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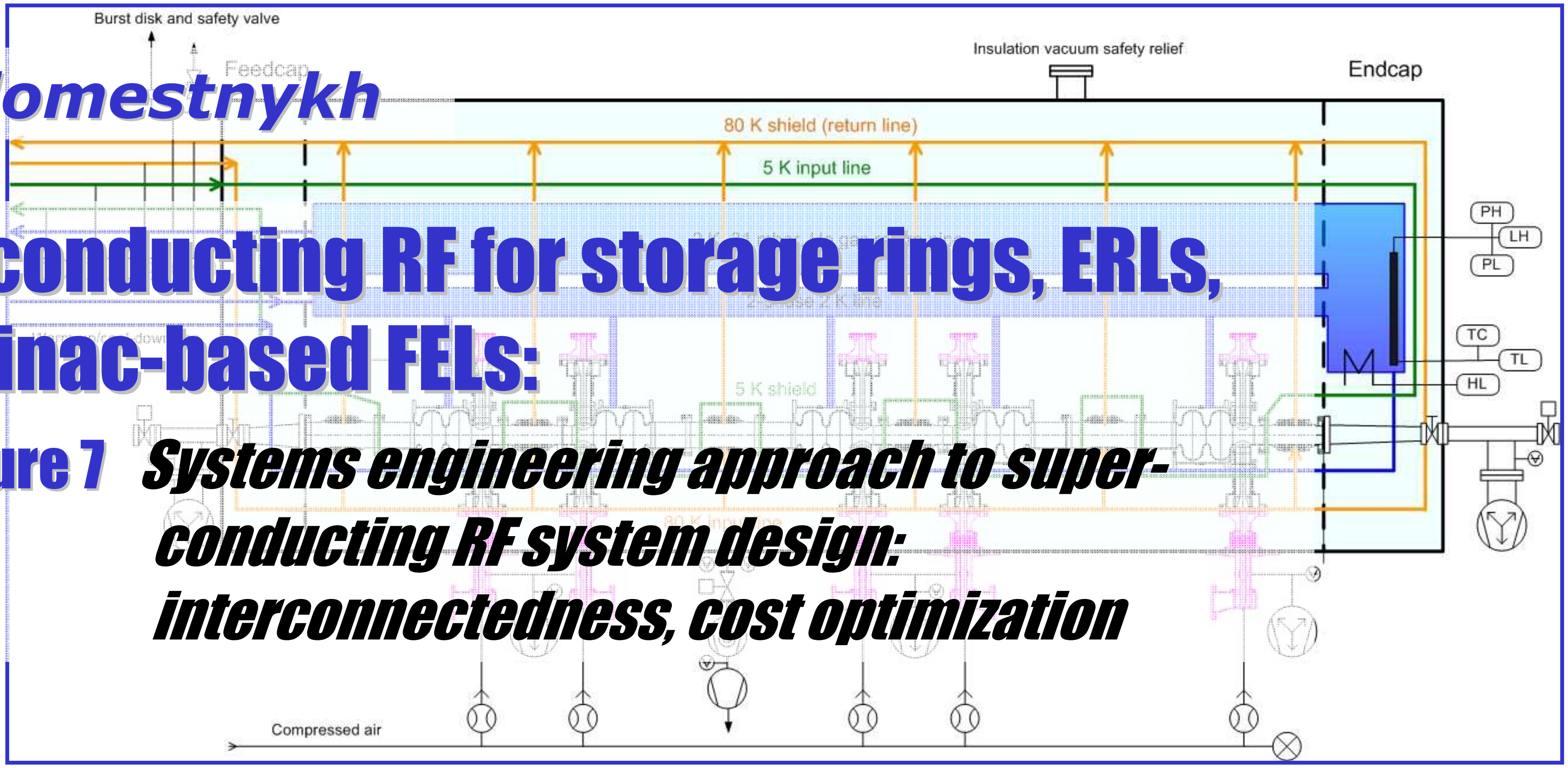
Laboratory for Elementary-Particle Physics

S. Belomestnykh

Superconducting RF for storage rings, ERLs, and linac-based FELs:

- **Lecture 7** *Systems engineering approach to superconducting RF system design: interconnectedness, cost optimization*



What is the systems approach?

From ***The Systems Approach*** by S. Ramo and R. K. St.Clair:

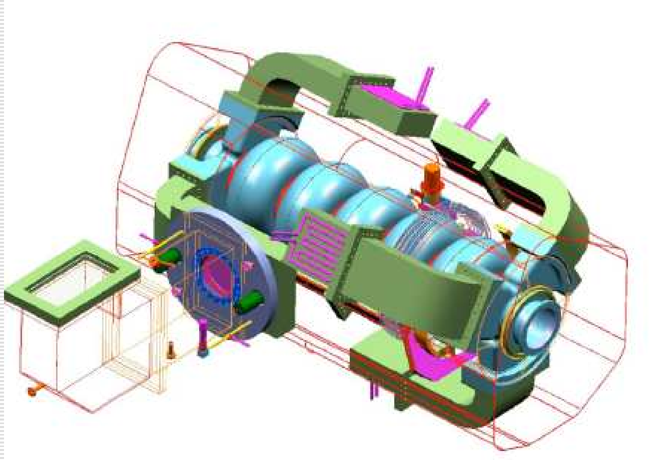
"It is … a reasoned and integrated, rather than fragmentary, look at problems."

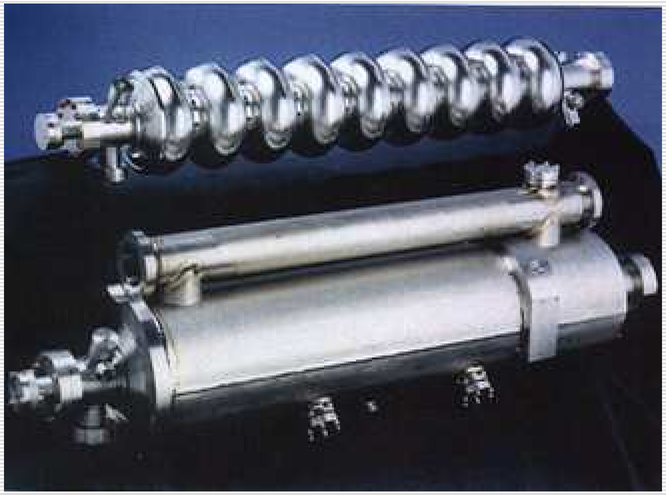
"It starts by definition of goals and ends with a description of a harmonious, optimum ensemble of the required humans and machines with such a corollary network of flow of information and materials as will cause this system to operate to solve the problem and fill the need."

I would like to impress upon you that regardless of how small your assigned task is, you should always try to understand the large picture first. That is, where the requirements are coming from? Is there better approach to your task in terms of technology, materials, etc.? Your goal should always be to participate in the system design, even if passively, keep your eyes open, be a team member. You must understand how the overall goals affect the particular sub-system or component you are working on and, vice versa, how your component is affecting the global design.

Accelerating RF systems

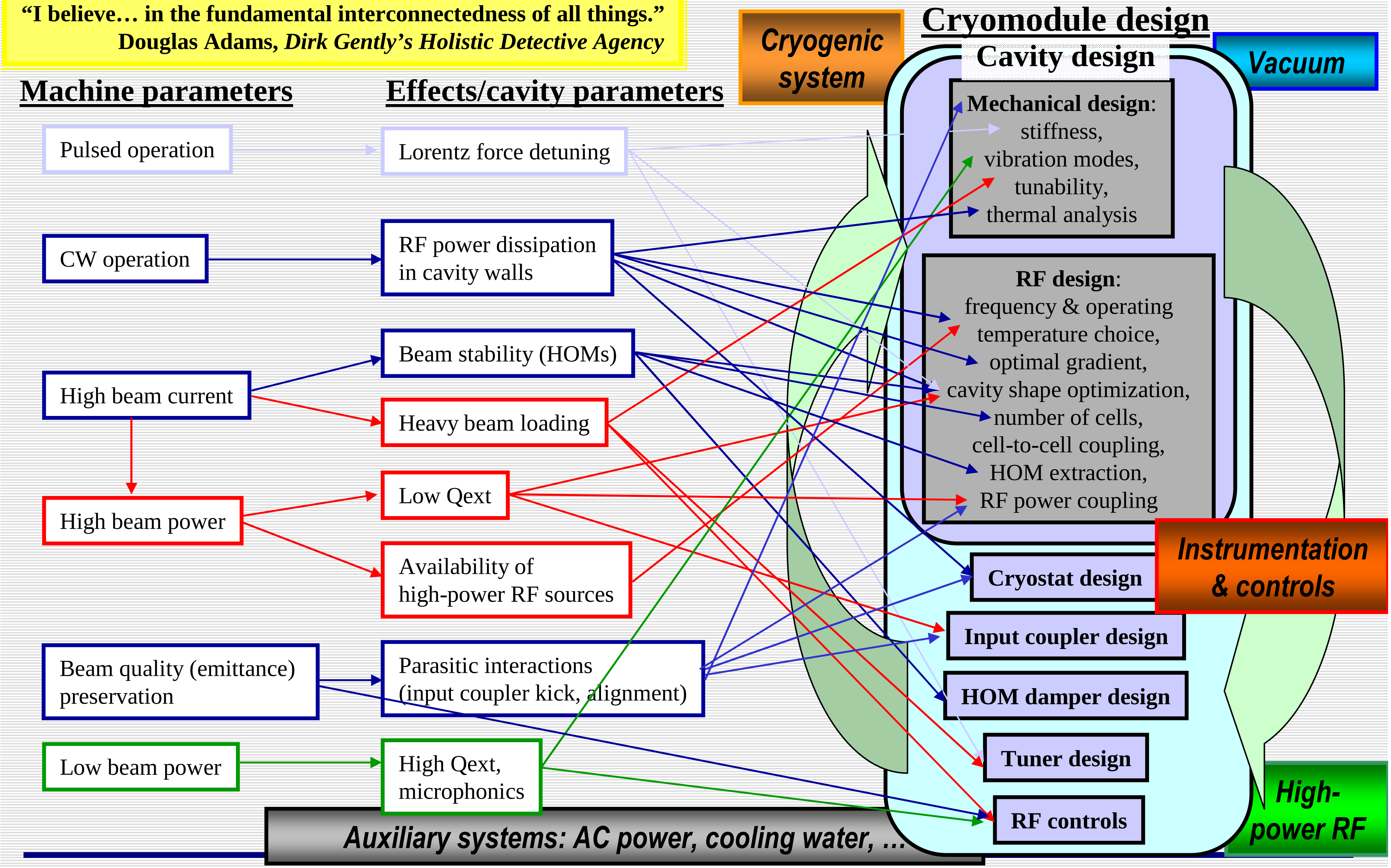
- The main purpose of using RF cavities in accelerators is to add (remove) energy to charged-particle beams at a fast acceleration rate.
- The highest achievable gradient, however, is not always optimal for an accelerator. There are other factors (both machine-dependent and technology-dependent) that determine operating gradient of RF cavities and influence the cavity design, such as accelerator cost optimization, maximum power through an input coupler, necessity to extract HOM power, etc.
- Moreover, although the cavity is the heart, the central part of an accelerating module and RF system, it is only one of many parts and its design cannot be easily decoupled from the design of the whole system.
- In many cases requirements are competing, hence using the systems engineering approach should be used.





SC RF system design issues

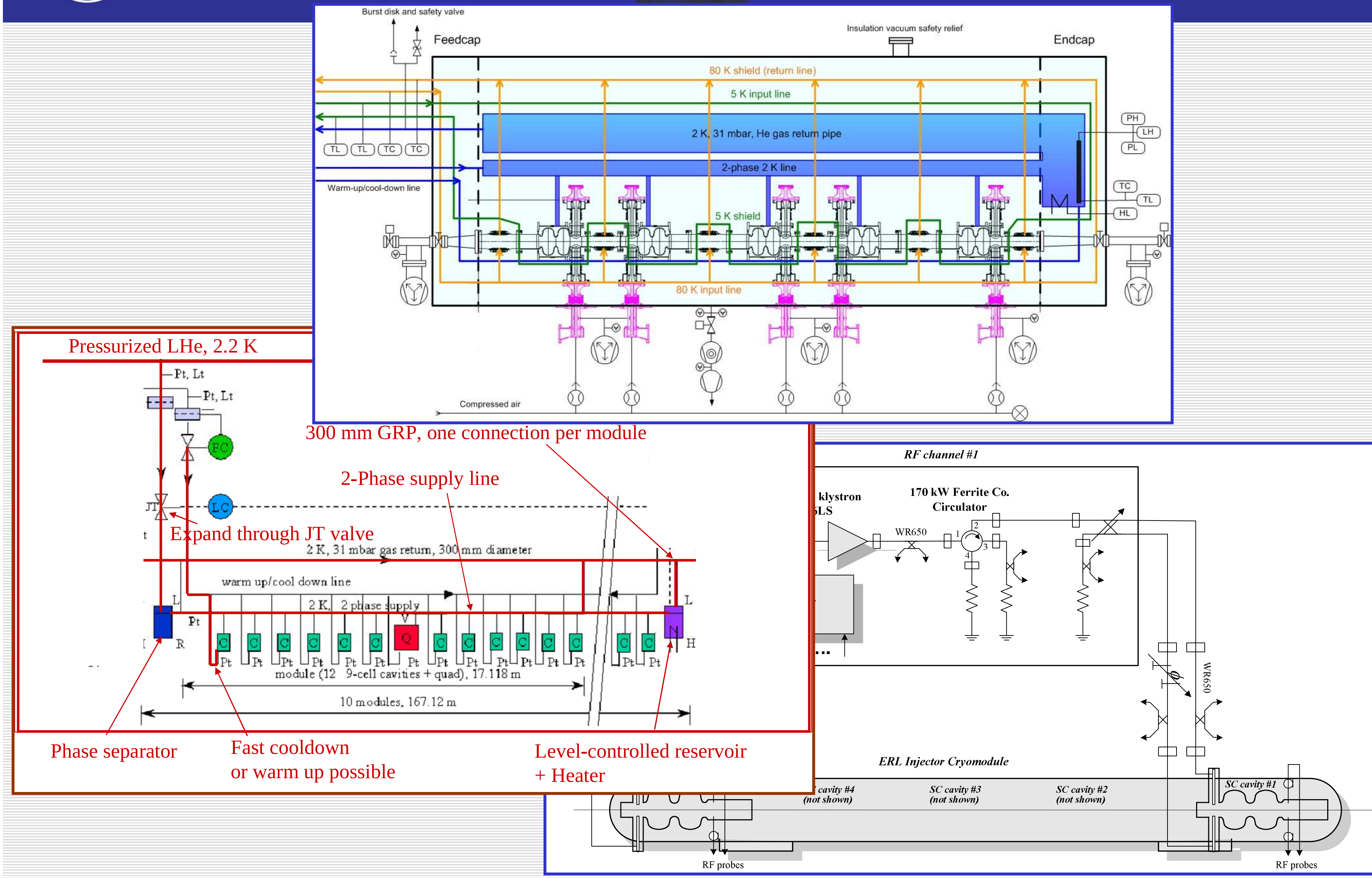
> **"I believe… in the fundamental interconnectedness of all things."**
> **Douglas Adams, *Dirk Gently's Holistic Detective Agency***



Some of machine-dependent issues

- **Pulsed operation** → Lorentz-force detuning → mechanical design, fast tuner for compensation, cavity shape optimization
- **CW operation** → RF power dissipation in cavity walls → cavity shape optimization, operating temperature choice, frequency choice, thermal analysis
- **High beam current** → beam instability due to interaction with cavity higher-order modes → cavity and HOM absorber design for strong damping
- **High beam current** → heavy beam loading → tuner design to compensate reactive component, RF controls
- **Beam quality (emittance) preservation** → minimize parasitic interactions (coupler kick, HOMs) → input coupler and cavity design, frequency choice
- **High beam power** → low Q_{ext}, availability of high-power RF sources → input coupler design, frequency choice
- **Low beam power** → high Q_{ext}, microphonic noise → mechanical design, feedbacks

SRF linac diagrams: big picture



SRF system optimization for an ERL

In order to not lose the forest behind the trees, we will consider an example of SRF system optimization for Cornell ERL as presented by M. Liepe at *ERL'09 Workshop*.
Most conclusions should be valid for other ERLs.

Objectives

- Minimize cost (capital and operational)
- Meet beam specifications
- Maximize availability and reliability

Constrains

- Cavity constrains (Q_0, field emission,…)
- Site constrains
- …

➢ *Optimization is only as specific as objectives and constrains can be specified.*
➢ *It is important to be realistic: neither too pessimistic, nor too optimistic.*

Need to identify risk / impact parameters

- Cavity intrinsic $Q \longrightarrow$ cost
- Microphonics level / peak cavity detuning $\longrightarrow$ cost
- …

Optimization parameters

Optimization:

- **Operating temperature and RF frequency → AC power (cost of operation)**
- **Operating field gradient, Q_0 → reliability and cost**
- **Loaded Q, RF power, and microphonics → cost**
- **Cavity design, HOM damping and BBU → beam specification, cost**

$$T_{cav},\ f_{TM010},\ E_{acc},\ Q_0,\ Q_L,\ P_{RF,peak},\ I_{BBU},\ldots = \ ?$$

Some of these parameters are given by the state-of-the-art in SRF technology, others are found by optimizations.

Principal beam parameters

Parameter	Cornell ERL	XFEL	consequence
operation mode	**CW**	pulsed	250 * 2K load per cavity, factor ≈3 larger total 2K load
linac energy gain	5 GeV	20 GeV	
average current	0.1 A* 2	$3\cdot 10^{-5}$ A	$(I_{ERL}/I_{XFEL})^2=4\cdot 10^7$ $(P_{HOM,ERL}/P_{HOM,XFEL})=400$
bunch charge	77 pC	1 nC	
bunch length	2 ps	80 fs - 1 ps	f < 100 GHz for HOMs
emittance (norm.)	0.3 mrad· mm	1.4 mrad· mm	Cavity alignment, …
energy spread (rms)	2e-4	1.25e-4	Similar, but much higher beam currents, Q_L!

Step I

Operating temperature and RF frequency

Dynamic cavity losses

- SRF resistance small but finite because Cooper pairs have inertia.
  ⇨ nc electrons "see" an electric field!

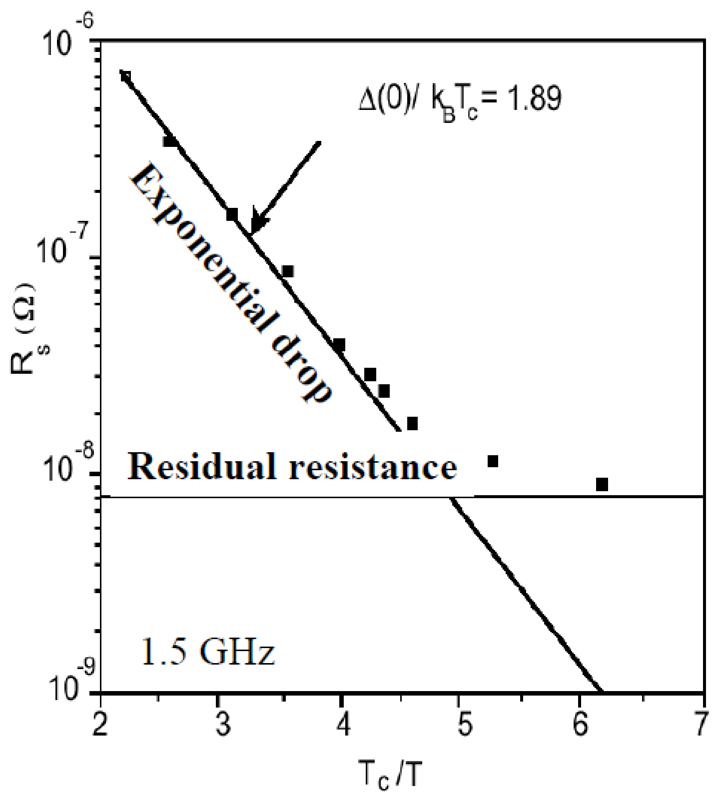
- BCS theory: Frequency and temperature dependence of surface resistance <u>at low RF fields</u> (T_c: S.c. transition temperature)

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

More resistance the more the electrons are jiggled around.

More resistance the more nc electrons are excited.

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



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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

$\Rightarrow$ minimize surface resistance R_s

$\Rightarrow$ operate cavity at temperature such that R_{BCS} < residual resistance R_{res}

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

$\Rightarrow$ For given accelerating field gradient E_{acc}:
P_{diss} / cavity length $\propto$ 1/f

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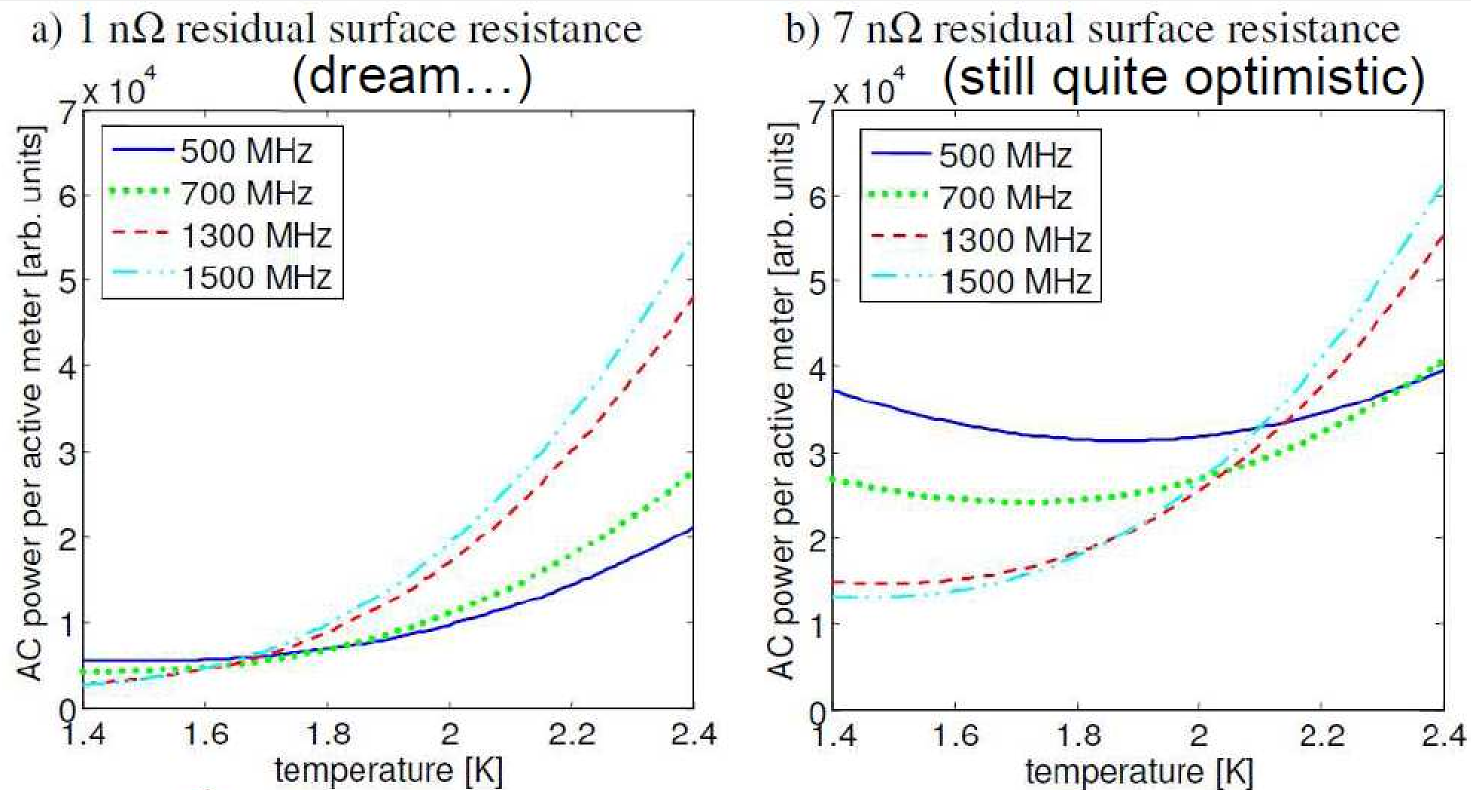
Cooling power for RF losses at a given *Eacc*



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

Choice of operating temperature

- Lowering the temperature seems to be effective 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 also: Talk by B. Petersen, ERL 2005

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Choice of operating frequency

- Unless extremely small residual surface resistances become reality in main linac cavities in some distant future, *higher frequency (~1.3 GHz)* SRF cavities give *smaller dynamic cavity losses* at optimized temperature
  - Important for multi-GeV ERLs!
  - Also: 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, …

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Choice of operating frequency (2)

- **Why chose <1 GHz anyway in highest current ERLs (BNL…)?**
  - **BBU threshold current ∝ 1/f (assuming same number of cells per cavity, same quality factor Q of HOMs)**
  - **Average HOM losses ∝ f^2**
  - **But: Construction cost increases with lower frequency!**
  - **But: Operational cost increases with lower frequency!**
  - **But: Risk of surface contamination increases with lower frequency.**

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Conclusion for step I

- 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 only potentially beneficial if highest BBU threshold is required
  - Can increase BBU threshold by factor of $\lesssim 2$ (for same number of cells per cavity)
  - Note: Other things can have similar / larger impact on the BBU threshold current
  - More later…

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Step II

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Operating field gradient, Q_0, reliability, and cost

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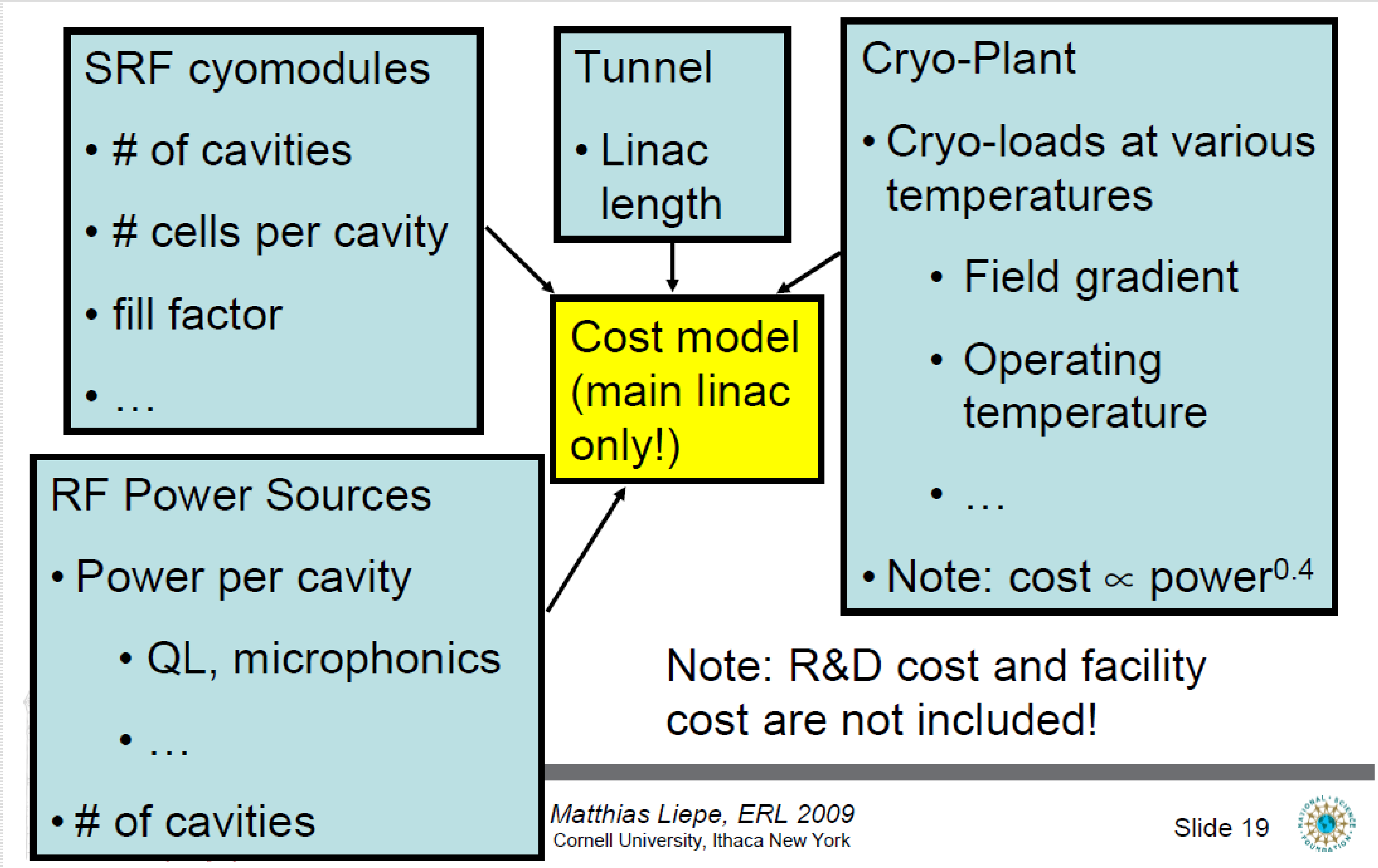
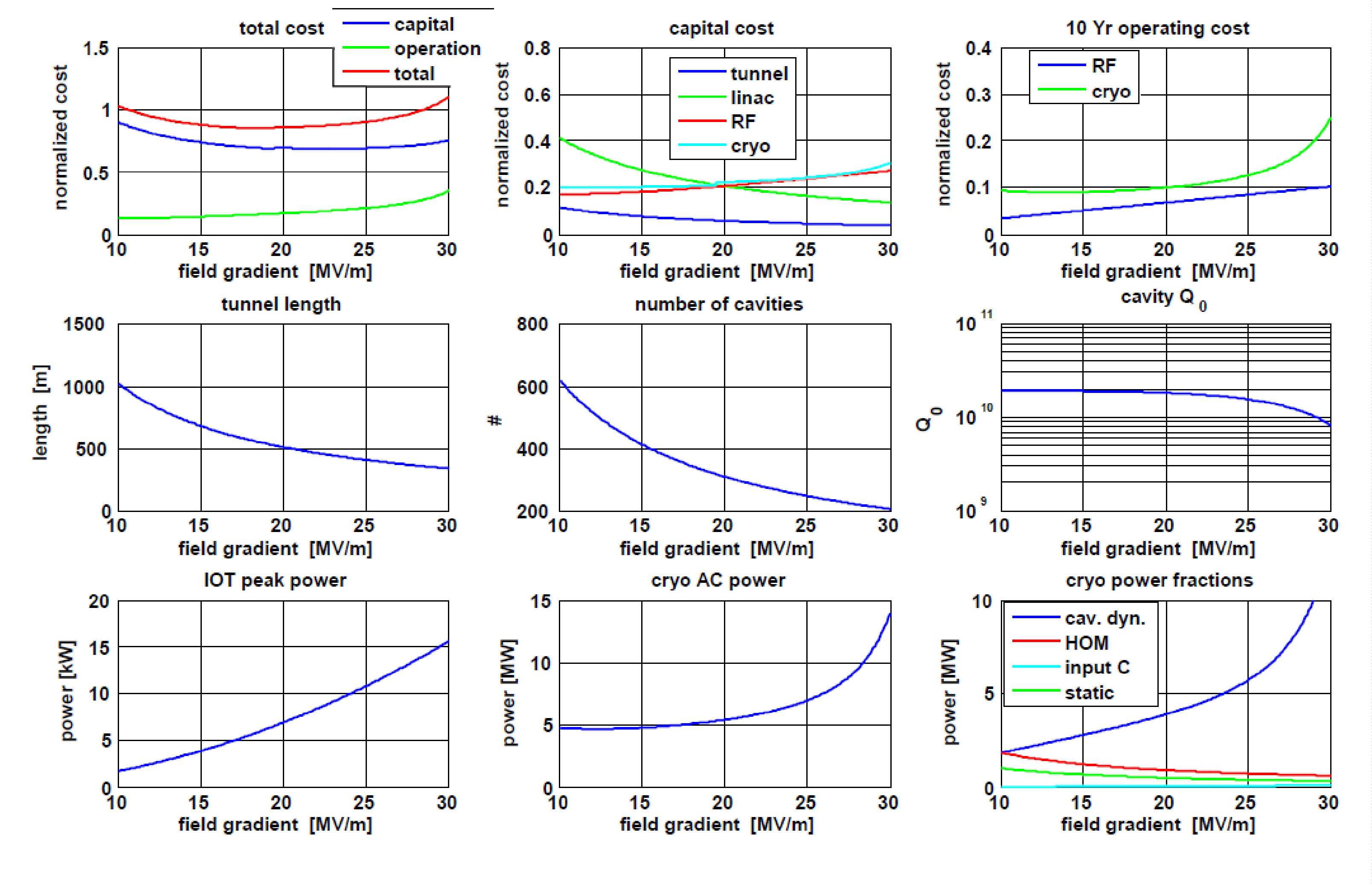
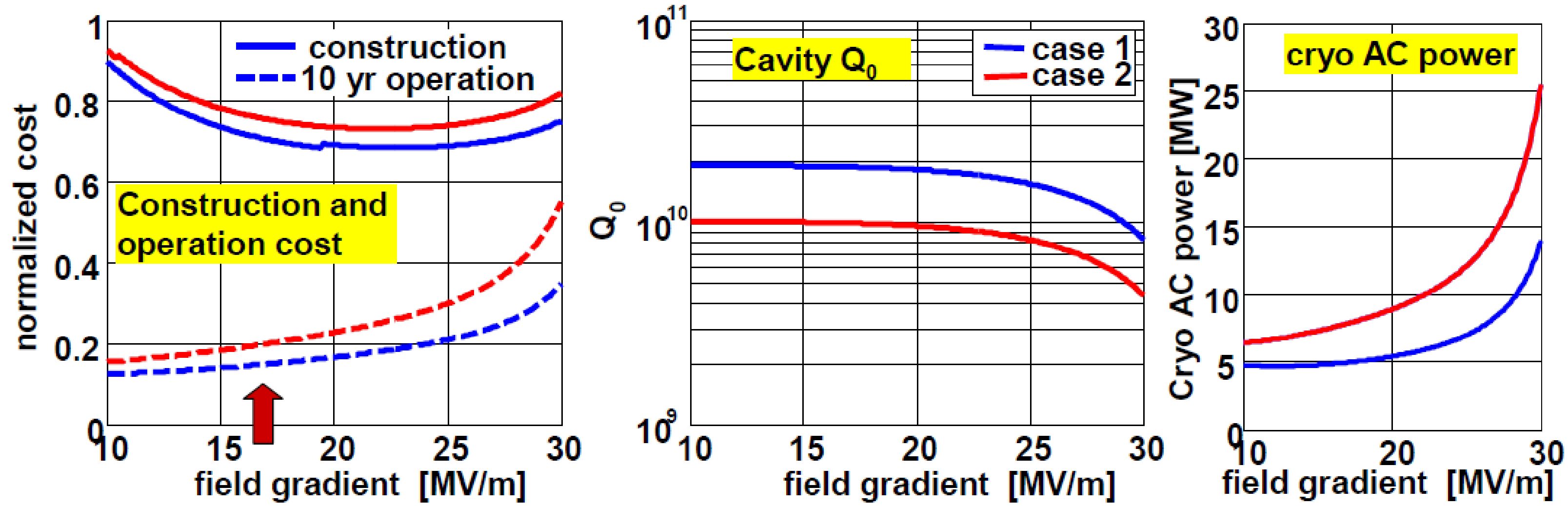
SRF linac cost estimate model



Cost dependence on *Eacc*



Optimal field gradient



- 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!***

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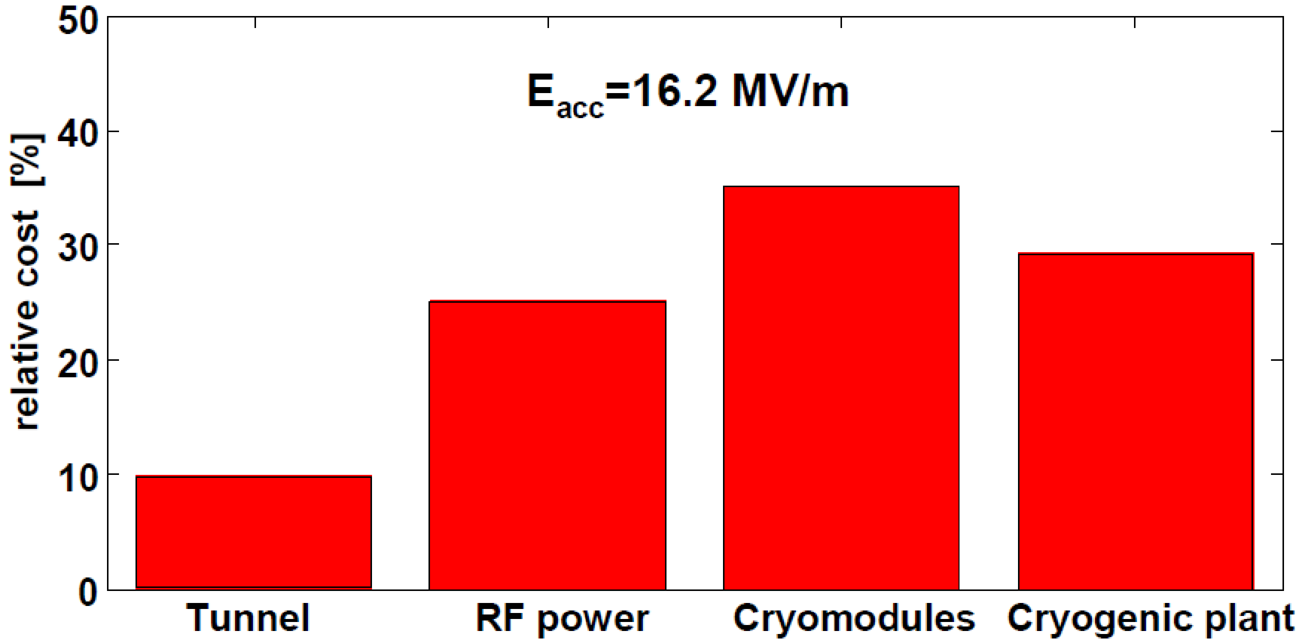
Main linac cost distribution



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

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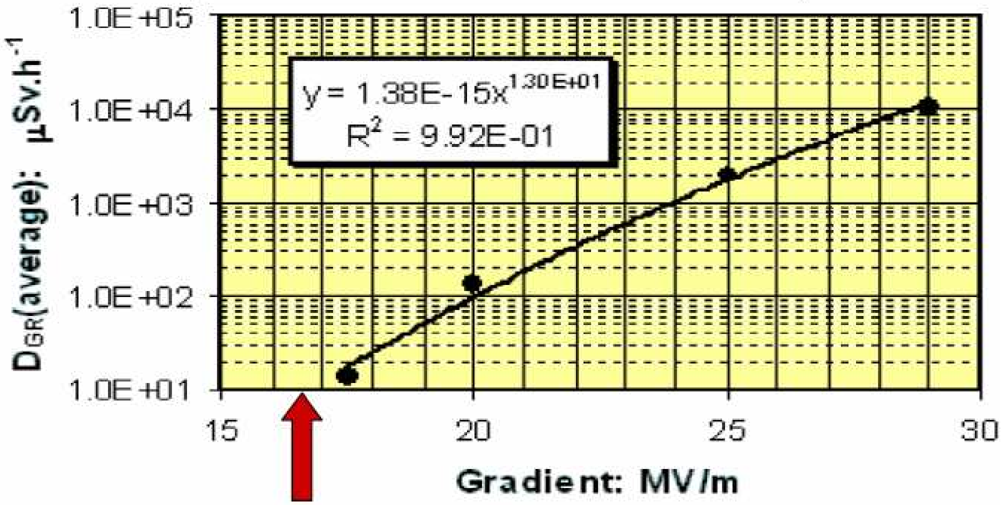
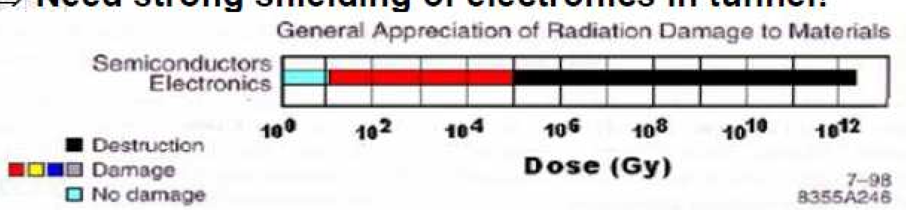
Field emission

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



- **For ERL : 10µGy/h * 200 (for cw)= <u>2 mGy/h = 0.2 rad/h</u>**
- **10 years of operation: <u>100 Gy = 10,000 rad</u> (at 5000h/year)**
- **Same as FLASH/XFEL at ~ 25 MV/m**

⇒ Need strong shielding of electronics in tunnel!



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

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Conclusion A for step II

- CW cavity operation in ERLs 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)

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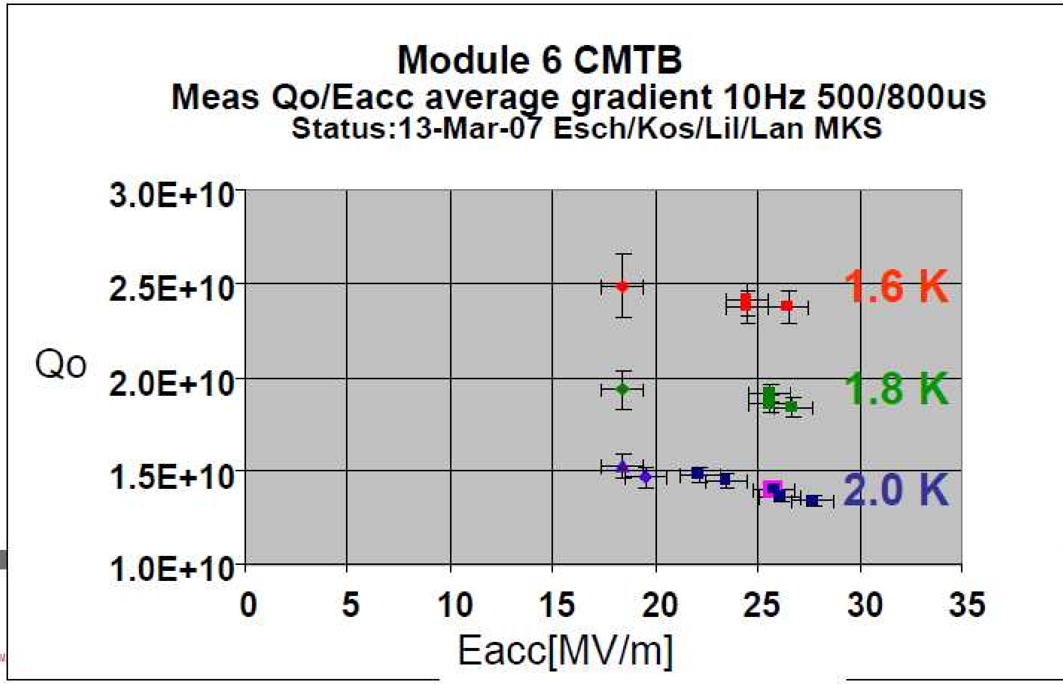
Conclusion B for step II

- 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)

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Step III

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Loaded Q, RF power, and microphonics

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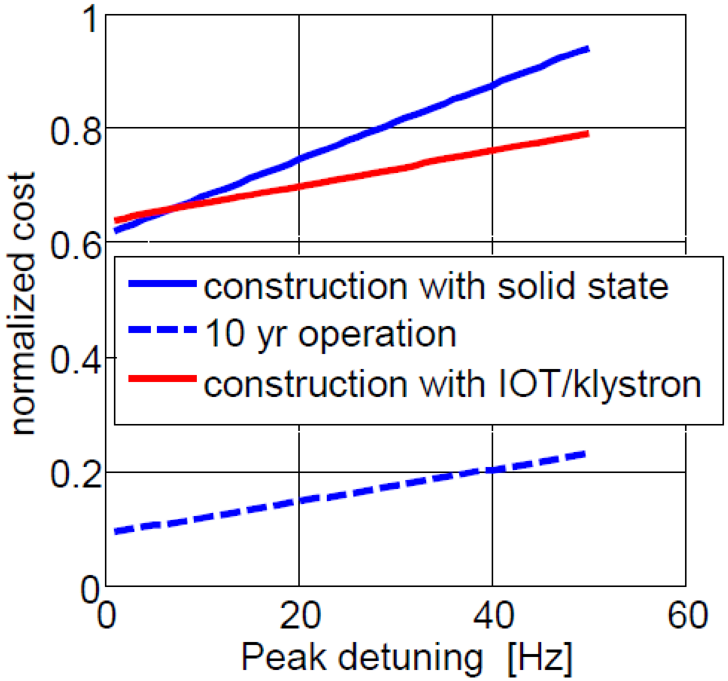
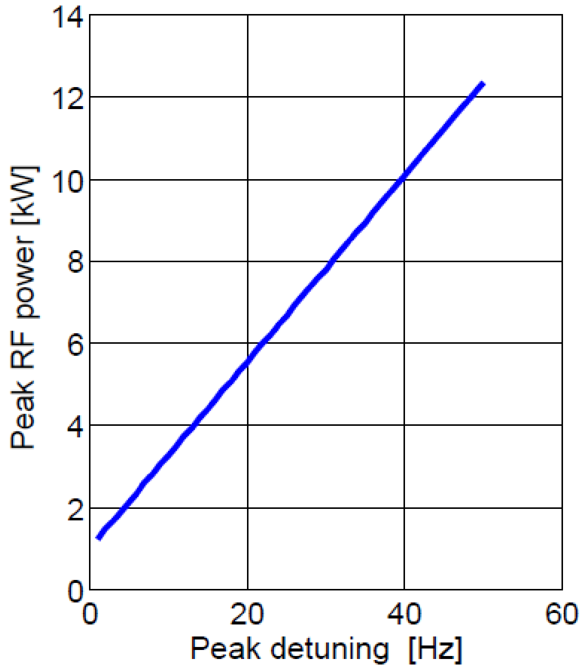
Cost vs. peak cavity detuning

For 16.2 MV/m, $Q_0=2\cdot10^{10}$, optimal Q_L:





⇒ <20 Hz peak detuning is highly desirable…

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Realistic level of microphonics

Machine	σ [Hz]	6σ [Hz]	Comments
CEBAF	2.5 (average)	15 (average)	significant fluctuation between cavities
ELBE	1 (average)	6 (average)	
SNS	1 to 6	6 to 36	significant fluctuation between cavities
TJNAF FEL	0.6 to 1.3	3.6 to 7.8	center cavities more quiet
TTF	2 to 7 (pulsed)	12 to 42 (pulsed)	significant fluctuation between cavities

$$Q_{L,\text{optimal}} = \frac{1}{2}\frac{f_0}{\Delta f} \qquad P_{g,\text{minimal}} = \frac{V_{acc}^2}{2R/Q}\frac{\Delta f}{f_0}$$

- Realistic: 10 Hz to 20 Hz peak detuning
- ⇨ $Q_L = 3.25 \cdot 10^7 \ldots 6.5 \cdot 10^7$
- Microphonics compensation is underway…

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Conclusion for step III

- Peak cavity detuning is a strong cost driver
  - 10 Hz peak detuning should be achievable
    - Needs good mechanical cryomodule design
    - Need to address / quantify substantial differences in microphonics levels beween individual cavities!

    $\Rightarrow$ **$Q_L = 6.5 \cdot 10^7$**

    - **Much higher $Q_L > 10^8$ is not much more beneficial:**
      - Extra power required for beam loading from path length errors, turn on transients, …

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Step IV

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Cavity design and HOM damping and BBU

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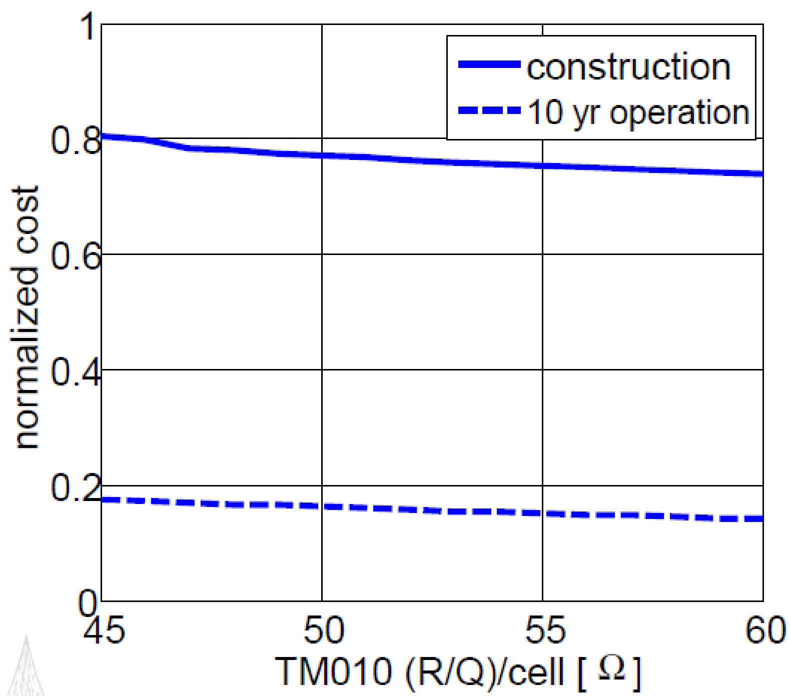
Cost vs. fundamental mode R/Q



- Cavity design should be optimized for low cryogenic losses of the fundamental mode.
- Few % decrease in (R/Q)G tolerable if modified cell shape improves HOM damping significantly

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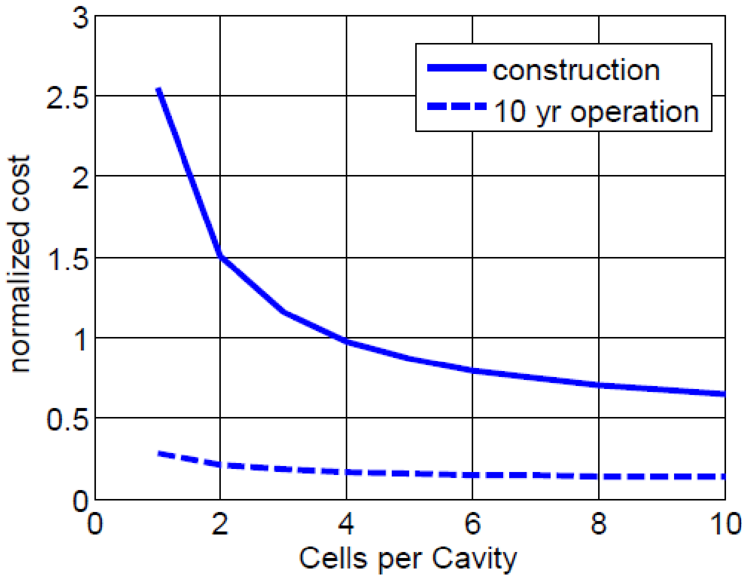
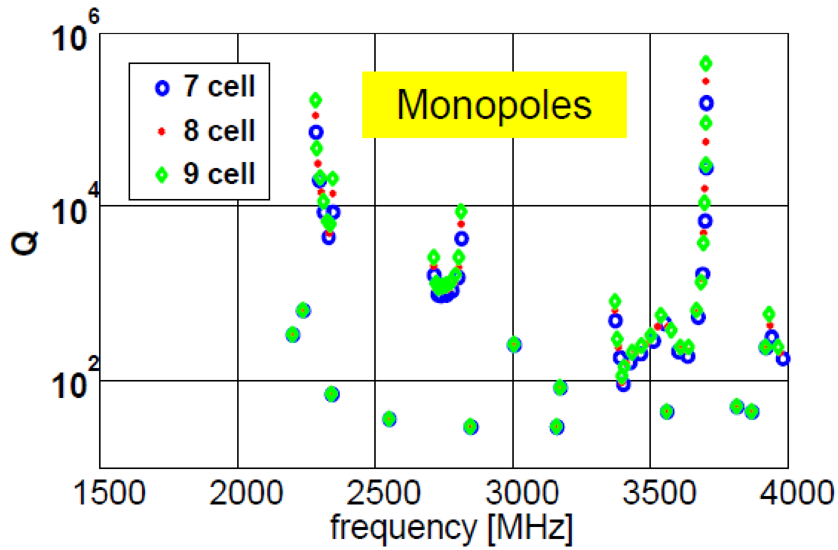
Cost vs. # of cells per cavity





- >6 cells per cavity desirable, if OK with BBU limit
  - Q and R/Q of HOMs will increase with number of cells
  - Risk of trapped modes with very high Q increases as (number of cells)^2

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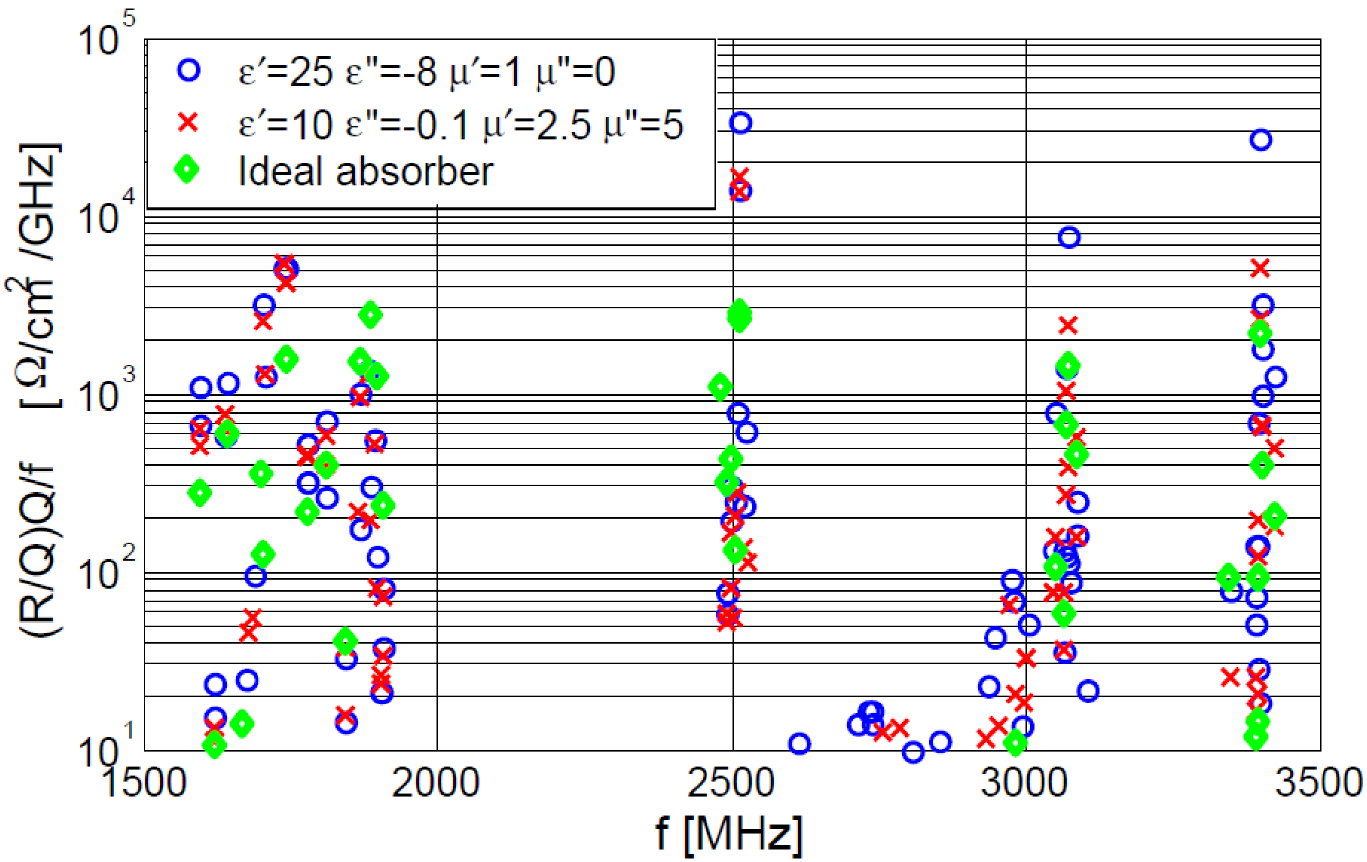
Be realistic!

- Goal of the game is to bring down the BBU figure of merit (R/Q)Q/f for the worst HOMs
  - For longer linacs: also (R/Q)G for fundamental mode important to minimize cryo-losses
- BUT:
  - **Real HOM absorber ≠ ideal absorber**
  - **Real cavity ≠ ideal cavity, as designed!**

HOM absorber: ideal vs. real



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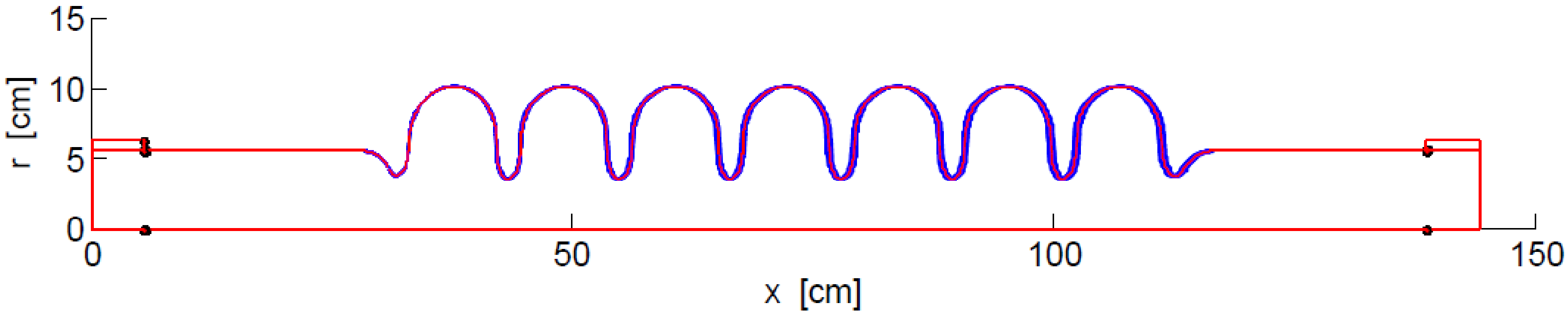
Effect of small cavity deformations

- Small cavity shape deformations introduce HOM frequency spread between cavities (good)
- But: they also influence the R/Q and Q of the HOMs (bad)!
  - Factors of 10 to 100 increases in real cavities have been observed for certain HOMs at TTF/FLASH and JLAB!
- To study this, we did set up parallel computing of HOMs in non-ideal cavities with CLANS/CLANS2 (cluster with 120 parallel processor cores)

7-cell cavities with small shape deformations

- Started by assuming +-1/16 mm **random** deformations of all cavity dimensions:



- All cavities have been re-tuned for the fundamental mode frequency and field homogeneity
- Calculated dipole modes a in large number of deformed (realistic!) cavities to be used in **realistic BBU simulations**

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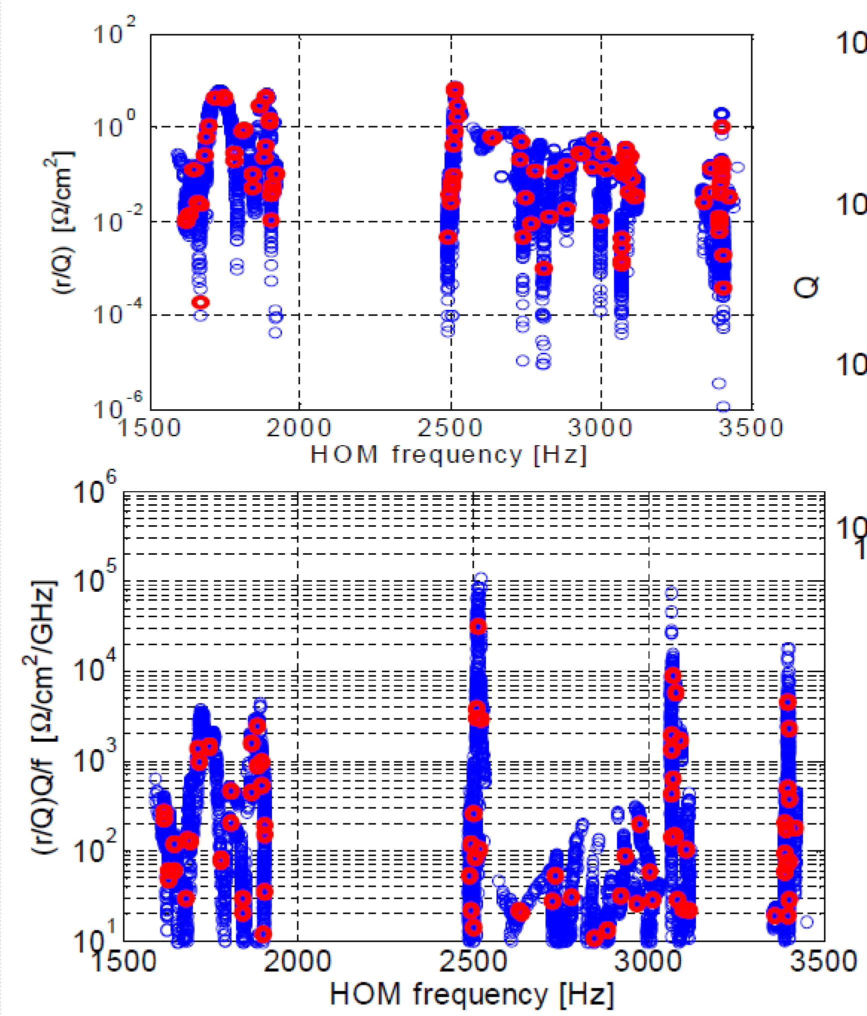
Simulation results for ±1/16 mm



Red: without deformations

Blue: with deformations (100 cavities)

⇒ Significant impact on BBU threshold current!

Conclusion for step IV

- Cost favors > 6 cells per cavity, if
  - HOM damping and BBU threshold current is sufficient
  - R/Q per cell is not lowered too much by requirement to increase iris diameter for increase cell-to-cell coupling in many-cell cavities
  - Sensitivity to small shape perturbations is under control
- Cornell ERL: **7-cell cavity with high (R/Q)G**

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Outlook

- Future might bring:
  - Higher Q_0 (R_{res}<10nΩ), lower field emission
    - $\Rightarrow$ higher optimal field gradients E_{acc}
  - New SRF cavity materials (Nb_3Sn)
    - $\Rightarrow$ higher optimal field gradients E_{acc}, higher operating temperature
  - < 5 Hz peak cavity detuning, $Q_L = 10^8$
    - $\Rightarrow$ lower RF power, simplified RF input coupler,…
  - More cells per cavity???
    - $\Rightarrow$ lower cost

None of these will happen tomorrow, though…

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What have we learned?

- Understand the large picture first!
- Machine parameters are always come first.
- All subsystems are interconnected and very often an iterative process is necessary.
- A carefully set up optimization algorithm and system model can sometimes bring unexpected results.
- It is important to be realistic: neither too pessimistic, nor too optimistic.

✪ Starting with the next lecture we will go step by step through design approaches to different components and subsystems.