Design and beam dynamics study on compact Nb3Sn accelerator

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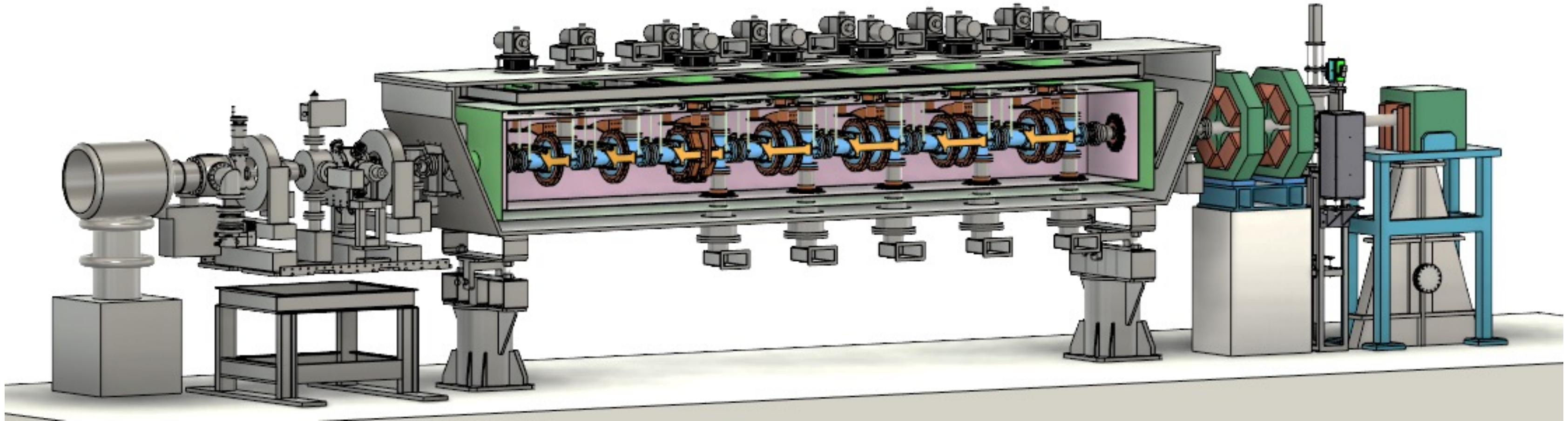
on behalf of Compact ERL beam dynamics group

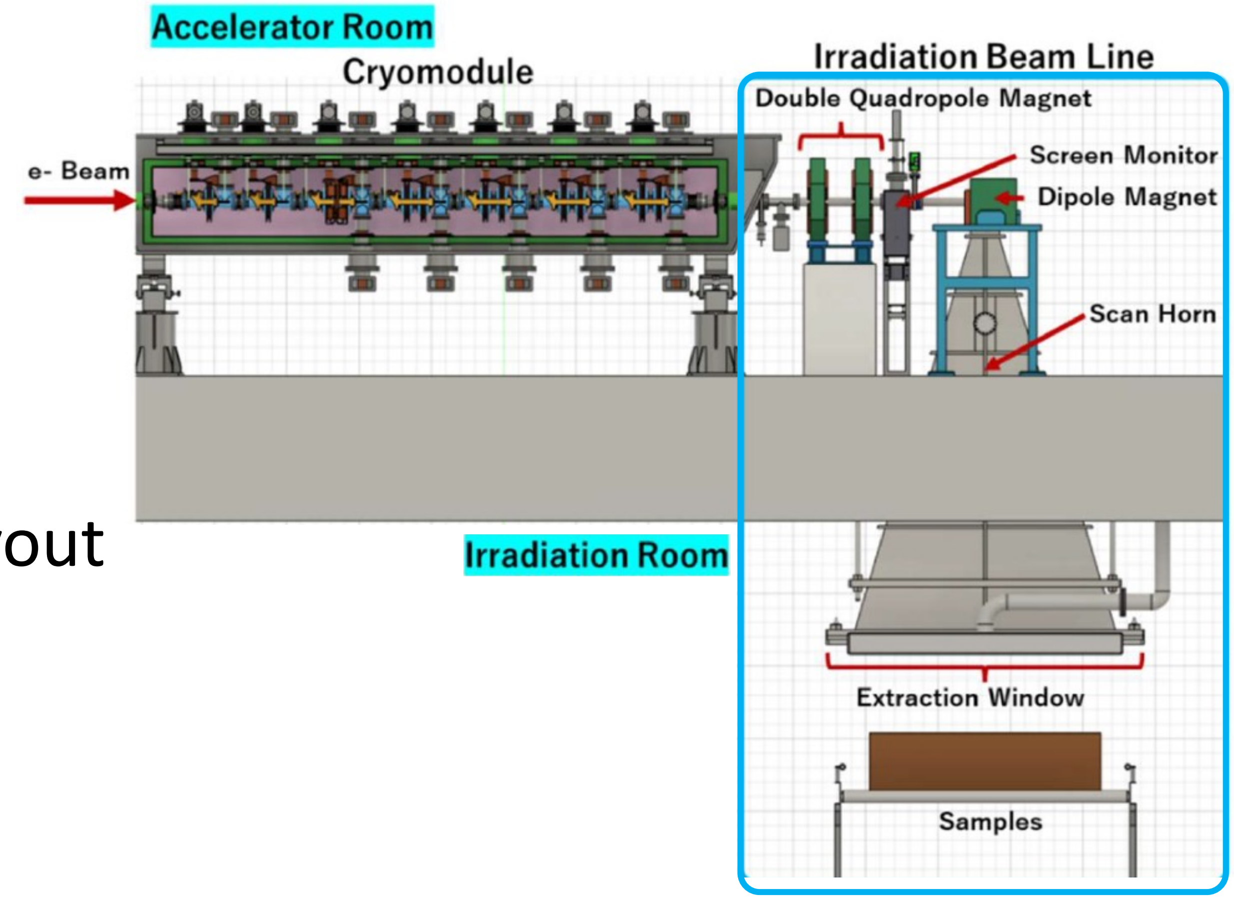
TTC2022 Aomori, TESLA Technology Collaboration

Link Station Hall Aomori, Medium meeting room

14:32 ~ 14:47



Outline



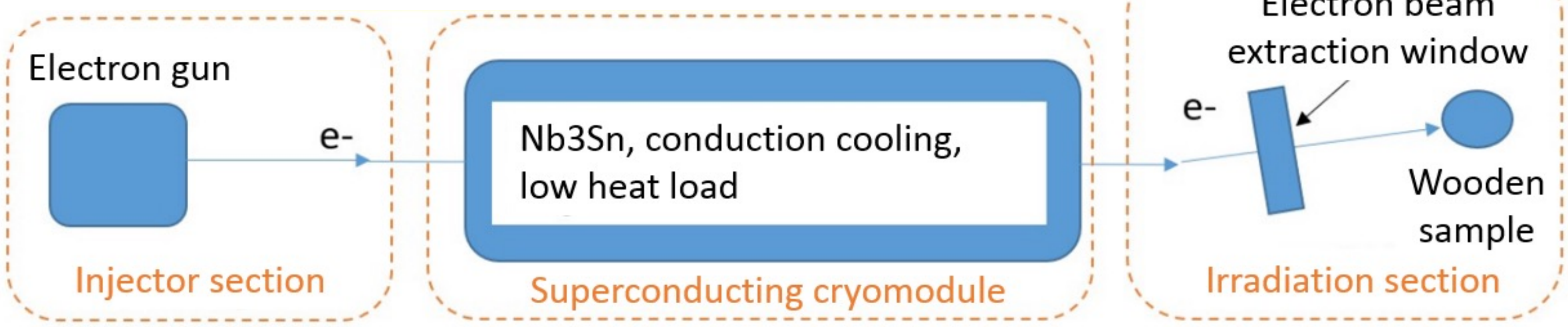
- Introduction and motivation
    - Accelerator components and layout
    - Injection section
    - Key technology
    - Superconducting cryomodule
    - Simulation setup and optimization strategy
- Beam dynamics summary
- Design summary

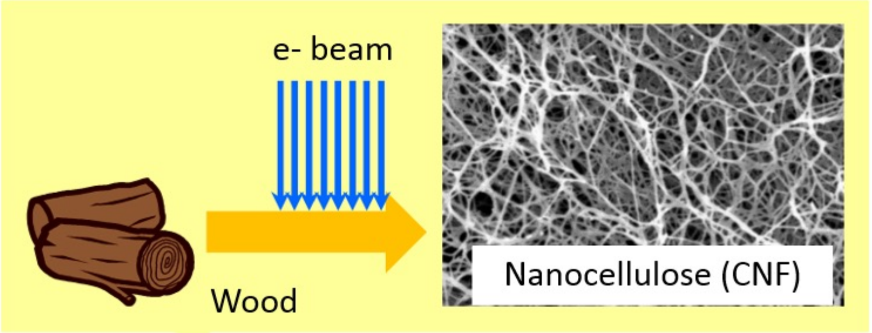
Introduction and motivation

- **We are designing a compact 10MeV 50mA accelerator for highly efficient production of nanocellulose by irradiation of wooden samples.**
- Proposed design involves **Nb_3Sn cavities** instead of conventional Nb cavities:
  - High-current operation (50mA) without particle loss become possible;
  - Very compact (8m x 1m x 2m) irradiation accelerator can be designed, since no conventional He refrigerator used;
  - Cooling load is reduced to several tens of percent compared to conventional Nb cavities.

→ Large beam current, miniaturization and power saving is possible by using a new Nb_3Sn cavity compared to the Nb superconducting cavity.

Schematic of the compact 10MeV 50mA accelerator





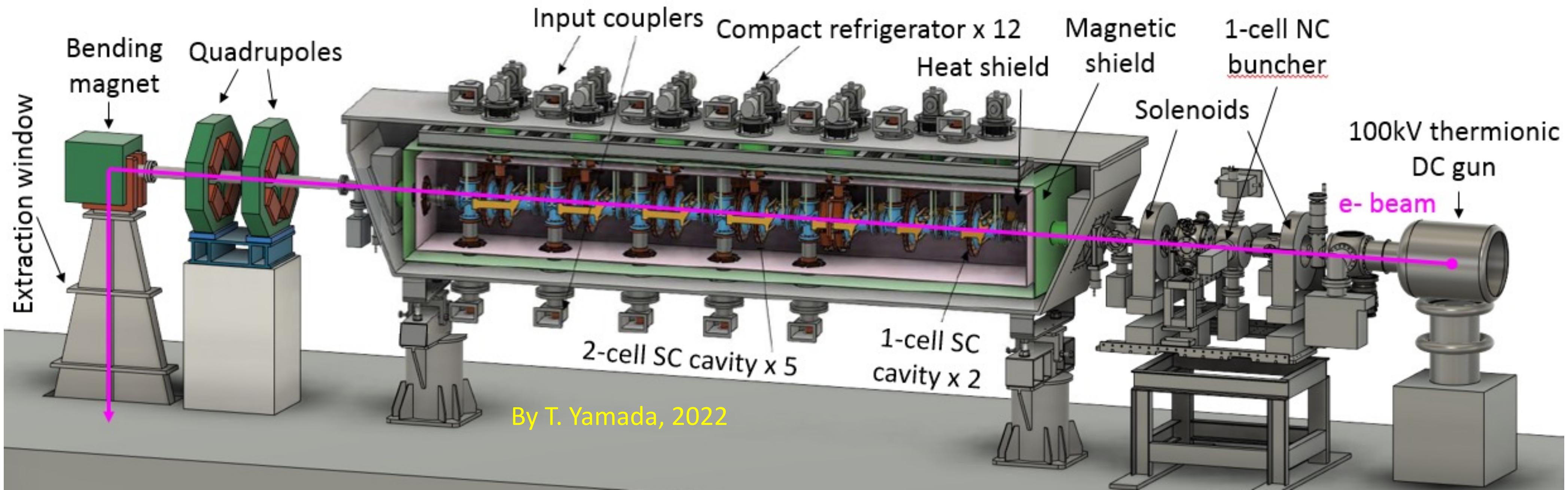
By H. Sakai, 2022

[1] R.C. Dhuley, I. Gonin, S. Kazakov, T. Khabiboulline, A. Sukhanov, V. Yakovlev, A. Saini, N. Solyak, A. Sauers, J.C.T. Thangaraj, K. Zeller, B. Coriton, and R Kostin, "Design of a 10 MeV, 1000 kW average power electron-beam accelerator for wastewater treatment applications", Physical Review Accelerators and Beams 25, 041601, 2022. (**Fermi Lab**)

[2] G. Ciovati, J. Anderson, B. Coriton, J. Guo, F. et al., "Design of a cw, low energy, high power superconducting linac for environmental applications", Phys.Rev.Accel.Beams 21 (2018) 9, 091601 (**Jefferson Lab**)

Accelerator components and layout

- A pulsed electron beam is generated by a **100kV thermionic DC electron gun** with a 650 MHz RF grid for bunch shaping and for more stable beam operation.
- The beam is accelerated up to 10MeV using a 650MHz **1-cell normal-conducting buncher cavity**, two **1-cell superconducting cavities (β = 0.8)**, and five **2-cell superconducting cavities.** The accelerating RF frequency is 1.3 GHz for all SC cavities.
- Two **solenoids** are installed before and after the buncher to provide transverse focusing. There are two **quadrupoles** placed 1.5 m downstream the cryomodule to adjust the beam size. The beam is bent downward by the **dipole** and reaches the **extraction window**.



Injection section

Injector design was developed based on the cERL injector[1] design.

Electron gun:

- The electron gun is a 100 kV thermionic DC electron gun with an RF grid that produces a repetitive longitudinally packed pulsed (bunched) electron beam at 650 MHz.
- A thermionic electron gun was selected since it can stably supply a large current of 10mA or more and an acceleration voltage of 100 kV.
- This design involves a gridded dispenser cathode (Y-845) synchronized with a 650 MHz RF grid for electron beam pulsing[2,3].

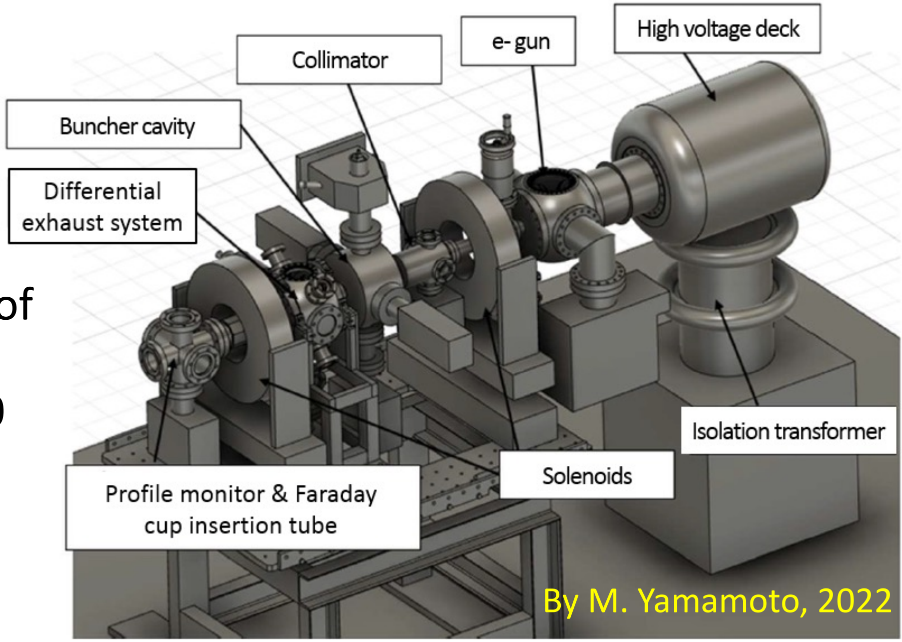
1-cell NC buncher cavity:

- cERL's buncher is used at 1.3 GHz. Since the initial beam longitudinal distribution assumed to be about 100ps on this Nb3Sn accelerator, it is difficult to compress the 100 ps bunch length with 1.3 GHz cERL buncher. Therefore, we redesign and apply the buncher cavity based on 650 MHz to increase the RF phase range and effectively perform bunch compression.

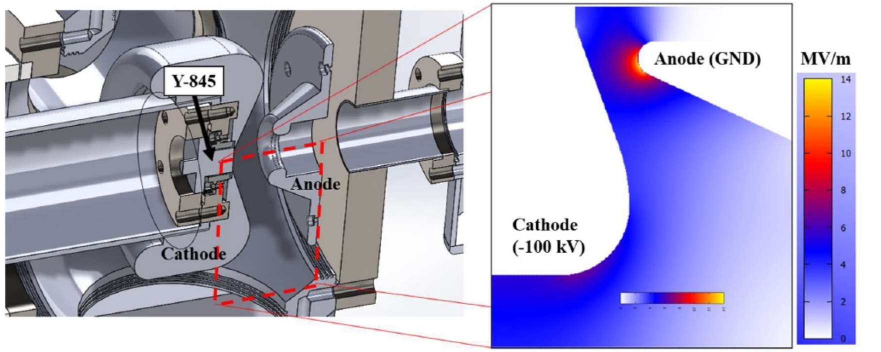
Collimation system:

- A collimator was installed to limit the formation of a vacuum pressure step between the electron gun and the superconducting accelerating cavity, to reduce the beam size, and to suppress the beam loss in downstream of the superconducting accelerating cavities.

+ Solenoid focusing



Electron gun cross section & electric field distribution near the cathode-anode

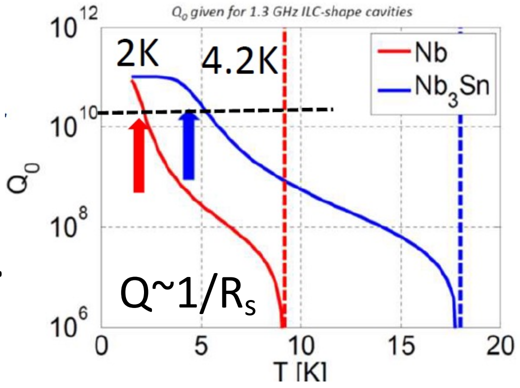


[1] M. Akemoto, et al., Nucl. Instrum. Methods Phys. Res., Sect. A, 877, 197-219 (2018).
[2] R.J. Bakker, et al., Nucl. Instr. Meth. Phys. Research A 307, 543 (1991).
[3] K. Fong, et al. "Design of an RF modulated thermionic electron source at TRIUMF", Proceedings of IPAC2018, THPMK095 (2018).

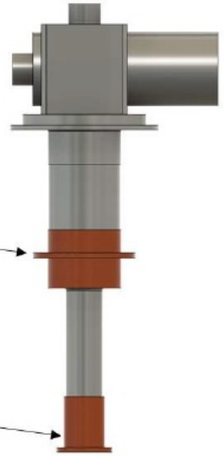
Key technology

Comparison of Q value by operating temperature[1]:

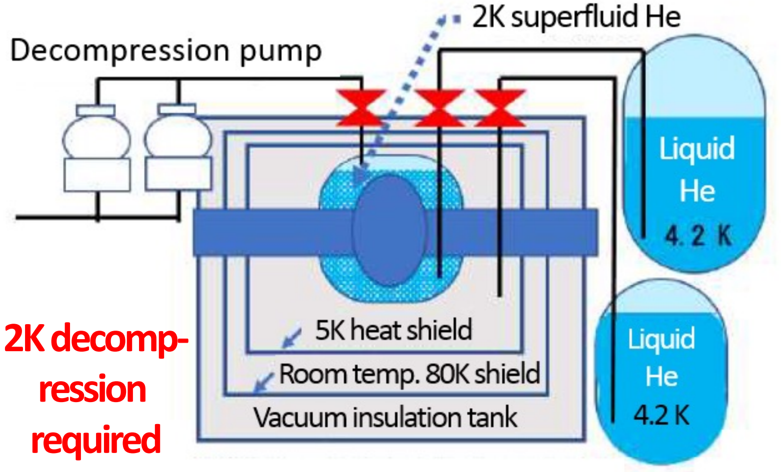
- The Q values of Nb(2K) and Nb3Sn(4.2K) are the same.
- It is possible to suppress the heat load to 1/3 - 1/5
- at 4.2 K.



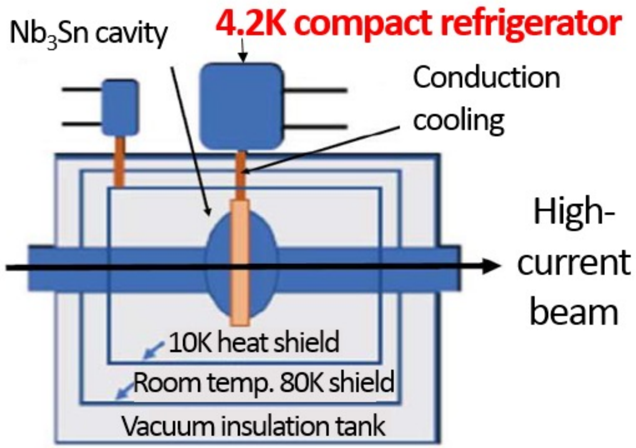
Schematic of 4.2K compact refrigerator



Operation of Nb cavity



Operation of Nb_3Sn cavity



By H. Sakai, 2022

- **Advantages of new Nb_3Sn superconducting cavities:**

✓ Simple because there is no piping for heat exchange in the insulation tank.

✓ No need for He jacket

✓ No need for high pressure gas regulation.

✓ At 4.2K, the heat load can be reduced to 1/3 ~ 1/5[2].

✓ Conduction cooling operation is possible with a small refrigerator.

- **Challenges of the conventional Nb cavity operation:**

– 2K decompression required.

– The resonator is immersed in superfluid helium and cooled inside the titanium shell.

– A large helium refrigerator facility is required.

[1] S. Posen and D. L. Hall. Superconductor Science and Technology, 30(3):033004, 2017.
[2] H. Sakai, et al., "Development of high-current electron beam accelerator using Nb3Sn superconducting RF accelerator for various materials", Proc. of PASJ2022.

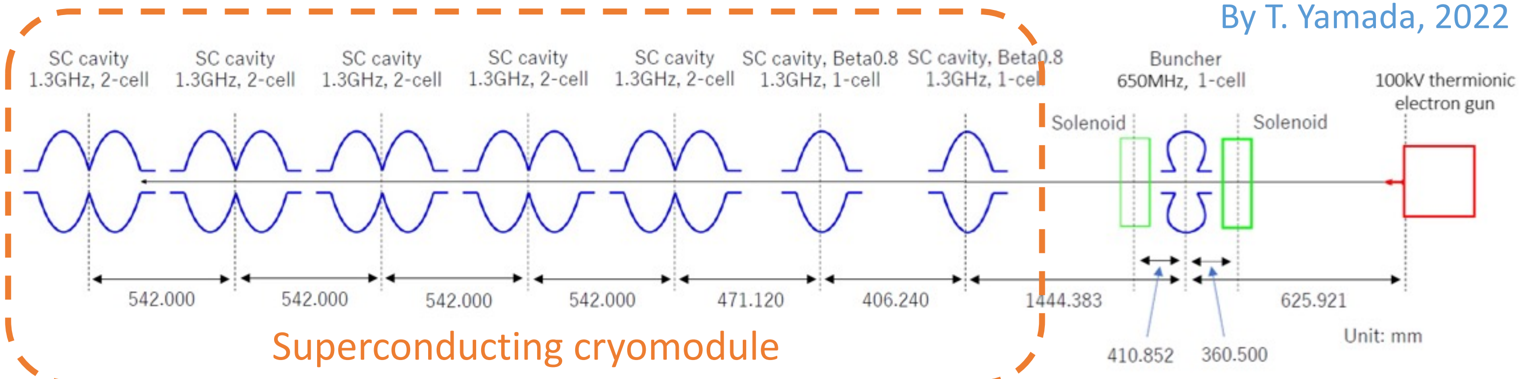
Superconducting cryomodule

The critical points in cryomodule design are:

(1) Acceleration gradient; (2) Heat load of the SC; (3) Maximum power of the input coupler required for beam acceleration.

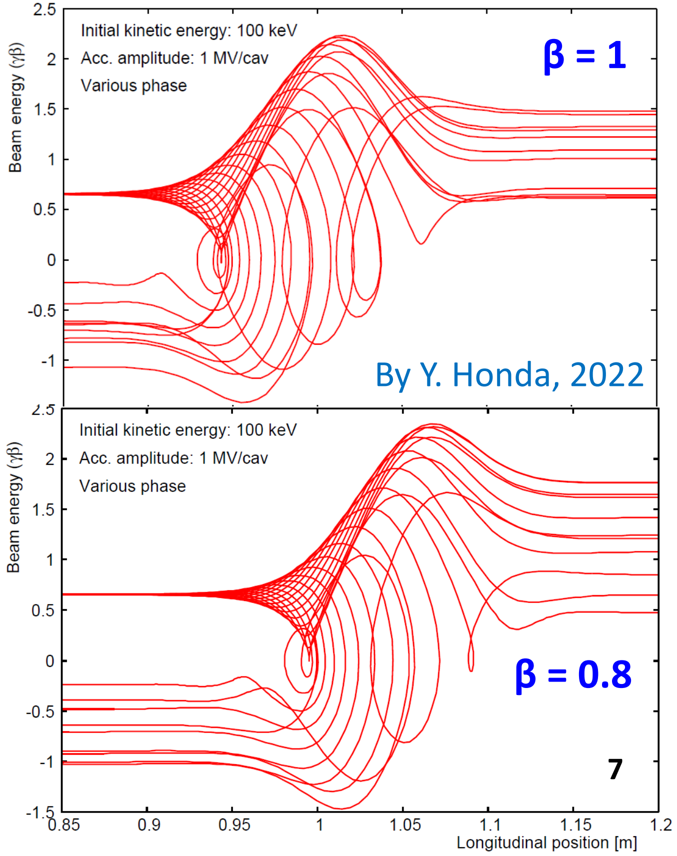
- The acceleration gradient is below 10 MV/m, which is feasible with Nb3Sn. The beam energy is increased up to 10 MeV by approximately 2 MV/cav. with five 2-cell cavities.

By T. Yamada, 2022



Beam dynamics issues in Superconducting Cavities (SC):

- **2-cell cavity[1]:** When accelerating in the 2-cell SC cavity after passing through the buncher, the acceleration does not occur immediately. This is because the energy of the beam (100keV) is in the non-relativistic region, and the speed of the beam is not close to the speed of light. The 2-cell cavity does not accelerate properly due to the mismatch of the cavity cells, resulting in loss of energy. In order to eliminate cavity mismatch, each cell of the 2-cell cavities is made independent, and the beam is slightly accelerated.
- **The 1st 2-cell cavity is used to suppress an over-bunching through the velocity bunching.**
- **1-cell (β = 0.8) cavity[1]:** As the graphs of the minimum speed of transportation read, if the minimum velocity is less than zero, the beam will run in the opposite direction, and it will be impossible to use it as an accelerator. If the amplitude of the cavity is increased too much, it will enter a region where the beam cannot be accelerated properly. The region that satisfies the condition that the energy finally rises without reverse run is wider for the β = 0.8 cavity.
- **1-cell cavities help to increase the beam energy prior the final acceleration up to 10 MeV.**



[1] H. Sakai, 2021.

Simulation setup and optimization strategy

Motivation: assuming an initial beam, optimization is performed by a simulation including the space charge effect of a multi-particle beam, so that the beam parameters at the exit of the accelerator should be confirmed.

Simulation setup:

- We started the calculation[1] by giving the particle distribution of the beam at the cathode of the electron source.
- For the electron gun[2], solenoids[3], buncher[3] and 2-cell cavities[3] simulation the 1D field distributions of cERL are used. For the 1-cell cavity, the gap length of the TESLA cavity was reduced β = 0.8, and the 1D field distribution was used[4].

Initial parameters of electron beam	
Bunch charge	77 pC (50 mA at 650 MHz)
Number of particles	2000 (optimization) 1 000 000 (tracking)
Electron source energy	100 keV
Cathode size	5.73 mm (uniform)
Initial bunch length	100 ps (Gaussian ±4σ)
Final energy	10 MeV

Optimized parameters			
SL1	2.75 A	SL2	1.24 A
Cavity name	**Amp. (MV/cav.)**	**Crest phase (deg.)**	**Phase offset (deg.)**
Buncher	0.0024	-58.8	-90.0
INJ1 (1-cell)	0.36	-62.8	0.0
INJ2 (1-cell)	0.35	-127.9	0.0
INJ3 (2-cell)	1.19	145.4	-85.9
INJ4 (2-cell)	1.88	-42.2	0.0
INJ5 (2-cell)	1.89	-174.5	0.0
INJ6 (2-cell)	1.90	56.4	0.0
INJ7 (2-cell)	1.91	133.6	0.0

Optimization strategy: for given layout of the accelerator, it is necessary to adjust the amplitudes and phases of cavities, and strengths of the solenoids to find the optimum conditions.

- To guarantee no loss during beam transport the cavities' phases must be well optimized so that the energy spread is kept minimal.
- For low velocity beams the parameters are intricately correlated. In addition, the influence of the space charge effect is also large. For this reason, simultaneous optimization of multiple parameters is necessary.

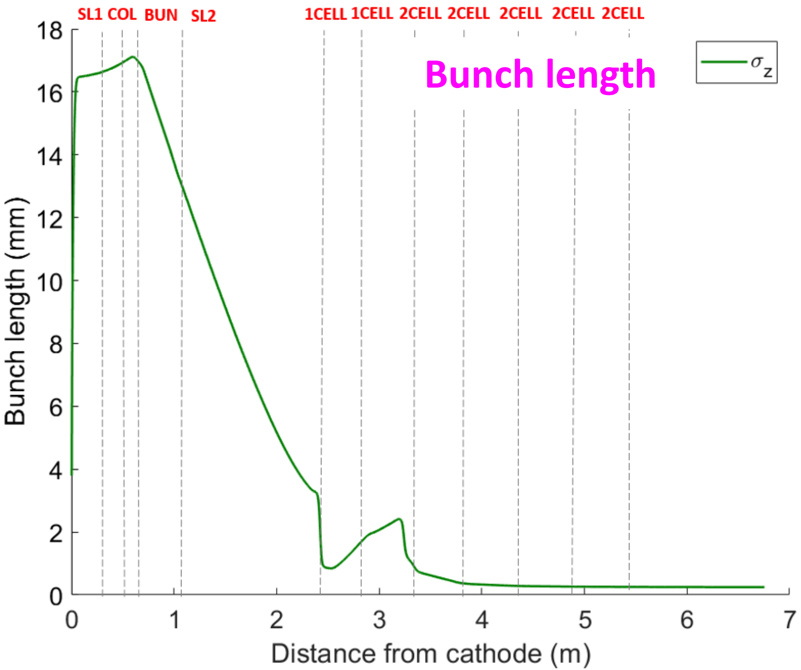
Optimization targets: minimize final bunch length, maximum beam size during transportation, final energy spread, and maximum amplitudes of the cavities. Final energy should be reached[5].

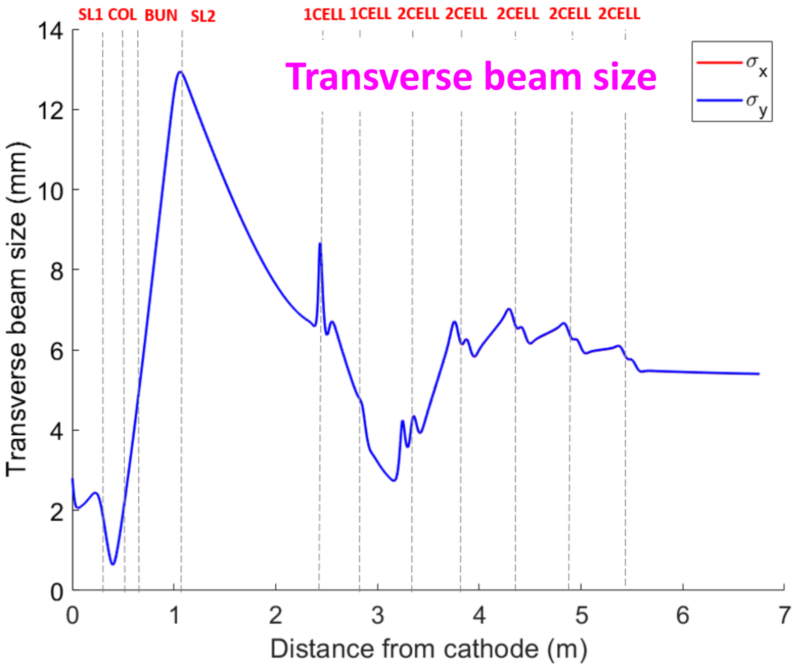
[1] General Particle Tracer, http://www.pulsar.nl/gpt/index.html
[2] M. Yamamoto, 2021.
[3] M. Ake197-219 (2018).
[4] H. Sakai, 2021.
[5] Y. Honda, in Proc. of PASJ2022.

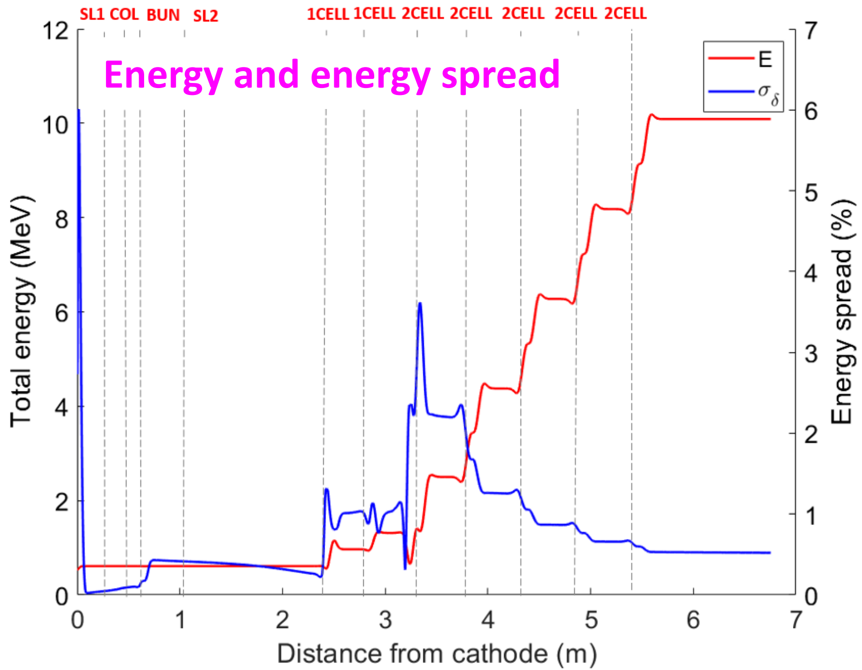
Beam dynamics summary

- Bunch length tuning knobs: buncher amplitude, 1st 2-cell cavity phase offset. Zero-cross bunching and velocity bunching techniques involved. Target compression achieved.
- Transverse beam size tuning knobs: solenoid focusing. Cavity focusing effect considered. Beam size at the exit of the cryomodule is good. Additional tuning available through 2 quadrupoles at the irradiation section.
- Energy tuning knobs: amplitudes of 2-cell cavities. The beam energy is accelerated up to 10 MeV by approximately 2 MV per cavity with five cavities. The acceleration gradient is below 10 MV/m, which is feasible with Nb3Sn.
- Comment on energy spread: increases after accelerating in two 1-cell cavities since those oppose a considerable fringe field effect on the beam.

Parameter	Value
Beam energy	10.09 MeV
Energy spread	0.52%
Transverse rms beam size	5.41 mm
Rms bunch length	0.29 mm / 0.86 ps







Design summary

Summary: by using the Nb_3Sn cavity, it is possible to accelerate 10 MeV and 50 mA without loss, and a very compact irradiation accelerator can be designed without the He refrigerator plant.

Key points of the design:

- A pulsed electron beam is generated by a 100kV thermionic DC electron gun with a 650 MHz RF grid for bunch shaping and for more stable beam operation.
- We redesign and apply the NC buncher cavity based on 650 MHz to increase the RF phase range and effectively perform bunch compression of the initial 100 ps bunch length generated in the electron gun.
- Beam focusing system: the 1^{st} solenoid focuses the beam, narrows the beam diameter to ϕ10 mm or less at the collimator position, and the 2^{nd} solenoid focuses the beam again. Since the maximum transverse beam size occurs at the 2^{nd} solenoid location, its adjustment helps to mitigate the particle loss at the injector.
- We adopted a collimation system to limit the formation of a vacuum pressure step between the electron gun and the superconducting accelerating cavity, to reduce the beam size, and to suppress the beam loss in downstream of the superconducting accelerating cavities.
- Nb_3Sn cavity technology addressed critical points in cryomodule design such as the acceleration gradient, heat load, and the maximum power to the input coupler required for beam acceleration.

Thank you for your attention!
Any questions?

Backup

Velocity bunching

- B. Aune and R. H. Miller, Report No. SLAC-PUB 2393, 1979.
- L. Serafini and M. Ferrario, AIP Conf. Proc. 581, 87 (2001).

Compressing more relativistic beams in the injector is still possible:

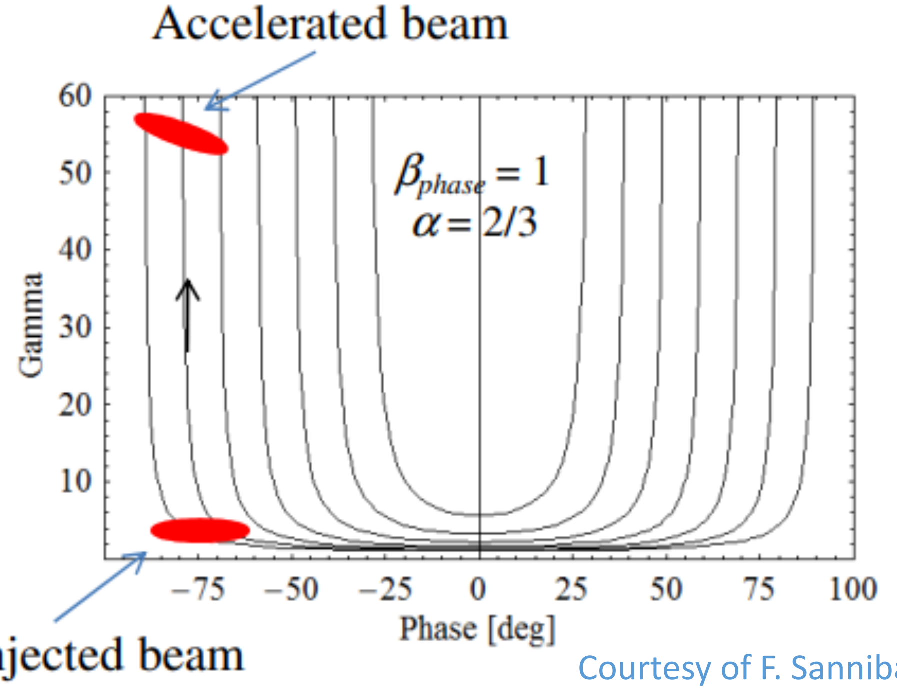
$$E_z = \hat{E}_z \sin(\omega t - kz - \psi_0) \quad with \quad \frac{\omega}{k} = c\beta_{phase}$$

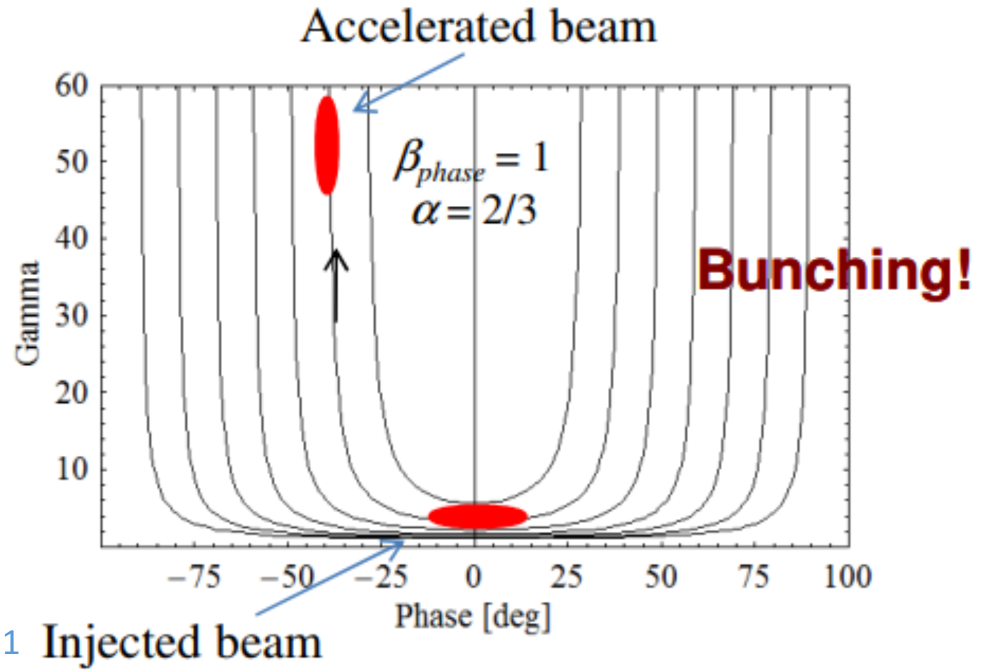
$$\begin{cases} \dfrac{d\varphi}{dt} = kc\left(\beta - \beta_{phase}\right) \\ \dfrac{dp}{dt} = -e\hat{E}_z \sin\varphi \quad with \ \varphi = \omega t - kz - \psi_0 \end{cases}$$

$$H = \gamma - \beta_{phase}\sqrt{\gamma^2 - 1} - \alpha\cos\varphi \quad with \ \ \alpha = \frac{e\hat{E}_z}{kmc^2}$$

$$and \ \ H \equiv constant$$

Particles trajectories in the γ, φ phase space





Courtesy of F. Sannibale, 2011