Construction of a compact electron injector using a gridded RF thermionic gun and C-band accelerator

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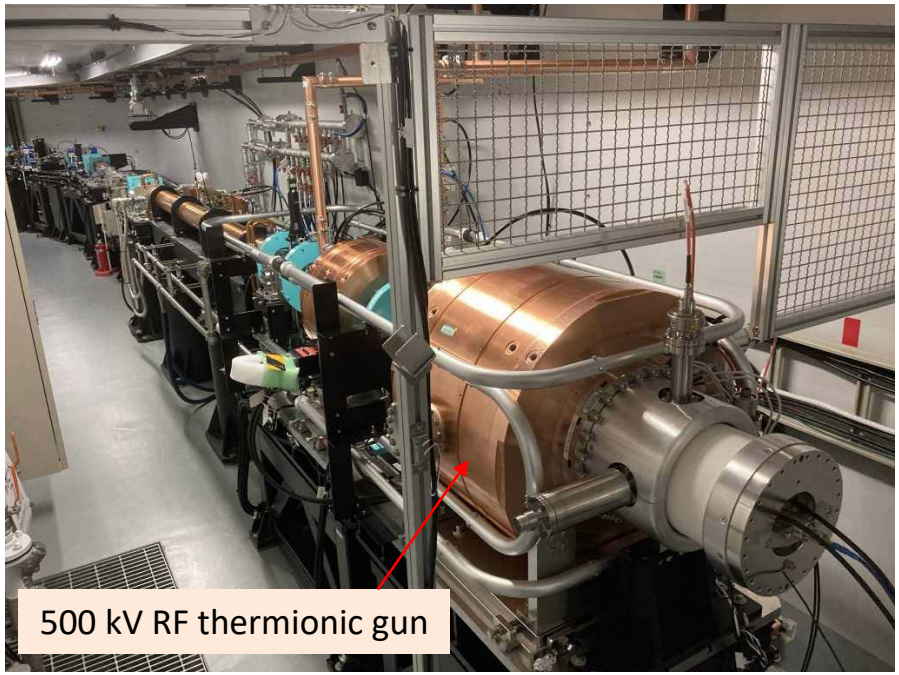
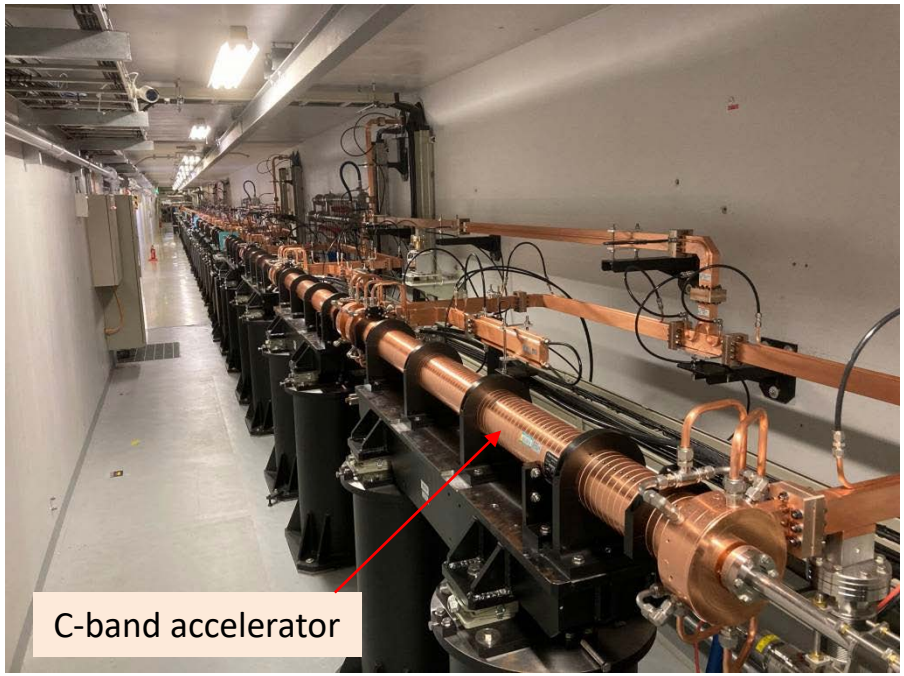
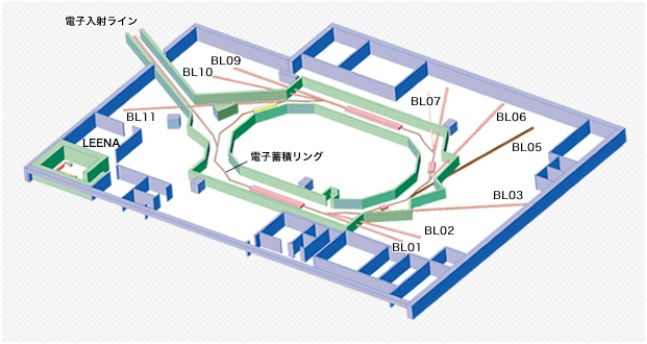




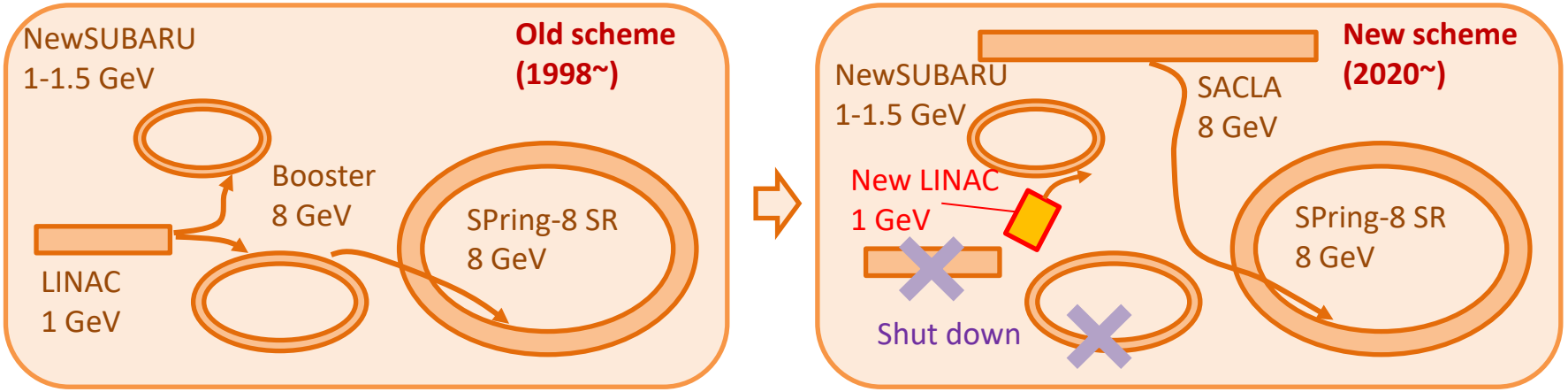
Introduction

- **NewSUBARU**: soft X-ray synchrotron radiation facility
  - Operated by LASTI, University of Hyogo, since 1998
  - Storage ring: 118 m,
  - 1 GeV (Top-up) or 1.5 GeV (ramped-up), 350 mA
  - 1 GeV beam injection from **SPring-8 LINAC**



- **SPring-8 upgrade project "SPring-8-II"**
  - Brilliant X-ray with low emittance ring <100 pmrad, 8 GeV → 6 GeV
  - Low emittance (<500 pm rad) beam injection from SACLA
    - Since 2020, SACLA Injection was started ahead of the ring upgrade.
    - Old injector system (booster synchrotron + **Linac) was shut down**.

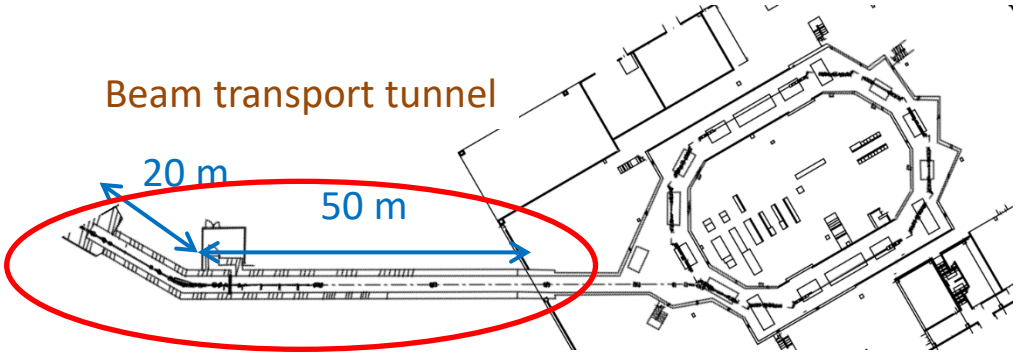
- We decided to construct **new injector dedicate for NewSUBARU**.



Requirements for NewSUBARU injector linac

NewSUBARU (~1998)
SX/EUV SR facility
oper. by LASTI, Univ. of Hyogo
1-1.5 GeV, 350 mA

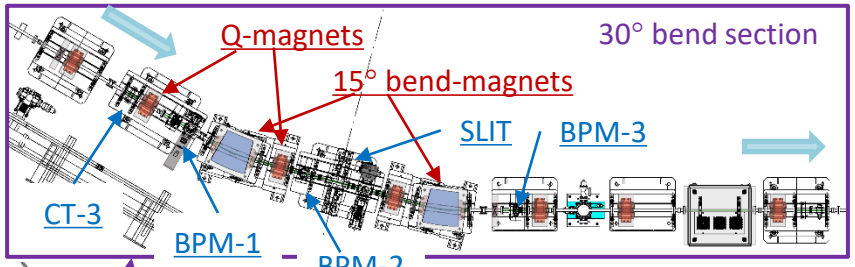
Required specification	
Beam energy	1 GeV
Bunch charge	100 pC
Energy acceptance	< ±0.85%
Injection efficiency	> 90%
Repetition rate	1 Hz

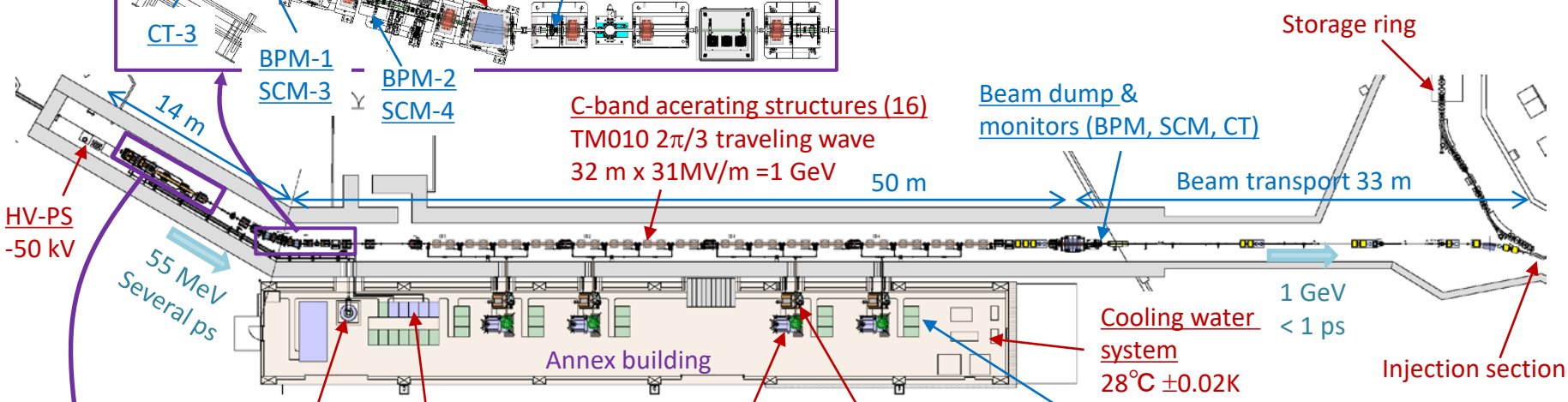


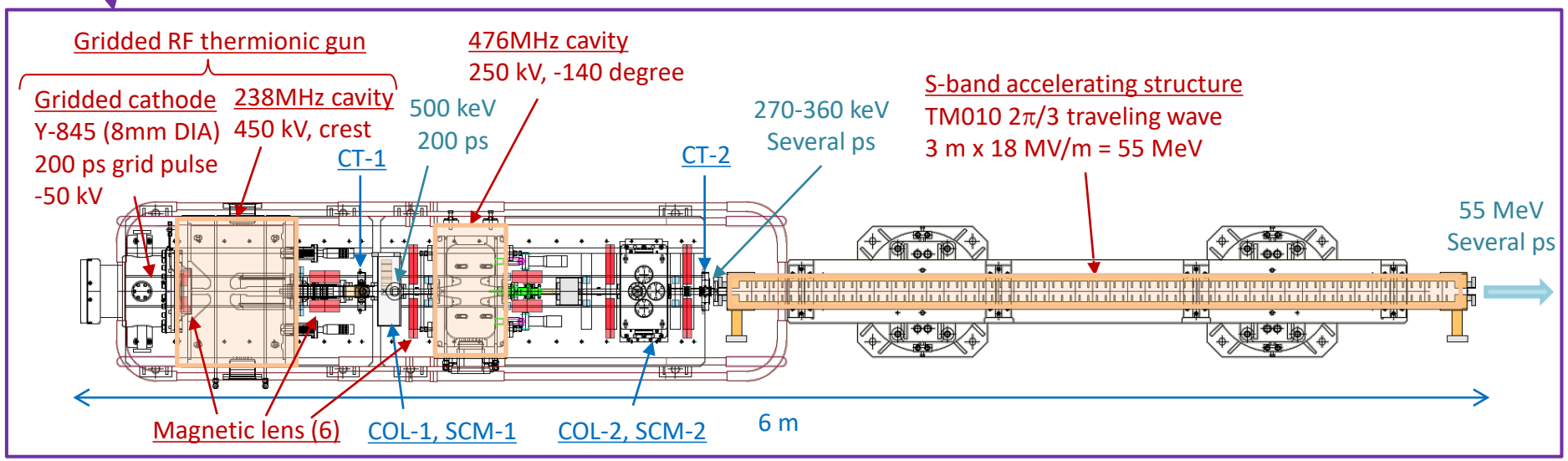
Concept

- **Compact** Fit to the existing transport tunnel (~70 m)
  - C-band high gradient accelerator 31 MV/m x 32 m = 1 GeV
    hardware are well proved at SACLA
- **High quality, stable beam** Daily operated by a few accelerator staffs
  - Gridded thermionic cathode RF gun 500 keV, 200 ps, 2 mm mrad beam
  - Bunch compression to several ps, conserving emittance of <10 mm mrad
- **Low cost**
  - Simple accelerator configuration 5 klystrons + 2 Solid-state amplifiers
  - Highly-integrated MicroTCA.4 based digital LLRF

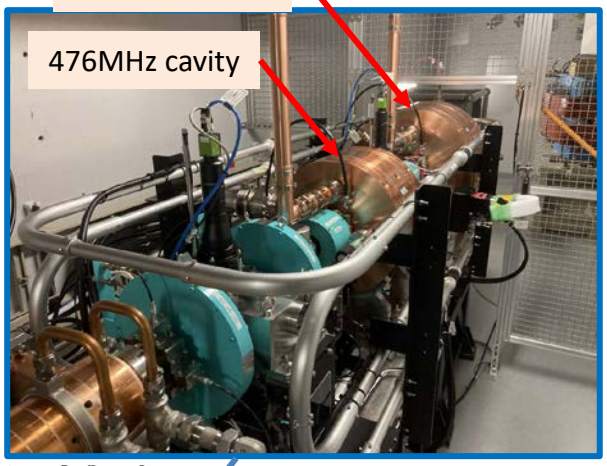
Injector linac layout

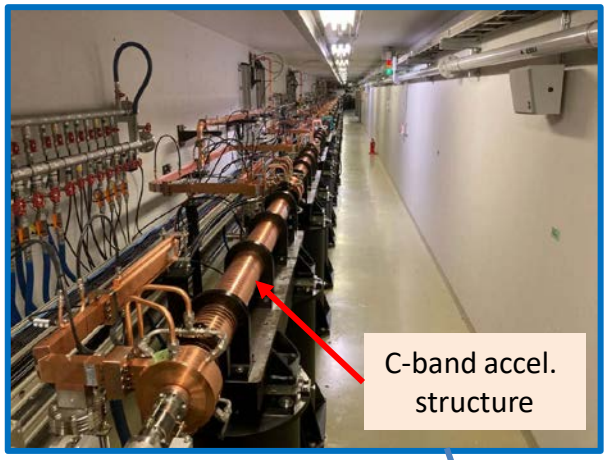


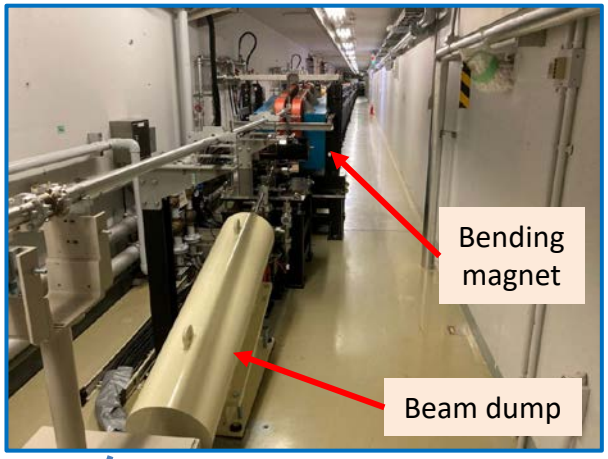


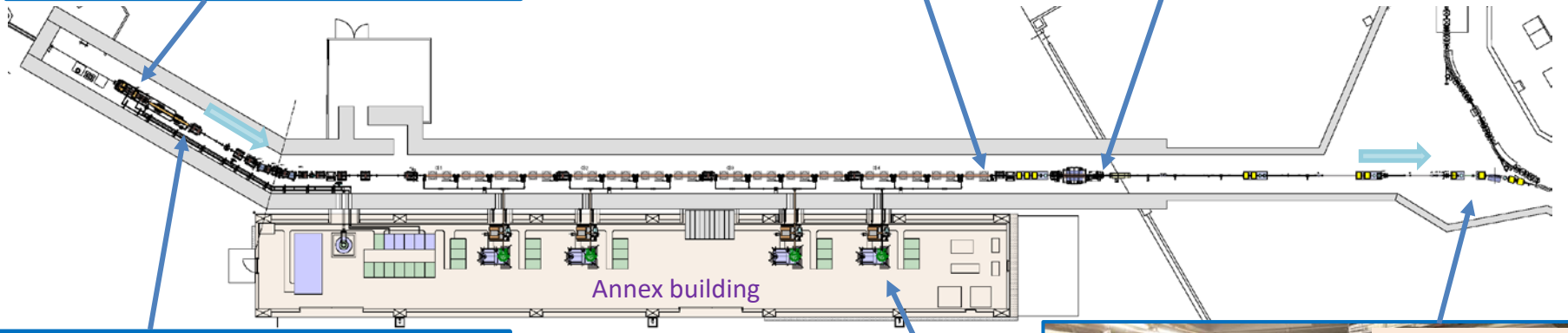


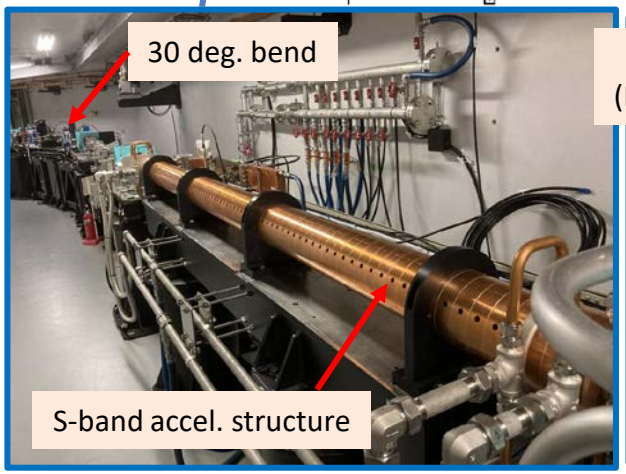
Machine photos

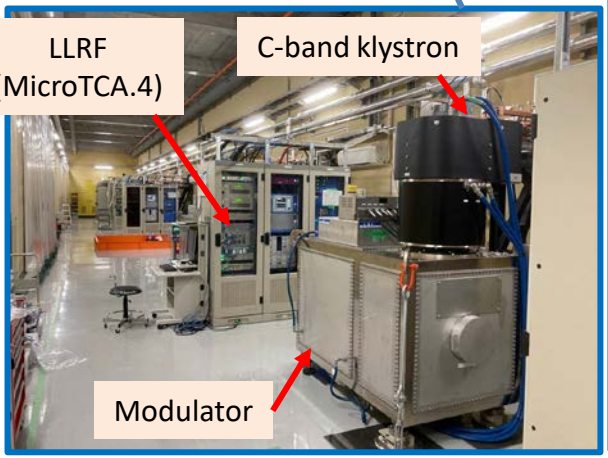


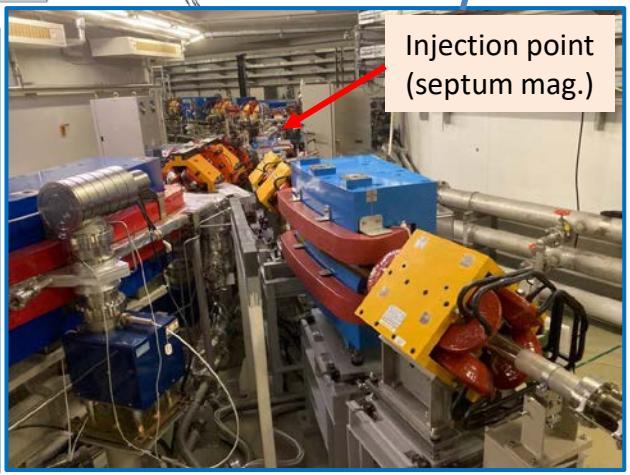












Construction history

Feb, 2017 Accelerator design

Mar. 2019 Annex building constructed

Jan. 2020 Install klystron & modulator

July. NewSUBARU shut down

Remove beam transport line

Oct. Install accelerator in tunnel

Jan. 2021 RF conditioning

Feb. Beam commissioning

1 GeV, 100 pC beam

Mar. First light at storage ring

Injection efficiency > 90%

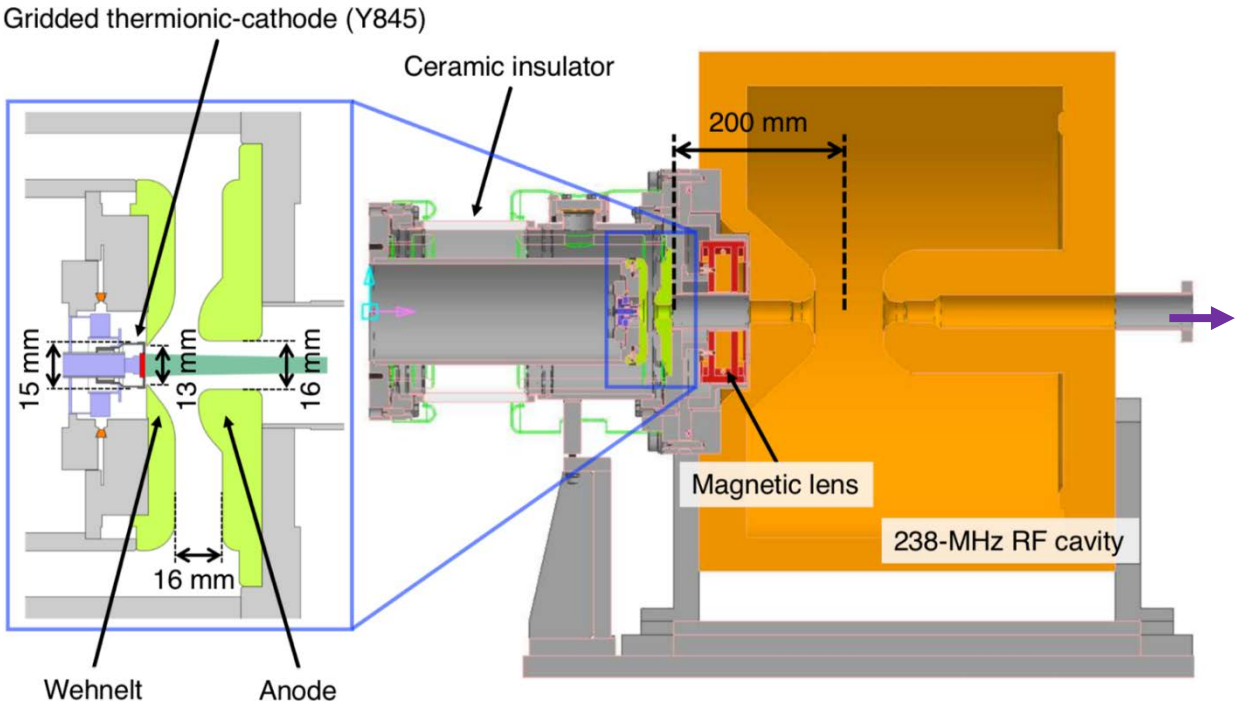
Apr. User run started

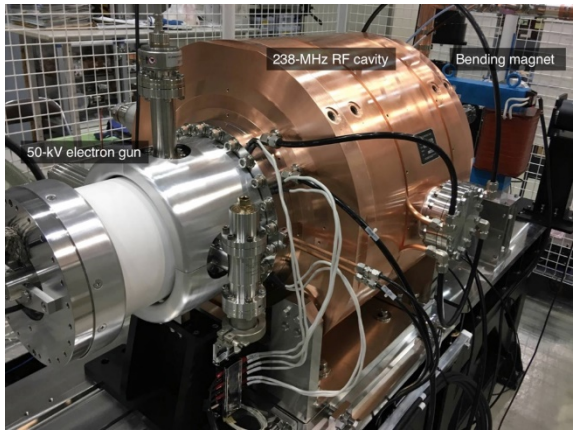
1-1.5 GeV, 350 mA Top-up operation

Combined RF gun using gridded thermionic cathode

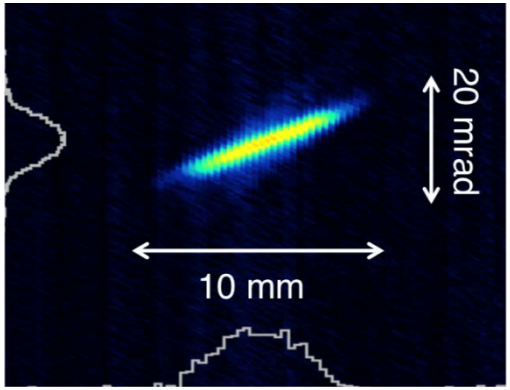
- **50 kV gun using gridded thermionic cathode** (Eimac Y845)
  - Stable beam emission, without special tuning
  - Short-pulsed beam
- **238 MHz cavity**
  - Accelerate beams 50 keV → 500 keV
    suppress emittance growth due to space charge
  - Driven by 42 kW solid state amplifier
  - Cathode and magnetic lens attached to the cavity

T. Asaka, et. al., Phys. Rev. Accel. Beams 23, 063401 (2020)



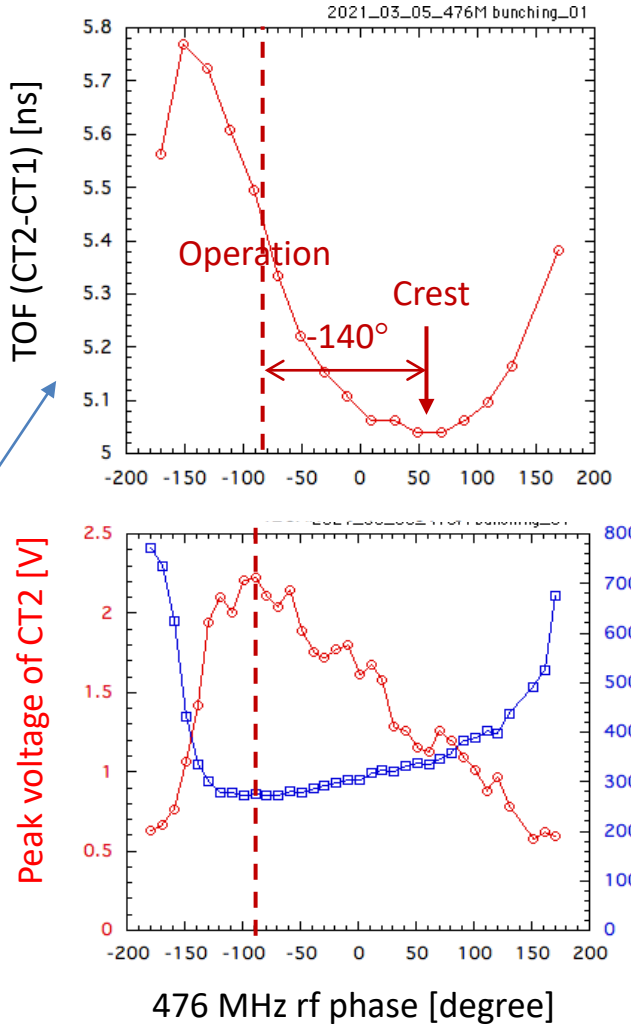


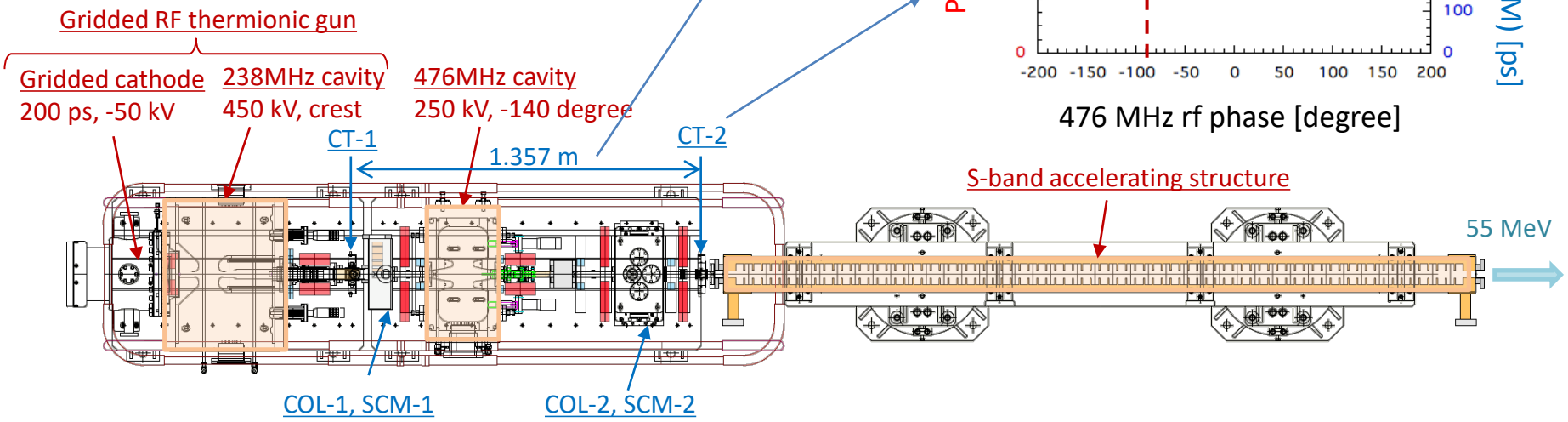
Measured beam parameters at prototype test	
Beam energy	500 keV
Charge	1 nC
E-spread	4.2 %
Norm. ε	1.7 urad (60%)



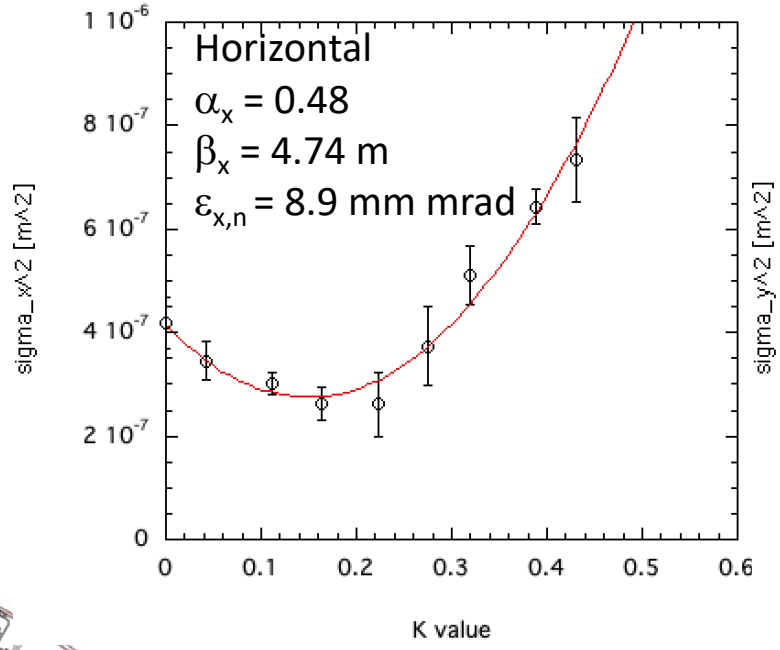
Velocity bunch compression at 476 MHz cavity

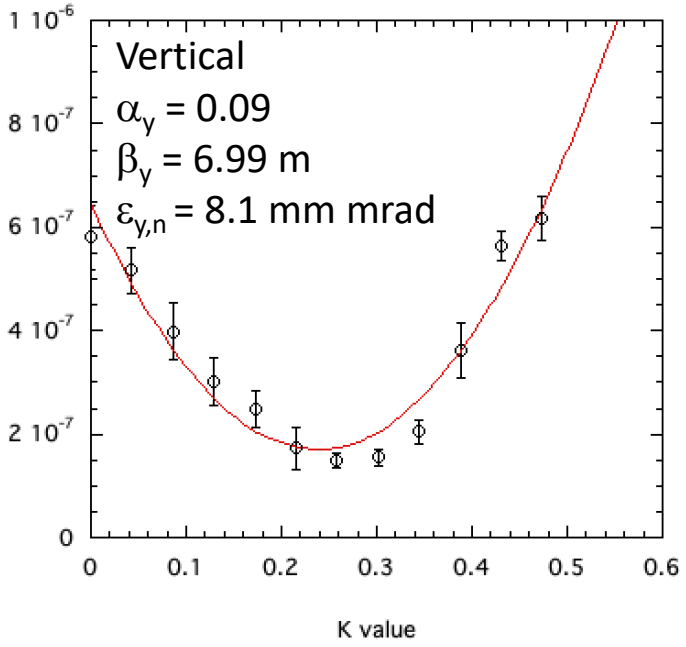
- 476 MHz cavity (250 kV, -140 degree)
  - Decelerate and provide the energy chirp
    500 keV → 270~360 keV
  - Velocity bunch compression
    200 ps (FWHM) → several ps
  - Bunch-up at S-band first cavity
- Beam diagnostics
  - TOF… confirm phase/ampl. of 476 MHz
  - CT2 signal …peak current of bunch



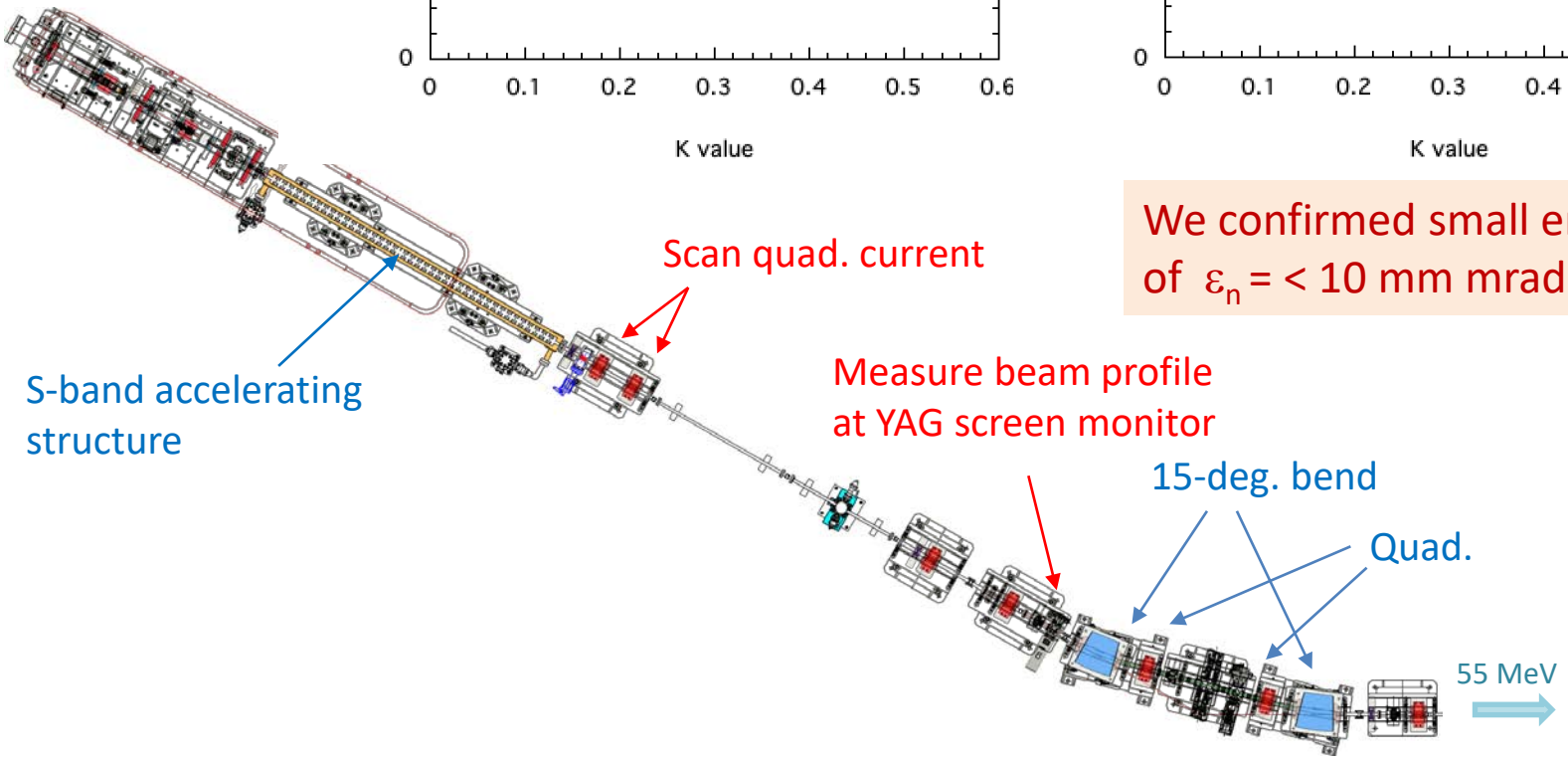


Beam emittance measurement by Quad. scan





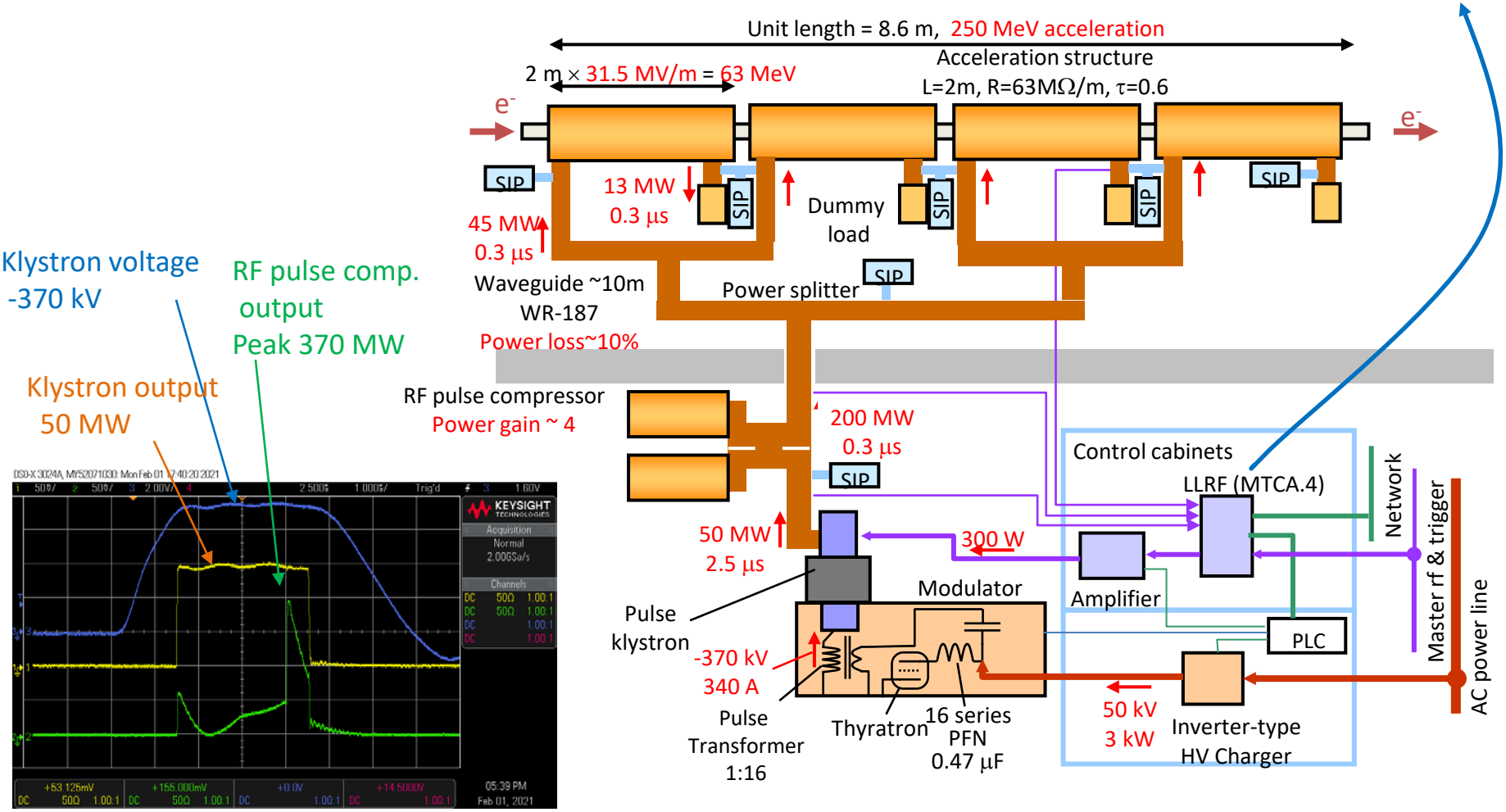
We confirmed small emittance of ε_n = < 10 mm mrad



C-band accelerator system

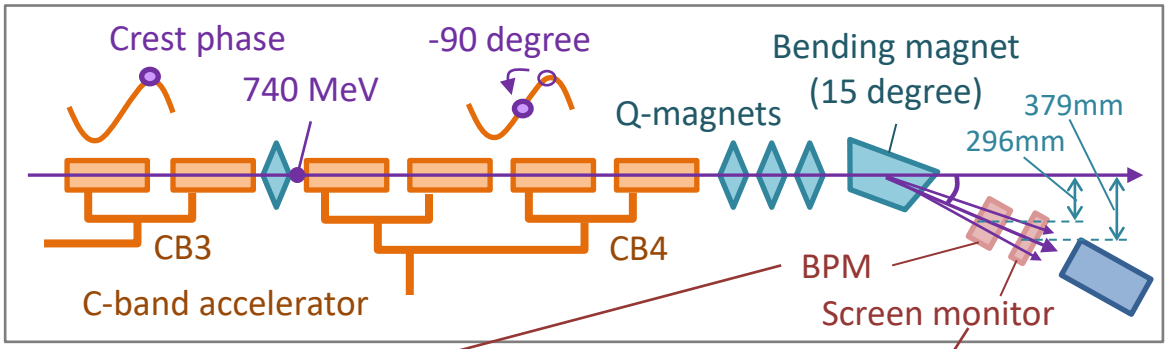
- High accelerating gradient ~31 MV/m
- Well proven at SACLA
  (T. Inagaki, et. al., PRST-AB 17, 080702 (2014), …)
- Ultra-stable (<100ppm) klystron modulator
- Highly integrated Micro-TCA.4 based digital LLRF

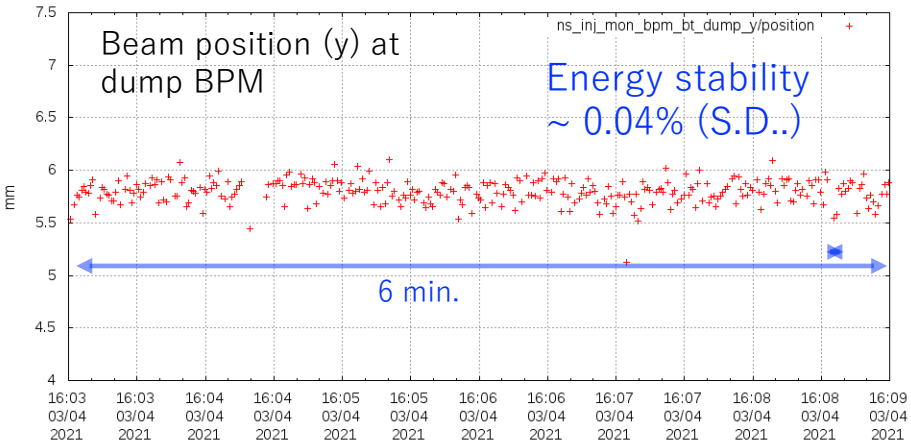
MicroTCA.4 based LLRF
-Digitizer (DAC, ADC)
-RF frontend
-Trigger delay
- EtherCAT connection
- CPU, FPGA

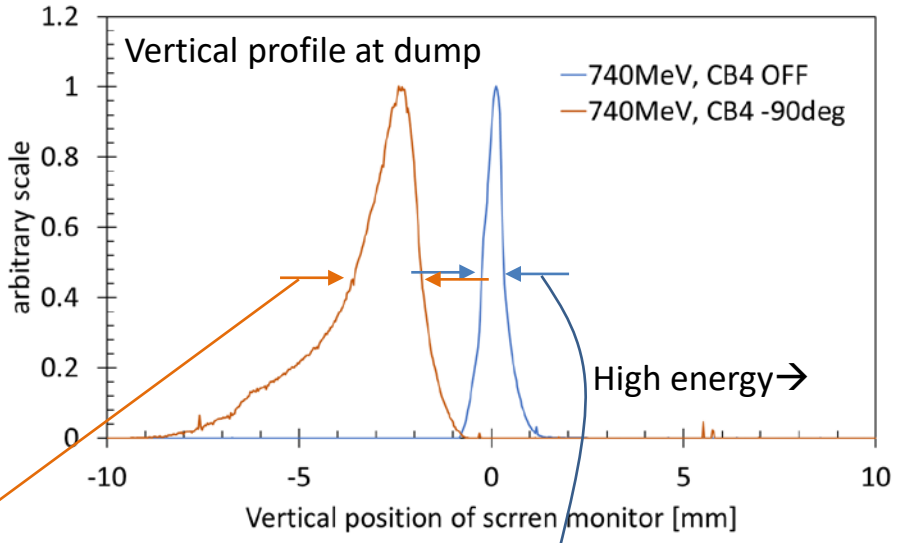


Beam energy profile at linac end

- Beam diagnostics
  before ring injection
  - Beam energy
  - Energy stability
  - Energy spread
  - Bunch length







Bunch length (zero phasing method)
…neglecting spatial spread (preliminary),
Δt = 1.6 mm x 1.95 MeV/mm /240 MeV x 175 ps/2π
= 350 fs (FWHM)

Energy spread (CB4 OFF)
…neglecting spatial spread (preliminary),
$\Delta E/E$ = 0.5 mm x 1.95 MeV/mm /740 MeV
= 0.14 % (FWHM)

Summary

- New 1 GeV injector linac for NewSUBARU was constructed.
  - Gridded RF themionic gun for stable, low emittance beam
  - C-band high gradient accelerator for compact accelerator length
  - Simple and sophisticated buncher & accelerator configuration.
- We obtained sufficient performance of the beam.
- The stability and the reproducibility of the beam is also good.
- This design of the injector linac is also used for the 3 GeV SR facility in Sendai.
- This electron linac with low-emittance, compact, and low-cost sets a new benchmark for the next generation of small and medium-sized linacs.

Parameters	Design	Measurement (typical)
Beam energy	1 GeV	1 GeV
Bunch charge	100 pC	100 pC
Normalized emittance	< 10 mm mrad	< 10 mm mrad
Energy spread	< ±0.5%	0.1 % (FWHM)
Energy stability		0.04% (STD)
Bunch length	5 ps (FWHM)	< 1ps (FWHM)
Injection efficiency	> 90%	> 90 %

Acknowledgements

The construction of the injection linac was greatly supported by RIKEN, JASRI and by Hyogo Prefecture. We would like to thank many staffs from RIKEN, JASRI and LASTI, University of Hyogo, SES, QST, and many other related companies, for their participation and cooperation.

Mar. 9, 2021, First light from new linac beam