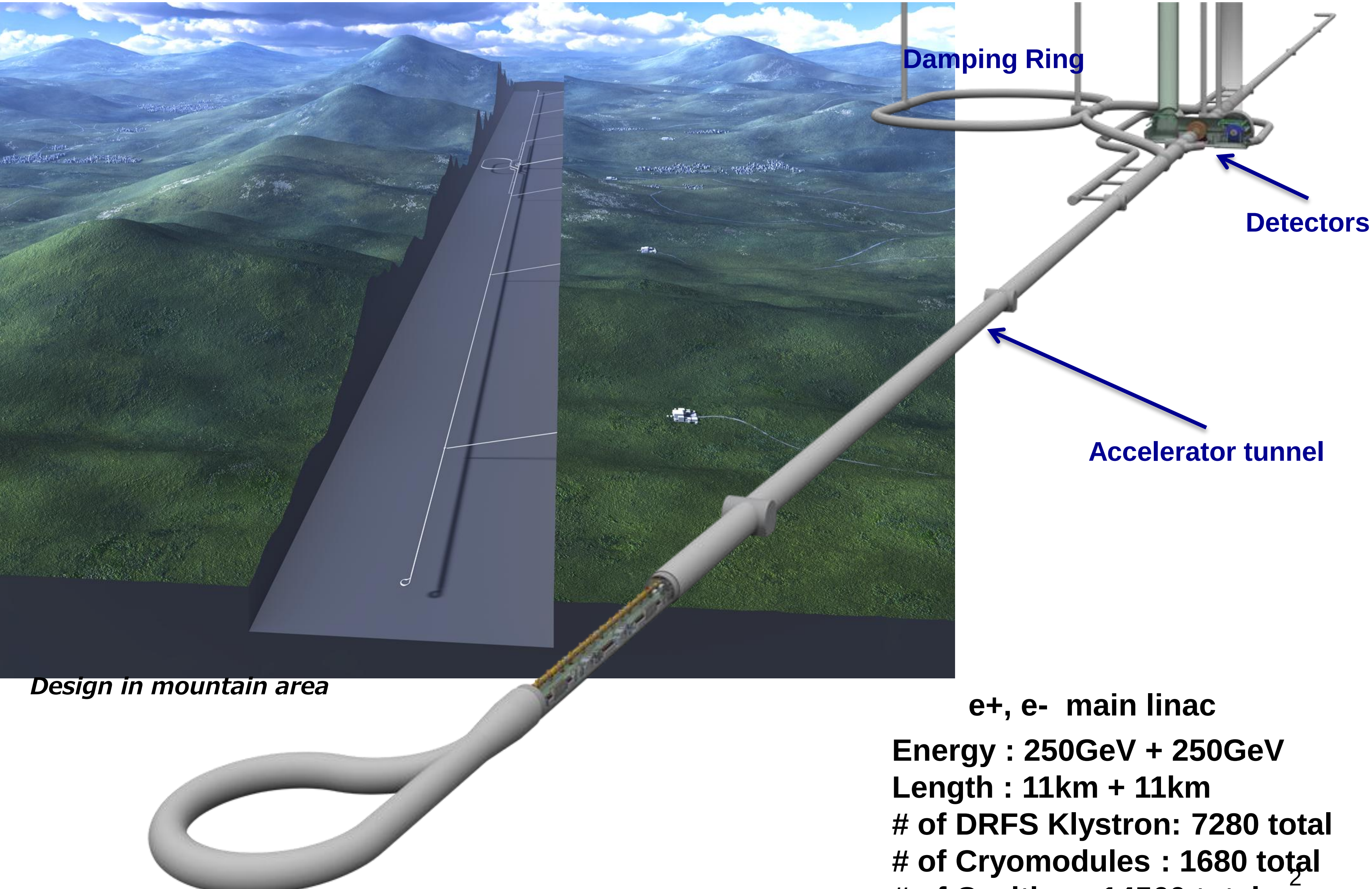
Superconducting RF cavity and its industrialization

加速器・物理合同　ILC夏の合宿2013
２０１３年７月２３日
（富山　呉羽ハイツ）

佐伯　学行(KEK)

International Linear Collier (ILC)



Design in mountain area

e+, e- main linac

Energy : 250GeV + 250GeV
Length : 11km + 11km
# of DRFS Klystron: 7280 total
# of Cryomodules : 1680 total
# of Cavities : 14560 total

ILC Cost Breakdown (RDR)

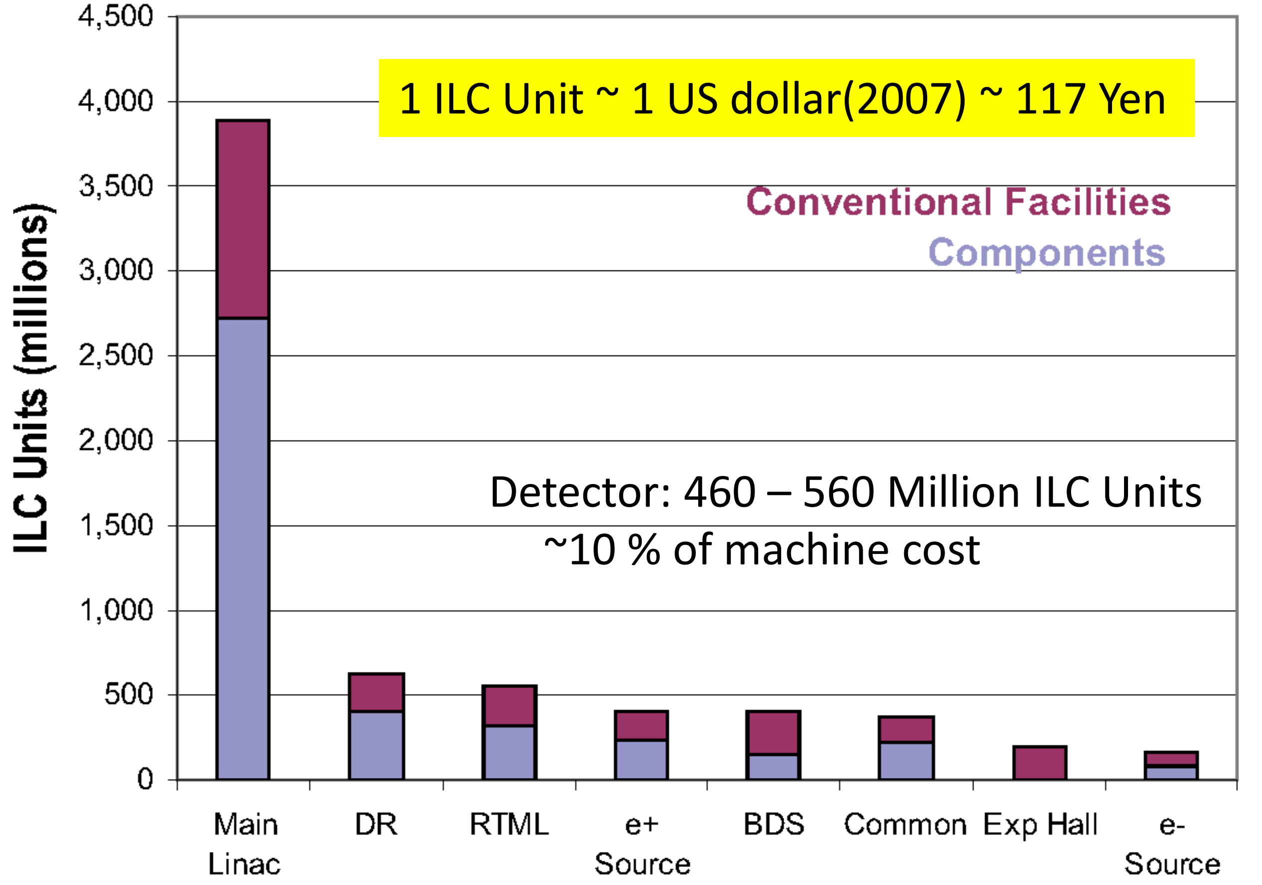


FIGURE 6.2-1. Distribution of the ILC value estimate by area system and common infrastructure, in ILC Units. The estimate for the experimental detectors for particle physics is not included. (The Conventional Facilities estimates have been averaged over the three regional site estimates.)

ILC Cost Breakdown (RDR)

TABLE 6.2-2
Distribution of the ILC Value Estimate by area system and common infrastructure, in ILC Units. The estimate for the experimental detectors for particle physics is not included. (The Conventional Facilities estimates have been averaged over the three regional site estimates.)

Area - M ILC Units	Total	Components	Conventional Facilities
Main Linac	3,894	2,723	1,172
DR	630	398	231
RTML	554	320	234
e^+ source	398	232	166
BDS	408	157	252
Common	369	229	140
Exp Hall	200	0	200
e^- source	165	87	78
Sum	6,618	4,146	2,472

コストドライバー
かつ見積もりが
難しい。

最もコストがかかるライナック部分の量産が見積もり通りにいかず、コストが膨らむことがあれば、ILCの建設・完成は非常に困難となる。
（SB2009 では、ダンピングリング周長を半分にし、トンネルを2本から1本にするなど、かなり大胆な設計変更をしたにも関わらず、コスト削減は13%にとどまった。つまりILCのコスト削減代はほとんどない。）

ILC(500GeV)の空洞生産台数の定義

クライオモジュールの台数(1.3GHz空洞を装荷するもの):総数1824台

6空洞クライオモジュール:4台(e^+booster)

8空洞クライオモジュール:560台(Main Linac)＋36台(RTML)＋24台(e^-source)＋18台(e^+booster)＋2台(e^+keepalive)＝640台

9空洞クライオモジュール:1120台(Main Linac)＋60台(RTML)＝1180台

使用する1.3GHz ILC空洞の総数＝15,764台　(RDRの定義)

35MV/m以上の性能の空洞をクライオモジュールに使用すると仮定し、
15764台をすべて35MV/m以上とさせるためには 9.9%多く生産しなければならない。

(ただし、これはRDRの定義ではない)

15764 x1.099＝**17,325台の空洞生産が必要**

もし、日本が1/3の製造担当をすると、

超伝導空洞　17325台/3 /(5年) = 1155台/年

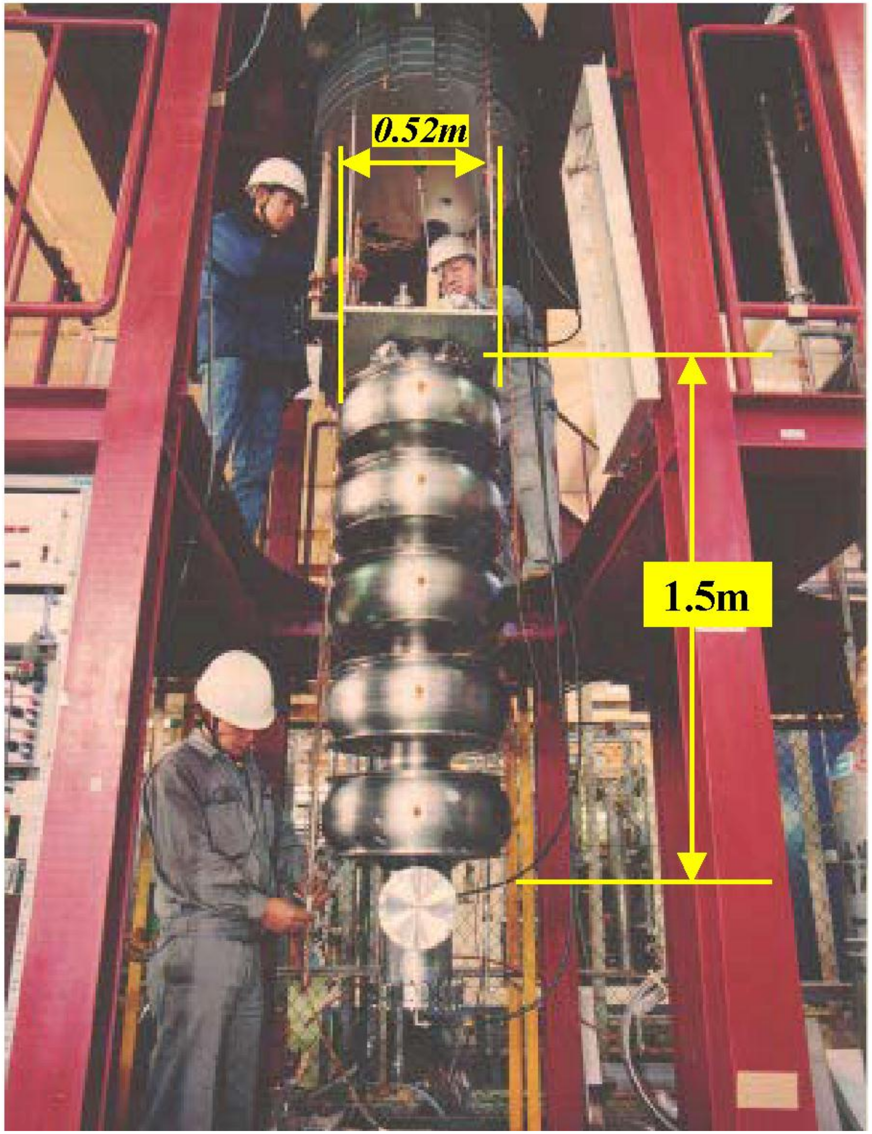
(1155台/200日 = 6台/日)

Hayano@AAA presentation

超電導空洞による加速器の歴史

プロジェクト	運転開始/終了	RF周波数 MHz	セル数	ユニット総数	Efffective Length m	Acc. Gradient MV/m	Total Voltage MV	コメント
TRISTAN KEK	1986/1995 1988/1995	509	5	32	48	5	200	Collider
HERA DESY	1990/2007	500	4	16	20	4	50	Collider
LEP/CERN LEP-II	1989/2000 1996/2000	352	4/NbCu	288	600	6	3400	Collider
CEBAF J-lab	1996~ 2008~	1500 1500	5 7	330 未定	165 増設	5->7.5 20	800->1200	recirculating
CESR Cornell	1997~	500	1	4	1.2	8	10	電流フロンティア
JlabFEL	1998~	1500	7				150	
KEKB KEK	1998~	509	1	8	2	6	12	電流フロンティア
SNS ORNL	2006~	805	6	33+48 Low-β/High-β	22+42	10(Low)/16(High)	892	陽子リニアック 1.3ms、60Hz
BEPC-II IHEP	2006~	500	1	1+1	0.25+0.25	1.6		Collider

TRISTAN @ KEK



TRISTANの超伝導空洞
ニオブ 508MHz ５セル空洞

世界で最初の大規模応用。
３２台を製造して使用した。

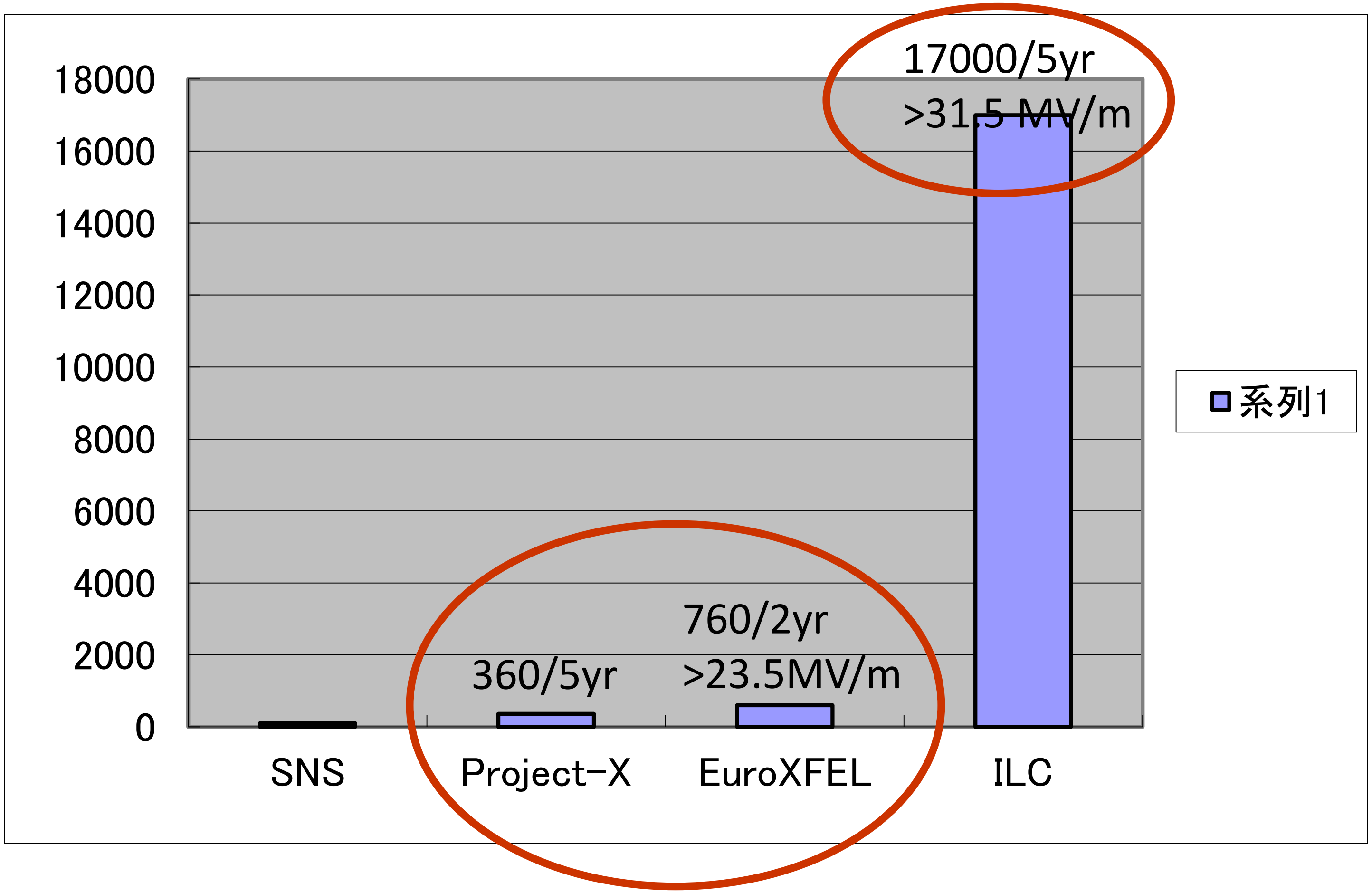
Superconducting Linac

- Designed and built by Jefferson Laboratory
- SCL accelerates beam from 186 to 1000 MeV
  - Reached 1011 MeV
  - Run at 890 MeV most of the time
- 81 Niobium cavities in 23 cryomodules (33 medium .61 beta, 48 high .81 beta)
- Cavities are now operated at 2.1 K
- Until Spring 2007 mostly run at 4.5 K (can run up to 30 Hz, 1.3 msec RF pulse width)

ILCの空洞製造数は文字通り桁違い

加速空洞
多セル超伝導
空洞の総数

ハイテック装置
の大量生産
品質管理
コストダウン

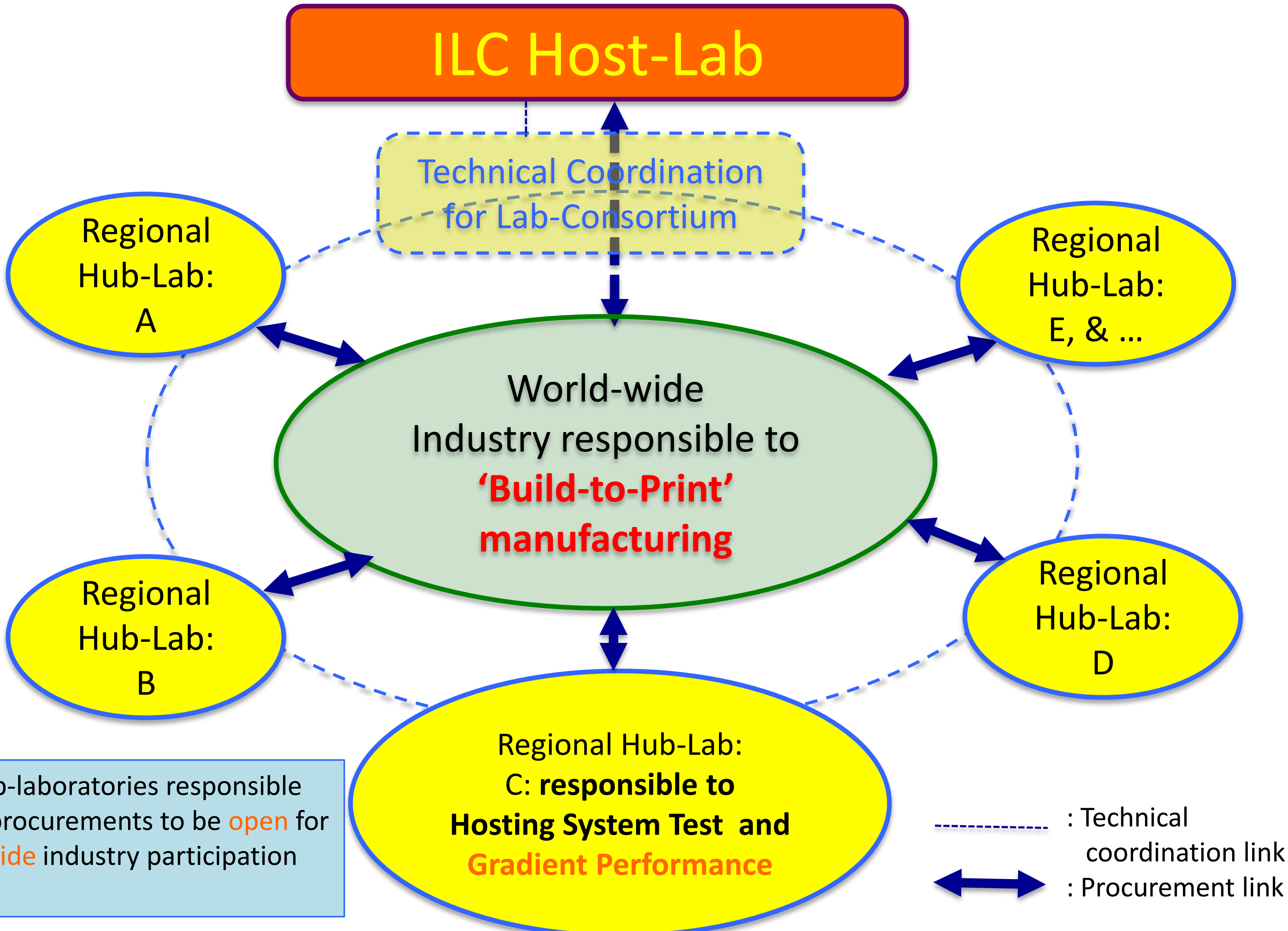


Toward Industrialization

- Global status of Industries
  - Research Instruments (ACCEL) and Zanon in Europe
  - AES, Niowave, Roak, PAVAC in Americas
  - MHI, Hitachi, Toshib, and others in Asia

Project Scope			Assuming 200 work-days/yr
SNS	~ 110	3years	< ~ 1 cavity / week
XFEL → ÷ 2 vendors	~760	2 years	380/yr : ~ 1.9 cavity/day → 0.95 /day/vendor
Project X	~360	4-5 years	72/yr : 1.8 cavity / week
ILC			
Single vendor model	~15,500 + spare	5 years	~3100/yr → 16/day ~3400/yr → 17/day
6 vender model (3 regions x 2)	same	same	→ ~ 570/yr → 2.8/day/vendor

SCRF Procurement/Manufacturing Model



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

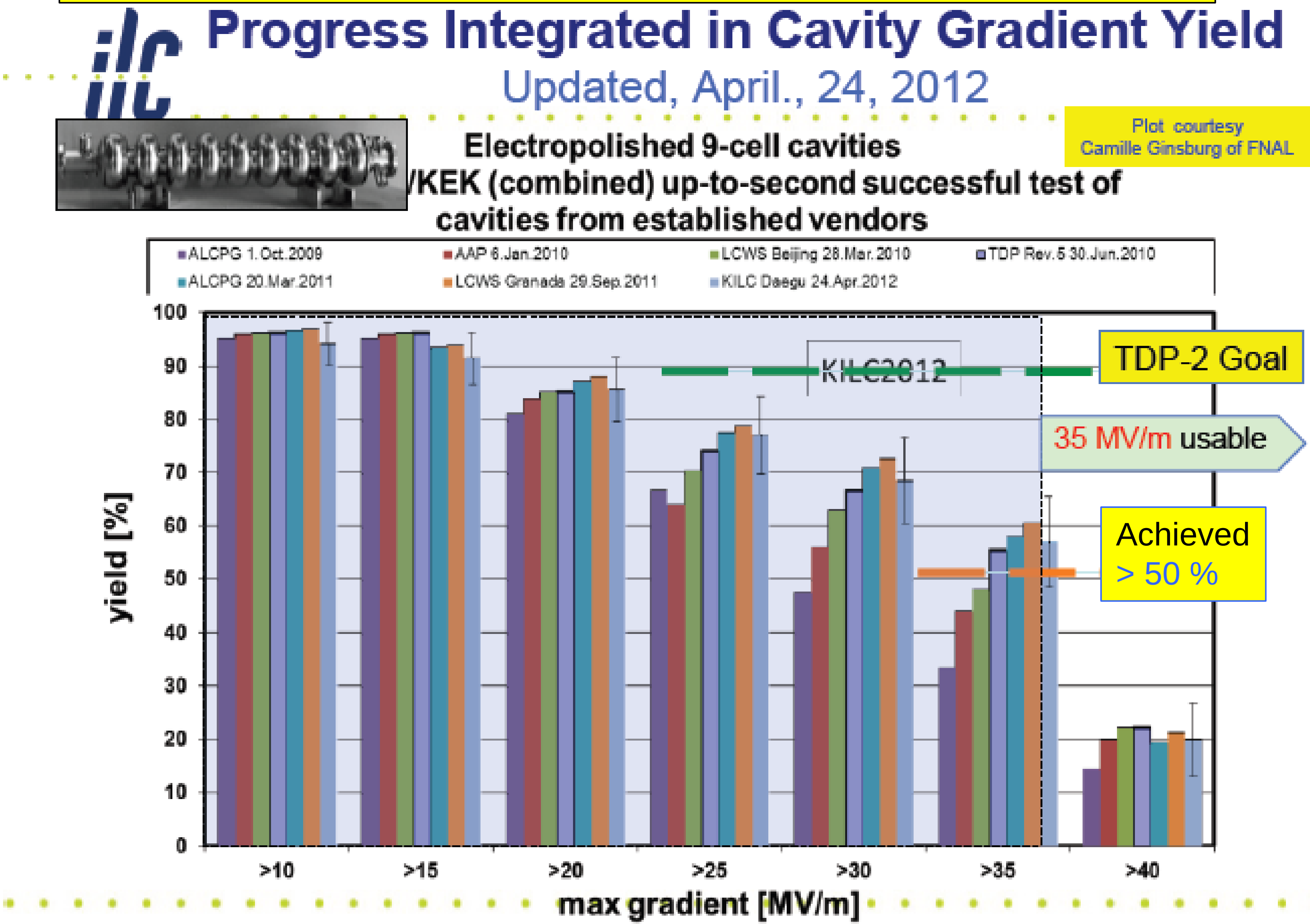
Visiting Companies in Progress
(and further plan)

	Date	Company	Place	Technical sbject
1	2/8	**Hitachi**	Tokyo (JP)	Cavity/Cryomodule
2	2/8	**Toshiba**	Yokohana (JP)	Cavity/Cryomodule, Magnet
3	2/9	**MHI**	Kobe (JP)	Cavity / (Cryomodule)
4	2/9	**Tokyo-Denkai**	Tokyo (JP)	Material (Nb)
5	2/18	**OTIC**	NingXia (CN)	Material (Nb, NbTi, Ti)
6	3/3	**(Zanon) mtg at INFN**	Verona (IT)	Cavity/(Cryomodule)
7	3/4	**RI**	Koeln (DE)	Cavity (Cryomodule)
8	3/14, (4/8)	**AES**	Medford, NY (US)	Cavity (Cryomodule)
9	3/15, (4/7)	**Niowave**	Lansing, MI (US)	Cavity/ (Cryomodule)
10	4/6	**PAVAC**	Vancouver (CA)	Cavity, EBW-machine
11	4/25	**ATI Wah-Chang**	Albany, OR (US)	Material (Nb, Nb-Ti, Ti)
12	4/27	**Plansee**	Ruette (AS)	Material (Nb, Nb-Ti, Ti)
13	5/24	**SDMS**	Sr. Romans (FR)	Cavity, Vessel, joint
14	7/6	**Heraeus**	Hanau (DE)	Material (Nb, Nb-Ti, Ti)
15	9/14	**Zanon**	Verona (IT)	Cryomodule
16	11/16	**SST**	Munchen (DE)	EBW-machine

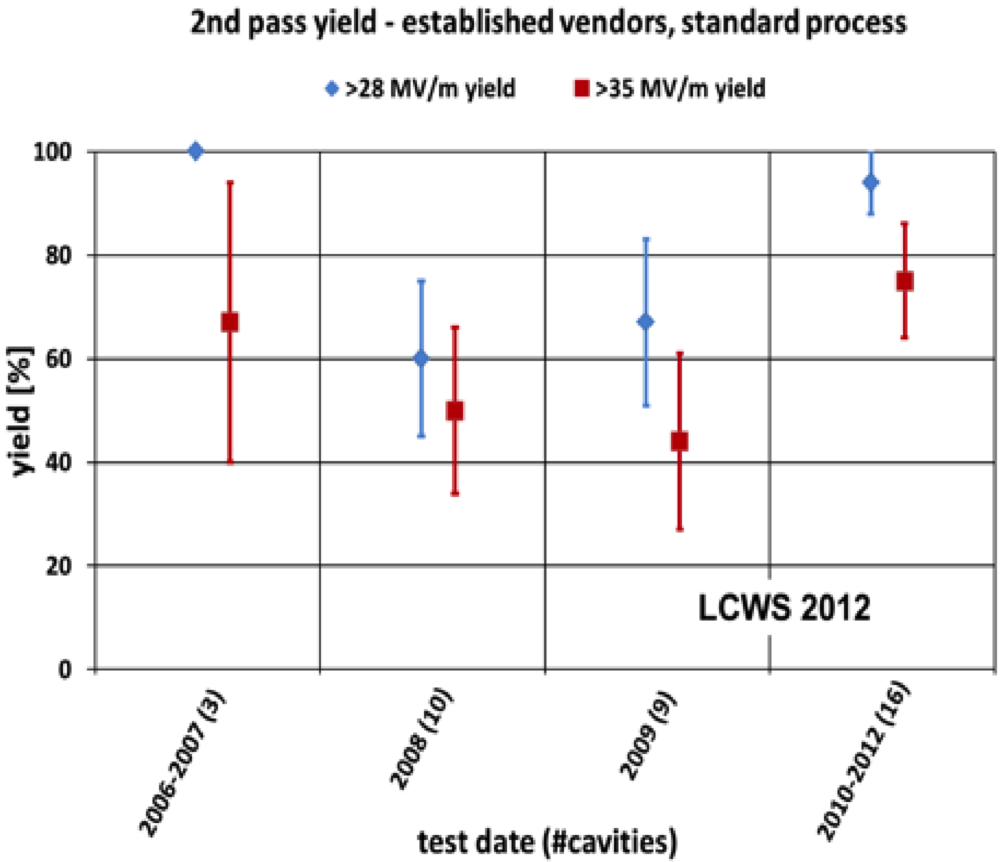
Slide by A. Yamamoto

世界の超伝導空洞性能（３極平均）

RDRでは、製造受け入れ性能>35MV/mで90%の歩留まり（Yield）を仮定している。



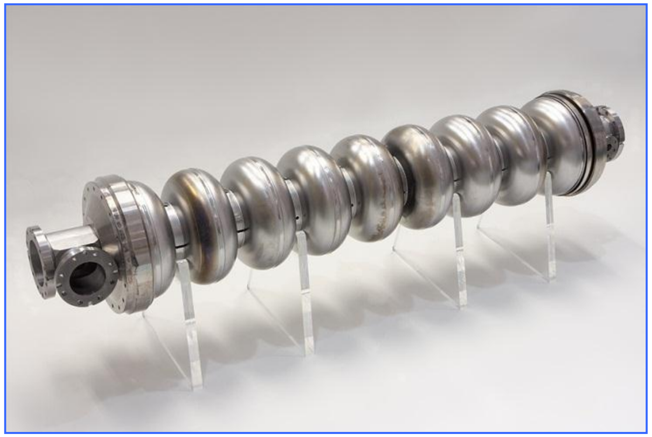
Progress in SCRF Cavity Gradient



Production yield:
94 % at > 28 MV/m,

Average gradient:
37.1 MV/m

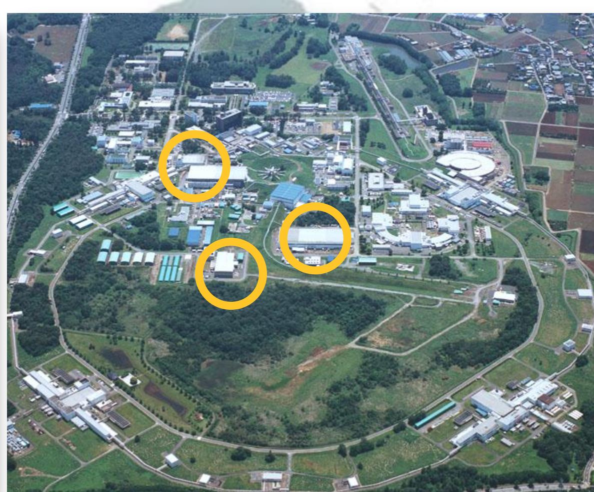
reached (2012)



Issues of mass-production:
High Quality Assurance (QA)
Cost Reduction

ILCの技術開発を行っている世界の主な研究所

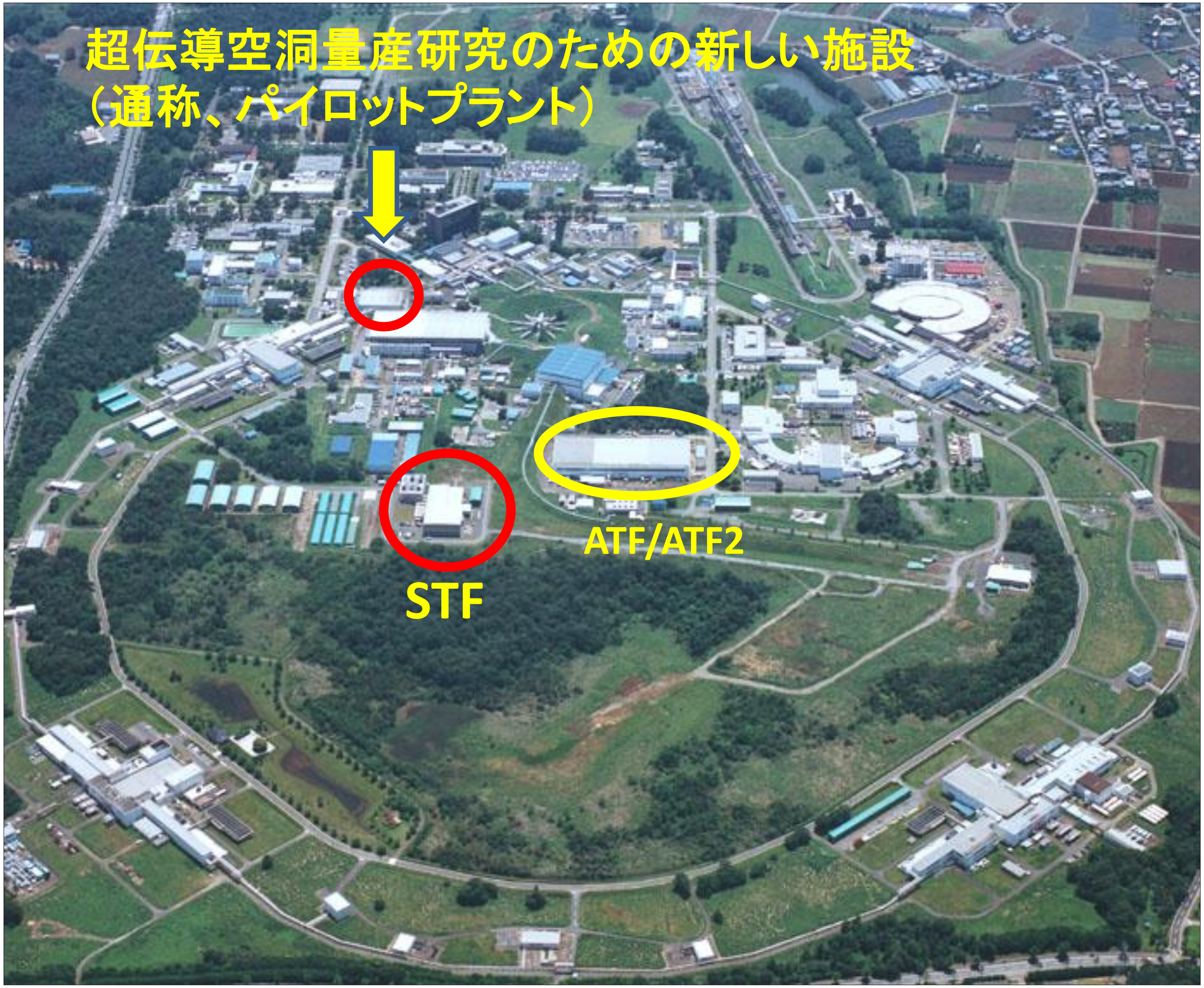
FLASH@DESY



STF@KEK

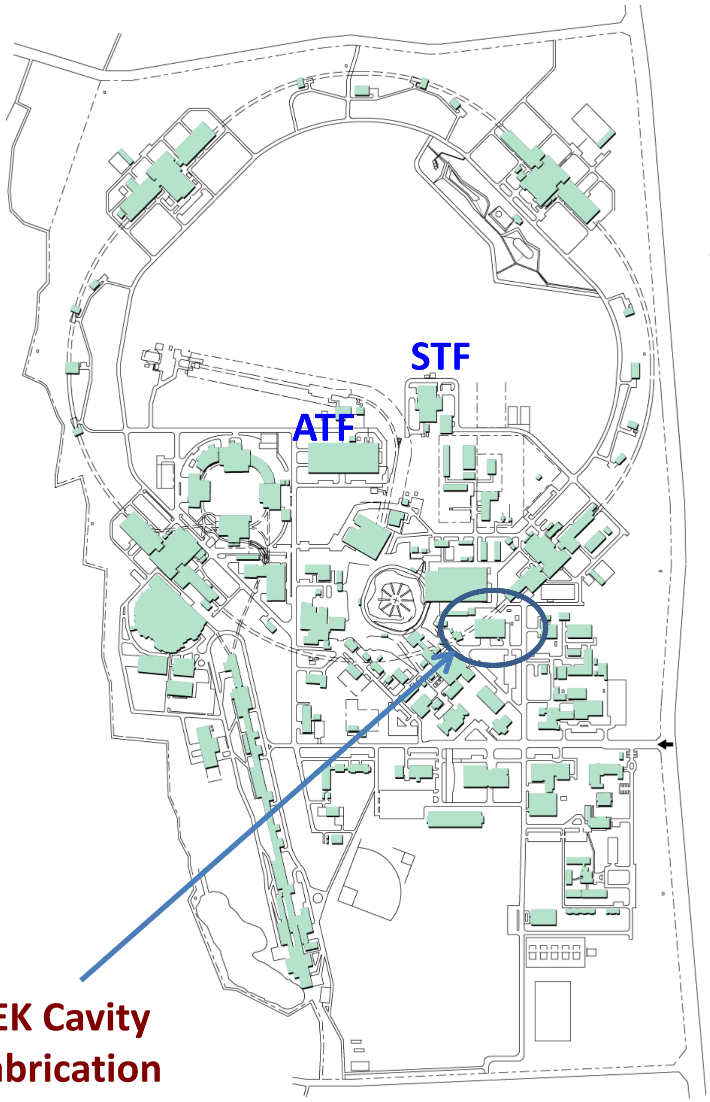
ILCTA@FNAL

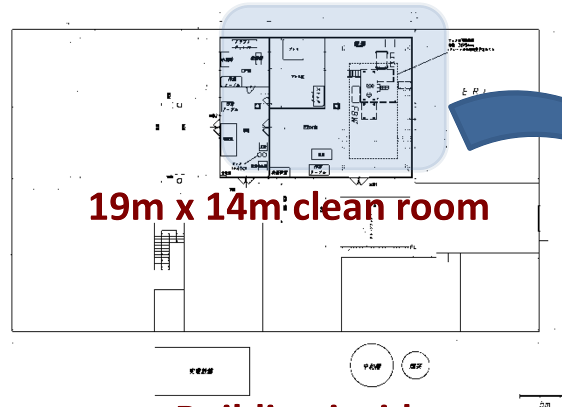
ILC Test Facilities at KEK

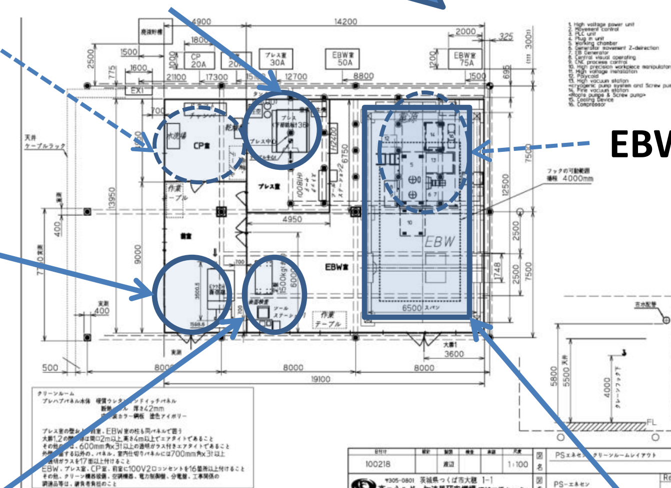


KEK　つくばキャンパス（北側上空より）

KEK Cavity Fabrication Facility







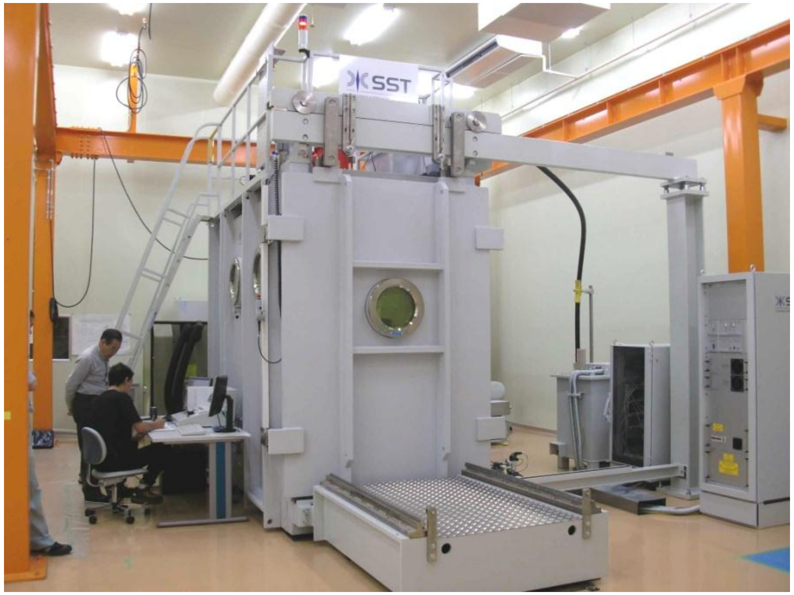
Slide by Hayano

EBW delivery on April 12, 2011

12th April 2011

Main Machines in the facility

EBW



SST EBOCAM KS-110 – G150KM
Chamber (Stainless Steel chamber)

Press

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

Trim

MORI VKL-253
Vertical CNC lathe

Tape-cut Ceremony on
July 13,2011
for
EBW operation start.

Chemi-room

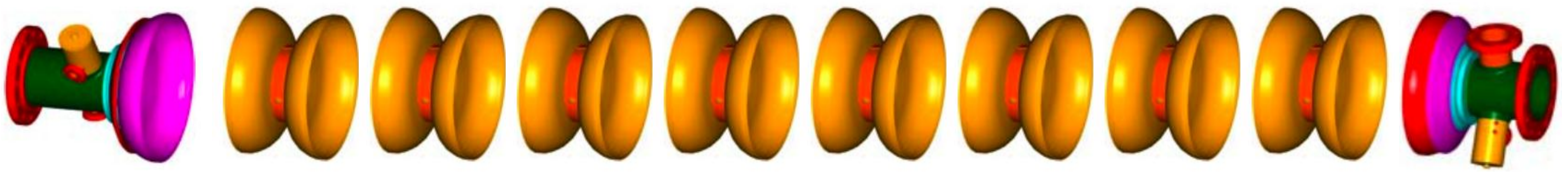
Production procedure of 9-cell cavity for ILC

Dumbbell = EBW of two cups:

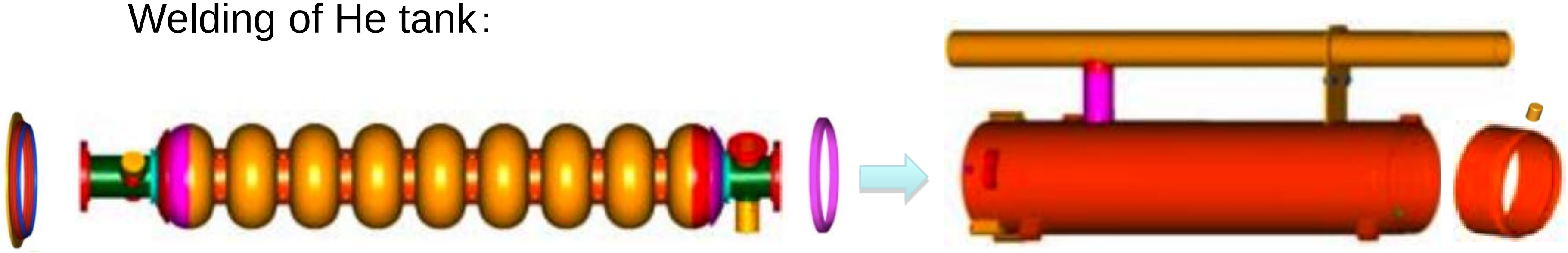
Dumbbell

8 dumbbells are needed for one cavity

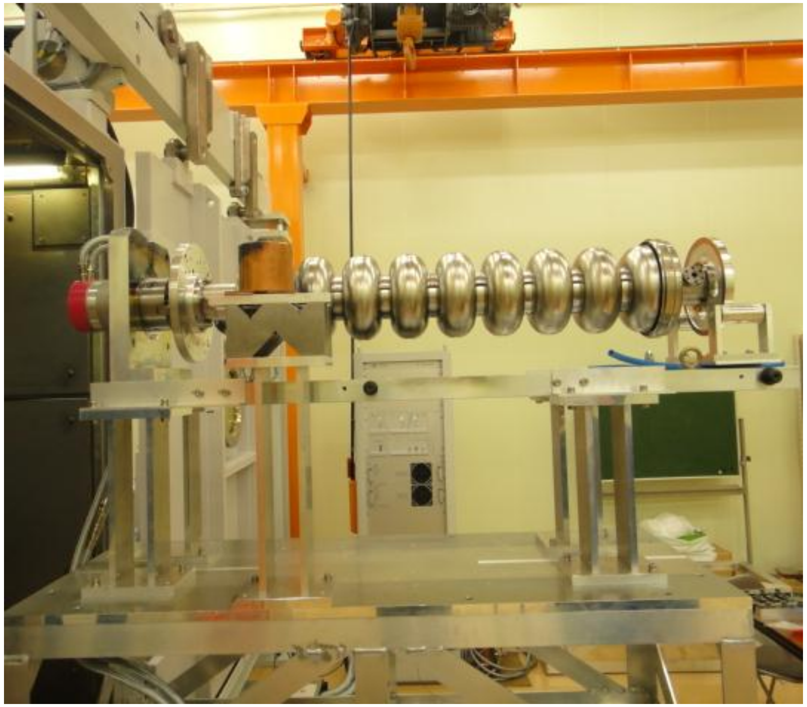
EBW assembly of all parts:



Welding of He tank:



KEK-0号機（試作機）　溶接作業



開先形状と溶接条件をKEKが管理して、
ジョブショップにて製作した部分

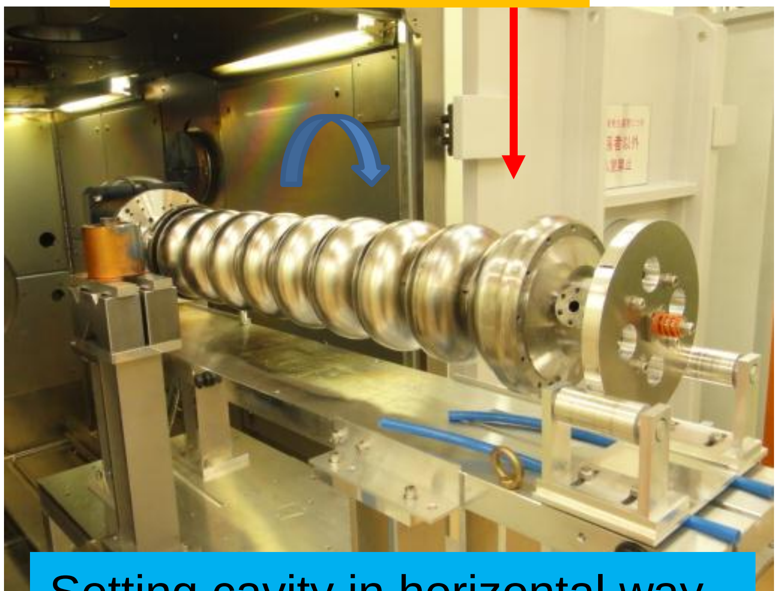
KEK内の空洞製造施設
にて溶接した部分

KEK内の空洞製造施設
にて溶接した部分

試作空洞の完成（2012年1月31日）

Configuration choice of cavity attitude and gun position

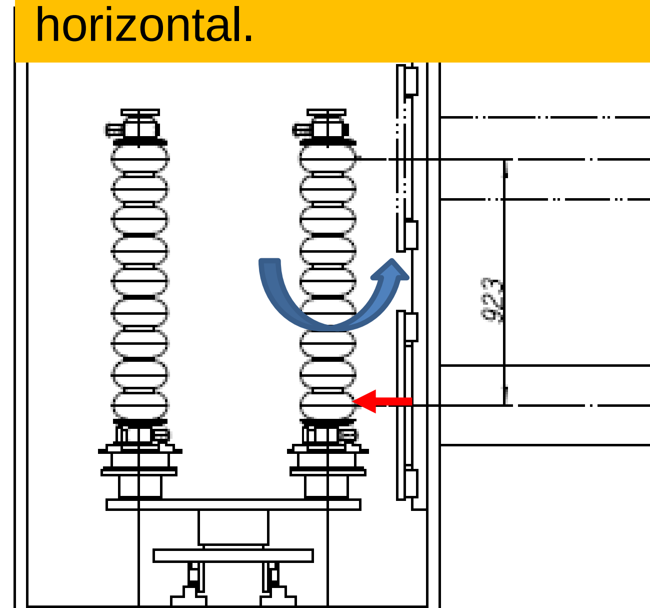
Direction of electron beam is vertical.



Setting cavity in horizontal way is rather compllicated (KEK-00).

Direction of gravity.

Direction of electron beam is horizontal.



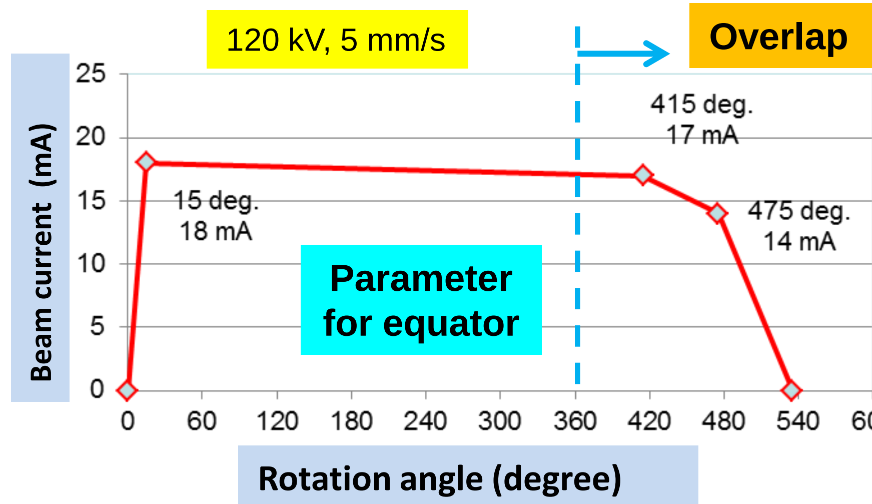
Setting cavity in vertical way is simple (KEK-01).

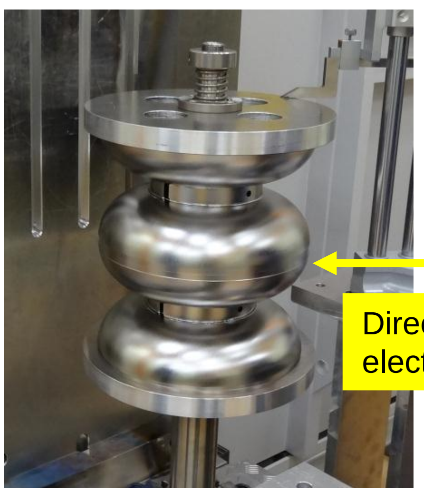
Stacking dumbbells is easy in the vertical configuration of cavity.

Better for mass-production.

Multi-dumbbell EBW at equator (KEK-01)

EBW test by a dummy Nb-pipe



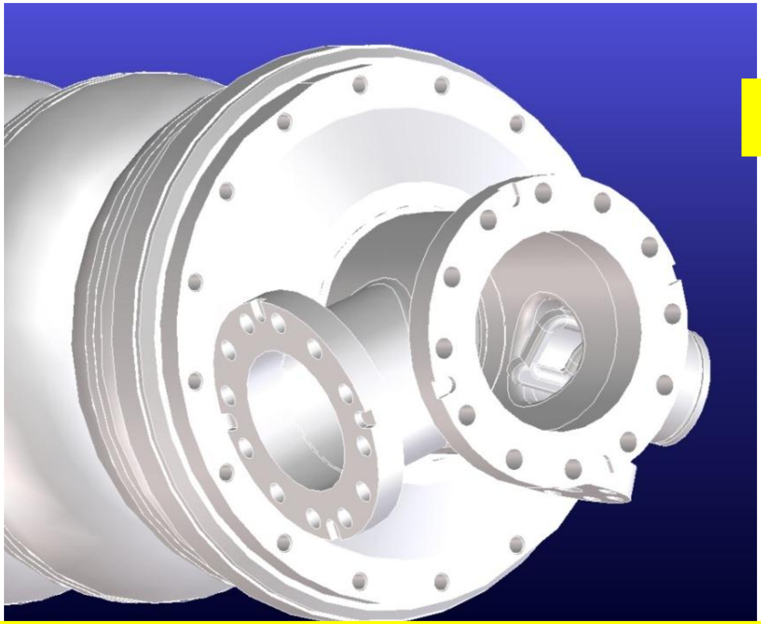


EBW of 2-dumbbell

EBW of 4-dumbbell

Smooth inner surface of welding-seam was achieved.

Complicated shapes of HOM couplers



HOM coupler

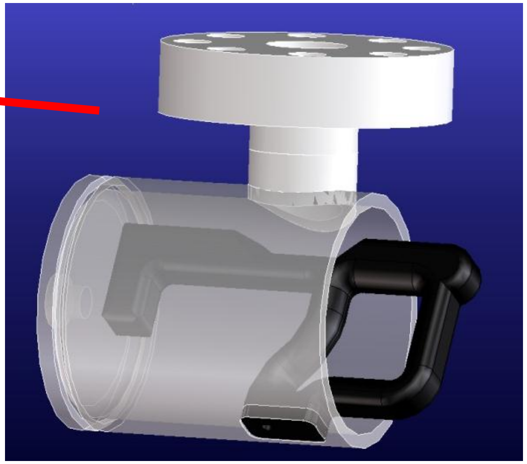
Complicated machining and EBW of parts is needed for fabrication of HOM couplers

HOM can

HOM antenna

Fabrication of HOM cup by deep-drawing for KEK-01

End-group shape is complicated and then there is a possibility of cost-reduction in fabrication.

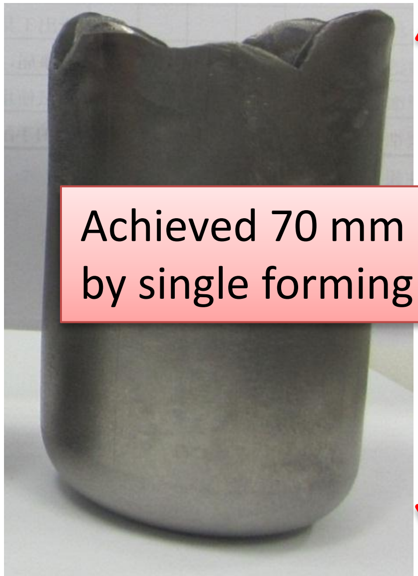


HOM cup（φ48×64）

Conventional method：Deep-drawing by multiple press-forming with annealing.

New method：Deep-drawing by single press-forming.

Nb sheet thickness: 2.8 mm



Achieved 70 mm by single forming

Trial to fabricate the freq. tuning tab by press-forming. (Under study)

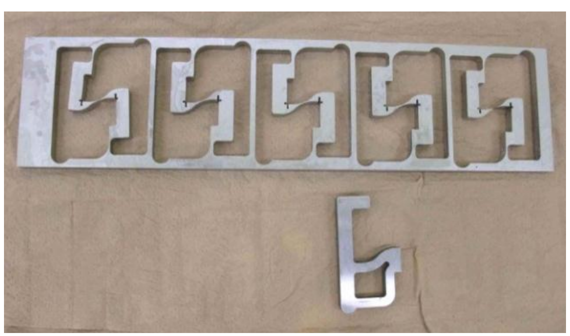
Collaboration with industry:
Shinohara Press Service Co. Ltd.

SHINOHARA

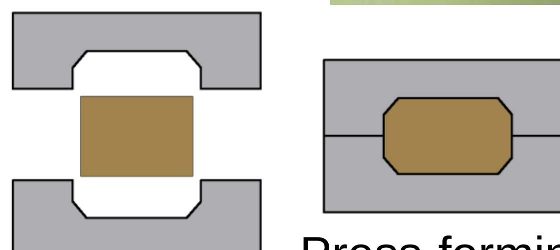
Fabrication of HOM antenna by water-jet cutting and press-forming for KEK-01

Conventional method: Machining
New method: Water-jet cutting
+ Press-forming

Water-jet cutting in a job shop



Collaboration with SHINOHARA

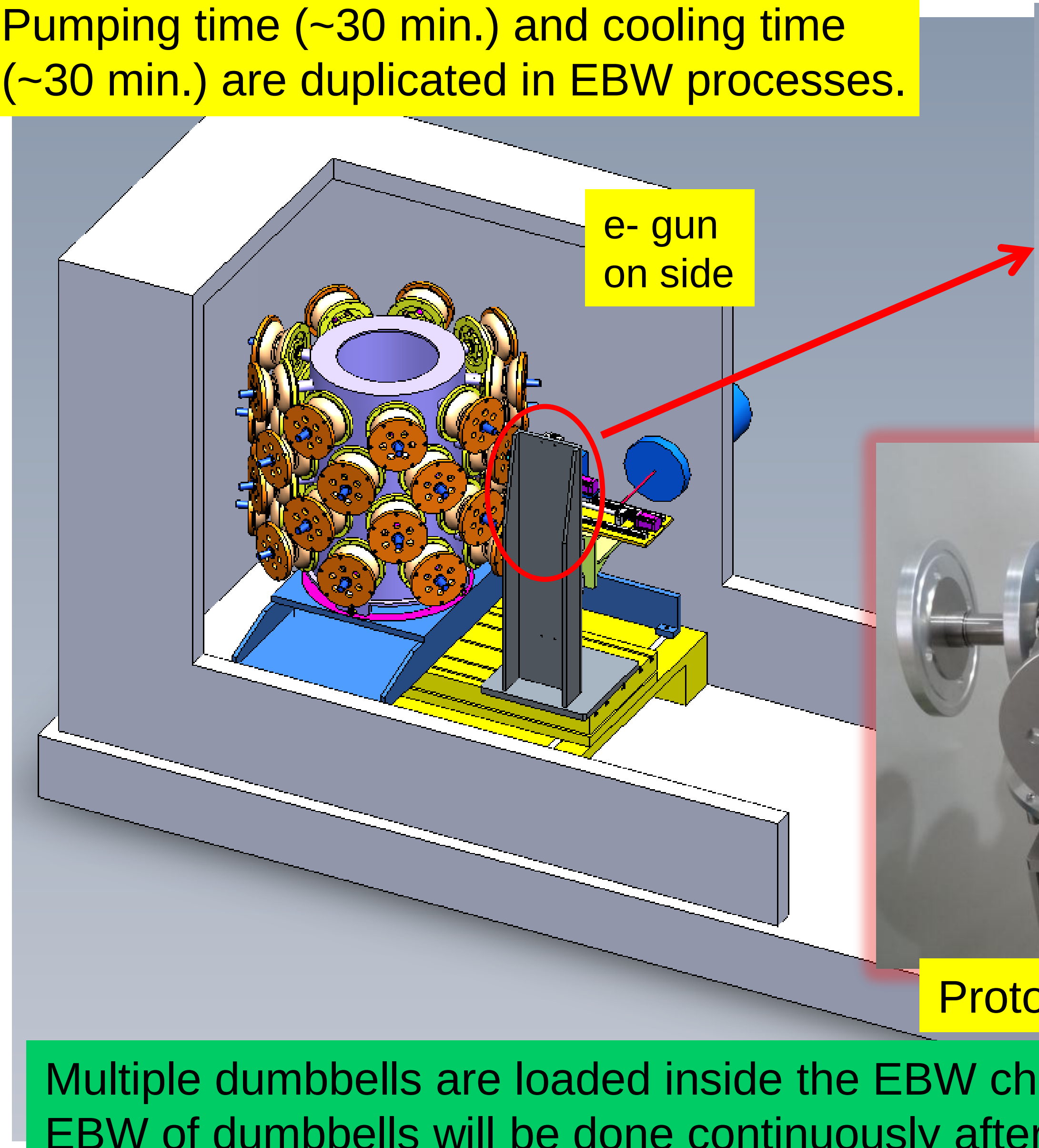


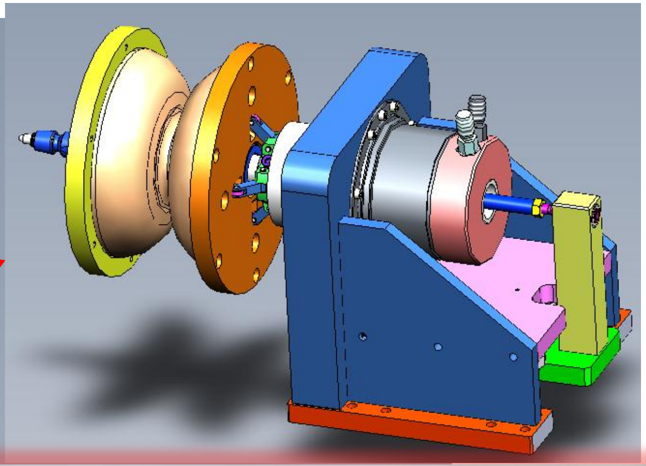
Press-forming

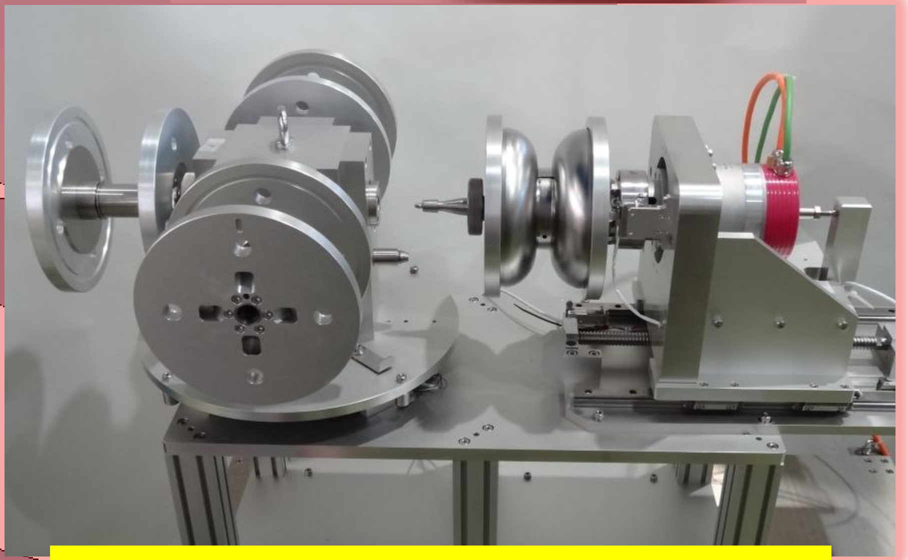
Result of low power test is OK. (Master thesis by F. Yasuda, Jan. 2013, the university of Tokyo, JAPAN)

Design of loader for multiple dumb-bells

Pumping time (~30 min.) and cooling time (~30 min.) are duplicated in EBW processes.



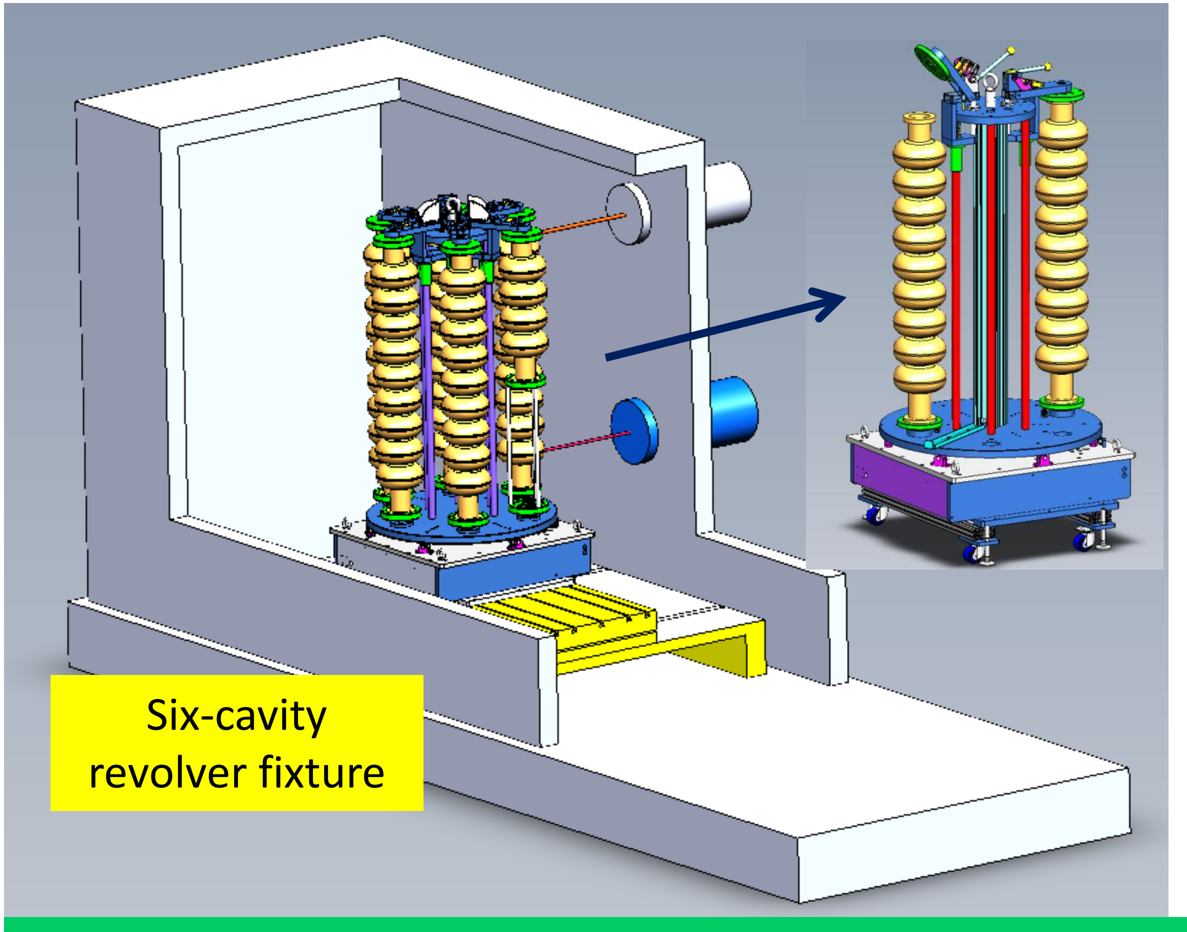




Proto-type of four-dumbbell loader

Multiple dumbbells are loaded inside the EBW chamber at once and the EBW of dumbbells will be done continuously after pumping down.

Design of 9-cell cavity fixture for EBW machine

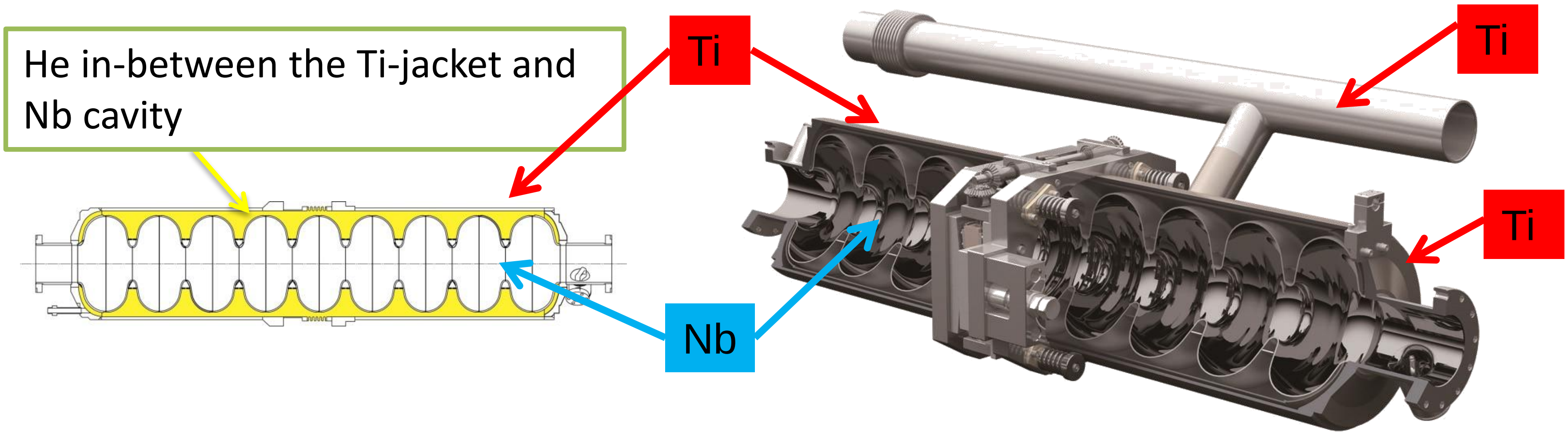


Six-cavity revolver fixture

Proto-type of revolver fixture

Pumping time (~30 min.) and cooling time (~30 min.) are duplicated in EBW process. The time is reduced if multiple-seams are welded in one pumping cycle.

Japanese High-Pressure Gas safety act



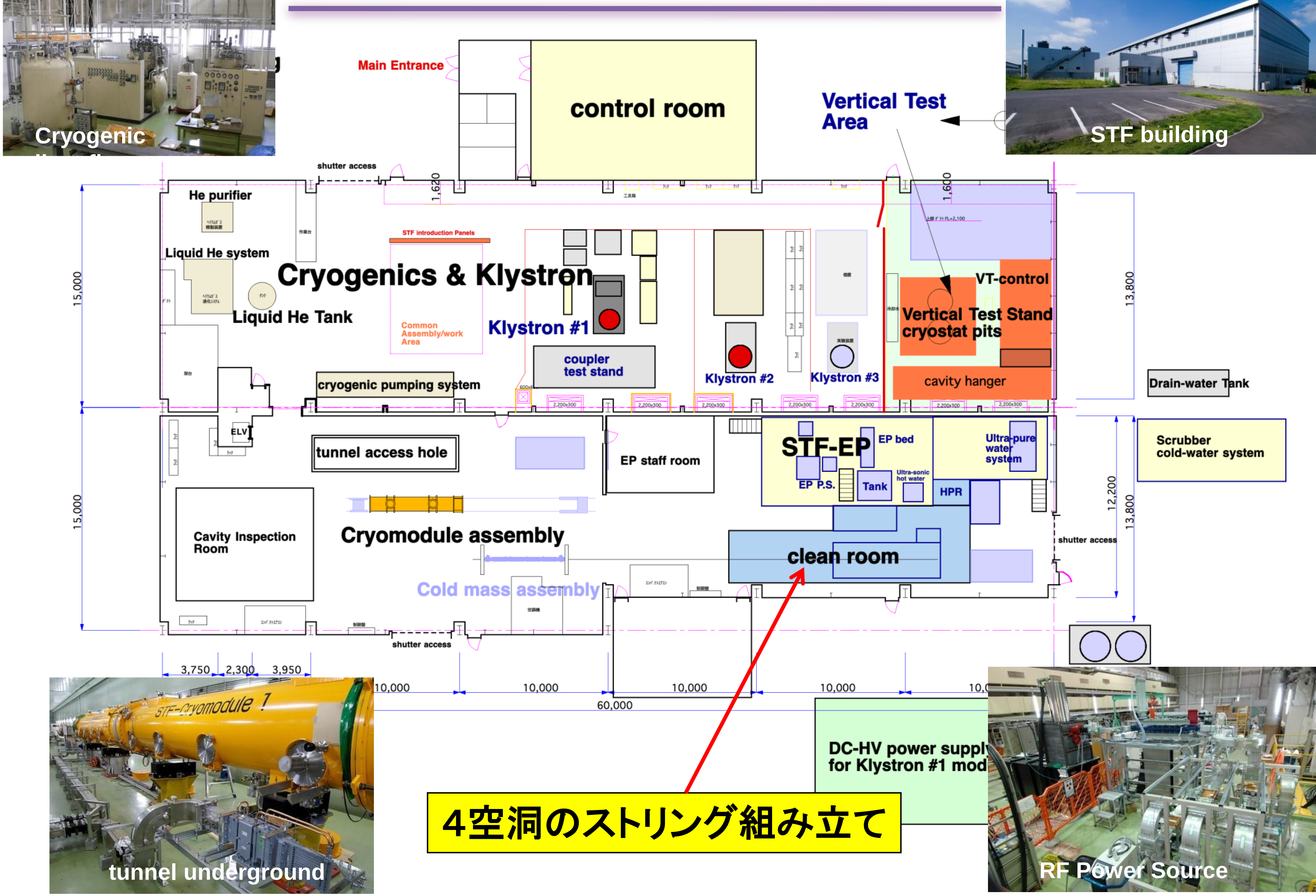
One must fabricate cavities complying with Japanese High-Pressure Gas (J-HPG) safety act if we use the cavities in accelerators.

For cavities by venders,
Manufacturer: KEK
Applicant: venders

For cavity KEK-03 in CFF,
Manufacturer: KEK
Applicant: KEK/CFF

In case of ILC in Japan, a significant fraction of cavities might be imported from foreign vendors. KEK/CFF can guide them for the procedures of J-HPG safety act.

STF (Superconducting RF Test Facility)



4空洞のストリング組み立て

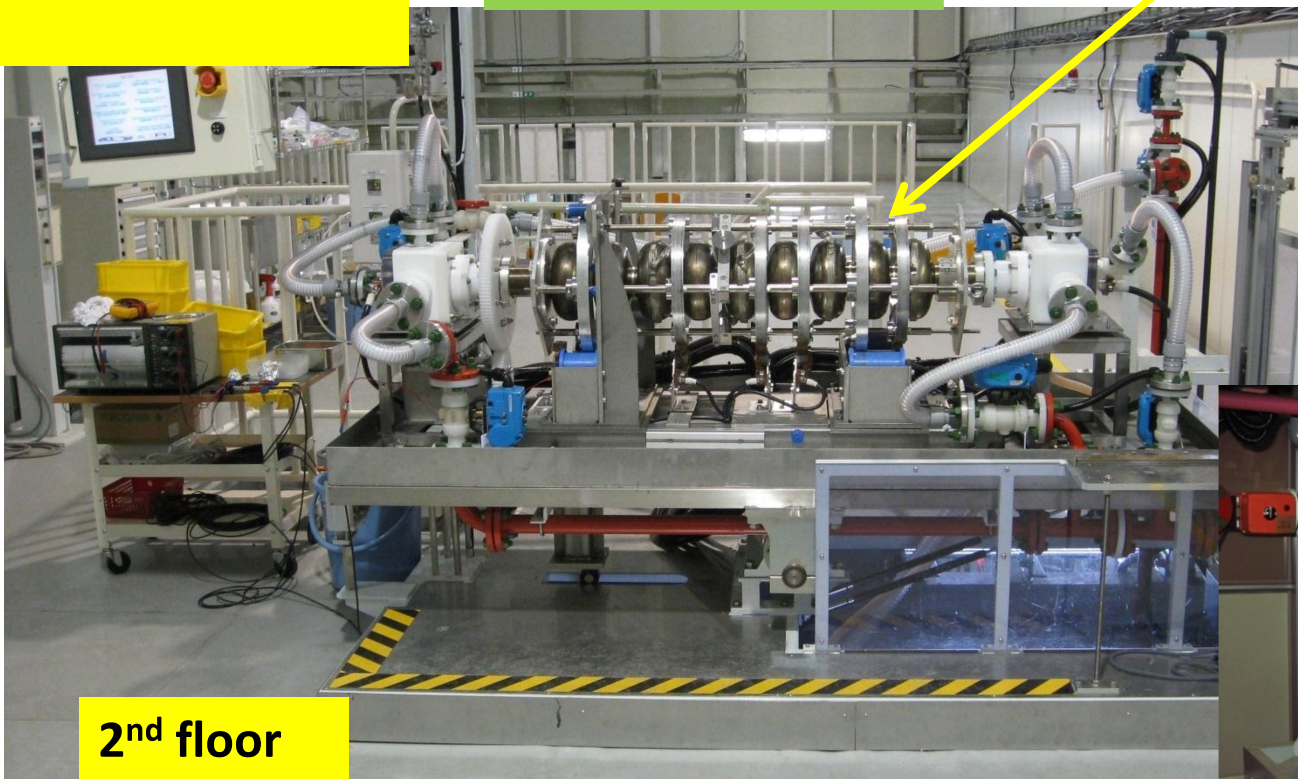
EP facility at STF/KEK

Automatic Operation Console

1st EP bed

9-cell cavity

EP acid: HF + H_2SO_4
Aluminum anode,
surface removal speed: 20μm/hour,
~18V ~270A ~30degC (for 9-cell)
cavity rotation: 1 rpm



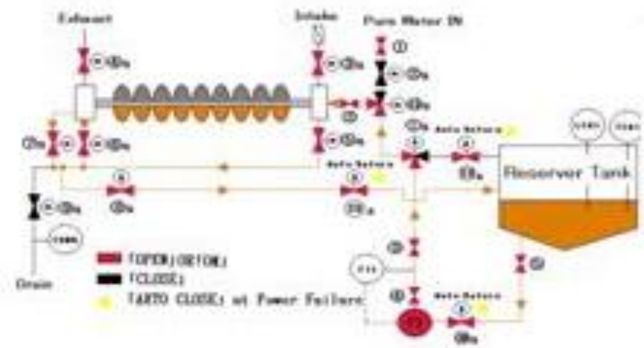
2nd floor

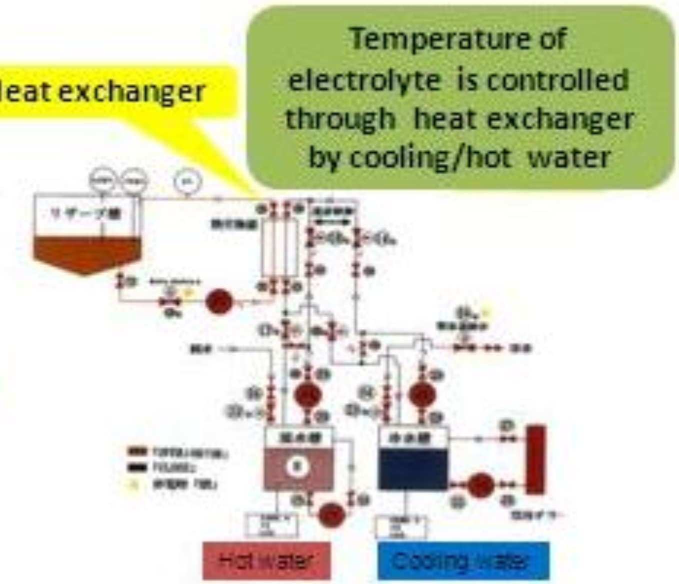
1st floor

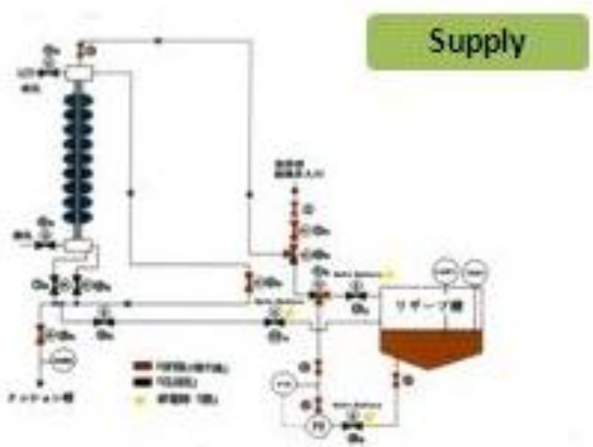
EP solution reservoir tank

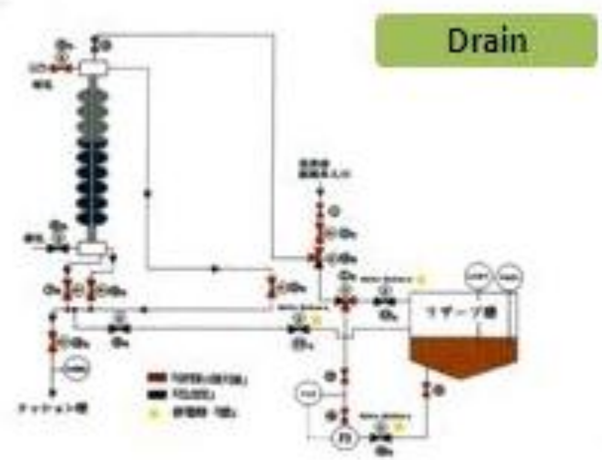
New EP facility at KEK was constructed in 2008, instead of old Nomura EP facility.

EP process at STF-KEK

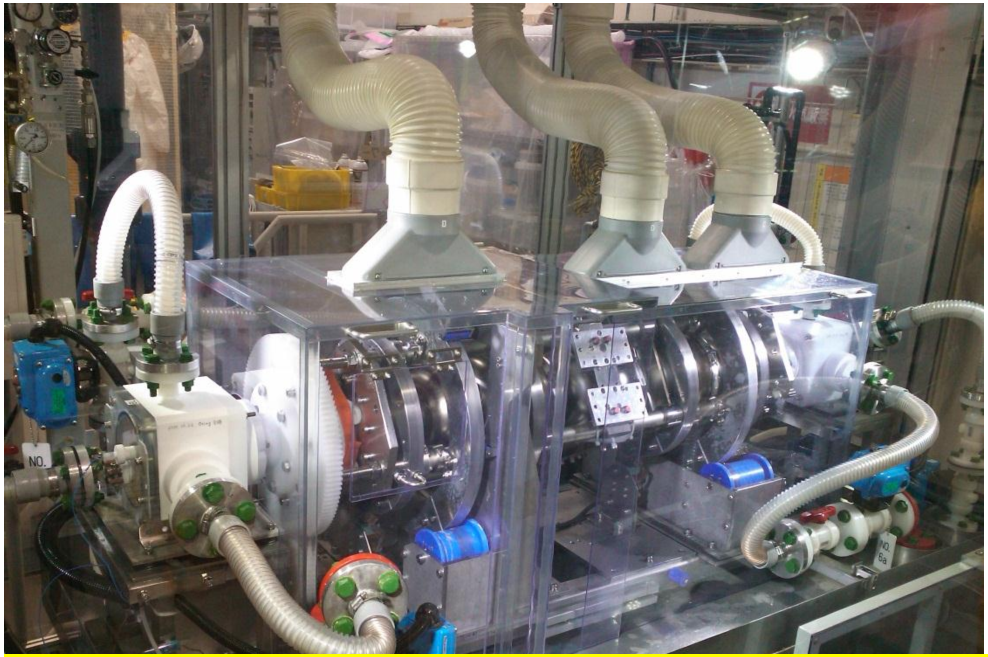








Surface treatment of 9-cell cavity (KEK-00) at STF/KEK



Bulk EP (100 um), Degreasing (50 ^{0}C, 30 min.), HPR (1.5 h), Annealing(4 h, 750 ^{0}C), and final EP (20 um)

HPR (7 hours)

Brushing

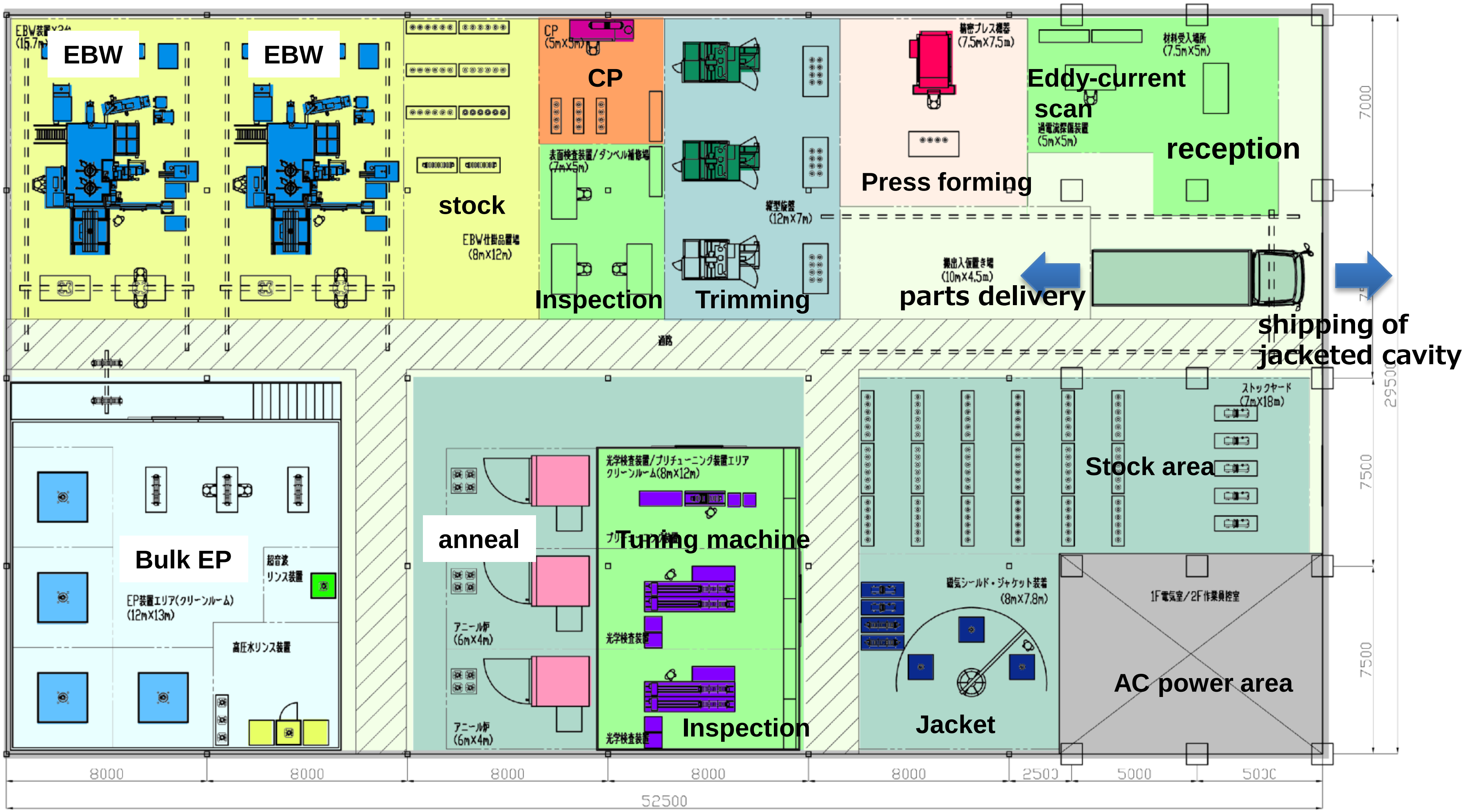
Brushing of beam-pipe and HOM antenna. Degreasing with detergent (FM-20 2%) in hot bath (50^{0}C, 30 min.)

Estimation of cavity production plant

Slide by Hayano

KEK-MHI

Plant Simulation study using CFF housing area (53m x 30m)



Assuming Nb plates for cell, fabricated end-group parts are input,
200 working days/year, 2 shifts/day with 30 people times 2 shifts

Max. production rate will be ~530 cavities/year, ~2650 cavities for 5years.

Assuming that final treatment and vertical test will be done in other place.

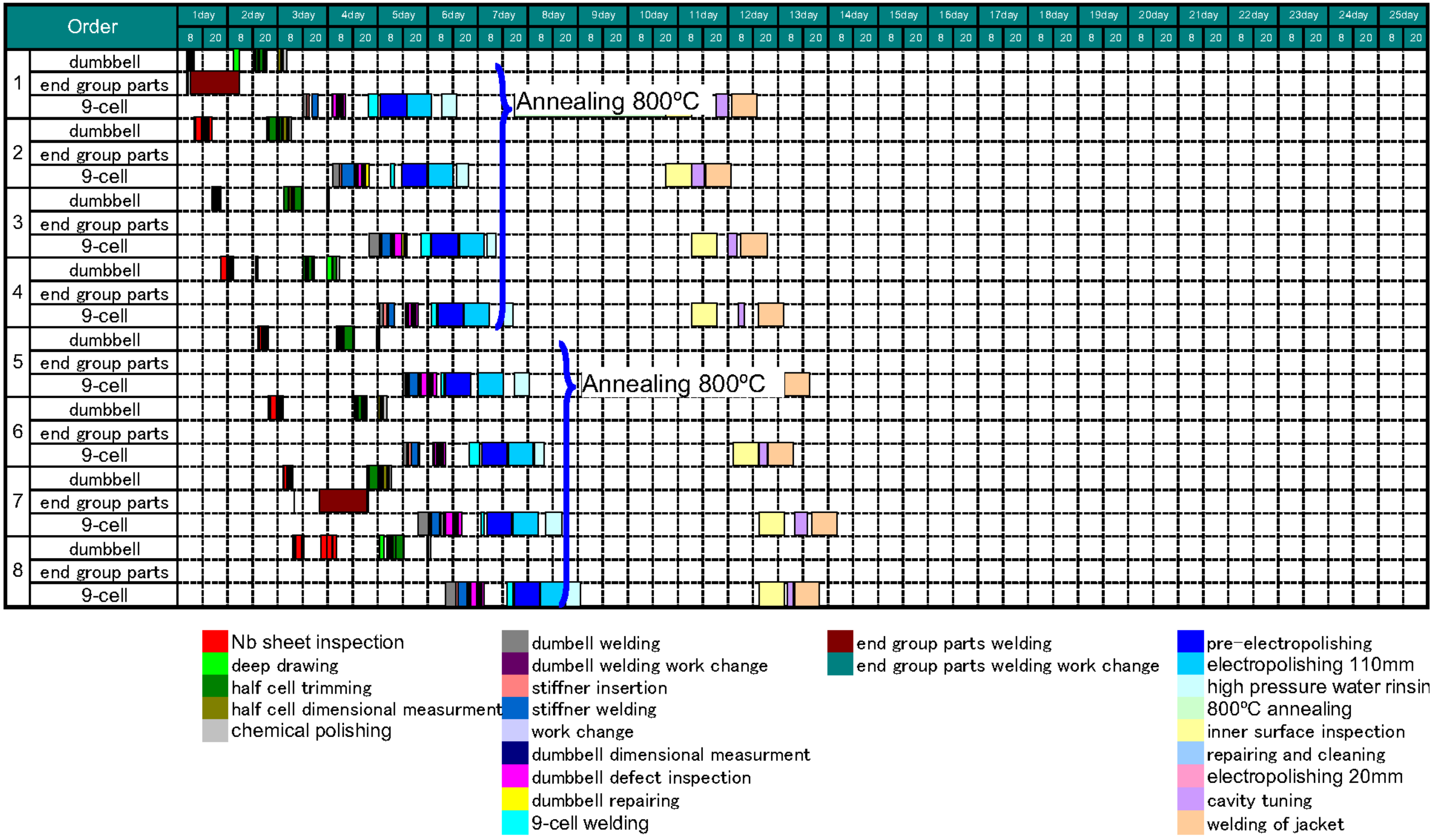
電解研磨設備の例

Saclay Vertical-EP

Cavity production Gantt chart

Slide by Ishii

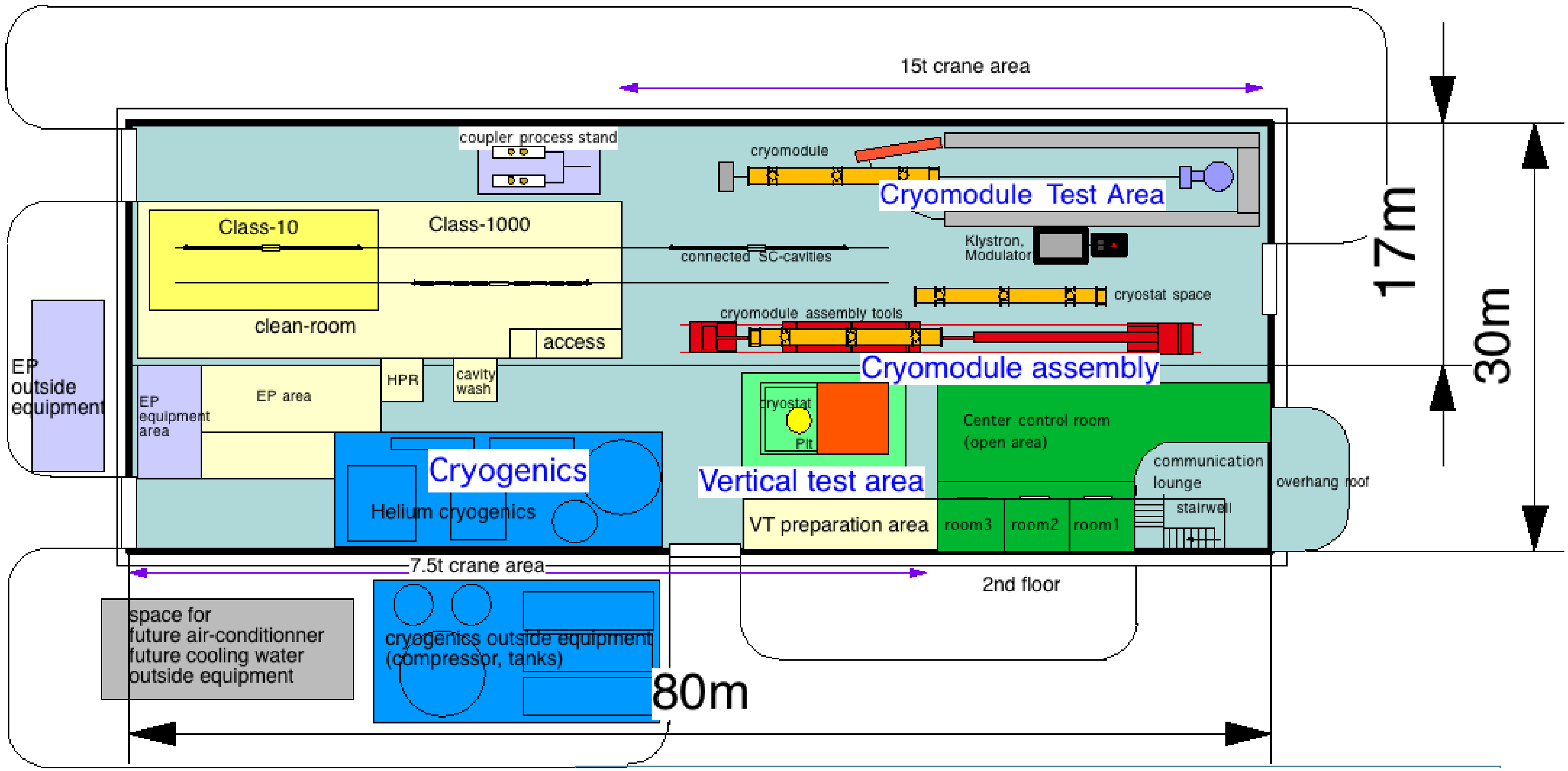
MITSUBISHI HEAVY INDUSTRIES, LTD.
TECHNOLOGY & INNOVATION HEADQUARTERS



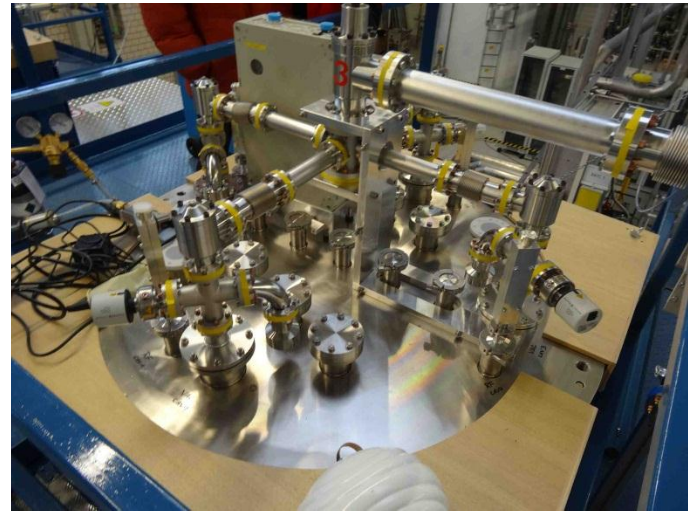
新規施設

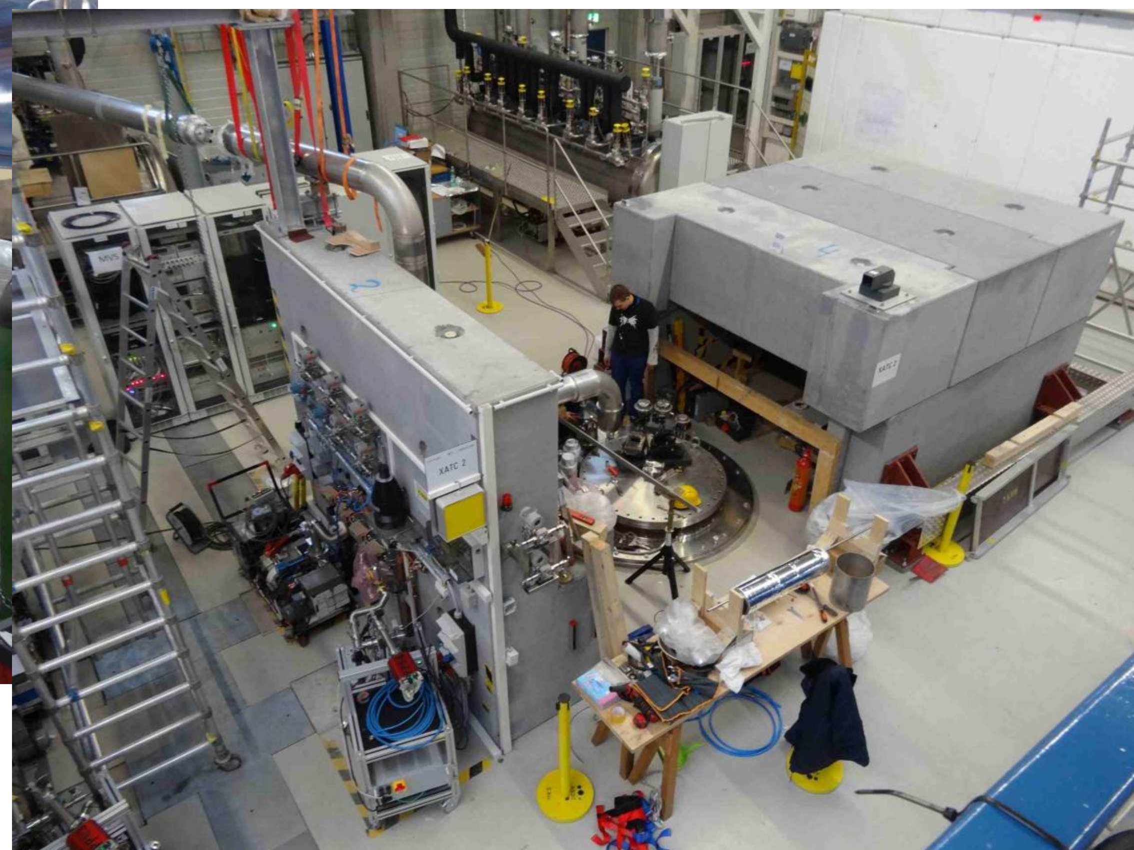
超伝導加速器利用促進化推進棟（新設）
30m
80m
2013年整備
革新的産学連携推進エリア
STF（既設）
STFトンネル（既設）
ATF
量子ビーム利用新機軸創出エリア

超伝導加速器利用促進化推進棟の機器配置図



4台空洞用　縦測定設





DESY AMTF

Accelerator technology - collaborative effort

Industrial study module assembly (M6 done, M8 autumn 2007)

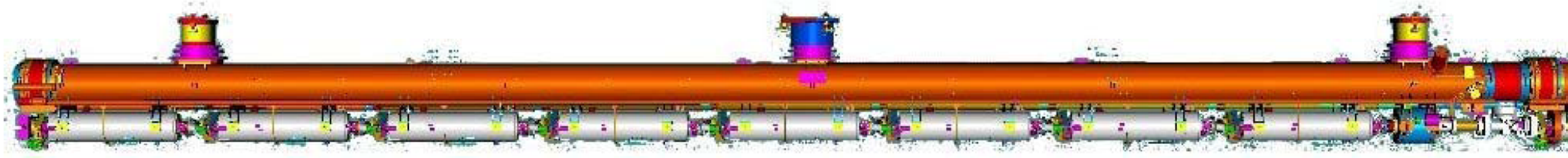
2 more cryostats (TTF3/INFN) delivered

Superferric magnet (CIEMAT)

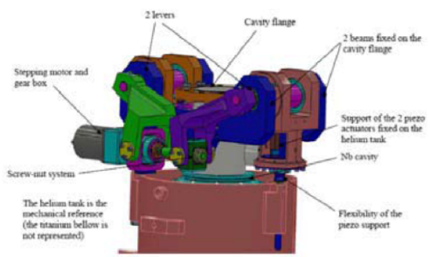
BPM (Saclay)

超電導空洞：760台

Integrated HOM absorber

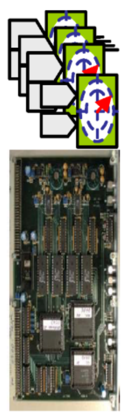


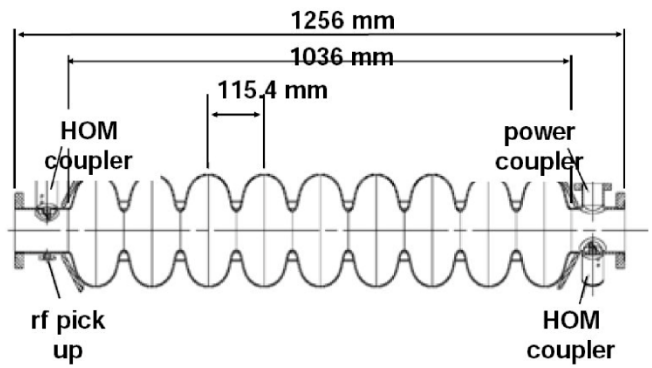
Length quantized n·λ/2 (possibility of ERL)



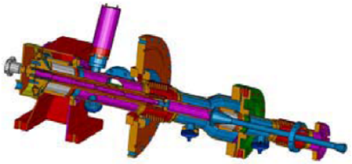
Tuner w/piezo (Saclay)

Industrialization in preparation





LLRF development (collab. Warsaw/Lodz)



TTF3-type coupler

Industrialization launched (Orsay)

ILCとほぼ同じtechnology

Civil Construction for the European XFEL

Slide by H. Weise

Civil Construction

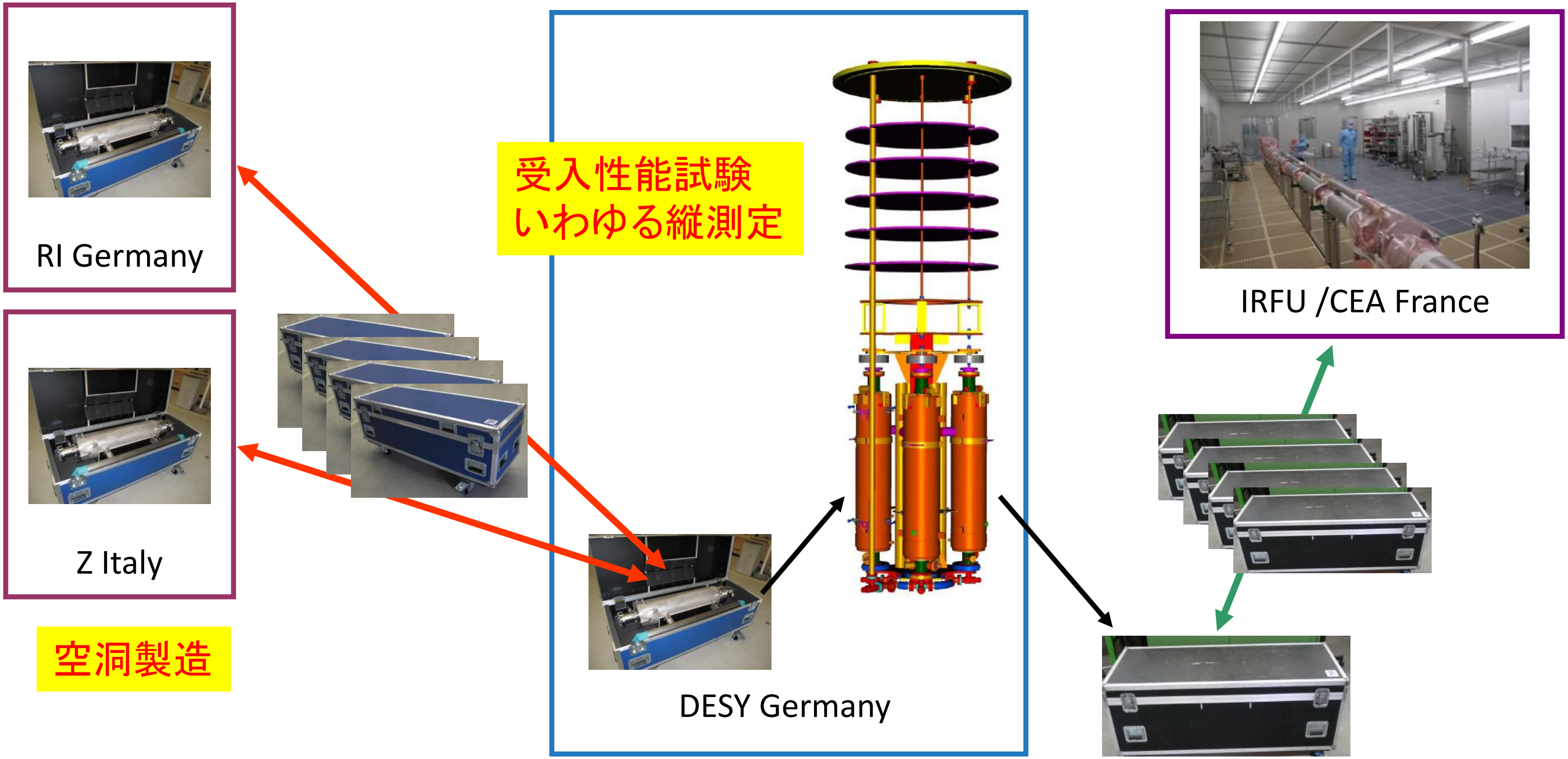
Slide by H. Weise

RI: 380 cavities / 2 year
Zanon: 380 cavities / 2 year
Total 760 cavities / 2 year

DESY

ストリング組立

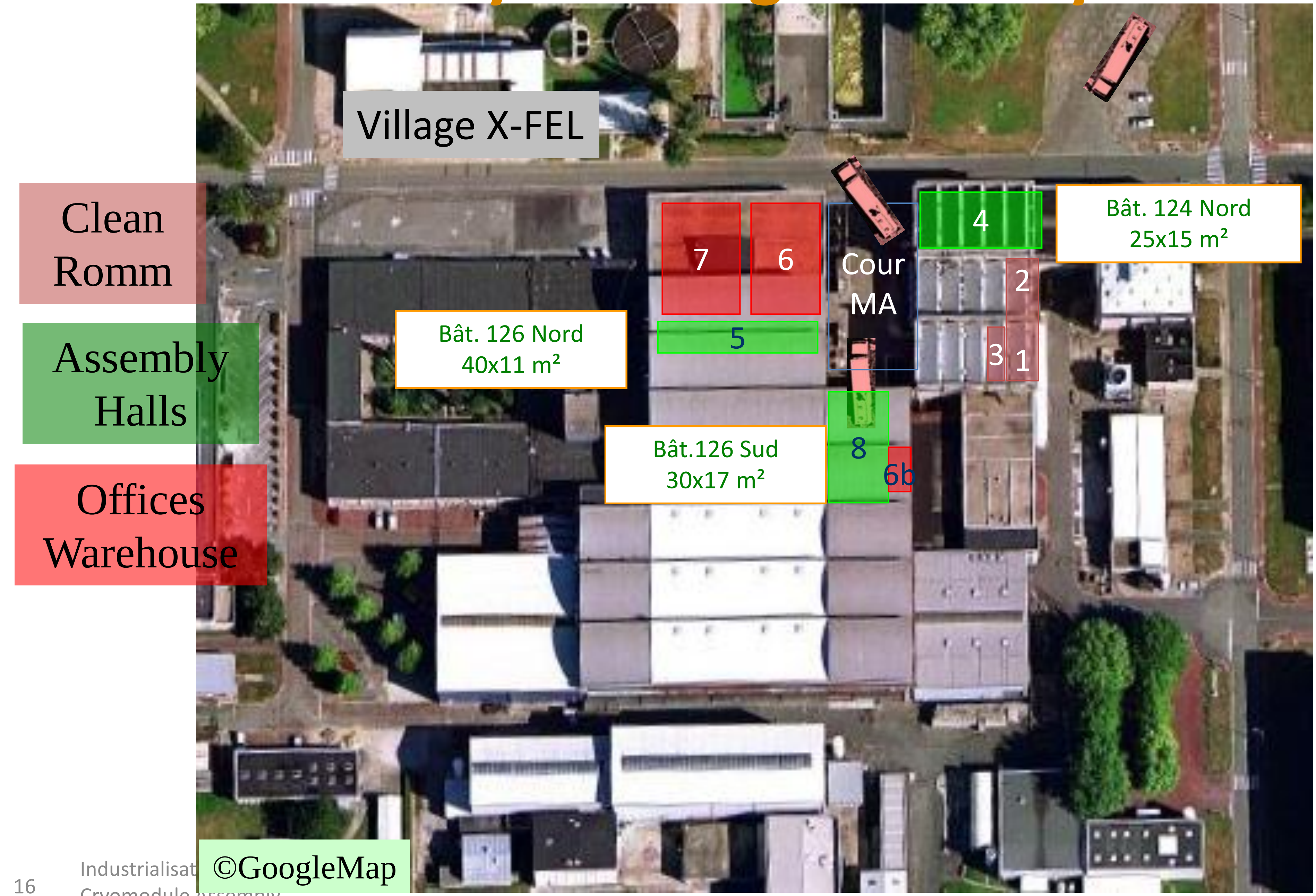
Saclay



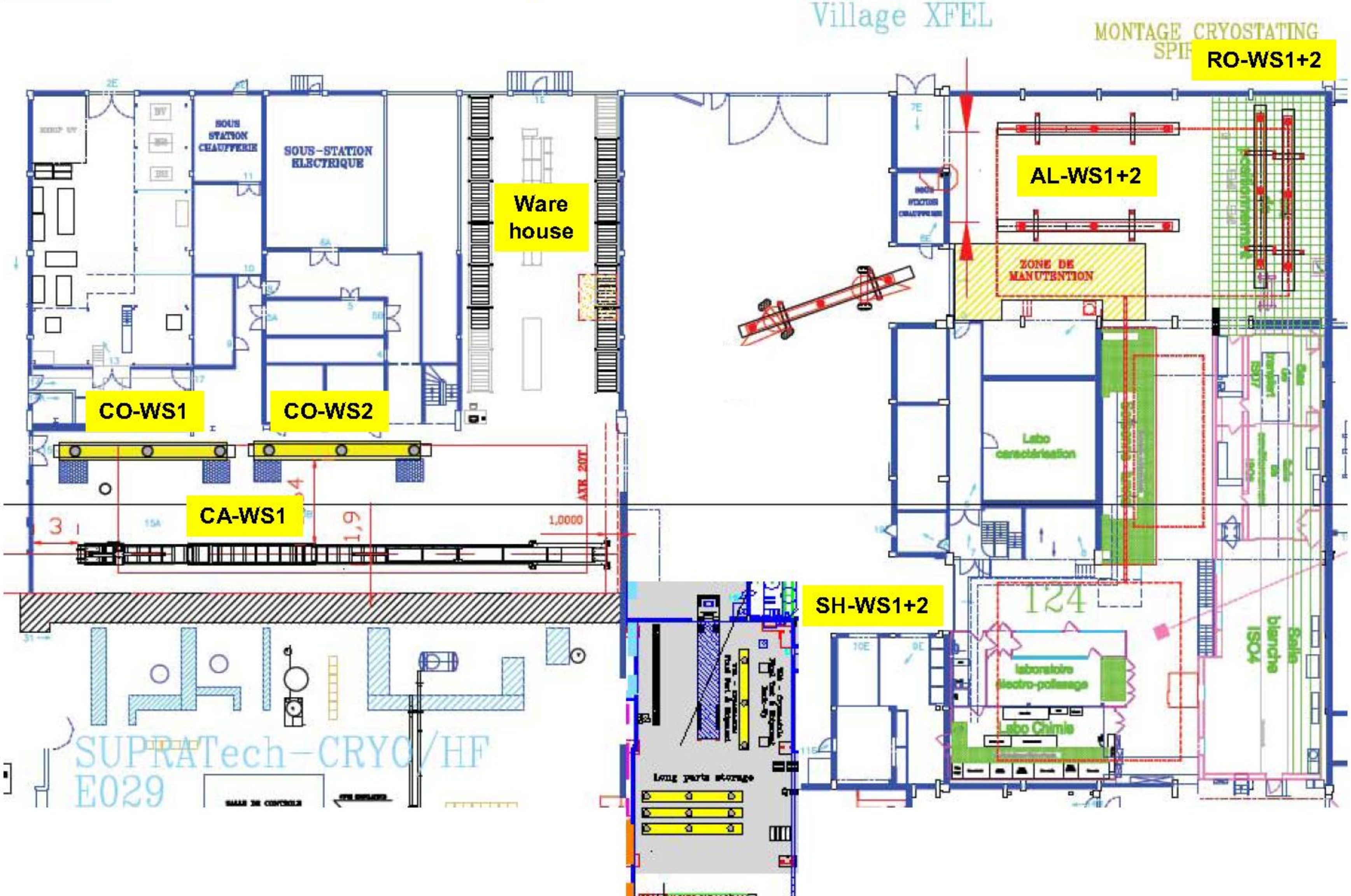
DESY takes care of installation / dismounting of cavities into / from test insert
Transport to CEA in transport boxes as well

Slide by H. Weise

Assembly Buildings at Saclay



Assembly Hall : Workstations



EURO-XFEL 空洞ストリング組立

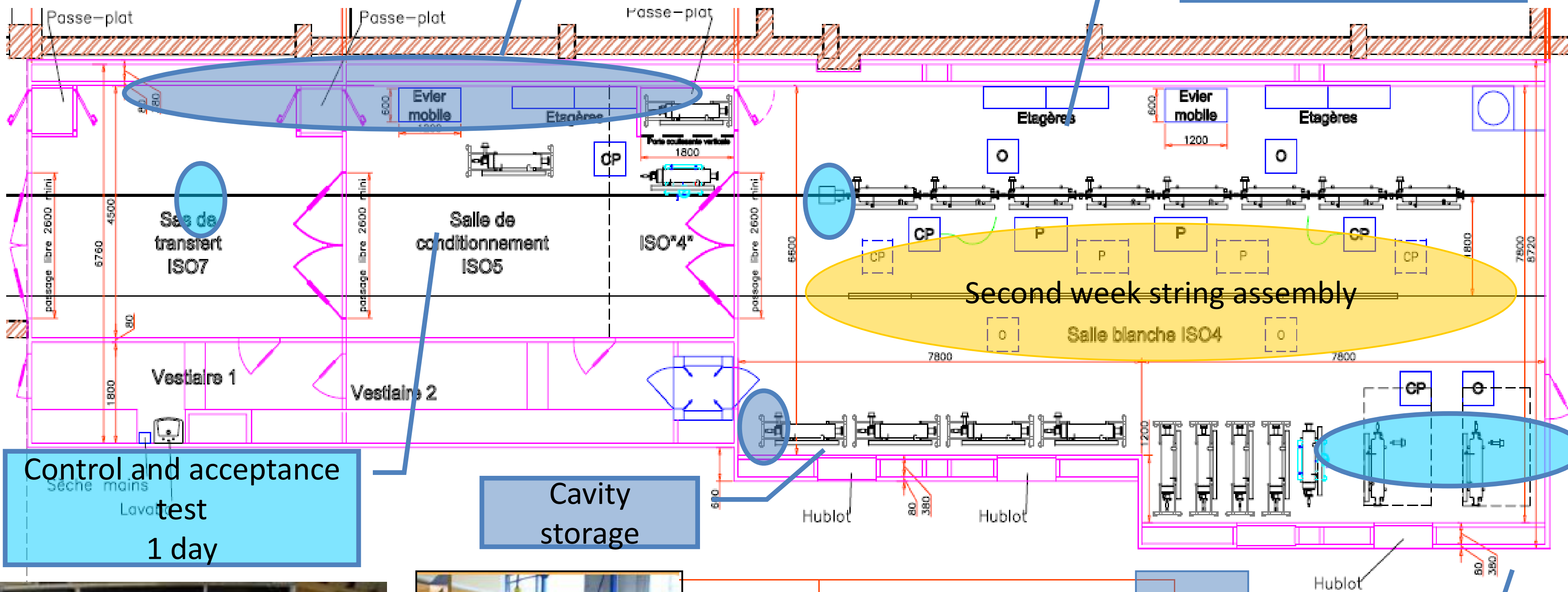
クリーンルーム内にて組立

1.3GHz ９セル超伝導空洞
~760 cavities (>23.5MV/m)をRI社(旧ACCEL)
とZANON社が製造
2015年からLinac commisioning開始予定

Clean Room Workstations at Saclay

Unpacking / packing and cleaning pieces

Cavity string assembly (1 string / week)



Second week string assembly

Control and acceptance test 1 day

Cavity storage

Cavity washer

Coupler cold part assembly (8 cavities / week)

Clean Room constructed (Sept'09)

Saclay

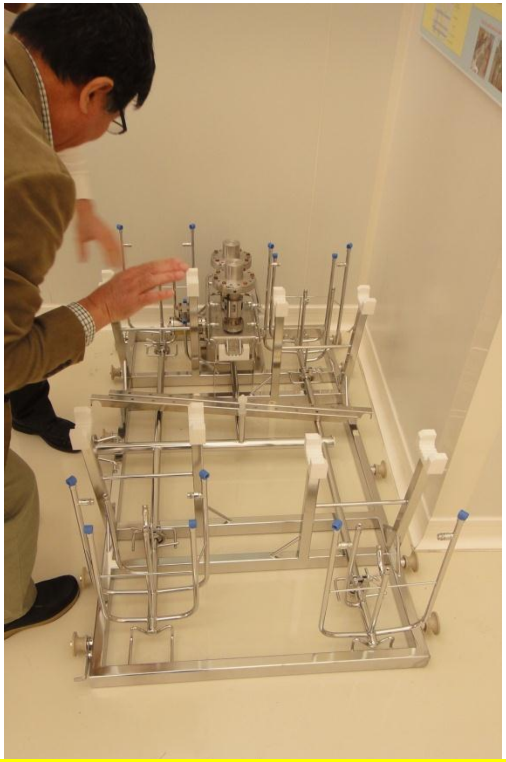
5 Mar. 2012



業者に渡す作業手順書の作成を行うための、手順の確認作業を行っていた。

Saclay(March 2011)

Clean room and low-pressure rinsing system



Platform with many nozzles for
Low-pressure rinsing system

High-pressure rinsing system for Spiral-2 cavity

Saclay

5 Mar. 2012

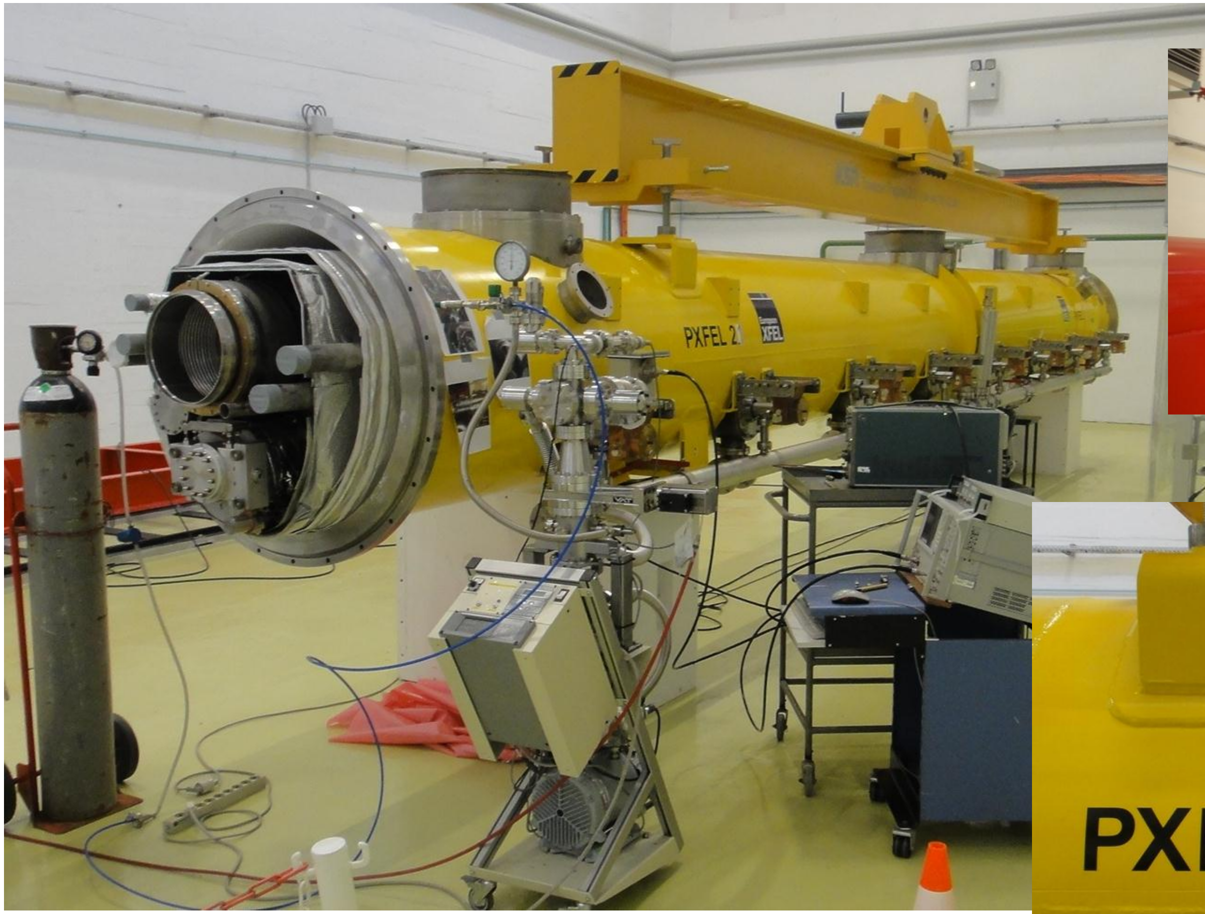



Full production（1 cryomodule/week）は、来年の1月頃になるだろうとのこと。

Saclay(March 2011)

Cold-mass carrier with electric motor with wireless-controller

Saclay (March 2011)



7 March 2011 at Saclay

PXFEL 2.1 (DESY >>> Saclay >>> transportation to DESY within a few weeks)

SaclayにおけるXFEL Cryomodule組み立てスケジュール

Phase 1: Preparation of Infrastructure and Tooling

2008→ April 2010

Phase 2: Training and Commissioning at Saclay with XFEL Prototype Modules (PXFEL2 and PXFEL3)

May 2010 → mid-2011

including Call for Tender for Assembly Contract by end 2010

Phase 3: XFEL module assembly by ind^{ial}. contractor

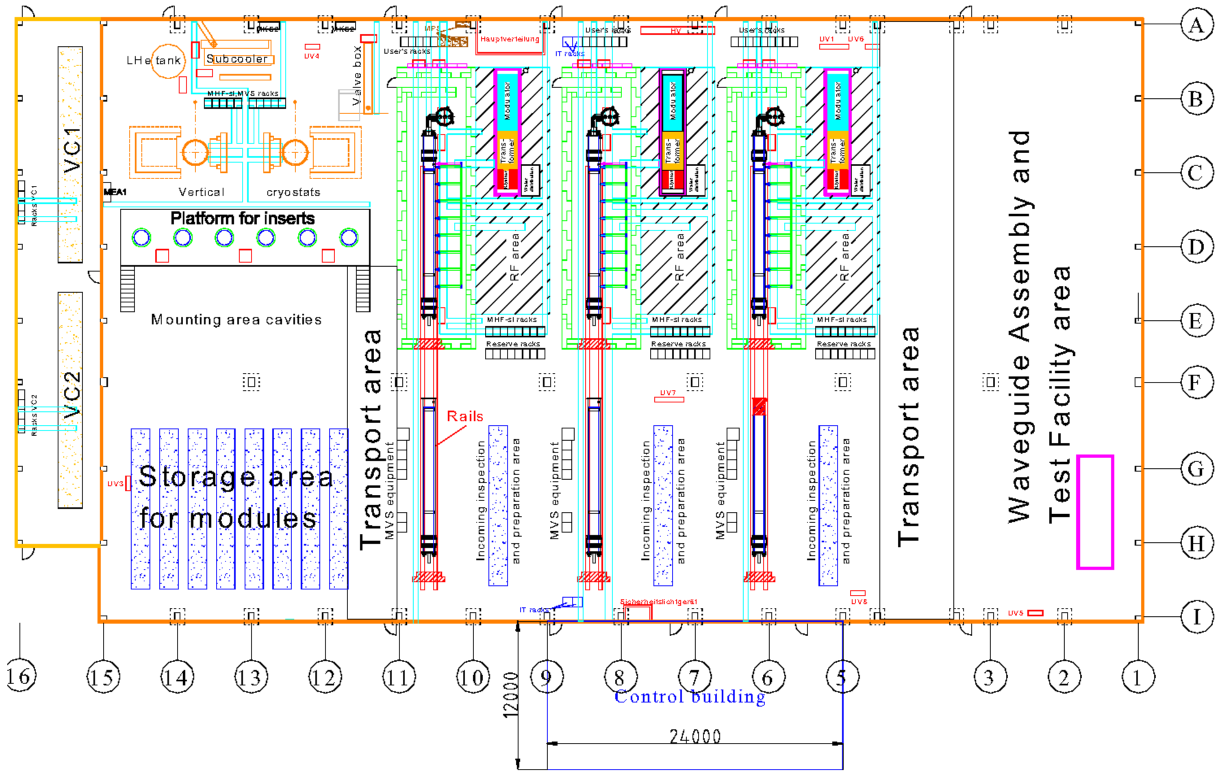
mid-2011 → mid-2014

DESY (March 2011)

Construction of Accelerator Module Test Facility (AMTF) hall is on going.

Three cryomodule test stands.

Accelerator Module Test Facility (AMTF) Including Single Cavity Tests



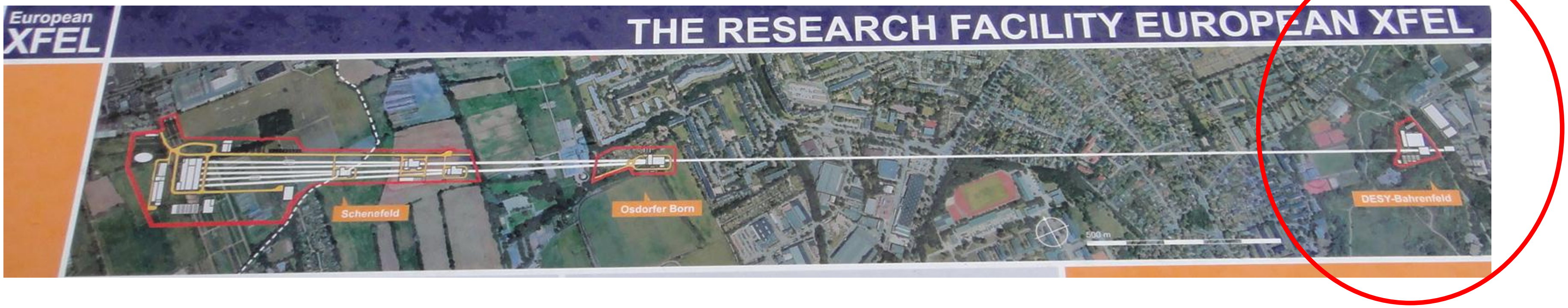
- Warm cryogenic piping 10/2010
- ISO- and UH Vacuum equipment 10/2010
- Vacuum compressors commissioning 11/2010
- cryo components (LHe sub cooler & He storage tank main transfer line & vertical cryostats) **are late** – fall 2011

- **Commissioning**
  - **- vertical tests late fall 2011**
  - **- horizontal tests end 2011**

Acc. Module Test Facility (AMTF) DESY / March 2011

Construction of Accelerator Module Test Facility (AMTF) hall is on going.

EURO-XFEL Injector (Mar. 2011)

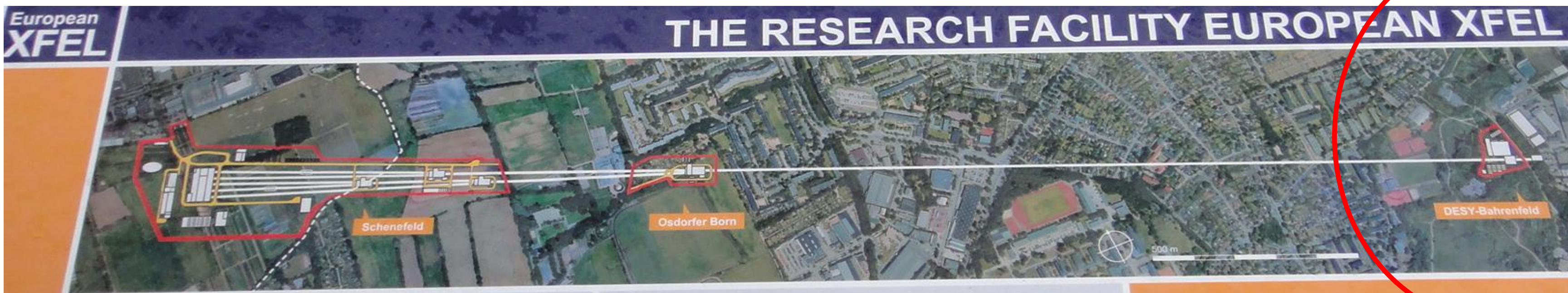


Construction of Injector hall is ongoing.

He tanks

Spring 2011

EURO-XFEL Injector (Mar. 2011)



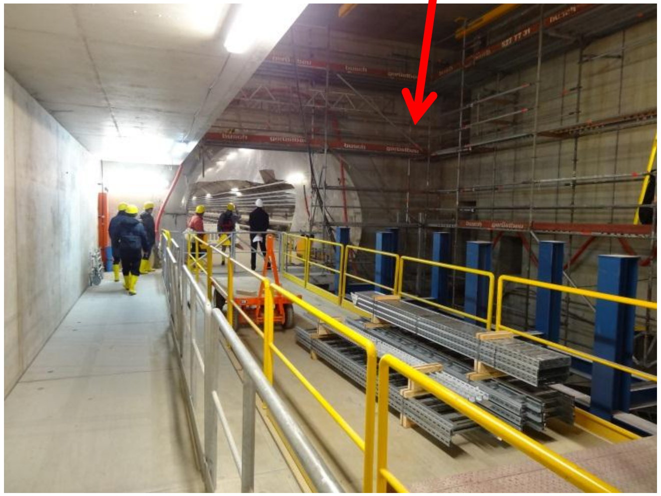
He tanks

Spring 2012

Construction of Injector hall is ongoing.

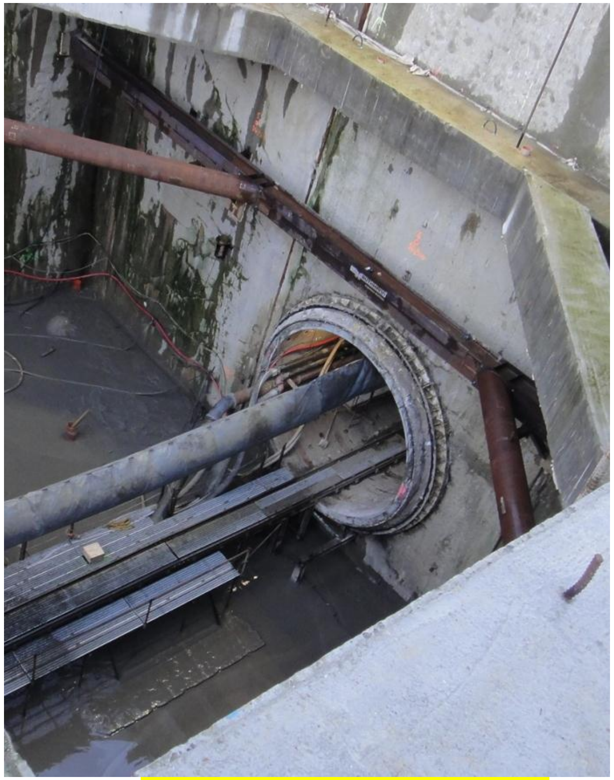
EURO-XFEL Injector

Feb 2013



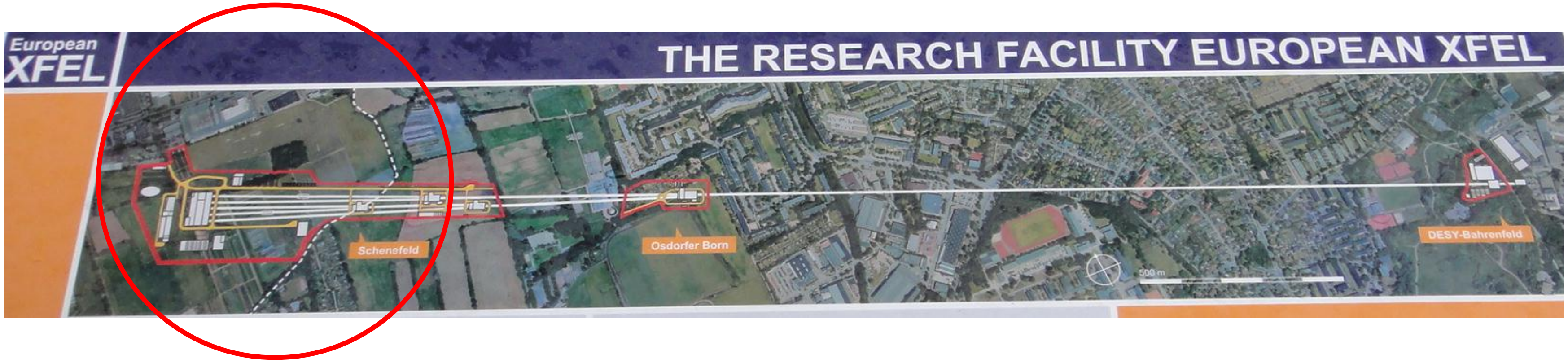
DESY (March 2011)

End of SRF linac. Entrance of tunnel bawling machines.



End of SRF linac

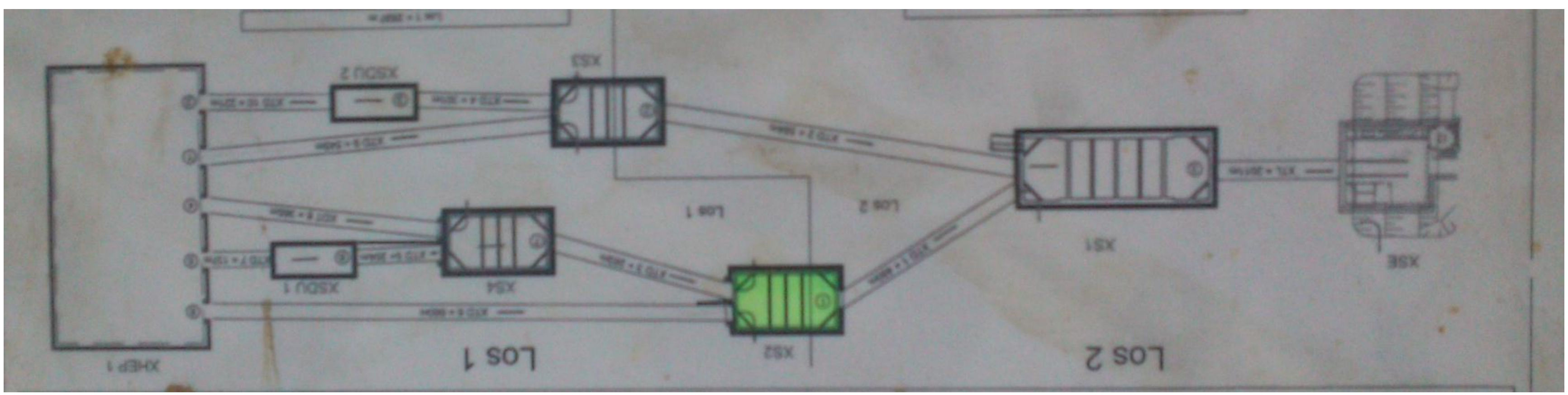
DESY (March 2011)



DESY is in this direction

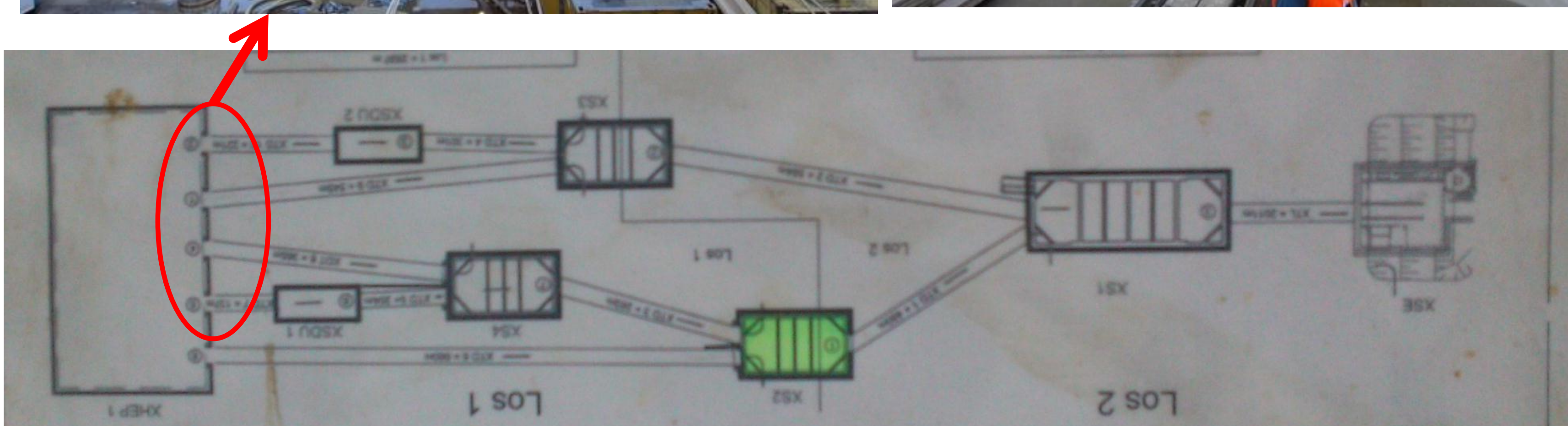
Construction of experimental halls is ongoing.

DESY (March 2012)

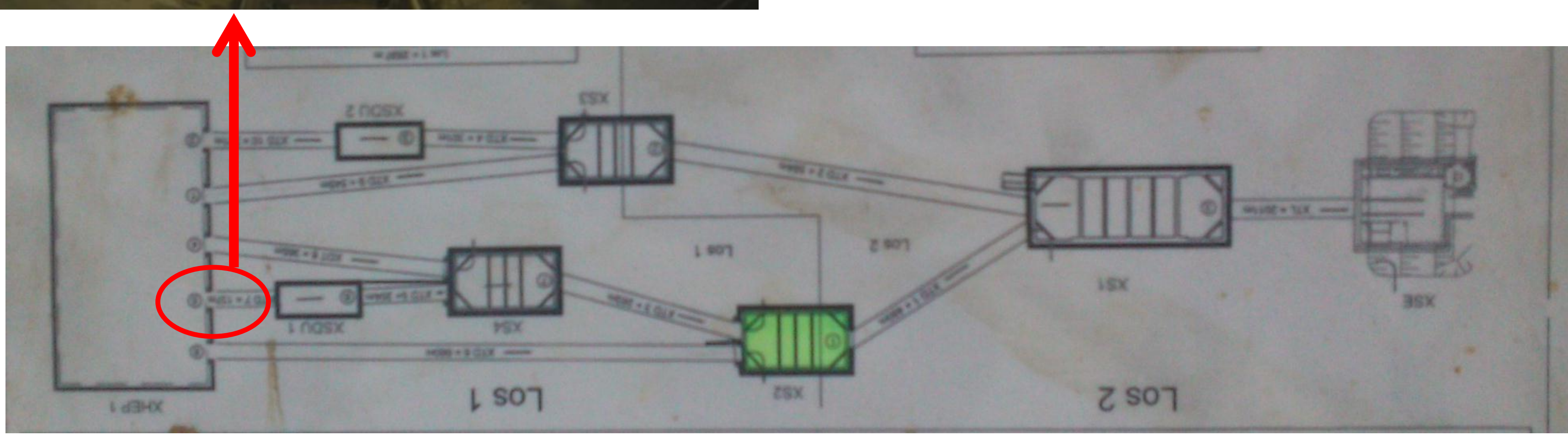


DESY (March 2012)

8 Mar. 2012

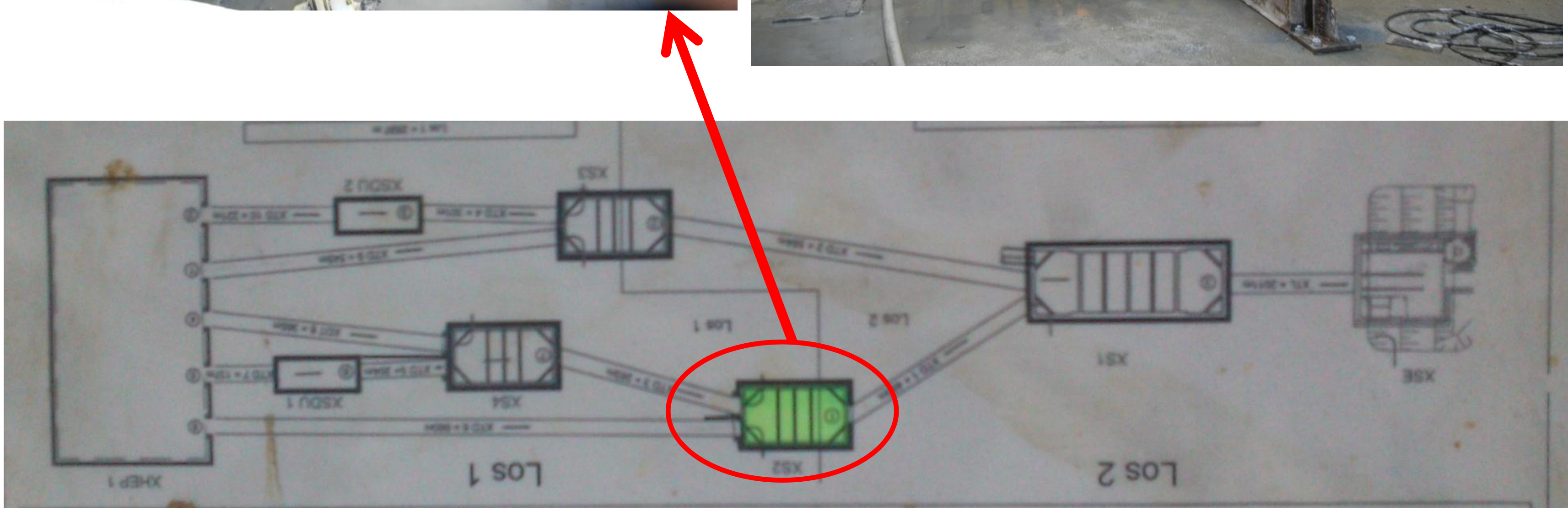


DESY (March 2012)



DESY (March 2012)

8 Mar. 2012



Courtesy: P. Lubrun (CERN), 1st WS, 2010

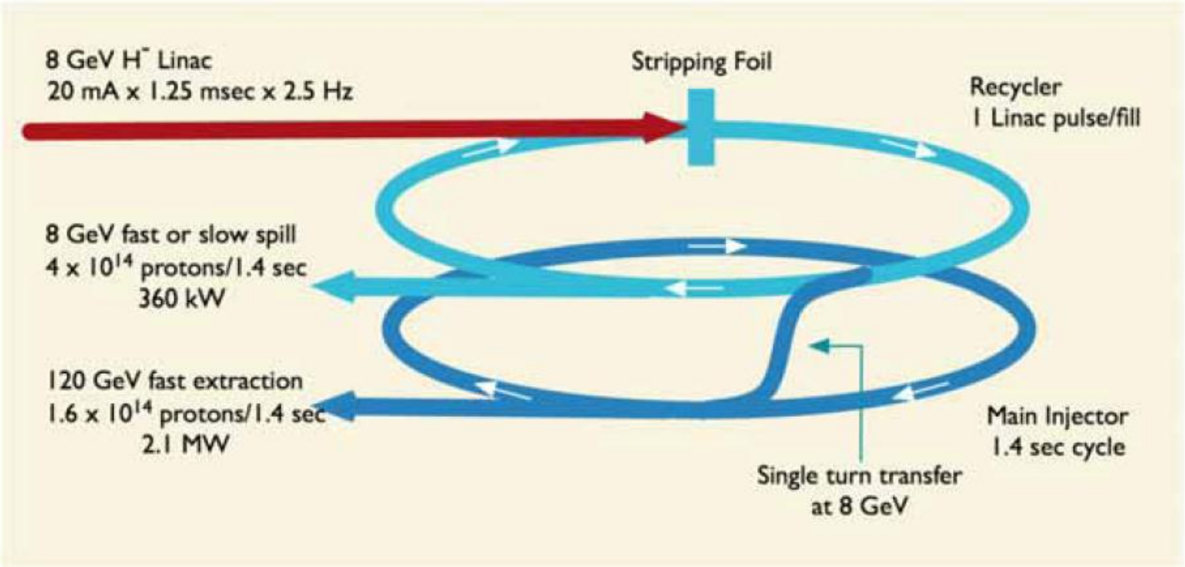
CERN's Experience from LHC Cryostating and Test

Bringing industry to the laboratory
Cryostat assembly by industry on CERN site

Producing in-house with industrial methods
Cryogenic magnet test station at CERN

Initial Configuration-1

- Initial Configuration-1



- Strong alignment with ILC technologies
- Initial Configuration Document-1 V1.1 released March 2009
  - Accompanying cost estimate ~$1.5B

Project X Linac Configuration

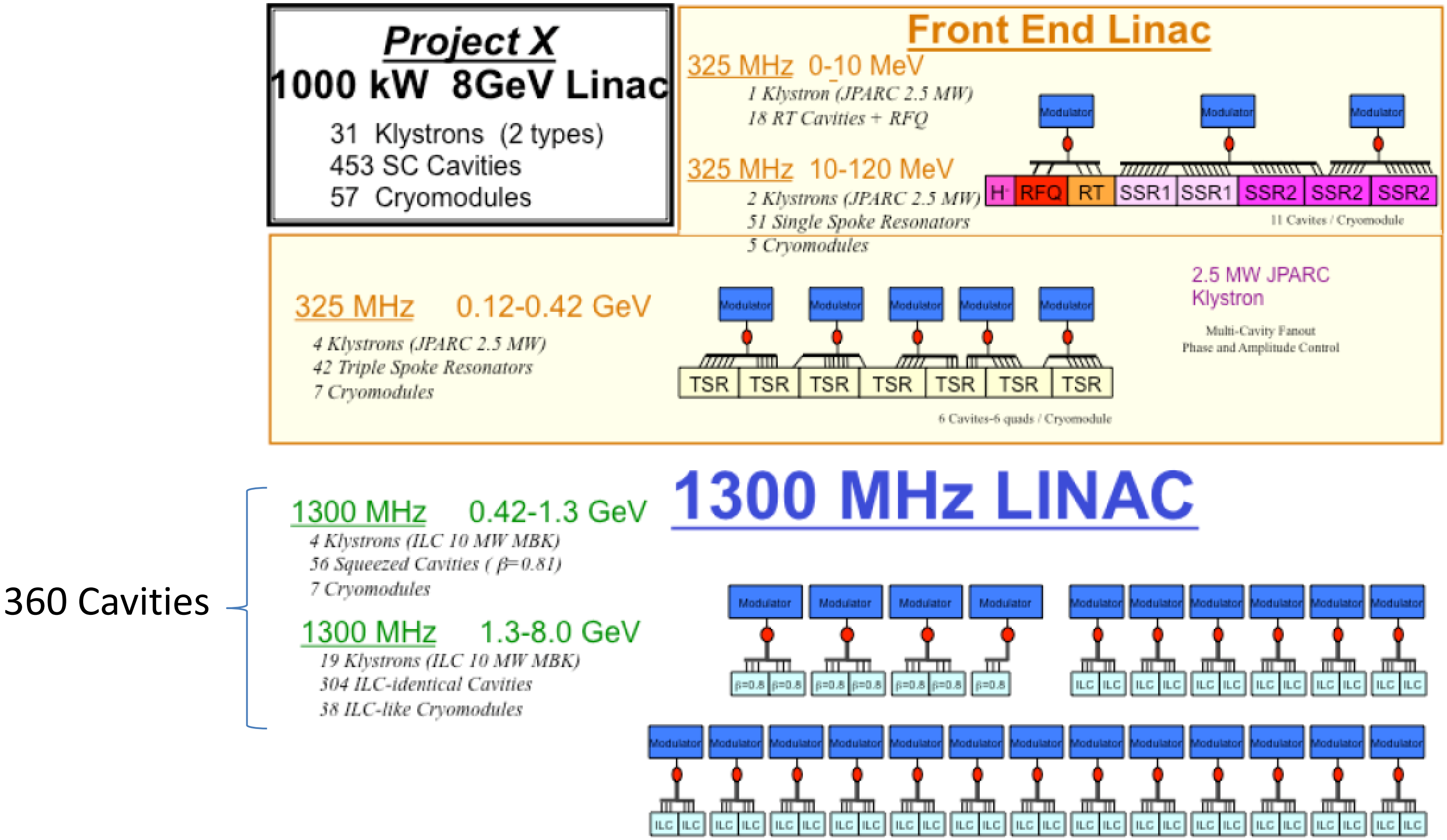
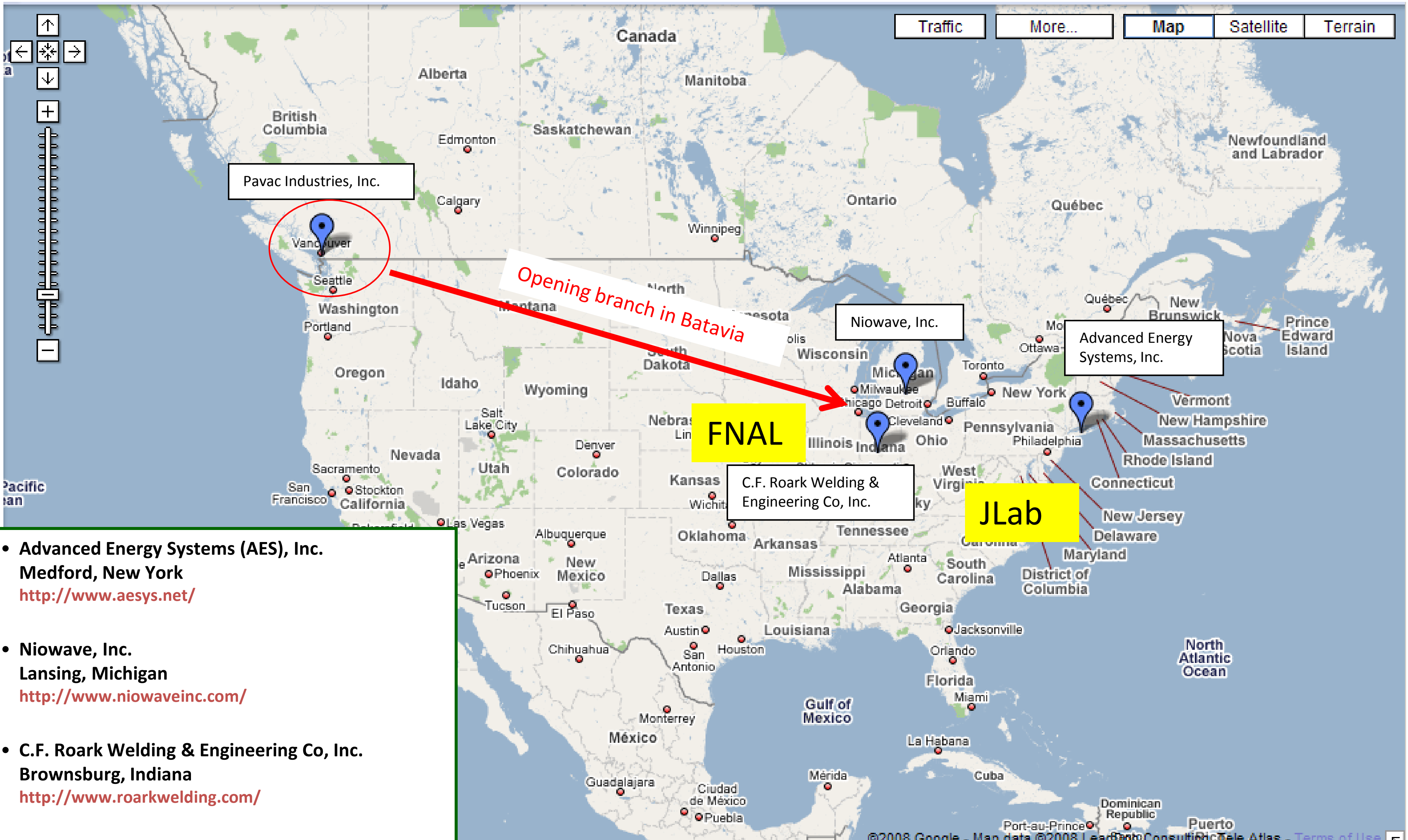


Figure III-3 : Layout and component counts for the initial Project X linac configuration

North American Cavity Vendors and laboratories



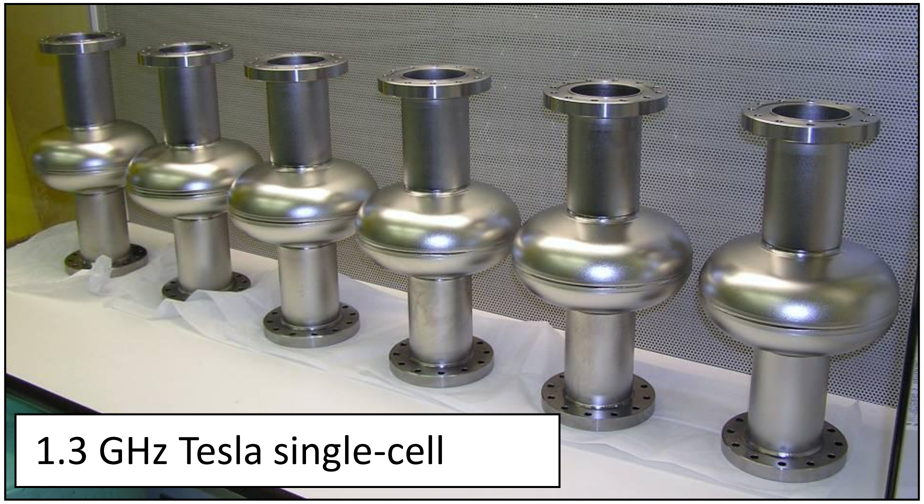
- **Advanced Energy Systems (AES), Inc.**
  Medford, New York
  http://www.aesys.net/

- **Niowave, Inc.**
  Lansing, Michigan
  http://www.niowaveinc.com/

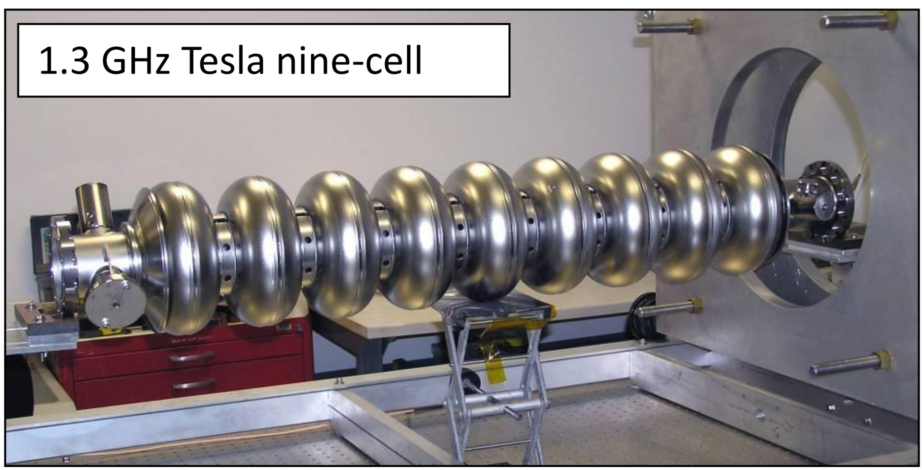
- **C.F. Roark Welding & Engineering Co, Inc.**
  Brownsburg, Indiana
  http://www.roarkwelding.com/

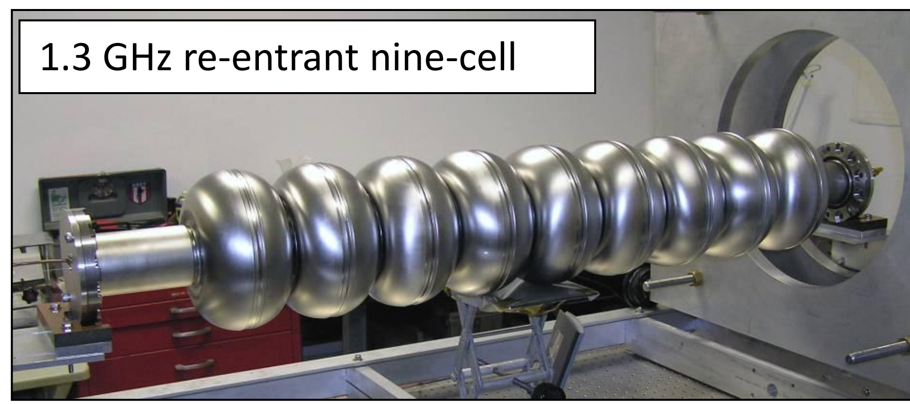
- **Pavac Industries, Inc.**
  Richmond, British Columbia
  http://www.pavac.com

AES has complete production capability on-site
10 nine-cells delivered; 6 more in April, 20 more ordered (ARRA)


1.3 GHz Tesla single-cell

Electron-beam welding facility


1.3 GHz Tesla nine-cell


1.3 GHz re-entrant nine-cell

Cryomodule activities at FNAL

CM1 String Assembly

MP9 Clean Room

Final Assembly

CM1

Move to NML

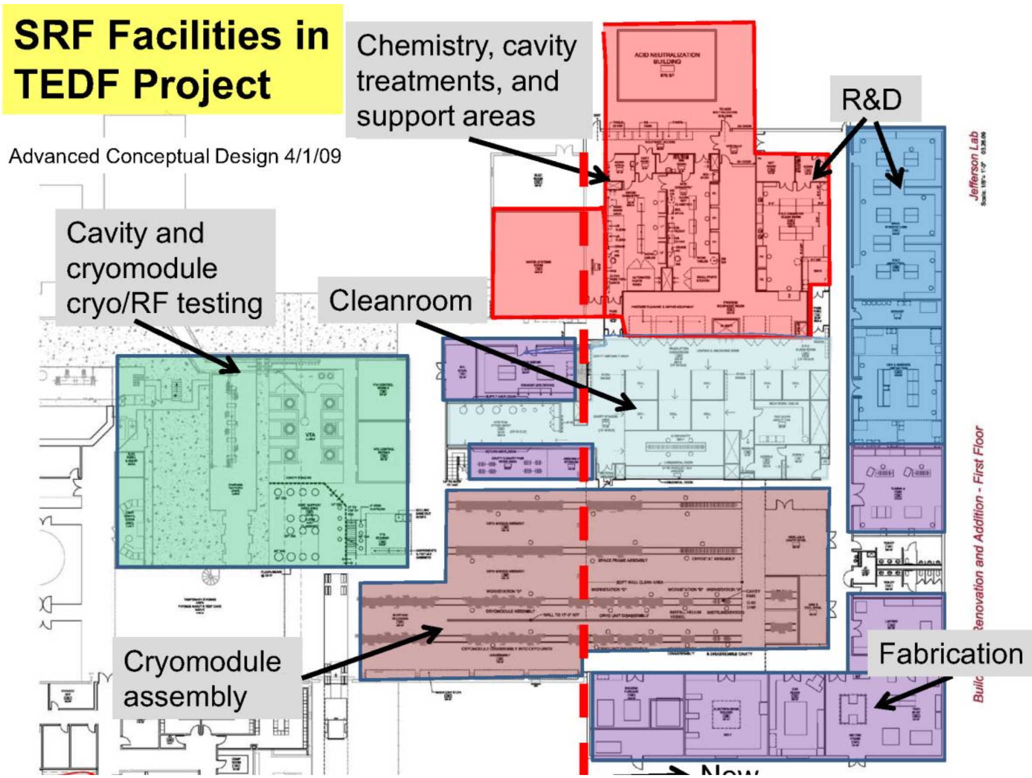
CM1 installed

Dressing cavities for CM2

FNAL S1 global
Cavities @ KEK

Jefferson Lab Technology and Engineering Development Facility Project (TEDF)

Presented by C. Reece at TTC(March 2011)

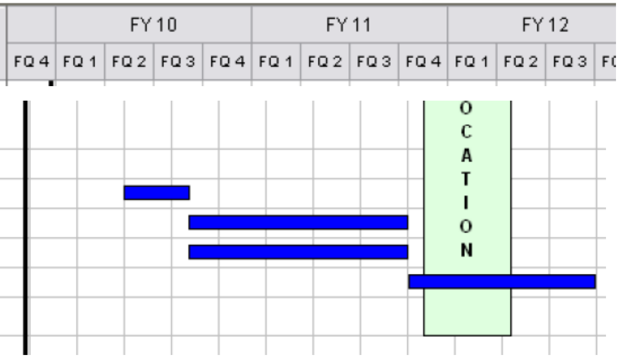


TEDF Summer 2010

TEDF Feb 2011

Only the VTA and Cryo-module Test Facility will be unchanged!

	Activity Name	Start Date	Finish Date
13	**TEDF Schedule**		
14	**Early Start/Finish**		
15	6.3.1.1 Civil/Site & Early Procurements	3/31/10	8/3/10
16	6.3.1.2 TED Building Construction	8/4/10	9/30/11
17	6.3.1.3 TL Addition Construction	8/4/10	9/30/11
18	6.3.1.4 TL Renovation	10/3/11	9/28/12
19			
20			



Summary

- ILCのコストは、約半分がmain linacのコストである。main linacの主componentである超伝導空洞の生産が見積もり通りに行えるかがILC建設において重要。
- 空洞の生産台数

  XFEL : 760台/2年

  Project X: 360台/5年

  ILC: 17000台/5年　　桁違いの生産台数
- しかし、6 vendor model を仮定すれば、factor 2 – 3 の規模拡張でILCに対応できる。

  既に 9 vendors が存在している。

  各vendorは、factor 2 程度の規模拡張は問題なく可能。
- Hub-laboratories の施設も同様に拡張が必要。

  EU: DESY + Saclay + CERN ....

  USA : FNAL + Jlab ....

  Asia : KEK ....

> Hub laboratories が多少の規模拡張を行えばILCの量産に対応可能！

- KEK（CFF）を核にして、日本におけるILC加速器の量産化の研究が進んでいる。
- KEK(CFF)において、高圧ガス保安法に準拠した空洞の製作を計画。

  その延長線上に、国内における空洞製造の多ベンダー化の促進、ILCのおける外国空洞の高圧ガス保安法準拠の実績作りがある。