Draft: 221012a

International
UON Collider
Collaboration

# Performance of ILC/TESLA type SRF Cavities
## for
# Muon Collider RCS Application

**Akira Yamamoto**
(KEK and CERN)

*Acknowledgements:* ***K. Umemori, Y. Yamamoto, and S. Michizono*** *(KEK)*
***H. Damerau, F. Batsch, I. Karpov, and A. Grudiev*** *(CERN)*

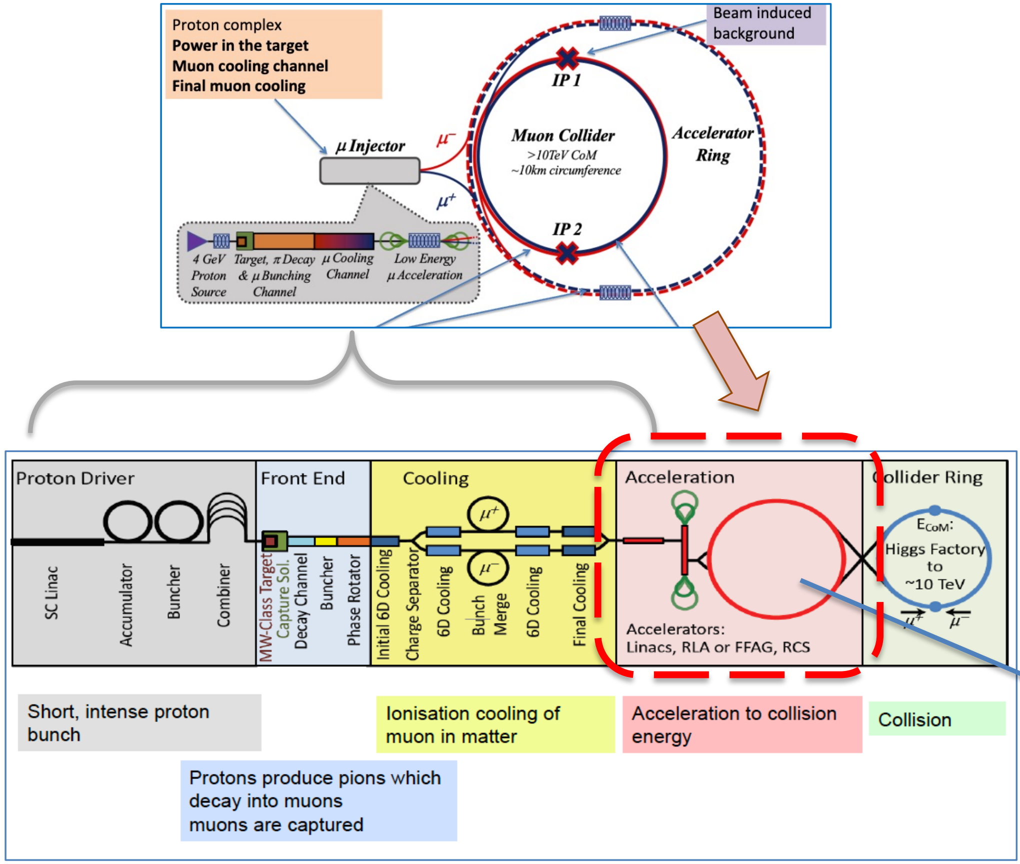
To be presented at the RF WG, MCC Annual Meeting 2022
12 October 2022

# Outline

- **Introduction:**
  - Requirements for SRF from MC-RCS (to be digested)
- **ILC SRF Technology**
  - State-of-Art Performance
- **Efforts for High-Gradient and High-$Q_0$**
  - Surface Process
  - Material: Nb3Sn
  - Traveling Wave
- **Prospect for Future**

Courtesy: H. Damerau, F. Batsch

# 1.3 GHz, pulsed SRF Technology Applicable for the Muon Acceleration to Collision Energy



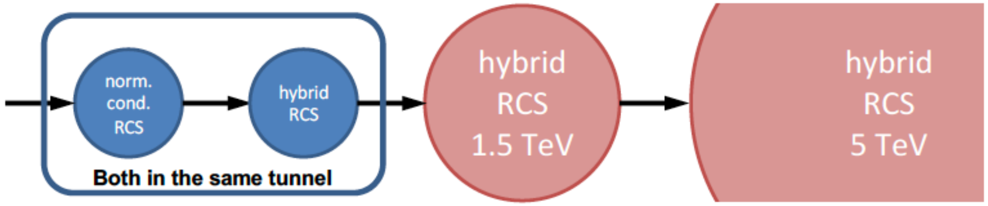

| Parameter | Unit | 3 TeV | 10 TeV | 14 TeV |
|---|---|---|---|---|
| L | $10^{34}$ cm$^{-2}$s$^{-1}$ | 1.8 | 20 | 40 |
| N | $10^{12}$ | 2.2 | 1.8 | 1.8 |
| $f_r$ | Hz | 5 | 5 | 5 |
| $P_{beam}$ | MW | 5.3 | 14.4 | 20 |
| C | km | 4.5 | 10 | 14 |
| <B> | T | 7 | 10.5 | 10.5 |
| $\varepsilon_L$ | MeV m | 7.5 | 7.5 | 7.5 |

Multiple RF station along Acc. RIng
with 1.3 GHz, pulsed SRF cavity (30 MV/m)
being studied by F. Batsch et al.,

Courtesy: H. Damerau, F. Batsch

# Pulse-duration Extend-ability to be investigated

- **Chain of rapid cycling synchrotrons, counter-rotating $\mu^+/\mu^-$ beams $\rightarrow$ 63 GeV $\rightarrow$ 0.31 TeV $\rightarrow$ 0.75 TeV $\rightarrow$ 1.5 TeV ($\rightarrow$ 5 TeV)**




- **Detailed parameter table (F. Batsch):** https://cernbox.cern.ch/index.php/s/I9VpITncUeCBtiz

| | RCS1 | FNAL | J-PARC |
|---|---|---|---|
| Circumference, $2\pi R$ [m] | 5990 | 468 | 348 |
| Energy factor, $E_{ej}/E_{inj}$ | 5 | 20 | 7.5 |
| Repetition rate, $f_{rep}$ [Hz] | 5 (asym.) | 15 | 25 |
| Magnetic ramp | Linearized | Sinus | Sinus |
| Number of turns | 17 | 42 k | 17 k |
| Max. RF voltage, $V_{RF}$ [MV] | 21000 | 0.86 | 0.44 |
| Energy gain per turn, $\Delta E$ [MeV] | 14800 | ~0.4 | ~0.2 |

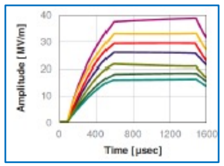
Significantly **more RF voltage than any other RCS**

**→N-cavity / RCS1** = 21,000 MV / (30 MV/m x 1.038) = ~ 674

- **Repetition rate of RCS chain: 5 Hz (as ILC)**
- **Minimum pulse length for RF system???**

| | RCS1 | RCS2 | RCS3 | (RCS4) |
|---|---|---|---|---|
| **Ejection energy, $E_{ej}$ [TeV]** | 0.31 | 0.75 | 1.5 | (5.0) |
| **Acceleration time, beam pulse length, $\tau_{acc}$ [ms]** | 0.34 | 1.1 | 2.4 | (6.4) |

→ **Pulse length ~1.6 ms same order as for ILC (beam pulse length 1 ms)**




| | ILC | RCS1 (& RCS2) |
|---|---|---|
| Number of bunches, $n_b$ | 1312 | 1 each $\mu^+$ and $\mu^-$ |
| Bunch spacing, $t_{bs}$ | 554 ns | $T_{rev}$ = 20 μs |
| Bunch intensity, $N_b$ | $2 \cdot 10^{10}$ p/b | $2.5 \cdot 10^{12}$ p/b |
| **Average beam current, $I_b$** | 5.8 mA | 2 × 20 mA |

Courtesy: H. Damerau, F. Batsch

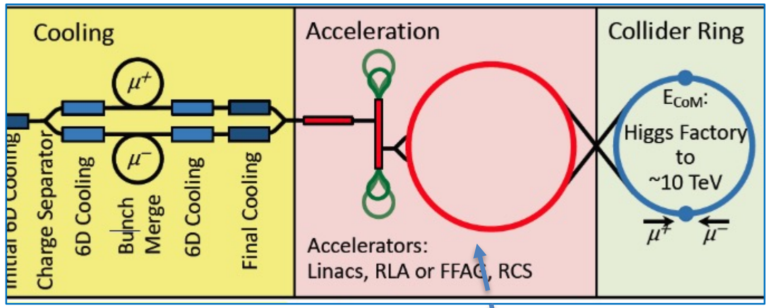
# 1.3 GHz, pulsed SRF Technology Applicable for the Muon Acceleration to Collision Energy

## Status of the studies for the RF of the pulsed synchrotrons

**F. Batsch**[1], I. Karpov, H. Damerau

Acknowledgements: A. Chance, A. Grudiev, D. Amorim, E. Metral, F. Boattini, L. Bottura

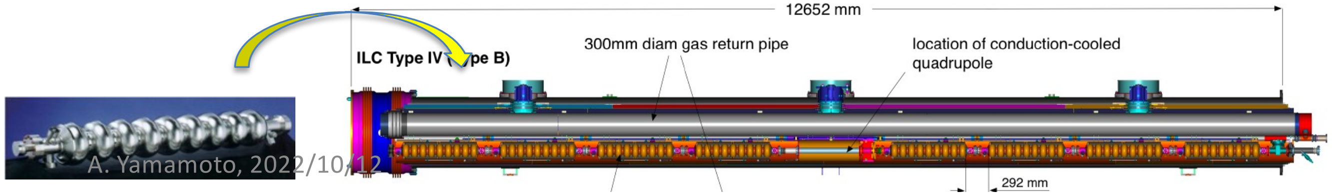
Accelerator design meeting
27/06/2022




- Studies for three RCSs [1] of the high-energy accelerator chain up from 63GeV to 1.5TeV, parameters summarized below [2] and in this table
- Using the BLonD code to observe effects of the synchrotron tune and the short-range wakefields, beam loading,...
- BLonD: (Beam Longitudinal Dynamics code) macro-particle tracking code, developed at CERN from 2014 on. Links: documentation and github
- Studies with multiple RF stations along ring, 1.3 GHz TESLA cavities, 30 MV/m in cavity

Number of straight sections: **30**

preferred




Acc. Voltage / CM-B
= 8 x 30 MV/m x 1.038 m / 12.56 m
= 249 MV / 12.56 m

Courtesy: H. Damerau, F. Batsch

# Summary of RF requirements

| Parameter | Value | Remark |
|---|---|---|
| Frequency, $f_{RF}$ | 1.3 GHz | |
| Tuning range (piezo), $\Delta f$ | 2.2 kHz | Sweep for acceleration, only hybrid RCS2/3/4 |
| Gradient, $V_{RF}/l$ | 30 MV/m | |
| Beam pulse length, $\tau_{acc}$ | 0.34 / 1.1 / 2.4 ms (6.36) ms | RCS-1 / -2 / -3/ ( -4) |
| Beam current, $I_{DC}$ | $2 \times 20$ mA | |
| Power to the beam (max., RCS1) | $2 \times 250$ MW | ~ $2 \times 430$ kW/cavity |

# Outline

- **Introduction:**
  - Requirements for SRF from MC-RCS (to be digested)
- **ILC SRF Technology**
  - State-of-Art Performance
- **Efforts for High-Gradient and High-$Q_0$**
  - Surface Process
  - Material: Nb3Sn
  - Traveling Wave
- **Prospect for Future**

Courtesy: S. Michizono

# ~ 1.3 GHz SRF Accelerators, worldwide

European XFEL
(in operation, 2017~)

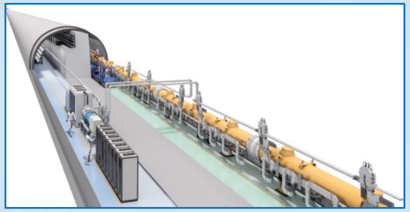
800 cavities
100 CMs
17.5 GeV (Pulsed)

**ESS (0.8 GHz)**
(under construction)

**SHINE**
(under construction)

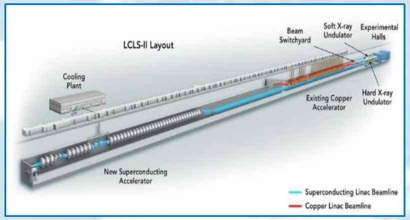
~600 cavities
75 CMs
8 GeV (CW)

S1 Global:
DESY, Fermilab, KEK
8-cavity string Test,
2010



**ILC** (planned)

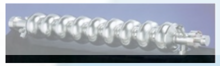
8,000 9-cell cavities
900 CMs
2 x 125 GeV (Pulsed)




**LCLS-II -HE**
(under construction)

-280+200 cavities
-35+25 CMs
- 4 +4 GeV (CW)

JLab-CEBAF(1.5 GHz)
(in operation)
40 CMs
6~12 GeV(CW)

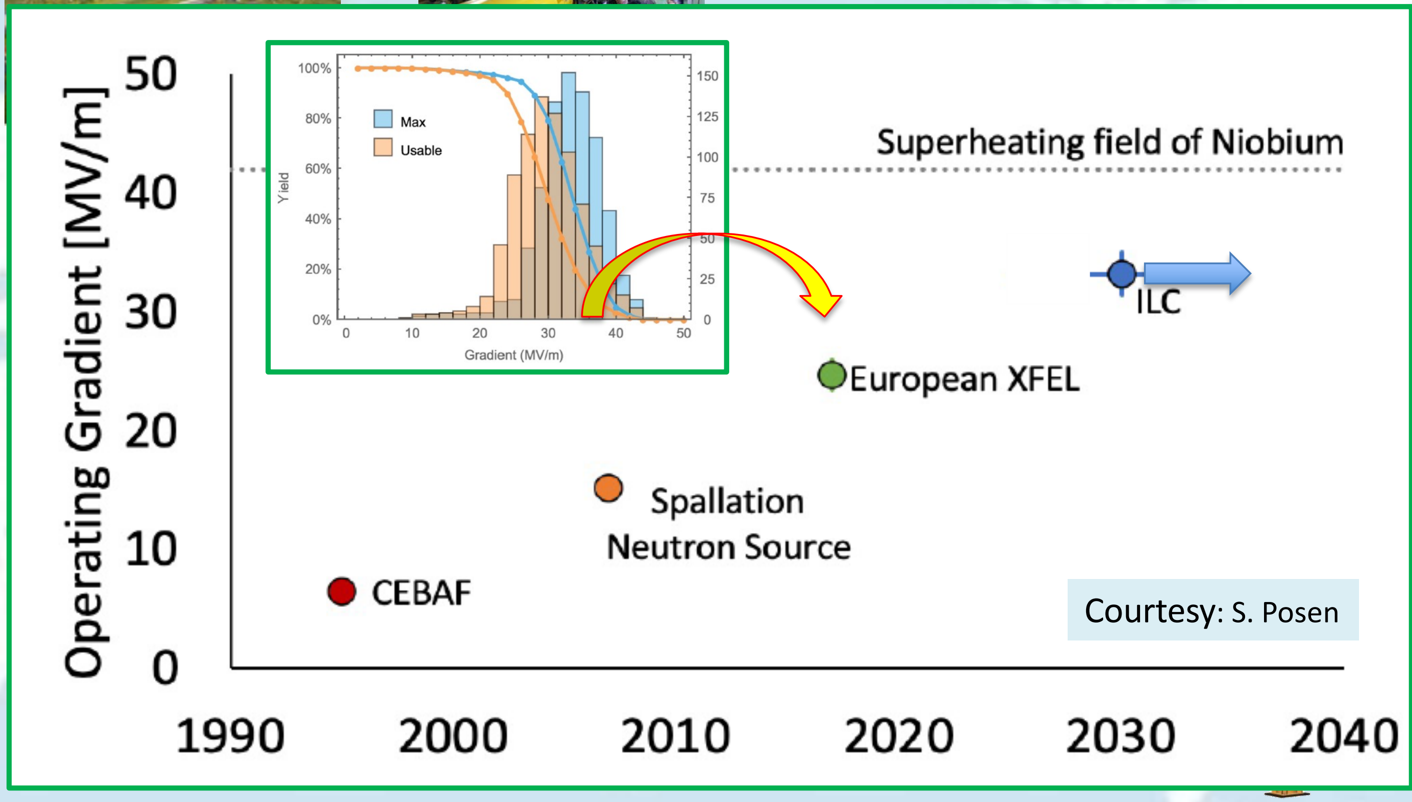


**~ 2,000** 1.3 GHz SRF cavities being realized, even in these 10 years !

# ~ 1.3 GHz, SRF Accelerators, worldwide

European XFEL
(in operation, 2017~)

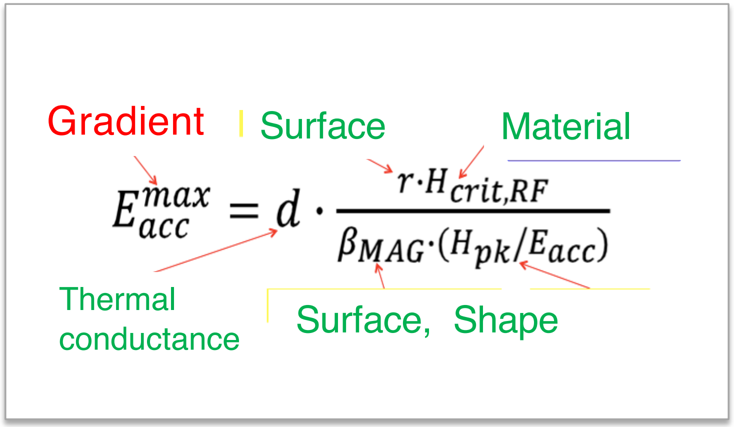
- -800 cavities
- -100 CMs
- -17.5 GeV (Pulsed)



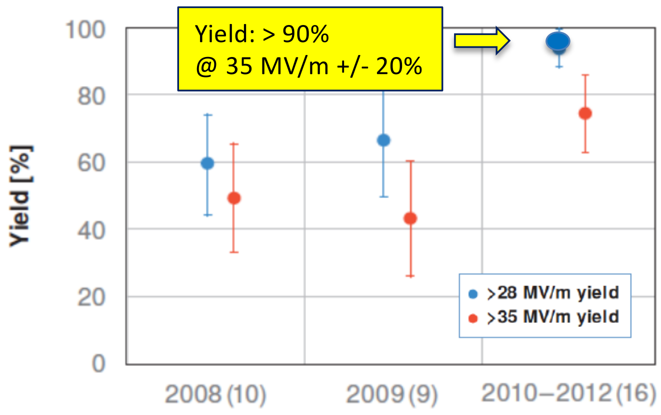

~ **2,000** 1.3 GHz SRF cavities being realized, even in these 10 years !

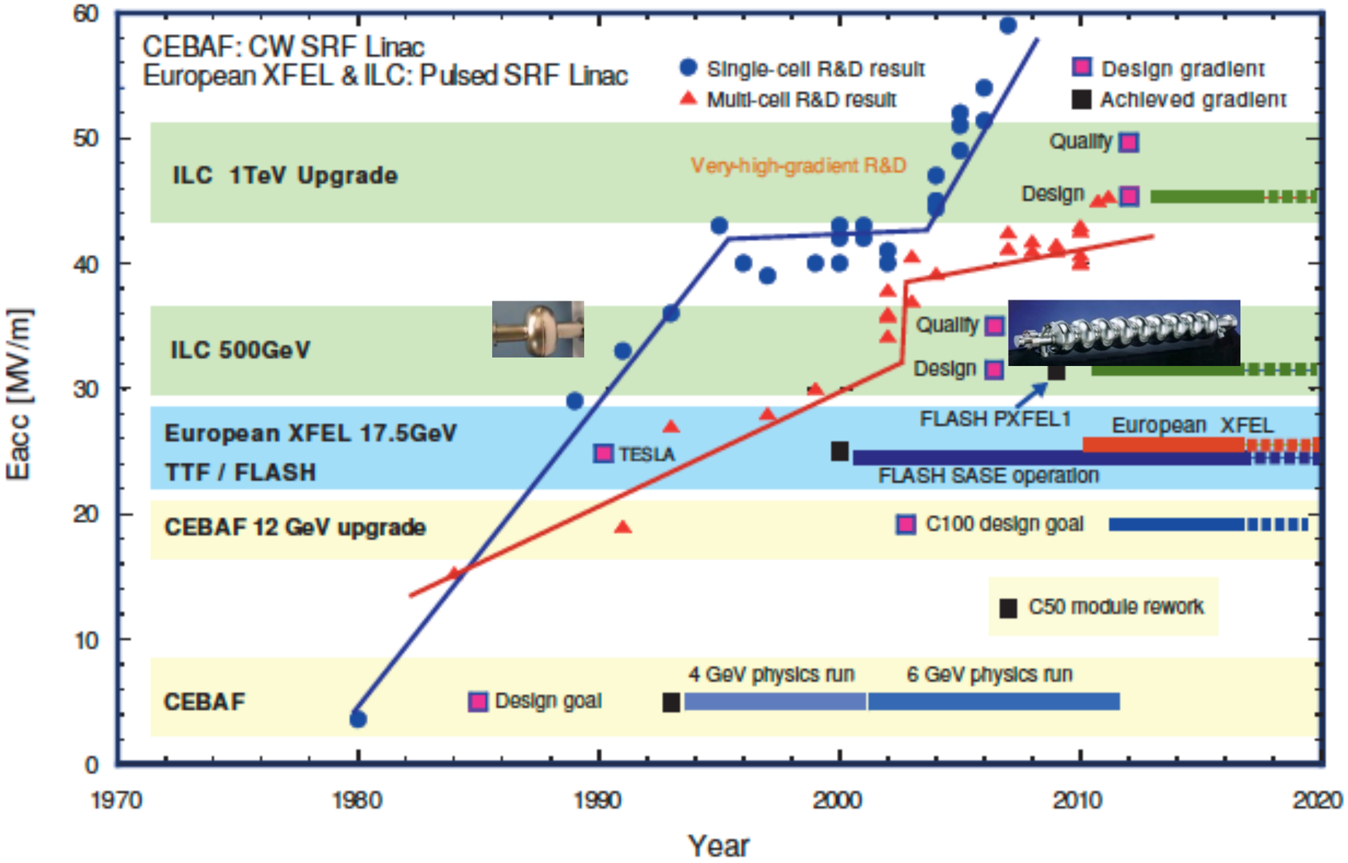
Courtesy: R. Geng,

# Advances in L-band (~ 1GHz) SRF Cavity Gradient




$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$



Courtesy, H. Weise, N. Walker

# European XFEL, SRF Linac Completed and in Operation

URL: http://www.desy.de/news/news_search/index_eng.html


2018/07/17

Back

## European XFEL accelerator reaches its design energy

Accelerator accelerates electrons to 17.5 GeV for the first time

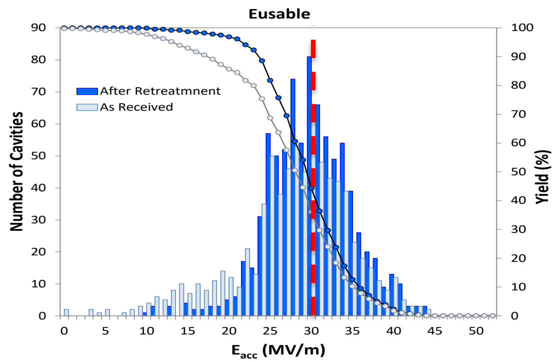
**Progress:**

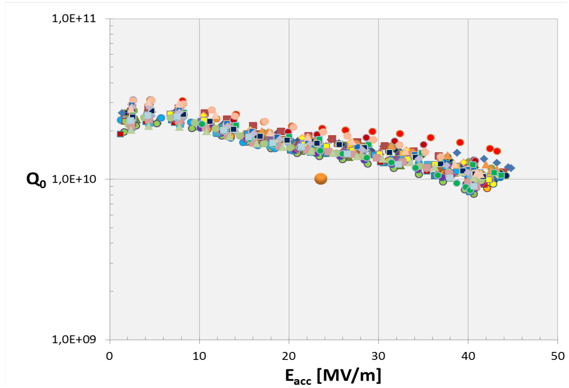
2013: Construction started

2016: E- XFEL Linac completion

2017: E-XFEL beam start

2018: 17.5 GeV achieved




**1.3 GHz / 23.6 MV/m**

**800+4 SRF acc. Cavities**

**100+3 Cryo-Modules (CM)**

***: ~1/10 scale to ILC-ML***

**<E-usable> : 29.8 MV/m**

(RI): 31 MV/m w/ 2° process

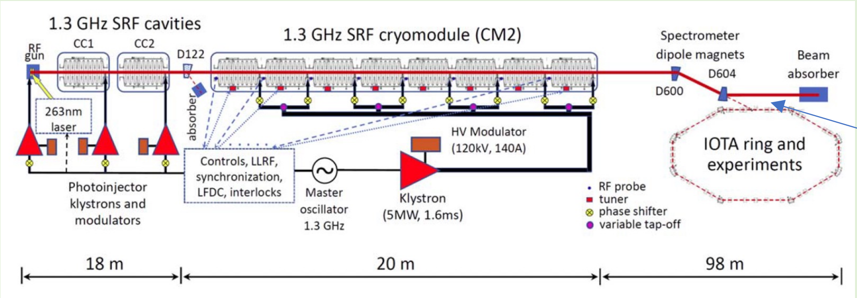
33 MV/m w/ 3° process

>10 % (47/420, RI) cavities exceeding 40 MV/m

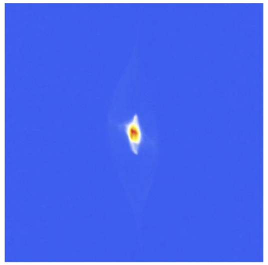
A. Yamamoto, 2022/10/12

Courtesy: V. Shiltsev, S. Michizono

# Fermilab achieved ILC Gradient Goal ≥ 31.5 MV/m with beam acceleration, 260 MeV



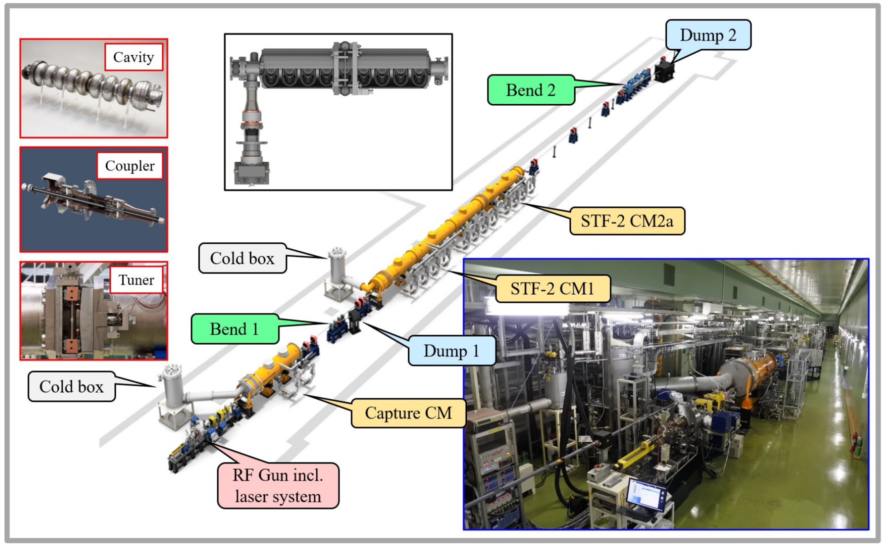

**Fermilab-FAST** Progress, 2017



Beam Acc. : 260 MeV by 8 Cavities,
<G> : 32.3 MV/m

# Beam Acceleration Achievement at KEK/STF

Courtesy, Y. Yamamoto
LINAC2022 @Liverpool+online




- ~70 m SC linac (1.65 ms/5Hz)
- SC cavities: 14 (1.3 GHz, 9-cell)
- Cryomodules: CCM, CM1/CM2a
- Klystrons: 3 (5 MW, 800 kW, 10 MW)
- Beam dumps: 2 (Dump2: 37.8 kW)

| **Parameters** | **Apr/2021** |
|---|---|
| # cavities incl. CCM used for operation | 12 + 2 |
| Beam energy | **384 MeV (40 MeV @CCM)** |
| Beam intensity | 1.8 μA |
| Beam power | 677 W |
| Total charge per pulse | 360 nC |
| RF power @RF Gun | 4.0 MW |
| Normalized emittance @CCM | 10-20 mm mrad |
| Normalized emittance @CM1/2a | 10-20 mm mrad |
| $E_{acc}$ from beam energy | **32.9 MV/m (9 cavities)** |
| $E_{acc}$ from RF power ($P_{tra}$) | 33.0 MV/m (9 cavities) |

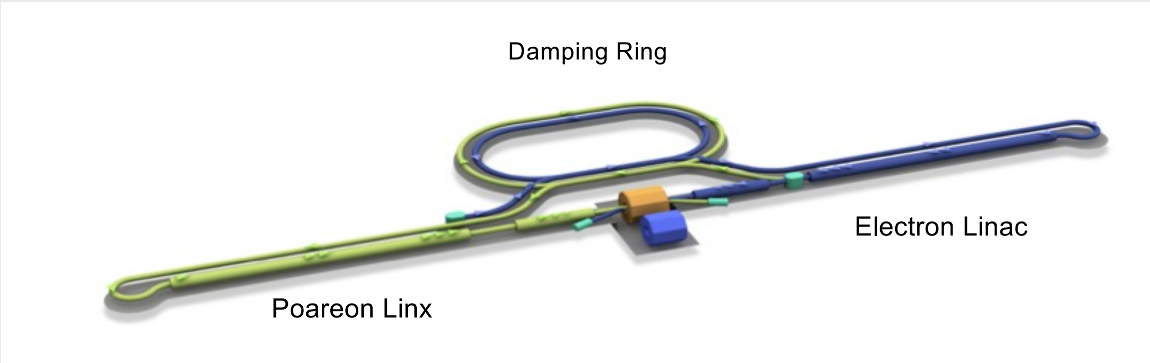
# Achievements at KEK/STF

We have demonstrated the SRF linac operation with the ILC specifications at STF!

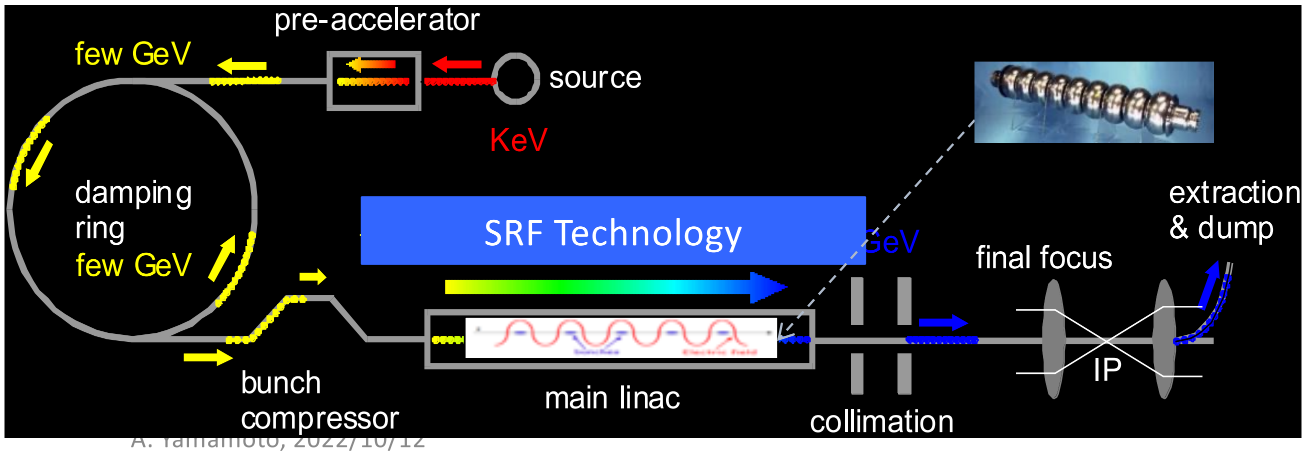
| **Parameters** | **Mar/2019** | **Apr/2021** |
|---|---|---|
| Number of cavities incl. CCM used for operation | 7 + 2 | 12 + 2 |
| Beam energy | 280 MeV (40 MeV @CCM) | 384 MeV (40 MeV @CCM) |
| Beam intensity | 0.28 μA | 1.8 μA |
| Beam power | 78 W | 677 W |
| Total charge per pulse | 56 nC | 360 nC |
| RF power @RF Gun | 2.5 MW | 4.0 MW |
| Normalized emittance @CCM | 10-20 mm mrad | 10-20 mm mrad |
| Normalized emittance @CM1/2a | 10-20 mm mrad | 10-20 mm mrad |
| $E_{acc}$ from beam energy | 33.1 MV/m (7 cavities) | 32.9 MV/m (9 cavities) |
| $E_{acc}$ from RF power ($P_{tra}$) | 33.8 MV/m (7 cavities) | 33.0 MV/m (9 cavities) |

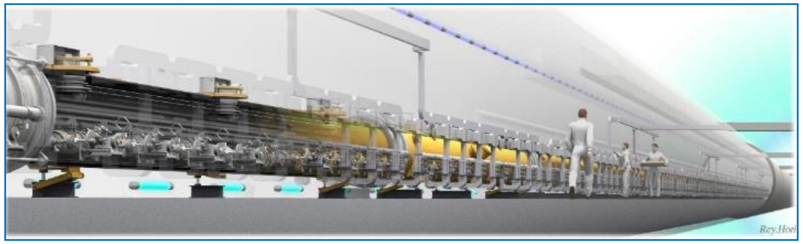
# International Linear Collider : ILC

https://linearcollider.org/technical-design-report/

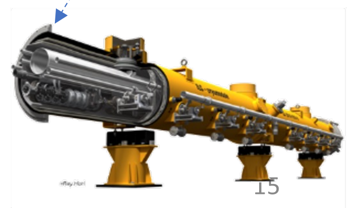






| Item | Parameter |
|---|---|
| Energy | 125+125 GeV |
| Repetition Rate | 5 Hz |
| Beam Pulse Width | 0.73 ms |
| Electric Gradient<br>$Q_0$ | 31.5 MV/m( +/-20%)<br>$Q_0$ = 1E10 |
| **# 9-cell Cavity (1.3 m)** | **~ 8,000 ( x 1.1)** |
| **# Cryomodule ((12 m)** | **~ 900** |



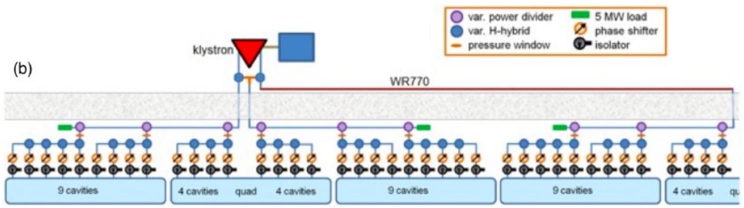
# ILC Accelerator Design Parameters

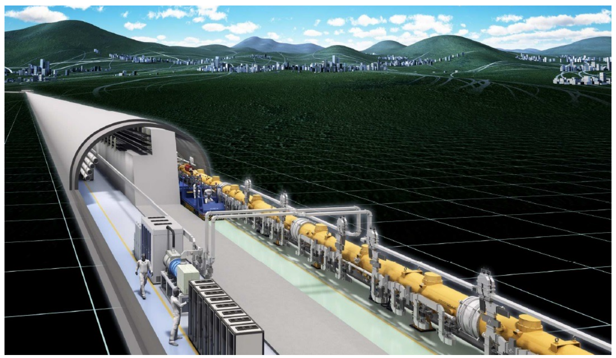
| Quantity | Symbol | Unit | Initial | $\mathcal{L}$ Upgrade | TDR | Z pole | Upgrades | |
|---|---|---|---|---|---|---|---|---|
| Centre of mass energy | $\sqrt{s}$ | GeV | 250 | 250 | 250 | 91 | 500 | 1000 |
| Luminosity | $\mathcal{L}$ | $10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ | 1.35 | 2.7 | 0.82 | 0.21 | 1.8/3.6 | 4.9 |
| Polarisation for $e^-/e^+$ | $P_-/P_+$ | % | 80/30 | 80/30 | 80/30 | 80/30 | 80/30 | 80/20 |
| Repetition frequency | $f_{\mathrm{rep}}$ | Hz | 5 | 5 | 5 | 3.7 | 5 | 4 |
| Bunches per pulse | $n_{\mathrm{bunch}}$ | 1 | 1312 | 2625 | 1312 | 1312 | 1312/2625 | 2450 |
| Bunch population | $N_{\mathrm{e}}$ | $10^{10}$ | 2 | 2 | 2 | 2 | 2 | 1.74 |
| Linac bunch interval | $\Delta t_{\mathrm{b}}$ | ns | 554 | 366 | 554 | 554 | 554/366 | 366 |
| Beam current in pulse | $I_{\mathrm{pulse}}$ | mA | 5.8 | 5.8 | 8.8 | 5.8 | 5.8 | 7.6 |
| Beam pulse duration | $t_{\mathrm{pulse}}$ | $\mu$s | 727 | 961 | 727 | 727 | 727/961 | 897 |
| Average beam power | $P_{\mathrm{ave}}$ | MW | 5.3 | 10.5 | 10.5 | $xx$ | 10.5/21 | 27.2 |
| Norm. hor. emitt. at IP | $\gamma\epsilon_{\mathrm{x}}$ | $\mu$m | 5 | 5 | 10 | $xx$ | 10 | 10 |
| Norm. vert. emitt. at IP | $\gamma\epsilon_{\mathrm{y}}$ | nm | 35 | 35 | 35 | $xx$ | 35 | 30 |
| RMS hor. beam size at IP | $\sigma^*_{\mathrm{x}}$ | nm | 516 | 516 | 729 | $xx$ | 474 | 335 |
| RMS vert. beam size at IP | $\sigma^*_{\mathrm{y}}$ | nm | 7.7 | 7.7 | 7.7 | $xx$ | 5.9 | 2.7 |
| Luminosity in top 1 % | $\mathcal{L}_{0.01}/\mathcal{L}$ | | 73 % | 73 % | 87.1 % | $xx$ | 58.3 % | 44.5 % |
| Beamstrahlung energy loss | $\delta_{\mathrm{BS}}$ | | 2.6 % | 2.6 % | 0.97 % | $xx$ | 4.5 % | 10.5 % |
| Site AC power | $P_{\mathrm{site}}$ | MW | 111 | 138 | 122 | 93 | 163 | 300 |
| Site length | $L_{\mathrm{site}}$ | km | 20.5 | 20.5 | 31 | 31 | 40 | |

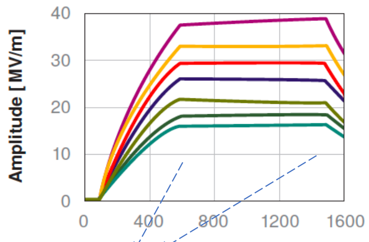
Table 4.1: Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration (with TDR parameters at 250 GeV given for comparison) and possible upgrades. A 500 GeV machine could also be operated at 250 GeV with 10 Hz repetition rate, bringing the maximum luminosity to $5.4 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [10]. *COMPLETE NUMBERS*

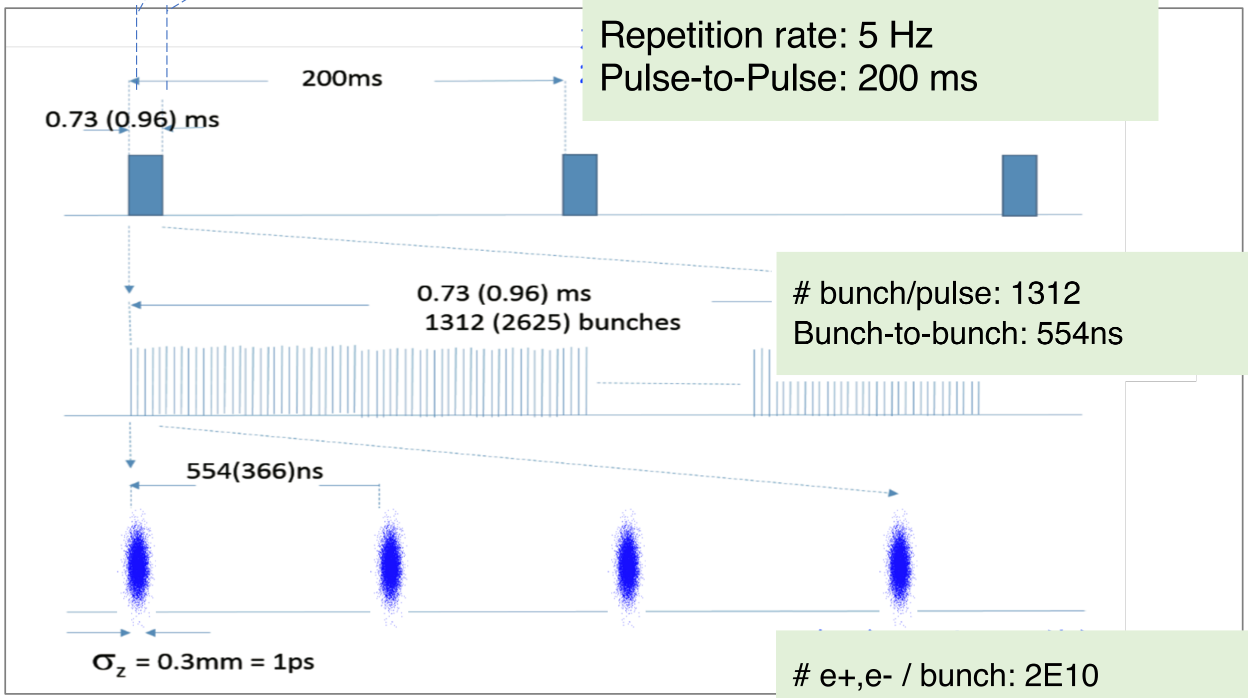
Courtesy: S. Michizono

# ILC SRF 5Hz Pulse Operation Scheme






Repetition rate: 5 Hz
Pulse-to-Pulse: 200 ms

# bunch/pulse: 1312
Bunch-to-bunch: 554ns

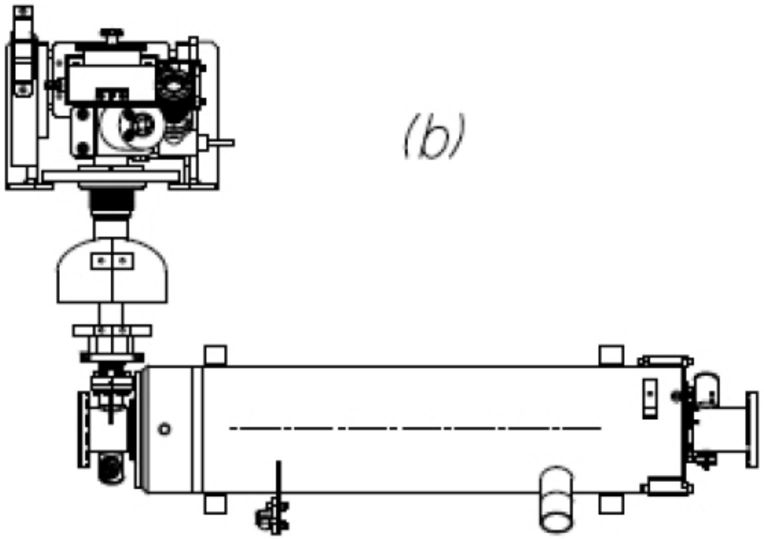
# e+,e- / bunch: 2E10

from ILC-TDR

# ILC 1.3 GHz SRF Cavity Parameters

| Parameter | Value |
|---|---|
| Type of accelerating structure | Standing wave |
| Accelerating mode | $TM_{010}, \pi$ mode |
| Type of cavity-cell shape | Tesla (or Tesla-like) |
| Fundamental frequency | 1.300 GHz |
| Operation: | |
| – Average gradient (range allowed) | 31.5 MV/m (±20% ) |
| – Quality factor (at 31.5 MV/m) | $\geq 1 \times 10^{10}$) |
| Qualification: | |
| – Average gradient (range allowed) | 35.0 MV/m (±20% ) |
| – Quality factor (at 35 MV/m) | $\geq 0.8 \times 10^{10}$ |
| – Acceptable radiation (at 35 MV/m) | $\leq 10^{-2}$mGy/min[†] |
| Active length | 1038.5 mm |
| Total length (beam flanges, face-to-face) | 1247.4 mm |
| Input-coupler pitch distance, including inter-connection | 1326.7 mm |
| Number of cells | 9 |
| Cell-to-cell coupling | 1.87% |
| Iris aperture diameter (inner/end cell) | 70/78 mm |
| Equator inner diameter | ~210 mm |
| $R/Q$ | 1036 Ω |
| $E_{peak}/E_{acc}$ | 2.0 |
| $B_{peak}/E_{acc}$ | 4.26 mT/(MV/m) |
| Tunable range | ±300 kHz |
| $\Delta f/\Delta L$ | 315 kHz/mm |
| Number of HOM couplers | 2 |
| $Q_{ext}$ for high-impedance HOM | $< 1.0 \times 10^5$ |
| Nb material for cavity (incl. HOM coupler and beam pipe): | |
| - RRR | ≥300 |
| - Mechanical yield strength (annealed) | ≥ 39 MPa |
| Material for helium tank | Nb-Ti Alloy |
| Max design pressure (high-pressure safety code) | 0.2 MPa |
| Max hydraulic-test pressure | 0.3 MPa |

† Example number taken from [16] — see text for more details

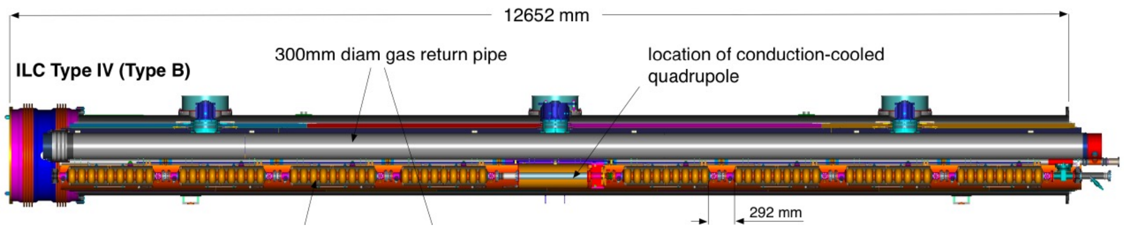



**Coupler and Tuner:**
See next talk by Y. Yamamoto

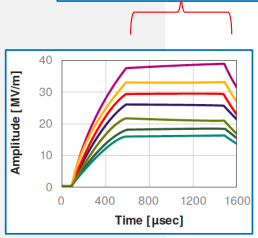
from ILC-TDR

# ILC 1.3 GHz SRF CM Parameters

| | | |
|---|---|---|
| *Cavity (nine-cell TESLA elliptical shape)* | | |
| Average accelerating gradient | 31.5 | MV/m |
| Quality factor $Q_0$ | $10^{10}$ | |
| Effective length | 1.038 | m |
| R/Q | 1036 | Ω |
| Accepted operational gradient spread | ±20% | |
| *Cryomodule* | | |
| Total slot length | 12.652 | m |
| Type A | 9 cavities | |
| Type B | 8 cavities | 1 SC quad package |
| *ML unit (half FODO cell)* | 282 (285) | units |
| (Type A - Type B - Type A) | | |
| *Total component counts* | | |
| Cryomodule Type A | 564 (570) | |
| Cryomodule Type B | 282 (285) | |
| Nine-cell cavities | 7332 (7410) | |
| SC quadrupole package | 282 (285) | |
| Total linac length – flat top. | 11027 (11141) | m |
| Total linac length – mountain top. | 11072 (11188) | m |
| Effective average accelerating gradient | 21.3 | MV/m |
| *RF requirements (for average gradient)* | | |
| Beam current | 5.8 | mA |
| beam (peak) power per cavity | 190 | kW |
| Matched loaded $Q$ ($Q_L$) | $5.4 \times 10^6$ | |
| Cavity fill time | 924 | μs |
| Beam pulse length | 727 | μs |
| Total RF pulse length | 1650 | μs |
| RF–beam power efficiency | 44% | |




Beam Pulse



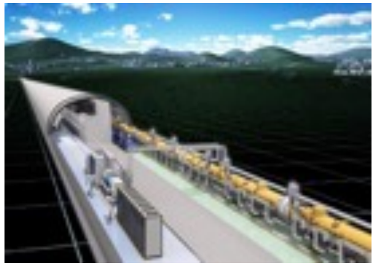

SRF cavity Physical **Filling Factor** (See next page):

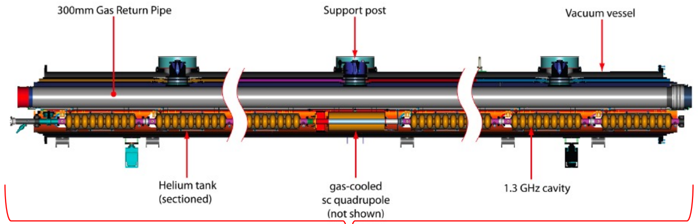
- **CM (Type-A) :**
  9 x 1.038 / 12.652 = **0.738**
- **CM (Type-B with SCQ)**
  8 x 1.038 / 12.652 = **0.656**

- **Cryo-Unit (standad):**
  (2x9+1x8) x 4 x 13 x 1.038 / 2008.7 = **0.699**

# ILC ML SRF CM Configuration

from ILC-TDR





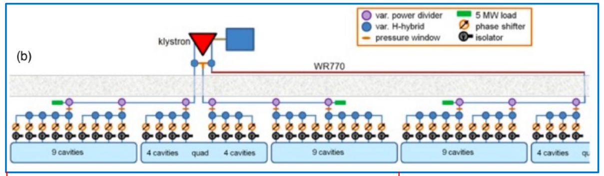
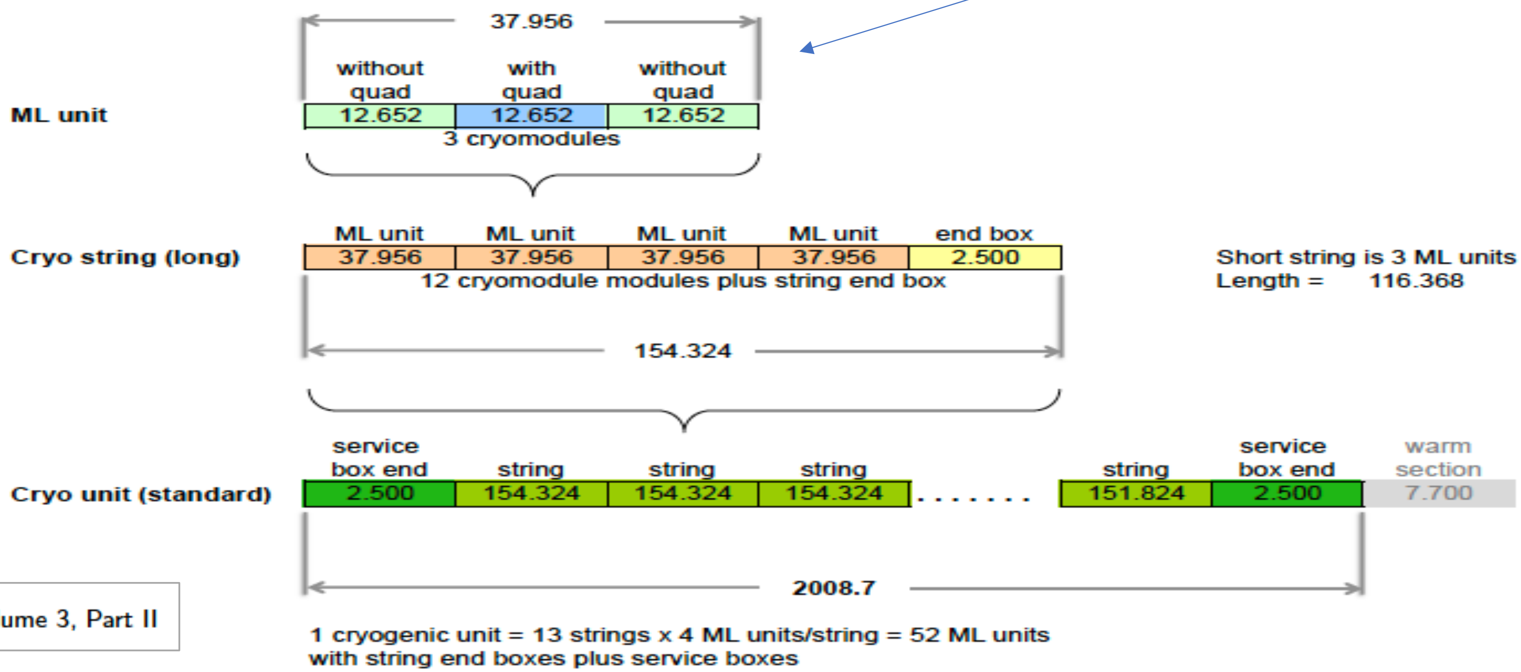




**Figure 3.2**
Basic cryogenic segmentation in the main linacs. Note that the length of the cryo units varies depending on the number of strings. (All lengths given in metres.)




42 ILC Technical Design Report: Volume 3, Part II

from ILC-TDR

# ILC-ML CM Heat Load and Cryogenics

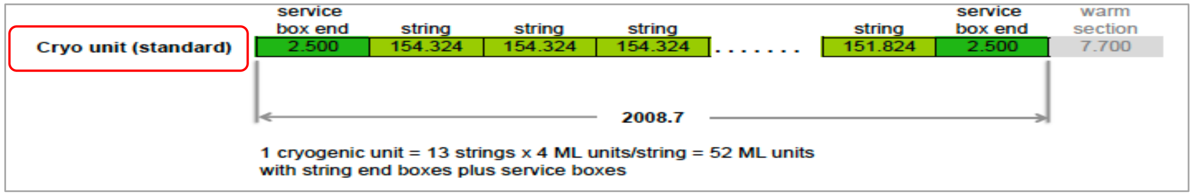
**Table 3.9** Average heat loads per module in a ML unit, for the baseline parameter in Table 3.1. All values are in watts [27].

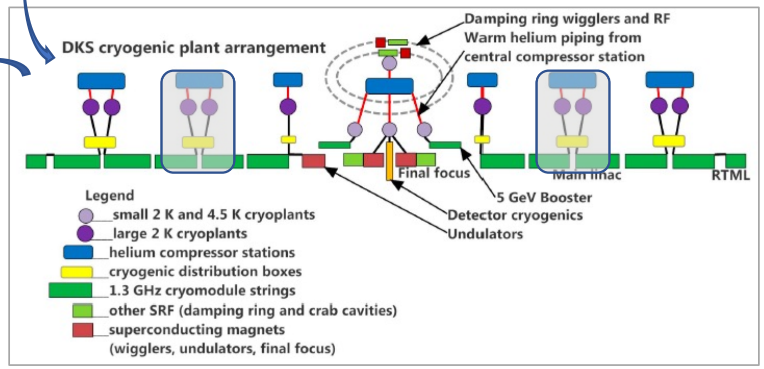
| | 2 K | | 5–8 K | | 40–80 K | |
|---|---|---|---|---|---|---|
| | Static | Dynamic | Static | Dynamic | Static | Dynamic |
| RF Load | | 8.02 | | | | |
| Radiation Load | | | 1.41 | | 32.49 | |
| Supports | 0.60 | | 2.40 | | 18.0 | |
| Input coupler | 0.17 | 0.41 | 1.73 | 3.06 | 16.47 | 41.78 |
| HOM coupler (cables) | 0.01 | 0.12 | 0.29 | 1.17 | 1.84 | 5.8 |
| HOM absorber | 0.14 | 0.01 | 3.13 | 0.36 | -3.27 | 7.09 |
| Beam tube bellows | | 0.39 | | | | |
| Current leads | 0.28 | 0.28 | 0.47 | 0.47 | 4.13 | 4.13 |
| HOM to structure | | 0.56 | | | | |
| Coax cable (4) | 0.05 | | | | | |
| Instrumentation taps | 0.07 | | | | | |
| Diagnostic cable | | | 1.39 | | 5.38 | |
| Sum | 1.32 | 9.79 | 10.82 | 5.05 | 75.04 | 58.80 |
| Total | 11.11 | | 15.87 | | 133.84 | |

**Table 3.11.** Main-linac heat loads and cryogenic plant size [34]. Where there is a site dependence, the values for the flat / mountain topographies are quoted respectively. (The primary difference is in the choice the number of cryo-plants, specifically 6 and 5 plants for flat and mountainous topographies respectively.)

| | | 40–80 K | 5–8 K | 2 K |
|---|---|---|---|---|
| Predicted module static heat load | (W/module) | 75.04 | 10.82 | 1.32 |
| Predicted module dynamic heat load | (W/module) | 58.80 | 5.05 | 9.79 |
| Number of cryomodules per cryogenic unit | | 156 / 189 | 156 / 189 | 156 / 189 |
| Non-module heat load per cryo unit | (kW) | 0.7 / 1.1 | 0.14 / 0.22 | 0.14 / 0.22 |
| Total predicted heat per cryogenic unit | (kW) | 21.58 / 26.40 | 2.61 / 3.22 | 1.87 / 2.32 |
| Efficiency (fraction Carnot) | | 0.28 | 0.24 | 0.22 |
| Efficiency in Watts/Watt | (W/W) | 16.45 | 197.94 | 702.98 |
| Overall net cryogenic capacity multiplier | | 1.54 | 1.54 | 1.54 |
| Heat load per cryogenic unit including multiplier | (kW) | 33.23 / 40.65 | 4.03 / 4.96 | 2.88 / 3.57 |
| Installed power | (kW) | 547/669 | 797/981 | 2028 / 2511 |
| Installed 4.5 K equiv | (kW) | 2.50 / 3.05 | 3.64 / 4.48 | 9.26 / 11.47 |
| Percent of total power at each level | | 0.16 | 0.24 | 0.60 |
| Total operating power for one cryo unit based on predicted heat (MW) | | | 2.63 / 3.24 | |
| Total installed power for one cryo unit (MW) | | | 3.37 / 4.16 | |
| Total installed 4.5 K equivalent power for one cryo unit (kW) | | | 15.40 / 19.01 | |

Cryo AC power: 4.2 MW / unit



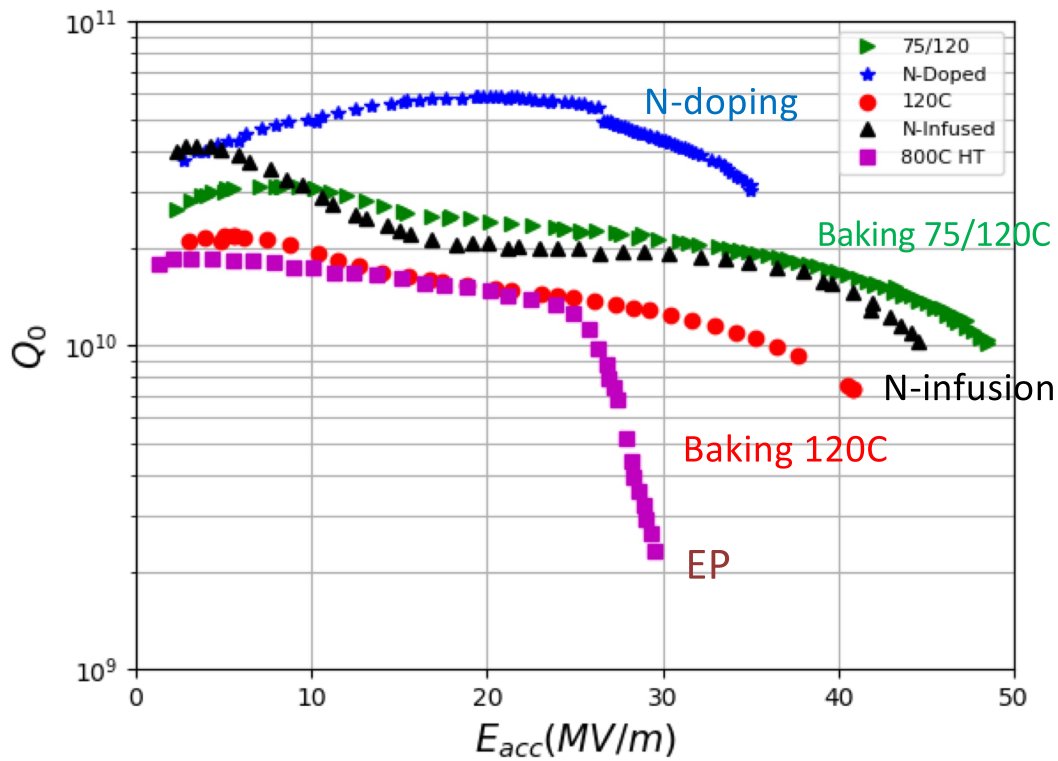

A. Yamamoto, 2022/10/12

# Outline

- **Introduction:**
  - Requirements for SRF from MC-RCS (to be digested)
- **ILC SRF Technology**
  - State-of-Art Performance
- **Efforts for High-Gradient and High-$Q_0$**
  - Surface Process
  - Material: Nb3Sn
  - Traveling Wave
- **Prospect for Future**

# State of the Art in High-Q and High-G (1.3 GHz, 2K)

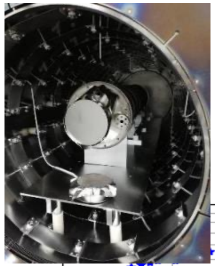
Courtesy: Anna Grassellino
- TTC Meeting, TRIUMF, Feb., 2019

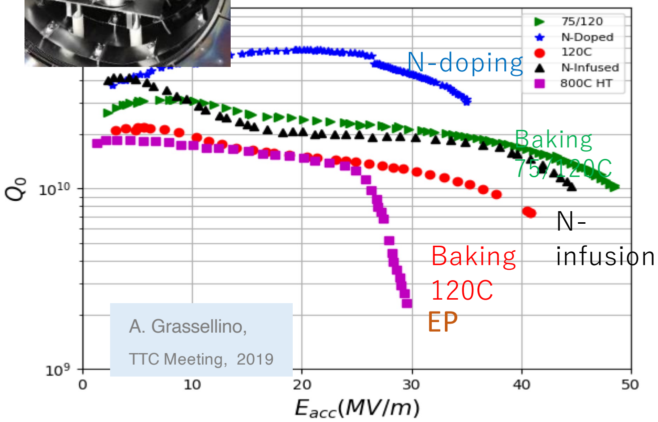


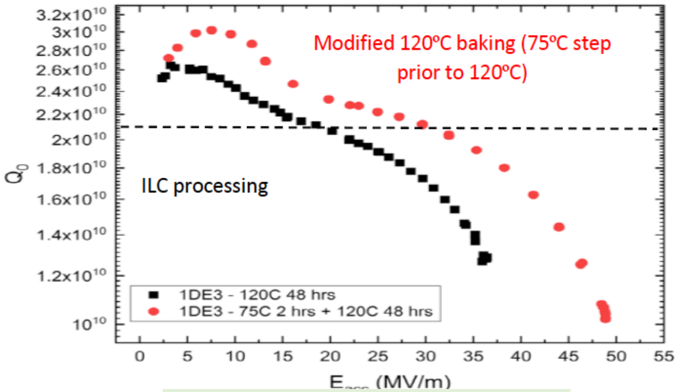

- **N-doping** (@ 800C for ~a few min.)
  - Q >3E10, G = 35 MV/m
- **Baking w/o N** (@ 75/120C)
  - Q >1E10, G =49 MV/m (Bpk-210 mT)
- **N-infusion** (@ 120C for 48h)
  - Q >1E10, G = 45 MV/m
- **Baking w/o N** (@ 120C for xx h )
  - Q >7E9, G = 42 MV/m
- **EP** (only)
  - Q >1.3E10, G = 25 MV/m

- **High-Q** by **N-Doping** well established, and
- **High-G** by N-infusion and **Low-T baking** still to be reproduced, worldwide.

# Various Surface Treatment Recipe






75/120 bake: A. Grassellino et al., arXiv: 1806/09824

## Baseline (EP+baking)

- EP-1 （ > 100 μm)
- ⇩
- Heat treatment ( > 800°C, 3h)
- ⇩
- EP-2（10~20 μm)
- ⇩
- HPR Assembly
- ⇩
- Baking ( 120°C, 48h)

## 75-deg. Baking

- EP-1 （ > 100 μm)
- ⇩
- Heat treatment ( > 800°C, 3h)
- ⇩
- EP-2（cold EP, 10~20 μm)
- ⇩
- HPR Assembly
- ⇩
- Baking ( 75°C, 4h + 120°C, 48h)

## Int. Med. T. baking

- EP-1 （ > 100 μm)
- ⇩
- Heat treatment ( > 800°C, 3h)
- ⇩
- EP-2（10~20 μm)
- ⇩
- Heat treatment ( 300~400°C, 3h)
- ⇩
- HPR Assembly

# 2-step Baking for High-G. & High-$Q_0$

Courtesy: K. Umemori

- Low-T EP
- 75C,4h＋120C, 48h Baking
- Fast Cooling（in Vertical Test）

High Gradient and High $Q_0$ achieved, reported by Fermilab

Cavity TE1AES022 post cold EP + 75/120C bake was tested at other labs (while always maintaining vacuum – no disassembly!)

**FNAL – Batavia, IL**

- Lower branch: ~43 MV/m
- Upper branch +50 MV/m (+210mT)!

**Jlab – Newport News, Virginia**

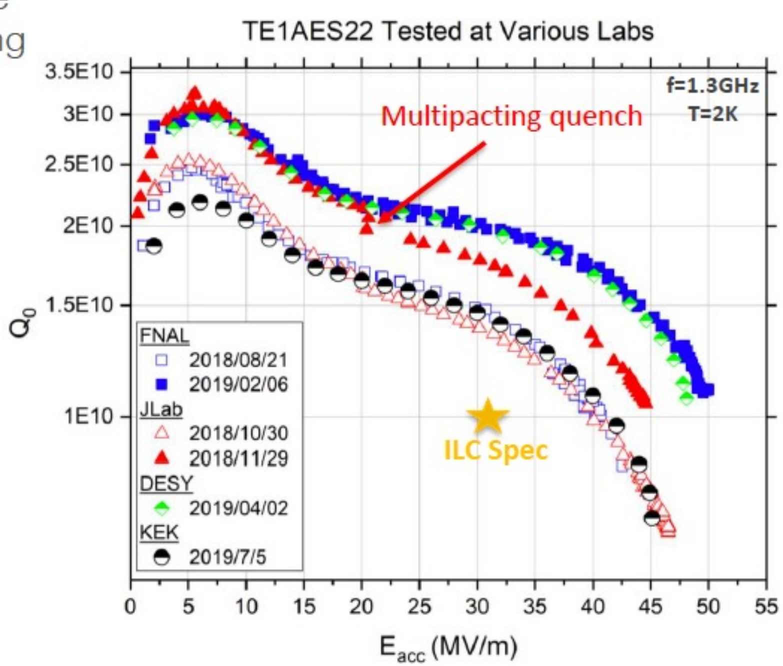
- Lower and Upper branch obtained

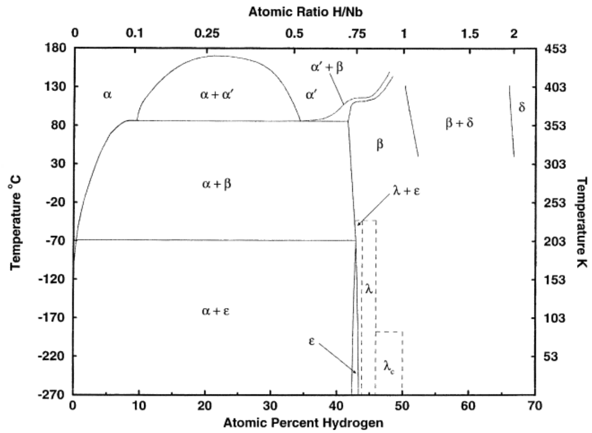
**DESY – Hamburg, Germany**

- Upper branch: +48MV/m confirmed

**KEK – Tsukuba, Japan**

- Lower Branch: +45MV/m confirmed




Because of phase transition of H/Nb ?

Sergey Belomestnykh, mini-Workshop on Cavity Performance Frontier, 16-17 February 2021

Courtesy, C.Z. Antoine, T. Kubo

# Superconducting Phases and Applications

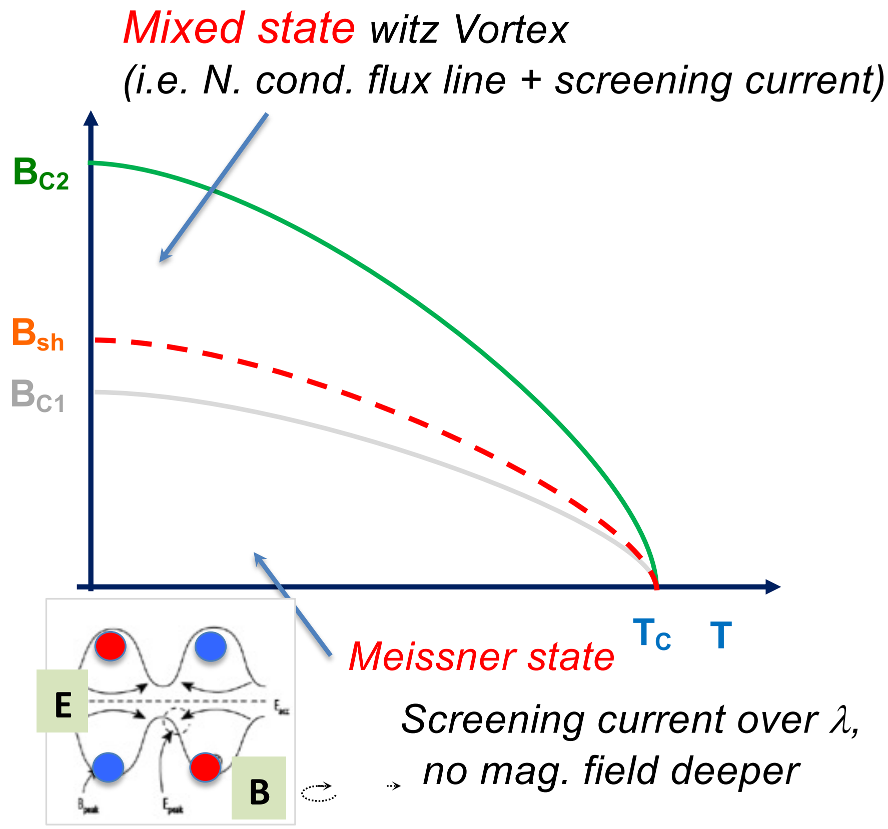
**SC magnet** → mixed state w. vortex

- $B_{c2}$ = ultimate lmit for SC magnet
  - NbTi (Hc2, Tc) : 11.5 T, 9.5 K,
  - Nb3Sn (Hc2, Tc) : 21.5 T , 18 K

**SRF** → Meissner state mandatory !

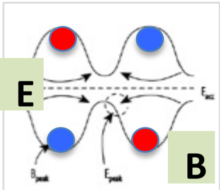
- $B_{C1}$ = upper-limit of Meissner state
  - $B_{c1\text{-}Nb}$ : ~ 180 mT
- $B_{sh}$ = upper limit of **metastable** Meissner state (ultimate limit for SRF)
  - $Bs_{sh\text{-}Nb}$ : **~ 240 mT** (calculated from GL theory)
  - $Bs_{sh\text{-}Nb3Sn}$: **~ 430 mT** (calculated from the BCS theory using $B_{sh}$ = 0.8 $B_c$)

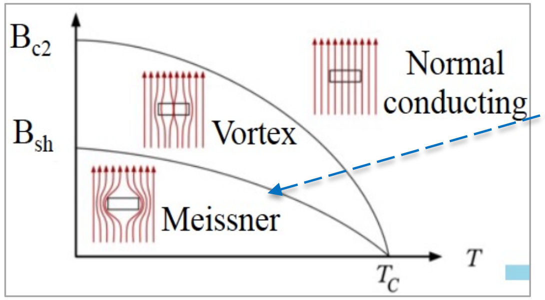

1. **G. Catelani and J. P. Sethna**, Phys. Rev. B **78**, 224509 (2008)
2. **F. Pei-Jen Lin and A. Gurevich**, Phys. Rev. B **85**, 054513 (2012)
3. **T. Kubo**, Phys. Rev. Research **2**, 033203 (2020)

Courtesy, S. Posen

# Recent Progress in SRF Technology

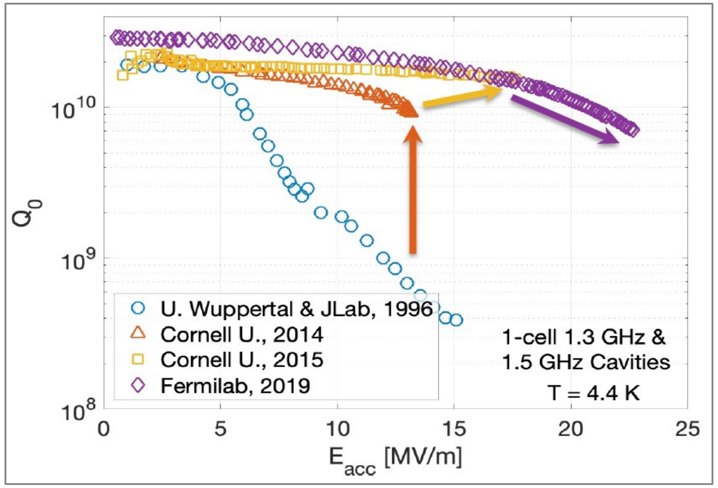


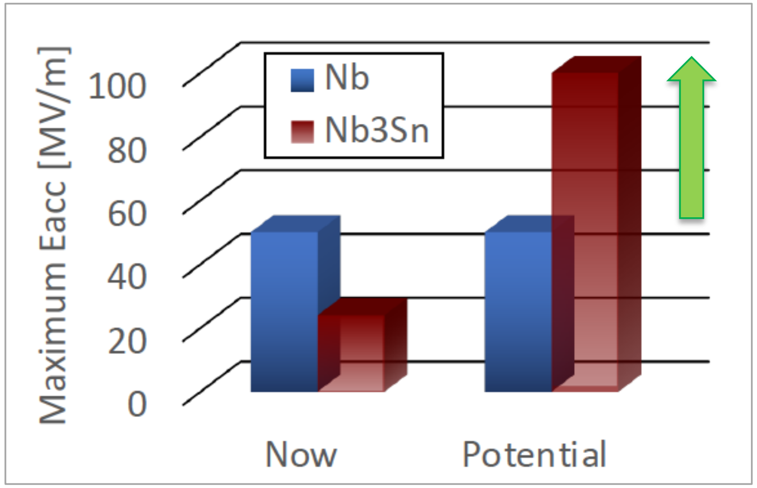




SRF cavity → require Meissner state

- $B_{sh}$ : ultimate limit for SRF
  - $Bs_{sh\text{-}Nb}$ : 240 mT
  - $Bs_{sh\text{-}Nb3Sn}$ : 430mT

x2



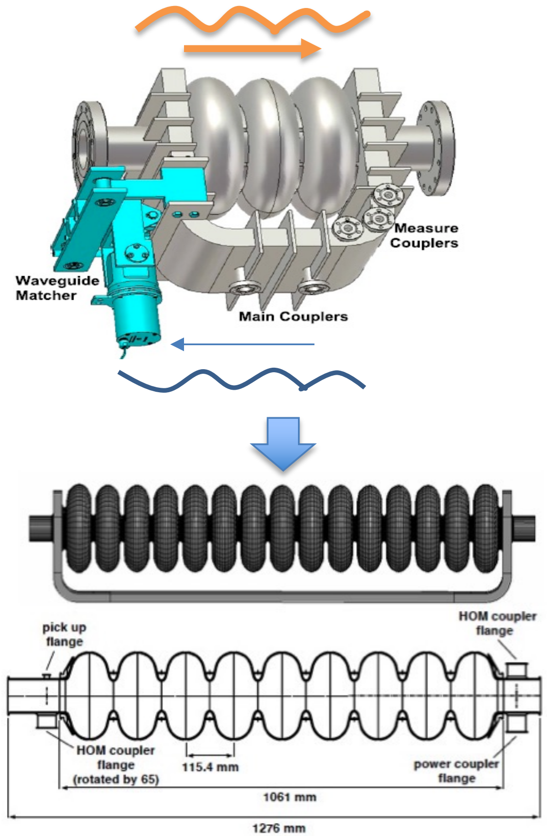




$Nb_3Sn$ progress at Fermilab.
S. Posen et al., SUST, 34, 02507 (2021)

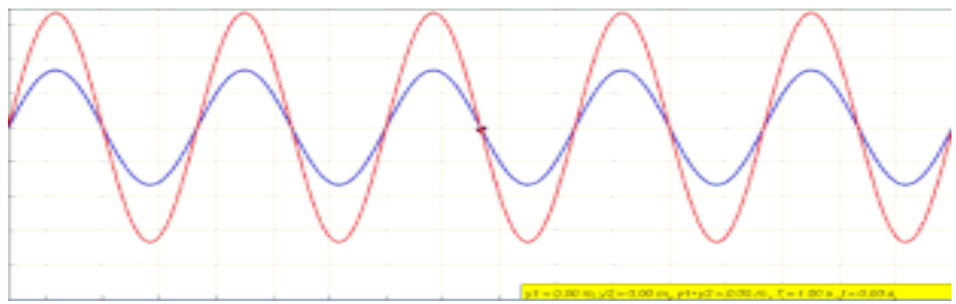
$Nb_3Sn$ Potential in high-G future

Courtesy: H. Padamsee, SRF-2021

# An new concept for SRF proposed: Travelling Wave (TW) vs Standing Wave (SW)




- **Red** standing wave – High Peak Fields
- **Green** (acceleration) and **Blue** (Return) Waves are Travelling Waves - Lower peak fields
- Guide blue wave in a return wave-guide to avoid SW peak fields – attached to both ends



S. Belomestnykh | HELEN collider
Snowmass 2021

# Advantages of TW Structures

- **Travelling wave (green) structures lower BOTH *Hpk/Eacc* and *Epk/Eacc***
  - Because RF power returns (blue) not through the accelerating structure (to form a standing wave (red) with harmful peaks)
  - But power returns through a separate return Nb waveguide
- + Travelling wave structures offer 2X higher *R/Q*
  - lowers Cryo power and RF power and lower AC power
- **By choosing the Low-Loss cell shape + reduced aperture (see below) it is possible to lower *Hpk/Eacc* by 48% over the TESLA structure!**
- **Opening the door to *Eacc* > 70 MV/m !!**
  - *Hpk* = 200 mT, *Epk* = 120 MV/m
- Lower aperture is allowed because bunch charge for 3 TeV will about 3 X less to get acceptable IP background…
- **Putting SRF on the Road to ILC – 3 TeV with Nb**
  - With Capital cost comparable to CLIC 3 TeV and AC power much less than CLIC 3 TeV
  - Without struggling with exotic new superconductors (sorry!)

Courtesy, T. Kubo, R. Laxdal,

# Possible Consideration and Layered Models

- 120C bake is known to manipulate mean free path at very near surface (~nm) on clean bulk Nb.
- A dirty (doped) layer at the surface seems beneficial in order to increase the quench field above Bc1.

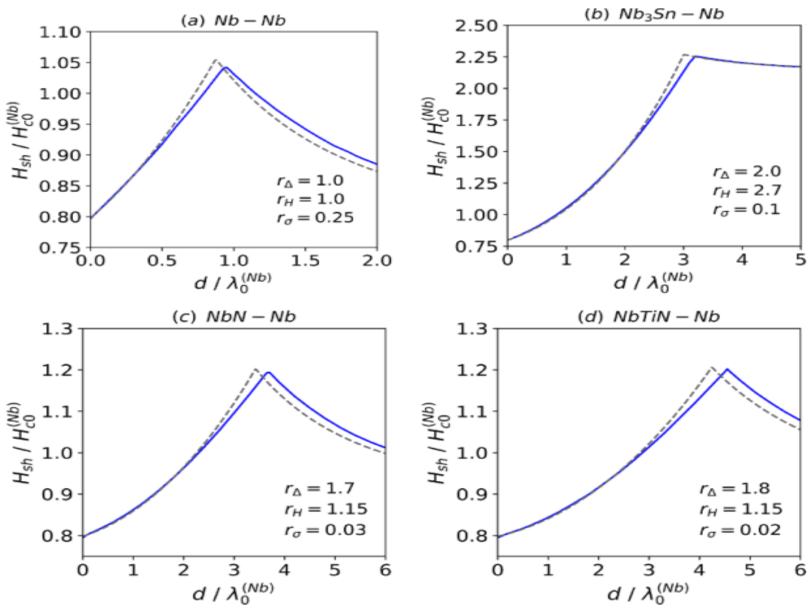
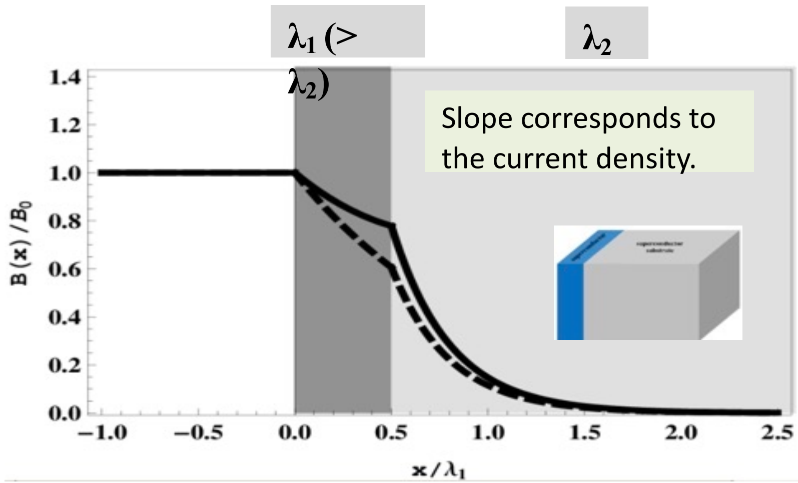



**Figure 5.** Superheating field of layered structures as functions of $d$. The solid curves are obtained from the self-consistent solutions of the coupled Maxwell–Usadel equations at $T \to 0$




Surface current is suppressed:

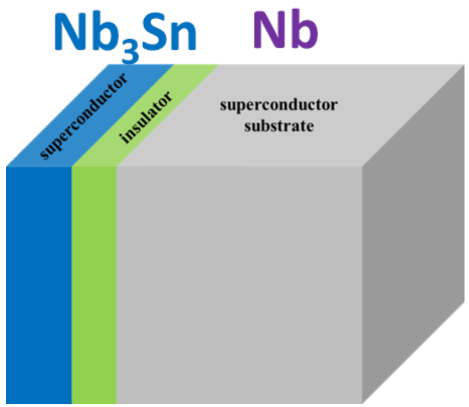
- means an enhancement of the field limit, because of the theoretical field limit to be determined by the current density.

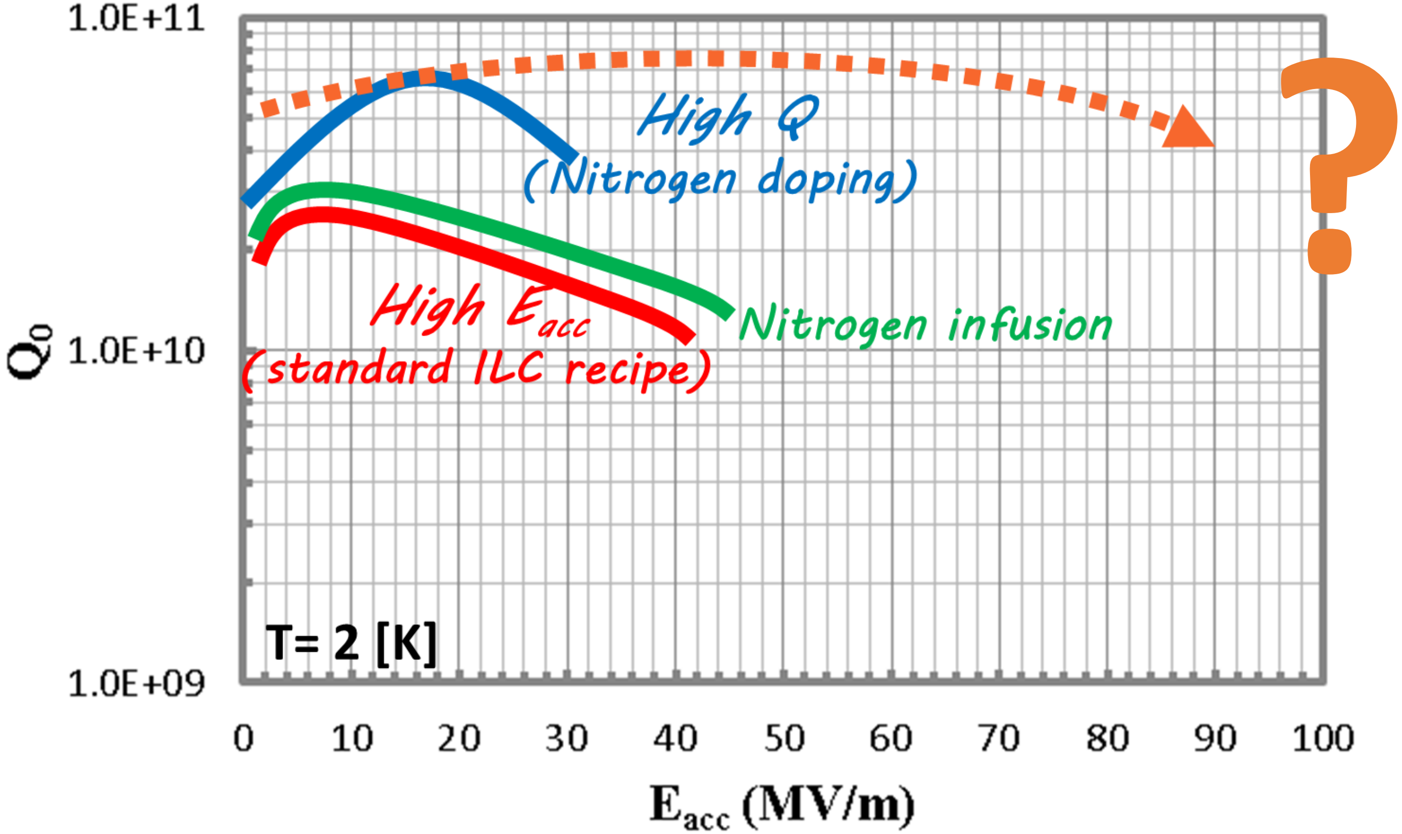
- C.Z. Antoine, et al. APL 102, 102603 (2013).
- T. Kubo et al, Appl. Phys. Lett. 104, 032603 (2014).
- A. Gurevich, AIP Advances 5, 017112 (2015).
- T. Kubo, Supercond. Sci. Technol. **30**, 023001 (2017)
- T Kubo, Supercond. Sci. Technol. 34, 045006 (2021

# Layered structures: Next

Courtesy: T. Kubo, K. Umemori

- Demonstrate the field-limit enhancement using cavities.
- Stay tuned!



# Outline

- **Introduction:**
  - Requirements for SRF from MC-RCS (to be digested)
- **ILC SRF Technology**
  - State-of-Art Performance
- **Efforts for High-Gradient and High-$Q_0$**
  - Surface Process
  - Material: Nb3Sn
  - Traveling Wave
- **Prospect for Future**

# Prospects for SRF Technology in Future Accelerators

- SRF technology has been **advanced to realize the ILC and future energy frontier accelerators**, based on **Euro-XFEL** successfully constructed and in stable operation since 2017.

- SRF high-G R&D effort may be extended for future upgrades.
  - **Nb-bulk, 40 – 50 MV/m (SW),**
  - **Nb3Sn, > 50 MV/m:** ~ 5 years for single-cell R&D and the following 5 – 10 years for 9cell cavities in longer time scale, and
  - **Nb-bulk, 70 MV/m (TW)** to be feasible in long-term future.

- The **1.3** GHz, **5** Hz SRF technology with G = **30** MV/m will be applicable for the muon beam acceleration at **MC RCS Accelerator --> Efficient, common synergy**

# Prospects for ILC-TeV and beyond

| | | ILC-250 Initial | ILC-500 TDR | ILC-1TeV TDR | ILC-3TeV Study for Future |
|---|---|---|---|---|---|
| Energy | TeV | 0.25 | 0.5 | 1 | 3 |
| Luminosity | $X10^{34}$ | 1.3 | 1.8 | 4.9 | 6.1 |
| SRF Gradient | MV/m | 31.5 (SW) | 31.5 (SW) | 35 ~ 45 (SW) | 70 (TW) |
| $Q_0$ | $10^{10}$ | 1 | 1 | 2 | 2 |
| AC Plug-Power | MW | 110 | 164 | ~ 300 | ~ 450 |
| Time scale for realizing acc. | Years | ~15 | ≥ 20 | >> 20 | Future |

| ← Muon Collider → |

# Issues for MC-RCS SRF

- Much higher beam current (2 x 20 mA) and RF power
    - **Fundamental Power Coupler**: power loss to be higher
    - **HOM loss** to be evaluated and the mitigation to be found

- SRF CMs to be distributed along RCSs, as high as possible
    - Resulting RF **filling factor to be lower**, and
    - **Cryogenics efficiency** to be lower, and **AC plug-power** to be larger

- **Frequency sweep** during RF pulse duration
    - Tunability of the SRF cavity frequency sweep

- Gradient: 30 MV/m as of today, and scope for future
- Others?

# Summary

- ILC, 1.3 GHz, pulsed SRF Cavity technology with 30 MV/ may be applicable for the MC RCS SRF.

- Further studies are necessary for:
  - **Gradient** and the limit, for SRF station faction to be smaller,
  - Fundamental **Input Coupler** to allow high beam current (2x20 mA)
  - **HOM** loss to be verified and the solution to be settled.
  - **Frequency sweep** availability with $\Delta F \sim$ 2kHz during beam pulse
  - Optimization of **# RF and Cryogenics units**/station to be a main issue

- The synergy to be maximized between ILC and MC will be anticipated

# Appendix

International MUON Collider Collaboration
11–14 Oct 2022
CERN

# Muon Collider Collaboration – Annual Meeting
## held at CERN, 11-14 Oct. 2022

https://indico.cern.ch/event/1175126/

The first Collaboration Meeting of the Muon Collider Study will take place **from October 11 to October 14, 2022**. The meeting will be held **in person, at CERN**. We are monitoring sanitary restrictions, and will consider alternative options at a later stage, if required.

We plan to cover at the meeting all areas of study and development, allowing ample time for both plenary and parallel sessions.

The main goal of the meeting will be to assess the progress of the study and to define the future work programme, in particular regarding how we will share the tasks among all Collaborators. This will include the organization of the MuCol Design Study for which we just received a positive answer from the EU.

This meeting is also supported by MUST, the MUon collider STrategy network, a part of the I.FAST European project. A specific objective of MUST is to review advances and promote collaboration on the moun source.

The Collaboration Board will meet for the first time at the Collaboration Meeting, and start activities within the scope of the study.