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Quantification of Q_0 requirements for cavities

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Outline

minimize cost (construction +operational)

Reduce cryo-power

Cavity frequency choice

Operating gradient choice

Operating temperature choice

Cavity preparation choice

Note: Particular importance for CW SRF linacs, e.g. Project-X, x-ray ERL.

Intrinsic Q – Power and Cost

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- R&D focus during the last years was on (and should have been) on achieving highest possible fields
- But: High gradients only economically usable if accompanied by high intrinsic quality factors

$$P_{diss,cavity} = \frac{1}{2} R_s \int_S \left|\vec{H}\right|^2 ds = \frac{V_{acc}^2}{2Q_0 (R/Q)_{cav}}$$

$$P_{total,linac} = \frac{V_{total} E_{acc}}{2Q_0 \frac{(R/Q)_{cav}}{L_{cav}}}$$

- Current typical Q-values: $1\cdot10^{10}$ to $2\cdot10^{10}$

⇒ Cost optimal gradient for ILC-type pulsed operation:~ 35MV/m

⇒ Cost optimal gradient for cw operation: 15 to 20 MV/m

Impact of high intrinsic Q

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- **Improve Q by factor of 2:**

  ⇒ **Increase energy by factor of $\sqrt{2}$ with same linac length and same cryo power (assuming no quench limitations)**

  ⇒ **Or: Reduce linac length by factor of 2 (double gradient)**

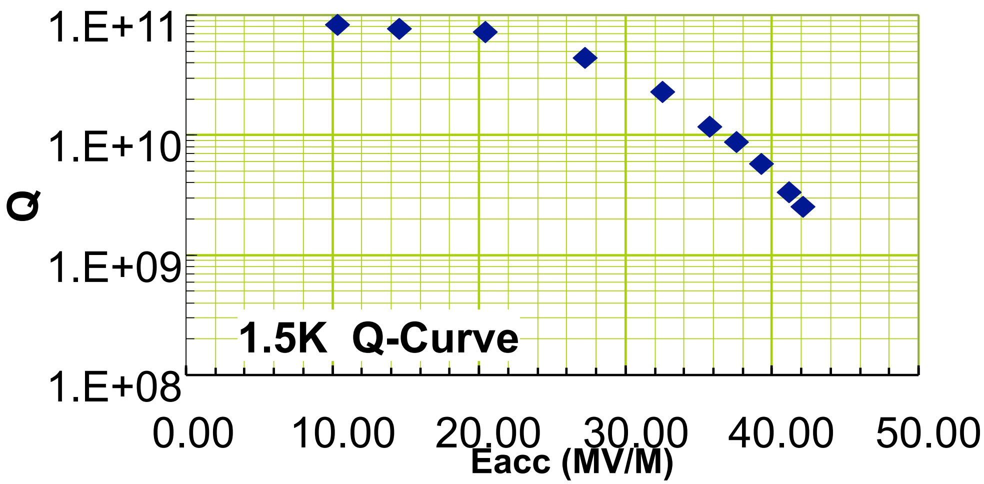
$$P_{total} = \frac{V_{total} E_{acc}}{2Q_0 \frac{(R/Q)_{cav}}{L_{cav}}}$$

  ⇒ **Intrinsic Q has high impact on cost and science potential!**

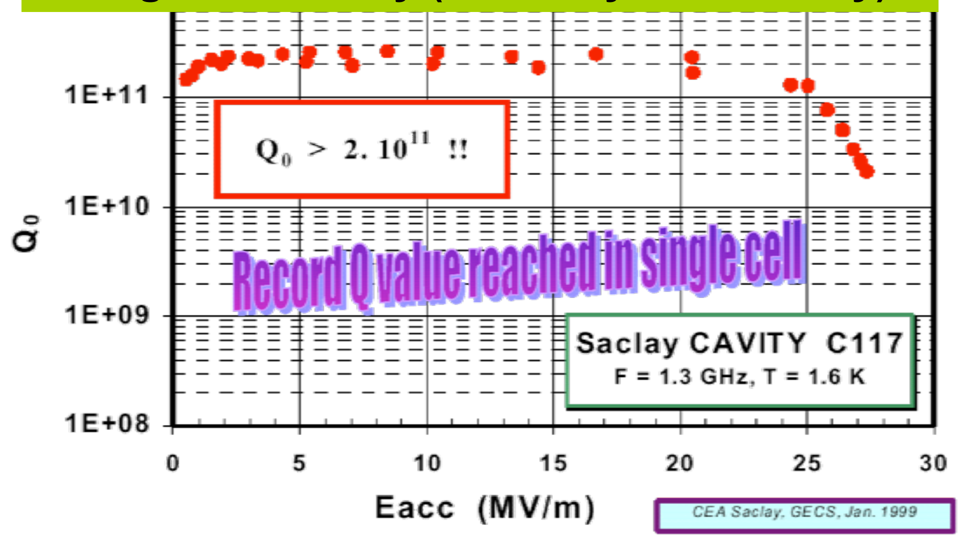
  ⇒ **Future accelerators (TeV lepton collider, FELs, ERLs, cw Project-X) would greatly benefit from intrinsic Q-values at or above $2 \cdot 10^{10}$**

Intrinsic Q – Outstanding Examples

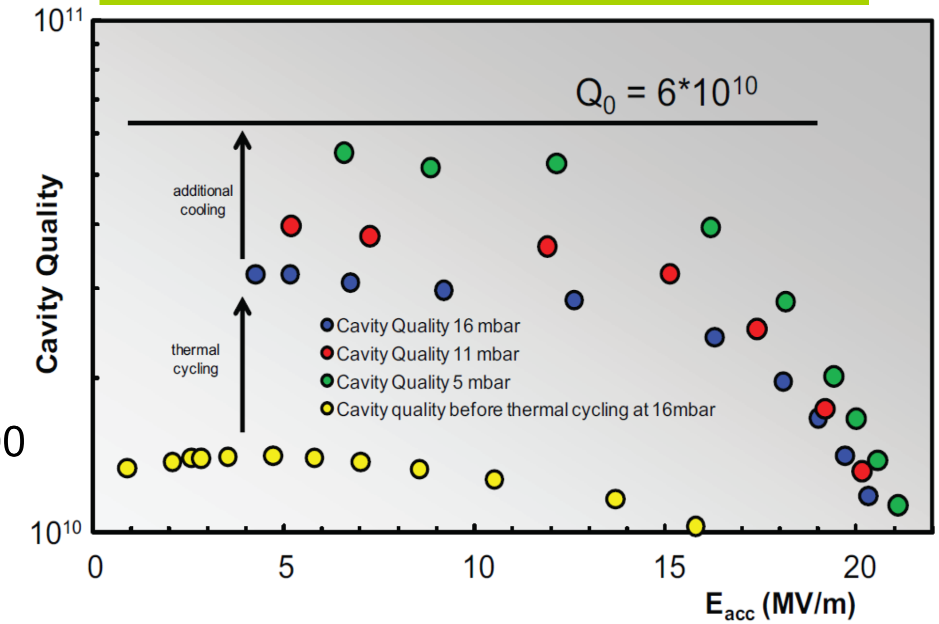
Single-cell cavity (Cornell)



Single-cell cavity (Courtesy CEA Saclay)



9-cell ILC cavity (Courtesy HZB)



- Exceptionally high intrinsic Q-values of $5 \cdot 10^{10}$ to $>1 \cdot 10^{11}$ have been achieved in a few cavities in vertical acceptance tests (i.e. not in full cryomodules)
- Huge potential…

Intrinsic Q – poor reliability

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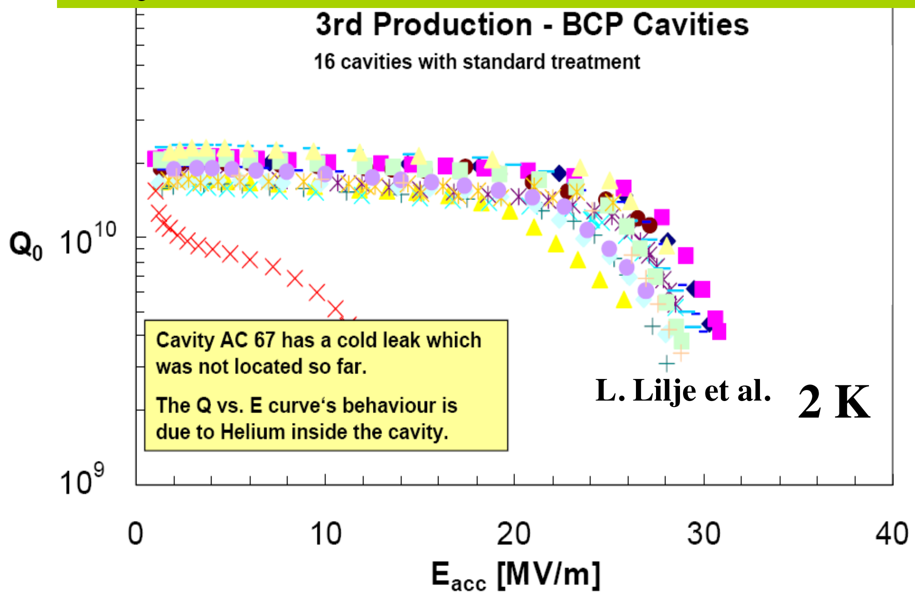
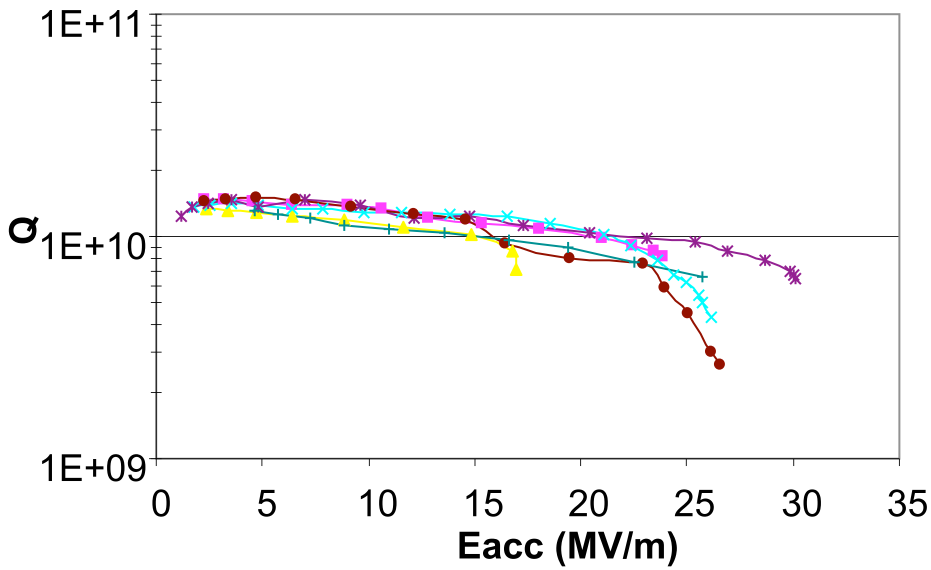
Q_0 versus Eacc: TTF 9-cell cavities



Q_0 versus Eacc: Cornell 9-cell cavities



- Significant variation in medium field Q-values
- Poor repeatability of high Q results
- No systematic understanding

Cavities inside cryomodules (1)

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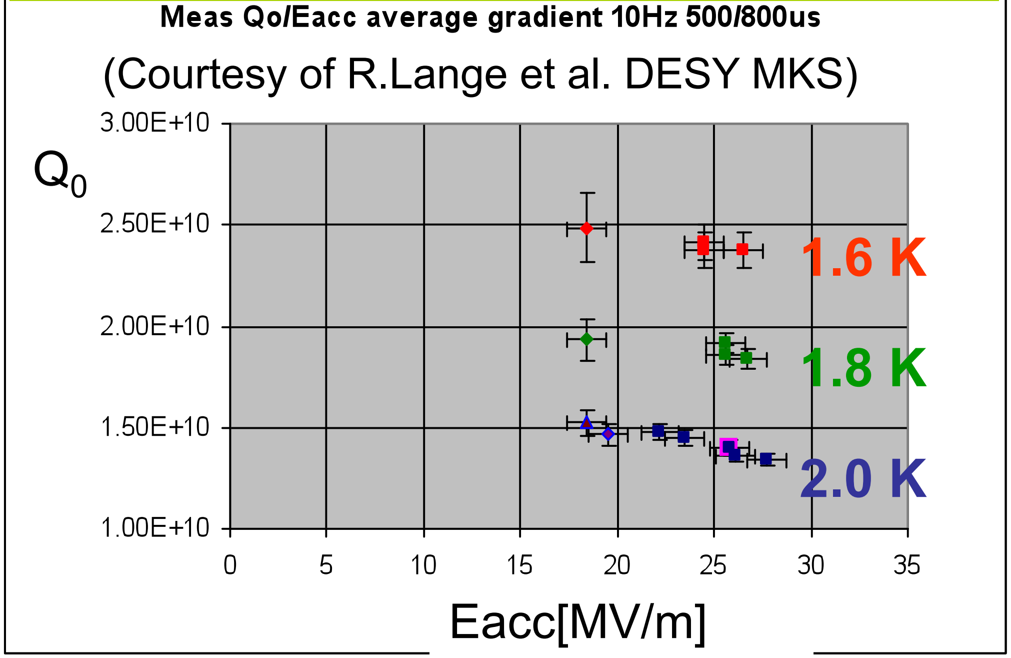
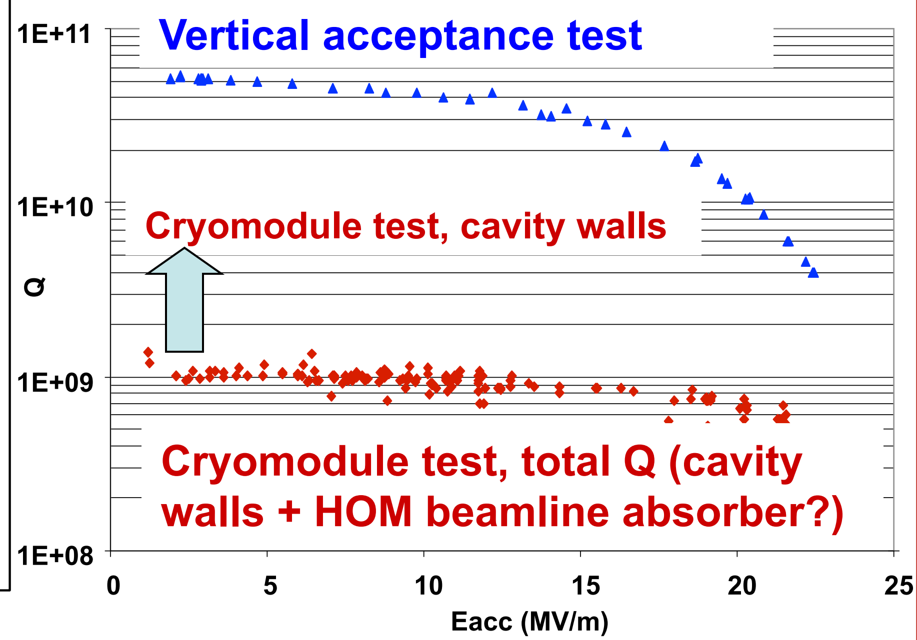
Complete TTF-cryomodule type III



Q_0 versus Eacc in the BNL ERL prototype cryomodule



- Cavities installed in cryomodules show more modest to much lower intrinsic quality factors, even at medium fields.
- Average Q-value for cavities in cryomodules significantly lower than in vertical acceptance tests
- No exceptionally high Q-values achieved so far ($>2.5 \cdot 10^{10}$)

Cavities inside cryomodules (2)

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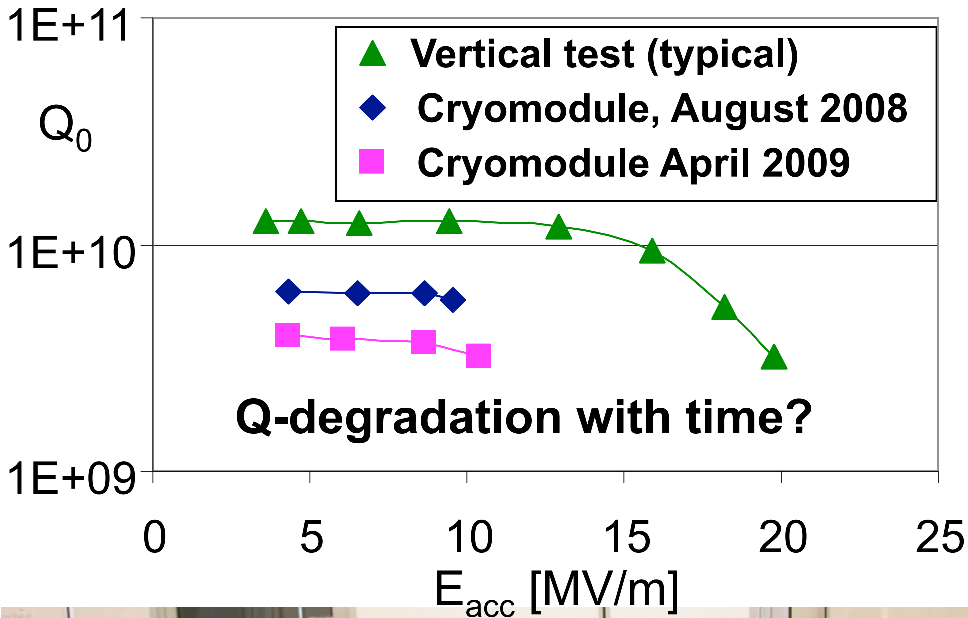
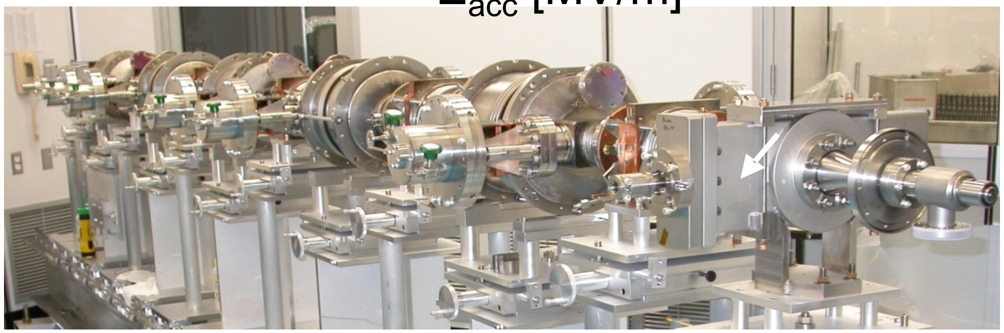
Q_0 versus Eacc in the Cornell ERL Prototype





⇒ Varying degrees of Q-degradation of cavities in real linac in cryomodules

- Potential reasons:
  - Q-degradation and field emission from dust introduction (beamline HOM absorbers?)
  - condensed gases,
  - insufficient magnetic shielding
  - …

RF frequency and Operating temperature

Dynamic Cavity Losses (1)

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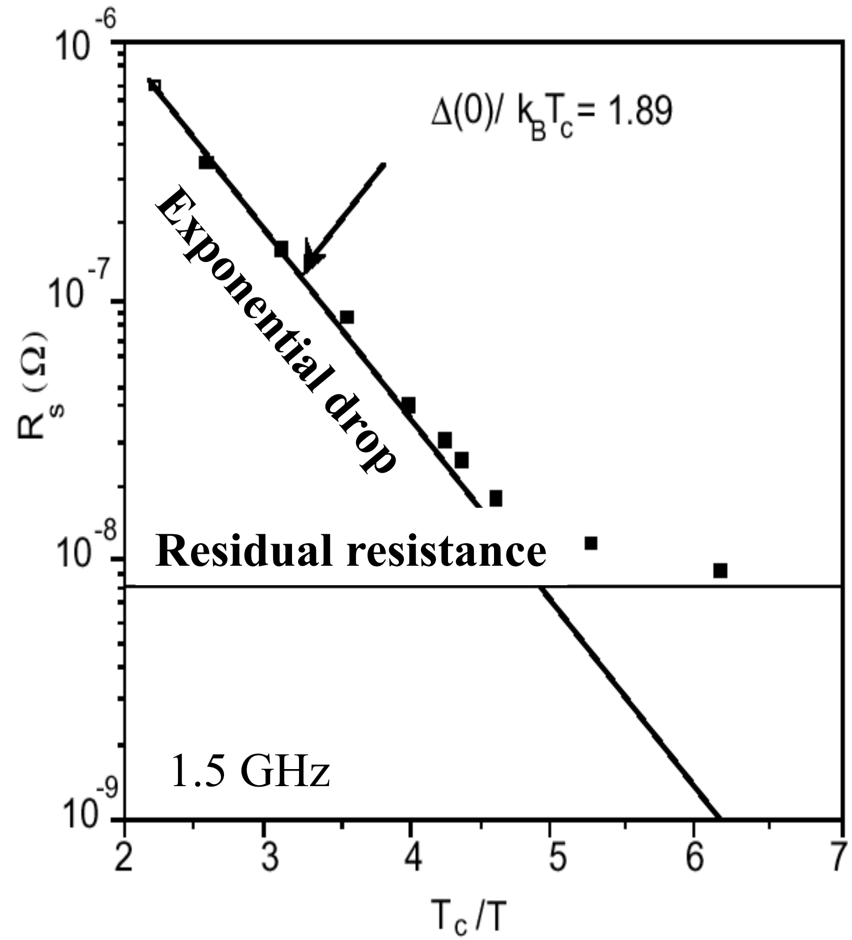
- BCS theory: Frequency and temperature dependence of surface resistance at low RF fields (T_c: s.c. transition temperature)

$$R_{BCS} \propto f^2 e^{(-const^*T_C/T)}$$

More resistance the more the electrons are jiggled around.

More resistance the more nc electrons are excited.

- Real live: $R_s = R_{BCS} + R_{RES}$



Dynamic Cavity Losses (2)

- Total power dissipated into cavity wall:

$$P_{diss} = \frac{1}{2} R_s \int_S \left|\vec{H}\right|^2 ds = \frac{V_{acc}^2}{R/Q \cdot G} R_S$$

- (R/Q)G given by cell shape and number of cells

⇒ minimize surface resistance R_s

⇒ operate cavity at temperature such that $R_{BCS} < R_{res}$

⇒ $R_s \approx R_{res}$, i.e. independent of frequency!

⇒ For given accelerating field gradient E_{acc}:

$$\frac{P_{diss}}{\text{active cavity length}} \propto \frac{1}{(R/Q)/\text{length}} \propto \frac{1}{f}$$

⇒ High frequency preferred in the regime $R_{BCS} < R_{res}$

Cooling Power for Dynamic Losses (for a given accelerating gradient)

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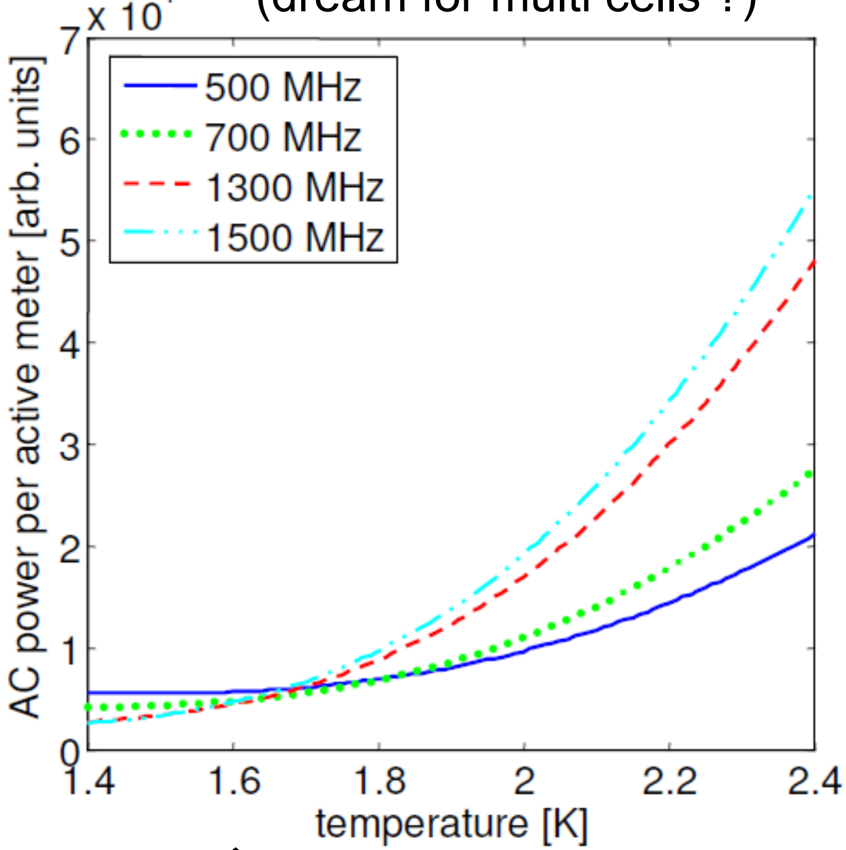
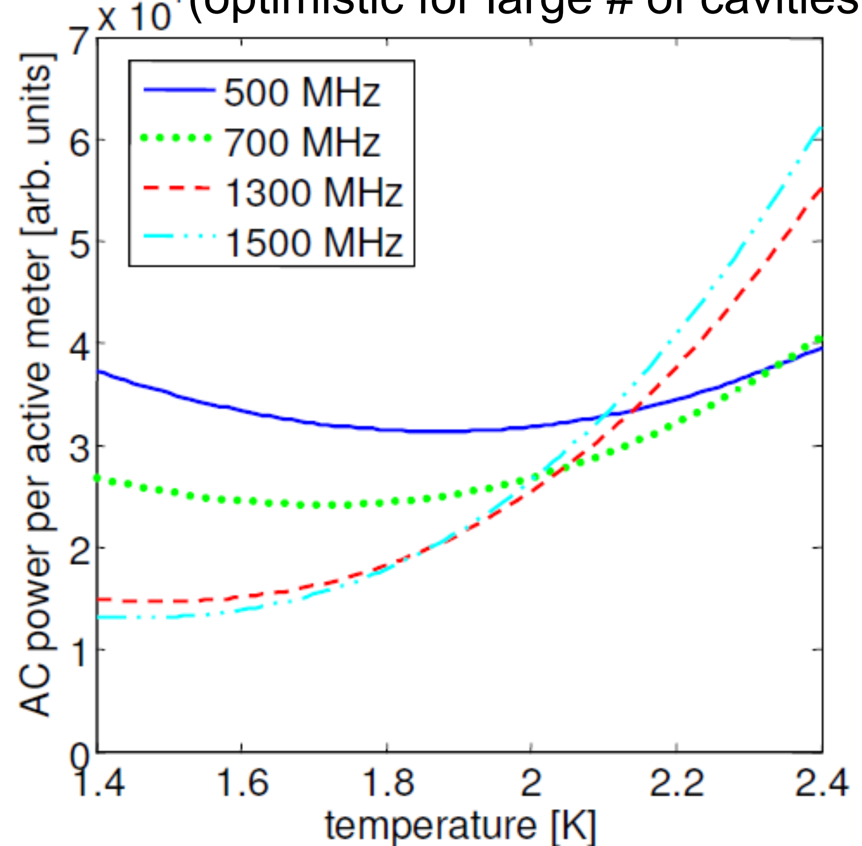
a) 1 nΩ residual surface resistance
(dream for multi cells ?)



b) 7 nΩ residual surface resistance
(optimistic for large # of cavities ?)



⇒ 1.8K. Note: Lower T is unproven and might cause instability in the cryo-system.

Choice of Temperature
The lower the better ?

- Lowering the temperature seems to be effective approximately as long as Q = Q(T) follows BCS and the temperature dependent dynamic loads dominate (reasonable lower limit 1.5 K)
- He-II cooling might become unstable below 1.8 K – tests required
- Another cold compressor stage is required for each 0.2 K temperature step to lower temperatures – investment costs and system complexity increase
- See for example: Talk by B. Petersen, ERL 2005

Choice of frequency (1)

- **Unless extremely small residual surface resistances become reality in SRF cavities in the future, *higher frequency (e.g 1.3 GHz)* SRF cavities give *smaller dynamic cavity losses* at optimized temperature**
  - **Important for multi-GeV cw linacs!**
  - **Additionally: Cavity surface area $\propto 1/f^2$**
    - **$\Rightarrow$ Higher frequency gives smaller risk of cavity performance reduction by surface defects, electron field emission by dust, …**

Choice of frequency (2)

- Why chose <1 GHz anyway in some cases?
  - Transit time factor considerations for $\beta<1$ linacs
  - HOM considerations for very high current linacs (>~100mA) to reduce beam breakup and HOM heating
  - …
  - But: Construction cost increases with lower frequency!
  - But: Operational cost increases with lower frequency!
  - But: Risk of surface contamination increases with lower frequency.

Conclusion (1)

- For 5 GeV, 100 mA ERL:
  - Fundamental mode frequency of **1.3 GHz** and realistic operating temperature of **~1.8 K** minimize AC cooling power
- Lower frequency would be beneficial if higher BBU threshold were required
  - Can increase BBU threshold 1/f (for same number of cells per cavity)
  - Note: Other things can have similar / larger impact on the BBU threshold current
  - The chrage per bunch increases when every bucket is filled, increasing space charge forces.

Q0 and Optimal Field Gradient

SRF Linac Cost Estimation

SRF cyomodules
- # of cavities
- # cells per cavity
- fill factor
- …

Tunnel
- Linac length

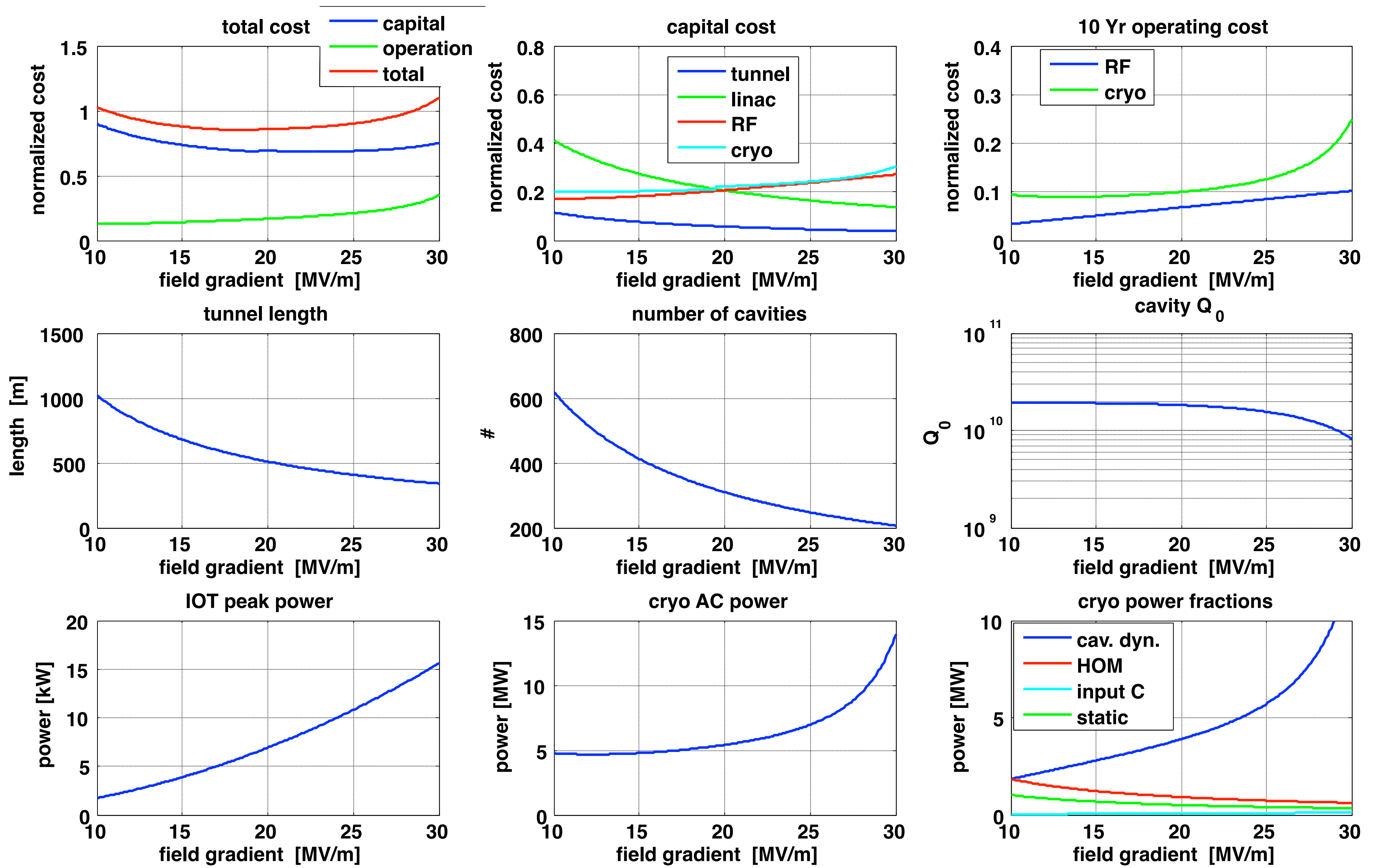
Cryo-Plant
- Cryo-loads at various temperatures
  - Field gradient
  - Operating temperature
  - …
- Note: cost $\propto$ power$^{0.4}$

Cost model (main linac only!)

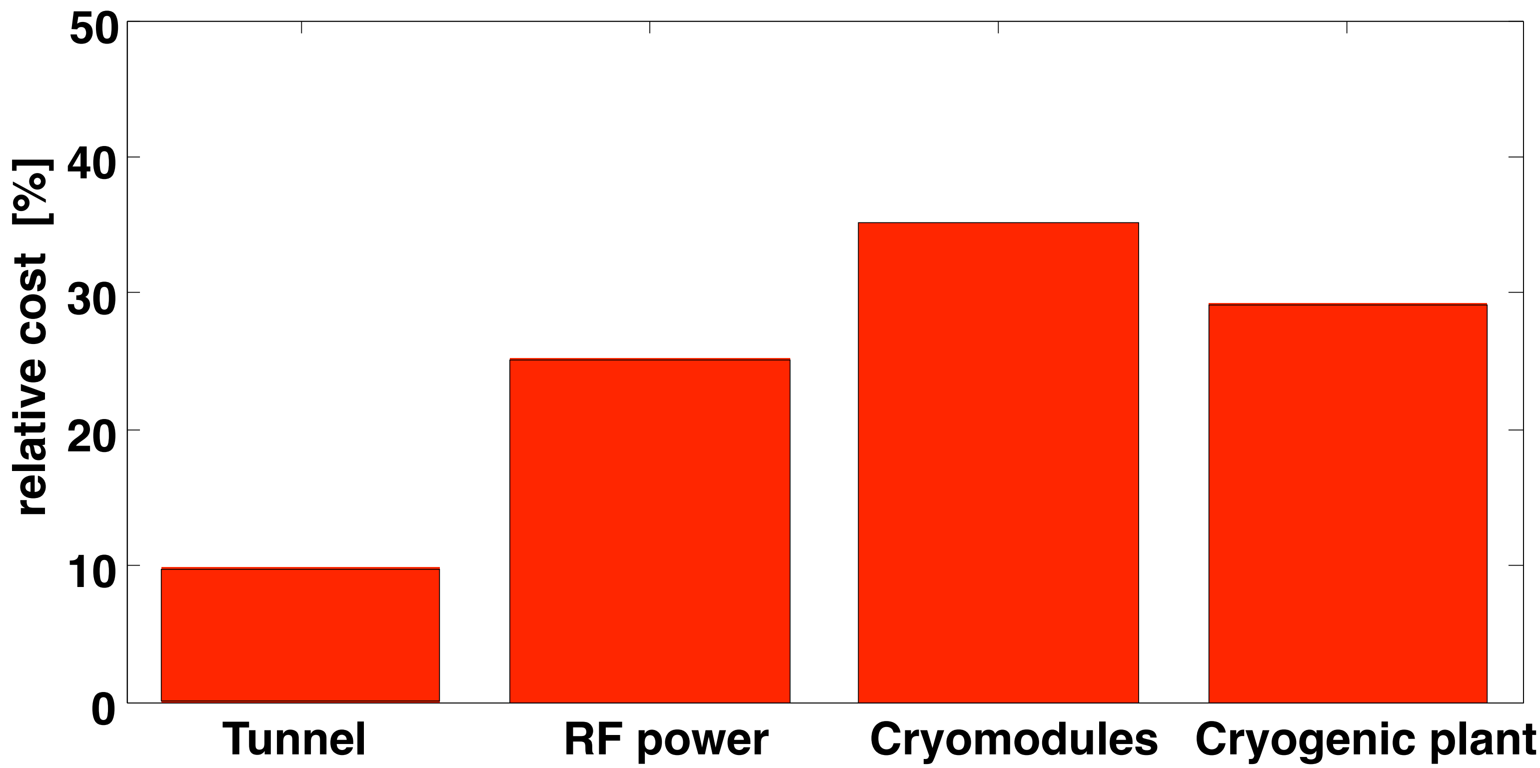
RF Power Sources
- Power per cavity
  - QL, microphonics
  - …
- # of cavities

Note: R&D cost and SRF facility cost are not included in following example of a 5GeV ERL !

Example: Cost dependence on accelerating field graident for 5GeV



ERL Main Linac cost distribution
For Eacc = 16.2MV/m



- **Costs for cryomodules, cryogenic plant, and the RF power sources are similar.**

Optimal Accelerating Gradient

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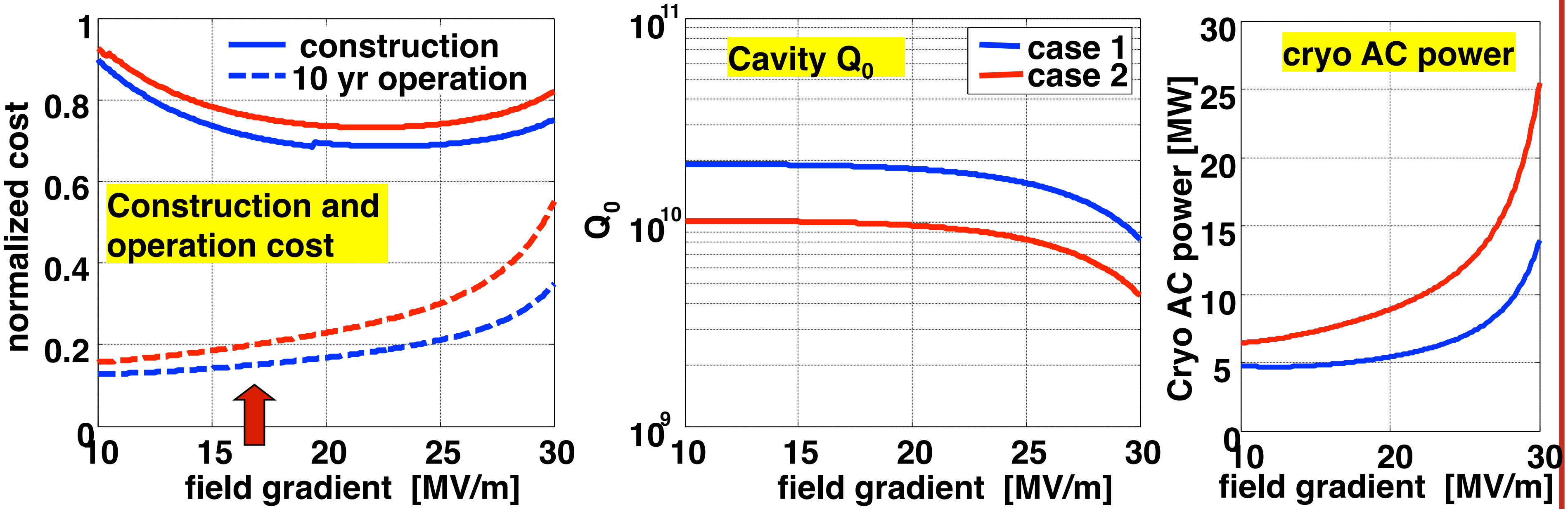
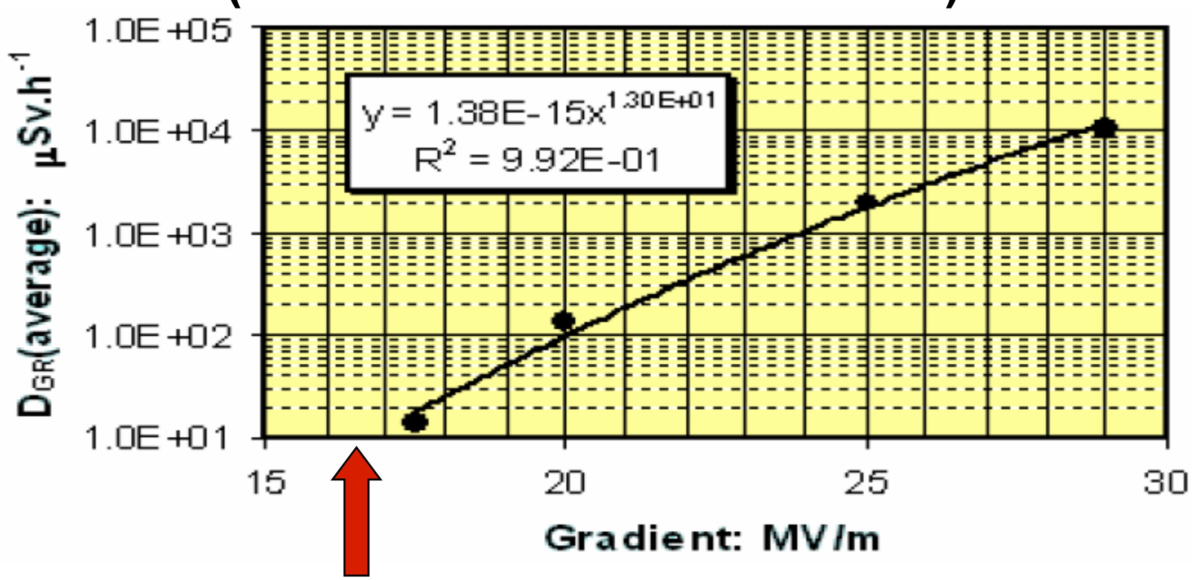


- Q_0-value has significant impact on cost (high impact and risk parameter)
- Construction cost changes only moderately for gradients between ~16 and ~27 MV/m
- Operating cost / AC power increases with gradient
- Select gradient at lower end: ***16.2 MV/m*** *⇒ Less risk for same cost!*

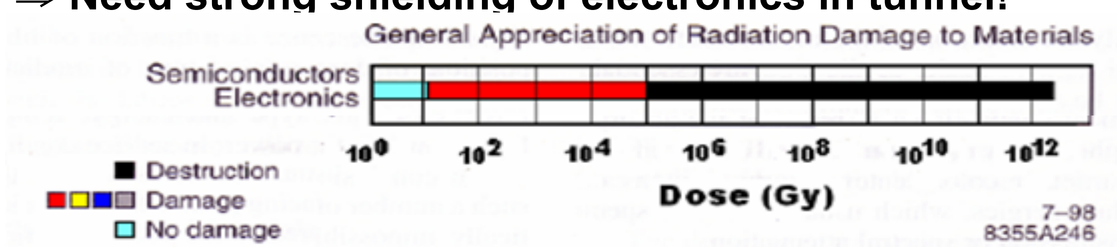
Field Emission

Gamma radiation measured at DESY/FLASH from cavity field emission (PULSED CAVITY OPATION!):



- **Exponential** growth in FE with gradient
- Serious problem in cw cavity operation
- Low trip rate essential for light source!
- Favors lower gradients
- High reliability: don't push gradient and RF power to limit
- *⇒ 16.2 MV/m*

•For ERL : 10µGy/h * 200 (for cw)= 2 mGy/h = 0.2 rad/h
•10 years of operation: 100 Gy = 10,000 rad (at 5000h/year)
•Same as FLASH/XFEL at ~ 25 MV/m
⇒ Need strong shielding of electronics in tunnel!



Conclusion (2)

- CW cavity operation favors operation at modest field gradients of **15 to 20 MV/m**
  - ⇒ Near cost optimum
  - ⇒ Reduced operation cost (AC power)
  - ⇒ Reduced risk of field emission and poor cavity performance
    - Note: Cavity designs with high surface electric peak fields might require operating at even lower fields!
  - ⇒ Increased reliability
  - ⇒ Simplified cavity preparation (compared to ILC)

Q_0 and cavity preparation

Residual Resistance

- Several sources are known to increase residual resistance:
    - Trapped flux for DC external field ⇒ magnetic shielding of Earth's magnetic field

$$R_{\Phi} \approx \frac{H_{\text{ext}}}{2H_{c2}} R_{n}$$

    - Q-disease from hydrides ⇒ Reduce H-concentration
    - But: Cavities with similar magnetic shielding show Q-values between $1 \cdot 10^{10}$ and $1 \cdot 10^{11}$!

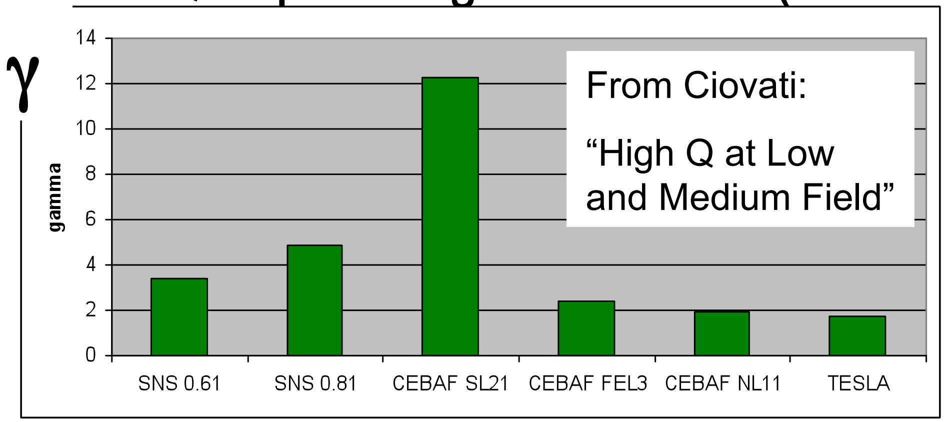
    ⇒ Several other factors must play an important role…

Medium field Q-slope – understood ?

- Most cavities show modest to significant reduction in Q from low to medium fields (5 -> 25 MV/m)
- Proposed models usually combine
  - Field depended surface resistance

$$\text{Surface Resistance:} \quad R_s(B) = R_{s0}\left[1 + \gamma\left(\frac{B}{B_c}\right)^2 + O(B^4)\right]$$

  - Thermal feedback $R_{BCS}(T)$
- But: medium field Q-slope strength varies a lot (factor 2 to 5)



- But: no good understanding of physics and best surface treatment to minimize Q-slope

Medium field Q-slope – EP / BCP

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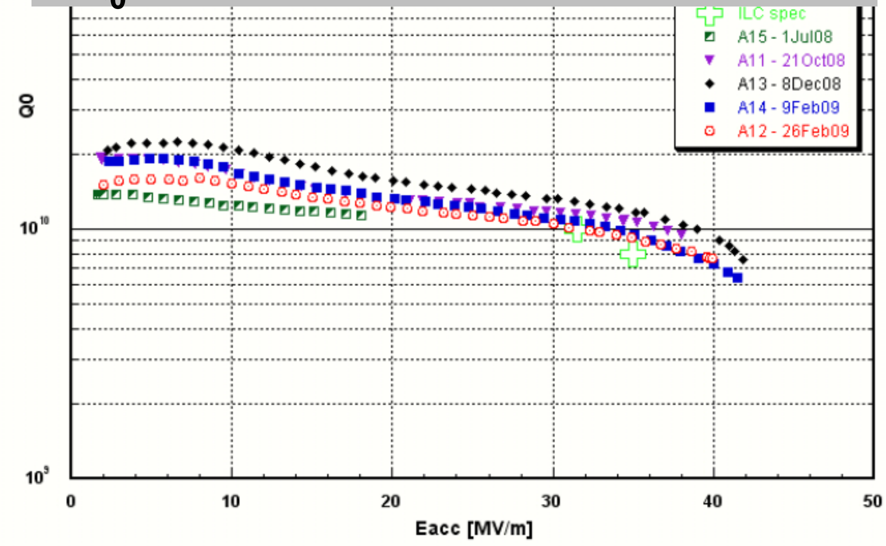
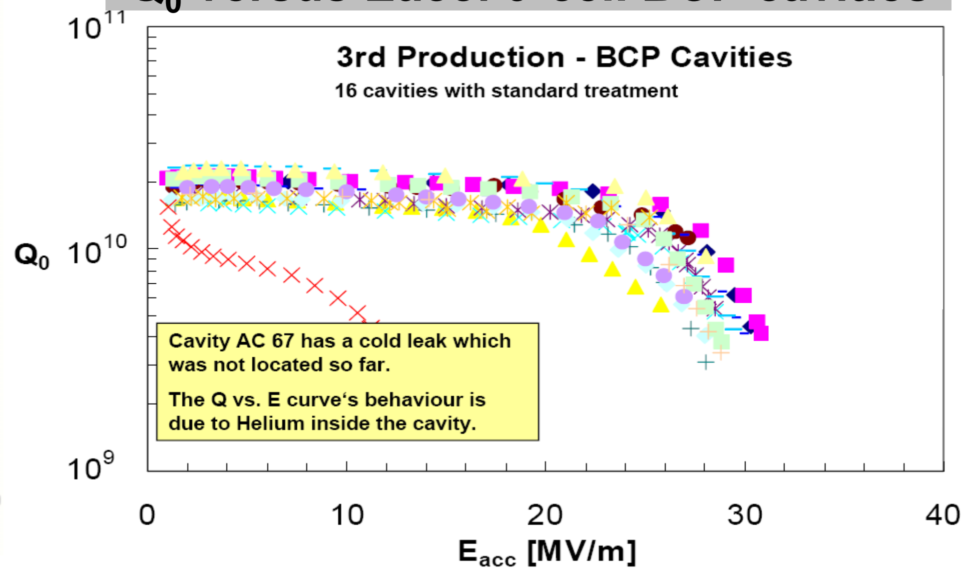
Q_0 versus Eacc: 9-cell EP cavities

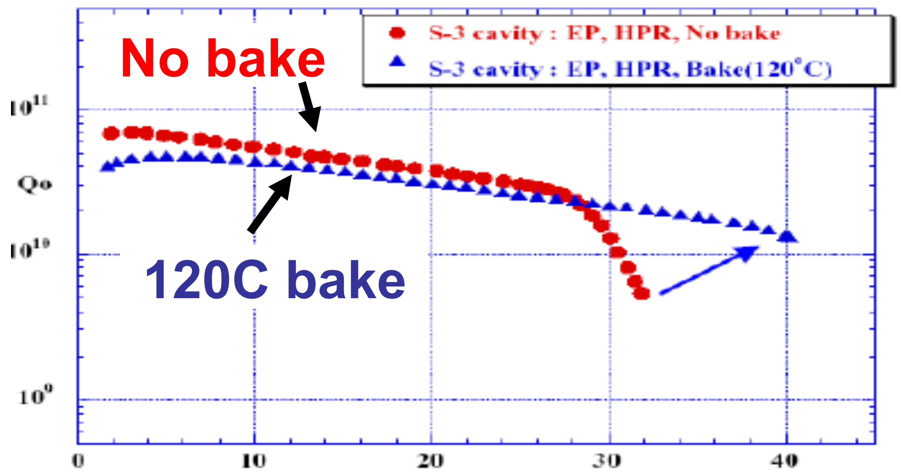


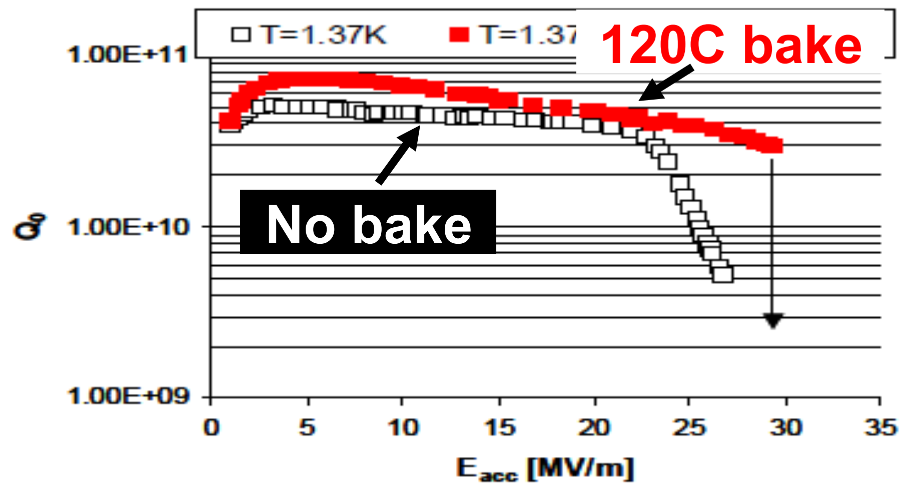
Q_0 versus Eacc: 9-cell BCP cavities



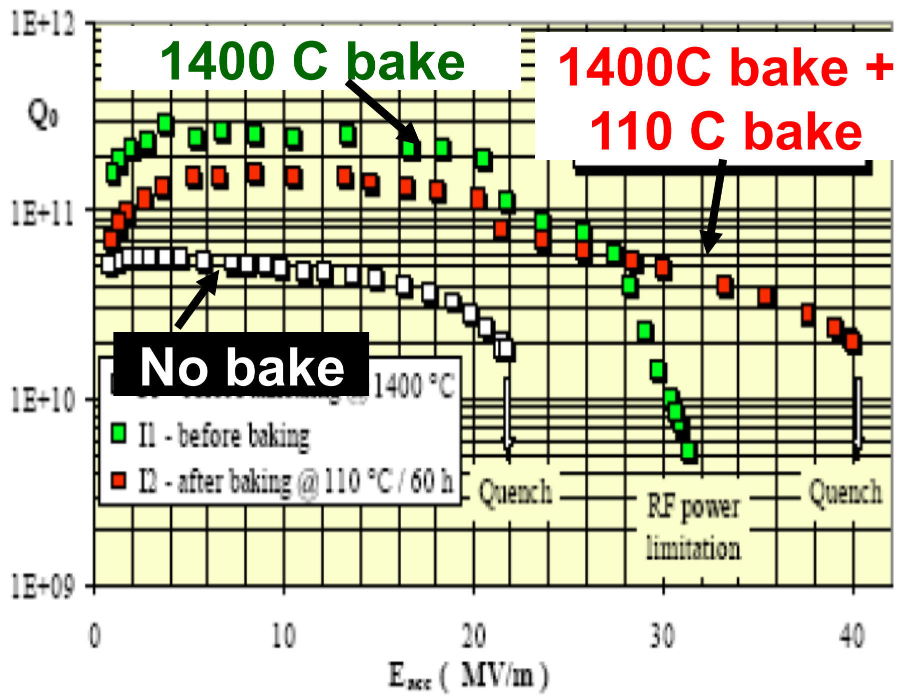
- Smaller medium field Q-slope in BCP cavities vs. EP cavities?
- Which surface treatment gives the highest Q-values realizably?

Medium field Q-slope – heat treatment





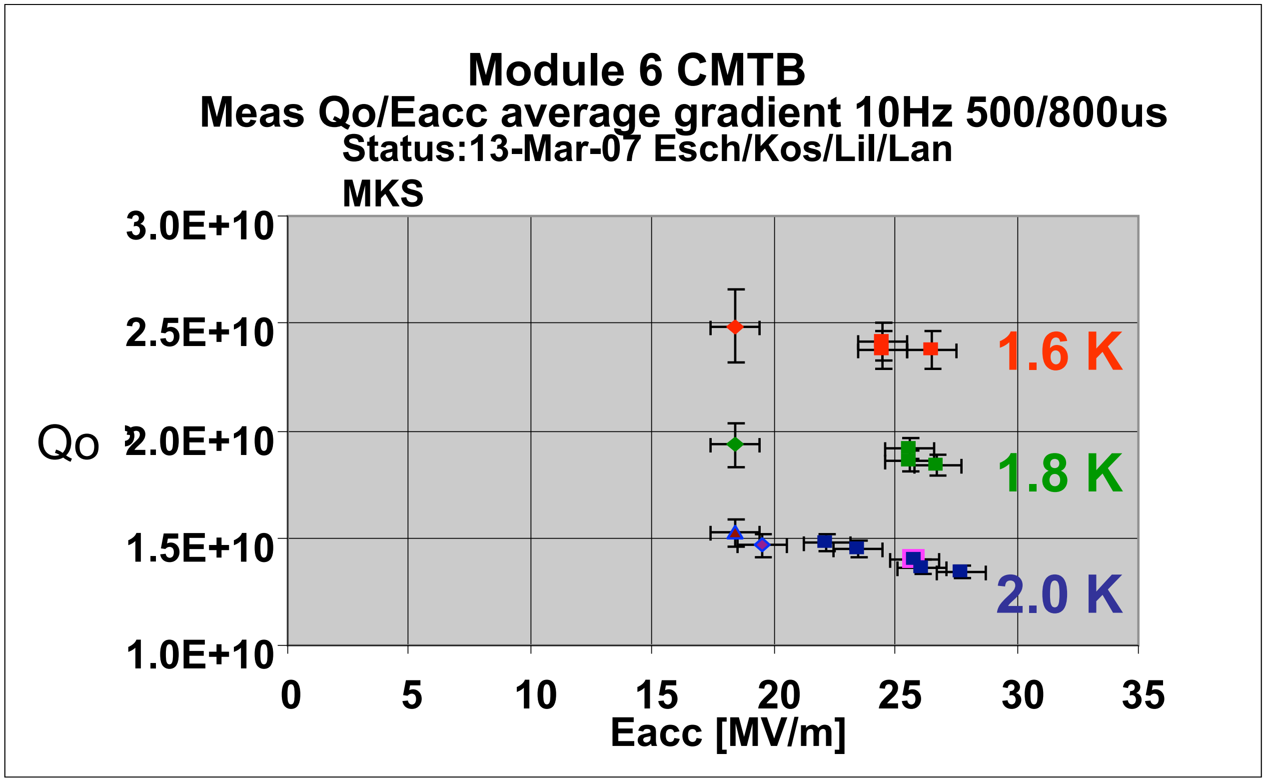
G. Ciovati–*J. Appl. Phys.* 96, p. 1591 (2004)



- Low (~120 C) and high temperature (800C to 1400C) heat treatments have been found to impact residual resistance and medium field Q-slop
- But: no coherent picture

Conclusion (3)

- Cavity quality factor <u>at operating gradient</u> has high impact on cost!
  - Q_0 of **$2 \cdot 10^{10}$ at 1.8 K** is realistic for the near future
    - Best performing TTF/FLASH module:



(Courtesy of R.Lange et al. DESY MKS)