International Linear Collider:

- Technical Status and Readiness -

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(KEK/LCC)

Presented at IAS Concerence, Hong Kong, 24 Jan., 2017

Outline

- **Introduction**
- **Technical Progress and Status**
  - Nano-beam technology
  - SRF technology
  - Civil engineering
- **Readiness for the Project**
  - Further effort for the cost reduction and the R&Ds
- **Summary**

ILC GDE to LCC

1980' ~ Basic Study

2004 | 2006 | '07 | '08 | '09 | '10 | '11 | '12 | '13 | '14 | '15 | '16 | '17

ILC-GDE

LCC

Ref. Design (RDR)

Selection of SC Technology

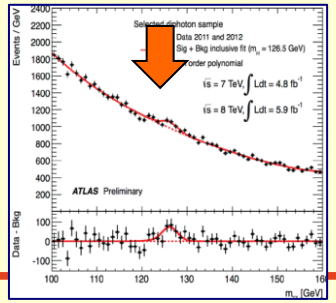
Technical Design Phase

TDP 2

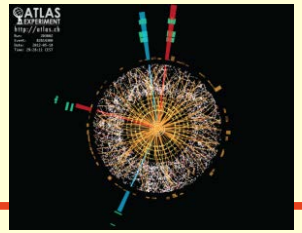
TDR publication

LHC

126 GeV

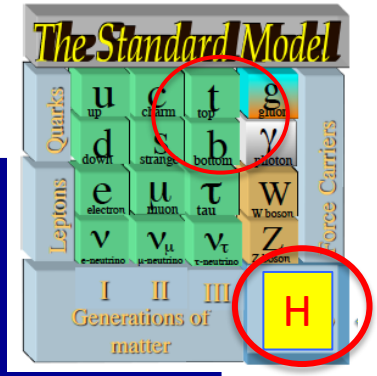


Higgs discovered



Important Energies in ILC

125 GeV Higgs discovery reinforcing the ILC importance



Integrated Luminosity (ab^{-1})

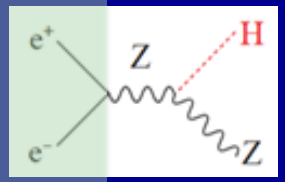
2

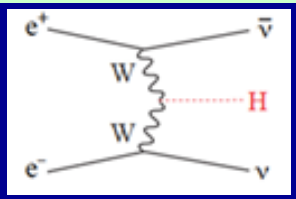
1

Physics confident:

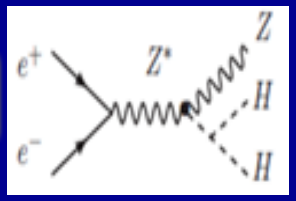
→ **Higgs** and **Top Quark**

- Learn "everything" about H (125)
- Probe dynamics of EWSB



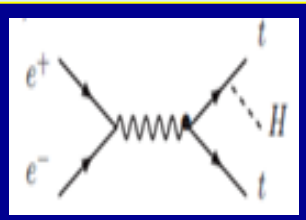


HHZ



New Physics beyond SM:

- Direct or indirect **DM searches**
- Evidence for BSM physics
- Hints of a new mass scale



HZ

$\bar{\nu}\nu H$

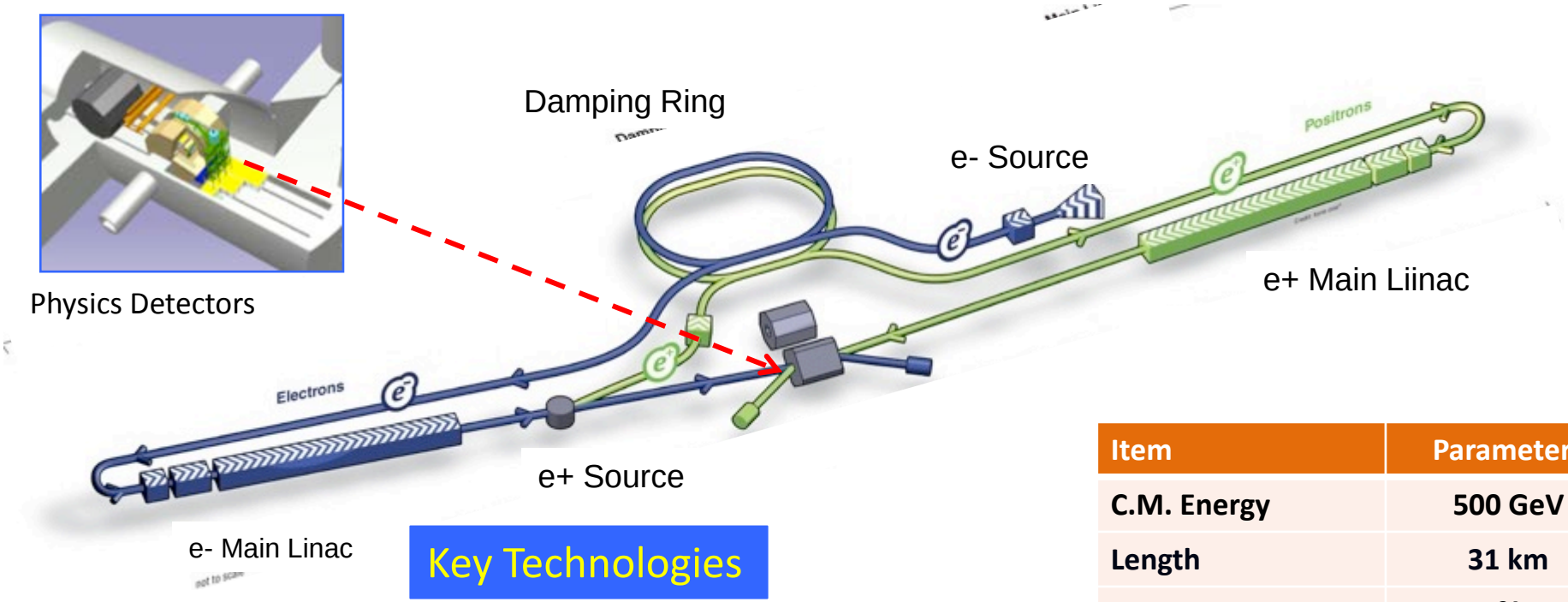
$t\bar{t}$

$t\bar{t}H$

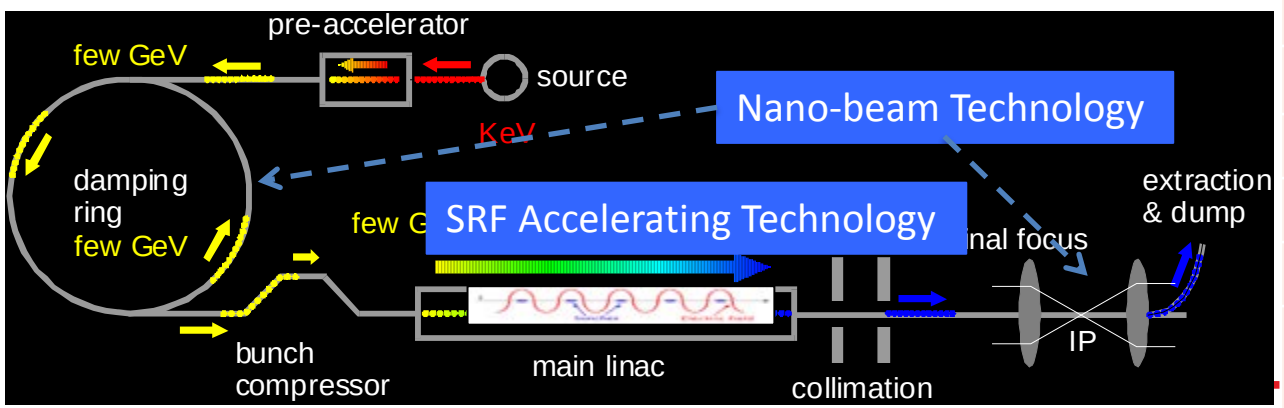
LEP reached→

200 300 400 500 600 E_{cm} (GeV)

ILC Acc. Design Overview (TDR)

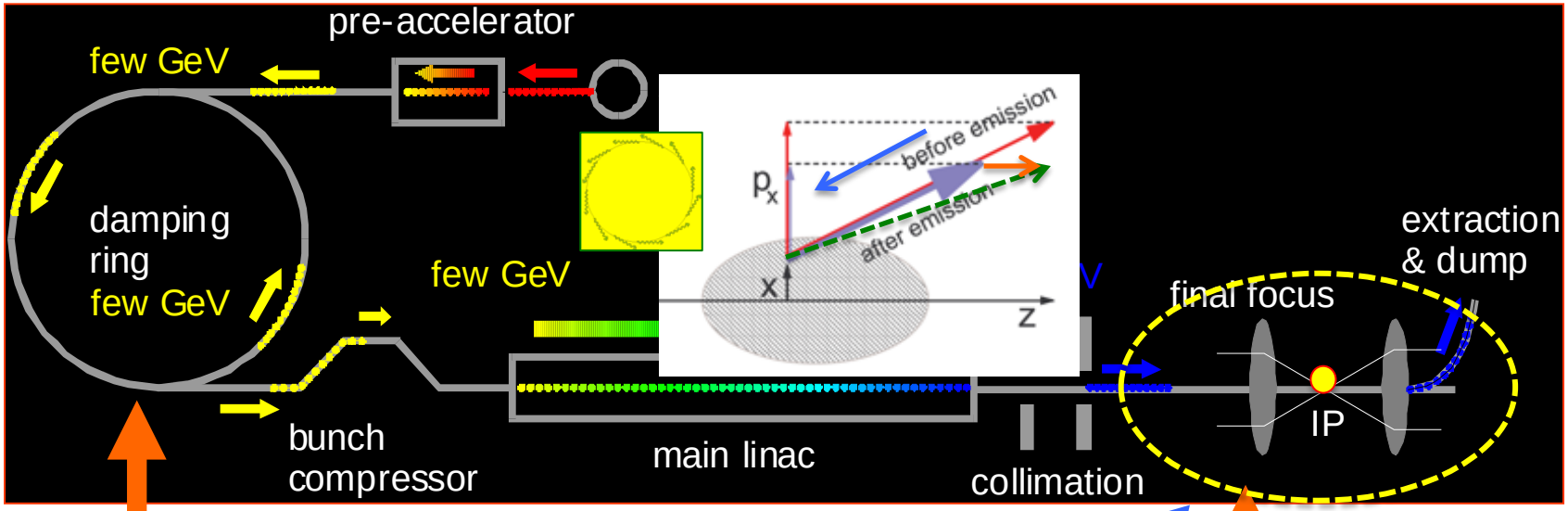


Key Technologies



Item	Parameters
C.M. Energy	500 GeV
Length	31 km
Luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Repetition	5 Hz
Beam Pulse Period	0.73 ms
Beam Current	5.8 mA
Beam size (y) at FF	5.9 nm
SRF Cavity G. Q_0	31.5 MV/m Q_0 = 1x10^{10}

Nano-beam Technology

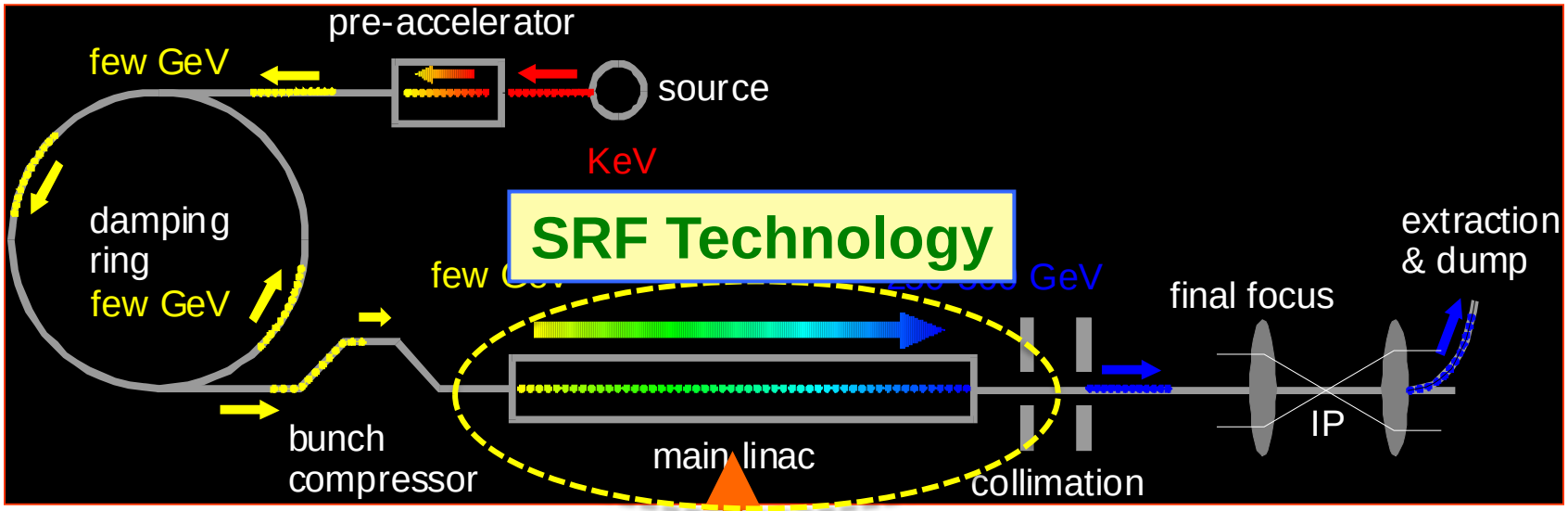


- Electron and Positron Sources (e-, e+) :
- Damping Ring (DR):
- Ring to ML beam transport (RTML) :
- Main Linac (ML) : SCRF Technology
- Beam Delivery System (BDS)

$$\mathcal{L} = f_{rep}\frac{n_b N^2}{4\pi\sigma_x^*\sigma_y^*} \times H_D$$

Nano-beam technology advanced by ATF Collaboration, hosted at KEK.

SRF Technology



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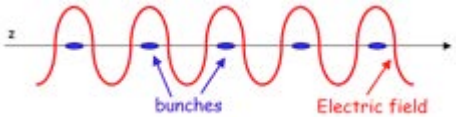
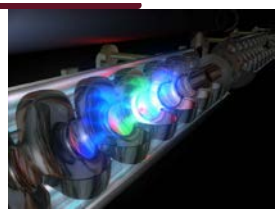


Advantage of Superconducting RF



- Ultra-high ($Q_0 = 10^{10}$):
  - small surface resistance → nearly zero power (heat) in cavity walls
- Long beam pulses (~1 ms)
  → intra-pulse feedback
- Larger aperture
  - → better beam quality w/ larger aperture - lower wake-fields
- Work necessary on engineering for:
  - Cryomodule (thermal insulation)
  - Cryogenics

Luminosity:

RF efficiency

RF power / beam current

$$L \propto \frac{\eta P_{RF}}{E_{CM}} \sqrt{\frac{\delta_{BS}}{\varepsilon_y}}$$

Vertical emittance (tiny beams)

- Luminosity proportional to RF efficiency ILC
  - ~160MW @ 500GeV
- Capable of efficiently accelerating high beam currents
- Low impedance aids preservation of high beam quality (low emittance)

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- SRF technology
- Civil engineering

Readiness for the Project

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Summary

Progress in Acc. Technology for the ILC, in ~ 2016

Two Key Technologies matured for the project realization !

- **Nano-beam Technology :**

  KEK-ATF2: FF **beam size (v)**: 41 nm at 1.3 GeV (to go 37nm, equiv. to 6 nm at ILC)

- **SRF Technology :**

  European XFEL: SRF Cavity completion, 100% (800) reaching <G> = ~ 30 MV/m.

  – Cryomodule (CM), 100% (100) reaching <G> =~28 MV/m

  – Installation into acc. Tunnel completed, and cool-down just started,

  Fermilab : CM (8 cavity string) reaching ILC gradient: <G> > 31.5MV/m

  – **New Surface process "N2 Infusion" demonstrated for High-Q and High-G**

  KEK: CM (8-cavity string) reaching : <G> > 31 MV/m

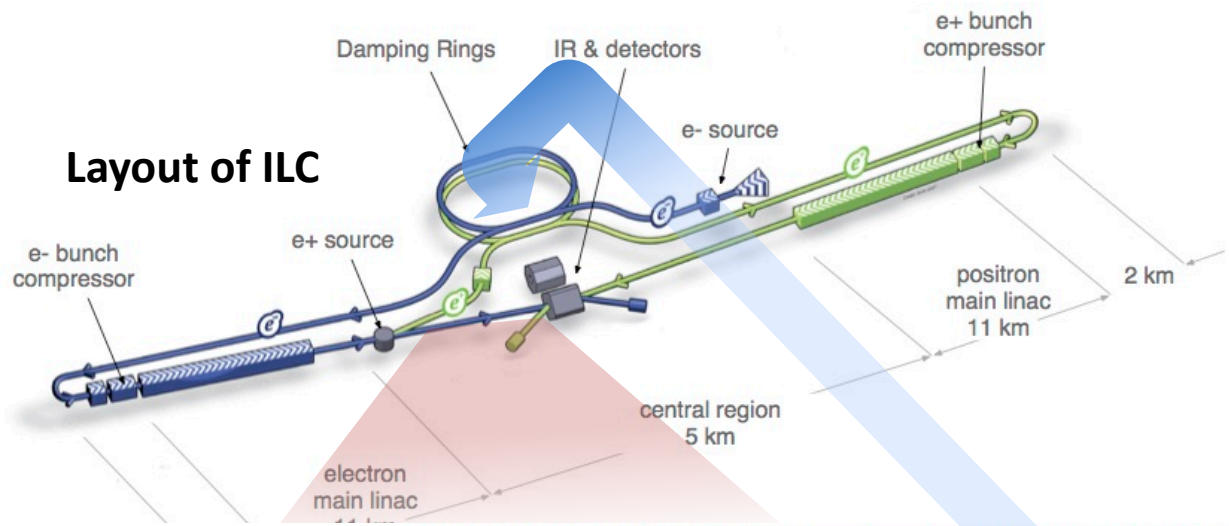
  US-Japan: Cost Reduction R&Ds started, reflecting recent technical advances

Issue and Prospect:

- Cost-reduction to start the project with the staging at C.E. 250 GeV, Higgs Factory, is to be studied, in addition to the cost-reduction R&D efforts

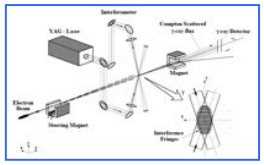
ATF/ATF2: Accelerator Test Facility

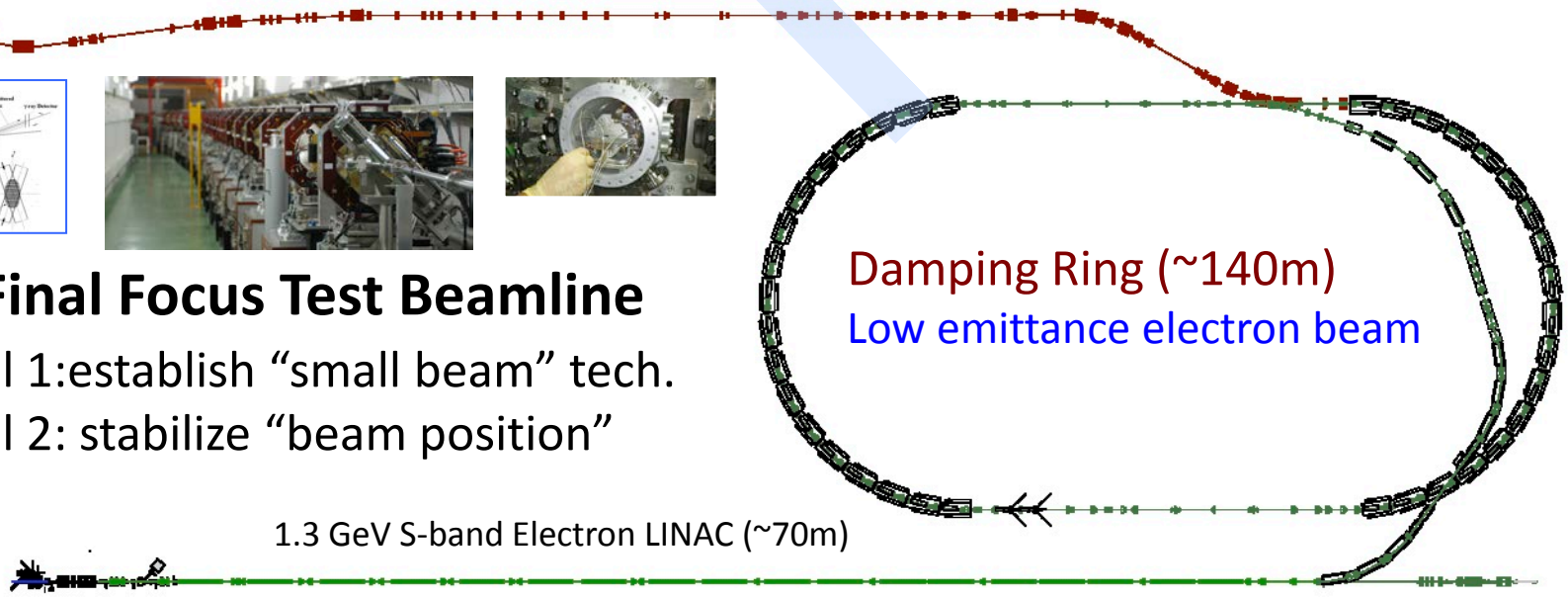
N. Terunuma



To develop the nanometer beam technologies for ILC

- Key for the luminosity
- 6 nm beam at IP (ILC)





ATF2: Final Focus Test Beamline

Goal 1:establish “small beam” tech.

Goal 2: stabilize “beam position”

- ATF International Collaboration -

relatively independent R&D teams

欧州原子核研究機構(CERN)
ドイツ(Germany)
- 電子シンクロトロン研究所(DESY)

フランス(France)
- IN2P3; LAL, LAPP, LLR

イギリス(UK)
- Univ. of Oxford
- Royal Holloway Univ. of London
- STFC, Daresbury
- Univ. of Manchester
- Univ. of Liverpool
- Univ. College London

イタリア(Italy)
- INFN, Frascati

スペイン(Spain)
- IFIC-CSIC/UV

ロシア(Russia)
- Tomsk Polytechnic Univ.

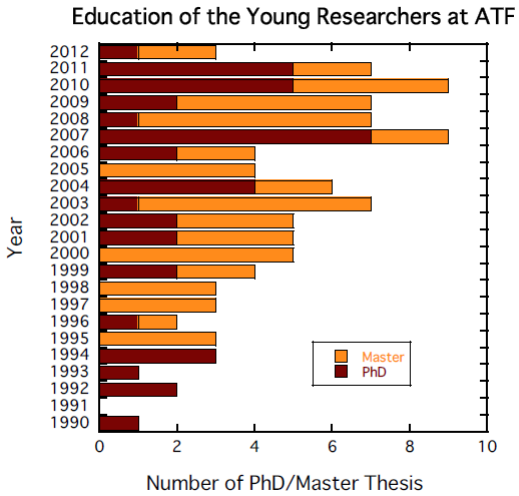
アメリカ(USA)
- SLAC国立加速器研究所
- ローレンス・バークレー国立研究所(LBNL)
- フェルミ国立加速器研究所(FNAL)
- ローレンス・リバモア国立研究所(LLNL)
- ブルックヘブン国立研究所(BNL)
- コーネル大学(Cornell Univ.)
- ノートルダム大学(Notre Dome Univ.)

日本(Japan)
- 高エネルギー加速器研究機構(KEK)
- 東北大学 (Tohoku Univ.)
- 東京大学 (Univ. of Tokyo)
- 早稲田大学(Waseda Univ.)
- 名古屋大学(Nagoya Univ.)
- 京都大学 (Kyoto Univ.)
- 広島大学 (Hiroshima Univ.)

中国(China)
- 中国科学院高能物理研究所(IHEP)

韓国(Korea)
- ポハン加速器研究所(PAL)
- キョンプク大学(KNU)

インド(India)
- Raja Ramanna Centre for Advanced Technology



Progress in FF Beam Size and Stability at ATF2

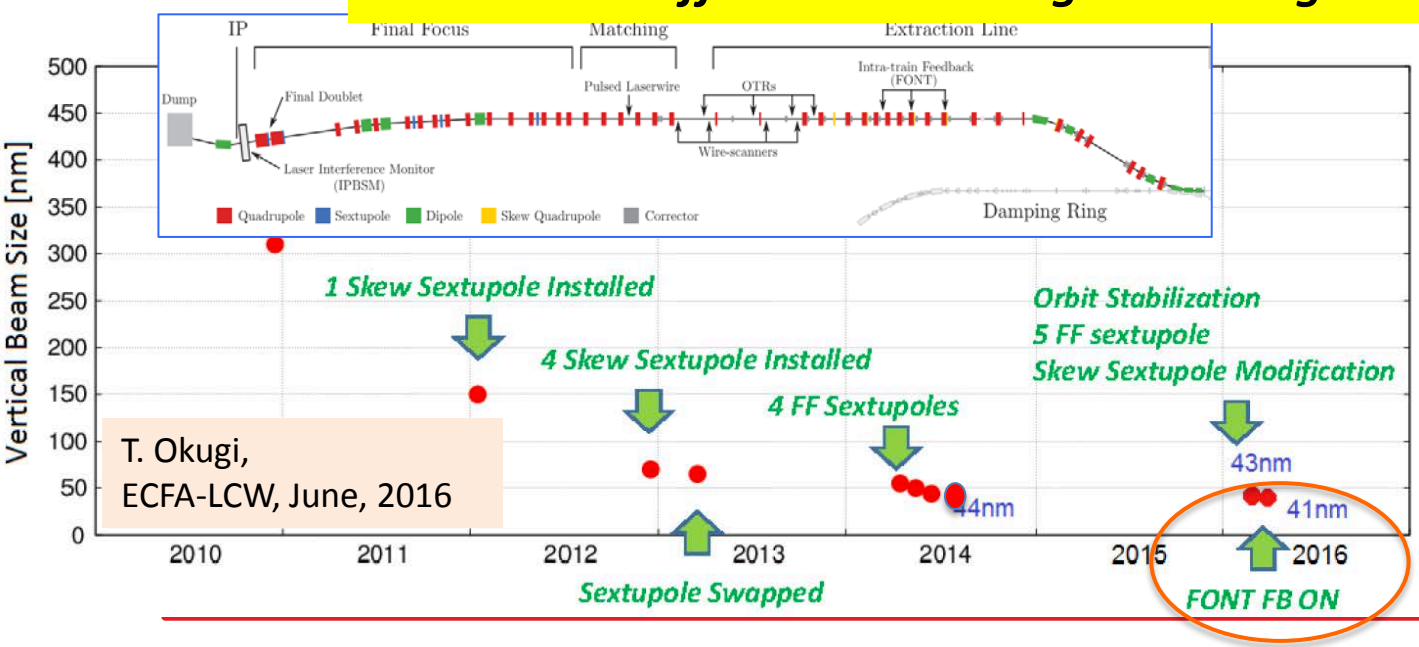
Goal 1:
Establish the ILC final focus method with same optics and comparable beamline tolerances

- ATF2 Goal : **37** nm → ILC **6** nm
  - Achieved **41** nm (2016)

Goal 2:
Develop a few nm position stabilization for the ILC collision by feedback

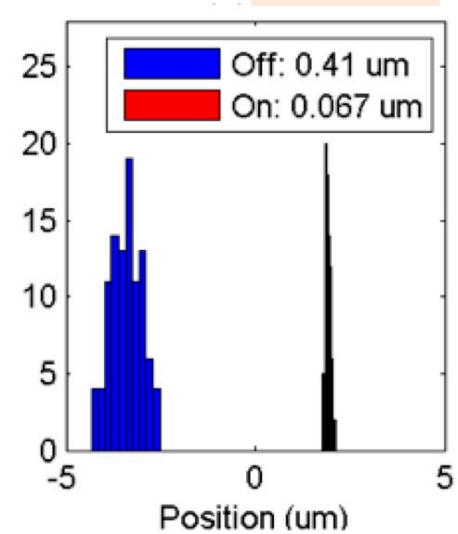
- **FB latency 133 nsec achieved**
  (target: < 300 nsec)
- **positon jitter at IP: 410 → 67 nm (2015)**
  (limited by the BPM resolution)

We continue efforts to achieve goal 1 and goal 2.



T. Okugi,
ECFA-LCW, June, 2016

K. Kubo



History and Progress in SRF Technology

T. Furuya

50 years after SC discovery.

1965 HEPL (Stanford U.), S-band. 3-cell, Pb plated cavity
Beam acceleration up to 1mA

1978 ATLAS (Argonne NL), Heaviy Ion Acc. with CW SRF

1988 TRISTAN (KEK)
509 MHZ、5-cell, x32 cavity, 5 MV/m, 200 MV
LEP-II (CERN), 352 MHz、4-cell x300 →3 GV

1990 Plan for TESLA (TeV Energy SC Linear Accelerator)。
TDR (2001)

1995 CEBAF (TJNAF) , 1.5 GHz ,5 -cell, 336 cavities
CW-4GeV,1mA。

1997 CESR (Cornell), KEKB (KEK)

2004: ILC: SC technology selected
1.3 GHz, 31.5MV/m (pulse)

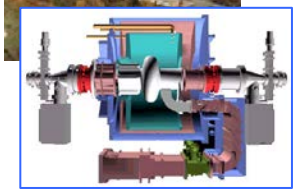
2016 EURO-XFEL (TESLA type :pulse, 23.6MV/m)

TBD realization of ILC








Major Accelerators Under Construction

2010 ~

Project	Notes	# cavities
CEBAF-JLAB (US)	Upgrade 6.5 GeV => 12 GeV electrons	80
XFEL-Hamburg (EU)	18 GeV electrons – for Xray Free Electron Laser – Pulsed)	840
LCLS-II – SLAC (US)	4 GeV electrons –CW XFEL (Xray Free Electron Laser)	300
SPIRAL-II (France)	30 MeV, 5 mA protons -> Heavy Ion	28
FRIB – MSU 8US)	500 kW, heavy ion beams for nuclear astrophys	340
ESS (Sweden)	1 – 2 GeV, 5 MW Neutron Source ESS - pulsed	150
PIP-II–Fermilab (US)	High Intensity Proton Linac for Neutrino Beams	115
ADS- (China, India)	R&D for accelerator drive system	> 200
Globally Int. Effort		> 2000

Global SRF Collaboration

Europian Collab.

Asian Collab.

America(s) Collab.

European XFEL: SRF Completed

Media.xfel.au, Dec. 2015

Progress:

2013: Construction started

2015: SRF cav. (100%) completed

CM (70%) progressed

Further Plan:

2016: E- XFEL acc. completion

2016/E: E-XFEL beam to start

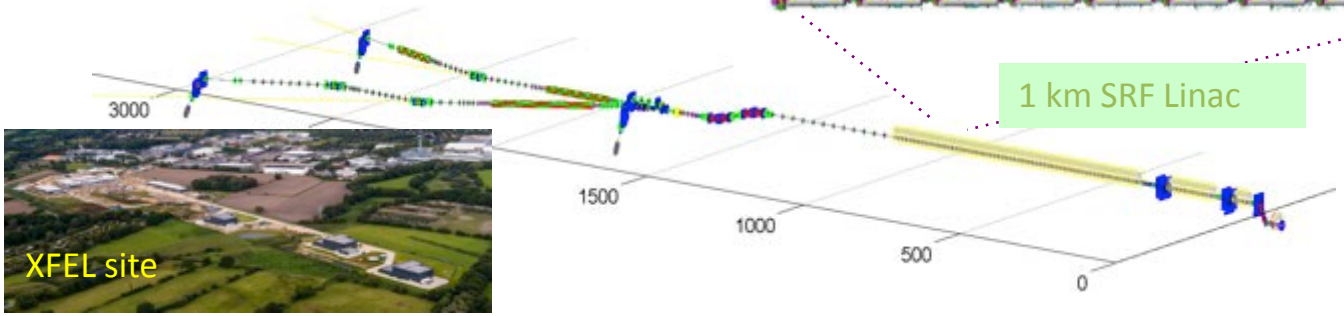
Acc. : ~ 1/10 scale to ILC-ML

SRF system: ~ 1/20 scale to ILC-SRF

1.3 GHz / 23.6 MV/m

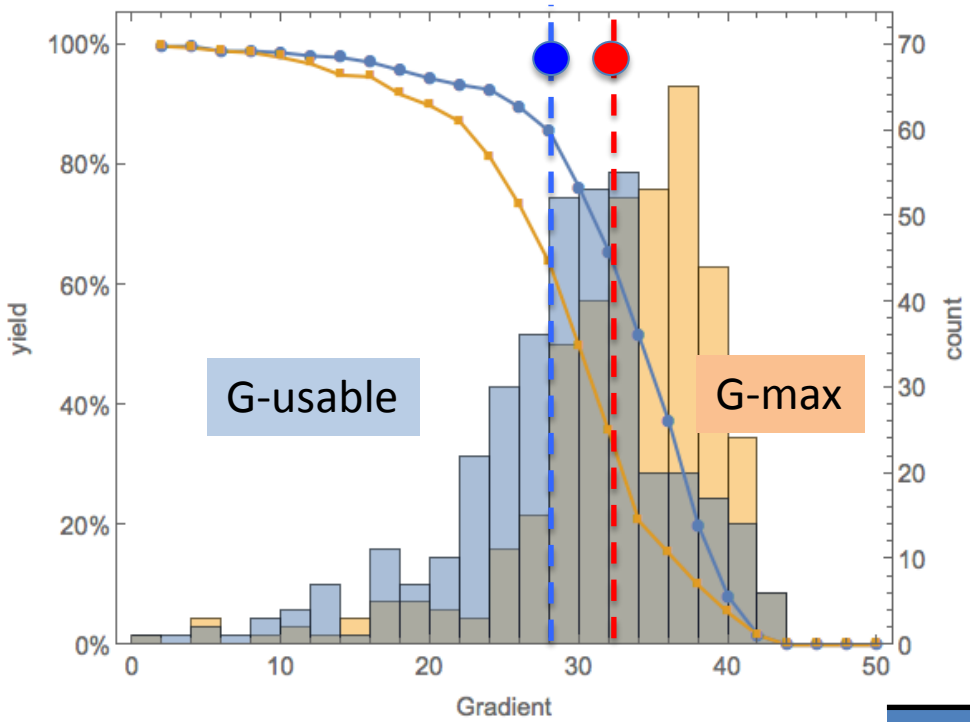
800+4 SRF acc. Cavities

100+3 Cryo-Modules (CM)



N. Walker, D. Reschke, SRF'15

E-XFEL: SRF Cavity Performance (as received)



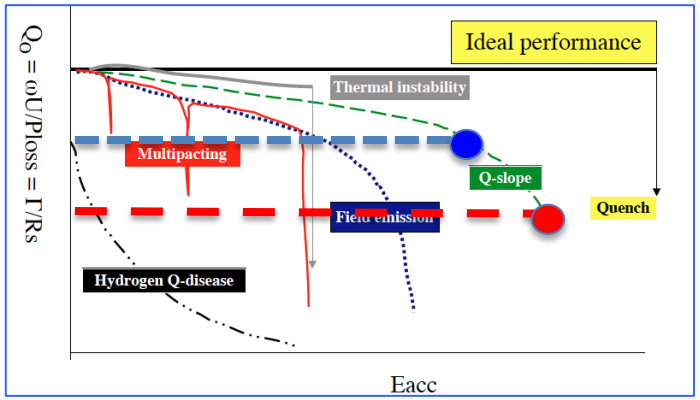
SRF cavity production/test ;

 # RI Cavities, 373 (as of Sept. 2015)

- Final process: 40 μm EP.
  - w/ same recipe to ILC-SRF's
- Tested at DESY-AMTF

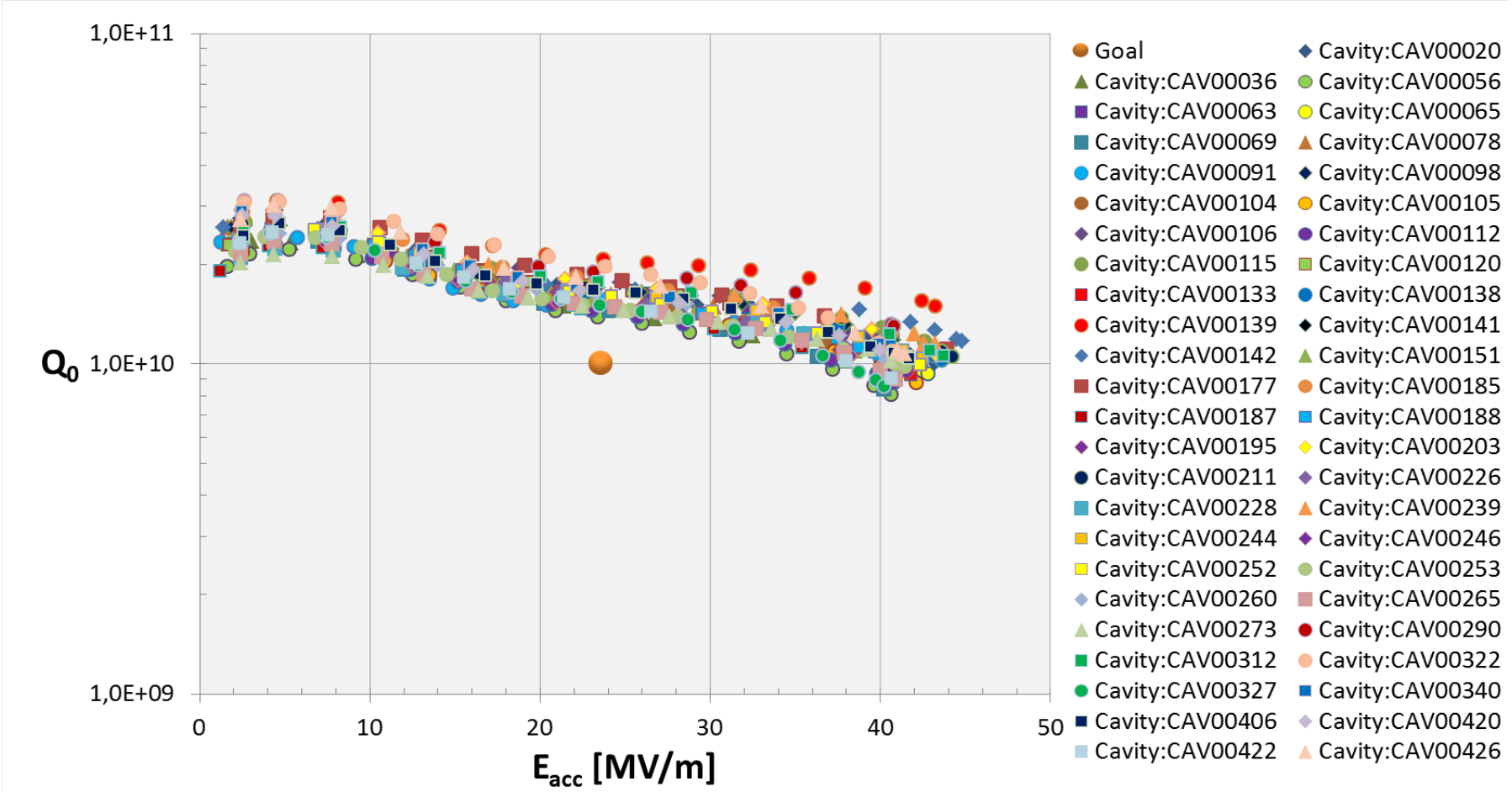
Notes::

- "Ultra-pure water rinsing as the 2nd process improving the gradient performance (> ~10%) for lower-performed cavities (not shown here).

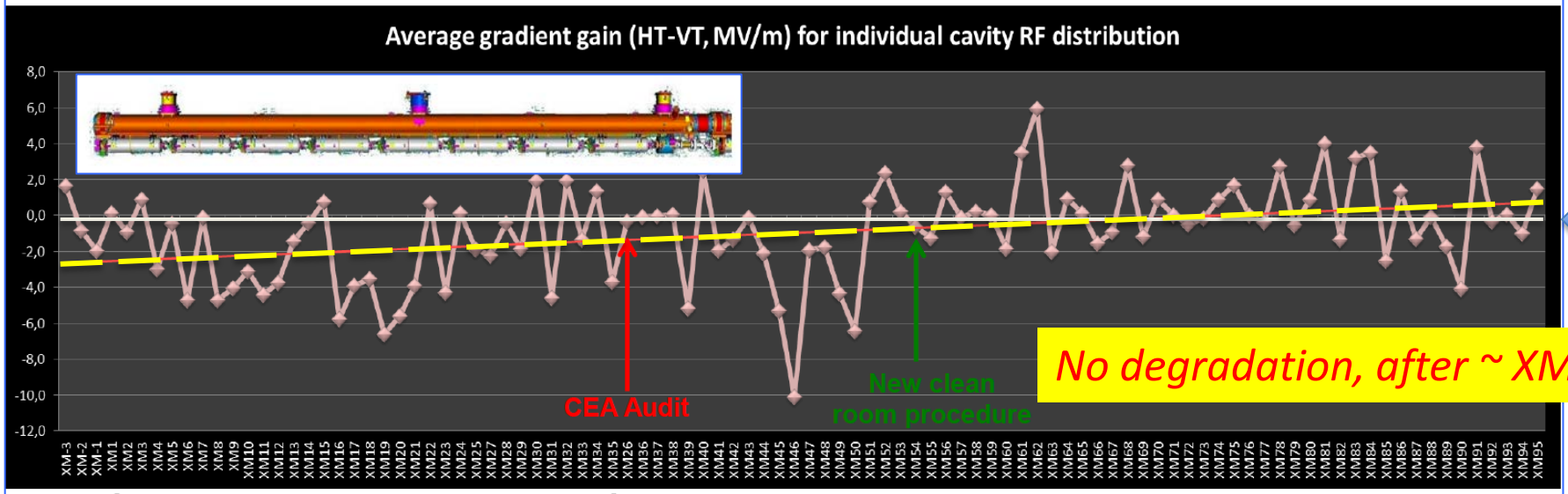


	G-usable ($Q_0 > 10^{10}$)	G-max	(ILC)
<G> MV/m	29.4	33	(35)
Yield at 28MV/m	66%	86%	(90%)

47 of 420 (> 10%) of RI cavity production exceed 40 MV/m



Cryomodule Performance: VT vs. MT



No degradation, after ~ XM54

1st sample of 34 series CM
ΔE_{op} = -2.1 MV/m

2nd sample of 19 series CM
ΔE_{op} = -1.7 (-0.9) MV/m

last 42 series CM
ΔE_{op} =+0.4 MV/m

- Significant gradient degradation from XM6 to XM23, while CEA and Alsyom put all their effort in achieving production goal of 1 CM/week: an audit of string and module assembly was conducted by CEA on XM26
- A simplification of the clean room procedures was introduced at XM54: **no degradation after**

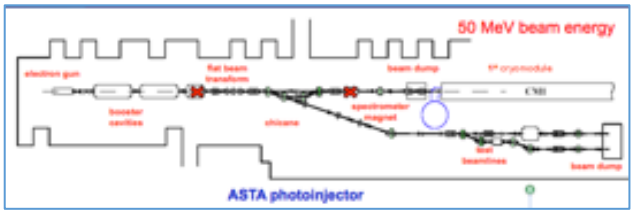
Fermilab : CM2 reached <31.5 MV/m >

CERN Courier December 2014

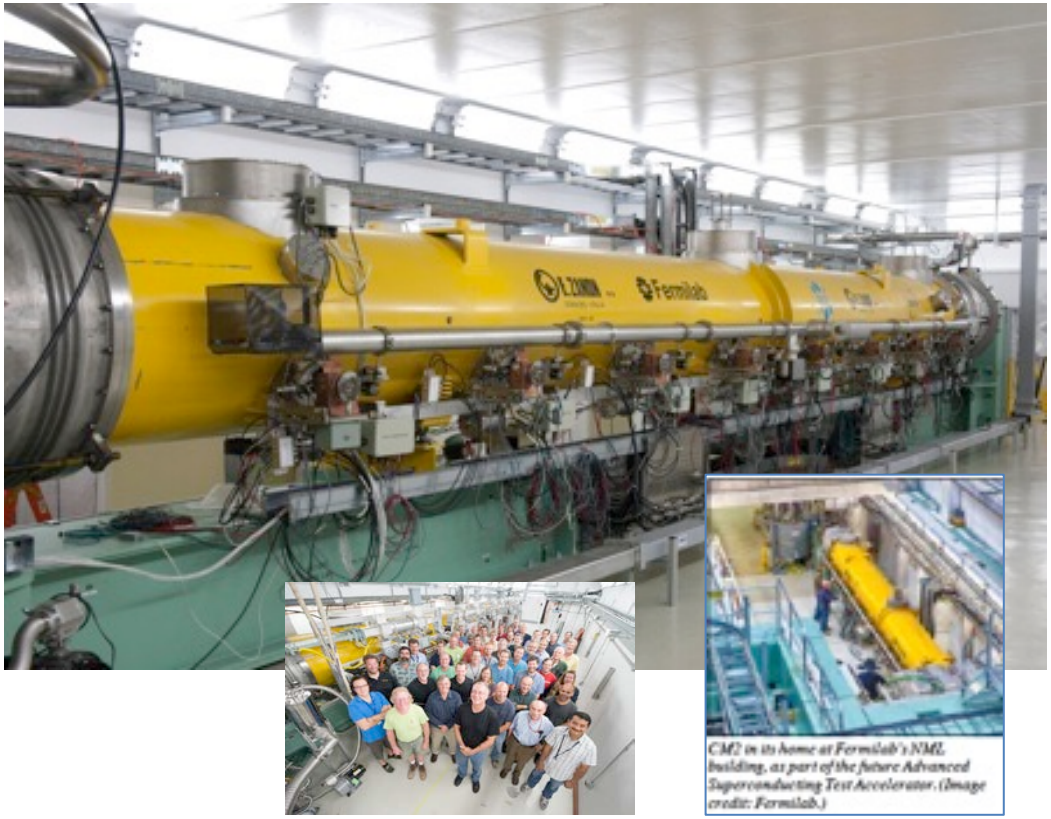
ACCELERATORS

ILC-type cryomodule makes the grade

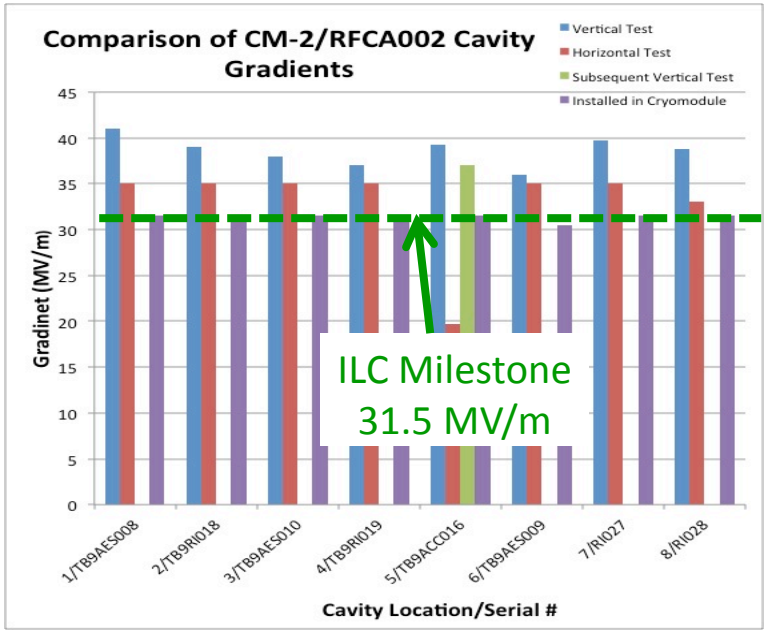
For the first time, the gradient specification of the International Linear Collider (ILC) design study of 31.5 MV/m has been achieved on average across an entire ILC-type cryomodule made of ILC-grade cavities. A team at Fermilab reached the milestone in early October. The cryomodule, called CM2, was developed to advance superconducting radio-frequency technology and infrastructure at laboratories in the Americas region, and was assembled and installed at Fermilab after initial vertical testing of the cavities at Jefferson Lab. The milestone – an achievement for scientists at Fermilab, Jefferson Lab, and their domestic and international partners in superconducting radio-frequency (SRF) technologies – has been nearly a decade in the making, from



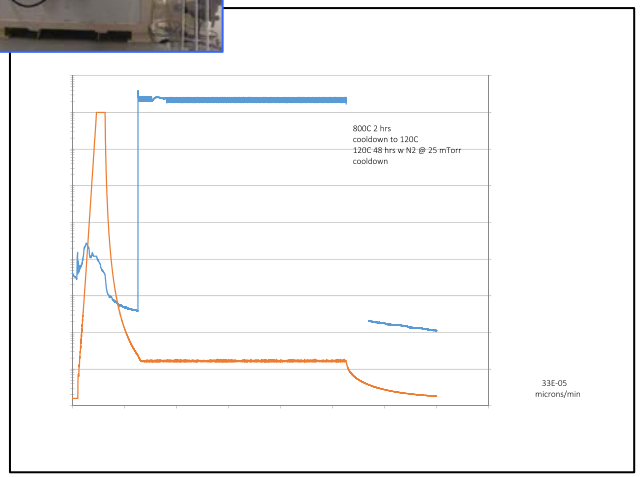
Cryomodule test at Fermilab reached < 31.5 > MV/m, exceeding ILC specification



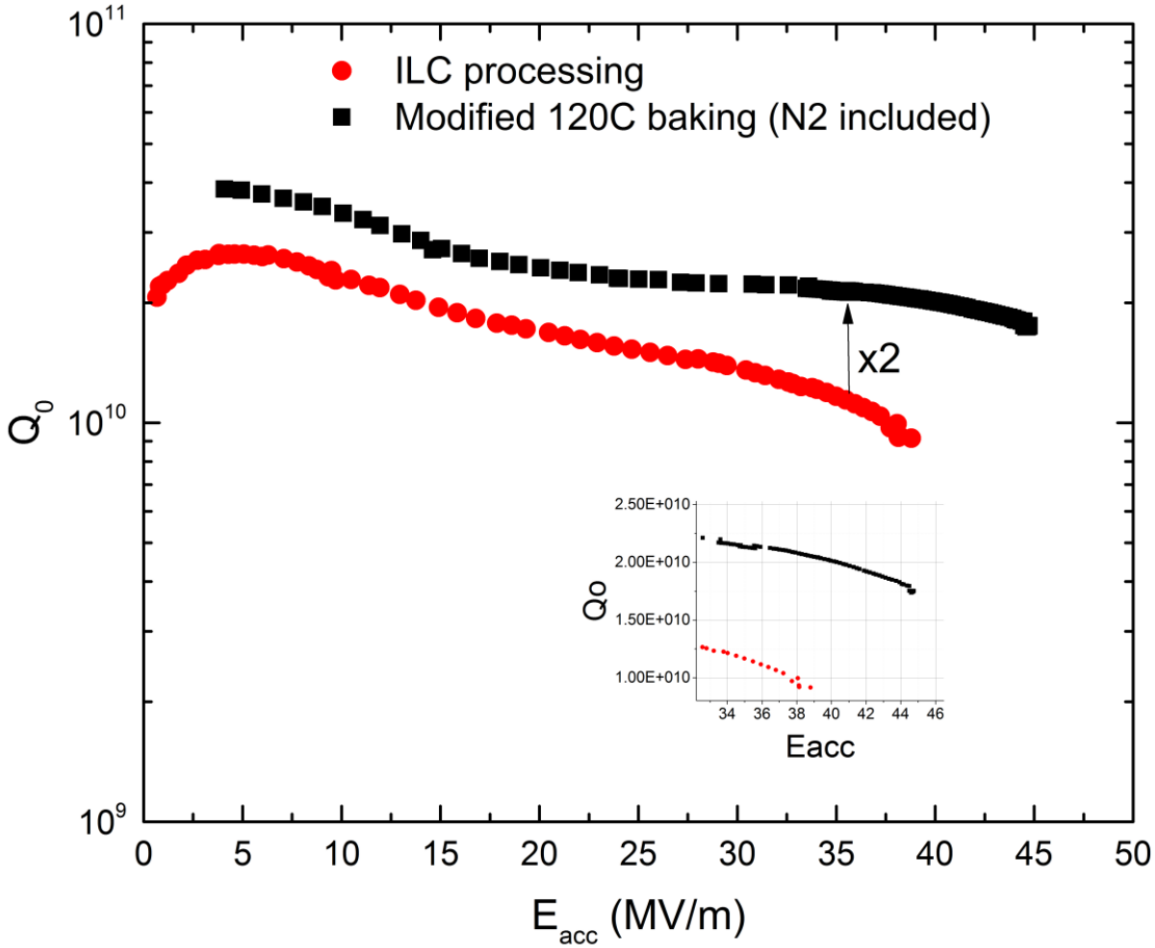
CM2 in its home at Fermilab's NML building, as part of the future Advanced Superconducting Test Accelerator. (Image credit: Fermilab.)



New Surface Process recently demonstrated at Fermilab, "N_2 Infusion at 120 C"



- N2 infusion at 120 C directly after heat treatment at 800 C,
- Same cavity, sequentially processed, no EP in b/w
- Achieved: 45.6 MV/m
  Q at ~ 35 MV/m : ~ 2.3e10



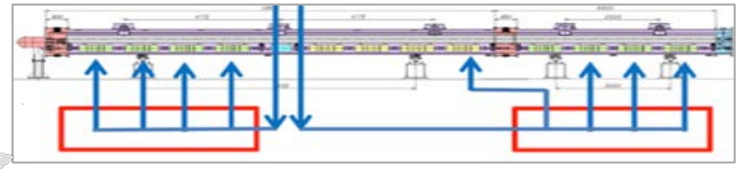
Y. Yamamoto, E. Kako, H. Hayano

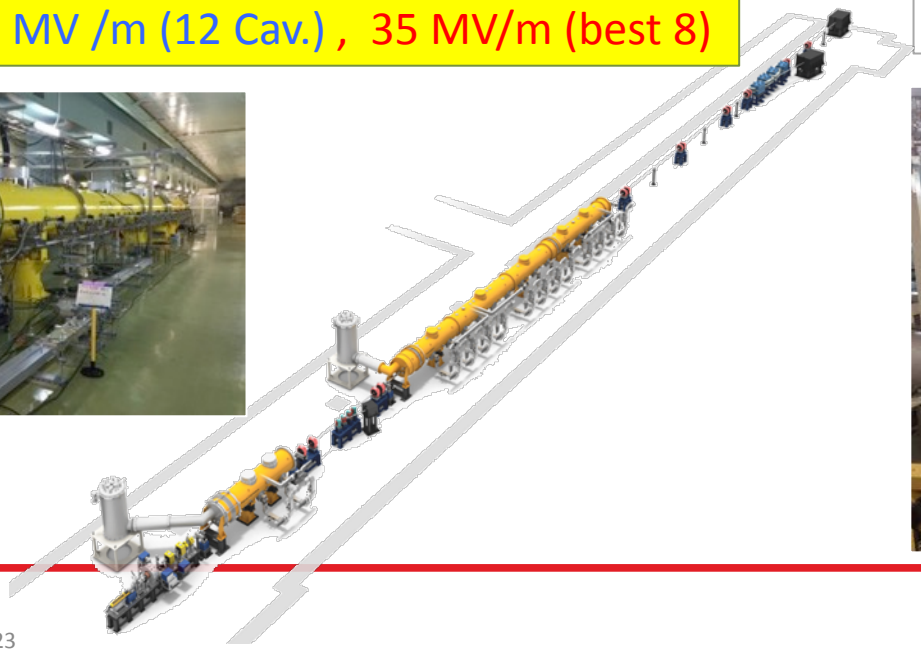
KEK-STF: Cavity/CM Performance, and RF and Beam Test Preparation

SRF cavity Gradient (MV/m) before/after CM Assembly												
Module	CM1a				CM1b				CM2a			
Cav. #	1	2	3	4	5	6	7	8	9	10	11	12
V. Test (CW)	37	36	38	36	37	35	39	36	12	36	32	32
in CM (pulse)	**39**	**37**	**35**	**36**	26	16	26	**32**	18	**34**	**33**	**32**
	Gradient stable				Degraded				Gradient stable			

*<G> : 30 MV /m (12 Cav.) , 35 MV/m (best 8)

FY14: CM1+CM2a (8+4) assembly
FY15: Cavity individually tested in CM
RF power system in preparation
FY16: **8-cavity** string to be RF tested
FY17: Beam Acceleration expected
(to reach > 250 MeV)

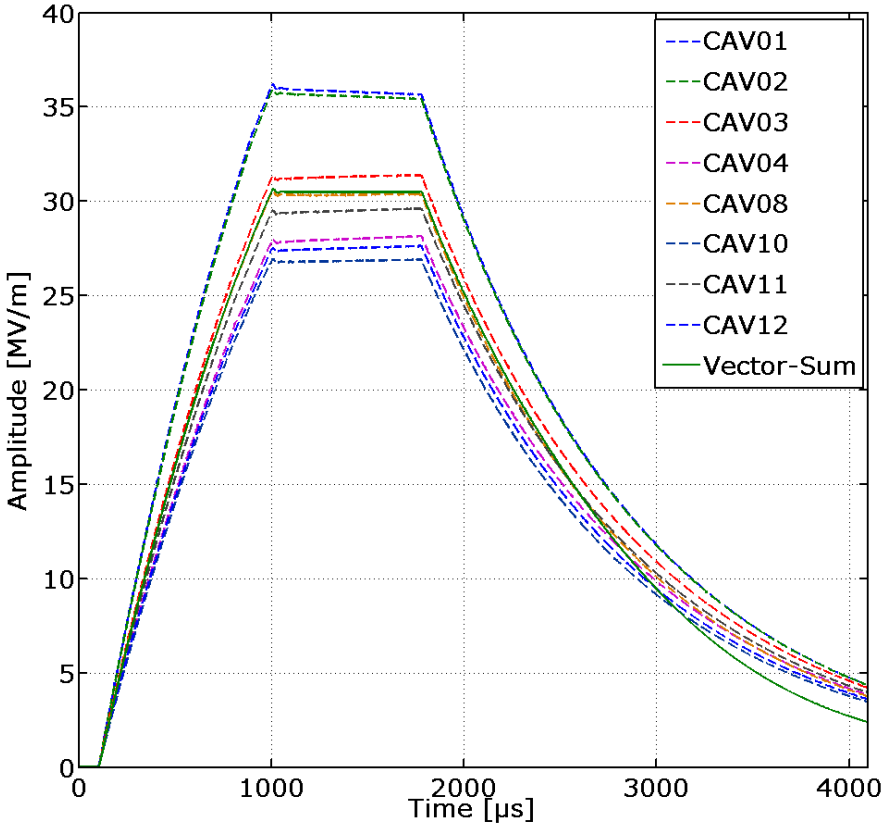


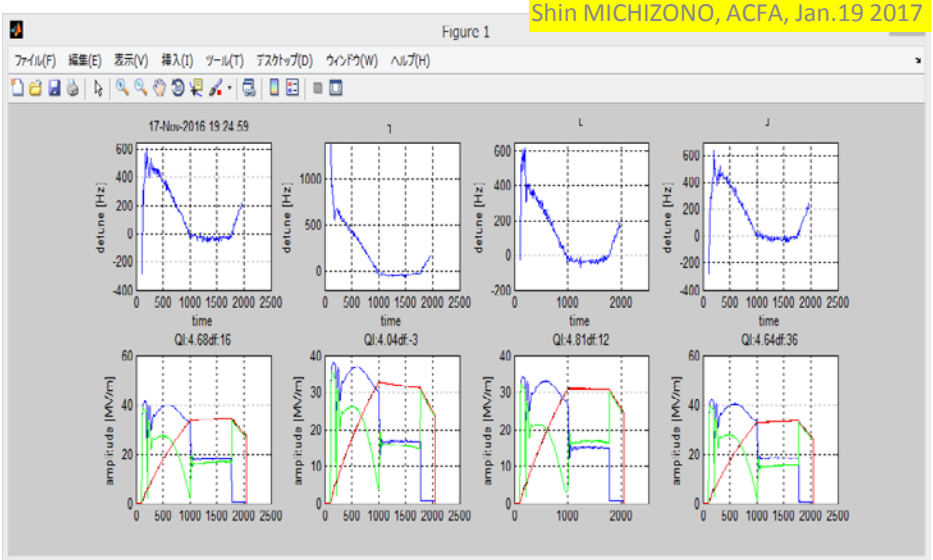


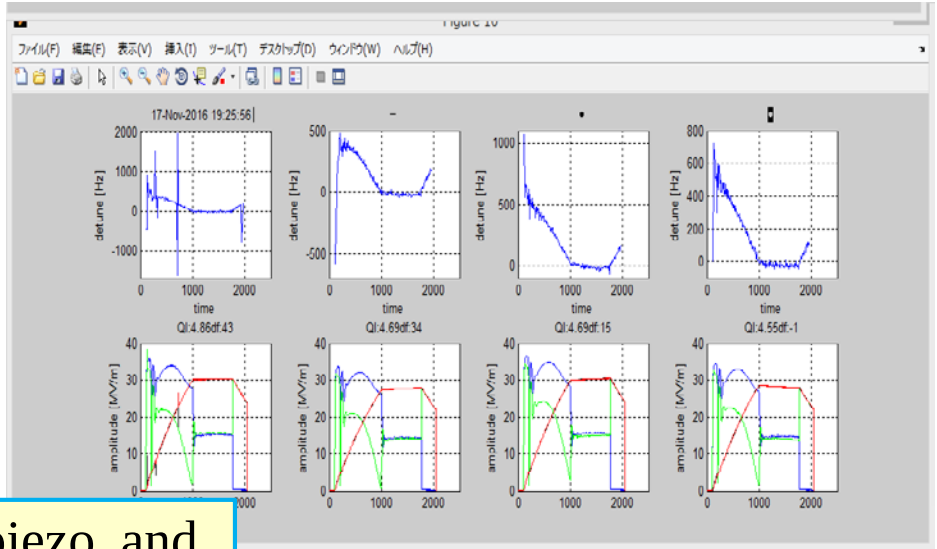
8 Cavities Operation by Vector-Sum @31MV/m (2016)

Shin MICHIZONO, ACFA, Jan.19 2017

Preliminary result



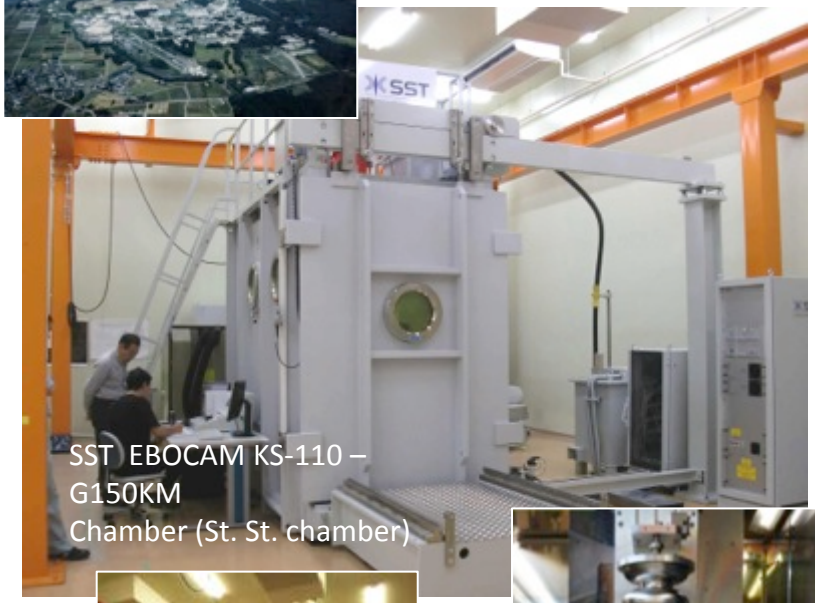




8 Cavities were tuned on resonance by piezo, and vector-sum operation was done at 31MV/m.

Effort to lead industrialization technology at KEK

EBW



SST EBOCAM KS-110 – G150KM
Chamber (St. St. chamber)

Press

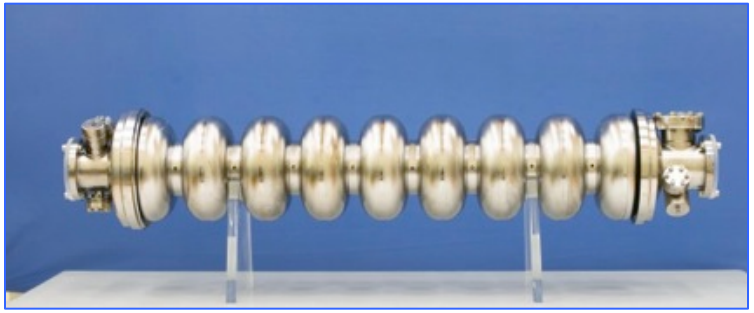
AMADA digital-servo-press
SDE1522
150t, 50stroke/min,
225mmstroke

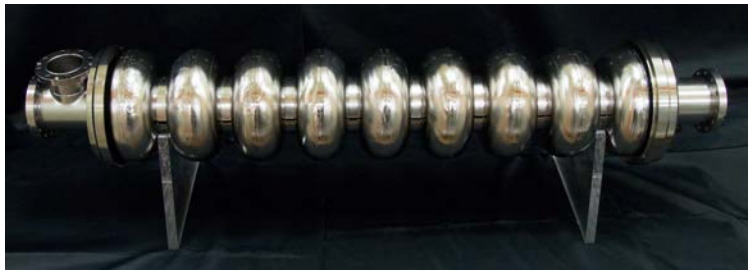
Trim

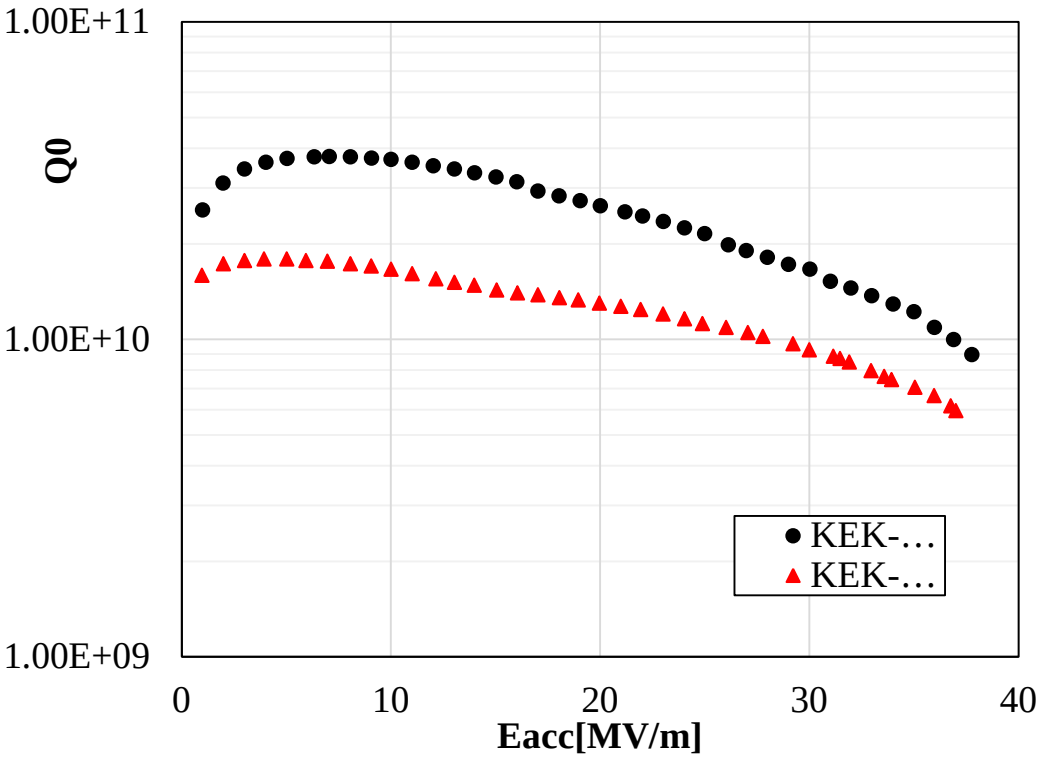
MORI VKL-253
Vertical CNC lathe

Chemical process

KEK 9-Cell Cavity (KEK-01/02)reached 36/38 MV/m





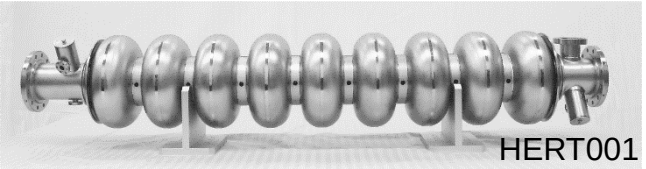


KEK-01 (Rolled, FG, 2014): Reached 36 MV/m
KEK-02 (Ingot-sliced, LG, 2016): Reached 38 MV/m

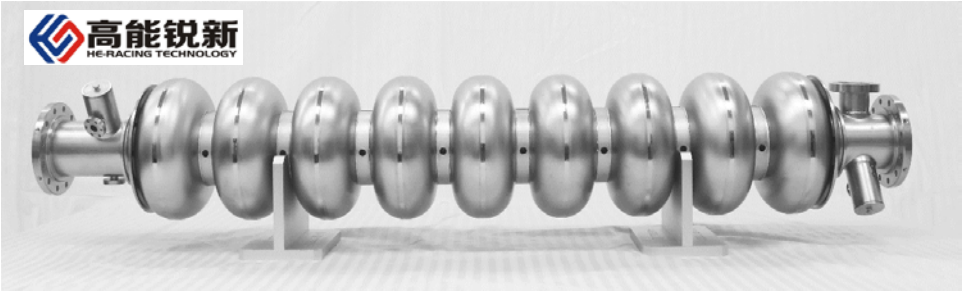
ILC 1.3 GHz SCRF R&D at IHEP

J. Zhai (IHEP), LCWS-2016

2016	9-cell **TESLA**, **fine grain** cavity with HOM, by High-Energy Racing, process and test at KEK
2014	9-cell **TESLA-like**, fine grain cavity with HOM, 16.8 MV/m by EP, process and test at KEK
2012	9-cell **Low Loss**, **large grain** cavity with HOM, 20 MV/m by EP, process and test at FNAL
2010	9-cell low-loss, large grain cavity without HOM, 20 MV/m by CP, test at KEK and JLAB
2008	single cell low-loss large and fine cavity, max. 40 MV/m by CP, process and test at KEK



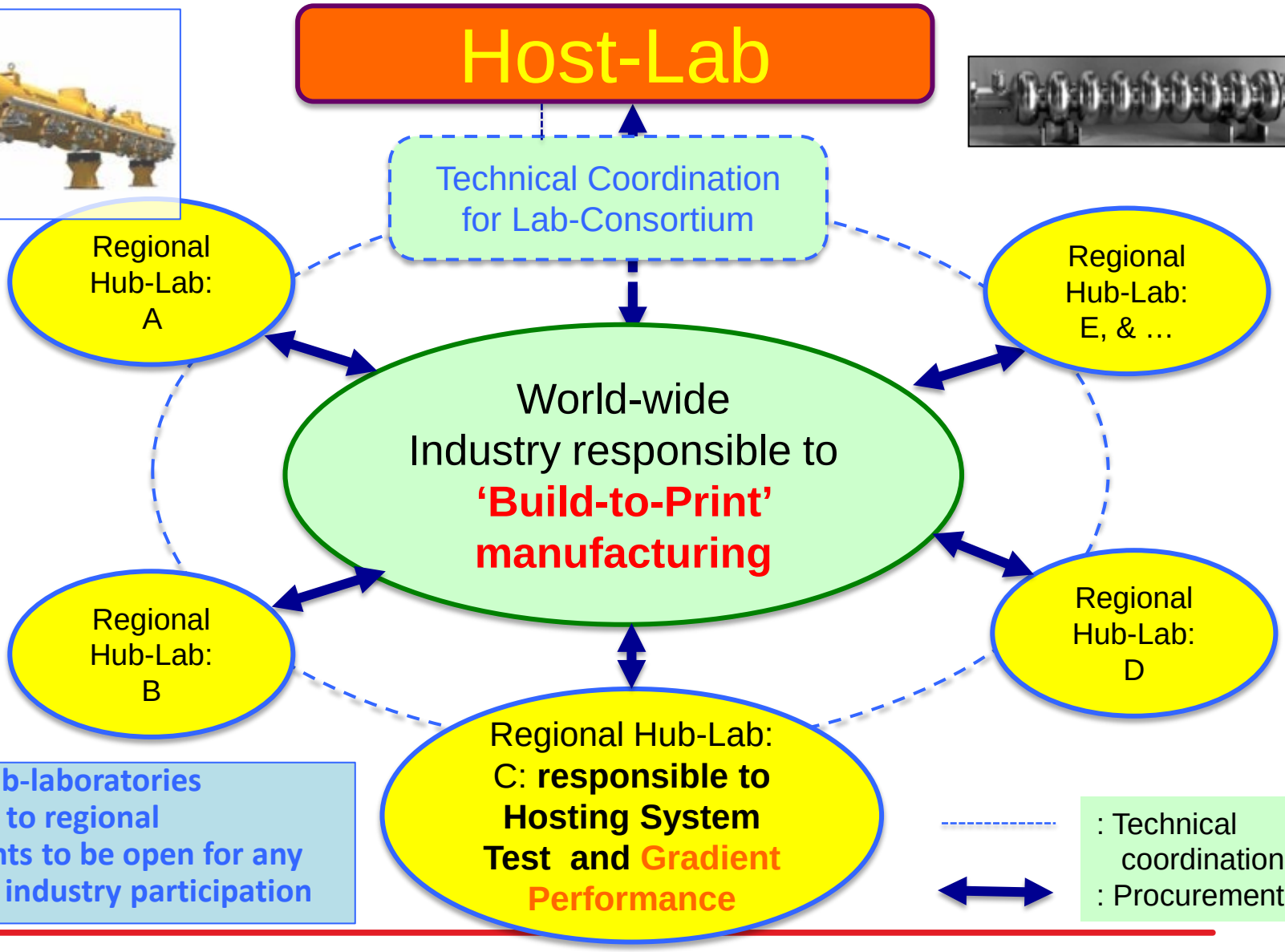
SCRF Industrialization in China



Quality control and cost reduction:

- **Niobium**: OTIC (EXFEL 35% 7 t, FRIB 50% 5 t, LCLS-II 50% 5.6 t …)
- **Cavity**: OTIC, HERT, BIAM (ILC, CADS, FRIB, HEPS, CEPC …)
- **Coupler**: HERT (ILC, CADS, RISP …), JNT
- **Cryomodule**: WXCX (EXFEL 60, LCLS-II 33, FRIB), HFJN (CADS)
  - LCLS-II cryomodule quality control (IHEP & SLAC-FNAL-JLAB collaboration)

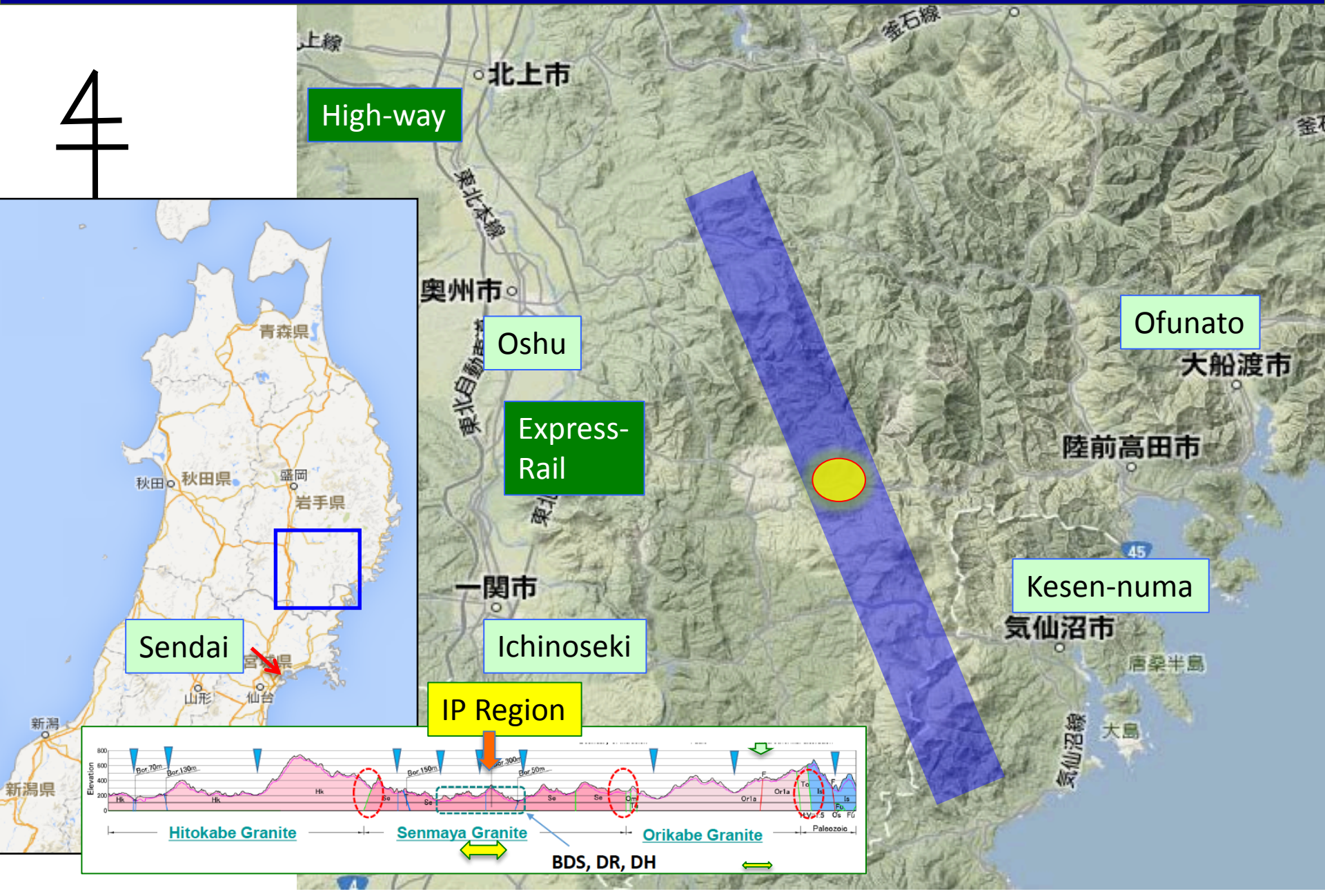
A SCRF Industrialization Model



Regional hub-laboratories responsible to regional procurements to be open for any world-wide industry participation

China has been already modelling/functioning as an industrialization partner

ILC Candidate Location: Kitakami, Tohoku



ARUP Tunnel Optimisation Tool (TOT) for 100km Circular

Tools

Choose alignment option

100km circular

Position of Shaft 1 from tunnel start: 9000m

Tunnel Depth: 310mASL

Gradient Parameters

Azimuth (°): -20

Slope Angle x-x (°): .4

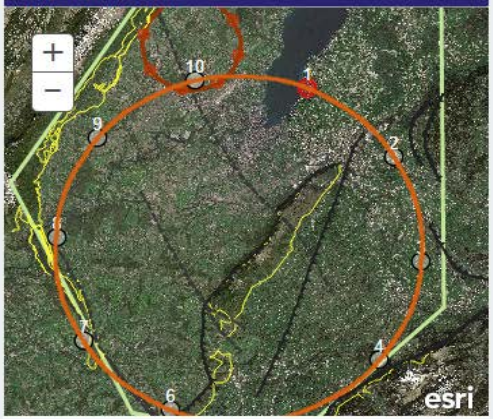
Slope Direction y-y (°): 0

CALCULATE

Alignment centre

X: 2498296 Y: 1106771

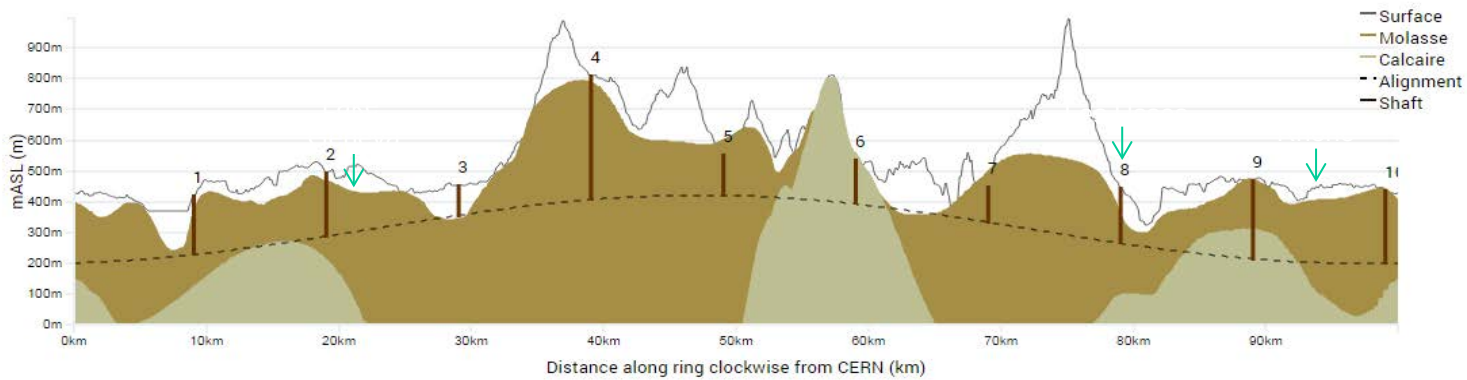
Alignment Location



Geology Intersected by Shafts / Shaft Depths

	Shaft Depth (m)				Geology (m)		
Shaft	Actual	Min	Mean	Max	Moraine	Molasse	Calcaire
1	236	230	238	247	0	244	0
2	255	258	259	260	0	163	96
3	181	169	186	205	83	98	0
4	114	70	111	160	0	164	0
5	144	136	144	151	0	0	170
6	130	122	141	167	0	181	0
7	404	400	409	422	20	384	0
8	99	97	98	102	99	0	0
9	209	207	217	231	28	181	0
10	192	159	185	209	65	127	0
Total	1964	1848	1988	2154	295	1541	266

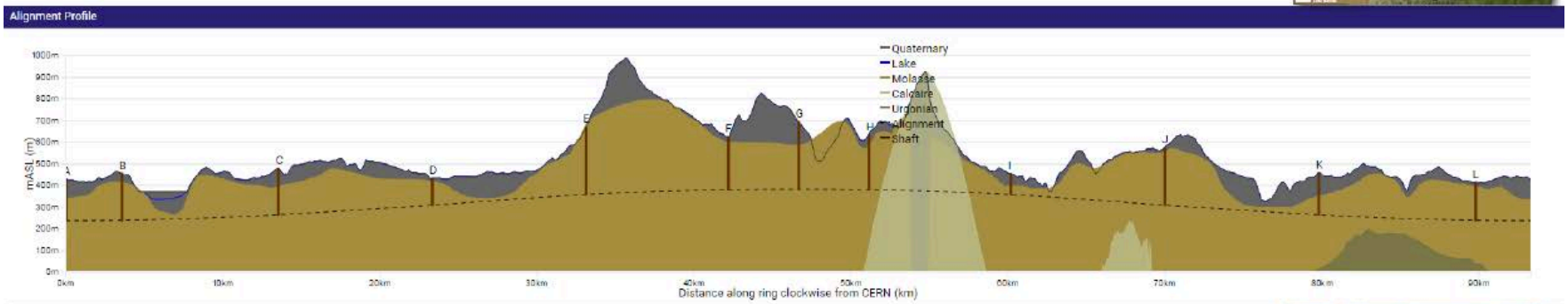
Alignment Profile



Geology Intersected by Tunnel

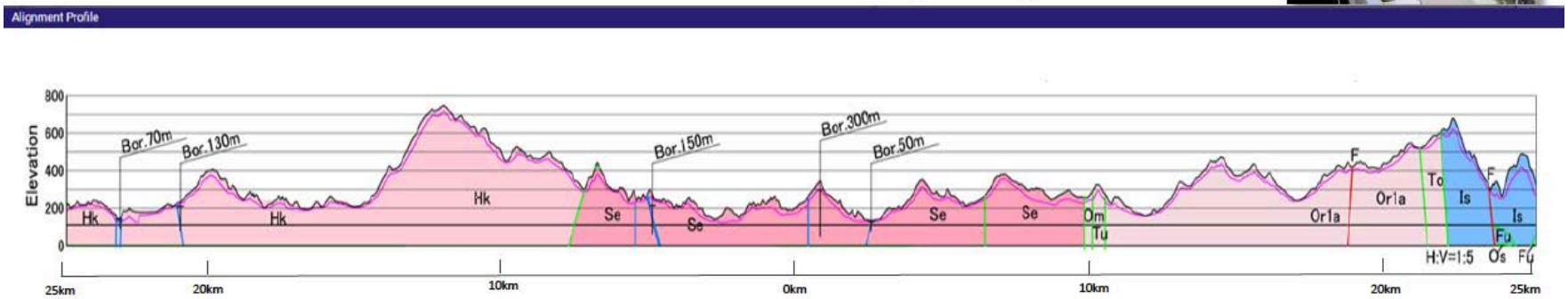
Common Mountainous Condition in FCC and ILC

Future Circular Collider (FCC)

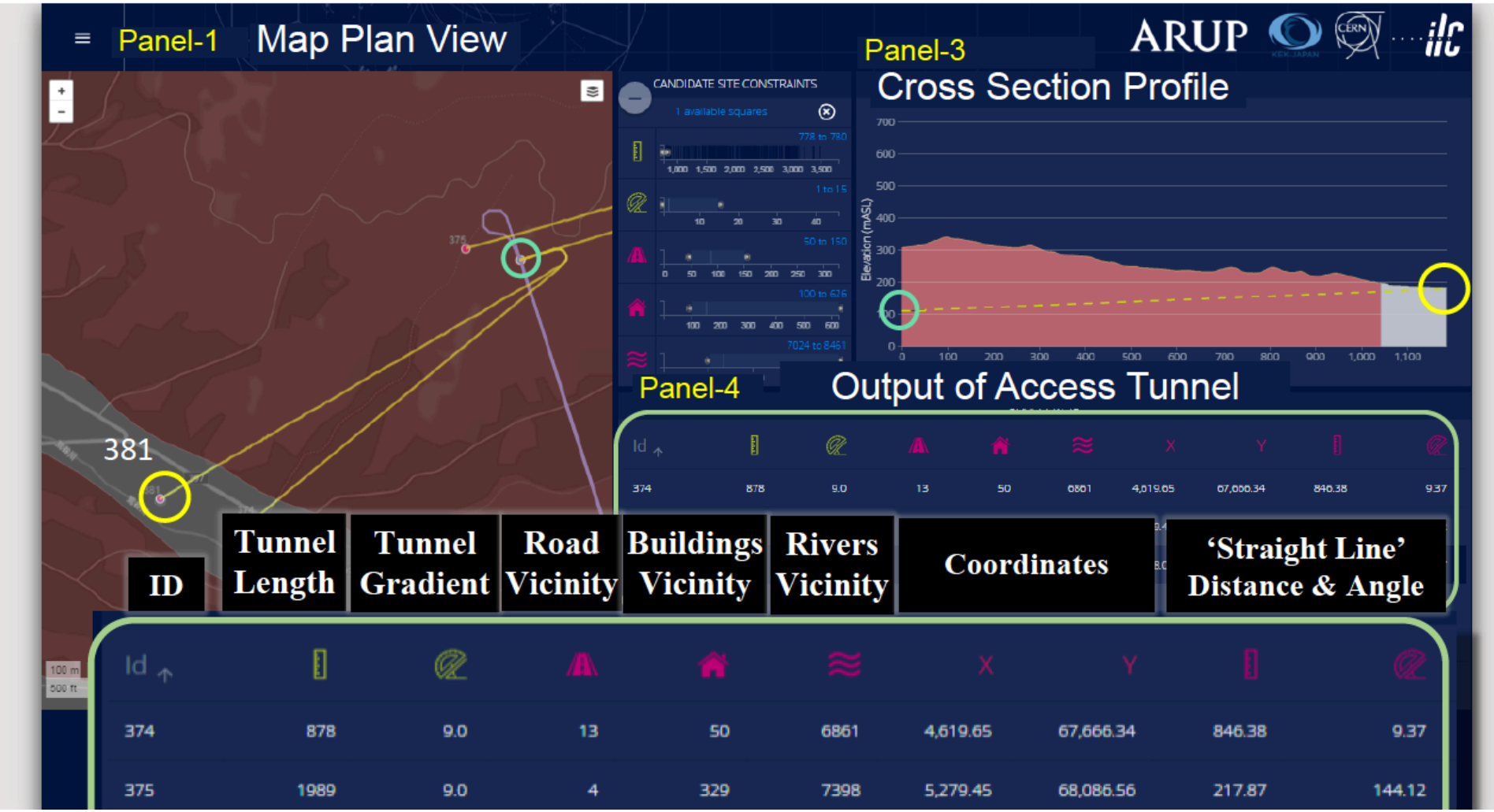


Elevation along the Circular candidate site

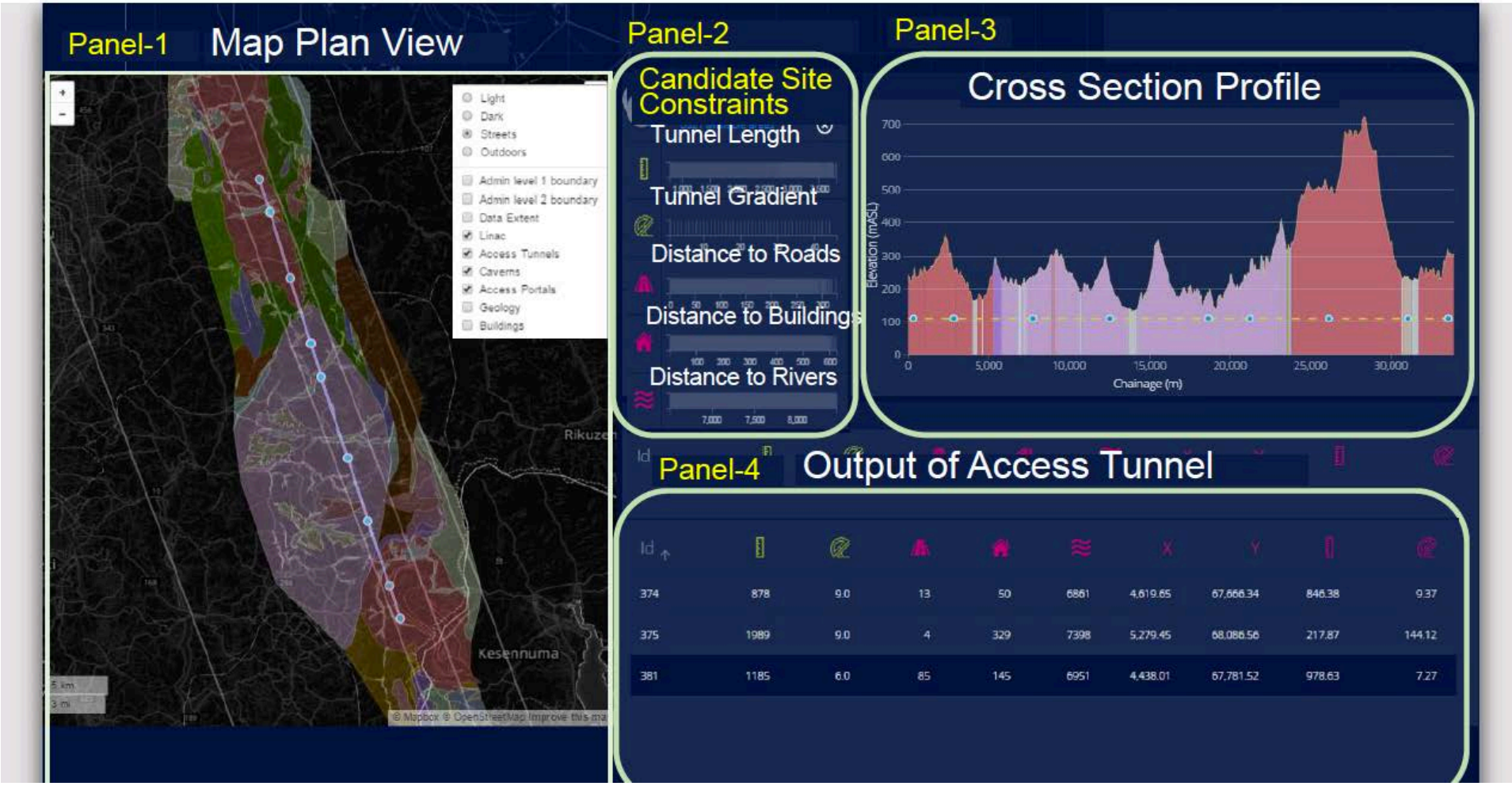
International Linear Collider (ILC)



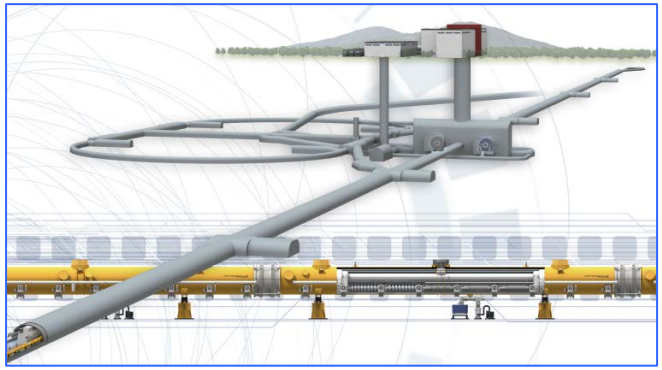
TOT: Automatic searching for the best access route



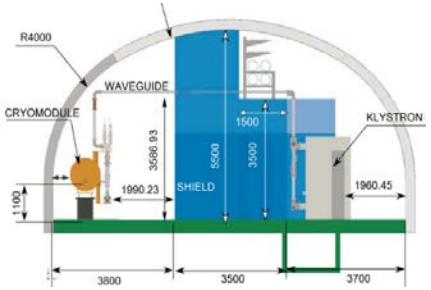
Visualization of TOT-ILC

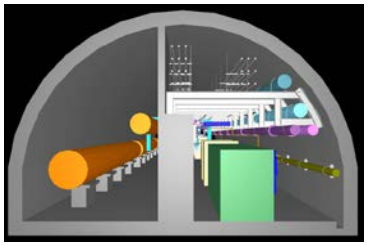


New Baselining of Civil-engineering,



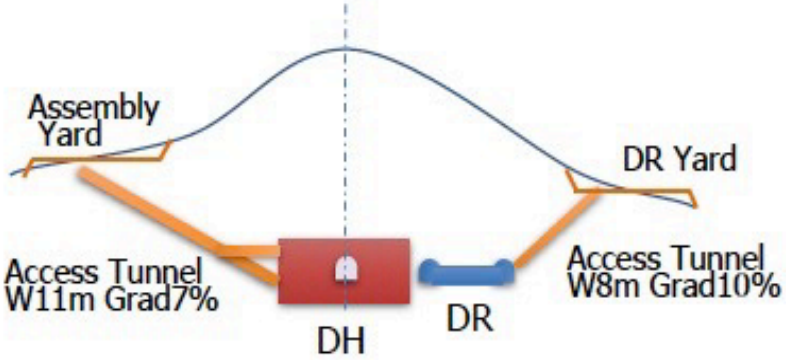
Beam Line

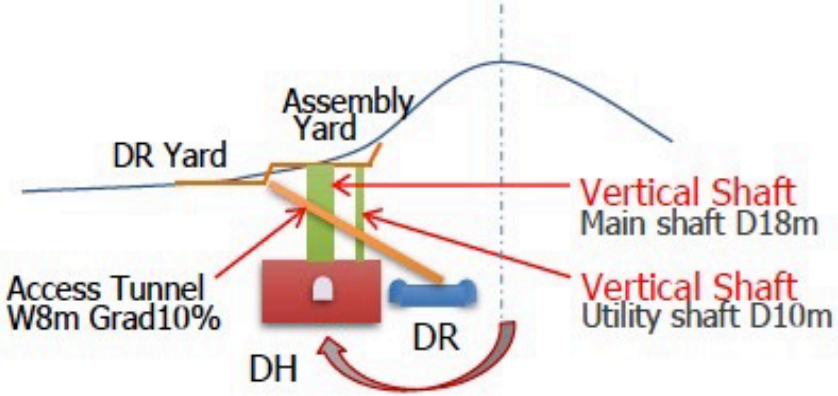




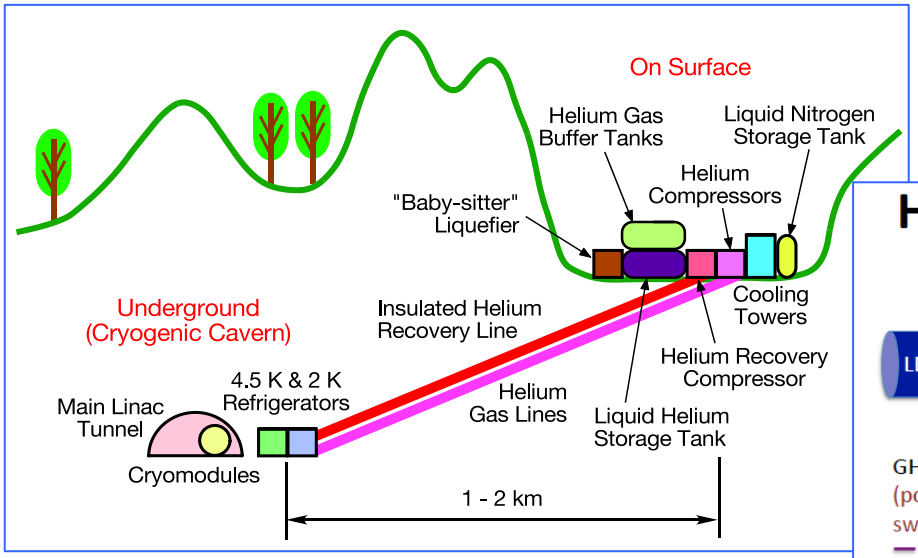
- Assembly Place: Surface Building/AH
- Access way to DHl underground
  - only Inclined Access Tunnel (AT)
  - Transport. by special long trailer

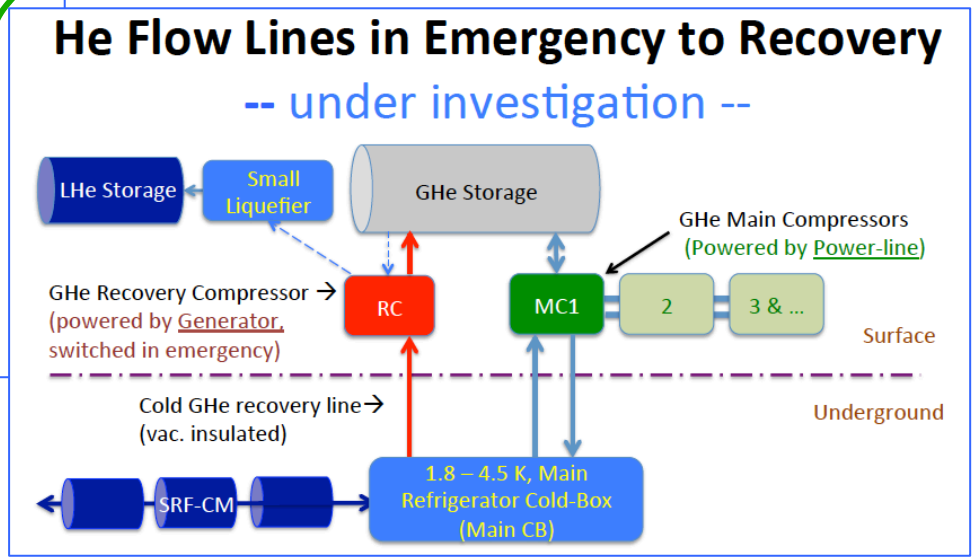
- Assembly Place: Underground/DH
- Access way to DH underground
  - mainly Vertical Shaft (VS)
  - Transport. by Gantry Crane





Cryogenics Layout with Further Safety and Conserving He Resource





Outline

Introduction

Technical Progress and Status

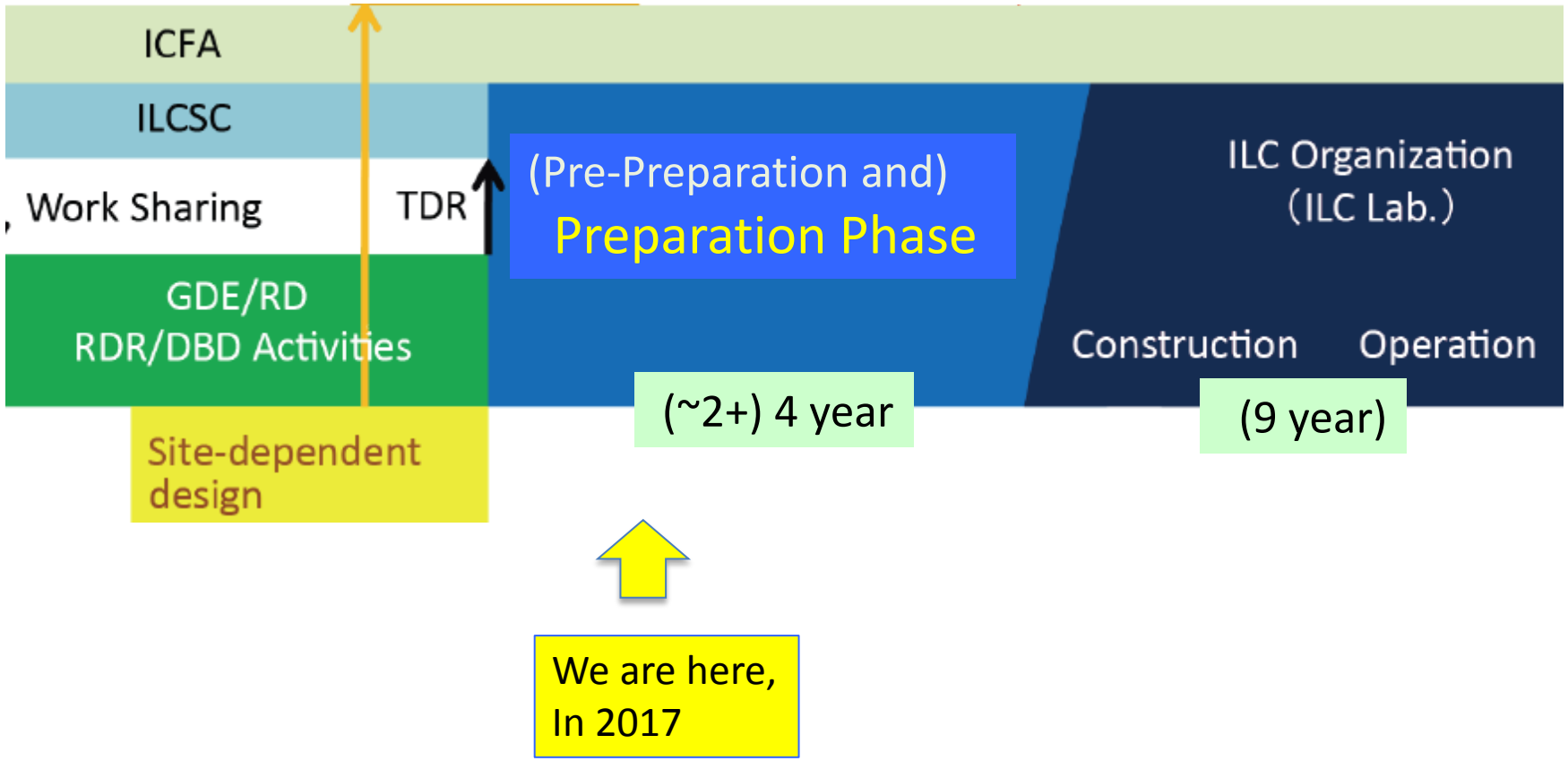
- Nano-beam technology
- SRF technology
- Civil engineering

Readiness for the Project

- Further effort for the cost reduction and the R&Ds

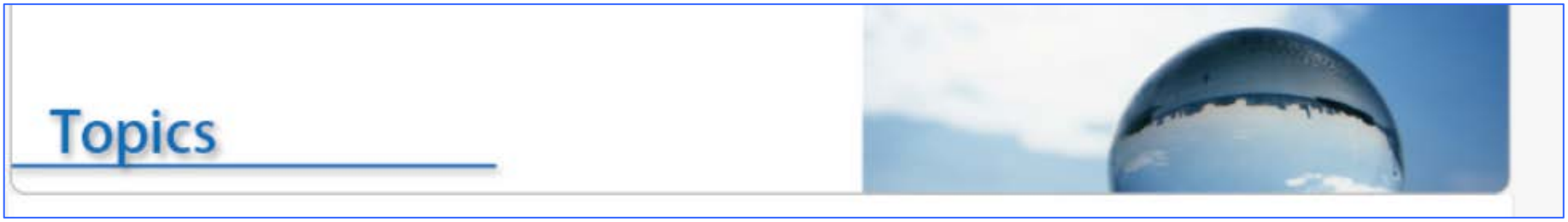
Summary

Status and Prospect for ILC



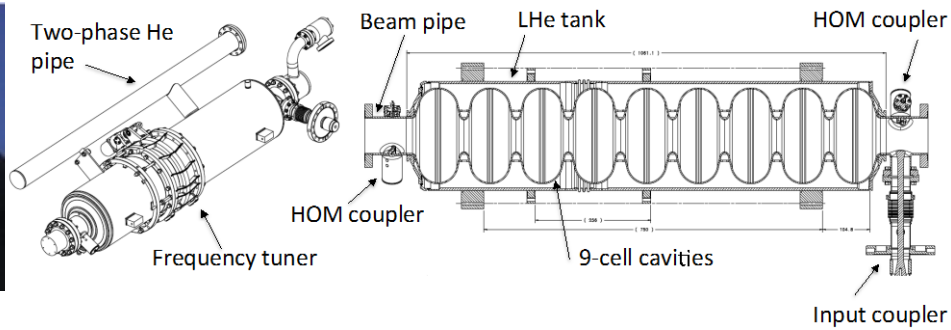
KEK-ILC Action Plan Issued, in Jan. 2016

https://www.kek.jp/en/NewsRoom/Release/20160106140000/



	Pre-Preparation Stage	Main Preparation Stage			
	present (we are here)	P1	P2	P3	P4
ADI	Establish main parameters	Verify parameters w/ simulations			
SRF	Beam acc. with SRF cavity string, Cost Reduction R&D (proposed)	Demonstrate mass-production technology, stability, hub-lab functioning, and global sharing			
Nano-beam	Achieve the ILC beam-size goal	Demonstrate the nanobeam size and stabilize the beam position			
e+	Demonstrate technological feasibility	Demonstrate both the undulator and e-driven e+ sources			
CFS	Pre-survey and basic design	Geology survey, engineering design, specification, and drawings			

ILC SRF ML Parameters



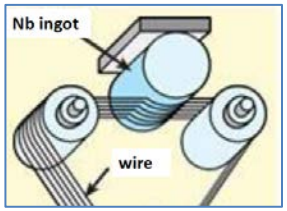
1.3 GHz Nb 9-cellCavities	16,024
Cryomodules	1,855
SC quadrupole pkg	673
10 MW MB Klystrons & modulators	~400

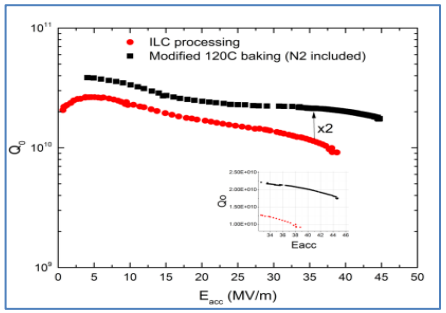
S. Michizono, S. Belomestnykh

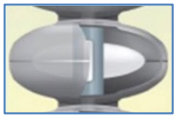
A plan for ILC Cost-Reduction R&D in Japan and US focusing on SRF Technology, in 2~3 years

Based on recent advances in technologies;

- Nb material preparation
  - w/ optimum RRR and clean surface
- SRF cavity fabrication for high-Q and high-G
  - w/ a new baking recipe provided by **Fermilab**
- Power input coupler fabrication
  - w/ new (low SEE) ceramic without coating
- Cavity chemical process
  - w/ vertical EP and new chemical (non HF) solution
- Others

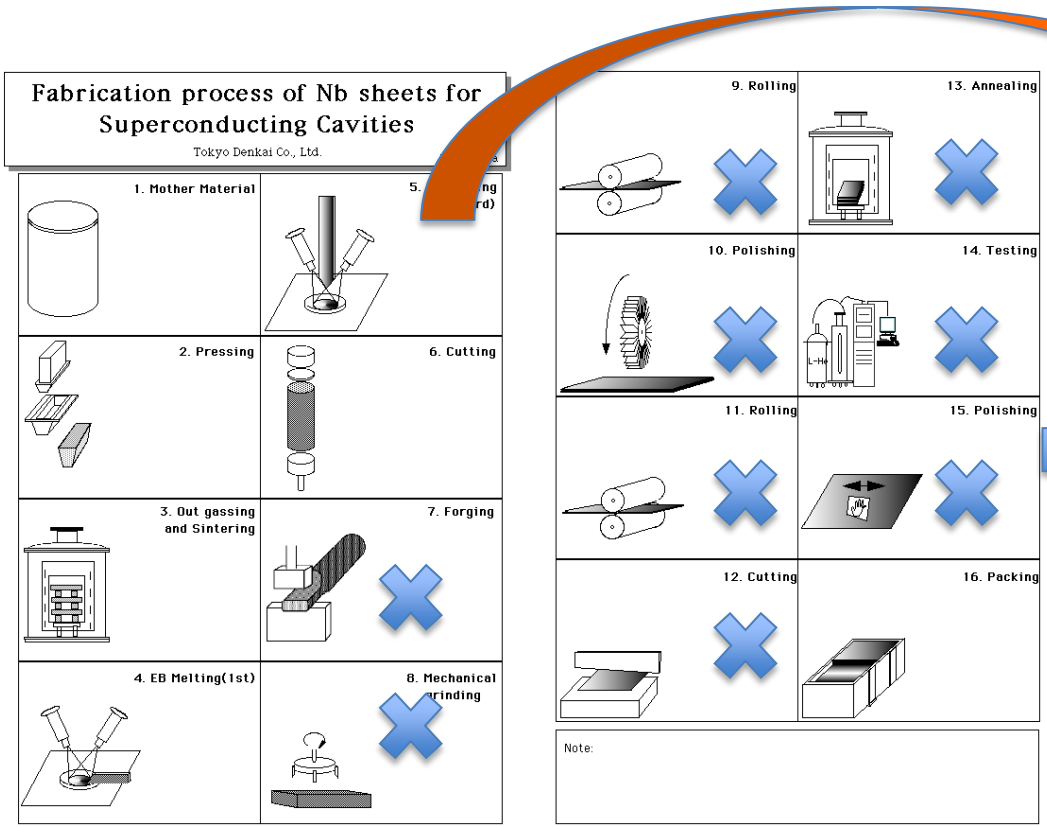


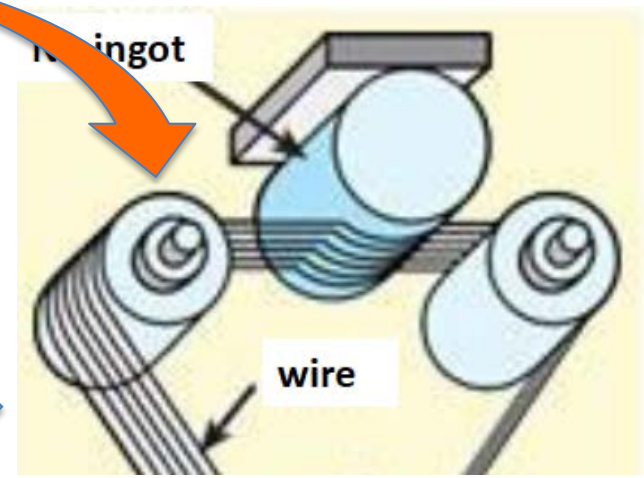


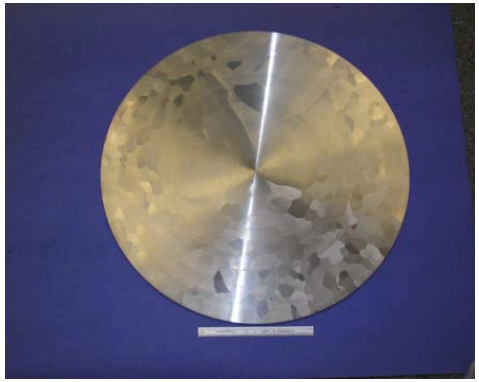


Courtesy: G. Myneni

FG-Nb rolled or LG-Nb sliced from Ingot

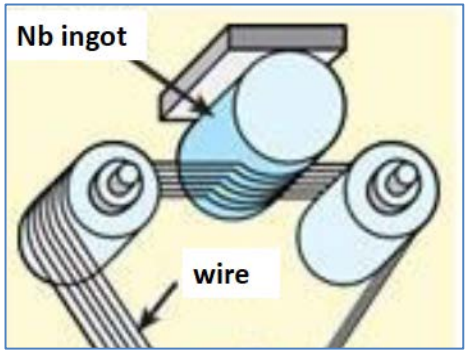


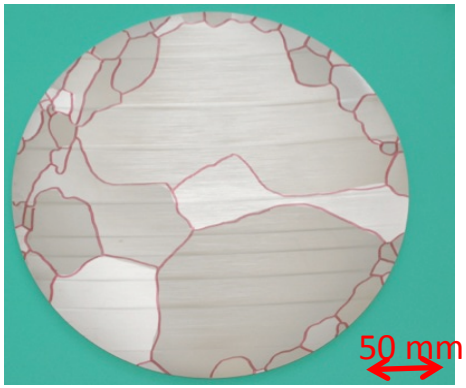


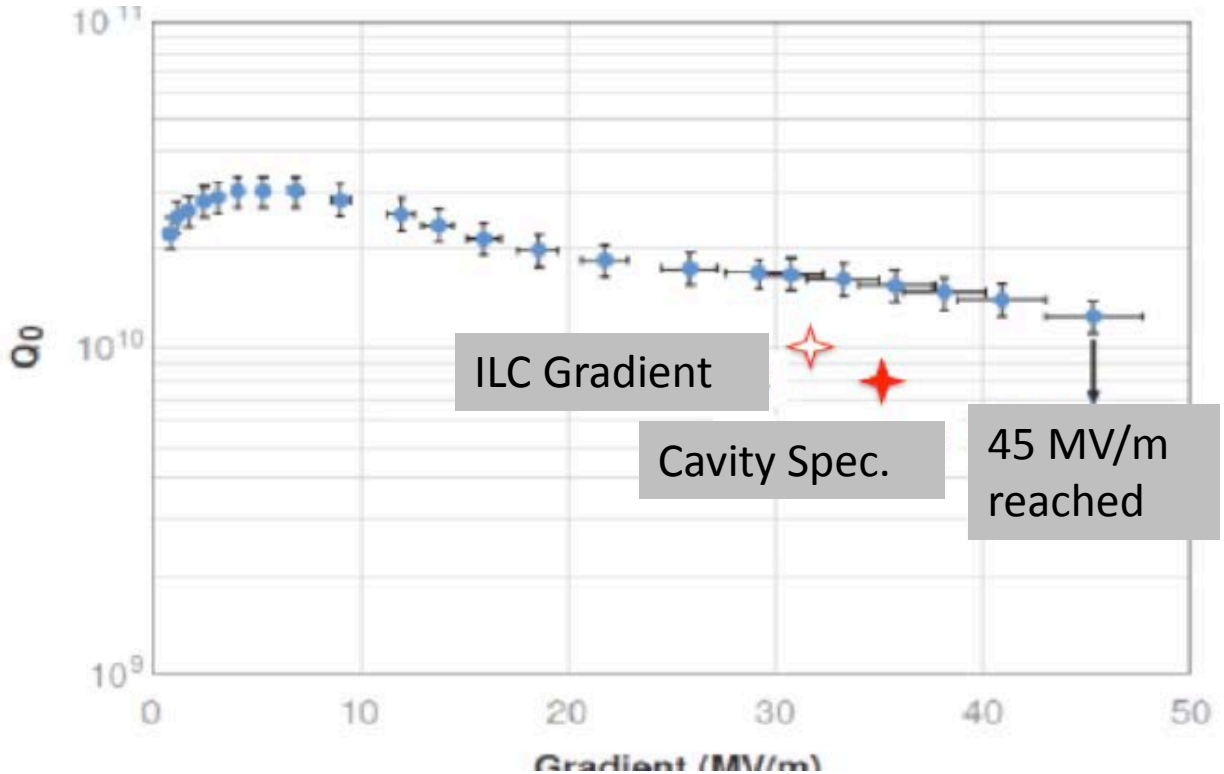


Cleanness highly secured

G. Reached with Nb-Ingot Sliced







Result from DESY

Standard Procedure Established

	Standard Fabrication/Process
Fabrication	Nb-sheet purchasing
	Component Fabrication
	Cavity assembly with EBW
Process	EP-1 (~150um)
	Ultrasonic degreasing with detergent, or ethanol rinse
	High-pressure pure-water rinsing
	Hydrogen degassing at > 800 C
	Field flatness tuning
	EP-2 (~20um)
	Ultrasonic degreasing or ethanol (or EP 5 um with fresh acid)
	High-pressure pure-water rinsing
	Antenna Assembly
	Baking at 120 C
Cold Test (vertical test)	Performance Test with temperature and mode measurement

Key Process

Fabrication

- Material
- EBW
- Shape

Process

- Electro-Polishing
- Ethanol Rinsing or
- Ultra sonic. + Detergent Rins.
- High Pr. Pure Water cleaning

Standard Procedure Established

	Standard Fabrication/Process
Fabrication	Nb-sheet purchasing
	Component Fabrication
	Cavity assembly with EBW
Process	EP-1 (~150um)
	Ultrasonic degreasing with detergent, or ethanol rinse
	High-pressure pure-water rinsing
	Hydrogen degassing at > 800 C
	Field flatness tuning
	[illegible]
	[illegible]
	[illegible]
	Antenna assembly
	Baking at 120 C
Cold Test (vertical test)	Performance Test with temperature and mode measurement

- N2 infusion at 120 C directly after heat treatment at 800 C

Key Process

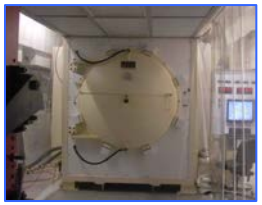
Fabrication

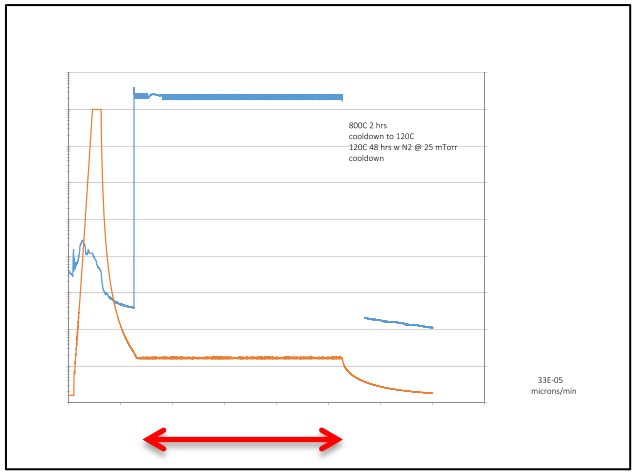
- Material
- EBW
- Shape

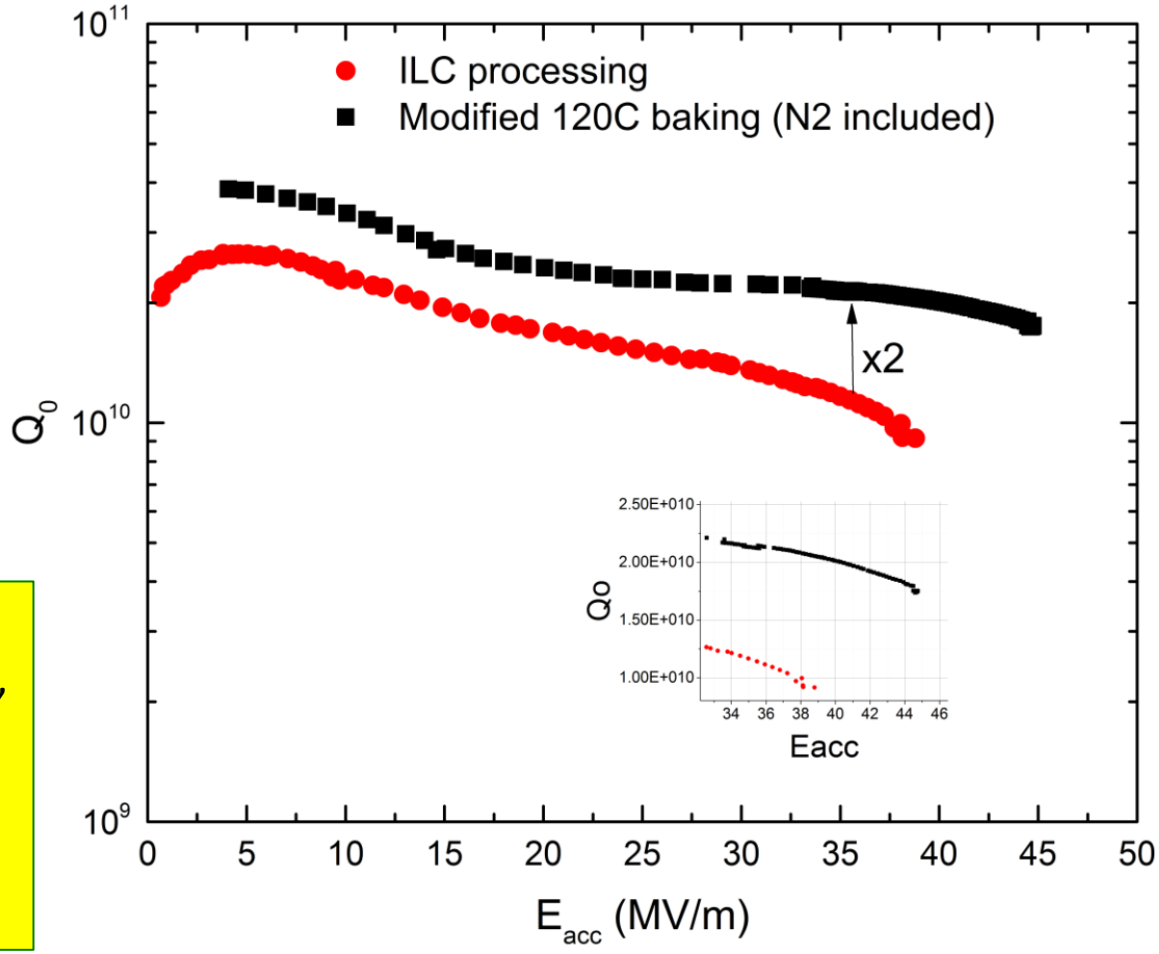
Process

- Electro-Polishing
- Ethanol Rinsing or
- Ultra sonic. + Detergent Rins.
- High Pr. Pure Water cleaning

New Surface Process recently demonstrated at Fermilab, "N_2 Infusion at 120 C"

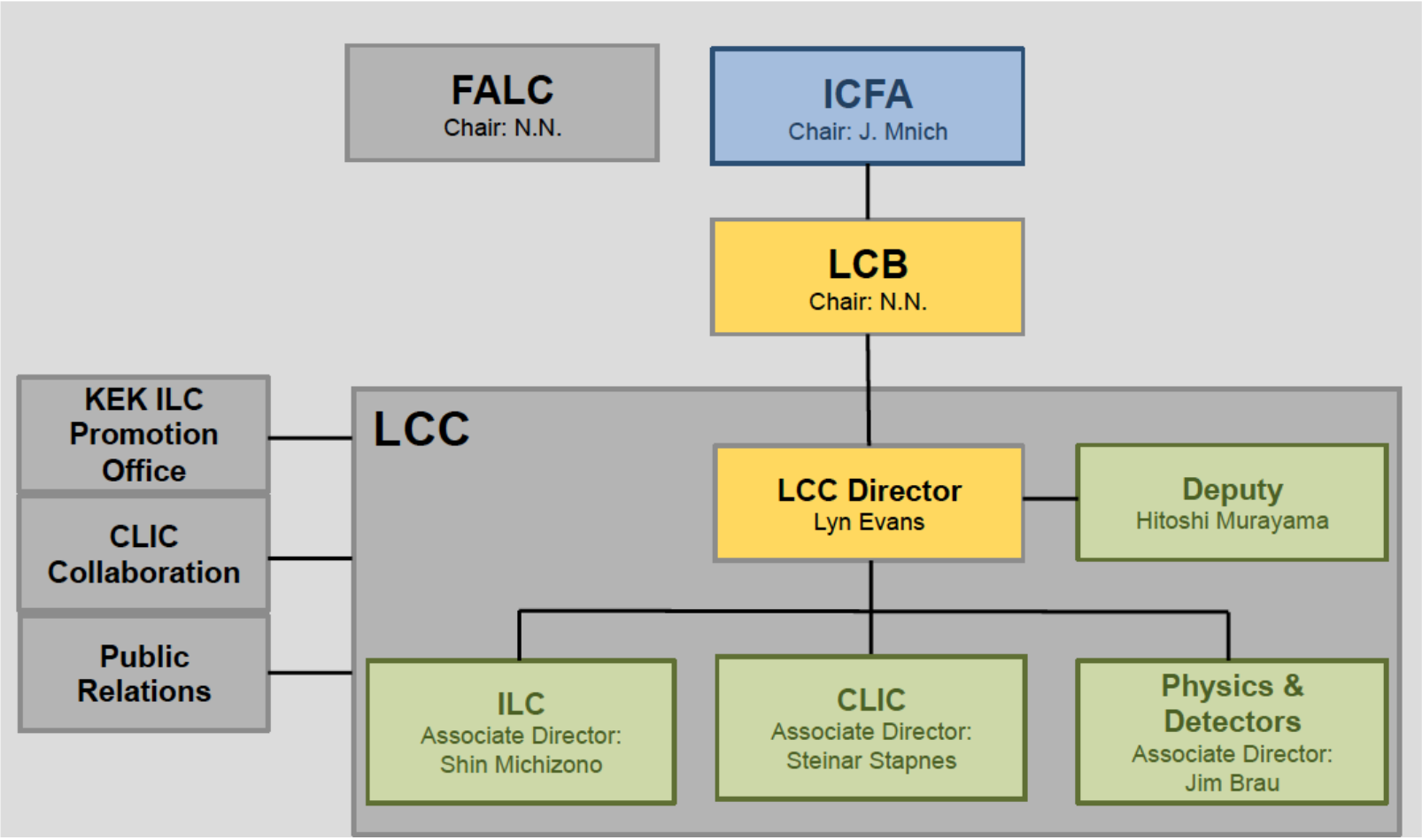






- N2 infusion at 120 C directly after heat treatment at 800 C,
- Same cavity, sequentially processed, no EP in b/w
- Achieved: 45.6 MV/m
  Q at ~ 35 MV/m : ~ 2.3e10

LCC, Next-term Organization 2017 ~ 2019



Stated by LCC Director L. Evans in LCWS2016, Morioka

Cost reduction

- All of these measures will reduce the cost by 10-20%, but that is not enough for a realistic project funding.
- The beauty of a linear collider is that it can be staged.
- Serious discussions must now start on realistic staging scenarios to bring the cost of the first stage down.

Worldsie R&D Plans in a few years

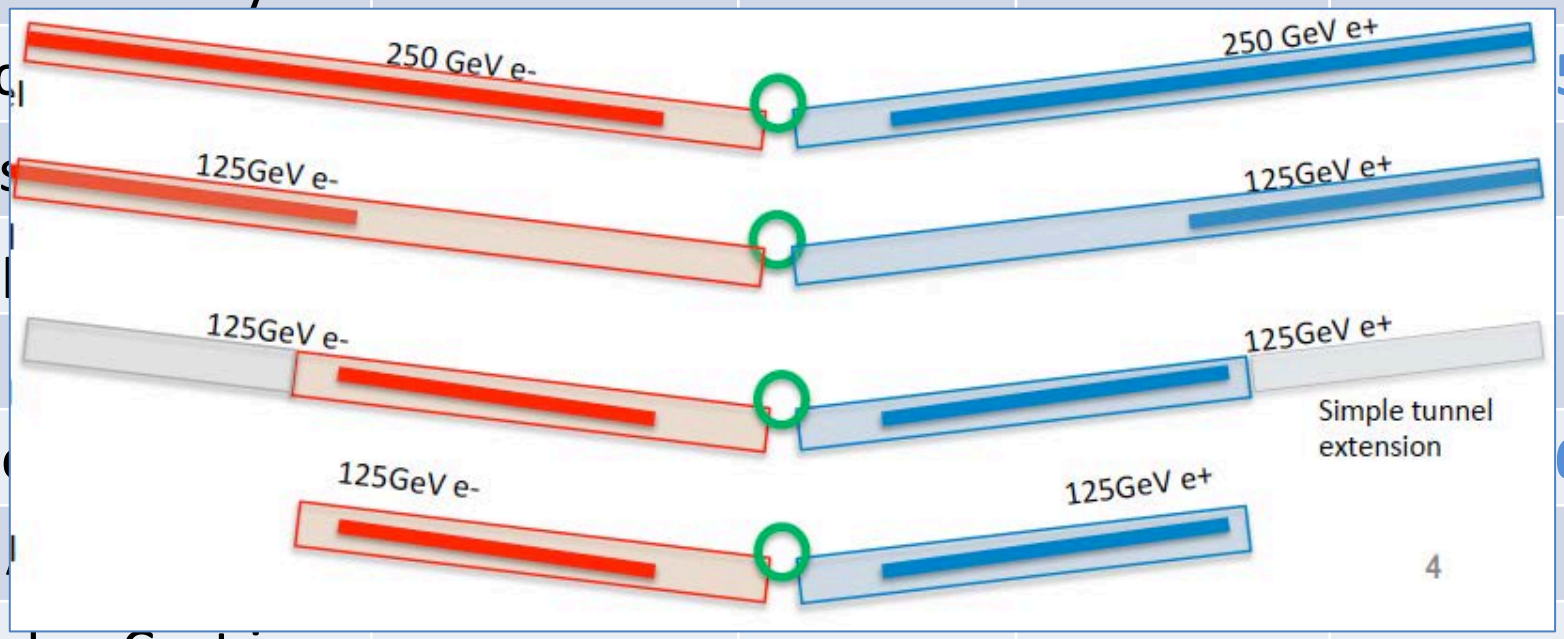
	Project	SRF Cavity	Assoc.	CM	RF
Fermilab	LCLS-II	N_2-infusion (HQ-HG)	Coupler		
JLab	LCLS-II	Nb-LG/FG (sliced/rolled) , N_2-infusion			
DESY	EXFEL	N_2-infusion Nano-Lab study		High-perform. CM	
INFN-LASA	ESS	Nb-LG/FG study for ESS			
CEA CNRS-LAL	IFMIF ESS, SARAF	Vertical EP (VEP), N_2-Infusion	Mag.shield Coupler	Assembly robotizing	
KEK	STF	Nb-LG/FG N_2-infusion	Coupler, Tuner, C C.		Marx M.
IHEP	ADS	N_2-infusion, In dustrialization		Industrial.	Marx M. h.e. Klystron
CERN	HL-LHC Hi-Isolde	Thin-film (Nb on Cu)	Coupler		h.e. Klystron
TRIUMF	ISAS-II, ARIEL	VEP, muSR			
(Cornell)		N_2-infusion, VEP			

ILC Staging to be studied

	Unit	ILC		
CoM. Energy	GeV	**250**	**500**	**1,000**
Site Length	km	**~21**	**31**	**50**
Luminosity	10^{34} $cm^{-2}s^{-1}$	**0.82**	**1.8**	**3.6**
Acc. Gradient	MV/m	**31.5**	**31.5**	**31.5/45**
Res. Frequency	GHz	**1.3**	**1.3**	**1.3**
Repetition rate	Hz	**5**	**5**	**4**
IR, v. beam-size	nm	**7.7**	**5.9**	**2.7**
Beam Power	MW	**2 x 2.9**	**2 x 5.2**	**2 x 13.6**
AC Power	MW	**129**	**163**	**300**
Value Cost in TDR	BILC	**TBD**	**7.98**	**TBD**

ILC Staging to be studied

	Unit	ILC		
CoM. Energy	GeV	**250**	**500**	**1,000**
Site Length	km	**~21**	**31**	**50**
Luminosity	10^{34} $cm^{-2}s^{-1}$	**0.82**	**1.8**	**3.6**
Ac				5
Res				
Re				
IR,				
B				6
Value Cost in TDR	BILC	**TBD**	**7.98**	**TBD**



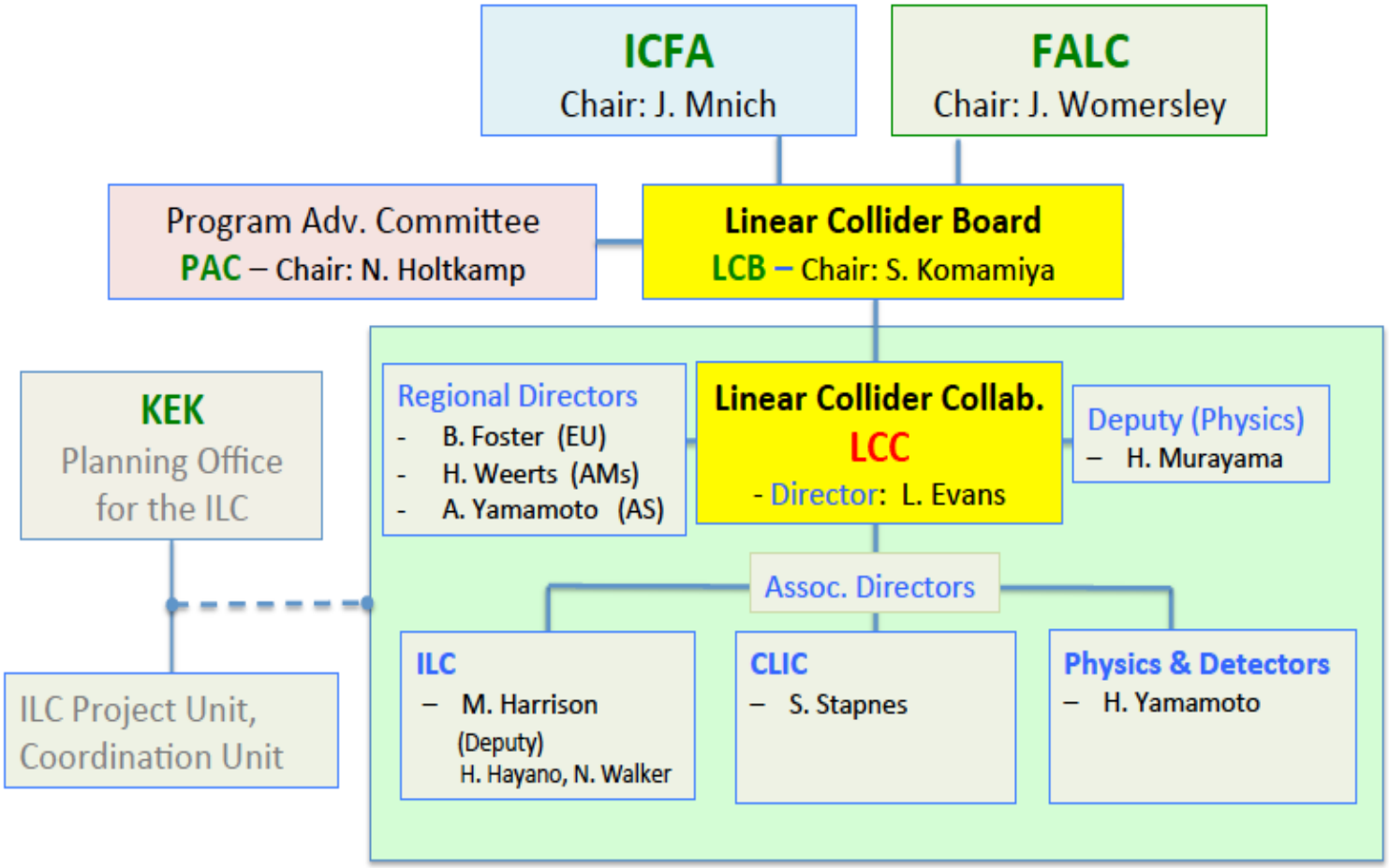
Summary

- **ILC** prepared for an e+e- collider, CE 500 GeV, extendable to 1 TeV.
- Nano-Beam technology demonstrated at **ATF hosted at KEK**
- SRF Technology advanced, and, particularly, **demonstrated at E-XFEL for mass-production, and at Fermilab for High-Q and High-G.**
- Cryogenics & Civil Eng/ works advanced, reflecting CERN-LHC exp.

- **Cost Reduction R&D work required for SRF technologies, reflecting recent technology progress,**
- **Study of the energy staging, starting at C.E. 250 GeV, to be studied for realizing the project sooner.**

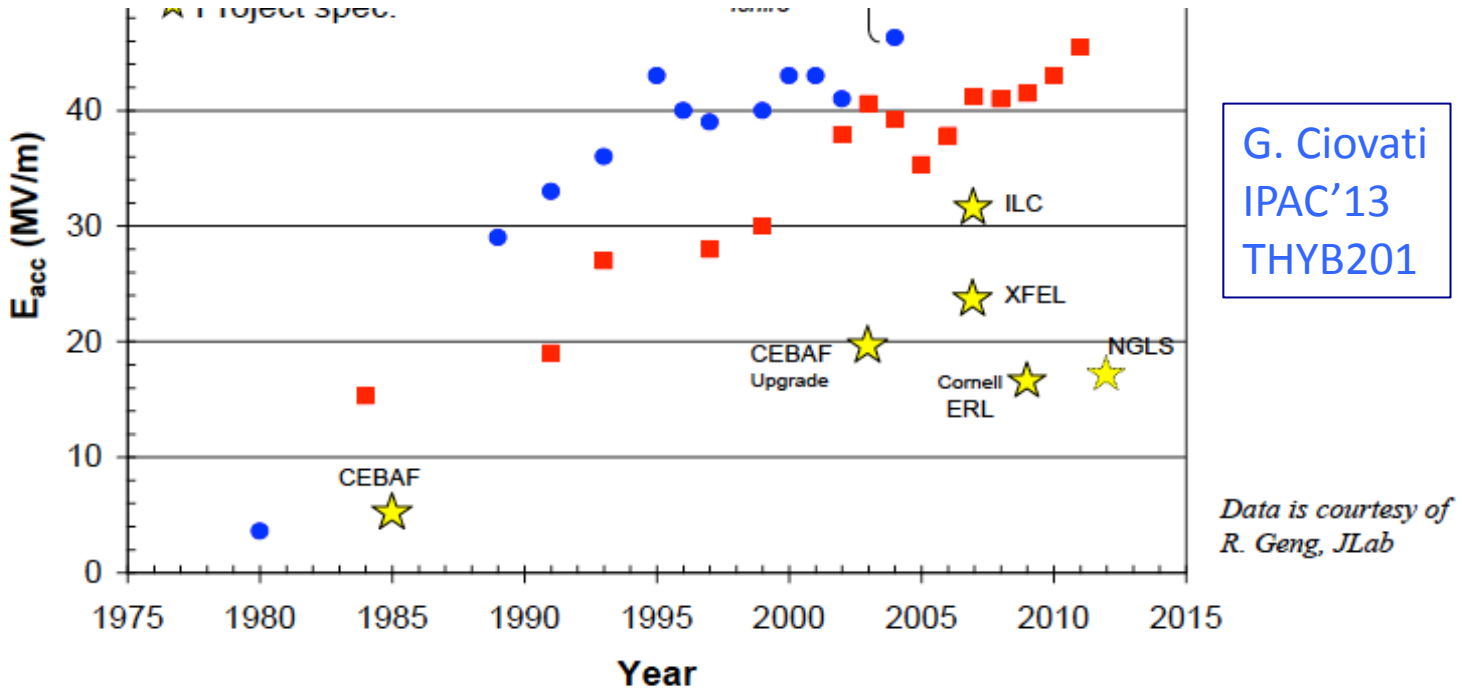
reserved

Linear Collider Collaboration (LCC)



Courtesy: G. Ciovati, R. Geng

Progress



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- E_{acc} > 50 MV/m is yet to be achieved in "low B_p" multi-cell cavities
- Average gradient specification of current and future projects is ~20 MV/m

Progress/Prospect in SRF Cavity Gradient

for Frontier Particle Accelerators

R. Geng