Status of iCASA

KEK
Shin MICHIZONO (KEK)

Innovation Center for Applied Superconducting Accelerator (iCASA)

- *Linear Collider R&Ds*

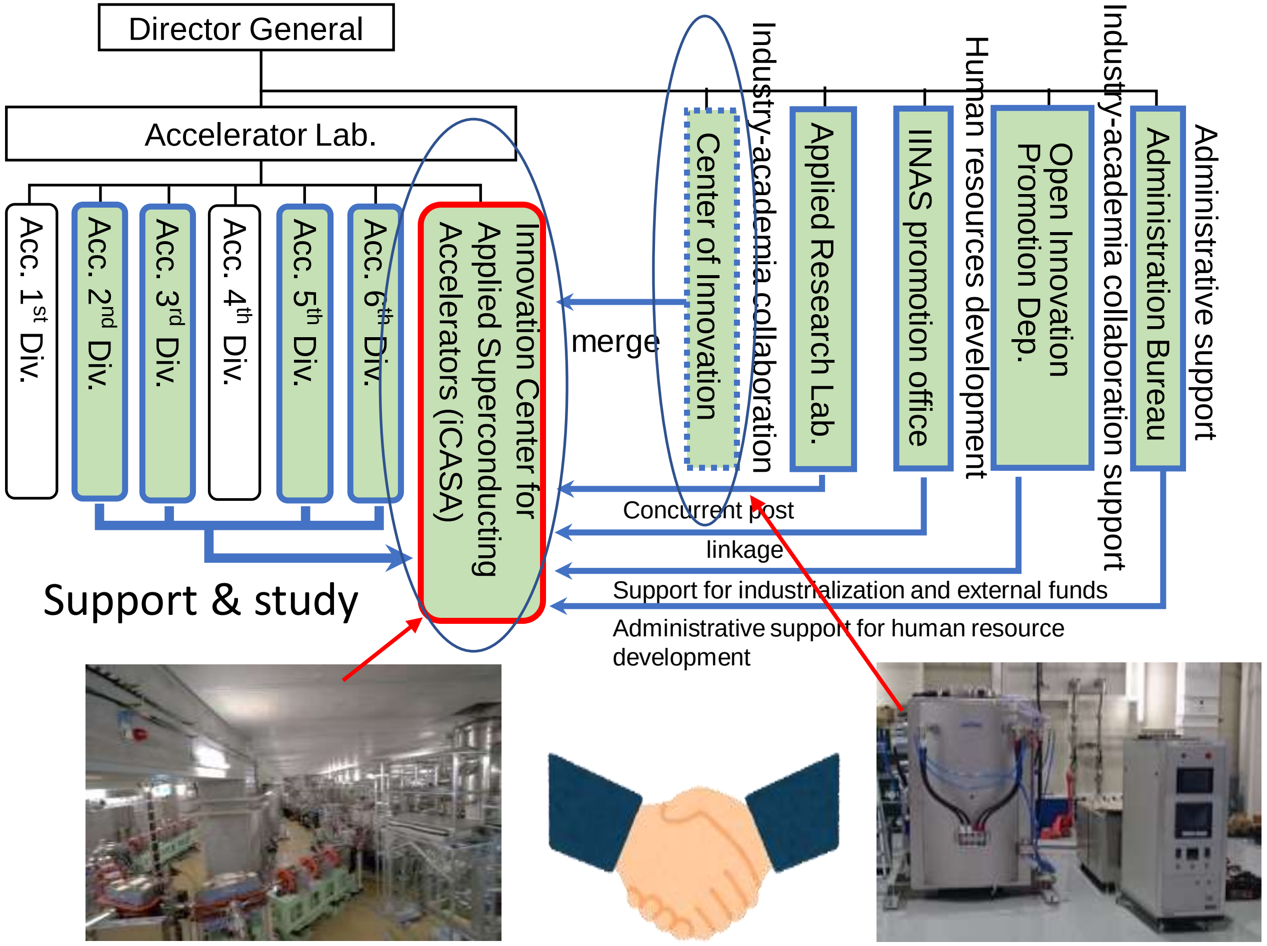
see 2023 CEPC workshop "Progress of the ILC and the CLIC"
https://indico.ihep.ac.cn/event/19316/timetable/?layout=room#all.detailed

- *Superconducting RF (SRF) accelerator's application*

Today's main focus

Establishment of iCASA
(how we will act for this purpose)

iCASA was established on April, 2022.
(COI merged to CASA → iCASA)



cERL @CASA

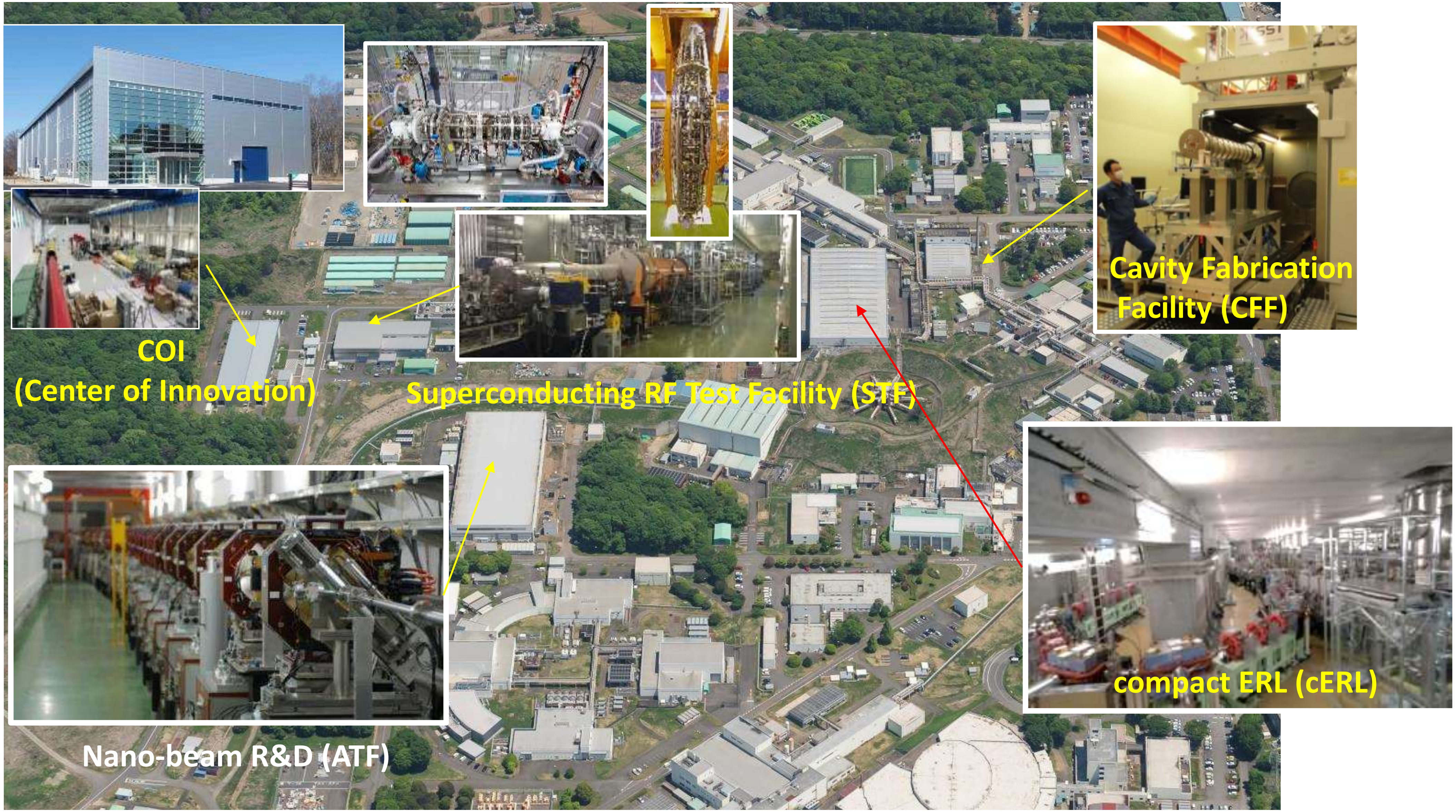
Nb$_3$Sn furnace @COI

Aims

- iCASA strengthens CASA's activities as the **core center for SRF development and the expansion of applied research** by using Superconducting technologies at KEK.

By iCASA at KEK, new applied research like EUV-FEL and making Nb$_3$Sn SRF accelerator for industrial use will be accelerated .

Advanced accelerator facilities at KEK



iCASA

Innovation Center for Applied Superconducting Accelerator

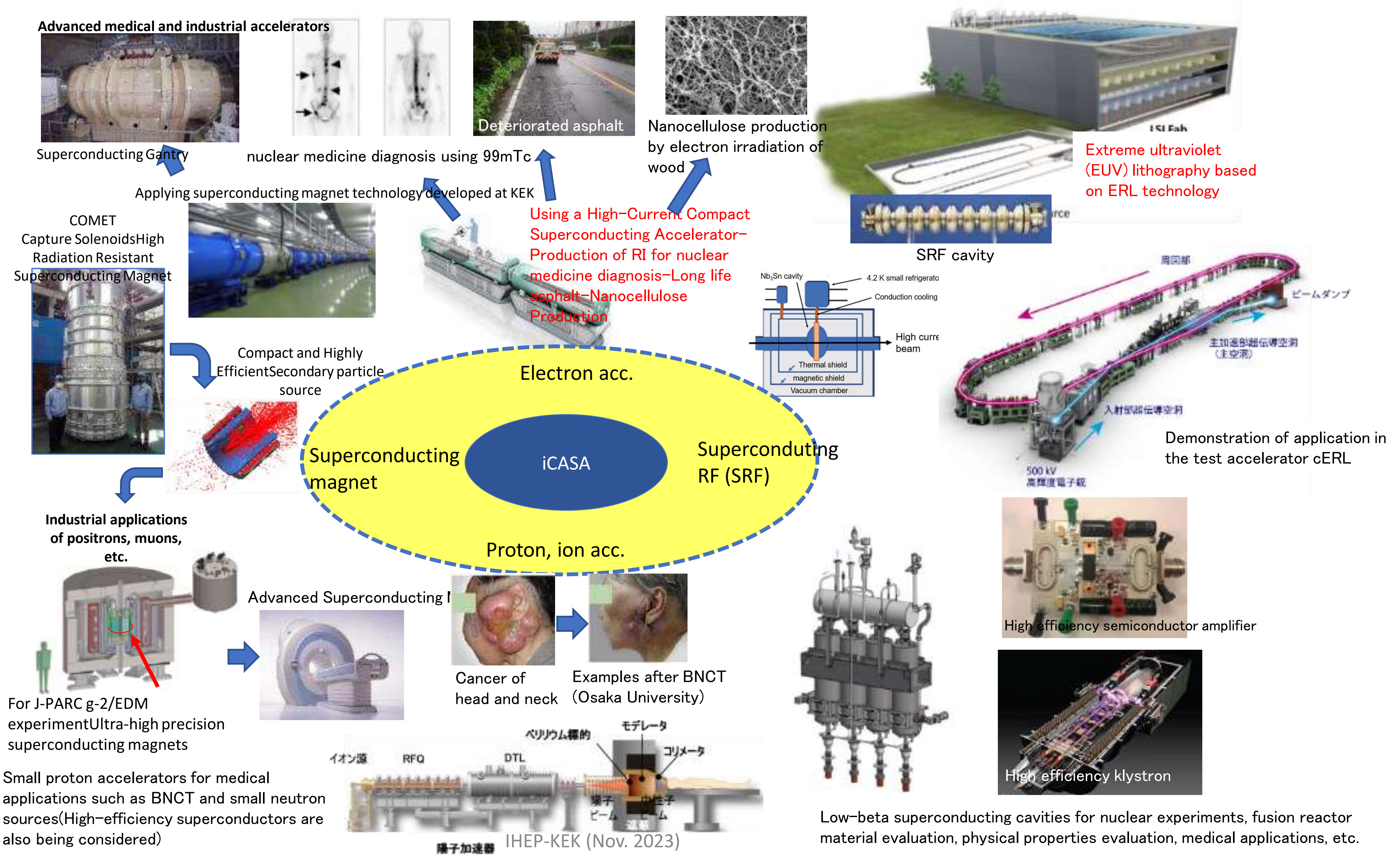
https://www.kek.jp/wp-content/uploads/2022/07/KEK-PIP2022.pdf

KEK-PIP2022:

3.1 Accelerator Development for Industrial and Medical Applications

This category includes the superconducting accelerator development that makes use of the Compact Energy-Recovery Linac (cERL) by the Innovation Center for Applied Superconducting Accelerator (iCASA) and the Ibaraki Boron Neutron Capture Therapy project (iBNCT). Both projects will continue, because both are important as KEK's contribution to society, which will also help improve KEK's visibility in society.

iCASA:Applying advanced accelerator technology to a wide range of industry and research



Superconducting RF (SRF) accelerator


508MHzTRISTAN (1989)


508MHzKEKB (1998)

SRF cavity R&D since 1980s
Experiences at TRISTAN/KEKB/SuperKEKB

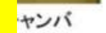
Direct slice Nb R&D for SRF cavities at KEK
by Takeshi Dohmae

STF (2005-) for Superconducting Cavity Evaluation

CFF(2011-) cavity fabrication facility


EBW

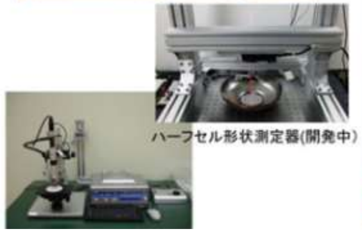
Chemical polishing

KEK has extensive experience in the development of SRF accelerator since TRISTAN.


S1 global (2010)
4 KEKs, 2 each from Germany and US Cavities


Vertical test stand

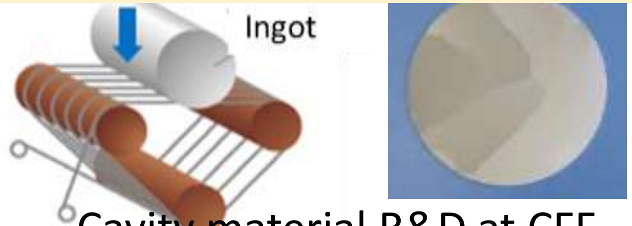


Surface Inspection


Press machine


Vertical lathe

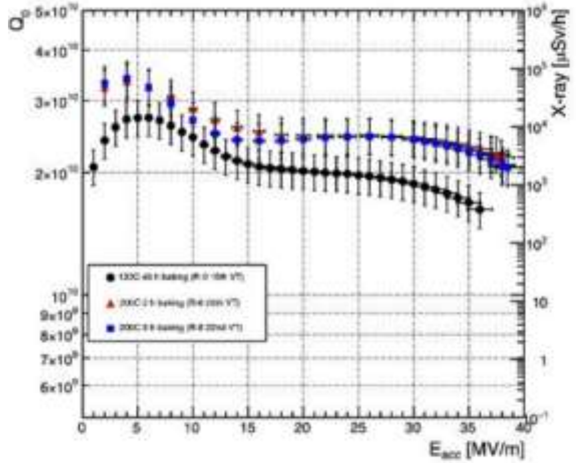

STF-2(2016～)
14 srf cavities



Cavity material R&D at CFF

Status of high-Q/high-G R&D at KEK by Ryo Katayama

High-Q/G R&D at STF



Example of SRF activities at KEK

Horizontal test stand

Horizontal test results of LG 9-cell cavity
by Kensei Umemori

Cavity inspection by Kyoto camera

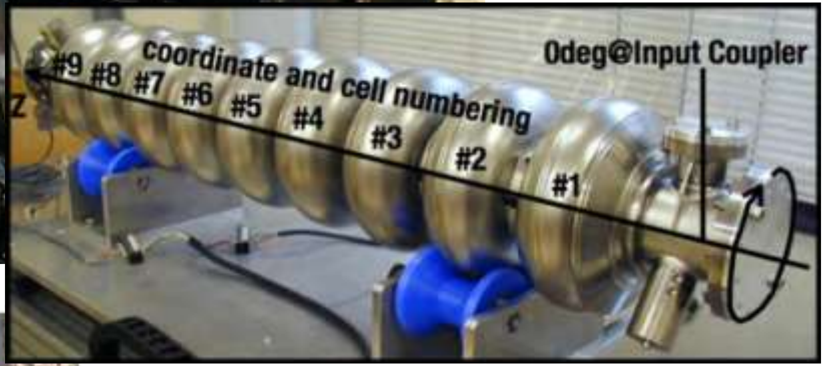


Figure 1: A defect observed with inspection camera.

Trial of defect finding using machine learning
by Hayato Araki

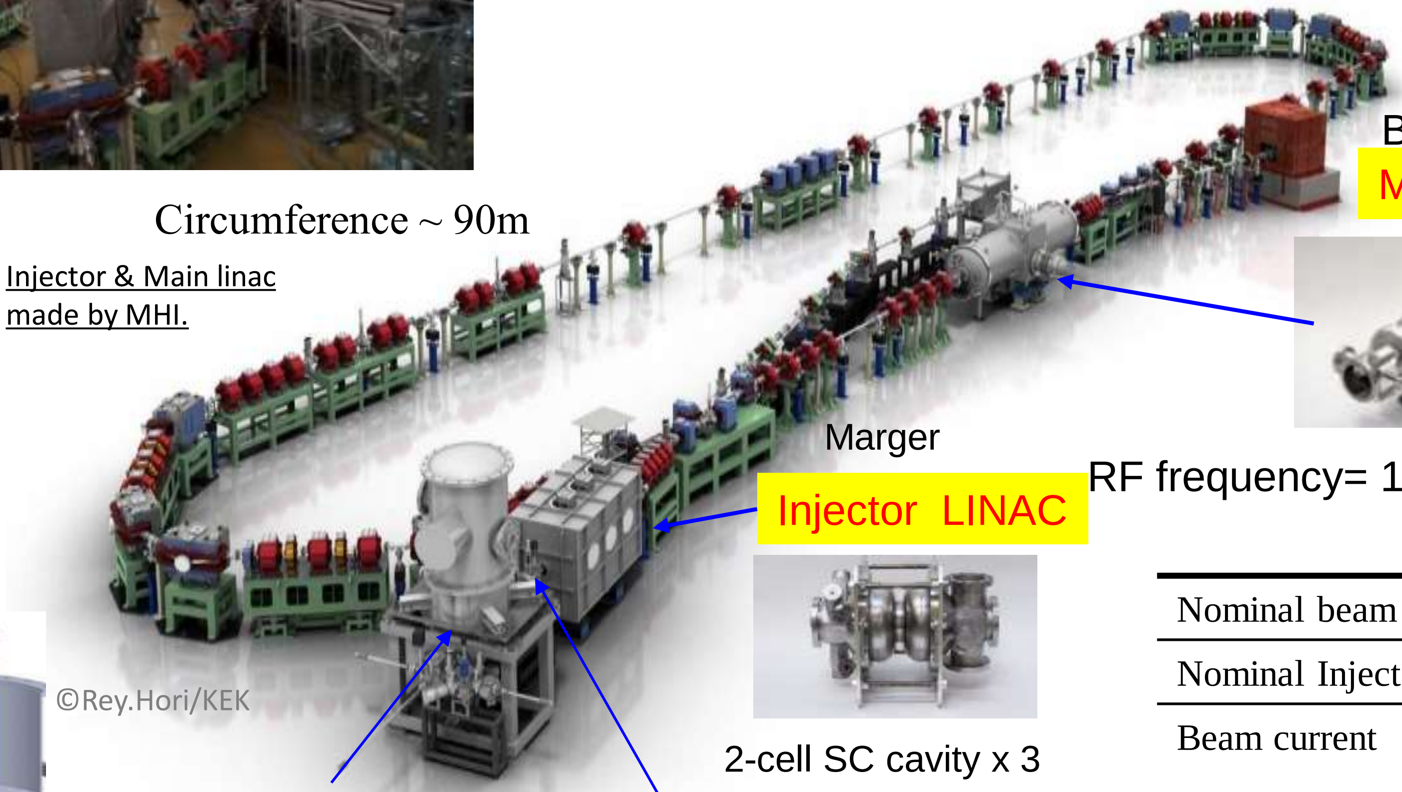
Compact ERL (cERL) in KEK

Compact ERL (**cERL**) has been constructed in 2013 at KEK to demonstrate energy recovery with low-emittance, high-current CW beams of more than 10 mA for future multi-GeV ERL with SRF cavities.

2019: cERL was re-organized under the (CASA) in KEK to promote the industrial application by using cERL.

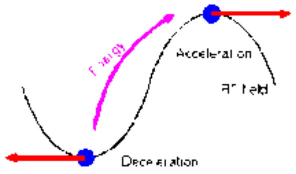
Circumference ~ 90m

Injector & Main linac made by MHI.



Beam Dump

Main LINAC



9-cell SC cavity x 2

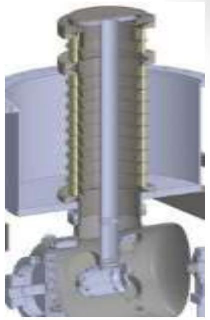
Marger

Injector LINAC

RF frequency= 1.3 GHz

17.5 MeV & 19MeV,0.3mA

2-cell SC cavity x 3



©Rey.Hori/KEK

Photocathode DC gun (Not SRF gun)

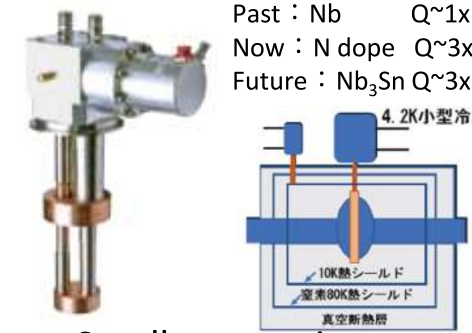
500kV DC Gun

Buncher

Nominal beam energy	20MeV
Nominal Injector energy	2.9MeV
Beam current	10 mA (initial goal) 100mA (final)
Normalized emittance	0.1 – 1 mm·mrad
Bunch length (bunch compressed)	1-3ps (usual) 100fs (short bunch)

R&Ds for applications of SRF accelerators

Past：Nb　　Q~1x10^{10} @2K
Now：N dope　Q~3x10^{10} @2K
Future：Nb_3Sn Q~3x10^{10} @~5K



Small cryogenics
Conduction cooling

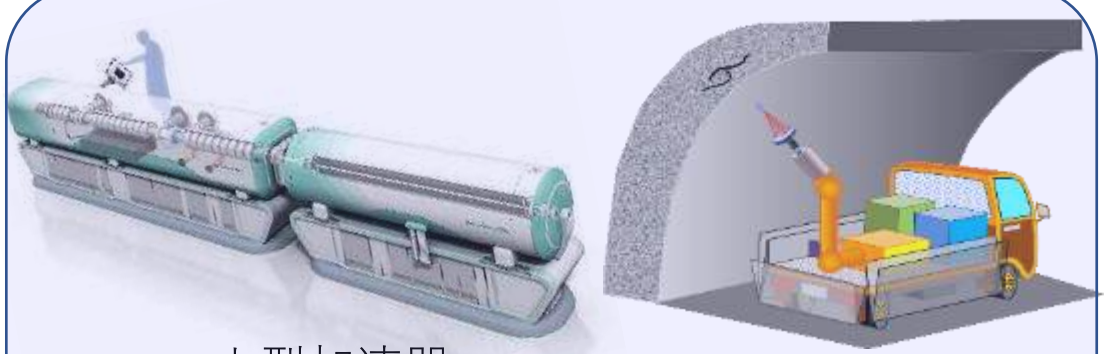
Large cryogenic plant

High performance cav.

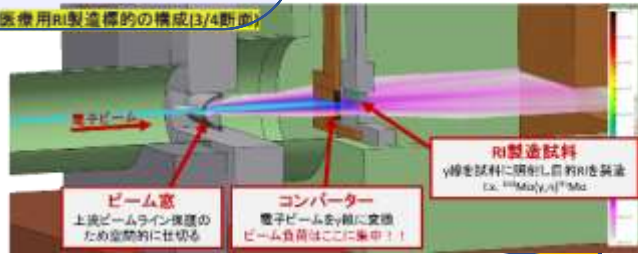
~20 years
Nb_3Sn/Cu
Low-cost cav.

~10 years
Nb_3Sn/Nb
De-(High Pressure Gas Safe , Act
& Large-scale cryo-plant)

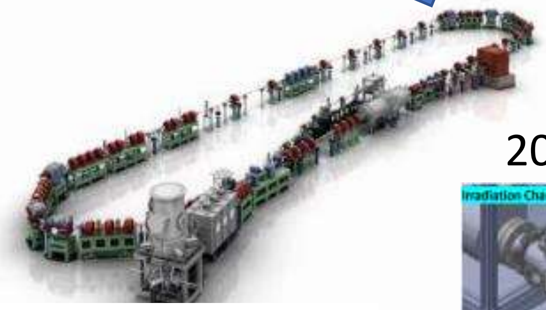
~5 years
High performance of Nb cavities
by new surface treatment
(N-doping, 2-step baking, etc.)



小型加速器　　車載型加速器

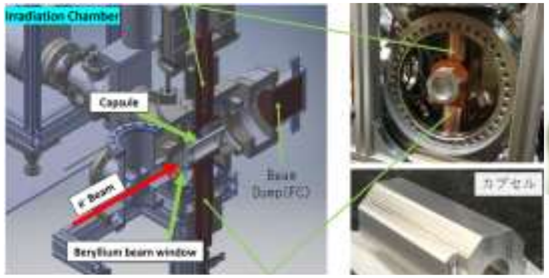


Window, target, etc. for high power beam

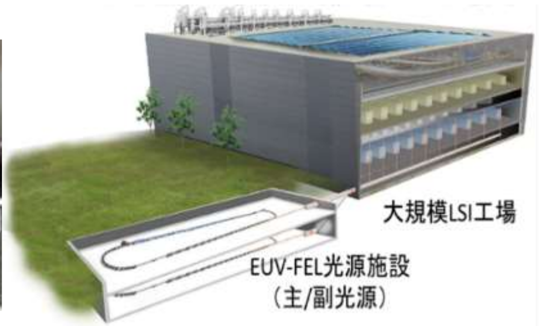


cERL for SRF
application study

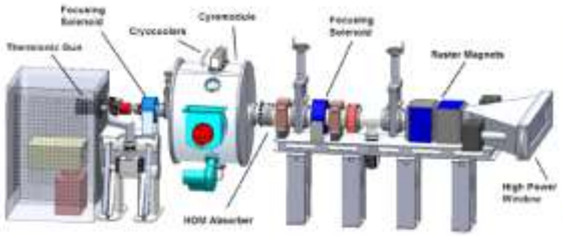
200 W
20 MeV 10uA

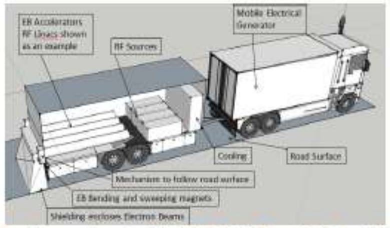


800 MeV 10 mA
EUV-FEL light source(~10kW)



～200 kW、5～30 MeV
^{99}Mo、 compact acc.





Technical issues and results to be addressed by iCASA

To realize 10kW-class high-intensity EUV-FEL light sources

Subject① : **FEL generation under 10mA operation and energy recovery**

- -2023:CW-ERL operation (0.3mA) with undulators

To realize a compact Nb_3Sn high-current superconducting accelerator

Subject② : High efficiency and gradient **Nb_3Sn cavity development** for industrialization

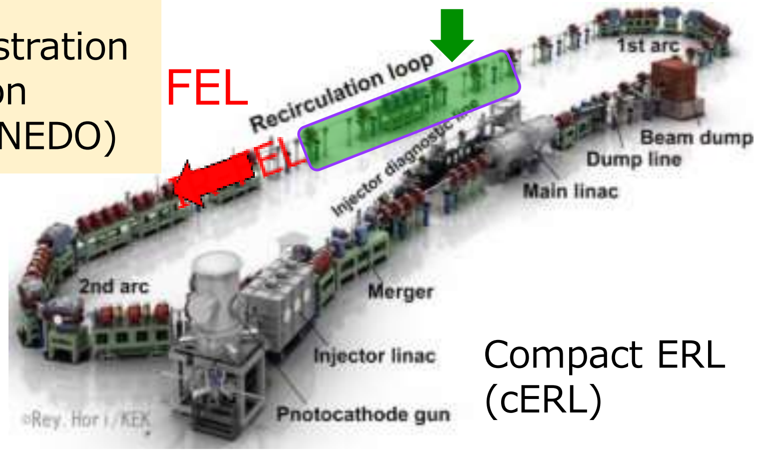
- -2023: Nb_3Sn coating on the cavity, Nb_3Sn high intensity accelerator design

Subject① 10mA energy recovery

・cERL
2016-18:1mA ERL demonstration
2019: Undulator installation
2020: FEL demonstration(NEDO)

Undulators

FEL



Compact ERL (cERL)

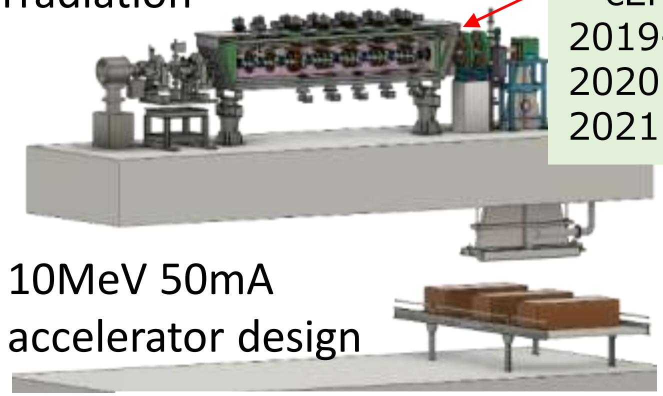
Demonstrate FEL at cERL with high current and energy recovery

Subject② Nb_3Sn cyromodule

Conduction cooling of Nb_3Sn cavity

e-irradiation

・cERL
2019-: ^{99}Mo generation
2020: Nb_3Sn cav. fabrication
2021: Nb_3Sn acc. design



10MeV 50mA accelerator design

Demonstrate a cryomodule with conduction cooling by a compact cryo-cooler

EUV-FEL

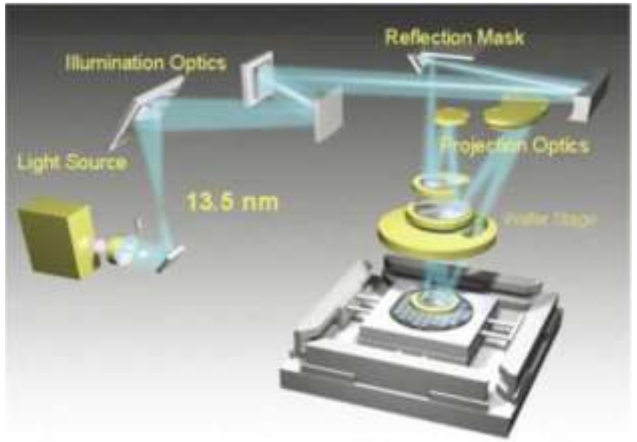
Introduction of EUV-FEL

- 10-kW class EUV sources are required in the future for Next Generation Lithography

In order to realize 10-kW class EUV light source, ERL-FEL is the most promising light source (High repetition rate (≦1.3 GHz) and high current linac system).

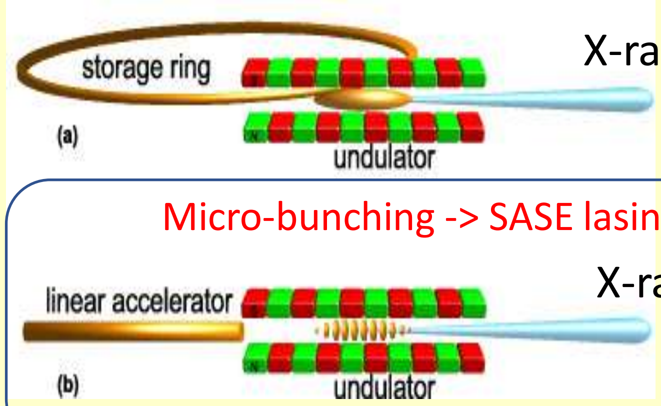
Schematic of EUV (13.5nm) exposure tool

H. Mizoguchi et al., Komatsu Technical Report 59-166 (2013)



EUV of 13.5 nm by LPP (Laser produced plasma) 250 W level now (peak 400 W)
Need breakthrough for higher EUV light (>1kW)

Breakthrough for EUV light by using FEL (with ERL)



X-ray pulse duration ~ 50 ps

Micro-bunching -> SASE lasing → high peak power

X-ray pulse duration ~ 10 fs

G. Dattoli et al., NIM-A (2001)

In case of normal conducting accelerator,
The repetition rate of FEL is less than 100Hz
→ High repetition with SC cavity is needed for kW laser

Challenges for future lithography (from the report of IRDS)

https://irds.ieee.org/editions/2022/irds%E2%84%A2-2022-lithography

- Beyond EUV -> wavelength tunability
- To avoid stochastics -> Higher-power
- Polarization control
- Cost reduction for exposure system

Table LITH-4 The Key Challenges of High-NA EUV Lithography

Key challenges
Resists meeting resolution requirements, with low levels of defects from stochastic phenomena and pattern collapse
Light sources that can support photon shot noise and productivity requirements
Solutions for meeting small depths-of-focus at 0.55 NA
Polarization control for maintaining high contrast at 0.55 NA
Computational lithography capabilities
Mask making and metrology infrastructure
Solutions for large dies
Cost of high-NA EUV lithography

Table LITH-2 Potential Solutions for Leading-Edge Logic Lithography

	2022	2025	2028	2031	2034	2037
Logic node	3 nm	2.1 nm	1.5 nm	1.0 nm	0.7 nm	0.5 nm
Node	G48M24	G45M20	G42M16	G40M16T2	G38M16T4	G38M16T6
Minimum ½-pitch	12 nm	10	8 nm	8 nm	8 nm	8 nm
Primary options for logic	EUV 0.33.NA multiple patterning	EUV 0.33.NA multiple patterning EUV 0.55.NA single patterning	EUV 0.55.NA single patterning EUV 0.55.NA multiple patterning	EUV 0.55.NA single patterning EUV 0.55.NA multiple patterning Beyond EUVL (λ=6.X nm)	EUV 0.55.NA single patterning EUV 0.55.NA multiple patterning Beyond EUVL (λ=6.X nm)	EUV 0.55.NA single patterning EUV 0.55.NA multiple patterning Beyond EUVL (λ=6.X nm)
Potential solutions for cost reduction, LER		Optical + DSA EUV + DSA	Optical + DSA EUV + DSA	Optical + DSA EUV + DSA	Optical + DSA EUV + DSA	Optical + DSA EUV + DSA

Partially modified from the presentation slide of Norio Nakamura: Presentation slide in MNC2022

Electricity Consumption & Cost

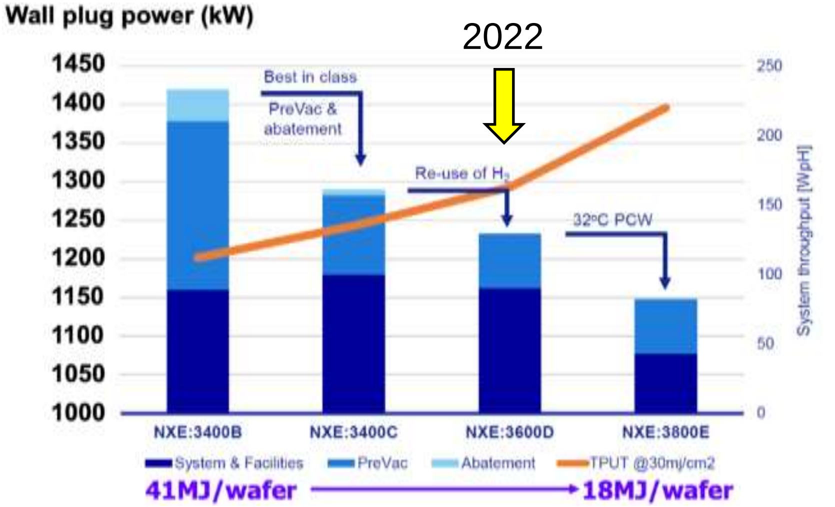
Sustainable semiconductor technologies & systems(SSTS) program

- CO_2 footprint of semiconductor manufacturing is rapidly rising.
- Environmental score is newly added to the traditional ones.

Requirements of chips in technology development

L. V. den Hove, Proc. Metrology, Inspection, and Process Control XXXVI, PC1205301(2022).

NXE:3X00 electricity consumption



M. van den Brink, ITF USA (2020)

Electricity consumption

- ➢ EUV-FEL : ~7.0 MW/10-kW EUV ⇒ ~0.7 MW/1-kW EUV(or scanner)
- ➢ LPP : ~1.1 MW/250-W EUV ⇒ ~4.4 MW/1-kW EUV(or scanner)

The EUV-FEL can greatly reduce the electricity consumption per scanner.

*) very rough estimation

- ➢ EUV-FEL cost: ~US$400M/10-kW EUV ⇒ ~US$40M/1-kW EUV (or scanner)
- ➢ LPP price : ~US$20M/250-W EUV ⇒ ~US$80M/1-kW EUV (or scanner)

EUV-FEL electricity consumption (tentative)

Items	Electric power
Refrigerator System	~3.2 MW
RF Source	~1.3 MW
Other components	~1.0 MW
Infrastructure	~1.5 MW
Total	~7.0 MW

Additional comments

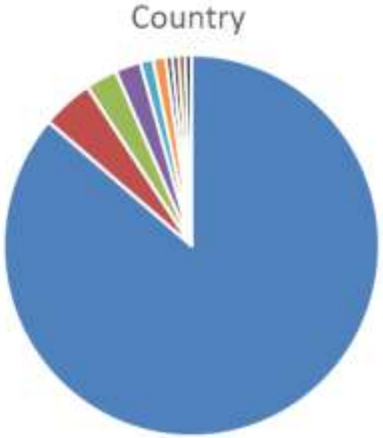
- ➢ EUV-FEL is expected to have no problem of the debris on mirror system

The EUV-FEL can reduce the construction & running costs per scanner.

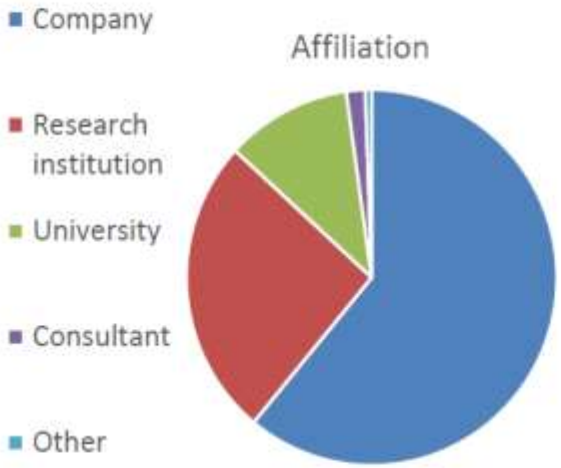
Participants

Number of registers; 186 @29/January/2023

Country	Number
Japan	161
United States	8
China	5
Taiwan	4
Belgium	2
Netherlands	2
Germany	1
Jersey	1
Korea	1
Romania	1
	186



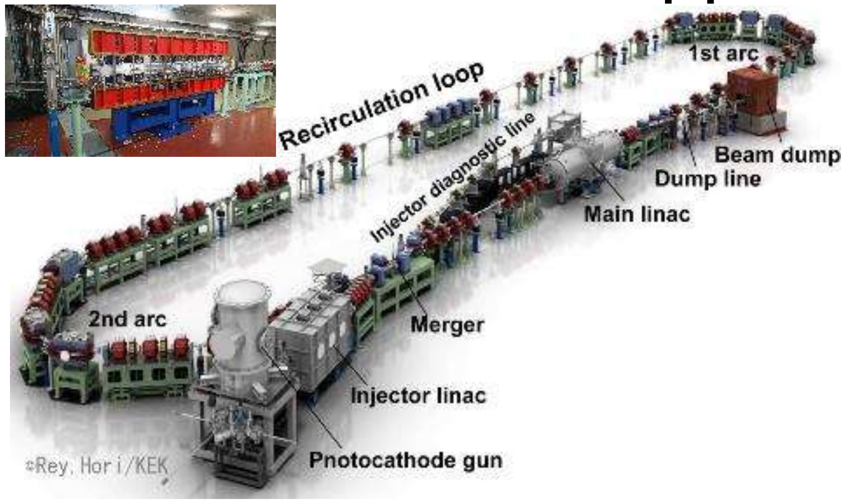
Affiliation	Number
Company	111
Research institution	51
University	20
Consultant	3
Other	1
	0
	0
	186



Total 186,
~15% from abroad

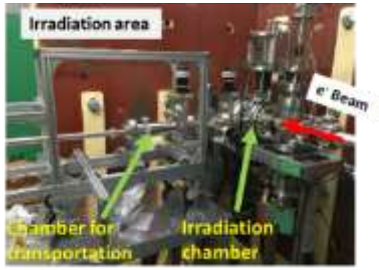
e-irradiation

Applications of SRF accelerator



"Development of high-power mid-infrared lasers for highly efficient laser processing utilizing photo-absorption based on molecular vibrational transitions." making SASE-IR-FEL with ERL.

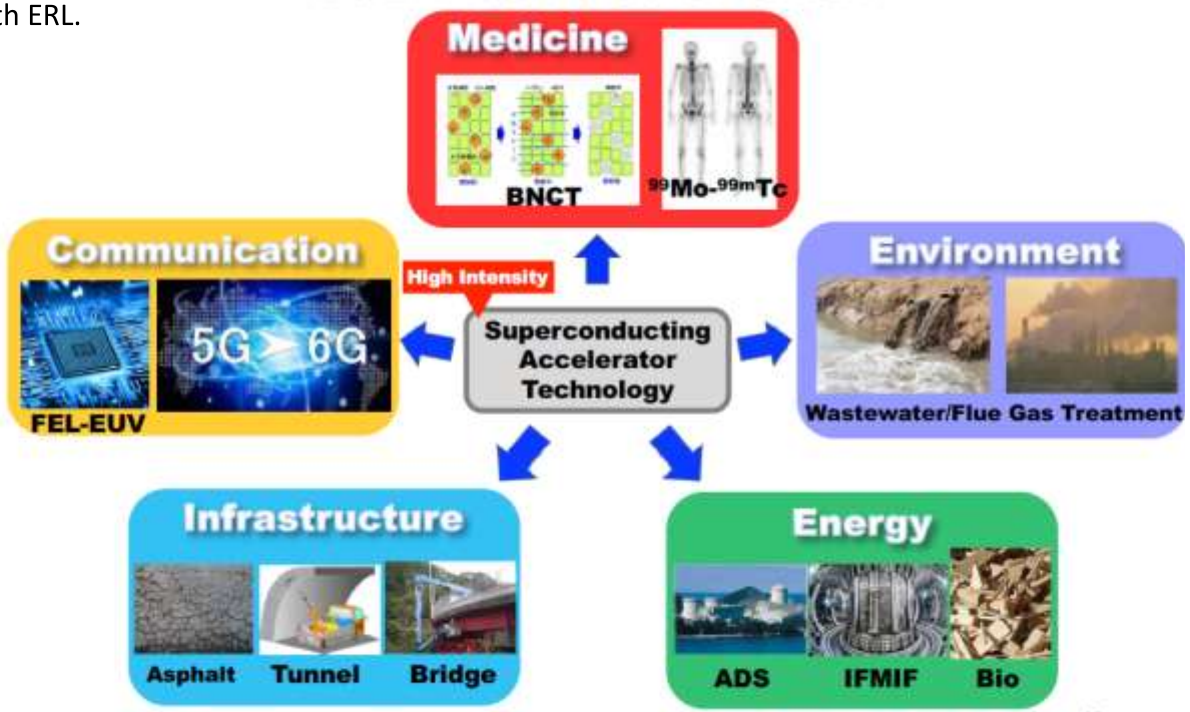
cERL (CW and SRF accelerator) is the key to applied research on accelerators.



Mo-99 production and technetium extraction at KEK's cERL (2019.10 KEK news)

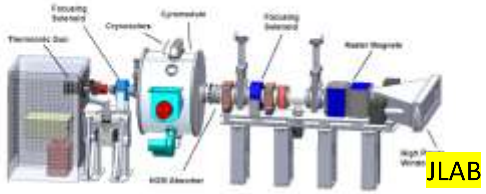
- Acquisition of external funds using cERL
  - Laser processing
  - Mo99
  - Asphalt
  - Nano-cellulose
- Under application/preparation
  - Water purification
  - EUV-FEL

Many application of e-irradiation

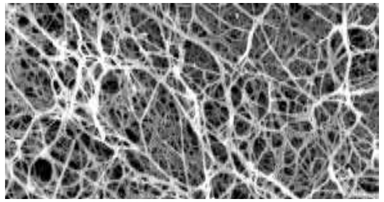


~10-kW EUV sources for Next Generation Lithography
ERL-FEL is the most promising light source

Electron beam onto asphalt to harden it and extend its life.



Water purification by electron beam irradiation (Japan-India)



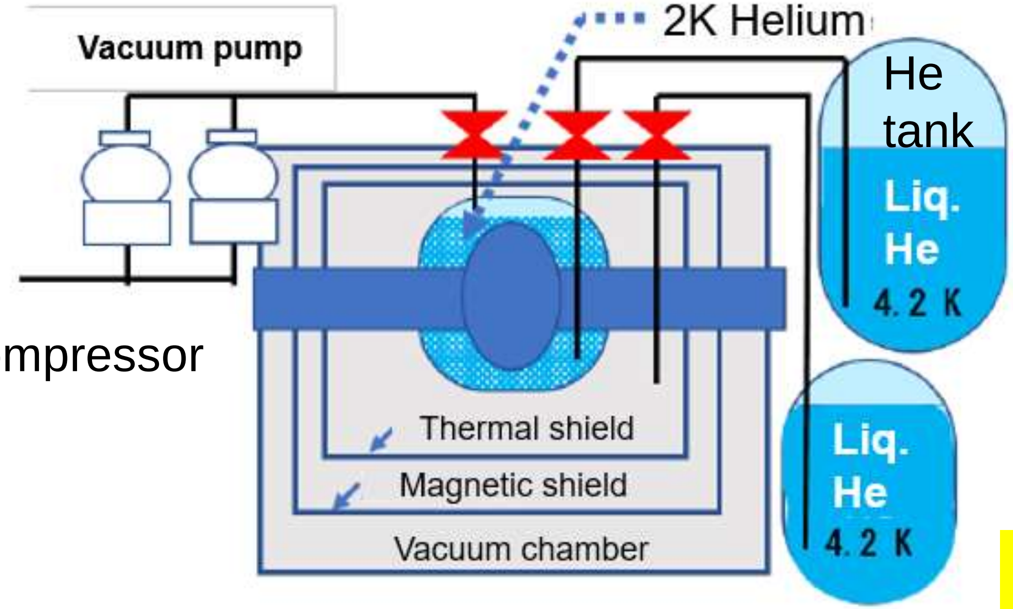
High efficiency and low cost of nanocellulose production by electron beam irradiation (collaboration with AIST) .

Comparison between Nb cavity and Nb_3Sn cavity

Nb cavities (based on cERL)

He refrigerator in cERL > 300 m^2 !!

Need large Helium plant



Compressor

Less heat loss

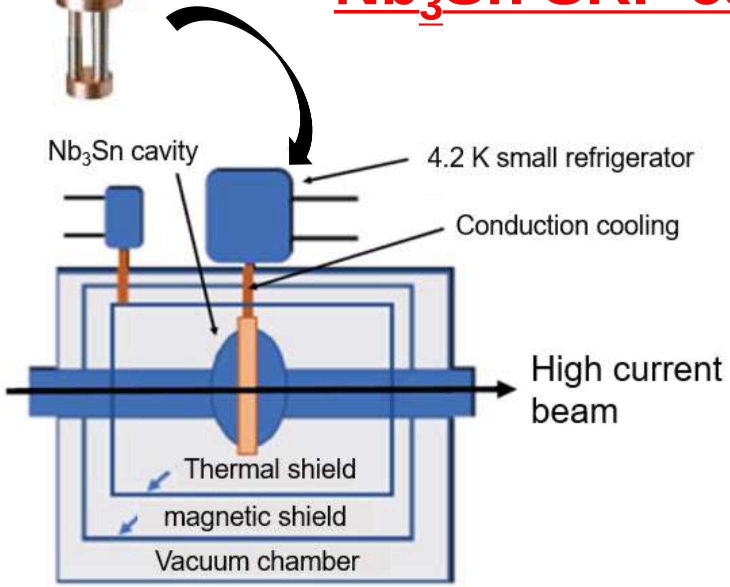
Replace large Helium plant to small cryocooler

>

Nb_3Sn cavities

Small refrigerator (< 0.1 m^2)→ put on cryomodule

Compact accelerator by Nb_3Sn SRF cavity



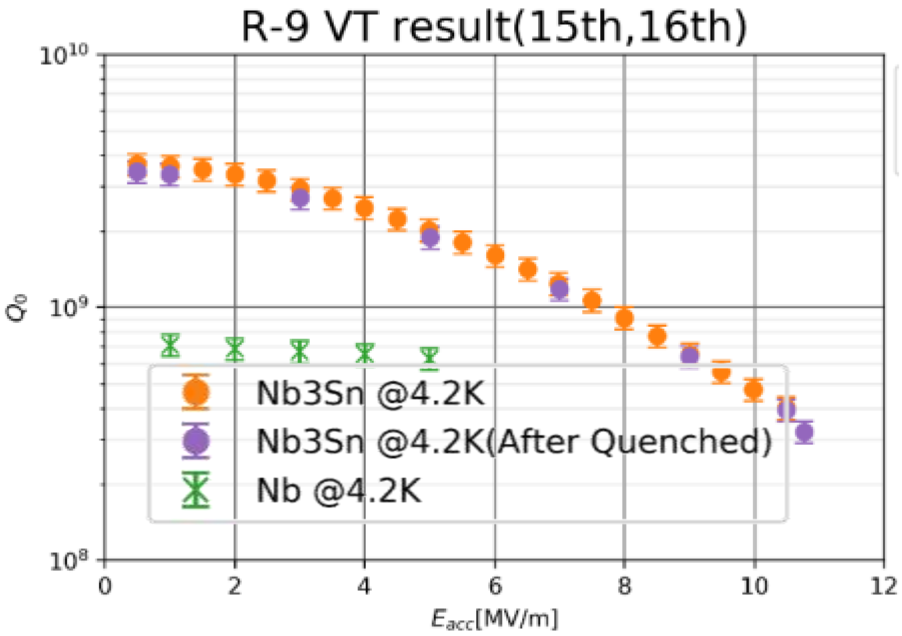
Turnkey system is possible ! & make compact accelerator with high current beam

Nb3Sn development at KEK
by Tomohiro Yamada

Nb$_3$Sn cavity R&D

Process of Nb$_3$Sn coating

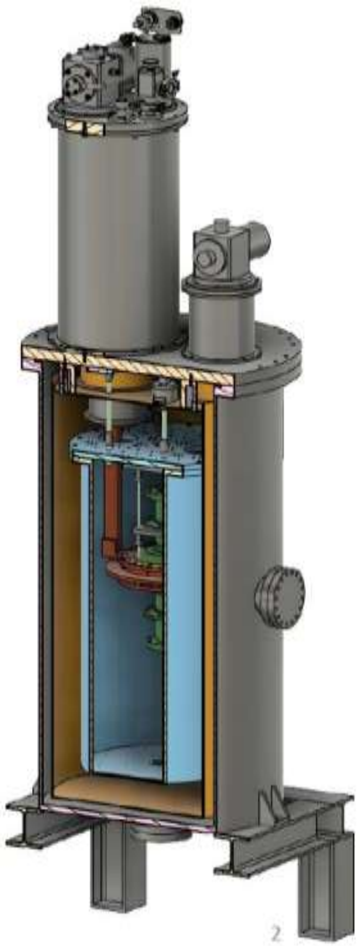
- Q value higher than Nb cavity at 4.2K
- Maximum acceleration gradient 10.8 MV/m
- Recently changed to a tin crucible with a large solid angle to ensure sufficient tin vapor pressure
- Maintenance of a clean booth to prevent contamination during deposition
- Use of Nb foils to ensure tin vapor pressure



Conduction cooling

Conduction cooling by compact cryo-cooler

- Conduction cooling test
- Preparation for cavity test



Examples of applied research by using high current beam irradiation by using superconducting accelerator（high-efficient CNF production）

New material made from wood：
[Cellulose Nanofiber (CNF)]
→need special chemical and multiple mechanical treatments → **Problem : High cost for production**

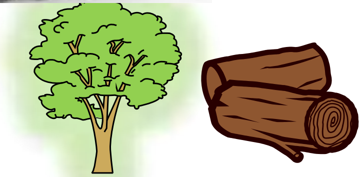
Merit for using accelerator：make CNF efficiently.
→CNF efficiency from a few 10% to 80% by irradiation (cERL)
CNF are produced with high-efficiency and results in low cost.

The market size for CNF composite resins is expected to several trillion JPY in 2030

Fig6. Timing of the practical application of CNF materials and market size
Source: Professor Yano, Kyoto University

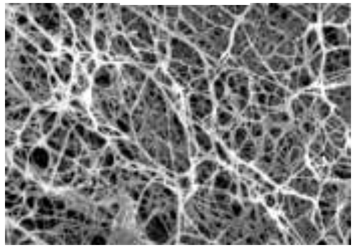
(source) Ministry of the Environment "Guidelines for the Utilization and Application of CNF (Summary)" http://www.env.go.jp/earth/ondanka/cnf.html

high current beam made by superconducting accelerator



Electron beam

CNF



accelerators： 500kW× 2 unit
（10MeV×50mA：our target）

Assume 80% production ratio by this accelerator

CNF production ratio＝ 24000t/year

Satisfy CNF demand

Future CNF demand is expected to 30000t/year

This CNF production is one example of using high power accelerator to stimulate new demand.
Key word for industrial application → compact and versatile superconducting accelerator

Summary

- To further promote industrial medical applications, iCASA was established in April 2022.
- In particular, the application of ERL (Energy Recovery Linac) to semiconductor lithography (EUV-FEL) and high-power electron irradiation using Nb_3Sn cavities are promising.
- EUV-FEL has advantages in energy efficiency. About 5 years of component development is planed before prototype construction.
- For electron irradiation accelerators, the Nb_3Sn cavity (with conduction cooling) has the potential to be a breakthrough that does not use liquid helium, and R&D is progressing worldwide.
- These will lead to applications such as ^{99}Mo, nanocellulose production, and asphalt modification.

Thank you for your attention