Superconducting RF and Magnet Technologies for International Linear Collider (ILC) and Compact Linear Collider (CLIC)

Akira Yamamoto (KEK/CERN)

for the

Linear Collider Collaboration (LCC)

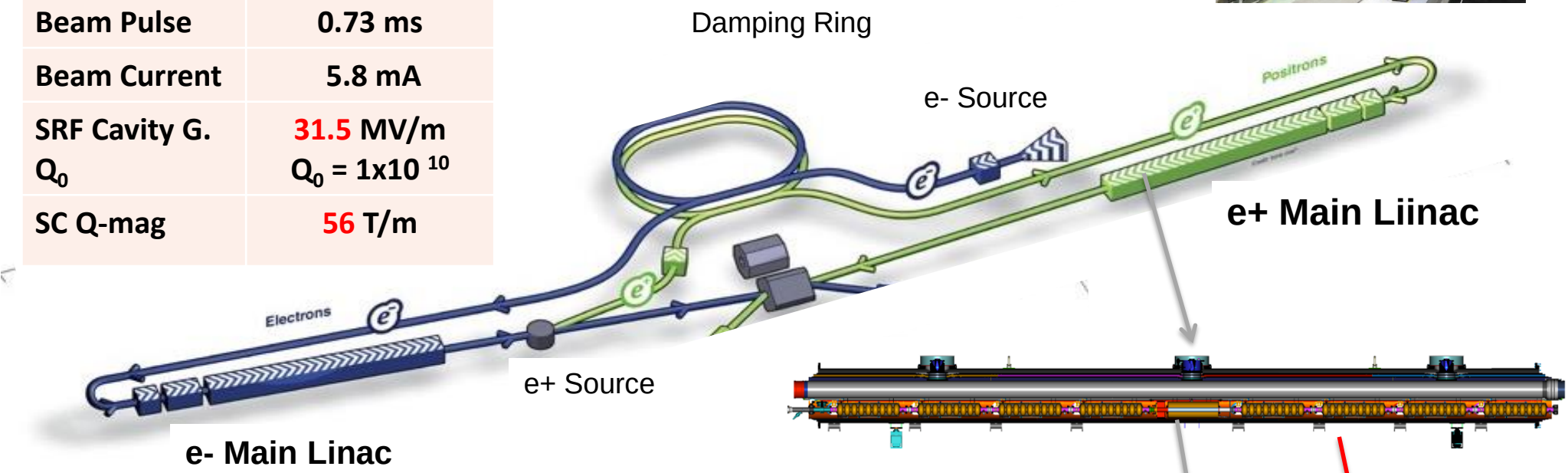
to be presented at EUCAS-2017, Geneve, 21 Sept., 2017

Outline

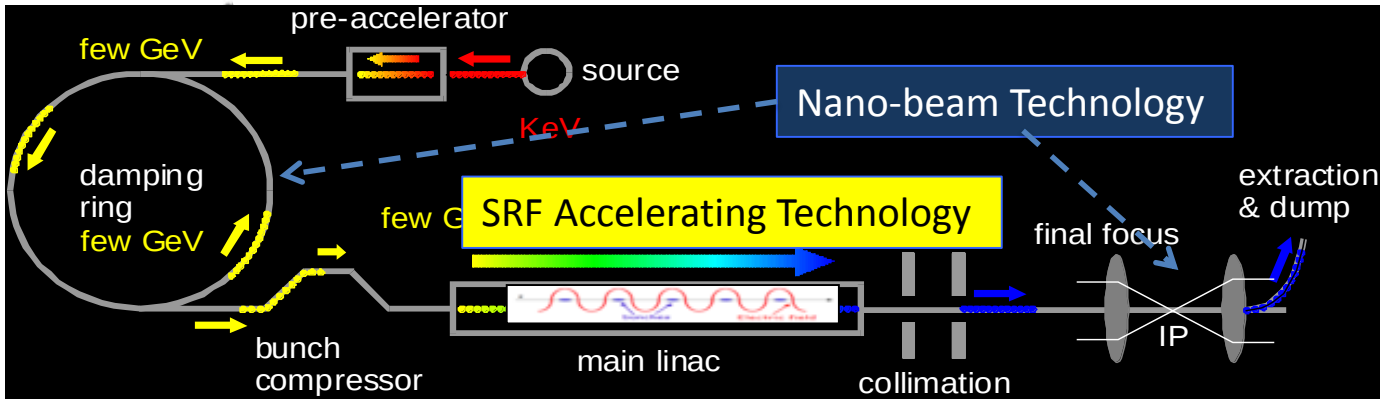
- **Introduction**
- **Superconducting RF (and Magnet) Technology**
  - Matured for the ILC realization
- **Superconducting Magnet Technology**
  - Applicable for CLIC Staging-380: Klystron Solenoid
- **Summary**

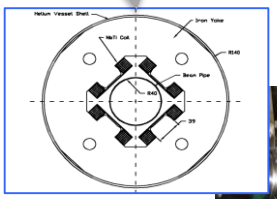
ILC Overview

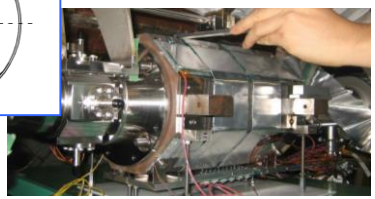
Item	Parameters
C.M. Energy	500 (250) GeV
Repetition	5 Hz
Beam Pulse	0.73 ms
Beam Current	5.8 mA
SRF Cavity G. Q_0	31.5 MV/m $Q_0 = 1\times10^{10}$
SC Q-mag	56 T/m



SRF cavity







SC Quad.

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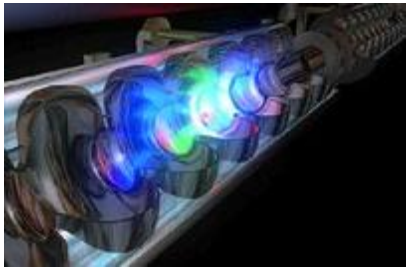
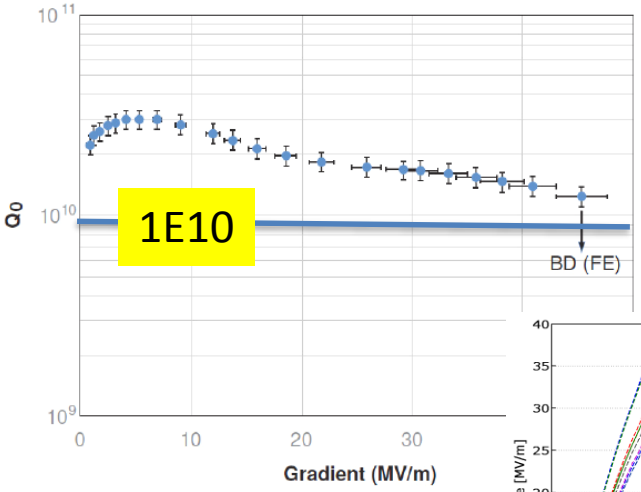
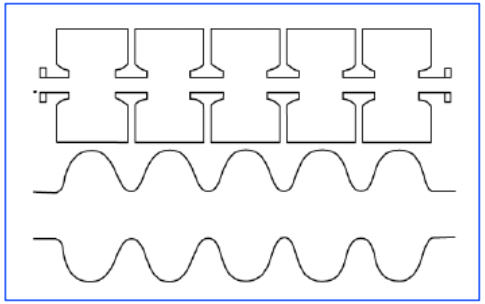
Features of Superconducting RF

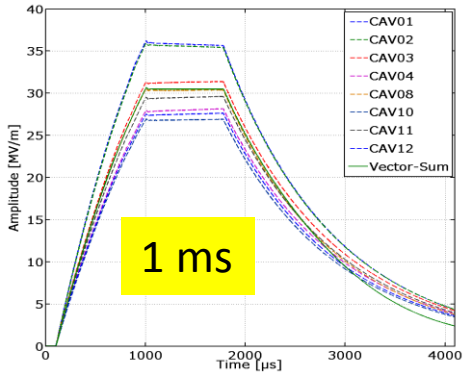
- **Higher efficiency:**
  - More beam power for less plug power,
- **Lower RF frequency:**
  - Relaxed tolerances & smaller emittance dilution



- **High Q_0 (~10^{10}):**
  - Small surface resistance → nearly zero
  - Capable of efficientl accelerating
    - ~160MW @ 500GeV (ILC)
- **Long beam pulses (~1 ms or CW) :**
  - intra-pulse feedback (in 1 ms pulse)
- **Large aperture**
  - better beam quality w/ larger aperture –
  - lower wake-fields
- Cryogenics required



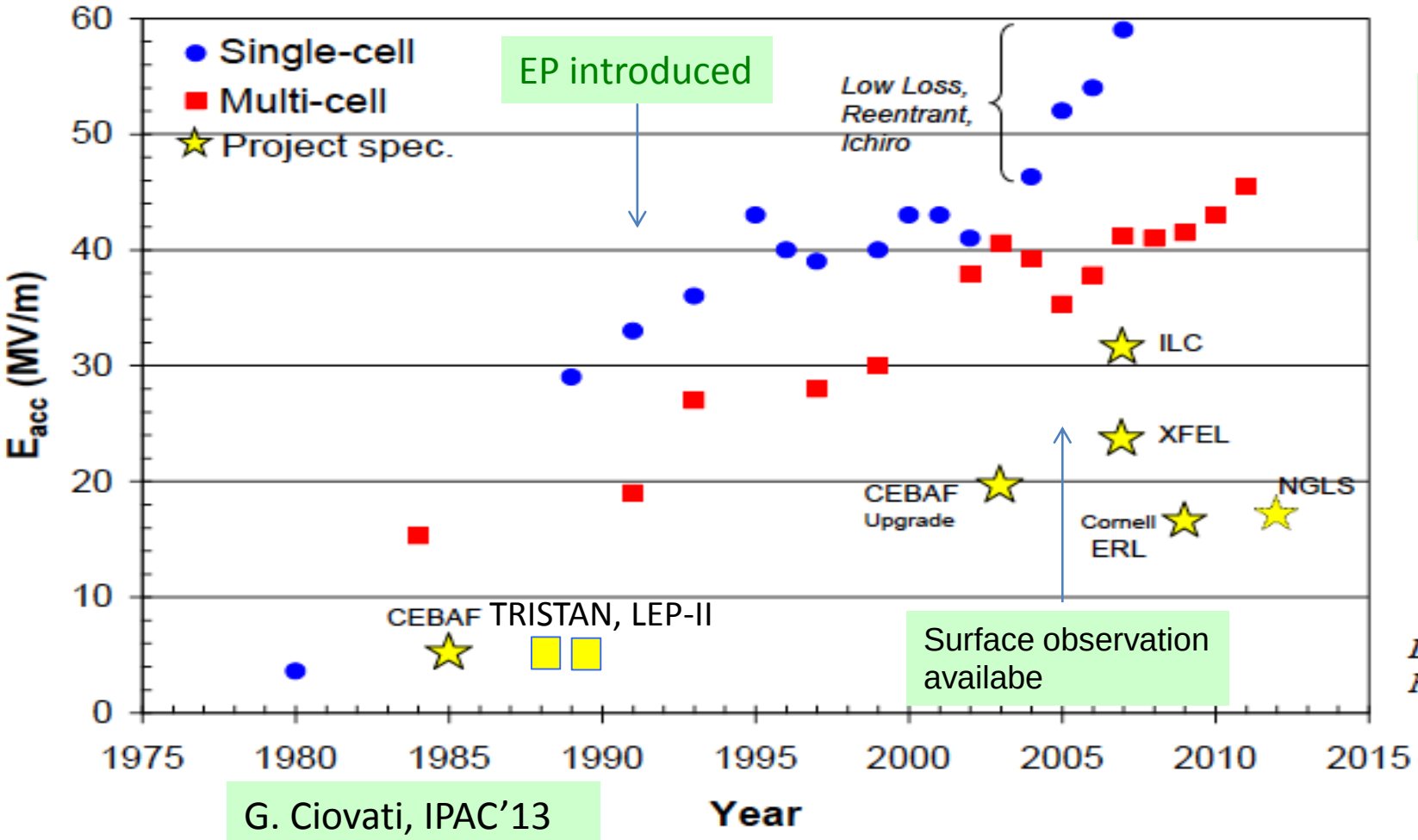




Large aperture

Courtesy: G. Ciovati, R. Geng

Advances in SRF Field Gradient



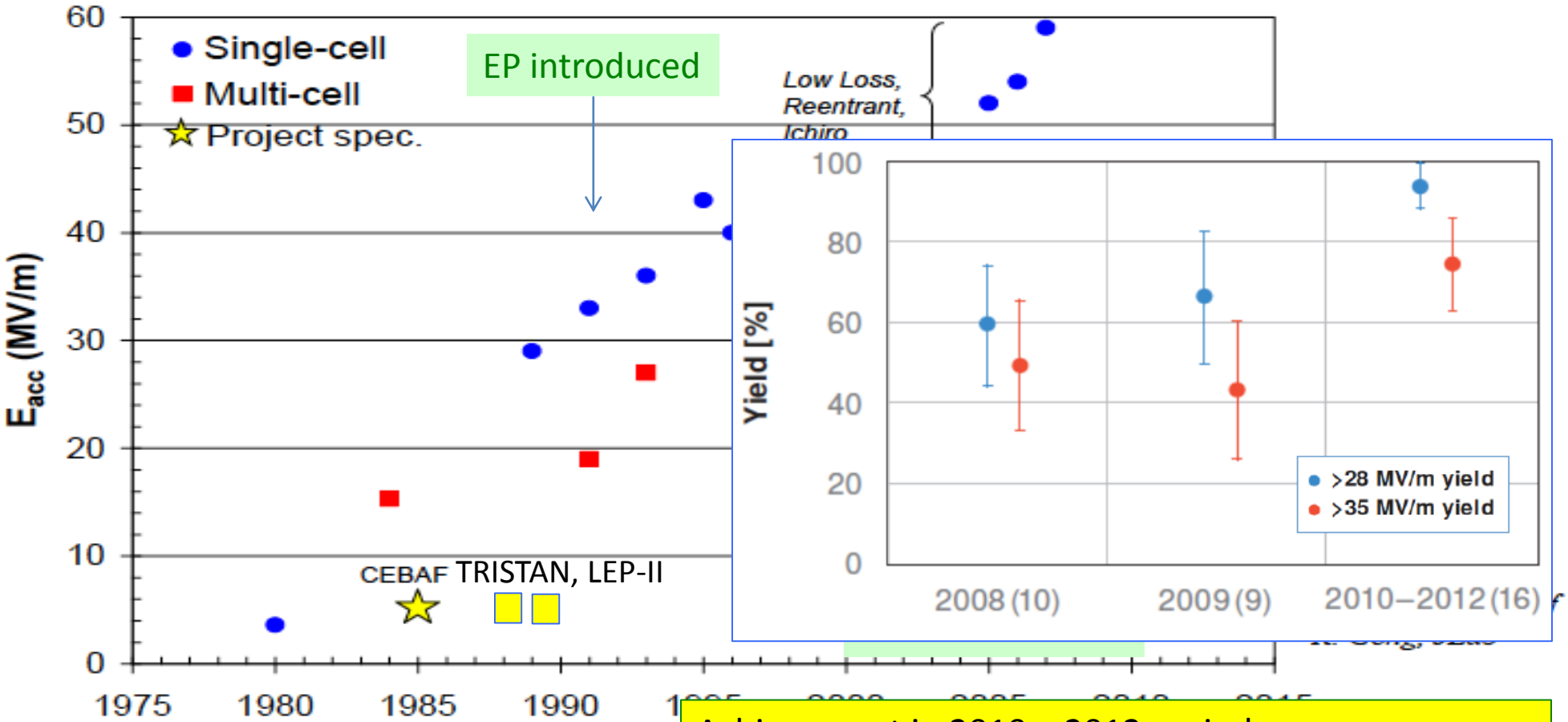
Gradient, > X 5 improved

Data is courtesy of R. Geng, JLab

G. Ciovati, IPAC'13

Courtesy: G. Ciovati, R. Geng

Advances in SRF Field Gradient



G. Ciovati, IPAC'13

Achievement in 2010 ~ 2012 period:
- Production yield: 94 % at > 28 MV/m,
- Average gradient: 37.1 MV/m

European XFEL SRF Linac becoming a prototype for ILC

Courtesy, H. Weise

Progress:

2013: Construction started

…

2016: E- XFEL Linac completion

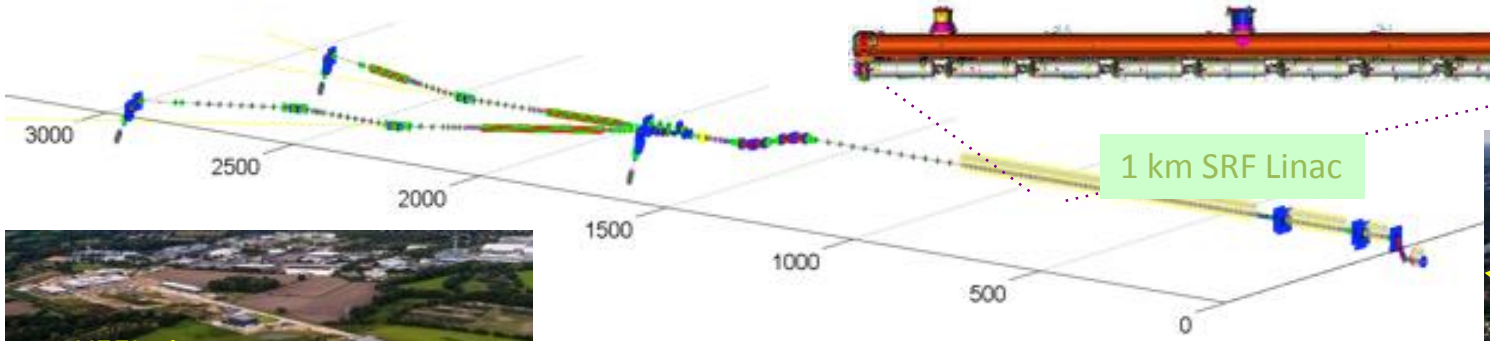
2017: E-XFEL beam start

Note : ~ 1/10 scale to ILC-ML

1.3 GHz / 23.6 MV/m

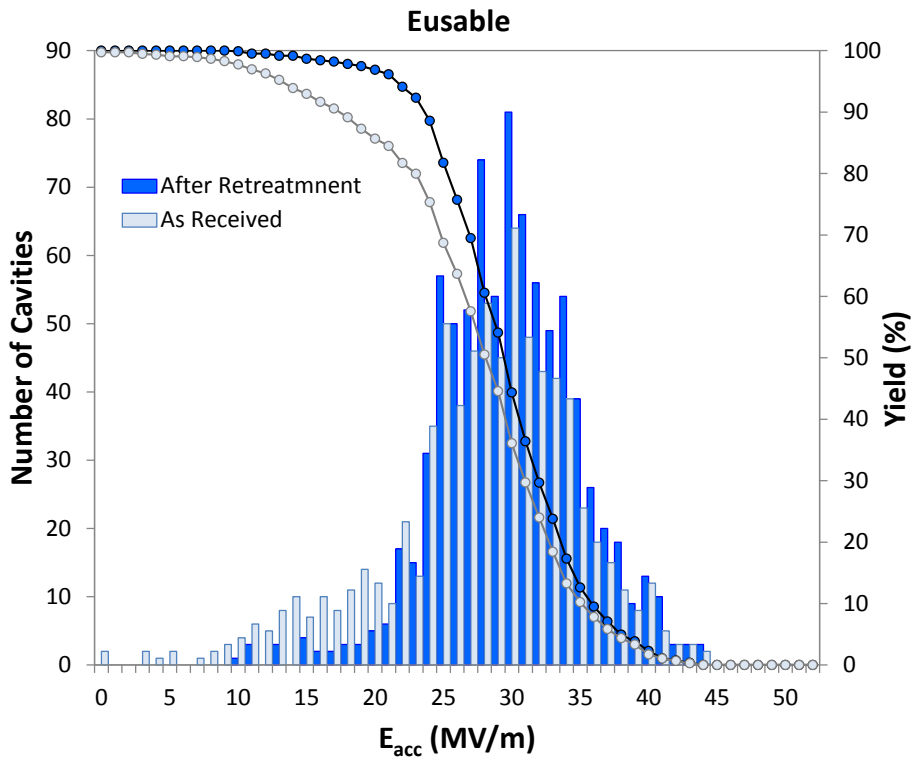
800+4 SRF acc. Cavities

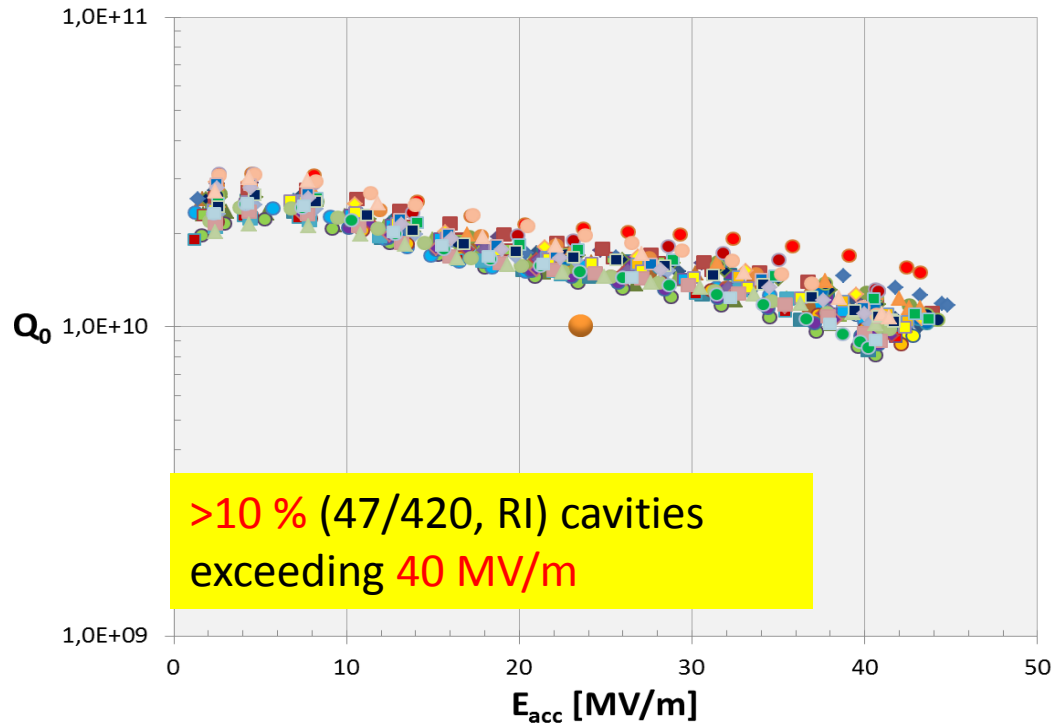
100+3 Cryo-Modules (CM)



Courtesy, D. Reschke , N. Walker, C. Pagani

European XFEL: SRF Cavity Performance





After Retreatment:

E-usable: 29.8 ± 5.1 [MV/m]

(RI): E usable 31.2 ± 5.2 [MV/m]), w/ 2nd EP

(EZ): E usable 28.6 ± 4.8 [MV/m]) , w/ BCP (instead of 2nd EP)

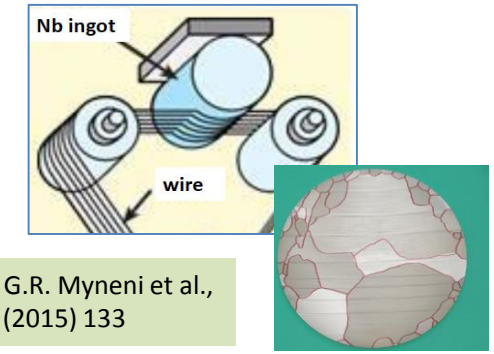
A. Yamamoto, 170921

S. Michizono, S. Belomestnykh

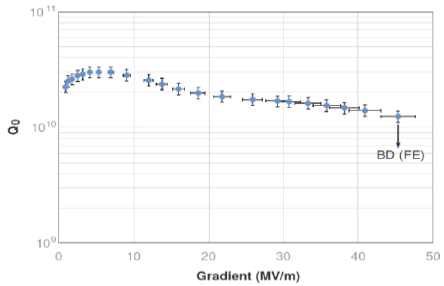
ILC SRF Cost-Reduction R&D in progress

Nb material : ingot directly sliced

- w/ optimum RRR (> ~ 250) &
- clean surface



P. Kneisel, G.R. Myneni et al., NIM A774 (2015) 133

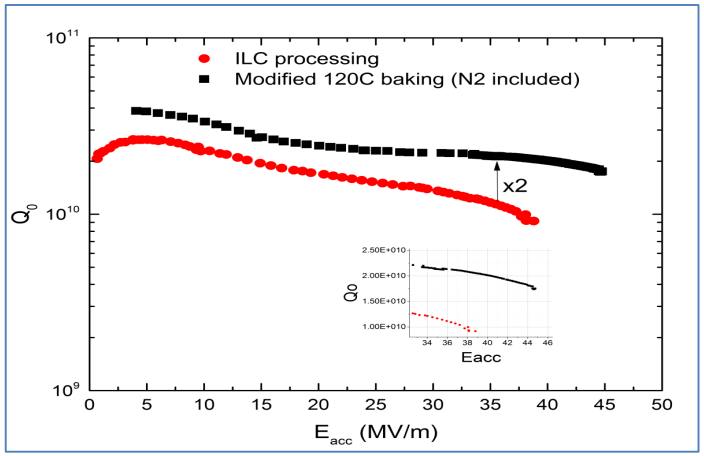


D. Reschke, SRF-11, Chicago, TUPO015 (2011)

SRF cavity fabrication for high-Q, high-G

-w/ a new baking recipe discovered at Fermilab

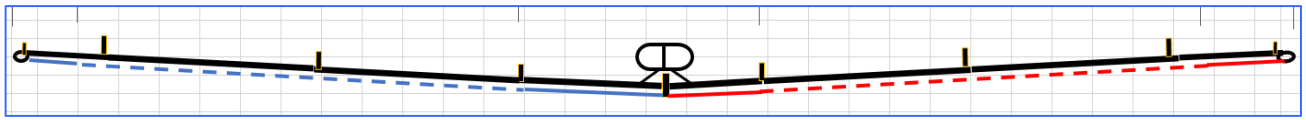
- N2 infusion at 120 C directly after heat treatment at 800 C,
  - Same cavity, sequentially processed, no EP in b/w
- Reached: G = 45.6 MV/m
  Q ~ 2.3e10 @ 35 MV/m :

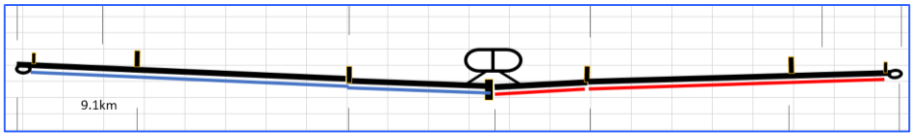


A. Grassellino et al., Superconductor Science and Technology, V30, No. 9 (2017) 094004

ILC Staging Study in Progress

	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	< 0.65	1	TBD





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Introduction

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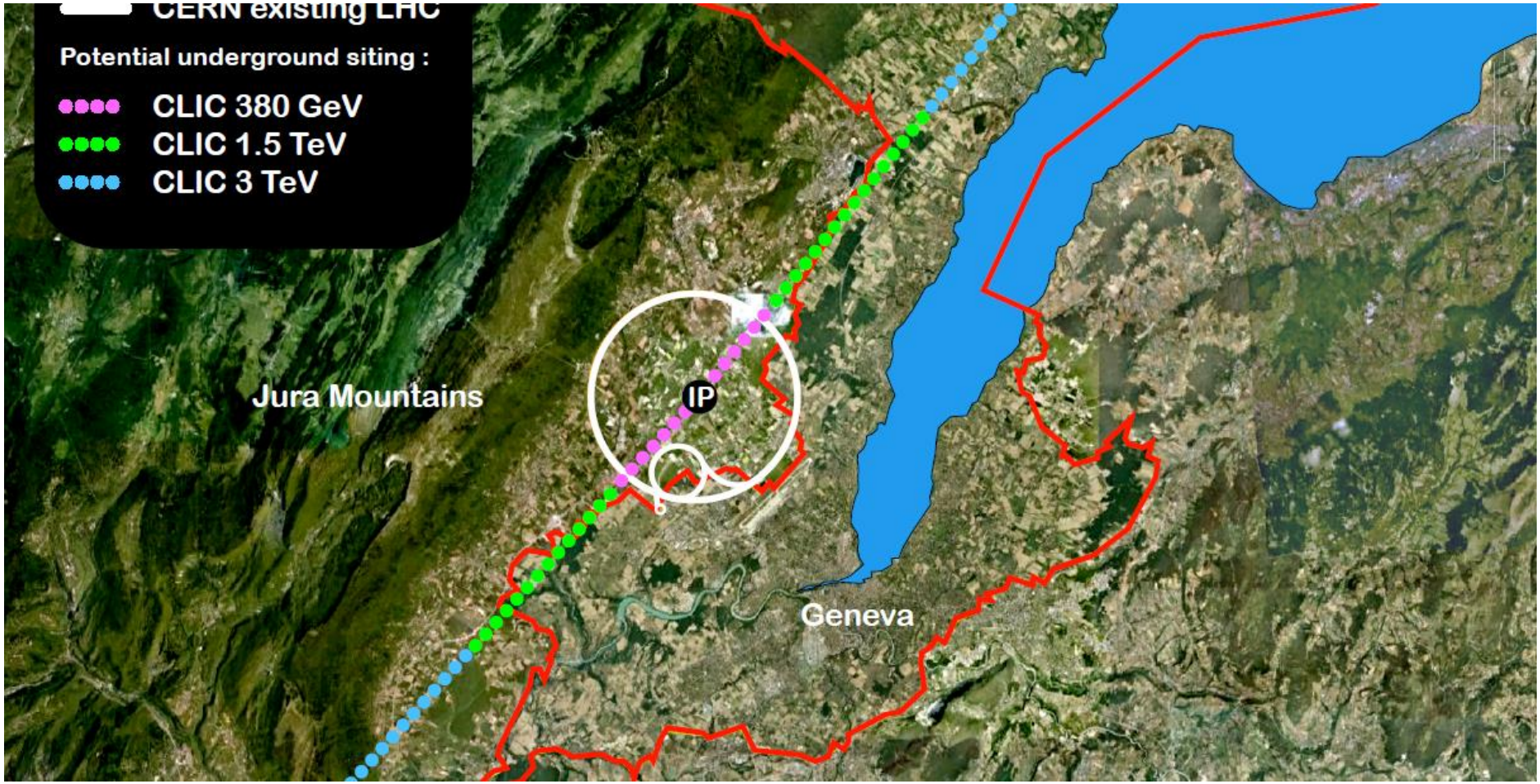
Superconducting Magnet Technology

- Applicable for CLIC Staging-380: Klystron Solenoid

Summary

CLIC Staging Scenario Proposed



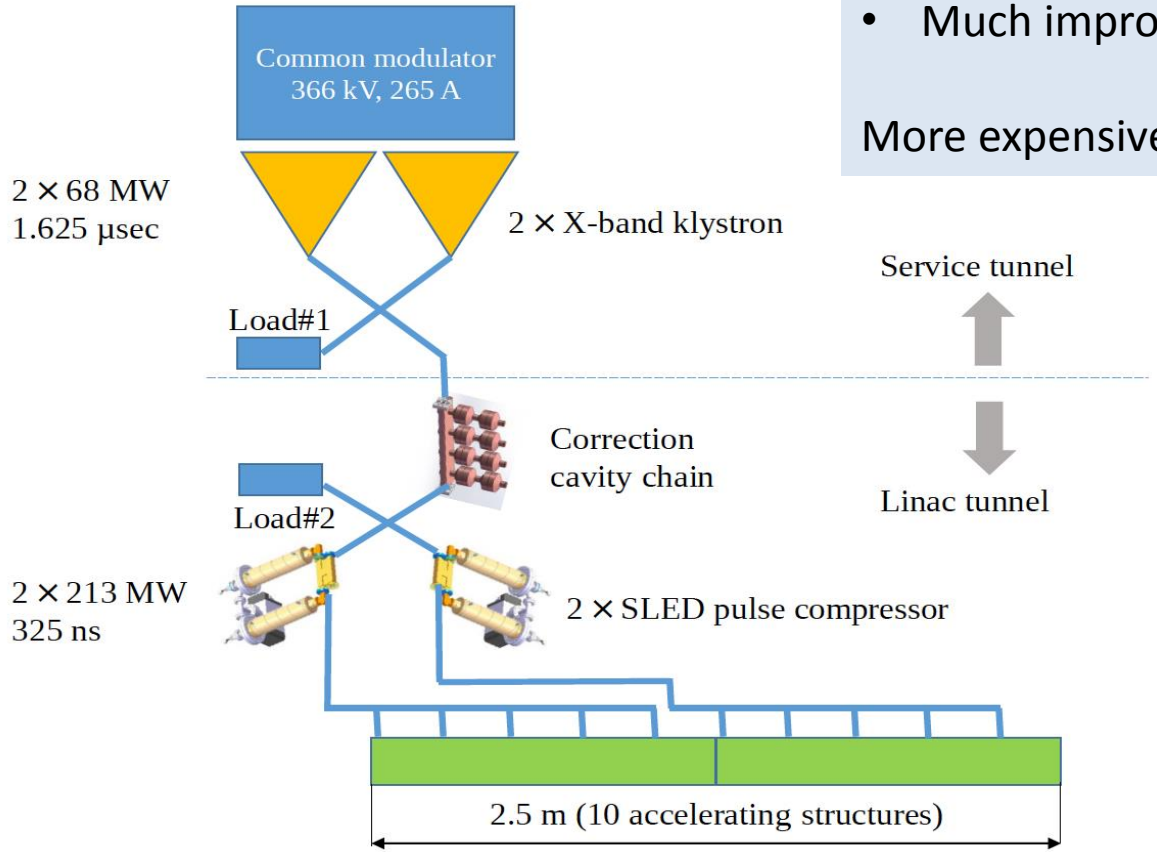
Klystron-based First Stage (380 GeV)

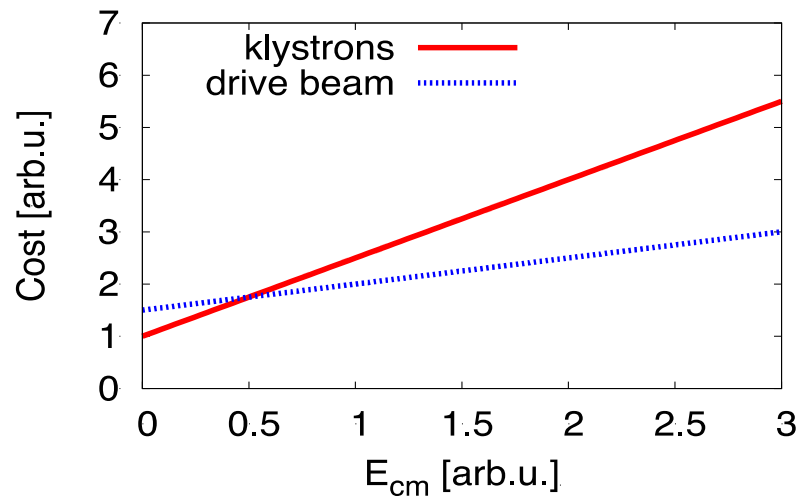
Example RF unit design
(I. Syratchev)

With simple cost model find similar cost than drive beam-based design at 380GeV

- Much improved RF unit design

More expensive at 3TeV

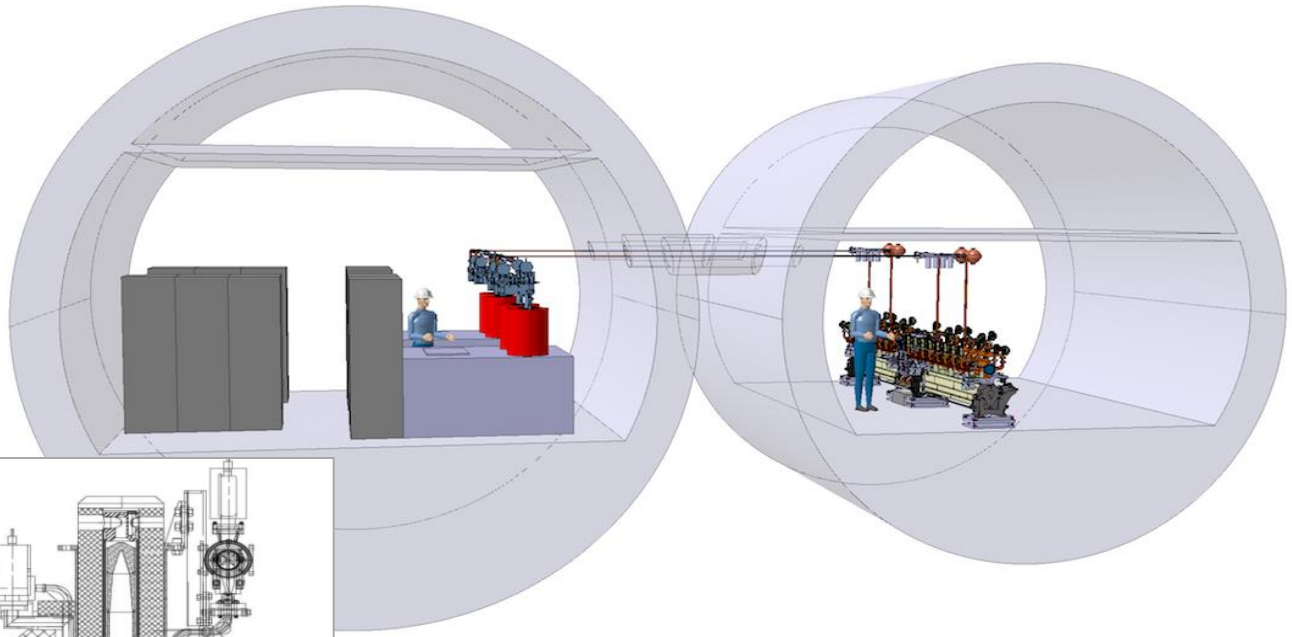




1076 units /beam

The pulse compressor used for parameter determination in the Baseline Report has been still a previous version
But used updated model

380 GeV Klystron Tunnel View



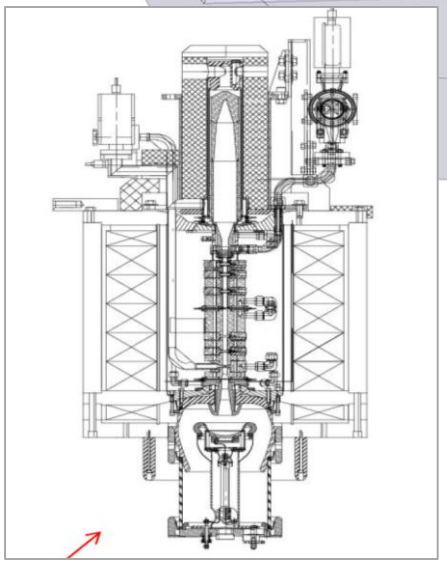


Figure 3: The XL5-1 klystron ready to ship.

Possible R&D Approaches

Objective

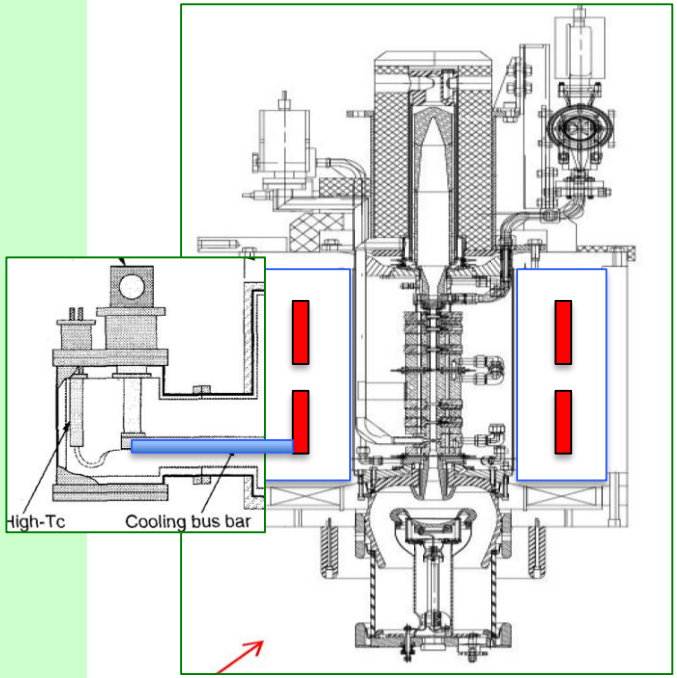
- Demonstrate SC-mag technology to be applicable & power saving

A full-scale model magnet to reach operation with Klystron

- A prototype solenoid using **MgB_2**
  - B = **0.8 T** (central field)
  - Coil size: ~ 0.35 m (dia.), ~ 0.35 m (length)
  - Cryostat size: ~ 0.25 m (ID), ~0.45 m (length)
  - Op. **Temp**. 20 K, conduction cooled by using a cryo-cooler
  - AC-plug power saving: **> 20 KW** → < 2 kW (→ 1/10)
- A goal with operation of the magnet assembled with an existing Klystron

Future:

- Pairing the solenoid, for reducing # CLs.
- HTS solenoid (if cost-effective),
- Cooling by using a dedicated cryogenic system for a series of Klystron & Solenoids to reach < 1 kW AC-plug power /system
- → Saving anticipated : ~ 20kW x 4,500 = ~ 90 MW in CLIC-staging380 .



Summary

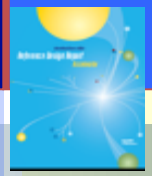
- SRF technology has been matured to realize ILC,
  - based on the progress in SRF cavity surface understanding , and on the successful European XFEL SRF accelerator.
- The staging at **250 GeV** is expected for early starting.

- SC magnet technology applying **MgB_2** may be a very effective approach for Klystron-Solenoid power to be greatly saved in the RF system at the CLIC staging scenario at 380 GeV.
- The feasibility is to be demonstrated.

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)

Technical Design Phase

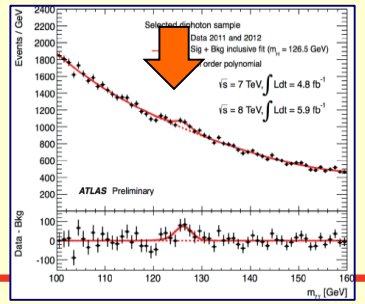
Selection of SC Technology

TDP 2

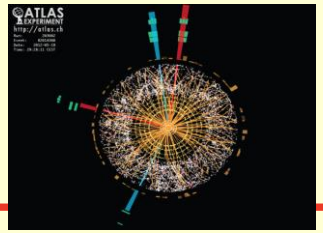
TDR publication

LHC

126 GeV



Higgs discovered

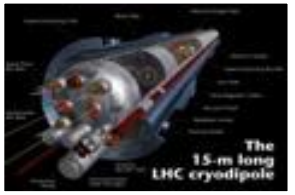


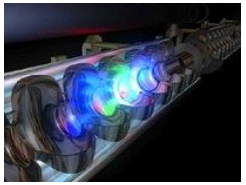
Courtesy, CZ. Antoine, H. Padamsee

Superconducting Phases and Applications

– **SC magnet → mixed state**

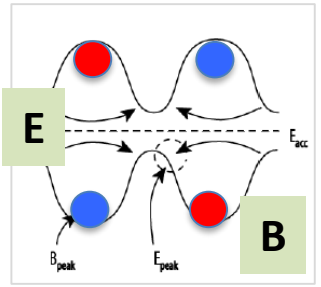
- **Bc2** = limiy for Magnet
  - NbTi : **11.5 T**
  - Nb3Sn : **21.5 T**
  - MbB2: 39 T
- Vortices dissipate in !



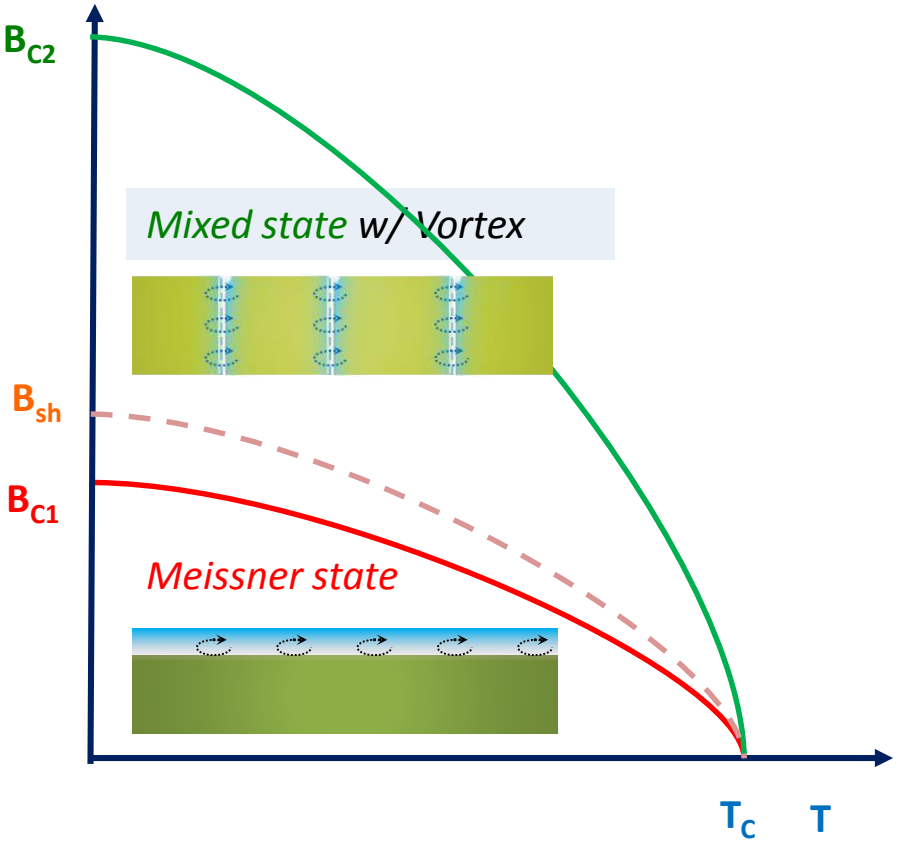


– **SC RF → Meissner state**

- **B_{sh} = limit for SRF**
  - **Nb : 0.21 T**
  - Nb3Sn : 0.43 T

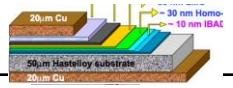


- B_{C1} = limit of Meissner state
  = ~ 0.8 B_{sh}



Courtesy, H. Padamsee, R. Flukiger, A. Ballarino

Possible Choices among SC Materials

Material	T_c [K]	$B_{c1}(0)$ [T]	$B_{sh}(0)$ [T]	$B_c(0)$ [T]	$B_{c2}(0)$ [T]	Pen. depth $\lambda(0)$ [nm]	
Nb	9.2	0.18	0.21	0.25	0.28	40	
NbTi	9.2 ~9.5	0.067	--	--	11.5 ~ 14	60	
NbN	17.3	(0.02)	--	--		150-200	
Nb_3Sn	18.3	(0.05)	0.43	0.54	28 ~30	80	
MgB_2	39	(0.03)	0.31	0.43	39	140	
$YBa_2Cu_3O_7$ (REBCO family)	92	0.01	--	1.4	100	150	
$Bi_2Sr_2Ca_1Cu_2O_8$ (BSCCO-2212)	94	0.025	--	--	>100/30	1800	
$Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO-2223)	110	0.0135	--	--	>100/30	2000	
Note Important for:		RF			Magnet		

Successful Yield in European XFEL SRF 9-cell Cavity Performance

Process & Test	Gradient (G) Yield (Y)	E-XFEL G (@ $Q_0 \geq 10^{10}$) Yield	ILC spec. G (@ $Q_0 \geq 10^{10}$) (Yield)
1st pass	$G_{av.}$ (MV/m) Y (%) at >28 MV/m	33.5 MV/m 63 %	≥ 35 MV/m 75 %
1st+2nd	$G_{av.}$ (MV/m) Y (%) at >28 MV/m	33.4 MV/m 82 %	**≥ 35 MV/m** **90 %**
1st+2nd +3rd	$G_{av.}$ (MV/m) Y (%) at >28 MV/m	**33.4 MV/m** **91 %**	

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

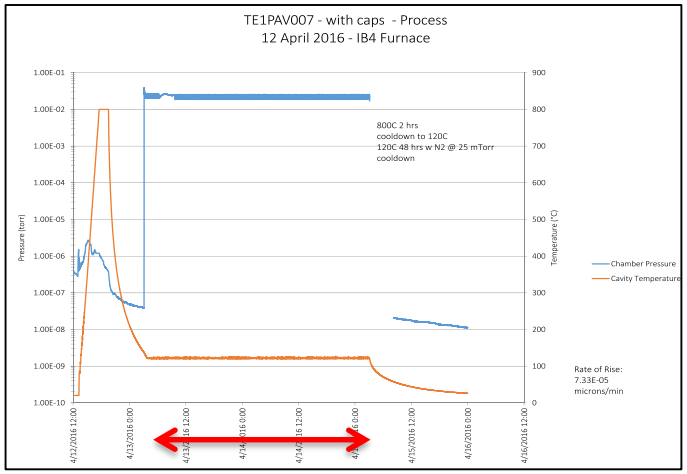
Fabrication

- Material
- EBW
- Shape

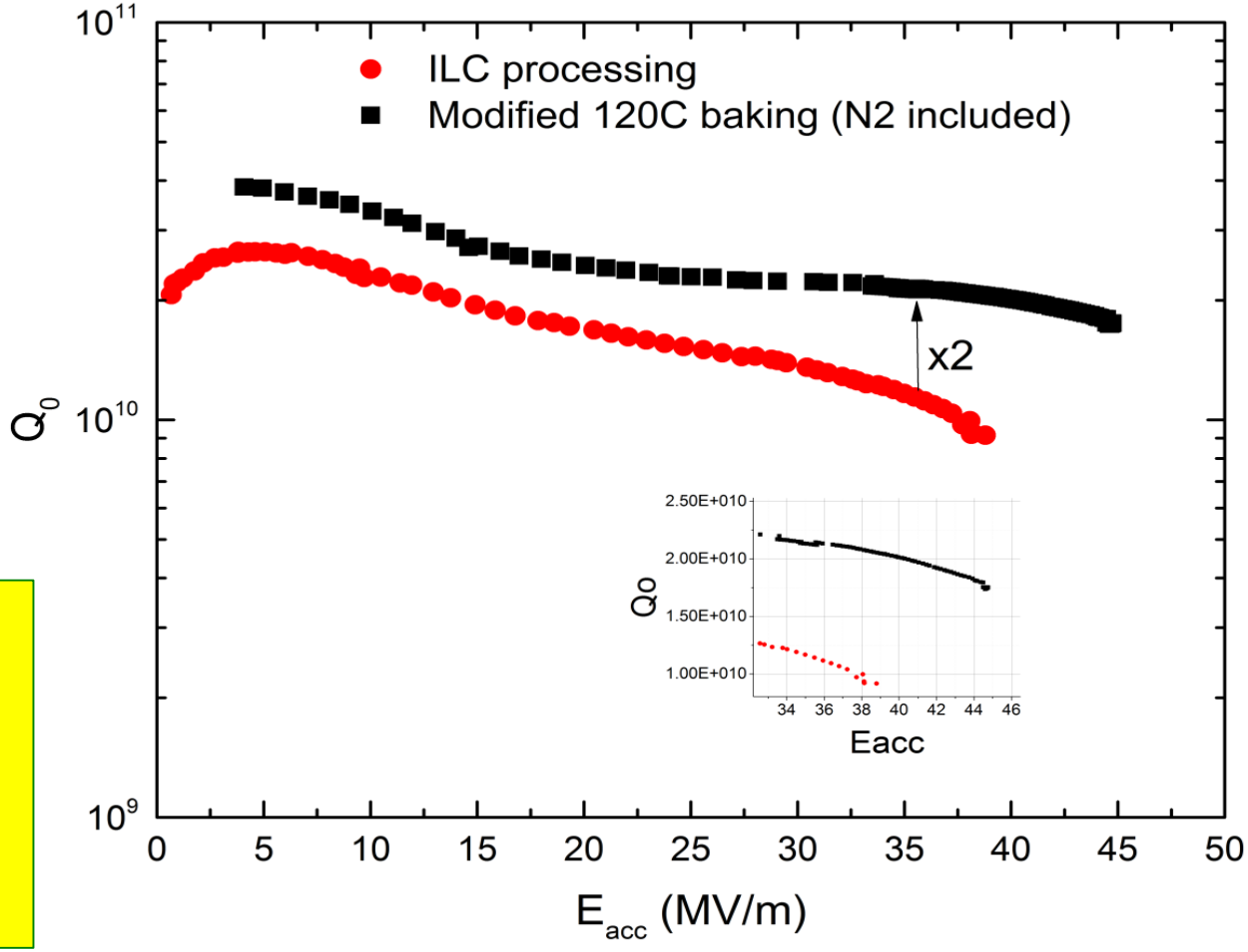
Process

- 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



Comparisons of Future Linear Colliders (as of 17/01/26)

	Unit	ILC H, tt_{-bar}, HHZ, $tt_{-bar}H$			CLIC tt_{-bar}, tt_{-bar}, . . .		
Technology		Linear SRF, Klystron-driven			Linear NRF, Two-beam-driven		
Energy (CoM)	GeV	250	**500**	1,000	**380**	500–A/B	**3,000**
Acc. Length	km	~21	31	50	11	13	48
Lumin. / IP	10^{34} $cm^{-2}s^{-1}$	**0.82***	**1.8 / 3.6**	**3.6**	**1.5***	**2.3**	**5.9**
Acc. Gradient	MV/m	31.5	31.5	31.5/45	72	80/100	100
Res. Frequency	GHz	1.3	1.3	1.3	12	12	12
IR, v. beam-size	nm	7.7	5.9	2.7	2.9	2.3	1
Beam Power	MW (2-beams)	2 x 2.9	2 x 5.2 / N/A	2 x 13.6		2 x 4.7	2 x 14
SR loss	MW						
AC Power	MW	**129**	**163 / 204**	**300**	**252**	**271**	**589**