Development and Operation of the JAERI ERL
(Superconducting Energy Recovery Linac)

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FEL Laboratory at Tokai, APRC, Kansai
Japan Atomic Energy Research Institute

What is
an Eenergy Recovery linac?

First, I would like to show you collected figures from Prof.T.Smith's ERL05 Talk!

Then, I would like to talk my JAERI ERL-FEL.

Electrostatic ERL-FELs

University of California Santa Barbara (UCSB)
College of Judea and Samaria, Israel
Korea Atomic Energy Research Institute, South Korea (KAERI)
FOM Nieuwegein, the Netherlands

RF LINAC ERL-FELs (Operating)

Jefferson Lab, Newport News, Virginia, USA
JAERI, Ibaraki, Japan
BINP, Novosibirsk, Russia

RF LINAC ERL-FELs (Planned)

KAERI
4GLS
NHFML-Florida
SACLAY

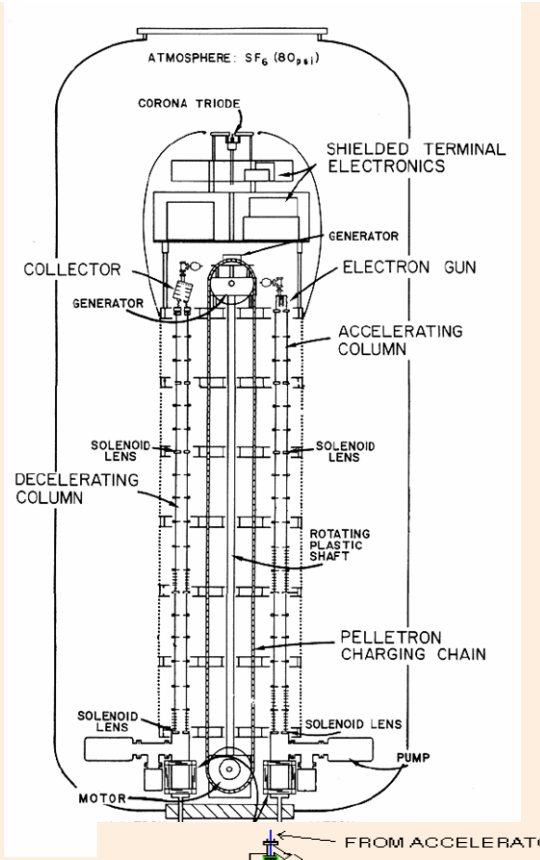
RF LINAC ERL-FELs (Advanced Concepts)

MAX-lab
TESLA
BNL
Budker

Electrostatic Accelerator based ER-FELs

UCSB [NIM **A**237 (1985) 203-206]
KAERI [NIM **A**375 (1996) 28-31]
Israeli EA-FEL [NIM **A**407 (1998) 16-20]
Dutch Fusion-FEM [NIM **A**429 (1999) 9-11]

References = First Lasing



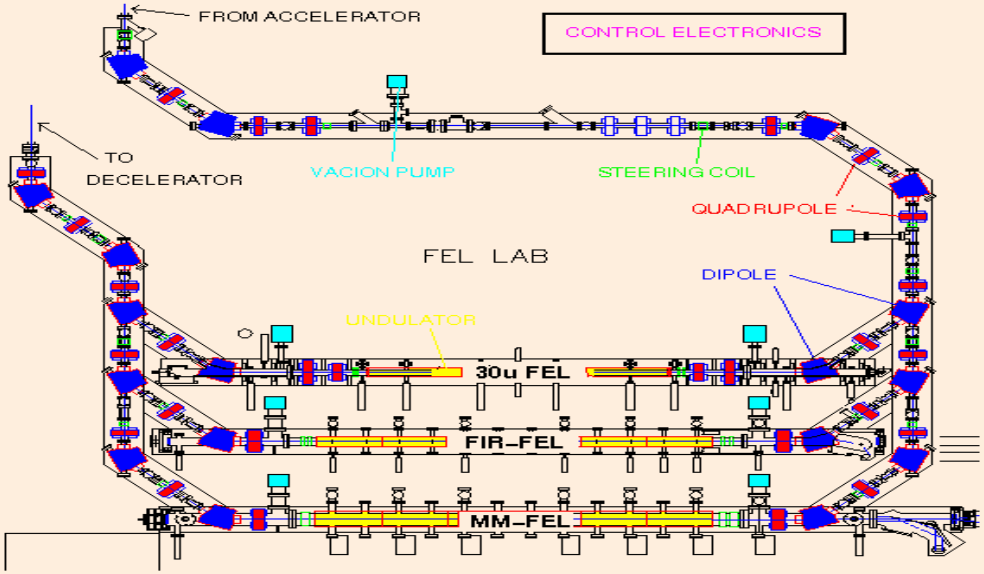
THE UCSB FREE-ELECTRON LASERS

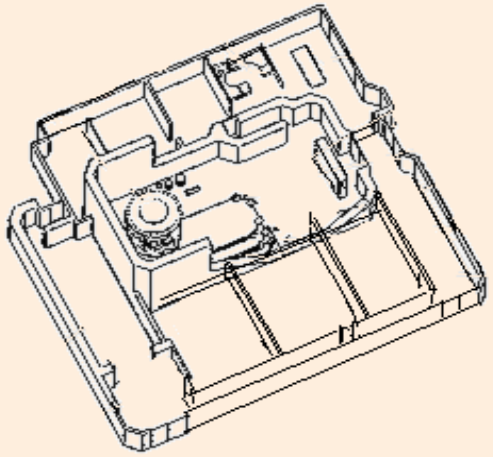
A SOURCE OF TUNABLE, COHERENT, HIGH POWER FAR-INFRARED RADIATION

Center for Terahertz Science and Technology

University of California, Santa Barbara

http://sbfel3.ucsb.edu/





RF Linac based ER-FELs

(History)

S.O. Schreiber and E.A. Heighway (Chalk River)

Double Pass Linear Accelerator - Reflexotron

IEEE NS-22 (1975) (3) 1060-1064

D.W. Feldman et al, (LANL)

Energy Recovery in the LANL FEL

NIM A259 (1987) 26-30

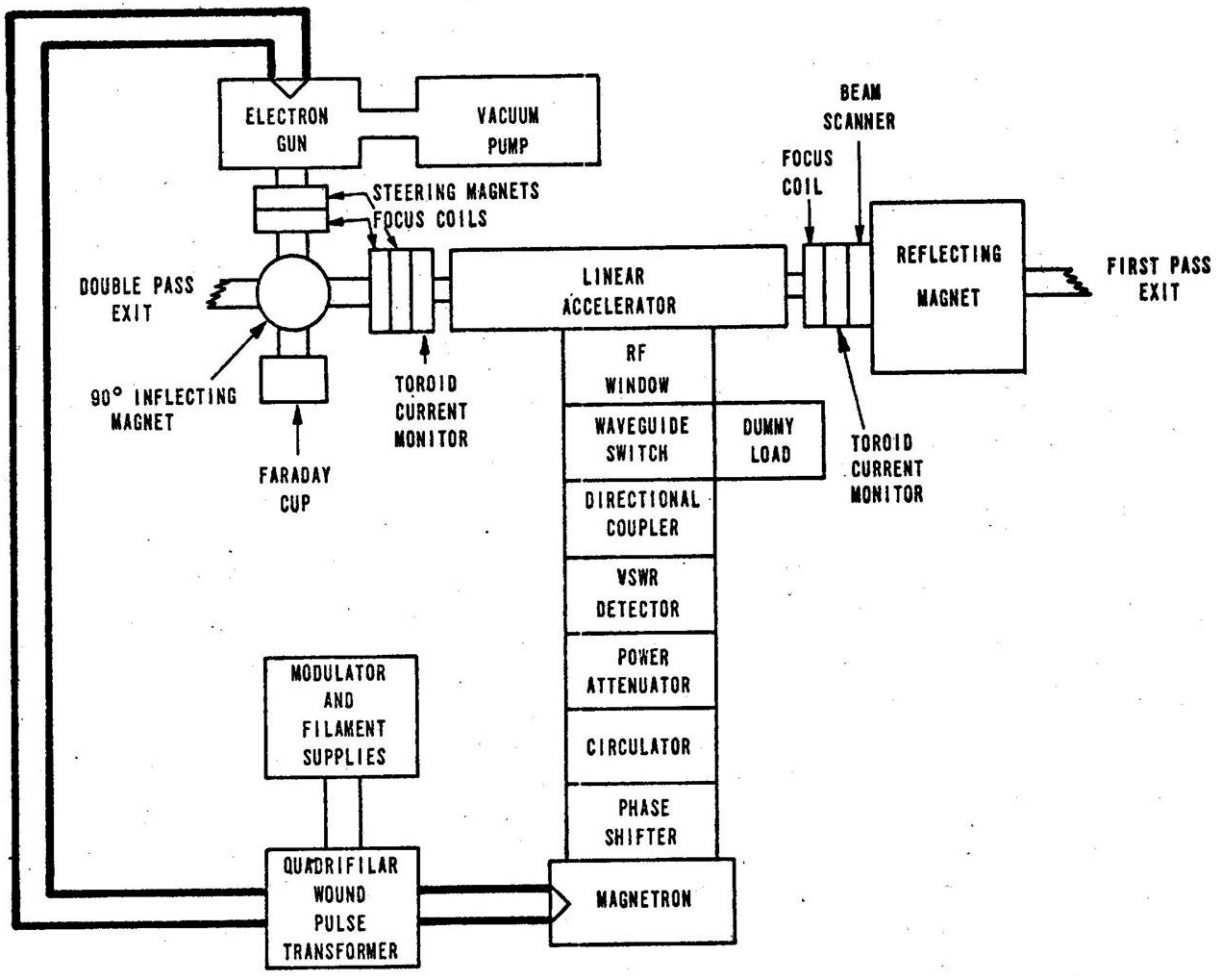
T.I. Smith et al, (Stanford University)

Development of the SCA/FEL for use in Biomedical and Materials Science Research

NIM A259 (1987) 1-7

S.O. Schreiber and E.A. Heighway (Chalk River)

Double Pass Linear Accelerator - Reflexotron



IEEE NS-22 (1975) (3) 1060-1064

D.W. Feldman et al,

Energy Recovery in the Los Alamos FEL

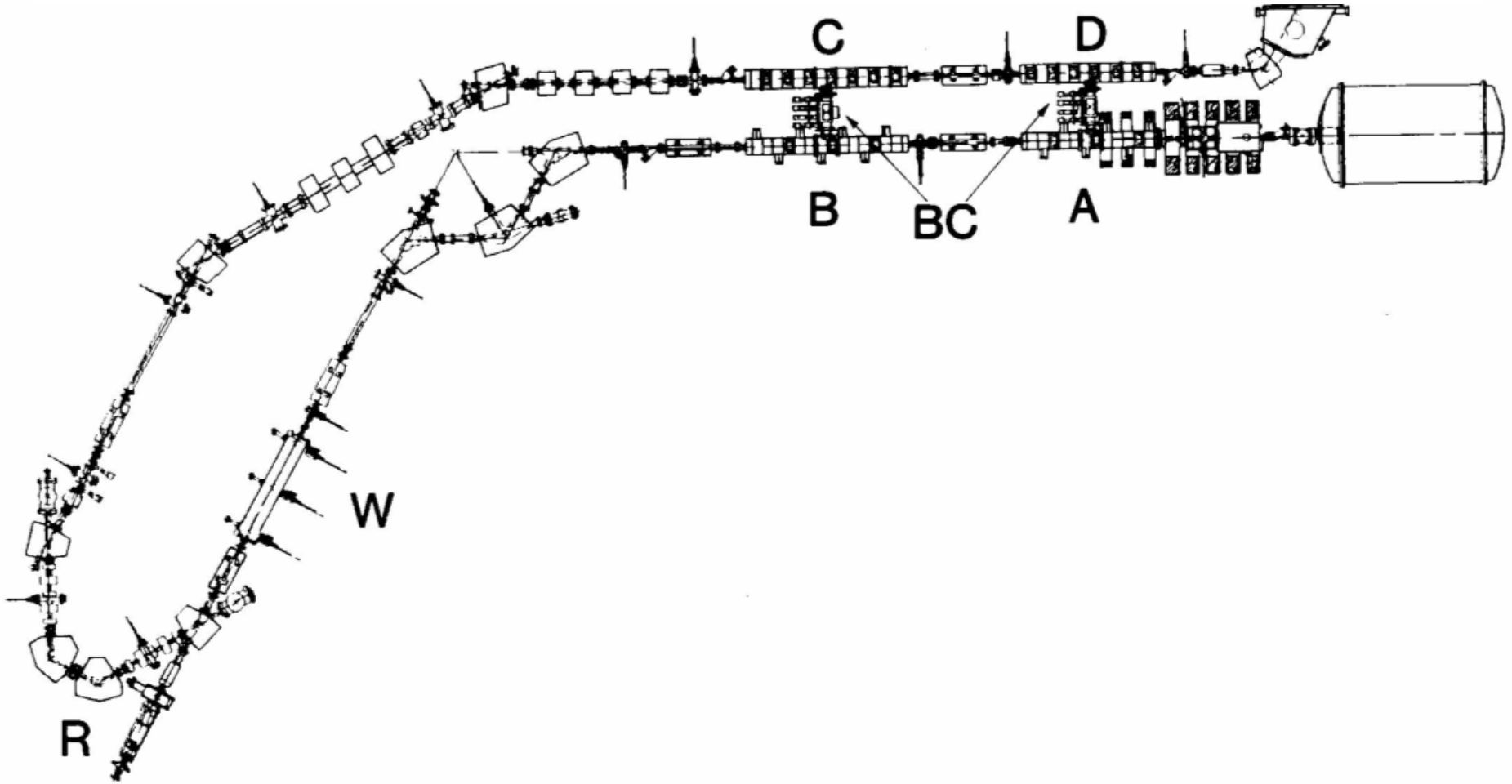
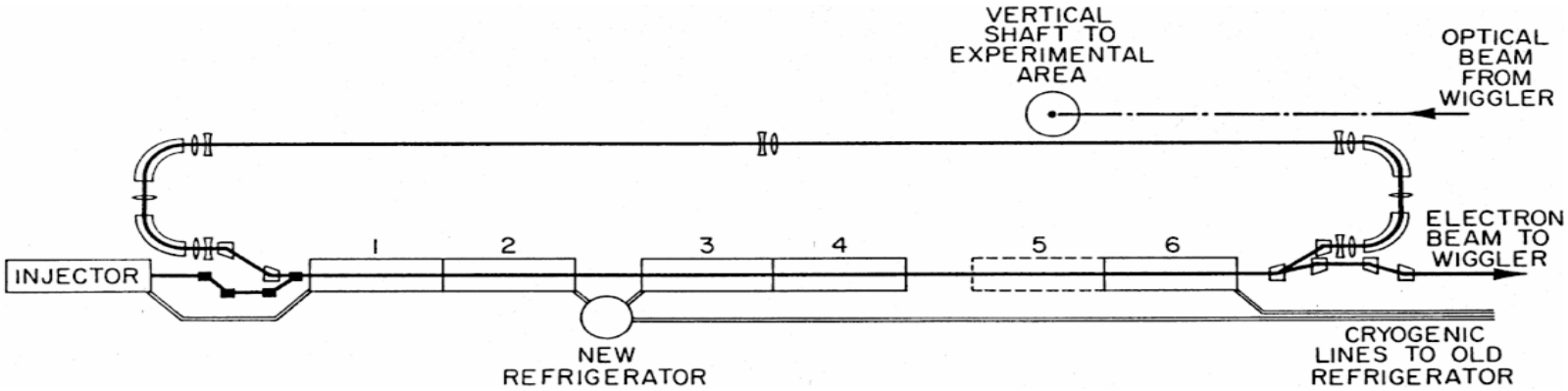


Fig. 1. Energy-recovery beamline arrangement.

NIM **A**259 (1987) 26-30

SCA as configured in 1986 for the Visible FEL Oscillator Experiment

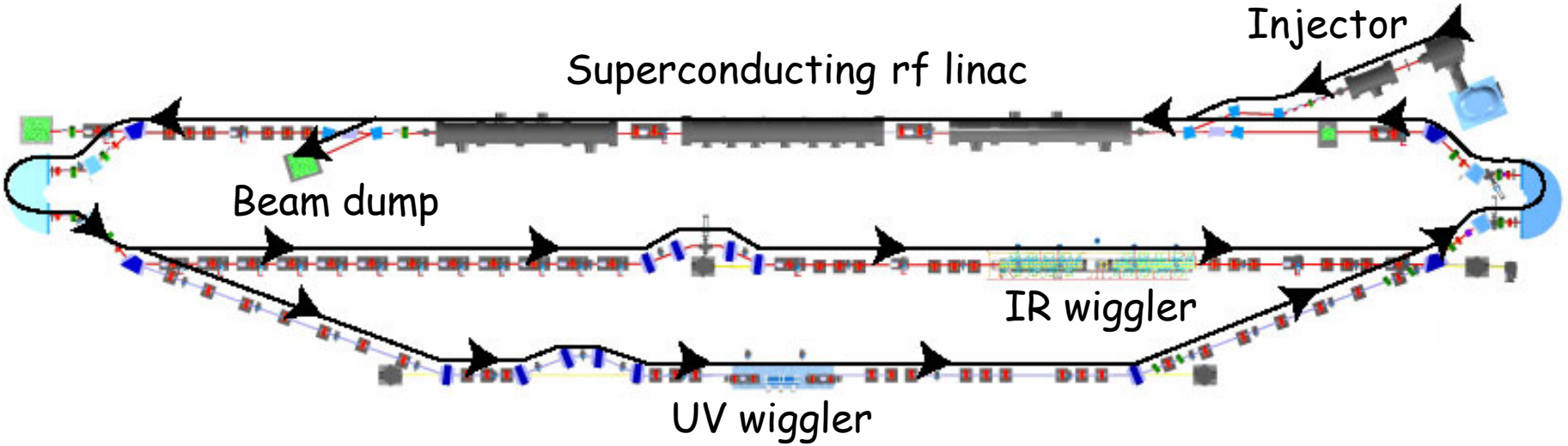


FEL 1986 Oral Presentation

Operating
RF Linac based ER-FELs

JLab [2004 FEL Conf. Proc., 229-232]
JAERI [2004 FEL Conf. Proc., 301-303]
BINP [2004 FEL Conf. Proc., 226-228]

JLab 10kW IR FEL and 1 kW UV FEL

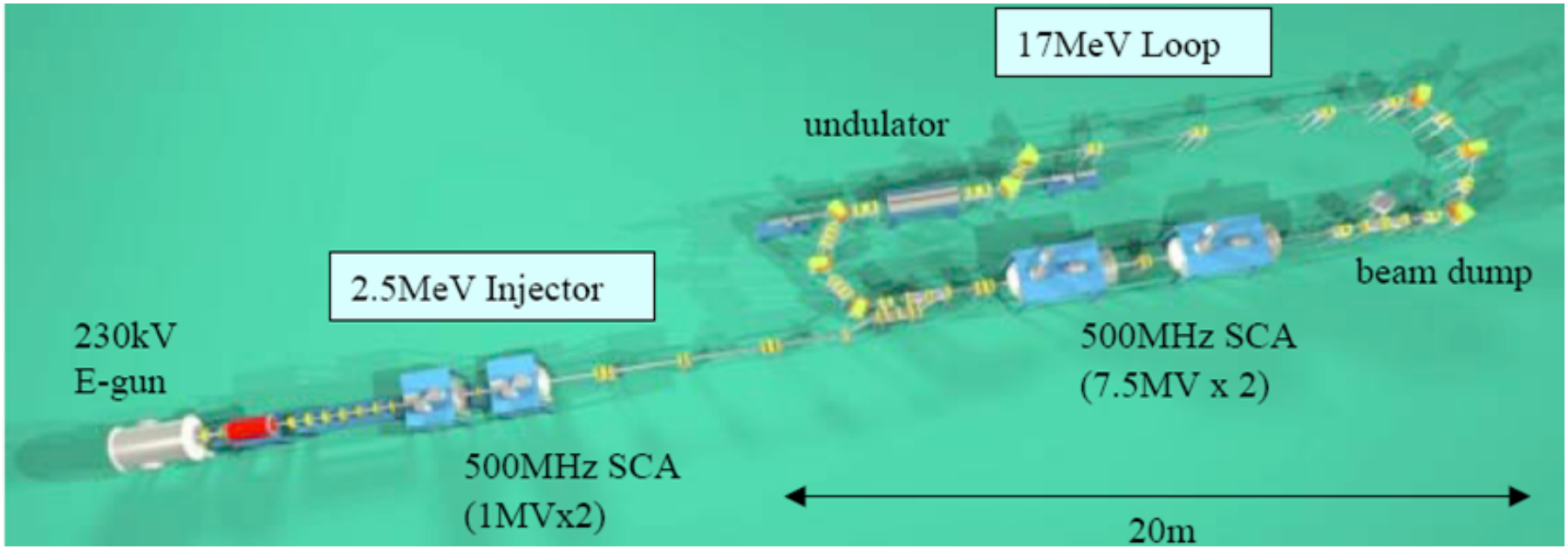


Output Light Parameters	IR	UV
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power / pulse (microJoules)	100 - 300	25
Laser power (kW)	>10	> 1
Rep. Rate (cw operation, MHz)	4.7 – 75	4.7 – 75

Electron Beam Parameters	IR	UV
Energy (MeV)	80-200	200
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50	0.13
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

S. Benson et al, *High power lasing in the IR upgrade at Jefferson Lab*, 2004 FEL Conference Proceedings, 229-232.

JAERI ER-FEL

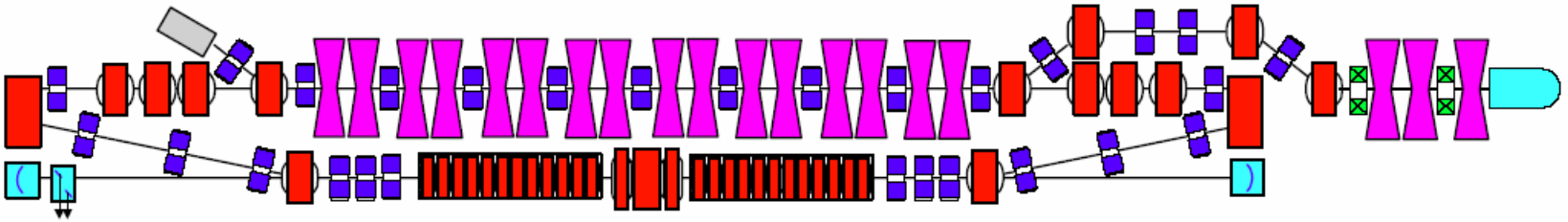


Output Light Parameters	Achieved	Goal
Wavelength range (microns)	22	22
Bunch Length (FWHM psec)	15	6
Laser power / pulse (microJoules)	10	120
Laser power (kW)	0.1	10
Rep. Rate (MHz)	10.4	83.2
Macropulse format	10ms 10Hz	CW

Electron Beam Parameters	Achieved	Goal
Energy (MeV)	17	16.4
Accelerator frequency (MHz)	500	500
Charge per bunch (pC)	500	500
Average current (mA)	5	40
Peak Current (A)	33	83
Beam Power (kW)	85	656
Energy Spread (%)	~0.5	~0.5
Normalized emittance (mm-mrad)	~40	~40
Induced energy spread (full)	~3%	~3%

R. Hajima et al, *Recent results of the JAERI Energy-Recovery Linac FEL*, 2004 FEL Conference Proceedings, 301-303

Novosibirsk Free Electron Laser



RF-Cavities Bending Magnets Quadrupoles Solenoids

Undulators Buncher Mirrors Outcoupler

Output Light Parameters	IR
Wavelength range (microns)	120-180
Bunch Length (FWHM psec)	50
Laser power / pulse (microJoules)	9
Laser power (kW)	0.2
Rep. Rate (cw operation, MHz)	22.5

Electron Beam Parameters	IR
Energy (MeV)	12
Accelerator frequency (MHz)	180
Charge per bunch (pC)	900
Average current (mA)	20
Peak Current (A)	10
Beam Power (kW)	240
Energy Spread (%)	0.2
Normalized emittance (mm-mrad)	20

V.P. Bolotin et al, , *Status of the Novosibirsk Terahertz FEL*, 2004 FEL Conference Proceedings, 226-228

Planned

RF Linac based ER-FELs

KAERI [NIM **A**528 (2004) 106-109]
4GLS [M.W. Poole et al, PAC 2003]
NHMFL [Proposal to NSF (Jan 2005)]
SACLAY [M.E. Couprie et al, EPAC 2004]

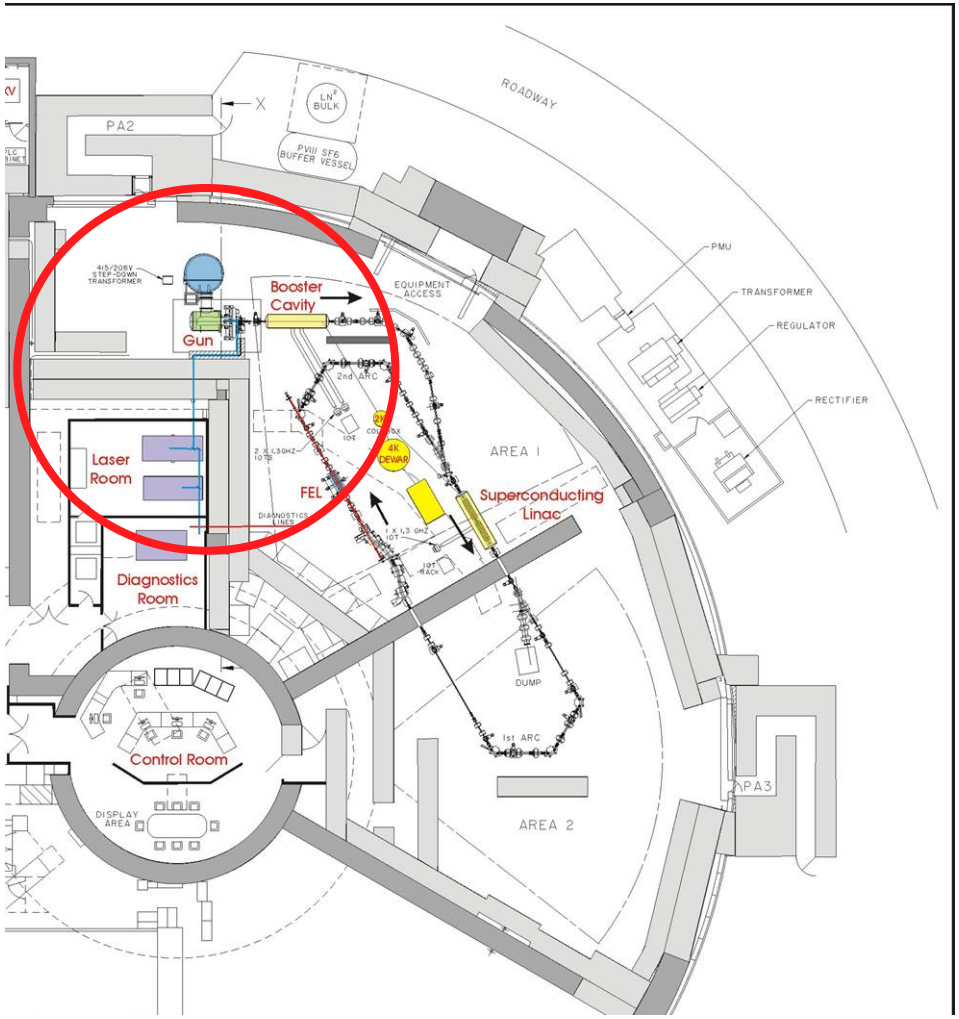
KAERI

Output Light Parameters	Goal
Wavelength range (microns)	3-20
Bunch Length (FWHM psec)	20-50
Laser power / pulse (μJoules)	50-250
Laser power (kW)	1-5
Rep. Rate (MHz)	22
Macropulse format	CW

Electron Beam Parameters	Goal
Energy (MeV)	20-40
Accelerator frequency (MHz)	352
Charge per bunch (pC)	500
Average current (mA)	10
Peak Current (A)	10-25
Beam Power (kW)	200-400

B.C. Lee, et al, *High-Power infrared free electron laser driven by a 352 MHz superconducting accelerator with energy recovery*, NIM **A**528 (2004) 106-109

ERL Prototype



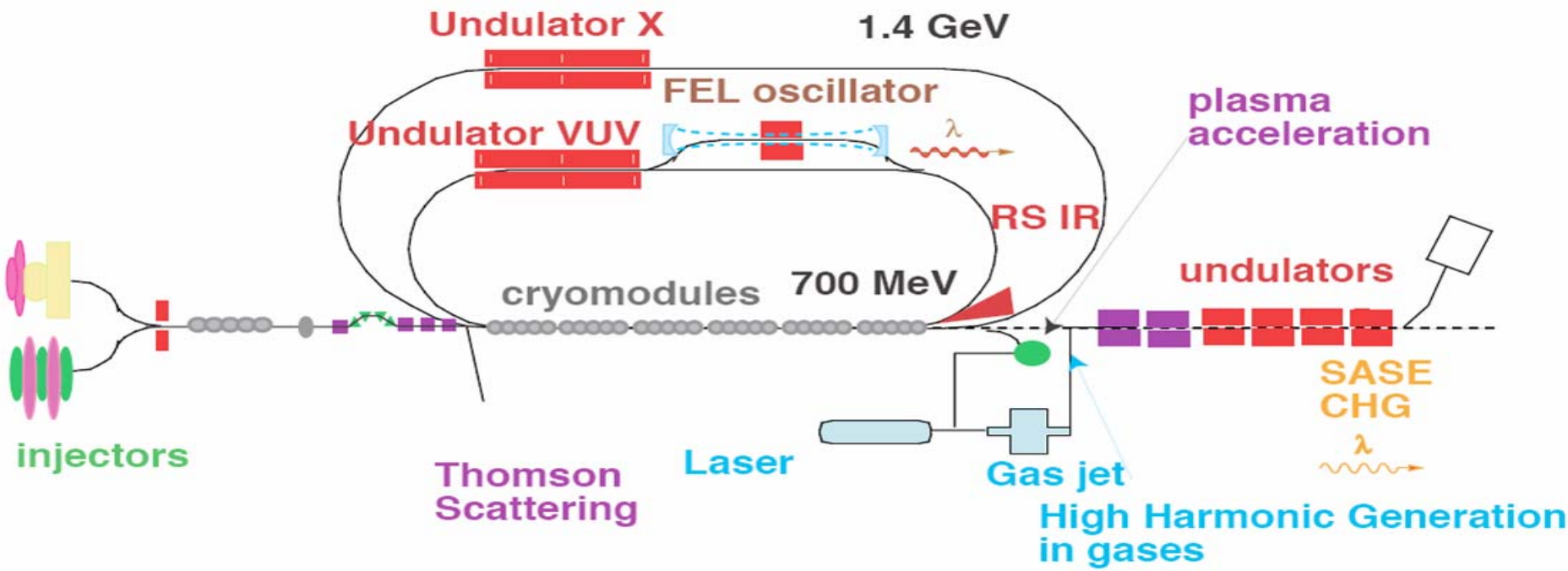
Electron Beam Parameters	Goal
Energy (MeV)	30-50
Accelerator frequency (MHz)	1300
Charge per bunch (pC)	>80
Average current (mA)	>0.8
Peak Current (A)	~150
Beam Power (kW)	~30

Output Light Parameters	Goal
Wavelength range (microns)	3-75
Bunch Length (FWHM psec)	0.1-few
Laser power / pulse (μJoules)	90
Laser power (kW)	0.9
Rep. Rate (MHz)	10
Macropulse format	CW

M.W. Poole et al, PAC 2003 *4GLS: A new type of 4th generation light source facility*

SACLAY

(ARC-EN-CIEL: Accelerator-Radiation Complex for ENhanced Coherent Intense Extended Light)



M.E. Couprie et al, *"ARC-EN-CIEL" A proposal for a 4th generation light source in France*, Proc. EPAC 2004, 366.

1. JAERI FEL Developmental Strategy 3 steps and NEXT

JAERI non ERL and ERL FELs

#1st STEP Super-Conducting Linac FEL Driver without ERL

1989-1995 Powerful FEL Driver

Other Possible e-Beam Applications

#2nd STEP Most Powerful FEL Lasing without ERL

1996-2000 Laser beam Applications

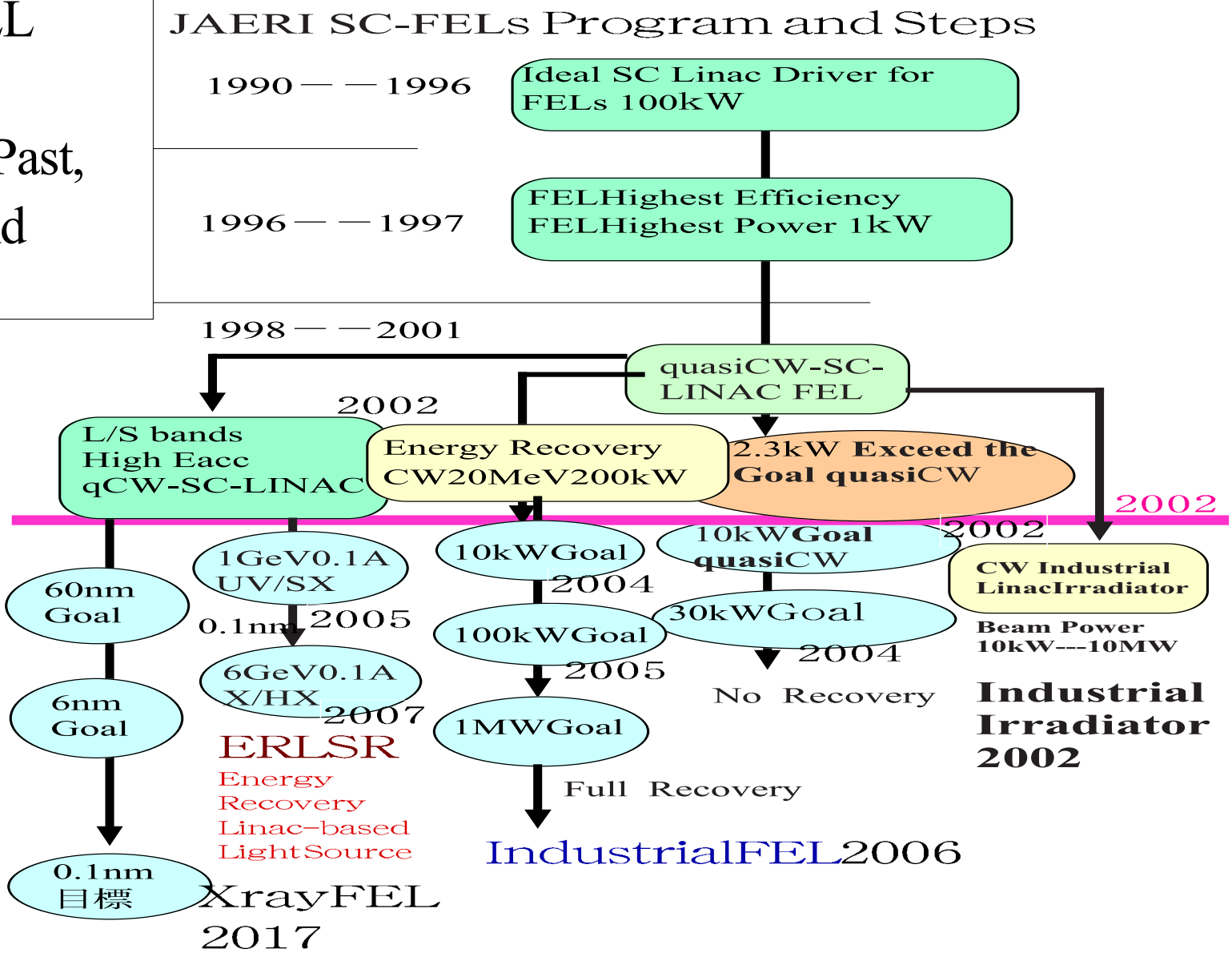
#3rd STEP ERL-FEL Efficient FEL Lasing Under Development

2001-2005 Large-scaled Laser Beam Applications

Nuclear Energy Industries

Next STEP ERL-LS Conceptual Design and Key Components

JAERI FEL Research Program, Past, Present and Future



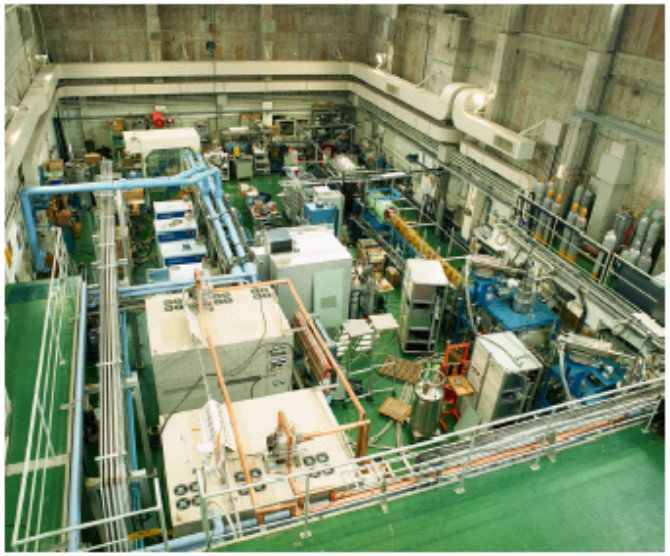
#1st STEP JAERI Non ERL Super-Conducting Linac FEL Driver

~100kW Beam Power for FEL Lasing

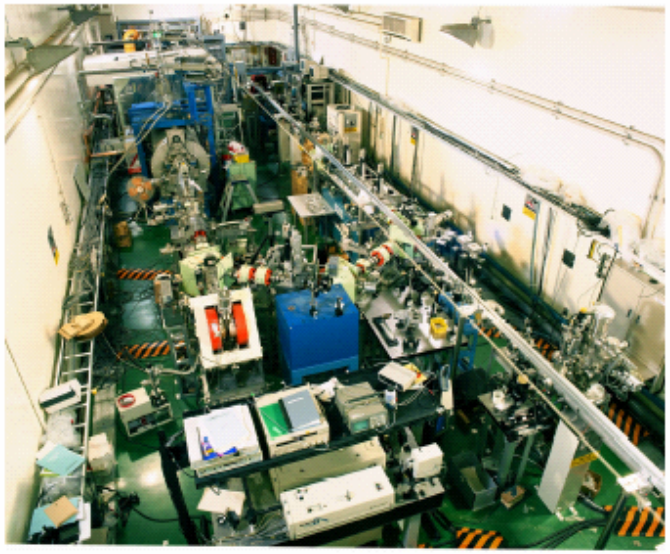
UHF SC Linac Driver and JAERI FEL at Tokai

Since 2001.April the JAERI FEL was shut-down and was under construction to assemble Energy Recovery Loop.

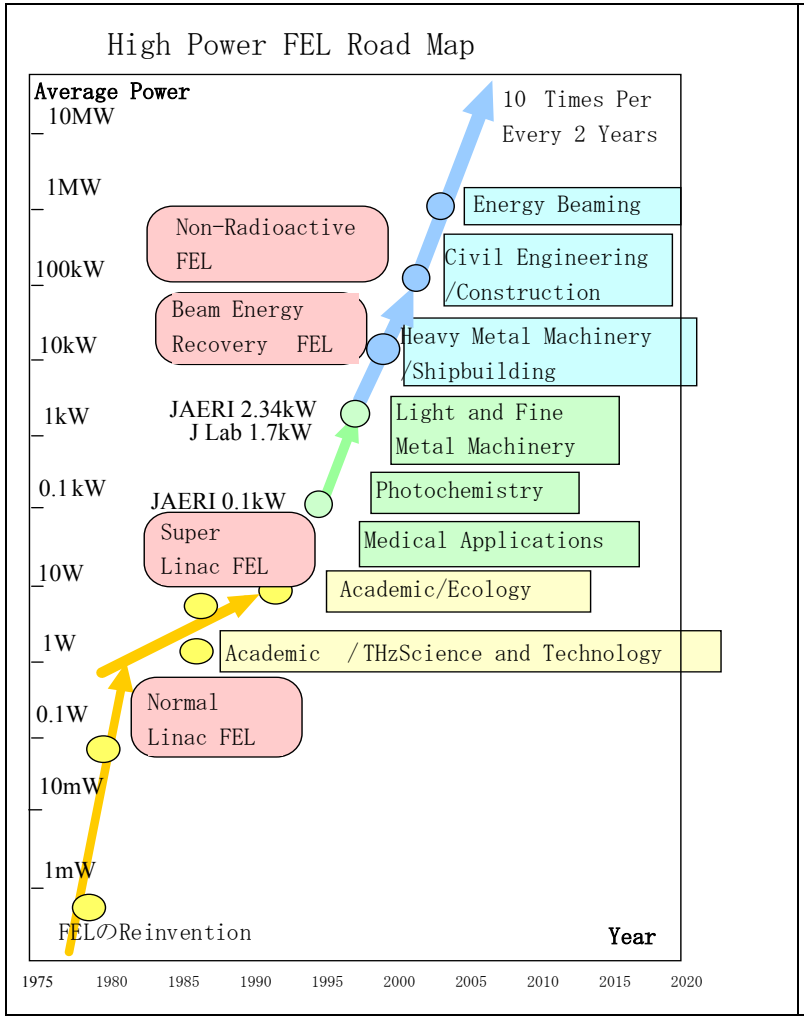
Old FEL Experimental Hall

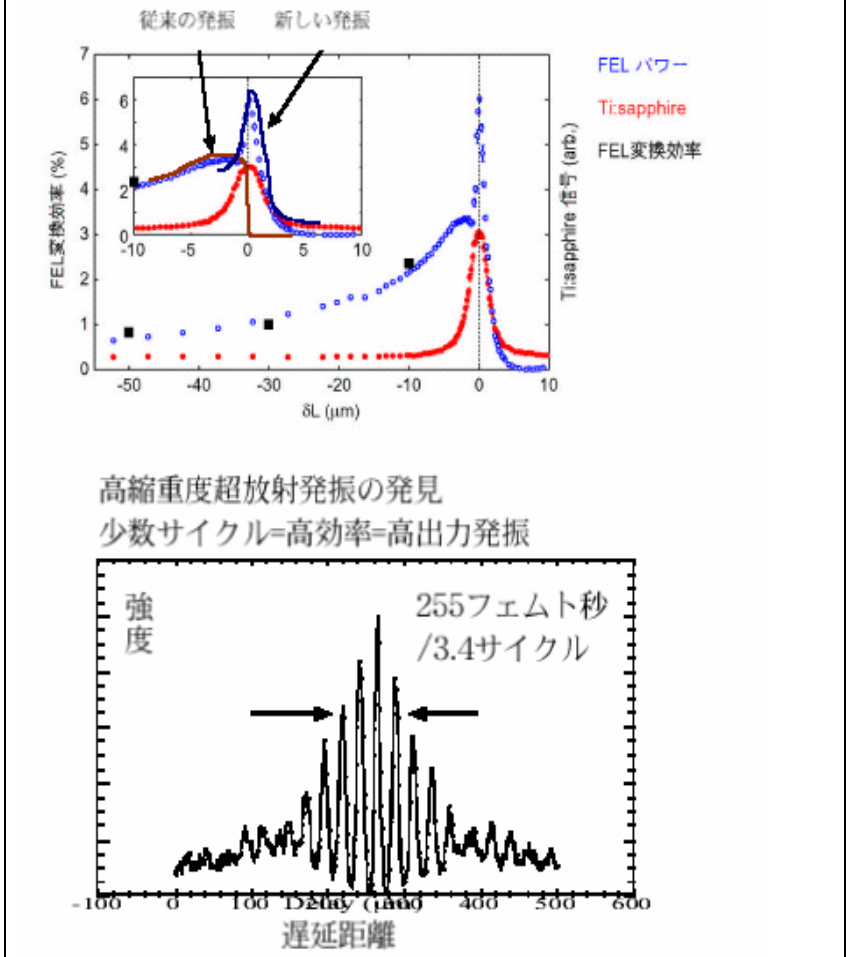


Old FEL Main Accelerator Vault



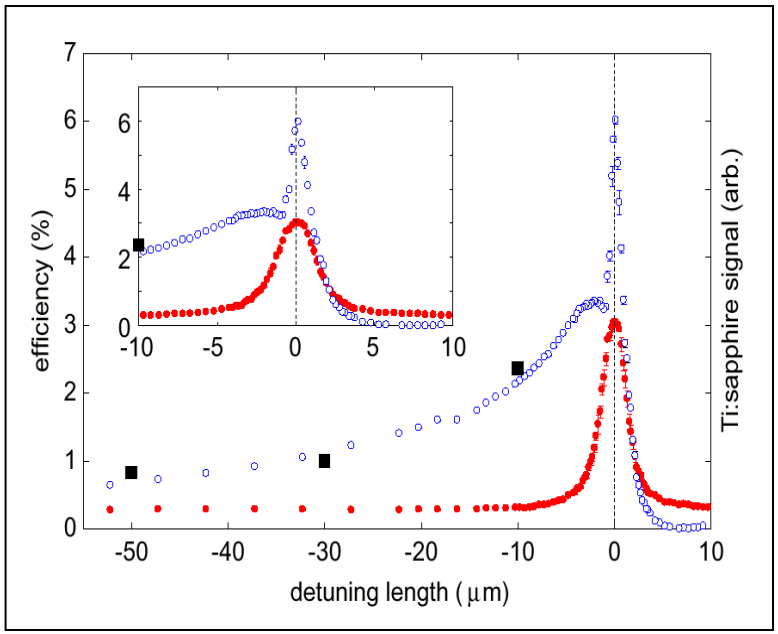
#2nd STEP Toward the Most Powerful FEL Lasing Up to Over 2kW

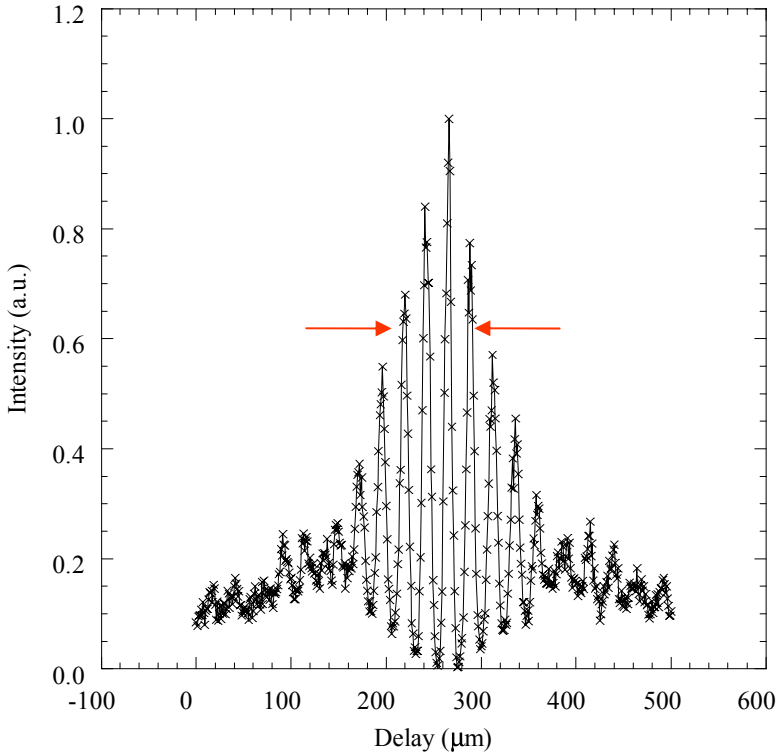




#2nd STEP Toward the Most Powerful FEL Lasing Up to Over 2kW

Energy = 16.5MeV
Bunch charge =510pC
Bunch length < 5ps
Bunch rep. = 10.4125MHz
FEL l = 16-23μm
FEL power = 2.34kW
High-efficiency η=6%



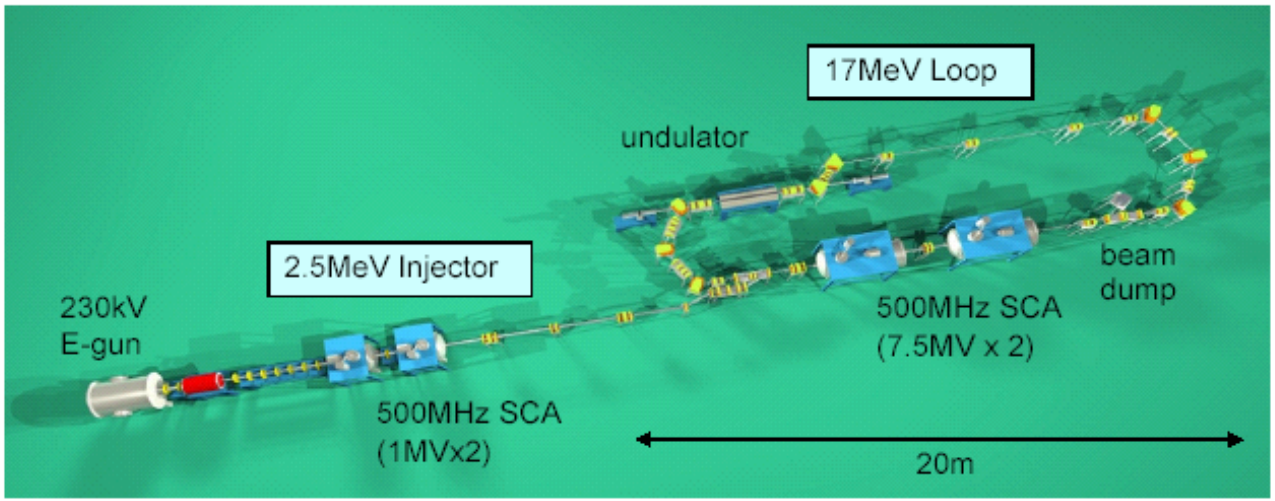


ultrashort pulse

255fs(FWHM) = 3.4 cycles

#3rd STEP ERL-FEL Most Efficient FEL Lasing Up to 10kW

JAERI Energy-Recovery Linac for 10kW FEL



- Natural extension of the original configuration.
- 8 times larger e-beam power.
- Fitting to the concrete boundary.

Energy = 17MeV

FEL : λ = ~22μm

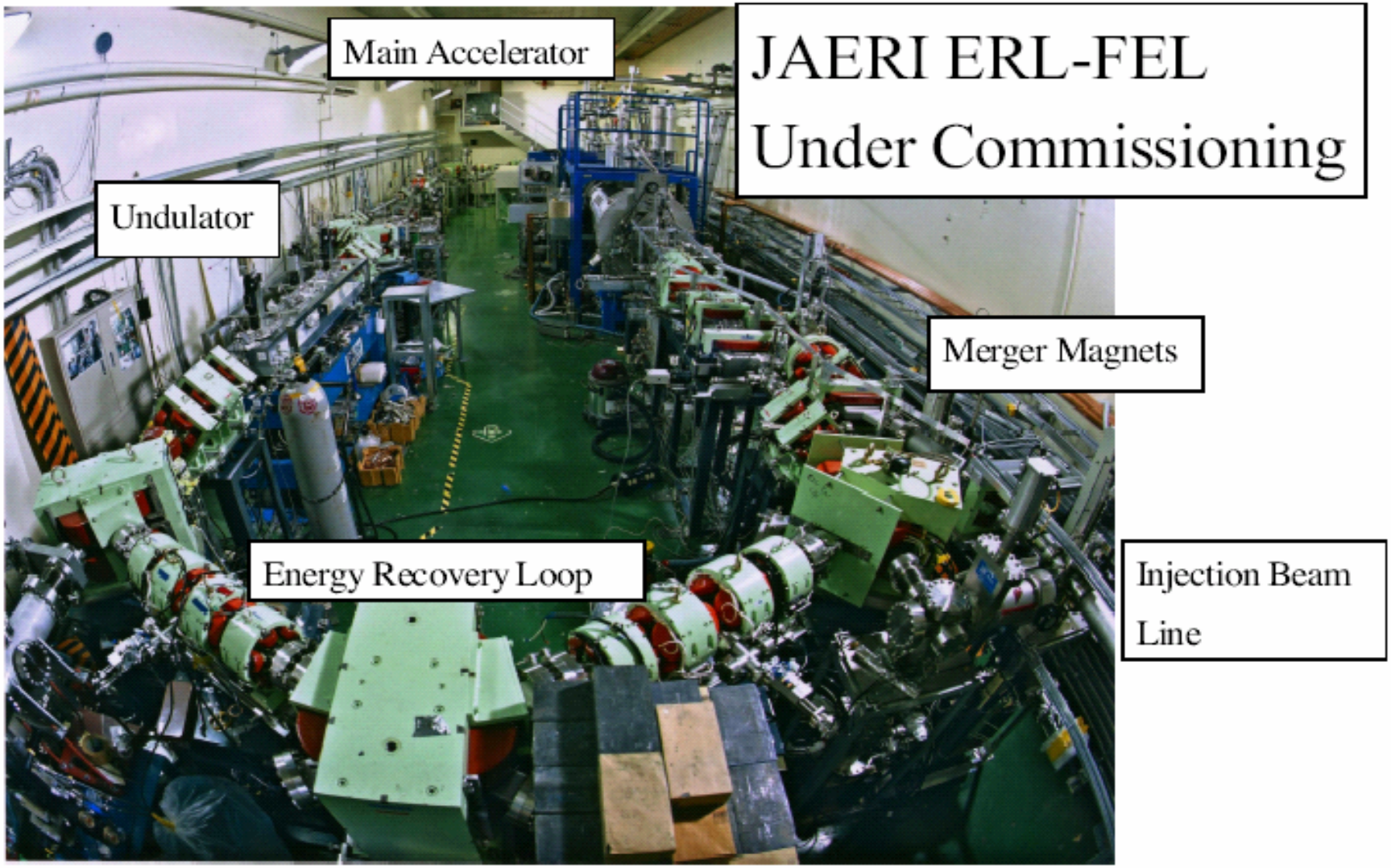
Bunch charge =500pC

Bunch length = ~15ps (FWHM)

Bunch rep. = 10.4MHz – 83.3MHz

Average current = 5.2mA – 40mA

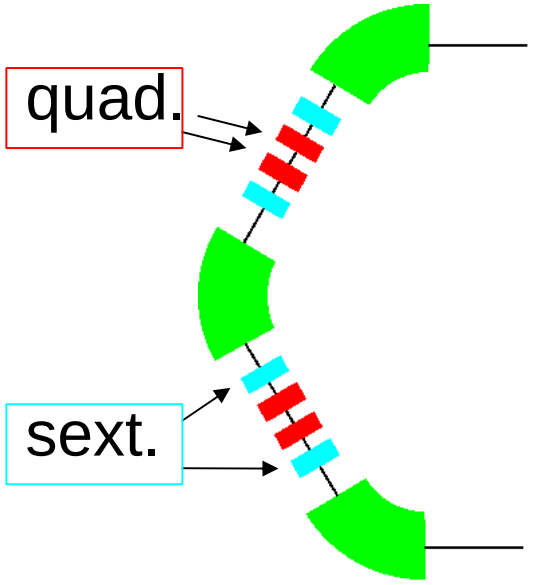
after injector-upgrade

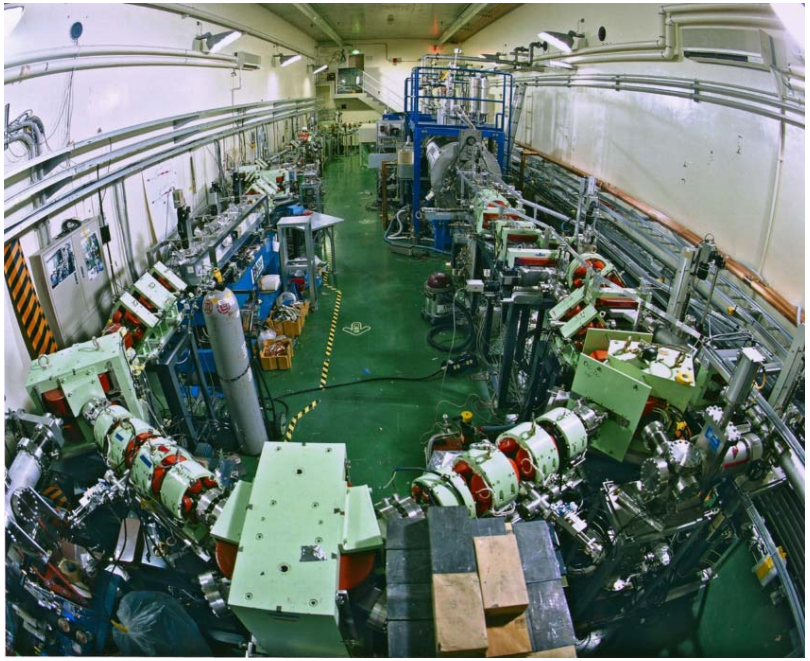

Main Accelerator
JAERI ERL-FEL
Under Commissioning
Undulator
Merger Magnets
Energy Recovery Loop
Injection Beam
Line

Design of JAERI ERL

Return arc --- triple bend, 180 degree arc.

- Variable R_{56} for energy-spread compression.
- Sextupoles to compensate second-order aberrations: T_{166}, T_{266}, T_{566}.
- Energy acceptance is 7% (full-width) for ε_n=30mm-mrad.

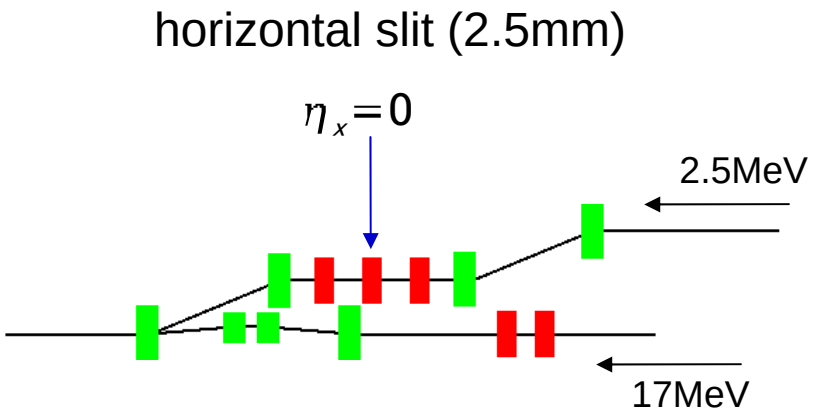


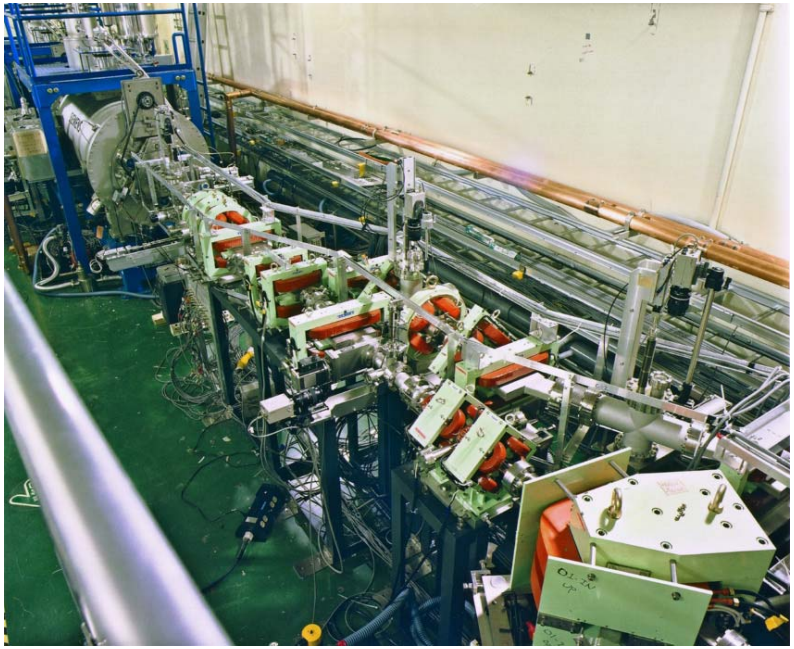


Design of JAERI ERL

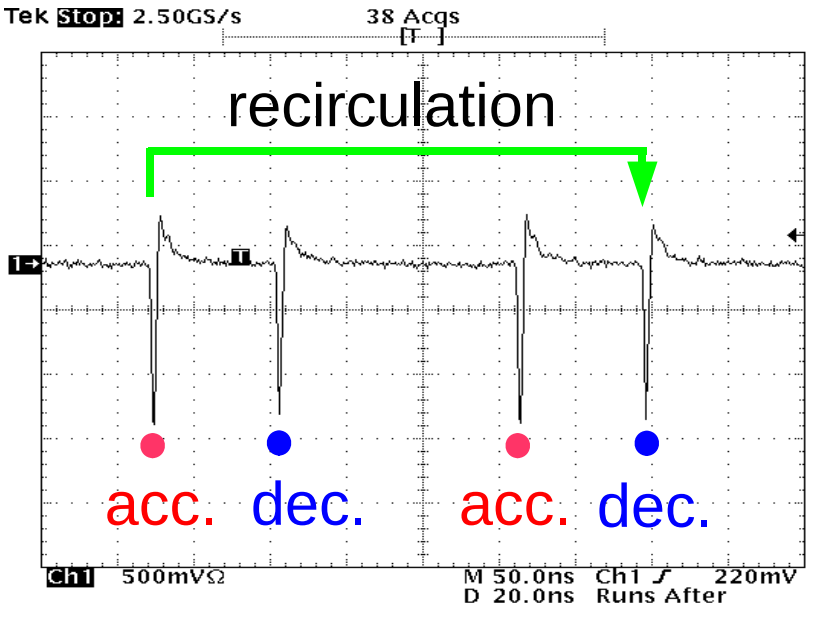
Injection merger --- two-step staircase.

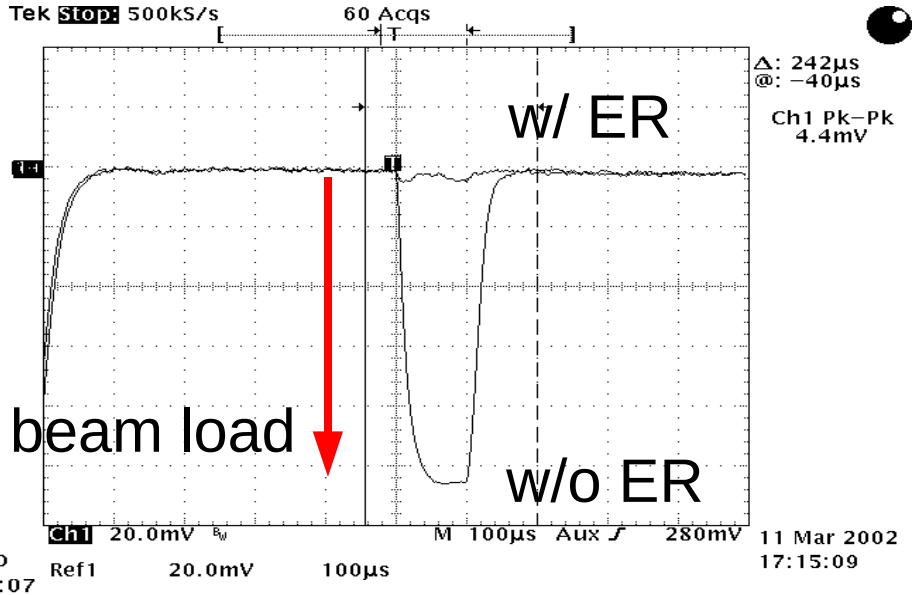
- achromaticity is realized by three quads.
- small angle (22.5 deg.) injection is preferable for small emittance.
- but, performance is sensitive to quads parameters.





Demonstration of Energy Recovery





Beam current at the exit of the second main module.

Bunch interval is 96ns, and recirculation time is 133ns.

RF amp forward power for the 1st main module.

Beam loading is almost completely compensated by energy-recovery.

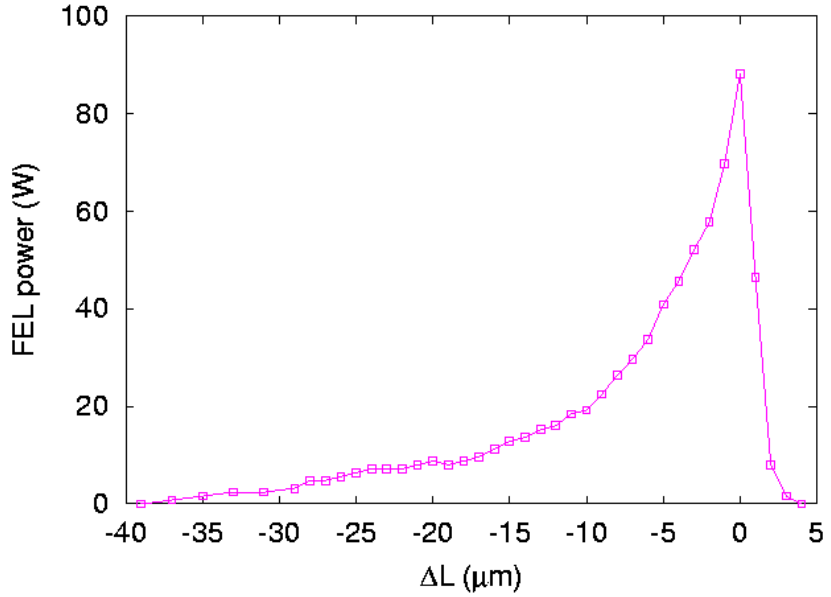
FEL Lasing with the ERL configuration

first lasing at Aug. 14, 2002.

FEL power is still low about ~ 0.1kW.

Gain, loss, spectral measurements have not been done, yet.

Macropulse structures suggest that single-supermode and superradiance appear depending on ΔL.



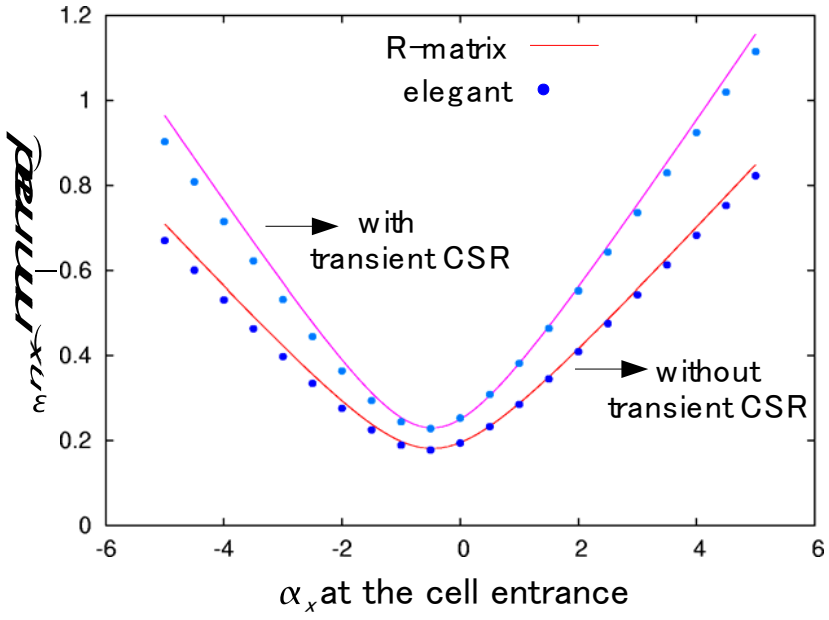
Cavity length detuning curve.

Study on CSR-induced emittance growth

CSR in a return arc --- dominant source of emittance growth in ERLs.

New analytical approach -- R-matrix

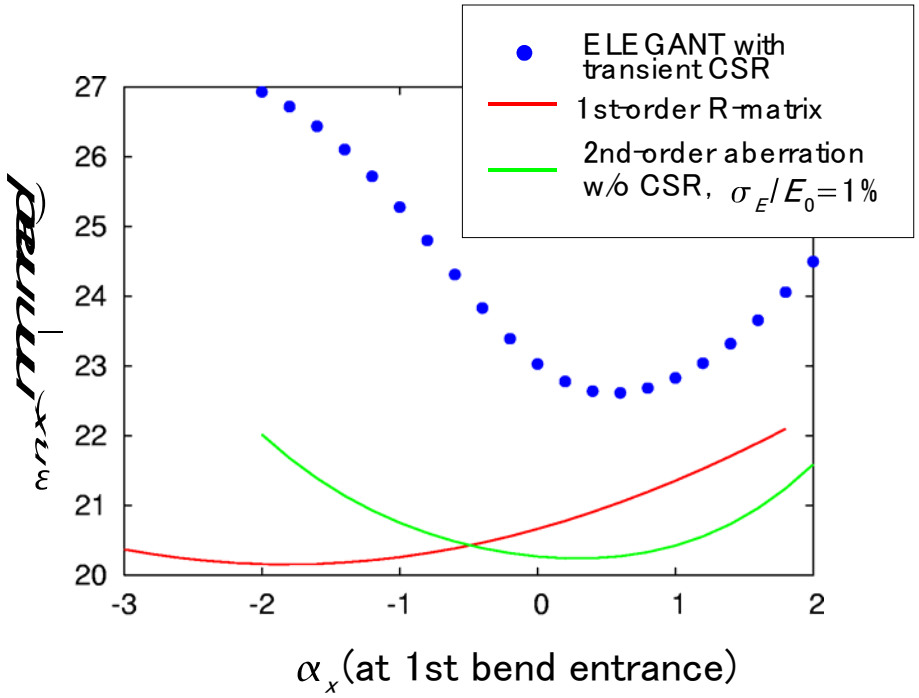
applicable to design “GeV ERLs".



R. Hajima, MOP15020.

for JAERI-ERL (17MeV)

CSR effects depends on the beam envelope in the arc.



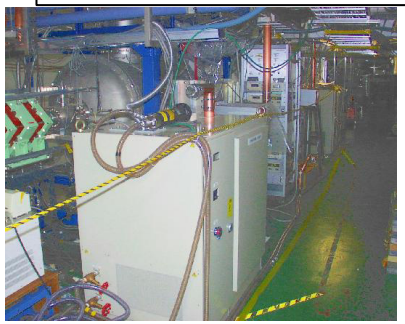
emittance measurements are in preparation

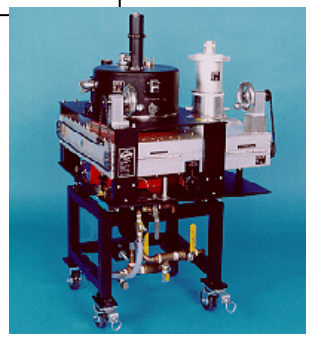
Upgrading in Injector

Original
0.5nC x 10.1425MHz = 5mA

After
0.5nC x 83.3MHz = 40mA

- New RF sources for the injector.

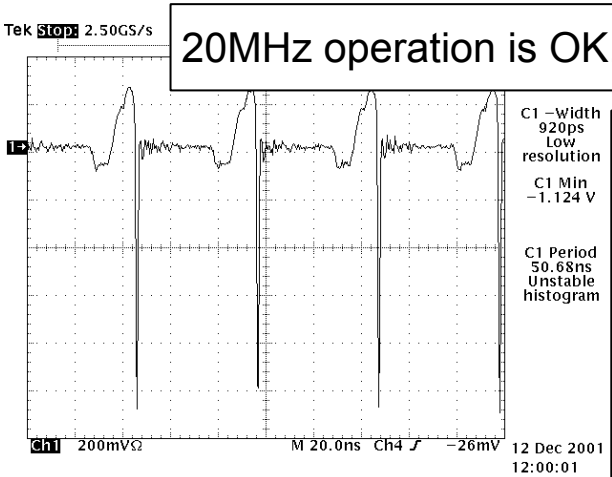




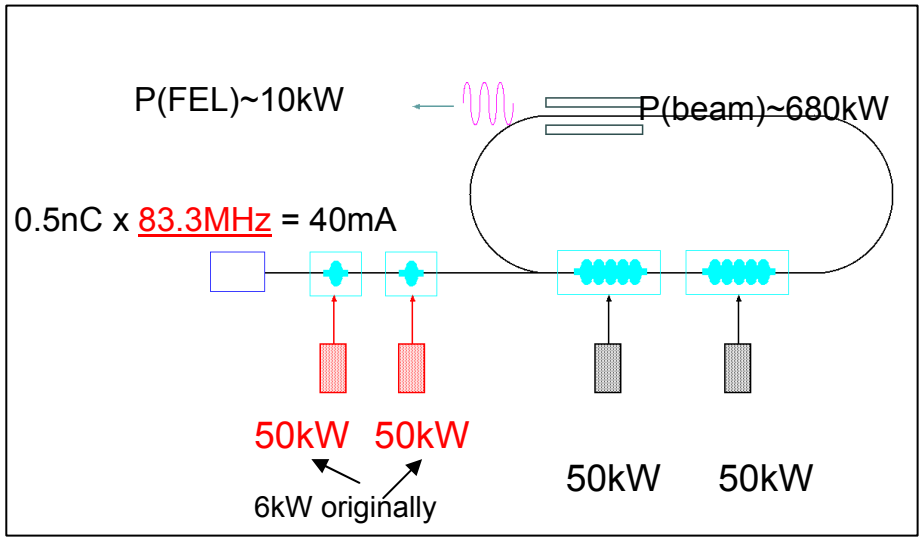
IOT-klystrode (50kW)

- New grid pulser for the e-gun

20MHz operation is OK.

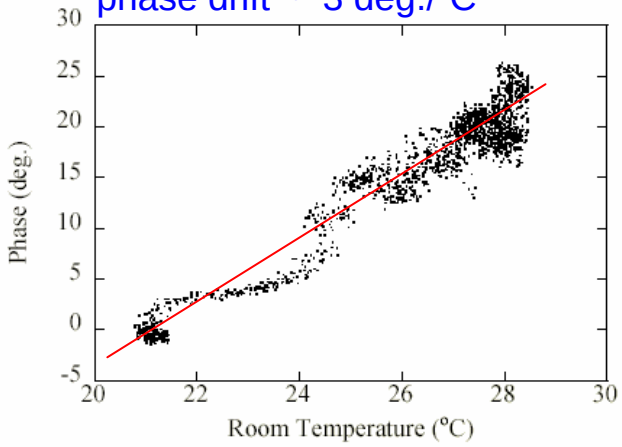


N. Nishimori et al. (THP-16029)

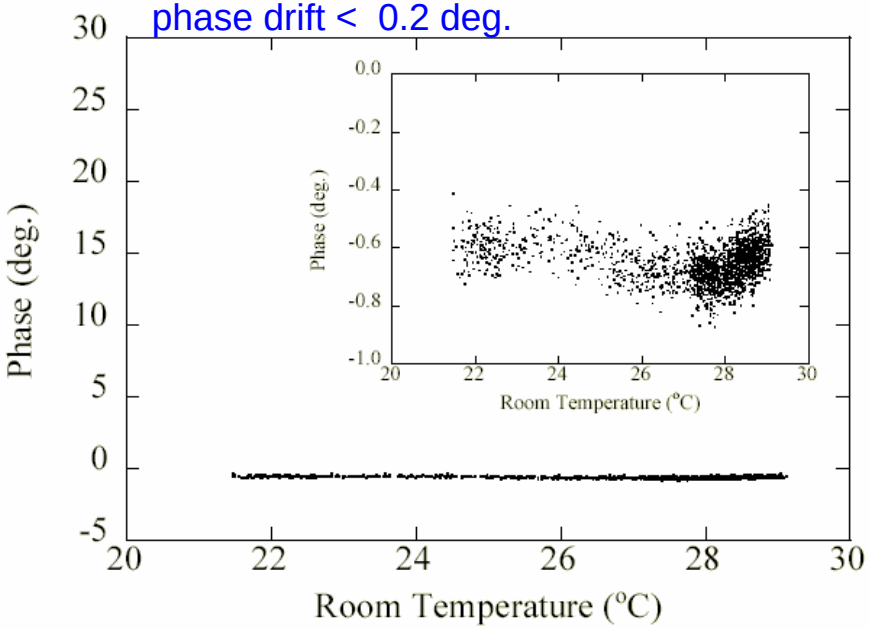


Improvement of RF Stability – new low-level controllers and reference-signal cables

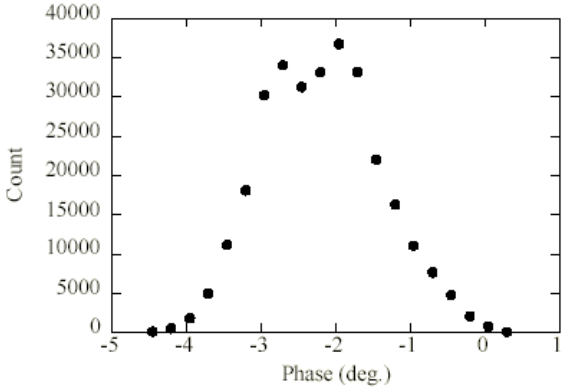
phase drift ~ 3 deg./°C



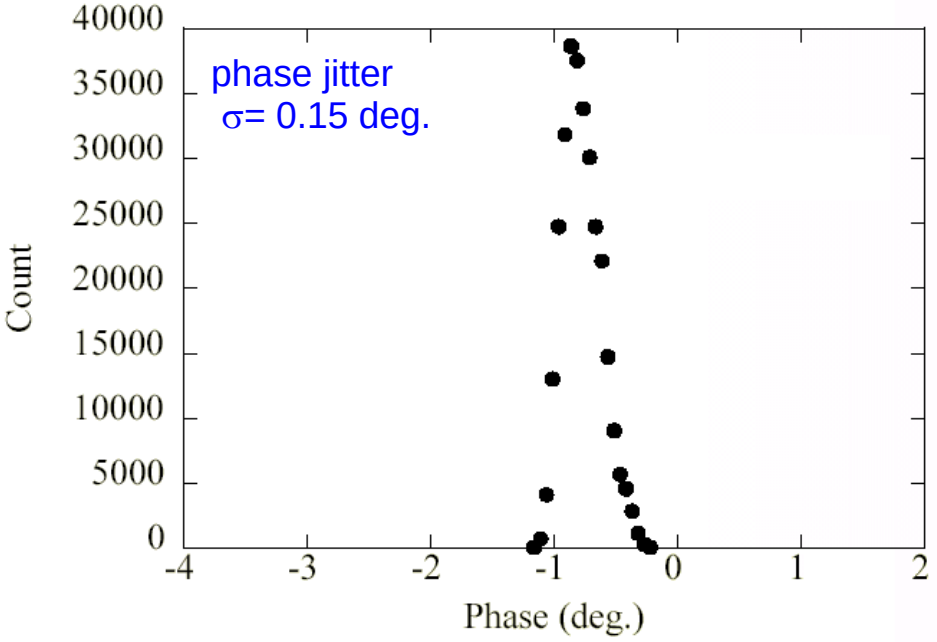
phase drift < 0.2 deg.



phase jitter
σ= 0.78 deg.



phase jitter
σ= 0.15 deg.

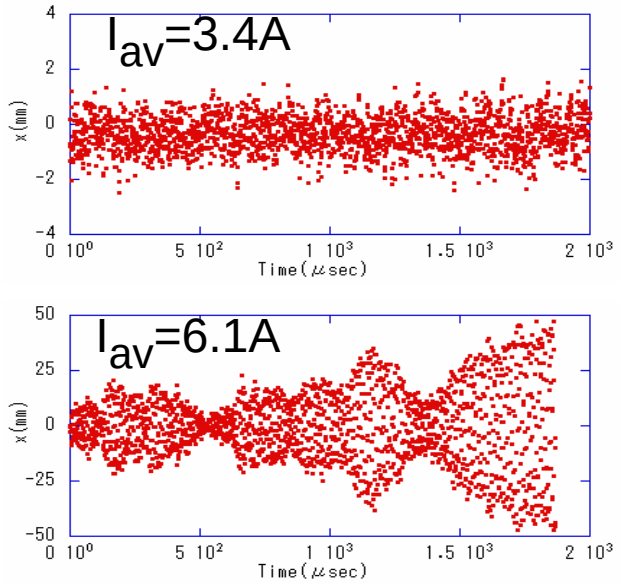


Study on HOM-BBU

Beam break-up by transverse HOM is the dominant phenomenon to limit the ERL beam current.

JAERI-ERL(500MHz) accepts HOM power larger than L-band ERLs.

Simulation by R-BBU

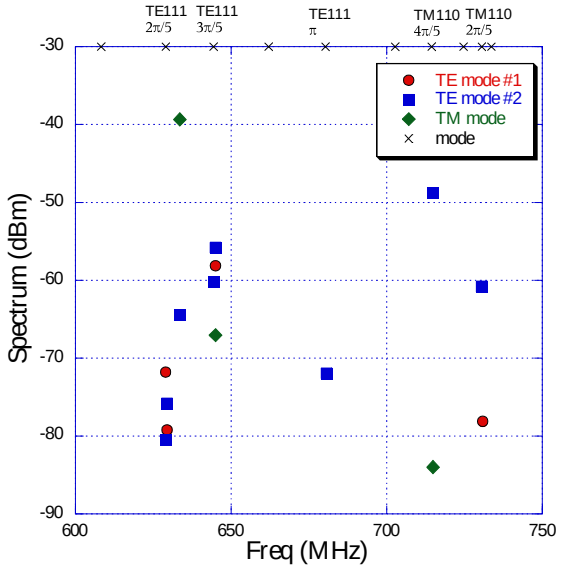


M.Sawamura et al., PAC-2003.

HOM-BBU is not a matter in JAERI-ERL.

But, it is useful to study HOM-BBU for future ERLs.

HOM measurements and comparison with simulations.

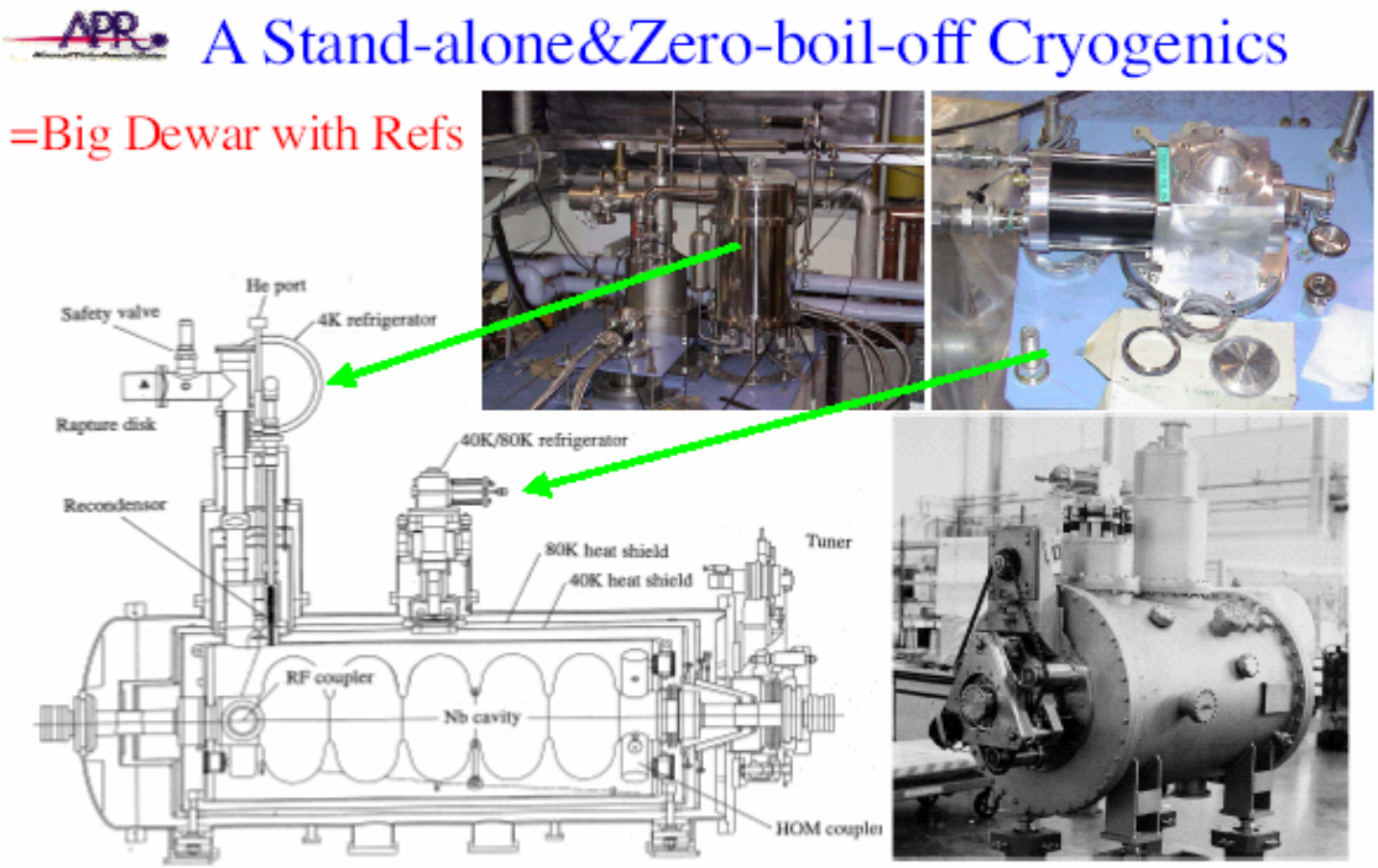


Artificial excitation of HOMs by beam deflector, and detection of HOM signals.

in preparation.

2. Refrigerator and Cyogenic Operation of JAERI SCA

JAERI Stand-alone Zero-Boil-Off Cryostat = Liq.He Container with refrigerators



Easiness in Maintenance and Operation of JAERI ERL-FEL

NonStopLowTempOperation or NoWarm-up Op

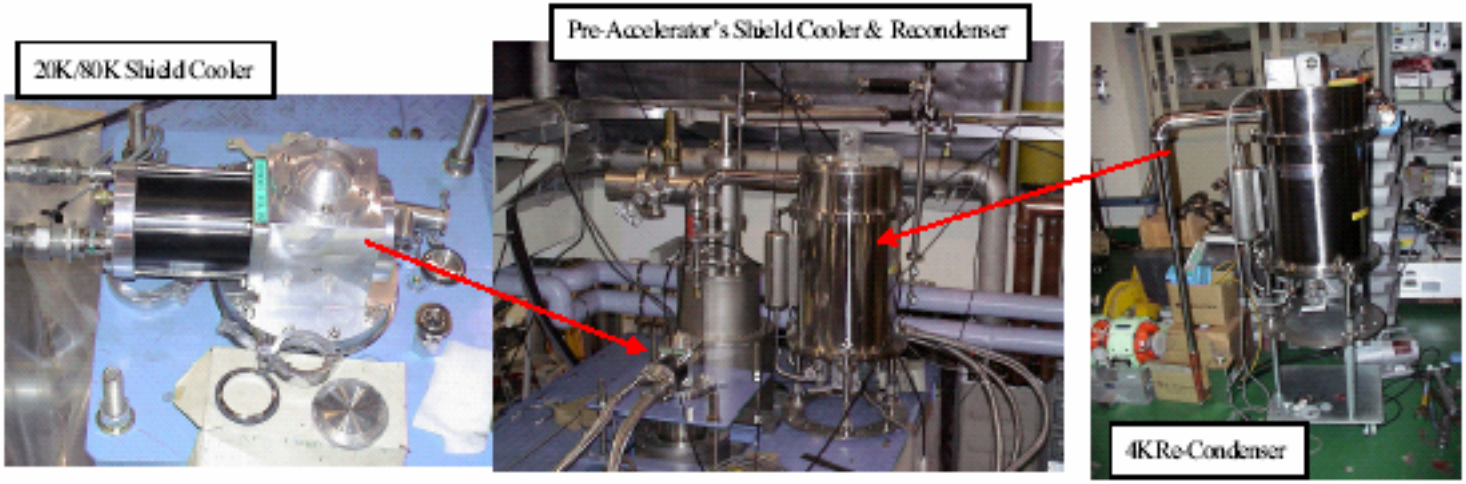
Possible Only for the JAERI Stand-Alone & Zero-Boil-Off ERL-SC linac ,

1)Cold Maintenance for Both Shield Cooler & Recondenser within a few tens minutes

2)No Liq.He Loss, 24hours Over 10-20years Continuous Operation. No need to reload

3)No Regulation of Domestic Pressure Vessel Code required for the Cold Maintenance

Bonus of the No Warm-up; (1) No Conditioning Required After the first , (2)Nearly No Deterioration of all the Cryogenic Components and Conditions, (3) Always Ready to fire,



Statistics of the continuous Zero-Boil Off Operation 1 Year Left and 3 years Right

#5 Whole Cryostat System Cold Over Twenty Years/Cold Maintenance

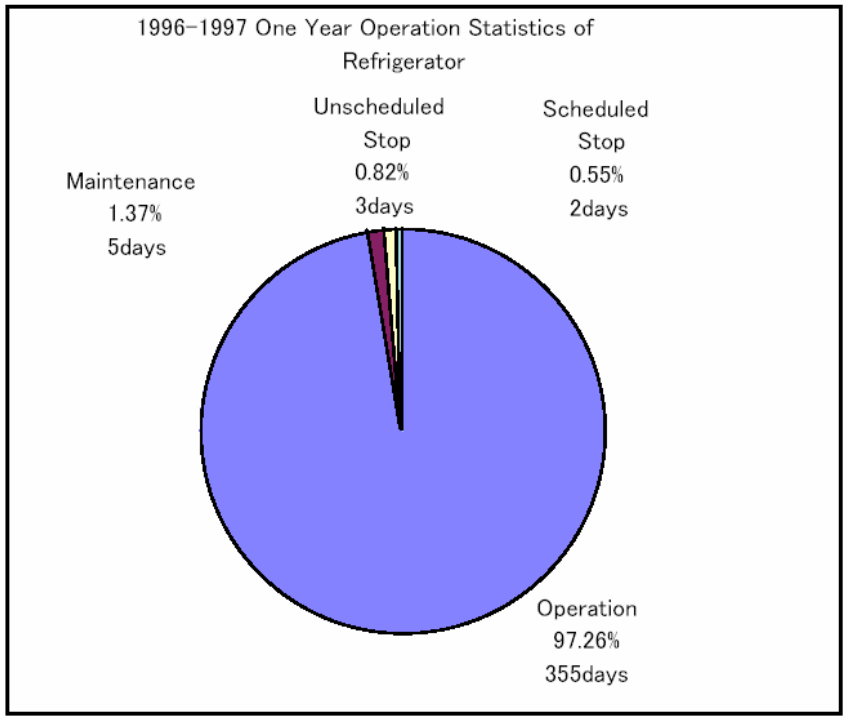


Figure 3a: Statistics of the cryogenic system operation in 1997 Japanese fiscal year

#6 Non-Stop and Continuous Operation of Cryogenic Refrigerator System Except for Unscheduled Emergency or Power Failure

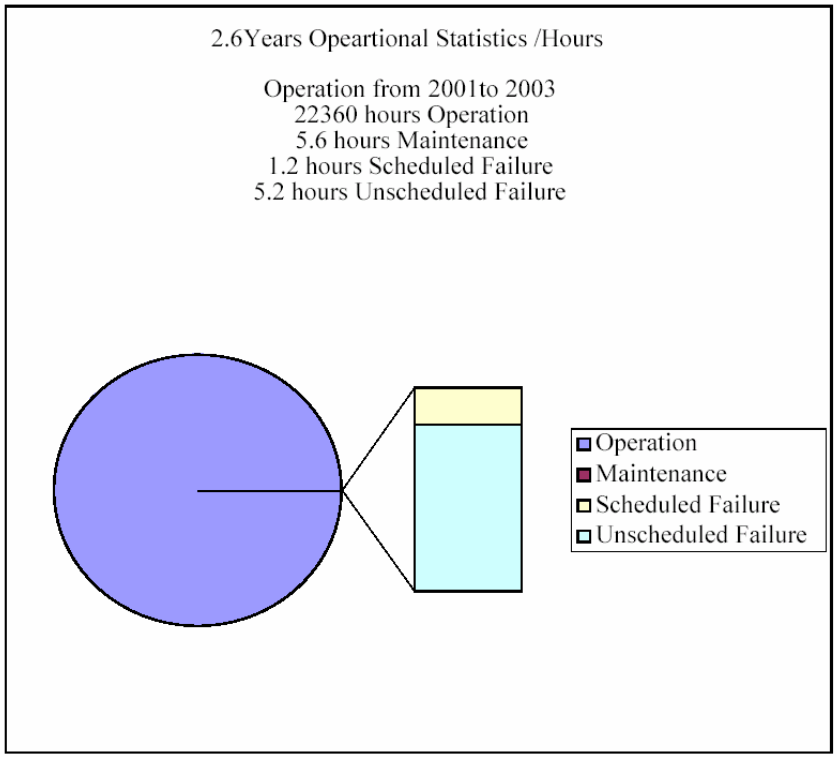
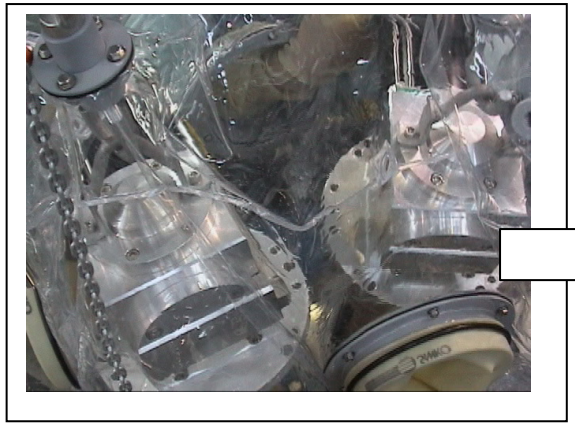


Figure 3b: Statistics of the cryogenic system operation in 2001-2003 Japanese fiscal year.

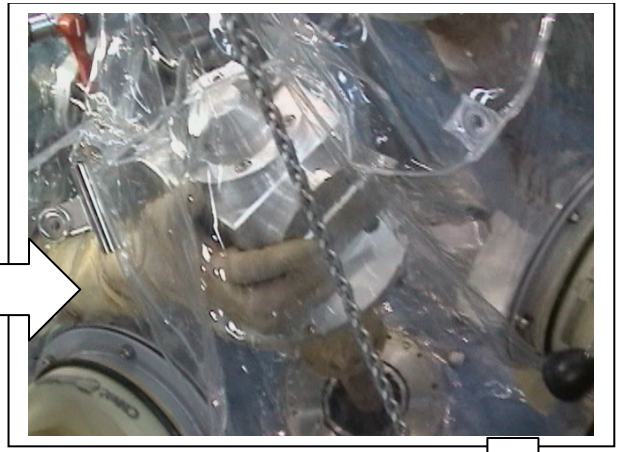
COLD GM Refrigerator Maintenance Pictures

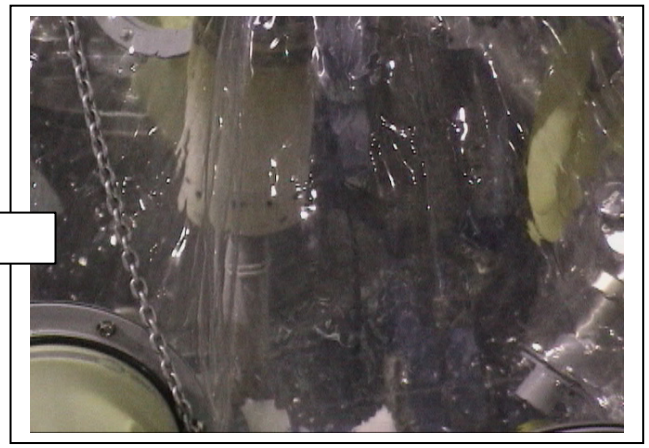
Before the Cold Maintenance

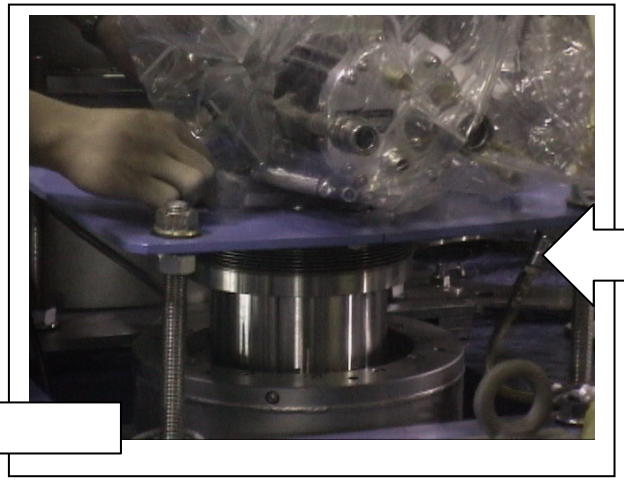
GM Refrigerator Engine in the Cryostat

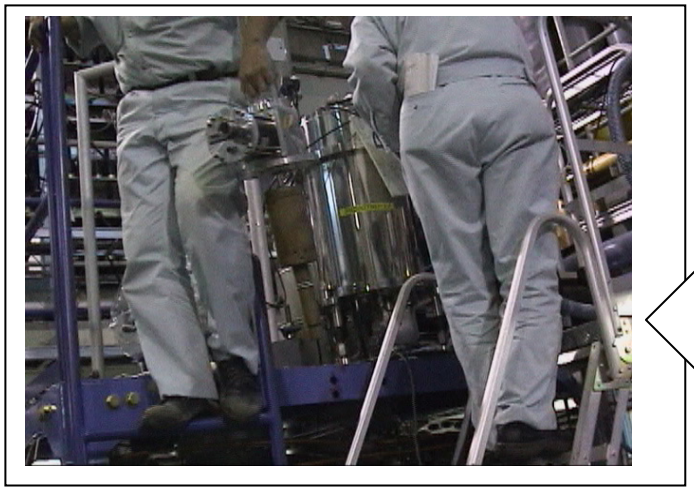


Lift the GM Engine inside Plastic Bag









Q (T) is linked to the BCS surface resistance

$$R_s = A\, f^2 \exp^{-\Delta/kT} \quad (+ R_0)$$

R_s : BCS surface resistance
A : material constant
f : frequency

R_0: residual resistance

Δ : BCS energy gap
k : Boltzmann constant
T : temperature

1.5 K is taken here as a reasonable lower limit of BCS Q=Q(T) dependence

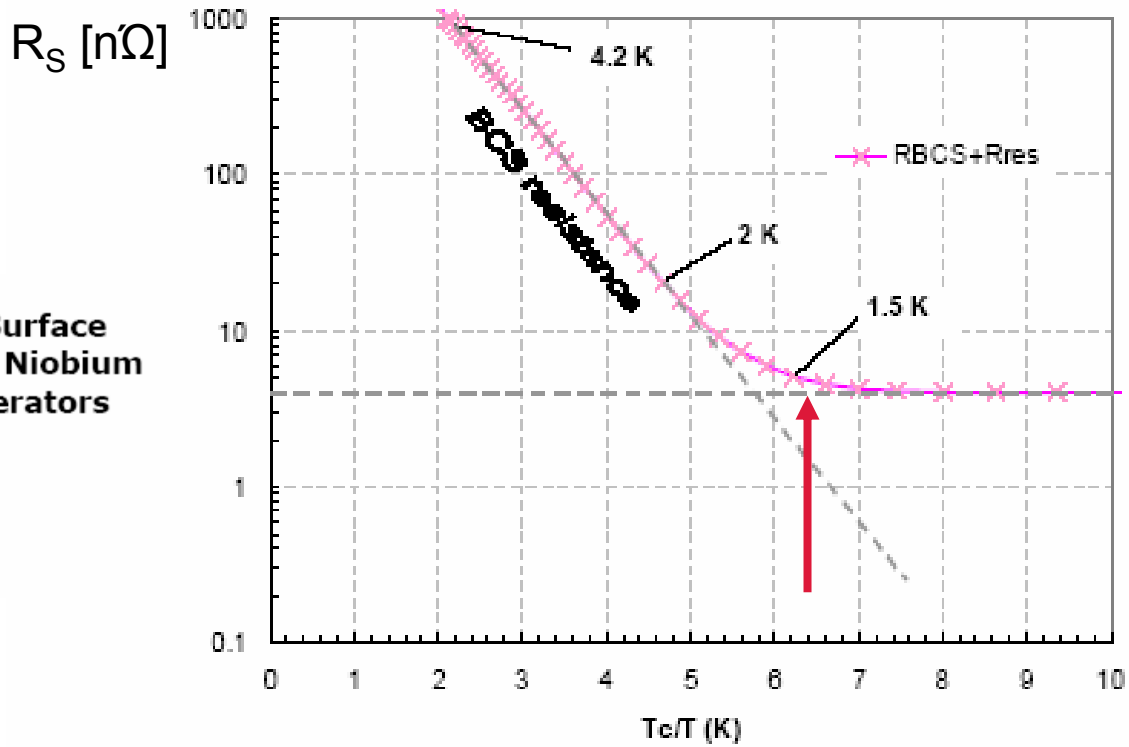
Diagramm taken from:

Review of Models of RF Surface Resistance in High Gradient Niobium Cavities for Particle Accelerators

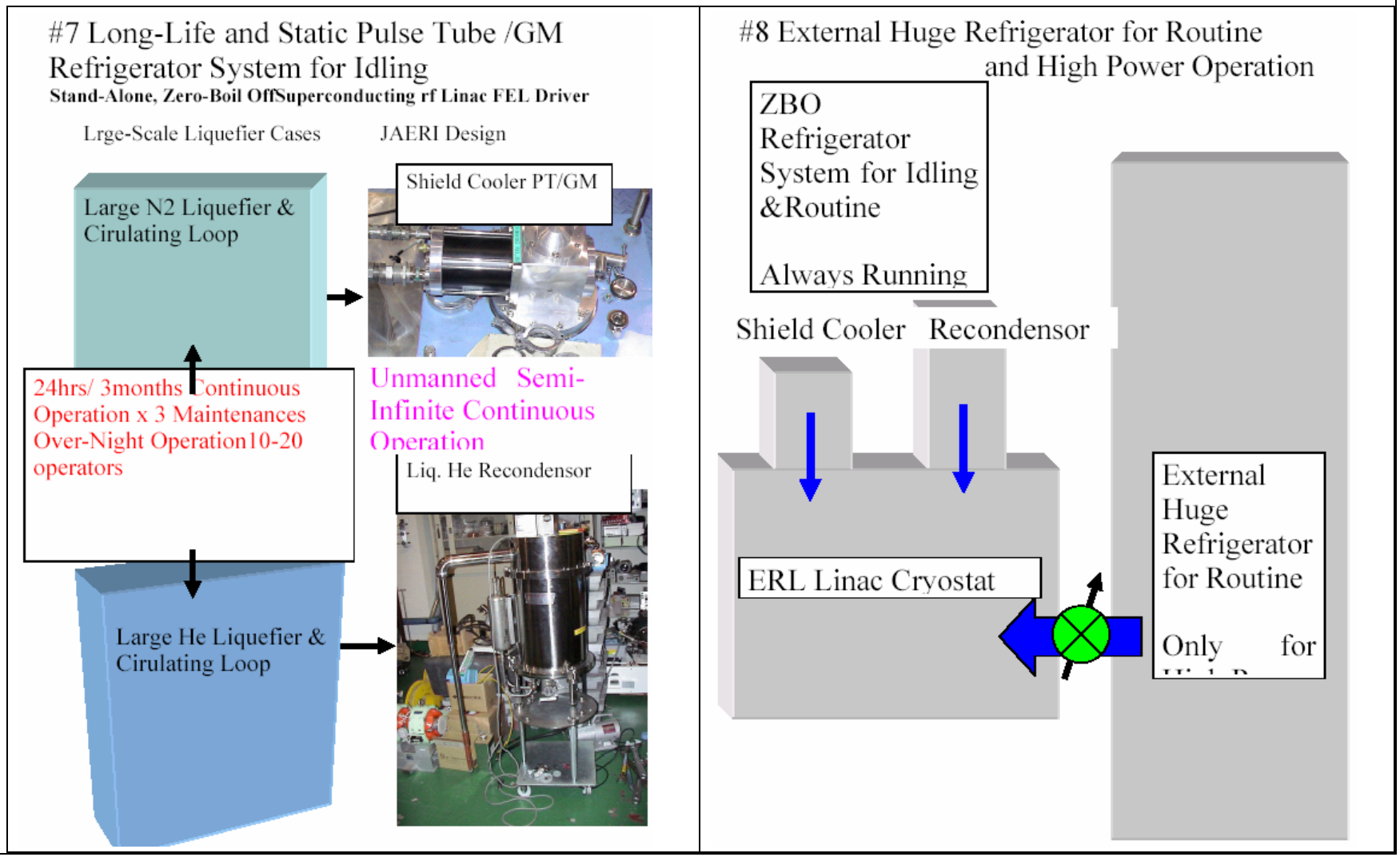
P. Bauer

Fermilab, Technical Division

TD-04-014, June 2004



Combination between Zro-Boil Off Cryostat and Large Scale 2K and 4K External Liquefier



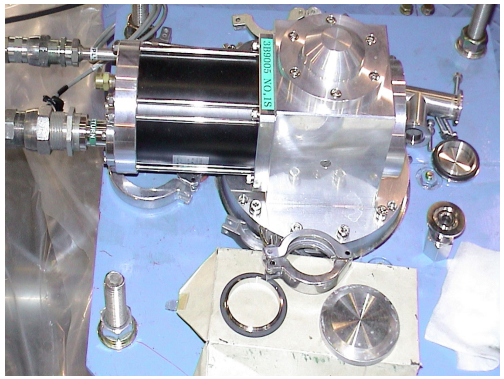
#7 Long-Life and Static Pulse Tube /GM Refrigerator System for Idling

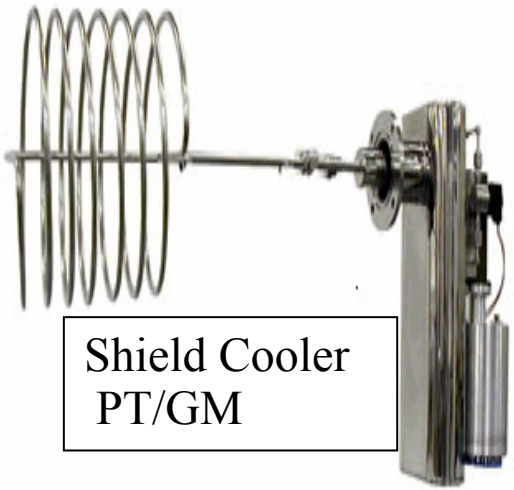
Stand-Alone, Zero-Boil OffSuperconducting rf Linac FEL Driver

Lrge-Scale Liquefier Cases **JAERI Design**

図 3

Large N2 Liquefier & Cirulating Loop





Shield Cooler PT/GM

24hrs/ 3months Continuous Operation x 3 Maintenances Over-Night Operation10-20 operators

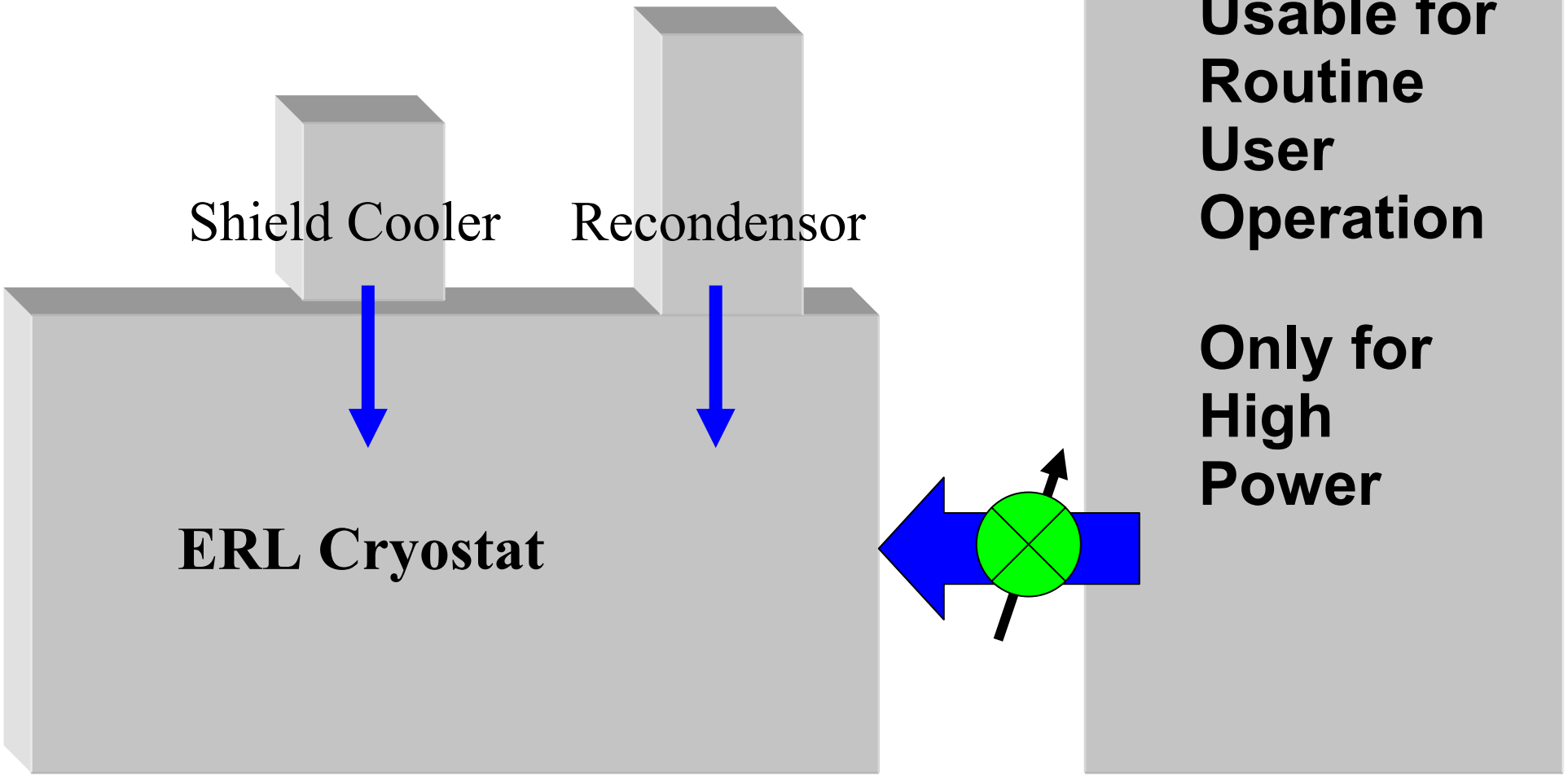
Unmanned Semi-Infinite Continuous Operation

Large He Liquefier & Cirulating Loop

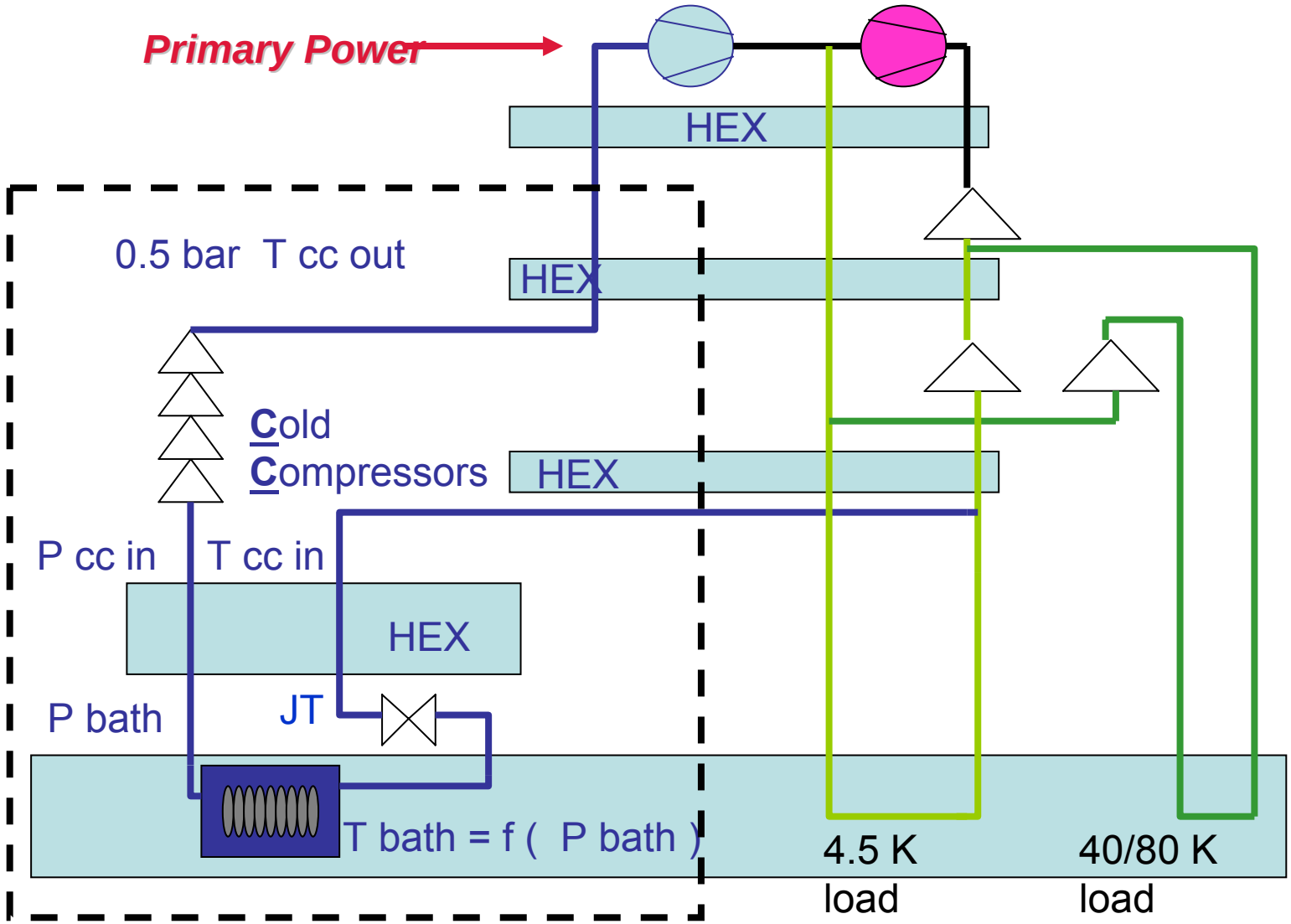
Liq. He Recondensor

#8 External Huge Refrigerator for Routine and High Power Operation

ZBO Refrigerator System for Idling &Routine Always Running



2K Cooling Scheme (simplified)



2.ERLTime Table and Required Refrigerator System

Present Status ERL-FEL 20MeV Quasi CW Operation

4K Zero-Boil Off Small Refrigerator

4.2K-32W/50Hz48W/60Hz, 20K-80W、80K-560W Semi-Perpetual Non-Stop Cooling Operation

No Liquefier – Like Air-Conditioner, No Commissioning Inspection, No Open Inspection

2005-2006

Modification ERL-FEL 20MeV CW 4KHybrid Refrigerator System

4K-200W Large Liquefier+10K/65K-200W Small GMRefrigerator Semi-Perpetual Non-Stop Cooling Operation

Liquefier Regulation, Required a governmental Commissioning Inspection、regular Open Inspection per 3 years

2006-2007

Construction ERL-LS Prototype 200MeV CW 1.8K/1.6K Hybrid Refrigerator System

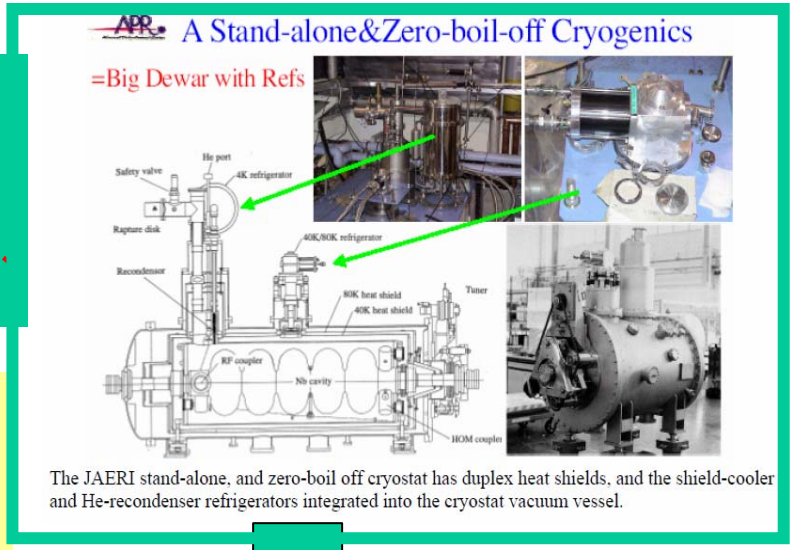
1.8K/1.6K-400W Large Liquefier+4K/10KSmall GM Refrigerator +65K PT Refrigerator Semi-Perpetual Non-Stop Cooling Operation

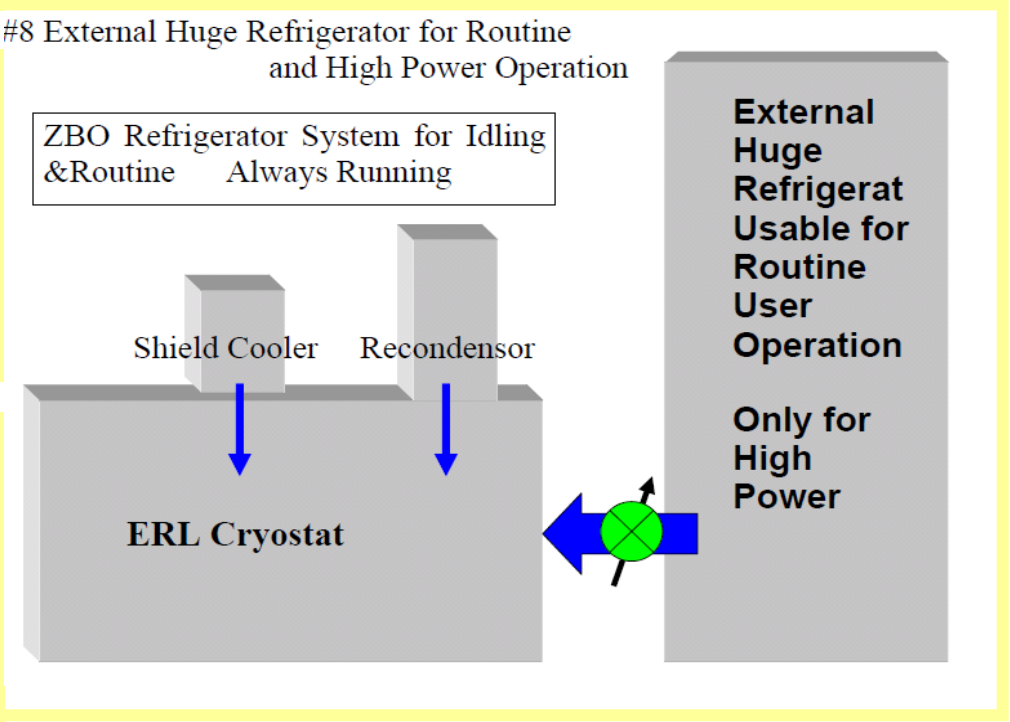
Liquefier Regulation, Required a few governmental Commissionings Inspection every year

2010-2011

Construction ERL-LS 6GeV CW 1.8/1.6K Hybrid Refrigerator System

1.8K/1.6K-6kW/3kW Large Liquefier+4K/10KSmal GMRefrigerator +65K PT Refrigerator Semi-Perpetual Non-Stop Cooling Operation Liquefier Regulation, Required a few governmental Commissionings Inspection every year





Current Activities :

Upgrading from Over2 kW to 10kWClass Lasing

#DC gun Capacity Improvement from 5mA to >40mA

#PreAcceleerators RF Amplifier Upgrading from 6kW to 50kW

#Main RF Amplifier Upgrading from Transister to IOT CW capability

#Amplitude and Phase Control Circuit Improvement

Reproducibility and Accuracy Up to 0.1Degree and 0.1%

#PC-based Control System Upgrading

Reliable and High Level Control Capability

#Beam Monitor Upgrading from Destructive to Non-Destructive

#Cable Network Upgrading to Low Temperature Coefficient Cable and

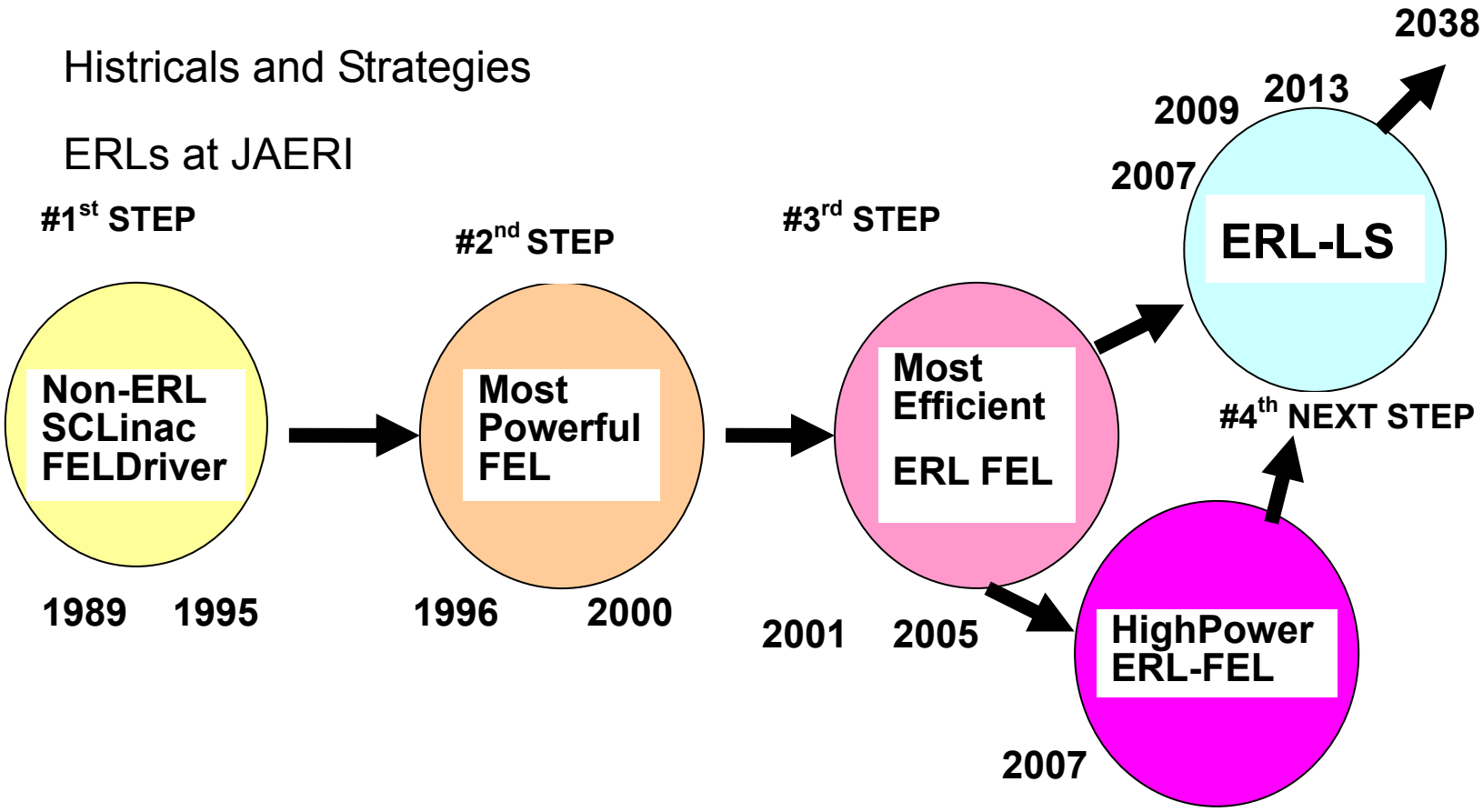
#Temperature Stabilized Network

#FEL Optical Transport System to FEL Experiment Rooms

4. JAERI ERL Future Plans and Programs

Histricals and Strategies

ERLs at JAERI



6GeV ERL light source planned in Japan

linac = 20MV/m x 457m x (300/457)

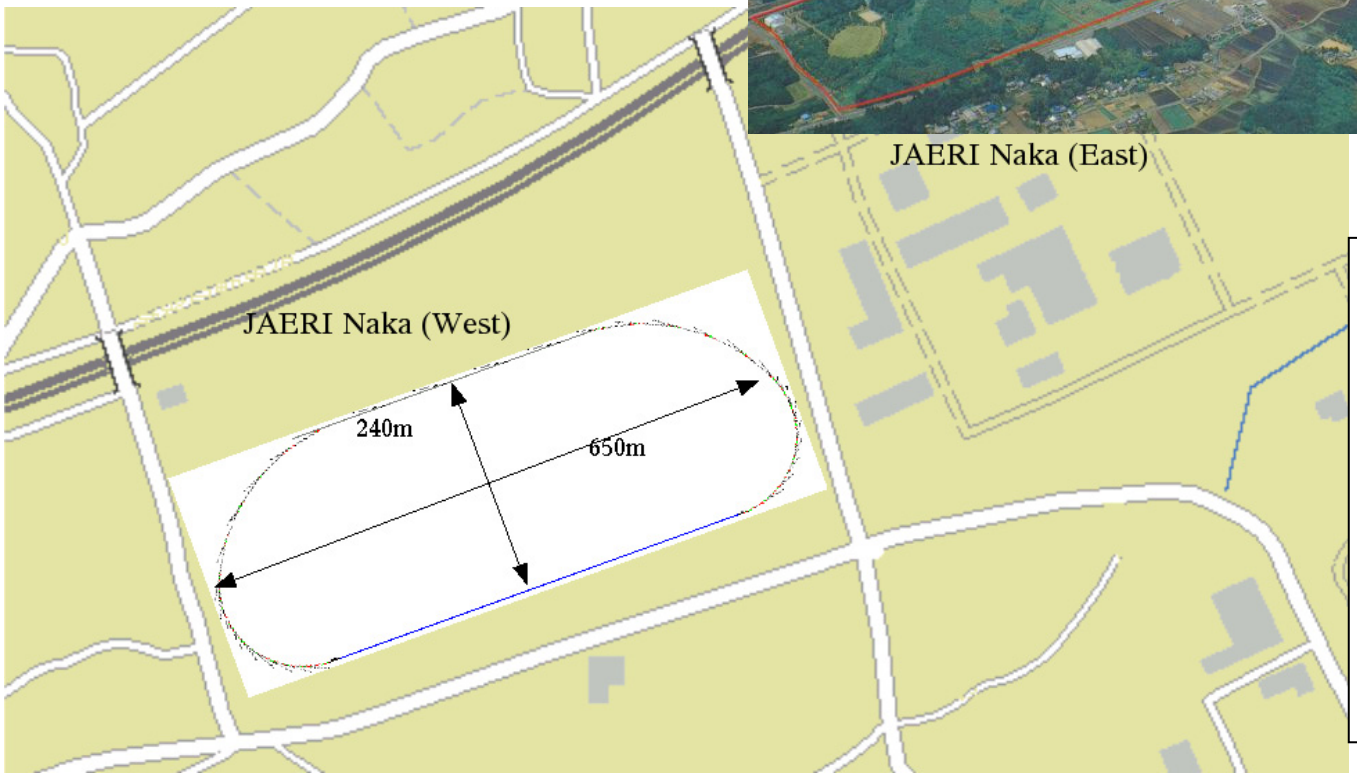
arc = 12deg. x 15 x 2

straight section = 5m x 20 + 27m x 10 + 270m

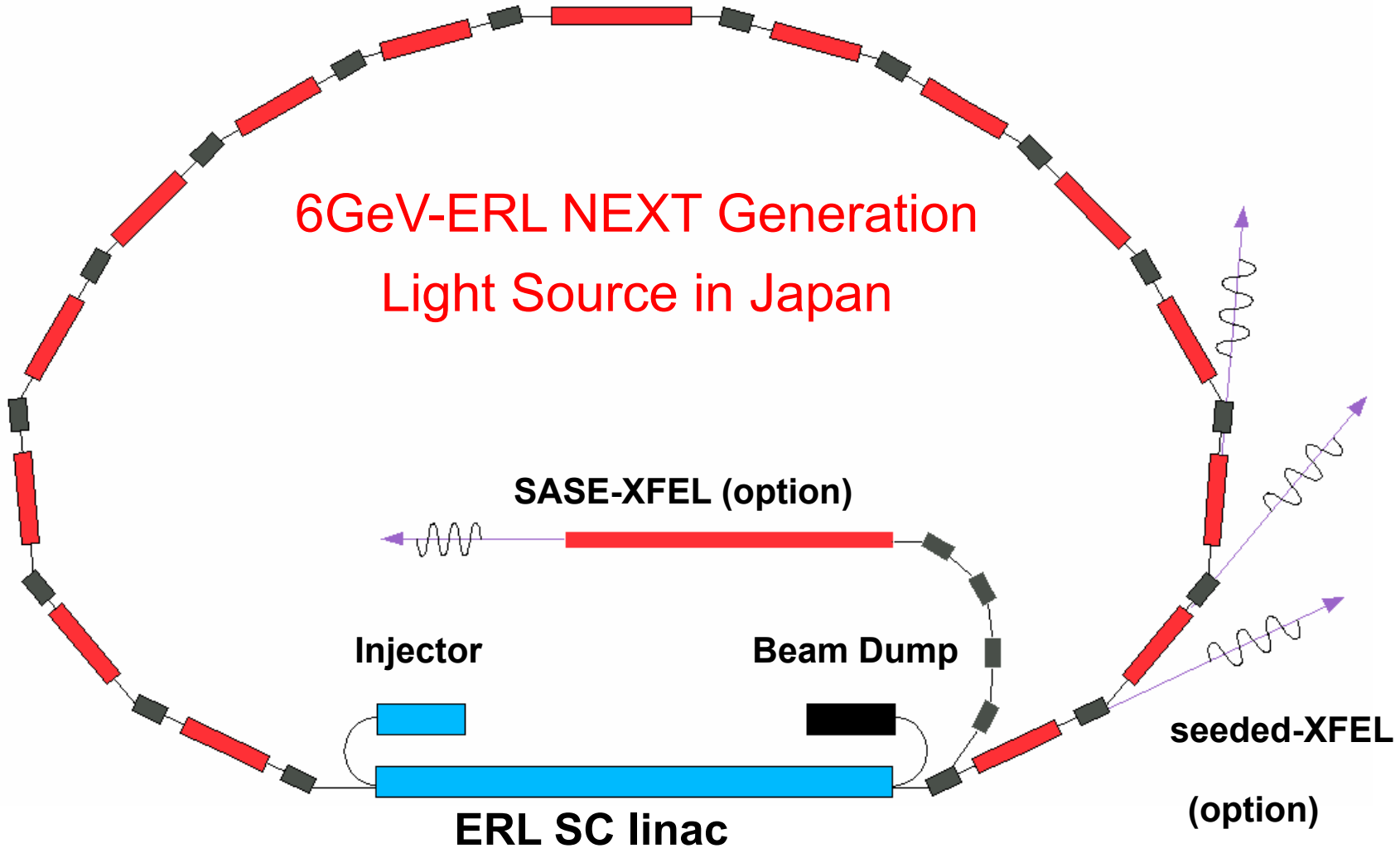
JAERI Naka-west

700m × 450m

JAERI Naka (East)



ERL light Source planned Site where is located in 140km North East from Tokyo, a several km from Tokai.

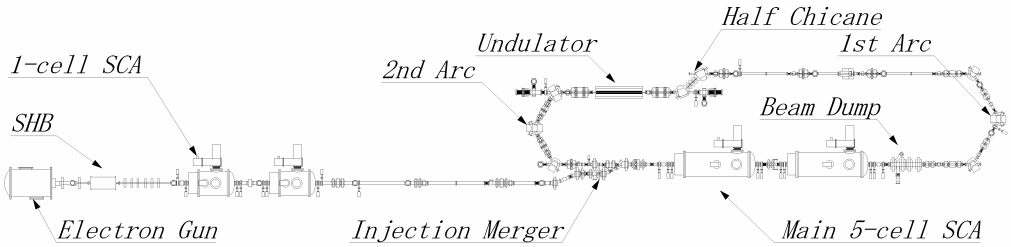

6GeV-ERL NEXT Generation
Light Source in Japan
SASE-XFEL (option)
Injector
Beam Dump
seeded-XFEL
(option)
ERL SC linac

1.Superconducting Energy Ercovery Linac(ERL) based FEL and Next Generation ERL Light Source Development

1.ERL-Proof Of Principle Demonstration

Tunable, Ultra-short, High Average Power, Highly Efficient Superconducting Energy **Recovery**（ERL）FEL、**Many Fields of Academic Uses and Industrial Applications**

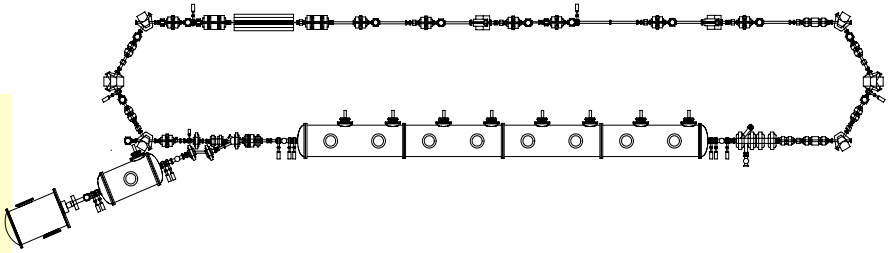
1989-2005JapaneseFiscalYear 20MeVERL-FEL



Up to Now Present Status、

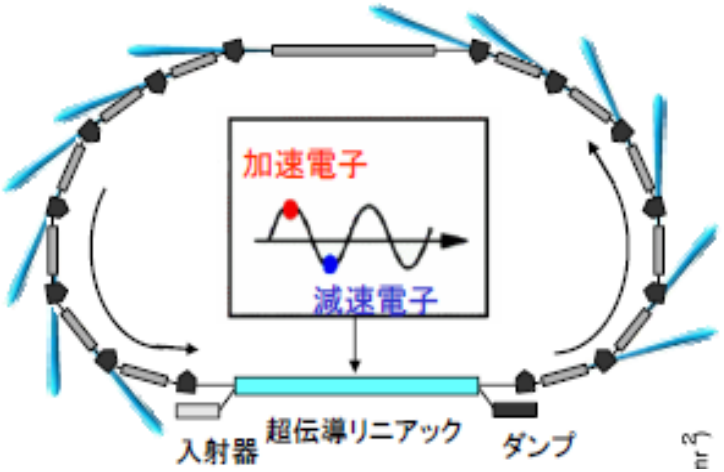
Below the Future Program

2006-2009JFY 200MeV ERL Prototype



2.ERL Technology and Next Generation Light Source Developmental Program（0.2GeV-ERLPrototype）

2010-2013JFY 6GeV ERL Light Source



3. High Power, Femtosecond, Coherent, Nanobeam X-Ray 6GeV-ERL LS Construction

Start the User Experiments and Industrial Applications

JAERI ERL Contributions in the Workshop Related with ERL-LS

#1 State-of-the-Art: Optics and Beam Transport R. Hajima
#2Linear matrix analysis of electron beamdynamics for the CSR effect in an ERLrecirculation loop R. Hajima
#3 Multi-parameter optimization of an ERLinjector R. Hajima, R. Nagai
#4 Velocity bunching in a main linac of ERL R. Hajima, H. Iijima
#5 Preliminary result of diamond film secondary-emission cathode T. Nishitani, E. J. Minehara, R. Hajima
#6 Beam-based Alignment with HOM couplers.M. Sawamura and R. Nagai
#7 Status of RF system for the JAERI Energy-Recovery Linac FEL M. Sawamura and R. Nagai
#8 Cryostat Design Consideration of the Energy Recovery Super-conducting Linac (ERL) Driven Light Sources and FELs E. J. Minehara
#9 Preliminary Report on Single and Multi-Crystal Diamond Electron Cathodes E. J. Minehara
#10BBU codes overview M. Sawamura
#11JAERI gun, and #12Superlattice GaAs photo cathode T.Nishitani

One Typical Example of our ERL LS Activities of Beam optics and Beam Transport at JAERI

ERL05 State-of-Art Optics and Beam Transport

Ryoichi Hajima, JAERI

Outline

Components

- Merger
- Main linac
- Loop
- Bunch compressor

(Injector will be discussed in WG-1)

Phenomena

- Emittance growth by space charge and CSR
- Beam instability, BBU
- Halo formation

Beam parameters

- high average current
- small emittance
- short bunch
- stability

Design and optimization methods to obtain beam parameters as we need, without any harmful phenomena.

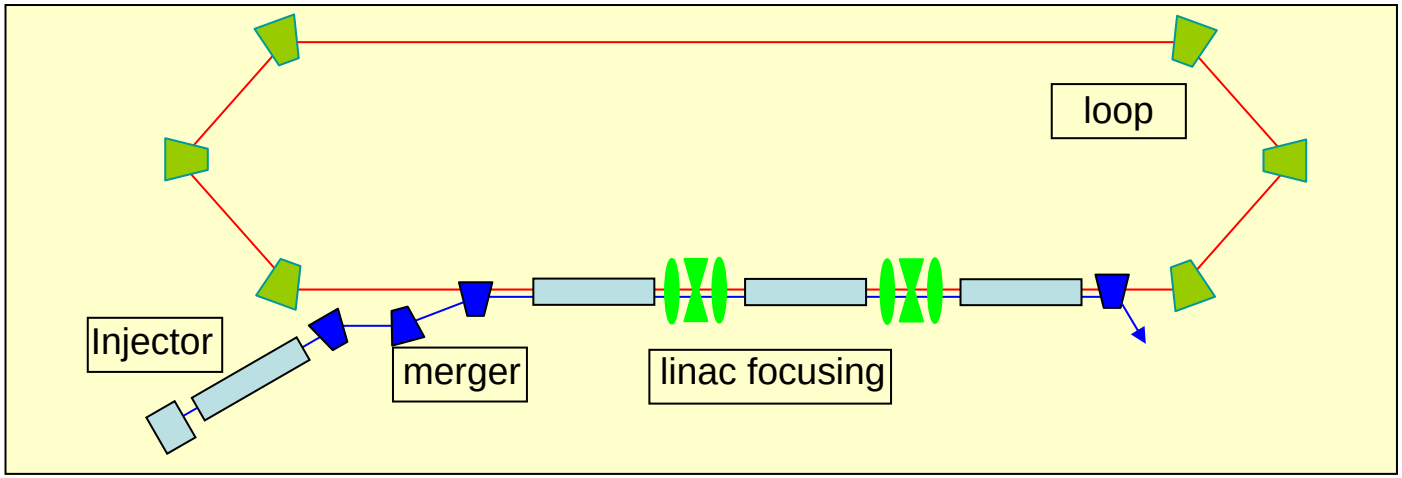
Technological challenge for each component.

Beam optics & dynamics in ERLs

Advantages of ERLs → high-average current
Advantages of ERLs → small emittance, short bunch

Beam transport design issues

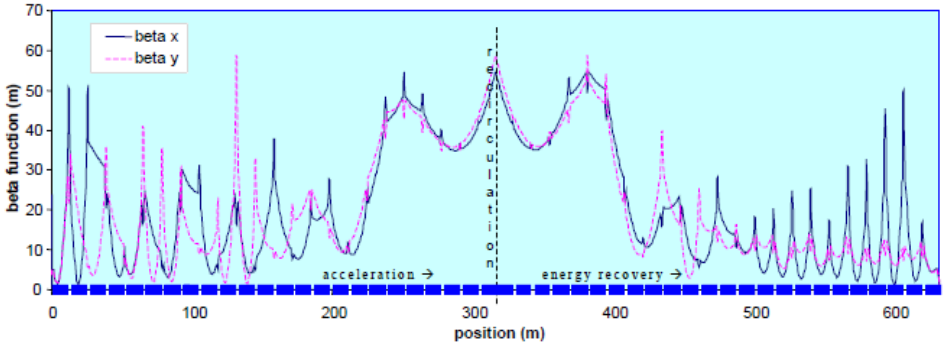
- Preserving emittance through injector – merger – linac – recirc. loop
- Bunch compression scheme
- Disturbance on beam motions
  - short-range (single-bunch) disturbance = space charge, CSR, wakes
  - long-range (multi-bunch) disturbance = HOM-BBU

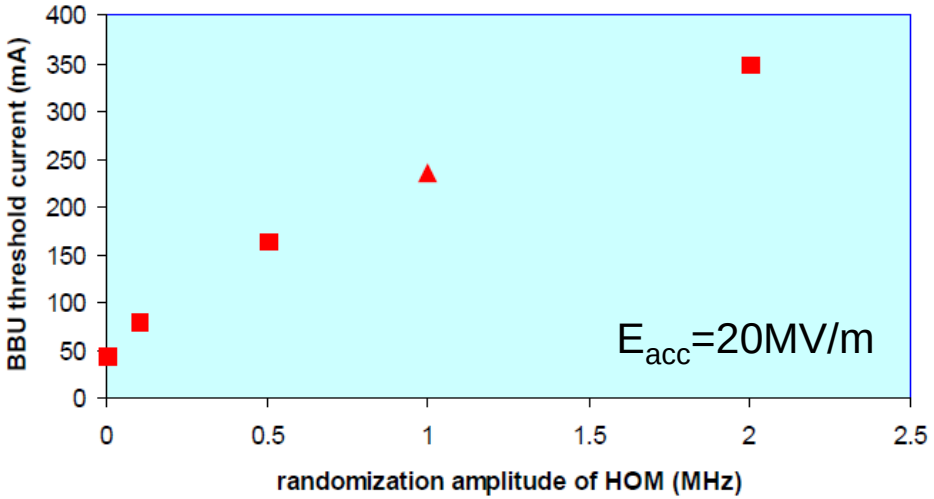


Linac focusing optimization

5GeV-ERL design study

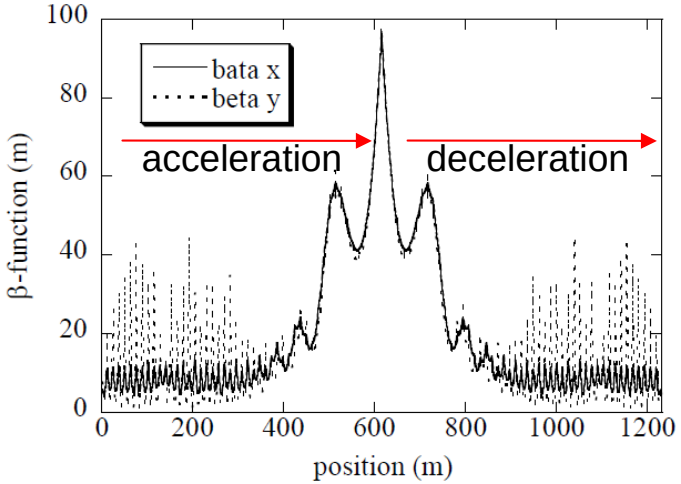
CHESS Tech-memo 01-003, JLAB-ACT-01-04

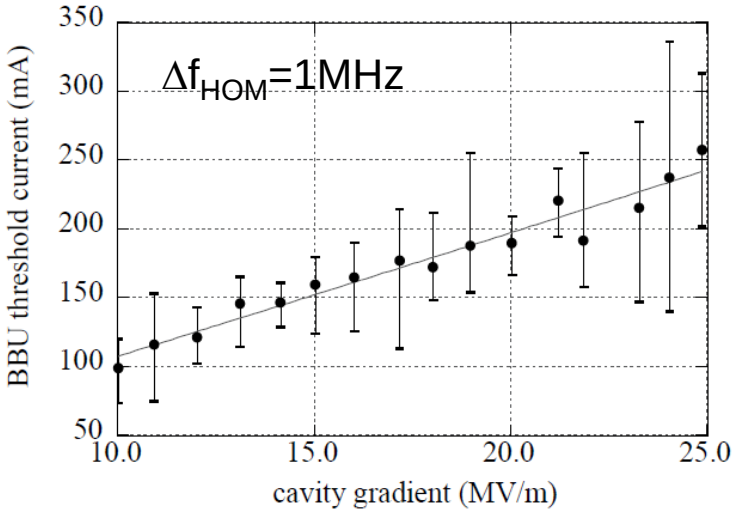




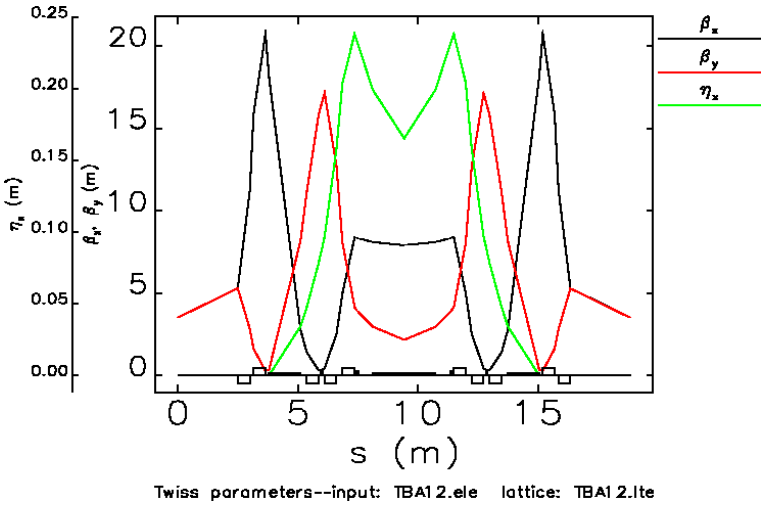
6GeV-ERL design study

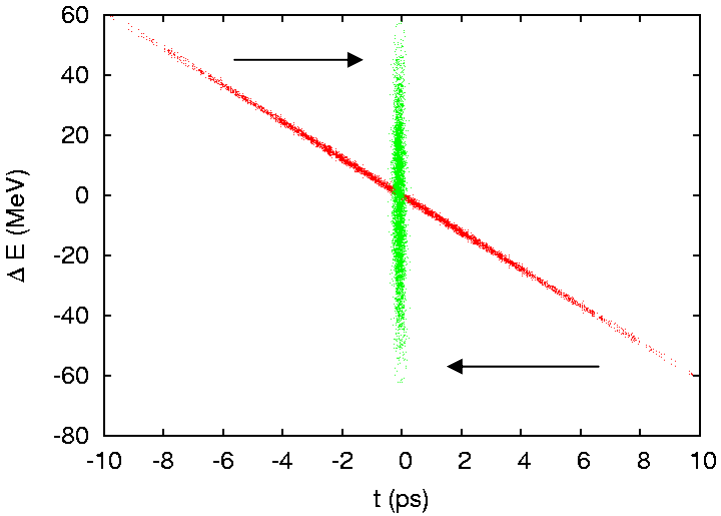
R. Nagai et al., Proc. PAC-03, 3443 (2003).



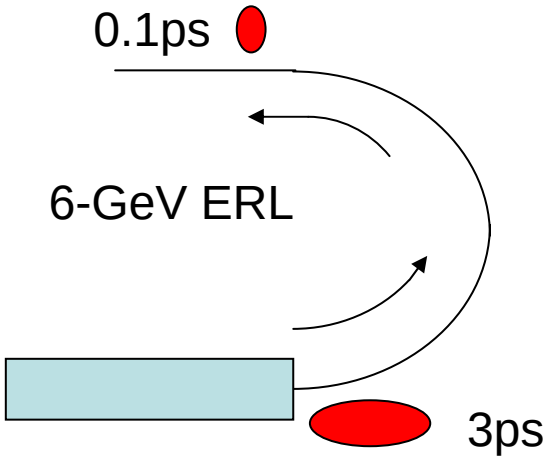


Bunch compression during an arc





ρ=25m, R_{56}=2cm / cell, 12-deg-TBA-cell x 15

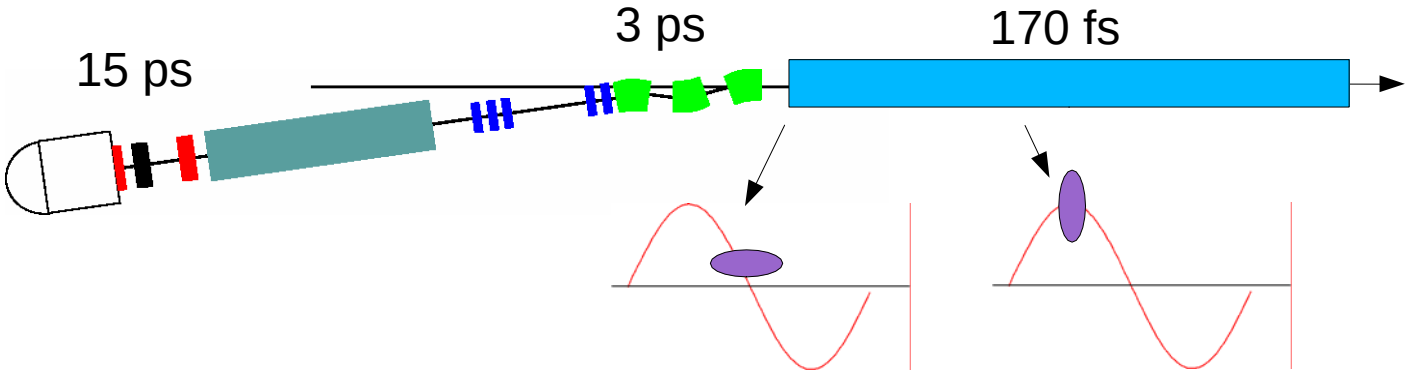


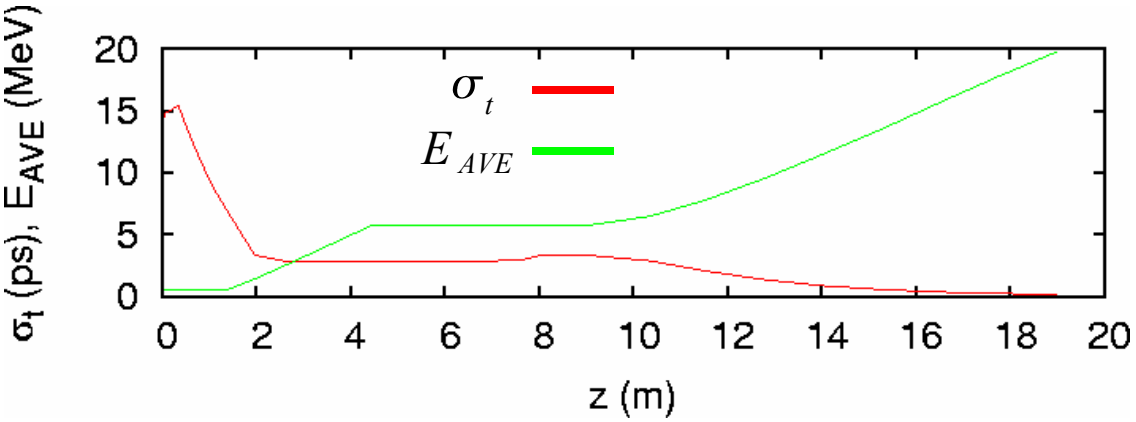
σ_t=3.3ps → 100fs

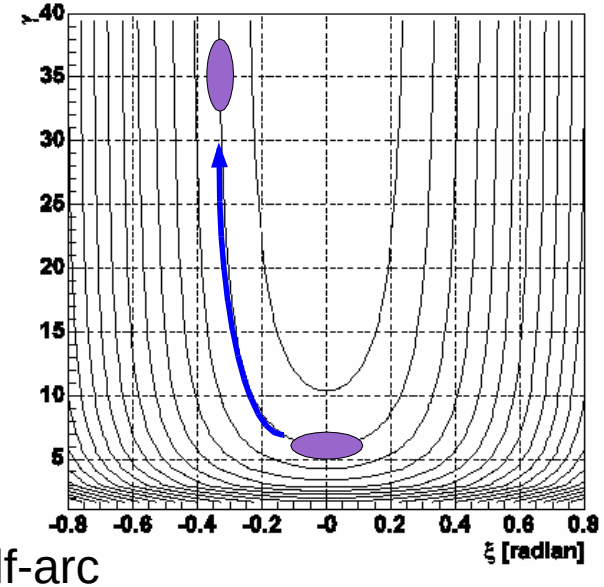
σ_E/E = 0.34%

- fairly linear compression with second-order correction by sextupoles
- however, relatively large energy spread remains, emittance growth by CSR effects exist.

Velocity bunching in a main linac







σ_t = 15ps → 3ps → 170fs (after 9-cell x 8-cavity)

- smaller energy spread than compression in a half-arc
- average current is restricted by imperfect energy-recovery
  --- 5mA for typical design.

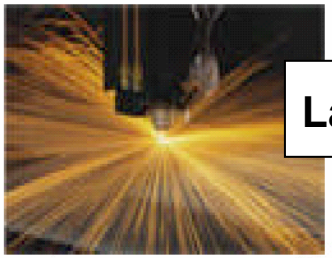
details are presented at WG2 session.

High power ERL-FEL Applications for Nuclear Energy Industries and Other Heavy Industries

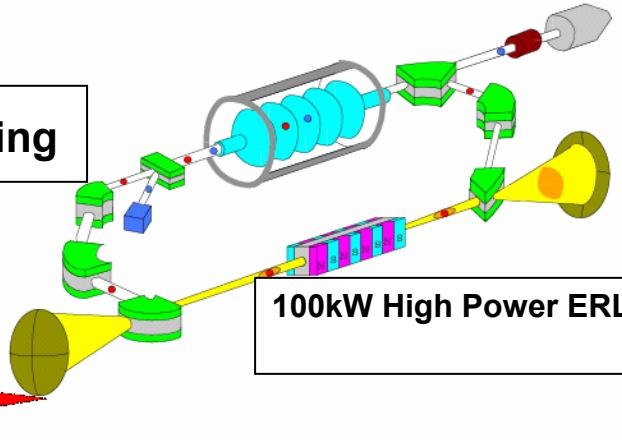
1.Nuclear Reactor De-Commissioning Application

2.Cold-Worked Stress Corrosion Cracking Prevention
Maybe Applicable to Many Other Fields

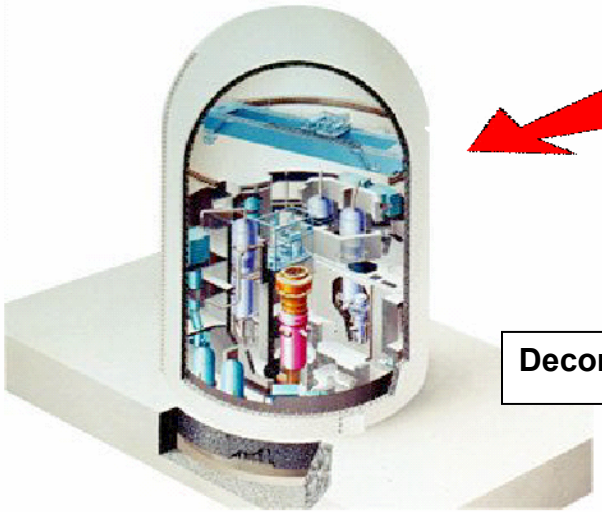
Narrow Cutting and Low RI Contamination Using 100kW High Power FEL



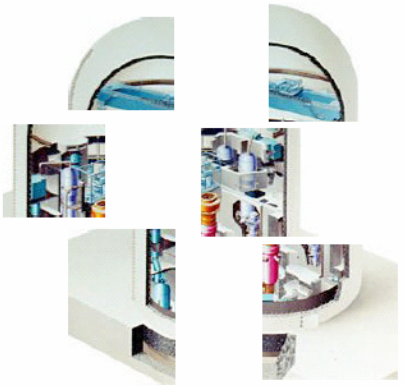
Laser Narrow Cutting



100kW High Power ERLFEL



Decommissioning

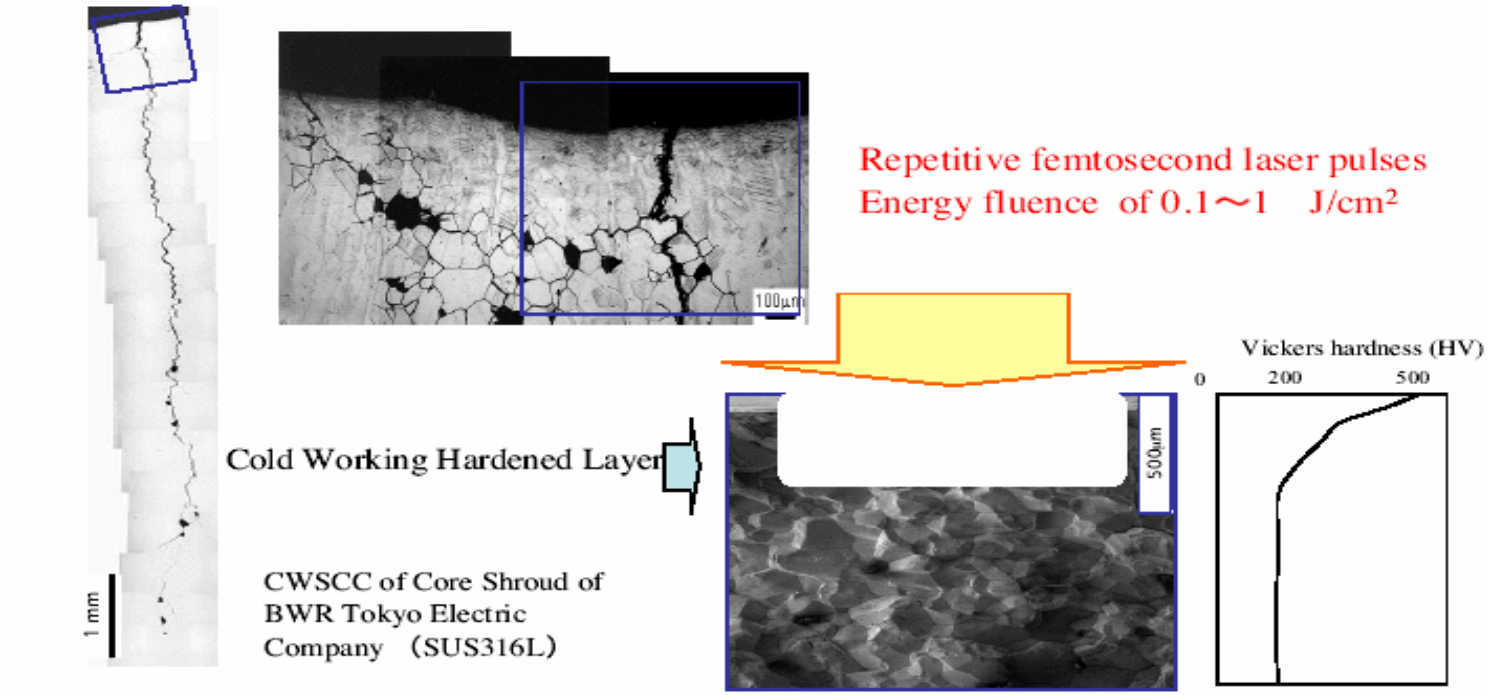


Decommissioning of the Nuclear power Plants

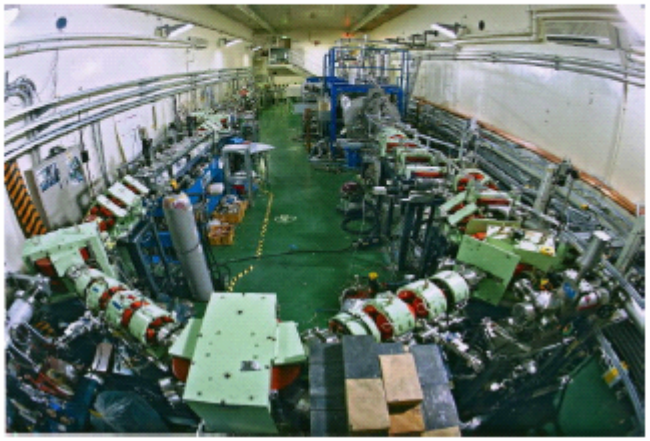
Nuclear Energy Industry Applications

Prevention of Cold-Worked SCC

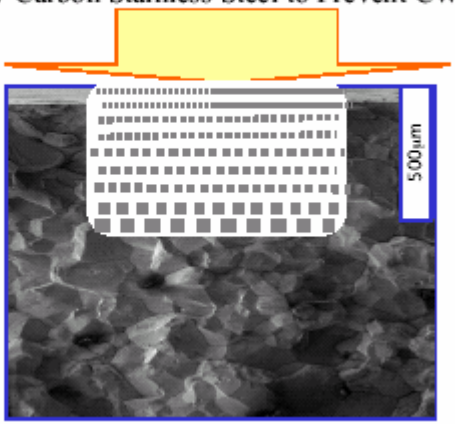
Femtosecond laser pulses can remove the cold-working hardened layer without thermal effects.

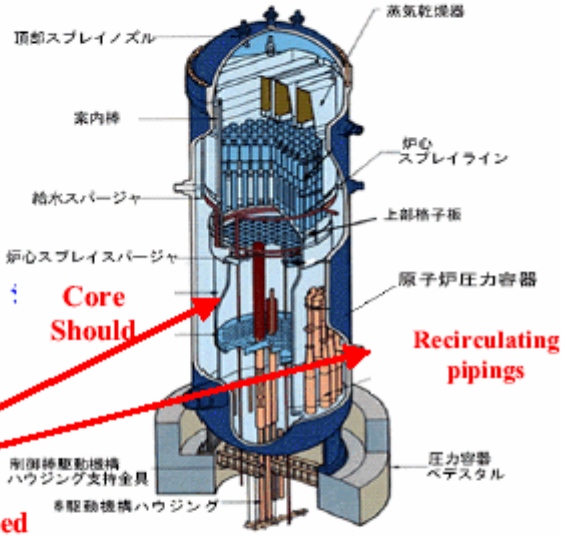


JAERI-Femtosecond High Average Power FEL Removes Residual Tensile Stress and Susceptible Materials without Heat Generation- Prevention of SCC and improve BWR lifetime and Safety

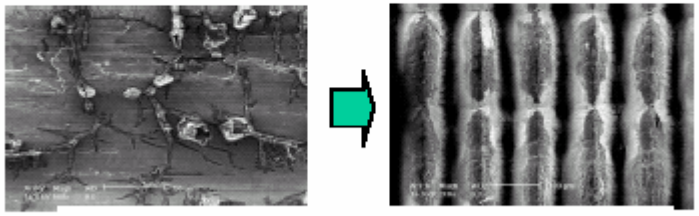


Femtsecond High RepitionJAERI-FELIrradiates
Low Carbon Stainless Steel to Prevent CWSCC





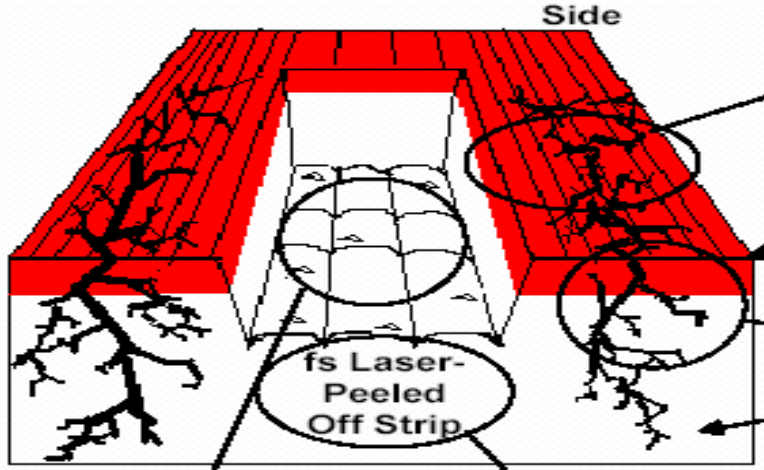
Adopt Cold Worked Compnents

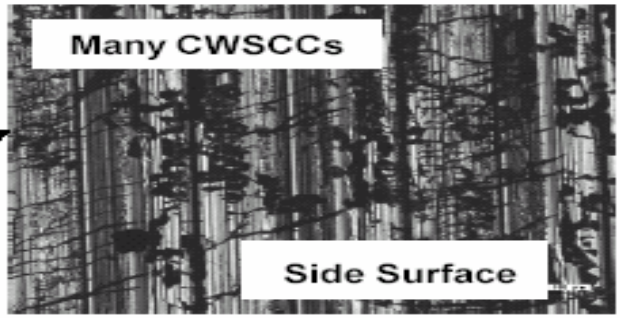


Modified Non-Susceptible Surface

(MgCl2 SCC Test Results)

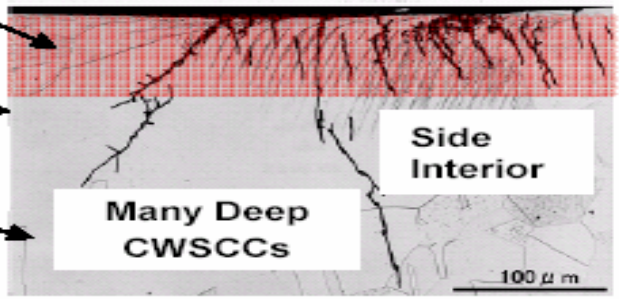
Stainless-steel Sample





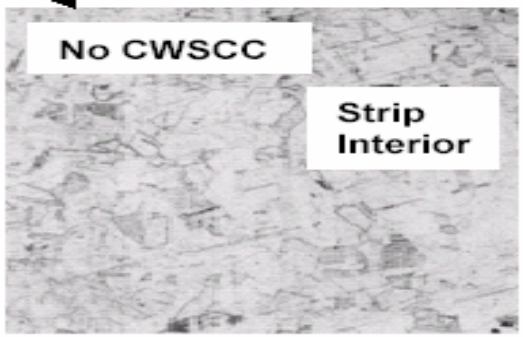
Hardened

Non-
Hardened



Non-Hardened
No Stress
No Susceptible

A few dips , but No CWSCC

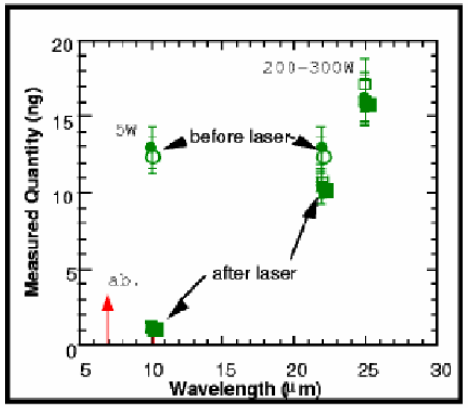


3.Chemical Reaction Control-

Harmful Chemicals Decomposition

Isotope and Element Separation

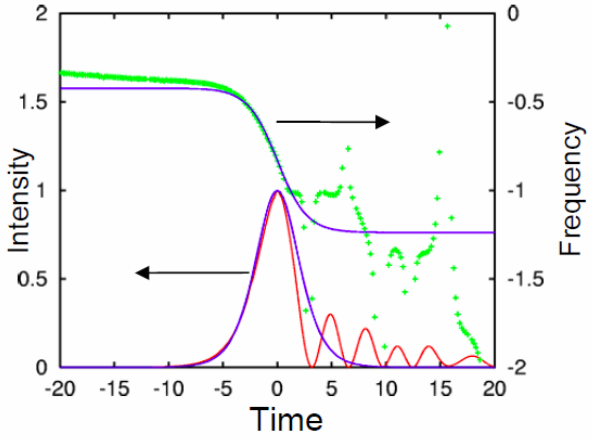
for chemical processes

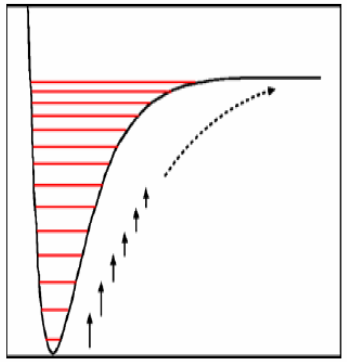


decomposition of PCDD

T. Yamauchi, Kankyo Kagakukai- Shi 14, 567 (2001)

more efficient method
--- using chirped FEL pulses





R. Hajima et al., PRL 91, 024801 (2003).
S. Chelkowski et al., PRL 65, 2355 (1990).

Summary

#0 Brief Introduction of ERL Examples

#1 Past and Current Activities of JAERI ERL FEL
Development and Operation, Especially About
Cryogenics and some items

#2 Activities in the 10kW Upgrading
Beam Power from 100kW to 800kW

#3 Preliminary Results of Nuclear Energy Industry
Applications
CWSCC prevention, Decommissioning in Nuclear
Reactors

#4 Some JAERI ERL Activities will be itemized as in the
ERL05 Workshop
Conceptual Design Activities of ERL-LS likeHOM-BBU,
CSR etc, PC gun Activities As Key Components