WG3 Summary
（6/12のまとめから抜粋）

ERL'09
Promise for a brighter future.

Convenors:
Peter McIntosh (Daresbury)
Frank Marhauser (JLab)

Friday 12th June, 2009

2009.6.25 阪井寛志

WG3 Goals

Working group focusing on the RF/SRF developments required for prototype and full scale ERL devices.

1. What are the key SRF challenges for ERLs?
2. What solutions are being investigated and have already been developed?
3. Which components still need more R&D work?
4. Organise R&D effort, to coordinate studies and identify possible collaborations.

WG3 Topic Areas

- **RF Guns (Joint WG1)**
  - SRF and NC
- **Cryomodules**
  - Thermal Shielding
  - Magnetic Shielding
  - Microphonics Performance
  - Thermal Management
- **Cryomodule Components**
  - Cavities
  - Input Couplers
  - Tuners
  - HOM Absorbers
- **RF Control**
  - LLRF
  - HPRF
  - Optimisation and Limitations
- **HOMs and Impedance Management (Joint WG2)**
- **RF System Optimisation**
  - Gradient
  - Cryogenic Losses
  - Cost

Talk Breakdown for WG3

Scheduled

Institution	Number of Talks
AES	1
BNL	3
Cornell	5
Daresbury	2
FNAL	1
FZD	1
HZB (formerly BESSY)	1
Jlab	2
KEK	3
PKU	1
Total	**20**

11 Institutes!

Un-Scheduled

ANL	1
HZB (formerly BESSY)	1
PKU	1
Total	**23**

←

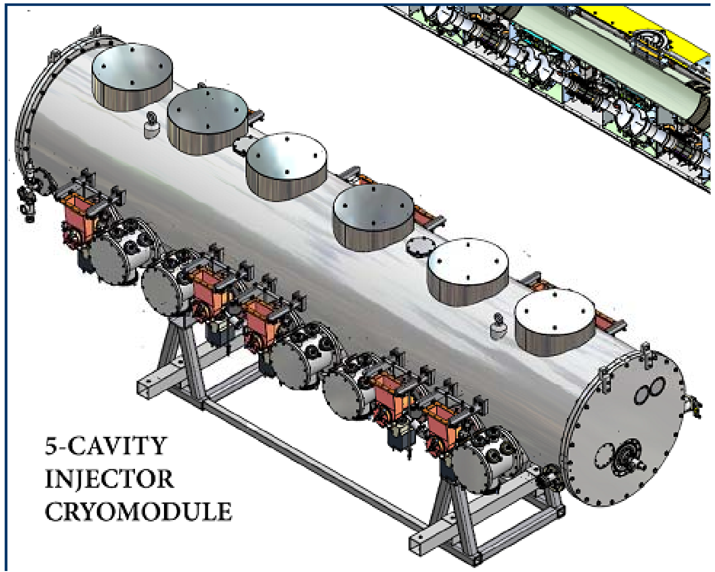
ここをもっと
多くすべき
By 阪井

Cryomodules

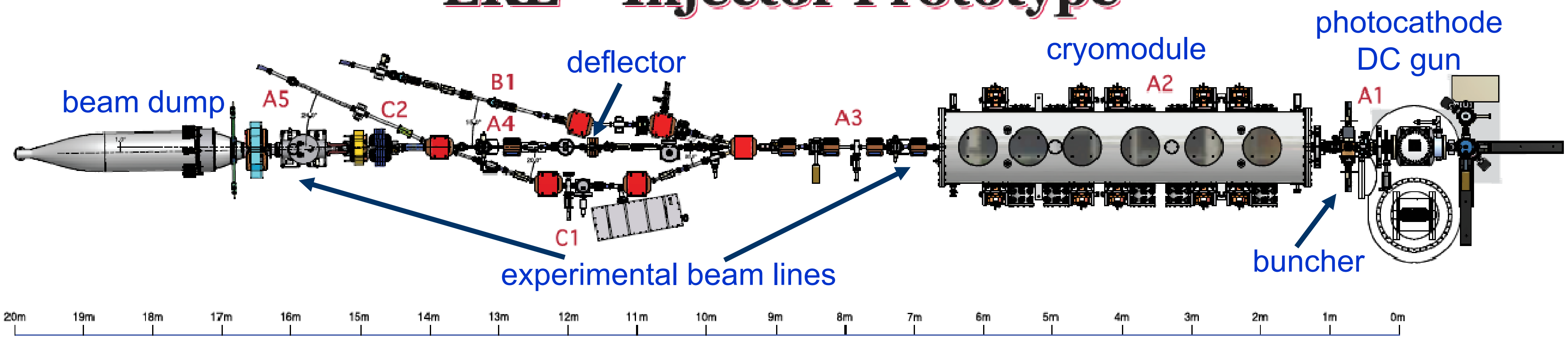
ERL'09
Promise for a brighter future.

Cornell ERL injector linac status, S Belomestnykh

- 100-mA Cornell SRF ERL injector linac commissioning progresses well.
- Comprises: NC buncher cavity, SRF accelerating cavities, NC deflecting cavity (pulsed mode). All at 1300 MHz.
- Buncher cavity processed to > 200 kV. Slow conditioning ⇒ multipacting in the narrow gap between tuner plunger and port and small vacuum leaks:
  - new tuners are ready for installation, ⇒ TiN coating
- Deflector cavity ⇒ very useful instrument for beam diagnostics.
- ICM first cooled in April of 2008, first RF turn on June, first beam in July. 4 mA average beam current achieved in December.
- After conditioning, ICM has total beam cceleration of 13.8 MV. Limited by heat flux in the chimneys at 2 K and the pump skid capacity at 1.8 K, caused by low intrinsic Q factors of all cavities.
- Concern, but not show-stopper. Cause of the low Q is still under investigation.
- Using RF and DC kicks from input couplers ⇒ residual highly non-linear magnetic field inside ICM in vicinity of cavity 3 ⇒ useful aperture extremely small. ICM was warmed up and area degaussed successfully (confirmed by beam scans).
- Future ICM work will focus on further cavity (FE) and input coupler (MP) conditioning, microphonics compensation studies, and high beam current effects.

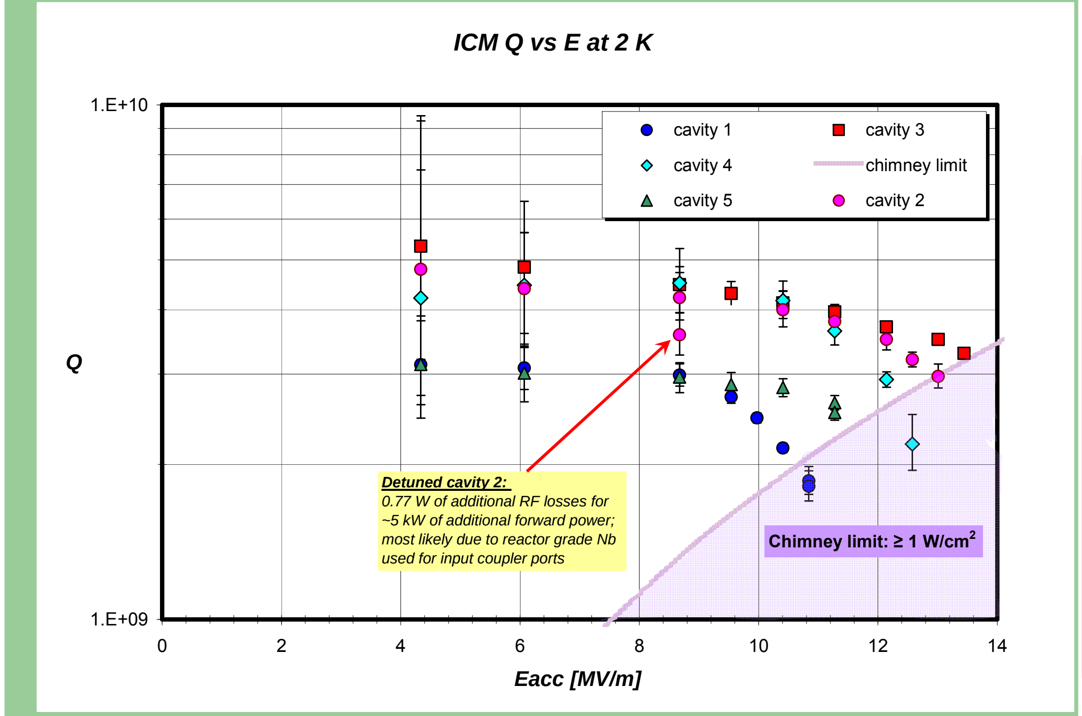

5-CAVITY
INJECTOR
CRYOMODULE

ERL – Injector Prototype



Nominal bunch charge	77 pC
Bunch repetition rate	1300 MHz
Beam power	550 kW
Nominal gun voltage	500 kV
SC linac beam energy gain	5 to 15 MeV
Beam current	100 mA at 5 MeV
	33 mA at 15 MeV
Bunch length	0.6 mm rms
Transverse emittance	< 1mm·mrad

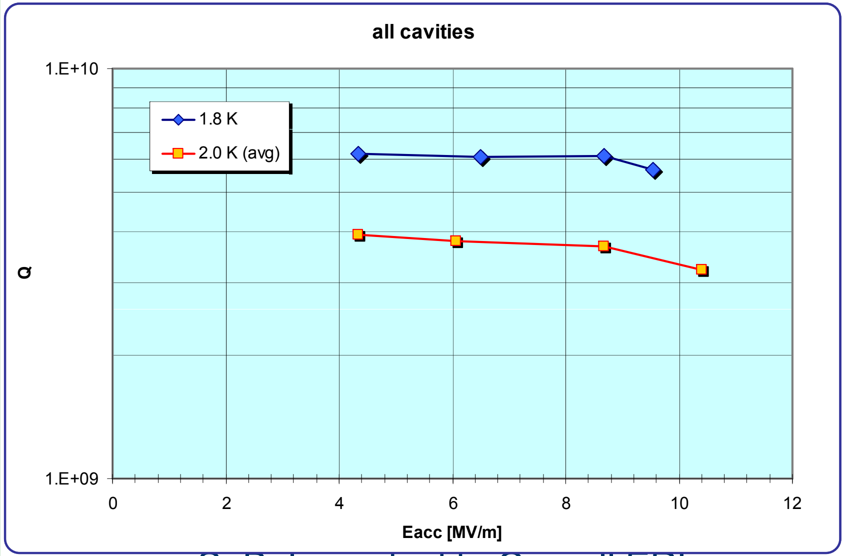
- While initial intrinsic Q was good, it degraded over time.
- Field emission at higher Eacc. Plan to do pulse processing to reduce field emission.
- Voltage limit is due to the chimney heat flux transfer at 2 K.
- At the moment the ultimate ICM accelerating voltage limit is determined by the chimneys and is 13.8 MV for 2 K operation, close to the maximum specification of 15 MV.
- The limit at 1.8 K (slightly lower than at 2 K) is due to heat removal capacity of cryogenic system.
- Cavities at the ICM ends have lower Q.

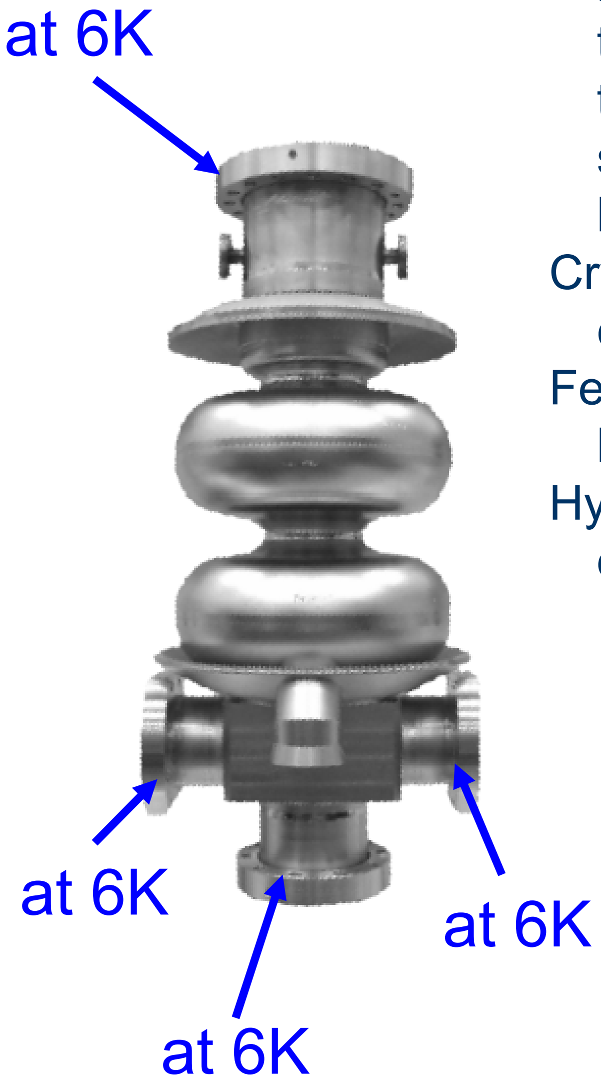


Detuned cavity 2:
0.77 W of additional RF losses for ~5 kW of additional forward power; most likely due to reactor grade Nb used for input coupler ports

Chimney limit: ≥ 1 W/cm^2

Q degradation over





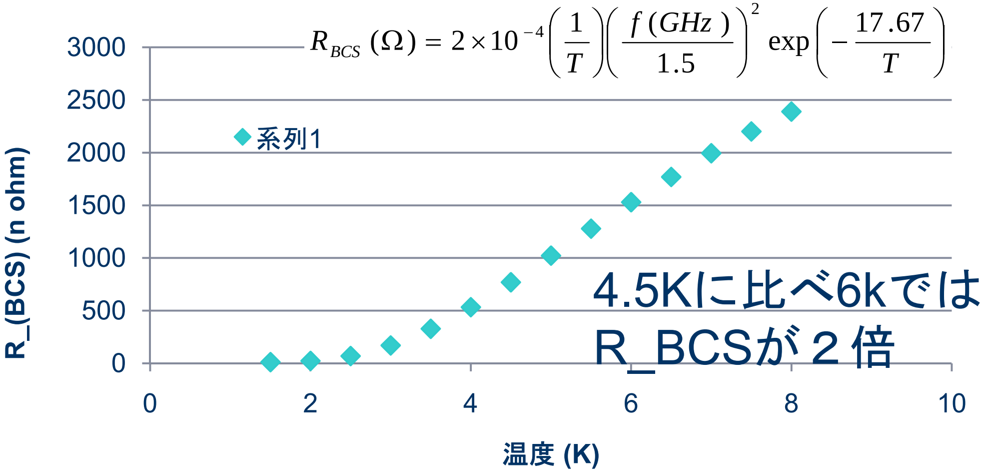
Possible reasons:

Simulations and measurements indicate that losses in the beam tube and coupler regions contribute significantly to the overall dynamic cavity losses. Cavity flanges are thermally anchored to a "4.5 K" cooling circuit, but: "4.5 K" system is actually at 6 K ⇒ increased BSC resistance in beam tube sections ($R_{\mathrm{BCS}} \propto \exp(T)$).

Cryopumping of residual gases: degradation over time, end cavities have lower *Q* factors.

Ferrite dust contamination. Was observed during HTC test, but lower Q than in the ICM.

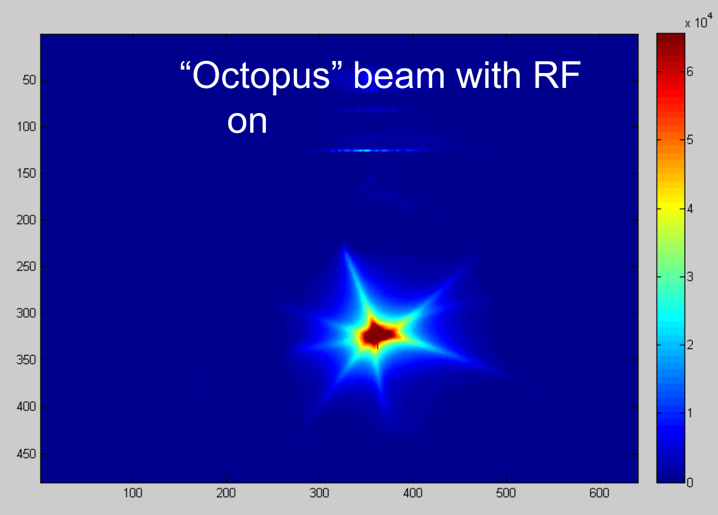
Hydrogen *Q*-disease: unlikely as 2 cavities were checked during vertical tests and no sign of this was found.



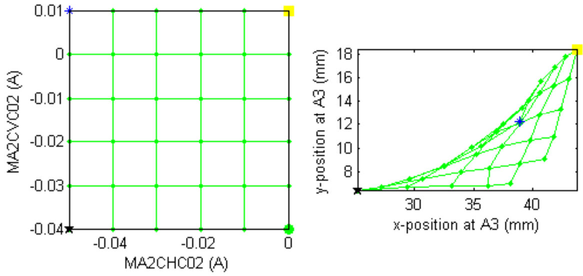
$$R_{BCS}(\Omega) = 2\times 10^{-4}\left(\frac{1}{T}\right)\left(\frac{f\,(GHz)}{1.5}\right)^{2}\exp\left(-\frac{17.67}{T}\right)$$

4.5Kに比べ6kでは
R_BCSが２倍

- Beam studies with and w/o RF indicated that there are remnant magnetic fields inside the ICM. "Pincushion" scans using corrector magnets inside the ICM proved very useful.
- Investigated different sources of magnetic field outside the cryomodule: shielded cold cathode gauges, no effect from ion pump magnets, put mu-metal dome on top of the ICS and narrow shield around the upstream end cylindrical surface, iron shields at cavity 2 input couplers.
- Improvements were marginal at best.
- Conclusion: the residual field is inside the ICM.
- As there is no BPMs inside the cryomodule, decided to use input couplers as "poor man" BPMs.
- Studied beam deflection with RF & DC coupler kicks, the orbit is straight in vertical plane, but has "banana" shape in horizontal plane.
- Also, the orbit indicates that the parasitic field is in the vicinity of the cavity 3 couplers.


"Octopus" beam with RF on

pincushion scan indicating bad field inside ICM

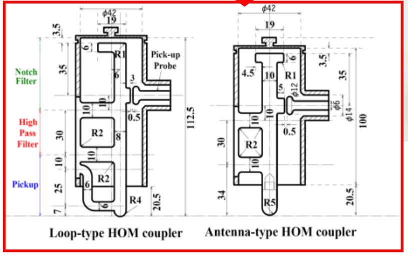


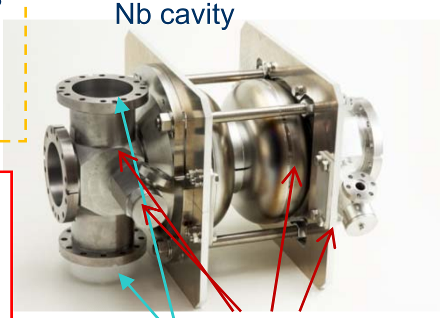
KEK ERL cryomodule development H Sakai

Target : 100mA cw operation for (compact) ERL

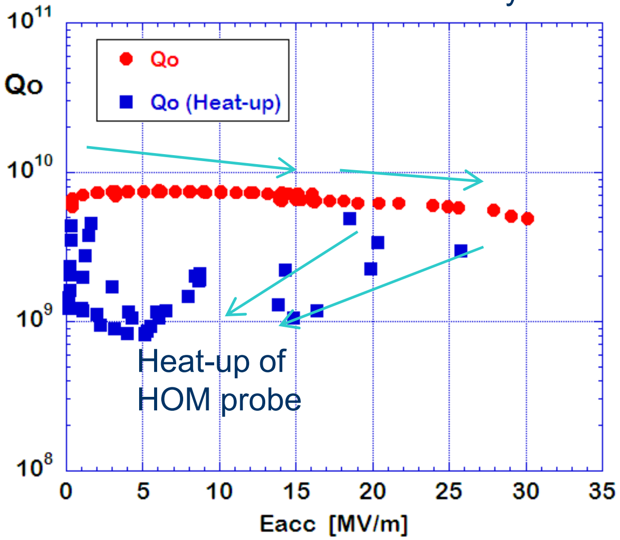
Injector SC

design
- 1.3GHz 2cell - 3cavities
- 14.7MV/m
- 167 kW / coupler
- modified HOM coupler





Results of vertical test of ERL 2cell cavity

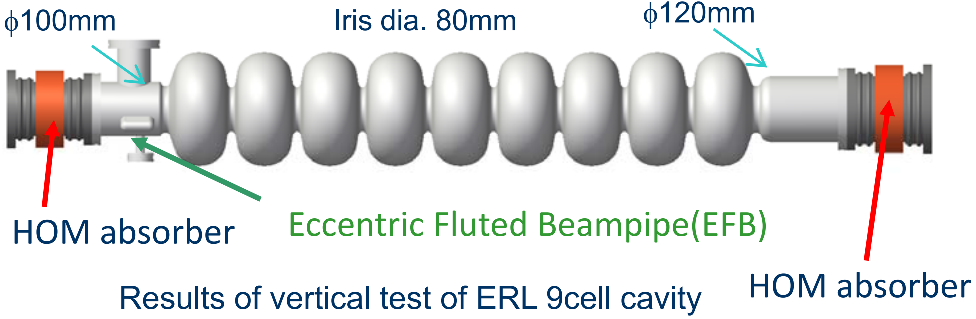


- Achieve 30MV/m for a short second
- Keep 15MV/m for 8 hours
- Heat-up of probe of HOM coupler is problem
- Assembly of cryomodule is scheduled in 2011

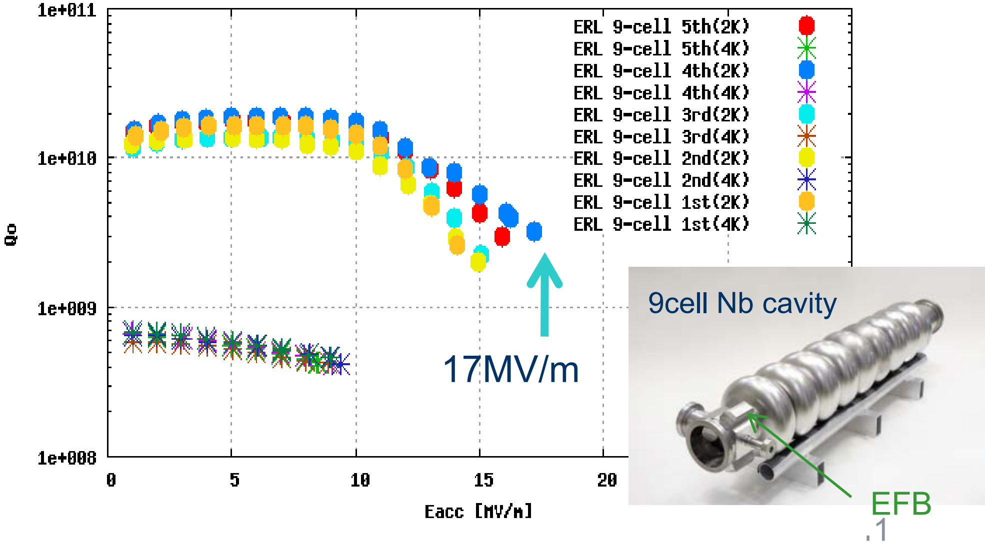
Main linac SC

design
- 1.3GHz 9cell
- 15-20MV/m
- Qo > 10^10
- 20kW power

Points
1) Large beampipe + HOM absorbers
2) Optimize cell shape → HOM-BBU up-to 600mA
3) EFB for extracting Quad HOMs



Results of vertical test of ERL 9cell cavity



- Maximum field is 17MV/m on 5 times VT.
- Field emission was started above 10MV/m.
- Assembly of cryomodule is scheduled in 2012

BNL ERL Cryomodule Testing Status, A Burrill

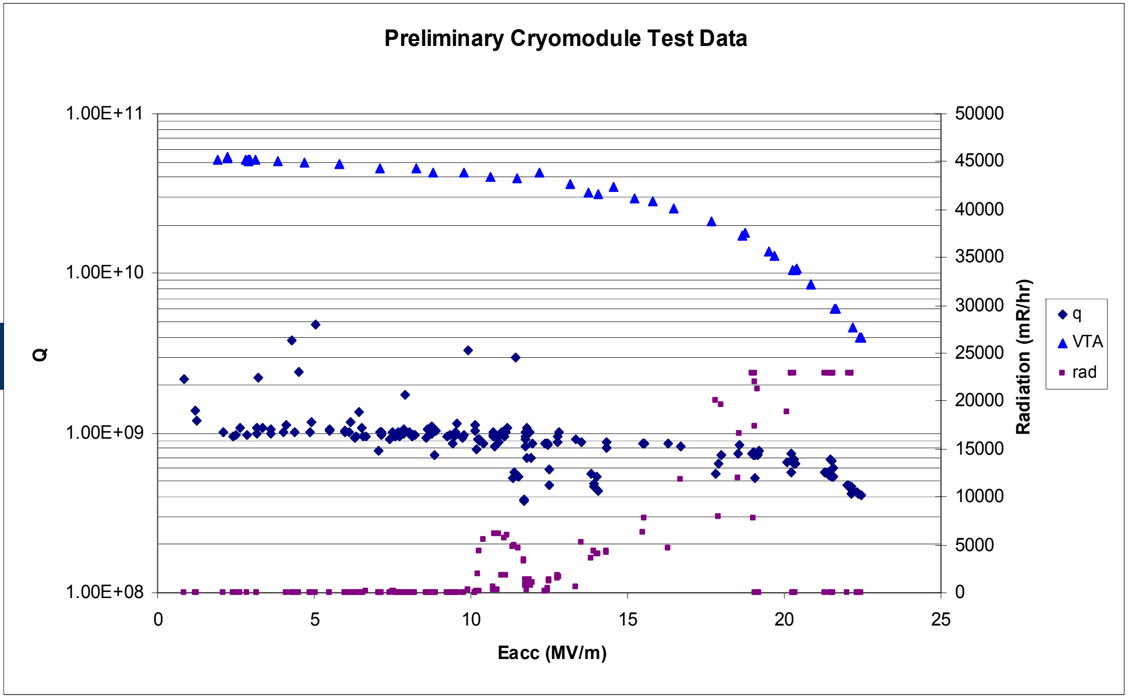
- 703 MHz, 5 cell LINAC cavity with 24 cm diameter beampipes employing ferrite HOM absorbers
- VTA measurements of 20 MV/m at Q = $1x10^{10}$
- Preliminary cryomodule testing underway to reproduce VTA results
- FPC re-conditioned with no vacuum or arcing events.
- RF and cryo systems work as designed, preliminary tests have given us new things to work on.

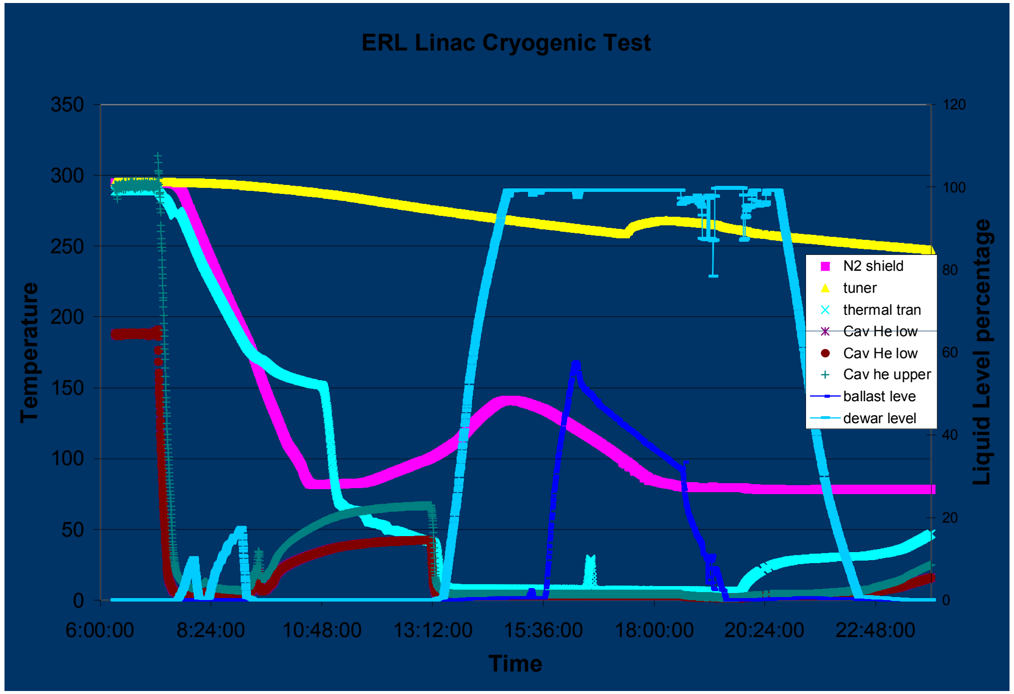
Testing Summary

- Overall test was a success!
  - Cavity gradient measured using pick-up probe
  - Q calculated using Ploss

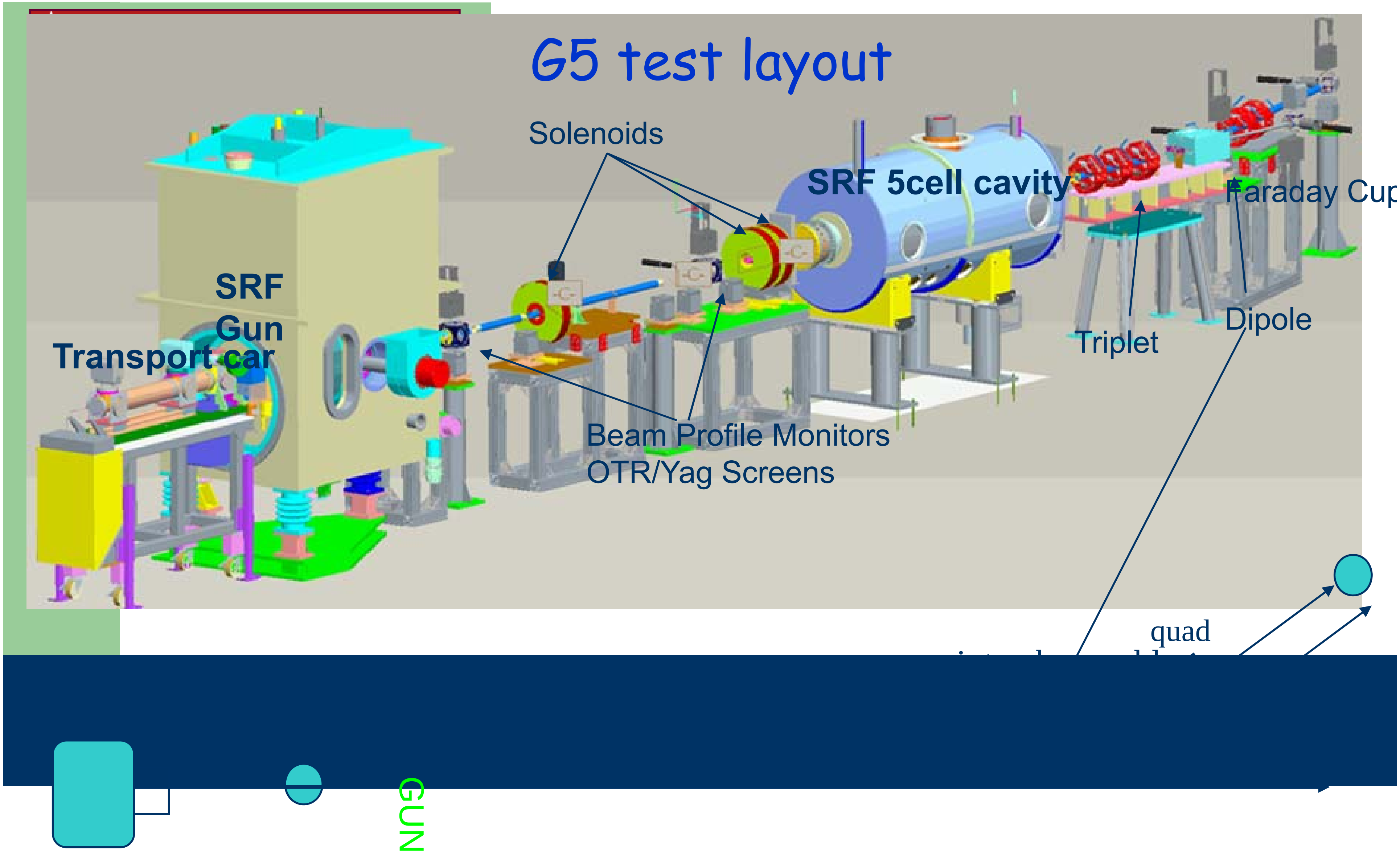
Ploss = Pi-Pr-Pt

  - Next test will use calorimetric Ploss
  - Multipacting barrier at 10-12 MV/m
  - Significant Field emission
  - Testing limited by LHe available



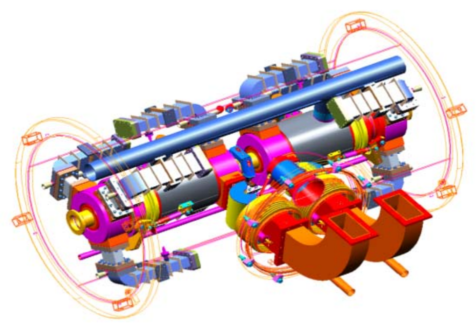


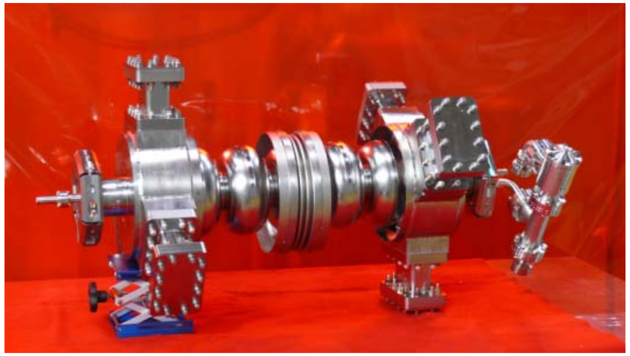
G5 test layout

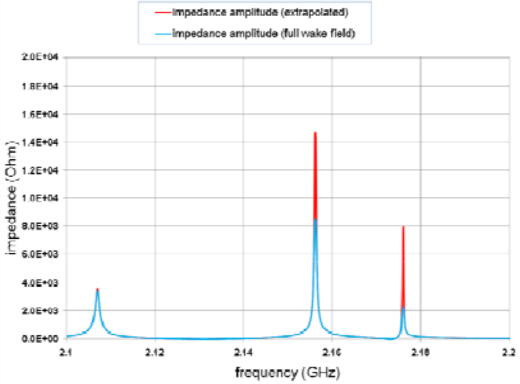


JLAB HC CM Development, F. Marhauser

- Very compact Ampere-class CM developed at < 1GHz and 1.3-1.5 GHz.
- First 2 Nb cavity prototypes (1.5 GHz) with waveguide endgroups exceeded goal of 16.7 MV/m CW at Qo=8e9 in VTA (one limited ~24 MV/m by available power, one quench limited ~19 MV/m (with 4” Nb extensions), no mulpipacting seen in cavities/waveguides.
- Design is different from conventional ERL cavities by relying on the benefits of waveguide and input power couplers rather than HOM beam tube loads and coaxial coupler.
- Benefits are:
  - HOM damping efficiency is very efficient with 6 waveguides (simulated and measured)
  - Warm RF window (based on PEP-II design) can handle very large power (1MW CW @ LEDA)
  - Warm HOM loads warm designed to handle kW of HOM load power
  - Challenges: FPC warm-to-cold transition needs to be optimized thoroughly to limit 2K heat leak
- New **full spectrum extrapolation scheme** presented, which can forecast the fully resolved impedance spectrum of cavities (very high Q SRF cavities) in time domain speeding up cavity optimization/analysis process (by weeks or even months!).

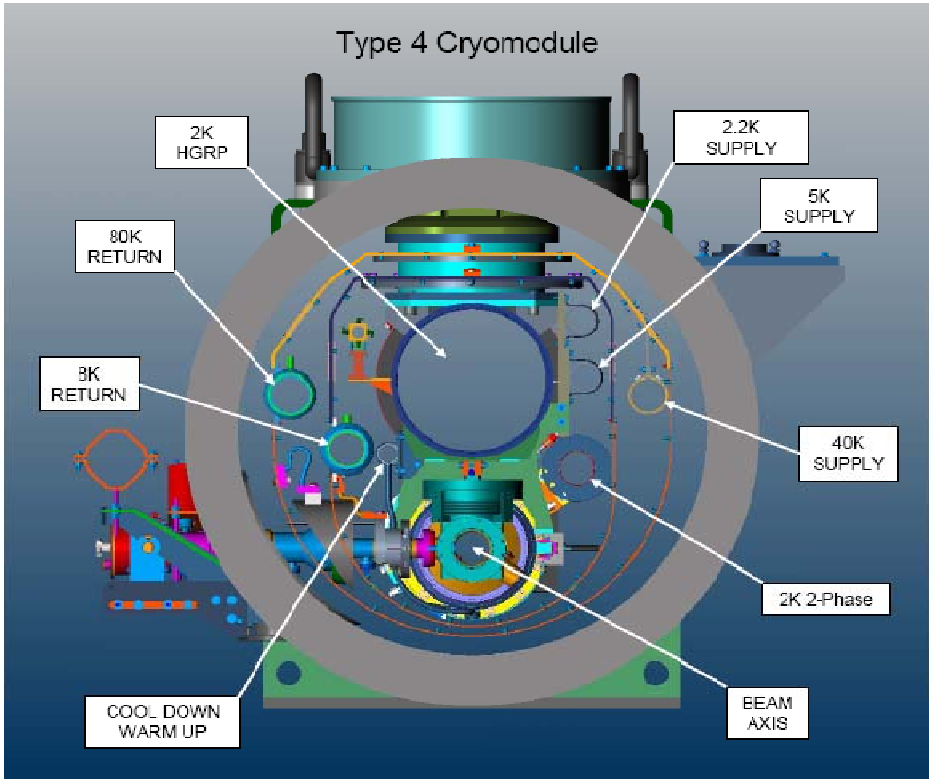

Conceptual design of a cavity-pair injector cryomodule (1497 MHz, L=2.6m)


Prototype 1497 MHz cavity with endgroups



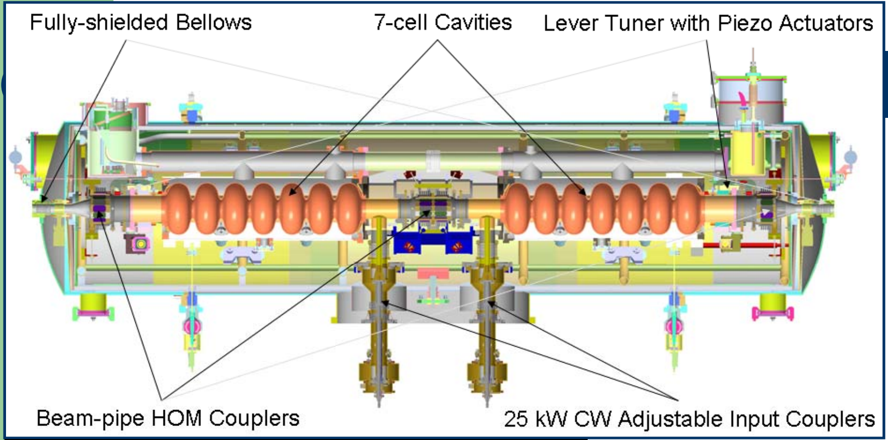
Impedance Spectrum Extrapolation Method

Type 4 Crymodule (T4CM), A Hocker



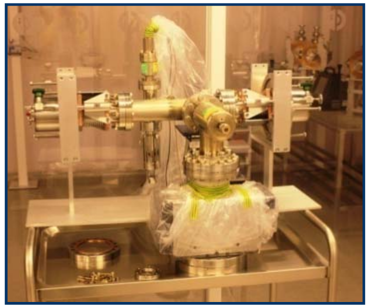
- Next step in evolution of TTF/XFEL cryomodule
- Magnet/BPM package moved from end to middle of CM
  - Directly under center support post for more stability
- Intended as a CM for large-scale HEP machine (ILC, Project-X, etc.)
  - High gradient, high packing factor, low RF duty factor
  - Dynamic heat load much less than typical ERL CM
- First T4CM to be built at FNAL in 2010, cooldown in 2011

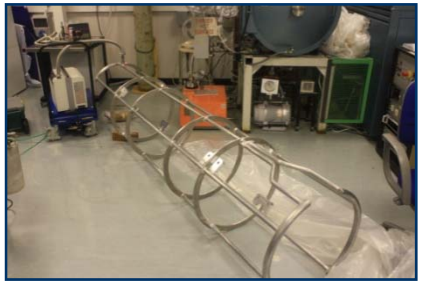
ERL CM Collaboration Update, P McIntosh

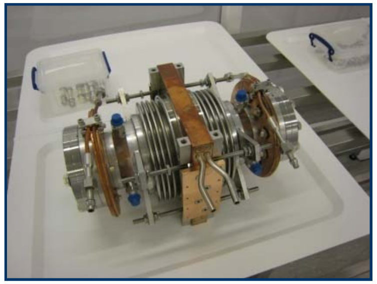


- Collaboration initiated early 2006:
  - Daresbury Lab
  - Stanford and Cornell Universities
  - LBNL
  - DESY
  - FZD Rossendorf
- New CM to be installed on ALICE for beam evaluation May 2010.

Parameter	Value
Frequency (GHz)	1.3
Number of Cavities	2
Number of Cells per Cavity	7
Cryomodule Length (m)	3.6
R/Q (Ω)	762
E_{acc} (MV/m)	> 20
E_{pk}/E_{acc}	2.23
H_{pk}/E_{acc} (Oe/MV/m)	46.9
CM Energy Gain (MeV)	> 32
Q_o	$>1 \times 10^{10}$
Q_{ext}	$4 \times 10^6 - 10^8$
Maximum Beam Current	100 mA
Max. Cavity Forward Power (kW)	25 SW





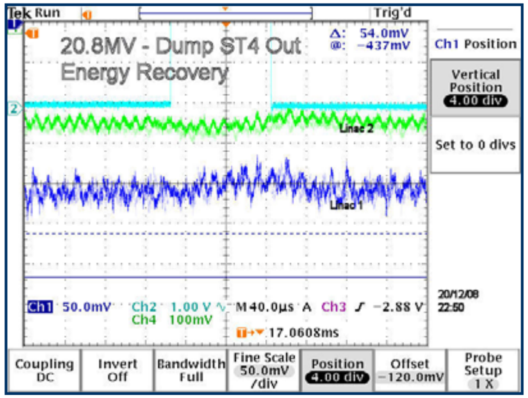


ERL Operation and RF Control

ERL'09
Promise for a brighter future.

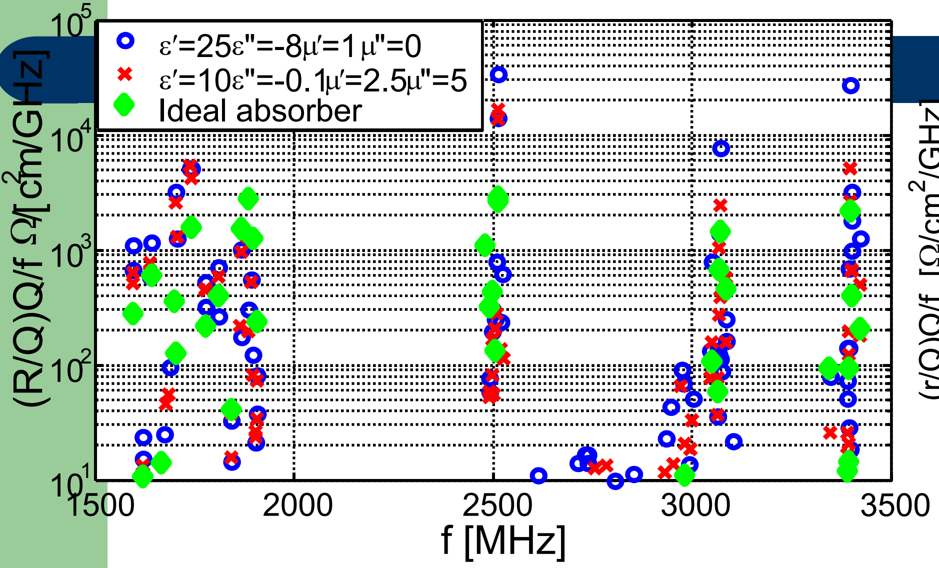
ALICE SRF Commissioning, A Wheelhouse

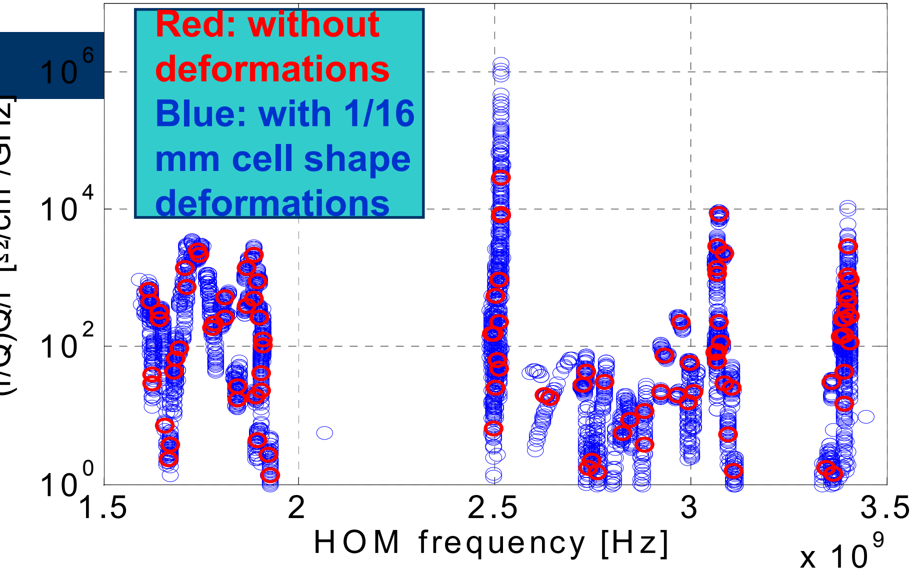
- SRF Commissioning:
  - Cavity Eacc reduction seen when tested at Daresbury c.f. DESY VTA tests.
  - FE radiation from ERL CM required introduction of lead wall:
  - LLRF electronic life extended from 1000hrs to 10,000hrs
  - Poor ancillary HVPS reliability resolved:
  - Future designs to ensure that the RF power sources are located with the HVPS
  - Beam loading effects resolved at low bunch charge levels by reducing Qext
  - Energy recovery achieved at 20.8MeV in December 2008
- Future Plans
  - Further investigations of Q0 v's Eacc ⇨ He processing of cavities
  - Further investigation of beam loading required for higher bunch charge and long pulse train lengths
  - Reduce Qext further
  - Improve LLRF response time
  - Investigate feed-forward
- Installation of new 7-cell linac cryomodule in May 2010



Cornell ERL Main Linac and LLRF Control, M Liepe

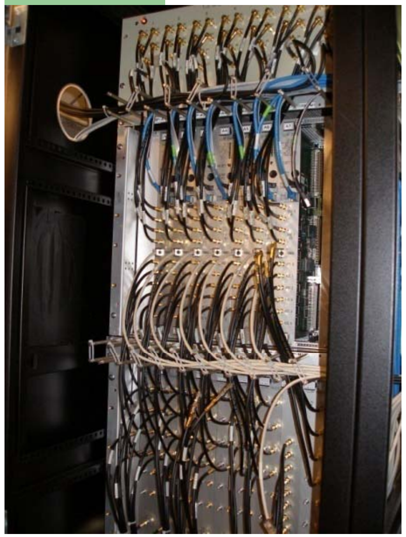
Real HOM absorber ≠ ideal absorber; Real cavity ≠ ideal cavity, as designed!



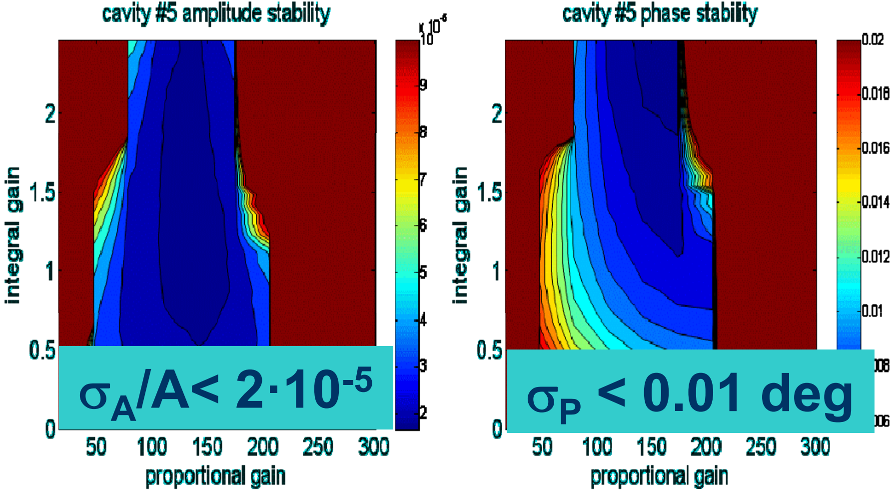


Red: without deformations

Blue: with 1/16 mm cell shape deformations



Cornell LLRF System



$\sigma_A/A < 2\cdot10^{-5}$

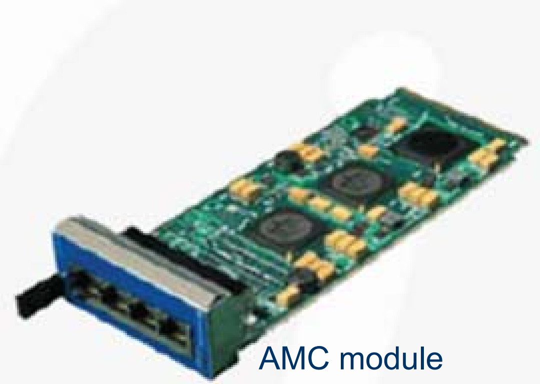
$\sigma_P < 0.01$ deg

Demonstrated:

- **Exceptional field stability at $Q_L = 10^6$ to 10^8**
- **Lorentz-force compensation and fast field ramp up**
- **Piezo microphonics compensation with ~20 Hz bandwidth**

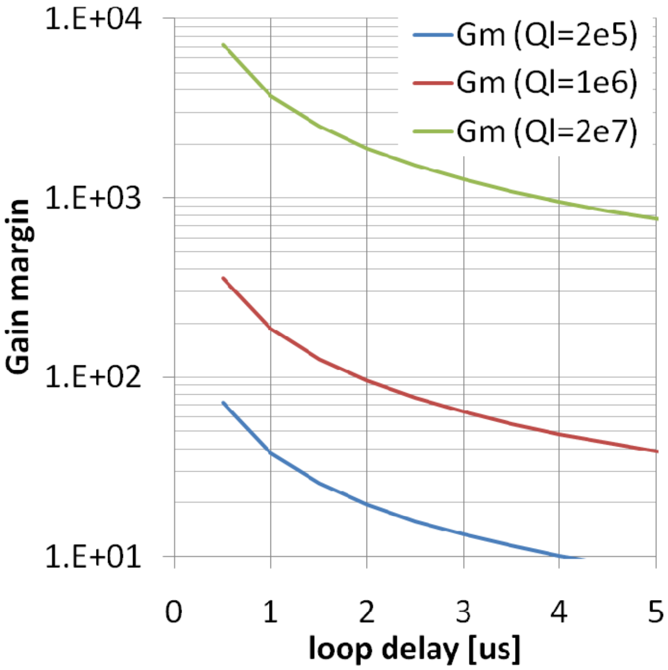
HLRF/LLRF for cERL@KEK, S MICHIZONO

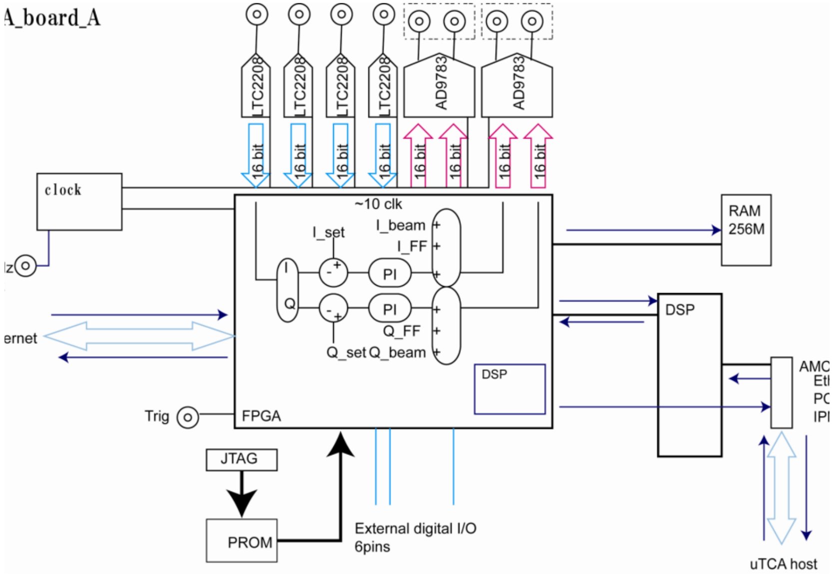
- 30/300kW Klystrons plus 30kW IOTs will be used at cERL.
- New custom FPGA board for LLRF developed based on uTCA (AMC module).



AMC module

30 kW klystron:
E3750 by Toshiba
~55%efficiency



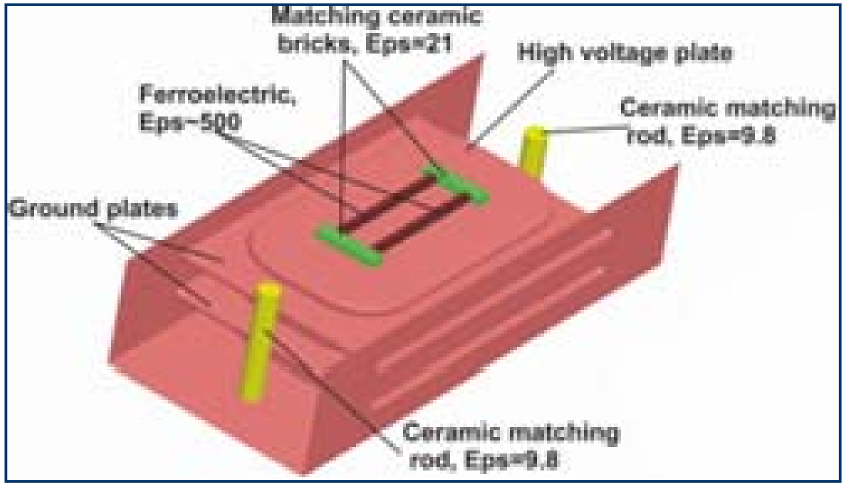


Custom FPGA board having four 16bit ADCs and four 16bit DACs with Virtex5.

Fast Ferroelectric Phase Shifter Design for ERLs, S Shchelkunov

- For ERLs, if beam loading is small:
    - RF power requirements determined by
        - 1) ohmic losses in walls,
        - 2) imbalance between the beam currents
        - 3) microphonics
        - each may require change in coupling between the cavity and feed line, typically results in bandwidth growth, and more power.
- If the beam loading is not small:
    - there are "beam-driven" phase instabilities;
    - the microphonics still are an issue;
    - thus again, there is requirement for more RF power.

- Phase shifters based on BST ceramic with eps ~500, that changes its dielectric constant with <50kV/cm external bias.
- Samples developed so far have shown fast switching (intrinsic time < 10 ns).
- 3 designs described for L-band, out of which 1) the planar-coax design is attractive, but the problem of parasitic modes must be addressed; and 2) sandwich-in-waveguide design was successfully built and "cold" tested.



HOM Management
(Joint WG2)

ERL'09

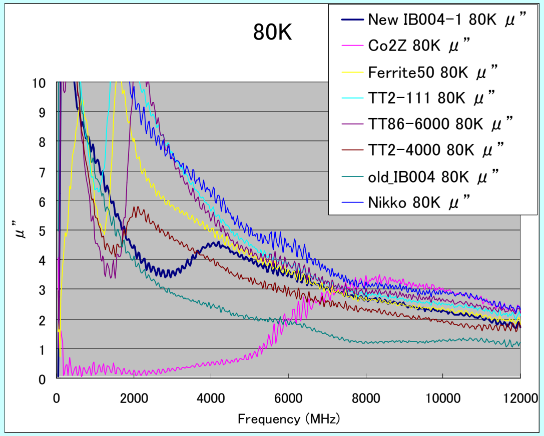
Promise for a brighter future.

KEK ERL HOM Absorber Development, M Sawamura

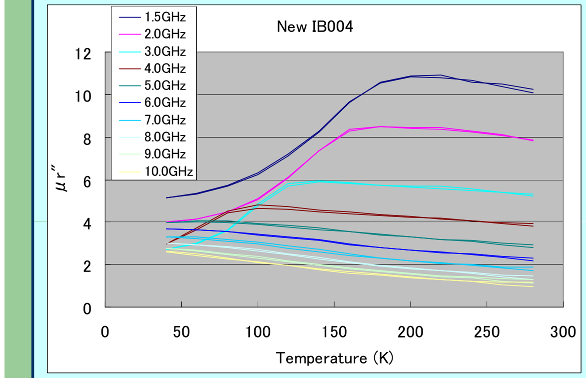
Measurement

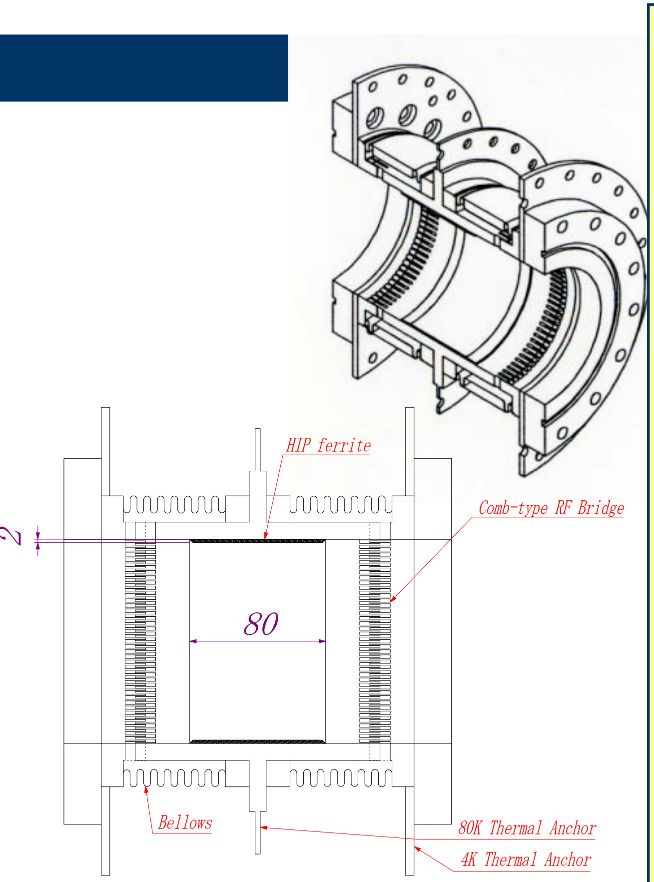
Ferrite properties (μ)

Frequency dependence



Temperature dependence

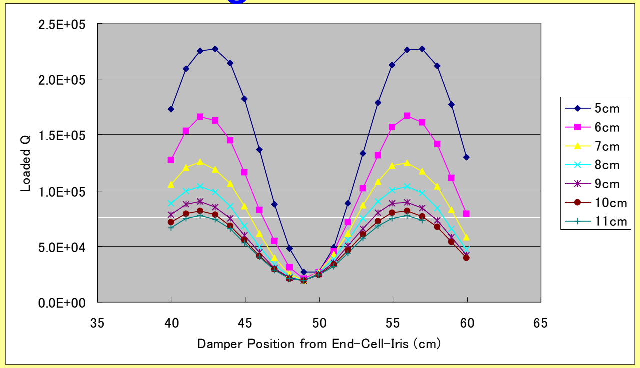




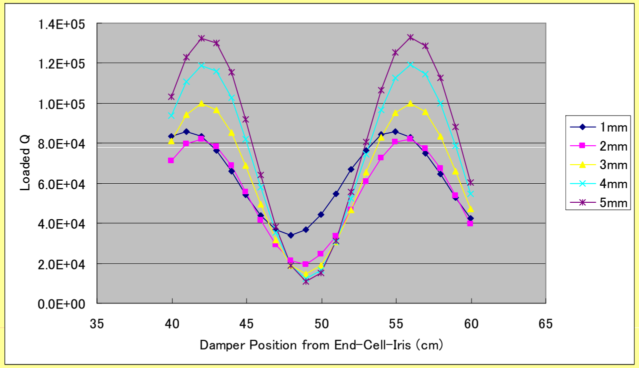
Calculation

Optimization of ferrite condition

Ferrite length



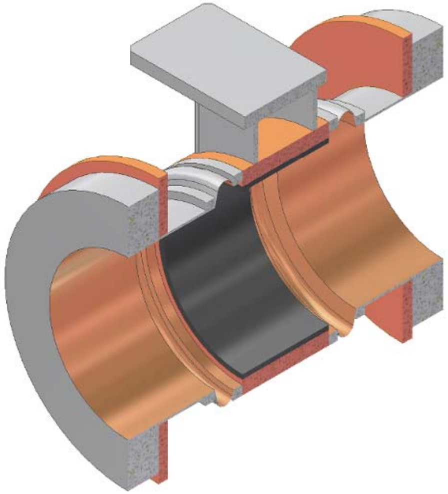
Ferrite thickness



- **HOM absorber model under design**
  - **HIP ferrite of new-type IB004**
    - Firm bonding between ferrite and copper
  - **Comb-type RF bridge**
    - Lower impedance and lower thermal conductance than finger-type

HOM Absorber Development for Cornell ERL Cryomodules, E Chojnacki

- A high bandwidth (1GHz – 100GHz) beamline HOM absorber is likely necessary for ERL BBU control.
- The Cornell ERL Injector load using 3 types of absorbing tiles can be modified to satisfy HOM absorption reliably.
- A simpler, lower cost beamline load using a unitary absorbing cylinder is still desirable, being developed at Cornell, DESY, KEK, BNL, and elsewhere.
- Carbon nanotube doping of ceramics may be the material to provide broadband loss at cryogenic temperatures.



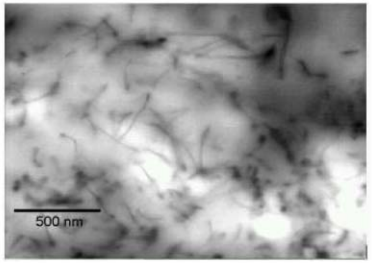
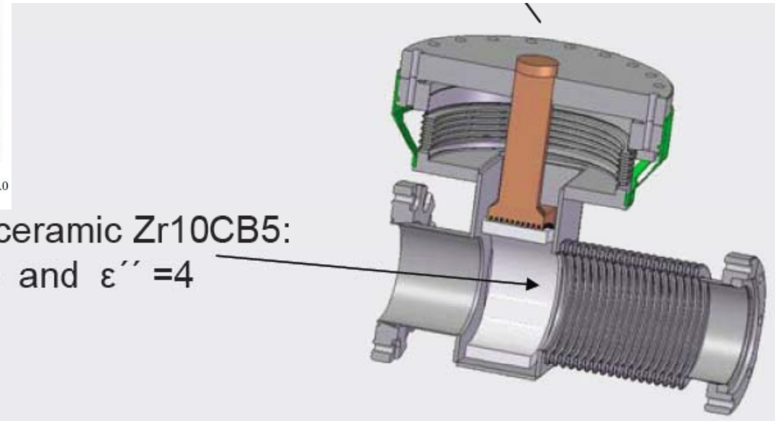
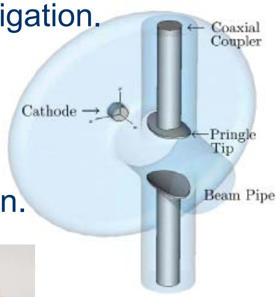


Fig. 10. TEM micrograph for the PCL nanocomposite containing 1.0 weight % of CNTs.

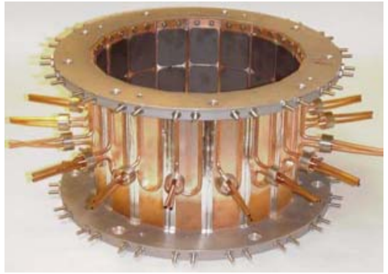


HOM Absorber Development for BNL ERL CMs, L Hammons

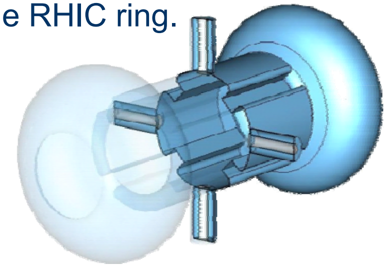
- Development of effective HOM absorbers crucial for R&D effort in three basic areas:
  - Prototype ERL facility
  - Coherent Electron Cooling experiments (CEC)
  - Medium energy electron-ion collider (MeRHIC)
  - Each of above have high-current, high-charge requirements and therefore require HOM mitigation.
- Prototype ERL facility is testbed for technology to support CEC and MeRHIC:
  - Features ceramic/ferrite loaded beamline HOM load for ½-cell SRF gun.
    - Ceramic break can be operated at nitrogen temperatures and serves as effective thermal transition.
    - Break can also protect superconducting structure from potential damage to ferrite tiles.
  - HOM mitigation through fundamental power coupler ports also found to extract HOMs in gun.
  - Facility also features ferrite HOM loads for five-cell RF cavity.



- 5-cell ERL cavity tested at room/SC temperatures and dipole passbands at 0.8 – 1 GHz and 1.6 – 1.8 GHz have been measured. Modes have also been simulated using MWS.



- Work commenced to develop damping concepts for MeRHIC:
  - Closely spaced RF cavities in highly modular CMs accommodated in a portion of the RHIC ring.
  - Project requires very compact damping structures.
    - Ferrite HOM loads
    - Loops and probes between RF cavities and inserted into existing ports in the RF cavity
    - Exponential pickup electrodes (similar to BPM electrodes)
    - Cloverleaf-shaped waveguides with coaxial pickups between cavities



Crymodule Components

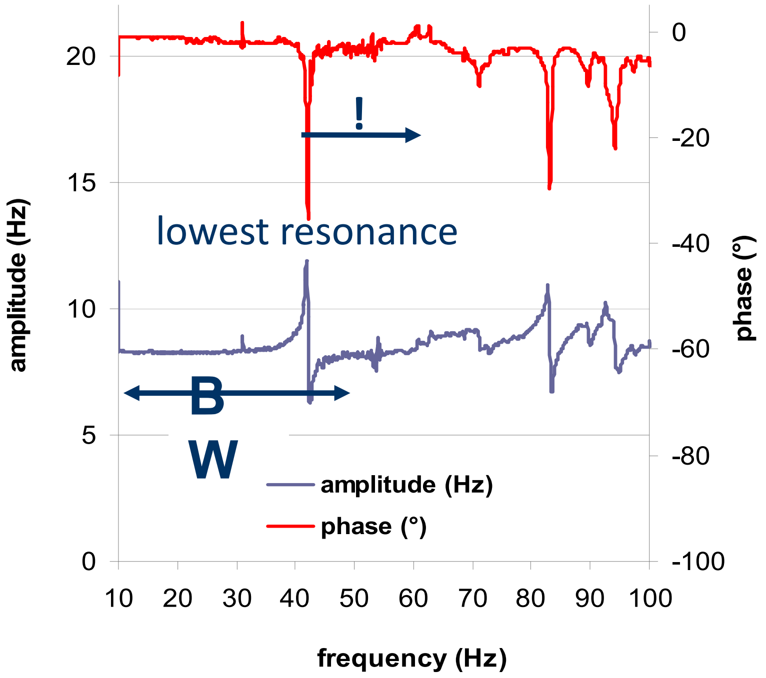
ERL'09

Promise for a brighter future.

Cavity Tuners, O Kugeler

- Combined cold stepper motor and piezo tuner is the tuner of choice for ERL machines, but:
- Most piezo tuners developed for pulsed operation!
- What could be improved in a **CW-only** tuner?
  - Stiffness (group delay) crucial for microphonics compensation
  - Sacrifice tuning range for stiffness: use shorter piezos
  - Shorter piezos also reduce hysteresis effects
  - Use high voltage piezos for stiffness
  - Use multiple piezos
  - Increase cavity wallsize to increase frequency of lowest tuner resonance
  - Improve stability of microphonics compensation algorithms
  - Incorporate piezo hysteresis into compensation algorithm in order to effectively increase piezo resolution
  - Use bipolar power supplies (and increase mechanical pre-stress on piezo)
  - Increase cavity stiffness to increase frequency of lowest resonance

Group delay $\tau = \dfrac{d\varphi}{d\omega}$



Transfer function of Saclay I tuner

Addressing SRF Input Coupler Design Challenges, V Veshcherevich

- Many couplers have been designed for different ERL cryomodules.
- Coaxial and waveguide couplers are predominantly used.
- Many coaxial coupler designs based on a few existing designs (TTF-III, TRISTAN coupler) though often with necessary upgrades or modifications.
- Coaxial couplers can be built with additional cold windows which give some advantages but make couplers more complex and expensive:
  - Cold windows cannot be used for very high power applications.
- Variable coupling leads to additional complexity. It may be used in machines built for accelerator research purposes. Not needed for user facility!
- Injector couplers are most challenging, ⇒ high power requirements.
- Problems with low energy beam motion ⇒ couplers should be placed symmetrically (in pairs) or compensating stubs should be used.
- Main linac couplers much easier to build ⇒ lower power:
  - Design should be cost efficient for multi-GeV ERL machines.

SRF Guns (Joint WG1)

WG1関係なのでここは飛ばします。

ERL'09
Promise for a brighter future.

Key WG3 Discussion Issues 1 (ここからはconvenerの私見)

- Cryomodules:
  - Many cavities showing low Qo performance, why?
    - Cornell (6e9 @ 8 MV/m) 2-cell – problem not yet identified
    - BNL (6e8 @ 20 MV/m) 5-cell – multipacting observed
    - KEK (5e9 @30 MV/m) 2-cell -- heating of HOM coupler probe above 16MV/m
    - KEK (3e9 @17 MV/m) 9-cell – limited by field emission
    - Are the large iris's causing a systematic problem for these ERL cavities?
    - Or is it ferrite contamination from the HOM absorbers?
      - Lively discussion, but no real conclusion!
  - L-band 9-cells vs 7-cells? Decided by assessment of:
    - Trapped HOMs
    - Peak surface fields
- Tuners:
  - Cold vs Warm tuner motors:
    - Cold:
      - Takes ~ 1 week to replace
      - Heat from motor needs to be dissipated inside CM
      - TTF show good reliability, need to gather more statistics!
    - Warm:
      - Motor costs are large
      - Warm piezos difficult to utilise for microphonics compensation
      - Easy access for replacement
      - Requires additional warm-cold transition

Key WG3 Discussion Issues 2

- Input Couplers:
  - Waveguide vs Coax?
    - L-band CW coax limit ~ 100 kW (injector issue)
    - Waveguide can deliver much higher CW power
    - Choice does not appear to be technically based, more driven by previous experience
    - Waveguide solution can remove the cold window
  - Cold vs Warm windows?
    - Cold coax window used to heat sink centre coax, main advantage.
    - No direct beam line of sight for cold coax window.
    - Dog-leg for waveguide can remove line of sight problem.
    - Multipacting controlled by bias for coax, however no problems observed for waveguide (JLab).
  - Adjustability not necessary for user facility, can be achieved externally over a wide range (>10 demonstrated) for both coax/wg

Key WG3 Discussion Issues 3

- HOM management:
  - If using beam-pipe absorbers, do we need loop couplers also?
    - Multipacting problems experienced with loop couplers.
    - Excessive fundamental power heating of probe.
  - How can we mitigate possible ferrite contamination?
    - Vendor coating of the material
    - Shield ferrites in beam-pipe with a ceramic tube
    - New materials being investigated
    - Variability in ferrite material requires tighter control
- RF Guns:
  - Problem calculating HOM power damping requirements
  - Would like BBU calculations performed, taking into account beam velocity change
  - Similar Qo degradation observed at ELBE, fabrication issues

WG2 SRF Worked Example Request

- Asked to evaluate SRF system requirements for:
  - 7 GeV ERL
  - Operating at 1.3 GHz
  - 20 MV/m
  - 100 mA beam current

ＷＧ３でdiscussionに時間を割いて行った議論。
Case study

Worked Example

	Parameter	Units	Pessimistic Value	Optimistic Value
10 MeV Injector (Cornell ICM)	Injector RF Power	kW	1000	1000
	Injector Cryo Heat Load	W	40	40
ERL	Eacc	MV/m	20	**16**
	Operating Temperature	K	2	**1.8**
	Qo		1.00E+10	**2.00E+10**
	Peak Microphonics	Hz	20	**10**
	Qe (Perfect ER)		3.30E+07	6.50E+07
	RF Power per Cavity (Perfect ER)	kW	6.4	2
	Pdiss per cavity	W	41.6	13.3
	Static Load per Cavity	W	2	**1**
	Second Pass Phase	Deg	**179.8**	**179.95**
	Qe (Imperfect ER)		2.10E+07	4.80E+07
	RF Power per Cavity (Imperfect ER)	kW	10	2.8
	Total Number of Cavities		337	421
	RF Power Overhead	%	25	10
	ERL RF Power (Perfect ER)	kW	2699	950
	ERL RF Power (Imperfect ER)	kW	4229	1286
	ERL Cryo Power	kW	14.7	6.0
Total	Total Dynamic Load	kW	14.1	5.7
	Total Static Load	kW	0.7	0.4
	Cryo Safety Factor	%	50	50
	Cryo Efficiency	ACW/W	800	800
	Total Cryo Capacity	**kW**	**14.8**	**6.1**
	Total AC RF Power (Perfect ER)	MW	7.4	3.9
	Total AC RF Power (Imperfect ER)	MW	10.46	4.57
	Total AC Cryo Power	MW	17.7	7.29
	Total AC Power (Perfect ER)	**MW**	**25.1**	**11.19**
	Total AC Power (Imperfect ER)	**MW**	**28.16**	**11.86**

設定加速勾配
Q0の目標値
Static loss per cavity
　→2K Heの冷凍機負荷が変わる。
Microphonicsの値
Returnのphaseのずれ
　→ 入力パワーが変わる。
冷凍機効率
　→Total の冷凍機負荷

どうも2*10^10くらいQ0が
欲しいという設計にしたいようだ。
実際は難しいであろう。

SRF Facility Survey (foster new ERL collaborations)

Institute	Gun Test	BCP	EP	HPR	VTF	HTF	Assembly	Module Test
ANL		YES	YES	YES	YES		YES	
BNL								
CORNELL	YES	YES	YES	YES	YES		YES	
Daresbury		YES		YES	YES		YES	
FNAL		YES		YES	YES	YES	YES	
FZD	YES						YES	
HZB						YES		
JLAB	YES	YES	YES	YES	YES	YES	YES	YES
KEK		YES	YES	YES	YES		YES	YES
PKU								
Others								

To be completed offline!

WG3 Collaborative Publications

- ERL SRF System Specifications:
  - Cornell, ANL, KEK, BNL – Coordinator A Nassiri (ANL)
- HOM Absorber Material Evaluation:
  - Cornell, KEK, BNL, Jlab – Coordinator M Liepe (Cornell)
- CM Microphonics Characterisation:
  - Cornell, BNL, FNAL, HZB, JLab, Daresbury – Coordinator O Kugeler (HZB)
- ERL RF Control Optimisation:
  - JLab, Cornell, KEK, BNL – Coordinator T Powers (JLab)

Achievement of WG Goals?

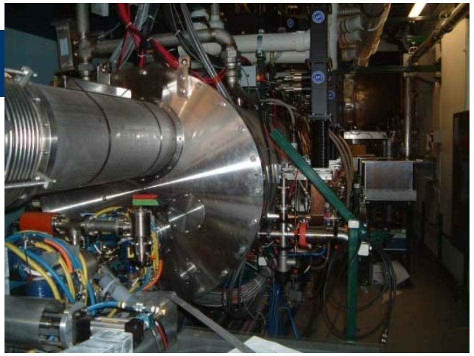
1. What are the key SRF challenges for ERLs?
   - Understand Qo degradation being observed
   - Cavity fabrication tolerance impact on HOMs highlighted, requires more realistic simulations to be performed using real boundary conditions
   - Need to understand ferrite magnetisation issues
   - Assess improved ferrite HOM absorber fabrication
   - Perform isolated HOM absorber characterisation, to determine performance variability
2. What solutions are being investigated and have already been developed?
   - Improved HOM damping materials identified and are being investigated
   - L-band 50 kW CW coax coupler demonstrated
   - $<0.01^{o}$ and $<2 \times 10^{-5}$ LLRF stability achieved
3. Which components still need more R&D work?
   - Minimisation of microphonics, drives RF power demand for an ERL
   - HOM absorbers, reduce cost, improve fabrication processes
   - Input couplers (coax and wg, cold/warm windows), simplify, reduce cost
   - Tuner (warm and cold) motors
4. Organise R&D effort, to coordinate studies and identify possible collaborations.
   - Collaborative WG publications are a start, to hopefully stronger collaborations

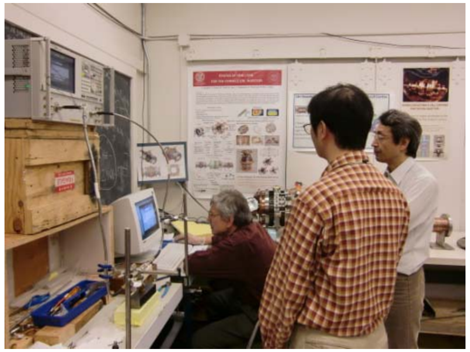
ここからは私の感想

- ERLに関して、超伝導空洞で２年前より、進歩している部分があったのが、KEK以外ではコーネル大、あとBNLくらいか？？ダラスベリーはERLの運転は実現まで持っていったが、自分たちで空洞の製作などを行っていないため、空洞の性能評価を行えれたかどうかは疑問？（辛口に言うと、まったく評価ができていない。）JLABは1A級の空洞の縦測定でわりといい結果を出しており、これからが期待。但し、wave guideを使った方式なので、入熱は度外視。
- Input Coupler, HOM damperなどのコンポーネントについては特にreviewのみで終わっている感があり、どこの部分がＲ＆Ｄ進んでいるなどの成長はあまり見受けられなかった。(Cornellだけが頑張っている印象。)
- 議論の時間を多く設けてくれていたようだが、convenerが超伝導空洞のことをそこまで理解しているわけでもなく、大した議論ができなかった。(もう少しいうと空洞製作側からの議論はない。)むしろ、発表を多く（ポスターなどにして発表できるようにする）して、参加者を増やして、いろいろ細かいdiscussionを個別で議論できる場が欲しかった。

ERL09言った収穫？？（主に超伝導空洞関係）

- コーネル大にてinjector部分を見て色々見学したが、特に縦測定の場合と違い、横測定や運転に際して、Q0が半分くらいであり、非常に入熱やfieldが出ないことが非常に問題であるという認識を得た。 向こうのS Belomestnykhや、E Chojnackiと話した時に先ほどのべたフランジの効果以外にoperation中にもQ0が下がることがあるとの話があり、それはGunや間のbuncherなどからガスなどが出ていて両端の空洞のQ0が下がっているのではないかとの見解があった。
- そのうえでコーネル大にてcryomoduleについて議論。特にalignmentの方法、組み立て方法を議論また入熱対策をもう一度見直し我々のmain linacの cryomoduleの原案を見てもらい、いろいろ議論した。
- こちらで作成したHOM damperの材料(TT2-111, IB004 with HIP)をいくつか持っていき、向こうの測定システムで吸収特性を見てもらい、我々の測定と同じかどうかをcheck。今後さらに材料を送り、40Ghzまでの吸収測定と時間があれば低温試験も行ってもらえることになった。

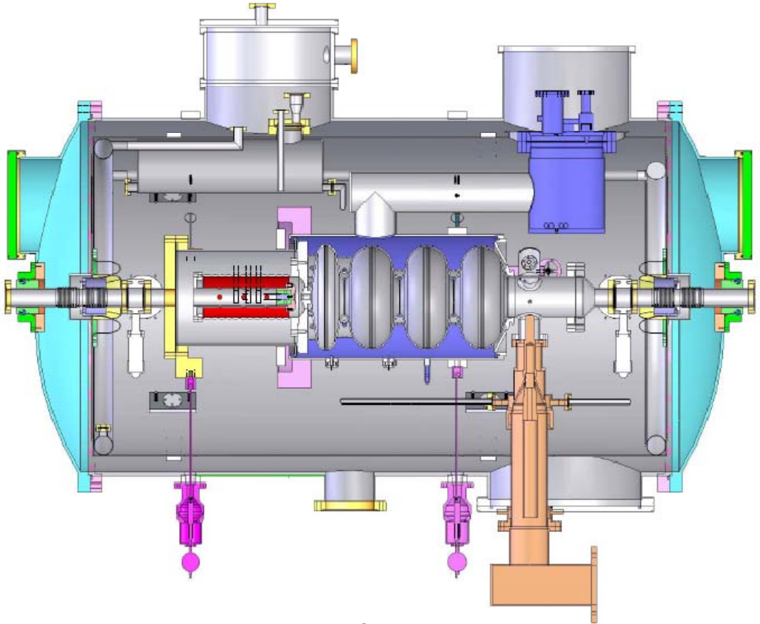




THANK YOU

Looking forward to ERL11

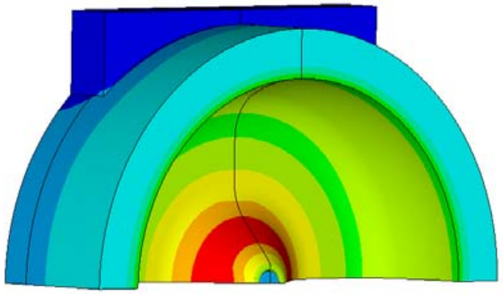
Peking SRF Gun Development, K Liu



- An upgrade DC-SC Photocathode injector has been developed at Peking university.
- The designed acceleration gradient is 13MV/m and energy gain is 5MeV.
- The first vertical test of large grain Nb 3.5 cell cavity is 7MV/m limited by field emission in the half cell. Further processing (Bake and BCP).
- Most parts of the cryostat has been completed and will be assembled soon.
- Commissioning of upgrade 3.5cell DC-SC photo-injector is expected in 2010.

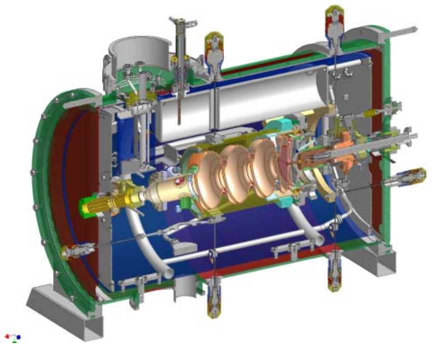
NC CW RF Gun, H Bluem

- CW 1.5 GHz NCRF gun developed (tested at JLab).
- All copper structure for simplified fabrication.
- Potential for simplified cooling channel structure.
- Capable of high cathode gradient (23 MV/m at 37 MV/m peak surface gradient) CW RF.
- Good RF efficiency with only 40 kW of power required for cavity wall losses.
- Calculated stress at 23 MV/m cathode gradient is within acceptable limits.
- Very small frequency shifts in simulations.
- 1 micron emittance at 1 nC electron bunch charge with suitable downstream booster accelerator system.
- Further optimization of RF design might be possible.
- On-axis coupling minimizes specialized outer wall disturbances that lead to high local heat loads and readily provides high coupling factors for high beam loading

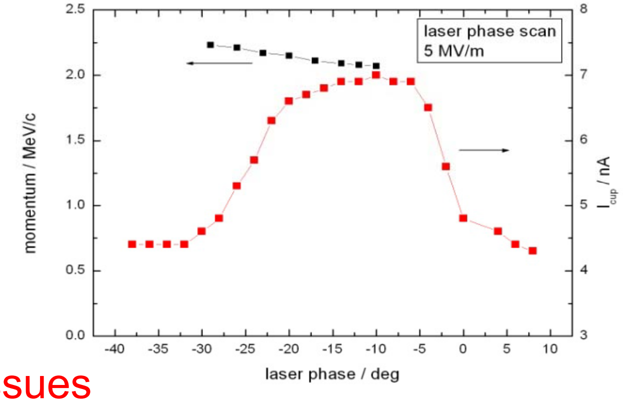


Parameter	**Value**	**Units**
Charge	1.00	nC
Beam Radius	2	mm rms
ε_{nx}	1	microns rms
Bunch length	2	mm rms
ε_{nz}	15	keV ps
Energy	6	MeV

FZD SRF Gun Development and Testing, J Teichert



- First Run of SRF Gun in 2008
- 2 MeV, about 100 h with Cu cathode, 400 h with Cs2Te
- Iav = 1 µA, total 5 C (diagnostic mode & radiation safety permission)
- basic principle (NC photo cathode) works well, no cavity degradation found
- Current Second Run in 2009
  - Cs2Te photo cathode with 1 % QE, up to now ca. 50 h lifetime
  - 2.2 MeV -> 3 MeV
  - Imax= 16 µA -> 100 µA (400 pC @ 250 kHz)



- Problems during commissioning
  - Cavity cleaning and low gradient – fabrication issues
  - wrong cavity π-mode frequency at 2 K (has been corrected now)
  - insufficient vacuum in cathode transfer system (under improvement)
  - multipacting in the gap between cathode and half-cell, DC voltage essential
  - depends on the cathode (surface quality of the Cu stem?)

Overall SRF System Optimization for ERLs

Matthias Liepe

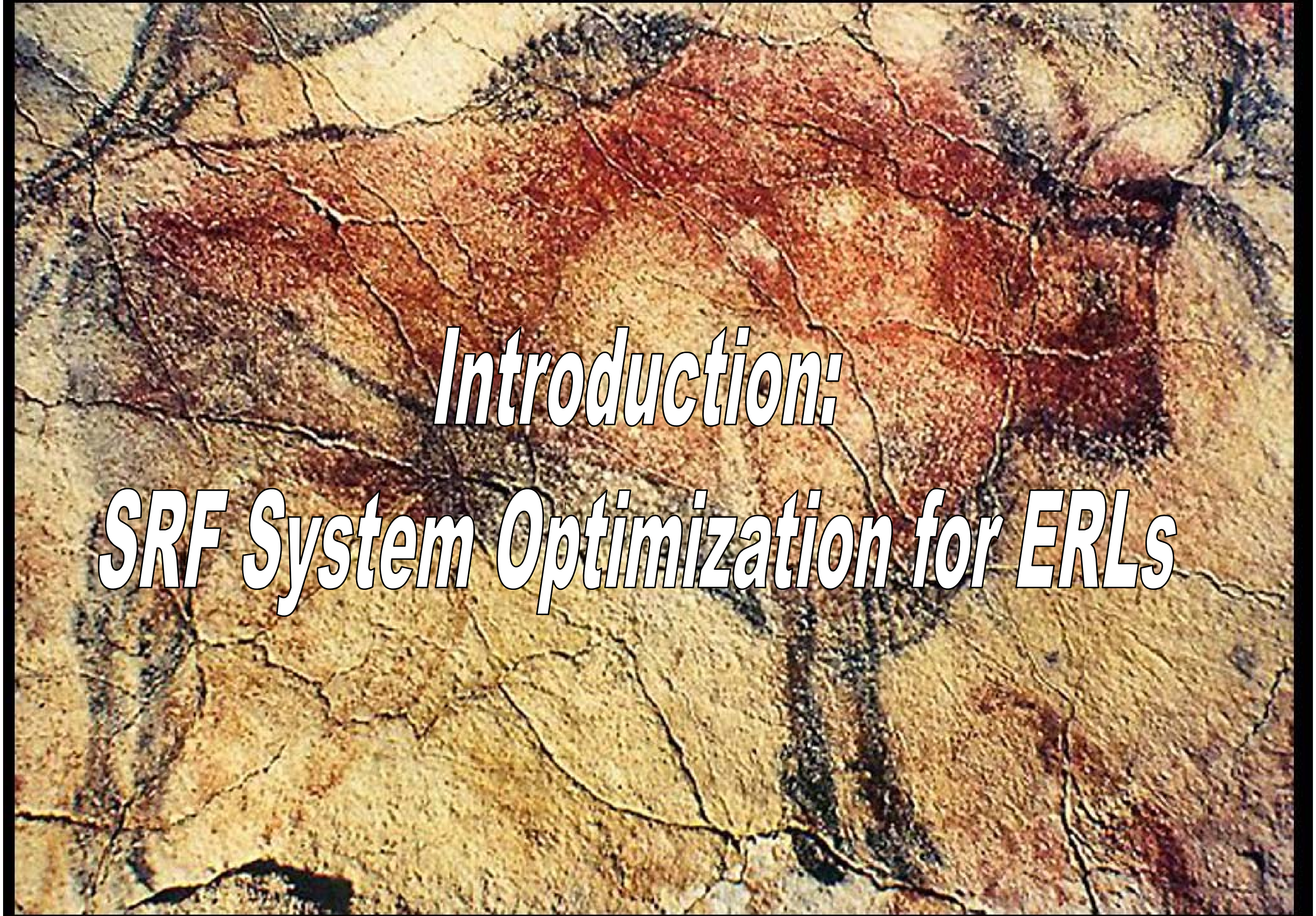
Cornell University

ERL'09

Promise for a brighter future.

Outline

- Introduction: SRF System Optimization for ERLs
  - *What we want*
- Optimization: *What we can get*
  - Operating temperature and RF frequency
  - Operating field gradient, Q_0, reliability, and cost
  - Loaded Q, RF power, microphonics
  - Cavity design and HOM damping and BBU
- Outlook: *What we might hope for*



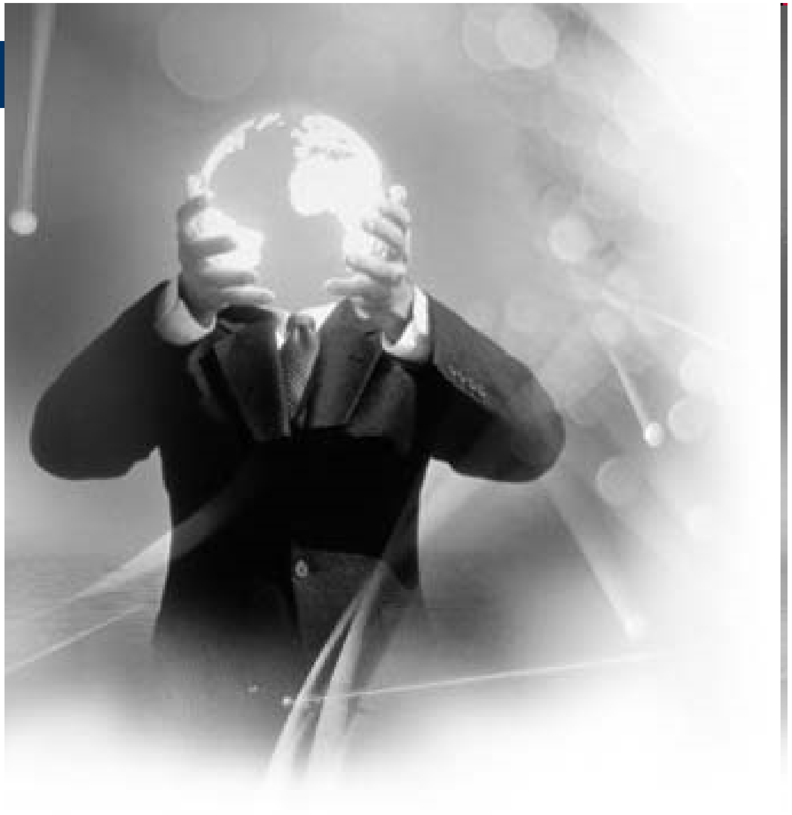
Introduction:
SRF System Optimization for ERLs

What we want

A miracle:

- [illegible]
- Great performance (at least meet specs)
- Perfect availability / reliability

… easy to simultaneously get 2 out of these 3…



Matthias Liepe, ERL 2009
Cornell University, Ithaca New York

Optimization (I)

Objectives:

- Minimize cost
- Meet specs
- Maximize availability

Constrains:

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

ERL'09 Promise for a brighter future.

Optimization (II)

- Important to be realistic, but not [illegible]
  - Remember: You may want to built your ERL in a few years from now…

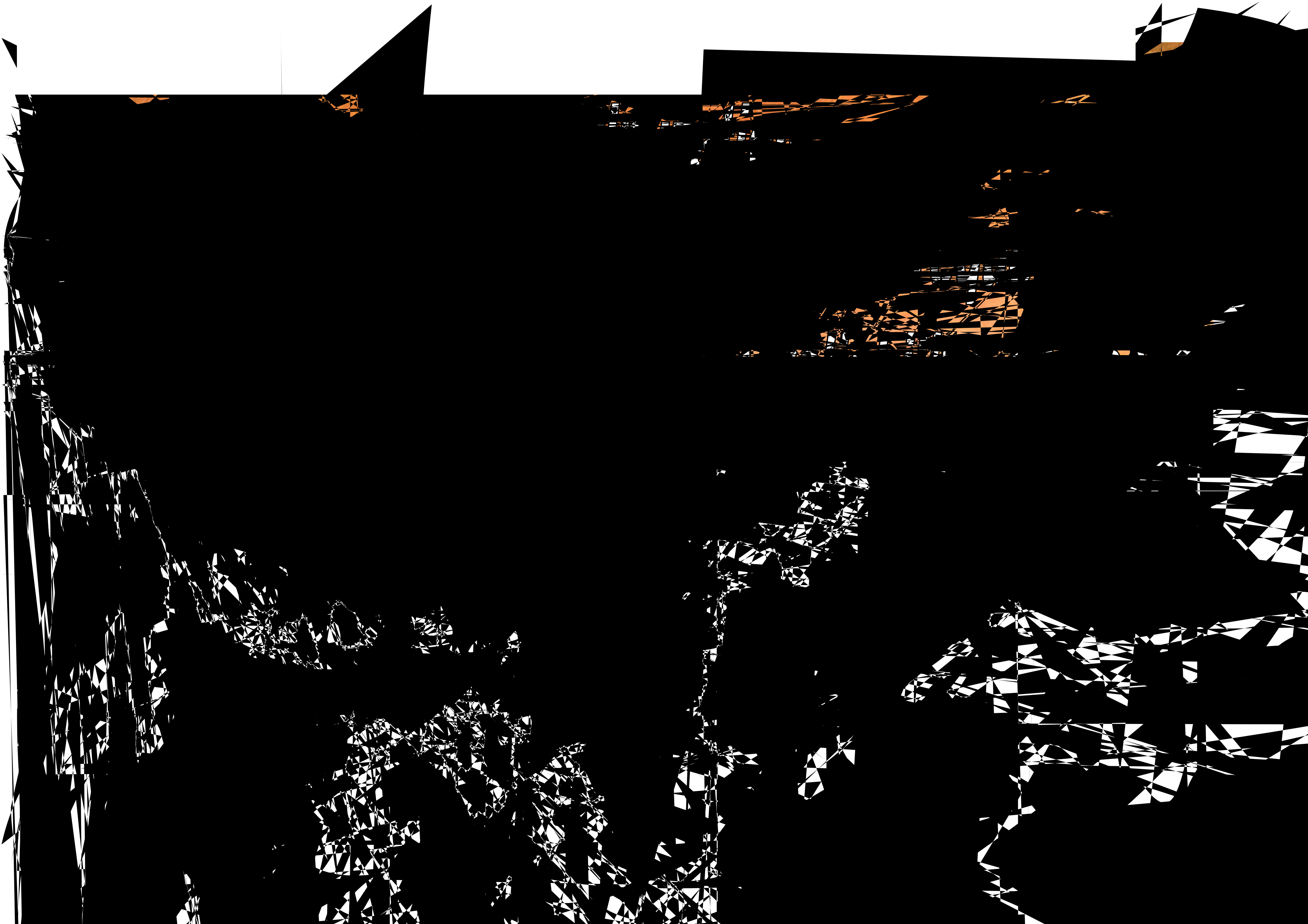
- Identify high risk / impact parameters
  - Cavity intrinsic Q_0 ($$$)
  - Microphonics level / peak cavity detuning ($$$)
  - …

Matthias Liepe, ERL 2009

Cornell University, Ithaca New York

Optimization (III)

- More truths:
  - [redacted]s are/can be specified
  - In the following, I'm not trying to optimize ERLs for all proposals out there…
    - Focus on Cornell ERL as example
    - But: most conclusions also valid for other ERLs
  - Not all of you will agree with all of my conclusions
    - "Optimization" influenced by my biases, background…



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	2e-4	1.25e-4	Similar, but much higher

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

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

Optimization discussed in the following is done for the beam parameters listed above.

Operating temperature and RF frequency

Dynamic Cavity Losses (I)

- SRF resistance small but finite because Cooper pairs have inertia.

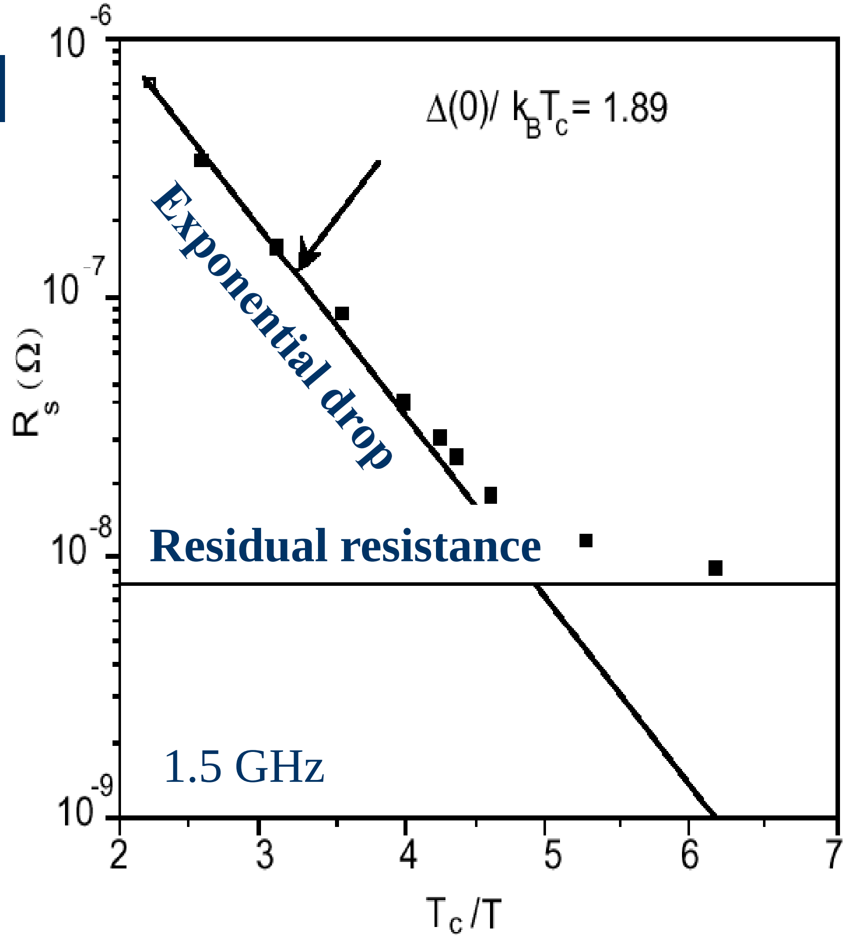
- BCS theory: Frequency and temperature dependence of surface resistance at low RF fields (T_c: S.c. transition temperature)

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

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 (II)

- 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

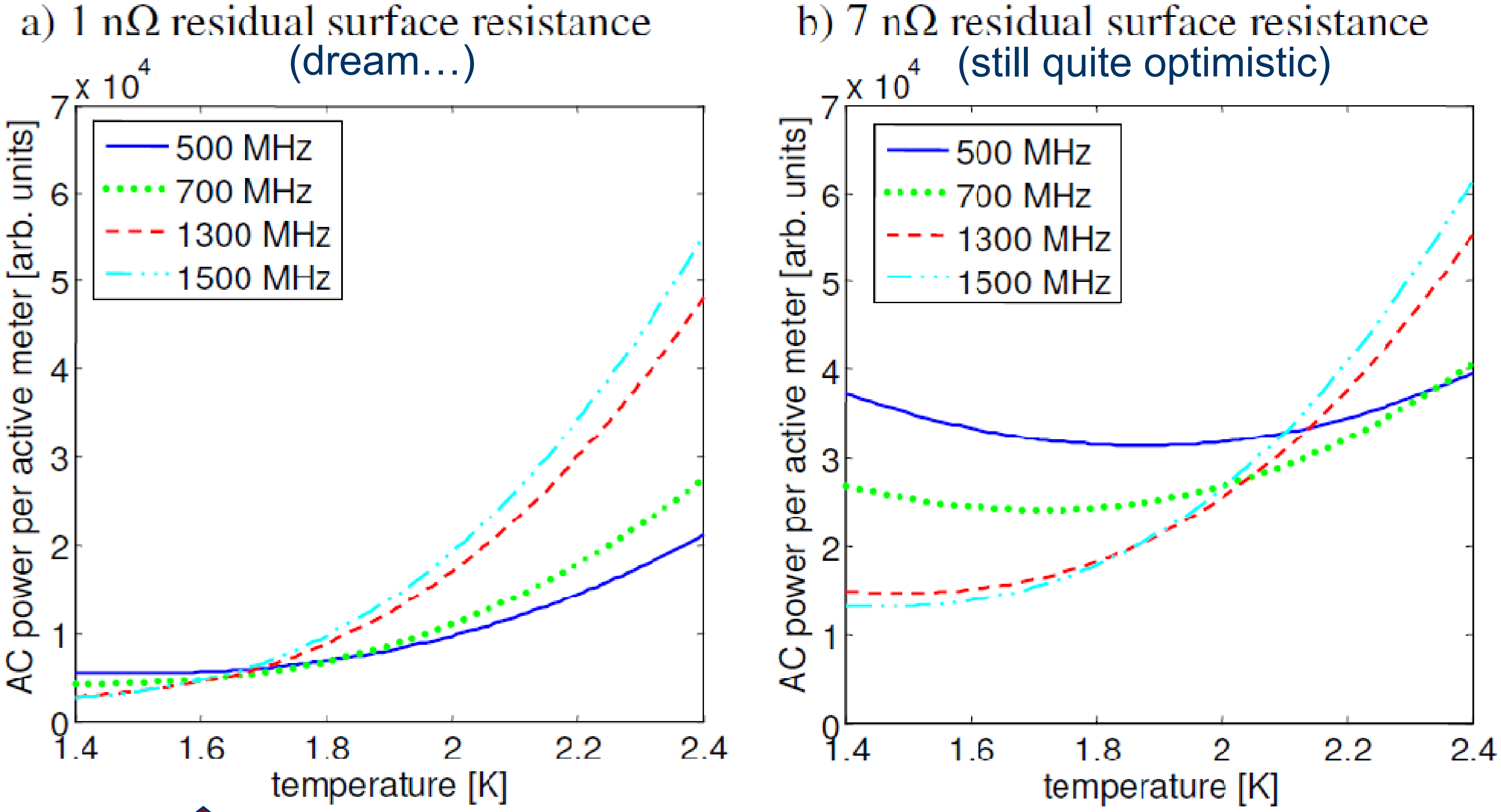
$\Rightarrow$ operate cavity at temperature such that R_{BCS} < residual resistance R_{res}

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

$\Rightarrow$ For given accelerating field gradient $\mathrm{E_{acc}}$:

$\mathbf{P_{diss}}$ / cavity length $\propto$ 1/f

Cooling Power for Dynamic Cavity Losses (f,T) for


a) 1 nΩ residual surface resistance

(dream…)

b) 7 nΩ residual surface resistance

(still quite optimistic)

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

Choice of Operating Temperature: The lower the better?

- Lowering the temperature seems to be effective [redacted] 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

Choice of Frequency (I)

- **Unless extremely small residual surface [illegible] 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, …**

Choice of Frequency (II)

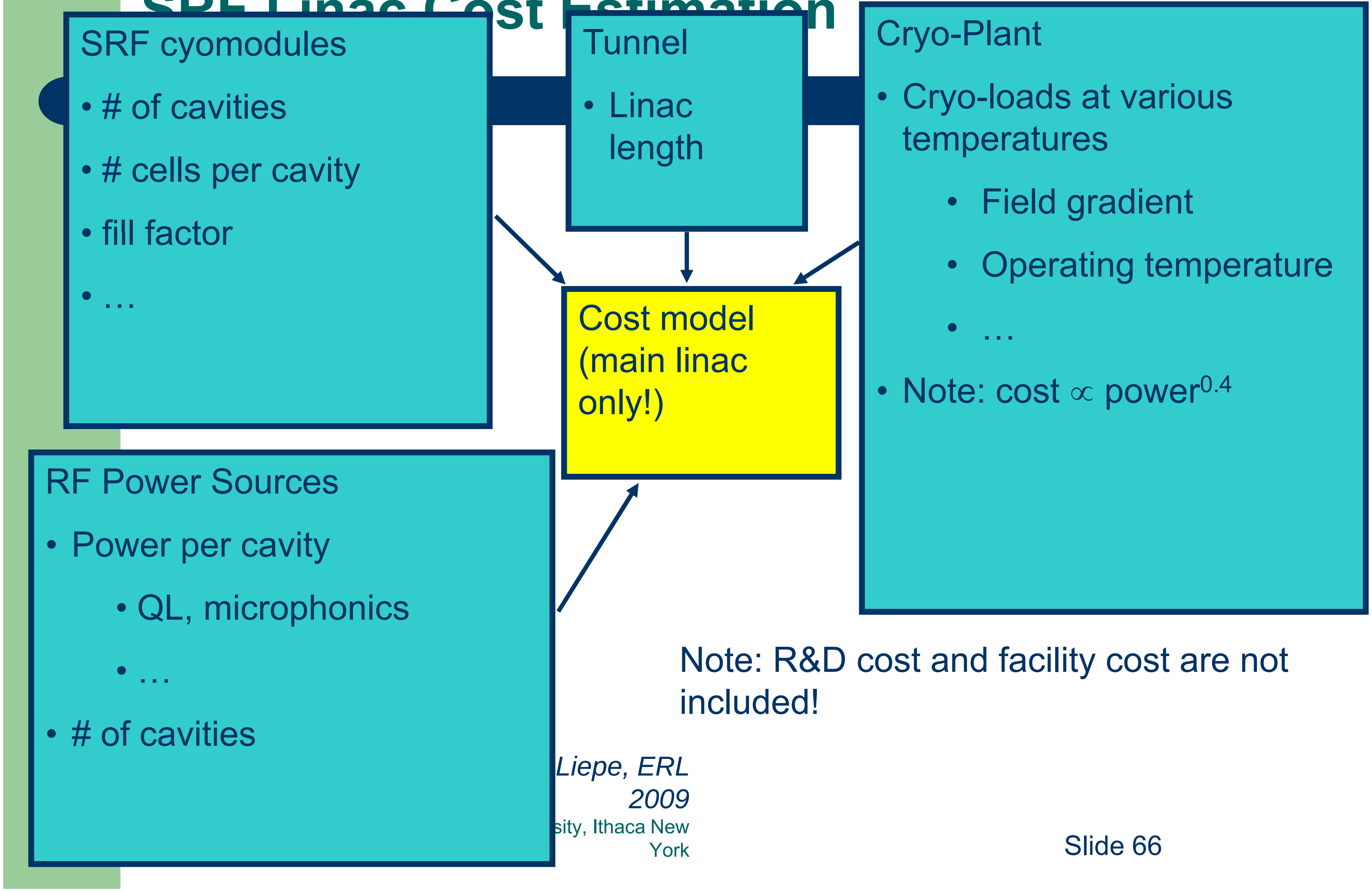
- **Why chose <1 GHz anyway in highest current [redacted]**
  - **BBU threshold current ∝ 1/f (assuming same number of cells per cavity, same quality factor Q of HOMs)**
  - **Average HOM losses ∝ f^2**
  - **But: Construction cost increases with lower frequency!**
  - **But: Operational cost increases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

Conclusion 1

- For 5 GeV, 100 mA ERL:
  - [redacted]
- Lower frequency only potentially beneficial if highest BBU threshold is required
  - Can increase BBU threshold by factor of ~ 2 (for same number of cells per cavity)
  - Note: Other things can have similar / larger impact on the BBU threshold current <
  - More later…

Operating field gradient, Q_0 , reliability, and cost

SRF Linac Cost Estimation



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

Tunnel
- Linac length

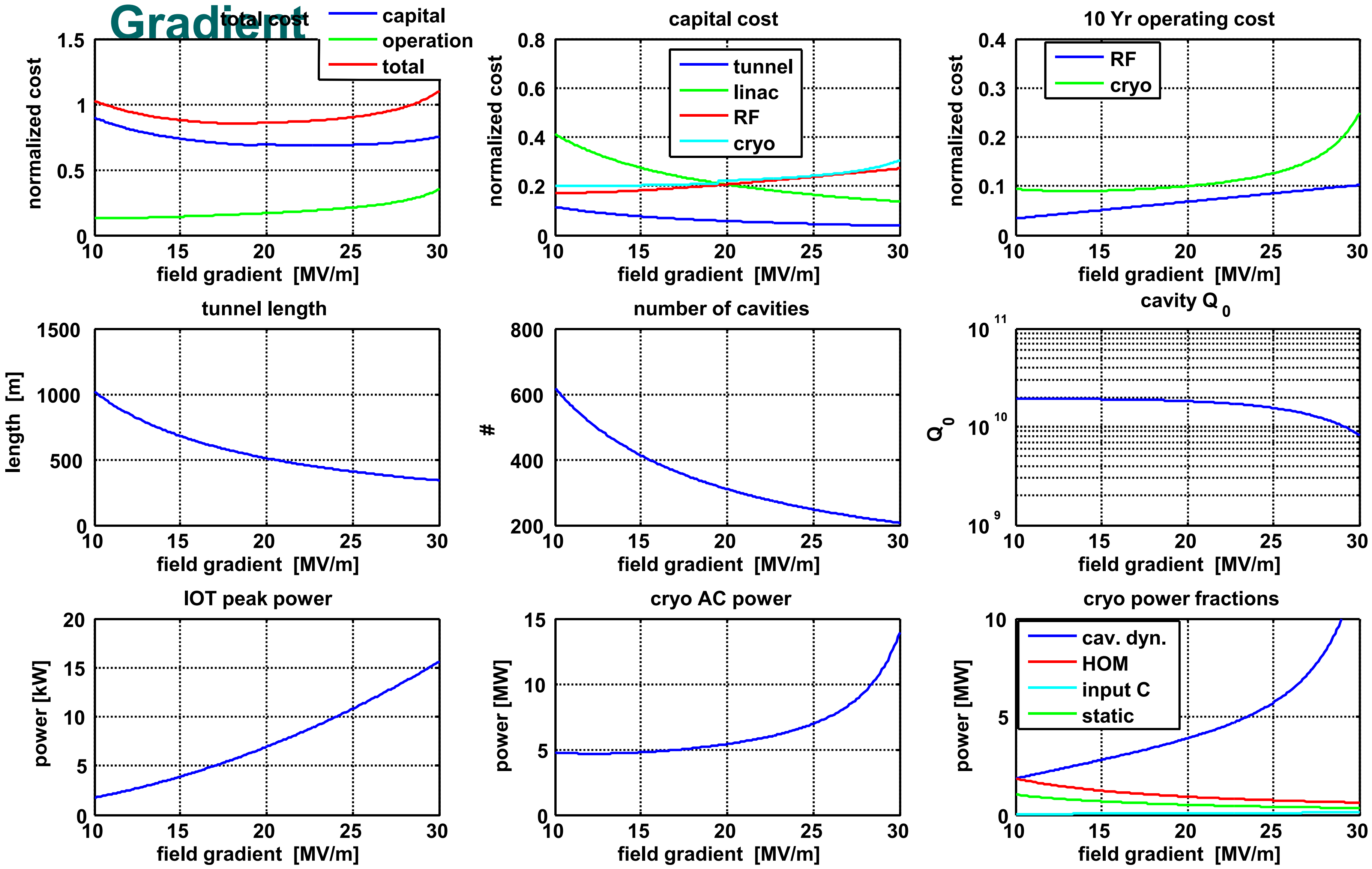
Cryo-Plant
- Cryo-loads at various temperatures
  - Field gradient
  - Operating temperature
  - …
- Note: cost ∝ power$^{0.4}$

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

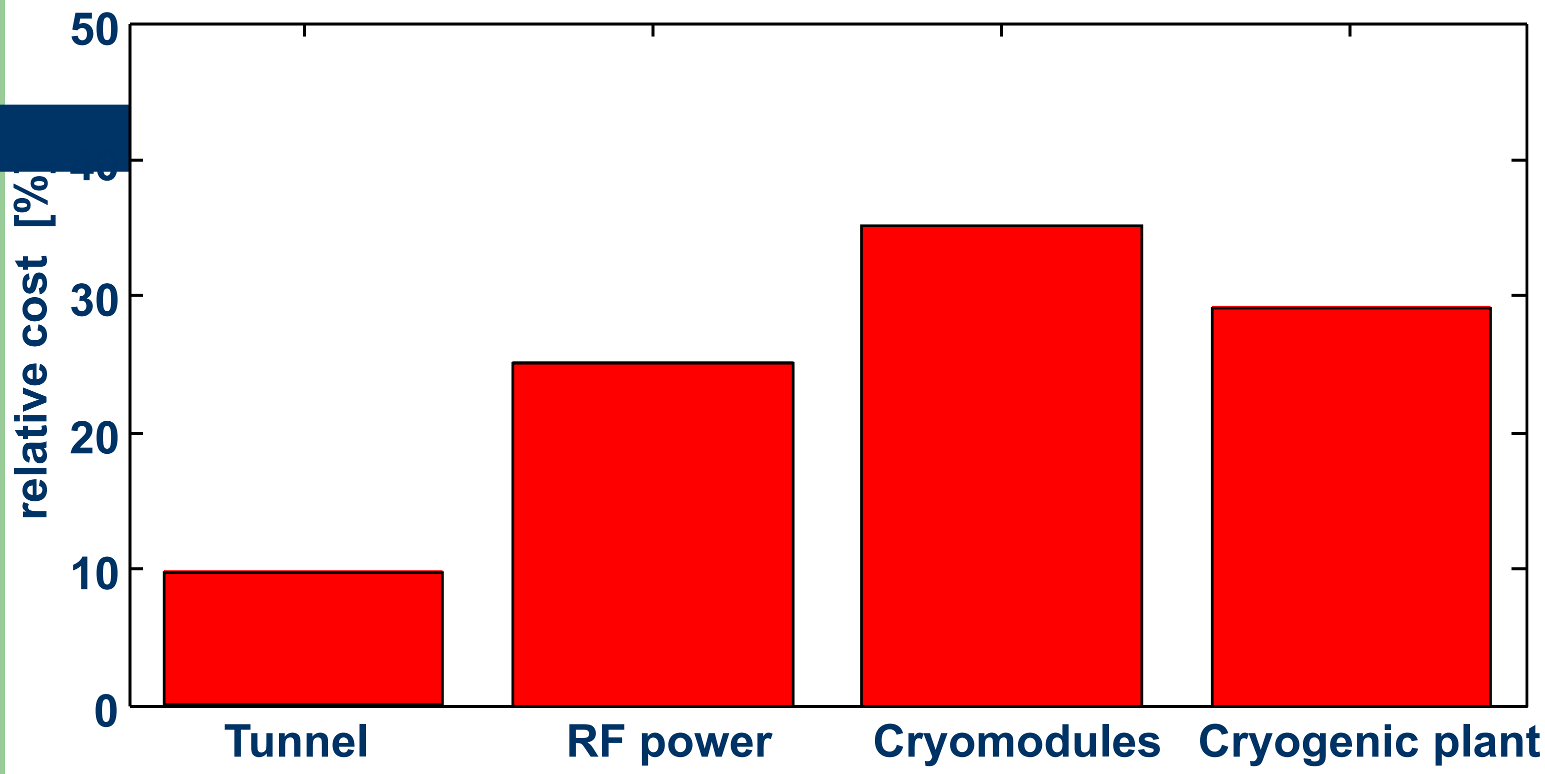
Cost model (main linac only!)

Note: R&D cost and facility cost are not included!

Example: Dependence on Accelerating Field Gradient

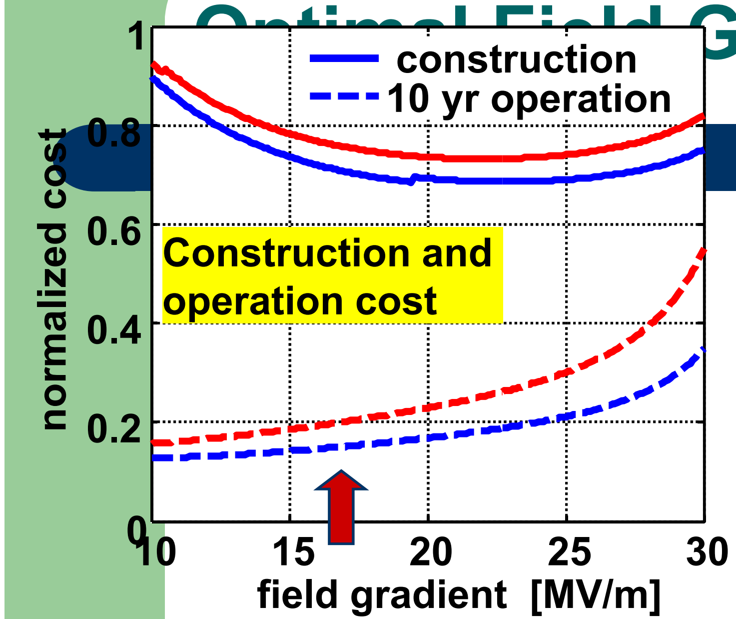


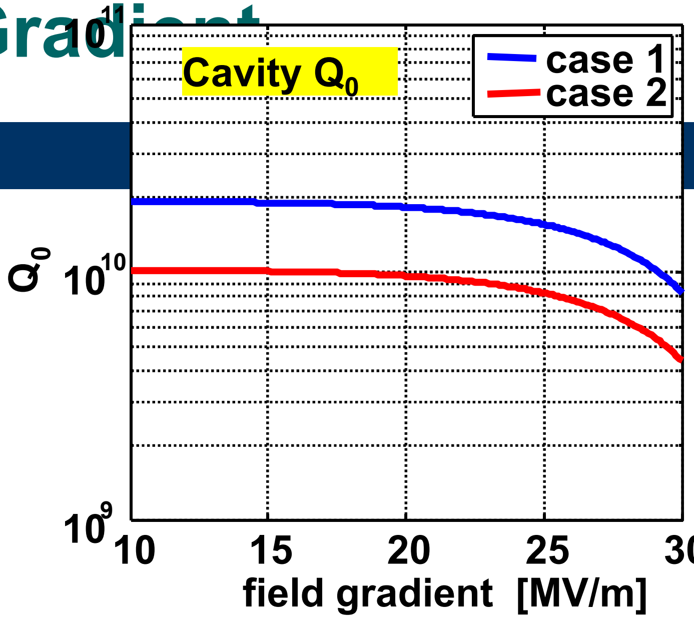
Main Linac Cost Distribution for E_{acc}=16.2 MV/m

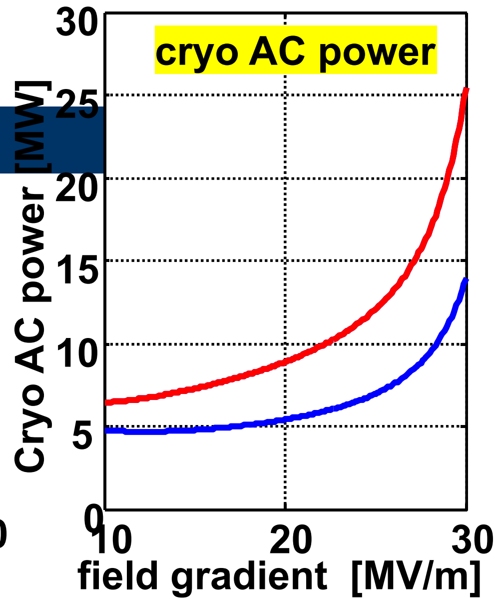


- **Costs for cryomodules, cryogenic plant, and the RF power sources are similar.**

Optimal Field Gradient





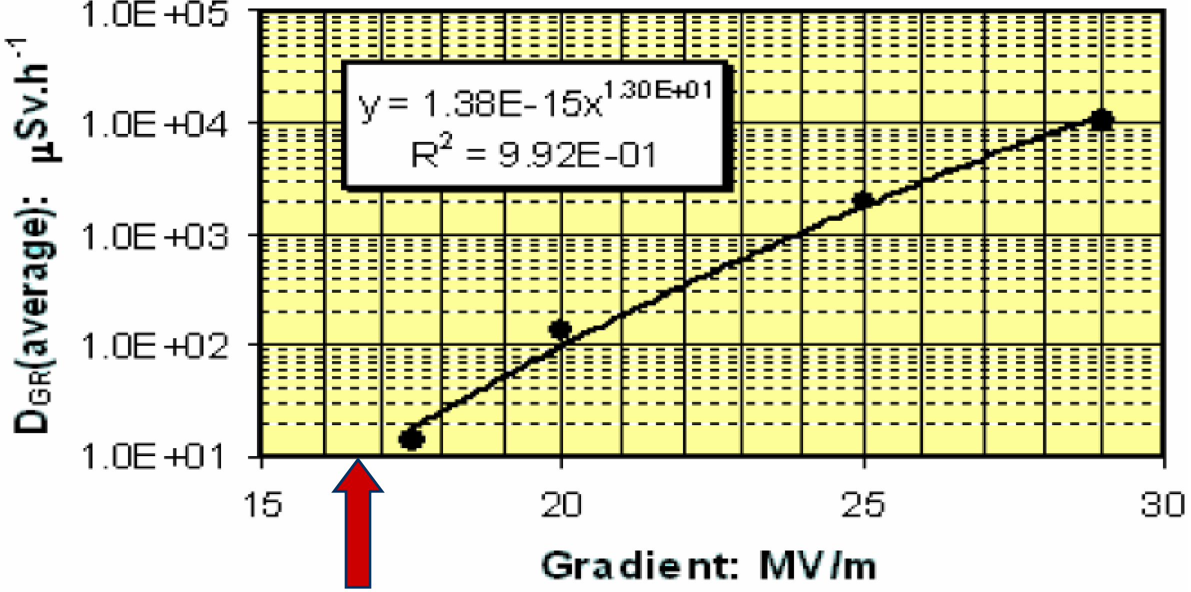


- Q_0-value has significant impact on cost (high impact and risk parameter)
- Construction cost changes only moderately for gradients between ~16 and ~27 MV/m
- Operating cost / AC power increases with gradient
- Select gradient at lower end: ***16.2 MV/m***

⇒ Less risk for same cost!

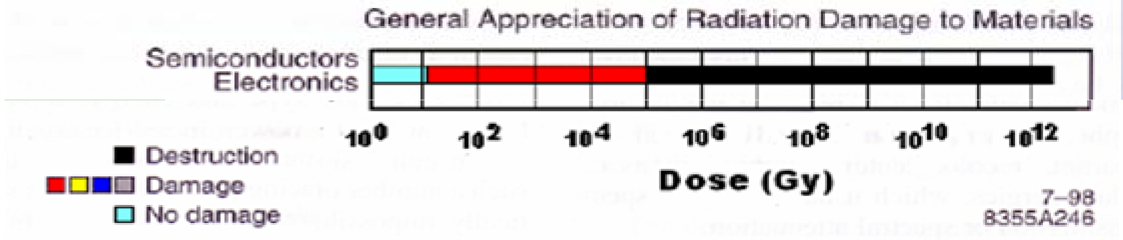
Field Emission

Gamma radiation measured at DESY/FLASH from cavity field emission



- **Exponential** growth in FE with gradient
- [redacted] 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 2A

- 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

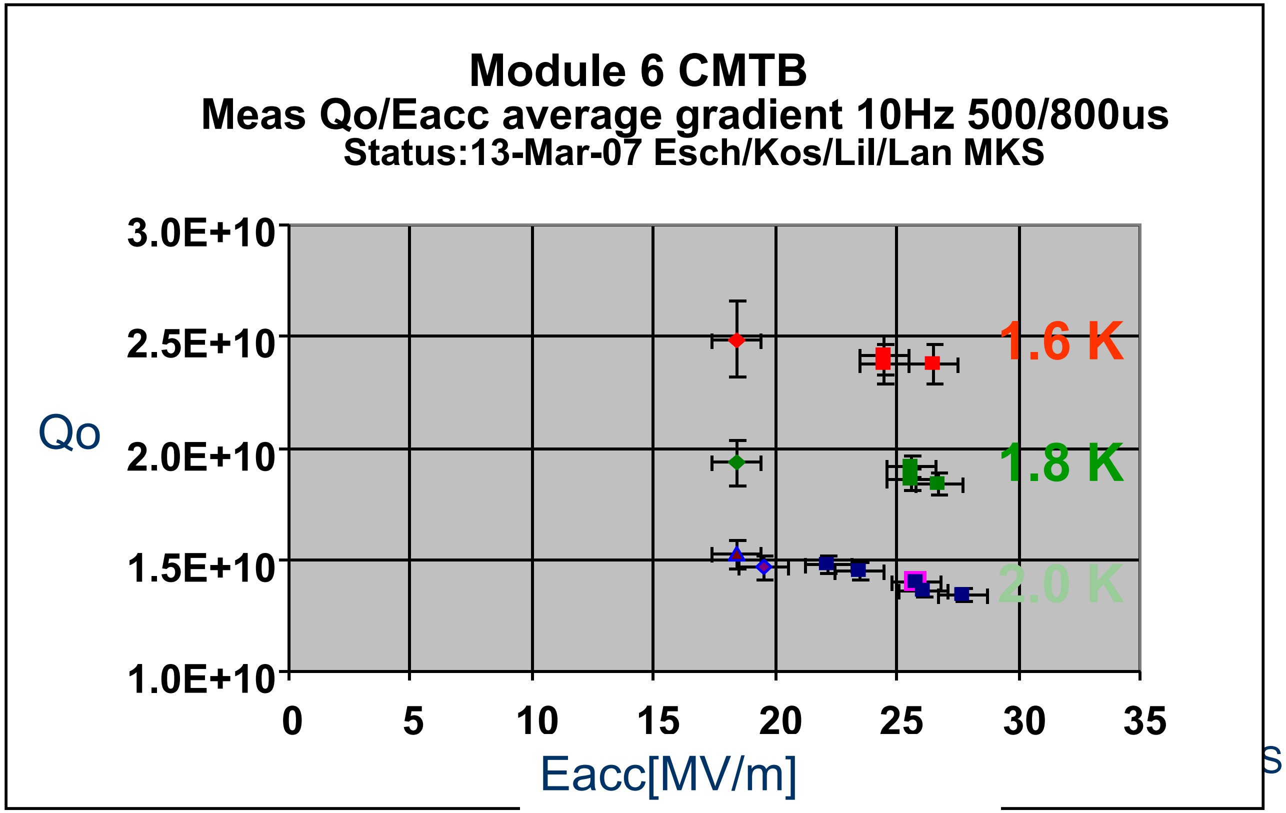
Note: Cavity designs with high surface electric peak fields might require operating at even lower fields!

⇒ Increased reliability

⇒ Simplified cavity preparation (compared to ILC)

Conclusion 2B

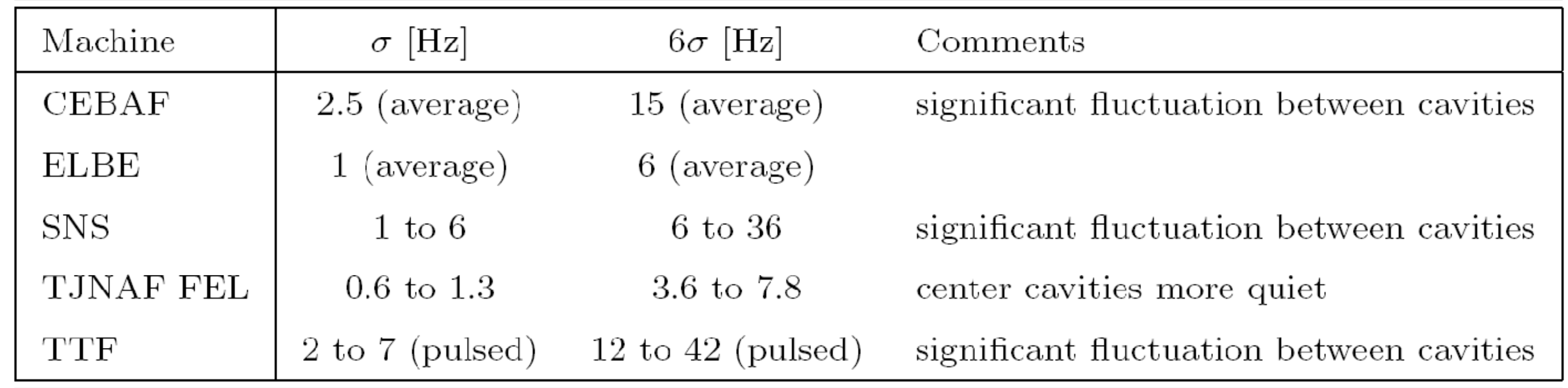
- Cavity quality factor at operating gradient has high impact on cost!
  - Q_0 of **$2 \cdot 10^{10}$ at 1.8 K** is realistic for the near future
    - Best performing TTF/FLASH module:



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

Loaded Q, RF power, and microphonics

[redacted]



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

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

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

Conclusion 3

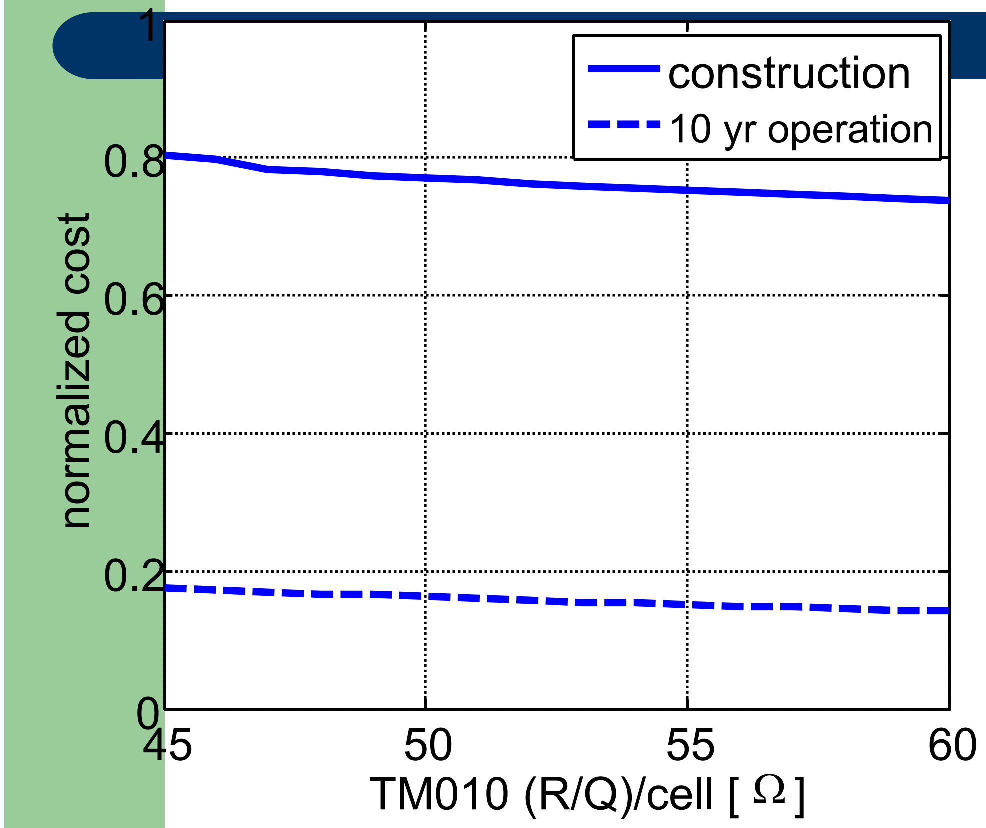
- Peak cavity detuning is a strong cost driver
  - Needs good mechanical cryomodule design
  - Need to address / quantify substantial differences in microphonics levels beween individual cavities!

  ⇒ **$Q_L = 6.5 \cdot 10^7$**

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

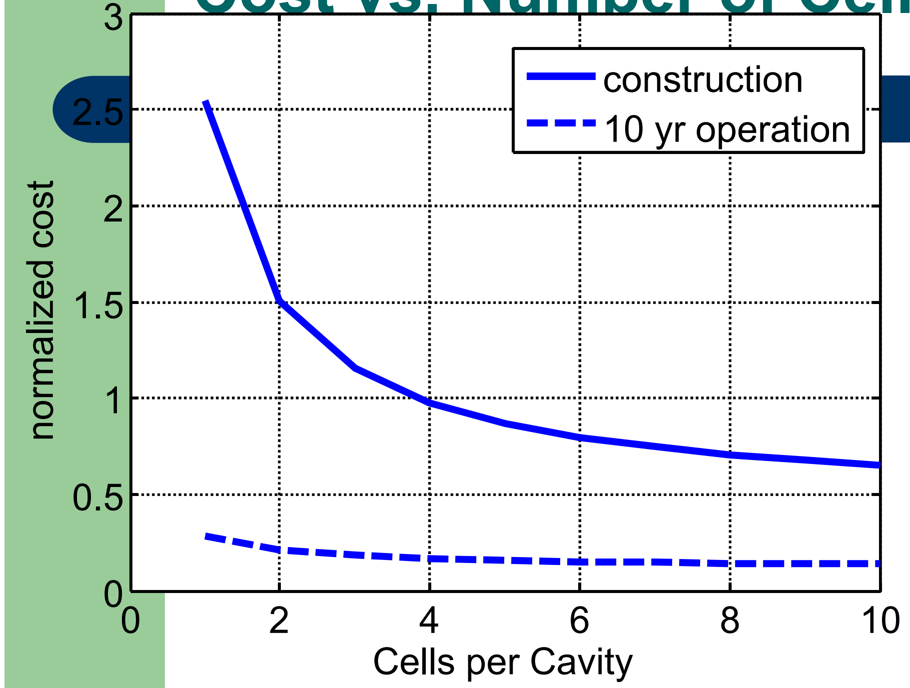
Cavity design and HOM damping and BBU

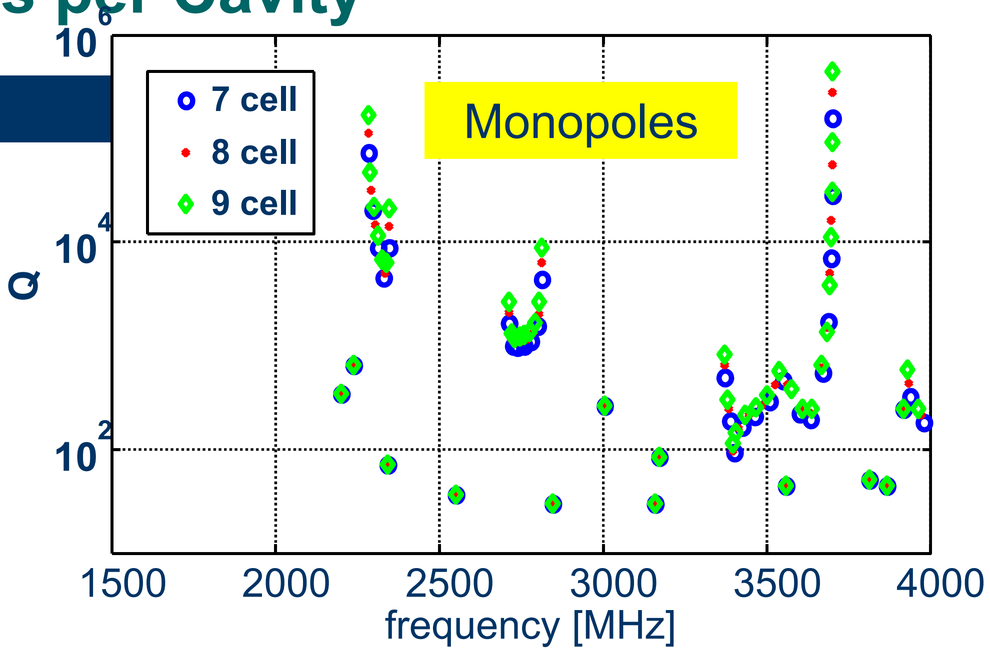
Cost vs. (R/Q) of Fundamental Mode (G=const)



- 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

Cost vs. Number of Cells per Cavity



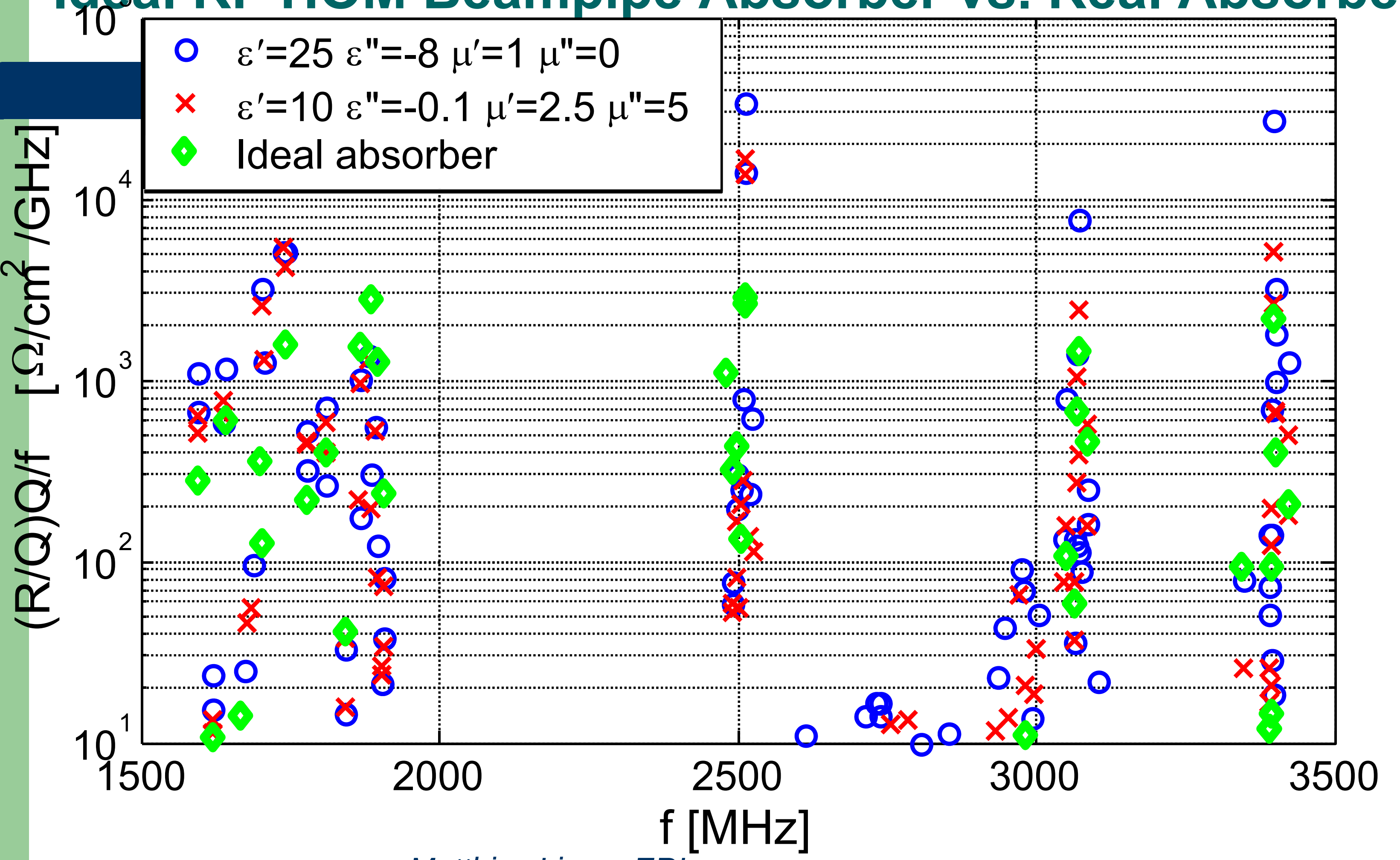


- >6 cells per cavity desirable, if OK with BBU limit
  - Q and R/Q of HOMs will increase with number of cells
  - Risk of trapped modes with very high Q increases as (number of cells)^2

ERL Cavity Design: Be realistic!

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

Ideal RF HOM Beampipe Absorber vs. Real Absorber

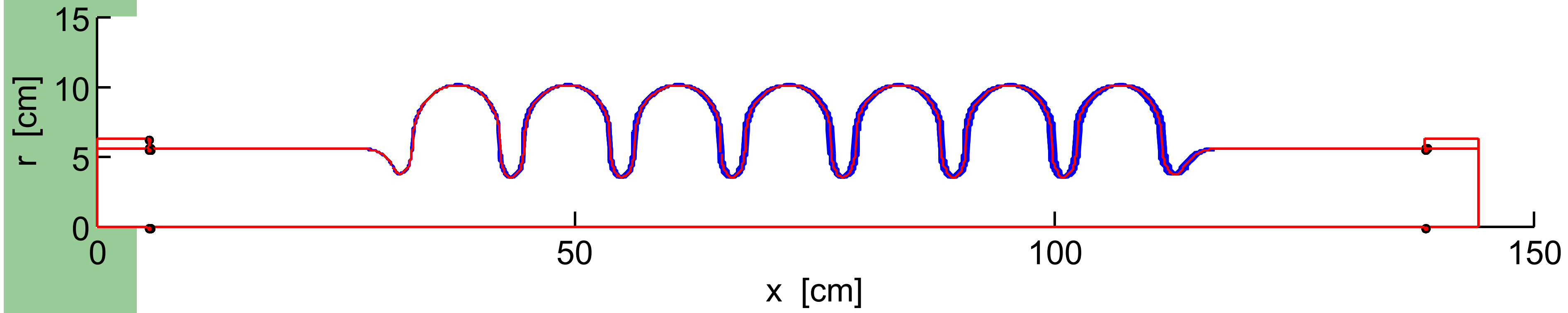


Effect of Small Cavity Deformations

- 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)

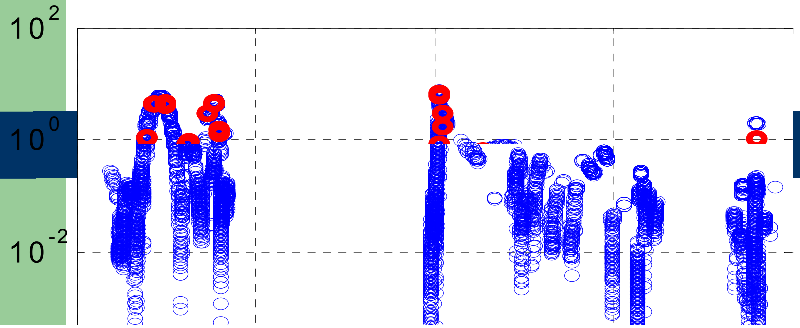
7-cell Cavities with Small Shape Deformations

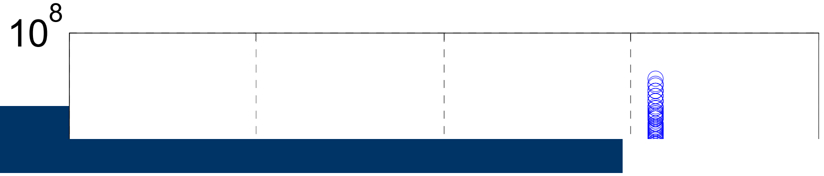
- Started by assuming +-1/16 mm **random**



- 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**

Example: Cavities with +-1/16 mm Deformations





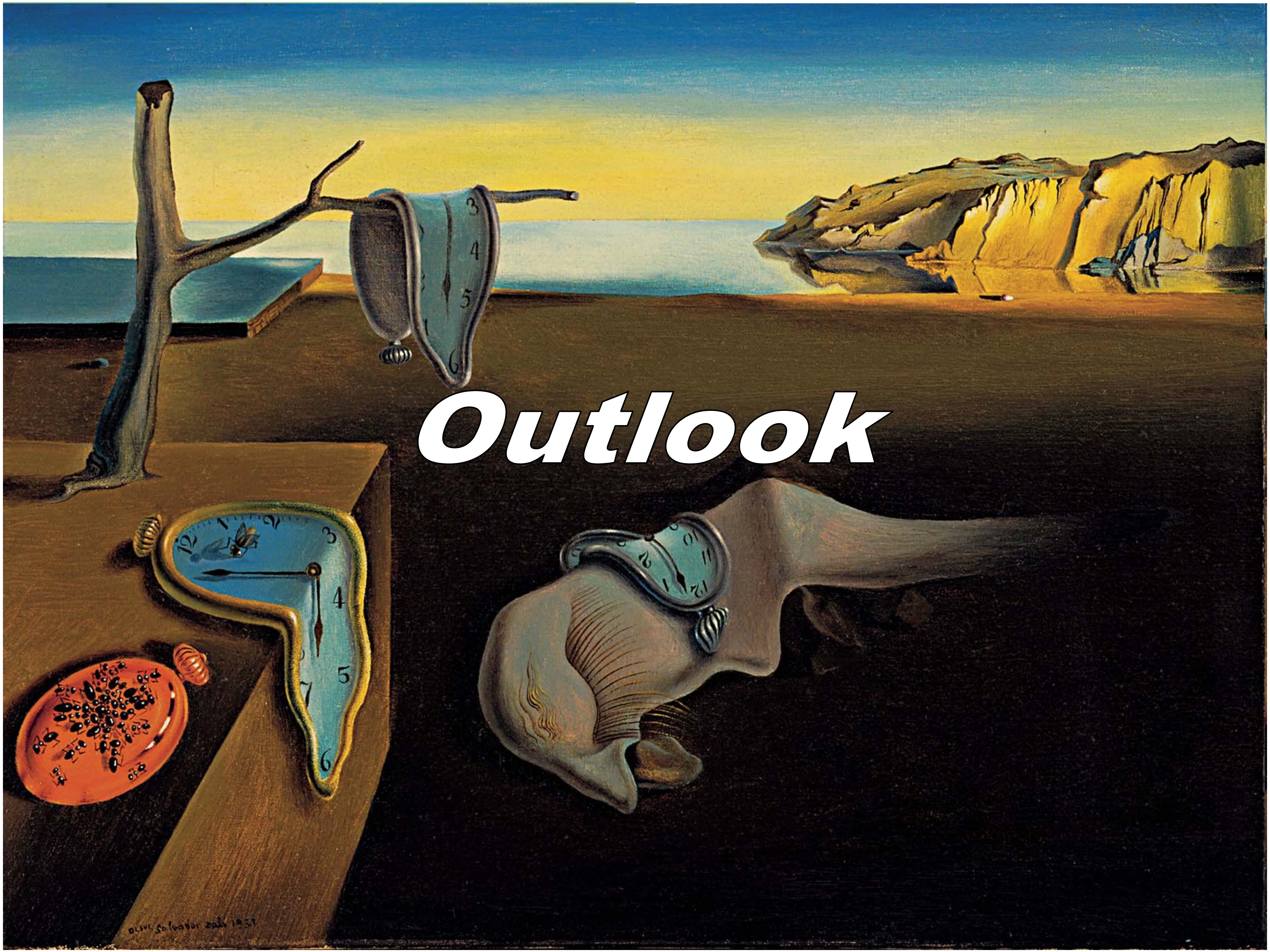
Conclusion 4

- Cost favors > 6 cells per cavity, if

  [illegible]

  - 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**

Outlook



Outlook

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

None of these will happen tomorrow, though…

The End