International Workshop on Breakdown Science and High Gradient Technology
April 19, 2012, KEK,Tsukuba

High gradient performance of C-band accelerator in SACLA

***S**Pring-8 **A**ngstrom **C**ompact Free Electron **La**ser*

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on behalf of C-band group

Outline

1) Overview of C-band accelerator system

2) Operational status

~ Accelerating gradient and trip rate ~

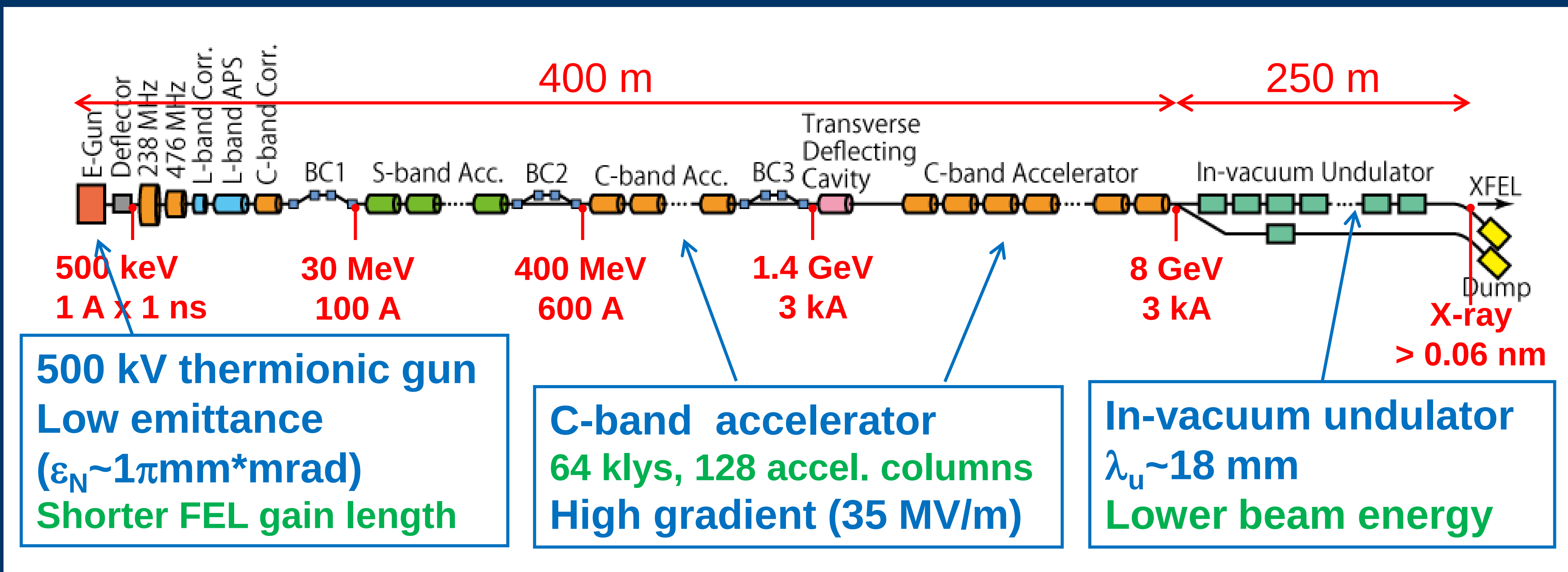
3) Dark current

4) Summary

Compact XFEL facility "SACLA"

X-ray FEL

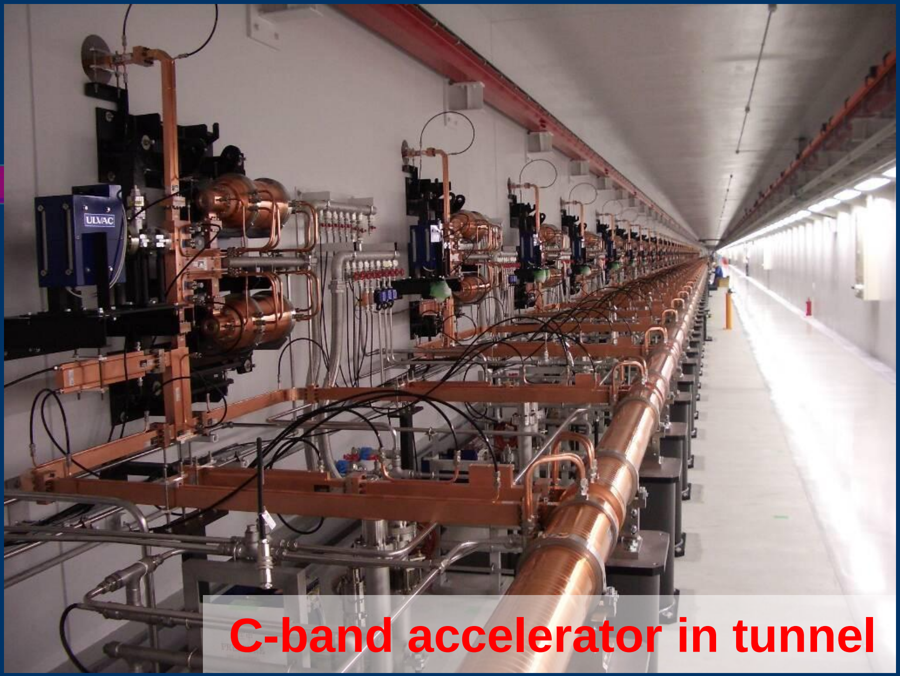
- Total length: 700 m (LCLS: 2 km, European XFEL: 3.5 km)
- Low construction cost ~ 450 M-USD
- Based on 3 key technologies;



Why we use C-band ?

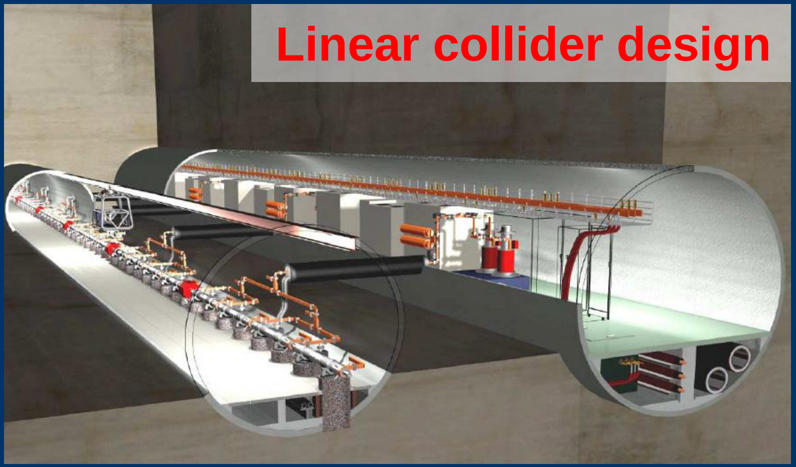
X-ray FEL

- **High accelerating gradient**
  - Nominal operation E_{acc} = 35 MV/m
  - $E_{surface}$ ~ 100 MV/m
    Achievable with present technology
  - 8 GeV / 35 MV/m ~ 230 m
    (+ Injector + chicane ~ 400 m)

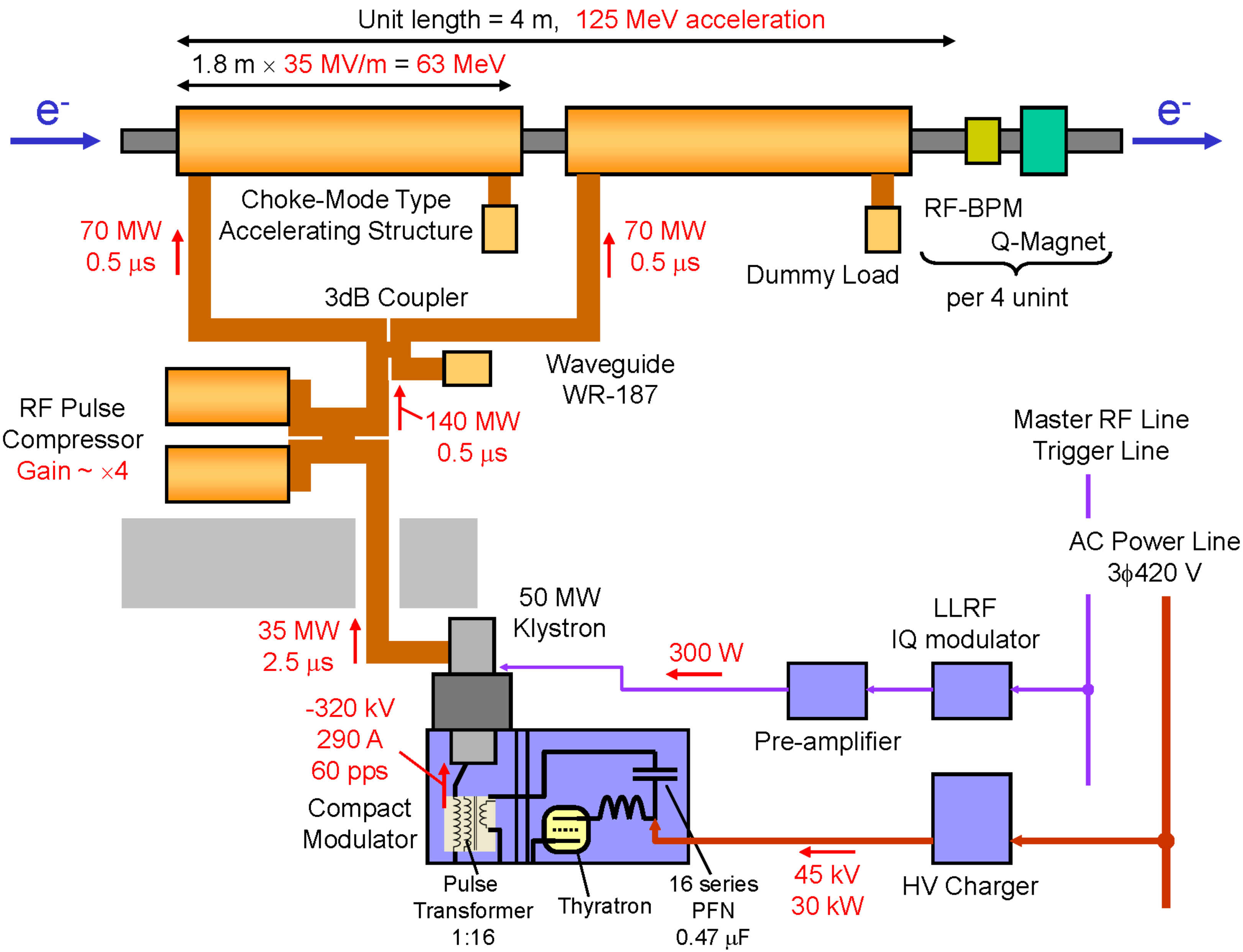


- **Normal conducting RF**
  - No cryogenic system
  - Repetition (60 pps) is suitable for experiments (CCD frame rate).

- **Components are available**
  - Initially developed at KEK for the linear collider project



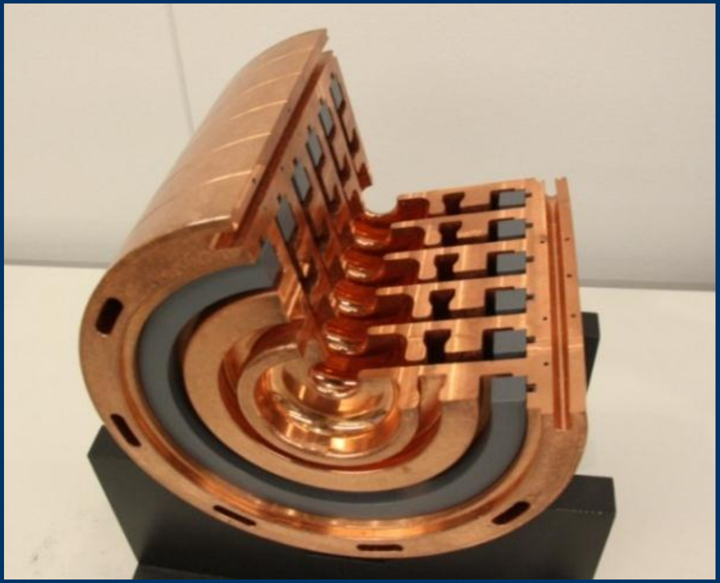
C-band (5712 MHz) RF system



To obtain high accelerating gradient

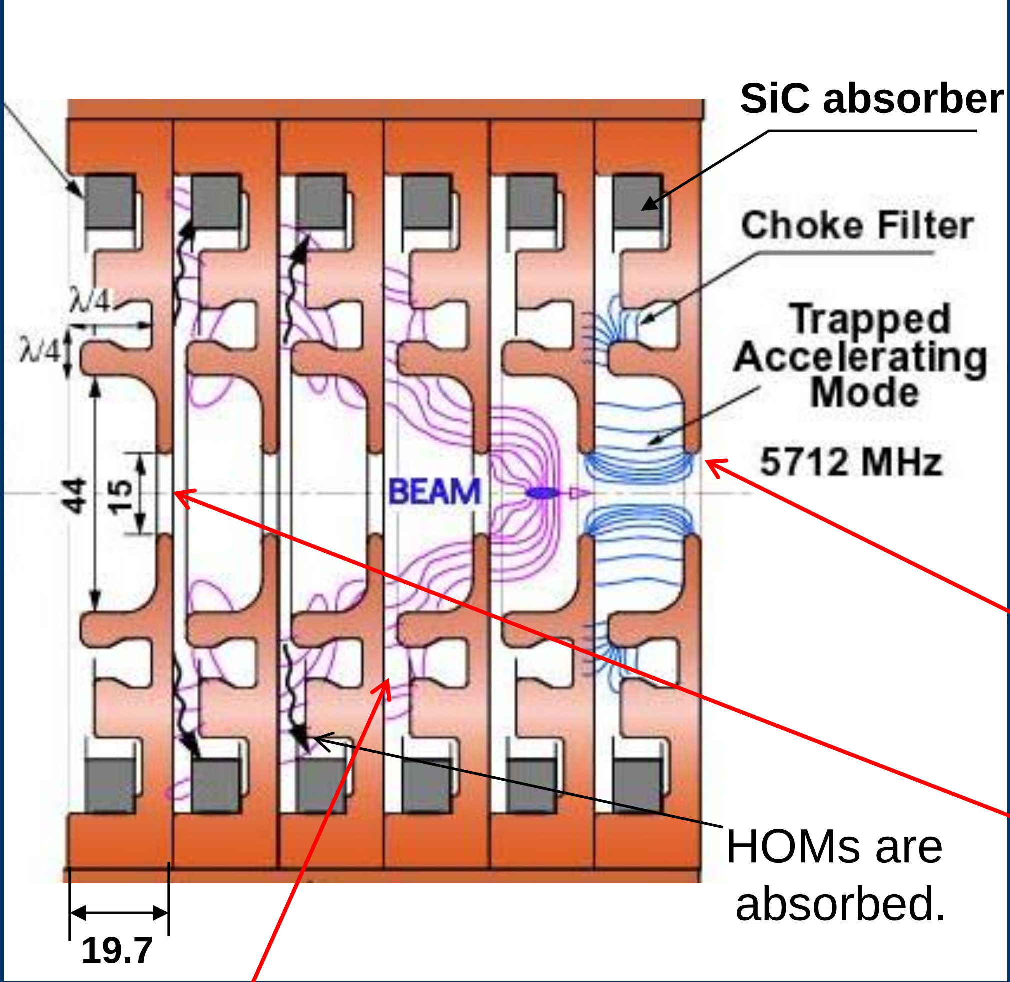
- Withstand high electrical field
- Low dark current , for undulator irradiated demagnetization

- **Lower surface field**
  - Cavity design
- **Good cavity surface**
  - High quality copper,
    no void, no contamination
  - Clean fabrication, no dust, no oil
  - Clean assembly and installation
- **Lower peak RF power**
  - Pulse modulation



C-band choke-mode type accelerating structure

X-ray FEL



Length	1.8 m
Number of cell	89 + 2 coupler
Accelerator type	TW, 3π/4 mode quasi-CG structure
Shunt impedance	49 – 60 MΩ/m
Attenuation constant	0.53
Filling time	300 nsec

Disk thickness: 4 mm, R=2 mm
Lower surface field (E_{max} ~100 MV/m)

Iris aperture: 2a=13.6~17.3 mm
Lower emittance growth
Alignment tolerance ~ 100 μm

Choke-mode structure (T. Shintake, 1992)
HOM damping for the multi-bunch operation.

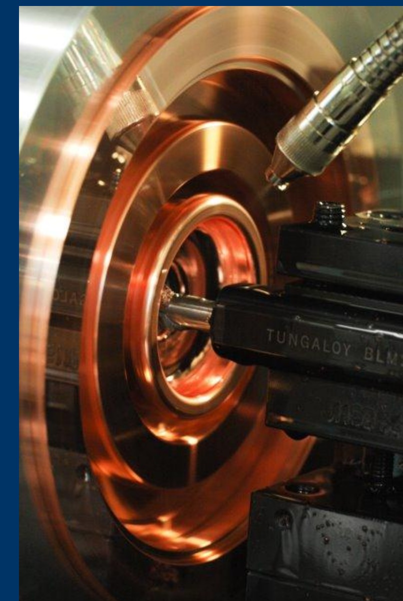
At Mitsubishi Heavy Industries, Inc.

Fabrication of the structure (2007-2009)

SACLA

X-ray FEL

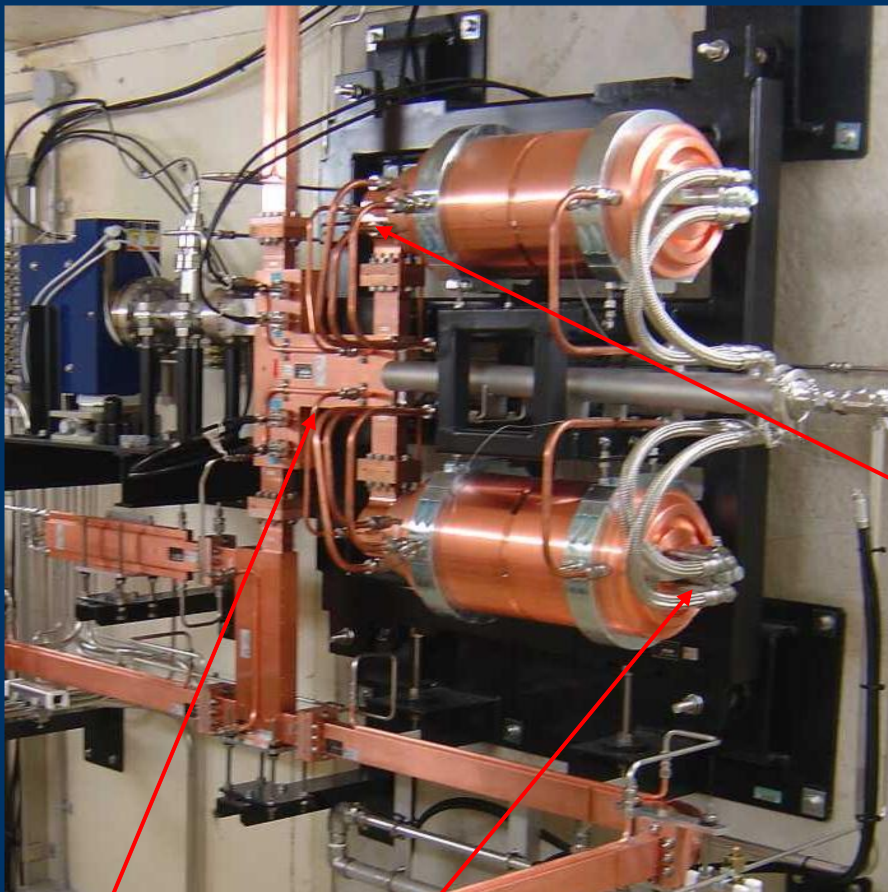
- **Copper**
  - OFC class-1, hot iso-static pressing (HIP)
- **Machining**
  - High precision lathe, with diamond bit, without lubricant oil
  - No electrochemical polishing, no rinsing (because of the choke-structure)
- **Vacuum brazing**
  - Assembly in the clean room
- **Inspection**
  - Bead measurement, no cavity tuning (dimpling)
  - Out gas measurement

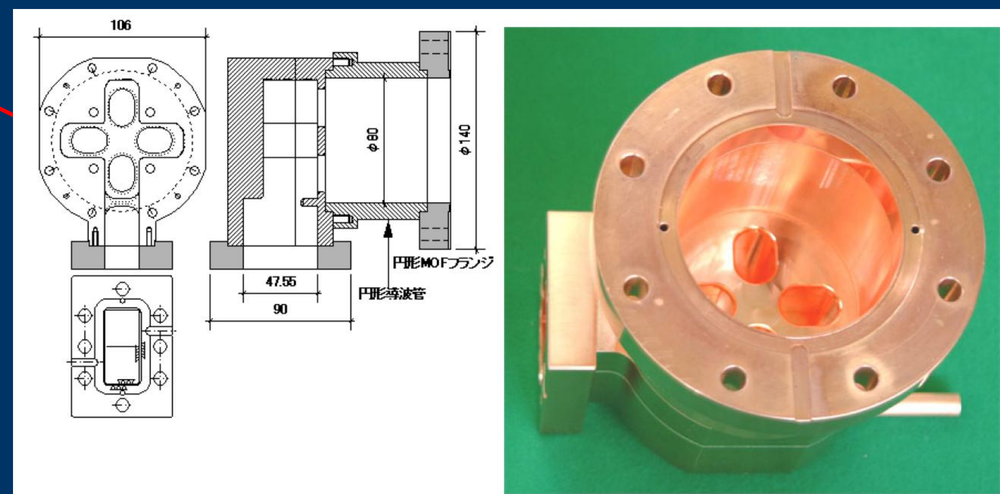


RF pulse compressor (SLED)

X-ray FEL

Cavity RF mode	TE0,1,15
Q_0	185 k
β	9 ~ 9.5
VSWR	<1.05





3dB coupler

Tuner

Diaphram structure with differential screw

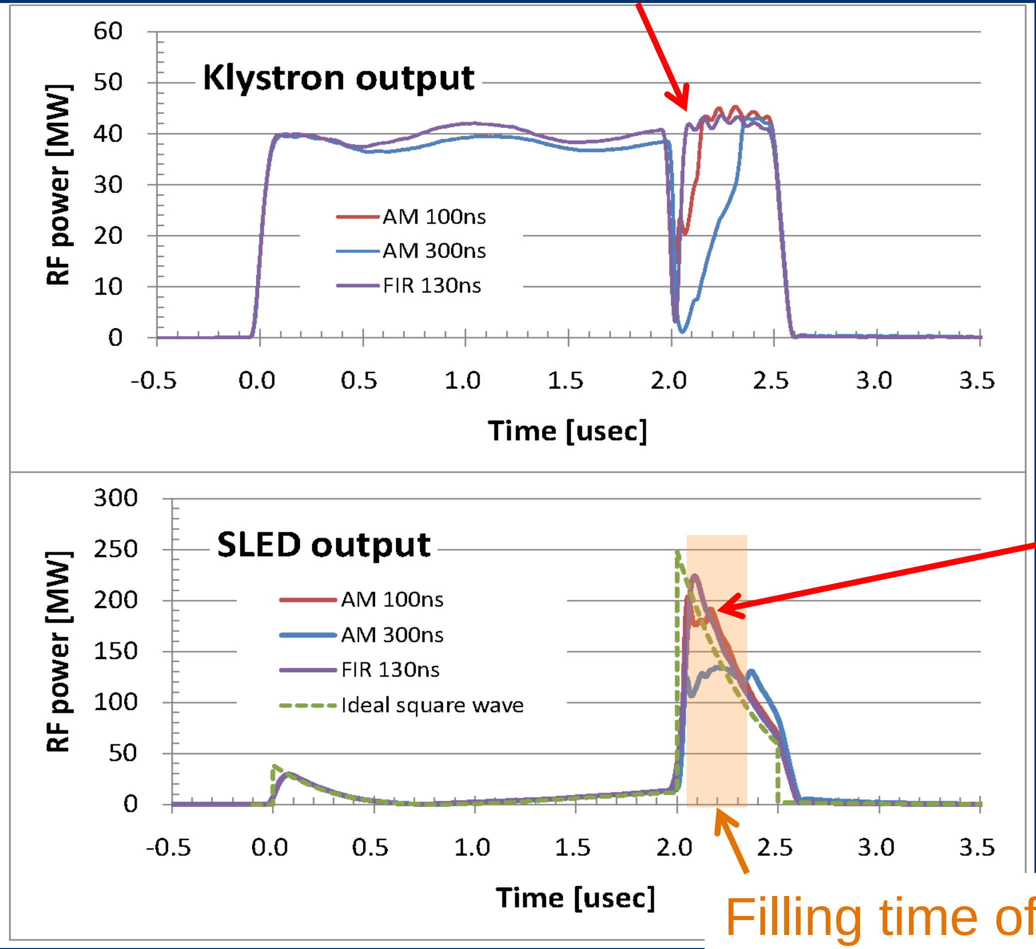
Mode converter

4 coupling holes reduce the iris field

Amplitude modulation for the peak power suppression

X-ray FEL

Phase reversal and amplitude modulation at LLRF



Klystron output ~ 38 MW

	Peak power	Average in 300 ns
Ideal	248 MW	171 MW
FIR filter	224 MW	167 MW
AM100ns	204 MW	166 MW
AM 300ns	135 MW	128 MW

Suppress spiky peak power,

Energy multiplication factor
E_{acc} (w/ SLED) / E_{acc} (w/o SLED) ~ 2

Filling time of accelerating structure
t_F ~ 300 nsec

History of C-band high power operation

2004 First high power test

without SLED, E_{acc}=33 MV/m

2007 250 MeV prototype accelerator

daily operated with E_{acc}=37 MV/m

2008-2009 High power test

confirm the quarity of mass-production,

E_{acc}=42 MV/m

2009-2010 Installation

2010 RF conditioning started at SACLA

After 500 hours of RF conditioning,

2011 Beam commissioning started

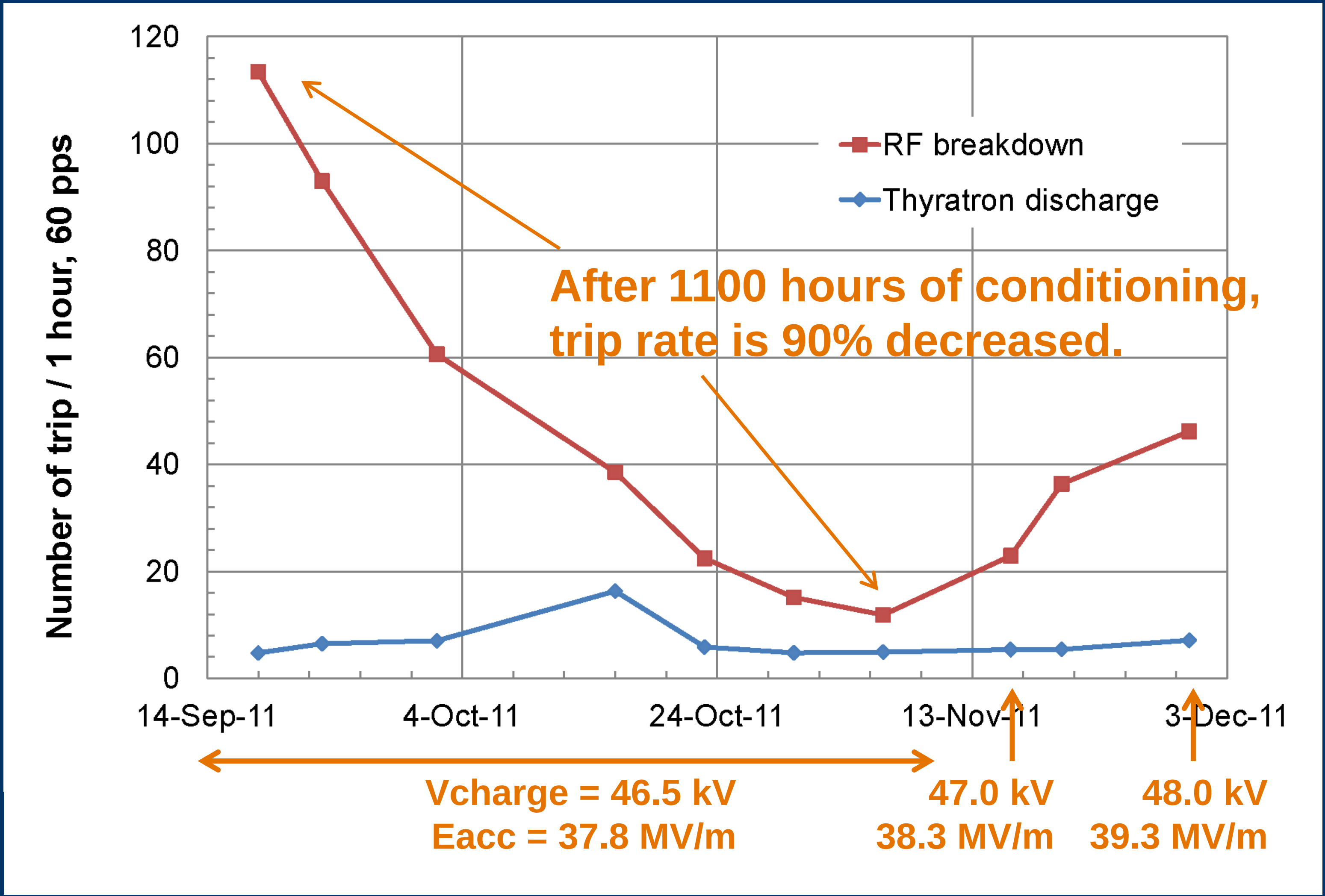
2012 X-ray user experiments started

Total RF run time ~ 8000 hours

Trip rate during the conditioning process

X-ray FEL

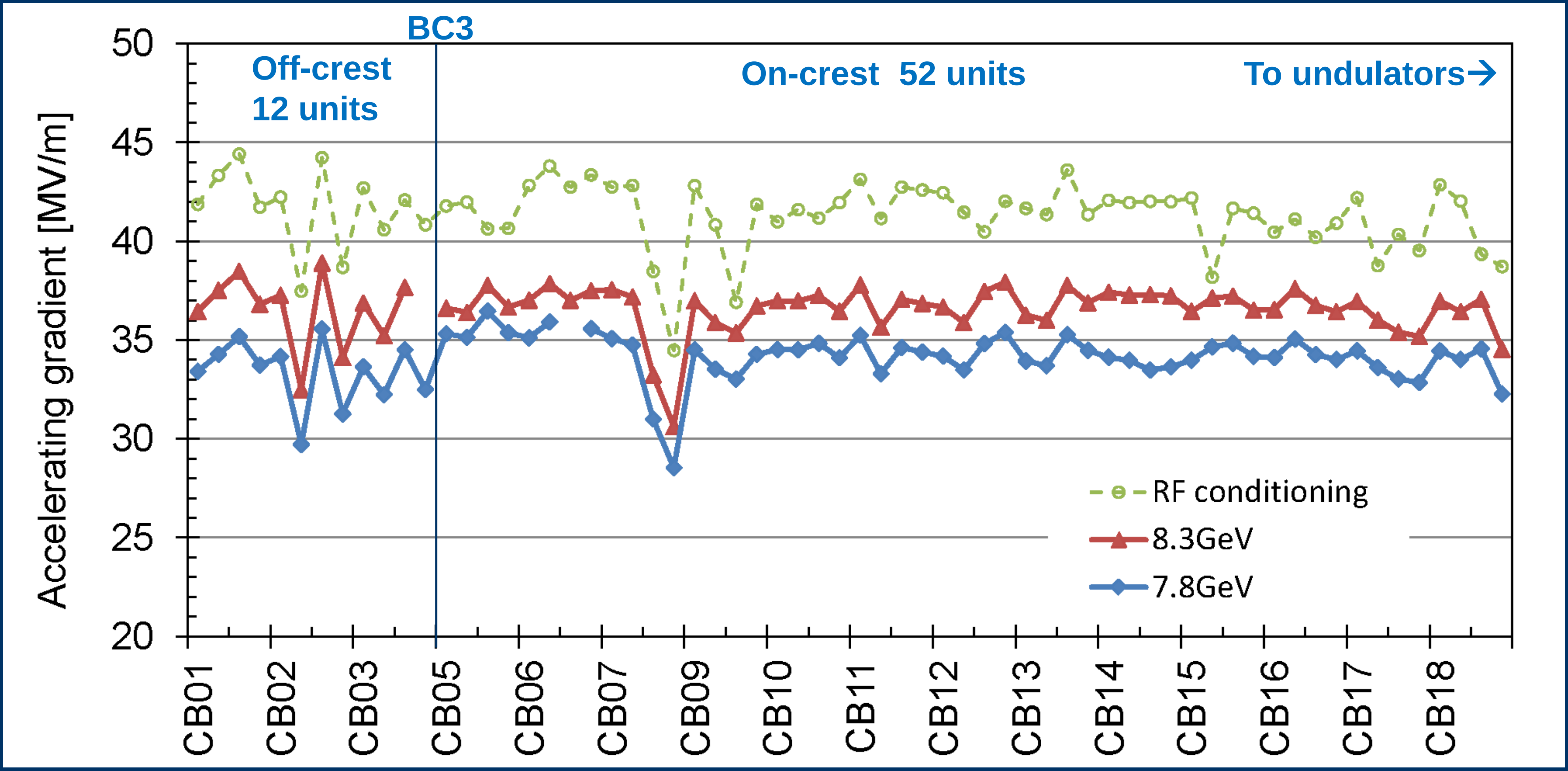
RF conditioning effectively reduces the trip rate.



Accelerating gradient

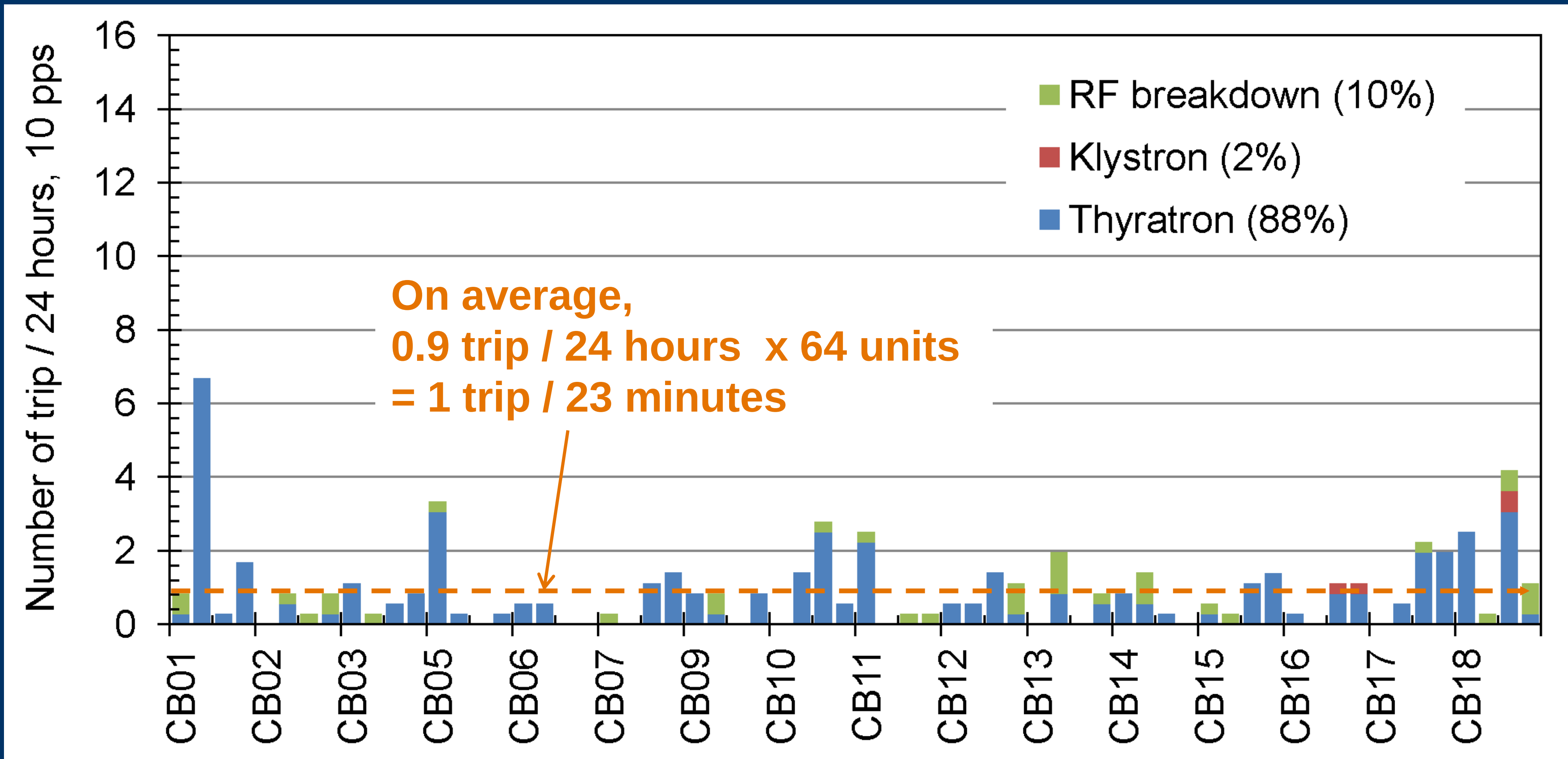
X-ray FEL

X-ray 12~17 keV, beam 8.3 GeV, E_{acc} ~ 37 MV/m (E_{max} ~ 104 MV/m)
10~13 keV, 7.8 GeV, 34 MV/m (95 MV/m)



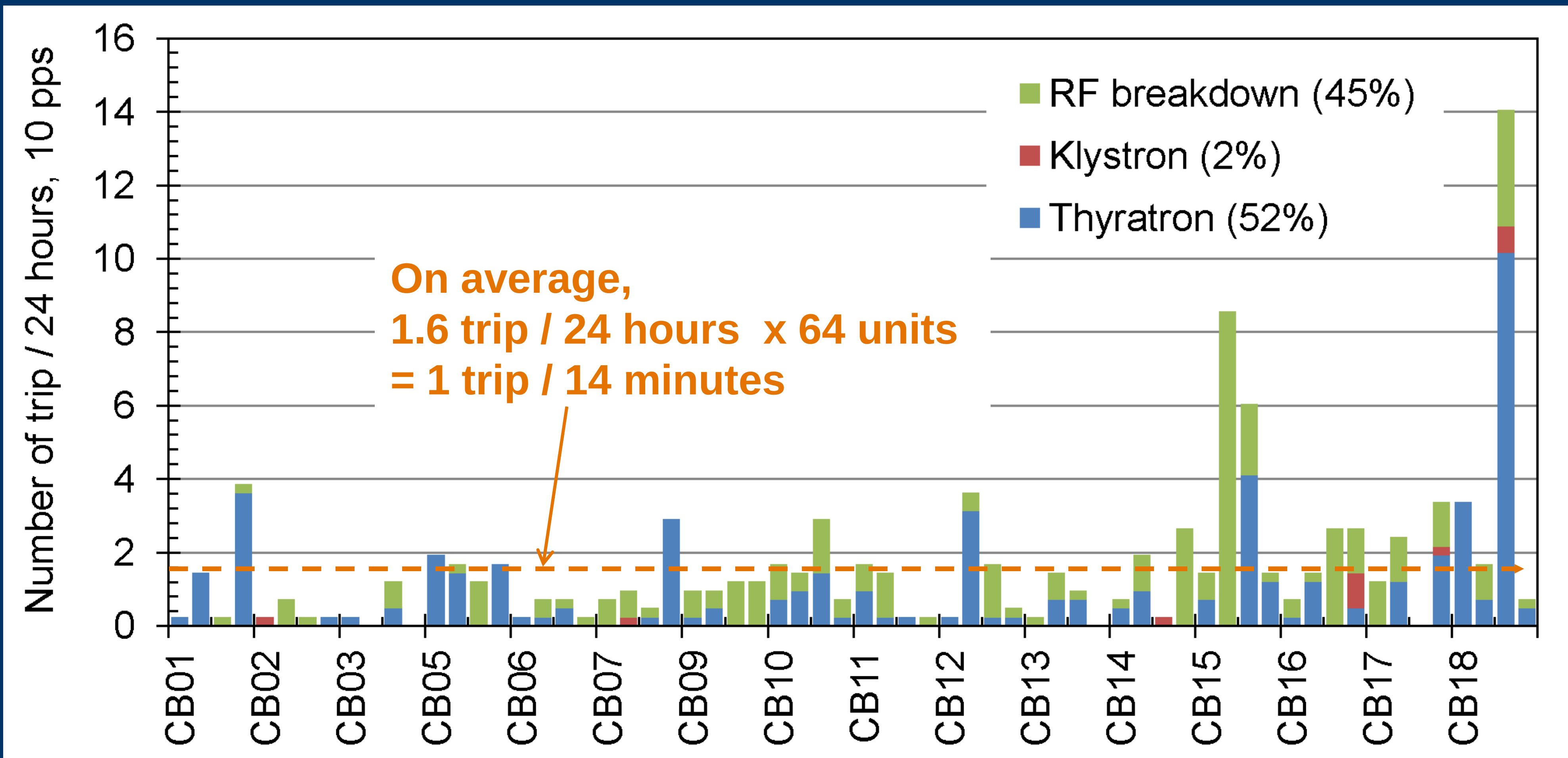
Trip rate in 7.8 GeV (34 MV/m) operation

Main source of trip is thyratron (self-discharge).
RF breakdown rate is much lower ($3x10^{-8}$ BD/pulse/m).

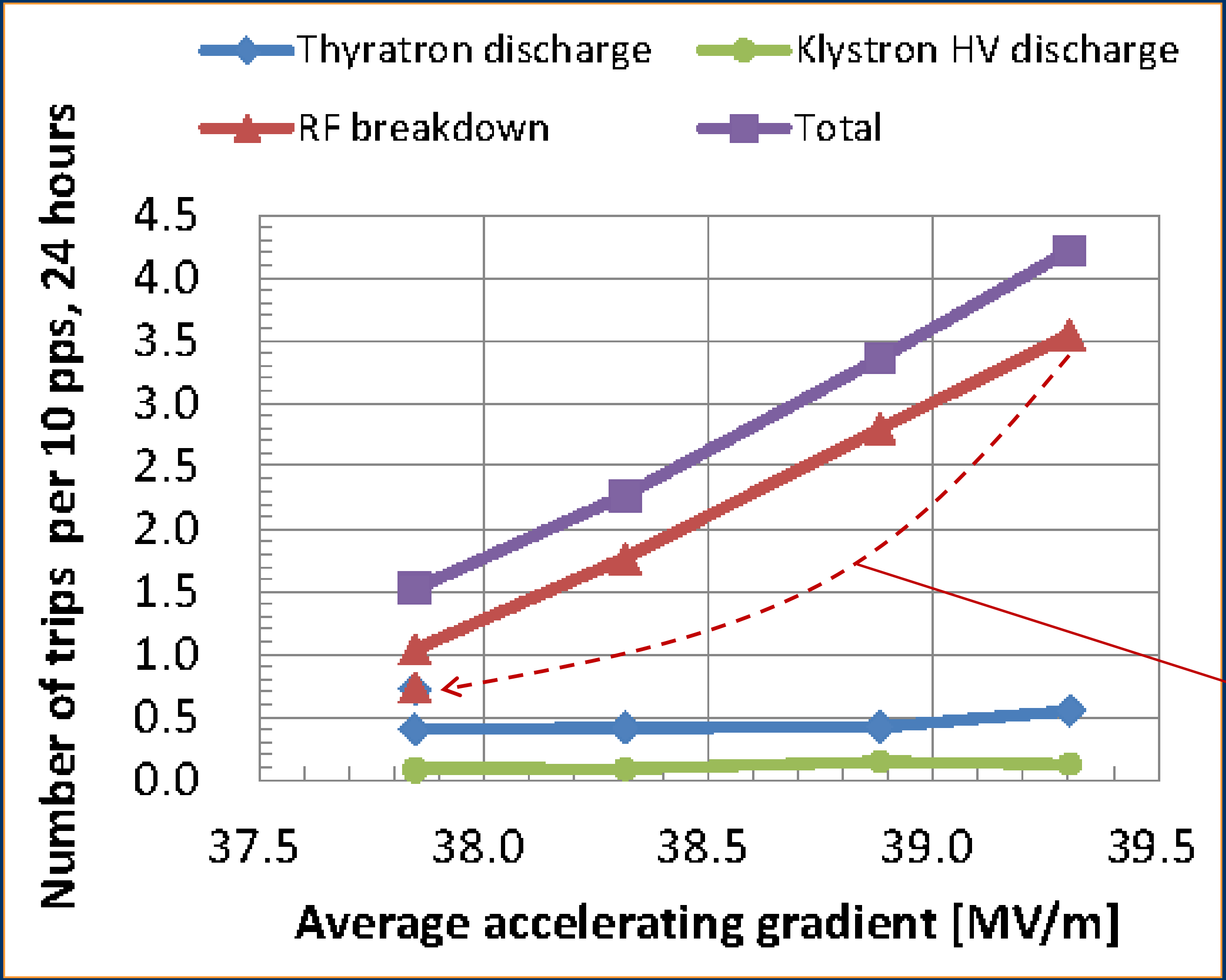


Trip rate in 8.3 GeV (37 MV/m) operation

RF breakdown rate ($2x10^{-7}$ BD/pulse/m) is acceptable in 10 pps operation.



Accelerating gradient vs. trip rate



- RF breakdown rate is still high at over 38 MV/m

- Other trip do not depend on the high voltage.

After measurement with 116 hours, the trip rate is 30 % decreased.

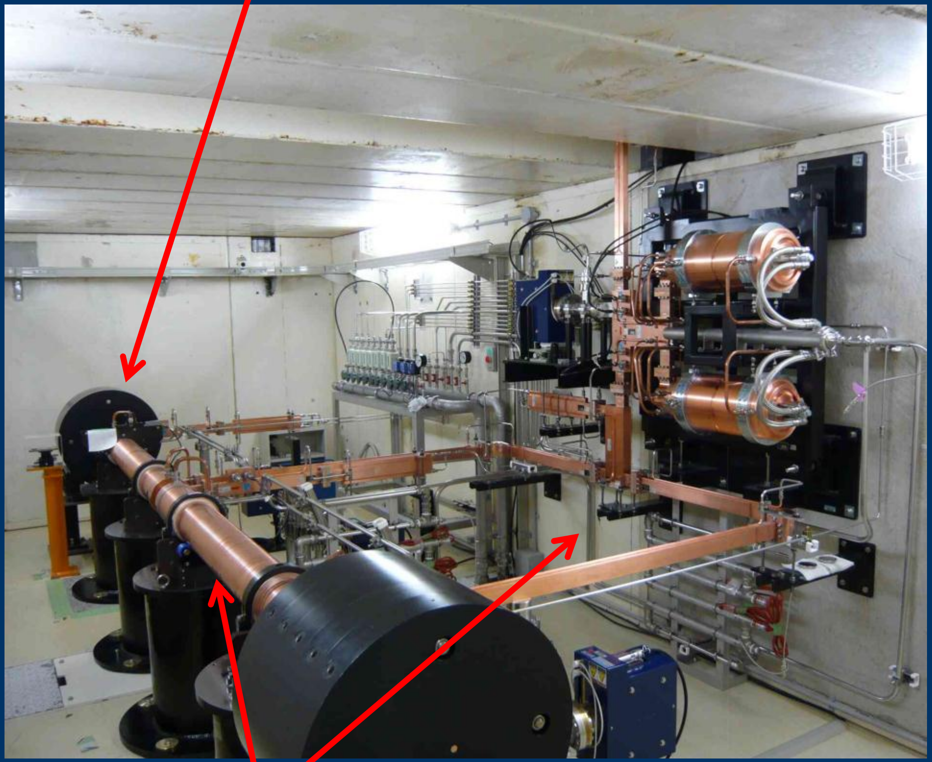
We plan to do further RF conditioning for energy upgrading.

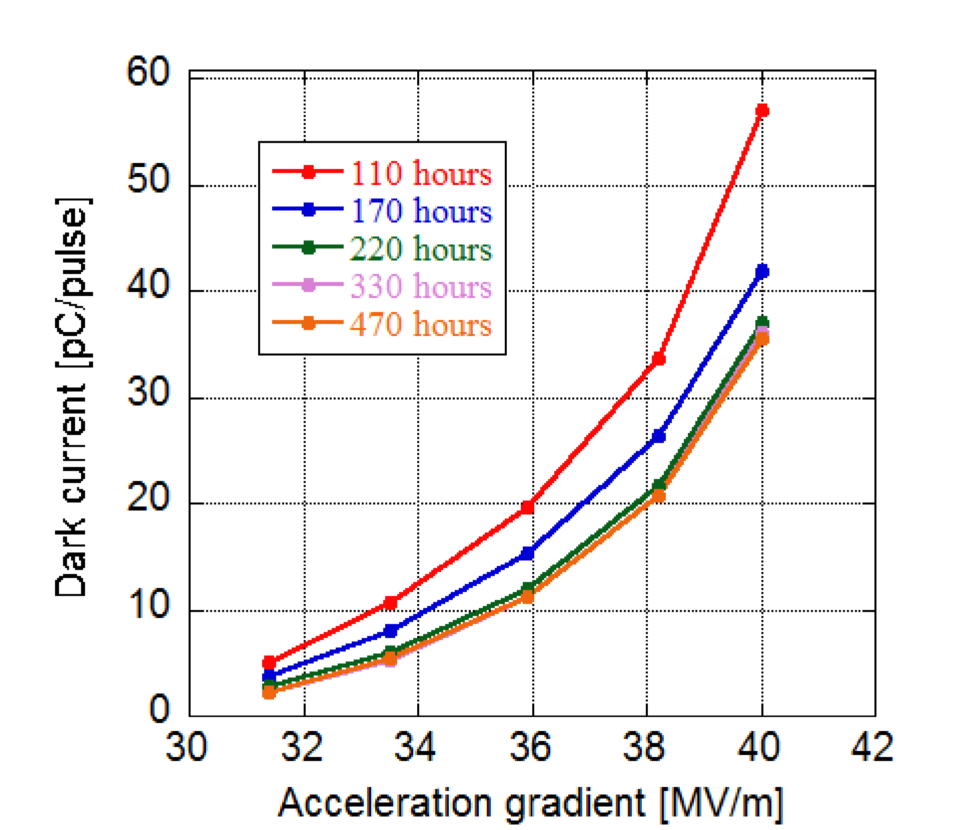
Dark current measurement at the test stand

X-ray FEL

Measured by the electrical charge at the beam dump

Order of 10 pC/pulse of dark current was observed.





One unit of C-band accelerator

Dark current measurement at SACLA accelerator

X-ray FEL

Measured by CT inserted in the C-band accelerator.

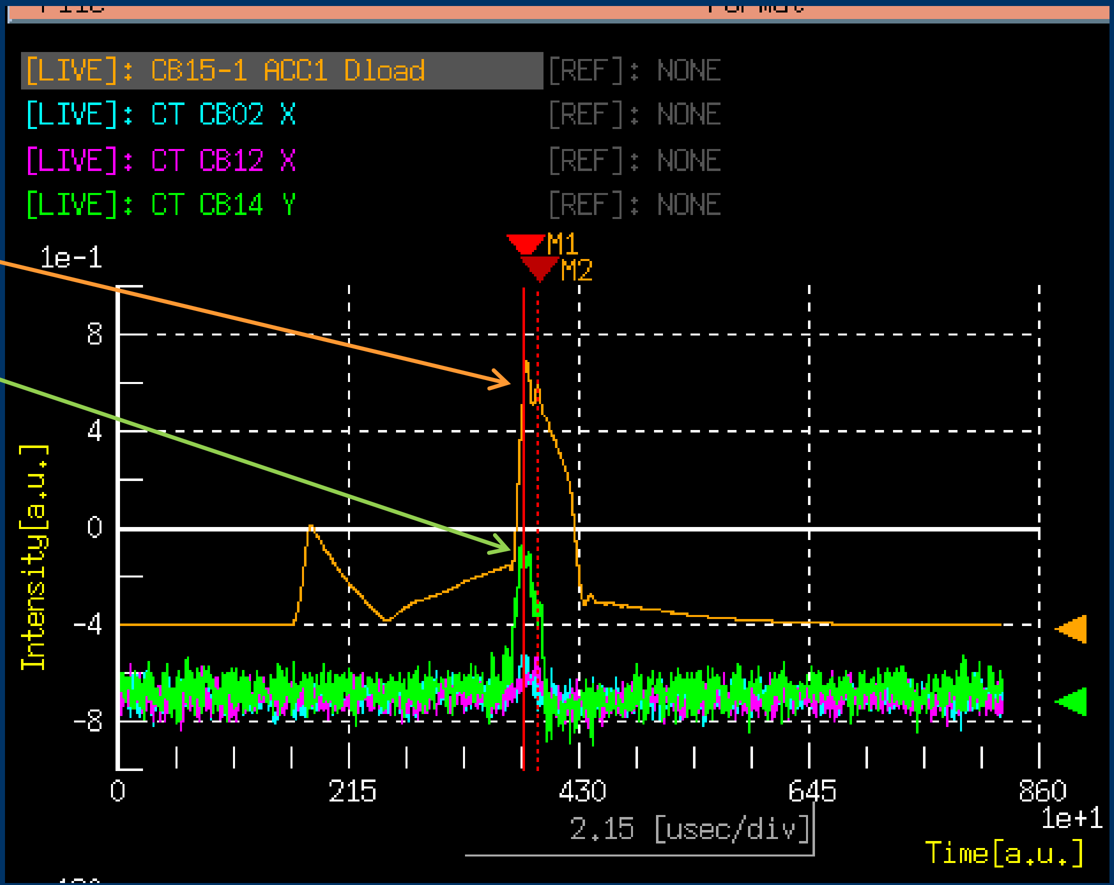
RF after the C-band structure

Dark current ~ 4 pC/pulse

(cf. Beam ~several 100 pC)

Most of the dark current is not captured at the downstream accelerating structures.

Actually the dark current is not the problem for the beam operation.



Summary and prospect

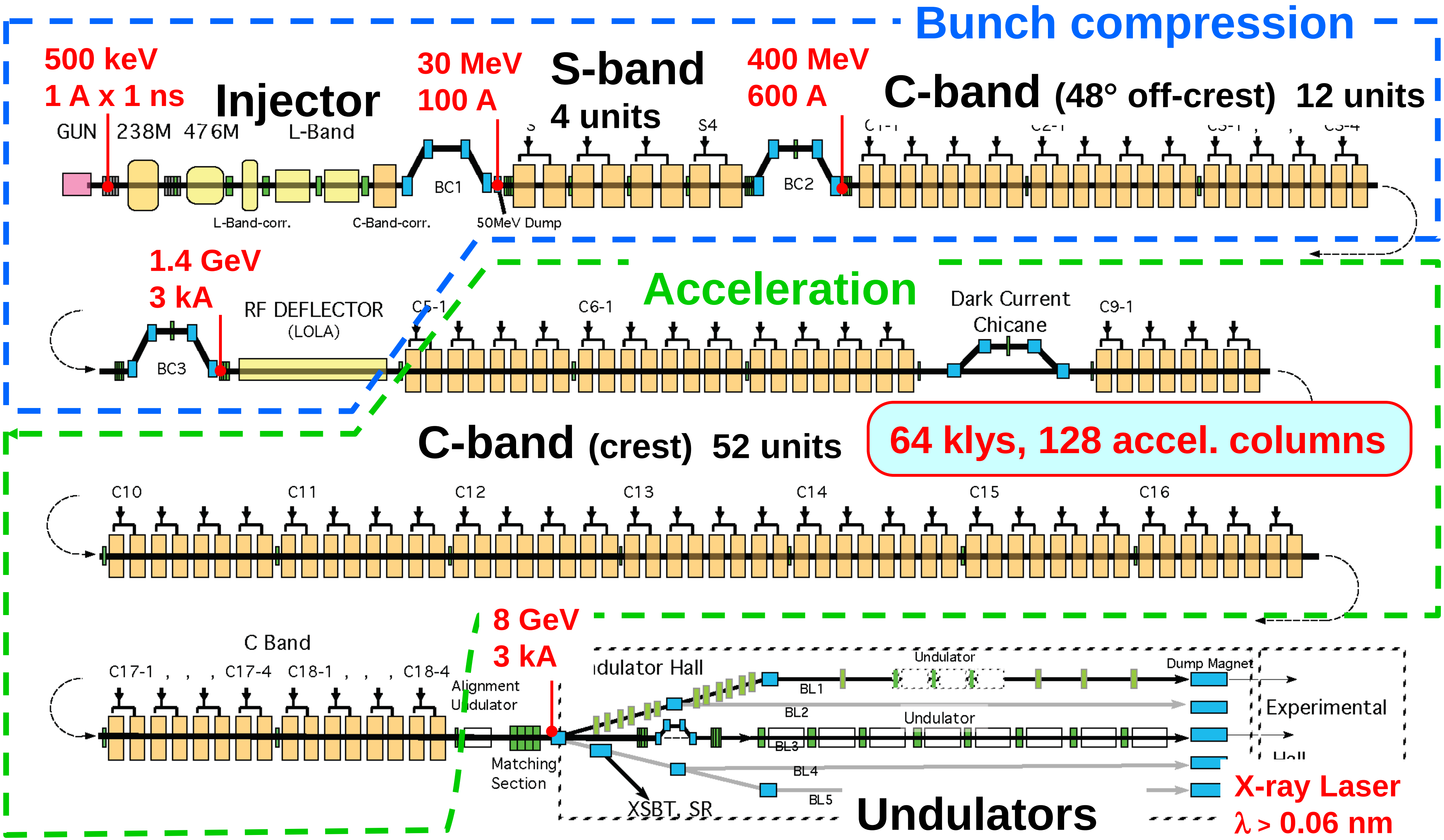
X-ray FEL

- Since 2011, 64 units of C-band accelerator has been well operated for X-ray FEL, to accelerate beam up to 8.3 GeV, with an average gradient of 37 MV/m.
- RF breakdown rate is low enough for 8 GeV (~35 MV/m) beam operation.
- For 8.3 GeV (37 MV/m), the trip rate is acceptable for 10 pps operation, although we plan to decrease the trip by further RF conditioning.
- We plan to increase the repetition 10 pps → 60 pps, after fixing other problems (thyratron, power supply,…).

- Dark current is actually low enough and no problem.

Spare slides

8 GeV XFEL Machine Layout



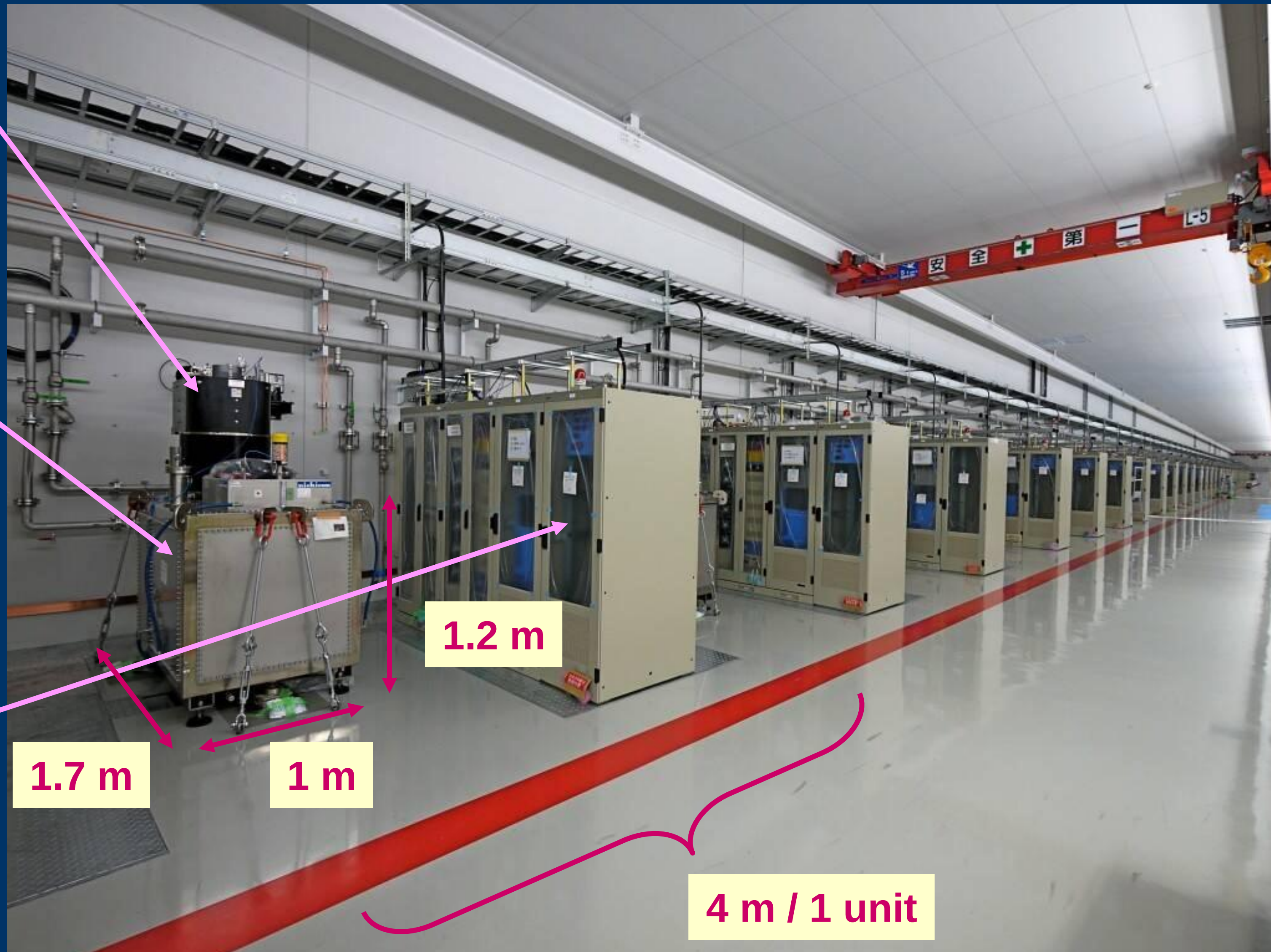
64 klystrons, modulators, and control cabients are installed in the klystron gallery

X-ray FEL

Klystron
50 MW

Modulator
350 kV
110 MW

Inverter-type HV charger
50 kV
35 kW
Stability ~
10 ppm (STD)



Stability of RF and beam energy

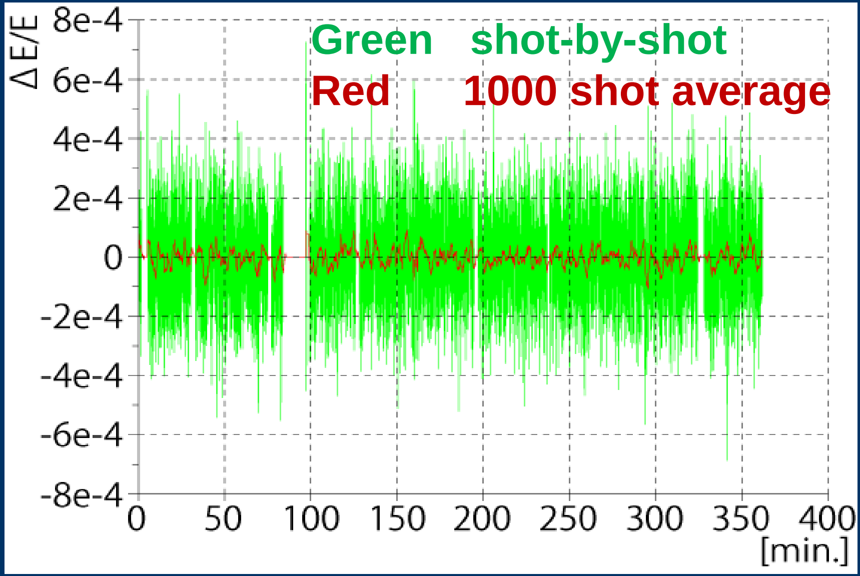
X-ray FEL

Short term (10 minutes) stability (rms) of RF after C-band structure

	Tolerance		Measurement	
	Voltage	Phase	Voltage	Phase
238 M SHB	0.01 %	0.01°	0.010 %	0.006°
476 M Booster	0.01 %	0.02°	0.004 %	0.009°
LB Correction	0.03 %	0.06°	0.02 %	0.02°
L-B APS acc. 1	0.01 %	0.06°	0.06 %	0.03°
L-B APS acc. 2	0.01 %	0.06°	0.03 %	0.05°
C-B Correction	0.2 %	0.06°	0.06 %	0.05°
SB 1 acc. 1	0.01 %	0.1°	0.04 %	0.03°
CB01-1 acc.1	0.01 %	0.2°	0.05 %	0.03°

within the measurement accuracy

Energy stability after the 7 GeV acceleration, measured by RF-BPM at chicane.



Shot-by-shot 1.4 x 10 $^{-4}$ (rms)

Drift < 1 x 10 $^{-4}$ with energy FB

Courtesy of T. Ohshima (PASJ-2011)

Courtesy of H Maesaka (2011)