Challenges to Realize the EUV-FEL High Power Light Source - Present Status on the EUV-FEL R&D Activities

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2017 International Workshop on EUV Lithography
(2017 EUVL Workshop)

June 12-15, 2017, The Center for X-ray Optics (CXRO), Lawrence
Berkeley National Laboratory, Berkeley, CA, USA

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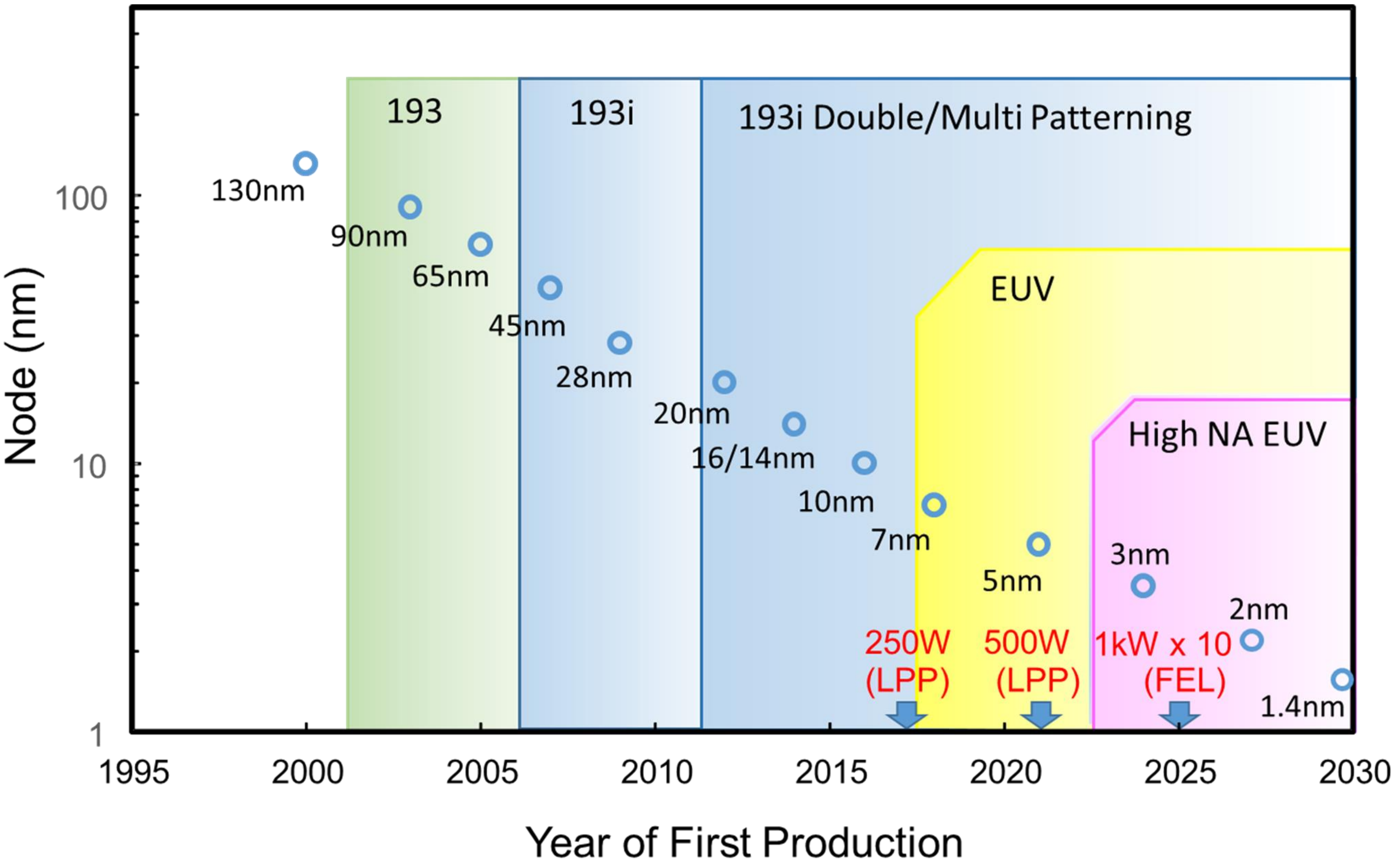
- Summary

Technology node trend of Logic LSI and expected power on EUV light source



Present Status and Future Development on EUV Lithography

Present Status

- The technologies on EUV Lithography system based on LPP light source are progressing, now.
- The system based on ~200 W LPP light source is starting point of the production phase.

Future Development

- It is expected that these on ~1kW source will be necessary to realize the production less than 3nm node, too.
- It is important to develop new type light source to realize higher power than ~1kW, and also the other technologies which are related on EUV lithography such as multi-layer-mirrors, masks, and resist materials, and so on.

Design study on high power EUV-FEL light source

Design concept

- High energy accelerator technologies bring us 10 kW class high power EUV light source based on Free Electron Laser (FEL).

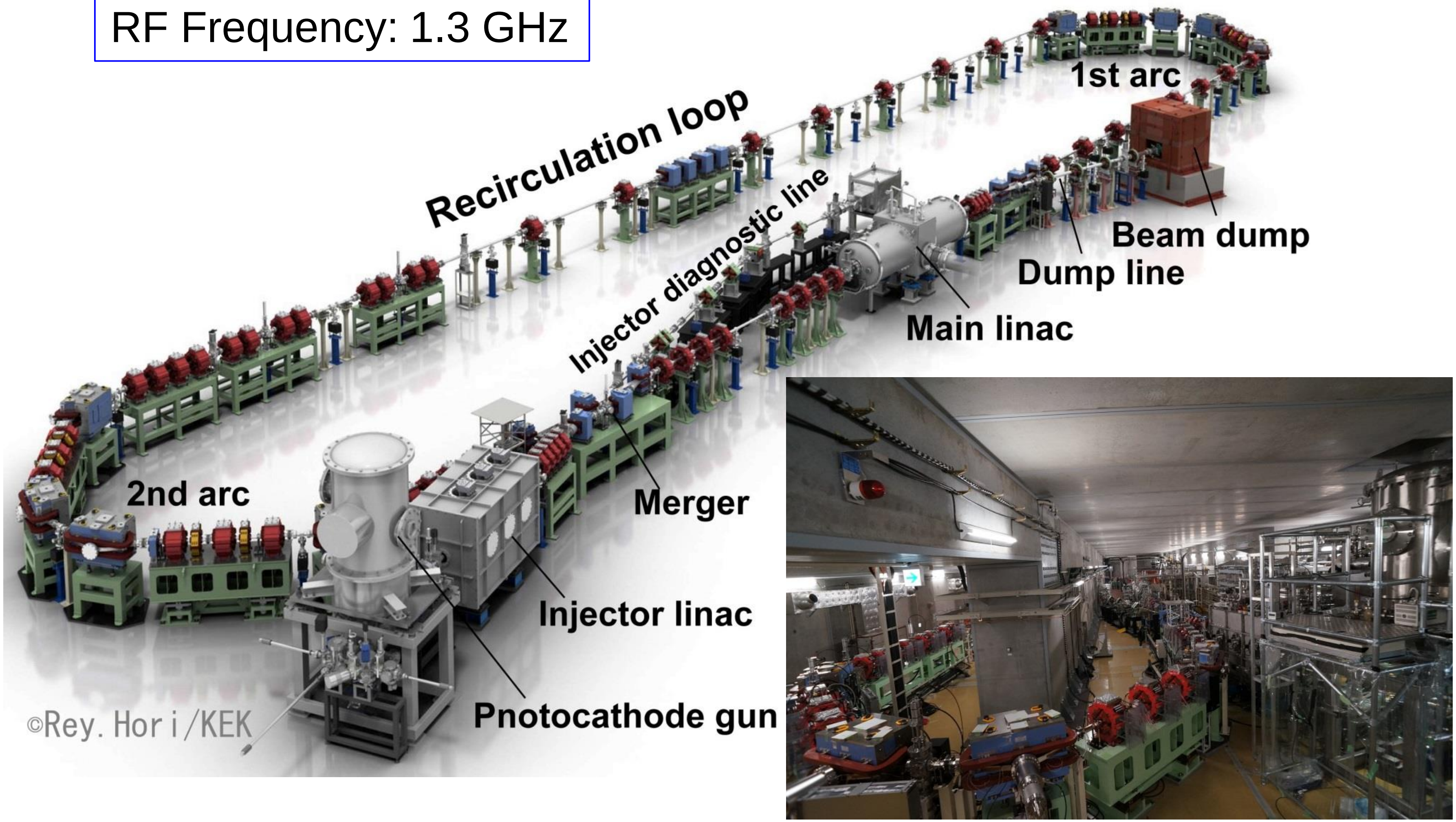
Key technologies

- Super conducting accelerator technologies with Energy Recovery Linac (ERL) (800MeV, 20 mA)
- High power FEL technologies (~30 kW)
- Accelerator elements, systems and operation skill, which are developed in cERL at KEK

Compact ERL(cERL) at KEK

Beam Energy: 20 MeV
RF Frequency: 1.3 GHz

in operation since 2013



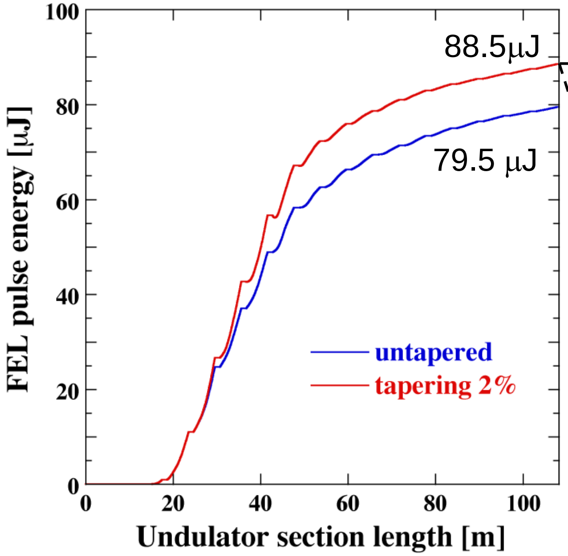
After the presentation at OSA workshop in Hiroshima (27-28/Oct.2016) presented by Prof. N. Nakamura

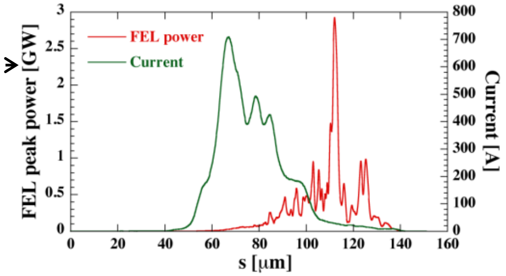
Prototype design of the EUV-FEL

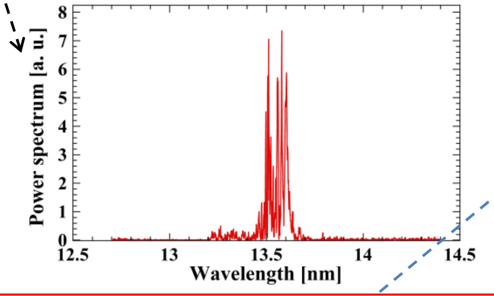
Items	Achieved values in cERL	Design Values at the EUV-FEL
Energy for injector (MeV)	2.9-6	10.5
Energy of Accelerator(MeV)	20	800
Charge /bunch (pC)	0.7-5	60
Repetition rate (MHz)	162.5-1300	162.5
Average Current (mA)	1.0	9.75
Emitance for electron beam (mm mrad)	0.3-1	0.6
Gradient of the accelerated energy (MV/m)	8.6	12.5
Wavelength of EUV-FEL (nm)	/	13.5
Average power of EUV-FEL (kW)	/	Higher than 10 kW

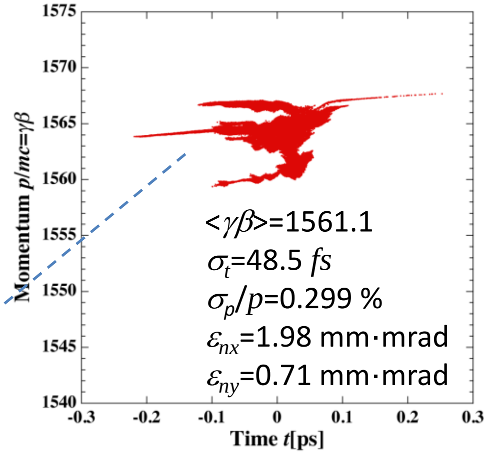
FEL Performance

Courtesy of N. Nakamura









$<\gamma\beta>=1561.1$

$\sigma_t=48.5\ fs$

$\sigma_p/p=0.299\ \%$

$\varepsilon_{nx}=1.98$ mm·mrad

$\varepsilon_{ny}=0.71$ mm·mrad

FEL power without tapering: 12.9/25.8 kW @ 9.75/19.5 mA (162.5/325 MHz)
FEL power with 2% tapering: 14.4/28.8 kW @ 9.75/19.5 mA (162.5/325 MHz)

(P_{FEL}=84 μJ x 162.5 MHz =13.7 kW, I_{av}=60pC x 162.5 MHz=9.75 mA)

Energy spread is increased.

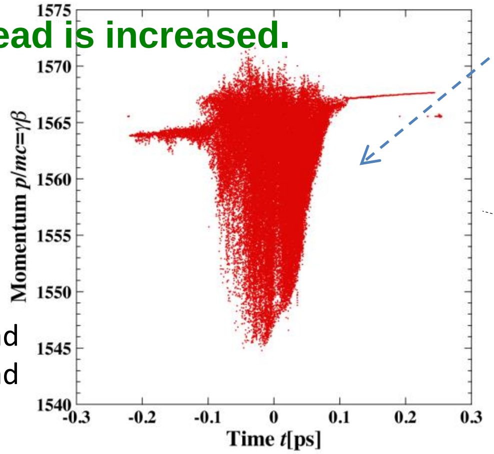
$<\gamma\beta>=1561.1$

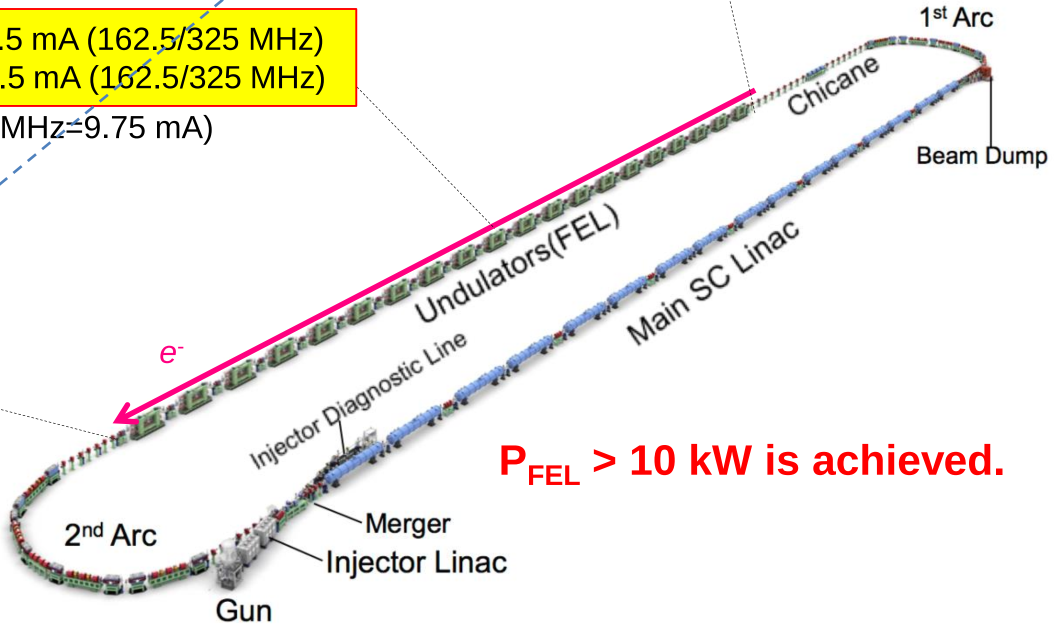
$\sigma_t=48.5\ fs$

$\sigma_p/p=0.299\ \%$

$\varepsilon_{nx}=1.98$ mm·mrad

$\varepsilon_{ny}=0.71$ mm·mrad





P_{FEL} > 10 kW is achieved.

Our previous presentation on EUV-FEL

9-11/Nov.2014 : Workshop on EUV and Soft X-Ray Sources (Dublin)

(Superconducting accelerator technology)

15-19/Jun./2015 : EUVL Workshop (Hawaii)

(Design of the total system)

6-7/July/2015: NGL Workshop (Tokyo) (in Japanese)

9-11/Nov.2015 Workshop on EUV and Soft X-Ray Sources (Dublin)

(Design of the total system ad superconducting technology)

13-16/Jun./2016 : EUVL Workshop (Berkeley)

(complete simulation result including the FEL production)

24-26/Oct./2016 : EUVL Symposium (Hiroshima)

(Complete design work and strategy to realize the system)

27-28/Oct./2016 : OSA Workshop on Compact EUV & X-ray light sources (Hiroshima)

7-9/Nov. /2016 : EUV Source Workshop (Amsterdam)

(Strategy to realize the system)

13/Dec./2016 : EUV-FEL Workshop (Tokyo)

(Discussion with end users and tool venders and accelerator developer)

13-15/Jun./2017: EUVL Workshop (Berkeley) → Now

EUV-FEL Light Source Study Group for Industrialization

THE UNIVERSITY OF TOKYO
S. Ishihara (Leader)

THE UNIVERSITY OF TOKYO
ISSP
I. Matsuda

宇都宮大学
UTSUNOMIYA UNIVERSITY
Utsunomiya Univ.
T. Higashiguchi

NewSUBARU
Univ. of Hyogo
H. Kinoshita

RISE
Waseda Univ.
M. Washio

ISIR
Osaka Univ.
T. Kozawa

Industries

TOSHIBA
Leading Innovation

MITSUBISHI HEAVY INDUSTRIES MECHATRONICS SYSTEMS, LTD.

Materials Mag!c
Hitachi Metals, Ltd.

GIGAPHOTON

EIDEC

Industrialization of High Power EUV light source based on ERL@KEK and FEL@QST

TAIYO NIPPON SANSO
The Gas Professionals

HITACHI

TOYAMA

TOSHIBA
Leading Innovation
TOSHIBA ELECTRON TUBES & DEVICES CO.,LTD.

MITSUBISHI ELECTRIC
Changes for the Better

NTT AT

QST
R. Hajima

KEK
H. Kawata et al.

National Institute of Advanced Industrial Science and Technology
AIST
N. Sei

EUV-FEL Workshop

Date: 13/ Dec. /2016 10:00-17:00
Site: Akihabara UDX 4F NEXT-1
Participants : > 100
(Source group, tool & material venders, end users etc.)
URL: http://pfwww.kek.jp/PEARL/EUV-FEL_Workshop/

EUV-FEL WORKSHOP : 2016.12.13 10:00-17:30

@AKIHABARA UDX 4F NEXT-1

http://pfwww.kek.jp/PEARL/EUV-FEL_Workshop/presentaions.html

<Program>

Time	**Title**	**Speaker**
09:30	Start accepting	
10:00-10:10	Opening message	Sunao Ishihara (The U. of Tokyo)
Keynote・Invited 10:10-12:00	**chairperson: Sunao Ishihara (The U. of Tokyo)**	
10:10-10:50	**-Keynote-** ”Neuromorphic Device for Cognitive Computing in the Big Data era”	Shintaro Yamamichi (IBM Japan)
10:50-11:25	**-Invited-** “Scaling of Semiconductor Integrated Circuits and EUV Lithography”	Hidemi Ishiuchi (EIDEC)
11:25-12:00	**-Invited-** "EUV Lithography Industrialization and future outlook"	Junji Miyazaki (ASML Japan)
	— Lunch —【12:00-13:15】	

Public talks chairperson: Hiroo Kinoshita (U. of Hyogo), Ryoichi Hajima (QST)
13:15-15：20

13:15-13:40	"Free-electron laser SACLA and its basics"	Yuji Otake (RIKEN)
13:40-14:05	"ERL-Based High-Power EUV-FEL Source"	Norio Nakamura (KEK)
14:05-14:30	"Development of damageless EUV multilayer mirrors for high intensity EUV sources"	Satoshi Ichimaru (NTT Advanced Technology)
14:30-14:55	"250W LPP-EUV Light Source Development for Semiconductor HVM"	Taku Yamazaki (Gigaphoton)
14:55-15:20	"Applications of Accelerators - from Basic Science to Industrial Use"	Kiyokazu Sato (Toshiba)
15:20-15:45	**-Invited-** "EUV free-electron laser requirements and considerations for semiconductor manufacturing"	Erik Hosler (GLOBALFOUNDRIES)

Panel Discussion " - To realize EUV-FEL light source- “
16：15-17：25

・Panelists： Takayuki Uchiyama (Toshiba), Yuji Otake (RIKEN), Norio Nakamura (KEK), Satoshi Ichimaru (NTT AT), Taku Yamazaki (Gigaphoton)

・Moderator ：Shinji Okazaki (Gigaphoton), Hiroshi Kawata (KEK)

17:25-17:30	Closing address	Yukihide Kamiya (KEK)

Panel Discussion (Summary)

1. Is it necessary to develop the high power EUV light source? And when?

- Absolutely Yes.
- Until 202?, the light source should be ready for HVM. (N3: 2023-2024)

2. What kinds of light source is possible? These feasibilities? (1)

- LPP: LPP will be a main player until 500W.
  - Present exposure system is designed to match the LPP light source.
  - One of the big problem is the debris of Sn at the collector mirror.
- ERL-FEL: It will be one of the promising player higher than 1kW.
  - The accelerator technologies of ERL have been partially satisfied the requirement.
  - However, from the view point of industrialization, it is necessary to develop the total system to realize the good quality of the beam at high current operation up to 10mA with a reasonable availability, and also size reduction.
  - cERL gives us a very nice site for such development.

2. What kinds of light source is possible? These feasibilities? (2)

- ERL-FEL: It will be one of the promising player higher than 1kW.
  - The optical systems like multilayer mirrors and so on should be check the performance under the high peak power and also high average power irradiation.
  - Several experimental results have been reported for the ablation at multi layer mirror. 45mJ/cm2@~10fs(FLASH), 40-60mJ/cm2@7ps, 200mJ/cm2@8.8ns
  - Resist(?)
  - Coherence(?)
  - Beam divergence(?) , Total reflection mirror optics
  - SACLA and high power soft X-ray laser at QST are very nice sites for such development .

3. What kinds of R&D items for industrialization?

- It is necessary to develop the total system to realize the good quality of the beam at high current operation up to 10mA.
  - Brash up the accelerator components: super-conduction cavity, electron gun, control systems and so on.
- Down size of the HVM ERL-FEL accelerator
- The optical systems like multilayer mirrors and so on should be checked the performance under the high peak power and also high average power irradiation.

4. What is necessary to realize the high power light source?

- Fundamental development should be done quickly and continuously.
- In order to push forward the progress, the coherent support messages from the related companies and communities are very important!
- The development should be done with the collaborative works between the related companies.

Challenge to upgrade the accelerator technologies

Availability Issues

Courtesy of N. Nakamura

Required availability for industrialization: ≥ 98 %

(non operation time ≤ ~ 1 week per year)

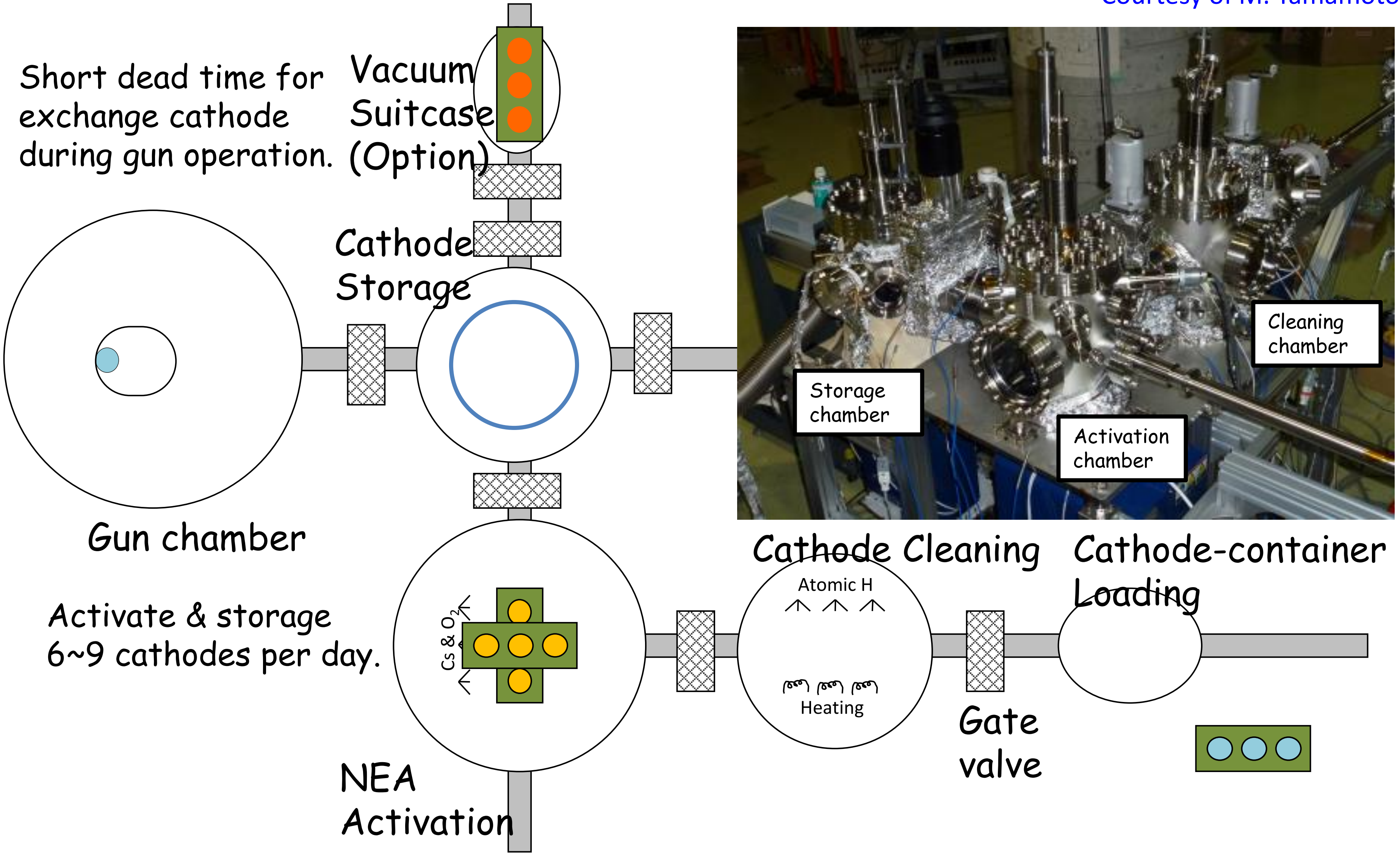
⬇

- Electron gun
  - Remote control of photocathode exchange
- SC Cavity
  - Reduction of trip rate
  - Pulse aging time for suppression of field emission increase
- Undulator
  - Demagnetization of permanent magnets
- Cryoplant
  - High pressure gas safety law reguration
  - Safety inspection per year (in Japan)

Cathode Preparation System

Courtesy of M. Yamamoto

Short dead time for exchange cathode during gun operation.



Vacuum Suitcase (Option)

Cathode Storage

Gun chamber

Storage chamber

Activation chamber

Cleaning chamber

Cathode Cleaning

Atomic H

Heating

Cathode-container Loading

Gate valve

Cs & O_2

NEA Activation

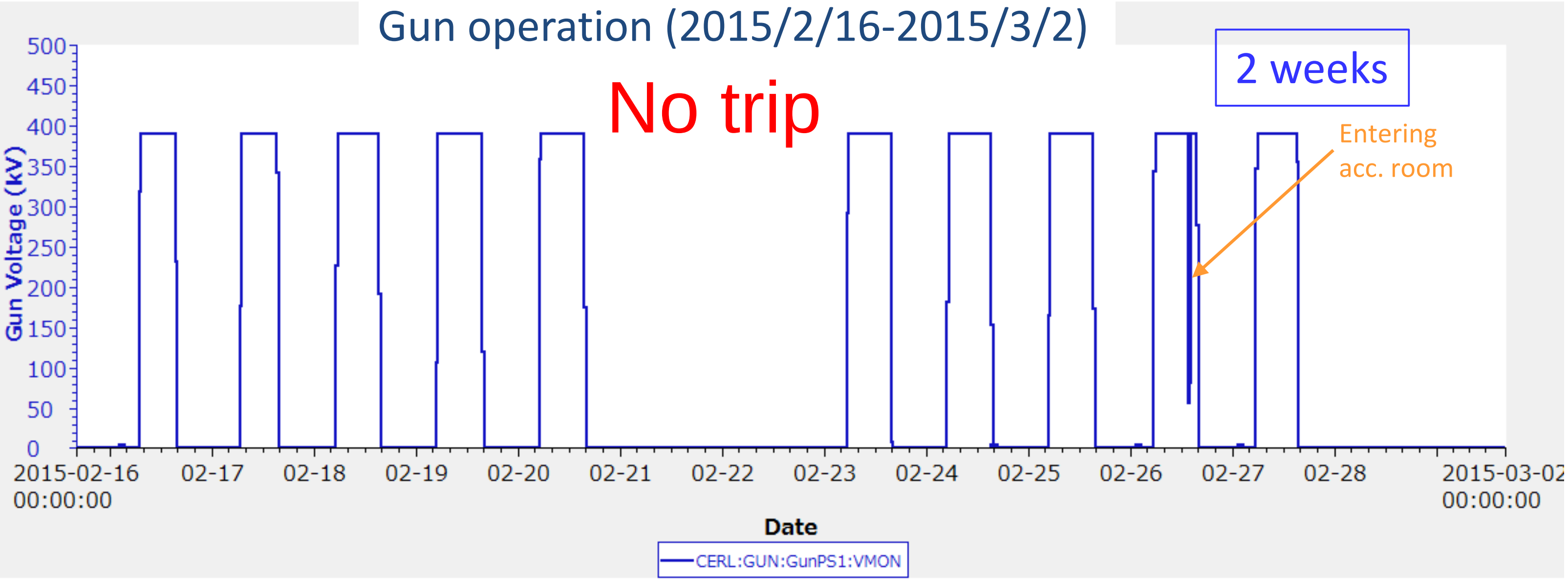
Activate & storage 6~9 cathodes per day.

Operation of Gun & ML Cavities

Courtesy of N.Nakamura

Gun

Gun voltage
(kV)


Gun operation (2015/2/16-2015/3/2)

No trip

2 weeks

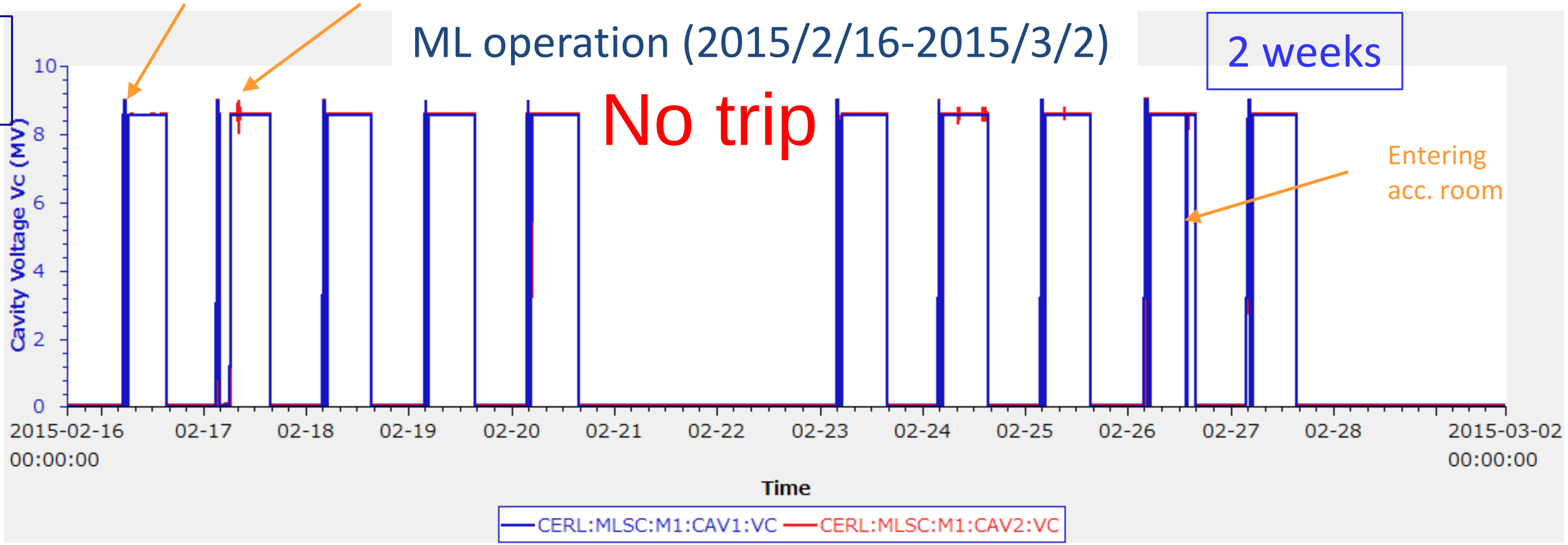
Entering
acc. room

Conditioning

Dispersion measurement

Main cavities
(ML-1, ML-2)

RF voltage
(MV)

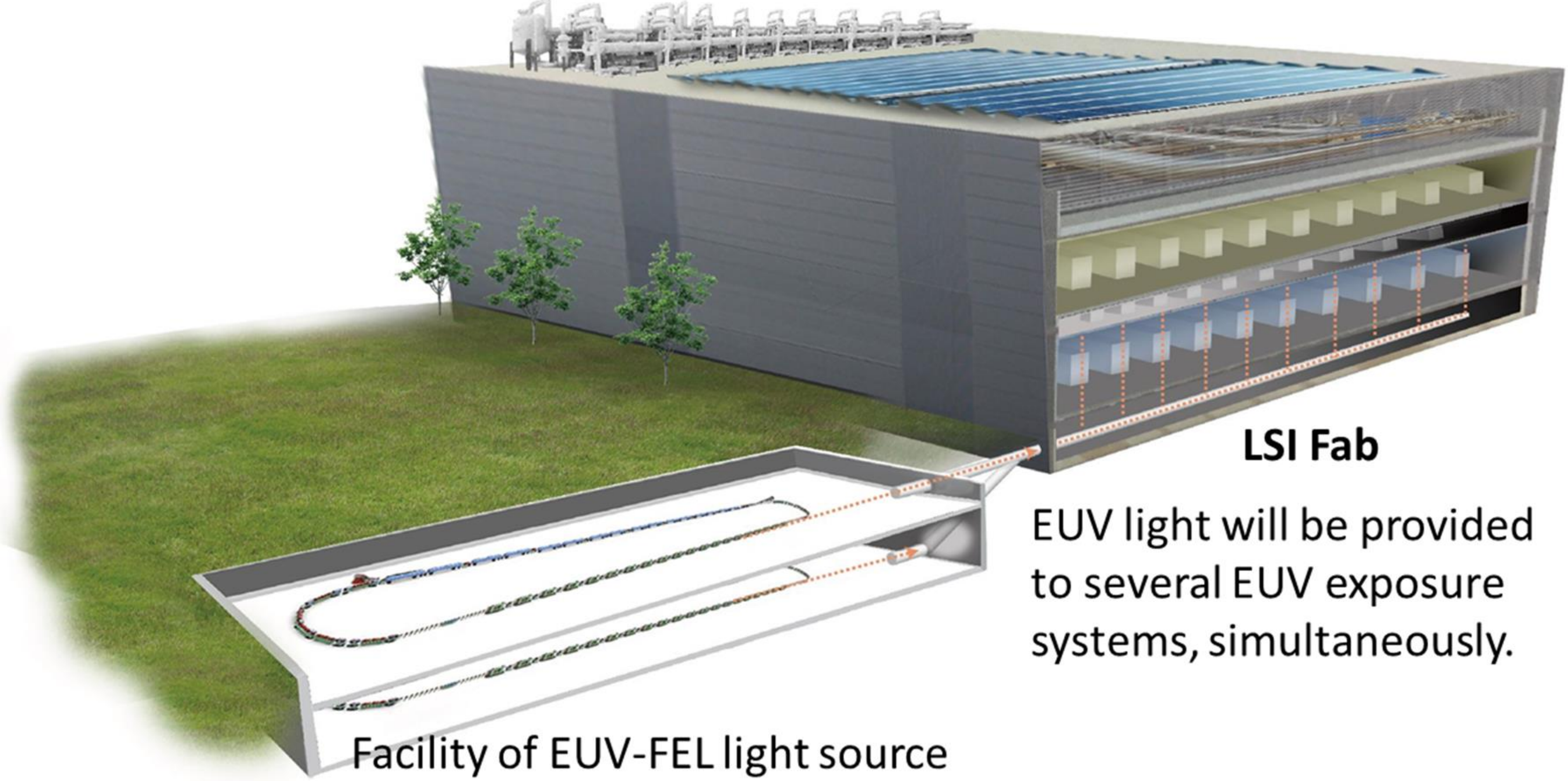

ML operation (2015/2/16-2015/3/2)

No trip

2 weeks

Entering
acc. room

Redundant System



LSI Fab

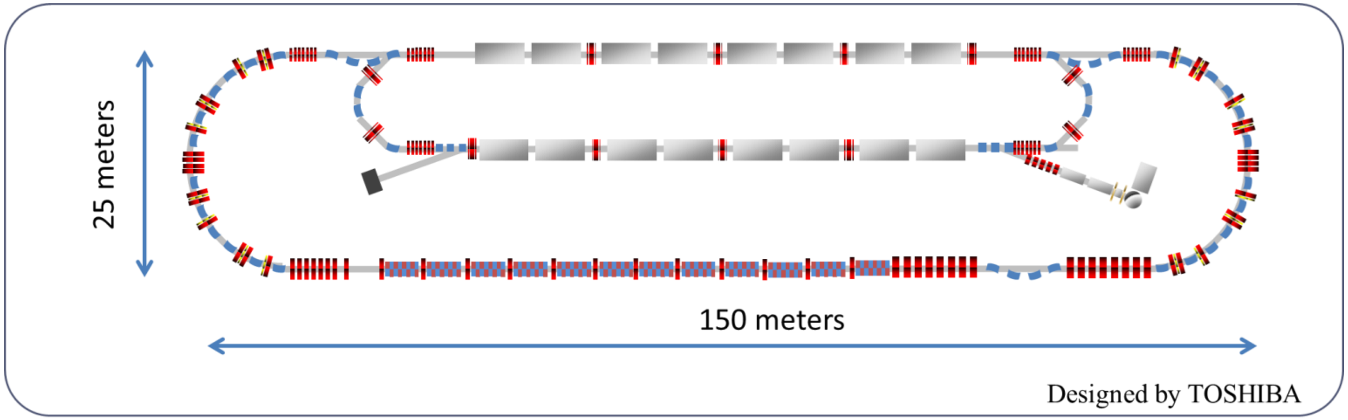
EUV light will be provided to several EUV exposure systems, simultaneously.

Facility of EUV-FEL light source
（Main/Sub light source）

Reduction of Source Size

Courtesy of N.Nakamura

- Higher field gradient of Main SC cavities
  - Increase of power consumption $\propto E_{acc}^2/Q$
  - High-Q SC cavity
- Lower Beam Energy
  - Shorter undulator period and stronger magnetic field
  - Increase of current or energy conversion efficiency for the same FEL power
- 2-loop/2-turn ERL
  - Optics design for CSR effect suppression
  - Increase of current for the same FEL power



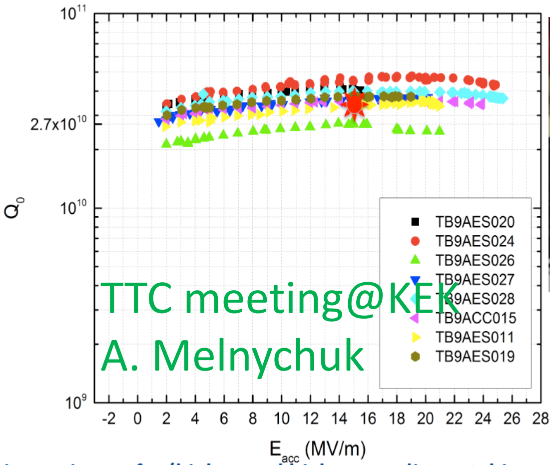
Designed by TOSHIBA

SRF challenge: High-Q

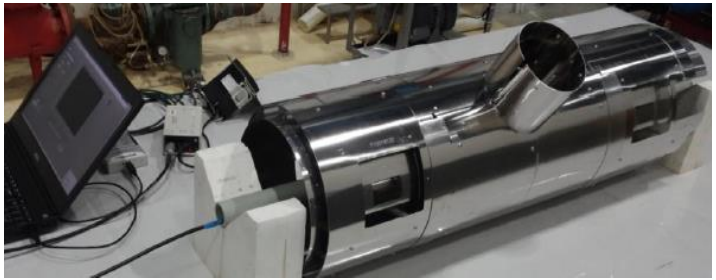
Courtesy of K.Umemori

State-of-the-art: LCLS-II CW cryomodule

TTC meeting@MSU G. Wu



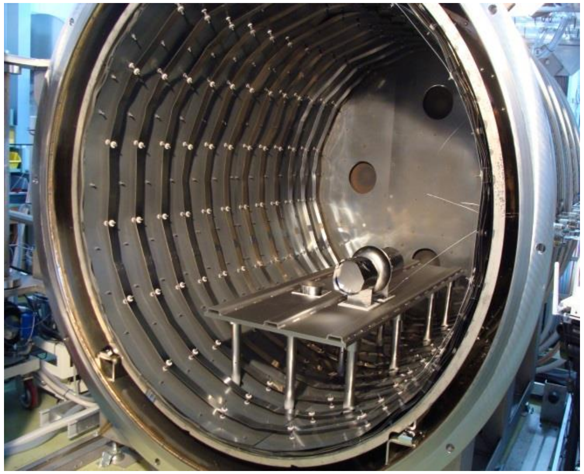
TTC meeting@KEK
A. Melnychuk

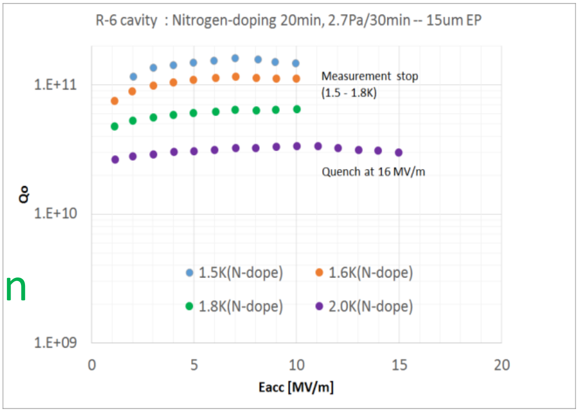


TTC meeting@MSU S.Chandrasekaran

LCLS-II cryomodule pushing CW high-Q operation

- ☐ Nitrogen doped SRF cavity
- ☐ optimal Nb material and treatment
- ☐ magnetic shielding, magnetic hygiene, demagnetize
- ☐ optimized cooling procedure





KEK also tried N-doping using J-PARC furnace and obtained good results for single-cell cavity.

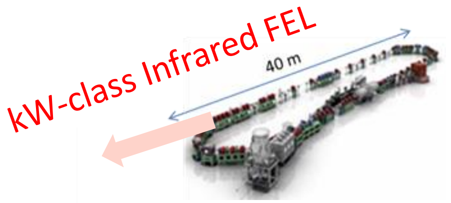
Staging to realize the EUV-FEL light source for Lithography

1. General understanding about EUV-FEL for Lithography
   - EUV-FEL Light source will be needed from the stage of 3nm Node (~2025).
   - It is important to develop the feasible technologies on ERL-FEL and also handling of the high peak power FEL light source for EUV optical components (multi-layer(ML) mirrors, photo resist materials, masks and so on)
2. Staging development processes

- 1st stage: Development of the feasible technologies
  - ERL-FEL: kW-class infrared FEL light will be demonstrated by using cERL
  - Handling of high peak power EUV FEL light : Material developments on ML mirrors and so on by using low repetition FEL sources like SACLA and so on.
- 2nd stage: Development center of EUV-FEL system and lithography
  - ☐ Phase 1: Establishment of the EUV-FEL system
    - ERL-FEL: 10kW-class EUV FEL light will be produced by prototype ERL-FEL
    - Handling of 10kW-class EUV FEL light: Interface optical systems to scanner and related materials will be established.
  - ☐ Phase 2: International Development Center of the EUV-FEL lithography
    - Collaborative development of EUV-FEL lithography and related process between equipment venders and end users

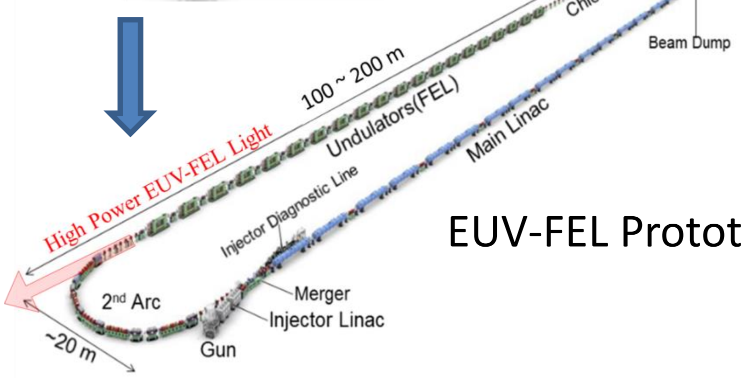
General concept of each stage

1st stage:
Development of the feasible technologies



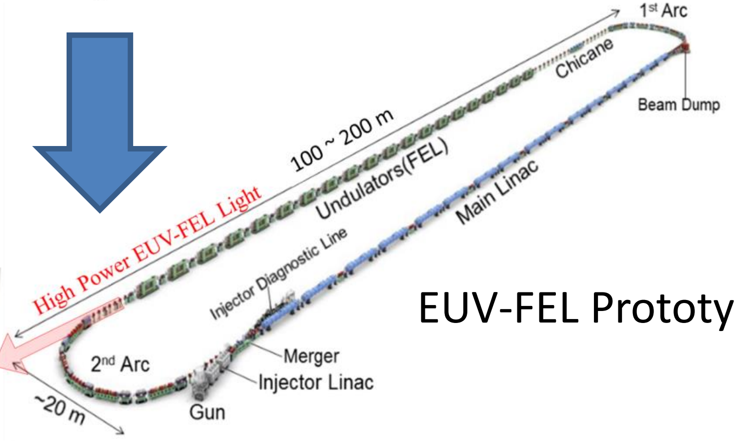
cERL

2nd stage Phase 1:
Establishment of the EUV-FEL Lithography system



EUV-FEL Prototype

2nd stage Phase 2:
International Development Center on the processing of EUV-FEL lithography



EUV-FEL Prototype

Clean room with EUV exposure system

The above concept is discussed under the collaboration between AIST, KEK, UTokyo and EIDEC

Summary

- Update of the EUV-FEL accelerator design is progressing from view points of end user demands.
- We organized EUV-FEL Workshop at last year and the R&D directions for accelerator technologies has been clarified; availability, size reduction, low operation cost, and so on.
- Staging procedure to the EUV-FEL light source for Lithography has been discussed with AIST, KEK, UTokyo, and EIDEC

EUV-FEL Design Group

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(QST) R. Hajima

(Tohoku Unv.) N. Nishimori

The design study has been done under collaboration with a Japanese company.

Thank you for your attention!