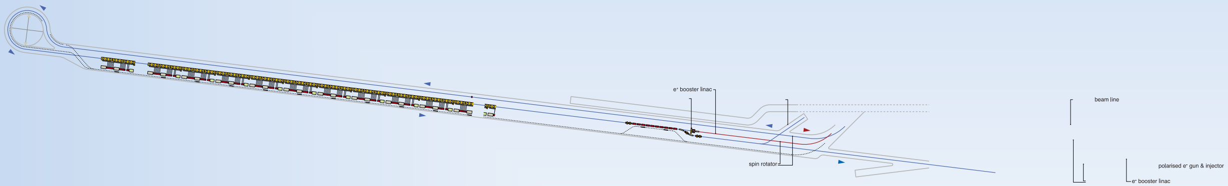
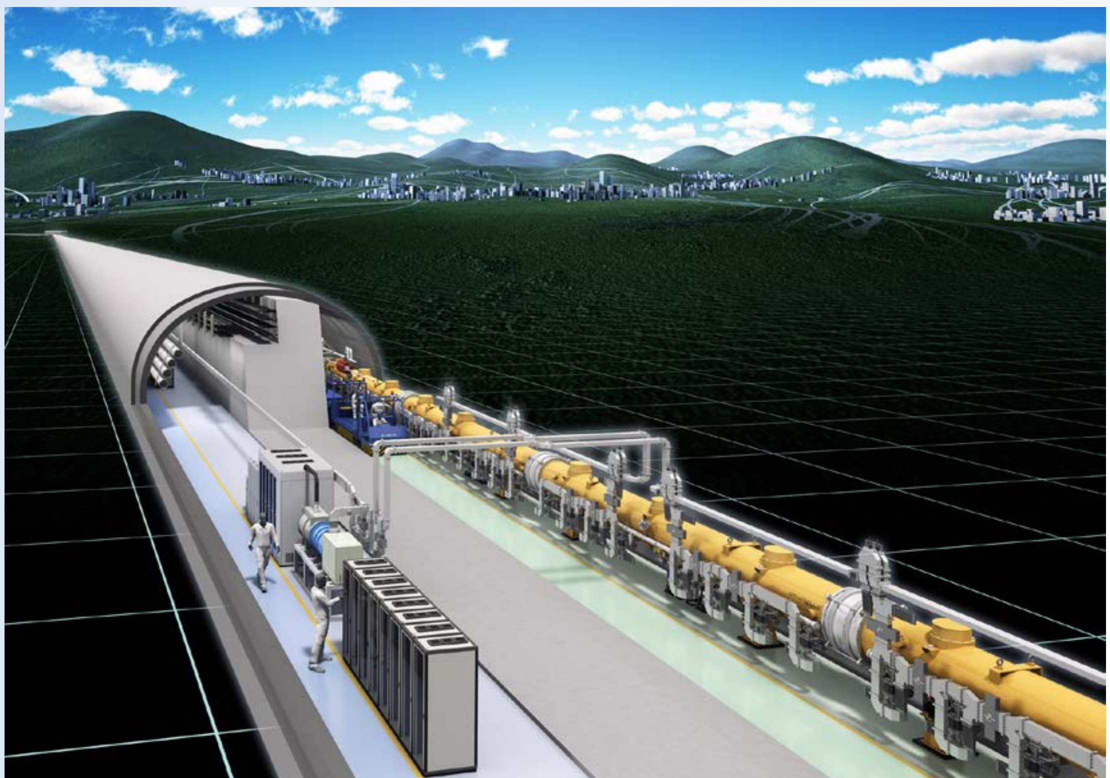
international linear collider



# ILC Main Linac accelerator development



Hitoshi Hayano, KEK, Tsukuba, Japan

07182013school@IPMU-Kavli

# Contents

# Introduction

- ILC, International Linear Collider, is designed by ILC-GDE (International Linear Collider, Global Design Effort).
  The main accelerator uses superconducting RF acceleration.

- The design development;
  2004: Superconducting RF acceleration was selected.
  2007: RDR (Reference Design Report) published.
  2009: SB2009 (cost reduction design) published.
  2009: Interim Report for technology development.
  2013: TDR (Technical Design Report) published.

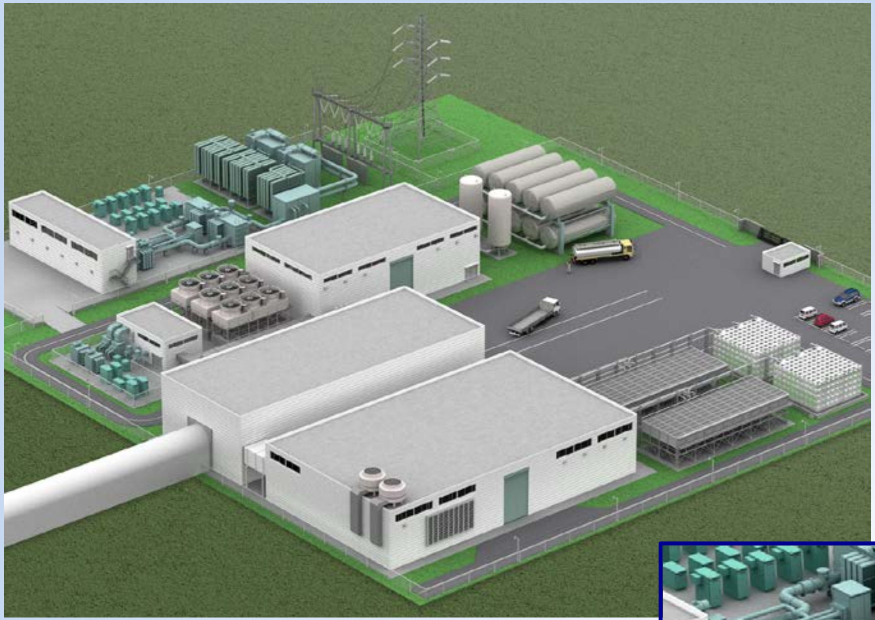
- Hardware development;
  Euro-XFEL accelerator (1/20 scale of ILC) is under construction in DESY.
  S1-Global cryomodule experiment was conducted in STF.
  ILC-type cryomodules are under test, construction in FNAL, KEK.

# ILC Accelerator Introduction

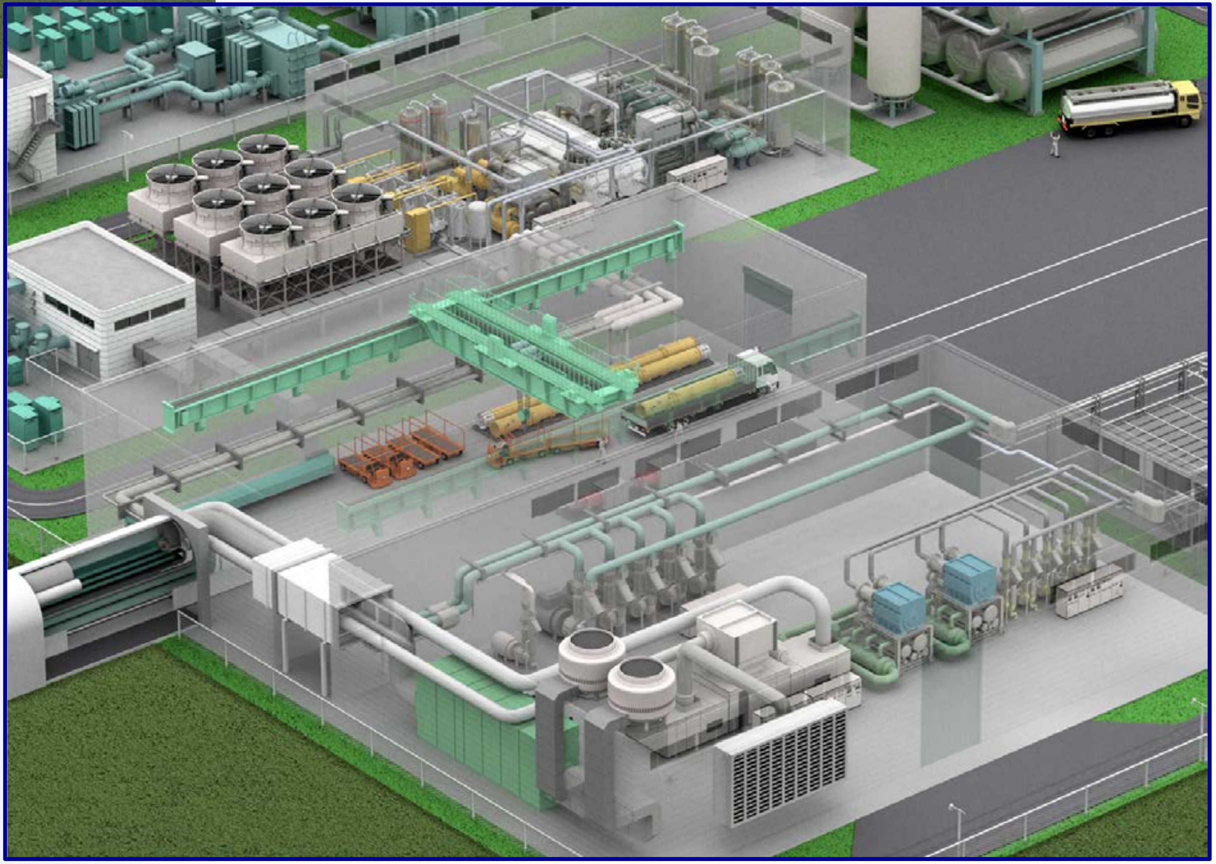
# Birds view of ILC (30km) –actual scale-

*Mountainous site Tunnel design*

日本の山岳地帯用
トンネルデザイン



# *Birds View of surface facility of access tunnel*

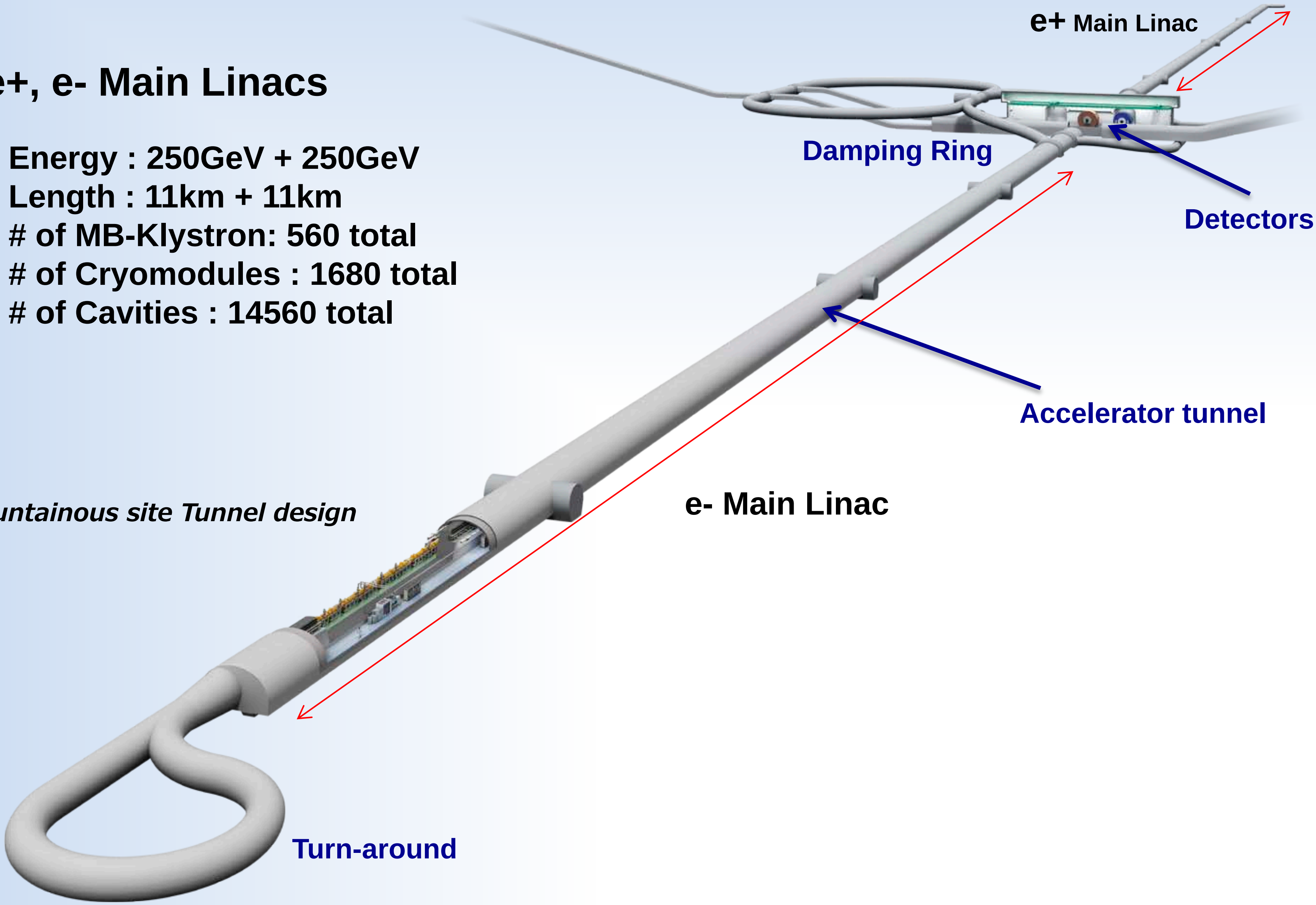


*Electric plant,*
*Helium plant,*
*Cooling water,*
*Heat exchanger of air*
*Cryomodule transportation*

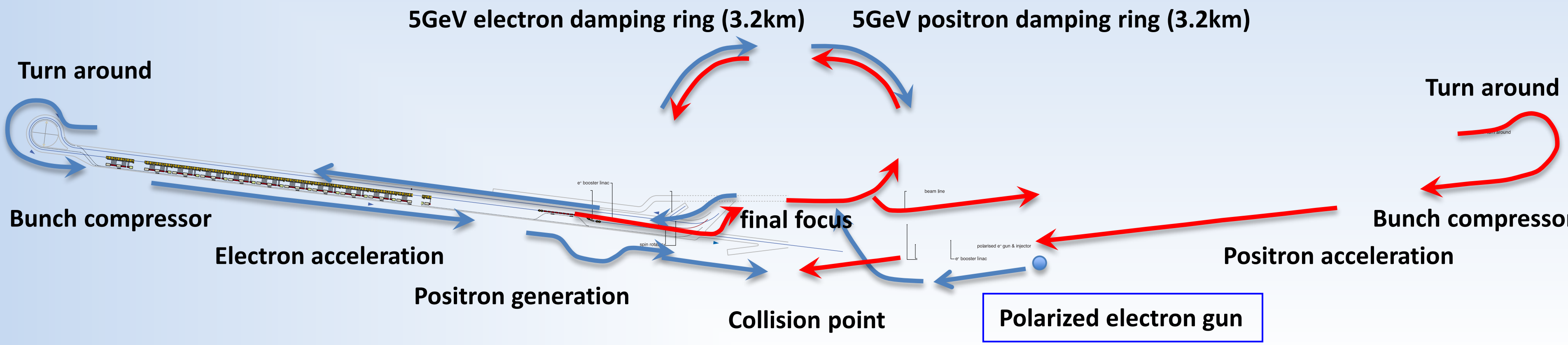
# *Birds View of ILC accelerator : compressed image*

## e+, e- Main Linacs

Energy : 250GeV + 250GeV
Length : 11km + 11km
# of MB-Klystron: 560 total
# of Cryomodules : 1680 total
# of Cavities : 14560 total

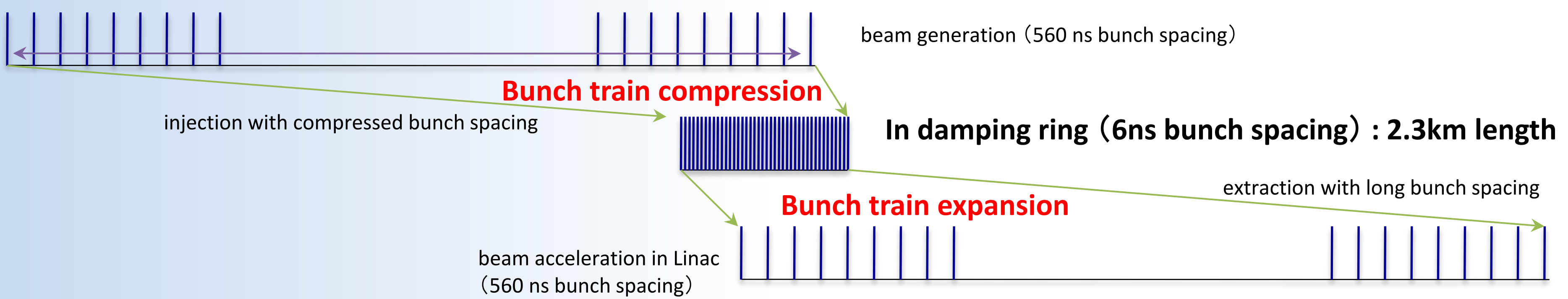


# Sequence of beam acceleration



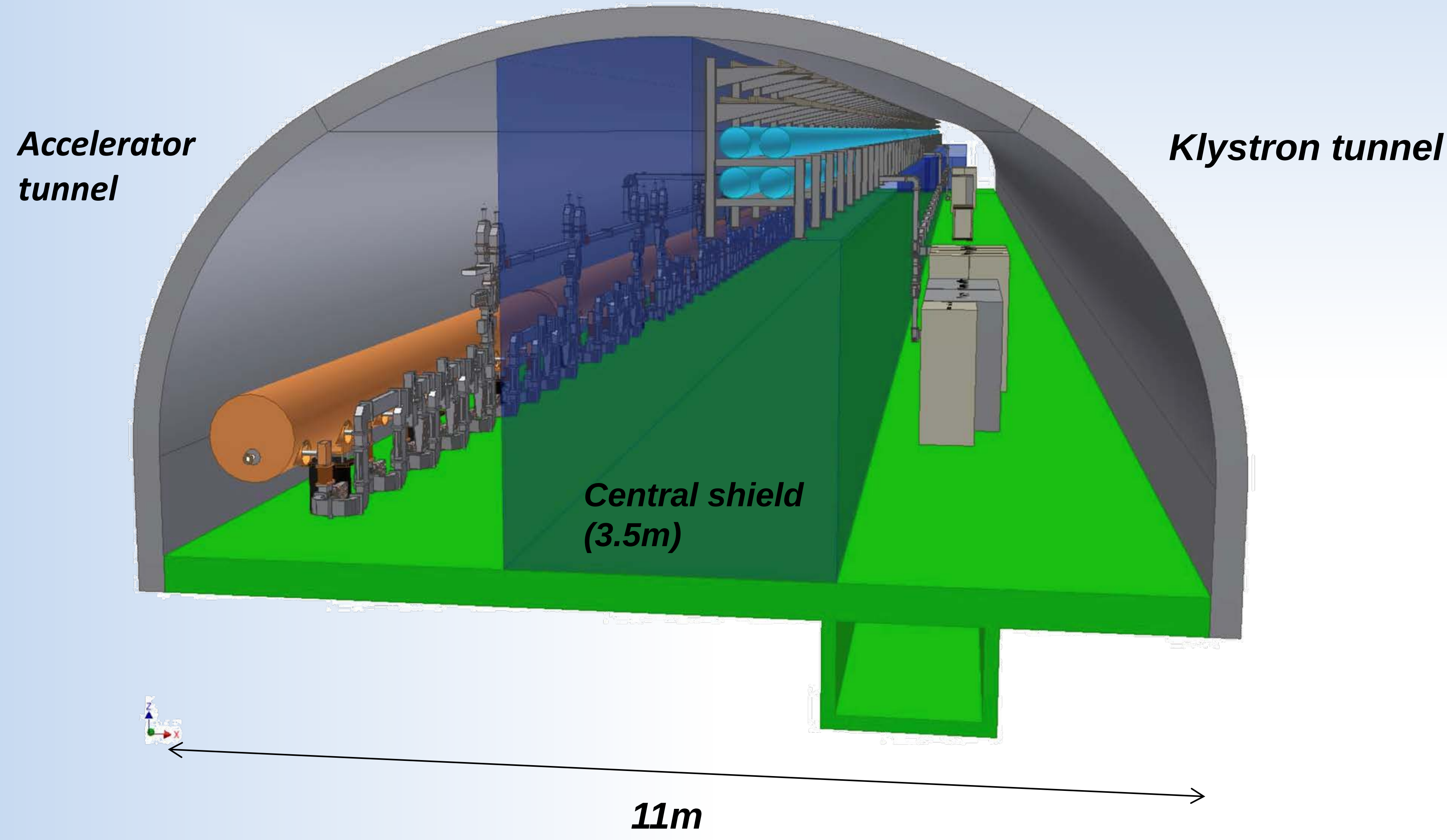

1ms bunch train includes

**1312 bunch (220km length)** —>very long train, con not inject into 3.2km damping ring



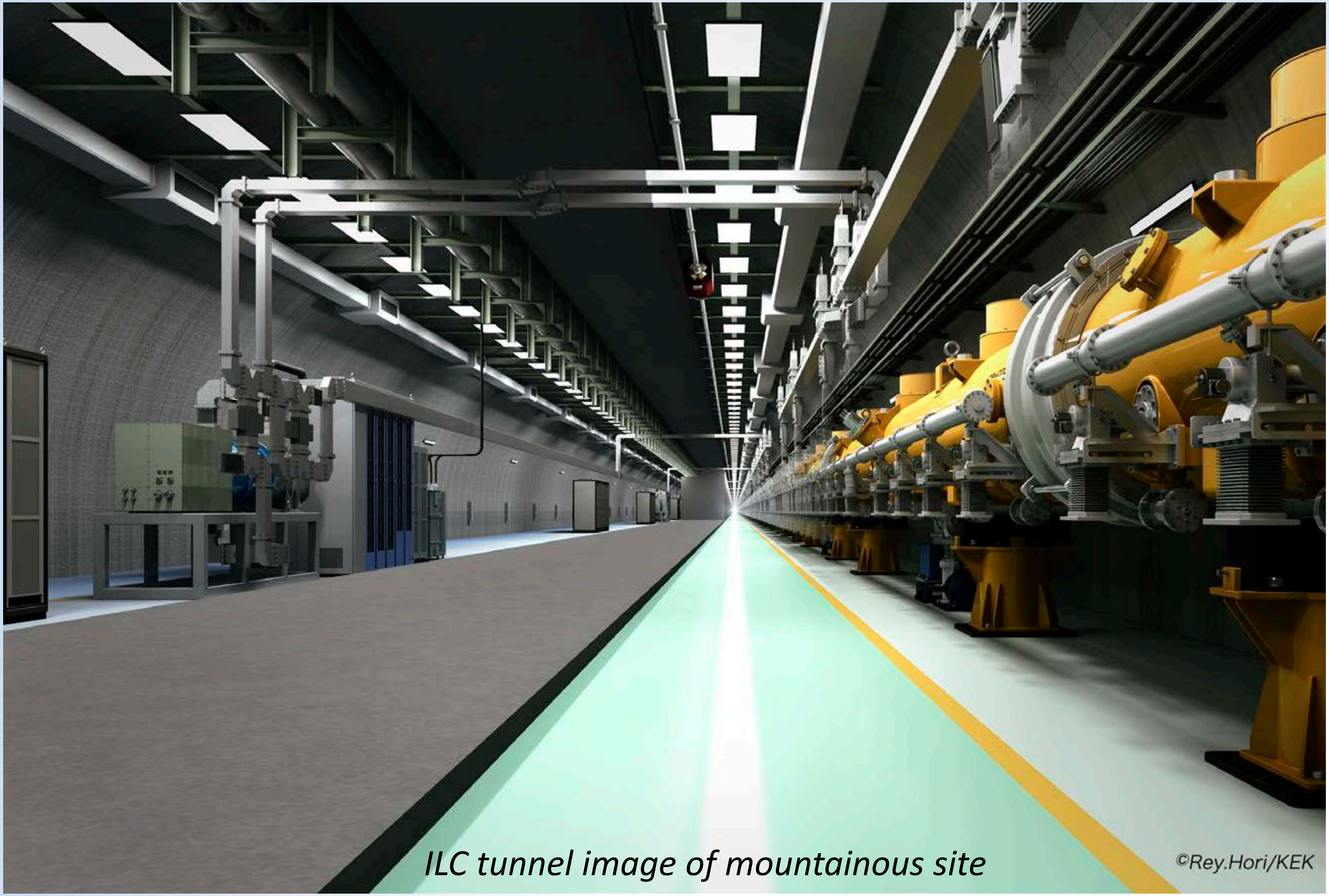

**1312 bunch (220km length)**

# Main Linac Tunnel Design for Mountainous site



# Perspective view of Main Linac Tunnel

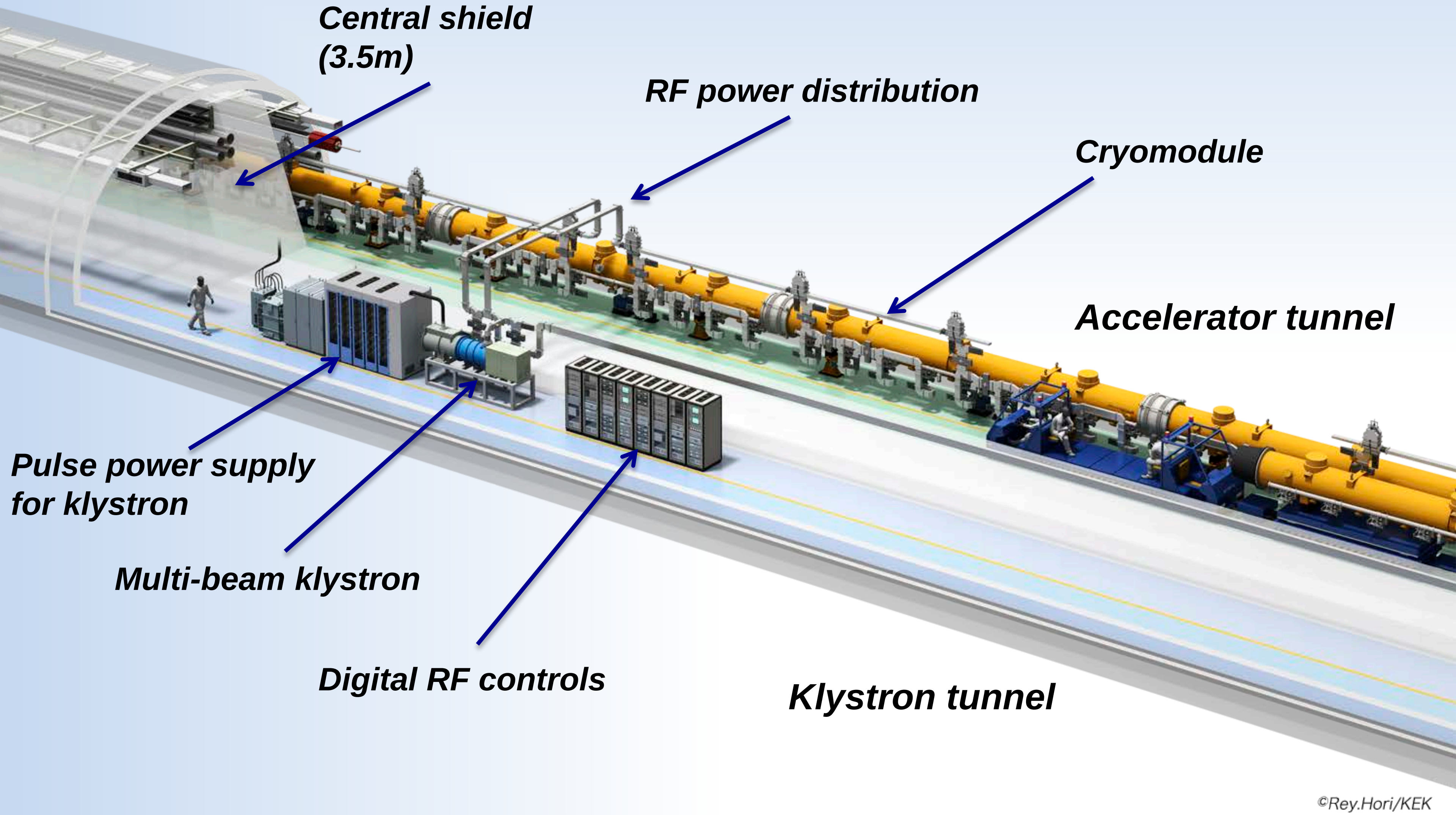
***Center shield wall is transparent for easy to view both tunnel***




*ILC tunnel image of mountainous site*

# Accelerator component details

# Main Linac Arrangement for Mountainous site Tunnel



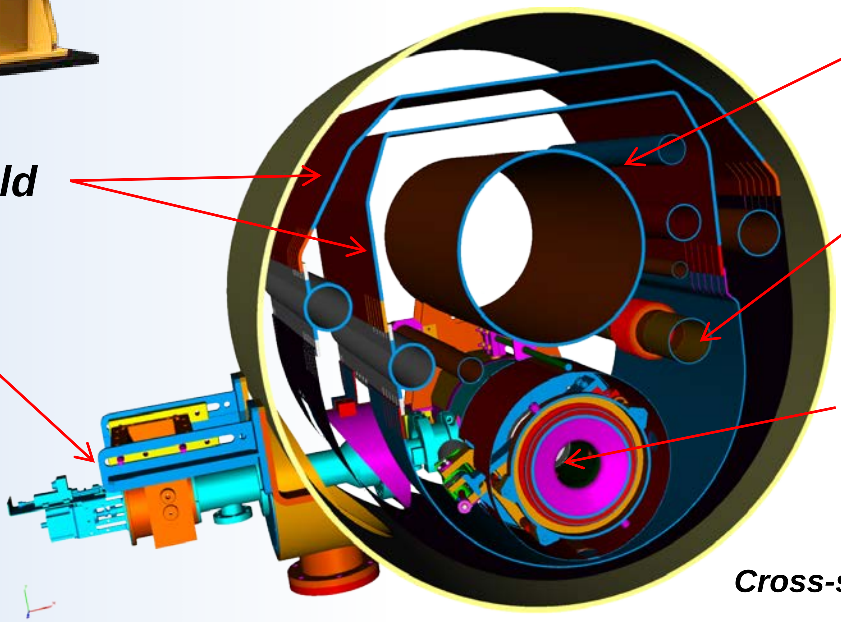
# Main Accelerator Module: Cryomodule

*9 Superconducting Cavities in the 12m length, 1m diameter cryostat*

*1701 unit (TDR)*

*ILC cryomodule (12.65m)*

©Rey.Hori/KEK



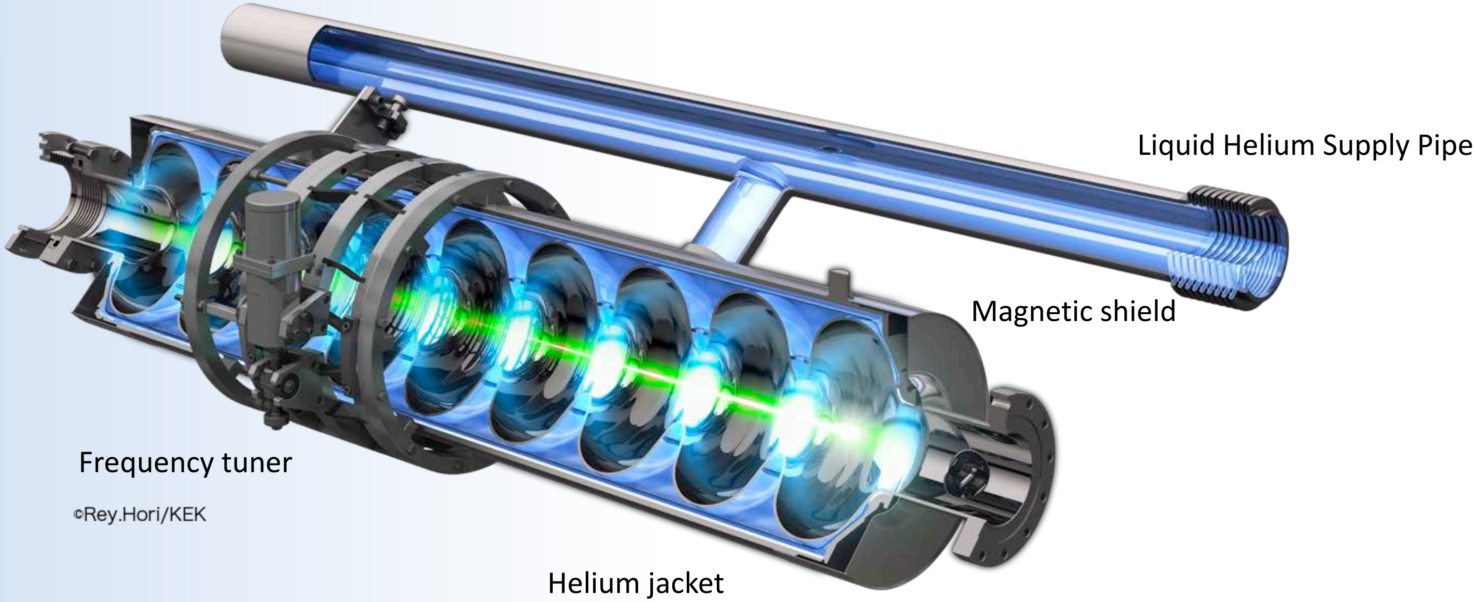

***Cross-section*** from D. Kostin

# *Superconducting Cavity made by pure Niobium*

*14560 unit (TDR)*

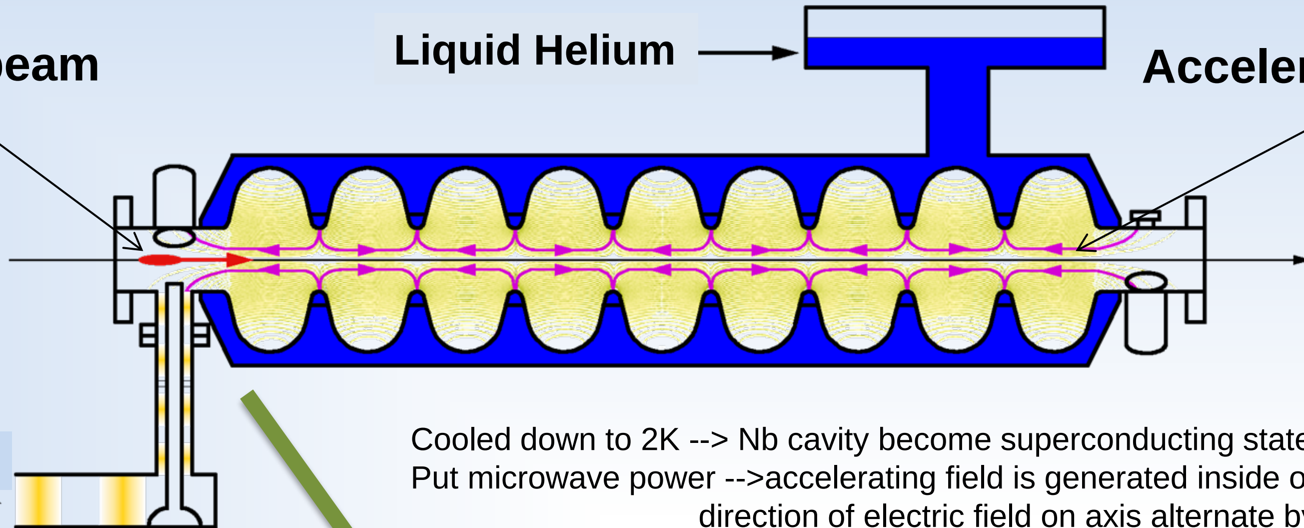
Picture of Superconducting Cavity ( length 1.2m, diameter 0.2m)
Cooled down at temperature 2K, then become superconducting state.

Long lasting High Accelerating Field by small input RF power ( RF wall loss is very small )

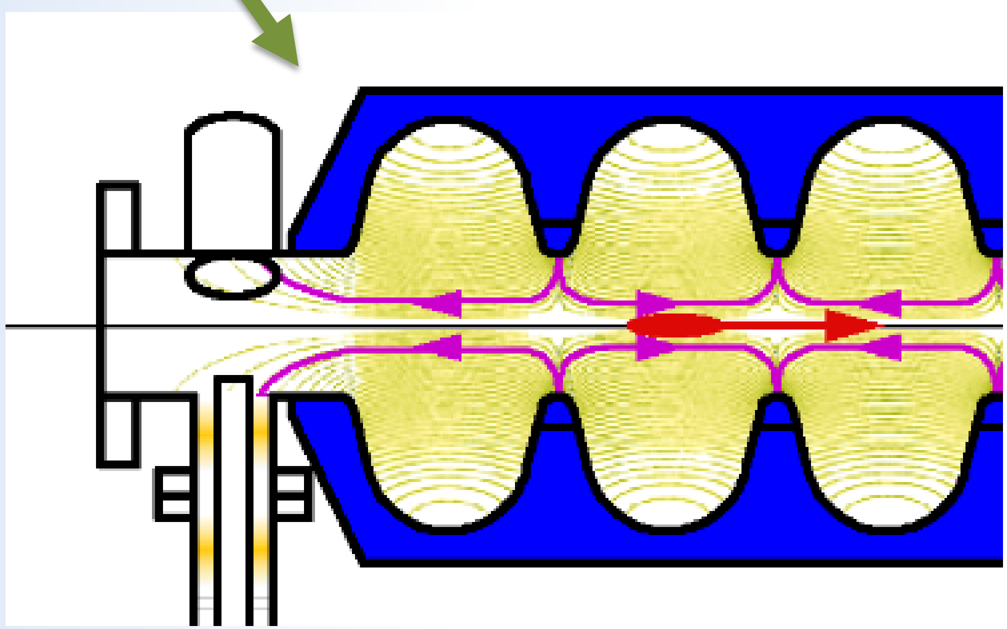



Helium jacket, magnetic shield, frequency tuners are installed around the cavity, then put into the cryomodule.

# *Principle of Electron beam Acceleration*



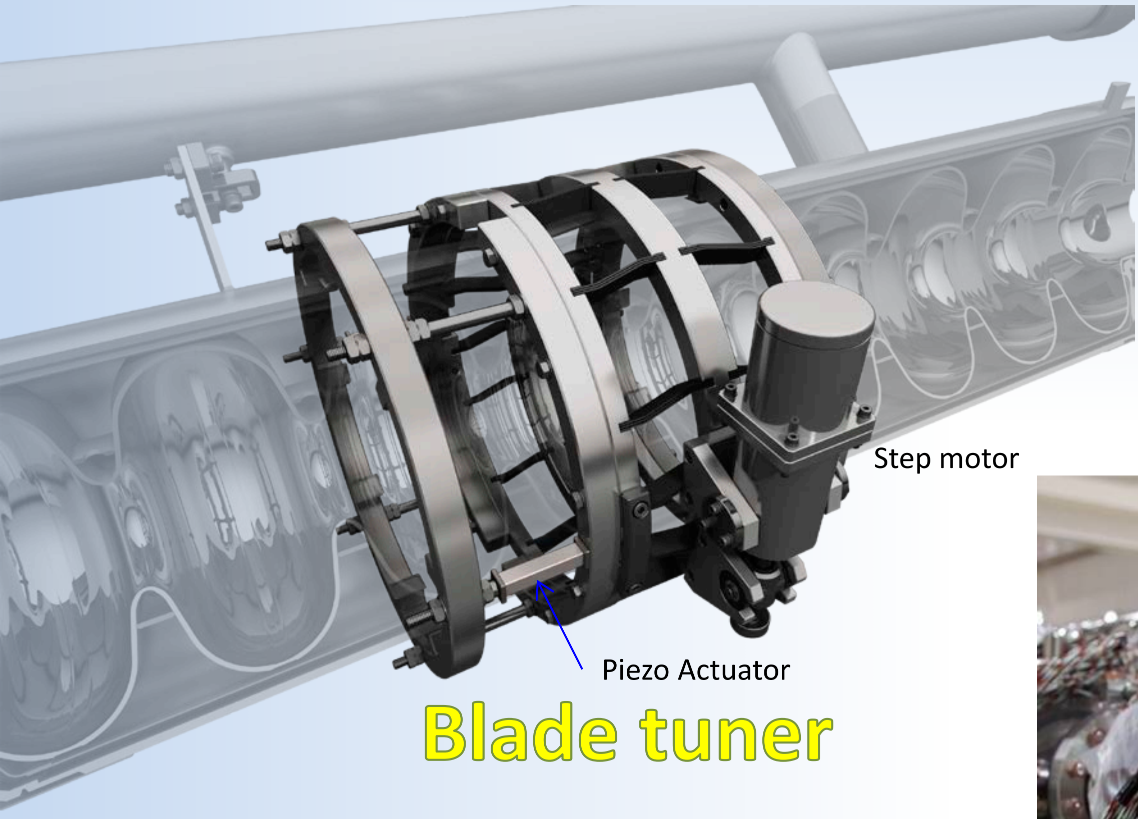

Cooled down to 2K --> Nb cavity become superconducting state.
Put microwave power -->accelerating field is generated inside of cavity.
direction of electric field on axis alternate by RF frequency.



**$TM_{010}$ π – mode**
**1.300 GHz**

# Frequency Tuner : Cavity Resonance Frequency Control

***Resonance frequency control mechanism by changing total cavity length.***

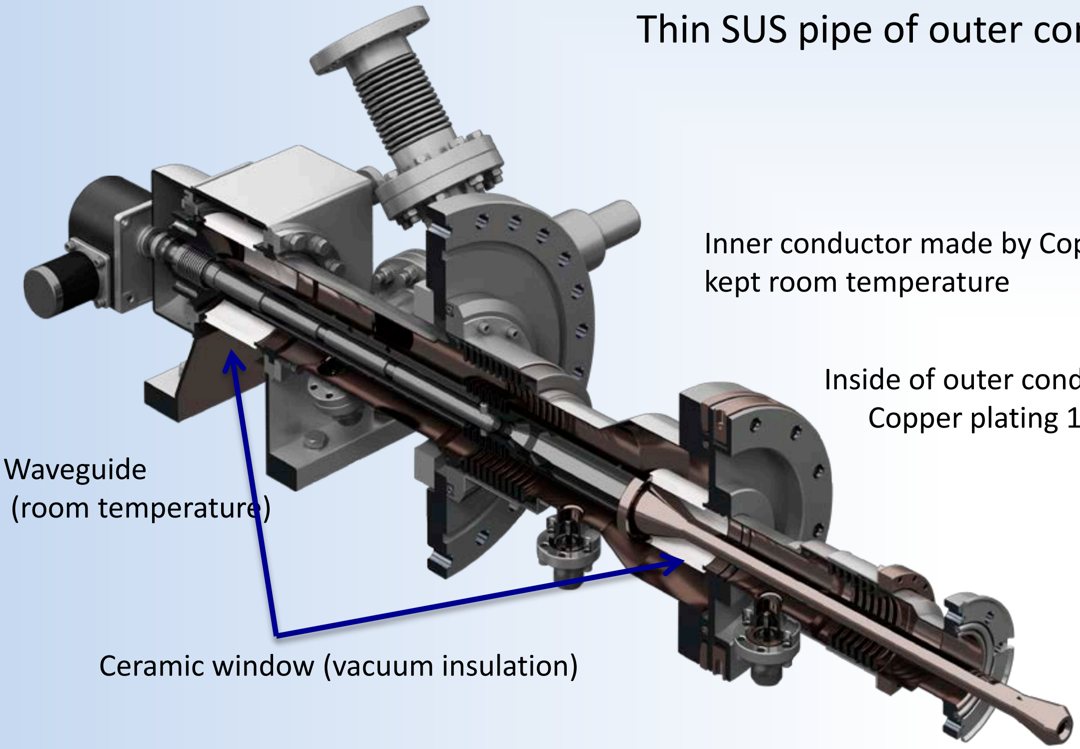



**Location: middle of He vessel**
**Motor: inside of module,**
**low temperature**
**Piezo: two low-voltage piezo**

**Design Stiffness: 30kN/mm**
**Nominal sensitivity: 1.5Hz/step**
**Piezo stroke at RM: 55 μm**

# Input Coupler : *transmit microwave power, cut heat flow*

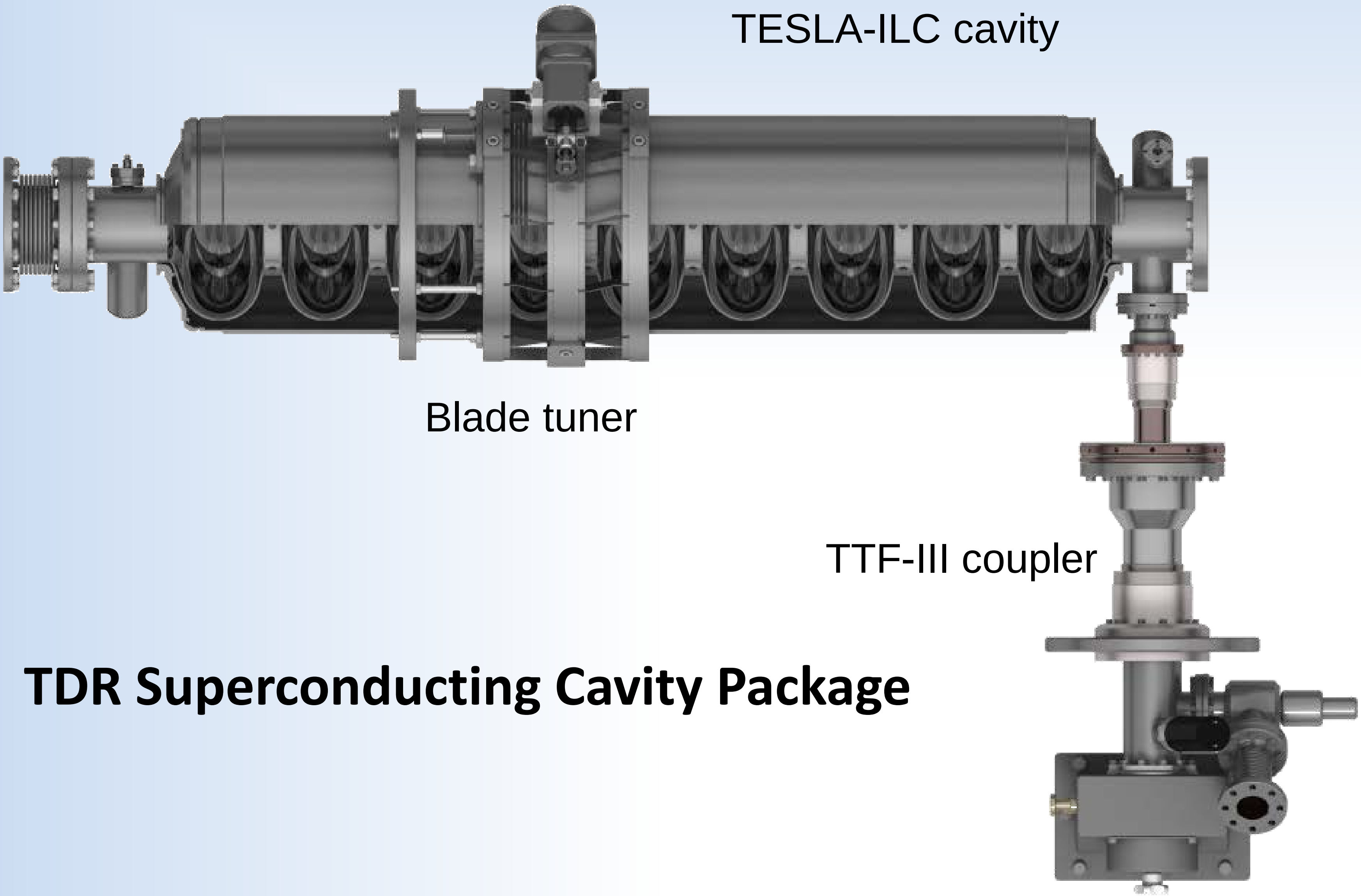
**Microwave power is introduced from waveguide (room temperature),**
**go through long coax line,**
**then put into 2k cooled superconducting cavity (dipole antenna radiation)**




## TTF III coupler

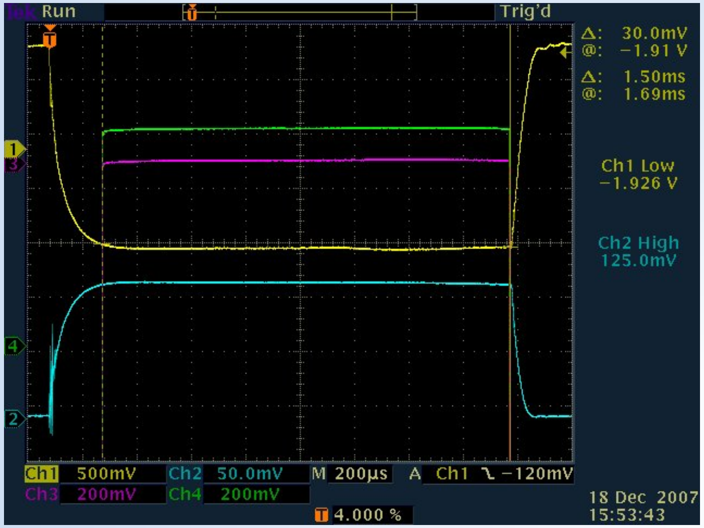
Type: coaxial to antenna
Window: two cylindrical,
cold window & warm window
Coupling: tunable
Interface: 40mm dia. cavity port
WR650 for waveguide
Power: 350kW, 1.5ms, 5Hz

**High Power Microwave (pulse) is put into Cavity**




# TDR Superconducting Cavity Package

# Multi-beam Klystron: generate high power pulsed microwave



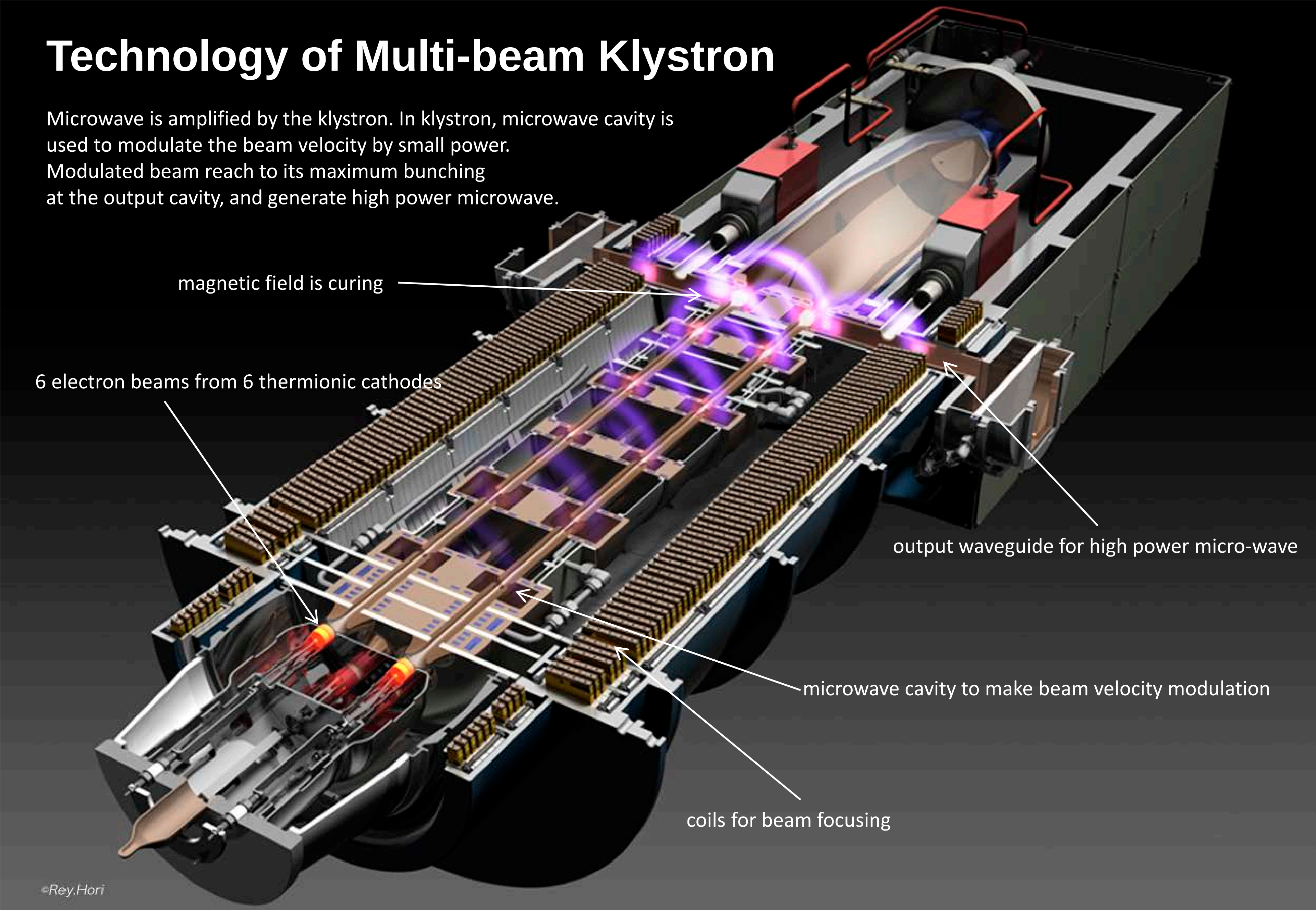

10MW 1.5ms
67% efficiency

**Scope picture of the klystron test. The lines show the klystron voltage (116 kV) in yellow, the current (128 A) in blue and RF output (5 MW each) in magenta and green.**


**Toshiba E3736H**

# Technology of Multi-beam Klystron

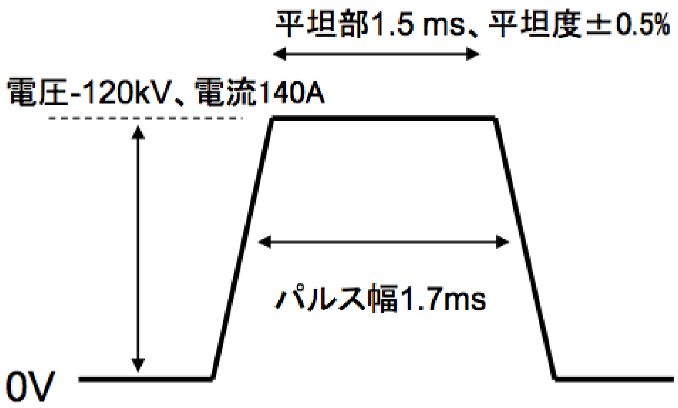
Microwave is amplified by the klystron. In klystron, microwave cavity is used to modulate the beam velocity by small power. Modulated beam reach to its maximum bunching at the output cavity, and generate high power microwave.



# Pulse high voltage power supply for klystron

*Accelerator Laboratory*

## *Specification of pulse power supply*



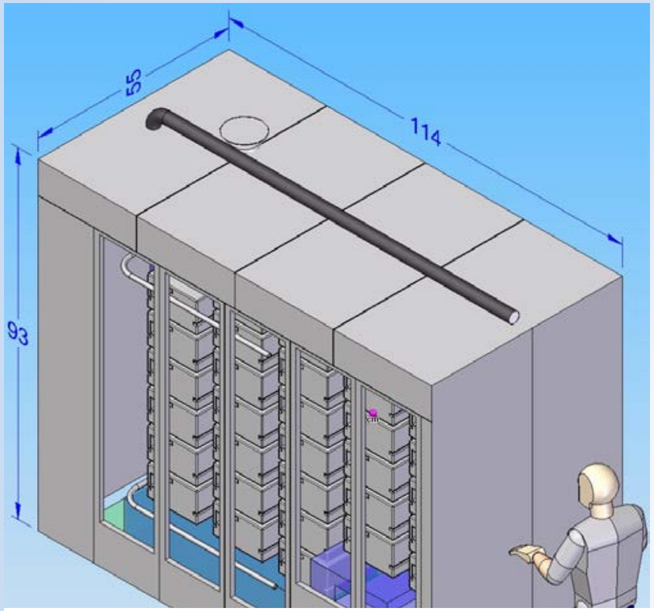

**Drive pulse form**

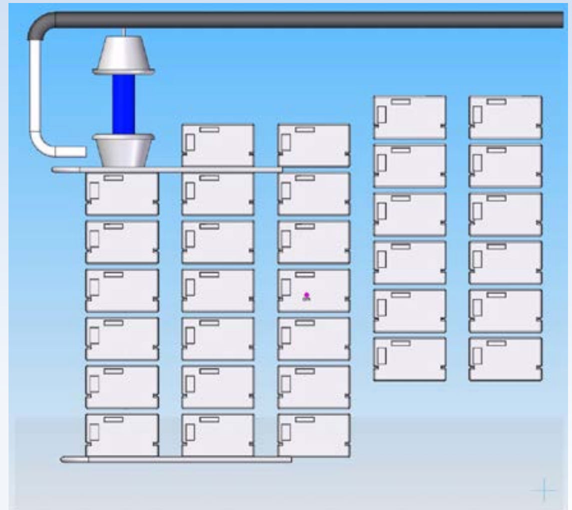
**Drive one 10MW multi-beam klystron**

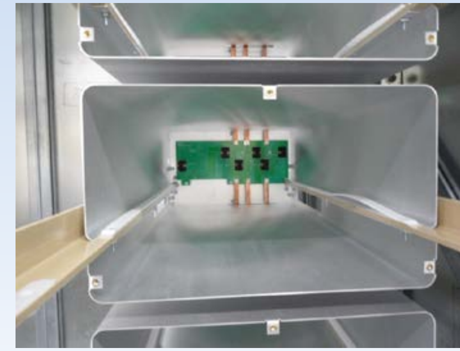
| | |
|---|---|
| RF width | 1.5 ms |
| Power supply pulse width | 1.7 ms |
| Rise-time, fall-time | 0.2 ms |
| Voltage | 120 kV |
| current | 140 A |
| Flatness of pulse flat-top | ±0.5% |
| Pulse energy | 29 kJ |
| Tolerable energy leak at klystron break-down | < 20 J |
| repetition | 5 Hz |
| efficiency | 85 % |
| Required AC power for one PS | 168 kW |
| Required AC power for whole Linac PS | 109 MW |
| Number of PS for whole Linac | 約650台 |

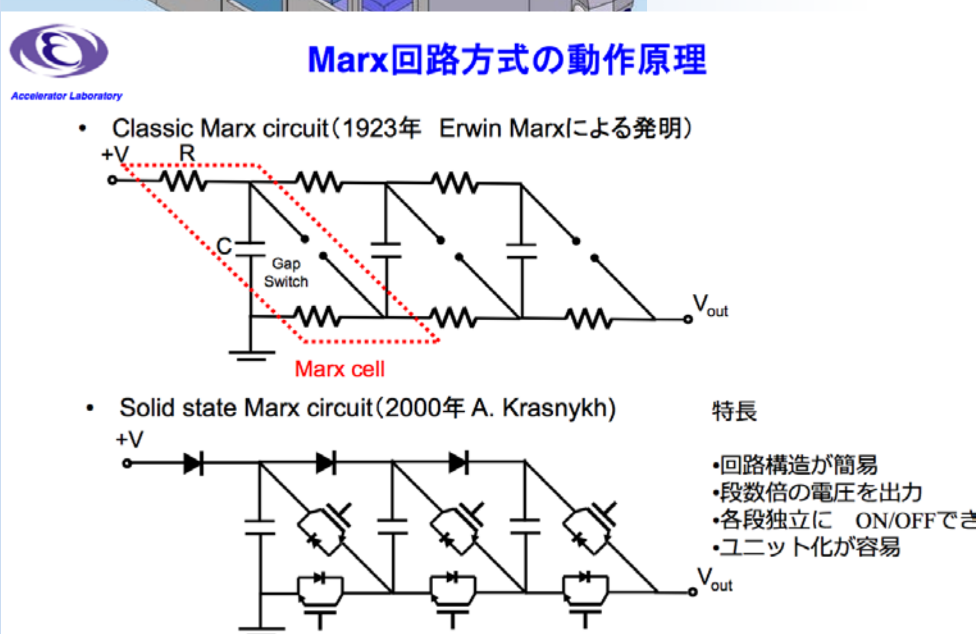
**Pulse width : 1.7ms**
**Flatness : +/-0.5% with 1.5ms top**
**High voltage, high current PS**

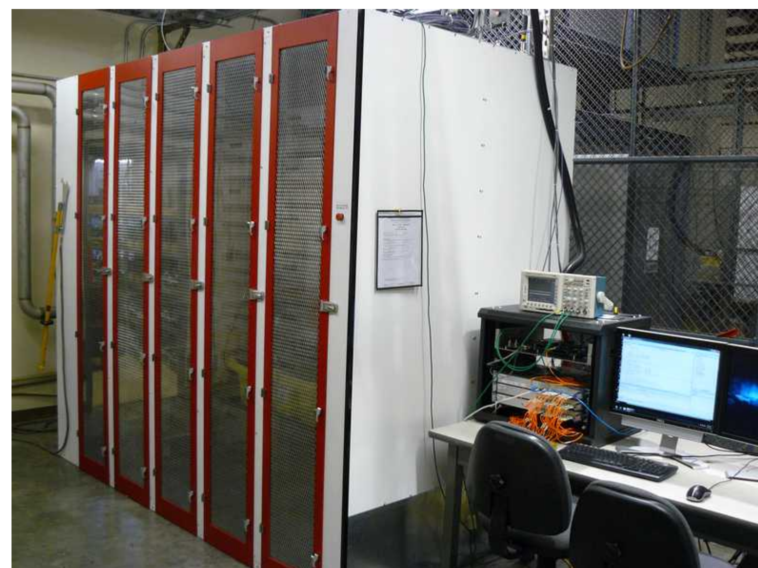
# TDR Pulse high voltage P.S.: Marx Generator



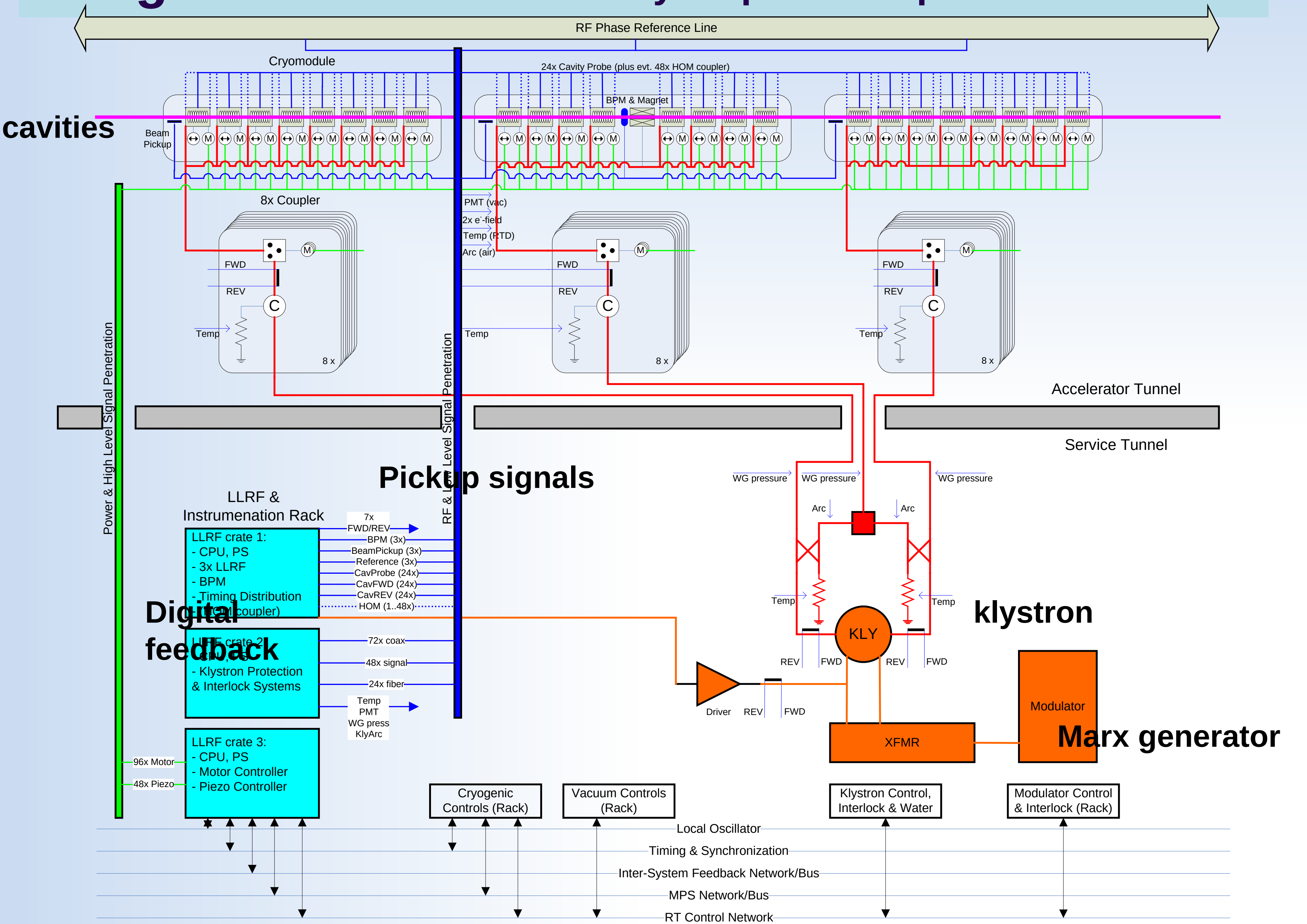







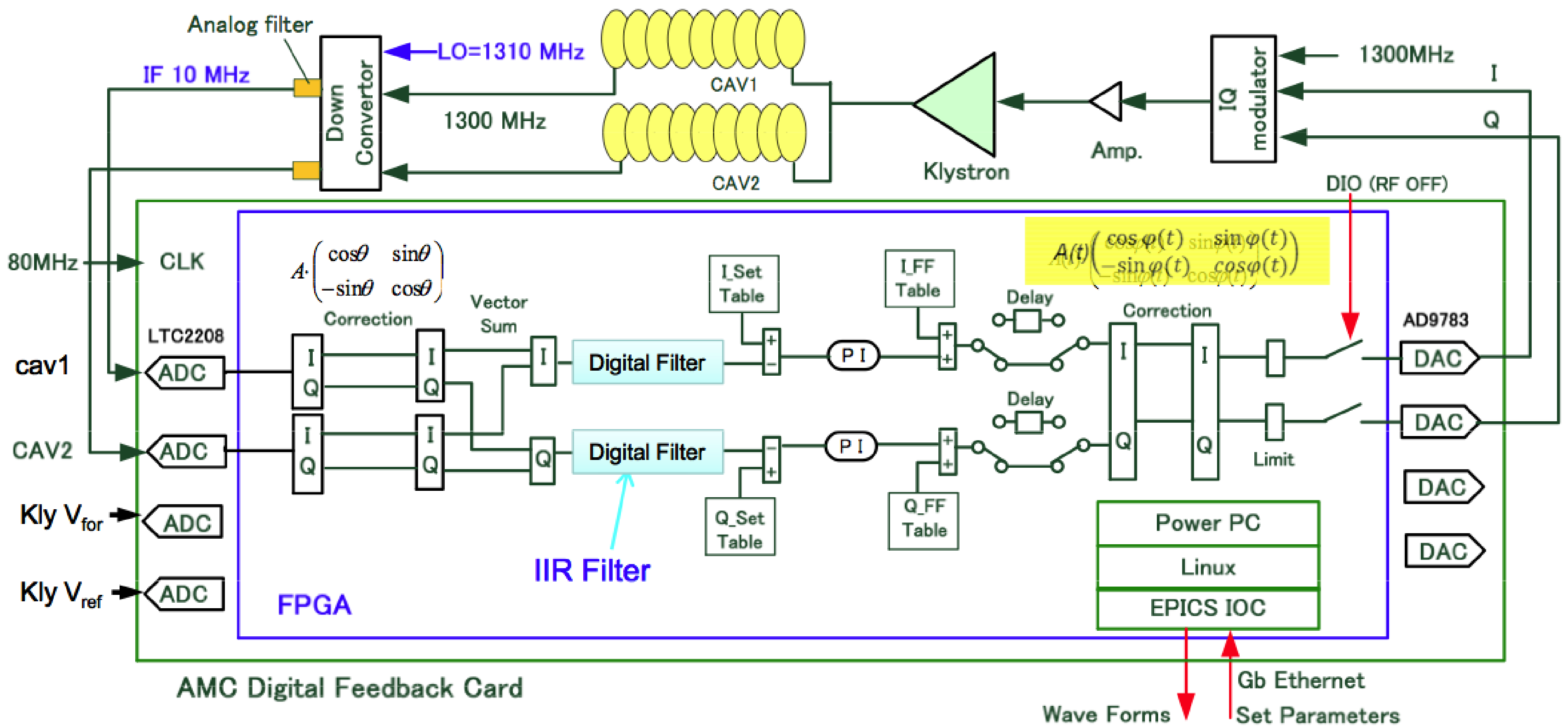



# Digital RF control: cavity amplitude & phase feedback



# Digital RF control System : LLRF (low-level RF control)

## Schematic diagram of LLRF system




IIR filter : 35kHz~150kHz LPF in normal operation

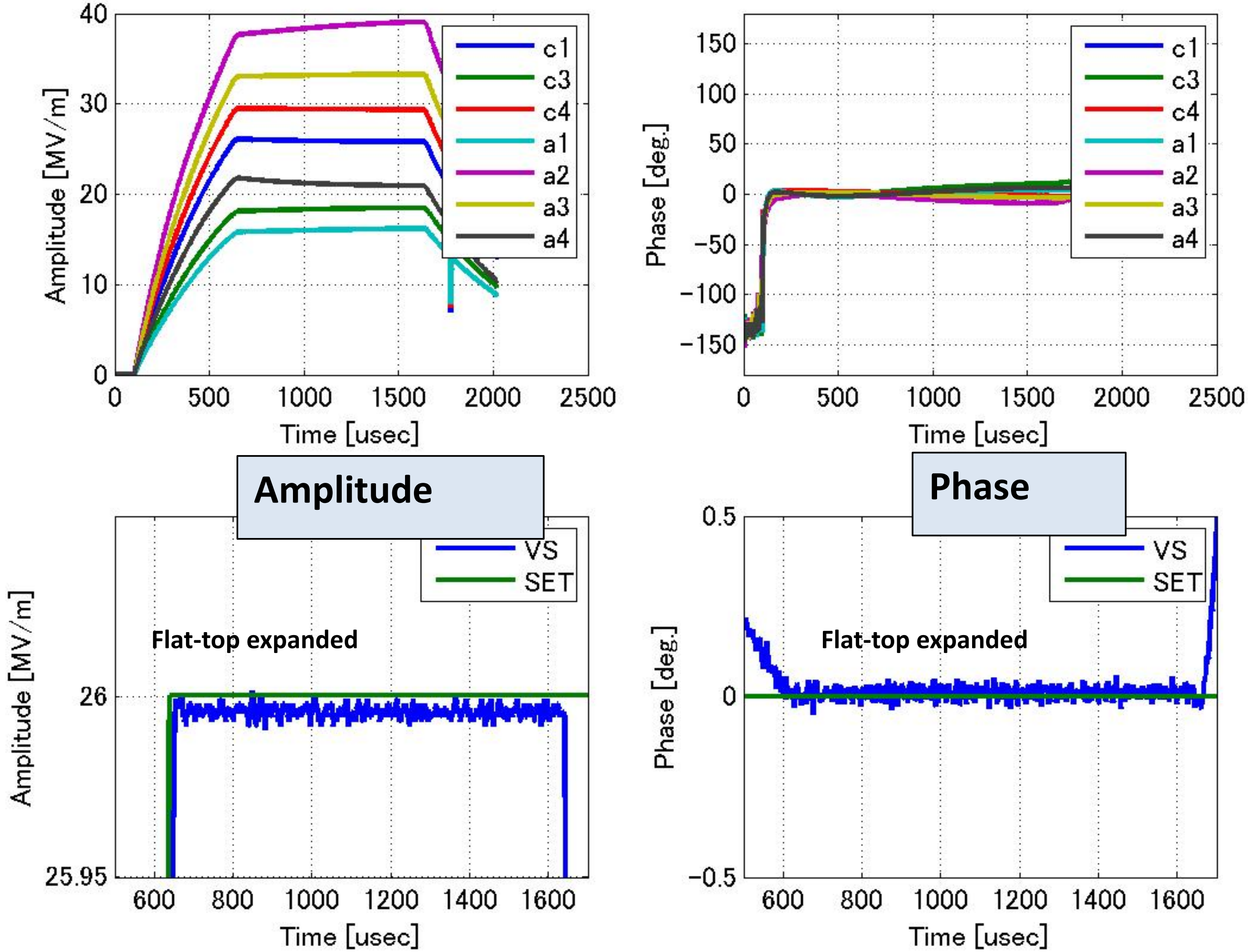
- 8/9π mode
- noise in ADC-input

→ rejected

<Latency of FB board>
ADC : 7.5 clock, DAC :15 clock @ 81.25MHz
IQ separation & Correction : 5 clock@40.625MHz
Calculation in FPGA : 23 clock @ 81.25MHz
Total 55.5 clock @ 81.25MHz (0.68 μs)

# Example of controlled amplitude & phase

**Vector sum operation of 7 cavities with LLRF control**




**0.005%.rms amplitude stability**

**0.015degree.rms phase stability**

# High Gradient Superconducting cavity development

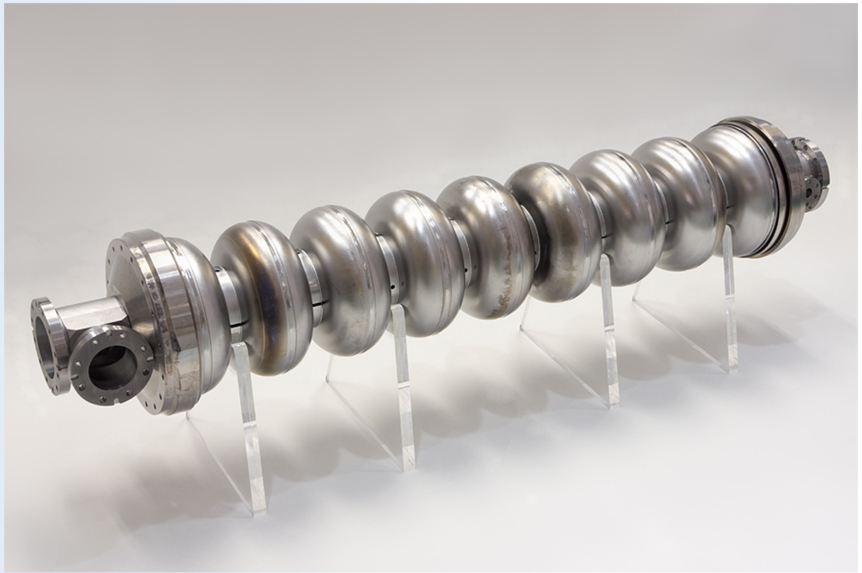
# Requirement for cavity performance

**ILC TDR Specifications**

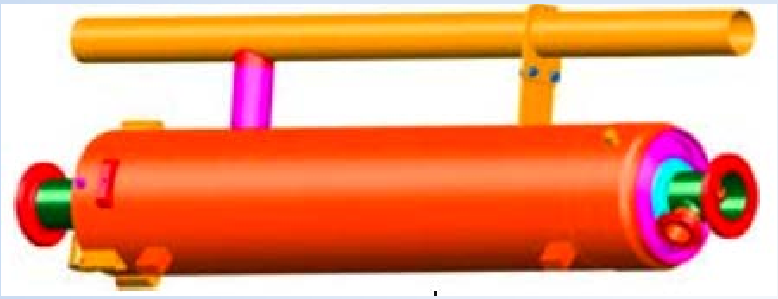
**ILC R&D target: > 35 MV/m with 90% yield**

**ILC fabrication: > 35 MV/m +/-20% (28 – 42 MV/m), with 90% yield**

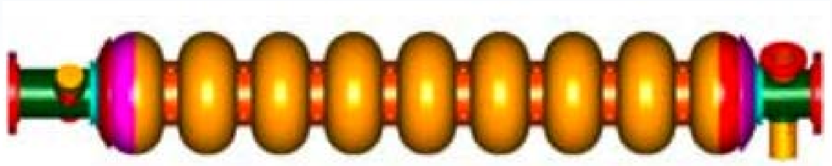
**ILC accelerator operation: 31.5MV/m +/-20% performance**



# *Fabrication of Cavity (in case of TESLA-cavity)*

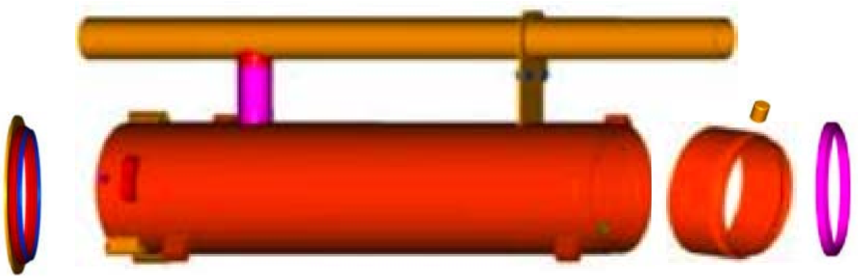


**Cavity package**



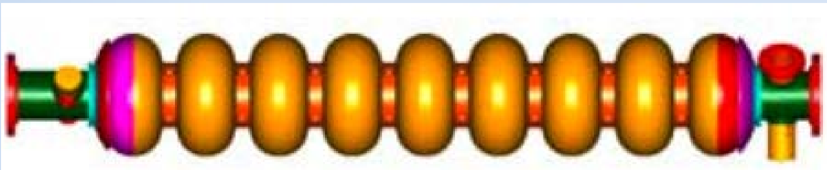
**Bare Cavity**

**Think them as two parts**



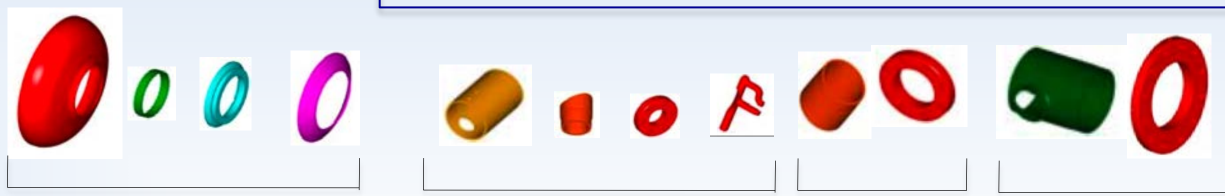
**Helium Tank Jacket**

# *Components for bare cavity*



**Number of components : 56 pieces**
**Number of EBW required : 48 seams**

ショートエンドグループ　１組
（部品12個）
EBW12ヶ所



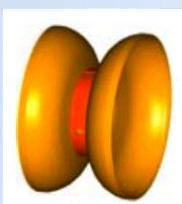
ショートエンドセル　４個

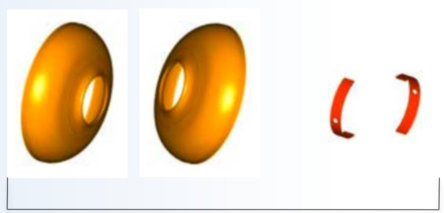
HOM1　４個

インプット
カップラー
ポート　２個

ビームパイプ
２個

ダンベル　８組（部品32個）
EBW24ヶ所

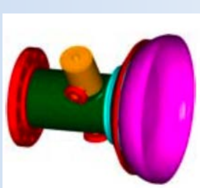


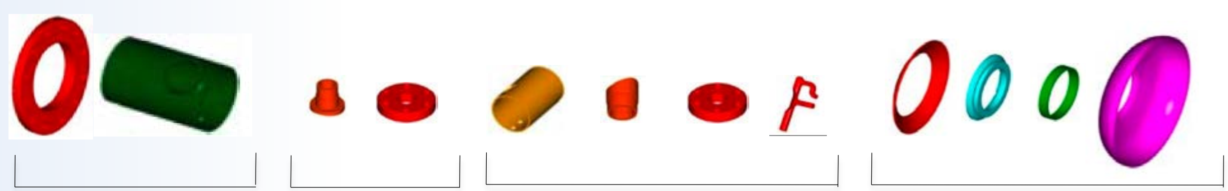


ダンベル　４個

× ８組

ロングエンドグループ　１組
（部品12個）
EBW12ヶ所





ビームパイプ　２個

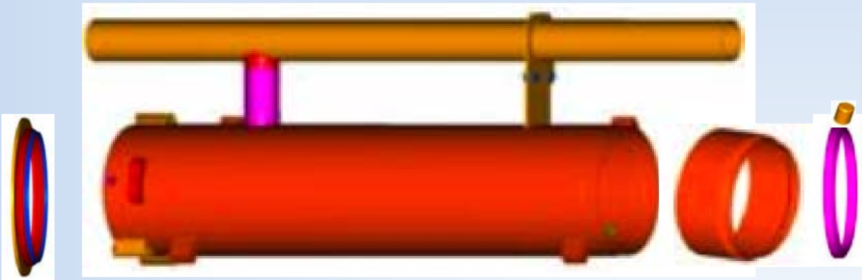
ピックアップポート
２個

HOM2　４個

ロングエンドセル　４個

# *Components for Helium tank jacket*

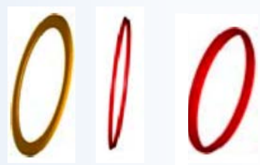
**Number of components : 23 pieces**
**Number of Tig-Weld required : 20 seams**



ヘリウムタンク、リング、ベローズ

エンドベローズ　１組　（部品3個）

Weld ２ヶ所

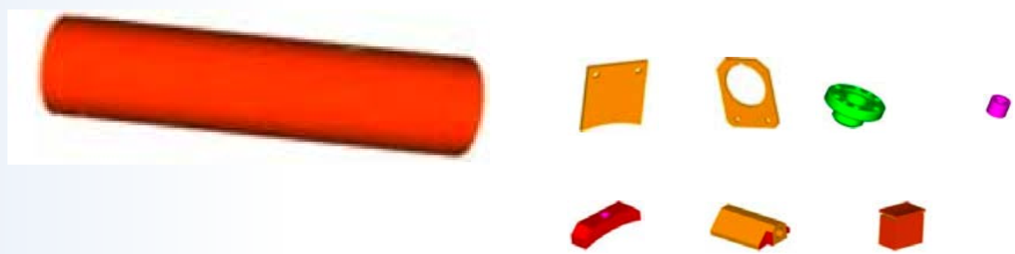


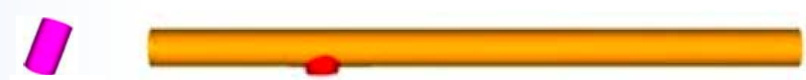
スライディングカラー　１組
（部品３個）

Weld ３ヶ所

ヘリウムタンク　１組
（部品１７個）

Weld １５ヶ所



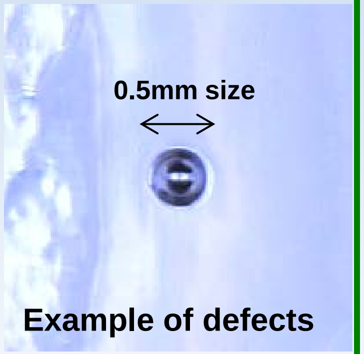



チューナー機構　１組
（部品??個）

# *Reasons to limit cavity gradient performance*

## (a) Fabrication issue (press, EBW)

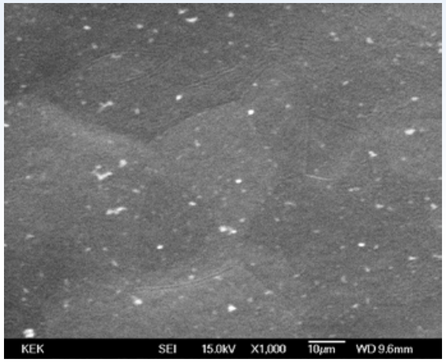
-> visible defects in cavity inside & EBW seam inside



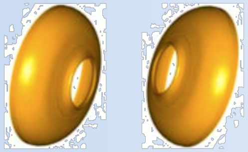

## (b) Surface treatment issue

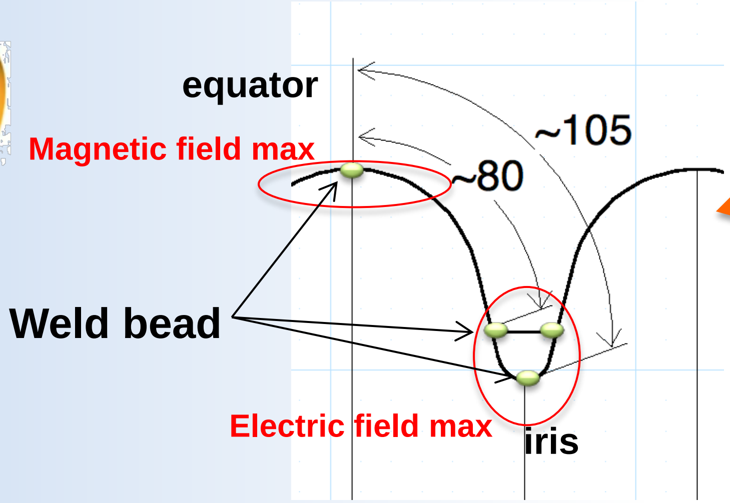
-> growth of defects

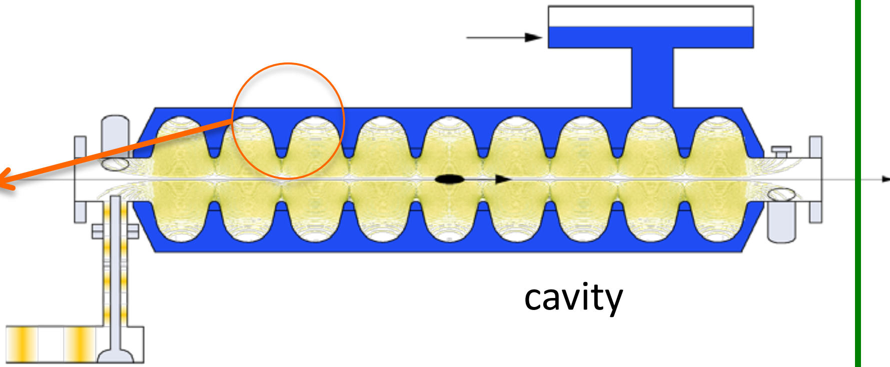
-> residual contamination on surface




Example of surface contamination (several 10μm size)





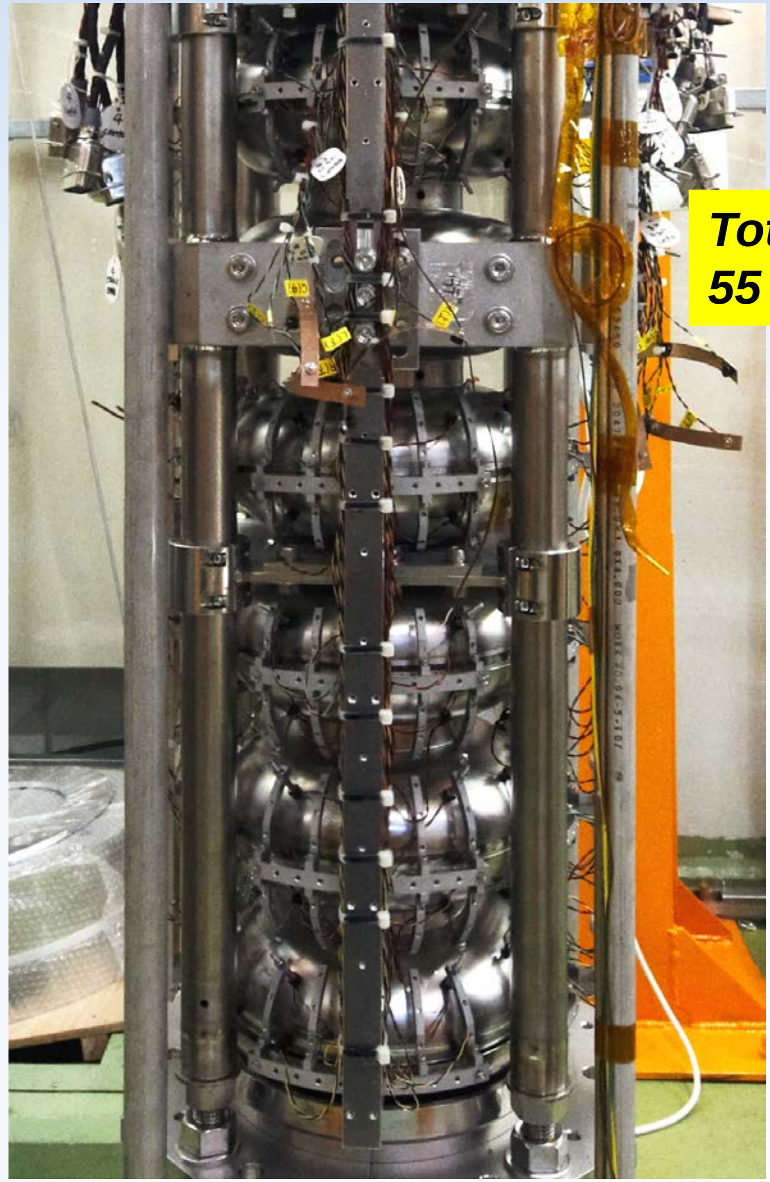



# *Temperature & X-ray mapping to localize quench location*

**To localize quench location,**

**Temperature sensors are attached on equator and cell-taper region**

352 carbon resistors
(Allen-Bradley, 50 or 100Ω)



***Total 494 sensors***
***55 sensors/cell***

**X-ray detectors on Iris region**

142 PIN diodes
(HAMAMATSU, S1223-01)

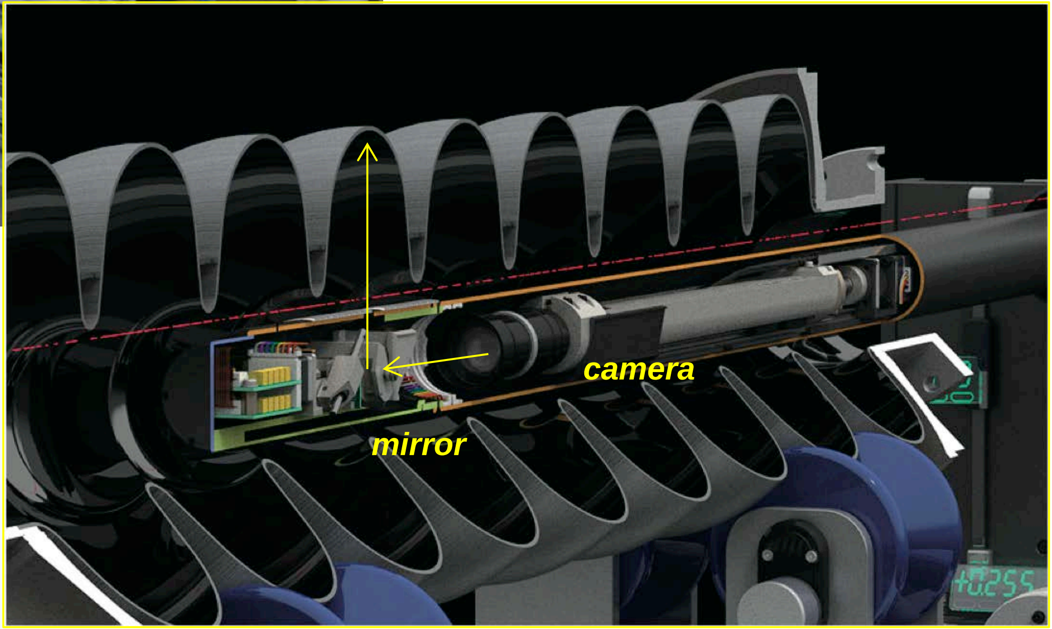
**Online display is available during cavity field test**

Yasuchika Yamamoto

# Inspection Camera to find defects inside of cavity

**High resolution camera inside of cylinder. Special arrangement of LED illumination makes possible to capture defect in shiny inner surface.**

*KEK, Kyoto development.*
*DESY, FNAL, JLAB, CERN introduced.*

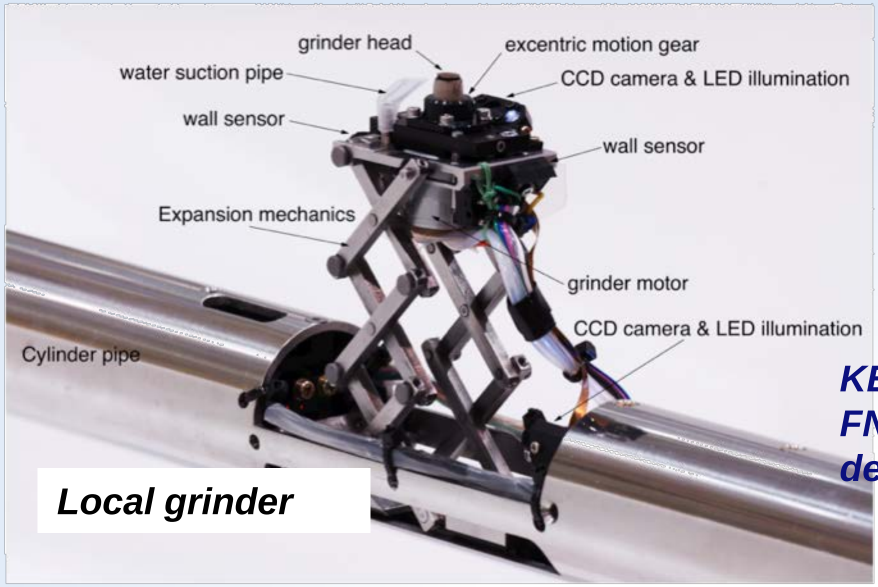



***High resolution camera(7μm), mirror angle controller, and illumination controller are in the cylinder.***

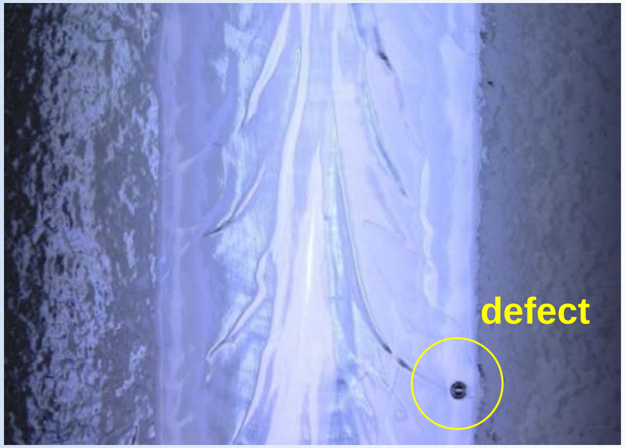
Ken Watanabe
KEK- Kyoto-Univ.

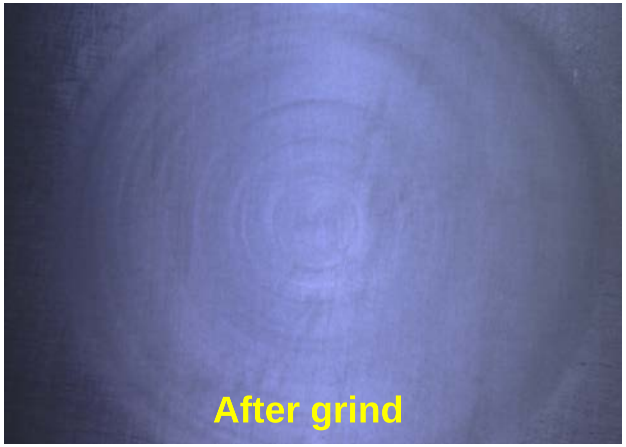
# Local grinder to remove defects inside of cavity

**Small grinder motor installed inside of cylinder, is designed to stretch into cavity inside**



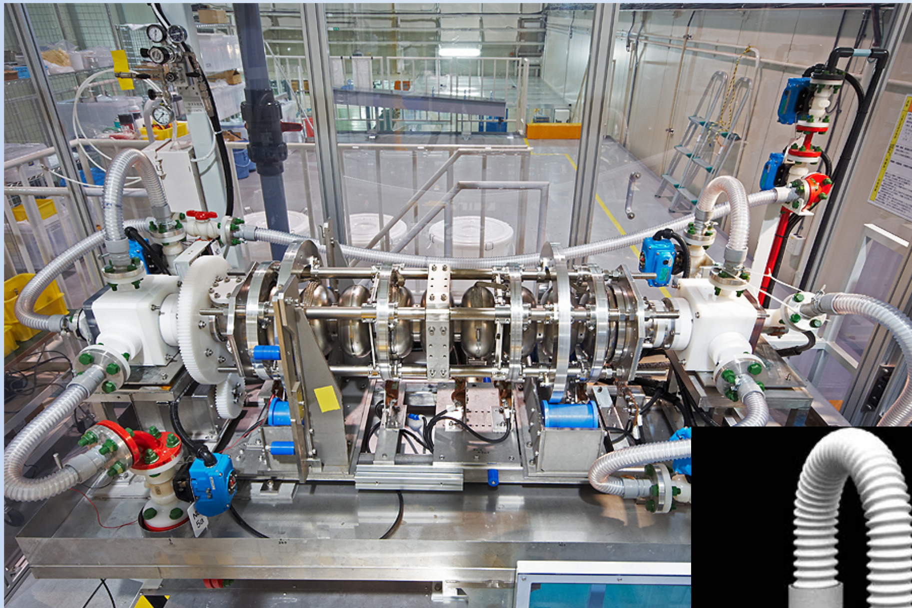

***KEK, Kyoto development***
***FNAL, JLAB cavity were treated, demonstrated its effectiveness***




Ken Watanabe

# Electro-polish for Cavity inner surface treatment

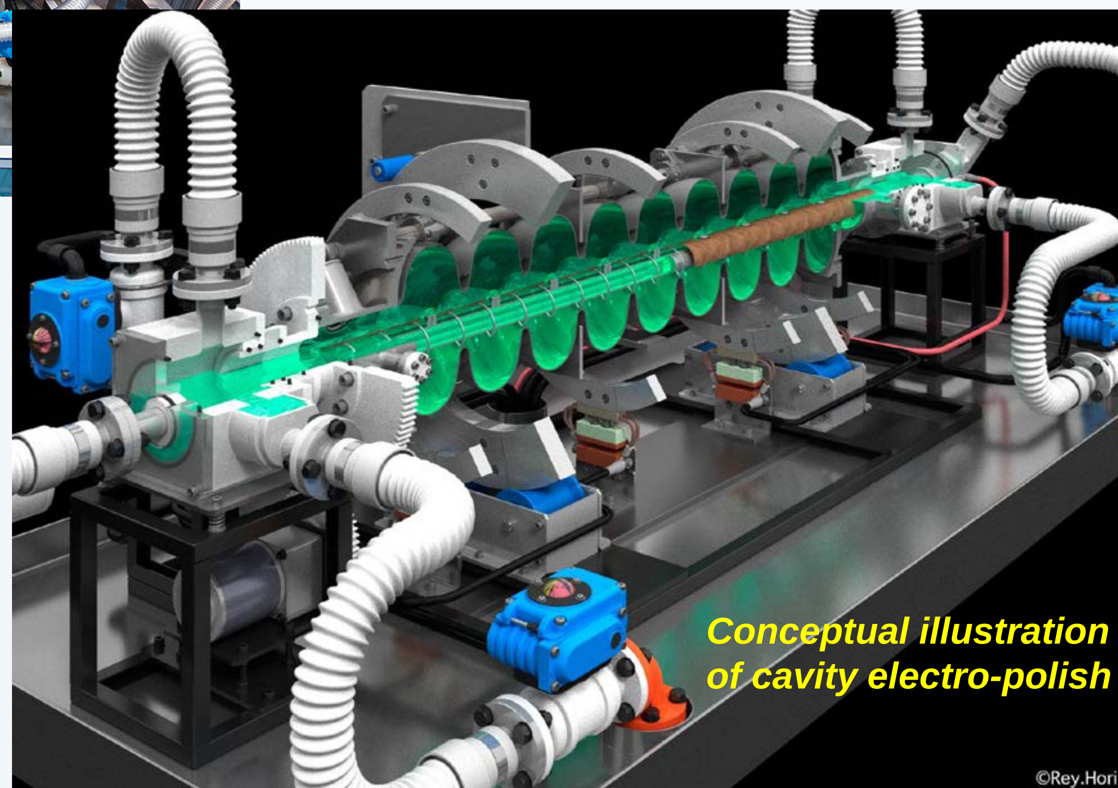


EP facility of KEK STF
(real picture)

## EP (Electro-Polish)

*Use of sulfuric acid + hydro-fluoride.*
*Apply voltage between Aluminum center conductor and niobium cavity. Then etching inner surface.*

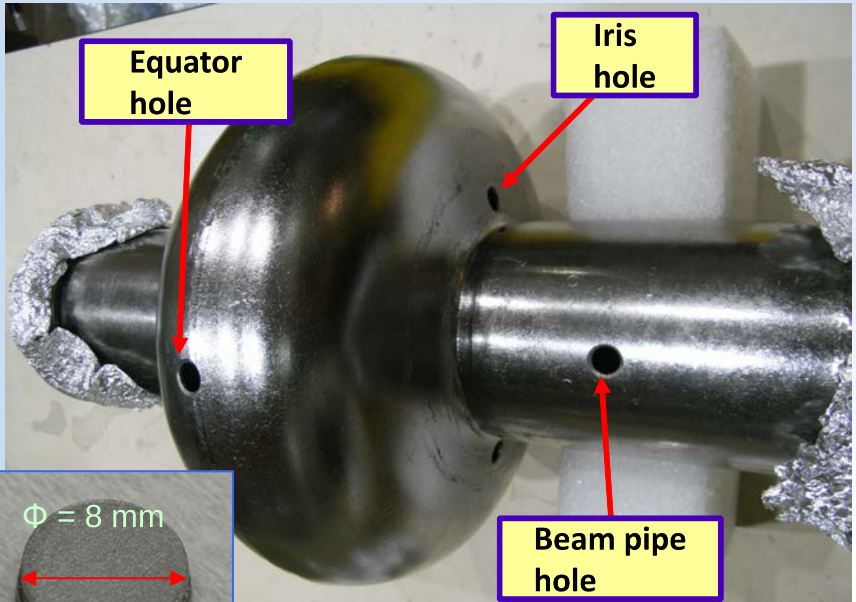
*Key technology is how to get smooth surface without residual contamination.*



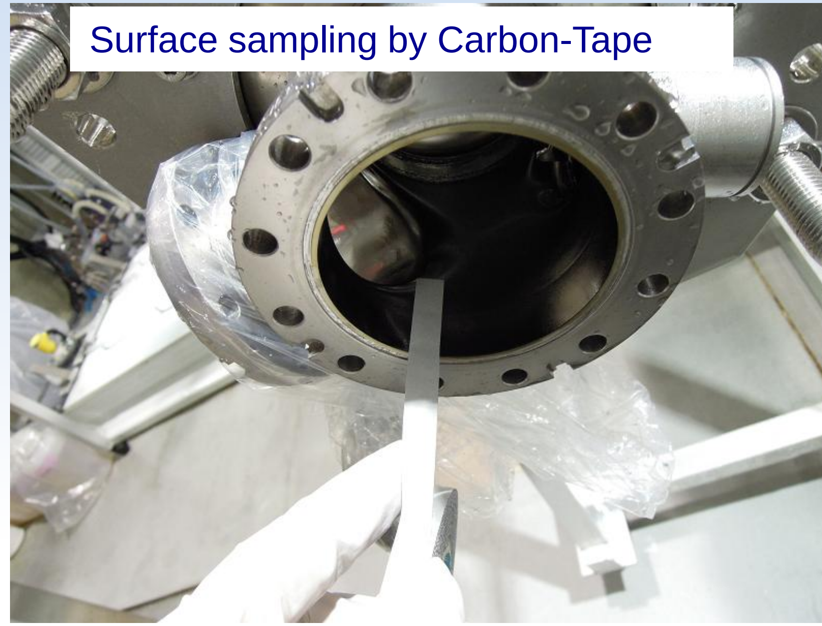

Conceptual illustration of cavity electro-polish

About 40 process/year
in KEK-STF EP facility,
Then achieved ILC spec. gradient
routinely.

# *Surface Monitoring for field emission reduction (1)*








**Process monitoring by Coupon on single-cell cavity**

**Optimization of surface treatment to reduce residual contamination**

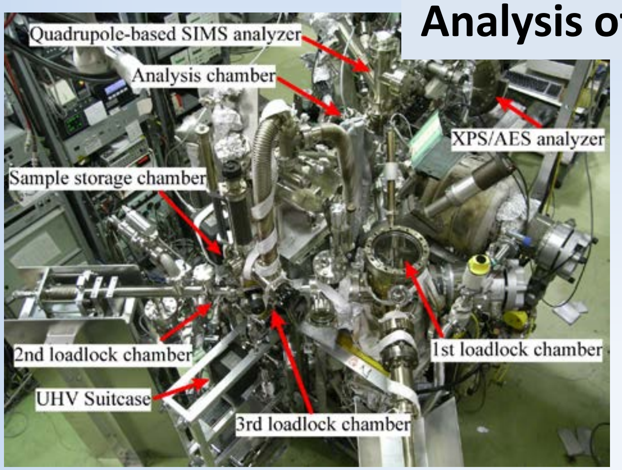
**(a) Electro-polish parameter optimization (low voltage, low temperature)**

**(b) Rinsing method development (water rinsing just after EP, brushing, ultrasonic rinsing, etc.)**

STF surface research team

# *Surface Monitoring for field emission reduction (2)*

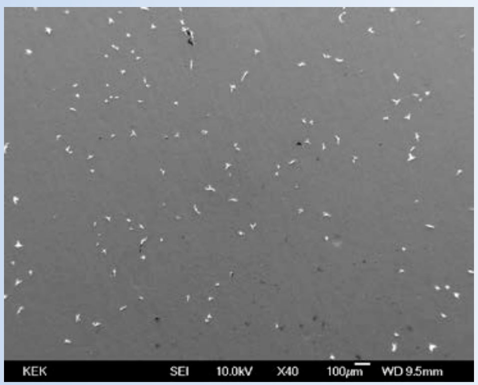
**Analysis of surface contamination**



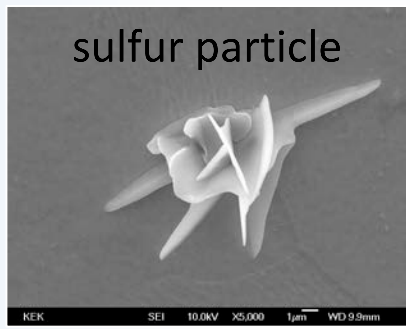

XPS,
SIMS

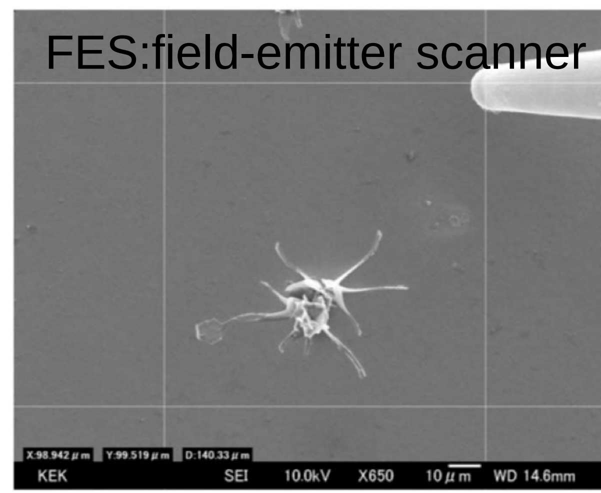
SEM + EDX

Raman
spectroscopy




expand




**mass-fraction analysis of surface residuals**

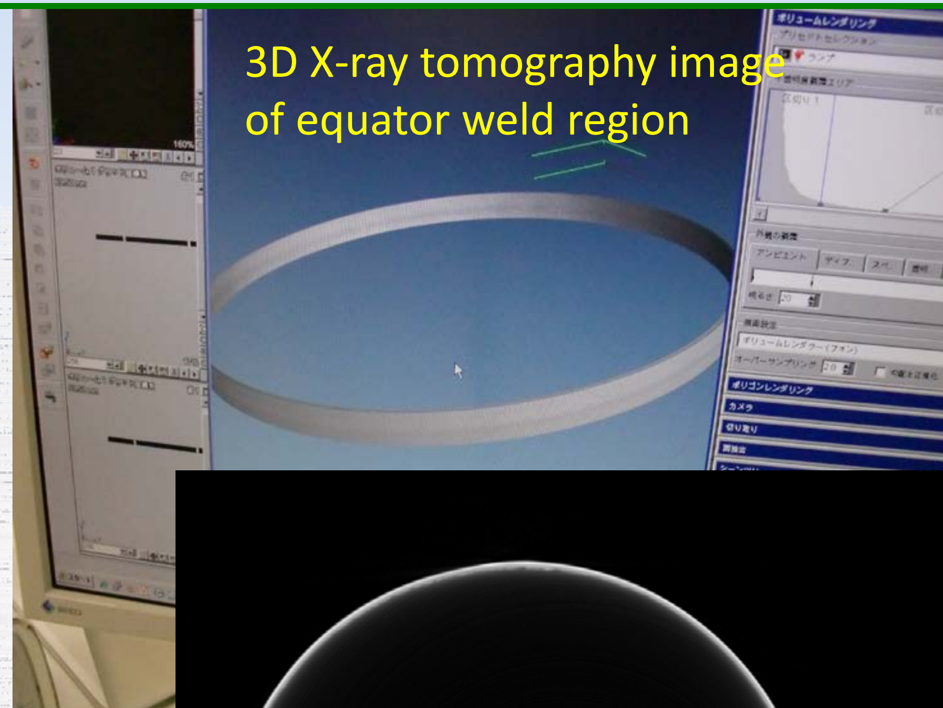
**Optimization of EP parameter, rinsing tools**

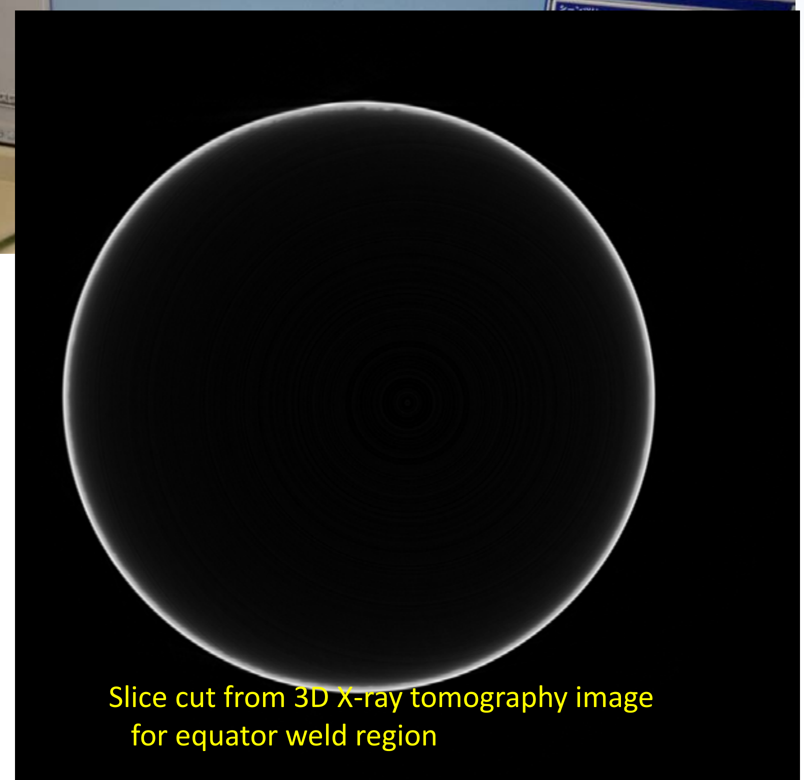
STF surface research team

# 3D X-ray tomography application

KEK - Kyoto Univ.

2D X-ray transparant image
of single-cell cavity



# *KEK Cavity performance, results of this development*

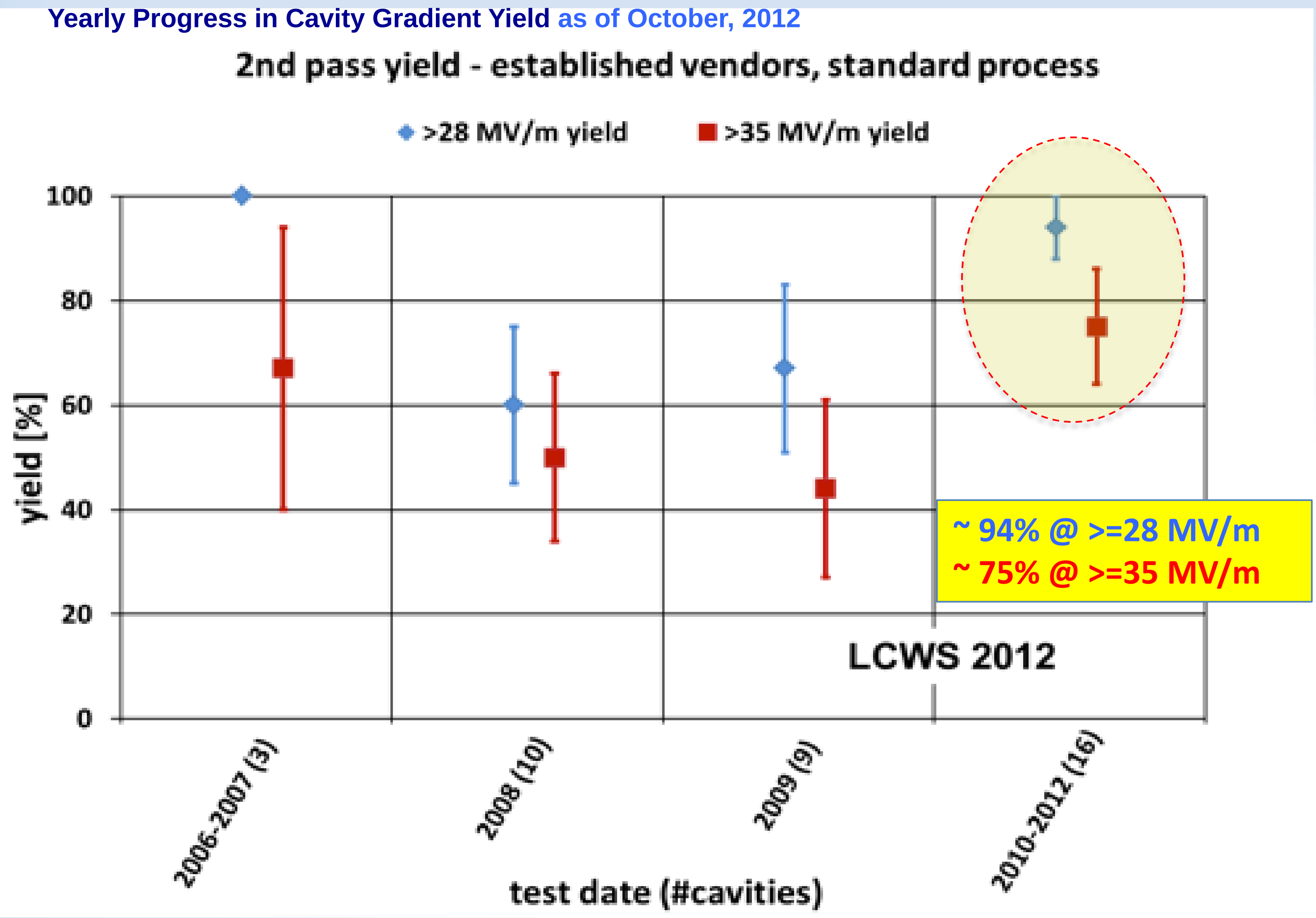
◎(>35MV/m), ◯(>=28MV/m) :ILC spec. clear

- **2010-2012 KEK cavities**

| | name | gradient | to be installed |
|---|---|---|---|
| ◎ | MHI-012 | 40.7MV/m | for capture cryomodule(2-nd VT) |
| ◯ | MHI-013 | 32.2MV/m | for capture cryomodule(2-nd VT) |
| | | | |
| ◎ | MHI-014 | 36.6MV/m | for CM-1 ILC cryomodule (3-rd VT) |
| ◎ | MHI-015 | 35.7MV/m | for CM-1 ILC cryomodule (4-th VT) |
| ◎ | MHI-016 | 33.8MV/m | for CM-1 ILC cryomodule (2-nd VT) |
| ◎ | MHI-017 | 38.4MV/m | for CM-1 ILC cryomodule (1-st VT) |
| ◎ | MHI-018 | 36.2MV/m | for CM-1 ILC cryomodule (4-th VT) |
| ◎ | MHI-019 | 37.0MV/m | for CM-1 ILC cryomodule (2-nd VT) |
| ◎ | MHI-020 | 35.1MV/m | for CM-1 ILC cryomodule (3-rd VT) |
| ◎ | MHI-021 | 38.9MV/m | for CM-1 ILC cryomodule (1-st VT) |
| ◎ | MHI-022 | 35.8MV/m | for CM-1 ILC cryomodule (2-nd VT) |

**Average gradient above 11 cavities = 36.4MV/m**
**ILC spec. achieved:11cavities(yield 100%, but max process repeat was 4)**

# *Cavity Yield Statistics (GDE wide)*

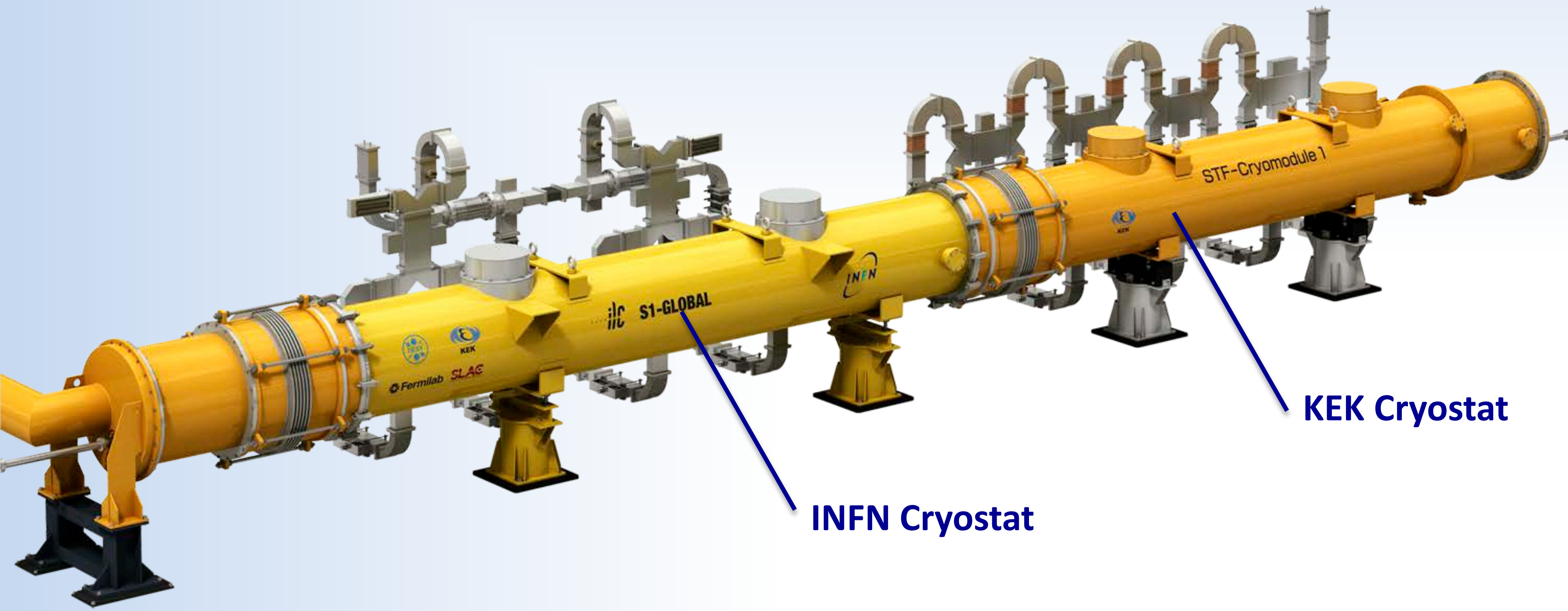


# Cryomodule development

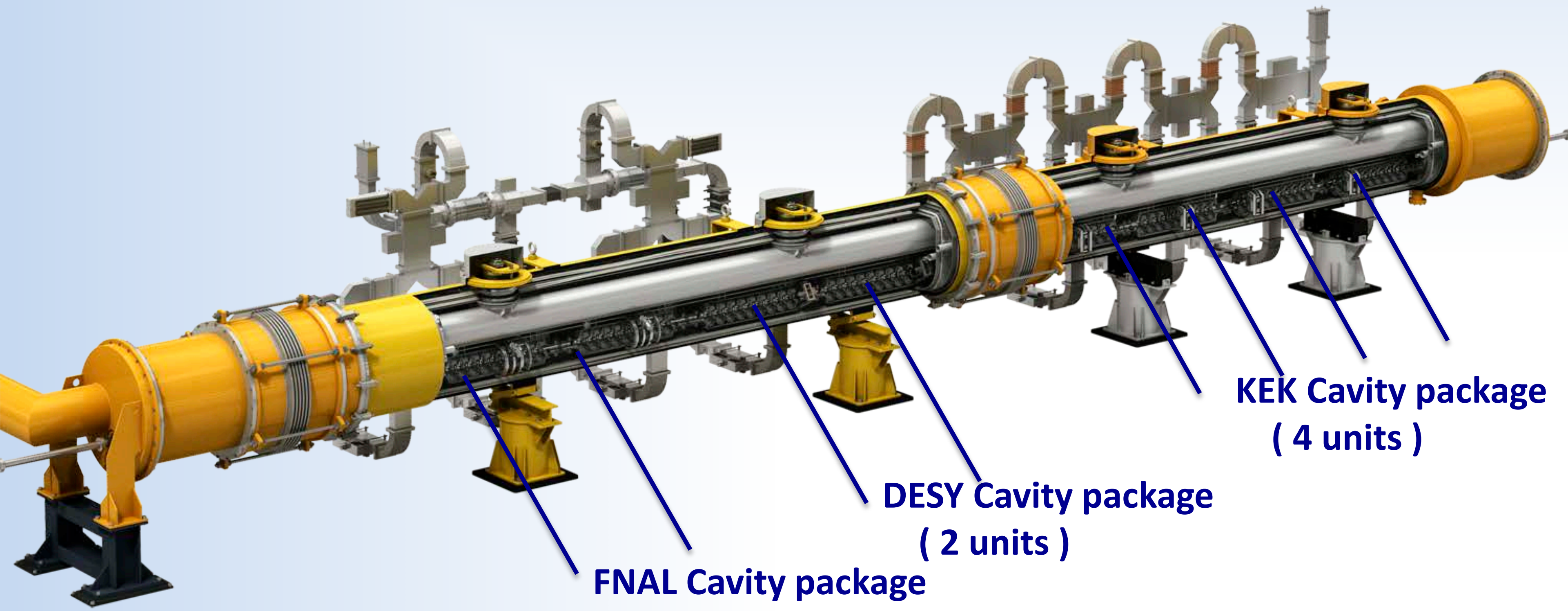
## *S1-Global cryomodule as an example.*

***S1-Global cryomodule:***
***international collaborative effort for***
***components were brought from DESY,FNAL,INFN,KEK***
***assembly and experiment hosted by KEK-STF, during 2009-2011.***

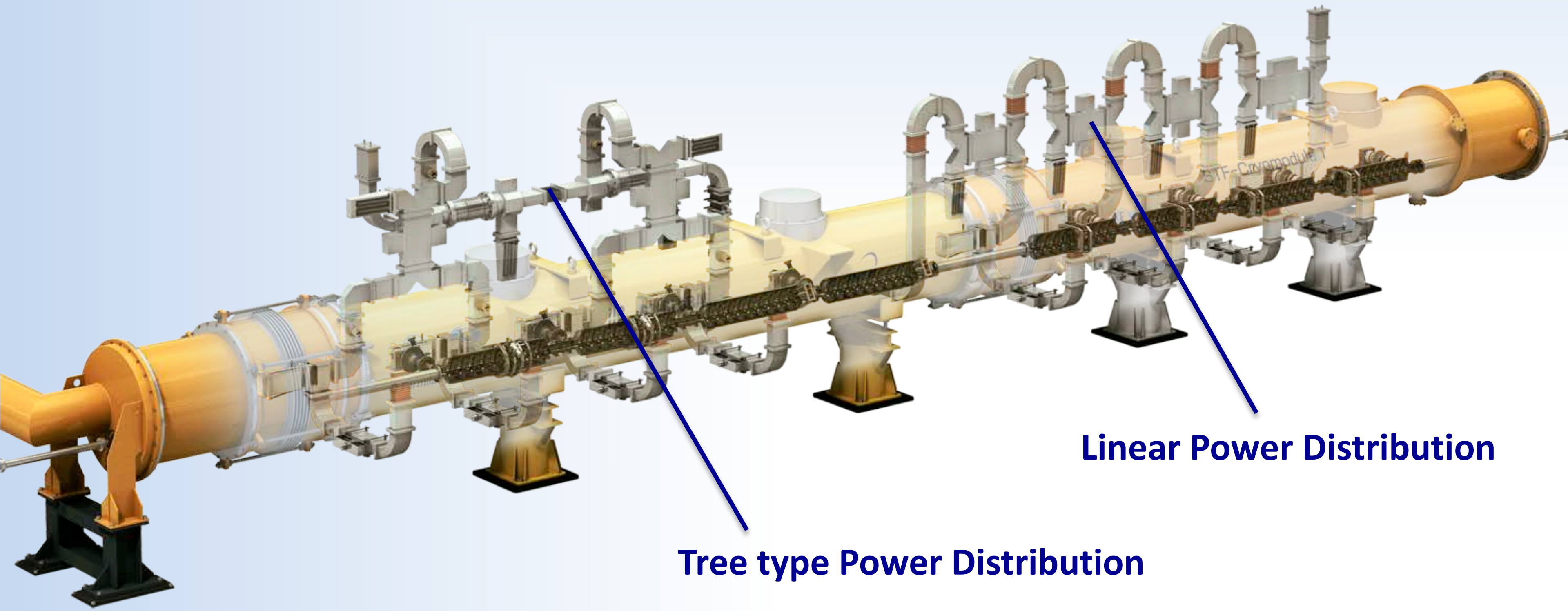
# S1-Global Cryomodule



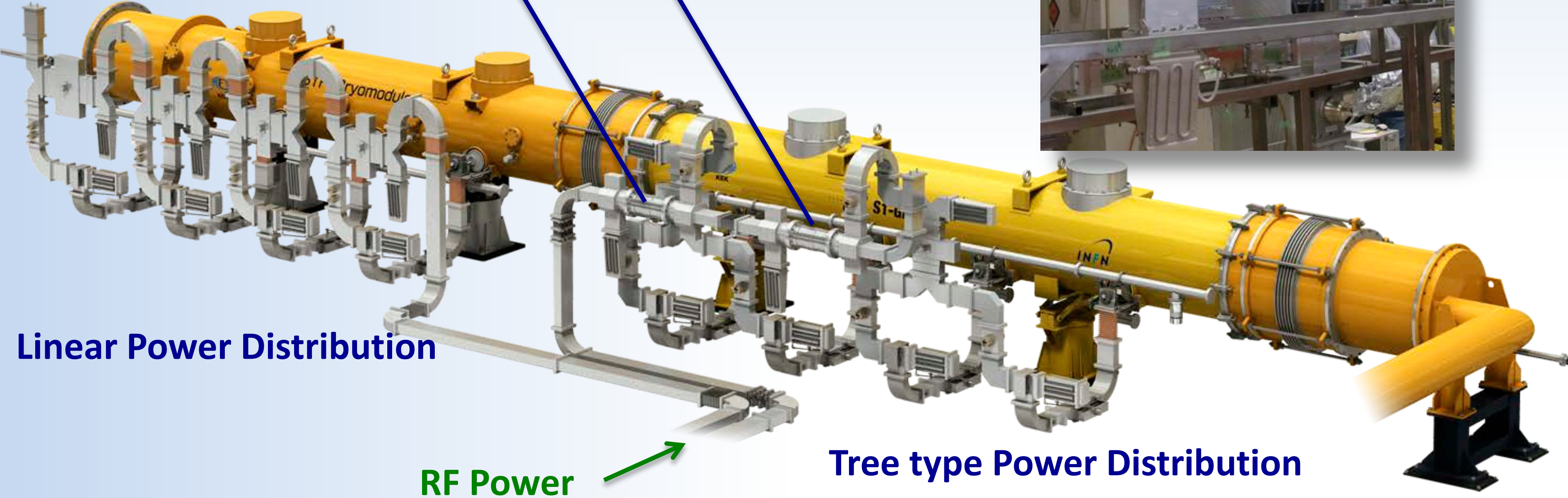
# S1-Global Cryomodule



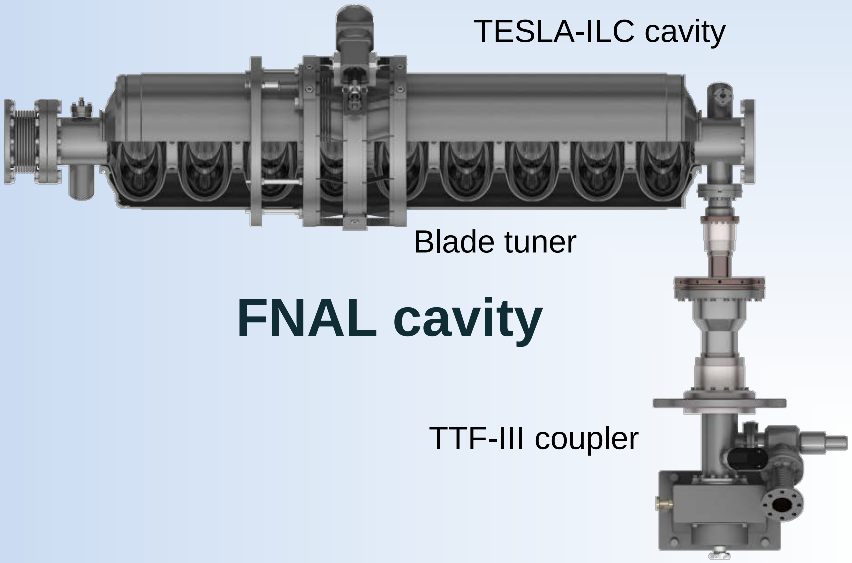
# S1-Global Cryomodule



# S1-Global Cryomodule

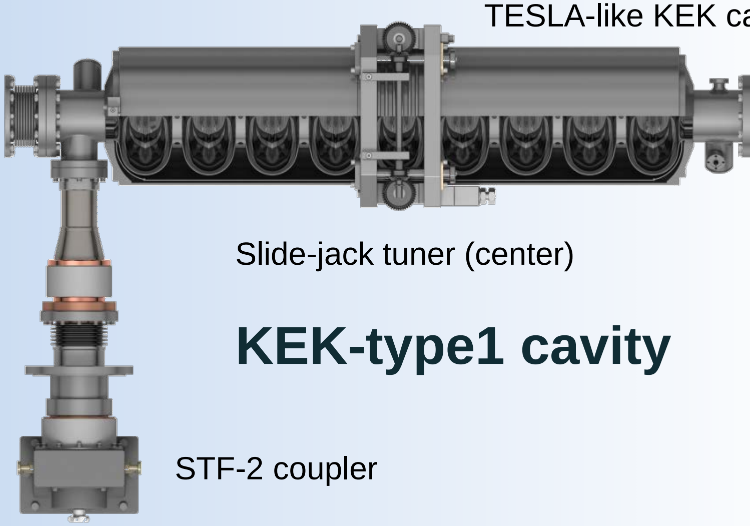



# S1-Global Cavity Packages




**FNAL cavity**


**DESY cavity**

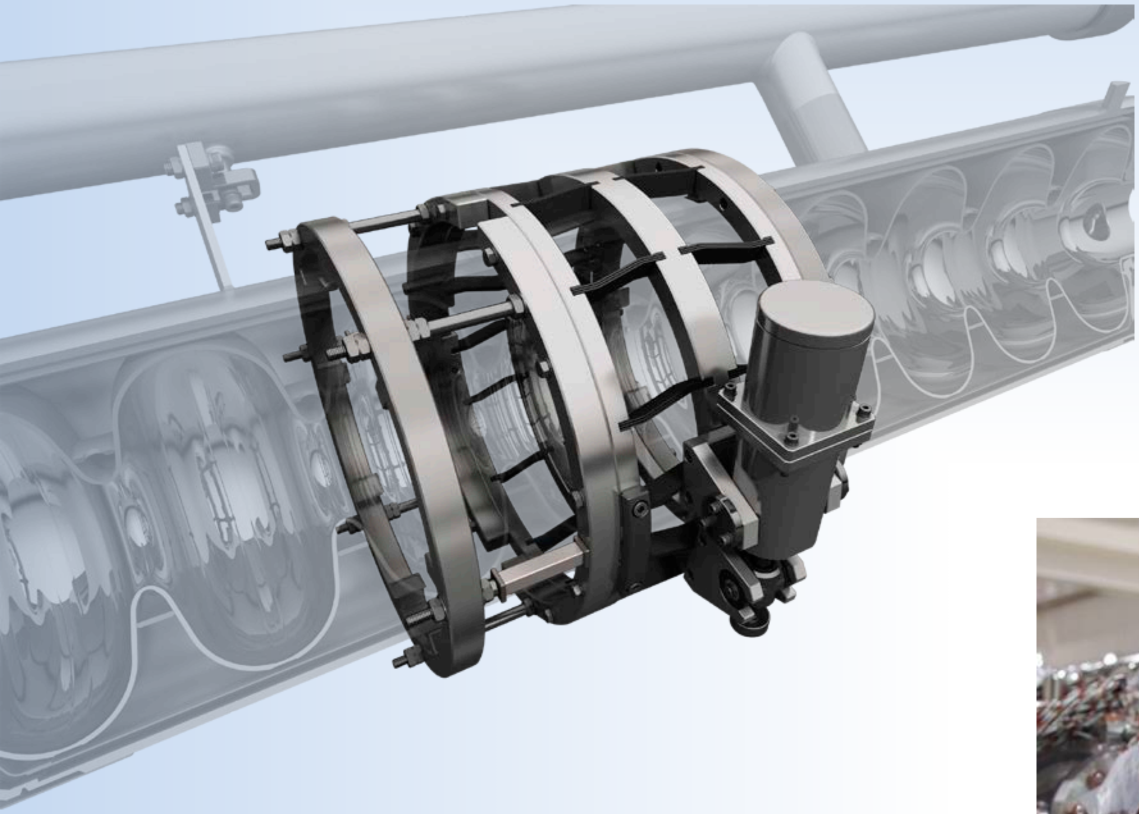



**KEK-type1 cavity**


**KEK-type2 cavity**

S1-Global Tuners

# Blade tuner (INFN/FNAL)

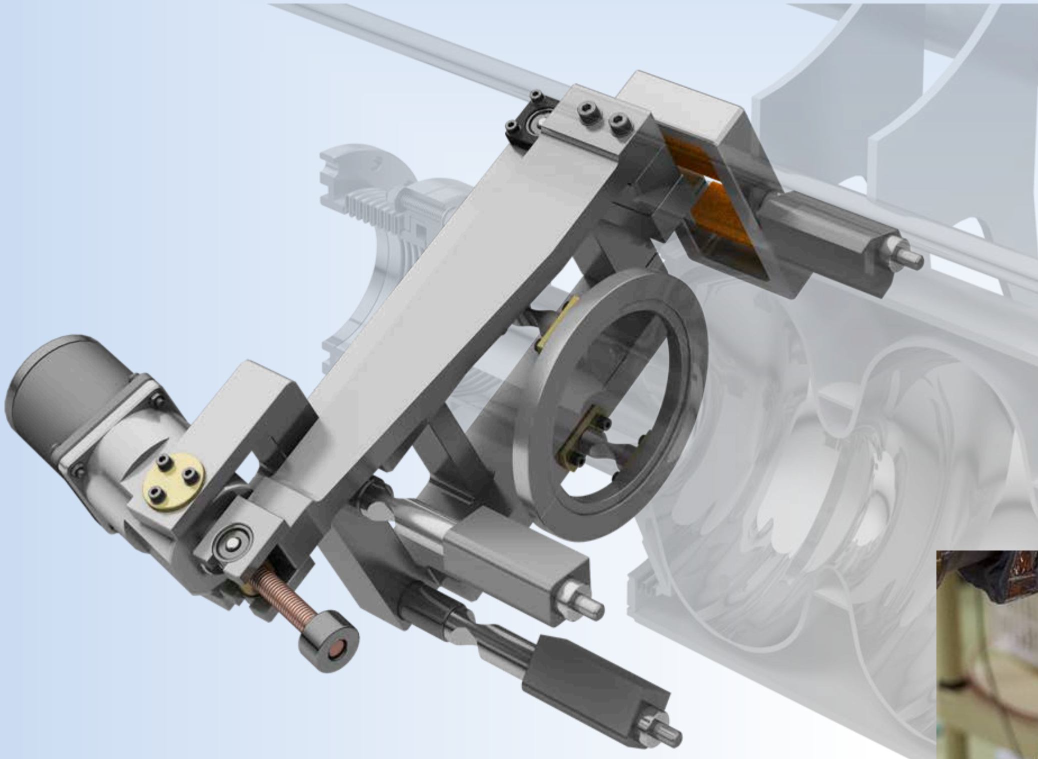


Location: middle of He vessel
Motor: inside of module,
low temperature
Piezo: two low-voltage piezo

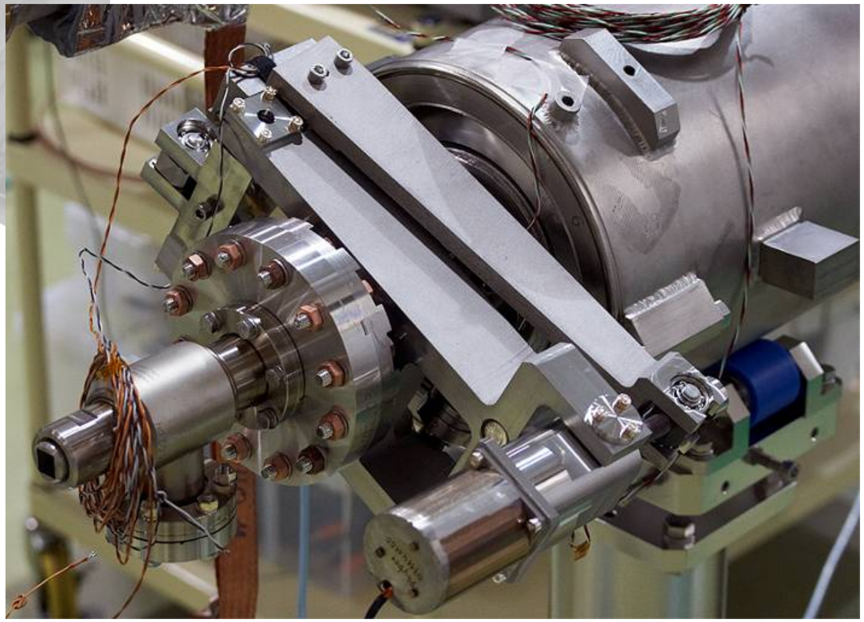
Design Stiffness: 30kN/mm
Nominal sensitivity: 1.5Hz/step
Piezo stroke at RM: 55 µm

S1-Global Tuners

# Lever-arm tuner (DESY/Saclay)



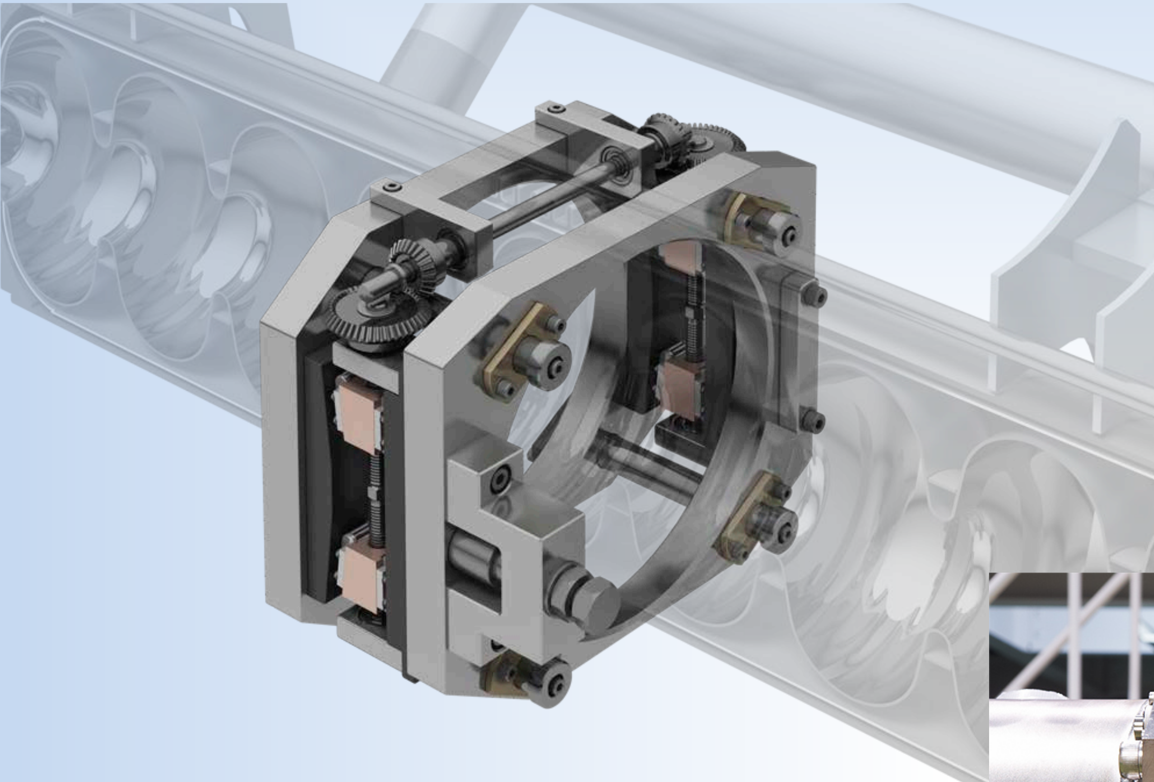
Location: end of He vessel
Motor: inside of module,
low temperature
Piezo: two low-voltage piezo



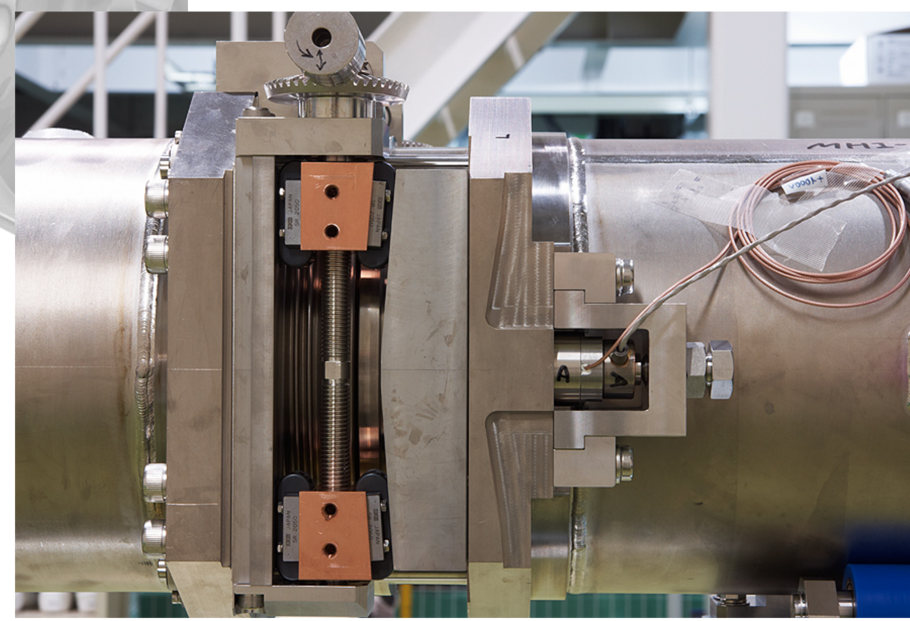
Design Stiffness: 40kN/mm
Nominal sensitivity: 1.0Hz/step
Piezo stroke at RM: 55 µm

S1-Global Tuners

# Slide-jack tuner (KEK)



Location: two types,
middle of He vessel
end of He vessel
Motor: outside of module,
room temperature
Piezo: one high-voltage piezo



Design Stiffness: 290 kN/mm
Nominal sensitivity: 3 Hz/step
Piezo stroke at RM: 40 µm

## S1-Global Input Couplers

# TTF III coupler (LAL)

**Type: coaxial to antenna**
**Window: two cylindrical,**
**cold window & warm window**
**Coupling: tunable**
**Interface: 40mm dia. cavity port**
**WR650 for waveguide**
**Power: 350kW, 1.5ms, 5Hz**

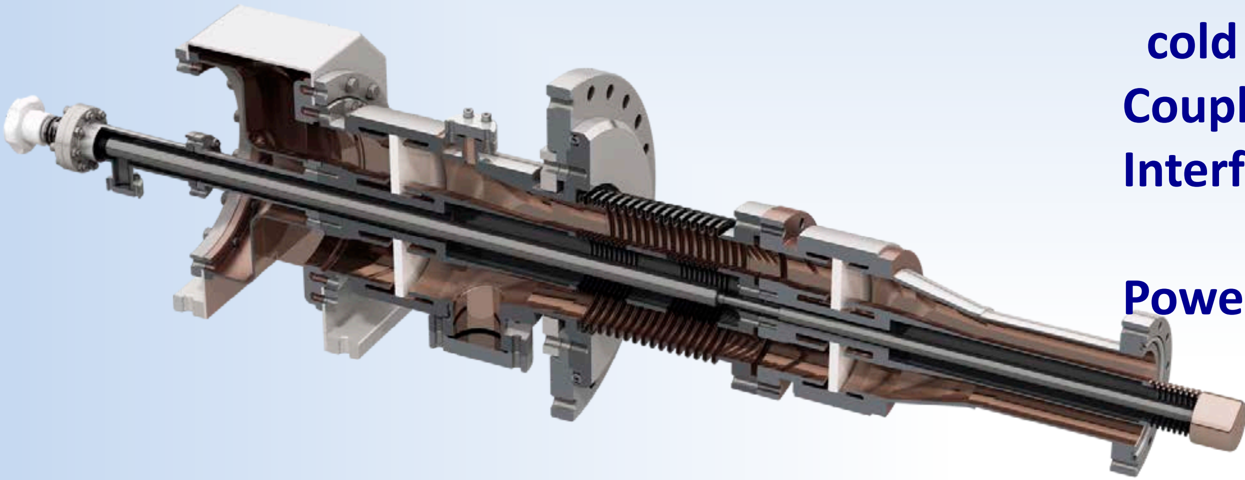
**TTF & FLASH (& FNAL) experience in many years,**

**Complicated assembly procedure is required.**

## S1-Global Input Couplers

# STF-2 coupler (KEK)

Type: coaxial to antenna
Window: two disk-type,
 cold window & warm window
Coupling: tunable
Interface: 60mm dia. cavity port
 WR650 for waveguide
Power: 350kW, 1.5ms, 5Hz



Extension of TRISTAN(CW) coupler,

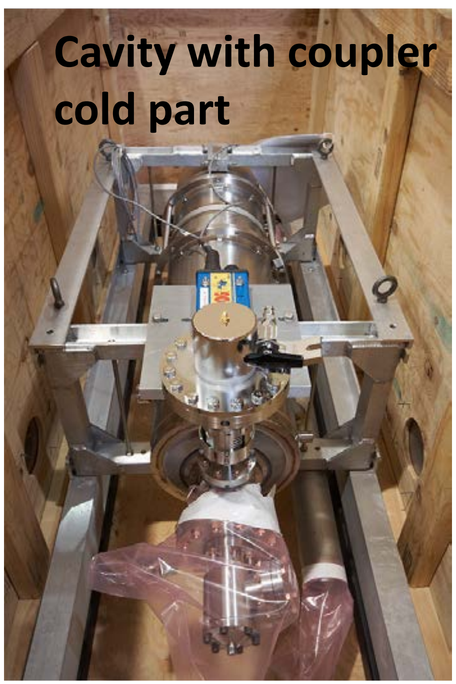
Simple assembly procedure by no bellows in cold part.
However, static heat loss increased 4 times.

# Assembly work

(December 2009 – May 2010)

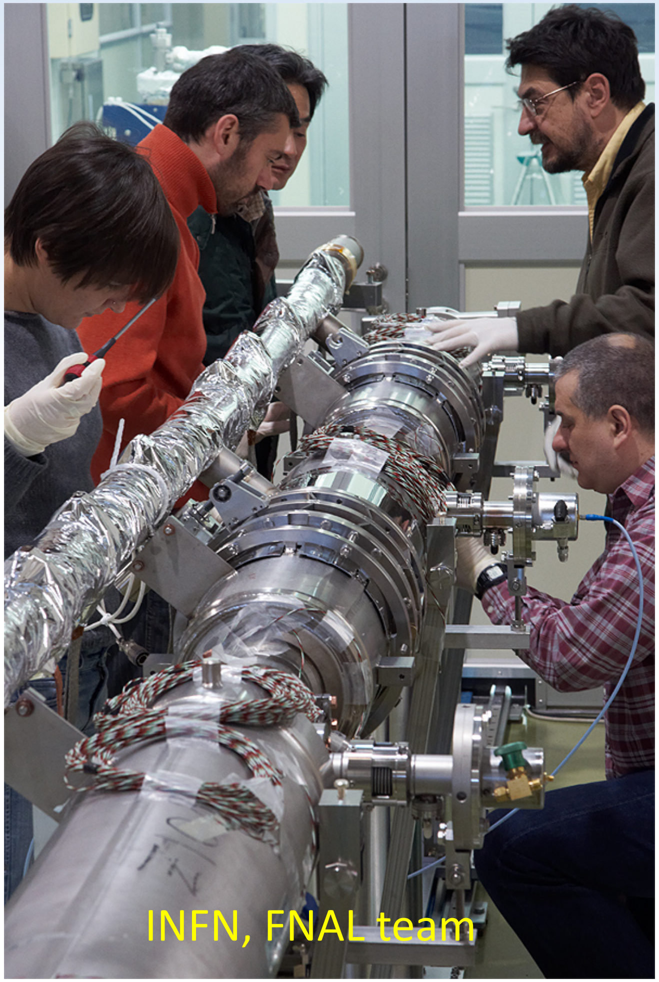
# Arrival of contributed components

December 2009





# Assembly work

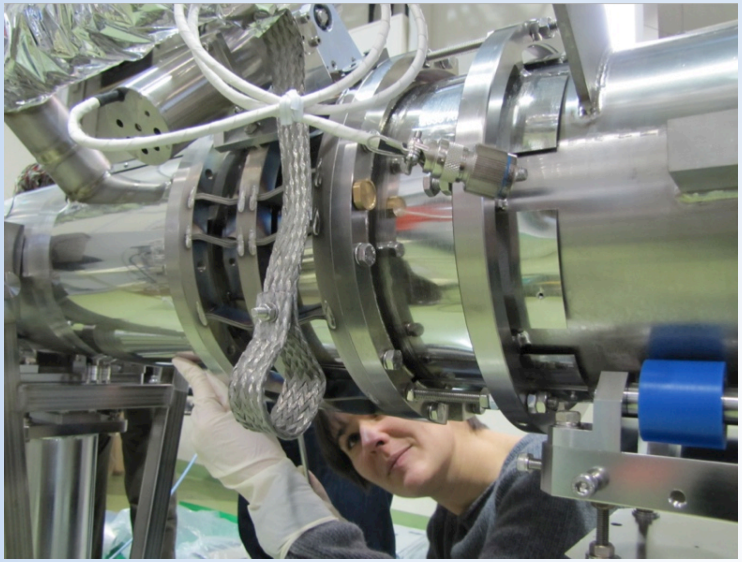




Tug Arkan
Brian Smith
Marco Battistoni
from FNAL

Manuela Schmoekel
Patrick Schilling
from DESY

Carlo Pagani
Angelo Bosoti
Rocco Pararella
from INFN
Serena Barbanott
from FNALi

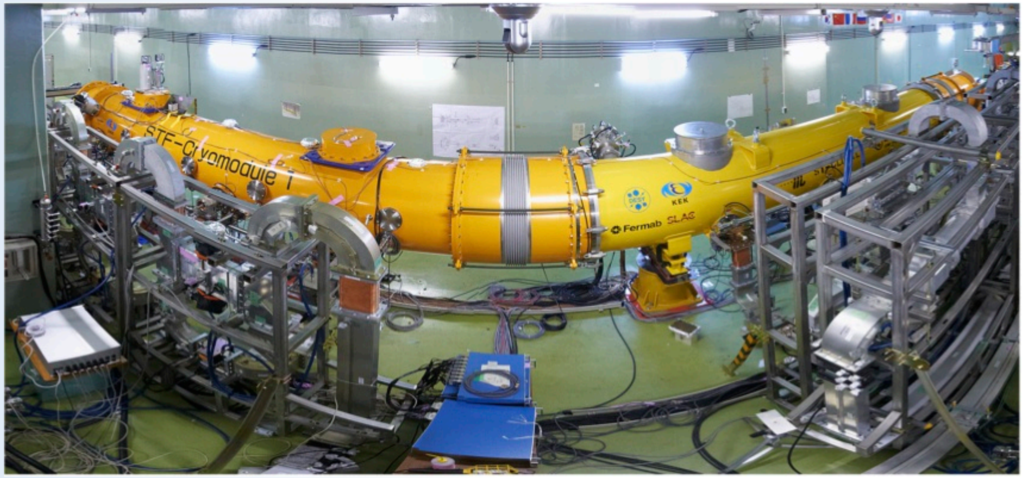
# Assembly work



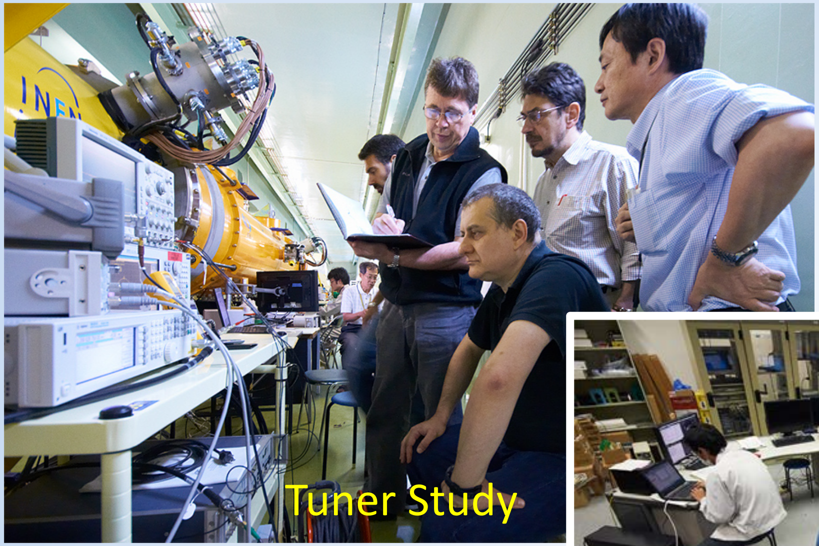
Serena Barbanotti from FNAL installed magnetic shield

Denis Kostin from DESY installed warm couplers

# Installation into STF tunnel



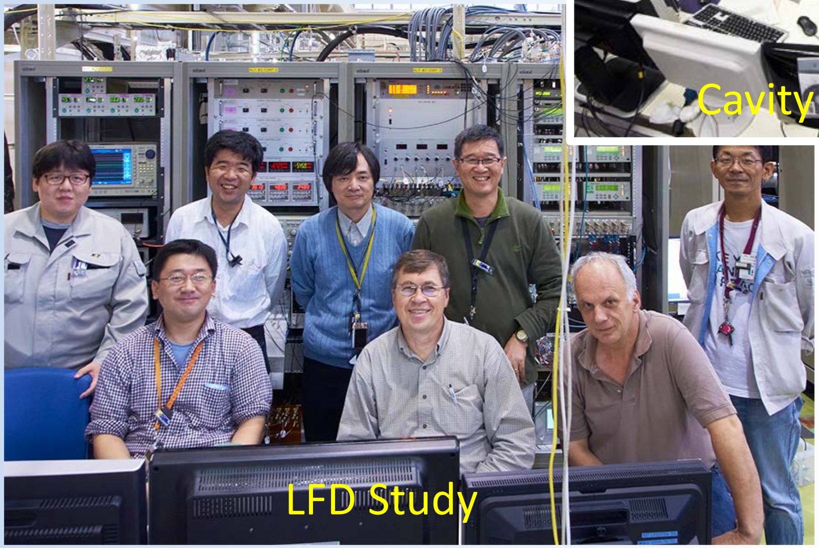
# Cryomodule experiment




Carlo Pagani (INFN)
Angelo Bosoti (INFN)
Rocco Pararella (INFN)
Yuriy Pischalnikov (FNAL)

Denis Kostin
(DESY)





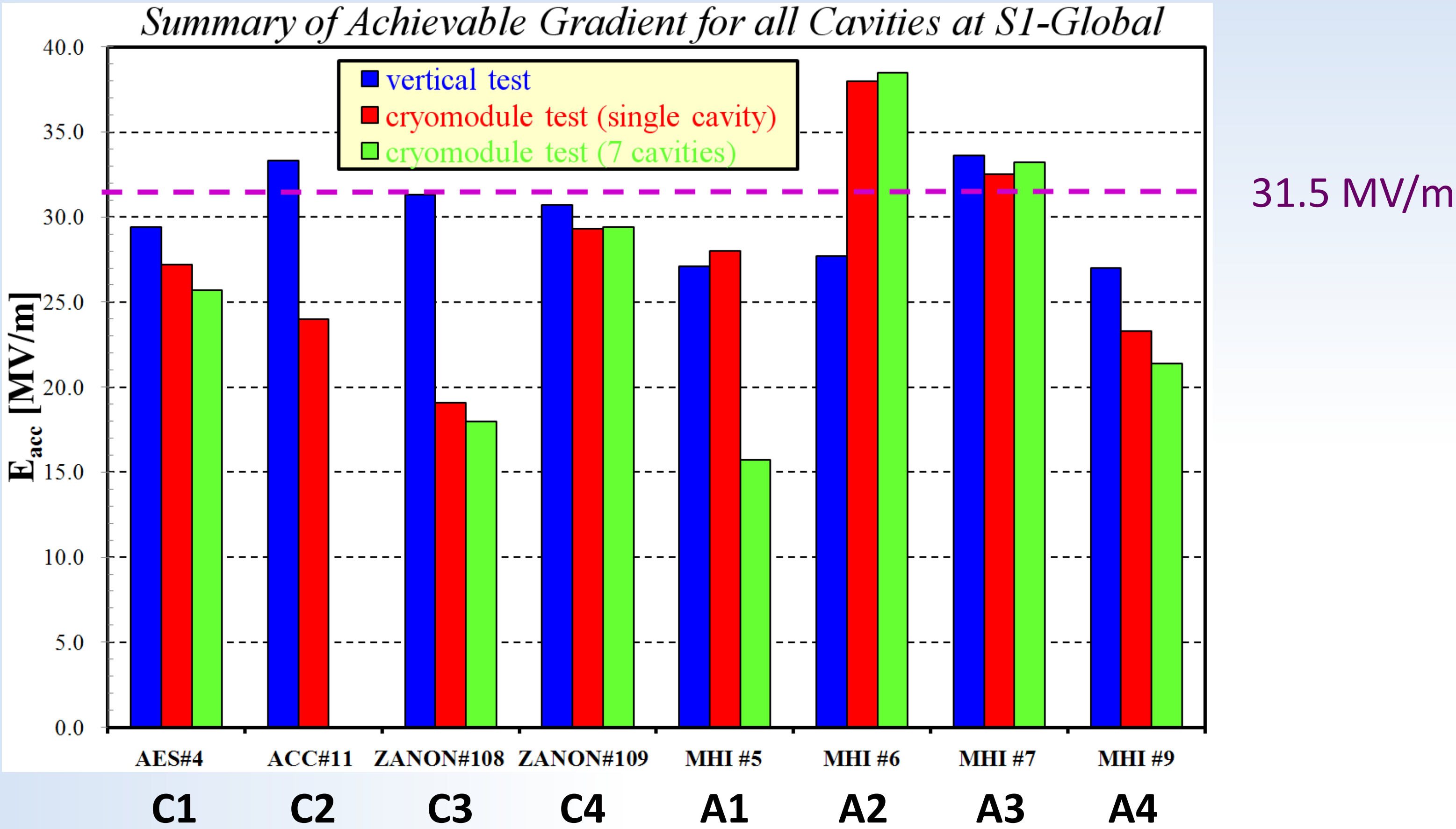

Yuriy Pischalnikov (FNAL)
Warren Schappert (FNAL)

# Results of Performance Test

(June 2010 – February 2011)

# Cavities Performance

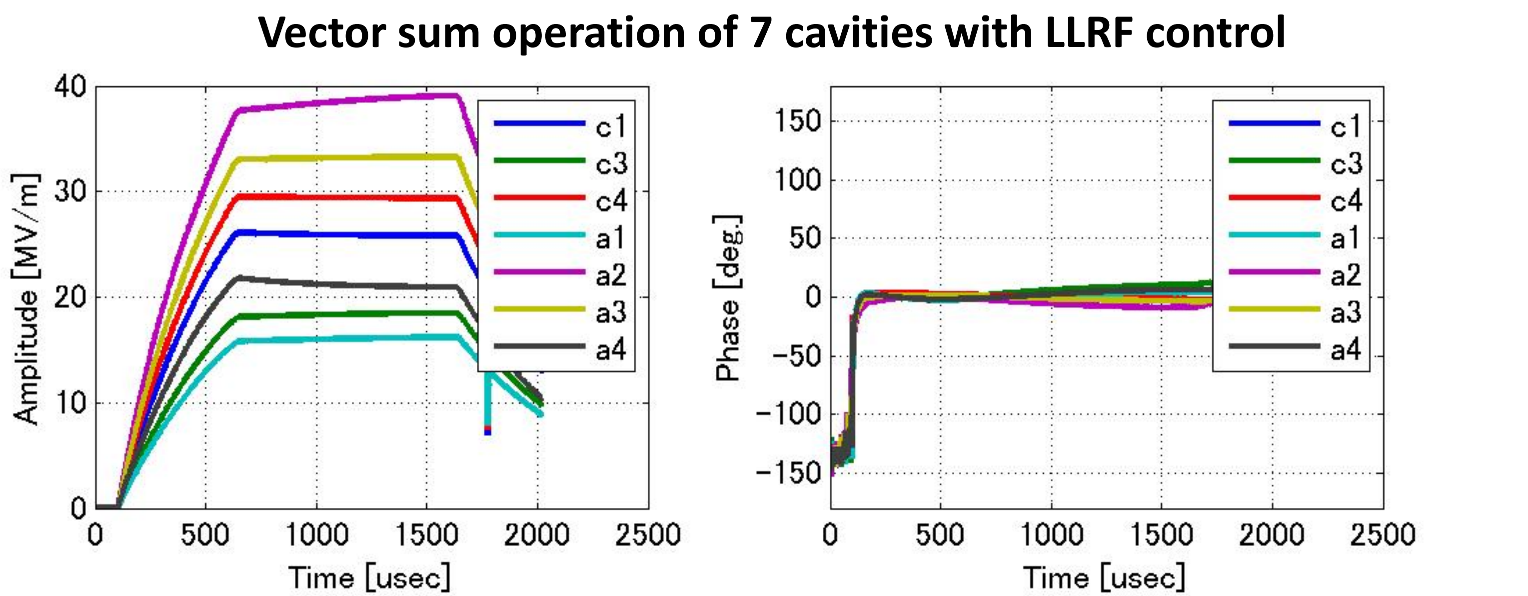
## gradient

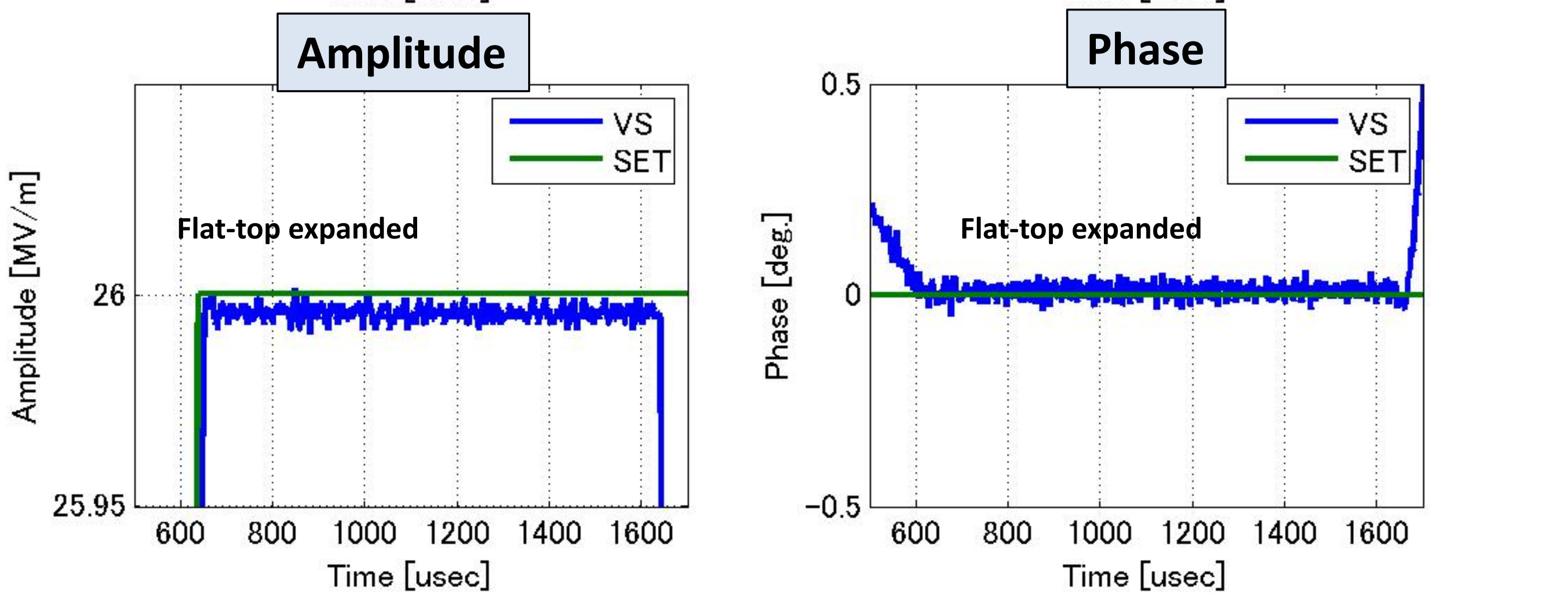



| | | |
|---|---|---|
| (blue) | Before cryomodule installation | Average 30.0MV/m |
| (red) | after cryomodule installation | Average 27.7MV/m |
| (green) | 7 cavities combined operation | Average 26.0MV/m |

# Cavities Performance

## Combined & feedback control

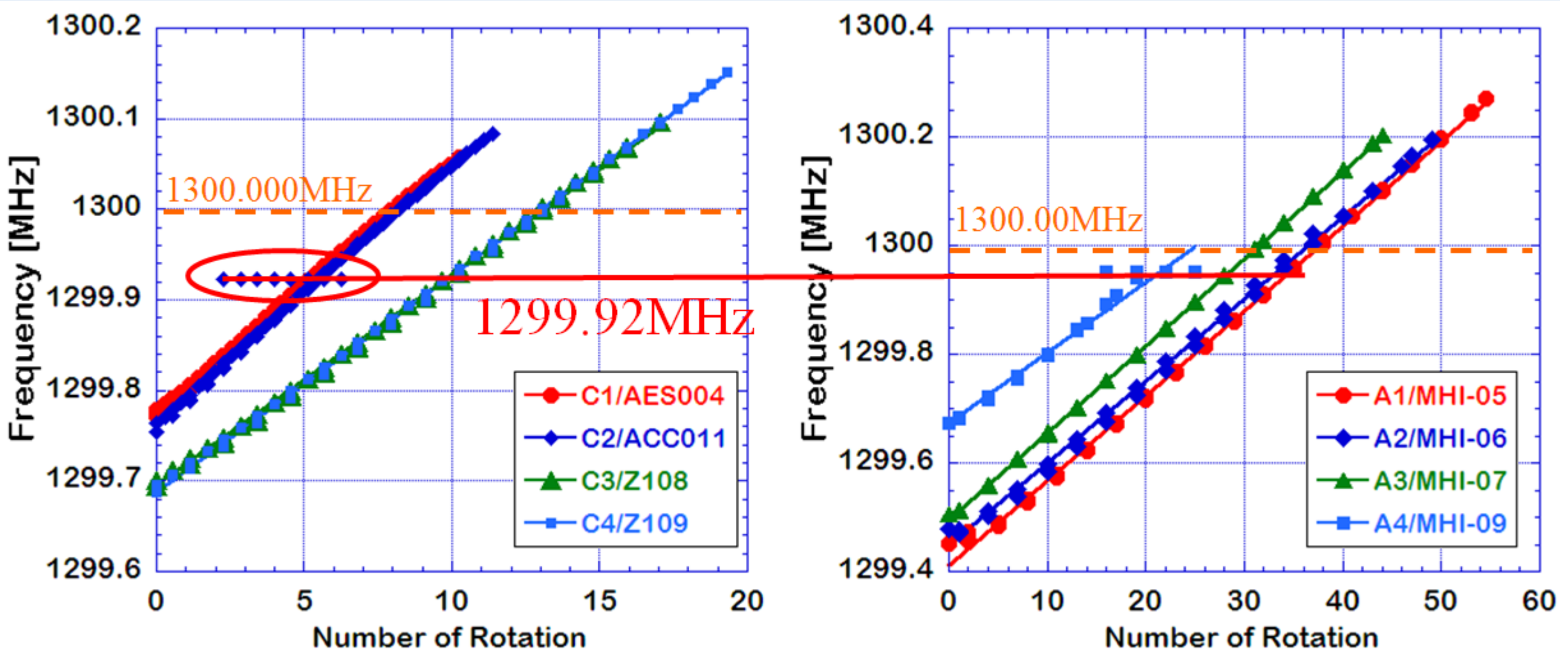


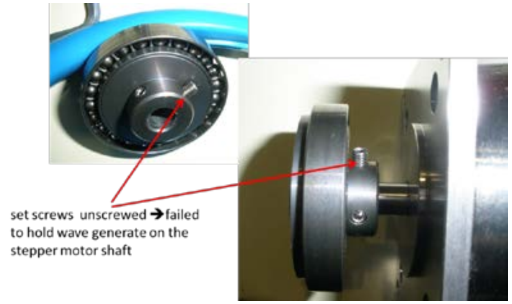

**0.005%.rms amplitude stability** **0.015degree.rms phase stability**

# Tuners Performance

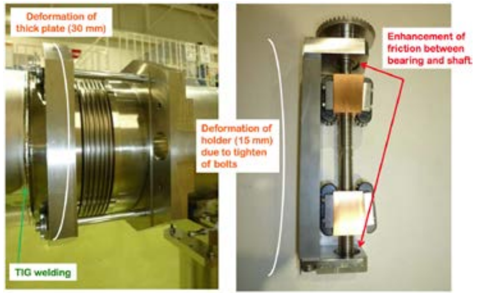
## Mechanical tuner




**C2 Blade tuner: failed after single excursion,**
**later, found set-screw slipping**
**-> improved in the next production**




**A4 Slide-jack tuner: failed during first excursion,**
**later, found jack-slope bending**
**-> improved in the next production**

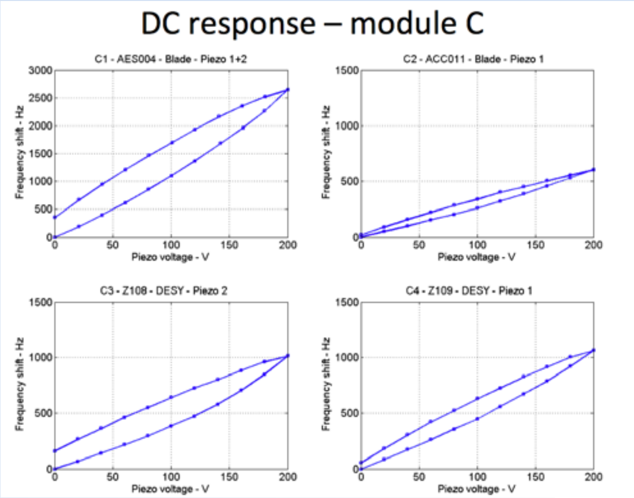


# Tuners Performance

# Piezo tuner

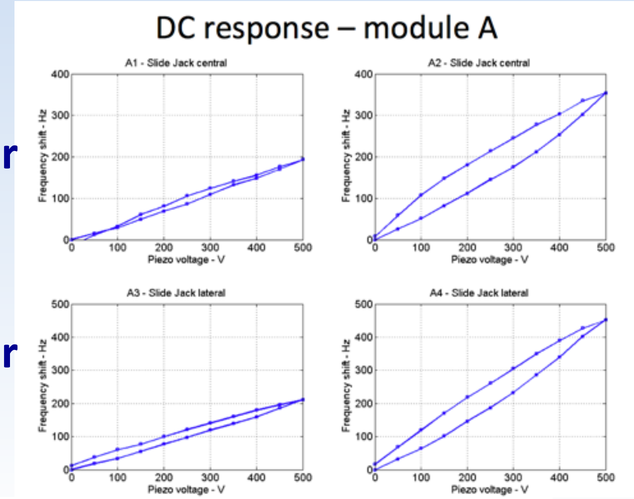
**Blade tuner**

**Lever-arm tuner**

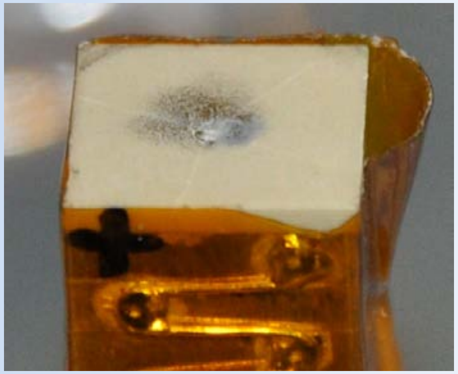


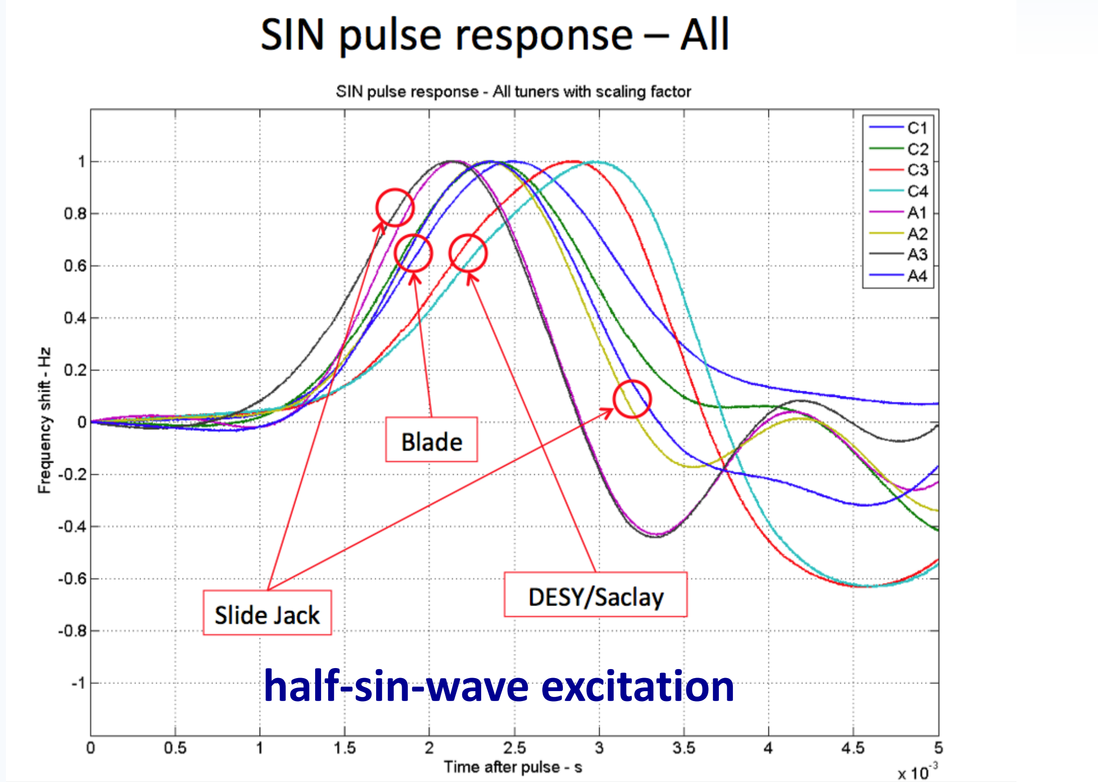

**Slide-jack tuner In center**

**Slide-jack tuner In end**



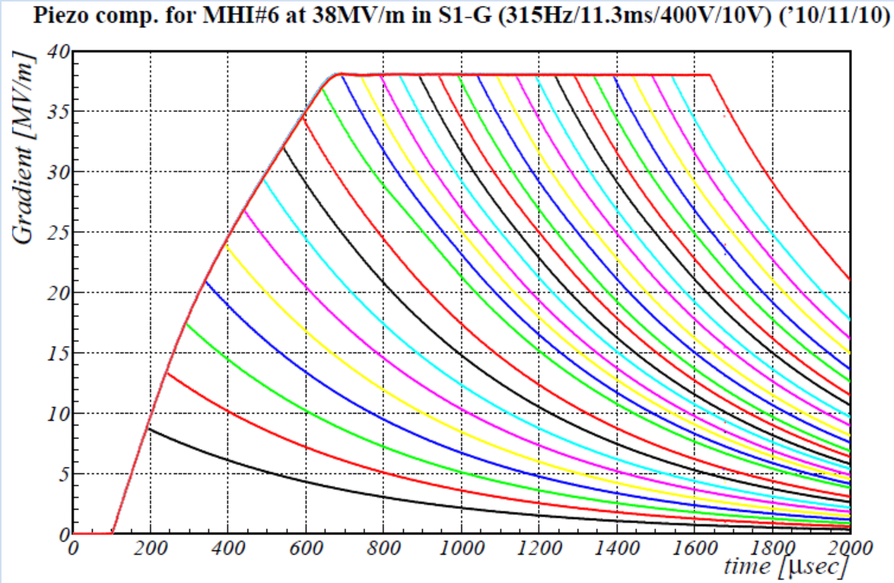

**C2 Blade tuner: one piezo breakdown, later, found crack on piezo -> improved in the next production**

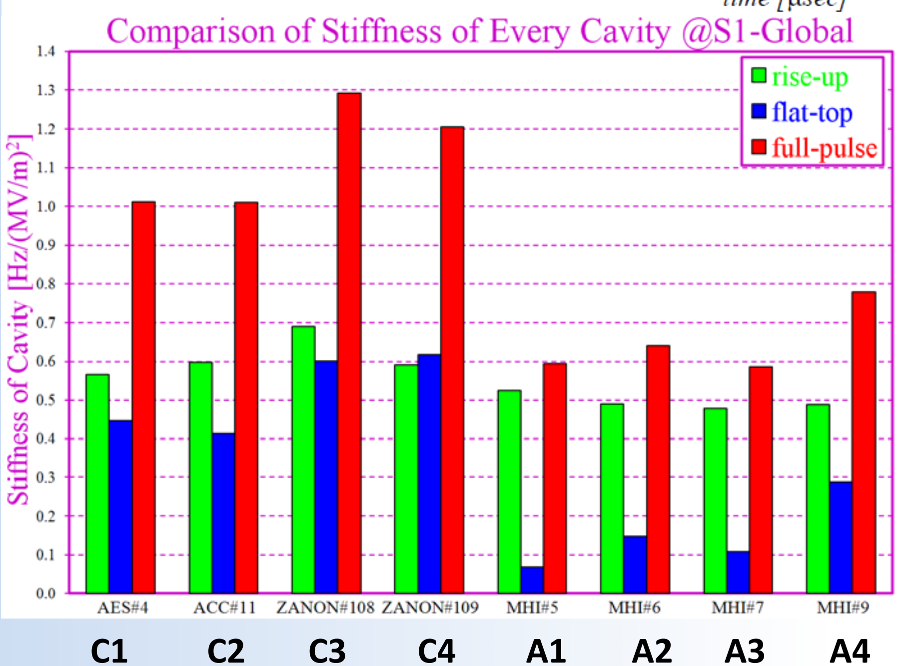




# Tuners Performance

## LFD measurement

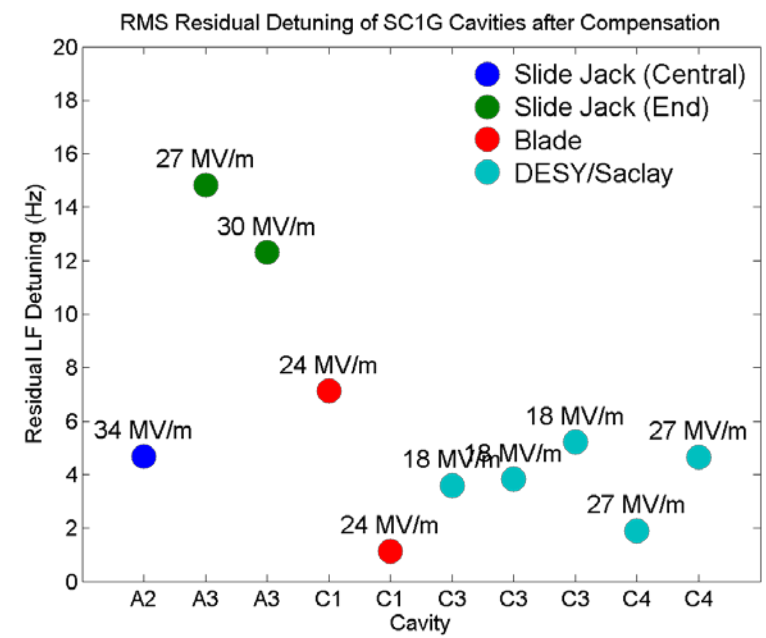



**Lorentz Force Detuning (LFD) were measured By Pulse-cut method.**

**Slide-jack tuners were 4 – 5 times stiffer than other tuners.**

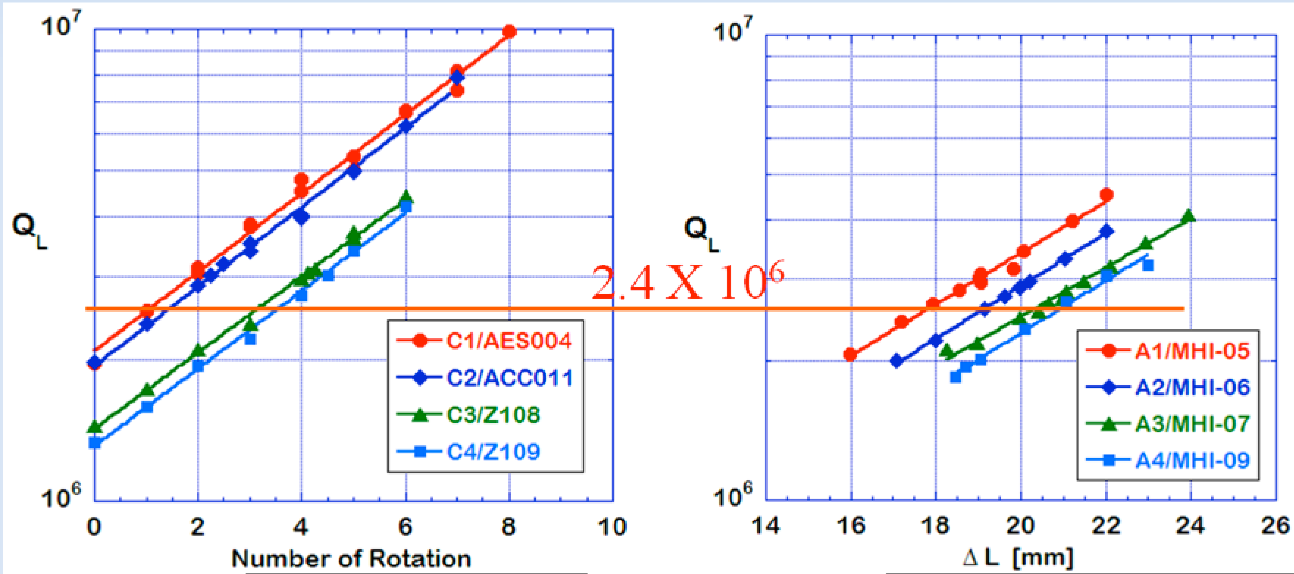
**Residual LFD were less than 15Hz for all tunes, by adaptive feed-forward control.**




**Adaptive feed-forward compensation**

# Couplers Performance

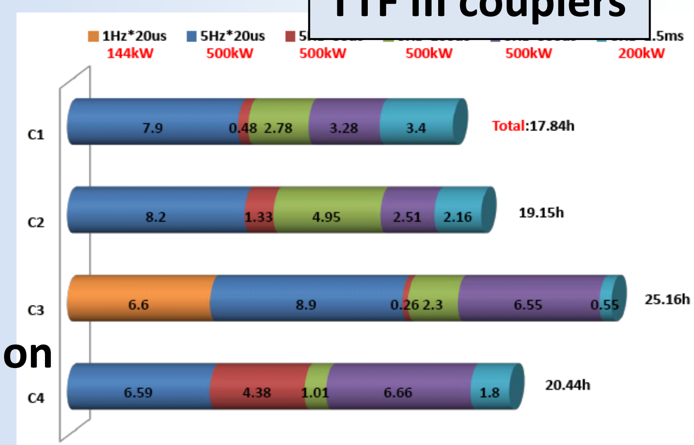
$Q_L$ tuning range



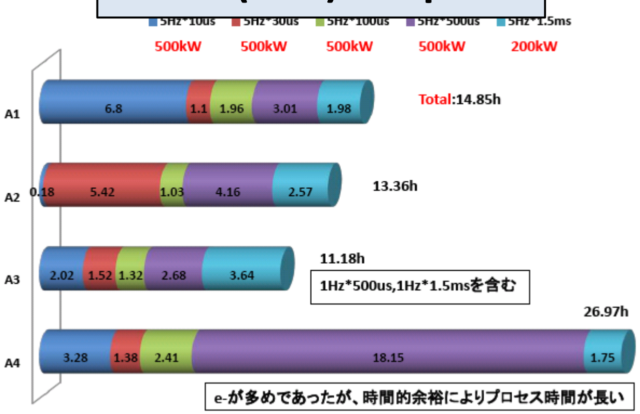

**TTF III couplers**

**STF-2 (KEK) couplers**

Process Time After installation




Average process time=21 hours




Average process time=15 hours

**A1 (KEK) coupler: trip at 15MV/m by vacuum increase. -> reason not yet identified**

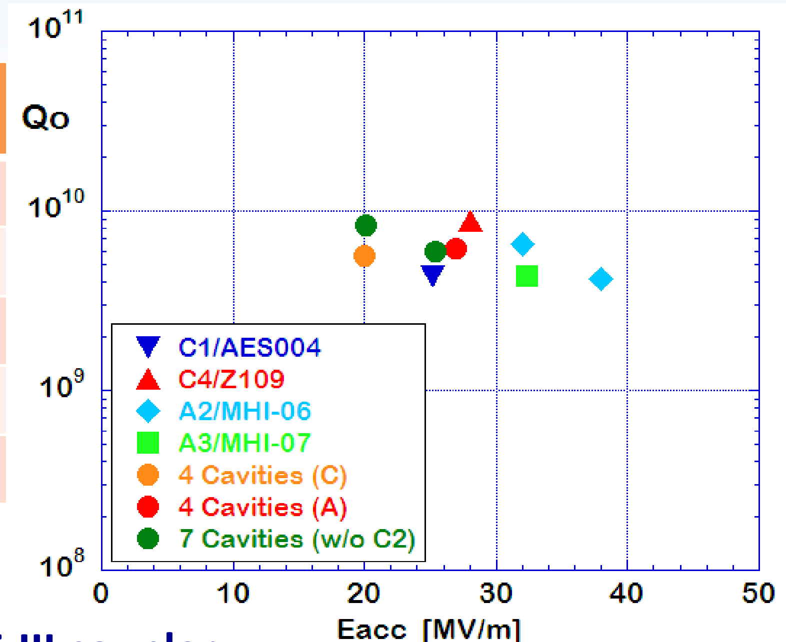
# Thermal Performance

## Static, dynamic loss

| Static loss | Module-C(INFN,FNAL,DESY) | Module-A (KEK) |
|---|---|---|
| 2K | 7.2 W [6.8 W estimation] | |
| 5K | 5.3 W [4.1 W] | 7.3 W [7.2 W] |
| 80K | 34.4 W [35.3 W] | 48.7 W [44.3 W] |

**The static loss were consistent with the estimation.**

| Dynamic loss | Module-C (4 cavities) | Module-C (4 couplers) | Module-A (4 cavities) | Module-A (4 couplers) |
|---|---|---|---|---|
| Gradient | 20 MV/m | 32 MV/m | 26.9 MV/m | 32 MV/m |
| Tune/detune | tune | detune | tune | detune |
| $Q_D$ [W] | 2.7 | NA | 6.9 | NA |
| $Q_{D\text{-}det}$ [W] | 0.2 | 0.5 | 2.5 | 4.6 |
| $Q_{D\text{-}cav}$ [W] | 2.5 | NA | 4.4 | NA |




**STF-2 (KEK) coupler had 9x large dynamic loss than TTF-III coupler.**
**Later, it was found it came from Cu 3µm inner coating layer heating.**
**→ It was improved in the next model, already.**

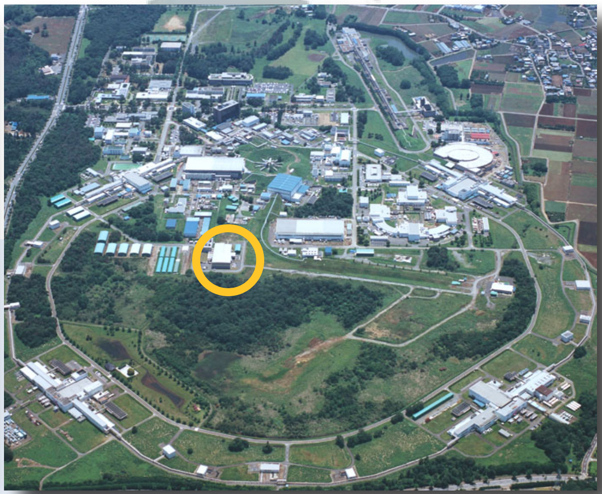
# Summary of S1-Global cryomodule experiment

- The design, fabrication, assembly, experiment, and disassembly of S1-Global were done by the international collaboration based on ILC-GDE, hosted by KEK STF.
- The achieved gradient performance of the contributed cavities was average 30.0MV/m before installation, 27.7MV/m for single cavity operation after installation, and 26.0MV/m for 7 cavities simultaneous operation.
- The plug-compatibility concept was demonstrated by building one set of cryomodule from brought-in cavities and couplers of each laboratories.
- Several important issues were identified and improved right after the experiment.

# World Test Facility of ILC Main Linac

# ILC-Main Linac development facility in the world


FLASH@DESY



STF@KEK

ILCTA@FNAL

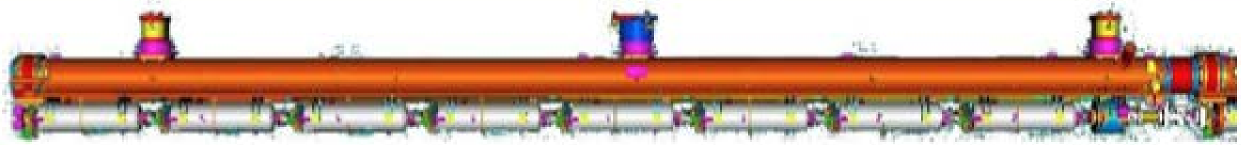
# FLASH accelerator for XFEL test stand

*FLASH Accelerator;*
*7 cryomodules,*
*1GeV SASE-FEL*
*(~6nm raising)*

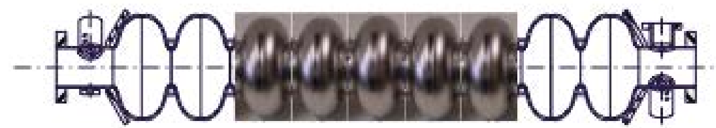
*Cryomodule Test Bench*

# Accelerator Complex 17.5 GeV Start-up Version

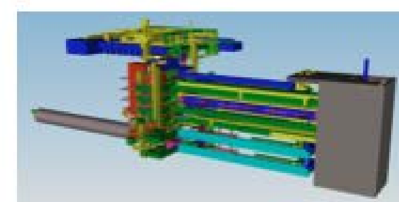
**100 accelerator modules**

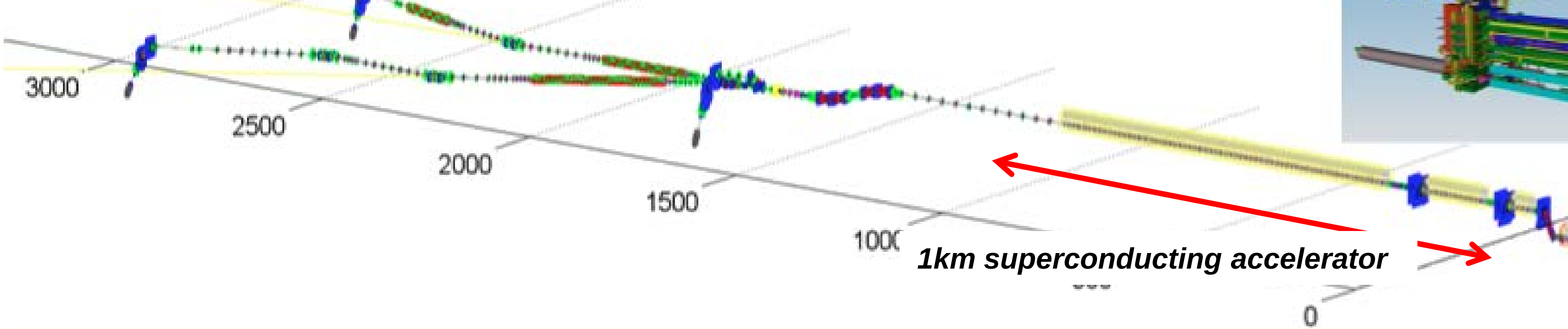


**800 accelerating cavities**
**1.3 GHz / 23.6 MV/m**




**25 RF stations**
**5.2 MW each**



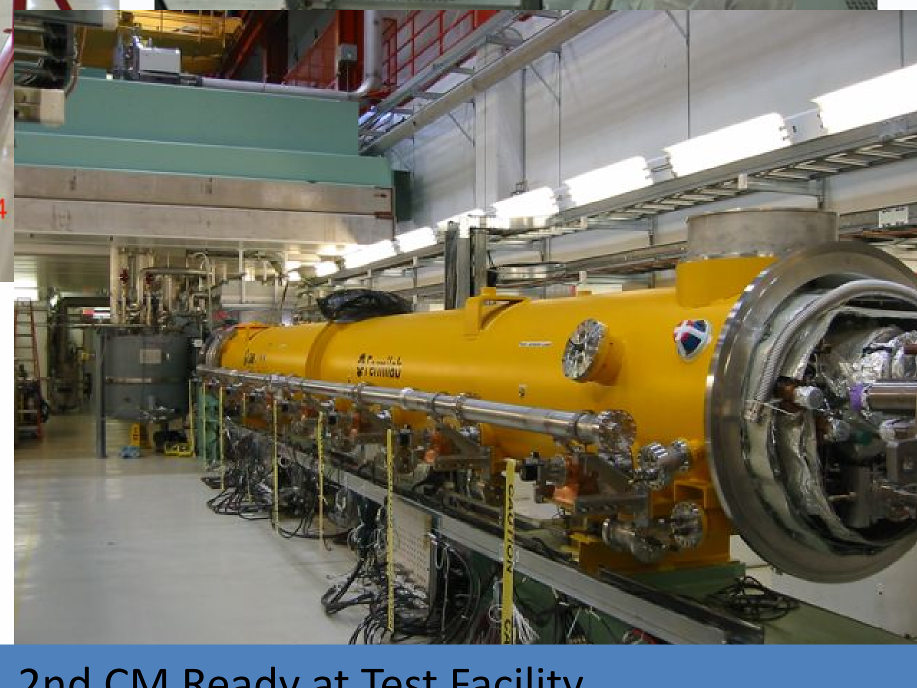


# Linac Tunnel: preparing the floor

**Tunnel is already completed.**
**The accelerator installation is going on in this two years.**

# FNAL  Cryomodule assembly facility


Cryomodule Assembly



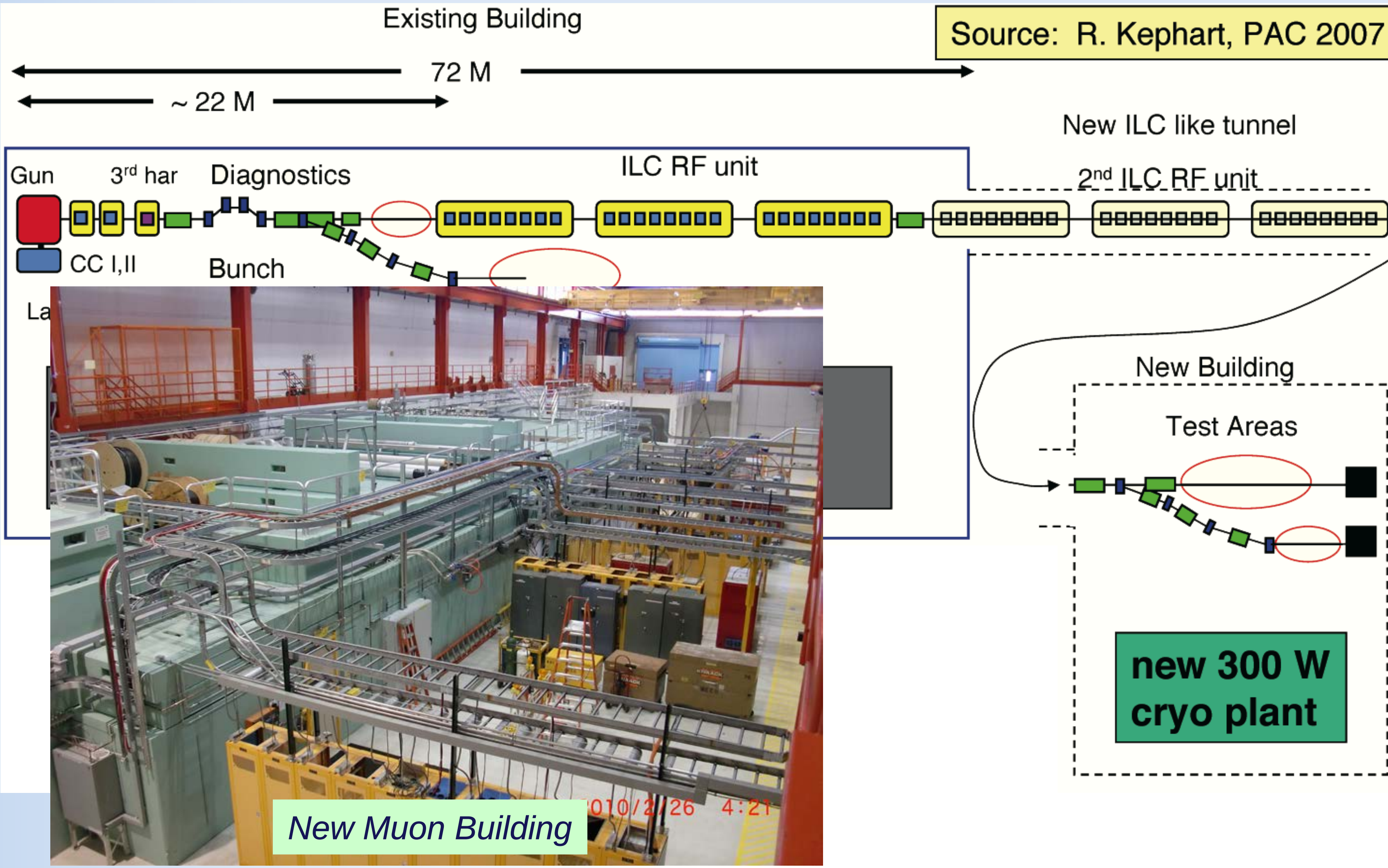
2nd CM Ready at Test Facility

***The first type III+ cryomodule is finished the test.***

***The second type III+ cryomodule is ready for test.***

# ILCTA-NML at FNAL

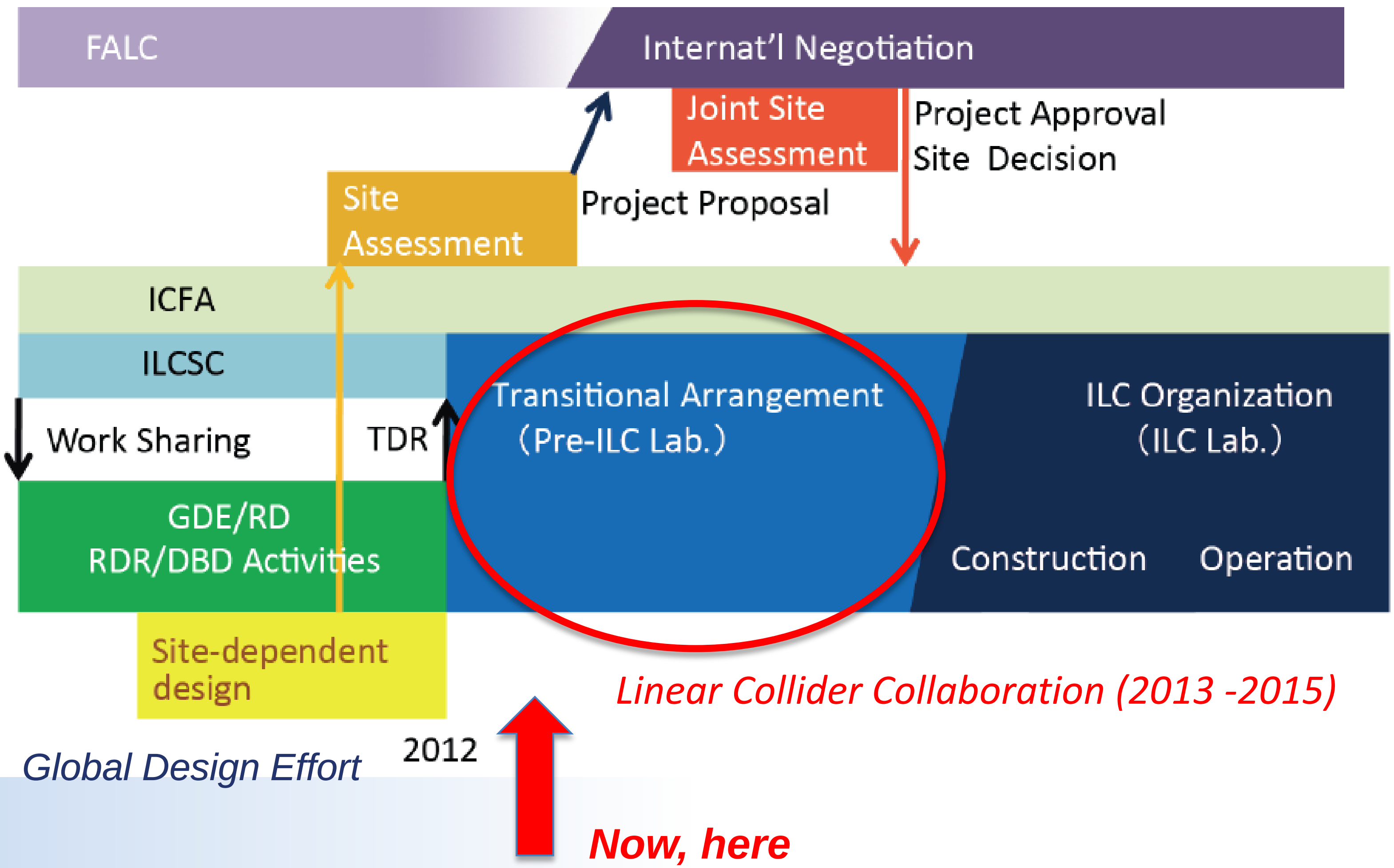
***200m Test Accelerator is now under construction***



***Prospect of ILC accelerator***

# Project Implementation Planning

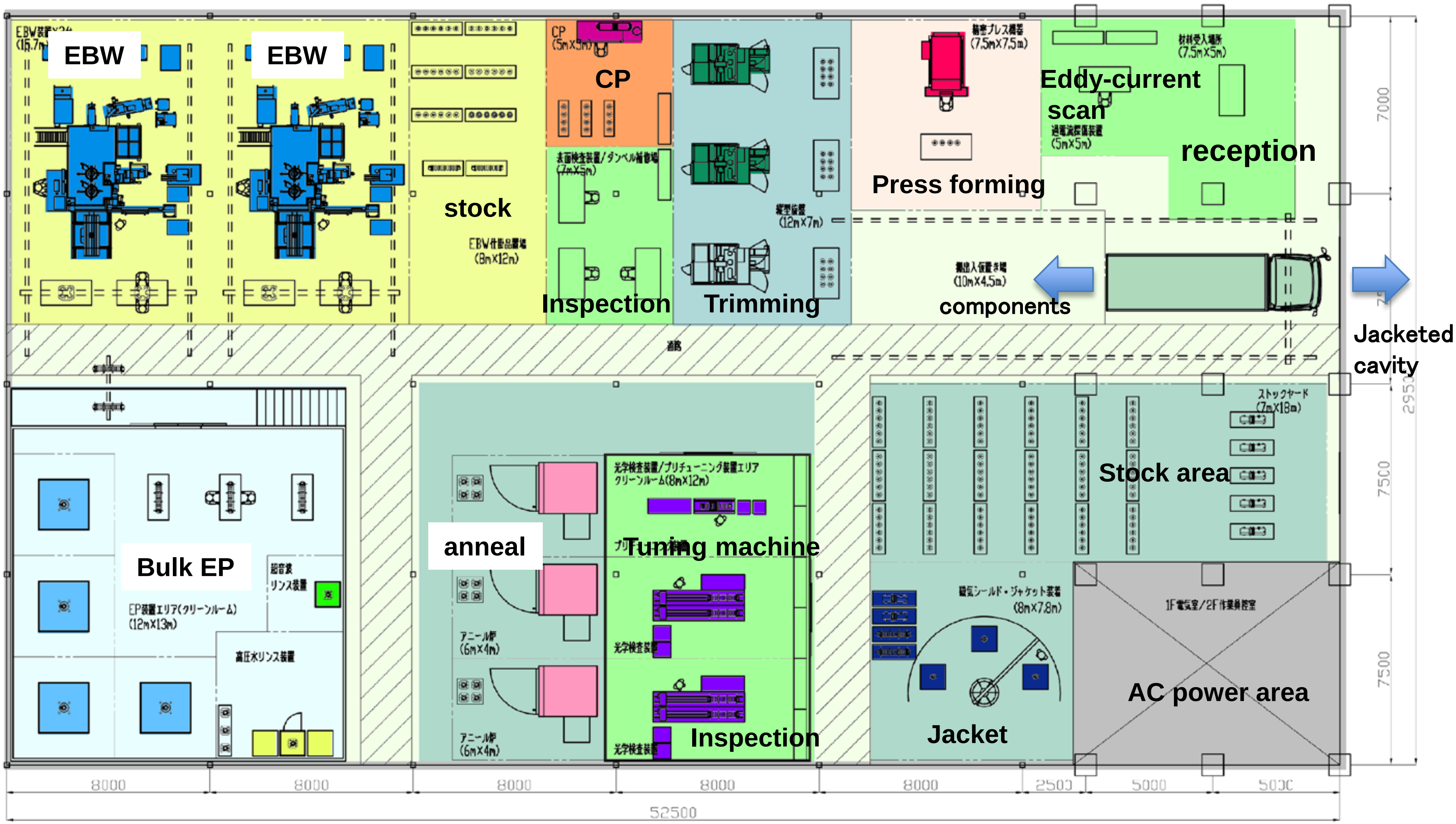
## Possible Roadmap to an ILC



# Study of Industrial plant of cavity mass-production



## Study of plant arrangement assuming existing building (53m x 30m)



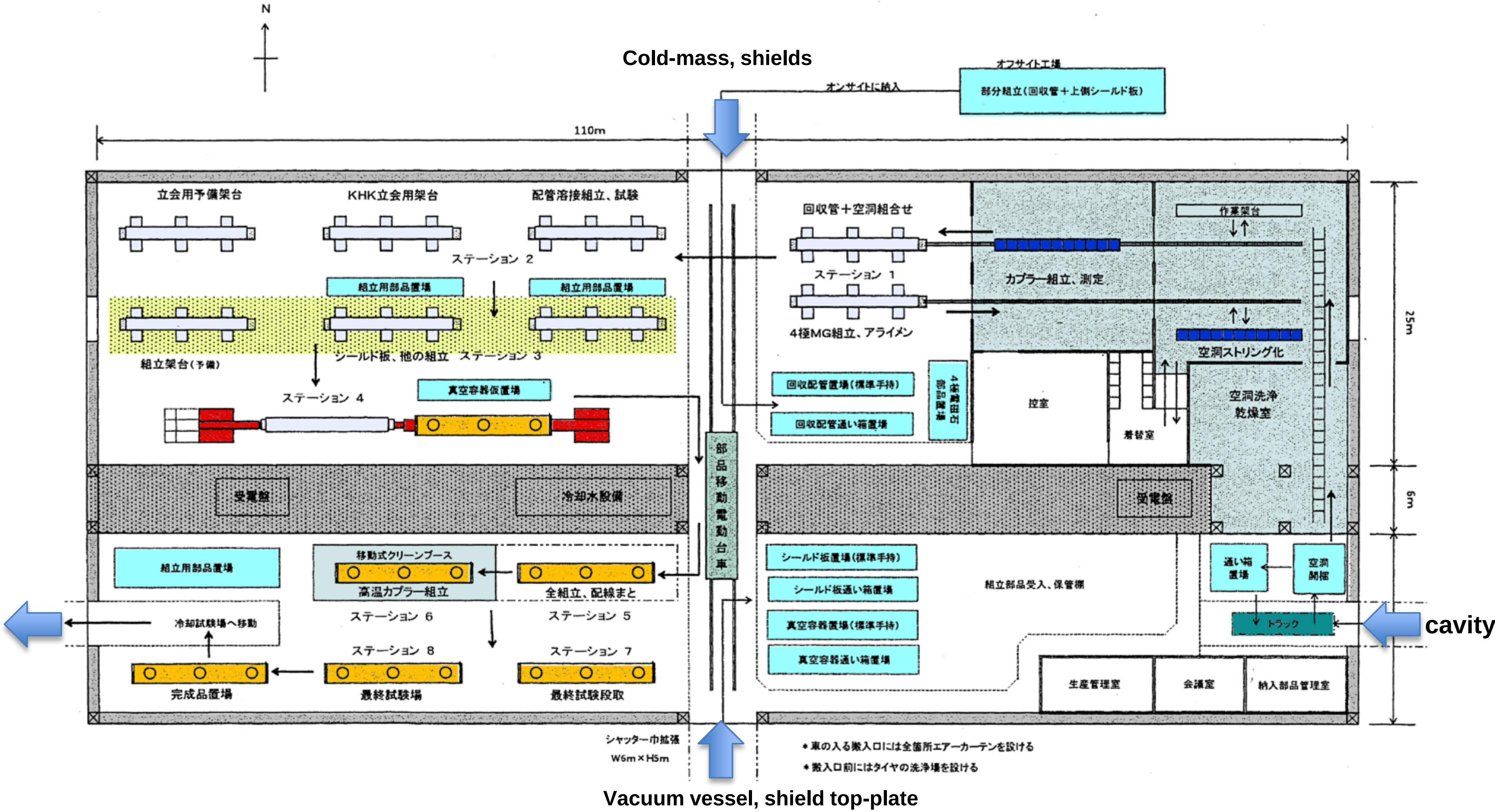

Nb plates and fabricated end-group parts are input
2 shifts/day for 200days/year work.
( about 30 people x 2 shifts/day )

Production capacity Max 530 cavity/year,
2650 cavities for 5 years (1/6 – 1/7 for ILC whole production)

Assuming final EP process and field test are done elsewhere.

# Study of Industrial plant of cryomodule assembly

## Study of plant arrangement assuming existing building (120m x 50m)




Tested cavity and fabricated parts are input
2 shifts/day for 200days/year work.
( about 37 people x 2 shifts/day )

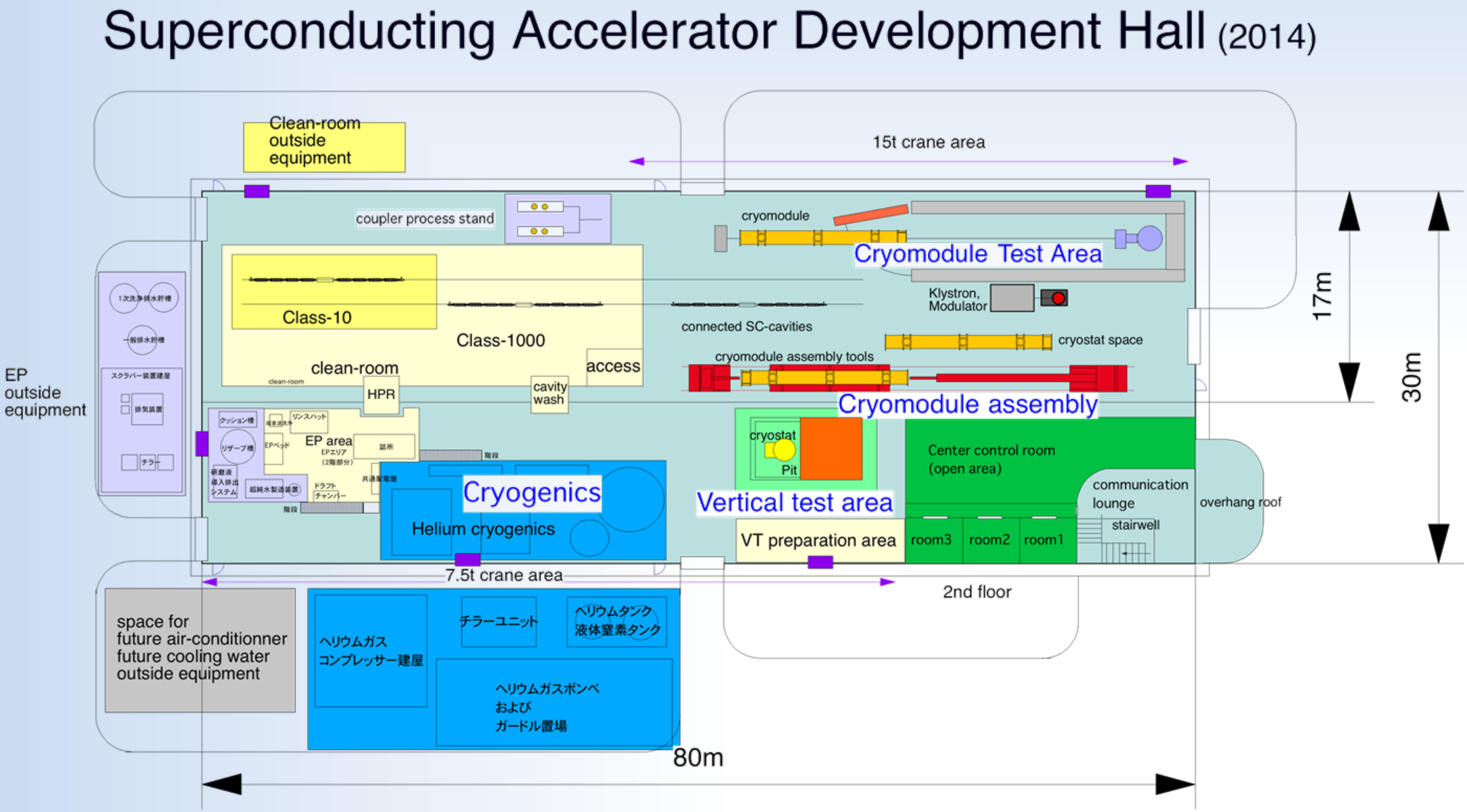
Production capacity Max 96 cryomodule/year,
480 cryomodule for 5 years (1/4 for ILC whole production)



Assuming cryomodule test is done elsewhere.

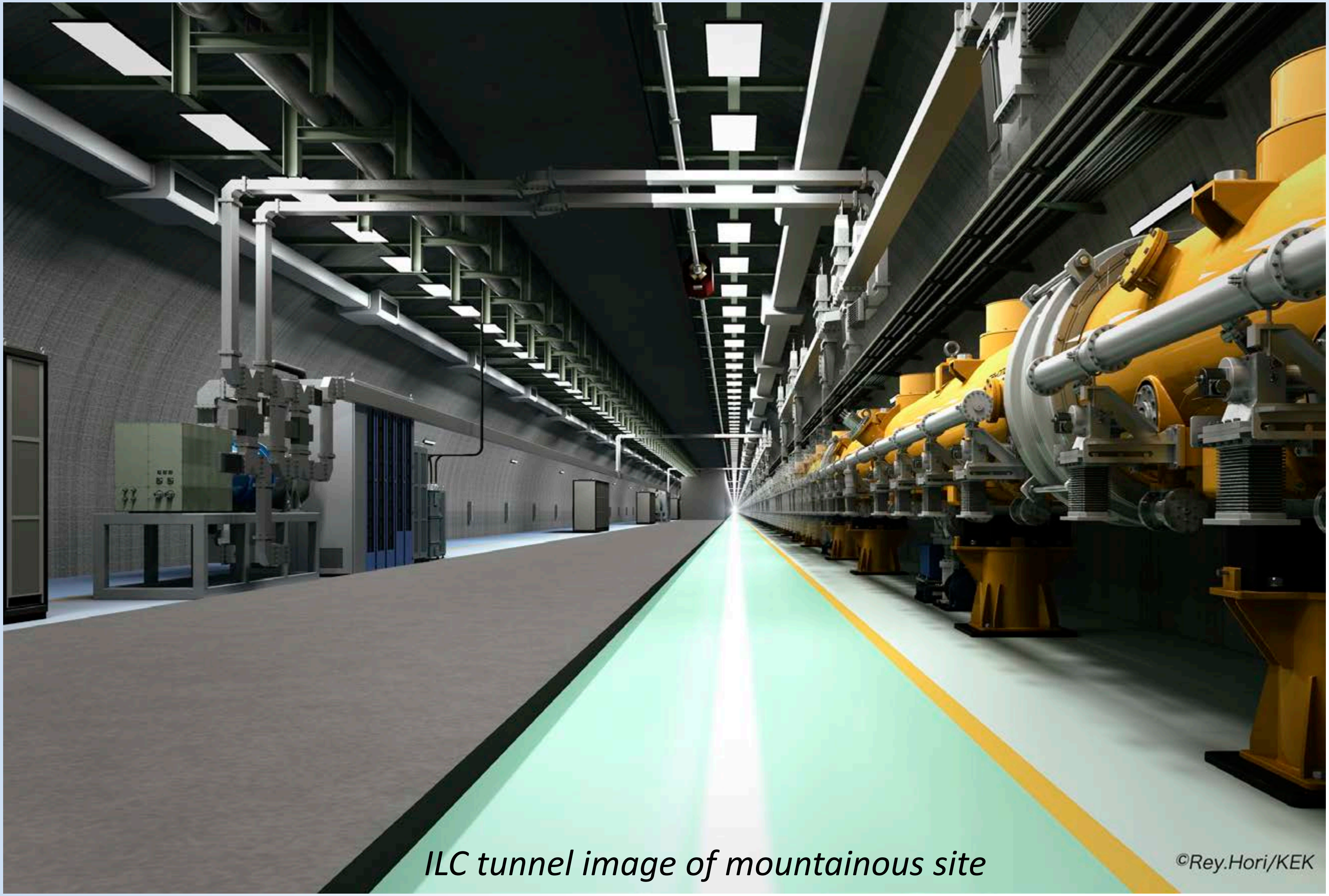
# Construction of facility : cavity & cryomodule test for ILC production

**New building (80m x 30m) to be completed in 2014 at STF north.**




**Cavity test equip. and Cryomodule test equip. development in KEK, followed to DESY test facility for Euro-XFEL.**

***Thanks to all the collaborator of ILC-GDE, LCC.***
***Hope to realize ILC, soon.***



*ILC tunnel image of mountainous site*

**End of slide**