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High Efficiency High Gradient Cavities

- Toward Cutting Down ILC Dynamic Heat Load by Factor of Four

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Why High Efficiency High Gradient Cavities

- High gradient
  - Linac energy reach >> enable discovery science
  - Shorter linac >> save capital cost
- High efficiency
  - smaller cryo plant >> save capital cost
  - Smaller dynamic heat load >> save operation cost
- Benefits
  - SRF accelerator in general
  - ILC in particular (large number of cavities)

Numbers

- ILC TDR – 500 GeV baseline design
  - On avg, 35 MV/m, $Q_0 = 8 \times 10^9$, 2K, cavity qualification
  - On avg, 31 MV/m, $Q_0 = 1 \times 10^{10}$, 2K, cavity operation
- ILC TDR – 1 TeV upgrade goal
  - 45 MV/m, $Q_0 = 2 \times 10^{10}$

Gradient Knobs

Main Issues at Very High Gradient (3)

"Knobs" for improved reproducibility in overcoming local quench at very high gradient of 40-50 MV/m

Achievable gradient

Cavity surface chemistry

Material
Nb: > 2000 Oe (exp.)
2400 Oe (the.)
Nb_3Sn: > 4000 Oe (the.)

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

Cavity wall thermal conductance

Cavity surface smoothness

Cavity shape

(1) Alternate cavity shape for reduced Hpk/Eacc ratio. In hand (LL, RE, LSF).
(2) Uniform cavity processing for reduced local "bad" spots. In hand (EP).
(3) Smooth surface for reduced local magnetic field enhancement. In hand(CBP & derivative + EP).
(4) Improved wall thermal conductance for increased local heating tolerance.
- Cavity heat treatment optimization for "phonon peak engineering"
- Use Nb/Cu composite material (such as explosion bonded material)

(5) The game-changing knob is a Nb replacement material (such as Nb_3Sn or Mg_2B w/ multi-layer).

Efficiency Knobs

Power dissipation

Voltage (energy)

$$P_d = \frac{V^2}{\frac{R}{Q} \cdot Q_0}$$

Cavity unloaded Q

Shape determined parameter

$$Q_0 = \frac{G}{R_{BCS}(T,B) + R_{res}(B)}$$

Intrinsic factor: material and surface

Extrinsic factors: ambient magnetic field, thermal history etc.

$$P_d = \frac{V^2 \cdot (R_{BCS} + R_{res})}{\frac{R}{Q} \cdot G}$$

Cavity shape

- Alternative cavity shape for increased G*R/G (RE, LL, LSF)
- Heat treated large-grain Nb for reduced flux trapping and reduced R_{res}
- Impurity doping (Ti, N) to tune R_{BCS}
- Lower bath temperature 1.8-1.9K (more later)

Bath Temperature

Lowering bath temperature is justified only when gain in lowering R_{BCS} over weights loss in Carnot efficiency

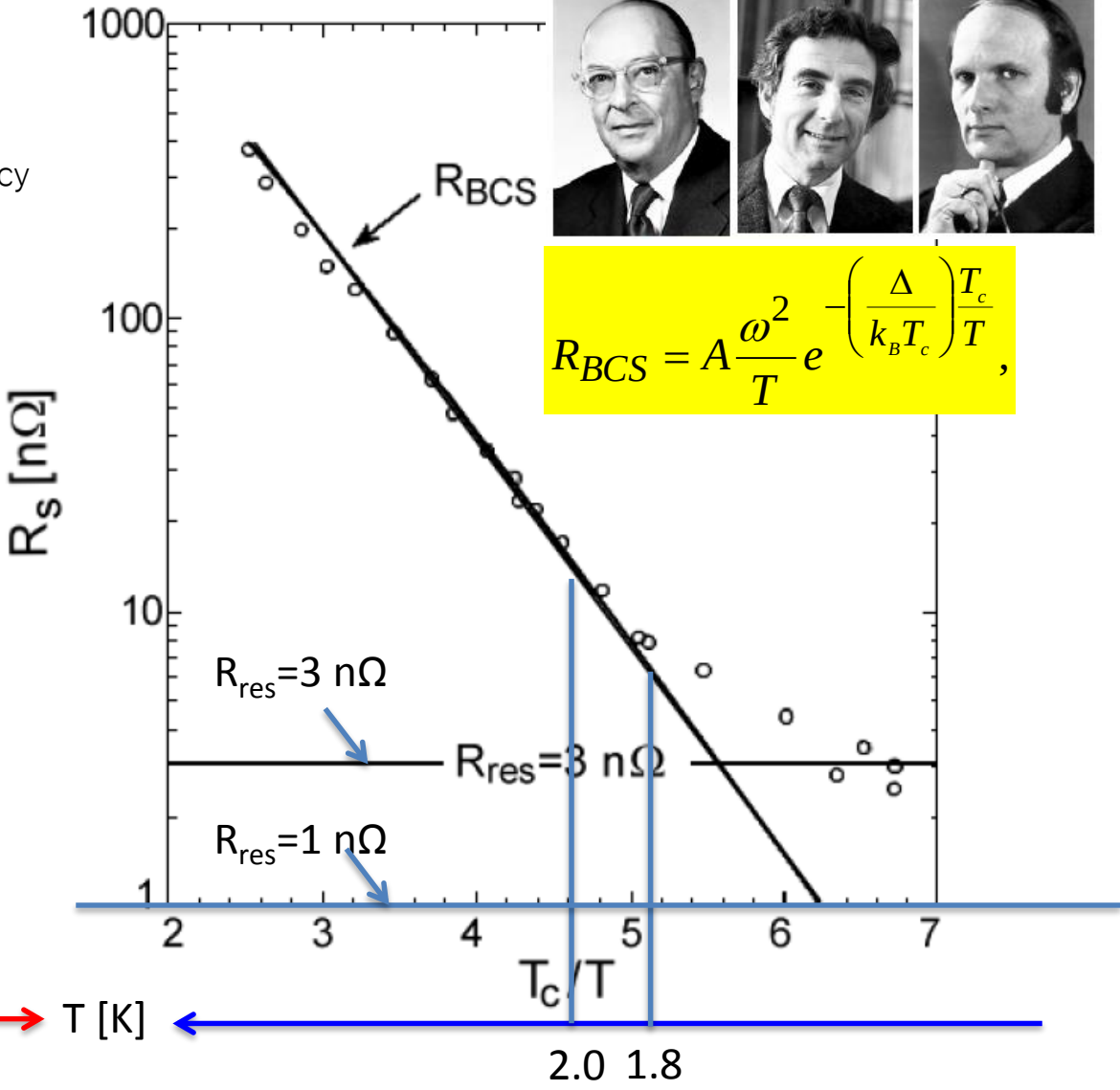
$$\frac{Q_0(1.8K)}{Q_0(2.0K)} \geq 1.33$$

Technical efficiency included

Carnot

$$n_c = \frac{T}{300 - T}$$

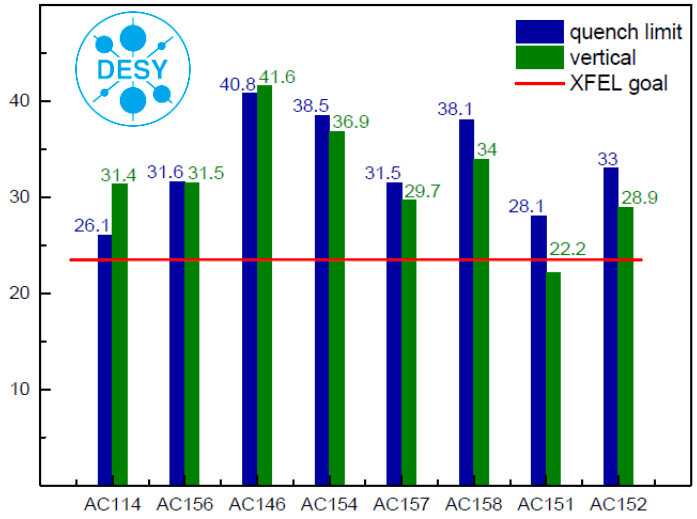
$$R_{BCS} = A\frac{\omega^2}{T}e^{-\left(\frac{\Delta}{k_B T_c}\right)\frac{T_c}{T}},$$



New Progresses since ILC TDR Publication

- Large-grain cavity cryomodule tested at DESY

  - 7 out 8 cavities are industrially built LG cavities
  - 9-cell, TESLA shape

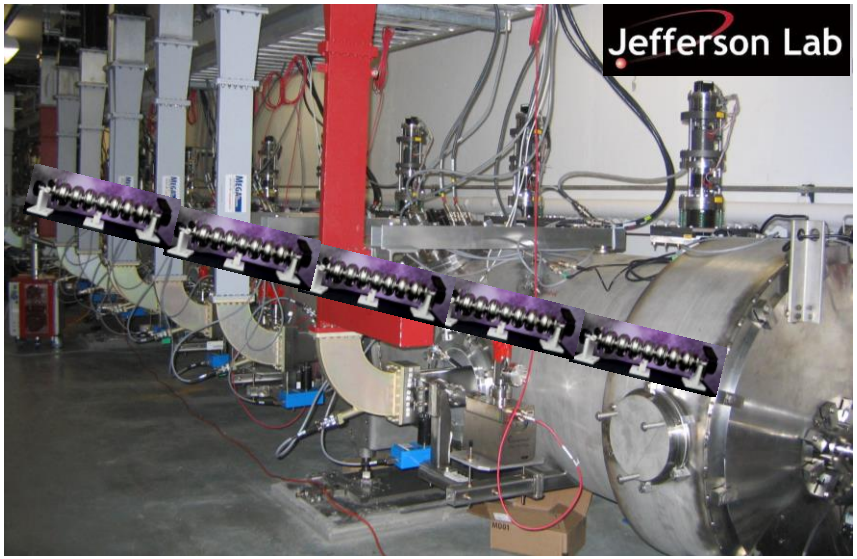


- Large-grain cavity long term beam operation

  - FLASH at DESY (~5 years)
  - DC-SC photo-injector at PKU (~2 years)

- Low-loss cavity cryomodule beam operation in CEBAF at JLab

  - 80 EACH 7-cell, low-loss shape
  - 1.5 GHz, fine grain Nb cavities



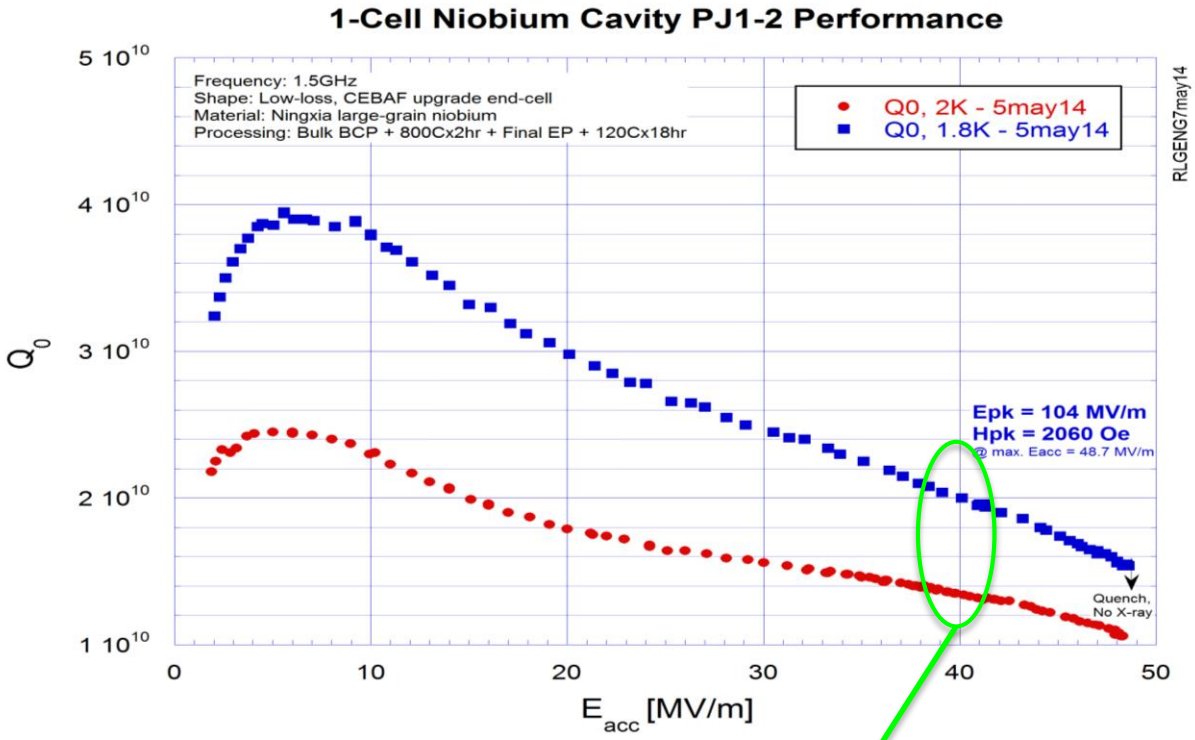
Large-Grain Niobium and New Shapes

- Introduction of Large-Grain Nb material in 2005 by Jefferson Lab
- Introduction of original "New" cavity shapes
  - 2002, Re-entrant (RE) shape, 1300 MHz, Cornell
    - Aim for HG in pulsed linac of 0.5-1 GeV linear collider
  - 2002, Low-loss (LL), 1497 MHz, JLAB/DESY
    - Aim for LL in CW linac of CEBAF 12 GeV upgrade
  - Further extension
    - 2004, LL/ICHIRO, 1300 MHz, KEK/DESY
    - 2007, LL, 1300 MHz, IHEP
    - 2008, LSF, 1300 MHz, SLAC

RF Parameters of Cavity Shapes

		TESLA	Low-loss/ICHIRO	Re-entrant	Low-surface-field
frequency	MHz	1300	1300	1300	1300
Aperture	mm	70	60	60	60
Epk/Eacc	-	1.98	2.36	2.28	1.98
Bpk/Eacc	mT/(MV/m)	4.15	3.61	3.54	3.71
Cell-cell coupling	%	1.90	1.52	1.57	1.27
G*R/Q	Ω^2	30840	37970	41208	36995

LG cavity PJ1-2 (JLab-PKU-OTIC collaboration)



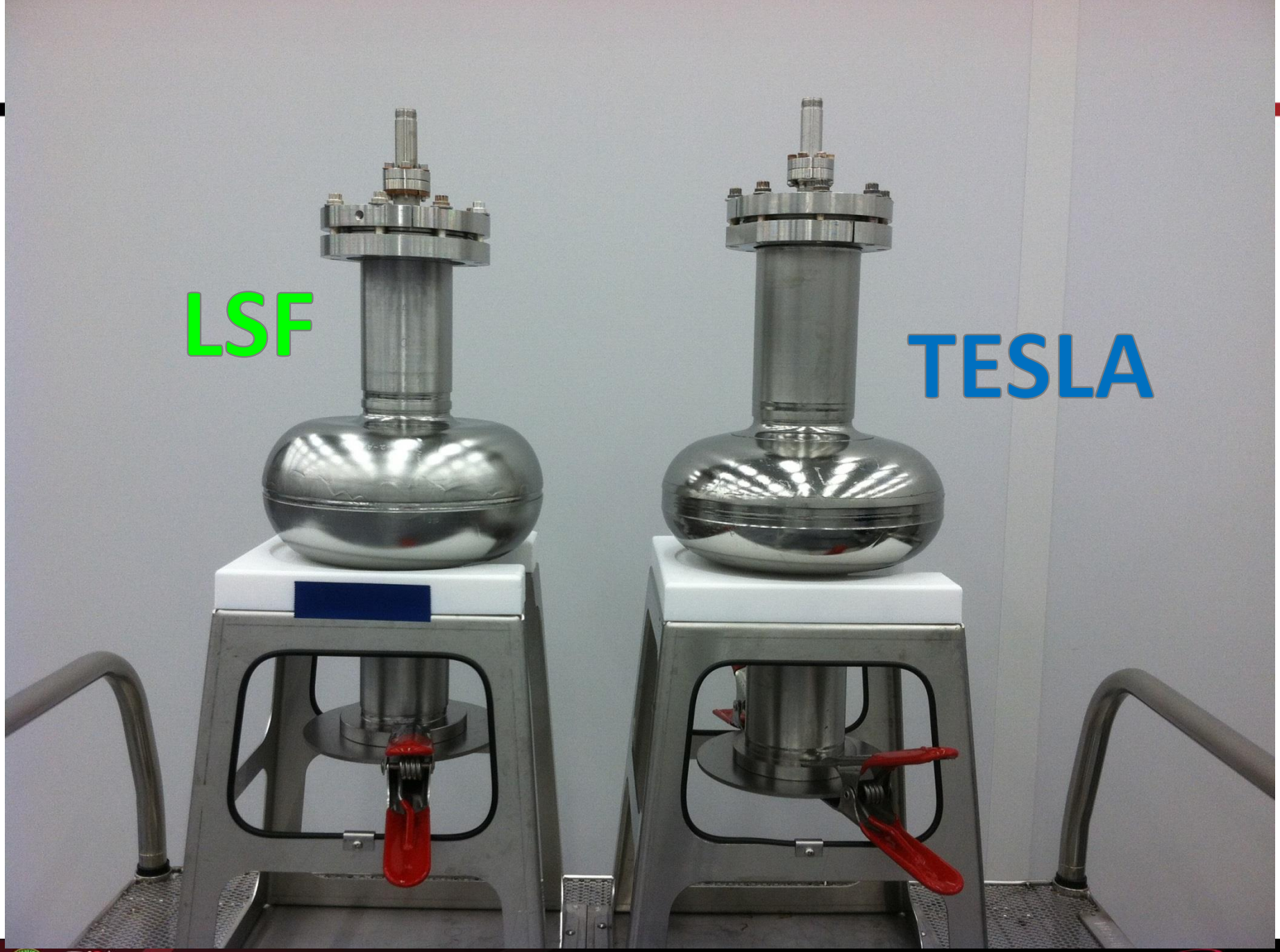
1.5 GHz, CEBAF upgrade Low-Loss Shape

OTIC Large Grain Nb

Cavity processing: Bulk BCP + 800Cx2hr

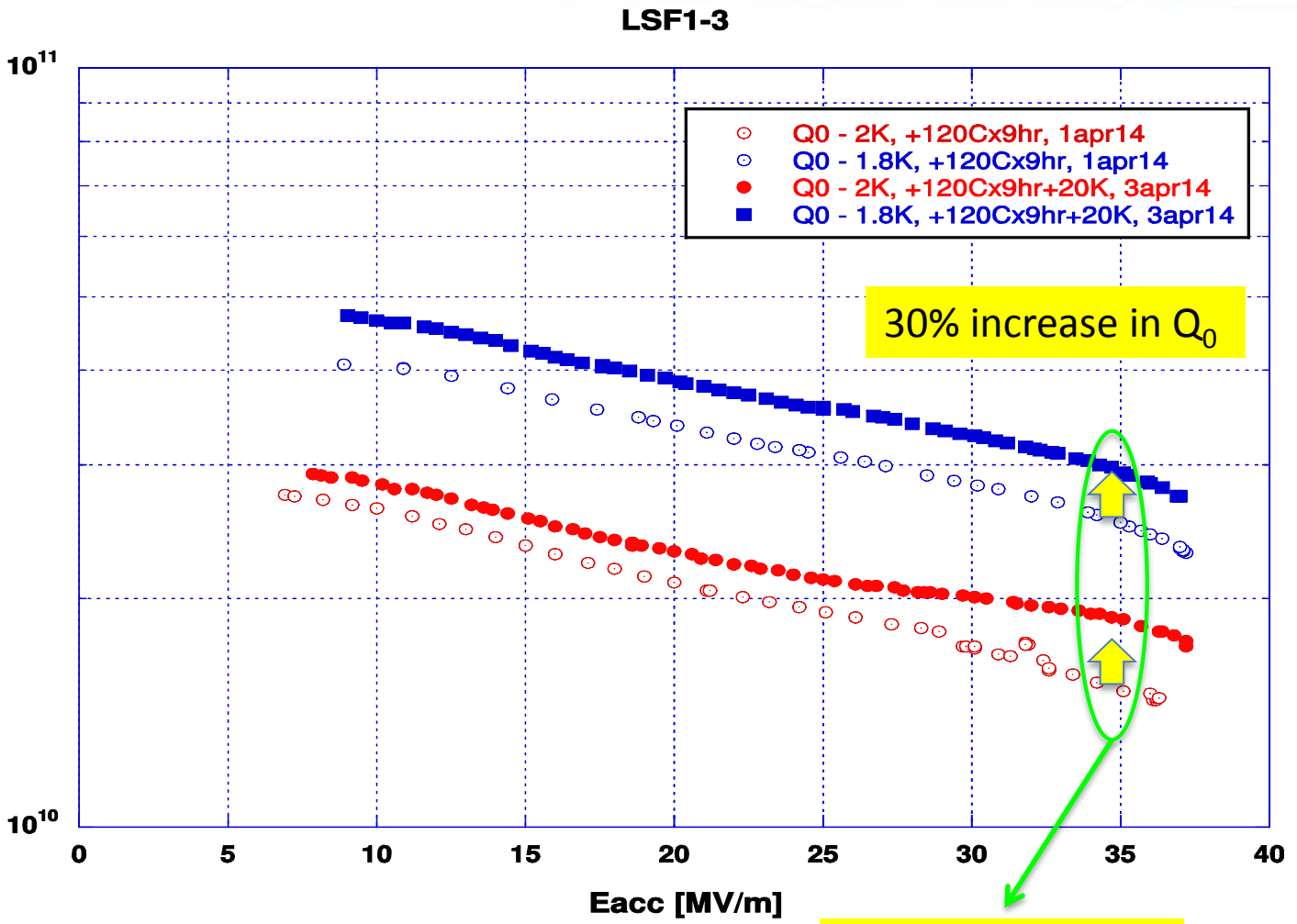
Final Processing: EP 30 um + 120Cx18hr

$$\frac{Q_0(1.8K)}{Q_0(2.0K)} \geq 1.43$$


LSF
TESLA

LG cavity LSF1-3 (JLab-SLAC-PKU collaboration)

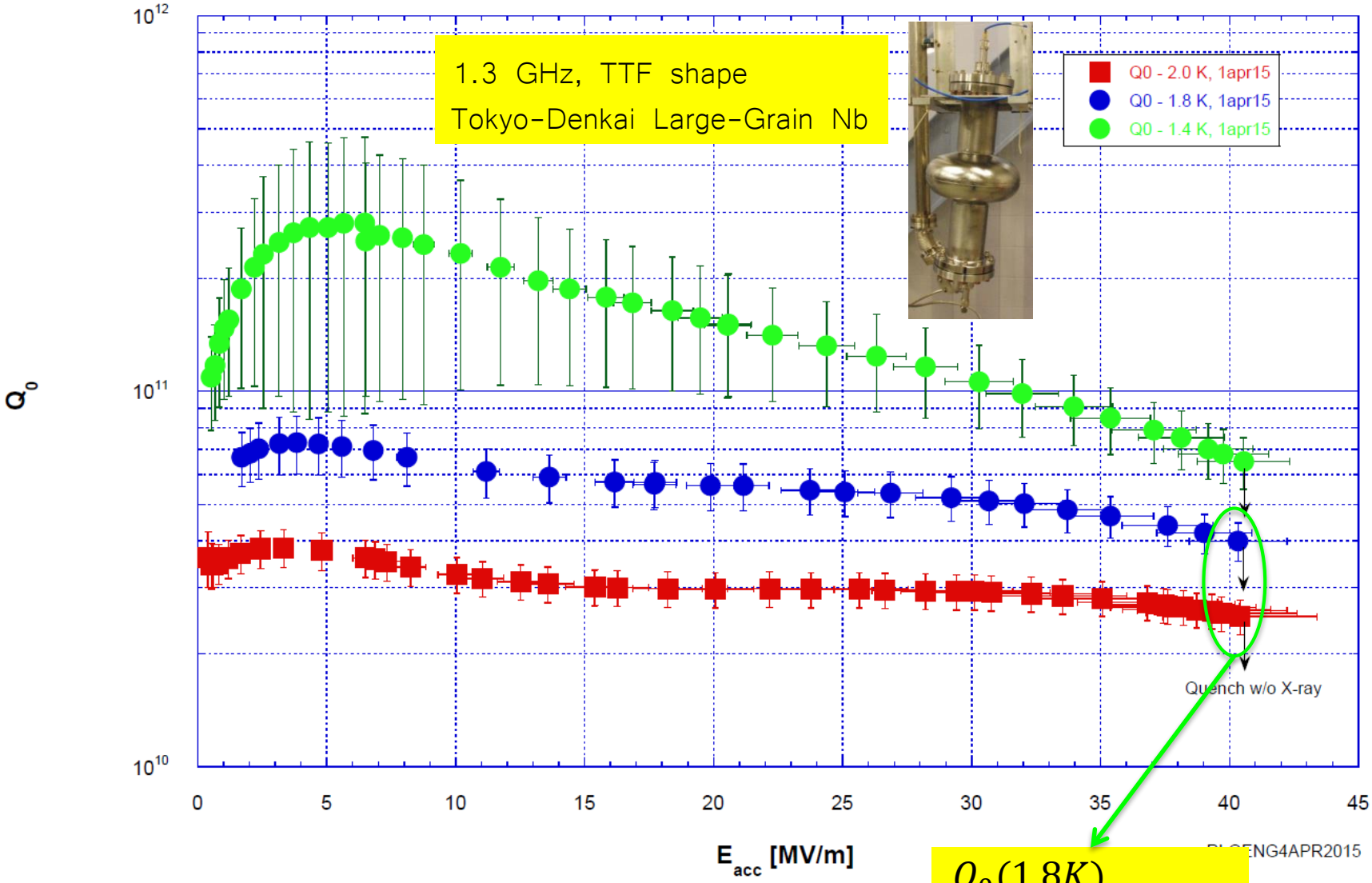
LSF1-3
1.3 GHz
LSF Shape
Large-Grain Nb



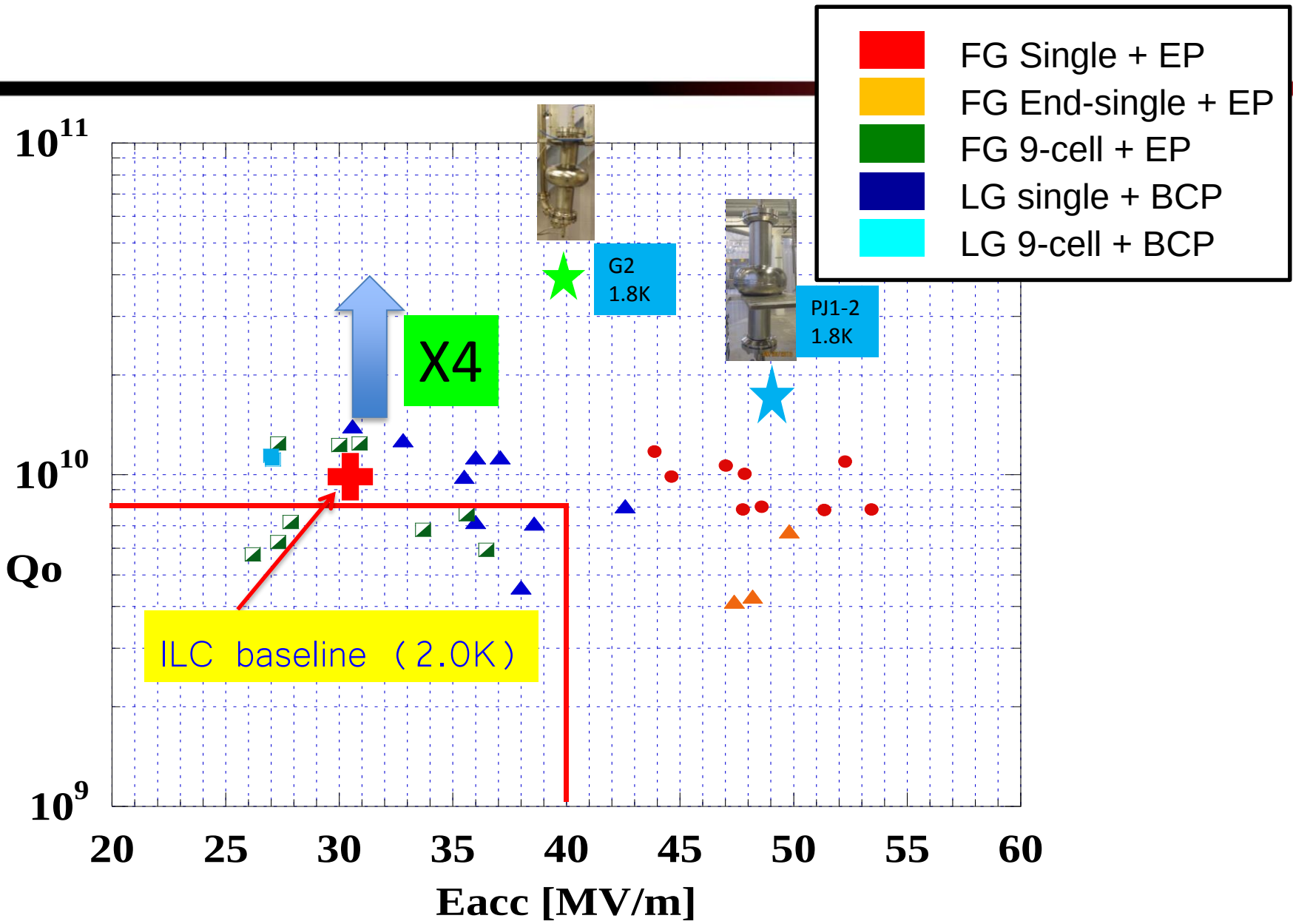
Cavity processing:
BCP 60 um + 800Cx2hr + BCP 20 um + 120Cx9hr

$$\frac{Q_0(1.8K)}{Q_0(2.0K)} \geq 1.56$$

JLAB SRF 1-Cell 1.3 GHz Large-Grain Niobium Cavity G2



$$\frac{Q_0(1.8K)}{Q_0(2.0K)} \geq 1.56$$



F. Furuta et al., International Symp. On Supercond. Sci. & Tech. of Ingot Niobium, Sept. 22-24, 2010.

Summary

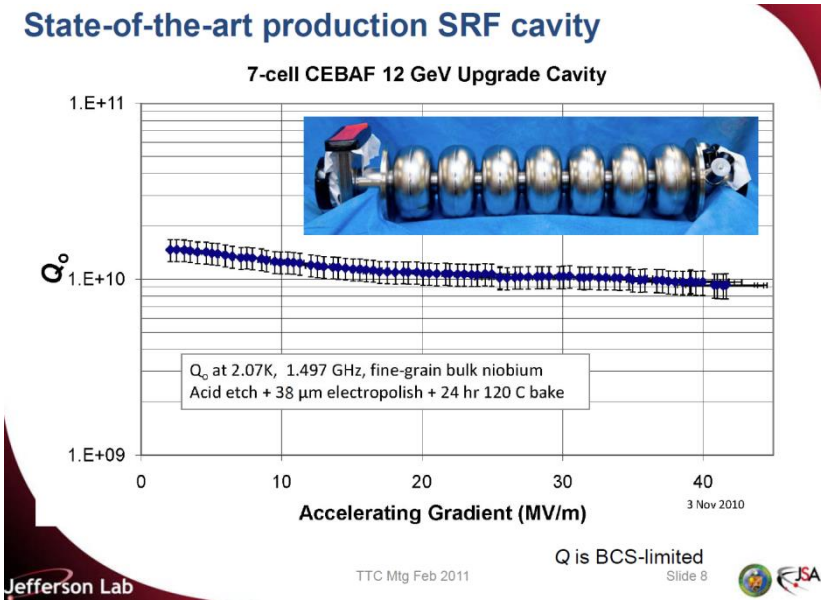
- New experimental results established the possibility of SRF cavity operation at high gradient (30-50 MV/m) with high efficiency cutting down dynamic heat load by a factor of 4
  - Large-Grain niobium
  - 1.8 K bath temperature
- Combing this progress with better cavity shape (LSF or others), there is an opportunity for clean operation of ILC at 500 GeV as well as 1 TeV
- Remaining challenges
  - Multi-cell Large-grain LSF shape cavity development
  - Reliable field emission control
  - New understanding and control of medium field Q-slope

Backup slides

Low-Loss Shape Cavity Accelerating Beam

CEBAF 12 GeV Upgrade Cavity

1.5 GHz, Low-loss Shape, 53mm bore dia.



C. Reece, TTC Meeting, Feb. 28-Mar.3, 2011

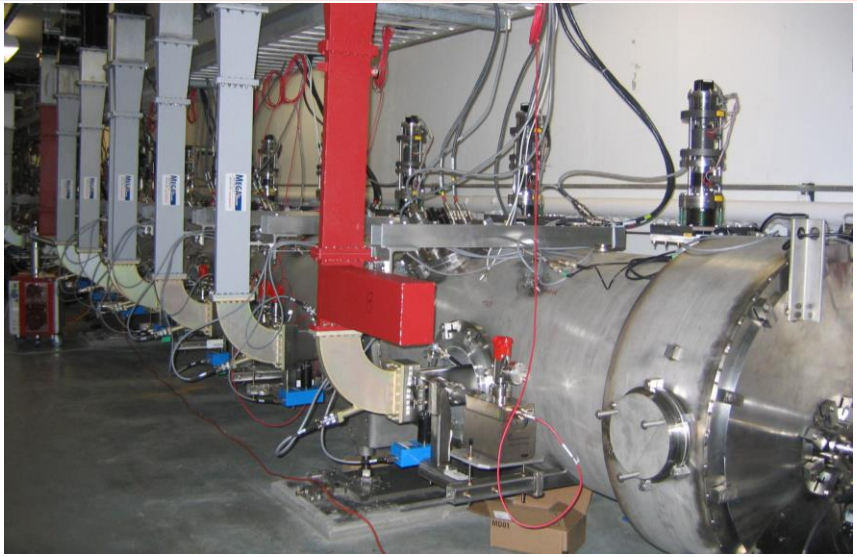


Table 2: C100 Commissioning Results

Cryomodule No.	Commission in CEBAF (MeV)	Operation with Beam (MeV)
C100-01	104.3	94.5
C100-02	109.6	108
C100-03	118.4	Jan 2014
C100-04	105.8	Jan 2014
C100-05	109.9	Jan 2014
C100-06	108.2	Jan 2014
C100-07	108.4	Jan 2014
C100-08	Oct 2013	Jan 2014
C100-09	113.7	Jan 2014
C100-10	109.8	Jan 2014

J. Hogan et al., PAC2013, WEZAA2

First 9-Cell Large-Grain Nb Cavities

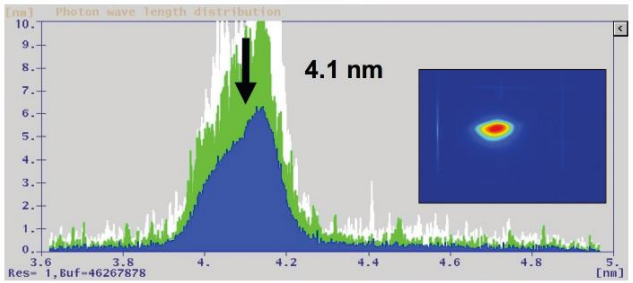
3 cavities: AC112, AC113, AC114

W. Singer, TTC meeting, April 23-26, 2007

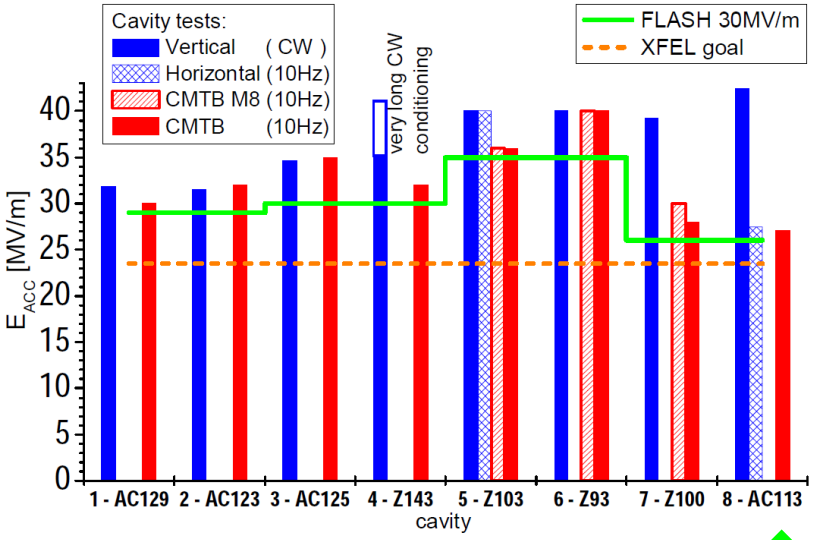
9-Cell Large-Grain Nb Cavity Beam Operation in FLASH at DESY

2 cavities, AC112 and AC113, in beam operation since 2010

Contribution to realization of 1.25 GeV beam and 4.1 nm laser



S. Schreiber, FEL2011



D. Kostin et al., SRF2009

Large-Grain

Large-Grain Nb Cavity in PKU DC-SC Photo-injector

1.3 GHz 3.5 cell
Large-Grain Nb Cavity

Photo curtsey Jiankui Hao, Peking University

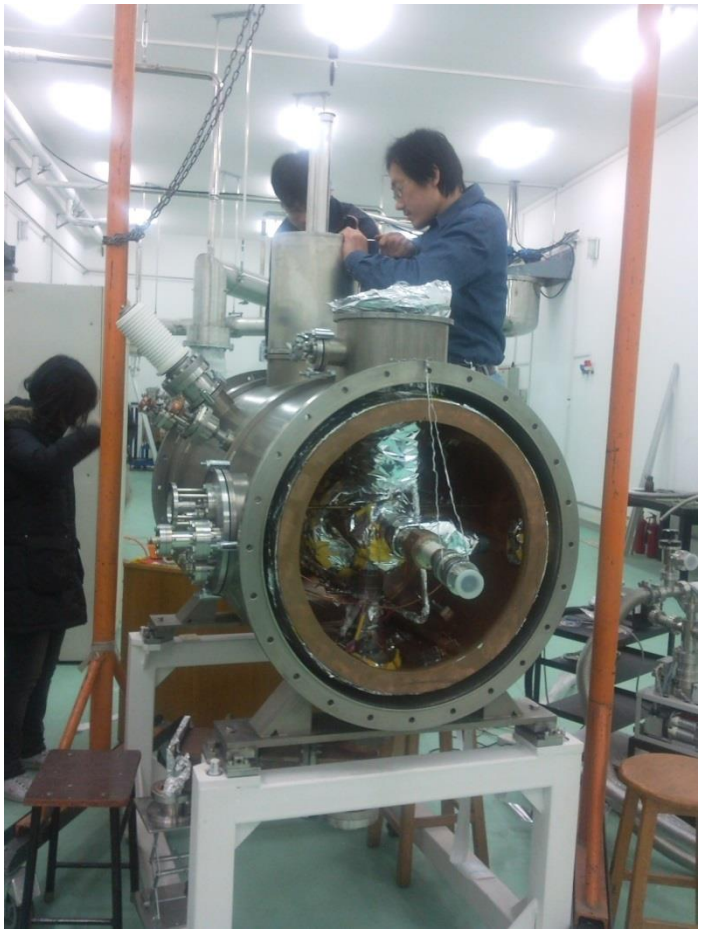
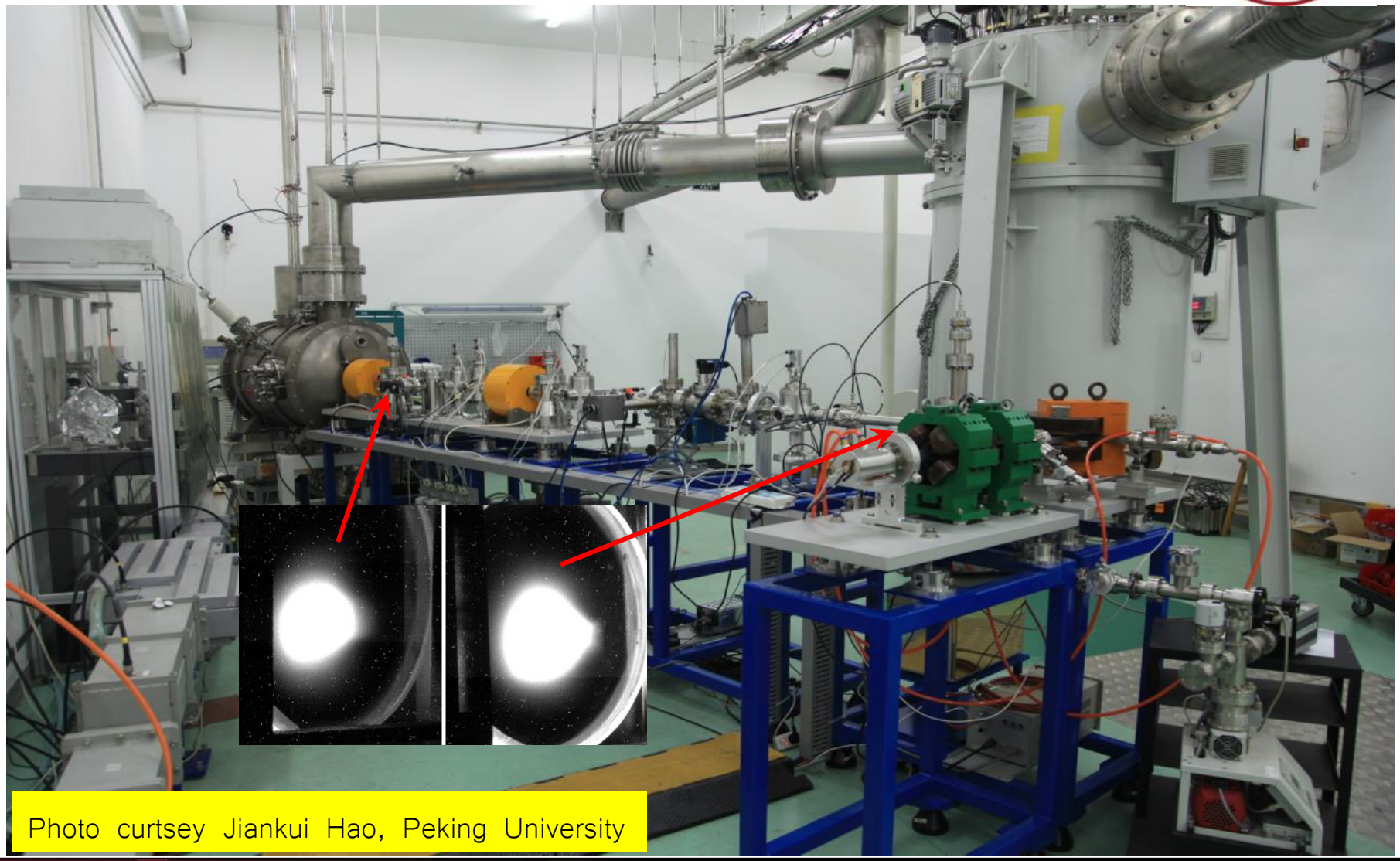


Photo-injector cryomodule

Large-Grain Cavity Beam Operation in PKU DC-SC Photo Injector Since 2013



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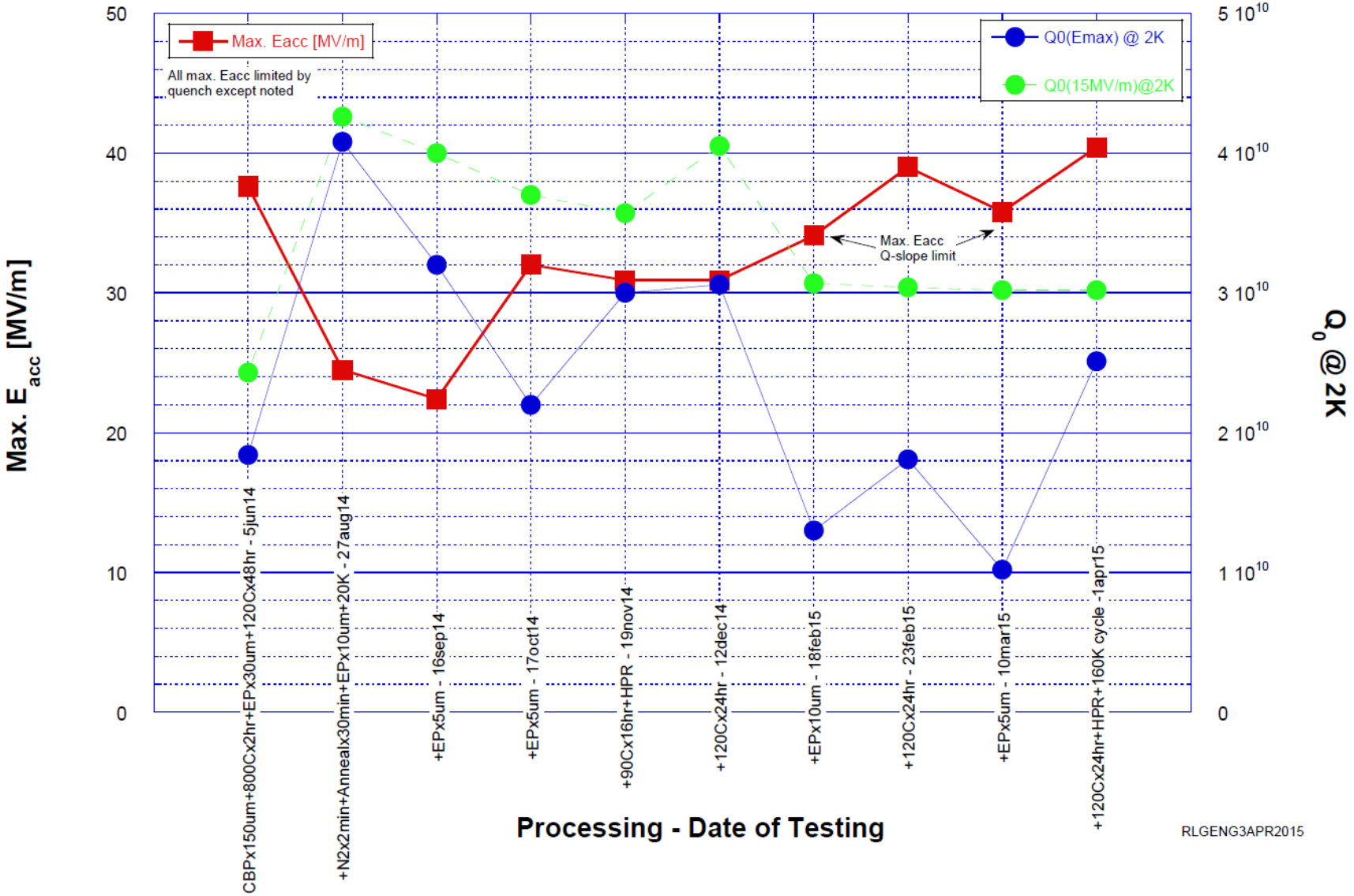
JLAB SRF 1-Cell 1.3 GHz Large-Grain Niobium Cavity G2 Performance Evolution