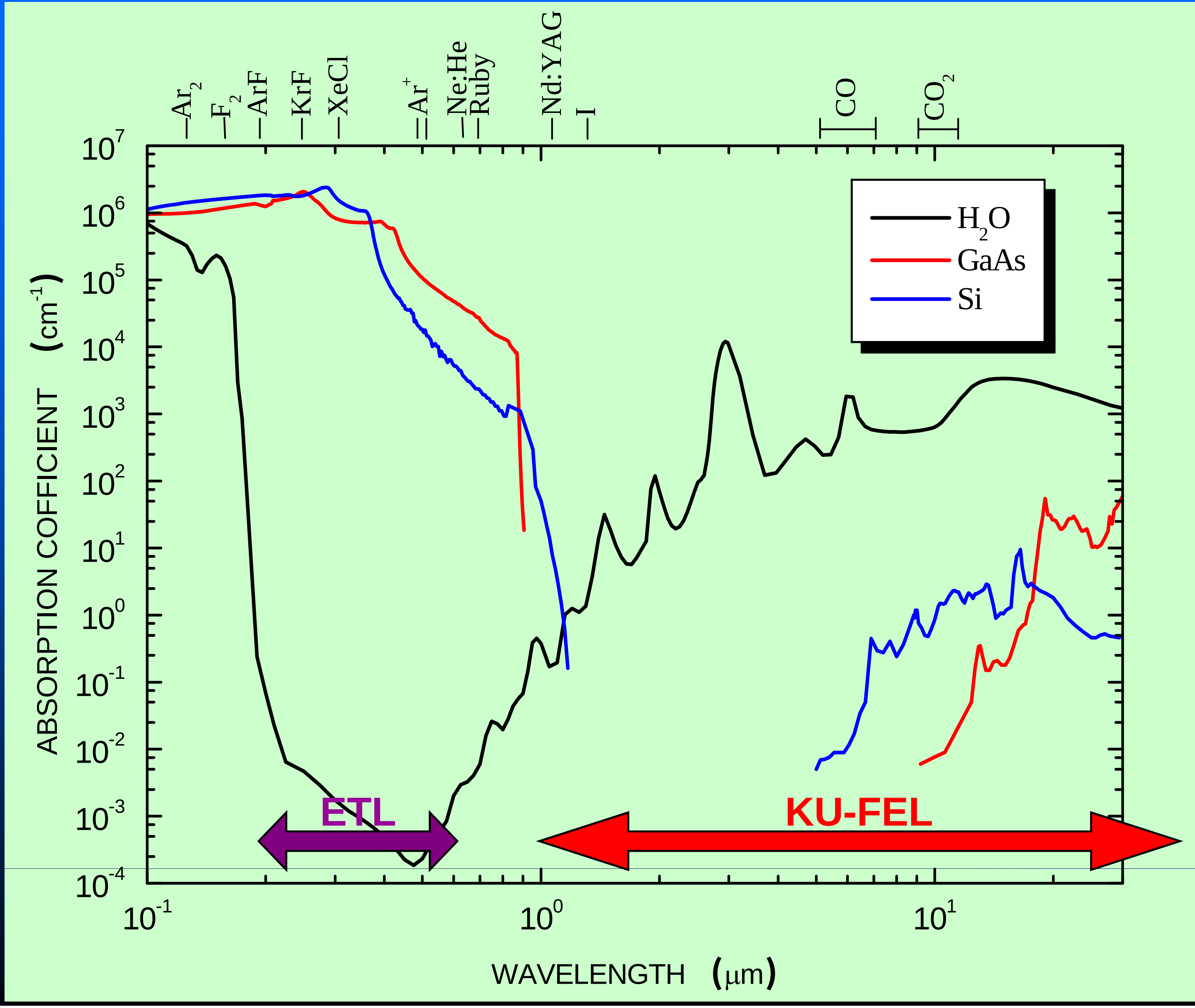
Low Efficiency of Accelerator

Unexplored Wavelength Region

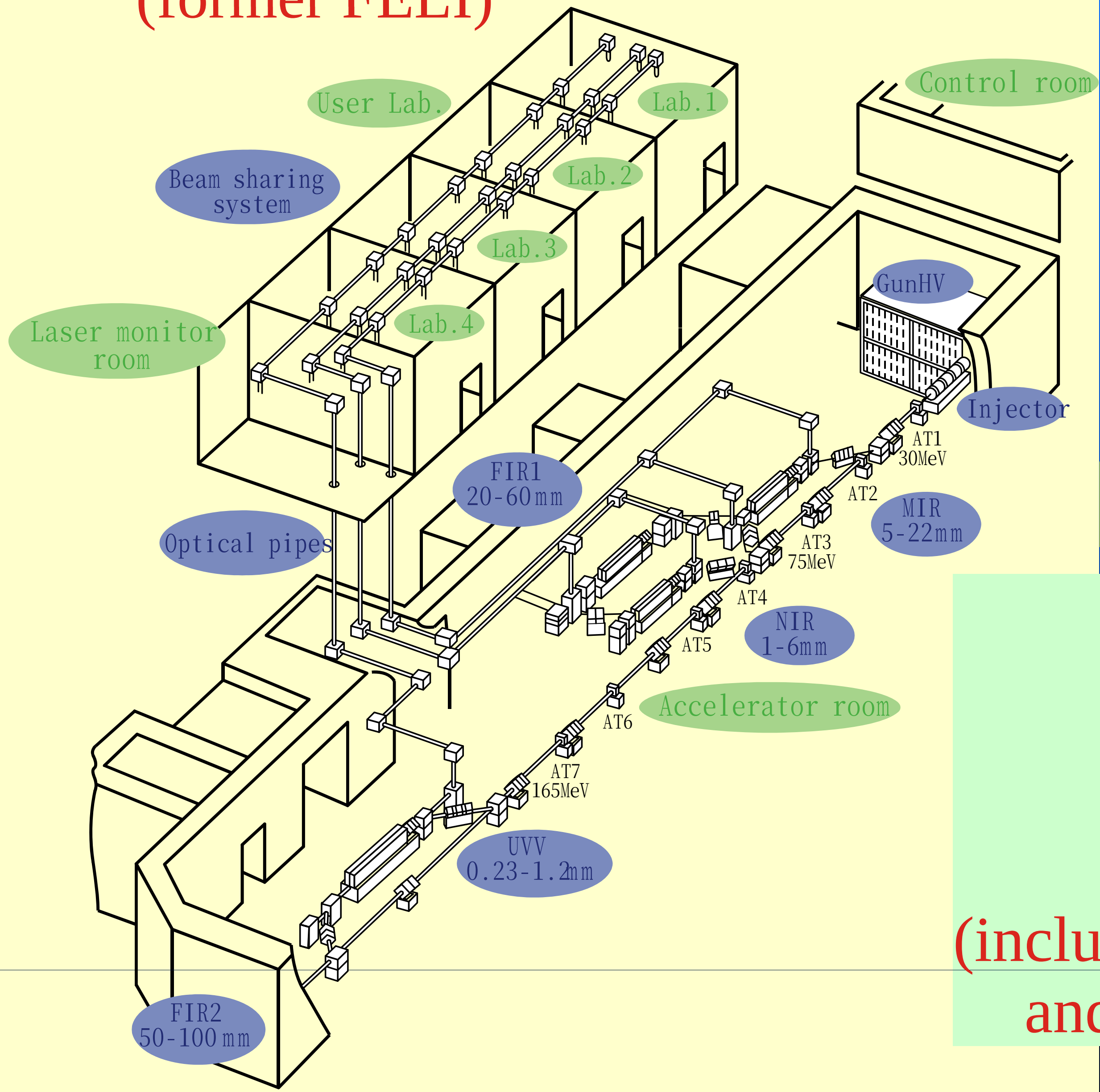
研究予算のスケーリング

大学 研究所	旧国立 研究所	旧国立直轄研究所 特殊法人研究所
小売商店	スーパー マーケット	デパート
国立大学法人 私立大学	旧電総研 産総研	KEK 原研 理研
予算 極小	予算 中規模	予算 極大

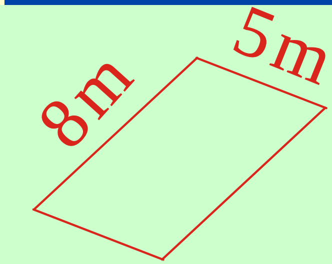
ABSORPTION CEFFICIENTS



iFEL (Osaka Univ.)
(former FELI)

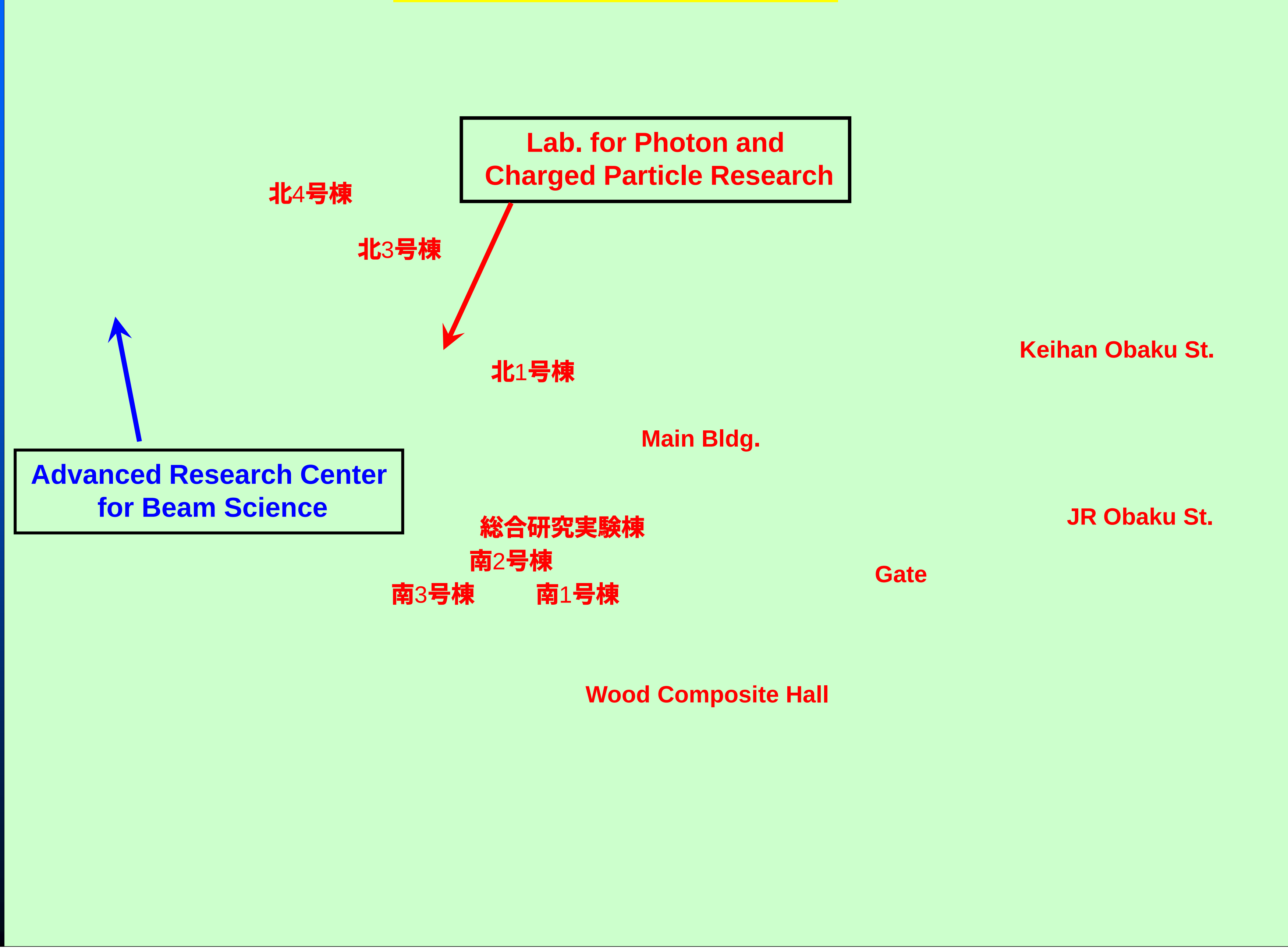


KU-FEL



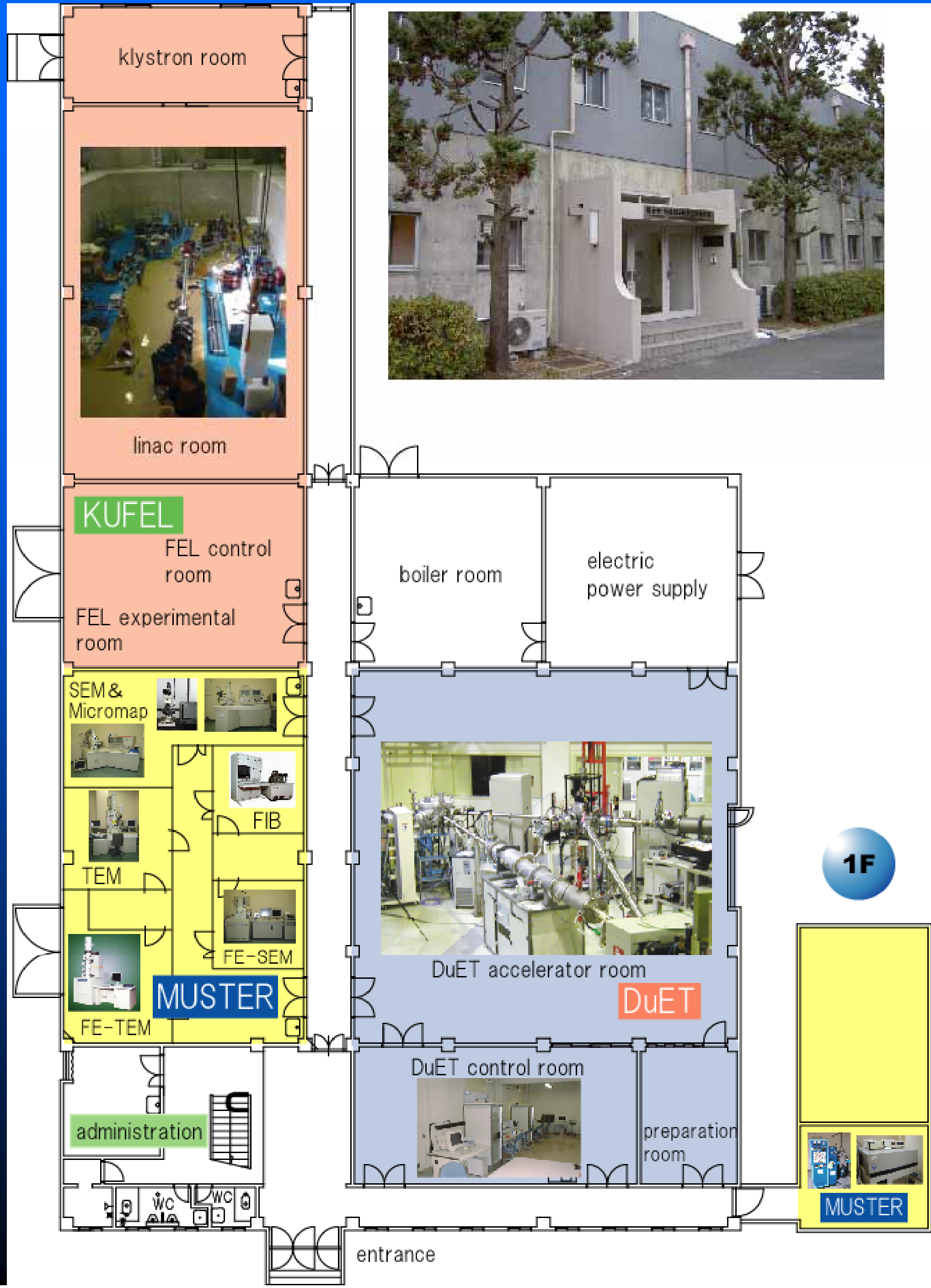
KUFEL
(including RF source
and drive laser)

UJI CAMPUS
KYOTO UNIVERSITY

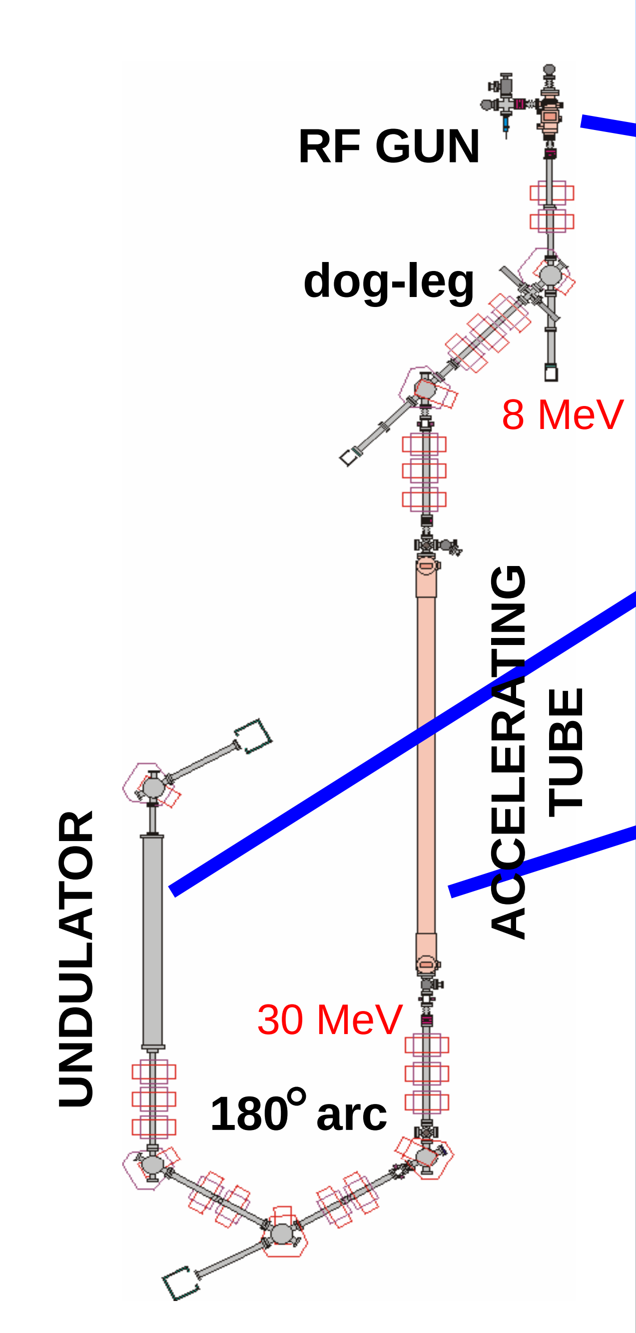


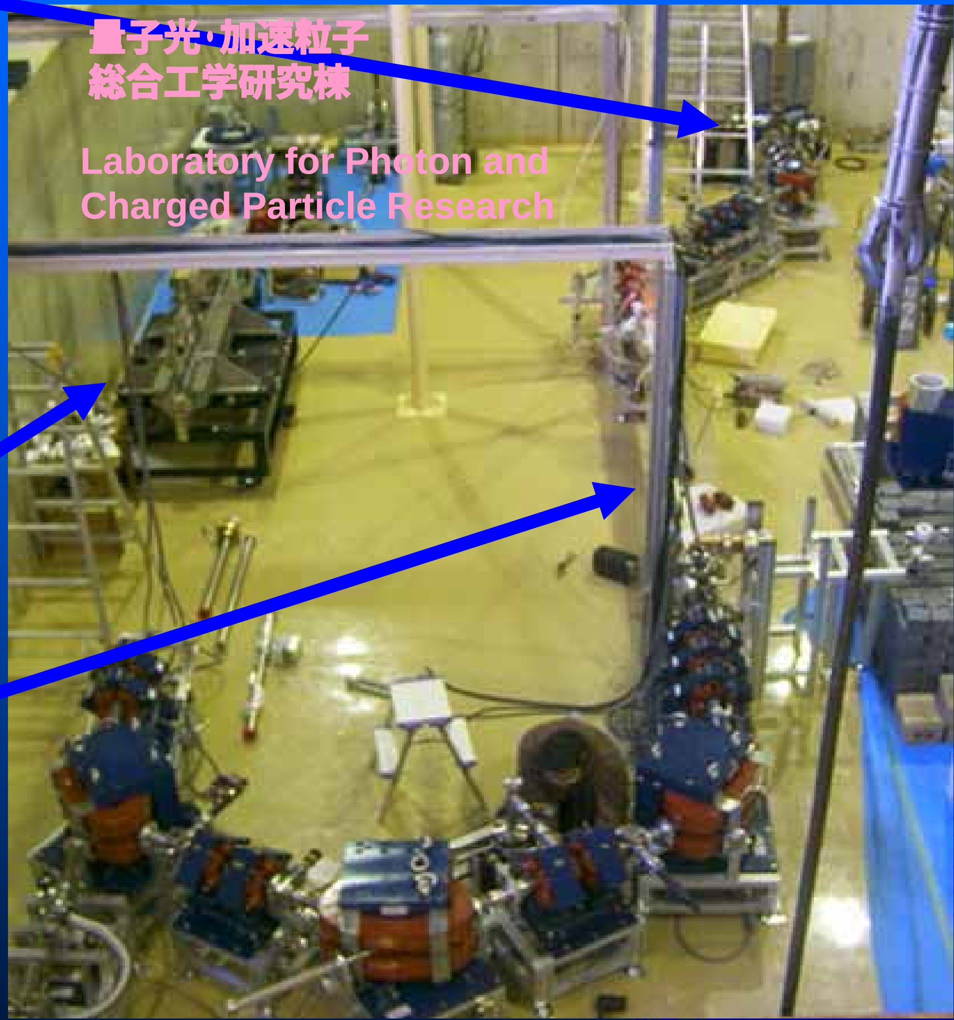
Laboratory for Photon and Charged Particle Research

量子光·加速粒子総合工学研究棟

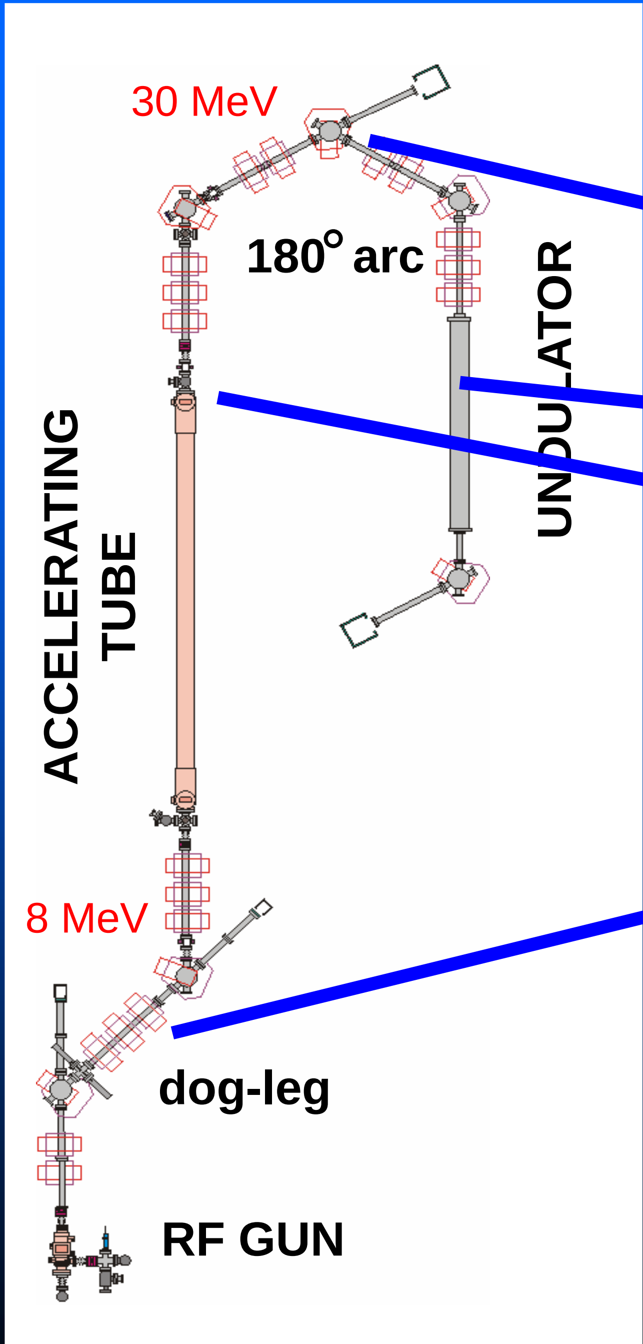


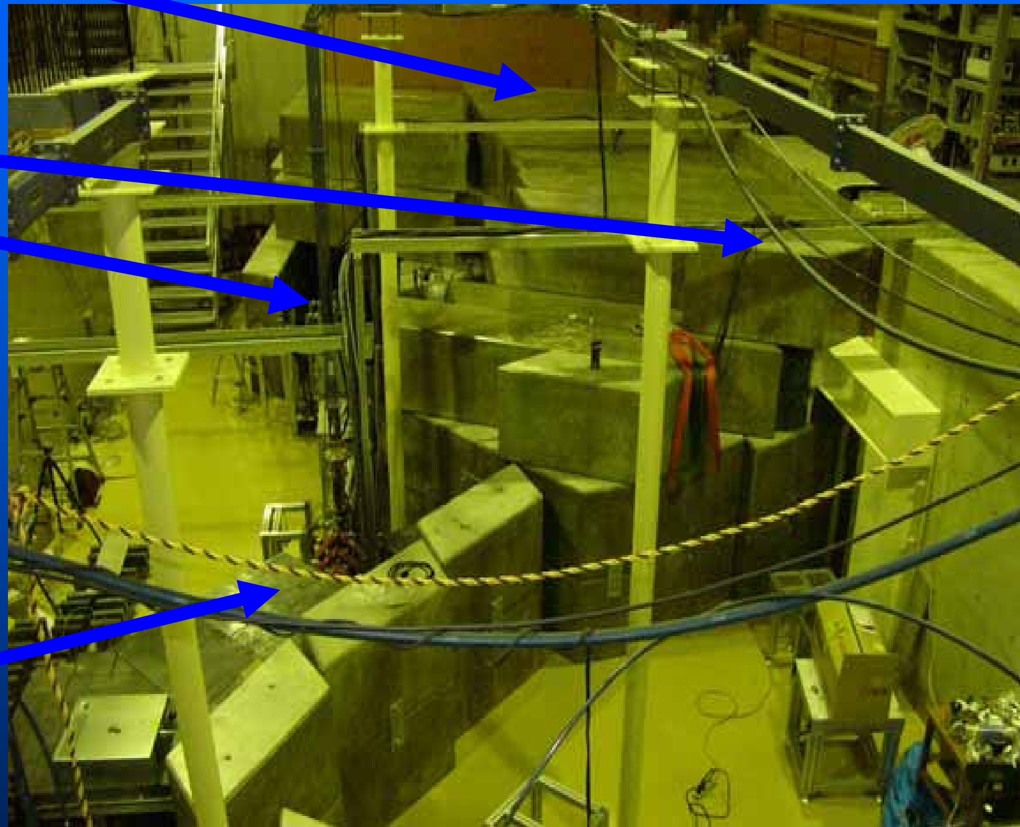
PRESENT KU-FEL





PRESENT KU-FEL





KU-FEL RESEARCH SUBJECTS

4.5-cavity Themionic RF Gun

Compact RF Modulators

Backbombardment Problem
- quantitative measurement
- application of dipole magnetic field
- modulation of RF waveform
- Triode-type RF gun

Emittance Measurement
- tomography method

Simulation of Electron-Beam Transport

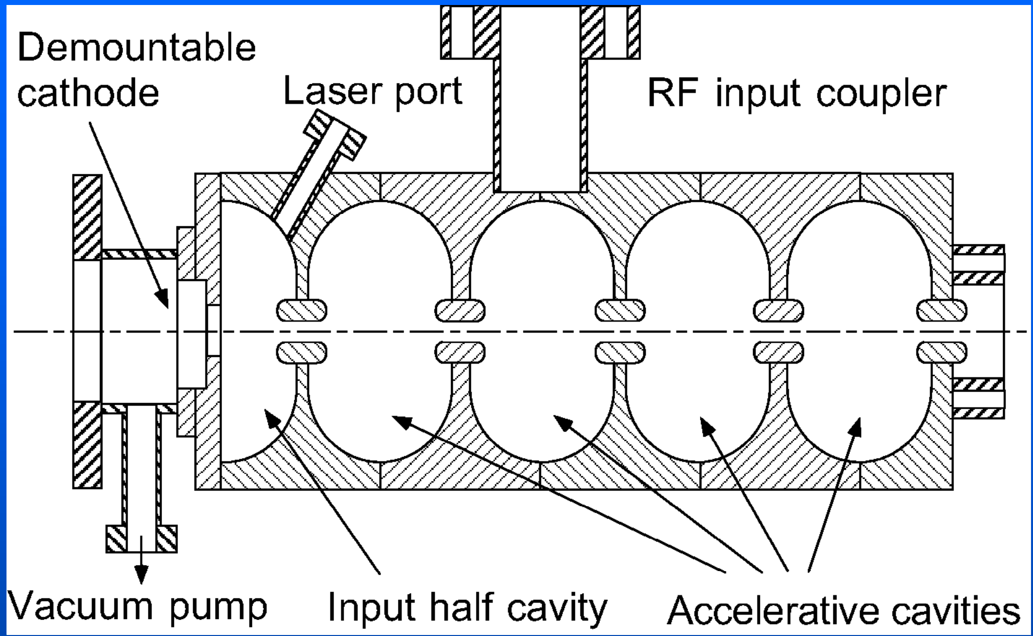
Photocathode RF Gun
- simulation study
- experiments, to be started

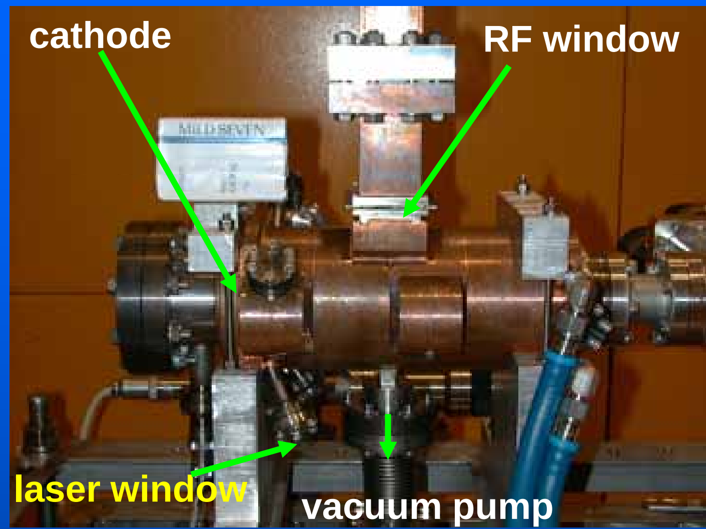
Simulation of FEL Process
- start-to-end simulation

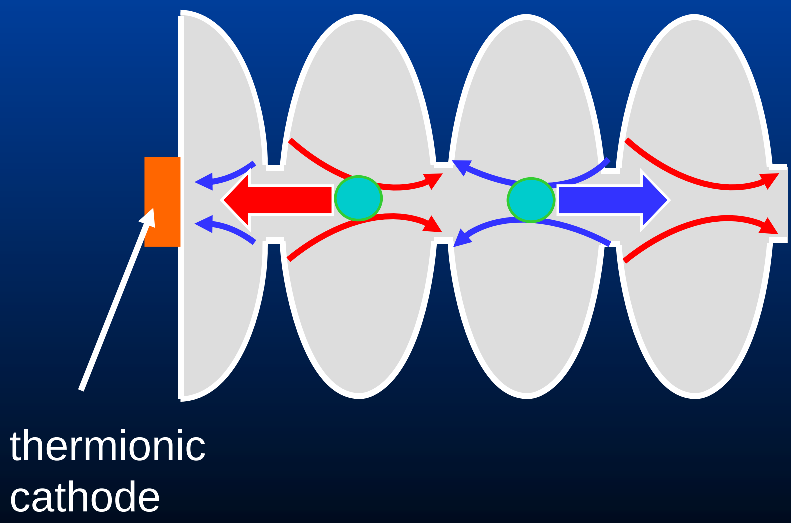
Design of undulators
- planar, circular, staggered array, SC

Energy Recovery Scheme
- simulation, radiation shielding

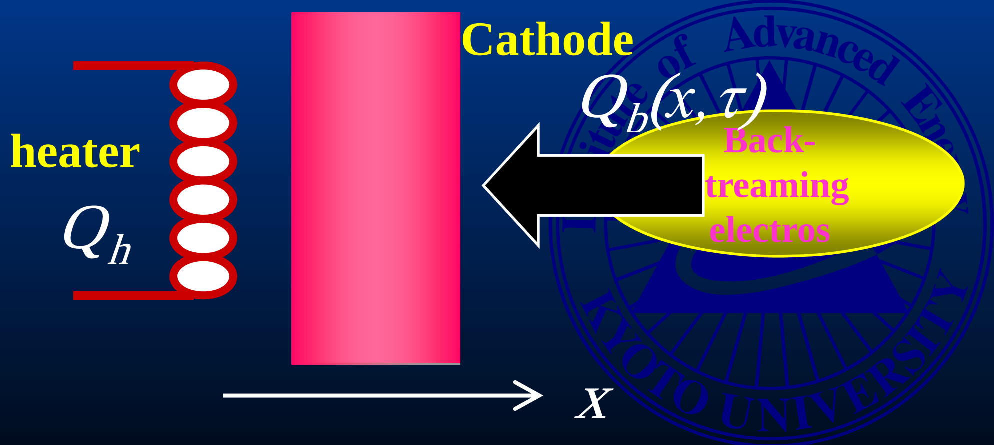
Problem in thermionic RF gun (1) ~ back bombardment ~

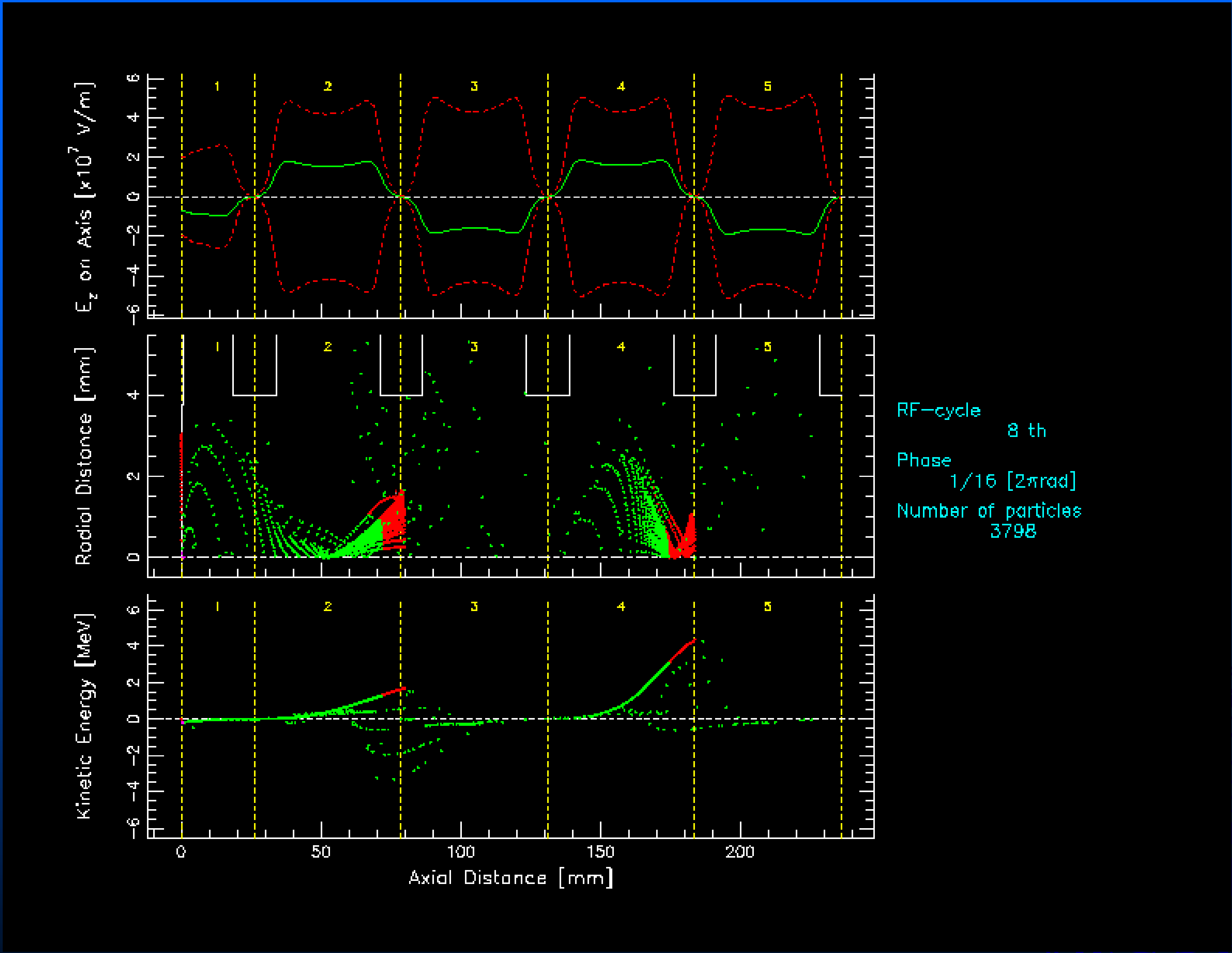






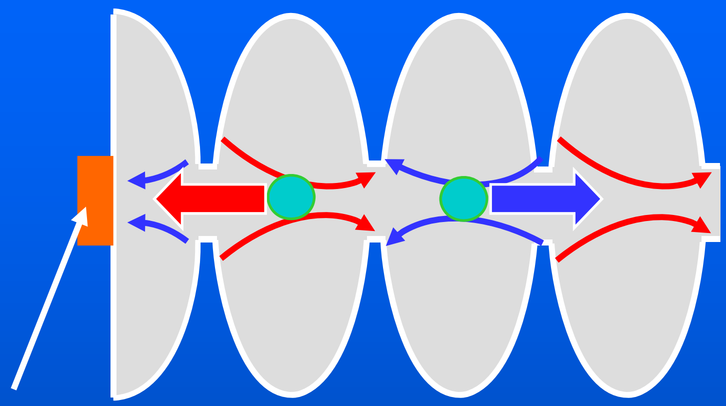
1 dimensional model





E_z on Axis [x10^7 V/m]
Radial Distance [mm]
Kinetic Energy [MeV]
Axial Distance [mm]
RF-cycle
8 th
Phase
1/16 [2πrad]
Number of particles
3798

Problem in thermionic RF gun (1) ~ back bombardment ~



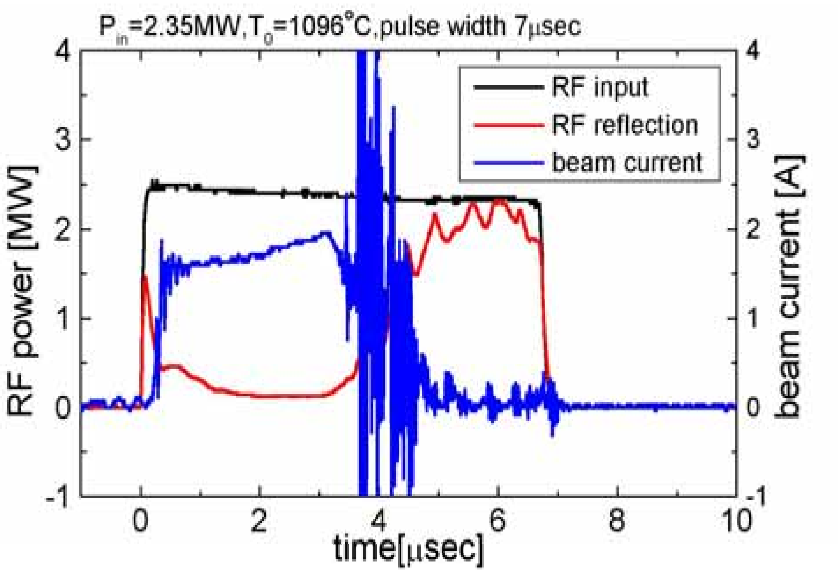
thermionic cathode

Back-streaming electrons hit the cathode.

Cathode temperature increases.

Current density on cathode surface increases.

Time evolution of electron beam and input/reflected RF power

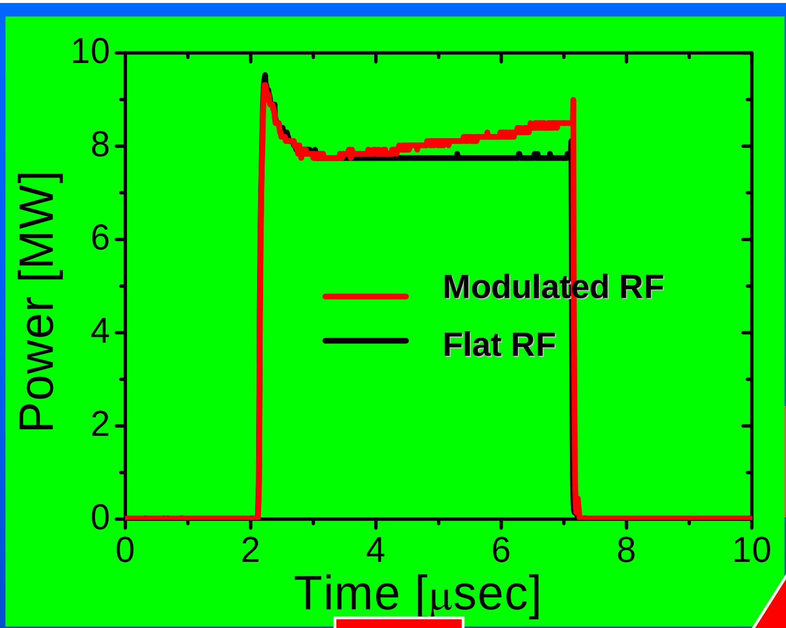


Beam loading increases and then resonant frequency of cavity changes.

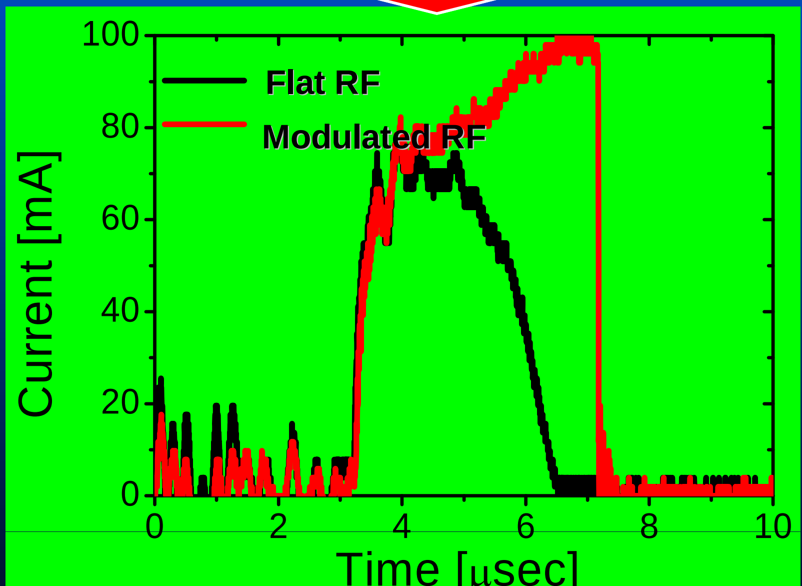
Beam current becomes unstable.

Maximum pulse duration is limited to at most several μ sec.

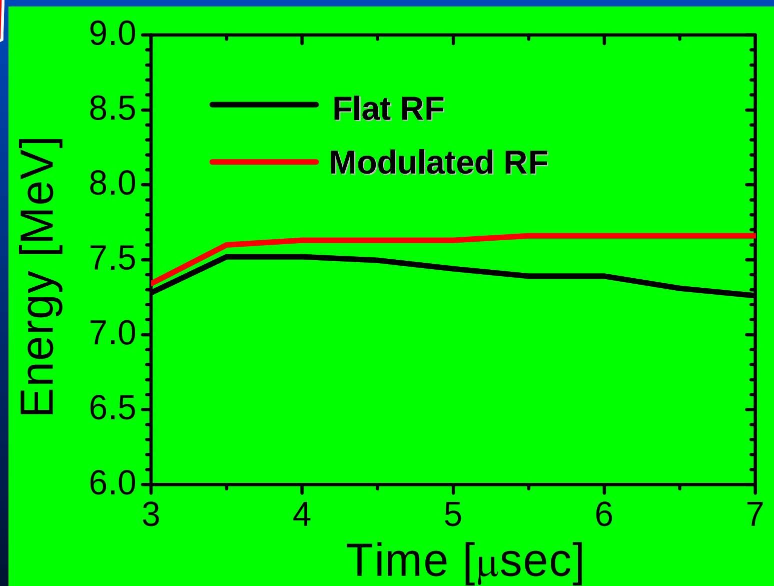
reducing the effect
of backbombardment
by adjusting the RF waveform
experimental



Adjustment of
the RF waveform

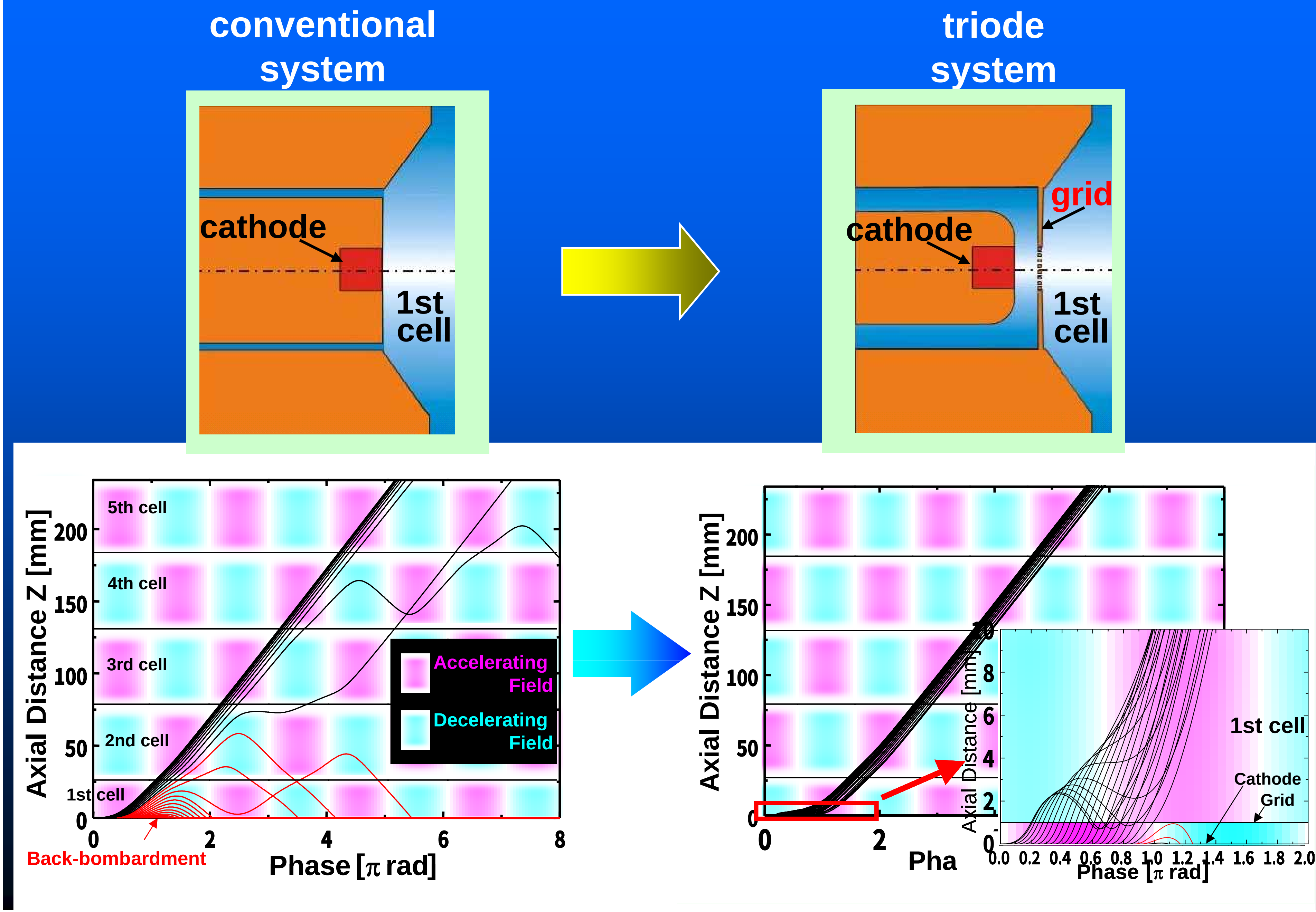


beam waveform

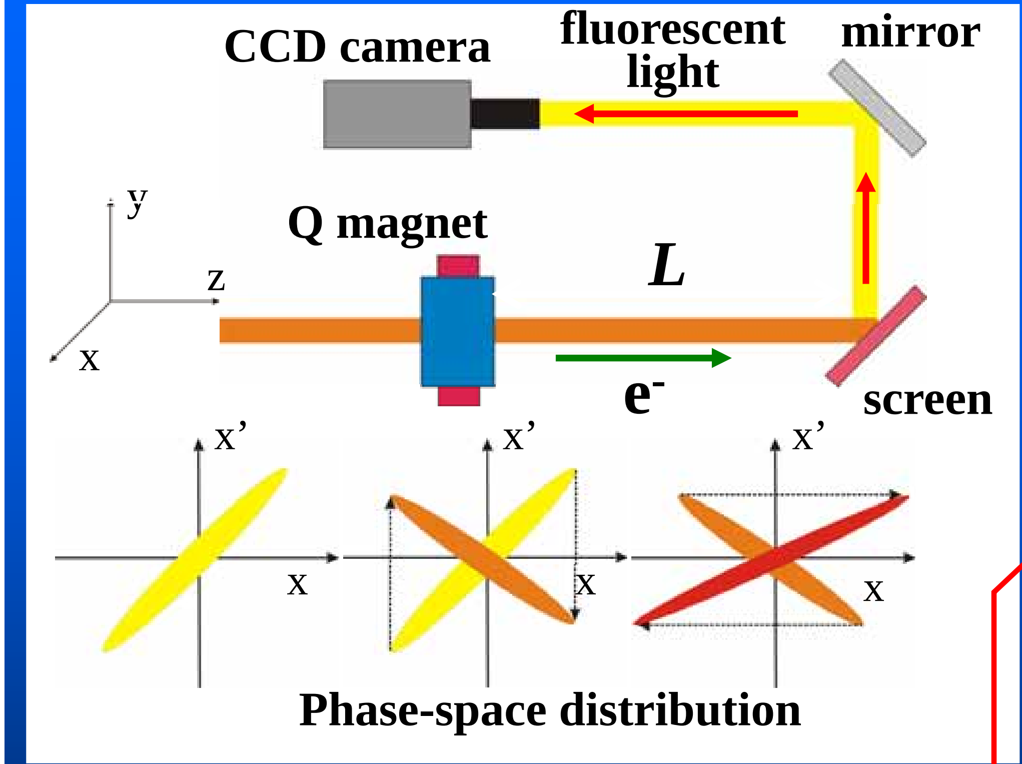


peak energy

TRIODE-TYPE RF GUN



EMITTANCE MEASUREMENT



Measurement of beam profile changing the Q-mag. strength

↓

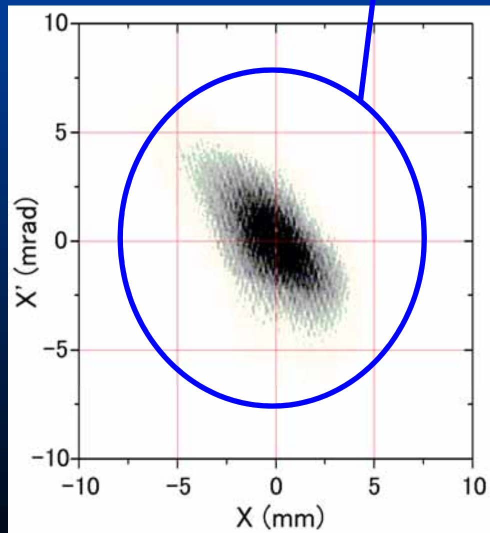
reconstruction of the distribution with tomography methods

↓

Electron density distribution in phase space

↓

emittance



$$\theta = \tan^{-1}\left(\frac{1}{L} - \frac{1}{f}\right)^{-1}$$

$$f = \frac{1}{k^2 z} = \frac{m_0 \gamma v_z r_0^2}{2\mu_0 e N I z}$$

μ_0 : magnetic permeability

R_0 : bore radius

N : no.of turns

m_0: electron rest mass

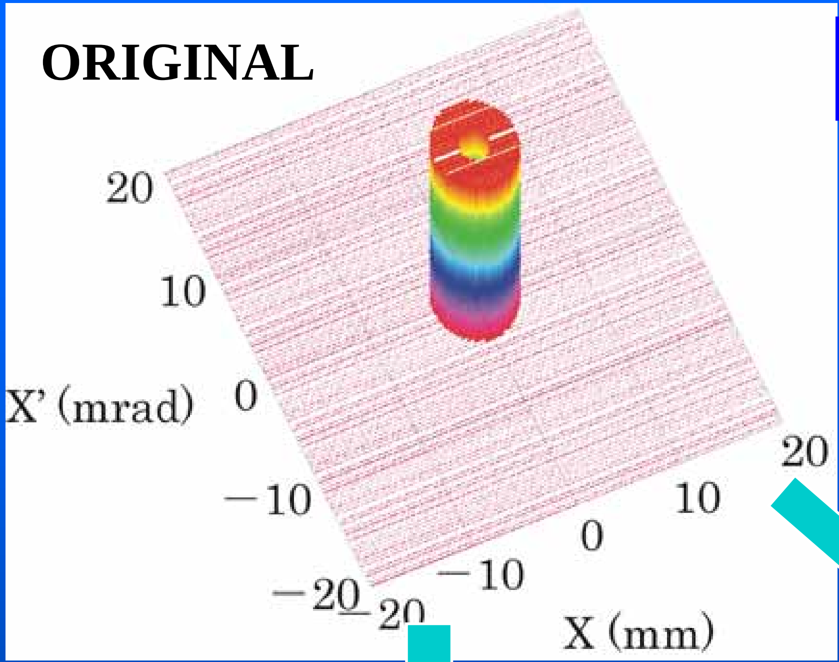
γ: Lorentz factor

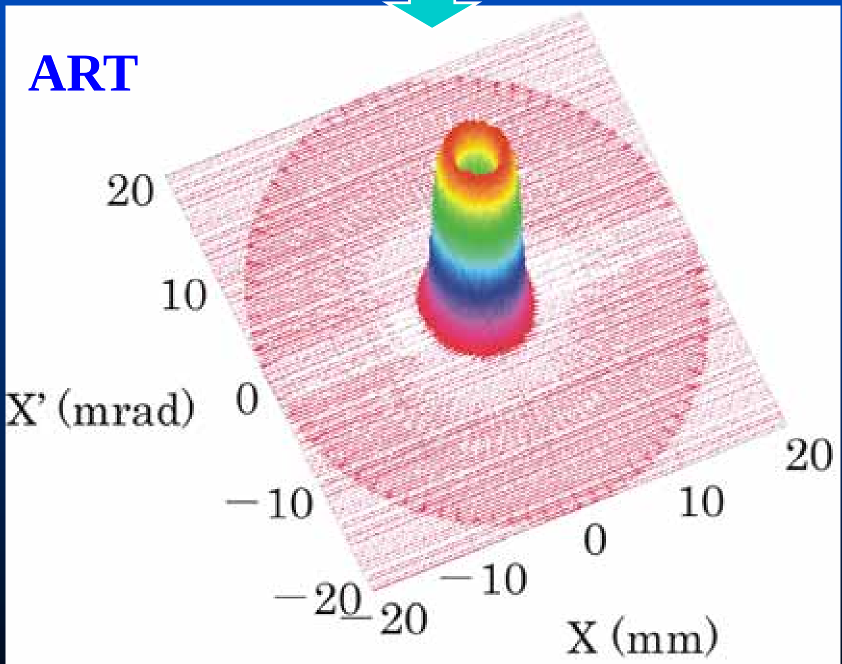
v_z : electron velocity

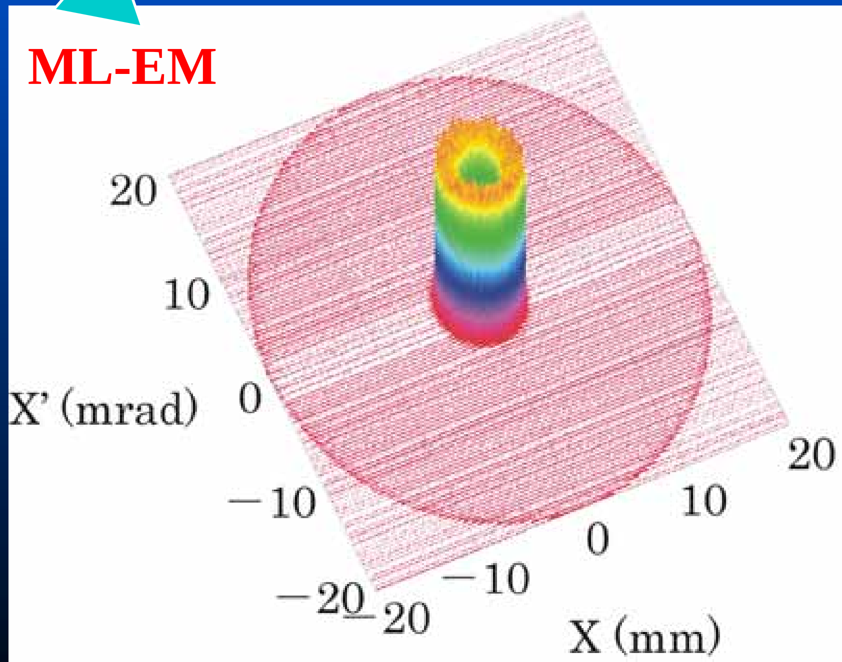
EMITTANCE MEASUREMENT

Tomographic Method

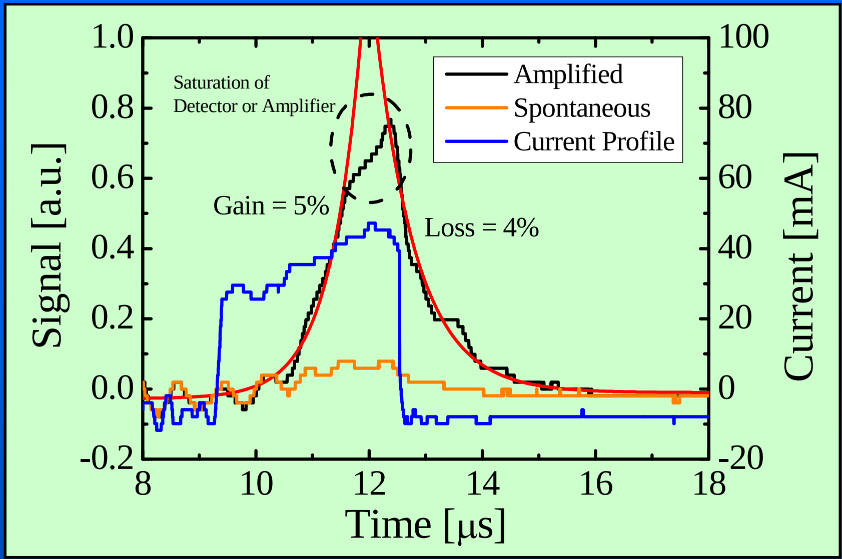
reconstruction of phase-space distribution

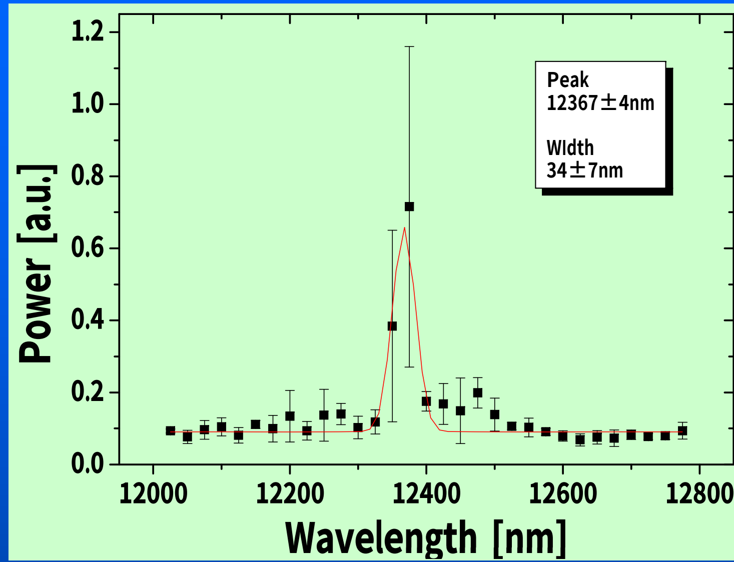




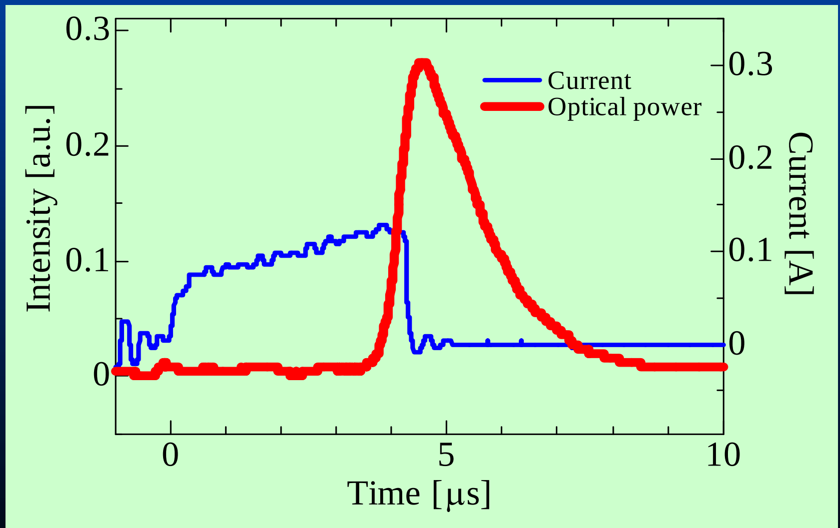


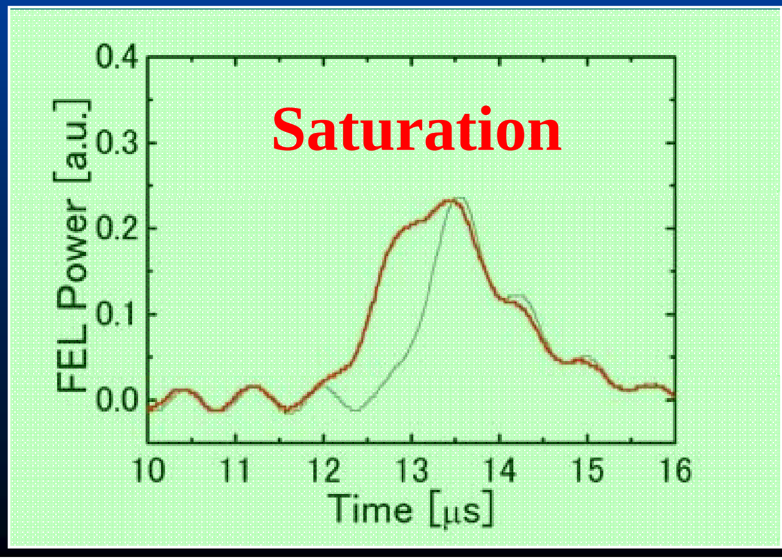
1st lasing in KU-FEL FACILITY!!



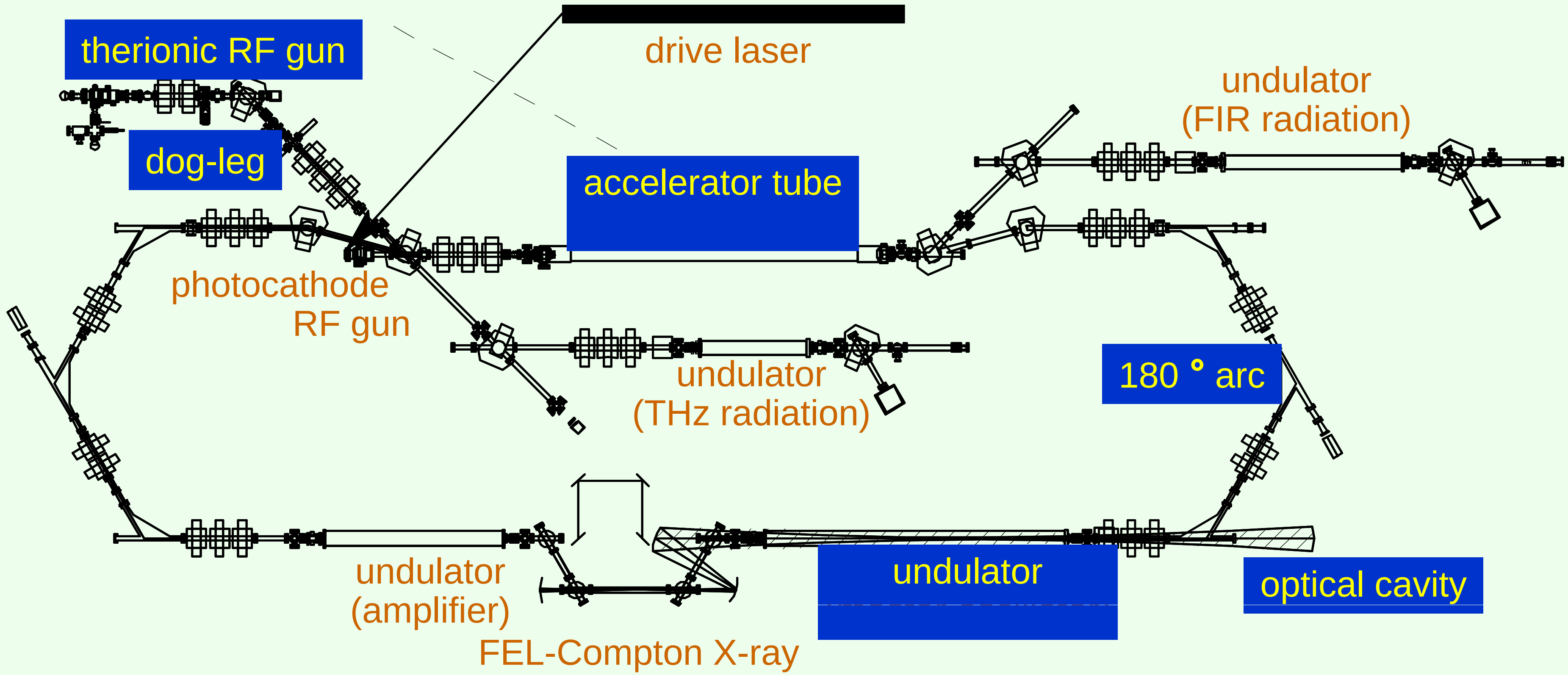


FEL Spectrum



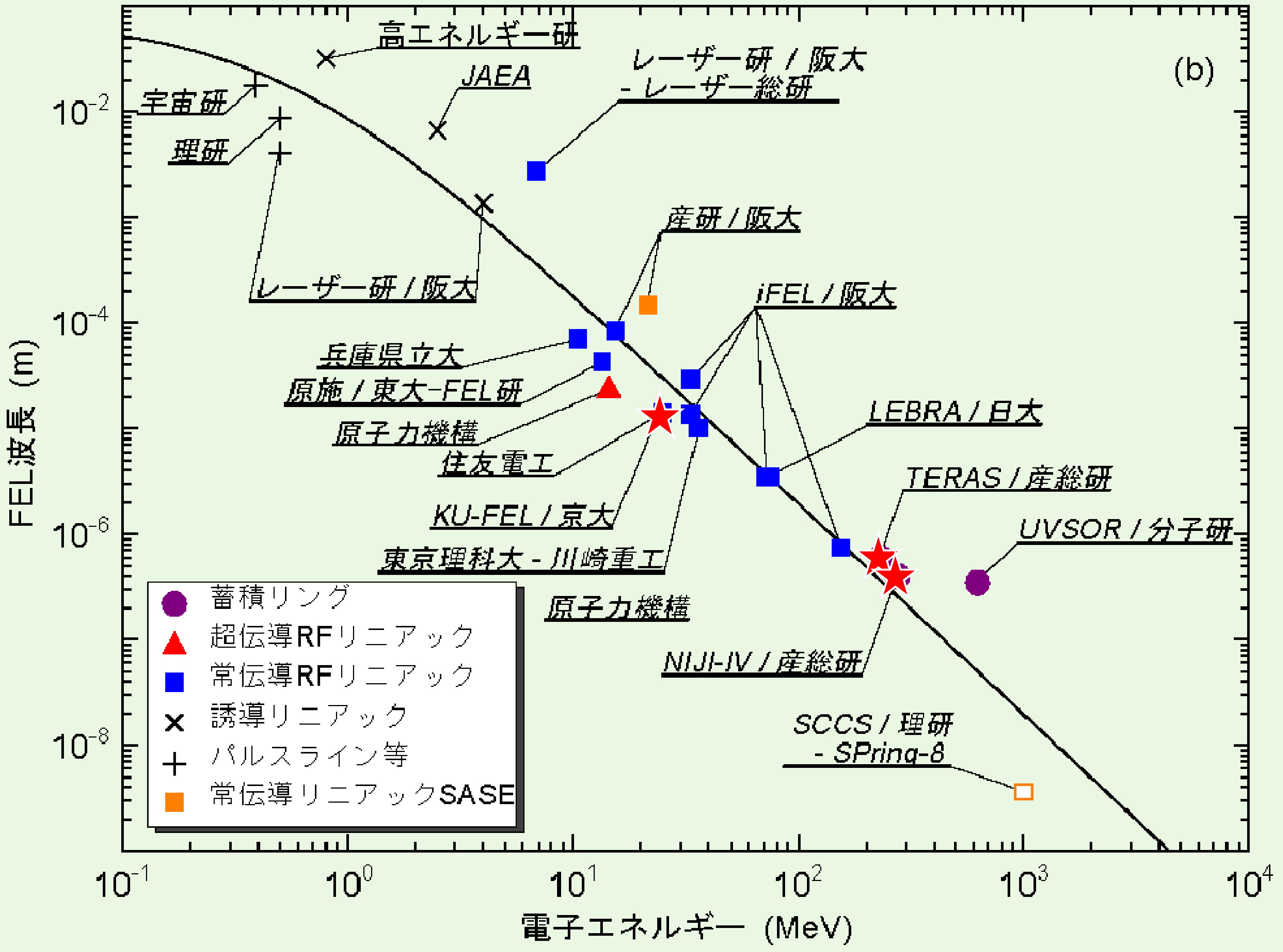


KU-FEL FUTURE UPGRADES

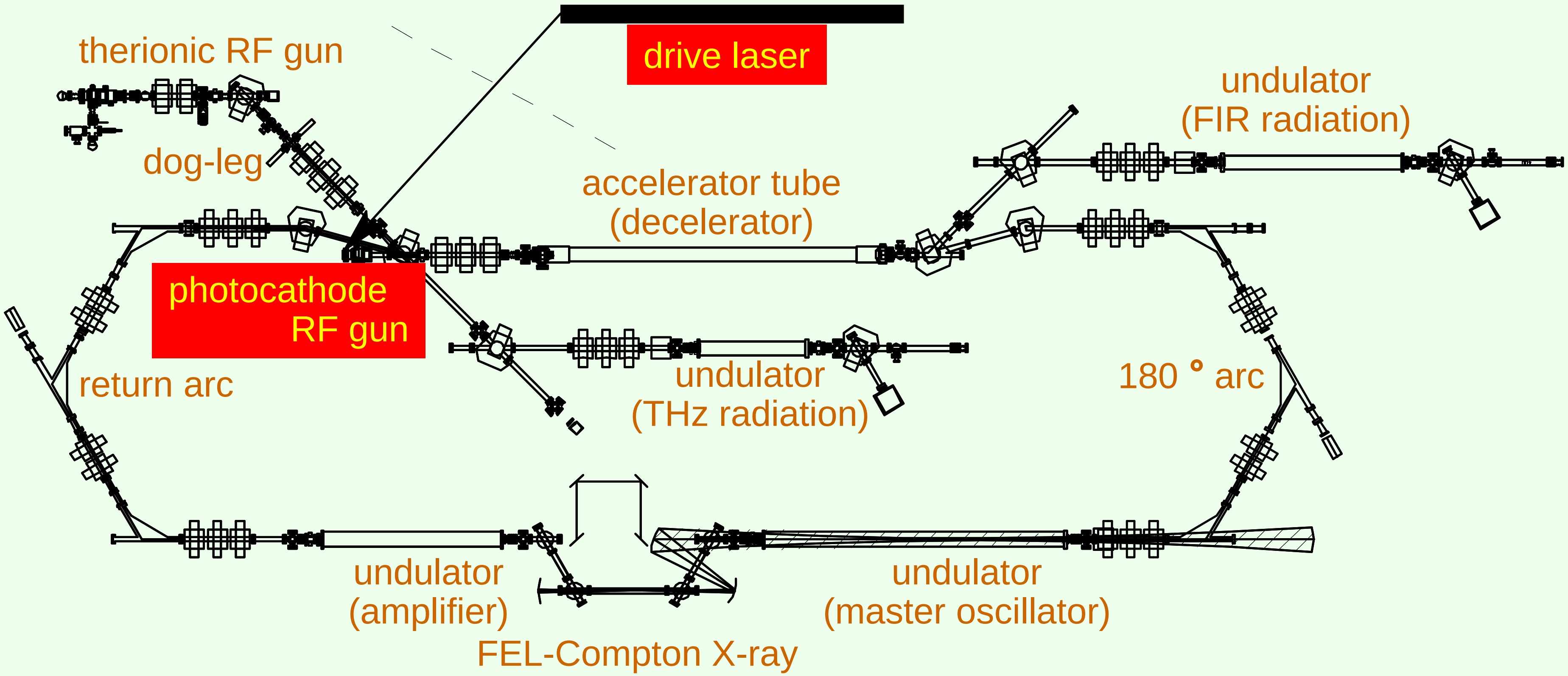


FEL PRJECTS IN JAPAN

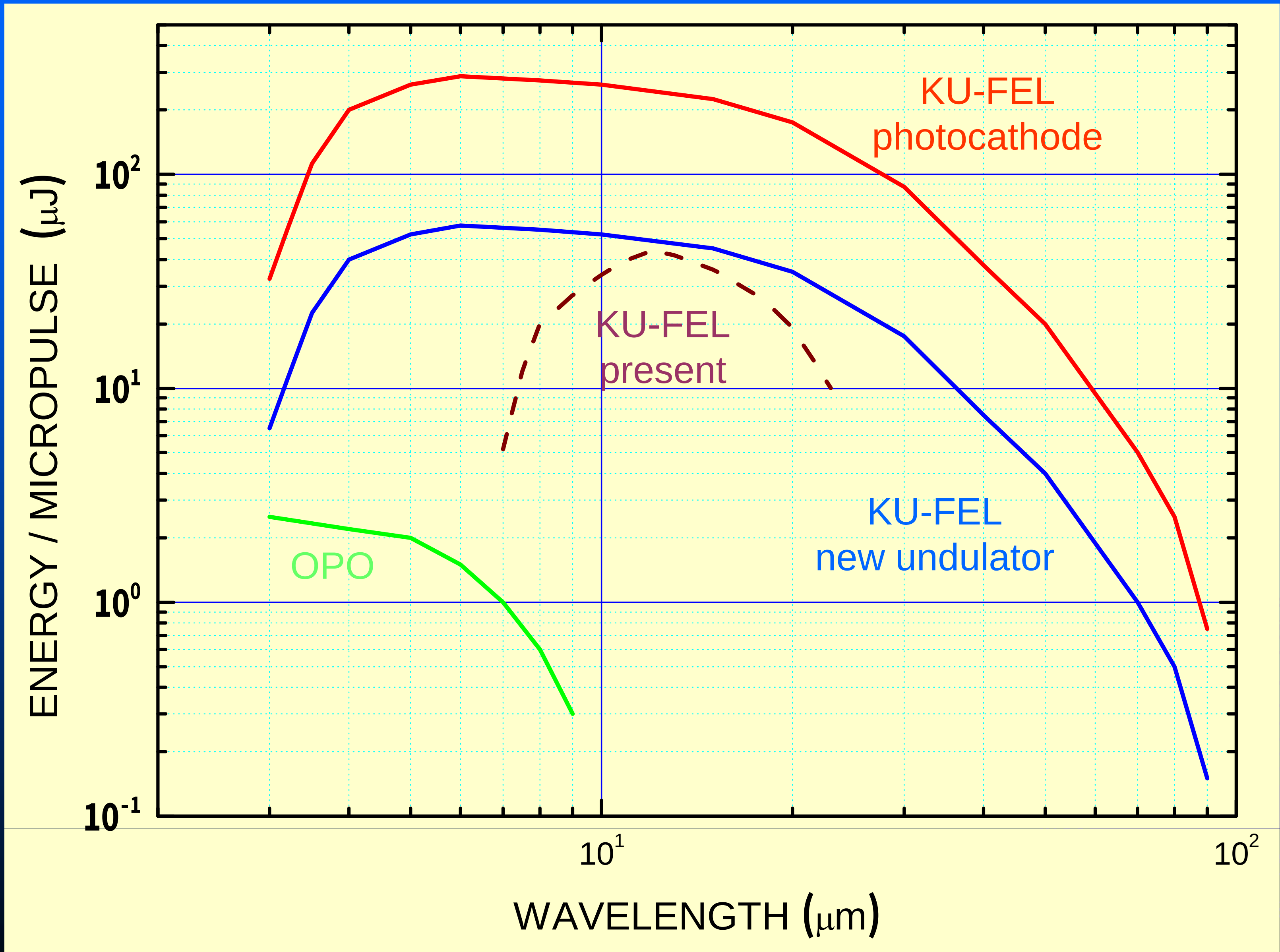
Mar. 29,2008

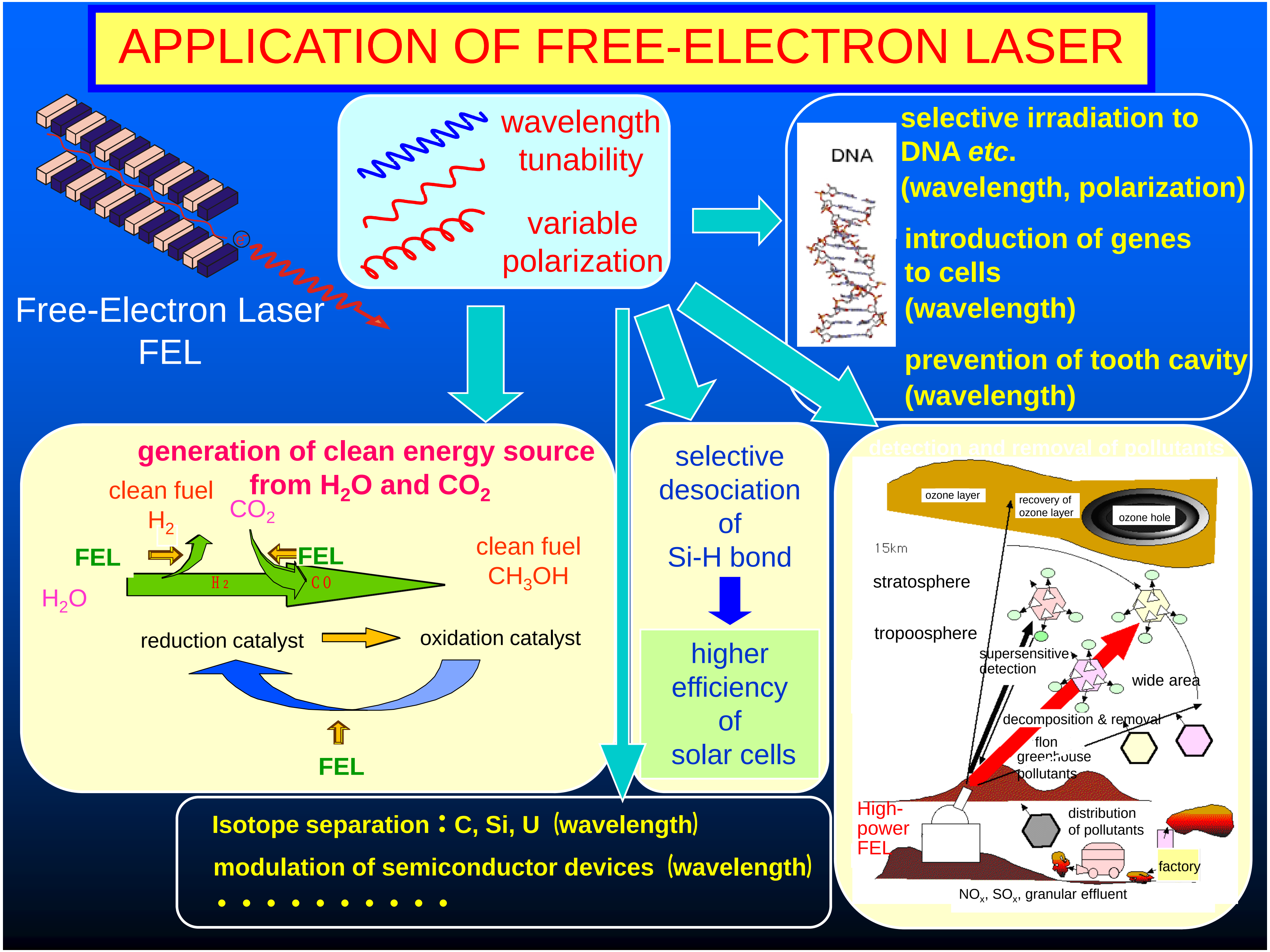


KU-FEL FUTURE UPGRADES

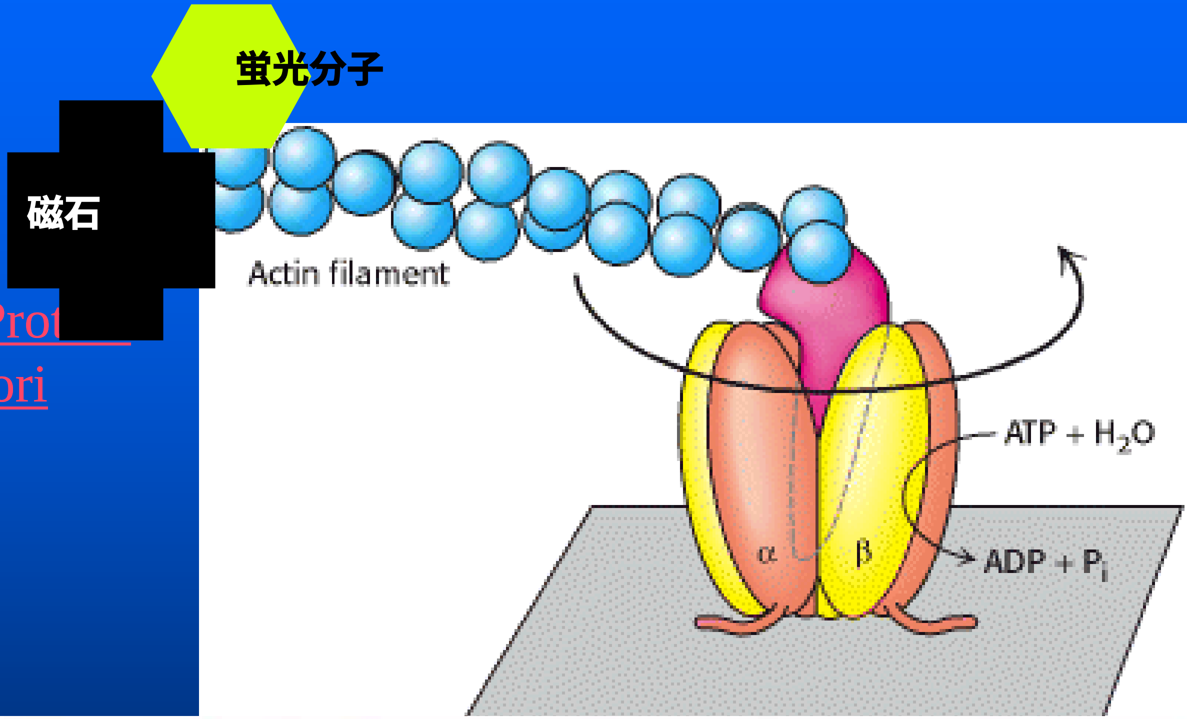


KU-FEL POWER PER PULSE




APPLICATION OF FREE-ELECTRON LASER
Free-Electron Laser
FEL
wavelength tunability
variable polarization
selective irradiation to DNA etc. (wavelength, polarization)
DNA
introduction of genes to cells (wavelength)
prevention of tooth cavity (wavelength)
generation of clean energy source from H2O and CO2
clean fuel
H2
CO2
FEL
FEL
H2
CO
clean fuel
CH3OH
H2O
reduction catalyst
oxidation catalyst
FEL
selective desociation of Si-H bond
higher efficiency of solar cells
detection and removal of pollutants
ozone layer
recovery of ozone layer
ozone hole
15km
stratosphere
tropoosphere
supersensitive detection
wide area
decomposition & removal
flon
greenhouse
pollutants
High-power FEL
distribution of pollutants
factory
NOx, SOx, granular effluent
Isotope separation：C, Si, U（wavelength）
modulation of semiconductor devices（wavelength）
・・・・・・・・・・

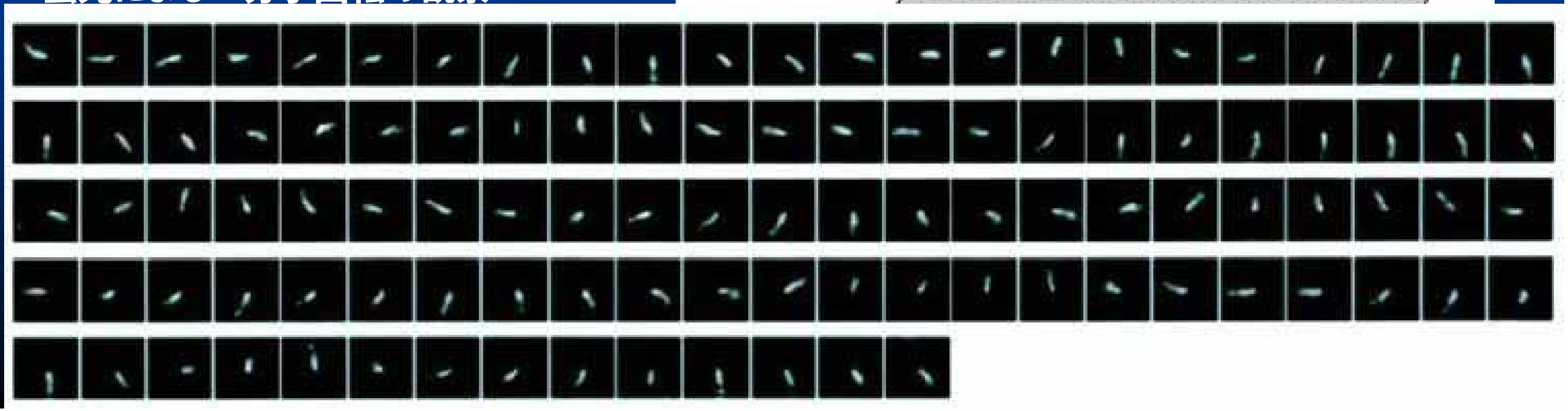
ATP合成酵素のF_1部分



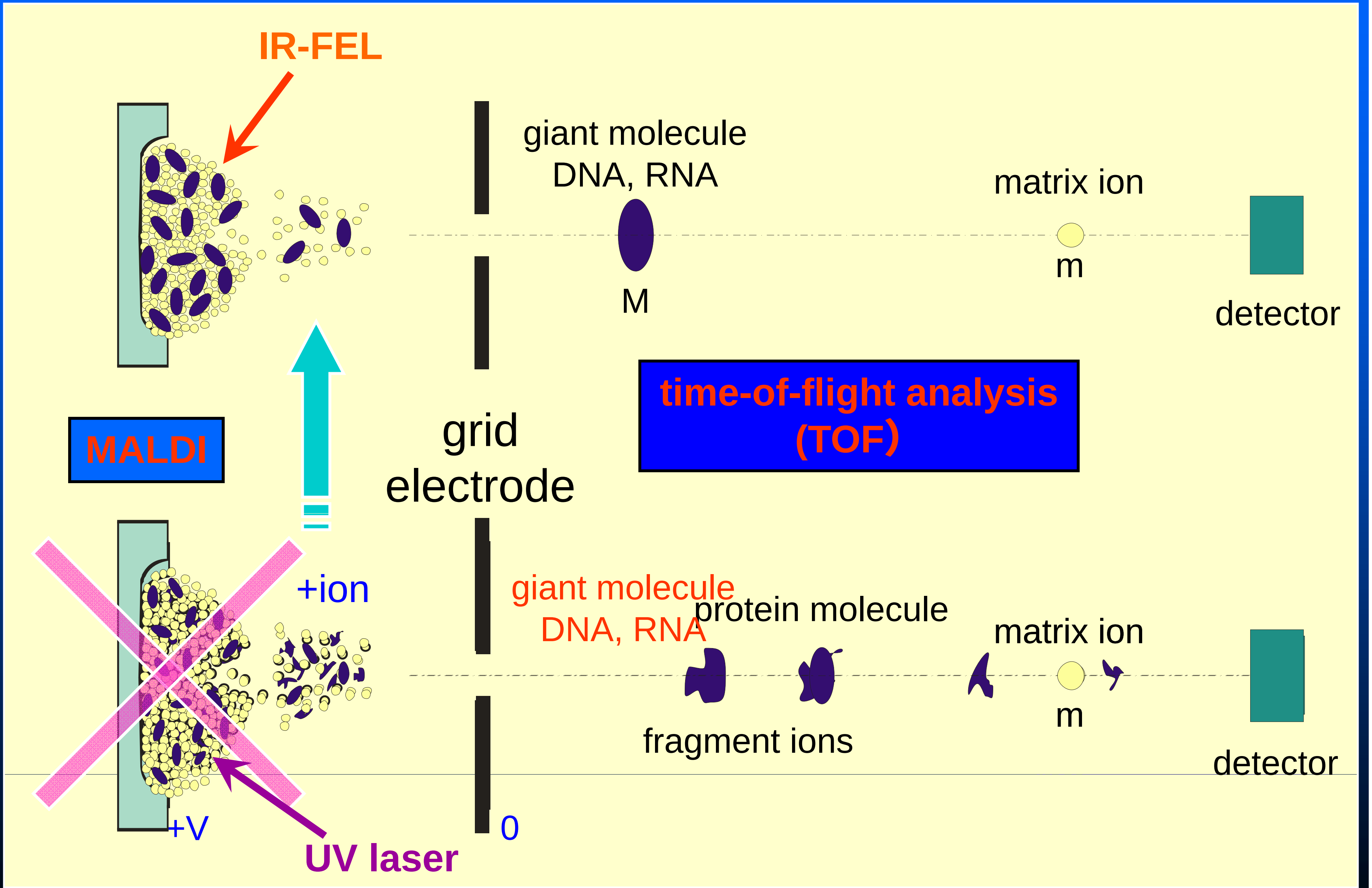
- ATP Syntase as a Motor Prot
  - by the Yoshida & Hisabori
  Lab

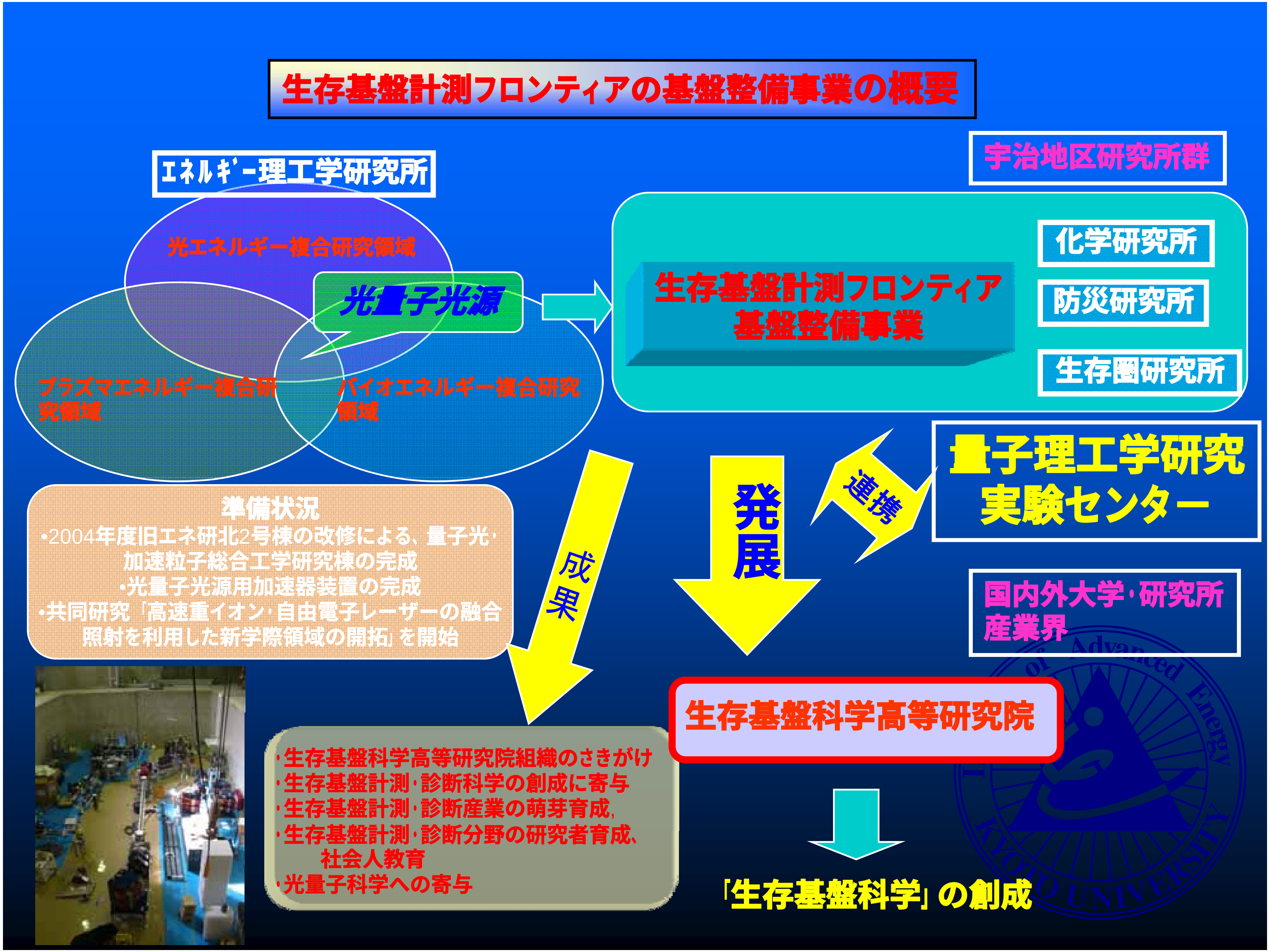
  東工大

蛍光による一分子回転の観察



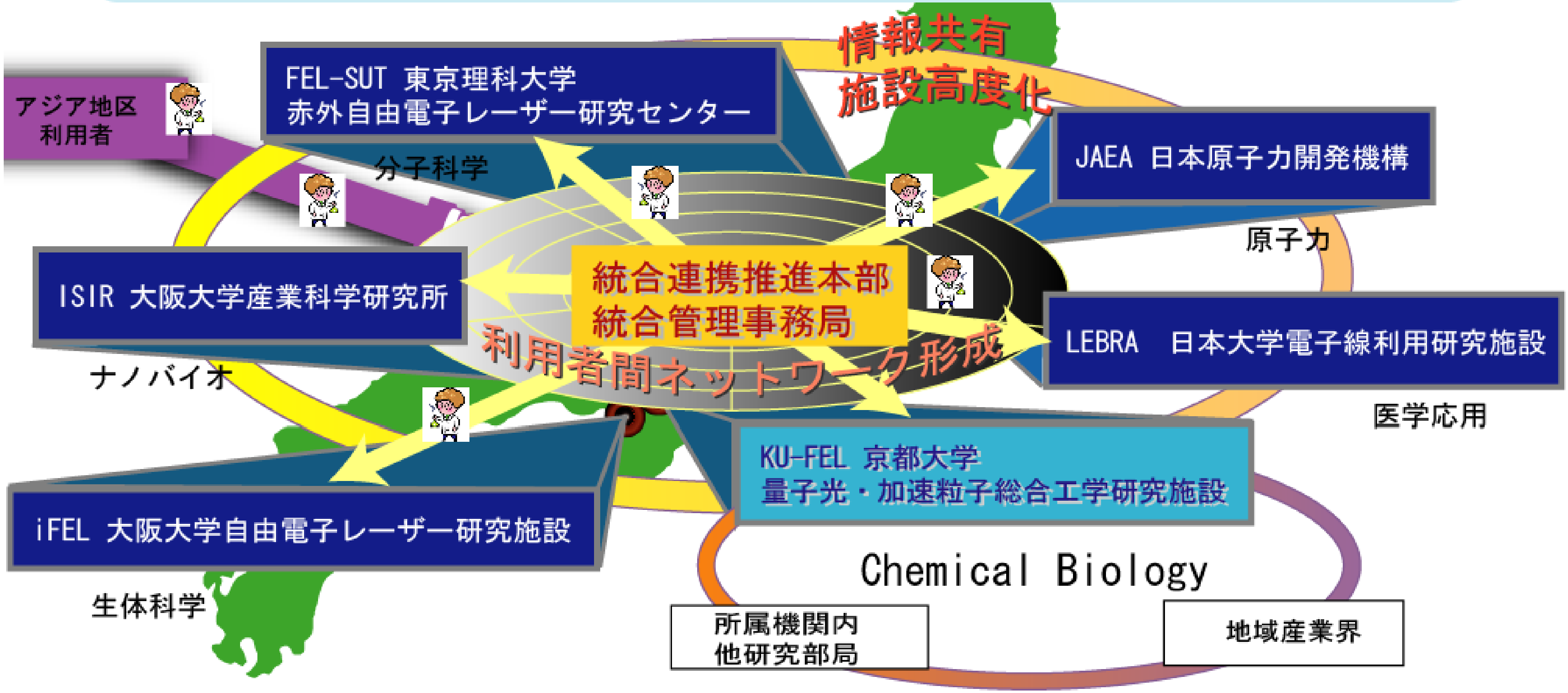
CONCEPTUAL SCHEME OF FEL MALDI TOF-MS




生存基盤計測フロンティアの基盤整備事業の概要
ｴﾈﾙｷﾞｰ理工学研究所
光エネルギー複合研究領域
光量子光源
プラズマエネルギー複合研究領域
バイオエネルギー複合研究領域
宇治地区研究所群
生存基盤計測フロンティア基盤整備事業
化学研究所
防災研究所
生存圏研究所
量子理工学研究実験センター
連携
発展
成果
国内外大学･研究所
産業界
準備状況
•2004年度旧エネ研北2号棟の改修による、量子光･加速粒子総合工学研究棟の完成
•光量子光源用加速器装置の完成
•共同研究「高速重イオン･自由電子レーザーの融合照射を利用した新学際領域の開拓」を開始
生存基盤科学高等研究院
･生存基盤科学高等研究院組織のさきがけ
･生存基盤計測･診断科学の創成に寄与
･生存基盤計測･診断産業の萌芽育成,
･生存基盤計測･診断分野の研究者育成、社会人教育
･光量子科学への寄与
「生存基盤科学」の創成

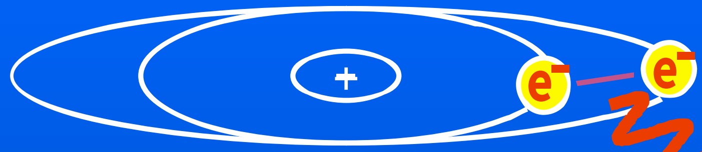
Multifunctional Molecule Scienceのための分散型赤外自由電子レーザー利用施設の形成

- 一元化された共同運営システム => 利用研究の円滑化
  => 利用者間交流促進 => Multifunctional Molecule Scienceの加速
- 機器共用 => 効率的運営
- 共同開発 => 効率的光源高度化

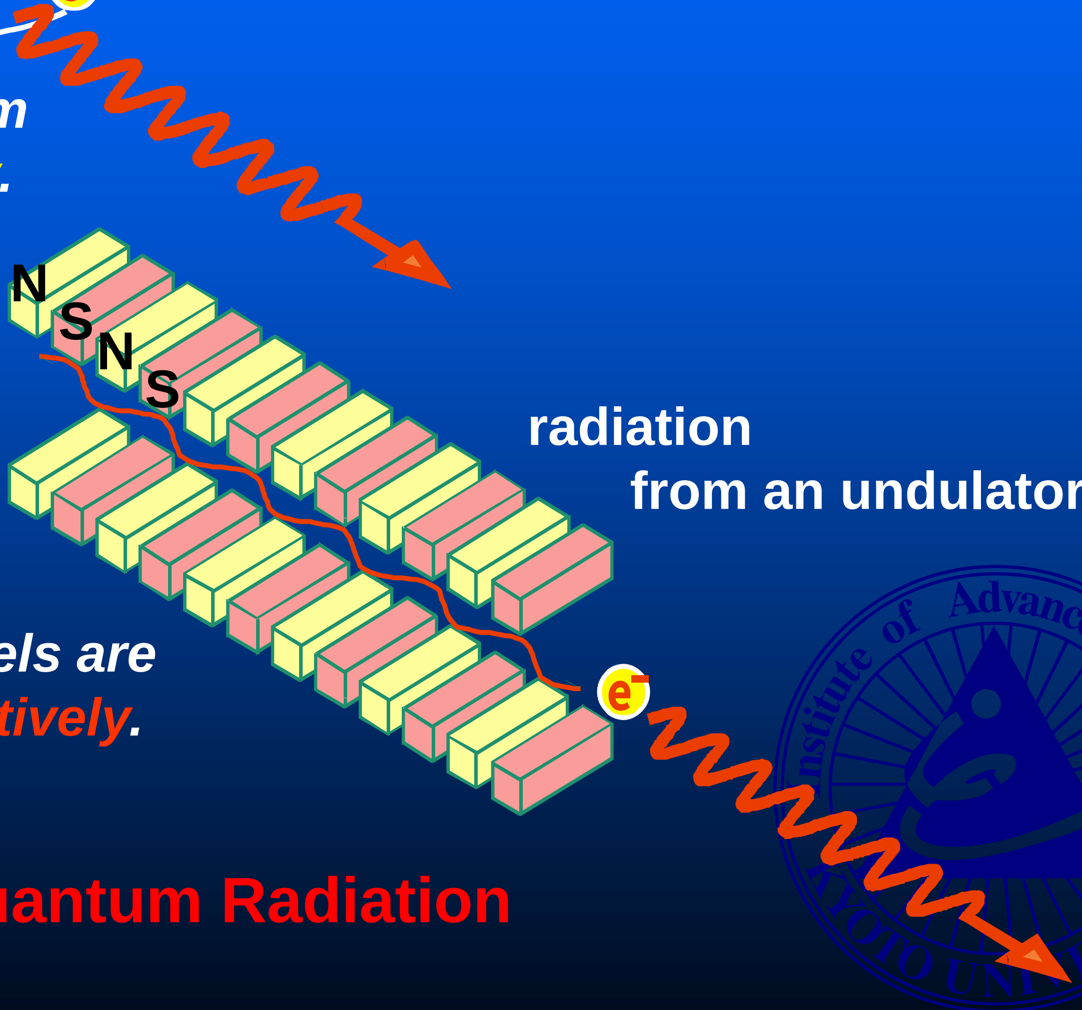


ACTIVE CREATION OF ENERGY LEVELS

radiation from an atom (laser)



Energy levels of an atom is used passeively.

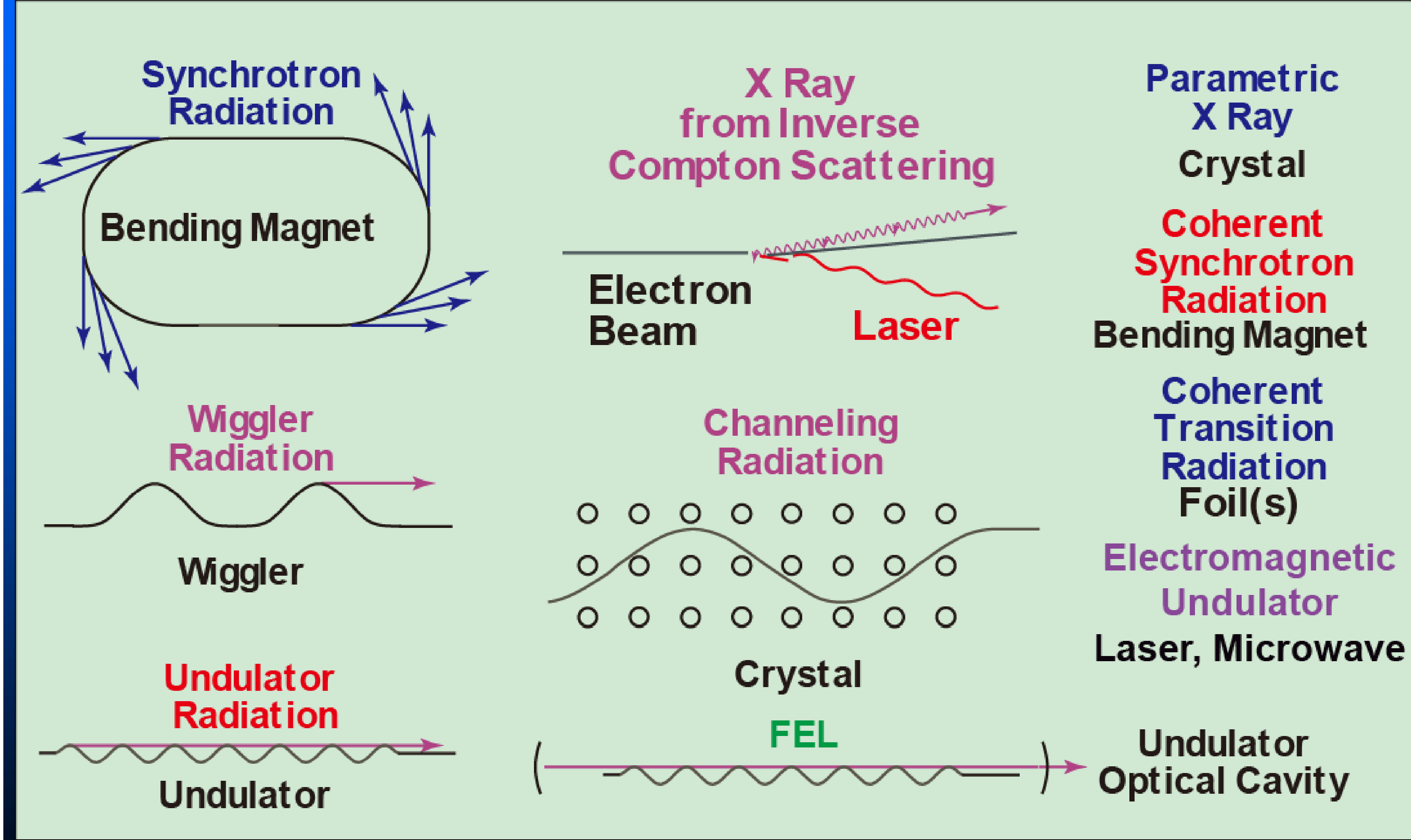


radiation from an undulator

Energy levels are created actively.

New Quantum Radiation

NEW QUANTUM RADIATION SOURCES



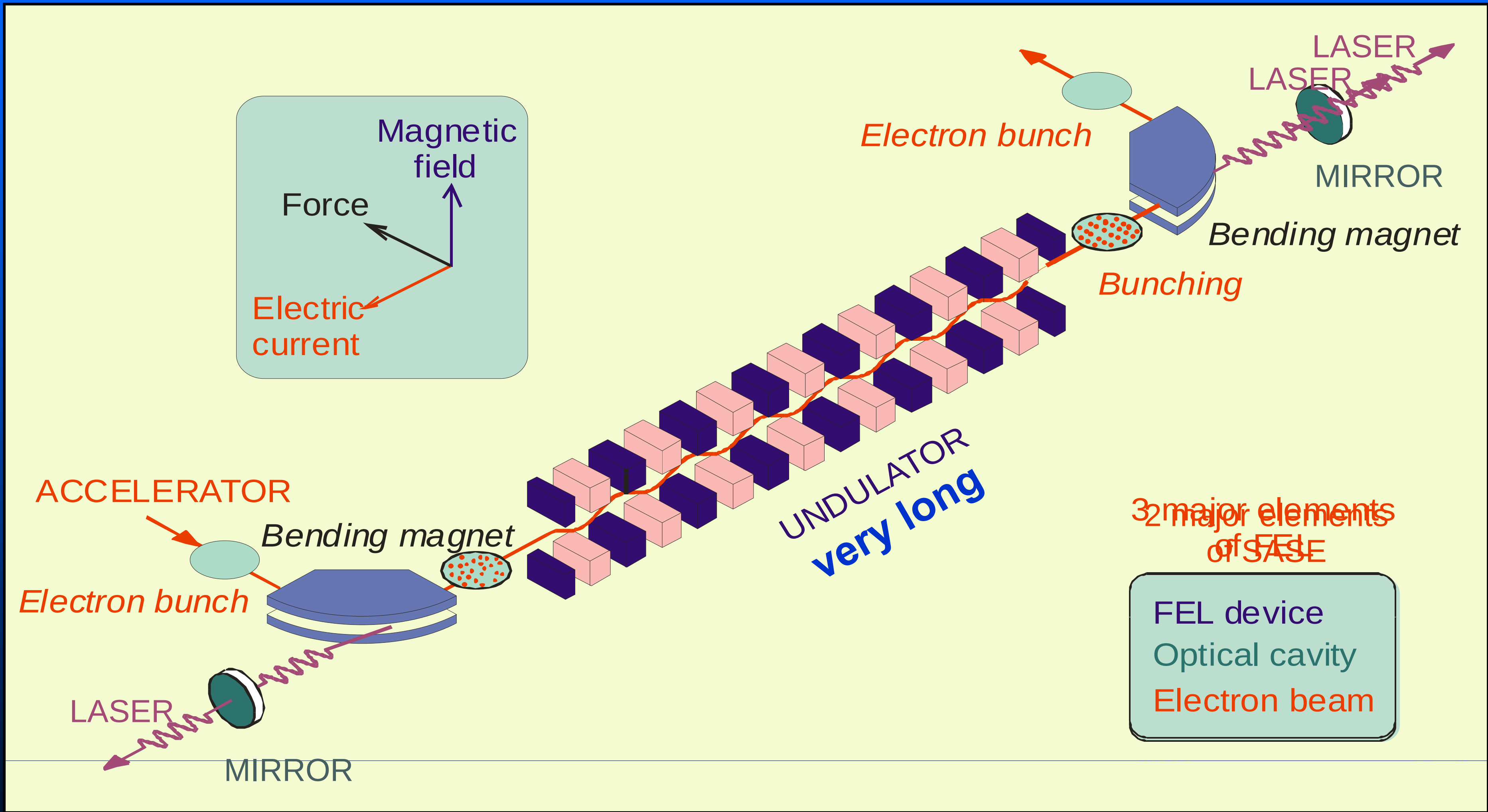
LIGHT SOURCES

Synchrotron Radiation

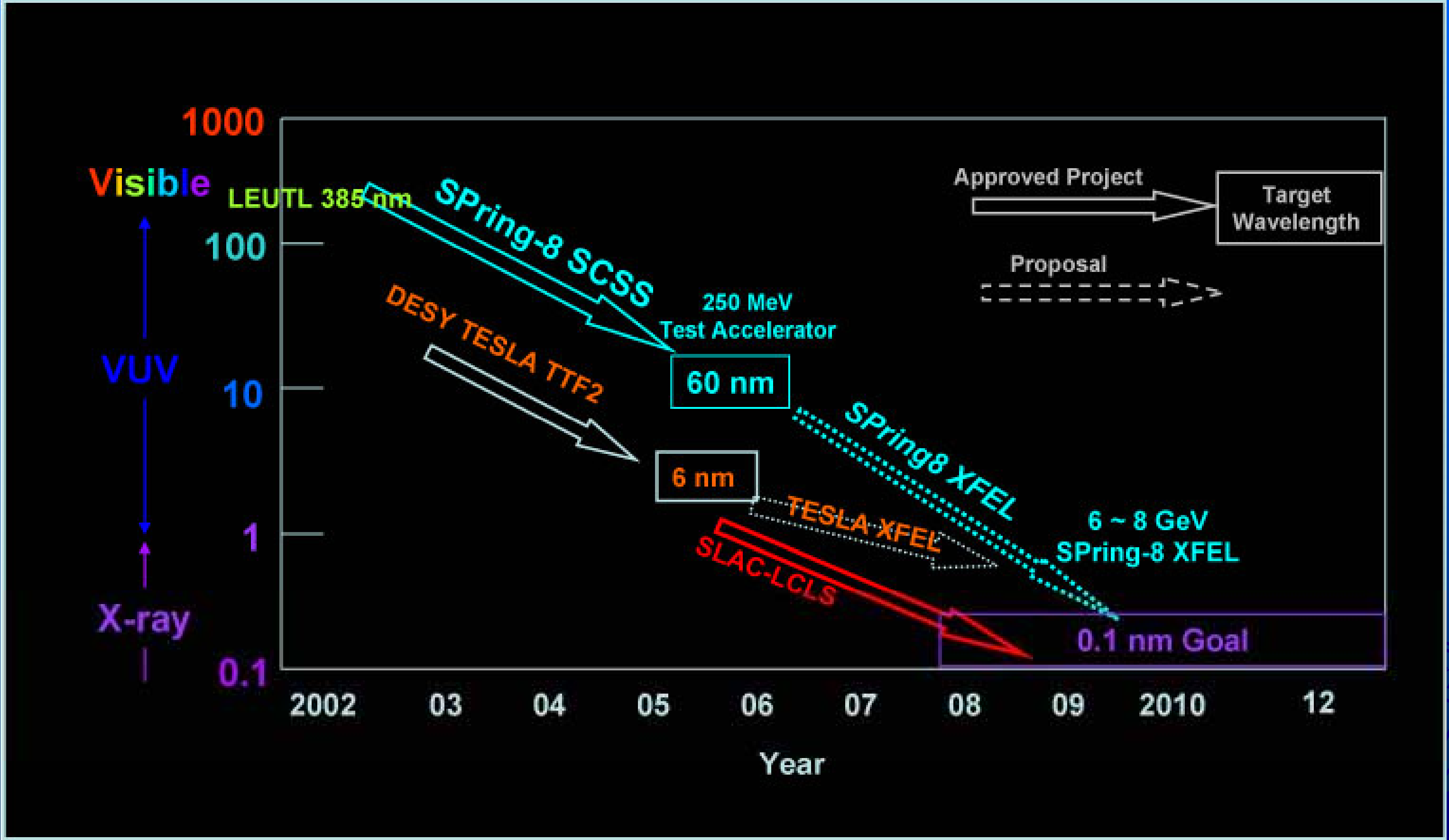
Free-Electron Lasers (FEL)
- **FEL Oscillators**
- **SASE FELs**

Energy-Recovery Linac (ERL) Light Sources
- **FELs**
- **X-ray Sources**
- **Electron Coolers**
- **Electron-Ion Colliders**

CONCEPTUAL SCHEME OF SASE



SASE PROJECTS



http://www-xfel.spring8.or.jp/cband/e/SCSS.htm#Milestone

CHALLENGES FOR SASE

ELECTRON BEAM

very low emittance of electron beam

$$\varepsilon < \frac{\lambda}{4\pi}$$

ε = 0.2 nm · rad for λ = 3 nm

ε_n = 0.4 μm · rad for λ = 3 nm @ 1 GeV

high-current guns

photocathode	thermionic
lifetime	emittance
RF gun	DC gun

current-dependent effects

BBU, CSR , HOM, halo problem, space charge, wake fields

bunch compression

magnetic, RF

tolerance on trajectories

BPMs, magnet alignment, stable stands, halo problem

CHALLENGES FOR SASE

UNDULATOR

tolerance on *K* values

1.5×10^{-4} = 50-μm vertical misalignment

radiation damage to undulators

RADIATION

stability and reliability

short pulse 1~3 fs

timing jitter

shot-to-shot instability

number of beamlines

And many more

CHALLENGES FOR ERL

ELECTRON BEAM

very low emittance of electron beam

emittance growth @ merger, etc.

high-current guns

photocathode	**thermionic**
lifetime	**emittance**
RF gun	**DC gun**

current-dependent effects

BBU, CSR , HOM, halo problem, space charge, wake fields,
limitation of energy gain?

bunch compression

magnetic, RF

tolerance on trajectories

non-destructive BPMs, magnet alignment,
stable stands

And many more

COMPARISON OF LIGHT SOURCES

	SR	ERL (SR)	SASE
energy	2-8 GeV	1-10 GeV	2-15 GeV
micropulse width	30 – 100 ps	10 fs – 1 ps	10 fs – 1 ps
emittance	1-20 nm (H) 0.1 – 1 nm (V)	0.1 - 1 nm	0.02 – 0.2 nm
repetition rate	10 – 500 Mpps	10 -1000 Mpps	10 – 500 pps
av. brilliance	$0.01 – 10 \times 10^{20}$ ph /s/.1%/mm^2/$mrad^2$	10^{22} -10^{23} ph /s/.1%/mm^2/$mrad^2$	10^{22} -10^{26} ph /s/.1%/mm^2/$mrad^2$
peak brilliance	10^{22} -10^{23} ph /s/.1%/mm^2/$mrad^2$	10^{25} -10^{26} ph /s/.1%/mm^2/$mrad^2$	10^{33} -10^{34} ph /s/.1%/mm^2/$mrad^2$
no. of beamlines	many	many	1 – 10

COMPARISON OF LIGHT SOURCES

	SR	ERL (SR)	SASE
electron beam	now available	low emittance CSR, HOM, wake very high stability emittance growth at mergers space charge (energy gain)	very low emittance CSR, HOM, wake very high stability
undulators	now available	now available	very long very high precision
radiation	now available stable many beamlines	high av. flux many beamlines	high peak brilliance shot-to-shot instability small no. of beamlines competition wt. X-ray lasers
	SR + FEL Compatible	ERL + SASE compatible?	

自分（達）は何をやりたいか？
そのためには何が必要か？

失敗を喜んで認める
失敗から回復する
いずれは必ず成功するという信念
成功しそうな時の確認

ライヴァルとの競争と協調
利用者との議論と協調
集中拠点と分散拠点

さまざまな量子放射源
総合的，境際的な視点
加速器技術の重要性

Thank you for your attention.

I have to thank many colleagues.

Electrotechnical Laboratory (AIST)

Eectron Accelerator Group

Takio TOMIMASU **(kyushu U.)**, Kawakatsu YAMADA,
Norihiro SEI, Hideaki OHGAKI **(kyoto U.)**,
Suguru SUGIYAMA **(retired)**, Tsutomu NOGUCHI **(retired)**,
Takeshi NAKAMURA **(JASRI)**, Tomohisa Mikado **(late)**,
Hiroyuki TOYOKAWA, Ryoichi SUZUKI, Toshiyuki OHDAIRA

Collaboration with

Kawasaki Heavy Industries Co.

M. KAWAI, M. YOKOYAMA, S. HAMADA, A. IWATA, K. OWAKI

Mitsubishi Electric Co.

N. SATO, H. USAMI

Sumitomo Electric Industries Co.

H. TAKADA, Y. TSUTSUI, ...

SR Users

....

I have to thank many colleagues.

KU-FEL Group

Institute of Advanced Energy, Kyoto University

Hideaki OHGAKI, Toshiteru KII, Kai MASUDA,
Kiyoshi YOSHIKAWA
GRADUATE STUDENTS

Quantum Science & Engineering Center, Graduate School of Engineering, Kyoto University

Koji YOSHIDA

Collaborators from

National Institute of Advanced Industrial Science and Technology
iFEL, Graduate School of Engineering, Osaka University
Nissin Electric Co.
FEL Users
…………………………