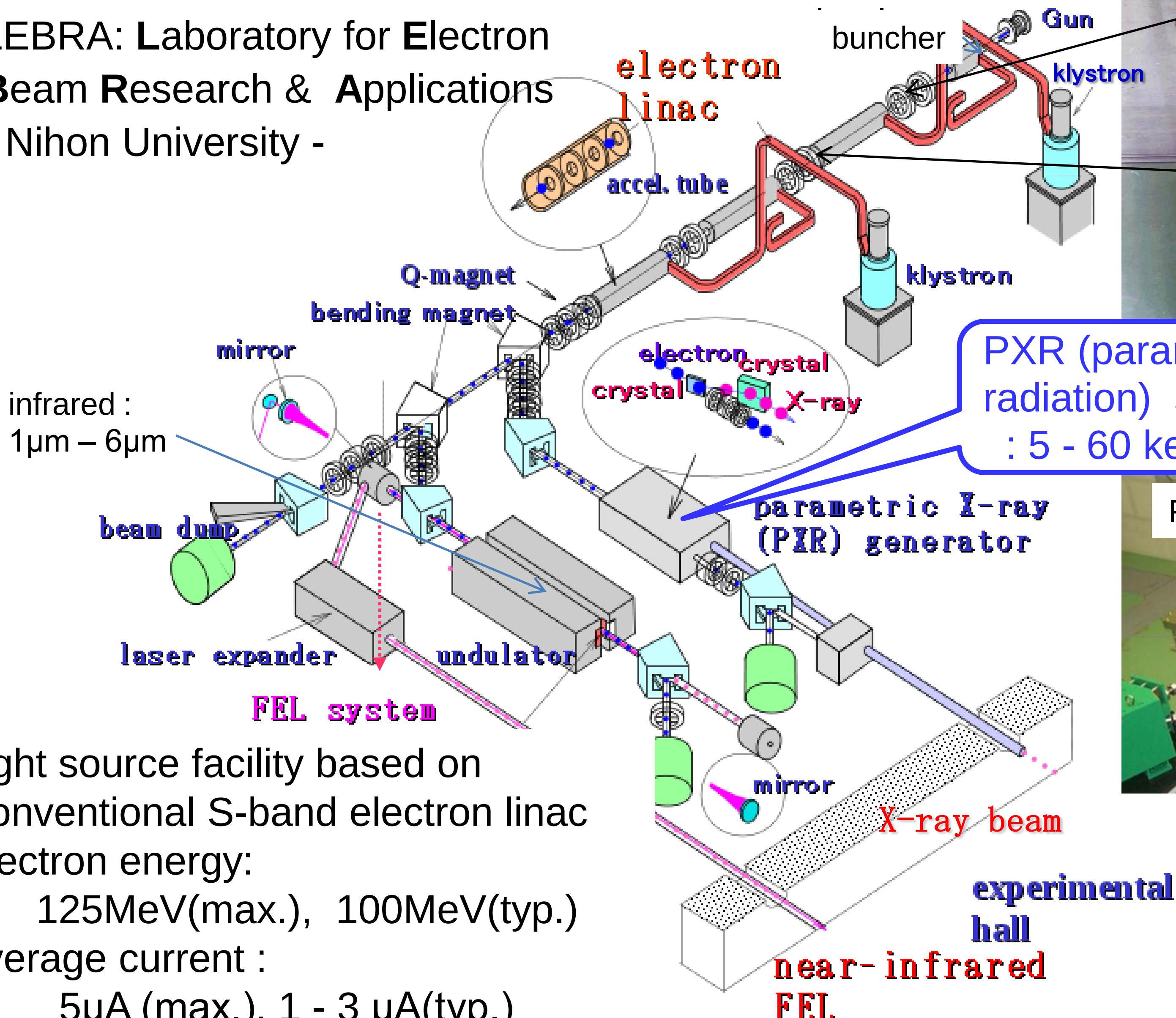
Proposal for a compact coherent x-ray source for use in medical imaging based on an energy recovery linac and parametric x-ray radiation

Y. Hayakawa[a], I. Sato[a], K. Hayakawa[a], T. Tanaka[a], M. Inagaki[a], T. Sakai[a], K. Nakao[a], T. Shintomi[a], T. Suwada[b], S. Yamaguchi[b], K. Ueno[b], S. Michizono[b], M. Sato[b], M. Yoshida[b], T. Takatomi[b], S. Fukuda[b], M. Wake[b], H. Hatanaka[c], A. Iino[c], C. Hyon[c], T. Iida[c], T. Maruyama[c], T. Mochizuki[c], <u>H. Takenaka[c]</u> and K. Endo[c]

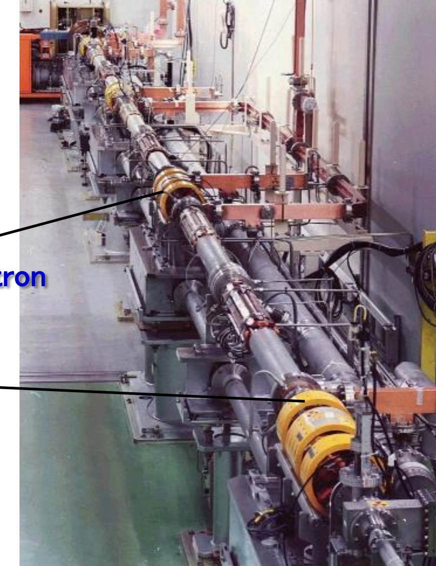
[a]Nihon University
[b]High energy accelerator research organization
[c]Toyama Co., Ltd.

LEBRA tunable light source facility

LEBRA: **L**aboratory for **E**lectron **B**eam **R**esearch & **A**pplications
- Nihon University -

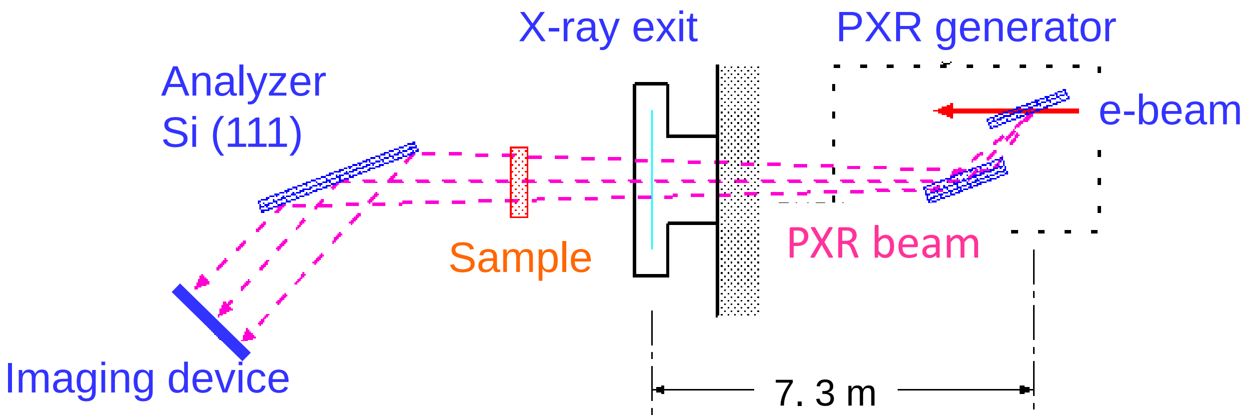


PXR (parametric X-ray radiation) source
: 5 - 60 keV



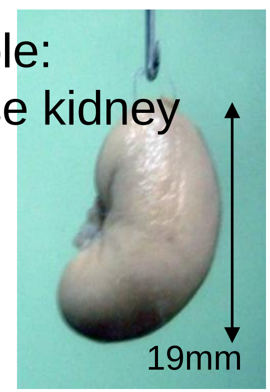
- Light source facility based on a conventional S-band electron linac
- Electron energy:
  125MeV(max.), 100MeV(typ.)
- Average current :
  5μA (max.), 1 - 3 μA(typ.)

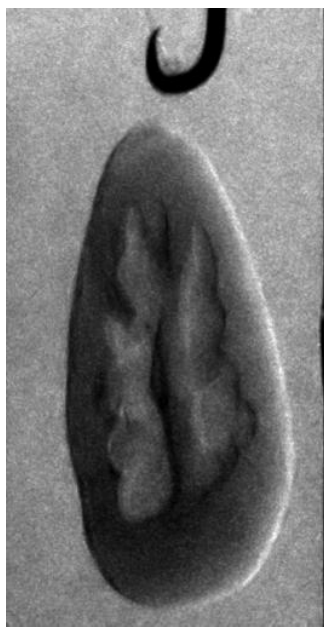
Applications: Imaging & X-ray absorption fine structure



Analyzer-based Phase-contrast imaging
(DEI: Diffraction-enhanced imaging)

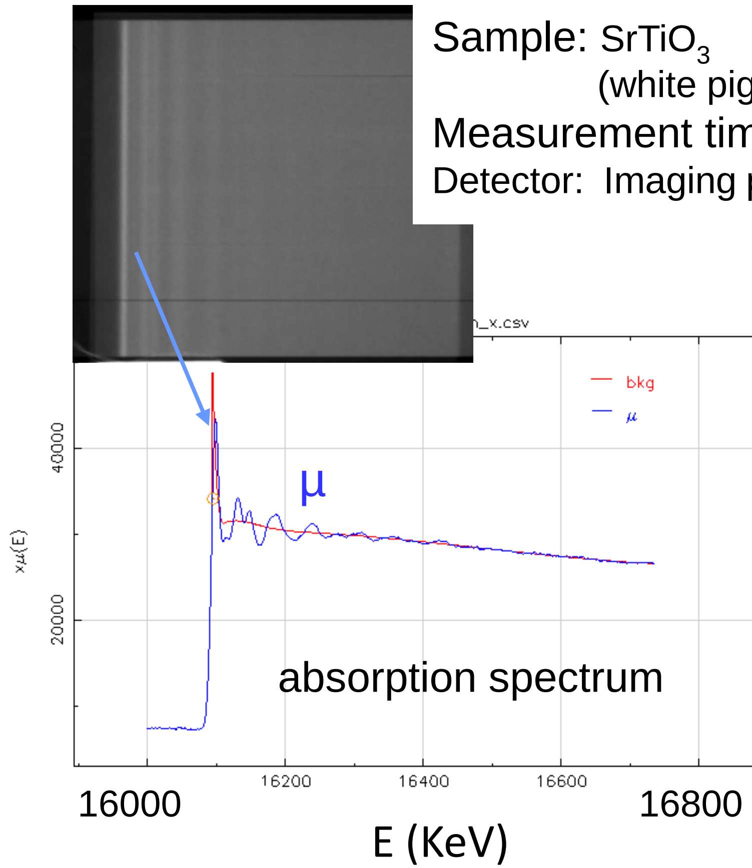
sample:
mouse kidney





PXR radiator: Si(111)
PXR energy: 17.5keV
e-beam: 2.6μA (average)
detector: CCD
exposure of
each image: 60s

Sample: $SrTiO_3$
(white pigments)
Measurement time: 30min
Detector: Imaging plate



To realize highly sensitive phase-contrast imaging for the material sciences, especially for soft materials, a PXR-based x-ray source is one of the most attractive candidates.

■ For practical imaging,

- High energy monochromatic x-rays with a flux of 10^9 - 10^{10} /s are needed

- A compact PXR-based x-ray source with easy access to the PXR working area is required.

Therefore, we are developing a new compact PXR-based x-ray source.

1. Production of high energy monochromatic x-rays with a flux of between 10^9 and 10^{10} /s

It is proposed that this x-ray flux can be obtained using a 75 MeV high duty cycle electron linac with an average current of 20-30 μA.

It is not too difficult to develop a linac with this level of performance.

2. With regard to a compact PXR-based x-ray source

Significant problems for applications using PXR are the size of the linac, the volume of the radiation shield, and having access to the working area of the PXR source.

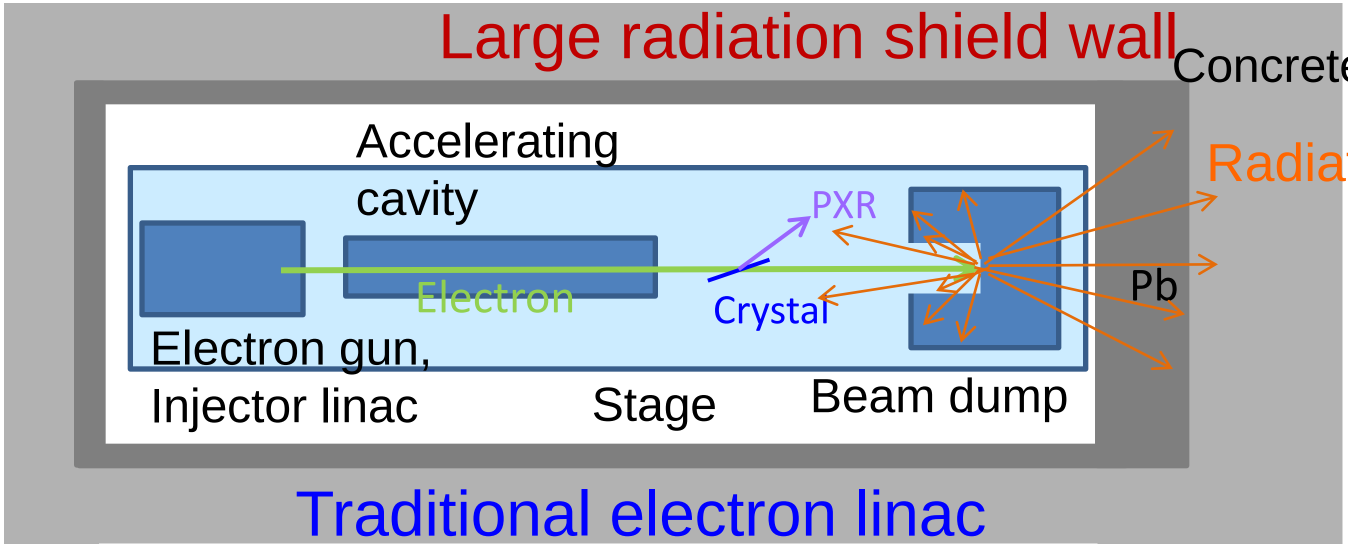
Why do we need a shield wall?

The reason is that :

- In conventional electron linacs, the e-beam is accelerated and strikes a target. The residual electrons are subsequently absorbed in a massive beam dump.

- The energy of the electrons is released from the beam dump as radiation in the form of γ-rays and neutrons.

Therefore, the linac needs a large shield wall to prevent this radiation from escaping.



We would like to reduce:

1. To reduce the size of the linac

A linac with a high acceleration gradient is desirable to reduce the size of the linac itself.

This can be achieved by using C-band high gradient accelerating and decelerating cavities, rather than the S-band accelerating cavity used in the traditional linac.

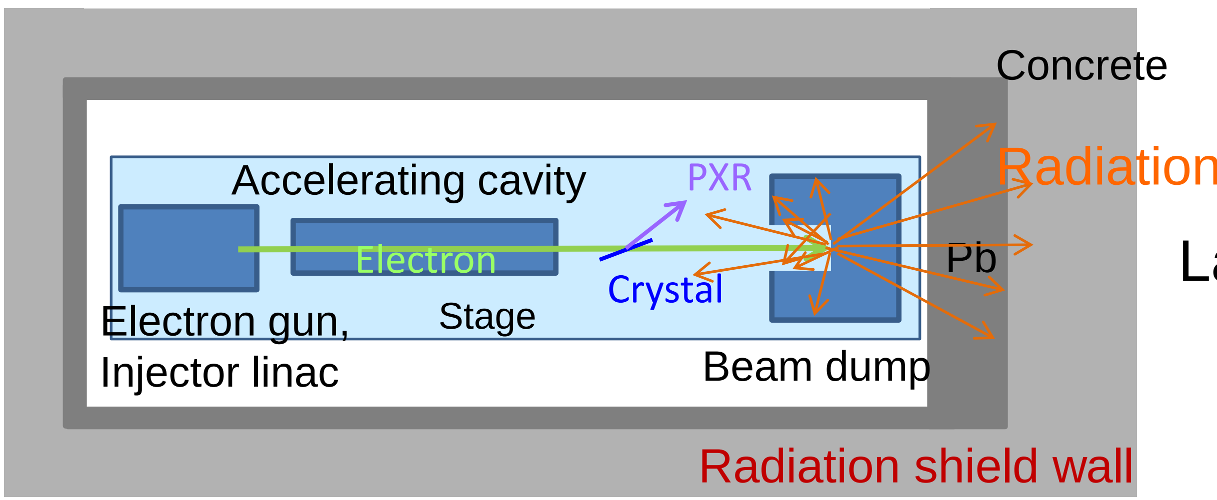
2. To reduce the size of the shield wall

Suppressing the background radiation, which is mainly produced at the beam dump, is a very effective means of reducing the dimensions of the PXR source.

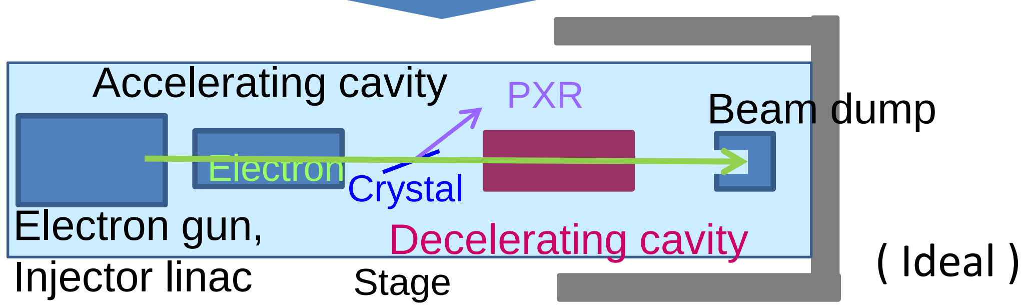
This can be done by introducing a decelerating cavity to remove energy from the electron beam.

- If we add a suitable decelerating cavity in front of the beam dump, the e-beam is decelerated and the linac generates either no radiation or only a very small amount of radiation.

- This system doesn't need a large surrounding radiation shield.



Large size

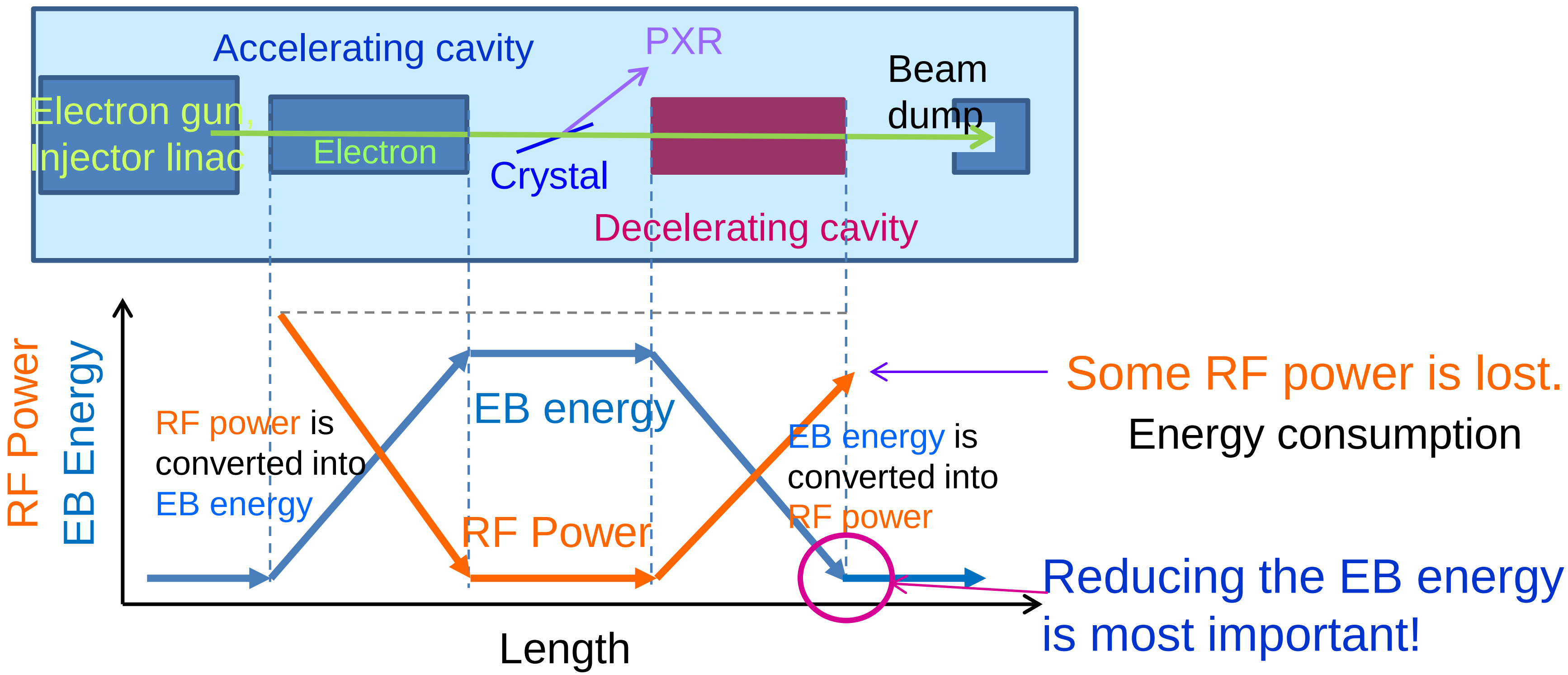


Small size

Reduction in size of the linac and the radiation shield

- In this system, the RF power is converted into electron beam (EB) energy in the accelerating cavity, and then the energy in the EB is used to generate the PXR. Subsequently, the energy in the EB is converted back into RF power in the decelerating cavity.

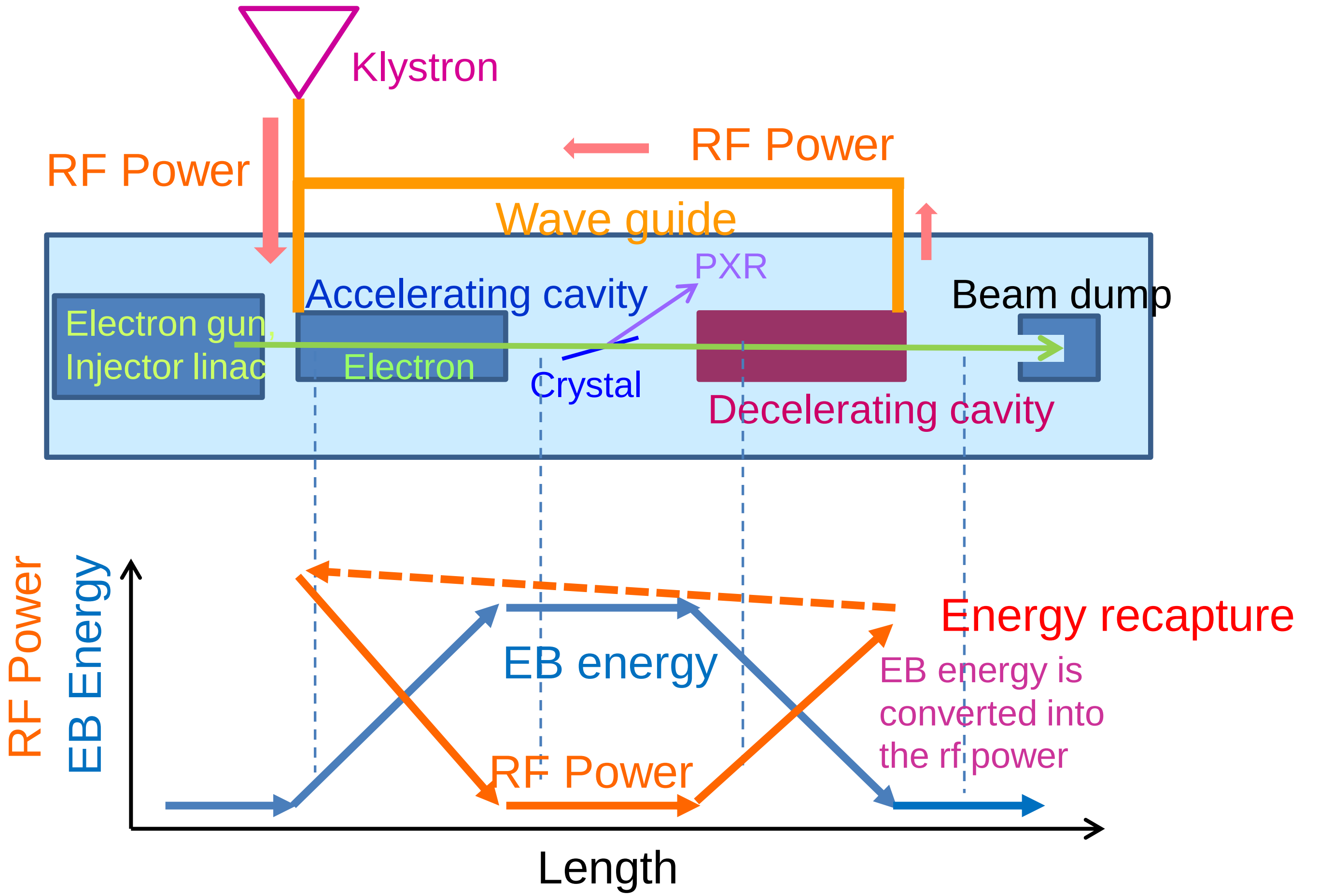
- The EB loses most of its energy in the decelerating cavity so that very little radiation is emitted from the beam dump.



- However, this system consumes all the energy transferred to the EB by the accelerating cavity.

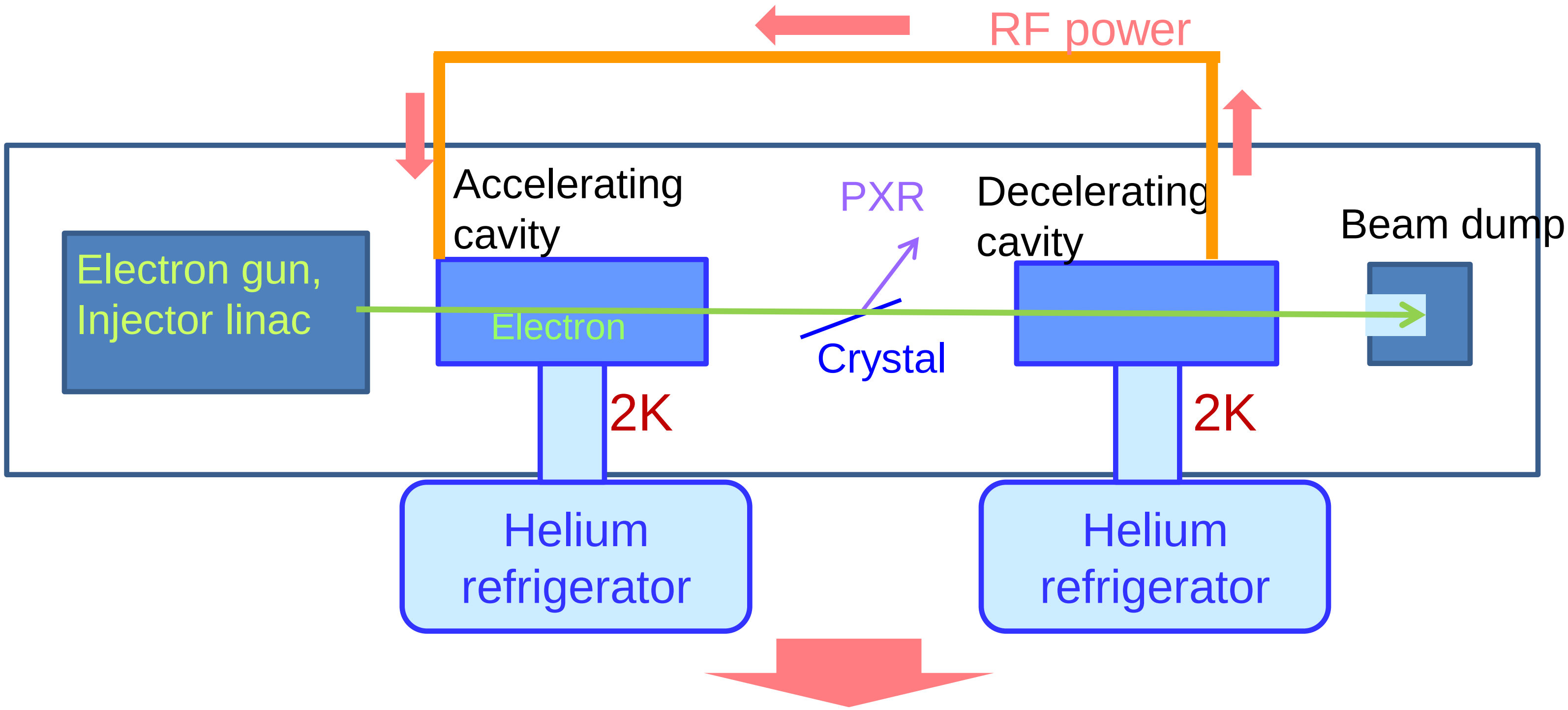
- Therefore, we proposed using an energy recovery linac (ERL) for the PXR source in order to reduce the surrounding radiation shield.

- In this system, the electron beam energy is converted into RF power, which is then added to the RF power from the klystron.



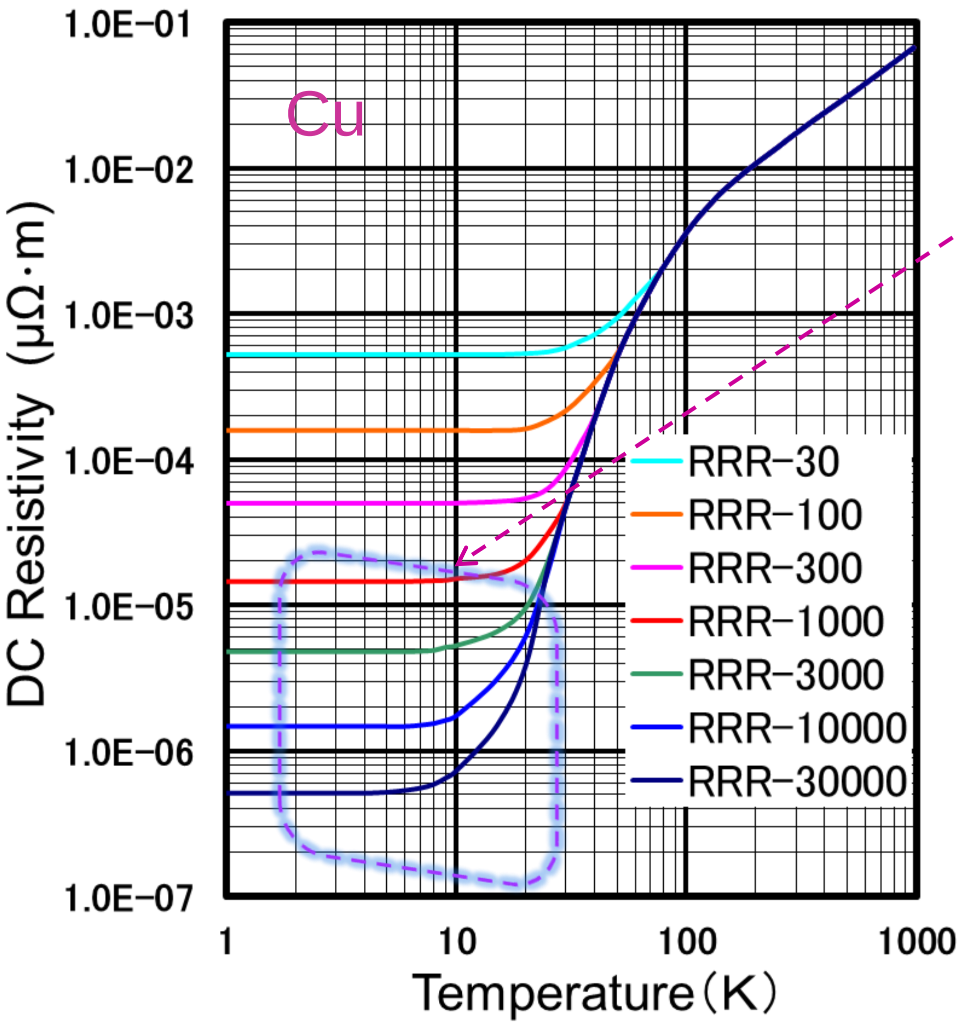
We originally planned to use superconducting RF (SRF) for the ERL system, but this would have required a helium refrigerator with high power, large size and high cost.

(RF cavities made from conducting materials such as ordinary Cu cannot be operated constantly with high electro-magnetic fields since the cavities would become too hot.)



We focused on using high-purity Cu as the cavity material, because this has low electrical resistance.

Temperature dependence of copper with various resistivities



RRR: Residual Resistivity Ratio
R(RT)／R(4.2K)

RT: room temperature

Cu with RRR>1000 has very low resistivity under 20K

The electric current flows near to the surface of the RF cavity due to the skin effect.

Even if this case, the RF cavity is expected to have a large electrical conductivity in the skin depth.

Electrical resistivity at RT and 4.2K of commercial high-purity Cu

Purity	Annealing Temp. (℃)	Time (hrs)	RRR
6N8	500	0.5	2130
6N8	500	3.5	6610
7N	500	3.0	6400
7N	500	3.0	6500
7N	non	0	57.6

RRR: Residual Resistivity Ratio
R(RT)／R(4.2K)

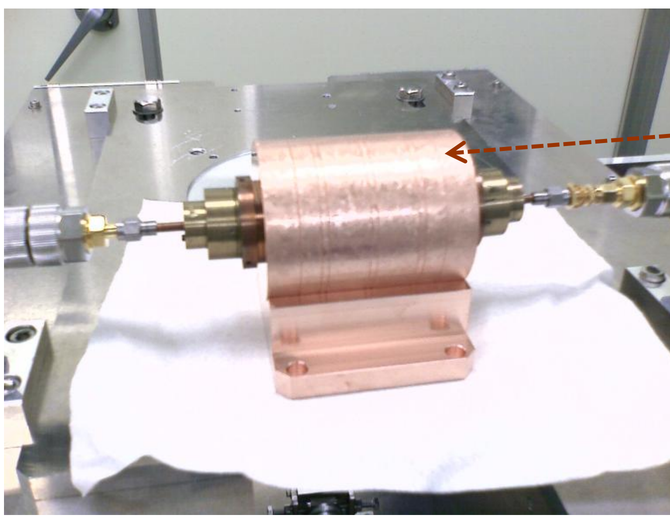
RT: room temperature

High purity Cu annealed at 500 C has a high RRR values, that is, very low resistivity.

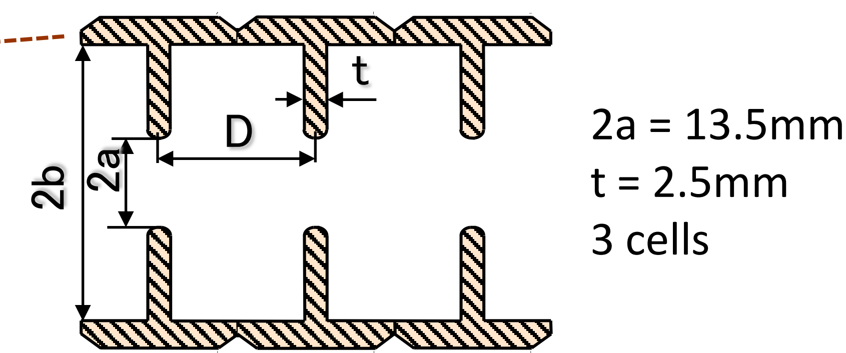
To estimate the efficiency with which energy is recovered, we need data giving the temperature dependency of the Q value of the high-purity Cu cavity.

We attempted to measure the Q value of the Cu test cavity.

A test cavity designed for the C-band $2\pi/3$ mode
was manufactured in high-purity copper (RRR- around 6000).



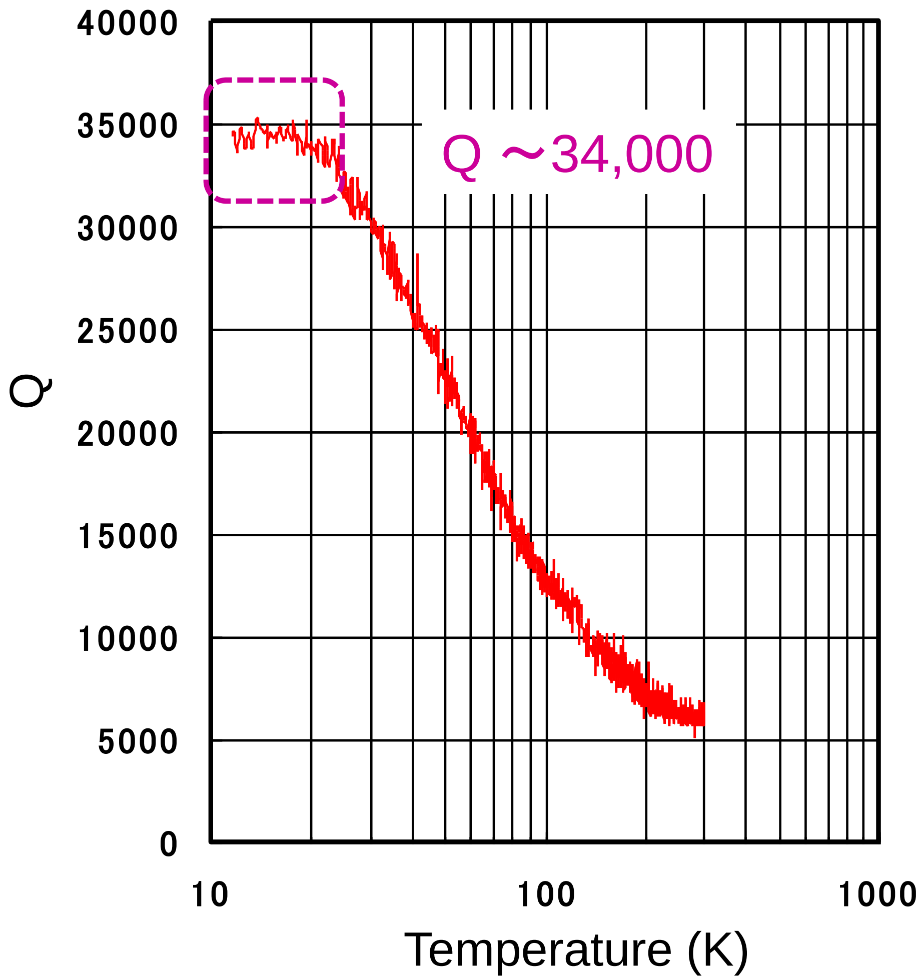
Test cavity fabricated using the diffusion bonding technique



Cross section through the test cavity

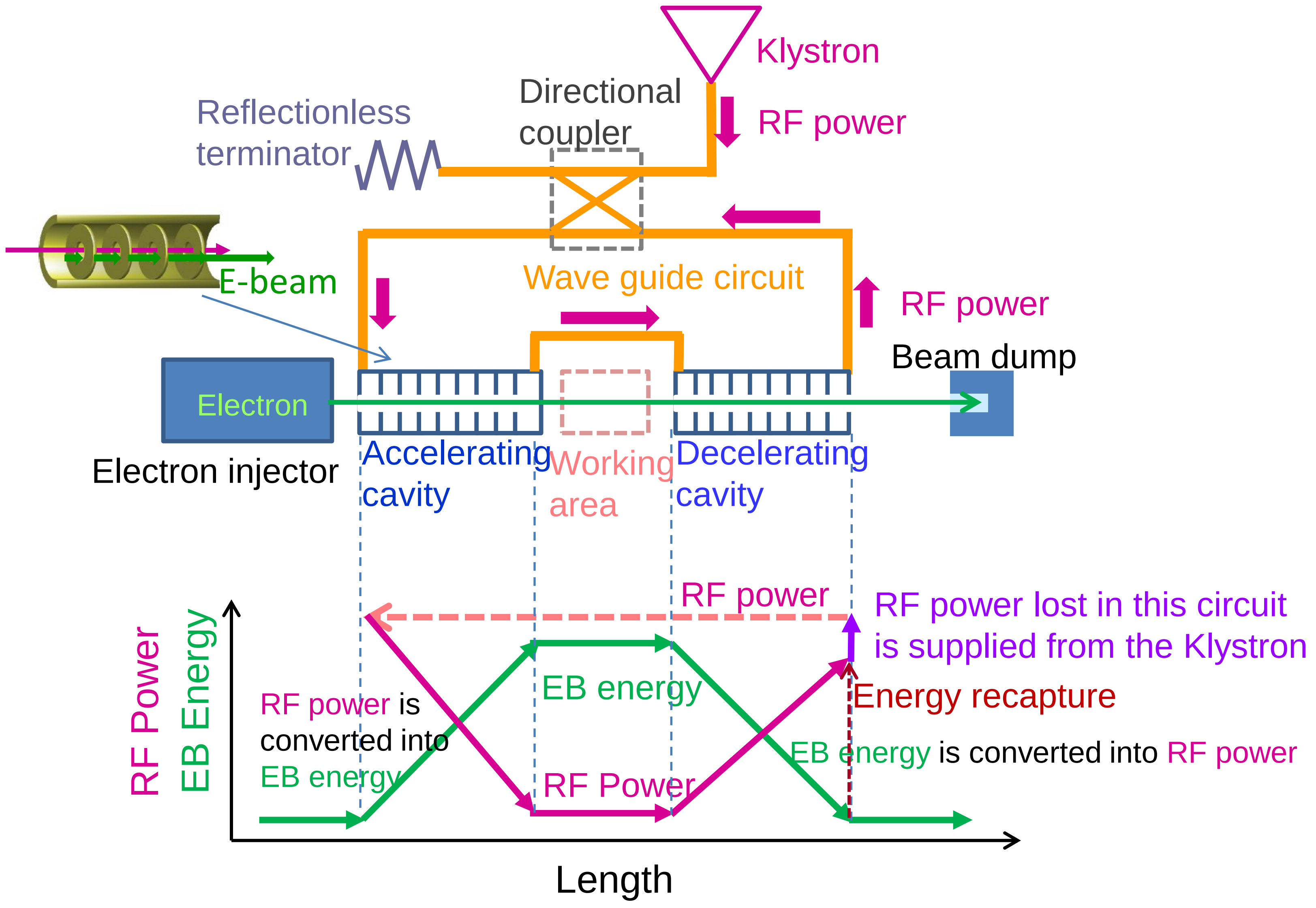
This test cavity was cooled to around 20K and the temperature dependency of the Q value was measured.

Obtained temperature dependence of the Q value of the test cavity



We used this Q value to calculate the RF power flow and the electron energy in our ERL model.

Model of the RF flow in a traveling-wave type ERL using RF cavities made from high-purity Cu



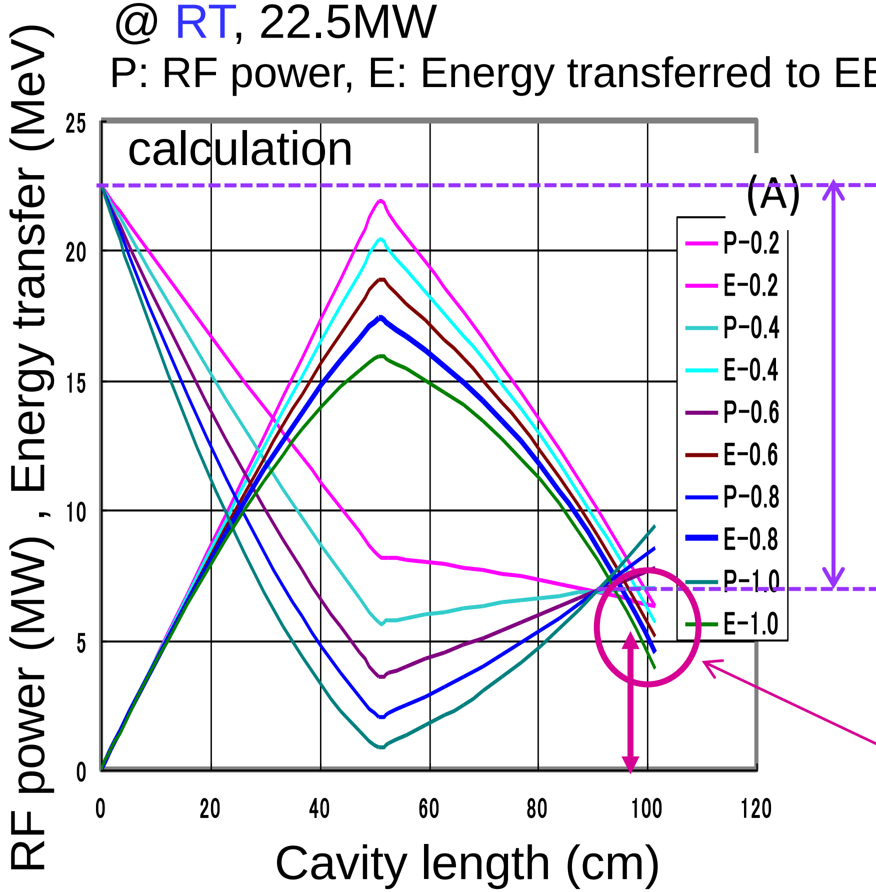
An example of the calculated relationship between the RF power and the energy transferred to the electrons in the cavity @ RT

ERL model showing the RF power flow and the energy transferred to the electrons.

Power flow & Energy transfer

@ RT, 22.5MW

P: RF power, E: Energy transferred to EB



Temperature:	RT (300K)
Accelerating energy:	75 MeV
Accelerating frequency:	5.712GHz
Accelerating mode:	2π/3
Accelerating & decelerating cavity:	disk-loaded traveling wave, 500mm
Input RF power:	22.5MW
Macro pulse beam current:	0.2 – 1.0A
Average beam current:	20-240μA
Q:	34,000

Large Power loss

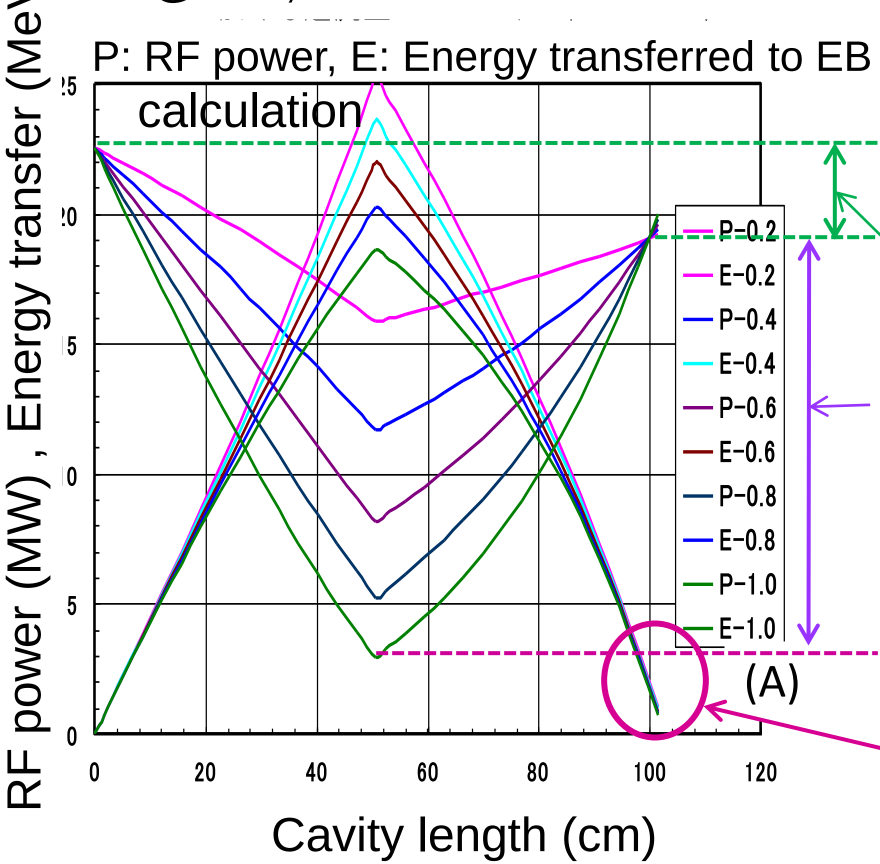
The efficiency of the energy recovery is not good, because RF power is lost due to the electrical resistivity of the accelerating and decelerating cavities.

A lot of energy is still left in the EB at the end of the decelerating cavity.

An example of the calculated relationship between the RF power and the energy transferred to the electrons in the cavity @ 20K

ERL model for the RF power flow and energy transferred to the electron beam.

Power flow & Energy transfer
@20K, 22.5MW



Temperature :	20K
Accelerating energy:	75 MeV
Accelerating frequency:	5.712GHz
Accelerating mode:	2π/3
Accelerating & decelerating cavity: disk-loaded traveling wave, 500mm	
Input RF power:	22.5MW
Macro pulse beam current:	0.2 – 1.0A
Average beam current :	20-240μA
Q:	34,000

Small power loss

The efficiency of the RF power recovery is good.

Much of the EB energy can be converted into RF power at low temperature

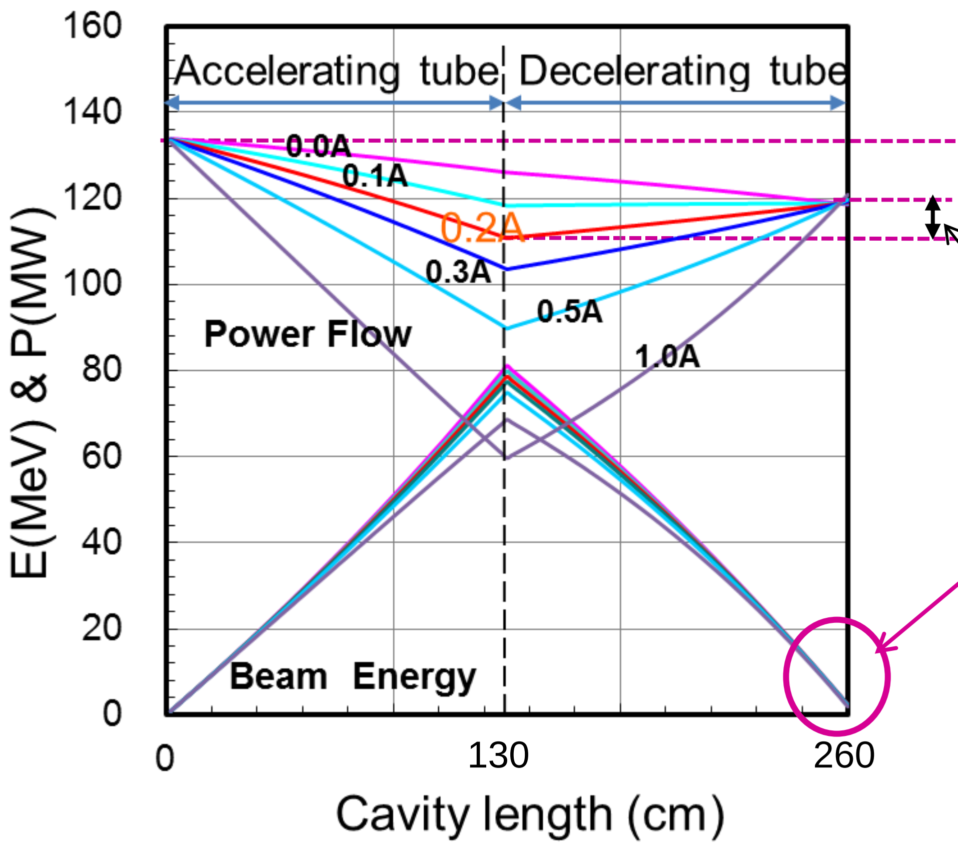
Only a small amount of energy is left in the EB at the end of the cavity.

Calculated relationship between the RF power and the energy transferred to the electron beam in the cavity of our proposed prototype machine.

Temperature :	20K
Accelerating energy:	75 MeV
Accelerating frequency:	5.712GHz
Accelerating mode:	2π/3
Accelerating & decelerating cavity: disk-loaded traveling wave, 1300cm	
Input RF power:	135MW
Macro pulse beam current:	0.0 – 1.0A
Average beam current :	20-240μA

Power flow & Energy transfer @20K, 135MW

P: RF power, E: Energy gain of EB



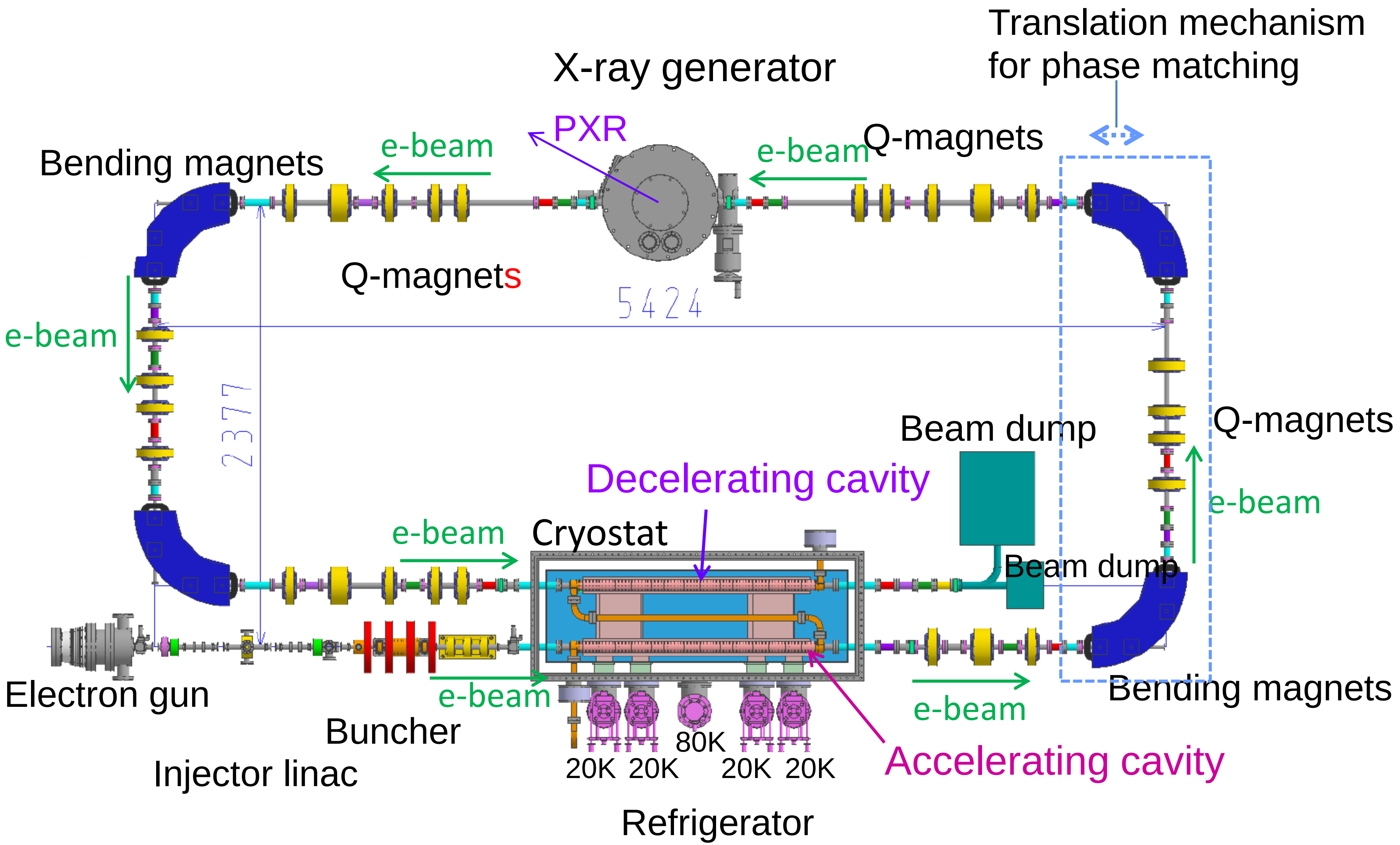
We plan to use a beam current of 0.2A in this first prototype.

At this beam current,
the recovered RF power is small.

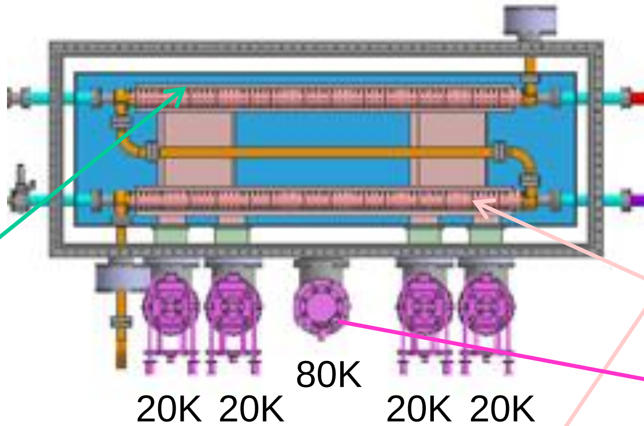
Accelerated EB loses almost all of it's energy.

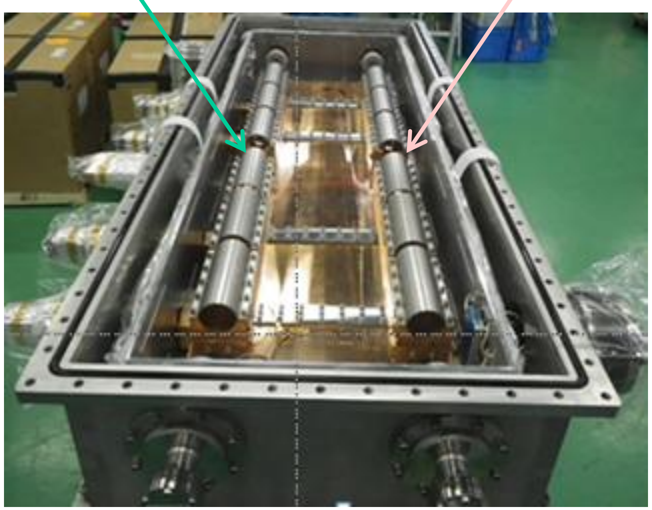
A very small amount of radiation is emitted from the beam dump

Designed normal-conducting compact cryo-linac

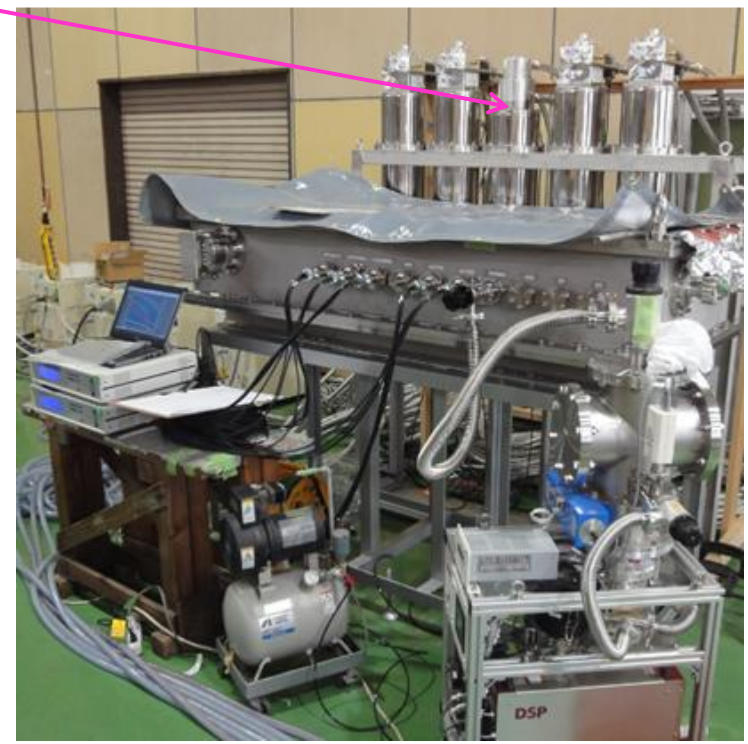


Cryostat



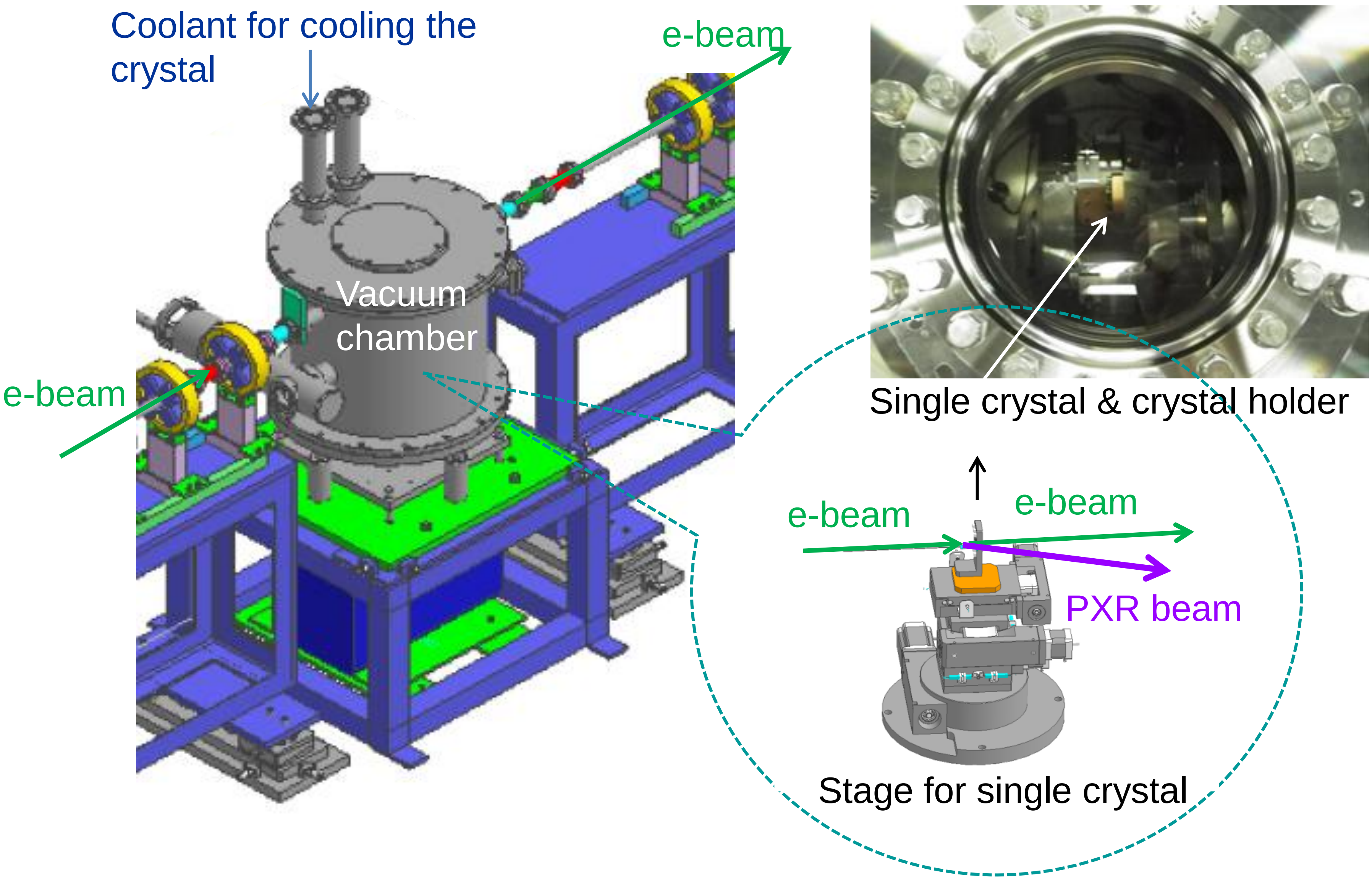


Inside the cryostat



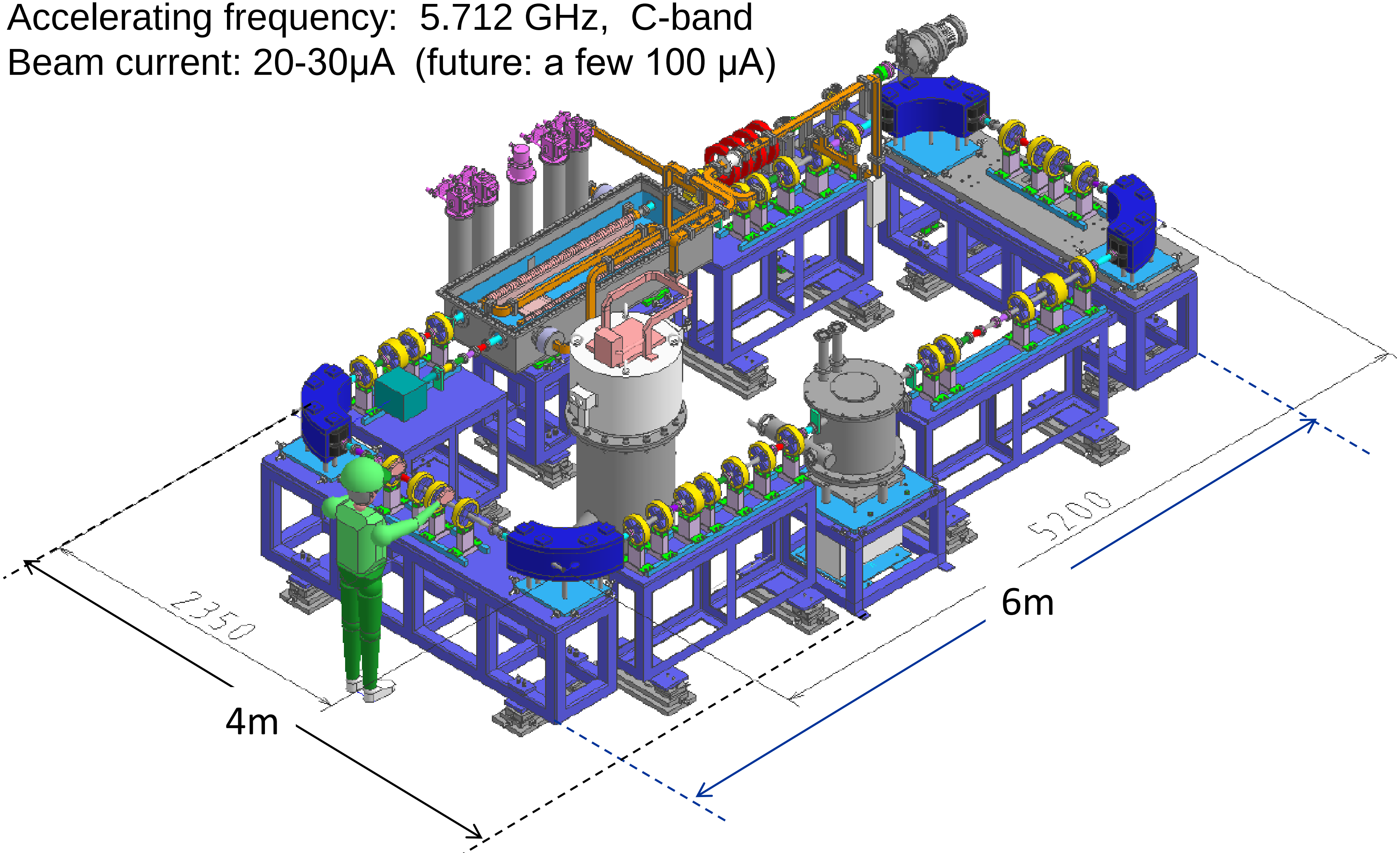
Cooling test set up for the cryostat

PXR generator



Schematic view of our proposed cryo-linac

Electron energy: 75-MeV
Accelerating frequency: 5.712 GHz, C-band
Beam current: 20-30μA (future: a few 100 μA)



Parameters of our proposed prototype cryo-linac

acceleration freq.	5.712 GHz
accelerating mode	2π/3
accelerating structure	disk loaded traveling wave
cavity material	pure copper (RRR-6000)
cavity length	1300 mm
cooling temp.	20 K
input RF power	45 MW
electron energy	~ 75 MeV
norm. emittance	< 5 π mm mrad
macro-pulse beam current	~0.2 A
macro-pulse length	~ 3.5 μS
average beam current	20 ~ 30 μA
total x-ray flux	10^9~10^{10} /s
variable x-ray energy	5 – 50 keV due to crystal rotation

Proposed cryo-linac under construction

Summary

- A compact electron linac with an average beam current of 20-30 μA at 75 MeV for PXR radiation is proposed.

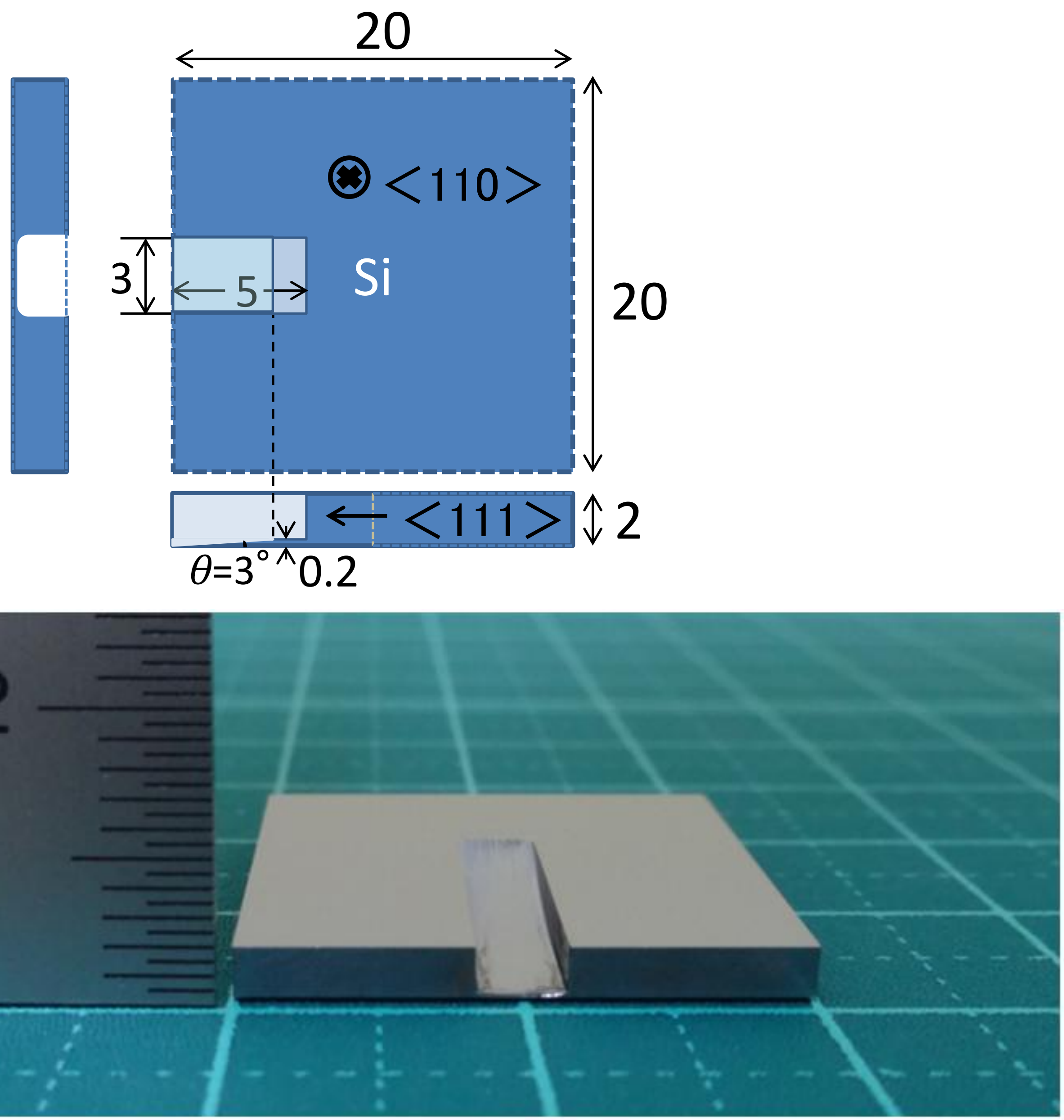
- A normal conducting high gradient C-band accelerating cavity with a high Q-value was studied.

- This study suggests that an ERL system using high-purity Cu for the cavity material in the temperature region below 20 K can be used to generate PXR radiation.

- Much of the EB energy can be converted into RF power in the decelerating cavity, thereby reducing the amount of radiation generated at the beam dump to a very low level.

-These benefits suggest that the system proposed here can be effective in many x-ray imaging applications, including medical imaging.

- The proposed cryo-linac is currently under construction.



Si crystal target

Cabinet

Inside

Klystron

Power source