<u>S</u>uperconducting <u>RF</u> Accelerator Technology and the Applications

Akira Yamamoto
(KEK)

To be presented at <u>I</u>ndian **S**mart **U**tility **C**onference, **ISUW-2025**

Session: Nuclear Renaissance and the role of SMR for the Net Zero

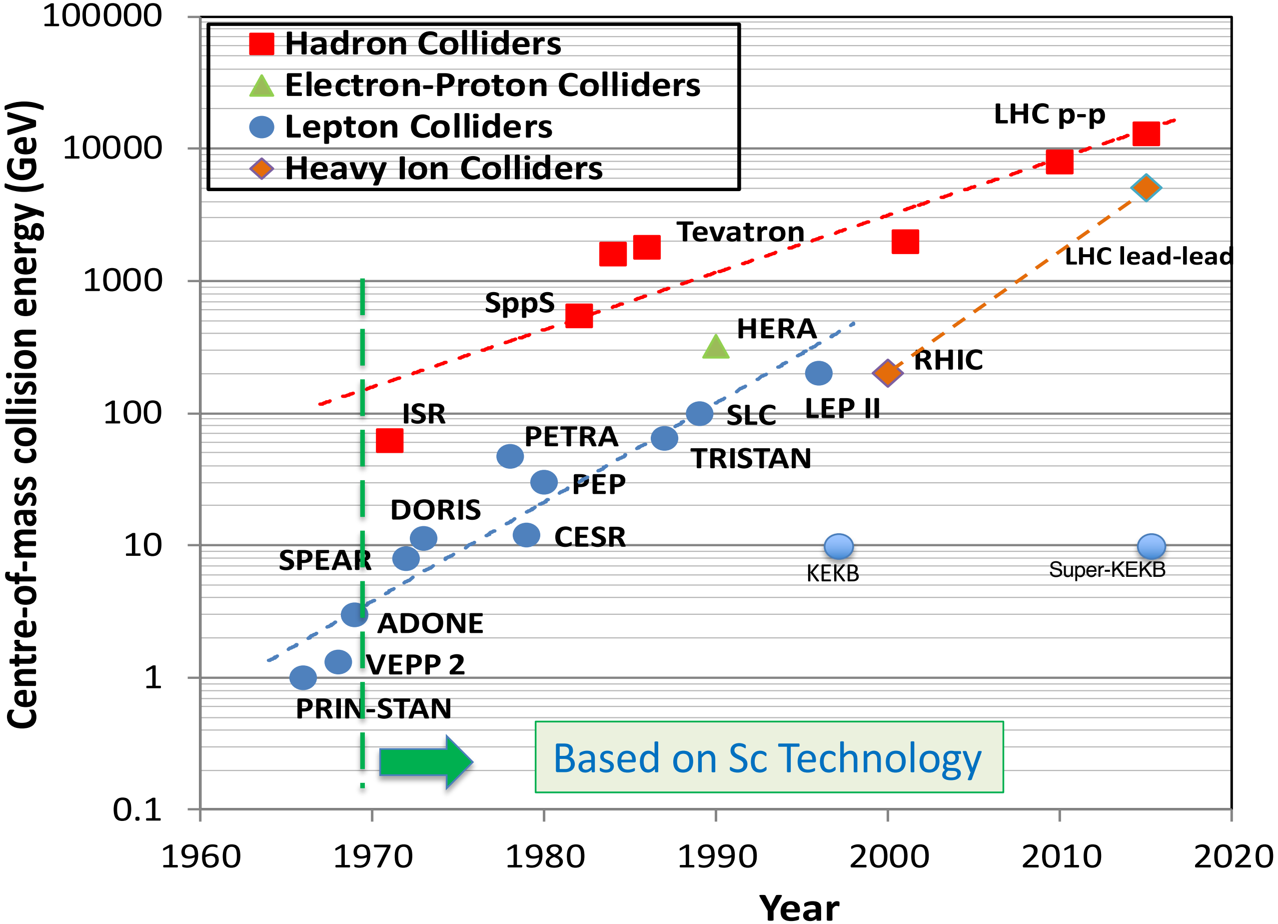
Day 3, March 20, 2025

Outline

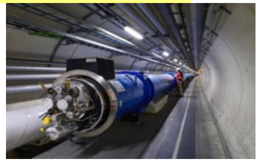
- Introduction:
- Compact ERL accelerator
- SRF Linac applications
- Future of the SRF technology
- Summary

Frontier Accelerators based on SC Technology

Courtesy, A. Ballarino



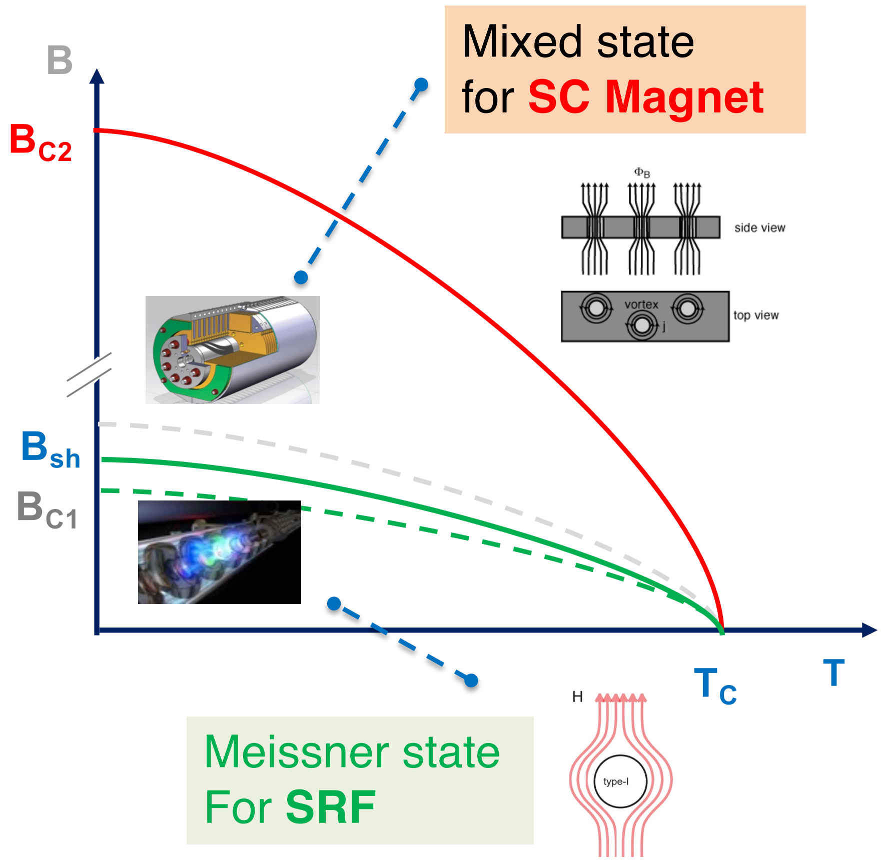
Colliders w/ Sc magnets



Colliders w/ Sc RF system

Superconductor Applications for Accelerator Magnet and RF

Material	T_c [K]	$B_c(0)$ [T]	$B_{c1}(0)$ [T]	$B_{sh}(0)$ [T]	$B_{c2}(0)$ [T]
Nb	**9.2**	(0.25)	0.18	**0.21**	**0.28**
NbTi	**~ 9.3**	--	0.067	**--**	**11.5 ~ 14**
Nb_3Sn	**~ 18.3**	(0.54)	(0.05)	**0.43**	**28 ~30**
Application				**RF**	**Magnet**



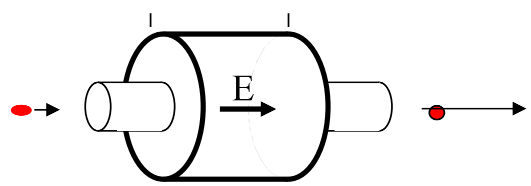
Features of Superconducting RF (SRF)

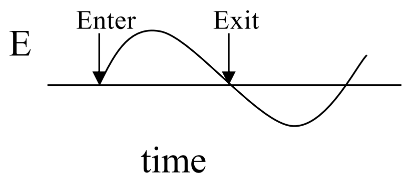
Features:

- **High Q_0 (> 10^{10}):**
  - Small surface resistance → nearly zero
  - Efficient acceleration & Low cryogenic load
- **Low Freq. (~ 1GHz) → Long beam pulses :**
  - intra-pulse feedback (in **1 ms** pulse)
- **Larger aperture(~ 70 mm ϕ) :**
  - better beam quality
  - lower wake-fields

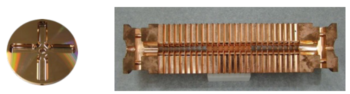
Drawback:

- **Cryogenics required → High Q_0 important**





SRF: 1.3 GHz
~ 70 mm ϕ



NRF: 12 GHz
~ 10 mm ϕ

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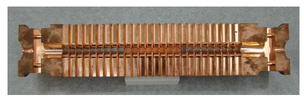
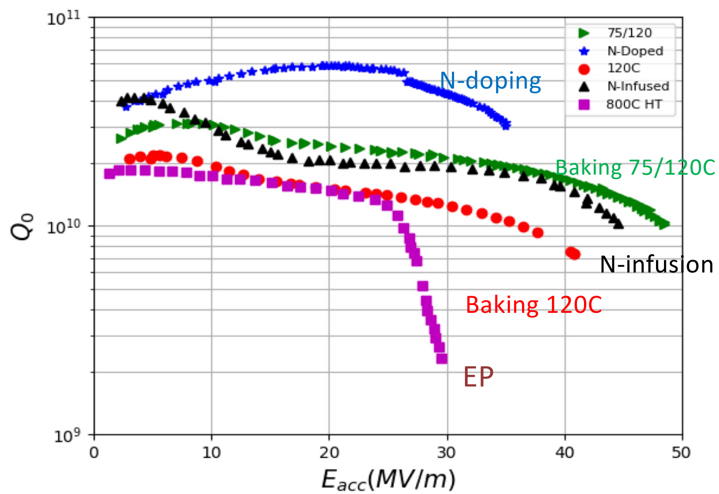


NRF: 12 GHz
~ 10 mm ϕ



Courtesy: S. Michizono

~ 1.3 GHz SRF Accelerators, worldwide

European XFEL
(in operation, 2017~)

800 cavities
100 CMs
17.5 GeV (Pulsed)

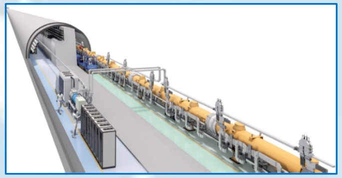
ESS (0.8 GHz)
(under construction)

SHINE
(under construction)

~600 cavities
75 CMs
8 GeV (CW)

S1 Globa (→ STFI):
DESY, Fermilab, KEK
8-cavity,,2010 → 14 cavities

cERL : KEK
2013~, 4 cavity



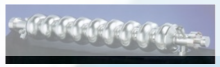
ILC (planned)

8,000 9-cell cavities, 900 CMs
2 x 125 GeV (Pulsed)

LCLS-II -HE
(under construction)

-280+200 cavities
-35+25 CMs
- 4 +4 GeV (CW)

JLab-CEBAF(1.5 GHz)
(in operation)
40 CMs
6~12 GeV(CW)



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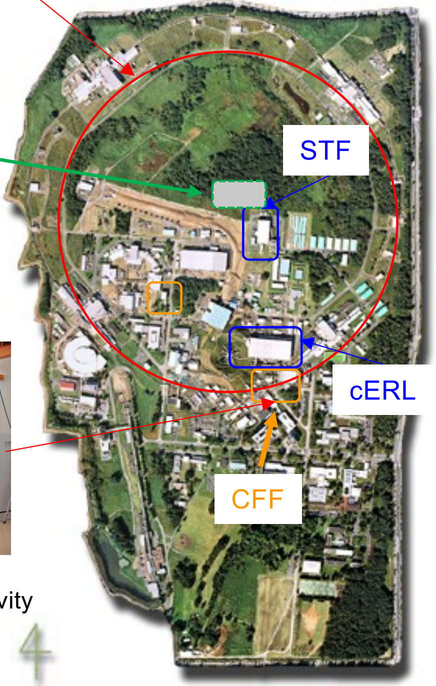
Past & present SRF development in KEK

KEK Tsukuba campus

iCASA

SuperKEKB
(circumference 3km)



COI building
(for new furnace)
& Nb_3Sn cavities

CFF

EBW & deep drawing of cavity
(Cavity fabrication)

New R&D of cavity fabrication was doen in CFF building and High-Q R&D & new material like Nb_3Sn was proceeded on COI building

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

508MHz TRISTAN (1989)

508MHz KEKB (1998)

iCASA

STF (2005-)
Cavity R&D, electro-polish, vertical test and cryomodule test

Long-pulse beam for ILC

Compact ERL (cERL)
(2013-)
Cryomodule test

For industrial application with CW beam

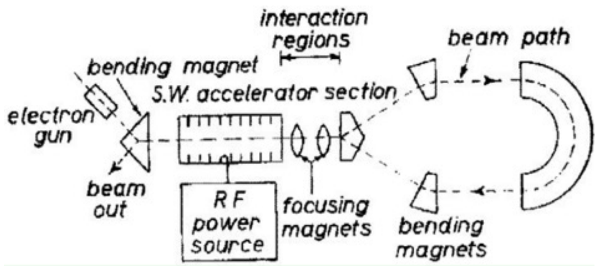
KEK has the long experience for the development of SRF accelerator since TRISTAN (1980s) to present (2024).

KEK & Tsukuba mountain

Compact ERL (cERL) in KEK

What is ERL (Energy Recovery Linac)

1965 M. Tigner
"A possible apparatus for electron clashing-beam experiments"



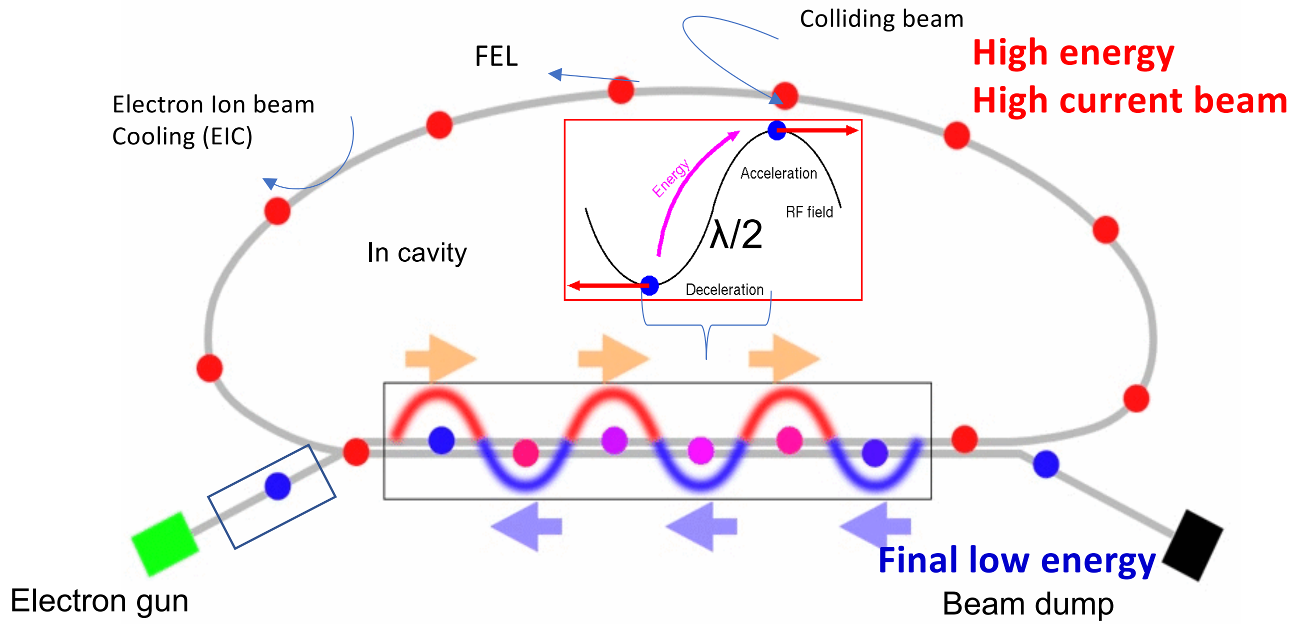


Figure of Merit of ERL

- **Linac beam with high current beam**
  - Low emittance beam (High quality beam)
  - Short bunch (< 100 fs) with high current beam (> 10 mA)
- It is difficult to fulfill these conditions by using storage ring
  → high current FEL and future HEP and beam cooling .

Key technologies for ERL

- **High brightness electron gun**
- **Superconducting RF (SRF) cavity**
- **Beam handling of energy recovery beam with high current**

Beam power was saved by energy recovery
→ ERL is a sustainable technology to **reduce an operational power**

To be discussed these technologies and applications in ERL workshop

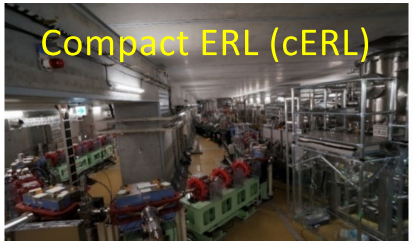
Compact ERL (cERL) in KEK

cERL developed the following key technologies and was **constructed in 2013**.

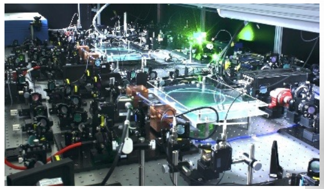
- **High current and high brightness** photo cathode DC gun.
- **CW superconducting cavity** for the high current beam operation.
- High current CW **energy recovery operation** achieved 1 mA ERL operation in 2016.

Circumference ~ 90m

Now cERL was used for **industrial application** by using stable high current beam.



CW laser



Two undulator for IR-FEL (2020)

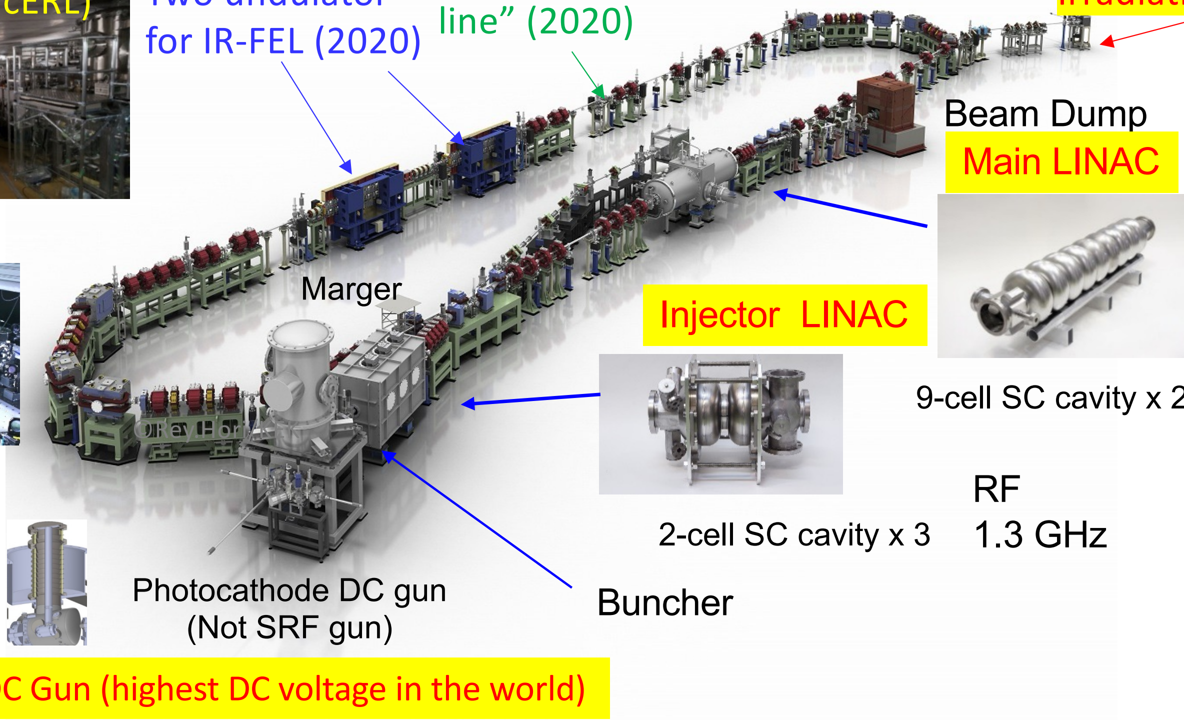
THz "test beam line" (2020)

Irradiation beam line with CW beam (2019)

Max 26 MeV 10μA

Beam Dump

Main LINAC



Marger

Injector LINAC

9-cell SC cavity x 2

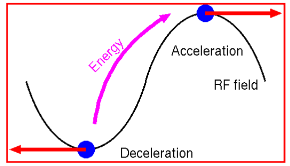
2-cell SC cavity x 3

RF 1.3 GHz

Photocathode DC gun (Not SRF gun)

Buncher

500kV DC Gun (highest DC voltage in the world)



17.7 MeV

Design parameters of the cERL

Nominal beam energy	35 MeV → 20MeV
Nominal Injector energy	5 MeV →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)

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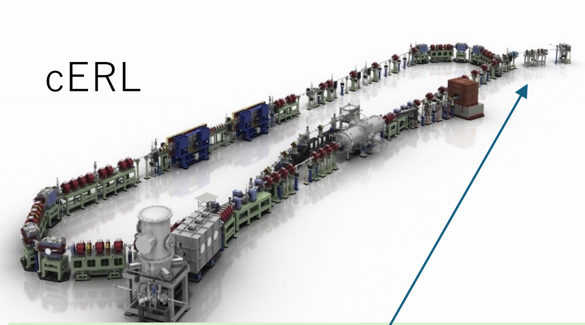
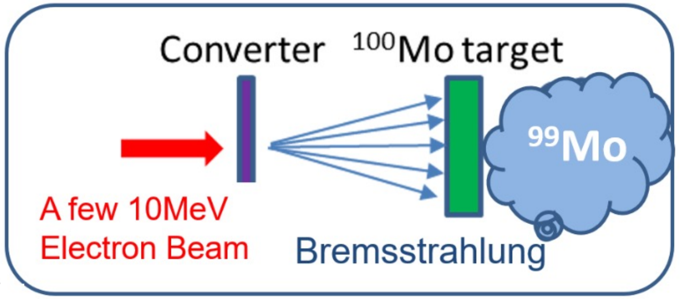
cERL – irradiation beam line (RI production)

Courtesy of Y.Morikawa, N.Higashi, K.Harada, M. Yamamoto, H.Matsumura and A. Toyoda



99Mo production already shown in ERL2019

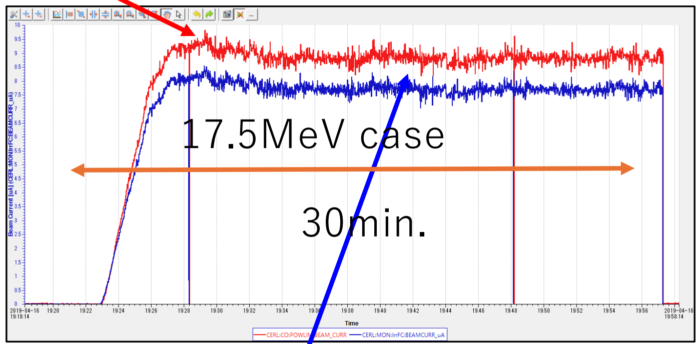
Development of RI manufacturing (^{99}Mo / ^{99m}Tc) by using accelerator for stable supply



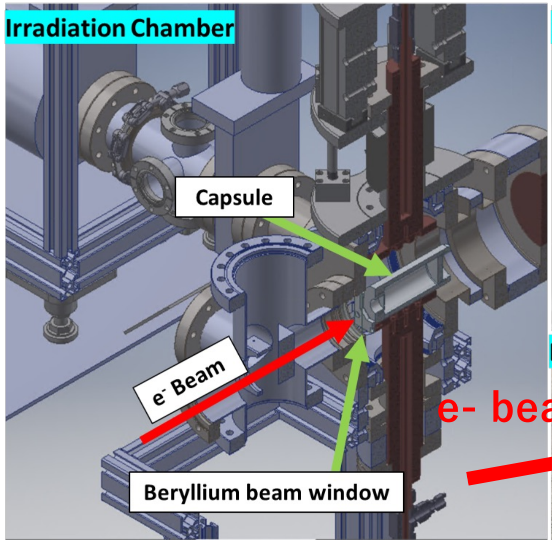
Gun current

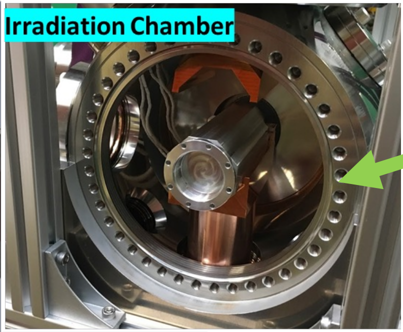
Beam current is very stable

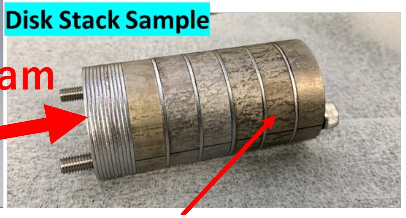
9 μA (CW)



Typical trend of beam current
(faraday cup set on the same position of target)

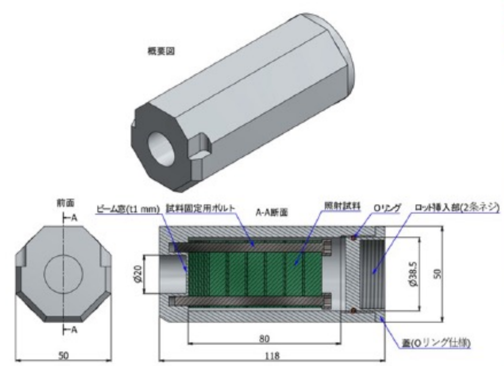






Aluminum capsule target holder

For another RI production



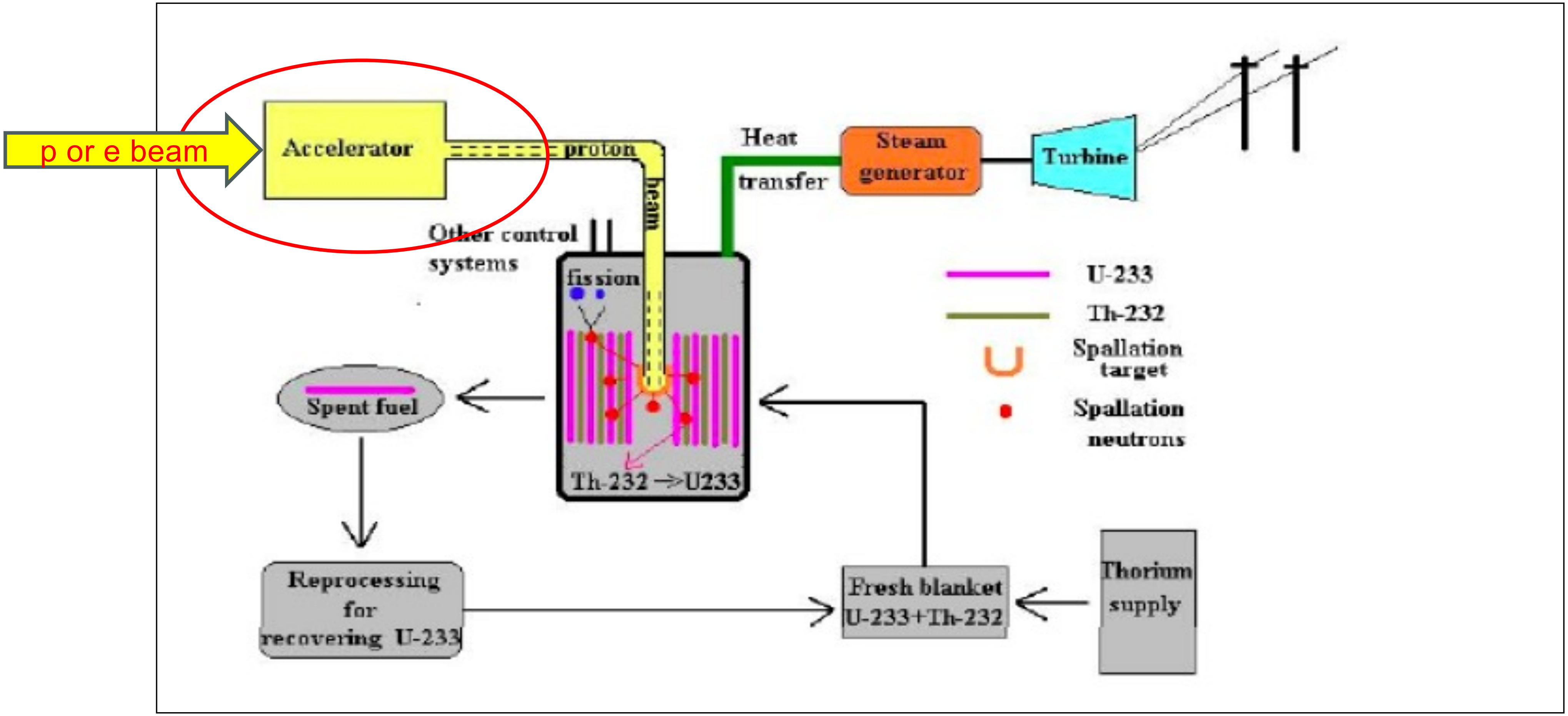
100Mo targets with 1mm disks and 9mm disks in target folder

Y. Morikawa, *et al.*, "New Industrial Application Beamline for the cERL in KEK", Proc. of IPAC2019, (Melbourne, Australia) p3475-3477, (2019)

Ref SRF2021

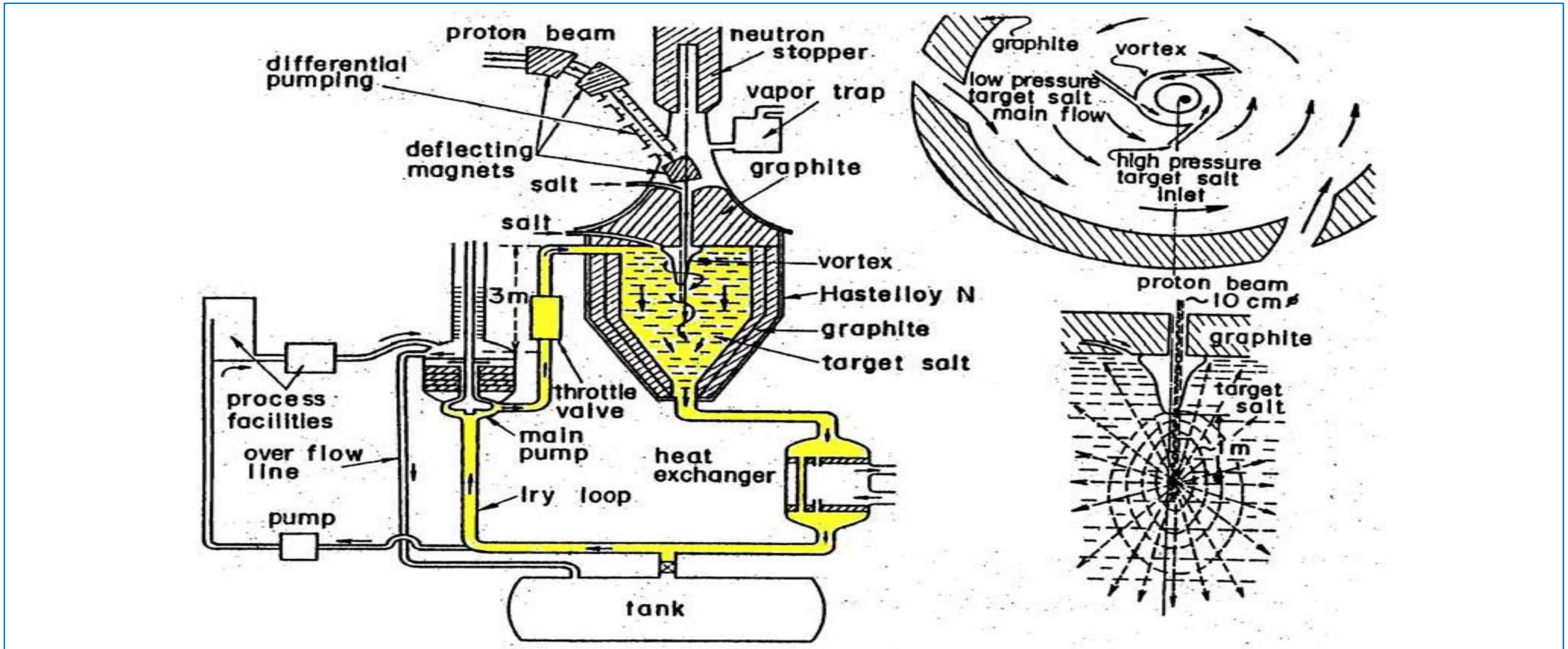
Higher energy was needed for 67Cu production from 68Zn. We operate the long pulsed operation to increase beam energy

India’s possible Thorium utilization scheme



Myneni Ganapati, KEK,
February 21 2025

A Proposal by K. Furukawa et al

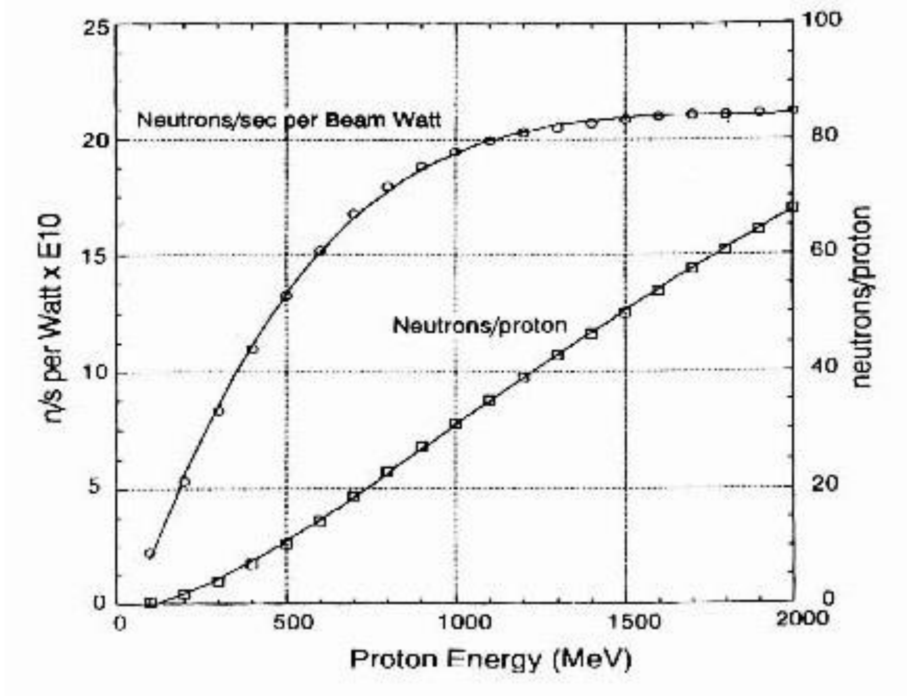


Energy Conversion and Management 49 (2008) 1832-1848

Myneni Ganapati, at KEK seminar, February 21 2025

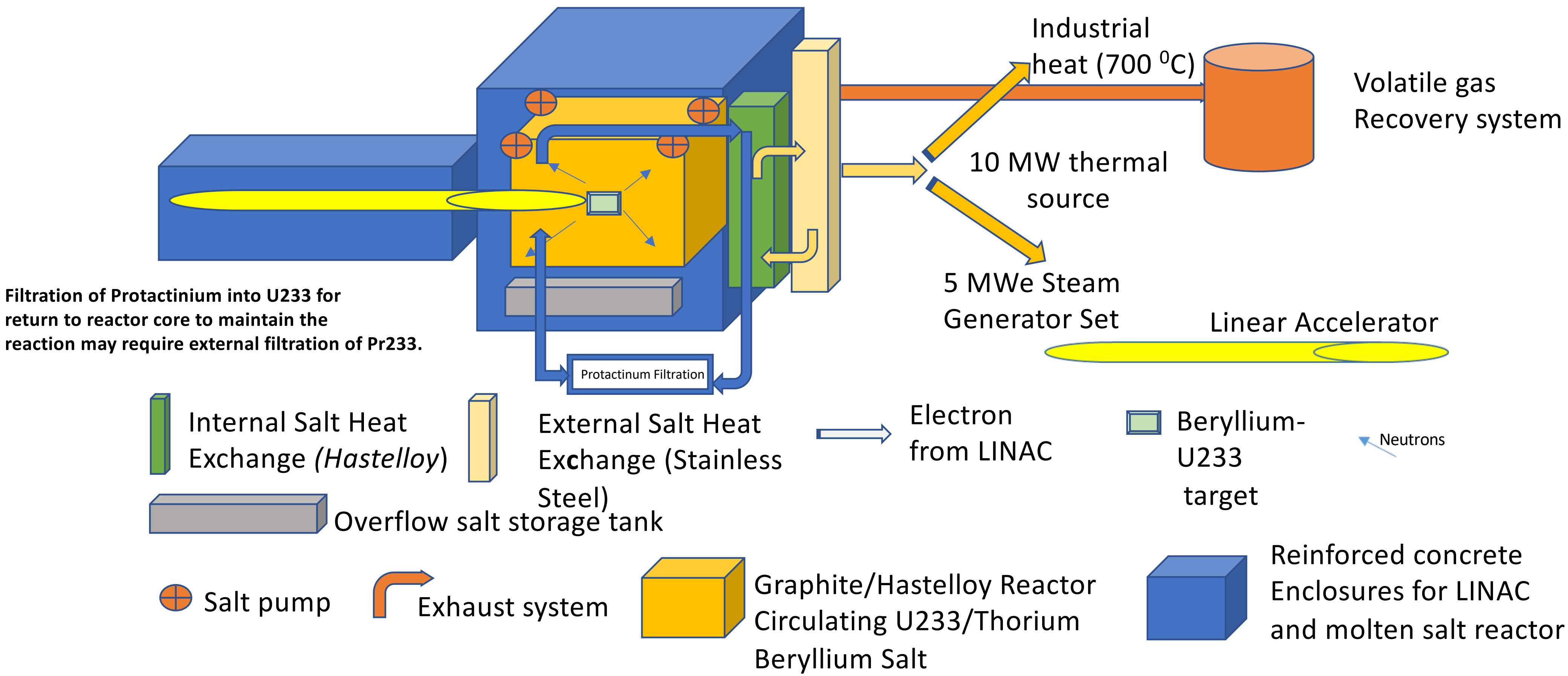
Accelerators & fissile materials

- **1950 –** U. E. O. Lawrence, high power accelerators for producing fissile materials
  - Accelerator Molten-Salt Breeders, **Kazuo Furukawa et al,** Energy Conversion and Management 49 (2008) 1832-1848
- **1952 –** W. B. Lewis, proposed use of thorium with intense neutron generators
  - India's ADS Program with proton linac (on hold)
  - BSCE Systems, Inc. ADS sub-critical micro-reactors with high power electron linacs (waiting for funding)



Protons Vs Electrons as ADS drivers

Subcritical Nuclear Reactor – 10 MWt/5 Mwe
Low Cost, Incremental Power Route to a Zero Carbon Future



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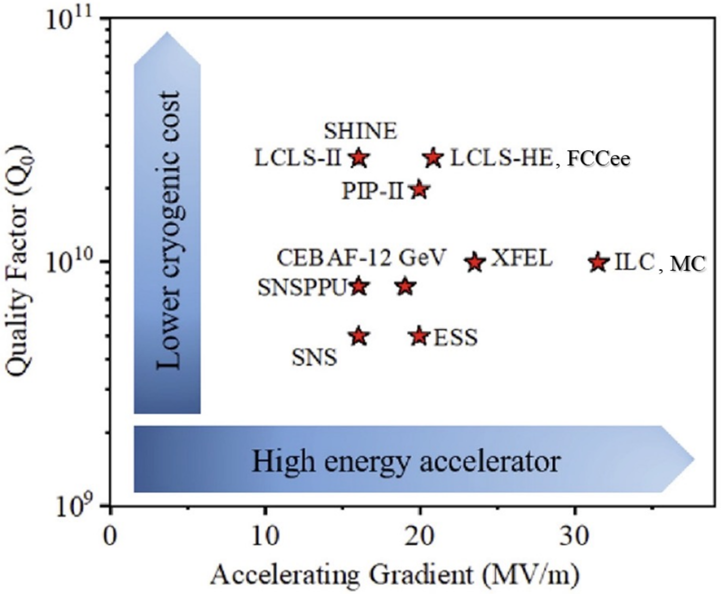
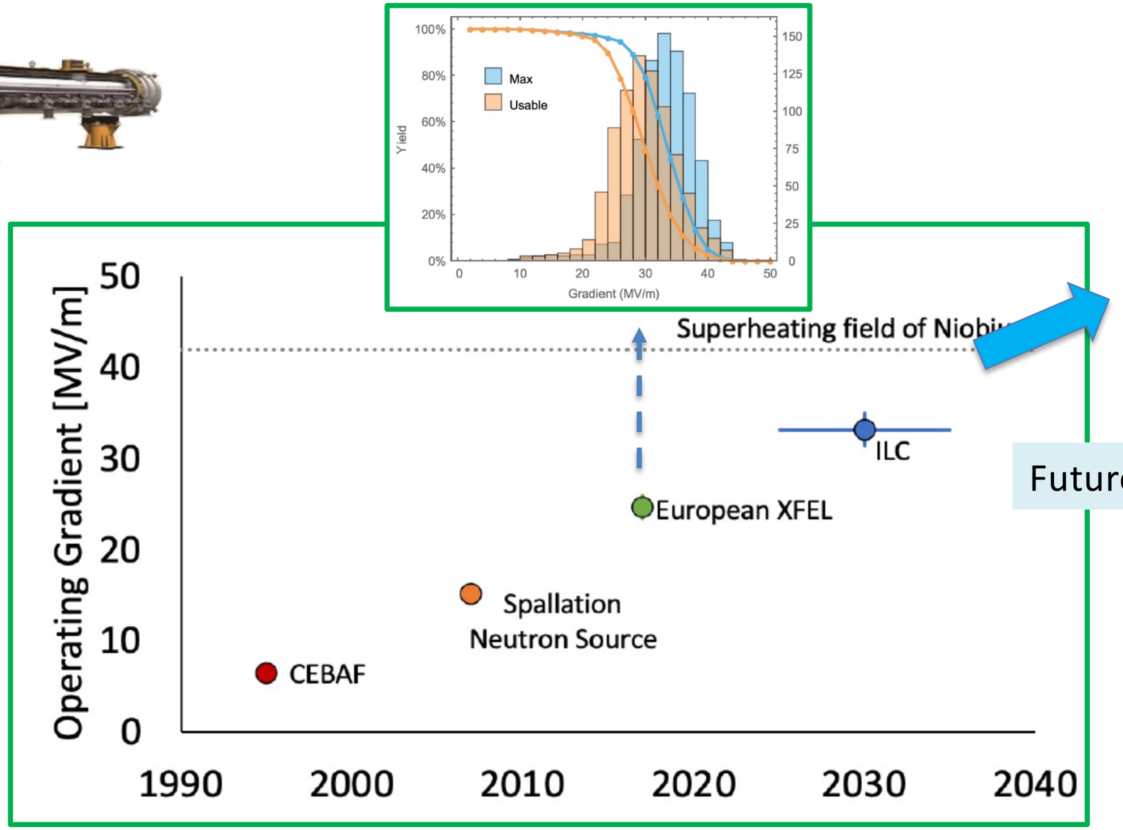
Courtesy: R. Geng

Advances in ~ 1 GHz, SRF Accelerators





S. Belomestynkh and S. Posen, arXiv:2204.01178v2

Courtesy: K. Umemori, S. Belomestnykh, S. Psen, M. Yamanaka, M. Garlasche, G. Rosaz

Prospects for High-Performance & Cost Reduction

High Performance: High -Gradient (-G) and –Q:

Nb-Cavity:

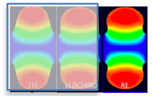
- **Shape** cavities will be limited by **~ 60 MV/m, as** B_{sh} ~ 200 mT
- **Tesla Type, Surface Process to reach G ~50 MV/m, Q = ~ 3E10 :**
  - Surface treatment, Heat treatment, **Thin film** coating etc…
- **Traveling Wave** (TW), Acc. structures
  - Expecting Effective Gradient to be **~ 70 MV/m** or higher

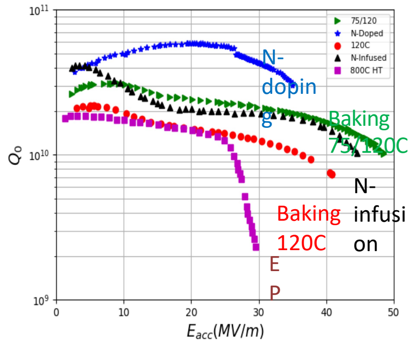
Nb3Sn-Cavity:

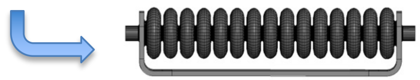
- **Gradient limit** expected to be **~ 80 MV/m**, at B_{sh} ~ 430 mT

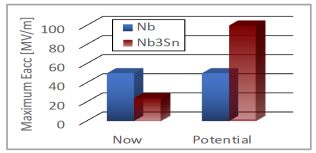
Cost Effective Production (for Nb Cavity):

- **L**arger/**M**edium Grain Nb material: clean and cost-reducted
- **Cu-hydroforming** followed by **thin-layer SC coating**









"**ILC:** The International Linear Collider -- Report to Snowmass 2021", Aryshev *et al.*, arXiv:2203.07622 (15 March, 2022)

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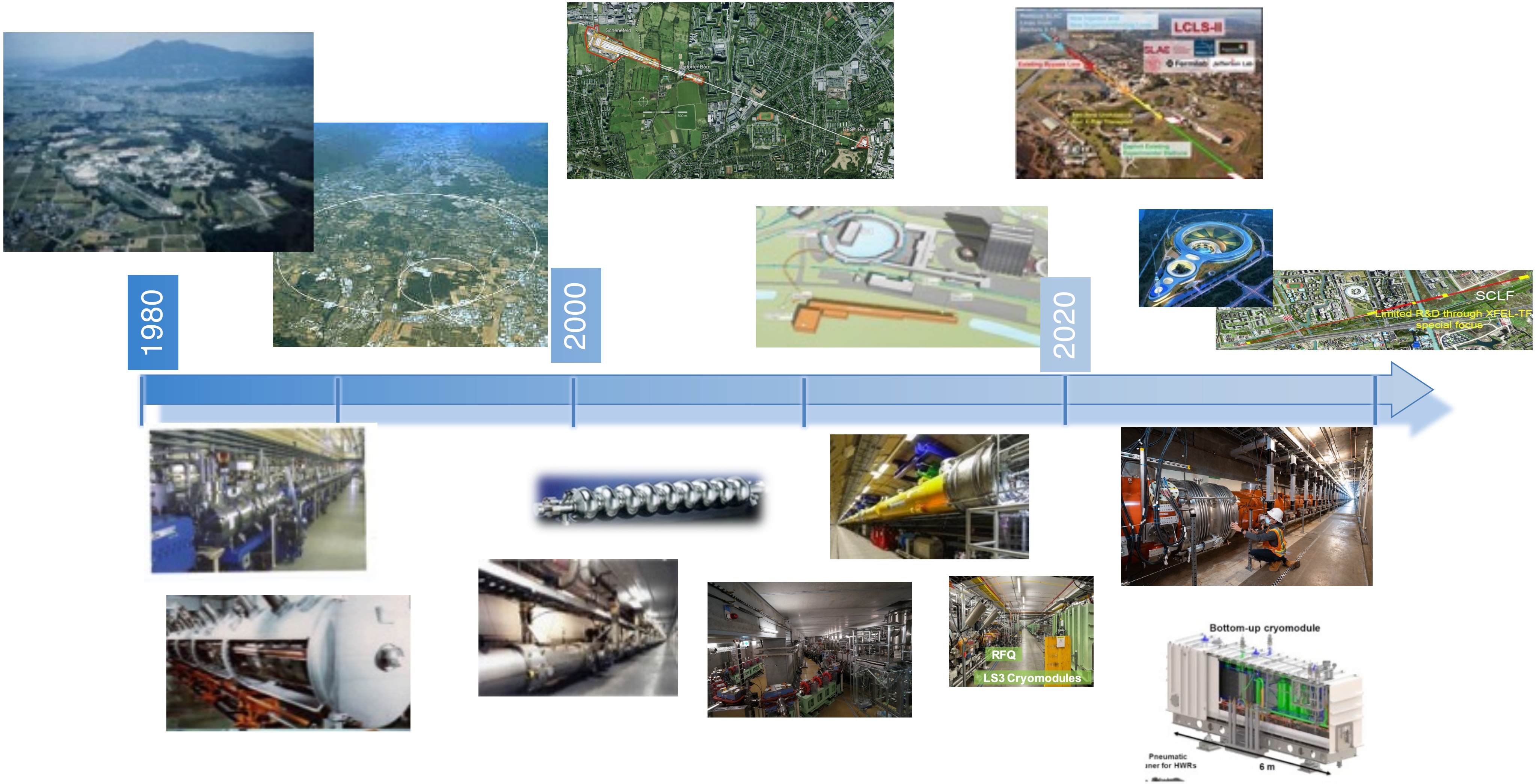
Summary and Prospects

- **SRF Technology** is a key technology for particle accelerators and various applications.
- **KEK cERL facility** is contributing to investigate the SRF accelerator technology application in particular:
  - ➢ **Medical isotope production** such as Mo99, critically important,
- **SRF electron accelerators** may be a cleaner and economical approach for:
  - ➢ **Thorium-based Energy creation**, taking great advantage of the natural availability, specially, in India.
- **Global R&D cooperation** effort in this field will be very important,
  - ➢ a **possible int'l cooperation** of KEK and Indian Institutions anticipated.

Reserved

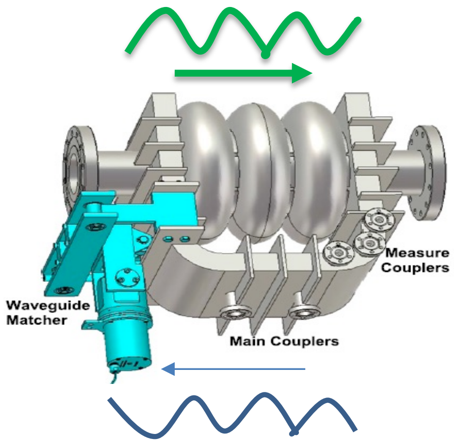
Advances in SRF Technology for Accelerators



Courtesy: H. Padamsee, S. Belomestnykh

For High Performance:

A new concept for SRF Acc. : Standing → Travelling Wave



- **Red:** standing wave ➔ High Peak Fields
- **Green** (acceleration) and **Blue** (return): travelling Waves → Lower peak fields

- Note: Guide blue wave in a return wave-guide to avoid SW peak fields – attached to both ends

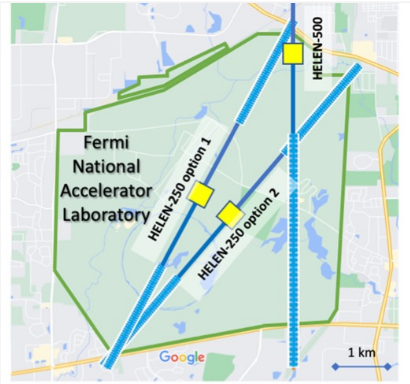
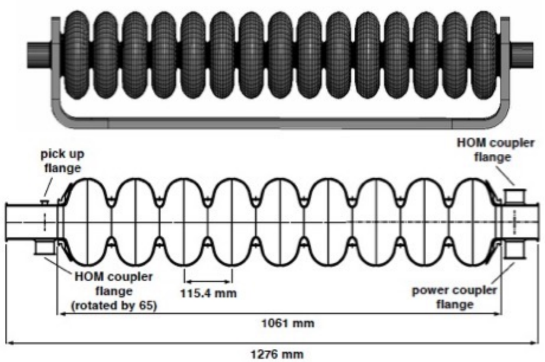
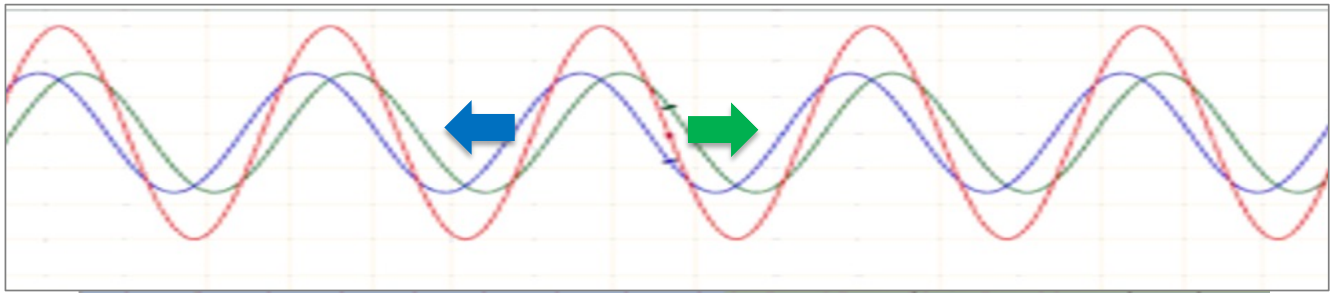


Figure 3: Options for HELEN collider at Fermilab.





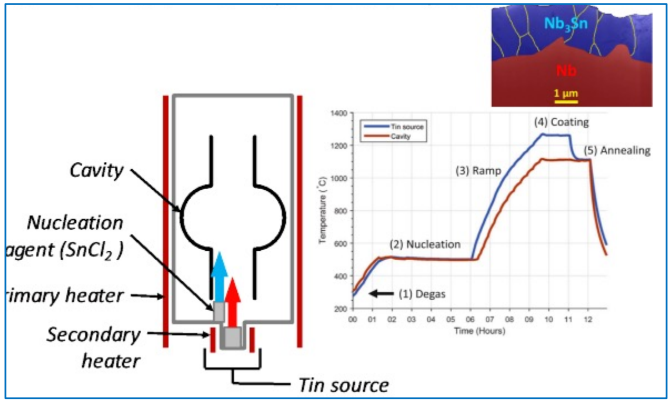
For High Performance: Nb_3Sn coating on Nb

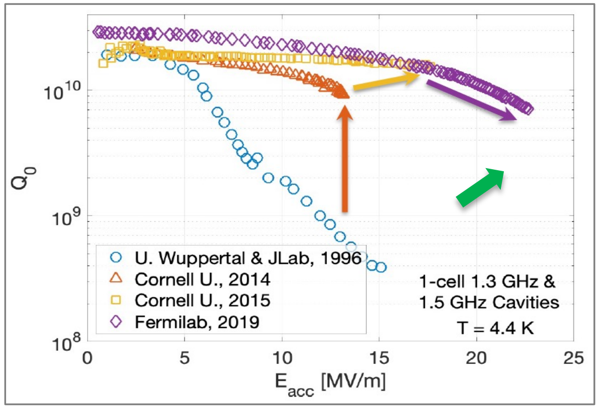
SRF cavity

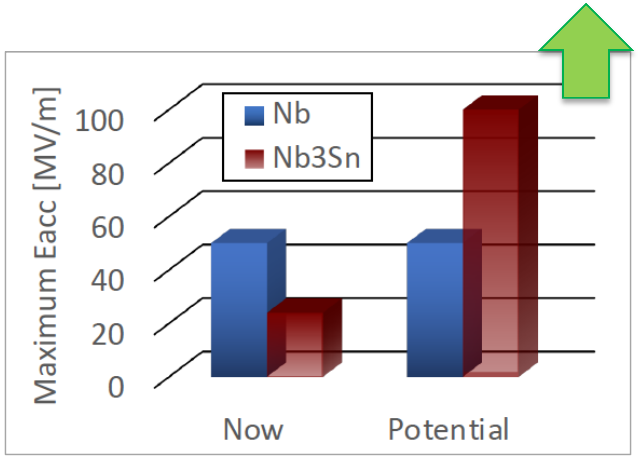
- B_{sh} = strict limit for SRF
  - $Bs_{sh\text{-}Nb}$: 210 mT
  - $Bs_{sh\text{-}Nb3Sn}$: 430mT

x2

Material	T_c [K]	$B_{c1}(0)$ [T]	$B_{sh}(0)$ [T]
Nb	9.2	0.18	0.21
Nb_3Sn	18.3	(0.05)	0.43
MgB_2	39	(0.03)	0.31







Nb_3Sn progress at Fermilab.
S. Posen et al., SUST, 34, 02507 (2021)

Nb_3Sn Potential in high-G future